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Michael F. Goodchild
Alessandro Annoni *Editors*

Manual of Digital Earth

International Society for Digital Earth

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ISDE
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Preface

In October 2015, the 10th Executive Committee Meeting of the International Society for Digital Earth (ISDE) was held in Halifax, Canada where I was elected as the third president of ISDE. I put forward a work plan for my tenure that included a proposal to publish a manual that would address questions regarding the relevance of Digital Earth, its future, and its potential to support scientific development and societal needs. The Executive Committee approved the proposal, and now, after 4 years and a culmination of efforts from numerous contributors, it is my great pleasure to present this manuscript, *Manual of Digital Earth*, for publication and release. The 1st International Symposium on Digital Earth was held in Beijing on November 1999, marking the humble beginnings of ISDE's Symposia 1 year after Mr. Al Gore famously put forward the concept of Digital Earth. Now, after two decades, it is a privilege for me to oversee preparations for the 11th International Symposium on Digital Earth in Florence, Italy, on September 2019.

Over the years, ISDE has successfully hosted 10 International Symposia on Digital Earth and 7 Digital Earth Summits in 11 countries. ISDE and its journals *International Journal of Digital Earth* and *Big Earth Data* launched in 2008 and 2017, have gained international recognition in academic circles. ISDE has become a participating member of the Group on Earth Observations and an affiliate member of the International Science Council since 2009 and 2017, respectively. This has been possible in large part due to its success in organizing intellectual events that appealed to the interests of researchers and scientists in the realm of Digital Earth. ISDE has also established a series of national committees and chapters that address Digital Earth issues. All of these recognitions and achievements have helped to provide the foundation for Digital Earth by developing numerous data platforms and research institutions, and by supporting academic meetings, papers, and monographs that have not only benefited our society but improved our understanding of the world and its Earth shaping processes. With great honor, I have the opportunity to personally experience all the milestone events of Digital Earth during the past two decades. As a witness, organizer and participant, I have been a part of Digital Earth and it has become a part of my life.

Presently, it is necessary for us to gain a profound understanding and make an in-depth analysis of the expanding scope of the concept of Digital Earth and the rapid advancements in Digital Earth technologies, as well as the impacts of Digital Earth on interdisciplinary science and social progress. As an evolving discipline, we need to answer the following questions: (1) What is the basic theory of Digital Earth? (2) What are the key technologies? and (3) What are its main applications? In terms of its content, we need to understand: (1) What are its core characteristics; (2) What is the difference between Digital Earth and geospatial technology? and (3) How does Digital Earth—a frontier interdisciplinary field of Earth science, information science, and space science—promote disciplinary integration and data sharing? To answer these questions, a focused monograph is necessary and relevant.

The manual has been designed to be simple yet academic in nature and professional in design. The information in the manual is forward-looking and will prove to be instrumental in developing the future concepts for Digital Earth. It presents a systematic analysis of the theories, methods, and technical systems of Digital Earth. It also presents a summary of the key achievements to date and predicts the likely direction and probable future developments within the discipline. Broadly, the manual includes information on the following: (1) theories on Digital Earth, the contents of Digital Earth science, and Digital Earth frameworks and platforms; (2) Digital Earth system technologies, including data acquisition, management, processing, mining, visualization, virtual reality, network computing, spatial data facilities, and information service technologies; (3) applications in climate change, natural hazards, digital cities, digital heritage, and global sustainable development goals of the United Nations; (4) regional applications of Digital Earth, especially in regions and countries such as Europe, Australia, China, and Russia; and (5) Digital Earth Education and Ethics and the outlook for the future development of Digital Earth.

Science and technology are continually involved in the process of development and innovation. Digital Earth is becoming even more relevant as the world is undergoing a profound digital revolution. The three frameworks of the United Nations, including Sustainable Development Goals, Climate Change, and Disaster Risk Reduction, along with the rise in digital economies have created more of a need for Digital Earth. The increasing volume of data amassed through Earth system science and geo-information science are prompting experts to investigate and experiment with highly automated and intelligent systems in order to extract information from enormous datasets and to drive future innovative research that will greatly benefit from developments in Digital Earth technologies and systems. Frontier technologies such as Internet of Things, big data, artificial intelligence, blockchain, and 5G are creating opportunities for the next stage of Digital Earth. Digital Earth could help bridge the information gap for the general public by integrating data and information from multiple sources including those from space, social networks, and economic data. By developing intelligent models and data-intensive computing algorithms, Digital Earth can generate useful information and scientific knowledge supporting social service functions as well as drive scientific discoveries.

This manual has only been possible by the support from ISDE, and it is sponsored by programs in the Chinese Academy of Sciences (CAS), “Research on the Development Strategy of the New Generation of Digital Earth” and “Research on the Development Strategy of Digital Earth Discipline” provided support from the CAS Academic Divisions. The CAS Strategic Priority Research Program supported the manual through “Big Earth Data Science Engineering Project (CASEarth)”.

Over 100 authors and editors from 18 countries contributed to this manual, and I would like to thank them for their hard work. Special thanks go to my co-editors, Dr. Michael F. Goodchild, and Dr. Alessandro Annoni, who reviewed the manual’s numerous contributions, the ISDE Council Members for their support, and Dr. Changlin Wang for his tremendous effort. Particularly, I would like to thank Dr. Zhen Liu for the work she has done over the past 2 years organizing all aspects of this publication, which would have been impossible without her efforts. Taking this opportunity, I would also like to express my appreciation to everybody who has contributed to Digital Earth. I sincerely wish Digital Earth continued success and strongly support its vigorous development.

Beijing, China
June 2019

Huadong Guo
President, International Society for Digital Earth

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Huadong Guo is a Professor of the Chinese Academy of Sciences (CAS) Institute of Remote Sensing and Digital Earth (RADI), an Academician of CAS, a Foreign Member of Russian Academy of Sciences, a Foreign Member of Finnish Society of Sciences and Letters, and a Fellow of TWAS. He presently serves as President of the International Society for Digital Earth (ISDE), Member of UN 10-Member Group to support the Technology Facilitation Mechanism for SDGs, Director of the International Center on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO, Science Committee Member of the Integrated Research on Disaster Risk (IRDR) Program of ISC and UNDRR, Chair of the Digital Belt and Road Program (DBAR), Chairman of the International Committee on Remote Sensing of Environment, and Editor-in-Chief of the *International Journal of Digital Earth* and the journal of *Big Earth Data* published by Taylor & Francis. He served as President of ICSU Committee on Data for Science and Technology (CODATA, 2010–2014) and Secretary General of ISDE (2006–2014). He specializes in remote sensing, radar for Earth observation and Digital Earth science. He is the Principal Investigator of Moon-based Earth Observation Project of National Natural Science Foundation of China and the Chief Scientist of the Big Earth Data Science Engineering Project of CAS. He has published more than 400 papers and 17 books, and is the principal awardee of 16 domestic and international prizes.

Michael F. Goodchild is Emeritus Professor of Geography at the University of California, Santa Barbara. He is also Distinguished Chair Professor at the Hong Kong Polytechnic University and Research Professor at Arizona State University, and holds many other affiliate, adjunct, and honorary positions at universities around the world. Until his retirement in June 2012, he was Jack and Laura Dangermond Professor of Geography, and Director of UCSB's Center for Spatial Studies. He received his BA degree from Cambridge University in Physics in 1965 and his Ph.D. in geography from McMaster University in 1969, and has received five honorary doctorates. He was elected member of the National Academy of Sciences and Foreign Member of the Royal Society of Canada in 2002, member of the American Academy of Arts and Sciences in 2006, and Foreign Member of the Royal Society and Corresponding Fellow of the British Academy in 2010; and in 2007, he received the Prix Vautrin Lud. He was editor of *Geographical Analysis* between 1987 and 1990 and editor of the Methods, Models, and Geographic Information Sciences section of the *Annals of the Association of American Geographers* from 2000 to 2006. He serves on the editorial boards of 10 other journals and book series, and has published over 15 books and 500 articles. He was Chair of the National Research Council's Mapping Science Committee from 1997 to 1999, and of the Advisory Committee on Social, Behavioral, and Economic Sciences of the National Science Foundation from 2008 to 2010. His research interests center on geographic information science, spatial analysis, and uncertainty in geographic data.

Alessandro Annoni is working in European Commission's Joint Research Centre since 1997. He has been the Head of the Spatial Data Infrastructure and the Digital Earth Units working on Information Infrastructures, advancing research on multidisciplinary-interoperability and ensuring the Technical Coordination of the INSPIRE Directive 2007/2/EC that lays down rules for the establishment of the European Spatial Data Infrastructure. Since 2016 is the Head of the Digital Economy Unit targeting the impact of Digital Transformation on economy and society and in charge of the European Artificial Intelligence Observatory (AI Watch). Alessandro graduated in Physics from the University of Milan. Before joining the European Commission, he worked for 20 years in the private sector and managed companies dealing with Digital Earth technologies. Alessandro has 40 years working experience in several domains (forestry, agriculture, oceanology, nature protection, … and more recently on digital economy) dealing with Spatial Planning, Spatial Analysis, Environmental Modelling, Spatial Data Infrastructures, Geo-Information, GIS technologies, Artificial Intelligence, Remote Sensing, Image Processing, System Design, and Software Development. He has participated in several European projects relevant for Geo-Information and Digital Technologies and is author, co-author, and editor of more than 100 papers and books. Since 2006, Alessandro served as co-chair of the Architecture and Data Committee of the Group on Earth Observations (GEO). He co-chaired the GEO Infrastructure Implementation Board and he is now member of the GEO Programme Board. He is a visionary member and Vice President of the International Society for Digital Earth (ISDE). Alessandro has been awarded the 2013 Ian McHarg Medal of the European Geosciences Union reserved for distinguished research in Information Technology applied to Earth and space sciences. In 2016, he received the Digital Earth Science and Technology Contribution Award from the International Society for Digital Earth for outstanding contribution to advancing the development of Digital Earth.

Chapter 1
Understanding Digital Earth

Zhen Liu, Tim Foresman, John van Genderen and Lizhe Wang

Abstract In the two decades since the debut of the Digital Earth (DE) vision, a concerted international effort has engaged in nurturing the development of a technology framework and harnessing applications to preserve the planet and sustain human societies. Evolutionary threads can be traced to key historic and multidisciplinary foundations, which were presciently articulated and represented at the first International Symposium on Digital Earth hosted by the Chinese Academy of Sciences in 1999. Pioneering groups in government, industry, and academia have cultivated this fertile futuristic conceptual model with technological incubation and exploratory applications. An array of space-age developments in computers, the internet and communications, Earth observation satellites, and spatially oriented applications sparked an innovative discipline. The *Beijing Declaration on Digital Earth* is recognized for its role in promulgating the series of International Symposia on Digital Earth to promote understanding of the impacts of DE technology and applications on behalf of humankind. Combinations of industrial, academic, and government organizations have rapidly advanced the technological components necessary for implementing the DE vision. Commercial leaders such as Google have accelerated the influence of DE for large segments of society. Challenges remain regarding requisite collaboration on international standards to optimize and accelerate DE implementation scenarios. This chapter provides an overview of the DE initiative and basic framework, the global response to DE, the evolution of DE, its relationship to key global science initiatives, and the response to global challenges.

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1.1 The Digital Earth Initiative

Three years after a human first stepped on the moon's surface, the space and information age launched with the Landsat series of Earth observation satellites. Beginning in 1972, Landsat data kick started the big-data epoch by capturing imagery of the whole Earth's surface every two weeks. From these space-age origins, a multitude of technologies have developed to address data storage, preprocessing, classification, interpretation, analysis, integration with computational models, and visualization in digital image processing workflows. Digital image processing has spread across science, medical, computer, gaming, and entertainment fields, creating multitudes of new industries. With the booming development of Earth observation, considered the first wave of big data, massive amounts of digital data about the Earth's surface and near-surface have been collected from an ever-growing constellation of various satellites and sensors. Increased information technology capacity, following Moore's Law, has fostered disruptive changes regarding applications of Earth system data within the scientific community, relevant industries, and by consumer citizens. 'Digital' refers to more than the electronic format of the data in bits and bytes or the automated workflow used to manage the data. The Digital Era encompasses the much wider and greater societal and technological transformations facing humans. "Digital Earth is the inevitable outcome of the space era in the history of information society development" (Chen 2004). Digital Earth captures this phenomenal extension to harness the 'digital' world in which we live.

The concept of Digital Earth, first coined in Al Gore's book entitled "*Earth in the Balance*" (Gore 1992), was further developed in a speech written for Gore at the opening of the California Science Center in 1998. In this speech, Digital Earth was described as a multiresolution and three-dimensional visual representation of Earth that would help humankind take advantage of geo-referenced information on physical and social environments, linked to an interconnected web of digital libraries (Gore 1999). The concept of Digital Earth was further explained as the use of "digital technologies to model Earth systems, including cultural and social aspects represented by human societies living on the planet. The model is a multidimensional, multiscale, multitemporal, and multilayered information system. Digital Earth is envisaged as a common platform to support national and international cooperation for global sustainable development, and a newly developing point of economic growth and social well-being" (International Society for Digital Earth 2012).

Digital Earth theories and relevant technologies have flourished across a range of disciplines and applications worldwide (Chen 1999; Goodchild 1999, 2008; Foresman 2008; Guo et al. 2009; Annoni et al. 2011; Craglia et al. 2012; Goodchild et al. 2012). This momentous turn in the histories of cartography, meteorology, and geography was made feasible by the confluence of enabling information technologies in computational science, mass storage, satellite imagery, broadband networks, interoperability, metadata, and unprecedented 'virtual reality' technologies. Powered by advances in semiconductor devices networked to telecoms, navigation, and Earth observation satellites, a new era of spatially enabled technologies transformed and fused multiple disciplines in the 21st century. As a system of interconnected systems, Digital Earth should be fully empowered with multiple sources of geospatial information, a 3D representation platform of the Earth, and a user interface, and act as the framework that combines these domains. As stated in the *Beijing Declaration on Digital Earth*, "Digital Earth is an integral part of other advanced technologies including: Earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, grid computation, etc." (International Society for Digital Earth 2009).

In addition to being a global strategic contributor to scientific and technological developments, Digital Earth was regarded as an approach for "addressing the social, economic, cultural, institutional, scientific, educational, and technical challenges, allows humankind to visualize the Earth, and all places within it, to access information about it and to understand and influence the social, economic and environmental issues that affect their lives in their neighborhoods, their nations and the planet Earth" (International Society for Digital Earth 1999). It is "a catalyst in finding solutions to international scientific and societal issues" (International Society for Digital Earth 2009). Contemporary local and global issues can be characterized as complex and interrelated. Solutions to challenging problems remain elusive under conventional governance. In this dynamic environment, better methods for organizing vast data and managing human affairs are sought at all organizational levels. While not a panacea, Digital Earth has been regarded as the most effective approach, organizing metaphor, or model, to turn raw and disaggregated data into understandable, visualized information to gain knowledge about the Earth and human influence (Goodchild et al. 2012). Consequently, it can aid in the sustainable development of all countries and regions (Chen 2004). Thus, Digital Earth plays "a strategic and sustainable role in addressing such challenges to human society as natural resource depletion, food and water insecurity, energy shortages, environmental degradation, natural disasters response, population explosion, and, in particular, global climate change" (International Society for Digital Earth 2009).

1.2 Basic Framework of Digital Earth

Digital Earth is described as a virtual globe constructed of massive, multiresolution, multitemporal, multityped Earth observation data and socioeconomic data combined with relevant analysis algorithms and models (Goodchild 2013; Grossner et al. 2008). From a scientific point of view, the basic implication of Digital Earth includes two aspects. First, Digital Earth represents a huge data and information system that aggregates and presents data and information related to the Earth. In addition, Digital Earth is a virtual Earth system that can perform reconfigurable system simulations and decision support for complex geoscience processes and socioeconomic phenomena (Guo et al. 2014).

1.2.1 Basic Scientific Problems

The basic scientific problems concerning Digital Earth comprise three aspects:

(1) How to construct Digital Earth provided that we have massive, multiresolution, multitemporal, multitype Earth observation data and socioeconomic data? And how to organize, map, and compute these data to generate the data ecosystem—a harmonious, multidimensional, multiscale, multitemporal, and multilayered information system for Digital Earth?
(2) How to discover knowledge in Digital Earth? Assuming a data ecosystem has been built well, the next task is to compute, analyze, and mine the data for knowledge discovery to understand the Earth system using physical models (e.g., climate change models, Earth system models) or artificial intelligence algorithms (machine learning, data mining, deep learning, etc.).
(3) How to operate and utilize Digital Earth? As various of types of Digital Earth exist, coordinating and operating multiple subsystems of a Digital Earth platform to deliver flexible, efficient and user-friendly service for Digital Earth users and applications is a basic scientific problem.

1.2.2 Theoretical and Methodological Framework

To target the aforementioned scientific problems, we need a theoretical and methodological framework for Digital Earth:

(1) The theory and methodology of Digital Earth construction and implementation

This task is to generate the data and computer systems to produce a basic platform and infrastructure for a Digital Earth. The related theories and methods include remote sensing, geography, cartography, Earth information science, database theory, cloud computing, information networks, software engineering, and information theory.

(2) The theory and methodology of Digital Earth knowledge discovery

This task is to comprise implementation of the change from data to knowledge to understand the Earth system, for example, how Earth has changed, what the next change is and how human activities affect the Earth system. The related theories and methods include information theory, artificial intelligence, data mining, and Earth system science.

(3) The theory and methodology of Digital Earth operation and utilization

This task is to comprise management of the Digital Earth system and a whole and delivery of services to users and applications. The related theories and methods includes software engineering, cloud computing, Earth Information science, visualization, and information networking.

1.3 Global Response to Digital Earth

Responding to the vision for Digital Earth, the US government established a NASA-led Interagency Digital Earth Working Group in 1999 (Foresman 2008). Although this working group lost momentum and government support after 2001, its influence remained, with many stakeholders maintaining keen interest in pursuing this initiative.

1.3.1 International Society for Digital Earth

In 1999, the first International Symposium on Digital Earth to promote Digital Earth as a global initiative was held in Beijing, China, sponsored by the Chinese government and hosted by the Chinese Academy of Sciences. More than one thousand scientists, engineers, educators and governors from nearly 40 countries worldwide attended. The attendees approved a milestone document for the movement, the *1999 Beijing Declaration on Digital Earth*. This symposium laid the foundation for the development of Digital Earth at the global scale, and kicked off the worldwide responses to the Digital Earth initiative.

During the symposium, an International Steering Committee of the International Symposium on Digital Earth was established to organize subsequent symposia in the coming years. In 2006, the International Society for Digital Earth (ISDE) was formally established with the secretariat hosted by the Chinese Academy of Sciences. The ISDE is a nonprofit international scientific organization that principally coordinates and promotes academic exchange, education, science and technology innovation, and international collaboration towards Digital Earth.

Following the 1999 symposium, a symposium has been held every two years at different locations around the world. In addition, since 2006, Digital Earth summits have been added to the biannual symposia schedule to focus on specific academic themes that have been identified as important. After 20 years of development, ten symposia and seven summits have been hosted in 11 different countries. The upcoming symposium will be held in Italy in 2019 and the summit will take place in Russia in 2020.

Important to the professional standing of the ISDE is the addition of an international peer-reviewed academic journal, the *International Journal of Digital Earth*

(IJDE). The highly rated journal is published jointly by the ISDE and the Taylor & Francis Group. Inaugurated in March 2008, the IJDE was accepted for coverage by the Science Citation Index. Expanded in August 2009, the journal had an impact factor of 2.746 in 2018, ranking 13th out of 30 remote sensing journals, and has been included in 12 large international citation databases.

The Digital Earth initiative fits within many global organizations' missions through sharing knowledge and ideas about Digital Earth and seeking global benefits using Digital Earth technology. In 2009, the ISDE joined the Group on Earth Observations (GEO), the world's largest intergovernmental organization on using geospatial data. The ISDE also has established partnerships with the Committee on Data for Science and Technology (CODATA), the International Eurasian Academy of Sciences, the Global Spatial Data Infrastructure Association, and the African Association of Remote Sensing of the Environment. In 2017, the ISDE was recognized as a member of the International Council for Science (ICSU, now is the International Science Council). In August 2019, ISDE becomes a member of the United Nations Committee of Experts on Global Geospatial Information Management—Geospatial Societies (UN-GGIM GS). The ISDE is now widely recognized globally as a leadership organization in geospatial information science research.

1.3.2 Group on Earth Observations' Membership

In 2005, delegations from nearly 60 countries endorsed a ten-year Implementation Plan for the 2005–2015 Global Earth Observation System of Systems (GEOSS) and further established the intergovernmental Group on Earth Observations (GEO) to implement the plan. The ISDE's membership in the GEO guarantees organizational and scientific harmonization with all major international communities.

One of the GEO's missions is to implement GEOSS to "better integrate observing systems and share data by connecting existing infrastructures using common standards" (https://www.earthobservations.org/geo_community.php). "GEOSS is a set of coordinated, independent Earth observation, information and processing systems that interact and provide access to diverse information for a broad range of users in both public and private sectors. GEOSS links these systems to strengthen the monitoring of the state of the Earth. It facilitates the sharing of environmental data and information collected from the large array of observing systems contributed by countries and organizations within GEO. Further, GEOSS ensures that these data are accessible, of identified quality and provenance, and interoperable to support the development of tools and the delivery of information services. Thus, GEOSS increases our understanding of Earth processes and enhances predictive capabilities that underpin sound decision making: it provides access to data, information and knowledge to a wide variety of users" (https://www.earthobservations.org/geoss.php). GEOSS currently contains more than 400 million open data resources from more than 150 national and regional providers such as NASA and ESA, international organizations such as the World Meteorological Organization (WMO), and groups in the commercial sector such as Digital Globe (now Maxar) (https://www.earthobservations.org/geo_community.php).

1.3.3 The Australian Geoscience Data Cube

The Australian Geoscience Data Cube (AGDC) aims to realize the full potential of Earth observation data holdings by addressing the big data challenges of volume, velocity, and variety that otherwise limit the usefulness of Earth observation data. The AGDC is a collaborative initiative of Geoscience Australia, the National Computational Infrastructure (NCI), and the Australian Commonwealth Scientific Industrial Research Organisation (CSIRO). The AGDC was developed over several years as researchers sought to maximize the impact of Land surface image archives from Australia's first participation in the Landsat program in 1979. There have been several iterations, and AGDC version 2 is a major advance on previous work. The foundation and core components of the AGDC are (1) data preparation, including geometric and radiometric corrections to Earth observation data to produce standardized surface reflectance measurements that support time-series analysis, and collection management systems that track the provenance of each data cube product and formalize reprocessing decisions; (2) the software environment used to manage and interact with the data; and (3) the supporting high-performance computing environment provided by the Australian National Computational Infrastructure (NCI) (Lewis et al. 2017).

A growing number of examples demonstrate that the data cube approach allows for analysts to extract rich new information from Earth observation time series, including through new methods that draw on the full spatial and temporal coverage of the Earth observation archives, such as extracting the intertidal extent and topography of the Australian coastline from a 28-year time series of Landsat observations. Sagar et al. outlined an automated methodology to model the intertidal extent and topography of the Australian coastline that leverages a full time series of Landsat observations from 1987 to 2015 managed in the Australian Geoscience Data Cube (AGDC) (Sagar et al. 2017). The Australian Government established a program to improve access to flood information across Australia. As part of this, a project was undertaken to map the extent of surface water across Australia using the multidecadal archive of Landsat satellite imagery. The "initial scoping of the full processing time required for the analysis indicated that one analysis of the entire Landsat archive for surface water was over four years. The analysis as conducted on the AGDC was completed in under 8 h, making it feasible to review and improve the algorithms, and repeat the analyses many times, where previously such an analysis was essentially not feasible" (Mueller et al. 2016).

The AGDC vision is of a 'Digital Earth' (Craglia et al. 2012) composed of observations of the Earth's oceans, surface and subsurface taken through space and time and stored in a high-performance computing environment. A fully developed AGDC would allow for governments, scientists and the public to monitor, analyze and project the state of the Earth and will realize the full value of large Earth observation datasets by allowing for rapid and repeatable continental-scale analyses of Earth properties through space and time. To enable easy uptake of the AGDC and facilitate future cooperative development, the AGDC code is developed under an open source Apache License, version 2.0. This open source approach is enabling other organizations including the Committee on Earth Observing Satellites (CEOS) to explore the use of similar data cubes in developing countries (Lewis et al. 2017). It creates the potential for expansion of the AGDC concept into a network of data cubes operating on large geoscientific and geospatial datasets, colocated in suitable HPC-HPD facilities, to address global and national challenges.

1.3.4 CASEarth Data Bank

The Earth observation community has entered into the era of big data. The CASEarth Data Bank, part of the Project on Big Earth Data Science Engineering (Guo 2018), provides big Earth data infrastructure that focuses on Earth observation data.

With new computing infrastructures, technologies and data architectures, the CASEarth DataBank system aims to meet the data management and analysis challenges that arise from the huge increase in satellite Earth observation data. The CASEarth DataBank system is designed to increase the value and impact of Ready to Use (RTU) products by providing an open and freely accessible exploitation architecture to broaden their applications for societal benefit (Guo 2018).

The CASEarth DataBank system is an intelligent data service platform that provides RTU products from multisource spatial data, especially satellite remote sensing data, and big Earth data analysis methods and high-performance computing infrastructure.

The CASEarth Databank consists of three main parts:

(1) Standardized long time-series RTU products from Earth observation data including (1) Chinese satellite data: ZY, GF, HJ, CBERS, FY, HY, and CASEarth satellites, with spatial resolutions from one km to submeter; (2) Landsat data received by the China Remote Sensing Satellite Ground Station since 1986, with 12 RTU products including digital orthophoto maps, regional image maps, top of atmosphere reflectance, land surface reflectance, top of atmosphere brightness temperature, land surface temperature, normalized difference vegetation index, ratio vegetation index, global environment monitoring index, normalized burnt ratio, normalized difference water index, and pixel quality attribute; and (3) other big Earth data sources: DEM, vector, and social data (He et al. 2015, 2018a, b). These RTU products provide consistent, standardized, multidecadal image data for robust land cover change detection and monitoring across the Earth sciences.

(2) The Software Environment. For the data engine, a databox was developed for time series data management and global tiling. For the CASEarth Data Bank system, a global subdivision grid was designed to effectively manage, organize and use long-term sequential RTU data and facilitate the integration and application analysis of multisource and multiscale geospatial information. The global subdivision grid was designed for RTU data based on the national standard of China (GB/T 12409-2009) (Guo 2018).
The computation engine consists of time series data analysis, computational modeling and data integration, middleware and tool modeling, data-intensive computing technologies, data-driven innovation, advanced manufacturing and productivity. It provides basic data analysis algorithms, a distributed parallel computing mechanism, and intelligent analysis solutions for big Earth data.
The visualization engine aids in data visualization in a pictorial or graphical format. With rich, interactive visuals such as graphs and charts, it is easy to discover insights hidden in the data due to the way the human brain processes information. It enables decision makers to see analytics presented visually. A visualization engine is being developed to better understand the data in the CASEarth Databank.
(3) Infrastructure and services. It provides a high-performance computing environment and services with 50P storage and 2PF computing capability. The infrastructures and systems of datafication for big Earth data include storage, management, computing, optimizing cloudification, architectural features, stateless processing, microservices, containers, open software and inherent orchestration.

1.4 Evolution of Digital Earth

Fundamental changes in society have occurred since the Digital Earth concept was proposed 20 years ago. Along with these social changes, technology advances have been incrementally achieved, resulting in the evolution of Digital Earth.

1.4.1 Visionary Incubation of Digital Earth

Based on command and control technologies, there are several virtual globe platforms, or geobrowsers, with associated visualization applications. Among them, the three major categories are location-based commercial platforms, science platforms based on Earth system sciences, and public platforms oriented towards regional sustainable development and decision support (Guo et al. 2017).

In 2001, based on a 3D Earth geographic teaching software 'Atlas 2000' by Microsoft, an original prototype of the Earth system was developed, which integrated large-scale remote sensing imagery and key point datasets into a global 3D model.

Following that, ESRI launched ArcGIS Explorer, and Google Earth was launched in 2005. These early geobrowsers were supported by geospatial tessellation engines operated within desktop computers using 3D technology. When integrated, these Digital Earth systems allowed for querying, measurement, analysis, and location services based on massive geospatial data (Grossner and Clarke 2007). Since then, a number of virtual globes have been produced, including WorldWind, Skyline Globe, GeoGlobe, and Bing Maps 3D. Keysers (2015) provides comparative descriptions of 23 virtual globes, demonstrating the early breadth of Digital Earth technology. This implies that the technology of virtual globes is not yet completely mature.

In addition, many other countries' governments and institutes have produced Digital Earth platforms for specific research purposes. The Chinese Academy of Sciences started research on a Digital Earth Prototype System in 1999 and released the Digital Earth Science Platform (DESP/CAS) in 2010 (Guo et al. 2009). The Jet Propulsion Laboratory created Eyes on the Earth to visualize in situ data from a number of NASA's Earth orbiting spacecraft (NASA 2009). The Australian government explored Blue Link and Glass Earth to observe and simulate the ocean and explore the top kilometer of the Australian continent's surface and its geological processes. A consortium of Japanese institutes developed the Earth Simulator to support environmental change research (Yokokawa 2002).

In 2011, a group of experts from the International Society for Digital Earth gathered at the "Digital Earth Vision to 2020" workshop in Beijing to discuss the developing trends of Digital Earth. This workshop discussed the achievements of Al Gore's first generation of the Digital Earth vision. Goodchild et al. (2012) indicated that the existing generation of Digital Earth (or Virtual Globes) represented great progress in Gore's vision. In Gore's vision, 3D representation of the Earth tops the list in realization of Digital Earth. 3D technology is derived from computer and 3D graphic technologies supported by the film and video game industries and is involved in the representation of the Earth, hence the name Digital Earth. Digital Earth is regarded as a "disruptive approach to the methods of geospatial analysis and visualization currently employed within the field of GIS that uses a virtual (3D) representation of the globe" and as a spatial reference model to visualize, retrieve, and analyze geospatial data at different levels (Mahdavi-Amiri et al. 2015). Data (including imagery, elevation data, vector data, 3D geometric data, and statistical data) are mostly assigned to discretized and hierarchical cells of the Earth, which is a structure known as Discrete Global Grid Systems (DGGSs) that serves as the backbone of the Digital Earth system (Goodchild 2000; Sahr et al. 2003). The first generation of these systems could also be extended and adapted to different user requirements, i.e., displaying the oceanography, atmosphere, or geomorphology of the surface and near-surface of the Earth. However, some aspects fall short of Gore's vision, such as the exploration of historical and future scenarios of the Earth, as well as limitations in the storage, retrieval, and sharing of the huge amount of collected information related to the Earth, and in visualization of the Earth (Goodchild et al. 2012).

1.4.2 Digital Earth in Support of Data-Intensive Knowledge Discovery

With the tremendous growth of the geospatial data collected from satellite-based and ground-based sensors, a fourth paradigm of science was required to characterize data-intensive knowledge discovery. High-performance computing capacity, international collaboration, and data-intensive analysis using high-end visualization have been developed to deal with the multisource data management hurdles. New awareness of the challenges Digital Earth could face has attracted attention to theoretical and scientific innovations in data-intensive geoscience knowledge discovery methods, massive data convergence and service models, and data-intensive geoscience computing and knowledge discovery (Goodchild 2013).

Various types of observation data represent essential foundations for the development of Digital Earth. Massive amounts of geospatial data including satellite-borne data are being processed, exploited and combined with other massive data sources, and delivered in near-real time to users in highly integrated information products. In the context of the widespread use of massive geospatial data, Digital Earth prototypes, popularly represented by Google Earth, began to use the internet to provide the world with high-resolution digital rendering services beginning in 2005. Google's game-changing Earth tessellation engine enabled the public to realize free and convenient access to conduct geo-spatial inquiry and mapping operations on Earth-related data using their personal computers (Goodchild 2013). The challenges inherent in intensive data provide Digital Earth an opportunity to play a significant role in scientific knowledge discovery.

1.4.3 Digital Earth with Multisource Data

As a complex system, Digital Earth increasingly embraces massive multi-resolution, multitemporal and multitype Earth observation data and socioeconomic data as well as relevant analysis algorithms and models (Guo 2012; Grossner et al. 2008). Data acquisition, organization, analysis and application all reflect the importance and necessity of effectively handling massive volumes of scientific data. With the rapid development of internet, mobile 5G network, and Web 2.0 technologies, significant improvements occurred in the collection of multisource spatial data. The availability of data providers is increasing as digital citizens are no longer limited to government agencies or professional companies. Ordinary civilian users can participate in and cooperate with others to maintain and update geographic information data. The idea that everyone can serve as a data collection sensor has become a reality. Goodchild (2007) termed this new geographical era neogeography. New sources of data from both citizen science and smartphone activity enable the public to become mass providers of data. Concepts that embrace this new public data collection, such as volunteered geographic information (VGI) (Goodchild 2007), crowdsourcing geospatial data (Giles 2006; Howe 2006; Heipke 2010), and generalized geographic information (Lu and Zhang 2014), have been highlighted. Although the concepts vary, all of them emphasize the transformation of geospatial data acquisition. The bottlenecks in acquisition due to reliance on traditional, professional or government mapping have been uncorked using diversified and increasingly accurate active or passive data provided by the public.

The aforementioned "Digital Earth Vision to 2020" workshop led to two scientific papers: *Next-Generation Digital Earth* published in the *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* (Goodchild et al. 2012) and *Digital Earth 2020: Towards the Vision for the Next Decade* published in the *International Journal of Digital Earth (IJDE)* (Craglia et al. 2012). Goodchild et al. (2012) proposed that inevitable new developments in internet communications and API services, multidimensional representation, and Earth observation visualization technologies would accelerate fulfillment of the Digital Earth concept and expand the potential of Digital Earth for all stakeholders. The next generation of Digital Earth is not projected to be a single system and will likely be multiple interconnected infrastructures based on professional standards for open access and horizontal participation across multiple technological platforms. Client-friendly and customized platforms will drive the growth of different audiences. One metaphor proposed Digital Earth as a digital nervous system for the globe, actively informing users about events happening on or near the Earth's surface by connecting to sensor networks and situation-aware systems (Foresman 2010). de Longueville et al. (2010) believed that Digital Earth is a powerful metaphor for accessing the multiscale 3D representation of the globe but, due to its non-self-aware feature, the inclusion of temporal and voluntary dimensions would be more helpful in a description of the real world. Craglia et al. (2012) articulated the main policy, scientific and societal drivers for the development of Digital Earth. These papers help illustrate the multifaceted nature of next-generation Digital Earth. The growth of Digital Earth is predicated in part on emphasizing its usefulness to the public. Continued development and evolution of internet bandwidth and improved visualization techniques can be expected to maintain the growth of Digital Earth applications. Equally important for public applications are social developments and the widespread adoption of social networks, which serve as key ways to communicate and turn citizens into force multipliers as providers of information.

1.4.4 Digital Earth in Big Data Era

Entering the big data era, national and regional governments responded by releasing relevant strategies accordingly. For example, in 2011 the European Commission announced a statement on "Open Data: An Engine for Innovation, Growth and Transparent Governance". In 2012, the United States released the "Big Data Research and Development Initiative" to enhance the capability of knowledge discovery through big data (http://www.whitehouse.gov/sites/default/files/microsites/

ostp/big_data_fact_sheet_final_1.pdf). Australia published "The Australian Public Service Big Data Strategy" in 2013. Subsequently, the Chinese government began emphasizing big data as one of the strategic resources of social development in 2013 and issued the "The Action Plan for Promoting Big Data Development" in 2015, including a proposal for "Developing Science Big Data". In 2012, the UN Global Pulse published "Big Data for Development: Opportunities and Challenges" to promote the significant role of big data in responding to climate changes. The International Council for Science (joined in 2017 with the International Social Science Council to form the International Sciences Council) published their "Strategic Plan 2012–2017", which emphasized the importance of data management in new knowledge discovery.

Big data has created a new computational perspective in the use of continuously collected data from various sources to explore trends in large volumes of data and to better understand world dynamics. Such advances bring great opportunities for Digital Earth to play its visionary role in integrating the massive amount of multidimensional, multitemporal, and multiresolution geospatial data as well as socioeconomic data in a framework for comprehensive analysis and application systems about the Earth.

Digital Earth has evolved into a new connotation of 'big Earth data'. Big Earth data incorporates the litany of powerful tools requisite to understanding and explaining the Earth system and to investigating sustainable global development. It focuses on the synthesis and systematic observation of Earth, as well as data-intensive methods for studying Earth system models with the goal of increasing knowledge discovery. Big Earth data can be expected to promote the Digital Earth vision by connecting multiple satellites and geographical information centers that rely on national spatial infrastructures and high-speed internet to complete the acquisition, transmission, storage, processing, analysis, and distribution of spatial data.

1.5 Relationship with Other Initiatives

1.5.1 Geospatial Information Infrastructures

The United States pioneered the development and implementation of the National Spatial Data Infrastructure (NSDI) in the 1990s. Clearly defined, the NSDI is the sum of the technologies, policies, standards, human resources, and related activities necessary to collect, process, publish, use, maintain, and manage geospatial data from all levels of government, private and nonprofit organizations, and academic communities. The NSDI makes existing and accurate geospatial data more accessible, greatly facilitates the collection, sharing, distribution and utilization of geospatial data, and has played an active role in economic growth, environmental quality and protection, and social progress in the United States.

The NSDI model has been accepted and adopted to fit the needs of many other countries that have implemented their own spatial data infrastructure plans. The federal government of Canada implemented the GeoConnections program in 1999, a national program of partnerships involving the federal government, provincial (district) governments, municipal and local governments, research institutes, universities, and private companies. The main role of GeoConnections is to establish the Canadian Geospatial Data Infrastructure (CGDI) and enable online access to Canadian geospatial databases and services. The CGDI is the sum of the policies, technologies, standards, access systems and protocols necessary to coordinate all geospatial databases in Canada and make them available on the internet. For more than a decade, the implementation of GeoConnections has enabled online access to Canadian geospatial databases and services, and effectively coordinated partnerships, investments and developments between federal, provincial, local government, private and academic communities.

In 2007, the Infrastructure for Spatial Information in Europe (INSPIRE) Directive came into force (https://inspire.ec.europa.eu/about-inspire/563). This directive established a web-based infrastructure to make more visible, shareable and usable environmental and geospatial information necessary to support European environmental policies that affect the environment such as transport, agriculture, and marine policy. INSPIRE is decentralized, i.e., the infrastructure builds on those set up and maintained by the 28 EU member states. It does not require the collection of new data and develops the technical, and organizational arrangements to achieve interoperability among the infrastructures in the member states and among the 34 data themes falling in the scope of the directive. INSPIRE will take more than 12 years to implement, from 2007 when the directive was adopted to 2019–20 and beyond. As this process takes place, it is important to consider the technological and policy developments that will shape the future data infrastructures so that the investments of today are open to the developments of tomorrow.

1.5.2 Earth Observation Program

Earth observation has been become a major part of many countries' environmental and defense programs since the final decades of the last century. Nations were influenced by the Planetary Mission of NASA's Earth Observation Program. The program was developed for the scientific research of the Earth systems. Its goals were to collect sufficient data on the Earth's systems to enable whole planetary assessments and conduct comprehensive research on the Earth. NASA's program consists of three parts: the scientific plan, Earth observation platforms, and data information systems.

A new generation of space-Earth observation continues and has been extended to incorporate observations of the land, atmosphere, ocean, ecosystem processes, water and energy cycles, and solid Earth.

The Global Monitoring for Environment and Security (GMES) program was jointly established by the European Space Agency (ESA) and the European Commission in 2003. The ESA created a series of next-generation Earth observation missions, including the Copernicus program. To meet the operational needs of the Copernicus program, the ESA developed the Sentinel program to replace older Earth observation missions. Each Sentinel mission is based on a paired satellite model to provide datasets for Copernicus Services and focuses on different aspects of Earth observation, including atmospheric, oceanic, and land monitoring.

Earth observations have expanded rapidly around the globe, as demonstrated by the fact that the GEO now has more than 100 member nations. Bringing Earth observation down to Earth with an ever-increasing number of Earth observation satellites with increasing spatial, temporal and spectral resolutions represents a critical data input to the Digital Earth concept.

1.5.3 National/Regional Digital Earth Programs

Dozens of countries such as Australia, China, Japan, Singapore, South Africa, and the European Commission have generated their own Digital Earth-related programs. There has been important progress in these efforts, such as Digital Earth Australia established by the Australia federal government in 2017, the Geoscience Australia Data Cube (supported by the Commonwealth Scientific and Industrial Research Organization, the National Computational Infrastructure, and the National Collaborative Research Infrastructure Strategy of Australia), Digital China promoted by the Chinese government, the Key Laboratory of Digital Earth Sciences established by the Chinese Academy of Sciences, and the IDEAS (International Digital Earth Applied Science Research Center) at Chubu University in Japan, as well as those at several universities with Digital Earth departments or laboratories (e.g., Austria and Malaysia). Some of these are described in detail in Part III of this manual.

1.6 Digital Earth in Response to Global Challenges

Correlated with and a derivative of many sciences dealing with the surface and near-surface of the Earth, Digital Earth was envisioned as an initiative for harnessing the Earth's data and information resources. With powerful tools to quantitatively describe a science-based representation of the planet, Digital Earth could serve as a tool to map, monitor, measure, and forecast natural and human activities. The prowess of the Digital Earth technology was envisioned as requisite to assist nations, organizations, and individual citizens in addressing the problems humans are facing in the 21st century. These challenges for all nations, such as climate change, natural disasters, and sustainable development, require the comprehensive scope and analytical capacity of Digital Earth technology.

1.6.1 Response to Climate Change

Since the middle of the 20th century, large-scale, high-intensity human activities and the rapid growth of the population and social economy have compounded global change problems such as global warming, air pollution, water pollution, land degradation, rapacious resource exploitation, and biodiversity decline. Global change threatens national security and all aspects of our lives, including economic and social development conditions from social, economic, living, and health perspectives. Sustainable development is now recognized as the most serious challenge facing human society.

The United Nations, in partnership with various intergovernmental coalitions, has organized and implemented a series of environmental research programs on global or regional scales, such as the World Climate Programme (WCP), the Man and the Biosphere Programme (MAB), and the International Biosphere Programme (IBP). Within the International Geosphere Biosphere Programme (IGBP), each country is challenged to address the natural resource and environmental issues caused by global change as a primary means to achieve sustainable approaches for socioeconomic development.

Global change is recognized as a significant threat to sustainable development worldwide. To address these multidisciplinary issues at a global scale, global change research faces the unpredicted challenge of obtaining copious data from the interacting subsystems of the Earth for analytical modeling and generating management decisions (Chen 1999; Shupeng and van Genderen 2008). Thus, it is important that Digital Earth facilitates the collection of data from various elements of the Earth system through monitoring the progress of global change in large-scale, long-term sequences, and aids in data processing, analysis, and simulation.

The Paris Agreement, which was negotiated by representatives of 196 countries, was endorsed at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in LeBourget, France on 12 December 2015. The Paris Agreement's long-term goal is to "strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius." The agreement states the need to "strengthen the ability of countries to deal with the impacts of climate change" as well as reduce the risks and effects of climate change (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement). Under this agreement, starting in the year 2020, a litany of financial policies and new technology frameworks will be put into action to support the realization of greenhouse gas emission mitigation, adaptation, and finance. Increasingly, scientists are documenting that the impacts of temperature increases in the polar regions indicate that our collective actions may be too little, too late.

Big Earth data should provide a wide range of long-term sequences and multiple spatiotemporal scales to cover all of Earth's systems including the atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere. To stock Digital Earth with big

Earth data requires the only known science approach, which is to amass a space-air-ground integrated Earth observation system and a global near-real time, all-weather Earth data acquisition network. Through continuous and long-term monitoring of the Earth system, scientists can use advanced geospatial processing technologies to simulate and analyze Earth's dynamic surface processes and reveal spatiotemporal change mechanisms. Stakeholders will need to formulate scientific strategies and take progressive actions to respond to global change for sustainable development at varying local and regional scales. In this sense, big Earth data provides strong support to the Digital Earth vision, which will hopefully strengthen new approaches to global change research.

1.6.2 Response to the UN SDGs

In September 2015, the United Nations General Assembly adopted "Transforming our World: The 2030 Agenda for Sustainable Development" (United Nations 2015). This international milestone provides a blueprint for action for all countries and stakeholders. This agenda defines 17 Sustainable Development Goals (SDGs) and 169 targets and creates a global indicator framework until 2030. The 2030 Agenda for Sustainable Development provides a new insight into the global actions and transformative policies necessary to guide our collective pursuit of sustainable development.

Achieving sustainable development presents all countries with a set of significant development challenges. These challenges are inherently embedded with spatial-temporal complexities, that is, they are almost entirely geographic in nature. Many of the structural issues impacting sustainable development goals can be analyzed, modeled, and mapped using Earth observation data, which can provide the integrative and quantitative framework necessary for global collaboration, consensus and evidence-based decision making.

Digital Earth is closely interrelated with the global sustainable development challenges and processes, as evidenced through national Earth observation agencies' efforts to connect and integrate big Earth data into the application of many social and environmental programs. Earth observation data provide a substantial contribution to the achievements of the SDGs in support of decision making by monitoring impacts and results, improving the standardization of national statistics, addressing cross-cutting themes such as climate and energy, and facilitating countries' approaches to working across different development sectors (Anderson et al. 2017).

At the United Nations World Geospatial Information Congress (UNWGIC) held in Deqing, Zhejiang Province in China from 19 to 21 November 2018, attention was paid to strengthening national geospatial information management and systems and national implementation of the 2030 Agenda for Sustainable Development (https://www.unwgic2018.org/). It has become important to the science and governance communities to understand, analyze and discover knowledge from huge geospatial data resources. This must be accomplished in a collaborative way among nations to effectively address local, regional, and global challenges and to share big Earth data worldwide as prerequisites to meet the requirements of sustainable development.

Effective transfer of all relevant technologies and Earth-related data represents an important challenge (Scott and Rajabifard 2017). However, under the Digital Earth framework, there are immense opportunities for digital transformation and sharing of resources. Achieving sustainable development will entail significant advances in overcoming political and technical bottlenecks to smooth the digital divide. Internet-based infrastructure with advancing 5G communication shows promise for expanding Digital Earth technologies to all nations.

1.6.3 Response to Disaster Mitigation

Addressing natural and human-caused disasters remains the highest priority of all nations. Climate change experts are in agreement that global warming will increase the frequency and intensity of storms and disruptive weather patterns. Therefore, application of the Digital Earth framework and technology for disaster response and mitigation is of paramount importance.

Recently, the Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai Framework) was adopted by the UN member states in March 2015 at the World Conference on Disaster Risk Reduction held in Sendai, Japan, and endorsed by the full UN General Assembly in June 2015. This 15-year development framework agenda contains seven targets and four priorities for action. The United Nations International Strategy for Disaster Reduction (UNISDR) has been tasked with supporting the implementation, follow-up and review of the Sendai Framework. The framework's central aim is to "reduce disaster risk… and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries" with the efforts of local governments, the private sector and other stakeholders within a voluntary, nonbinding agreement (https://www.unisdr.org/we/coordinate/sendai-framework).

Notably, disaster-related applications have been prominent since the inception of the Digital Earth community. Chen's (2004) comprehensive review of Digital Earth science in China includes examples of research on flood, coastal, river, and other disasters. The International Society for Digital Earth has sponsored or cosponsored many disaster-oriented workshops and symposia. Importantly, the collaboration with UNISDR, GEO and CODATA and other international associations has been anchored by the common commitment to collaboration and focus on applications for disaster response. Chapter 15 addresses these applications.

1.7 Conclusions/Structure of the Manual

In this manual, the Digital Earth vision has been introduced in the first chapter. Part I has eleven chapters about various Digital Earth technologies; Part II has seven chapters describing the role of Digital Earth in multidomain applications; and Part III contains four chapters showing how the Digital Earth concept has developed from Al Gore's original vision to its current implementation as employed around the world through four regional/national chapters of the International Society for Digital Earth. Part IV considers Digital Earth education and ethics. The concluding chapter of this Manual of Digital Earth describes some of the key challenges and future trends for the development of Digital Earth over the coming years.

Digital Earth is an evolving concept that is strongly influenced by the evolution of technology and the availability of new data. In a couple of years, the Earth will be revisited several times a day by the new generation of satellites, and real-time observation will no longer be a chimera. As we look to the future, it is unlikely that a unified vision of Digital Earth will capture all the perspectives of all stakeholders. A one-size-fits-all Digital Earth would not be appropriate for all nations and cultures. The current social and technological trends expressed in the literature prescribe a robust and comprehensive list of likely characteristics for an updated version for Digital Earth, which closely follows the original vision. There will be a series of connected perspectives of Digital Earth based on varying priorities and applications of the same framework data sources operating with different user-specified functionalities. In the future, the concept and vision of Digital Earth will evolve with the development of science and technology.

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Part I
Digital Earth Technologies

Chapter 2
Digital Earth Platforms

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Abstract In this chapter, we provide a thorough discussion on Digital Earth with particular focus on Discrete Global Grid Systems (DGGS), which are a standardized representation of the Earth. We describe the necessary components of a DGGS, such as the underlying 2D representation, indexing system, projection, and cell types. We also discuss a selection of well-known public and commercial DGGSs followed by current DGGS standards.

Keywords Discrete Global Grid · OGC Standard · Digital Earth

2.1 Introduction

Digital Earth is a framework for geospatial data management. In this model, data are assigned to locations on a 3D model of the Earth and analyzed at multiple resolutions, each representing data at a specific level of detail. To locate and retrieve data sets associated with the Earth, mechanisms are needed for data representation, region addressing, and the assignment and retrieval of data for a region of interest. Digital Earth provides a reference model that can handle all of these queries.

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Two main approaches have arisen for the creation of a Digital Earth: Discrete Global Grid Systems (or DGGSs for short), and datacubes. In a DGGS, the surface of the Earth is discretized into a set of highly regular spherical/ellipsoidal cells. These cells are then addressed using a data structure or indexing mechanism that is used to assign and retrieve data. Datacubes are n-dimensional arrays that store geospatial data, ordered according to various attribute/coordinate axes, which can be spatial or non-spatial in nature.

In this chapter, we focus particularly on Discrete Global Grid Systems, which have global scope, more readily support interoperability than datacubes, are generally compatible with conventional datacube approaches, and can be used to provide the back-end support for a datacube implementation (Purss et al. 2019). The following section discusses DGGS as well as its components and their characteristics in detail.

2.2 Discrete Global Grid Systems

The traditional approach to discretizing the Earth is to use a latitude/longitude coordinate system on a sphere (Cozzi and Ring 2011), in which the 2D domain (or planar map of the Earth) is partitioned into a grid of cells by discretizing the 2D latitude/longitude domain. These cells may be further subdivided to increase the resolution and mapped to the sphere through the use of spherical coordinate equations and/or an appropriate spatial projection. The resulting spherical cells are primarily quadrilateral, though singularities and triangular cells appear at the poles, and the areas of the cells vary according to the latitude.

In order to better represent the Earth with more uniform cell structures, a polyhedron with the same topology as the sphere can be used. With an initial discretization of the Earth into planar cells (typically produced by considering the planar faces of an approximating polyhedron), the initial cells may then be refined to an arbitrary resolution and mapped from planar cells to spherical cells via some projection method (see Fig. 2.1). Given a regular refinement, a multiresolution hierarchy between cells (in which each cell has a coarser resolution parent and a number of finer resolution

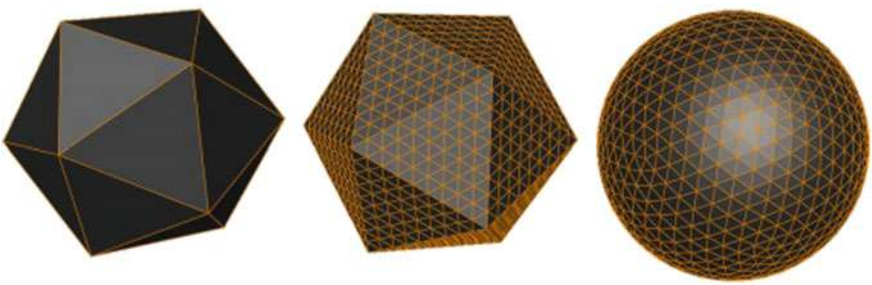

Fig. 2.1 An initial polyhedron that has been refined and projected onto the sphere

children) with a semiregular cell structure can be systematically defined. To query and render cells, they are then typically addressed via an indexing mechanism.

DGGSs are defined in terms of several different components. The main components of a DGGS include the initial planar or piecewise domain, cell type, projection, indexing, and refinement. In the following, we discuss each of these components in more detail in the context of DGGS construction.

2.2.1 Initial Domain

The simplest domain for a DGGS is a 2D map of the Earth, of which latitude/longitude grids are the standard. As these tend to exhibit large distortions across the globe and singularities at the poles, complicating queries and data analysis, a spherical polyhedron can instead be used for the initial domain of a DGGS. Such DGGSs are also known as Geodesic DGGSs (Sahr et al. 2003).

The most common choices for an initial polyhedron are the platonic solids—the tetrahedron, cube, octahedron, dodecahedron, and icosahedron—in addition to the truncated icosahedron. Each of these polyhedra offers distinct benefits. For instance, the octahedron defines a simple and symmetric domain, and can be unfolded into a very simple quadrilateral domain. Cubes are made of quadrilateral facets that are appropriate for the generation of quadrilateral cells. In comparison to other polyhedra, the icosahedron and truncated icosahedron undergo less angular distortion when processed through an equal area projection (Snyder 1992).

2.2.2 Cell Type

There are three main cell types that are used in a DGGS: hexagonal, triangular, and quadrilateral. If the initial domain is a polyhedron, other extraordinary cell types may be present, such as pentagons in a truncated icosahedron. However, the number of extraordinary cells is fixed no matter the resolution. Each of the three main cell types presents some advantages over the others that ought to be considered when selecting the base cell of a DGGS. For instance, quadrilateral cells are congruent, compatible with Cartesian coordinate systems, easy to index, and compatible with standard rendering libraries. Triangular cells are planar, easy to use, compatible with standard rendering techniques and libraries, and congruent. Hexagonal cells are the best for sampling, with the smallest quantization error, and they have uniform adjacency. Depending on the initial domain of a DGGS and the application that the DGGS was designed for, any of these types of cells can be employed as the DGGS cell type.

2.2.3 Refinement

Refinements are used to produce finer cells from an initial set of coarse cells. In a DGGS, they can be used to construct cells at multiple resolutions on the sphere by refining the faces of a polyhedron. Refinements are in part characterized by a ratio known as the aperture, or factor, of the refinement. This ratio relates the number of coarse cells to the number of fine cells at the next resolution, and several different apertures have been employed in DGGSs. After applying a refinement, the resulting fine cells may be assigned to a coarse *parent* cell as *children* of that cell, producing a hierarchical structure that is useful for many grid and spatial processing operations. Traversing from a parent cell to its children or from a child to its parent is known as hierarchical traversal.

In addition to the factor of refinement, other aspects play an important role in characterizing a refinement, such as congruency and alignment. In a congruent refinement, a coarse cell encompasses precisely the same area as a union of finer cells at the next resolution (see Fig. 2.2). For example, the 1-to-4 quadrilateral refinement shown in Fig. 2.2a is congruent while the 1-to-3 hexagonal refinement shown in Fig. 2.3b is not. Assigning a set of fine cells to serve as the children of a coarse cell is trivial in congruent refinements, as children are uniquely covered by a single parent cell and, therefore, the handling of hierarchical traversal queries is simplified. In contrast,

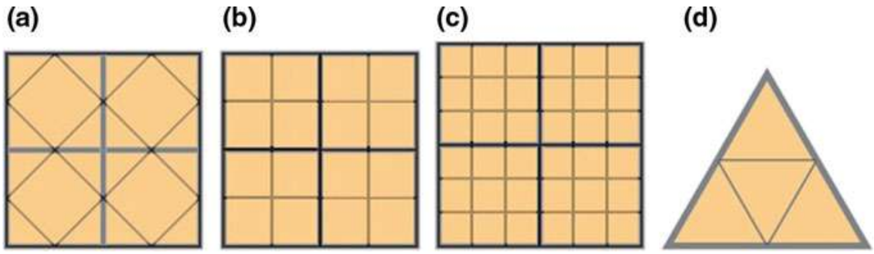

Fig. 2.2 (**a**) A center-aligned 1-to-2 refinement that is not congruent. (**b**) A vertex-aligned and congruent 1-to-4 refinement. (**c**) A center-aligned and congruent 1-to-9 refinement. (**d**) A center-aligned and congruent 1-to-4 refinement for triangles. The boundaries of coarser cells are highlighted using thicker lines

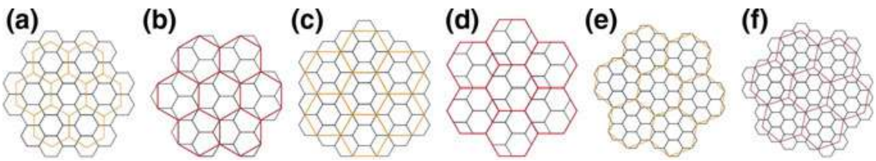

Fig. 2.3 (**a**) Center-aligned and (**b**) vertex-aligned 1-to-3 refinements. (**c**) Center-aligned and (**d**) vertex-aligned 1-to-4 refinements. (**e**) Center-aligned and (**f**) vertex-aligned 1-to-7 refinements. Note that each of these refinements is incongruent

incongruent refinements create ambiguity in the assignment of a child to a coarse cell, since there may exist several potential parents for a fine cell (Fig. 2.3).

If, after applying a refinement, every coarse cell shares its centroid with a fine cell, then that refinement is called center-aligned. Any DGGSs that employ such refinements are likewise called center-aligned. If such a property does not hold for the refinement, then it is usually vertex-aligned, meaning that the parent and child cells share a vertex (Fig. 2.2).

Various types of refinements exist for quadrilateral, triangular, and hexagonal DGGS cells. However, whereas many different refinements have been employed in DGGSs based on quadrilateral and hexagonal cells, DGGSs represented using triangular cells generally use 1-to-4 refinements (see Fig. 2.2d). Quadrilateral refinements can be congruent whilst hexagonal refinements never are (see Fig. 2.3). Consequently, parent-child relationships must always be explicitly defined in a hexagonal DGGS. However, once defined, this becomes a static feature of the DGGS infrastructure, allowing for consistent hierarchical traversal of the grid system, and incongruent refinements still exhibit characteristics that can be useful in a DGGS. Hexagonal 1-to-3 refinement has the lowest aperture of all hexagonal refinements; while hexagonal 1-to-4 refinement produces rotation-free lattices at all levels of resolution (simplifying hierarchical analysis in contrast to other refinements). Of the refinements shown in Fig. 2.3, fine cells in the 1-to-7 refinement cover the hexagonal coarse shape better than other refinements, and therefore more closely resemble congruency and provide a simpler hierarchical relationship between the cells. As a result, there is growing interest in this type of refinement (Middleton and Sivaswamy 2005).

2.2.4 Projection

Projections have traditionally been used to create maps of the Earth. Various forms of projection can be used to flatten the Earth (usually treated as spherical), and these can be categorized into different types, such as conformal, gnomonic, or equal area (Grafarend et al. 2014). When a spherical projection is used, some unavoidable distortions appear that one may try to reduce. In the following, we discuss several spherical projections in more detail.

2.2.4.1 Traditional Cartography

In traditional cartography, a spherical projection is a transformation from a point on the Earth (a sphere) to a point on a 2D map. Such a projection can be represented as a function: $P' = F^{-1}(P)$, where P lies on the sphere, and P' lies on the 2D map (see Fig. 2.4). The simplest method that can be used to create a 2D map from a spherical representation of the Earth is to use spherical coordinates $((\theta, \varphi))$. Doing so involves cutting the Earth (e.g. along a meridian) and unfolding it to form a 2D square, with θ (the longitude) and φ (the latitude) serving as the two main axes of

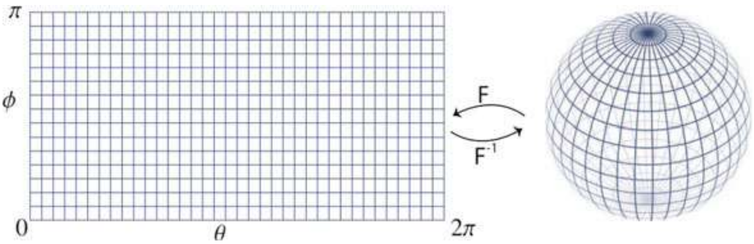

Fig. 2.4 2D domain and its corresponding sphere

the 2D domain. This 2D domain and its corresponding sphere are related through the following equations:

$$F(\theta, \varphi) = \begin{pmatrix} Rcos(\theta)\sin(\varphi) \\ Rsin(\theta)\sin(\varphi) \\ Rcos(\theta) \end{pmatrix}$$

$$F^{-1}(x, y, z) = \begin{pmatrix} \theta \\ \varphi \end{pmatrix} = \begin{pmatrix} tan^{-1}\left(\frac{y}{x}\right) \\ cos^{-1}\left(\frac{z}{R}\right) \end{pmatrix}$$

where R is the radius of the sphere: $R = \sqrt{x^2 + y^2 + z^2}$.

As can be observed from Fig. 2.4, perfect squares on the 2D domain are mapped to distorted quadrilateral or even triangular cells (at the poles) on the sphere. In order to reduce different distortions, it is possible to define alternative mappings, which can be equal-area, conformal (angle-preserving), or possibly stretch-preserving. Since the purpose of a DGGS is to use planar or piece-wise planar (i.e. polyhedral) domains to sample the spherical surface of the Earth, the use of an equal-area projection (in which data values sampled from the Earth occupy similar areas in the DGGS) is often desired (White et al. 1992). Here, we describe some of the most commonly used equal-area projections. There are several traditional options, such as the projections proposed by Lambert (cylindrical and azimuthal), Mollweide, and Werner (see Fig. 2.5) (Snyder 1992).

Among these projections, the Lambert azimuthal equal-area projection is particularly interesting, since it serves as the base projection for a number of equal-area polyhedral projections. In this projection, a point P on the sphere S is projected to a point P' on the 2D domain (2D map). To find P', a plane ρ which is tangent to S at another point C is used. Then, P' is the intersection of ρ with a circle that has its origin at C, passes through P, and is perpendicular to ρ (see Fig. 2.6). Note that the antipode of C (i.e. the point diametrically opposite C) is excluded from the projection as its intersecting circle is not unique. In addition, C is projected to itself along a circle of radius 0. This projection and its inverse can be explicitly described using simple mappings:

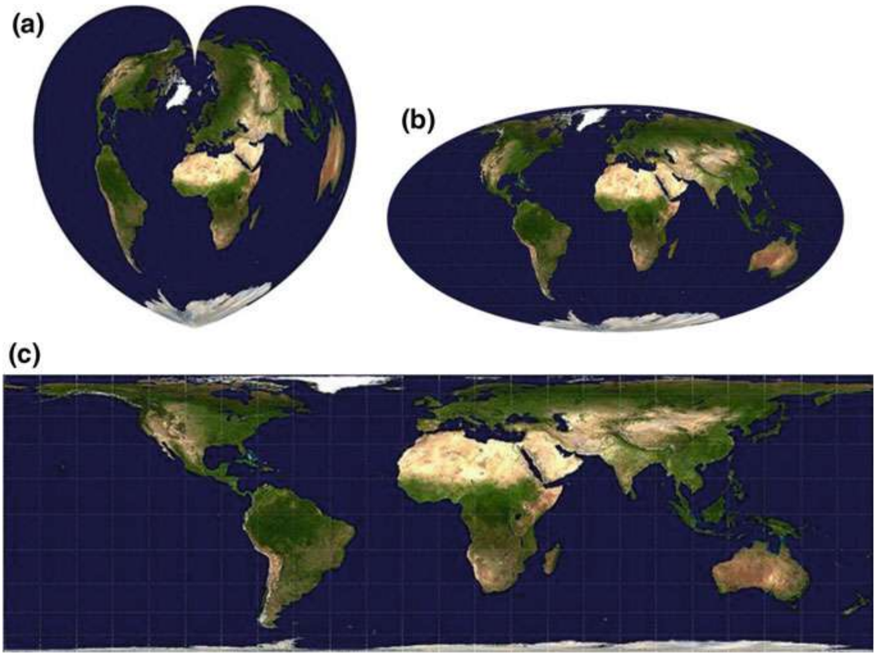

Fig. 2.5 (**a**) Werner, (**b**) Mollweide, and (**c**) Lambert (cylindrical) projections

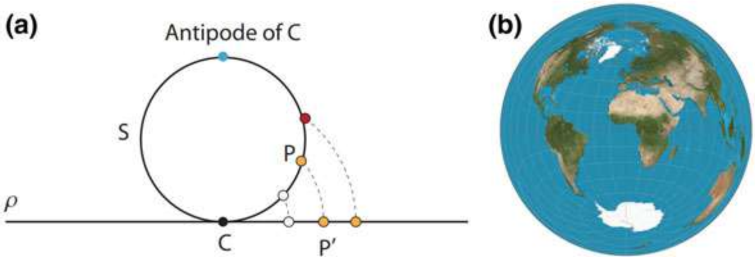

Fig. 2.6 (**a**) Lambert projection from sphere S to plane ρ. (**b**) 2D domain of the Earth resulting from Lambert Azimuthal equal-area projection. The second image is taken from Wikipedia

$$F(x, y, z) = \left(\sqrt{\frac{2}{1-z}}x, \sqrt{\frac{2}{1-z}}y\right),$$

$$F^{-1} = \left(\sqrt{1 - \frac{X^2+Y^2}{4}}X, \sqrt{1 - \frac{X^2+Y^2}{4}}Y, -1 + \frac{X^2+Y^2}{2}\right).$$

2.2.4.2 Projection for Polyhedral Globes

A projection defined for a given polyhedron is characterized by a function F that maps each point P on the sphere to a face of the polyhedron. Consequently F^{-1} is defined as a function that maps points on the polyhedron to the sphere. Often, in order to construct these projections, a traditional projection defined between the sphere and a plane is used individually on each face. For instance, Snyder's equal-area projection (which is commonly used in DGGSs) employs Lambert azimuthal equal-area projection individually for each face. The problem is reduced to projection for right triangles by splitting the faces of the polyhedron along lines of symmetry (see Fig. 2.7). A scaling factor is then found between the radii of two spheres: one with the same area as the (spherical) polyhedron, and another that circumscribes the polyhedron. Finally, a triangle on the polyhedron (whose area matches that of the corresponding spherical triangle that encompasses point P) is generated. The final equation for Snyder's projection is presented in closed form as:

$$x = \rho \sin(Az'),$$

$$y = \rho \cos(Az'),$$

in which the ratio ρ and angle Az' are defined in terms of a set of trigonometric functions and known constants that are provided in (Snyder 1992).

While the forward form of the Snyder projection is presented in a simple closed form, its inverse calculation requires finding the roots of a nonlinear equation (Snyder 1992). Snyder suggests the use of the Newton-Raphson iterative technique to compute the inverse projection, which can slow down the process of mapping points from the polyhedron to the sphere. To reduce this inefficiency, Harrison et al. (Harrison et al. 2011, 2012) worked to optimize the inverse Snyder projection by providing initial estimates to the Newton-Raphson technique that are close to the roots of the nonlinear

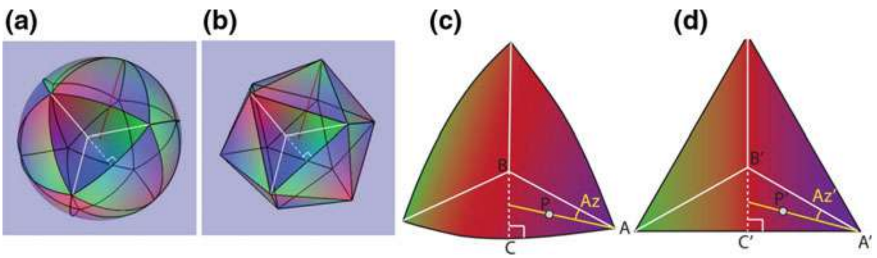

Fig. 2.7 An icosahedron (**a**) after and (**b**) before projection to the sphere. (**c**) The projection operates on right triangles by splitting the initial triangles. Each spherical triangle is associated with a triangle of the polyhedron. Each point P in (**c**) is associated with some point ṕ in (**d**). Az' is the angle between A and the great circle arc passing through P and A

equation. These initial estimates are found using a polynomial curve that fits the roots of the non-linear equation.

In addition to Snyder's projection, other types of equal-area projection have also been used in DGGSs. For instance, Roşca and Plonka's projection (Roşca and Plonka 2011) was used in the one-to-two Digital Earth, which is a cube-based Digital Earth (Mahdavi-Amiri et al. 2013), and extended to the octahedron in (Roşca and Plonka 2012). This equal-area projection describes a mapping from a cubic domain Ω to a spherical domain Δ. The main idea behind this projection is to map each face f of Ω onto a partition of Δ. To this end, an intermediate domain, called a curved square, is used. As a result, the projection involves two steps. First, f is mapped to a curved square on the tangent plane of Δ, parallel to f, using an equal-area bijection denoted by T. Then, the curved square is mapped to a partition of Δ using inverse Lambert azimuthal equal-area projection, denoted by F^{-1} (Fig. 2.8).

HEALPix (see Fig. 2.9) is also a cube-based equal-area projection, and is a hybrid projection of Lambert cylindrical equal-area projection and Collignon pseudo-cylindrical equal-area projection (Gorski et al. 2005). Lambert cylindrical projection is used for equatorial regions of the Earth while Collignon is used for the polar regions.

These equal-area projections are not the only projections that can be used in a DGGS but are examples of projections that have been used already. Naturally, a DGGS designer should always use a projection suited to the needs of their application.

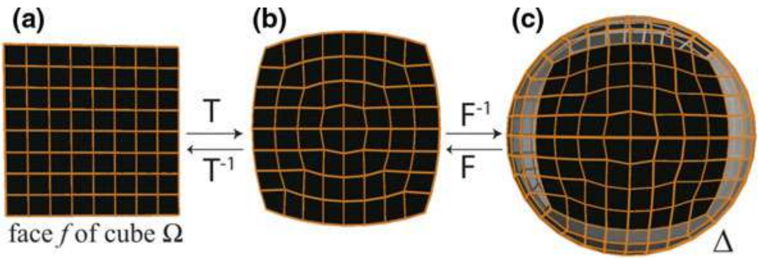

Fig. 2.8 Steps of the spherical projection. Points on a face f of Ω (**a**) are projected onto a curved square (**b**) and then projected onto a portion of the unit sphere Δ (**c**)

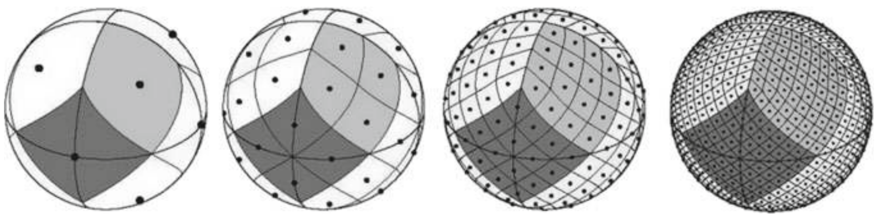

Fig. 2.9 HEALPix projection at four successive resolutions

2.2.5 Indexing

In order for a Digital Earth to handle queries related to location-based data efficiently, a hierarchical approach to data storage is needed. Hierarchical data structures such as quadtrees have been used in various Digital Earth frameworks (Fekete and Treinish 1990; Tobler and Chen 1986), but are typically shelved in favor of indexing methods in order to avoid the cost of expensive tree structures that record node dependencies. Given an indexing method for a DGGS, the method must ensure that, at each resolution, each cell receives an index that uniquely identifies the cell. This index may then be used with reference to a data structure or database in order to retrieve data associated with the cell.

Although various types of methods exist to index the cells of a DGGS, they are typically derived from three types of general indexing mechanisms: hierarchy-based, space-filling curve-based, and axes-based. In the following, we describe each category and provide some examples.

2.2.5.1 Hierarchy-Based Indexing

Applying refinements to a polyhedron produces a hierarchy that can be used to index cells. When a refinement is applied to a set of coarse cells, fine cells are created and assigned to coarse cells through a parent-child relationship. It is possible to use this relationship to define an indexing system by assigning an initial index to each cell at the first (i.e. lowest) resolution, and then using each cell's index as a prefix to the indices of its children. Formally, if a coarse cell has index $Id_0d_1 \ldots d_{r-1}$, then its children receive indices of the form $Id_0d_1 \ldots d_{r-1}d_r$, where d_r is an integer whose range is known as the base of the indexing method, denoted by b (i.e. $d_i \in [0, b-1]$).

The base is used to define algebraic operations on indices, such as conversion to and from the Cartesian coordinate system, or neighborhood finding (Tobler and Chen 1986; Vince and Zheng 2009). Hierarchy-based indexing is very efficient in supporting hierarchical queries, although neighborhood-finding tasks may require complex algorithms, depending on the base of the indexing method and the algebra defined for the indexing system. An example of this type of indexing was proposed in (Gargantin 1982) for quadrilateral cells resulting from 1-to-4 refinement (see Fig. 2.10). Here, the children resulting from 1-to-4 refinement on a quadrilateral with index I receive indices I_0, I_1, I_2, I_3.

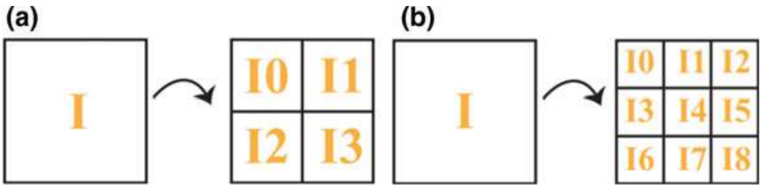

Fig. 2.10 Hierarchy-based indexing systems in (**a**) base four and (**b**) base nine

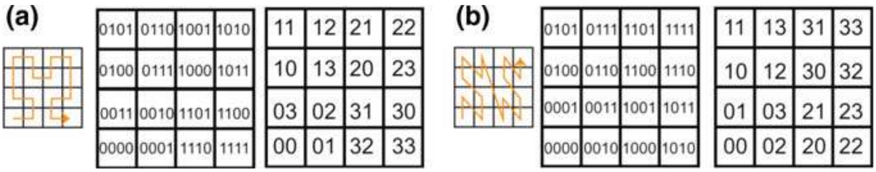

Fig. 2.11 (**a**) (Left) Hilbert SFC. (Middle) Indexing in base two. (Right) Indexing in base four. (**b**) (Left) Morton SFC. (Middle) Indexing in base two. (Right) Indexing in base four

2.2.5.2 Space-Filling Curve Indexing

Another method for indexing cells in a DGGS is to use a space-filling curve (SFC) as a reference for the indexing (Mahdavi-Amiri et al. 2015b). SFCs have been used in many applications, such as compression, rendering, and database management, and are 1D curves (often recursively defined) that cover a particular space.

Recursively defined SFCs start from a simple initial geometry defined on a simple domain (usually a square). The domain is then refined and the simple geometry is repetitively transformed to cover the entire refined domain. Typically, if the initial geometry covers i cells, a 1-to-i refinement is suitable for use in generating a refined domain. In this way, each SFC is associated with a refinement. To index cells based on an SFC, decimal numbers can be employed, though the corresponding indices do not directly encode the resolution. To resolve this issue and obtain a compact indexing, a base b for the indexing that is compatible with the refinement is often chosen. With a 1-to-i refinement, this usually means that the base of the indexing method is taken to be i or $\sqrt{i}$ (see Fig. 2.11). For instance, the refinement associated with the Hilbert and Morton curves is 1-to-4. Therefore, when using a Hilbert and Morton curve, a base four or base two indexing is appropriate.

Indexing methods derived from SFCs have been widely used in DGGS and terrain rendering. For instance, in (Bai et al. 2005; White 2000), Morton indexing was used to index cells resulting from 1-to-4 refinements on the icosahedron and octahedron, while in (Bartholdi III and Goldsman 2001), the Sierpinski SFC was used to index triangular cells refined with a factor of two.

2.2.5.3 Axes-Based Indexing

Another mechanism for indexing is to use a coordinate system with m axes, U_1 to U_m, that span the entire space on which the cells lie. Then the cells' indices can be expressed as m-dimensional vectors $(i_1, i_2, \ldots, i_m)$, in which the i_j are integer values that indicate the number of unit steps taken along each axis, U_j. If, alternatively, a 1D

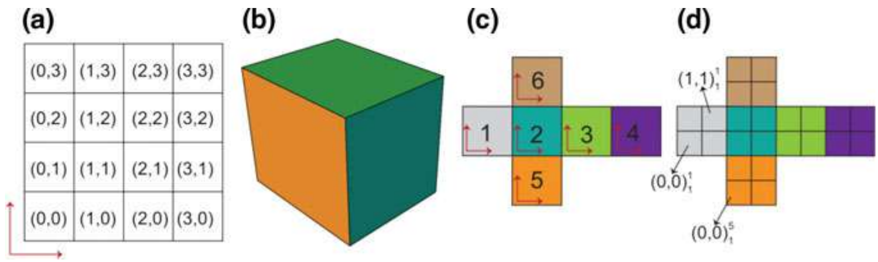

Fig. 2.12 (**a**) Integer indexing of cells using Cartesian coordinates. (**b**) A cube. (**c**) The unfolded cube in (**b**) and coordinate systems for each face. **d** Indices of some cells after one step of 1-to-4 refinement

index is required, these integer values can be appended together in a string, separated using a delimiter character. A simple example of such an indexing can be used to index a quadrilateral domain with Cartesian coordinates, as illustrated in Fig. 2.12a. When a refinement is applied to the cells, a subscript r is appended to the index in order to encode the resolution. In the proposed axes-based indexing methods for DGGSs, m is typically taken to be two or three. For instance, 3D indexing was used in (Vince 2006) by taking the barycentric coordinate of each cell to be its index.

A 2D indexing method can be applied on the polyhedron used to construct a DGGS by embedding the polyhedron's faces into a 2D domain and defining a coordinate system over that domain (Mahdavi-Amiri and Samavati 2012). In this way, each face can be given its own coordinate system (Mahdavi-Amiri et al. 2013, 2015a; Mahdavi-Amiri and Samavati 2014). Figure 2.12 illustrates an indexing for the quadrilateral cells of a cube after 1-to-4 refinement, where each face has its own coordinate system. In order to distinguish between the cells associated with each face, an additional component that refers to the initial polyhedral face can be added to the indices. For example, index $(a, b)_r^f$ refers to cell (a, b) in face f at resolution r (Fig. 2.12d).

2.2.5.4 Remarks on Categorization

Note that this categorization of index types is primarily intended to reflect the core idea used to construct the indexing methods and can be used to easily identify which operations can be handled naturally by a particular indexing system. For example, hierarchy-based indexing methods naturally lead to efficient hierarchical traversal operations. However, well-designed indexing methods must necessarily also consider other properties and support other operations. For example, it is certainly possible to handle neighborhood finding in hierarchy-based indexing methods, although not as efficiently or as naturally as with axes-based techniques. Based on the pattern of indices, some indexing methods can be interpreted as belonging to two categories (e.g. SFC or hierarchy-based). However, an indexing method is either constructed through use of a parametrized curve or it inherits the index of its parent. It is possible to use a parametrized SFC that indexes the children and prefixes the parent's index.

This indexing method is considered to be SFC-based, since the construction of the indexing is based on the parametrization of the SFC and not on the hierarchy of the cells.

2.3 Scientific Digital Earths

Now that we have discussed the various components that define different DGGSs, let us examine some specific DGGS constructions that have been proposed in the literature. Note that some proposed DGGSs are left for the following section, in which we survey some of the existing Digital Earth implementations.

Among the earliest proposed DGGSs are those designed by Digital Earth pioneers M. Goodchild and G. Dutton. Goodchild's HSDS (Hierarchical Spatial Data Structure (Goodchild and Shiren 1992)) is built upon an initial octahedron. Unlike many other DGGSs, the faces of this octahedron are inverse projected to the sphere before the generation of finer cells, and the refinement (a congruent, 1-to-4 refinement) is applied directly on the resulting spherical triangles (using geodesic rather than Euclidean midpoints). The child cells are also spherical triangles, and are indexed using a hierarchical base-4 numbering scheme (see Fig. 2.13). Unfortunately, the projection implied by the refinement method is neither equal-area nor conformal.

Dutton's QTM (Quaternary Triangle Mesh (Dutton 1999)) is also constructed using congruent 1-to-4 refinement on an initial octahedron but utilizes the more typical refine-then-project approach (see Fig. 2.14). Here, the employed projection is a specially designed projection that is also neither equal-area nor conformal—the ZOT (Zenithal Orthotriangular Projection (Dutton 1991))—which tries to have similar facets with vertices spaced uniformly in latitude and longitude, as well as low areal distortion. Indexing is performed similarly to the HSDS, with the faces of the initial octahedron indexed 1 through 8, and child cells indexed hierarchically in base 4.

SCENZ-Grid (SEEGrid 2019) is a DGGS that is constructed based on an initial cube polyhedron, and which was created through a collaboration between Landcare Research and GNS Science primarily for the purpose of environmental monitoring.

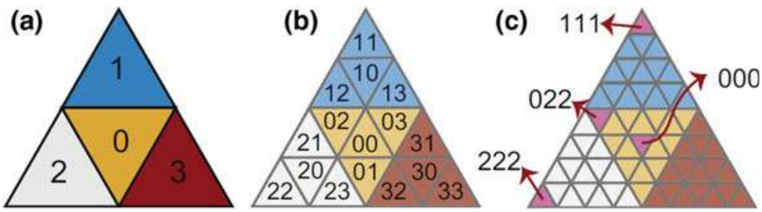

Fig. 2.13 (**a**, **b**) The hierarchical indexing system of the HSDS. (**c**) Indices of descendant cells after three refinements

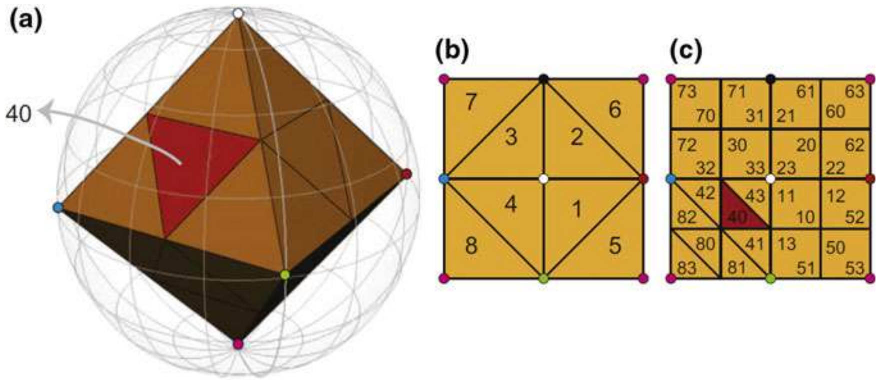

Fig. 2.14 The QTM DGGS. (**a**) The initial octahedron, embedded in a sphere. (**b**, **c**) The hierarchical indexing system of the QTM

The faces of the initial cube are refined using a 1-to-9 congruent and aligned quadrilateral refinement, and the resulting cells are inverse projected using the HEALPix projection method (see Sect. 2.2.4.2). A hierarchical base-9 indexing system is used to address the cells (see Fig. 2.15).

Quadrilateral cells are also found in Crusta (Bernardin et al. 2011), a DGGS based on a rhombic triacontahedron. Each of the initial 30 quadrilateral faces undergoes a 1-to-4 refinement, and the generated vertices are normalized to the geoid. Crusta's primary motivation includes support for high-resolution topographical data and images.

A number of hexagon-based DGGSs have also been proposed and have garnered much research attention. The ISEA3H (Icosahedral Snyder Equal Area Aperture 3 Hexagonal) DGGS is a particularly notable example which starts from an icosahedron (or truncated icosahedron) that undergoes an aligned 1-to-3 hexagonal refinement (US Patent No. 8400451, 2004; Sahr 2008). The resulting cells are inverse projected to the sphere using Snyder's equal-area projection. Note that as the refinement scheme

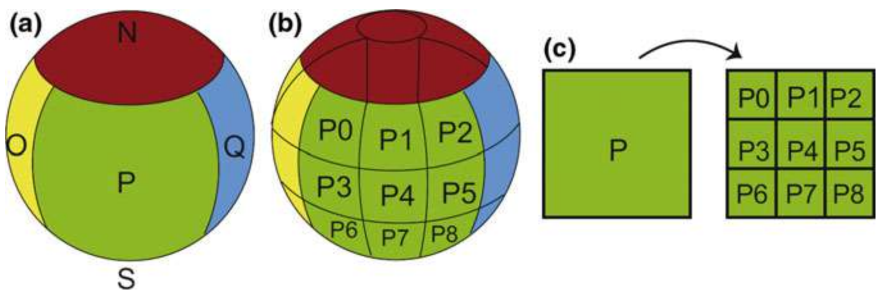

Fig. 2.15 (**a**), (**b**) SCENZ-Grid is created from a refined cube inverse projected to the sphere. (**c**) The hierarchical indexing system of SCENZ-Grid

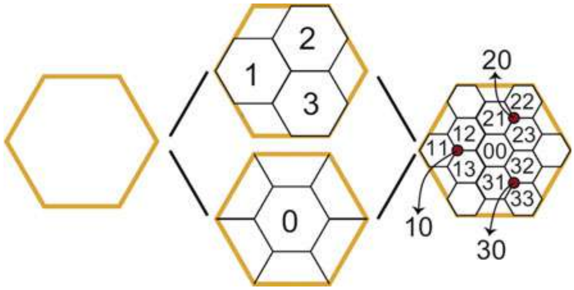

Fig. 2.16 Two types of 1-to-4 hexagonal refinement can be combined, allowing a triangular cell hierarchy to be established and indexed

(and, indeed, any hexagonal refinement scheme) is not congruent, special care must be taken to define the cell hierarchy and indexing scheme. Several different indexing schemes have been proposed for the ISEA3H DGGS. These include the hierarchical indexing of PYXIS (US Patent No. 8400451, Peterson 2004), CPI (US Patent No. 9311350, Sahr 2016), coordinate-based indexing mechanisms (Sahr 2008; Mahdavi-Amiri et al. 2015a; Vince 2006), or the algebraic encoding scheme of (Ben et al. 2018).

The icosahedron can also be refined using 1-to-4 hexagonal refinement, as in the construction of the HQBS (Hexagonal Quaternary Balanced Structure (Tong et al. 2013)). The resulting cells are also inverse projected using Snyder's projection. In order to mitigate the incongruity of the hexagonal refinement, two different 1-to-4 refinements are employed (aligned and unaligned; see Fig. 2.16). This allows a triangular hierarchy to be defined (aligned with the edges of the initial icosahedron) and for lattice points to be indexed. By taking the index of the point at the cell's centroid to be the cell's index, a base 4 hierarchical indexing system can be established on the cells.

Other hexagon-based DGGSs include the OA3HDGG and OA4HDGG (Octahedral Aperture 3/4 Hexagonal Discrete Global Grid (Vince 2006; Ben et al. 2010)). As implied by the name(s), both DGGSs are constructed from an octahedron that undergoes a hexagonal refinement. The OA3HDGG utilizes a 1-to-3 hexagonal refinement, and its cells are indexed using a coordinate-based system. The vertices of the initial octahedron are assigned the coordinates $(\pm 1, 0, 0)$, $(0, \pm 1, 0)$, and $(0, 0, \pm 1)$; and the cells are assigned indices based on their barycentric coordinates with respect to these vertices. A similar indexing system is applied to the OA4HDGG, which utilizes a 1-to-4 hexagonal refinement.

While most DGGSs discretize only the surface of the Earth, certain types of geospatial data (e.g. earthquake data, airspace delineations, etc.) are volumetric in nature and require a volumetric Earth representation. Hence, volumetric DGGSs such as SDOG (Spheroid Degenerated-Octree Grid (Yu and Wu 2009; Yu et al. 2012)) have also been proposed. SDOG, which was designed to represent the global lithosphere, divides the Earth into an initial set of eight octants. Each octant is associated with a degenerated octree, and undergoes a non-uniform refinement that prevents cell degeneracies at the Earth's core (see Fig. 2.17). Cells are indexed using two different

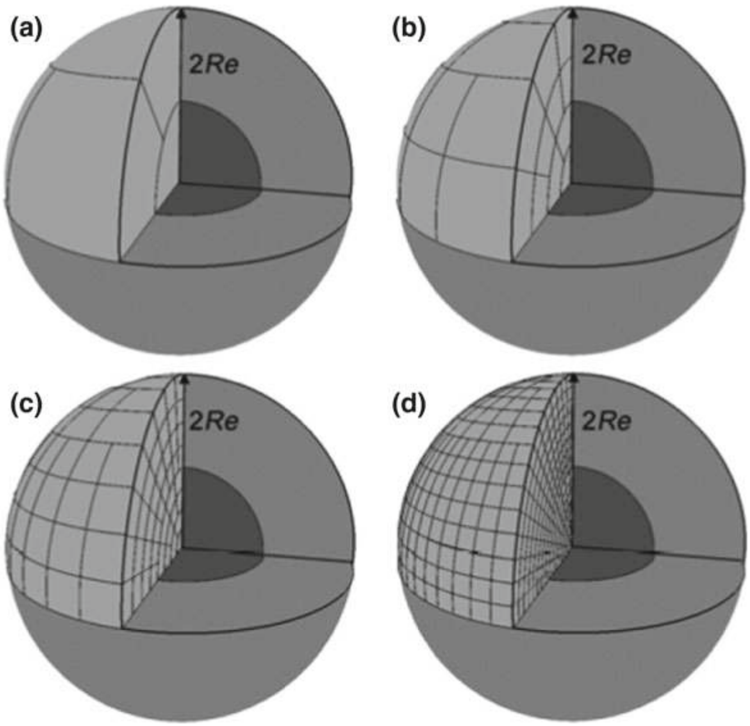

Fig. 2.17 The SDOG volumetric DGGS at three successive resolutions

curve-based schemes, both based on a modified Z-curve. The SDZ (Single Hierarchical Degenerated Z-Curve Filling) method indexes the cells of a single resolution in base 10 (see Fig. 2.18), while MDZ (Multiple Hierarchical Degenerated Z-Curve Filling) serves as a hierarchical indexing scheme in base 8 (see Fig. 2.19).

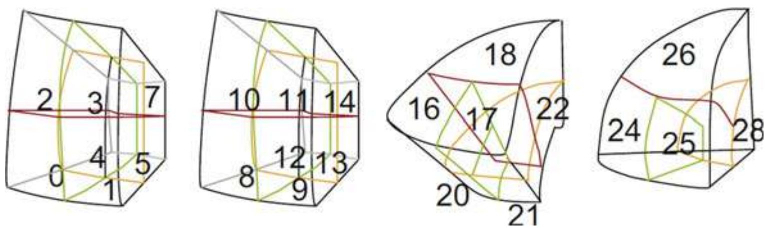

Fig. 2.18 SDZ defines a base 10 indexing for cells at a single resolution

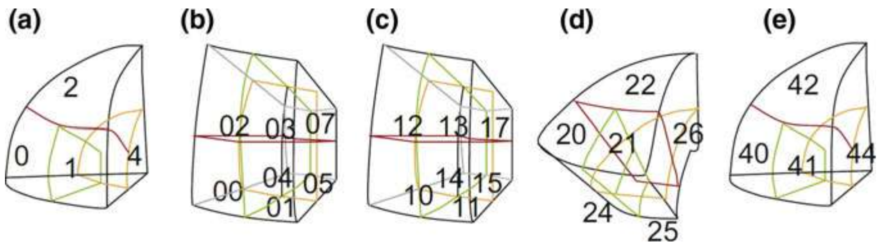

Fig. 2.19 MDZ defines a hierarchical indexing scheme on the SDOG cells. (**a**) A refined octant with child indices. (**b**), (**c**), (**d**) and (**e**) Cells 0, 1, 2, and 4, respectively, refined with child indices

2.4 Public and Commercial Digital Earth Platforms

Naturally, a number of DGGSs and other Digital Earth concepts have been implemented and made available for public use as either free or paid software.

2.4.1 Latitude/Longitude Grids

Due to their ease of use and long history, latitude/longitude grids remain a popular choice for Digital Earth implementations despite the potential issues associated with non-uniform DGGS cells. Chief among these implementations in terms of name recognition is Google Earth (Google Inc. 2019a). Google Earth is created upon a latitude/longitude grid using a simple cylindrical projection, with textures processed via clip-mapping (Bar-Zeev 2007). Clip-Maps are a modified form of mip-map that impose a maximum image size on the mip-map hierarchy (Tanner et al. 1998), causing the image hierarchy to more closely resemble an obelisk than the traditional pyramid (see Fig. 2.20). The capped image size ensures that textures can fit into memory and be rendered in real-time.

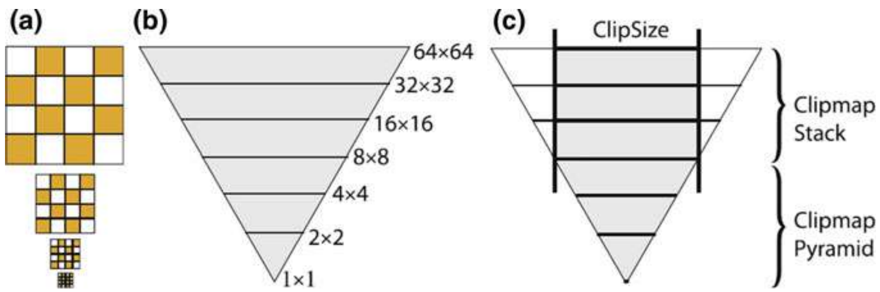

Fig. 2.20 (**a**) An image at multiple resolutions. (**b**) The image's mip-map pyramid. **c** Clip-Maps impose a maximum size on the mip-maps

Although not presented in 3D globe format, Google Maps and Bing Maps are supported using methods that echo the fundamentals of a DGGS (See Figs. 2.21 and 2.22). In particular, Google Maps uses the Mercator projection on a latitude/longitude grid that is refined using a 1-to-4 refinement. Each "tile" of the hierarchical grid is associated with a 256 × 256-sized texture, and is indexed using an axis-based coordinate system. Here, the top-left tile is indexed as (0, 0), with x values increasing towards the east, and y values increasing towards the south (Google Inc. 2019b).

Fig. 2.21 Three resolutions of Bing Maps' hierarchy-based indexing

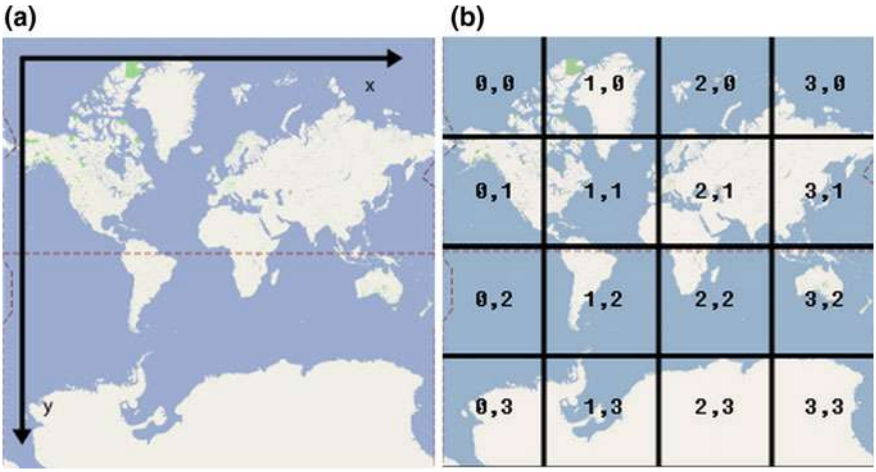

Fig. 2.22 (**a**) Google Maps' latitude/longitude grid. (**b**) Cell indices at the second resolution

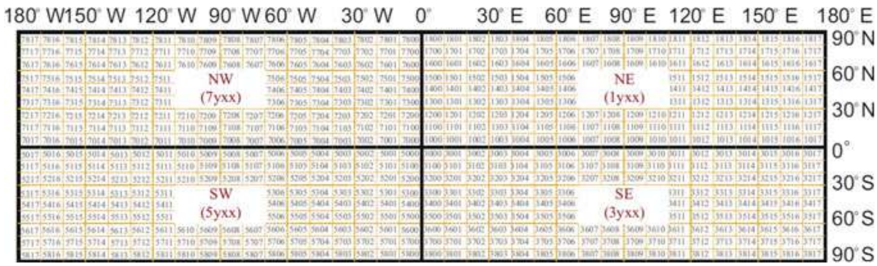

Fig. 2.23 C-squares indexing system

Bing Maps also uses the Mercator projection on a 1-to-4 refined grid, but its indexing system is hierarchical and based on quadtrees (Schwartz 2018). For an illustration, see Fig. 2.21.

The OGC CDB (Common Database) API from Presagis (2019) is designed to address one of the main issues with latitude/longitude DGGSs, namely the shrinking of cells near the poles. The CDB divides the Earth into five zones depending on proximity to the poles, with each zone utilizing a different spacing between lines of longitude. While the CDB is available as an open commercial standard, a Pro license can be purchased for additional features.

Unlike other DGGSs, C-squares (Concise Spatial Query and Representation System (Rees 2003)) discretizes only a single resolution of the Earth. Here, the latitude/longitude grid is divided into four quadrants (NE, NW, SE, and SW), which are then divided into finer grids based on latitude and longitude (Fig. 2.23). The cells of this discretization are indexed as *iyxx*, where *i* corresponds to the cell's quadrant, *y* to the cell's latitude, and *xx* to the cell's longitude. This system was created by CSIRO Marine and Atmospheric Research, Australia for the purposes of mapping, spatial search, and environmental assessment. Converters and source code can be found on their website (CSIRO 2019).

Other Digital Earths based upon latitude/longitude grids include NASA's open source WorldWind API (NASA 2019); Skyline's software products, TerraExplorer client and SkylineGlobe server (Skyline Software Systems 2019); and two DGGS libraries for web-based globe visualization—GlobWeb and CesiumJS (Telespazio 2019; Cesium Consortium 2019). GlobWeb is provided by Telespazio France under the GNU LGPL v3 license, while CesiumJS was founded by the Cesium Consortium and is open source.

CesiumJS in particular is a complete 3D mapping platform built using WebGL. It is a cross-platform and cross-browser map engine that runs on a web browser without plugins, and is now used in industries as diverse as archaeology, engineering, construction, and sports visualizations. An accompanying tool, Cesium ion, provides a point-and-click workflow to create 3D maps of users' geospatial data that can be visualized, analysed, and shared. It can be used to host datasets in 3D tiles, including imagery, terrain, photogrammetry, point clouds, BIM, CAD, 3D buildings, and vector data; and provides tools for analytics including measurements, volume and visibility computations, and terrain profiles.

2.4.2 Geodesic DGGSs

Of course, not all DGGSs are based on singular 2D domains such as a latitude/longitude grid; while comparatively rarer, different implementations of Geodesic DGGSs do exist and are available for use. For instance, a library that implements the well-studied ISEA3H DGGS—known as geogrid—is offered on GitHub (Mocnik 2019). This library is developed and maintained by Franz-Benjamin Mocnik, and is licensed under the MIT license.

A propriety implementation of the ISEA3H can be found at the core of the Digital Earth system developed by Global Grid Systems (formerly the PYXIS innovation (PYXIS innovation 2011; Global Grid Systems 2019)), and is one of the few commercially available Geodesic DGGSs (Fig. 2.24). This system indexes the ISEA3H's hexagonal cells using the patented PYXIS indexing scheme (US Patent No. 8400451, 2004).

Other software platforms include implementations of the ECM (Ellipsoidal Cube Map) and HEALPix (Hierarchical Equal Area isoLatitude Pixelization of the sphere) DGGSs. ECM (Lambers and Kolb 2012) is produced by applying 1-to-4 refinement on the quadrilateral faces of a cube that circumscribes the ellipsoidal Earth. Areal and angle distortions are minimized by using a Quadrilateralized Spherical Cube (QSC) projection. A Linux implementation is available on Martin Lambers' website, licensed under the GNU GPL v3 (Lambers 2019).

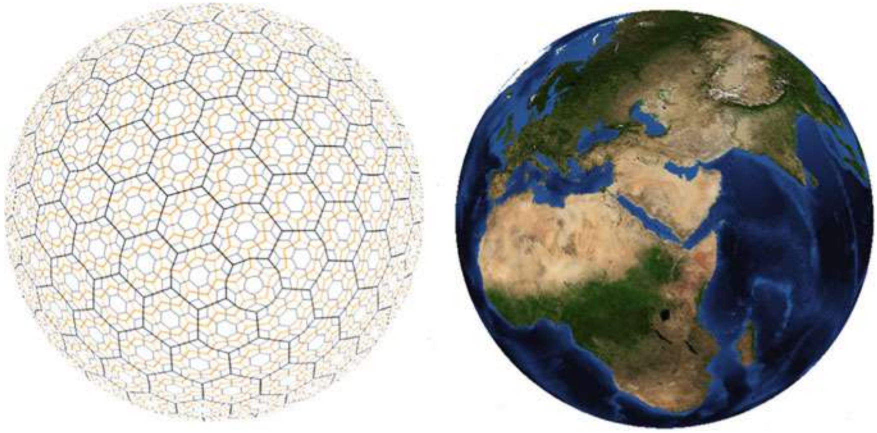

Fig. 2.24 Global Grid Systems' ISEA3H DGGS

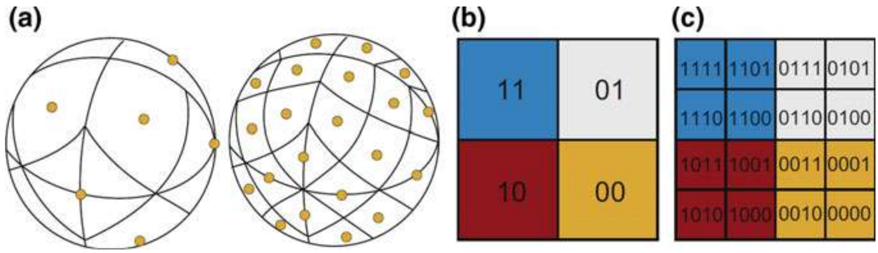

Fig. 2.25 The HEALPix DGGS. (**a**) HEALPix uses a 1-to-4 refinement. (**b**) The hierarchical HEALPix indexing system

The HEALPix DGGS (Gorski et al. 2005) is based on a rhombic dodecahedron that undergoes a congruent 1-to-4 refinement, indexed using a base-2 hierarchical indexing system (see Fig. 2.25). Two different projection schemes are employed: Lambert cylindrical equal-area projection for equatorial regions, and Collignon equal-area projection for polar regions. A software package from the Jet Propulsion Laboratory that supports spherical harmonics, pixel queries, data processing, and statistical analysis can be found online (Jet Propulsion Laboratory 2019).

2.4.3 Installations: DESP

One of the largest scale Digital Earth undertakings can be found at the Chinese Academy of Sciences (CAS), where an interactive visualization environment called the Digital Earth Science Platform was developed (Guo et al. 2017). Based on the Digital Earth Prototype System Initiative that launched in 1999 (Guo et al. 2009, 2010), the Digital Earth Science Platform (DESP) was established by the CAS in 2010 in order to integrate state-of-the-art techniques and meet the increasing requirements of geoscience applications.

The DESP is a technical platform that supports spatial data and information services, as well as associated applications. It integrates 2D and 3D geographic information systems, distributed storage and computing, virtual reality, wireless sensor networks, and other technologies. A 600 m^2 fully immersive, interactive visualization environment was established at the CAS Institute of Remote Sensing and Digital Earth (RADI) to support experiments with 3D visualization and to provide decision support for emergency response applications. This installation is equipped with VR/AR devices, sensors, a 3D Stereo Projection System, and a high-performance computing system, as shown in Fig. 2.26.

The DESP has already played an important role in the modeling of global change, evaluation of natural disasters, and monitoring of natural resources and human settlement through the integration of multi-sensor, multi-temporal remote sensing images, in situ ground survey data, socio-economic data, and interdisciplinary scientific models (Fan et al. 2009). For example, the influence of sea level rise on the Earth's major

Fig. 2.26 The DESP visualization environment at RADI

river deltas has been modeled and analyzed in a comparative study by using the DESP. Emergency monitoring and response systems based upon the DESP have been developed for disaster monitoring and post-disaster relief after earthquake events (Fig. 2.27).

As a part of the ongoing Big Earth Data Science Engineering (CASEarth) initiative (2018–2022), which is supported by the Strategic Priority Research Program of the CAS, a new generation of the Digital Earth Science Platform will be developed to provide a new impetus for interdisciplinary, cross-scale, macro-scientific discoveries in the Era of Big Data to promote sustainability (Guo 2017).

Fig. 2.27 The DESP was used for disaster assessment and relief after the 2013 Ya'an earthquake

2.5 Discrete Global Grid System Standards

The myriad ways in which one can construct a Digital Earth platform provide a great deal of flexibility that can help cater to a vast range of specific uses; however, this can also create barriers to interoperability. This creates a real challenge as we move into the Era of Big Data (and beyond), where interoperability and distributed analysis is critical.

In the Era of Big Data, geoscience can only achieve its full potential through the fusion of diverse Earth observation and socio-economic data together with information from a vast range of sources. In this type of environment with multiple data providers, fusion is only possible with an information system architecture based upon open standards (Percivall 2013). Without a common and standardized means of defining and integrating various Digital Earth Platforms, our ability to transform the increasingly massive amounts of data that are being acquired about the Earth into actionable information is significantly limited.

2.5.1 Standardization of Discrete Global Grid Systems

Recognizing the issues that non-standard global grid system implementations pose and their potential impacts, in 2014, the Open Geospatial Consortium embarked on the ambitious goal of standardizing DGGS. The goal of this endeavor was not to identify the one DGGS that ought to be used by everyone, but to define the common qualities of a variety of DGGSs that can be used to support interoperability while providing some flexibility in choice, thus allowing implementers to tailor DGGS infrastructures to their specific uses. In July 2017, the OGC published the first ever international standard governing the design and implementation of DGGS (Purss et al. 2017). This standard aims to promote awareness and reusability of DGGS implementations, and integration between them, and, through this, to demonstrate a path towards the realization of the "Digital Twin"—where our engagement and understanding of the physical Earth can seamlessly interact with the Digital Earth, and vice versa.

The core of the OGC DGGS standard is primarily based on an appropriate subset of the well-accepted criteria for optimal DGGS design proposed by Goodchild (2000) and Sahr et al. (2003).

2.5.2 Core Requirements of the OGC DGGS Abstract Specification

Along with the categorization provided earlier, under the OGC DGGS Abstract Specification, a compliant DGGS must define a hierarchical tessellation of equal area cells that both partition the entire Earth at multiple levels of granularity and provide a global spatial reference frame. In addition to these structural components, the system must also include encoding methods to address each cell, assign quantized data to cells, and perform algebraic operations on the cells and the data assigned to them.

The requirement of functional components for the infrastructure sets an OGC DGGS apart from other grid frameworks or Coordinate Reference Systems. It also provides a common operational basis for supporting communication and interoperability between different compliant DGGS infrastructures.

2.5.2.1 Structural Requirements

The reference frame of a DGGS consists of the fixed structural elements that define the spatial framework on which the DGGS functional algorithms operate. These fixed structural elements include:

1. **Domain completeness and position uniqueness**: The DGGS must be defined over a global domain without any overlapping cells. Goodchild defines a global domain to be achieved when the areal cells defined by the grid "*exhaustively cover the globe without overlapping or underlapping*" (Goodchild 2000);
2. **Multiple levels of resolution**: The DGGS must define multiple discrete global grids forming a system of hierarchical tessellations, each with progressively finer spatial resolution and linked via a common cell refinement method;
3. **Preservation of domain completeness and position uniqueness**: The DGGS must preserve the total surface area (i.e. the global domain) throughout the entire range of hierarchical tessellations. This facilitates the consistent representation of information at all resolutions within the DGGS;
4. **A simple geometric structure for each cell**: In order for the DGGS to achieve the requirement of a global domain, it is necessary for the shape of all cells defined by the DGGS to be simple polygons on the surface model of the Earth. The cell shapes derived from the five (5) Platonic solids and thirteen (13) Archimedean solids (triangle, quadrilateral, pentagon, hexagon, and octagon) are all simple polygons that have the following properties:
    a. The edges meet only at the vertices;
    b. Exactly two edges meet at each vertex; and,
    c. The polygons enclose a region which always has a measureable area.
5. **Equal-area cells**: The DGGS must be based on a hierarchy of equal-area tessellations. Equal-area cells provide global grids with spatial units that (at multiple resolutions) have an equal probability of contributing to an analysis. Equal-area cells also help minimize the confounding effects of area variations in spatial analyses, where the curved surface of the Earth is the fundamental reference frame;
6. **An initial polyhedral tessellation**: To consistently achieve equal-area cells, the DGGS must be constructed by mapping a polyhedron to the surface model of

the Earth. This initial tessellation can then be refined to produce equal-area child cells for all subsequent levels in the hierarchy of tessellations;

7. **Unique identifiers for each cell**: In order to efficiently operate as a spatial data integration engine, the cells of the DGGS must each be defined by a globally unique identifier. This ensures that the reference to each and every cell is immutable. While the OGC DGGS Abstract Specification requires each cell to be uniquely identified, it does not prescribe or enforce how the implementer must achieve this;
8. **Each cell referenced at its centroid location**: Each DGGS cell must be referenced at its centroid. This is because the centroid is the only location that provides a systematic and consistent spatial reference point for all cells, regardless of shape.

2.5.2.2 Functional Requirements

The ability to locate and perform algebraic operations on data assigned to a DGGS is critical for a DGGS to be able to support connectivity and hierarchical operations on cells and to facilitate interoperability between DGGS implementations (as well as other spatial data infrastructures or interfaces). Accordingly, the OGC DGGS Abstract Specification requires the DGGS to specify definitions for:

1. **Quantization operations**: Assigning data to and retrieving data from cells;
2. **Algebraic operations**: Performing algebraic operations on cells and the data assigned to them, in addition to performing cell navigation; and
3. **Interoperability operations**: Translating cell addresses to other Coordinate Reference Systems (CRS), such as conventional latitude/longitude.

Again, the OGC DGGS Abstract Specification enforces no specific implementations of these functional elements, but requires their inclusion (in some form) in any compliant DGGS implementation. This both facilitates flexibility and innovation in the design of individual DGGS implementations and ensures the widest scope for interoperability between compliant DGGS implementations. By focusing on end-point functional requirements and not on the methods by which they are achieved, the OGC DGGS Abstract Specification supports interoperability across multiple social and technical domains. This approach also allows for advancements in the technologies that support these functional elements, without requiring the standard to be constantly re-written.

2.5.3 The Future of the DGGS Standard

In support of the wider adoption and implementation of compliant (and interoperable) DGGS implementations, there are a number of initiatives currently underway within both the OGC and the International Standards Organization (ISO). These initiatives include:

1. The publication of the OGC DGGS Abstract Specification as an ISO standard (ISO 19170). By publishing this standard as an ISO standard, it will be possible to reach a wider community of potential DGGS implementers and thus increase the adoption of DGGS technologies.
2. The establishment of an OGC Registry of compliant DGGS implementations. This will facilitate the certification and publication of compliant DGGS implementations and increase the awareness of the choices of available DGGS implementations that can be applied to a Spatial Data Infrastructure. This will be similar in nature to the Coordinate Reference System Registry. The first release of the OGC DGGS Registry is anticipated to occur by the end of 2018.
3. The development of a standardized specification of a common API language for DGGS. This work is in its early phase but is expected to result in the drafting and publication of a new OGC implementation standard that specifies a common API language supporting and facilitating interoperability between different DGGS implementations. A common API language for DGGS implementations will further lower the technical barriers to the wider implementation of DGGS technologies.

2.5.4 Linkages Between DGGS and Other Standards Activities

As a technology, DGGSs have the potential to impact on almost all spatial technologies and their related standards. Consequently, a number of international standards activities have included references to DGGSs and their potential applications to several scenarios relevant to these initiatives. Two examples of this include:

1. The Joint OGC-W3C Spatial Data on the Web Best Practices (Van Den Brink et al. 2019), where DGGS was proposed as an enabling component of QB4ST (an extension of existing RDF Datacube vocabularies to support spatio-temporal data).
2. The Global Statistical Geospatial Framework (GSGF), adopted during the 6th Session of the United Nations Committee of Experts on Global Geospatial Information Management in August 2016, refers to DGGS and acknowledges that these technologies have the potential to help realize the implementation of the GSGF.

As the number of DGGS implementations increases, so too will the suite of international standards that support them and their applications. The challenge for the International Standards Community will be to keep the number and complexity of these standards to an acceptable level in order to ensure that the DGGS standards do not become a barrier to adoption in themselves.

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Chapter 3
Remote Sensing Satellites for Digital Earth

Wenxue Fu, Jianwen Ma, Pei Chen and Fang Chen

Abstract The term remote sensing became common after 1962 and generally refers to nonintrusive Earth observation using electromagnetic waves from a platform some distance away from the object of the study. After more than five decades of development, humankind can now use different types of optical and microwave sensors to obtain large datasets with high precision and high resolution for the atmosphere, ocean, and land. The frequency of data acquisition ranges from once per month to once per minute, the spatial resolution ranges from kilometer to centimeter scales, and the electromagnetic spectrum covers wavebands ranging from visible light to microwave wavelengths. Technological progress in remote sensing sensors enables us to obtain data on the global scale, remarkably expanding humanity's understanding of its own living environment from spatial and temporal perspectives, and provides an increasing number of data resources for Digital Earth. This chapter introduces the developments and trends in remote sensing satellites around the world.

Keywords Remote sensing · Digital Earth · Satellite · Earth observation

3.1 Development of Remote Sensing

Remote sensing is a core technology for Earth observation. It covers information collection, in-orbit processing, information storage and transmission, ground reception, processing for applications, calibration, verification, applied research, and basic research, providing fundamental data resources for Digital Earth (Guo 2012).

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3.1.1 Overview of Remote Sensing

3.1.1.1 Remote Sensing Platforms

Remote sensing refers to various observation and exploration activities of the environment involving humans and photoelectronic devices carried by satellites, spacecraft (including space shuttles), aircraft, near-space vehicles, and various terrestrial platforms. Artificial satellites that carry sensors to capture images of Earth's surface are referred to as remote sensing satellites. Satellites can successively observe the whole globe or an assigned part of it within a defined time period (Guo et al. 2016). Aircraft often have a definite advantage because of their mobilization flexibility. They can be deployed wherever and whenever weather conditions are favorable. Satellites and aircraft collect the majority of base map data and imagery used in remote sensing, and the sensors typically deployed on these platforms include film and digital cameras, light-detection and ranging (LiDAR) systems, synthetic aperture radar (SAR) systems, and multispectral and hyperspectral scanners. Many of these instruments can also be mounted on land-based platforms such as vans, trucks, tractors, and tanks. In the future, the Moon will also be an ideal remote sensing platform (Guo et al. 2014a, 2018).

3.1.1.2 Remote Sensing Sensors

There are several types of Earth observation sensors: photographic sensors, scanning imaging sensors, radar imaging sensors, and nonimaging sensors. Photographic sensors work like a digital camera. Scanning imaging sensors capture two-dimensional images by scanning point by point and line by line in a time sequence. These are widely used today; such sensors can be further divided into surface scanning and image scanning sensors. Imaging radar is an active sensor that emits electromagnetic waves to form a lateral profile. Currently, most Earth observation satellites carry SAR systems that feature very high resolutions.

In the early stage of spaceborne Earth observation, traditional film-based imaging devices, return beam vidicon (RBV) TV cameras, and optical scanners were the main devices used for Earth observation. Images obtained from these devices were mainly color and black-and-white representations of Earth's surface and cloud layer, covering the visible light and near infrared ranges. After the first land observation satellite, Landsat 1, was launched in 1972, the new multispectral scanner (MSS) it carried sent data that was processed in the form of a digital time sequence array. This marked a progressive step in the development of digital image processing.

Compared with optical remote sensors, SARs work in various weather conditions and can penetrate some surface objects. In contrast to passive sensor systems that only receive reflected solar light or infrared radiation, radar systems act as active sensors and emit electromagnetic waves on their own. A radar sensor sends pulses of energy to the Earth's surface and part of that energy is reflected and forms return signals. The strength of the return signal depends on the roughness and dampness of the Earth's surface and the inclination of surface objects toward the waves sent by radar.

3.1.2 Development of Remote Sensing Satellites

Based on a life cycle of approximately thirteen years, Earth observation satellites have gone through four generations (Fig. 3.1) (Zhou 2010).

(1) The first generation, beginning spaceborne Earth observation: 1960–1972

CORONA, ARGON, and LANYARD were the first three imaging satellite observation systems. Data obtained from these satellites were used for detailed terrestrial reconnaissance and regional mapping. In the early years, satellite images were made by combining hundreds or even thousands of photos, most of which were black-and-white, with a small number of color photos or three-dimensional image pairs. These images covered most parts of Earth. For example, images obtained using the KH-5 camera covered most of the Earth's surface with a 140-m pixel resolution. However, these images did not form systematic observations like those achieved later with Landsat data.

(2) The second generation, experimental and tentative application: 1972–1986

Landsat-1 was launched on July 23, 1972, marking the start of modern satellite-carried Earth observation. It provided a novel high-resolution Earth image database to international science organizations, making further exploration of Earth's resources possible. Landsat-1 carried an MSS that received four bands with wavelengths from 0.5 to 1.1 μm with a spatial resolution of 80 m, frame width of 185 km, and revisit cycle of eighteen days. Notably, Landsat-1 transmitted data in digital form for the first time. The foundation for multispectral processing was laid in the 1970s and organizations involved in this field included NASA, Jet Propulsion Laboratory (JPL), United States Geological Survey (USGS), Environmental Research Institute of Michigan (ERIM), and Laboratory for Applications of Remote Sensing (LARS). Ten years

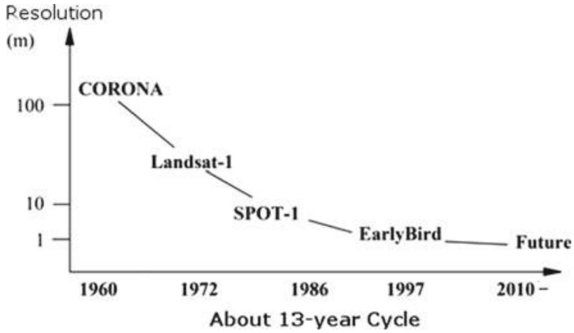

Fig. 3.1 History of the thirteen-year cycle of Earth observation satellite development (Zhou 2010)

later, Landsat accommodated four more MSS wavebands as Landsat TM emerged during 1982–1984 with a spatial resolution of 30 m covering seven spectral bands. Soon afterwards, the famous SPOT HRV system was launched in 1986 with a spatial resolution of 10 m for the panchromatic wavebands and 30 m for three other multispectral bands.

(3) The third generation, wide application: 1986–1997

After 1986, the technology and applications of satellite Earth observation developed rapidly. SPOT-1, launched on February 22, 1986, carried a high-resolution visual sensor and was the first use of pushbroom linear array sensors. It was also the first satellite system capable of cross-track three-dimensional observation. Later, the ESA launched the ERS-1 SAR on July 17, 1991. ERS-1 was an active microwave satellite that provided images with a spatial resolution of 30 m. Japan launched its JERS-1 in February 1992 with an L-band SAR, building up the overall observation capacity of SARs. Data provided by these active microwave sensors played an important role in enhancing the observation and understanding of environmental and climatic phenomena, and supported the categorization of sea ice and research on the coastal zone.

(4) The fourth generation, high-resolution and hyperspectral imaging: 1997–2010

This comprises the latest generation of Earth observation satellites equipped with the most advanced technologies that are still gradually maturing. The main features are a spatial resolution of 1 m or less, coverage of 200 wavebands ranging from 0.4 to 2.5 μm in wavelength, a spectral resolution of 10 nm, revisit cycles less than three days, capability of multiangle and three-dimensional observation, and precise spatial positioning with GPS. The major advantage of high-resolution imaging is that it allows for identification of buildings, roads, and modern construction projects as well as change detection. As a result, high-resolution imagery products are mainly used in GIS and special-purpose mapping.

At this stage, attention was primarily focused on spatial and temporal resolutions, spectral coverage, orbital height, revisit capability, mapping bandwidth, image dimensions, capacity for three-dimensional observation, imaging models, data storage, and the market demand for satellites.

(5) The fifth generation, a new era of satellite Earth observation

Next-generation Earth observation satellites are expected to be highly intelligent and integrate Earth observation sensors, data processing devices, and communication systems. Global surveying and real-time environmental analysis of Earth will become possible. More experts as well as casual users will be involved in remote sensing, photogrammetry and GIS, and data inversion products will also be updated more frequently. To achieve real-time data acquisition, improve applications and spare casual users the trouble of understanding complicated data processing, image providers will offer mature imaging products that directly meet various demands (Guo et al. 2014b).

3.2 Land Observation Satellites

Land observation satellites have been developed for land resource investigation, terrestrial environment research, crop condition forecasting, and natural disaster monitoring. Terrestrial variables have a specific "ground object spectrum" and radiation scattering; terrestrial variables can be retrieved by considering the direction, scale, and sensitivity to establish the relationship between electromagnetic waves and ground surface variables for space observation.

3.2.1 US Land Observation Satellites

The United States launched its first land satellite, Landsat 1, on July 23, 1972. For the first time in human history, satellites were consistently providing Earth images with a certain resolution, making it possible to use satellites to survey Earth's resources. Since then, the country has launched seven satellites in the Landsat series (the launch of Landsat 6 failed). They are currently the world's most widely used land observation satellites (Table 3.1).

Later, the United States launched a series of high-resolution commercial remote sensing satellites. The IKONOS satellite, launched on September 24, 1999, was the world's first commercial remote sensing satellite providing high-resolution images. After that, the country launched the QuickBird, WorldView-1, GeoEye-1, and Wor1dView-2 satellites in October 2001, September 2007, September 2008, and October 2009, respectively, with improved resolutions from 0.61 to 0.41 m (multispectral) (Aguilar et al. 2013).

3.2.1.1 Landsat Program

The Earth Resources Satellite Program involves a series of Earth observation satellites jointly managed by NASA and the United States Geological Survey (USGS). These satellites collect information about Earth from space. They have been providing digital photos of Earth's continents and coastal regions for more than 40 years, enabling researchers to study Earth from various aspects and evaluate the impacts of natural and human activities on the dynamics of the Earth system.

(1) Landsat 7

Landsat 7 moves around Earth on a near-polar sun-synchronous orbit, with an orbital altitude of 705.3 km and an operation cycle of 98.9 min, covering Earth once every sixteen days. During the day, it operates on a descending orbit, crossing the equator at 10:00 AM. The orbit is adjusted so that orbital inclination is kept within a certain limit and the deviation of the satellite transit time from the nominal time is kept within ±5 min.

Table 3.1 Land satellites launched by the United States

Satellite code	Type of orbit	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch date
Landsat-1	Sun-synchronous orbit	917	103.1	99.2	1972.6.23
Landsat-2	Sun-synchronous orbit	917	103.3	99.2	1975.1.22
Landsat-3	Sun-synchronous orbit	917	103.1	99.1	1978.3.5
Landsat-4	Sun-synchronous orbit	705	98.9	98.2	1982.7.16
Landsat-5	Sun-synchronous orbit	705	98.9	98.2	1984.3.1
TRMM	Inclined orbit	405	93.5	35	1997.11.27
Landsat-7	Sun-synchronous orbit	705	98.9	98.2	1999.4.15
Terra	Sun-synchronous orbit	705	99	98.2	1999.12.18
ACRIMSAT	Sun-synchronous orbit	716	90	98.13	1999.12.20
GRACE	Polar orbit	400	94	89	2002.3.17
Aqua	Sun-synchronous orbit	705	98.8	98.2	2002.5.4
ICESat	Inclined orbit	600	97	94	2003.1.12
SORCE	Inclined orbit	600	90	40	2003.1.25
Suomi NPP	Sun-synchronous orbit	824	101	98.7	2011.10.28
Landsat-8	Sun-synchronous orbit	705	99	98.2	2013.2.12

Table 3.2 ETM+ bands

Waveband	Wavelength range (μm)	Ground resolution (km)
1	0.45–0.515	30
2	0.525–0.605	30
3	0.63–0.690	30
4	0.75–0.90	30
5	1.55–1.75	30
6	10.40–12.50	60
7	2.09–2.35	30
Pan	0.52–0.90	15

The ETM+ of Landsat 7 was developed based on the TM of Landsats 4 and 5 and the ETM of Landsat 6. It is a multispectral vertical-orbit scanning radiometer that performs Earth imaging directly facing the nadir and obtains high-resolution ground images. Its scanning width is 185 km. Similar to the previous Landsats, the EMT+ uses a scan line corrector to eliminate the interline overlap or interline spacing caused by the scanning operation or orbital motion.

In the visible and near-infrared (VNIR) range, ETM+ has four color bands and one panchromatic band. Each of the six sounder arrays in the visible, near-infrared and SWIR bands has sixteen sounders staggered along the orbital direction, and each sounder corresponds to a ground area of 30 × 30 m. The LWIR sounder array has eight sounders, each corresponding to a ground area of 60 × 60 m, with a resolution twice as high as that of the previous thermal infrared TM. The panchromatic band was a new addition to Landsat 7. The sounder array consists of 32 sounders, each corresponding to a ground area of 15 × 15 m. The bands of ETM+ are described in Table 3.2.

(2) Landsat 8 (LDCM)

Landsat 8, also referred to as LDCM, carries two main payloads: one operational land imager (OLI) and one thermal infrared sensor (TIRS). Compared with the payloads of previous Landsats, the performance of the OLI and TIRS are much improved.

Landsat 8 can capture at least 400 images per day (its predecessors could only capture 250). This is because Landsat 8 is more flexible in monitoring an area (Ali et al. 2017). Previous Landsats could only monitor a certain swath of land directly under their flight path, but the remote sensor of Landsat 8 can capture information about land that deviates from the flight path by a certain angle, which the previous Landsats could do only in subsequent laps. This advantage helps capture imagery needed for multitemporal comparison (such as images concerning disasters).

The main parameters of Landsat 8 are: a Worldwide Reference System-2 (WRS-2) flight path/line system, a sun-synchronous orbital altitude of 705 km, global coverage cycle of sixteen days (except for high-latitude polar regions), 233 orbits per cycle, an orbital inclination of 98.2° (slightly to the right), an operation cycle of 98.9 min, and a 170 × 185 km imaging area. The satellite crosses the equator at 10:00 AM ±

15 min. Its image directory is prepared in the same way as those of Landsats 4, 5 and 7, and it supports the ability to capture the main image and images that deviate from the nadir point to a limited extent (±1 flight path/line).

3.2.1.2 GRACE Satellite Program

The Gravity Recovery and Climate Experiment (GRACE) satellite program aims to obtain the features of medium and long waves of Earth's gravity field and the time-varying characteristics of the global gravity field (Melzer and Subrahmanyam 2017) and to sound the atmospheric and ionospheric environment. The GRACE satellite was launched on March 17, 2002 from the Plesetsk Launch Center in northern Russia. Its working principle is shown in Fig. 3.2.

The satellite adopts a low-low satellite-to-satellite tracking mode with two simultaneously launched low Earth orbit satellites that travel on the same orbit with a distance of 220 km in between them. Satellite-borne GPS receivers can accurately determine the orbital position of the two satellites and measure their distance and the changes in distance accurate to the micron level. A triaxial accelerometer is used to measure nonconservative forces. The observation data of each satellite, including the data of gravity-related measurements and GPS occultation measurements, are transmitted to the ground station via S-band radio waves.

The scientific objectives of the GRACE satellite project are (1) to determine Earth's mediumwave and longwave gravity field with a geoid precision of 0.01 cm and 0.01 mm for 5,000 km and 500 km wavelengths, respectively, which is two orders of magnitude higher than that of the CHAMP satellite (Ditmar 2004); (2) to

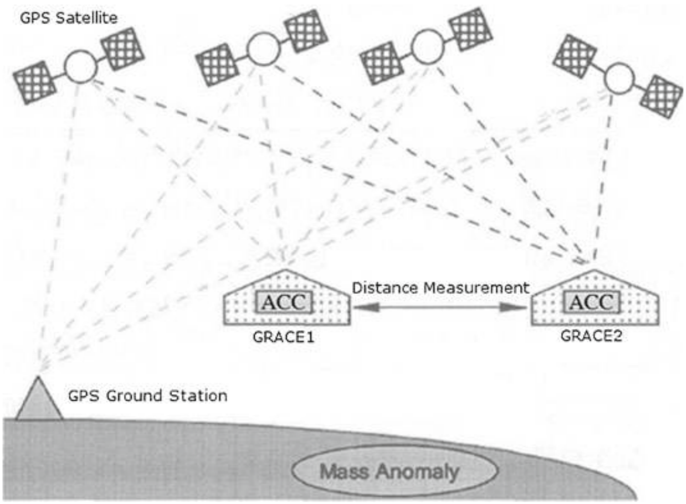

Fig. 3.2 GRACE working principle (Lu 2005)

determine changes in the global gravity field based on observation data from 2 to 4 weeks or longer, with an expected geoid determination precision of 0.001 mm/y; and (3) to sound the atmospheric and ionospheric environment. As the GRACE satellites provide highly accurate information about Earth's mediumwave and longwave gravity field and its time-dependent changes, they mark the beginning of a new era of satellite-based gravity research (Liu 2009).

3.2.1.3 Commercial Remote Sensing Satellites

On September 24, 1999, the IKONOS satellite was successfully launched at Vandenberg Air Force Base, marking the start of the era of high-resolution commercial satellites. On March 31, 2015, IKONOS was retired after 15 years of over service, a working lifetime more than twice of that in the design. IKONOS was a commercial satellite that acquired 1-m resolution panchromatic images and 4-m resolution multispectral images. Additionally, the resolution of the integrated color image with the panchromatic and multispectral images was up to 1 m. The IKONOS revisit period was 1–3 days imaging from the 681 km orbit.

The QuickBird satellite was launched in October 2001 with a panchromatic spatial resolution of 0.61 m and multispectral resolution of 2.44 m. The WorldView-1 satellite, launched on September 18, 2007, was the commercial imaging satellite with the highest resolution and the fastest response speed in the world at that time. WorldView-1 has an average revisit period of 1.7 days in a sun-synchronous orbit at an altitude of 496 km and inclination angle of 98°. The large-capacity panchromatic system can capture images up to 550,000 km^2 with 0.5-m resolution every day. The satellite also has high geolocation accuracy and quick response, which provides quick aiming at the target to effectively perform on-track stereo imaging. Its acquisition capacity is four times that of the QuickBird satellite. Parameters of the WorldView-1 satellite are shown in Table 3.3.

WorldView-2, launched in October 2009, was the first commercial remote sensing satellite in the world to provide 8-band high resolution data, greatly enhancing the customer service ability of DigitalGlobe. In June 2014, with the consent of the US Department of Defense and the State Department, the US Department of Commerce formally approved DigitalGlobe's application for the sale of 0.25-m resolution satellite image data.

With the implementation of the new policy, WorldView-3, the third-generation remote sensing satellite, was successfully launched in August 2014 and is the world's first commercial multipayload, hyperspectral and high resolution satellite, providing 0.31-m panchromatic imagery and 1.24-m multispectral imagery. The WorldView-4 commercial remote sensing satellite was launched in November 2016 and has greatly improved the overall data acquisition capability of the DigitalGlobe constellation group. It can image any point on the Earth 4.5 times a day, with a ground sampling distance (GSD) of less than 1 m.

Table 3.3 WorldView-1 satellite parameters

Parameter	Value
Orbit	Solar synchronization at a height of 450 km
Satellite size, weight and power supply	3.6 m high, 2.5 m wide; the total span of the solar panels is 7.1 m; weight of 2500 kg; 3.2 kw solar cells
Remote sensor band	Panchromatic
Resolution	Subsatellite point: 0.45 m (GSD)
Swath	Subsatellite point: 16 km
Altitude measurement and control	Tri-axial stability
Data transmission	Image and auxiliary data: 800 Mbit/s, X-band
Data acquisition for each orbit	331 Gbit
Maximum continuous imaging area of a single-circle orbit	60 × 60 km (equivalent to 4 × 4 square images); 30 × 30 km (equivalent to 2 × 2 square images)
Revisit period	While imaging with 1 m GSD: 1.7 days

3.2.1.4 Satellite Images for Google Earth

Google Earth's images come from multisource data composed of satellite images and aerial data. Its satellite images mainly come from the QuickBird commercial satellite, GeoEye satellite and IKONOS satellite of the DigitalGlobe Company of the United States, as well as the SPOT-5 satellite of France.

The GeoEye series of satellites are the next generation of the IKONOS and OrbView satellites. The GeoEye-1 satellite, launched on September 6, 2008 from Vandenberg Air Force Base in California can acquire black-and-white (panchromatic) imagery with 0.41-m resolution and color (multispectral) imagery with 1.65-m resolution, and can accurately locate the target position with 3 m accuracy. Therefore, it has become the most powerful commercial imaging satellite with the highest resolution and accuracy in the world. The GeoEye-1 satellite runs in a solar synchronous orbit with an altitude of 681 km and inclination angle of 98°, an orbit period of 98 min and a revisit period of less than 3 days. The satellite's launch mass was 1955 kg, and the design life is 7 years. The payload of the GeoEye-1 satellite is a pushbroom imaging camera consisting of an optical subsystem (telescope module, aperture 1.1 m), a focal plane module and a digital electronic circuit. The main parameters of the GeoEye-1 satellite are shown in Table 3.4.

Table 3.4 The main parameters of the GeoEye-1 satellite

Parameter		Values
Resolution		Subsatellite point panchromatic: 0.41 m, side-looking 28° panchromatic: 0.5 m, subsatellite point multispectral: 1.65 m
Swath		Subsatellite point: 15.2 km; single scene 225 km^2 (15 × 15 km)
Camera mode		Panchromatic and multispectral simultaneous (panchromatic fusion), monochromatic and monochromatic
Revisit period		2–3 days
Wavelength	Panchromatic	450–800 nm
	Multispectral	Blue: 450–510 nm
		Green: 510–580 nm
		Red: 655–690 nm
		Near-infrared: 780–920 nm

3.2.2 European Land Observation Satellites

3.2.2.1 ESA Satellites

(1) *CryoSat-2*

On April 8, 2010, the ESA launched CryoSat-2 using a Dnepr rocket. As one of the primary missions of the European Earth Observation Program (EOP), CryoSat uses a radar altimeter to measure the thickness of Earth's land ice and sea ice sheets, especially polar ice and oceanic floating ice, to study the effects of global warming. Earlier, in October 2005, the launch of CryoSat-1 was unsuccessful due to a rocket failure.

SIRAL is the main payload of CryoSat-2, weighing 62 kg (Dibarboure et al. 2011). It is mainly used to observe the internal structure of ice shields and study sea ice and landforms. SIRAL has three measurement modes: the low-resolution measurement (LRM) mode, which is only used to measure relatively flat polar and oceanic ice sheets; the SAR mode that is used to measure sea ice with an along-track resolution of 250 m; and the InSAR mode that is used to study ice sheets in more complex and steep areas with a measurement accuracy of 1 to 3 cm (Wingham et al. 2006). In contrast to traditional radar altimeters, the delay Doppler radar altimeter (DDA) adopted by SIRAL can emit continuous pulse trains and can make efficient use of Earth's surface reflection power via full Doppler bandwidth. SIRAL was designed based on existing instruments but has improved performance compared with the radar altimeters on board ERS-1, ERS-2 and ENVISAT. SIRAL has two pairs of Cassegrain antennas that are used to transmit radar signals and receive signals reflected from the ground to obtain accurate information about polar and sea ice thickness. SIRAL can accurately measure irregular and steep edges of land ice, and can obtain data from sea and river ice. The characteristics of SIRAL are shown in Table 3.5.

Table 3.5 SIRAL characteristics

Parameter	Mode of measurement		
	LRM	SAR	InSAR
Receiving chain	1 (left)	1 (left)	2 (left and right)
Sampling interval (m)	0.47	0.47	0.47
Bandwidth (MHz)	350	350	350
Pulse repetition frequency (PRF) (Hz)	1,970	17.8	17.8
Transmitter pulse width (μs)	49	49	49
Effective echo width (μs)	44.8	44.8	44.8
Pulse duration (ms)	None	3.6	3.6
Color synchronization pulse	None	64	64
Color synchronization pulse period (ms)	None	11.7	46.7
Tracking pulse bandwidth (MHz)	350	350	40
Average tracking pulse/46.7 ms	92	32	24
Data transmission rate (Mbps)	0.051	11.3	11.3 (2)
Power consumption (W)	95.5	127.5	127.5

(2) *Copernicus Program*

The Copernicus program, formerly Global Monitoring for Environment and Security (GMES), was a major space development program launched by the European Union in 2003. Its main purpose is to ensure Europe's sustainable development, enhance international competitiveness, security and to realize real-time dynamic monitoring of the environment by coordinating, managing and integrating the observation data of existing and future European and non-European (third-party) satellites.

In terms of EOS infrastructure development, the GMES program is divided into three parts. The first part is the space-based observation for which ESA is responsible. New satellites will be launched and the existing satellites are divided into six mission groups (see Table 3.6). The second part is the ground-based observation for which the European Environment Agency (EEA) is responsible. The third part is data sharing, which calls for building capacity for comprehensive and sustainable observation data applications and the construction of network entrances for data access; data services are mainly provided by the ESA, French Space Agency (CNES), and EUMETSAT.

3.2.2.2 France's Satellites

On February 22, 1986, France launched its first Earth resources observation satellite, SPOT-1. Thus far, seven SPOT satellites have been sent into space. The sounders adopted by these satellites have unique characteristics and the imaging method is also unique. Additionally, SPOT satellites are the world's first remote sensing satellites

Table 3.6 The Copernicus (GMES) space segment

Satellite	Function	Purpose	Launch date
Sentinel 1	SAR imaging	Continuous all-weather monitoring of ships and oil spills, other applications	Sentinel 1A: 2014.4.3 Sentinel 1B: 2016.4.25
Sentinel 2	Multispectral imaging	Land applications such as for cities, forests, agriculture, etc.	Sentinel 2A: 2015.6.23 Sentinel 2B: 2017.3.7
Sentinel 3	Ocean and land monitoring	Ocean color, vegetation, sea surface and land surface temperatures, sea wave height, etc.	Sentinel 3A: 2016.2.16 Sentinel 3B: 2018.4.25
Sentinel 4	Geosynchronous orbit—atmospheric monitoring	Monitoring of atmospheric composition and boundary layer pollution	
Sentinel 5	Low-orbit atmospheric research satellite	Monitoring of atmospheric composition	Sentinel 5P: 2017.10.13
Sentinel 6	Non-sun-synchronous orbit at 1,336 km mean altitude	Providing reference continuity and a high-precision ocean topography service after Jason-3	

to have stereo imaging capability. Basic information on the SPOT series is shown in Table 3.7.

The CNES launched the SPOT-5 remote sensing satellite in May 2002, with a design life of five years and total mass of 3,030 kg. Compared with the first four SPOT satellites, SPOT-5 has significantly improved observation capability and incorporated new instruments (Table 3.8), including the following: (1) An HSR with a panchromatic spectral resolution of 10 m, (2) two HRGs with working bands that differ from HRV and HRVIR, and (3) a VEGETATION-2 imager that could achieve global coverage almost every day with an imaging resolution of 1 km.

SPOT-6 was launched by India's Polar Satellite Launch Vehicle on flight C21 on September 9, 2012 and SPOT-7 was launched on PSLV flight C23 on June 30, 2014. They form a constellation of Earth-imaging satellites designed to provide continuity of high-resolution, wide-swath data up to 2024. EADS Astrium took the decision to build this constellation in 2009 based on a perceived government need for this kind of data. SPOT-6 and SPOT-7 are phased in the same orbit as Pléiades 1A and Pléiades 1B, which are at an altitude of 694 km, forming a constellation of 2-by-2 satellites that are 90° apart from one another.

Table 3.7 SPOT satellite information

Satellite	Launch date	Sensor	Service period (year)	Width (km)	Altitude (km)
SPOT-1	1986.02.22	Stereo imaging system with a pushbroom scanner (HRV)	1986–1990	2 × 16	830
SPOT-2	1990.01.22	Stereo imaging system with a pushbroom scanner (HRV)	1990–2006	2 × 16	830
SPOT-3	1993.09.26	Improved HRV, solid altimeter, laser reflector	1993–1996	110–2,000	832
SPOT-4	1998.03.24	Improved HRV, HRVIR	1998–2013	110–2,200	1,334
SPOT-5	2002.05.03	HRG, HRVIR, HSR	Still in operation	60 × 60–60 × 120	830
SPOT-6	2012.09.09	Multispectral Imagery	Still in operation	60 × 60	695
SPOT-7	2014.06.30	Multispectral Imagery	Still in operation	60 × 60	695

Table 3.8 Technical parameters of the three sensors on board SPOT-5

Type of remote sensor	Waveband	Wavelength range (μm)	Resolution (m)	Width (km)
HRG	Panchromatic	0.49–0.69	2.5 or 5	60
HRVIR	Multispectral	0.49–0.61	10	60
		0.61–0.68	10	60
		0.78–0.89	10	60
		1.58–1.75	20	60
		0.43–0.47	1,000	2,250
		0.61–0.68	1,000	2,250
		0.78–0.89	1,000	2,250
		1.58–1.75	1,000	2,250
HSR	Panchromatic	0.49–0.69	10	120

3.2.2.3 Germany's Satellites

CHAMP is a small satellite mission for geoscience research, atmospheric studies, and applications headed by the German Research Centre for Geosciences (GFZ) (GFZ 2018; Guo et al. 2008). As a near-polar, low Earth orbit satellite equipped with high-precision, multifunction, completely satellite-borne instruments (magnetometer, accelerometer, STAR sensor, GPS receiver, laser mirror, ion drift meter). CHAMP had a design life of five years, and ended on September 19, 2010. Its shape and onboard instruments are shown in Fig. 3.3. It could simultaneously measure Earth's gravitational and magnetic fields with high precision and detect their temporal and spatial changes (Baduraet al. 2006).

The CHAMP mission had three main goals: (1) to accurately determine the long-wavelength characteristics of the Earth's gravitational field and its temporal changes; (2) to estimate, with unprecedented accuracy, temporal and spatial variations of the magnetic field of the Earth's main body and crust, and all components of the magnetic field; and (3) to study temperature, water vapor, and electrons using a large amount of globally distributed GPS signal refraction data generated by the atmosphere and ionosphere.

TerraSAR-X is a German SAR satellite mission for scientific and commercial applications that was launched on June 15, 2007. The project is managed by the DLR (German Aerospace Center). In 2002, EADS Astrium GmbH was awarded a contract to implement the X-band TerraSAR satellite (TerraSAR-X) on the basis of a public-private partnership agreement (PPP). In this arrangement, EADS Astrium funded part of the implementation cost of the TerraSAR-X system.

The science objectives are to make multimode and high-resolution X-band data available for a wide spectrum of scientific applications in fields such as hydrology, geology, climatology, oceanography, environmental and disaster monitoring, and cartography (DEM generation) using interferometry and stereometry.

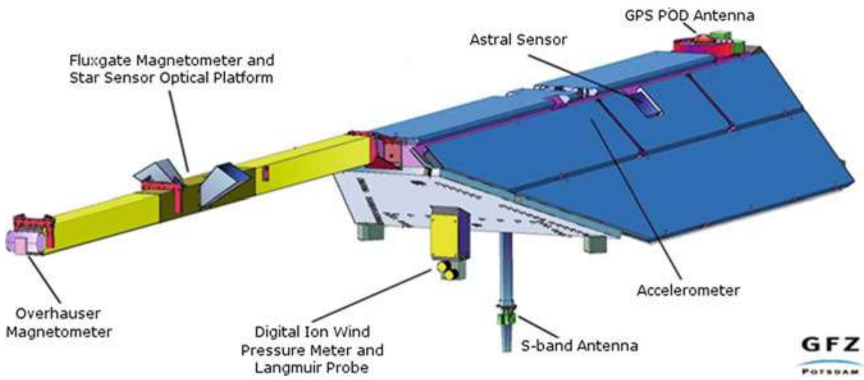

Fig. 3.3 CHAMP satellite structure (GFZ 2018)

3.2.3 China's Land Observation Satellites

3.2.3.1 Resource Satellites

Resource satellites are used to survey the Earth's natural resources and carry out scientific research on the Earth system. China has developed a series of satellites for land observation.

(1) *CBERS satellites*

The China-Brazil Earth Resource Satellites (CBERS) were jointly developed by China and Brazil using their combined investment in accordance with an agreement signed by both countries in 1988. CBERS was shared by the two countries after being put into operation. The first CBERS (CBERS-1) was successfully launched in 1999 as China's first-generation transmission-type Earth resource satellite. CBERS-02 was the successor to CBERS-01 and had the same function, composition, platform, payload, and nominal performance parameters as its predecessor. CBERS-02 was launched from the Taiyuan Satellite Launch Center on October 21, 2003.

The payload and orbital parameters of CBERS-01/2 are listed in Table 3.9 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004). The CBERS-1/02 payload included three kinds of sensors: a charge-coupled device (CCD), an infrared multispectral scanner (IRMSS), and a

Table 3.9 Basic parameters of the CBERS-01/2 sensors

	CCD camera	Wide field imager (WFI)	Infrared multispectral scanner (IRMSS)
Type of sensor	Pushbroom	Pushbroom (discrete camera)	Oscillating scanning (forward and reverse)
Visible/near infrared band (μm)	1: 0.45–0.52 2: 0.52–0.59 3: 0.63–0.69 4: 0.77–0.89 5: 0.51–0.73	10: 0.63–0.69 11: 0.77–0.89	6: 0.50–0.90
Shortwave infrared band (μm)	N/A	N/A	7: 1.55–1.75 8: 2.08–2.35
Thermal infrared band (μm)	N/A	N/A	9: 10.4–12.5
Radiation quantization (bit)	8	8	8
Swath (km)	113	890	119.5
Number of pixels per band	5,812 pixels	3,456 pixels	Bands 6, 7 and 8: 1,536 pixels; band 9: 768 pixels
Spatial resolution (nadir) (m)	19.5	258	Bands 6, 7 and 8: 78 m; band 9: 156 m

Table 3.10 CBERS-02B technical parameters

Payload	Band no.	Spectral range (μm)	Resolution (m)	Swath (km)	Side view ability	Repetition period (d)	Data transmission rate
Panchromatic multispectral camera	B01	0.45–0.52	20	113	±32°	26	2 × 53
	B02	0.52–0.59	20				
	B03	0.63–0.69	20				
	B04	0.77–0.89	20				
	B05	0.51–0.73	20				
High-resolution camera (HR)	B06	0.5–0.8	2.36	27		104	60
Wide field imager (WFI)	B07	0.63–0.69	258	890		5	1.1
	B08	0.77–0.89	258				

wide field imager. Other loads included a high-density digital recorder (HDDR), a data collection system (DCS), a space environment monitor (SEM), and a data transmission system (DTS).

(2) *CBERS-02B*

CBERS-02B was an Earth observation satellite jointly developed by China and Brazil. The satellite was sent into orbit on September 19, 2007 from the Taiyuan Satellite Launch Center, and the first batch of Earth observation images was received on September 22, 2007. The satellite is no longer in operation. Its technical parameters are shown in Table 3.10.

CBERS-02B was equipped with three spatial resolutions: high, medium, and low. A combination of the CCD and HR images sent back from the satellite helped accurately identify and interpret residential areas, roads, forests, mountains, rivers, and other ground features. It could monitor the expansion of urban areas and provide a basis for urban planning and construction. Furthermore, it could provide support for decision making for precision agriculture. CBERS-02B could also be used to produce detailed maps such as dynamic land use maps and to update large-scale topographic maps.

(3) *ZY-1 02C*

The ZY-1 02C resource satellite was launched on December 22, 2011. It weighs approximately 2,100 kg and had a design life of three years. ZY-1 02C carries a panchromatic multispectral camera and a high-resolution panchromatic camera.

The satellite has two notable features. First, its 10-m resolution P/MS multispectral camera boasts the highest resolution of the multispectral cameras installed on China's civilian remote sensing satellites. Second, the two 2.36-m resolution HR cameras it carries make the monitoring swath as wide as 54 km, which greatly increased the data coverage and significantly shortened the satellite's repetition period. ZY-1 02C's payload parameters are shown in Table 3.11 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

Table 3.11 ZY-1 02C sensor parameters

Parameter		P/MS camera	HR camera
Spectral range (μm)	Panchromatic	B1: 0.51–0.85	0.50–0.80
	Multispectral	B2: 0.52–0.59	
		B3: 0.63–0.69	
		B4: 0.77–0.89	
Spatial resolution (m)	Panchromatic	5	2.36
	Multispectral	10	
Width (km)		60	Single camera: 27; double camera: 54
Side view ability (°)		±32	±25
Repetition period (d)		3–5	3–5
Coverage period (d)		55	55

(4) *ZY-3*

The ZY-3 resource satellite was launched on January 6, 2012. It weighs approximately 2,650 kg and had a design life of five years. The satellite's mission is to continuously, reliably, and rapidly capture high-resolution stereo images and multispectral images of all parts of the country for a long period of time.

ZY-3 is China's first high-resolution civilian optical transmission-type stereo mapping satellite that integrates surveying, mapping, and resource investigation functions. The onboard front-view, rear-view, and vertical-view cameras can capture stereoscopic pairs in the same region from three different viewing angles to provide a wealth of three-dimensional geometric information. The image control and positioning precision are greater than one pixel. The swath of the front-view and rear-view stereoscopic pairs is 52 km wide and the baseline-height ratio is 0.85–0.95. The vertical image is 2.1 m, meeting the demand for 1:25,000 topographic map updates. ZY-3's payload parameters are shown in Table 3.12 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

In 2012, ZY-3 sent back 1,590 batches of raw data, totaling 250 TB. The valid data covered 7.5 million square kilometers in China and 30 million square kilometers across the world. Imagery of Dalian, China, captured by the ZY-3 satellite is shown in Fig. 3.4.

3.2.3.2 Environment and Disaster Reduction Satellites

The environment and disaster reduction satellites are collectively referred to as the "China Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting" ("Small Satellite Constellation" for short). The constellation is capable of using visible, infrared, microwave remote sensing and other means of observation

Table 3.12 ZY-3 sensor parameters

Platform	Payload	Band no.	Spectral range (μm)	Spatial resolution (m)	Width (km)	Side view ability (°)	Revisit time (d)
ZY-3	Front-view camera	–	0.50–0.80	3.5	52	±32	3–5
	Rear-view camera	–	0.50–0.80	3.5	52	±32	3–5
	Vertical-view camera	–	0.50–0.80	2.1	51	±32	3–5
	Multispectral camera	1	0.45–0.52	6	51	±32	5
		2	0.52–0.59				
		3	0.63–0.69				
		4	0.77–0.89				

Fig. 3.4 Image of Dalian, China, acquired by the ZY-3 satellite

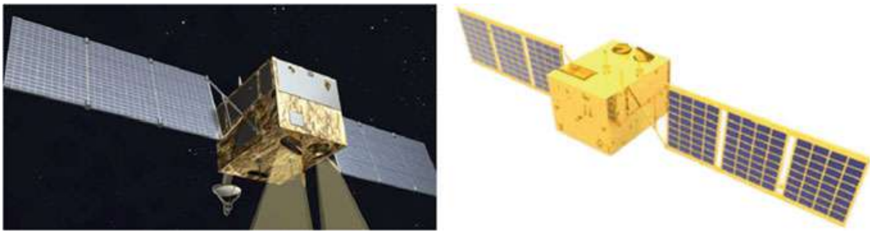

Fig. 3.5 The HJ-1A (left) and HJ-1B (right) satellites

to meet the needs of all-weather, 24-h observation and forecasting of natural disasters and environmental events.

(1) *HJ-1A/B*

The HJ-1A and HJ-1B environment and disaster reduction satellites were launched at 11:25 on September 6, 2008. HJ-1A carries a CCD camera and hyperspectral imager (HSI) and HJ-1B is equipped with a CCD camera and infrared scanner (IRS). HJ-1A and HJ-1B are equipped with the same type of CCD camera. The two cameras were placed symmetrically across the nadir, equally dividing the field of view. The cameras make parallel observations to achieve pushbroom imaging in four spectral bands with a 700-km Earth observation swath and a ground pixel resolution of 30 m. Additionally, the HSI on HJ-1A realizes pushbroom imaging in 110–128 spectral bands with a 50-km Earth observation swath and a ground pixel resolution of 100 m. HSI has a side view ability of ±30° and an onboard calibration function. The IRS on board HJ-1B completes imaging in four spectral bands (near, short, medium and long) with a 720-km Earth observation swath and a ground pixel resolution of 150/300 m. The two satellites are shown in Fig. 3.5.

(2) *HJ-1C*

HJ-1C is China's first S-band small SAR and environment and disaster reduction satellite, launched on November 9, 2012. HJ-1C has a mass of 890 kg and a sun-synchronous orbit at an altitude of 500 km. The local time of the orbital descending node is 18:00. Together with HJ-1A and HJ-1B, HJ-1C constitutes the first stage of China's environment and disaster reduction satellite constellation.

HJ-1C is equipped with an S-band SAR. Its payload works in two modes (strip mode and scanning mode) and employs a 6 × 2.8 m foldable mesh parabolic antenna. The SAR antenna was unfolded once HJ-1C entered orbit. It went into a swath imaging work mode after preparation. The onboard SAR has two imaging swaths: 40 and 100 km. The SAR's single-view spatial resolution is 5 m and the four-view spatial resolution is 20 m. Most of the HJ-1C's SAR images are taken in a multiview mode. The HJ-1C satellite is shown in Fig. 3.6.

The payload parameters of HJ-1C are shown in Table 3.13 (Satellite Environment Center, Ministry of Environmental Protection 2010a).

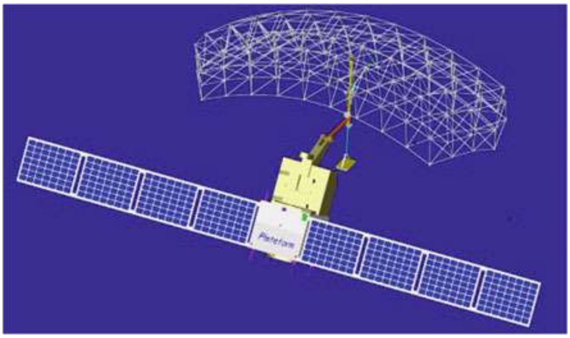

Fig. 3.6 The HJ-1C satellite

Table 3.13 HJ-1C's payload parameters

Parameter	Value
Operating frequency (MHz)	3,200
Side view	Side-looking
Spatial resolution (m)	5 m (single-view); 20 m (four-view)
Width of imaging swath (km)	40 (strip mode); 100 (scanning mode)
Radiometric resolution (dB)	3
Polarization mode	VV
Viewing angle (°)	25–47

3.2.3.3 Satellites of the High-Resolution Earth Observation Program

Globally, the United States was the first country to develop high-resolution Earth observation systems. Other countries such as Israel, France, and India have only one or two of these satellites each. Currently, China has no high-resolution satellites. According to the China Geographic Surveying and Mapping Information and Innovation Report (2012), although China has achieved success in satellite remote sensing technology, it is still behind in high-resolution civilian remote sensing satellite technology and its commercial applications.

GF-1 (Gaofen-1) was the first satellite of China High-resolution Earth Observation System (CHEOS) and was launched using an LM-2D rocket from the Jiuquan Satellite Launch Center on April 26, 2013. GF-1's development helped China master key technologies such as high spatial resolution, multispectral sensors, optical sensors, wide coverage, multipayload image mosaic fusion, precise and stable altitude control, and high-resolution data processing. Additionally, the development of GF-1 helped improve the capability for independent development of high-resolution satellites, and enhanced the self-sufficiency of high-resolution remote sensing data. The design life of GF-1 is five to eight years (Ding 2013).

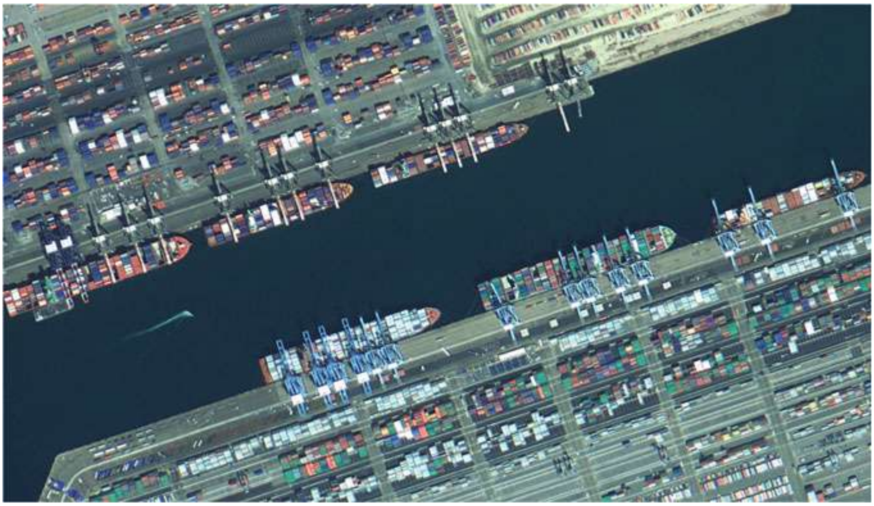

Fig. 3.7 GF-2 image (resolution: 0.8 m)

On April 28, 2013, GF-1 began imaging and sending data. Data were received by the RADI Miyun Ground Station and processed by the China Center for Resource Satellite Data and Application. The first batch of images included four types: 2 m panchromatic, 8 m multispectral, 16 m multispectral, and 2 m panchromatic fused with 8 m multispectral.

GF-2 was launched successfully from Taiyuan Satellite Launch Center using an LM-4B carrier rocket on August 19, 2014. The successful launch was a result of special high-definition projects, indicating that Chinese remote sensing satellites were entering a submeter "high-definition era". GF-2's spatial resolution was 1.0 m and the swath width was 45 km, which was the largest imaging width of similar satellites of other countries (Fig. 3.7). GF-2 will be used for geographic and resource surveillance, environmental and climate change monitoring, precision agriculture, disaster relief, and city planning. The satellite is equipped with two cameras with the same resolution. The GF-2 camera can "twist its neck" to observe a range of ±35° in 180 s. GF-2 can swivel on its axis 35° to either side. Additionally, GF-2's five-year lifetime is longer than that of most other Chinese satellites, but the desired goal is eight years.

The GF-3 satellite is a new high-resolution SAR imaging satellite launched by an LM-4C rocket at 06:55 on August 10, 2016. It blasted off at the Taiyuan Satellite Launch Center in Taiyuan, the capital of northern China's Shanxi Province. As China's first C-band SAR imaging satellite that is accurate to one meter, it covers the globe with an all-weather, 24-h observation service and will be used for disaster warning, weather forecasting, water resource assessments, and the protection of maritime rights. With 12 imaging modes, the high-definition observation satellite can take wide pictures of the Earth and photograph detailed scenarios of specific areas. GF-3 is also China's first low orbit remote sensing satellite that has a lifespan

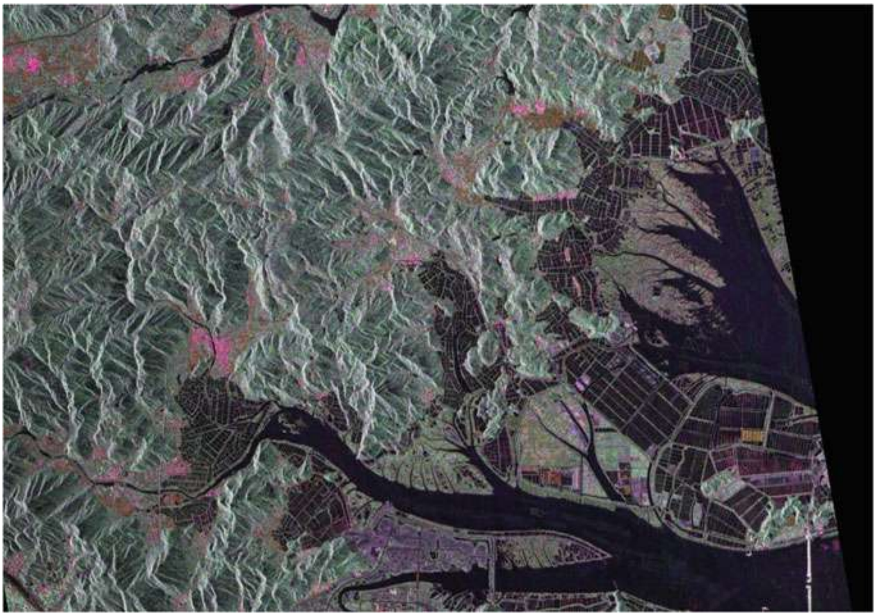

Fig. 3.8 GF-3 image (full polarization)

of eight years. It provides high-definition remote sensing data for its users over long periods of time. GF-3 is a polar orbit satellite with a high spatial resolution (Fig. 3.8) that can play a role in observing slowly changing objects such as water bodies, ice, and snow.

On June 26, 2015, China successfully launched the high-definition Earth observation satellite GF-8 into orbit from the Taiyuan Satellite Launch Center. GF-8 is an optical remote sensing satellite used in land surveying, urban planning, land delineation, highway and railway network design, crop yield estimation, disaster prevention and reduction, and other fields. The GF-9 satellite was launched from the Jiuquan Satellite Launch Center using an LM-2D carrier rocket on September 14, 2015. GF-9 is also an optical remote sensing satellite under CHEOS. The satellite can provide pictures with a ground pixel resolution of less than 1 m. It will be used in land surveying, urban planning, road network design, agriculture, and disaster prevention and relief.

On December 29, 2015, GF-4 was launched from the Xichang Satellite Launch Center in the southwestern province of Sichuan on board an LM-3B carrier rocket. It was the 222nd flight of the Long March rocket series. In contrast to GF-1 and GF-2, which orbit at low elevations (600–700 km) around Earth, GF-4 orbits 36,000 km away and moves synchronously with Earth. It can spot an oil tanker at sea using the CMOS camera, and features the best imaging capability among global high-orbit remote sensing satellites. GF-4 is China's first geosynchronous orbit HD optical imaging satellite and the world's most sophisticated HD geosynchronous orbit remote

Table 3.14 GF satellite parameters

Satellite	Sensor
GF-1	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-2	1 m panchromatic/4 m multispectral
GF-3	1 m C-SAR
GF-4	50 m stationary gazing camera
GF-5	Visible shortwave infrared hyperspectral camera Full-spectrum spectral imager Atmospheric aerosol multiangle polarization detector Atmospheric trace gas differential absorption spectrometer Main atmospheric greenhouse gas monitor Ultrahigh-resolution infrared atmospheric sounder
GF-6	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-7	High space three-dimensional mapping instrument

sensing satellite. It will be used for disaster prevention and relief, surveillance of geological disasters and forest disasters, and meteorological forecasting.

The GF-5 and GF-6 satellites were launched on May 9 and June 2, 2018, respectively. GF-5 was designed to run on a sun-synchronous orbit and carries six payloads: an advanced hyperspectral imager (AHSI), a visual and infrared multispectral imager (VIMI), an atmospheric infrared ultraspectral sounder (AIUS), a greenhouse gases monitoring instrument (GMI), an environmental trace gases monitoring instrument (EMI), and a directional polarization camera (DPC). The GF-6 satellite has a similar function to the GF-1 satellite but has better cameras, and its high-resolution images can cover a large area of the Earth, according to the State Administration of Science, Technology and Industry for National Defence. GF-6 can observe the nutritional content of crops and help estimate the yields of crops such as corn, rice, soybeans, cotton and peanuts. Its data will also be applied in monitoring agricultural disasters such as droughts and floods, evaluation of agricultural projects and surveying of forests and wetlands.

Parameters of the GF satellites are shown in Table 3.14.

3.2.3.4 Remote Sensing Microsatellites

Microsatellites are a new type of satellite that is low-cost and has a short development time and more flexible operation than conventional spacecraft that are heavy, costly, and time-consuming to develop. The spatial and temporal resolutions of Earth observation can be significantly improved using a distributed constellation of microsatellites. As a result, microsatellites are becoming more widely used around the world. China has launched several series of microsatellites for Earth observation, such as the “SJ” series, “Tsinghua-1”, “NS-2”, and “Beijing-1”, which have improved and enriched the Chinese satellite observation system.

SJ-9A and SJ-9B are a new generation of microsatellite launched in 2012. They are the first satellites in the "New-tech Civilian Experimental Satellite" series. SJ-9A is equipped with a high-resolution multispectral camera with a panchromatic resolution of 2.5 m and multispectral resolution of 10 m. SJ-9B carries longwave infrared focal plane components for optical imaging with a resolution of 73 m. As of August 2013, the "SJ" satellite series had developed up to SJ-11E and provided adequate services for China's space science and technology experiments (Guo et al. 2013).

3.2.3.5 Remote Sensing from the Shenzhou Spacecraft

China has successfully developed and launched ten Shenzhou spacecraft, representing the country's achievements and capability in space science and technology. A series of scientific experiments such as space measurement, environmental monitoring, and Earth observation have been carried out in space with the support of the Shenzhou spacecraft. The Shenzhou spacecraft have accelerated the development of Earth observation technology in China.

In 2011, China's first space laboratory, Tiangong-1, was successfully launched. It was the starting point for Chinese space station development and signified that China had the ability to build short-term untended space stations. In the same year, Tiangong-1 successfully docked with the Shenzhou-8 unmanned spacecraft, revealing that China had achieved a series of key technologies such as space rendezvous and docking and operation of combined bodies. Shenzhou-9 and Shenzhou-10 were launched in 2012 and 2013, respectively. Shenzhou-11 was launched on October 17, 2016. For the first time, China realized space rendezvous and docking of manned spacecraft, and Chinese astronauts carried out teaching activities in space, marking an important step forward in China's space laboratory development (Jiang 2013). Figure 3.9 shows the development timeline of the Shenzhou series of spacecraft.

3.2.3.6 Commercial Remote Sensing Satellites

China's government is encouraging more participation from the private sector in commercial space programs to ensure the sustainable growth of the nation's space industry, and some commercial remote sensing satellites and missions have been launched or are planned, including Jilin-1, Beijing-2, SuperView-1, and Lishui-1.

The Jilin-1 satellites are China's first self-developed remote sensing satellites for commercial use and were launched from the Jiuquan Satellite Launch Center in northwestern China's Gansu Province on Oct. 7, 2015. The system includes one optical remote sensing satellite, two satellites for video imaging and another for testing imaging techniques. Jilin Province is one of China's oldest industrial bases and is developing its satellite industry as a new economic driver. The Jilin-1 GP 01 and 02 satellites for multispectral imaging were launched on a Long March 11 rocket from the Jiuquan Satellite Launch Center on January 21, 2019. By 2020, the plans

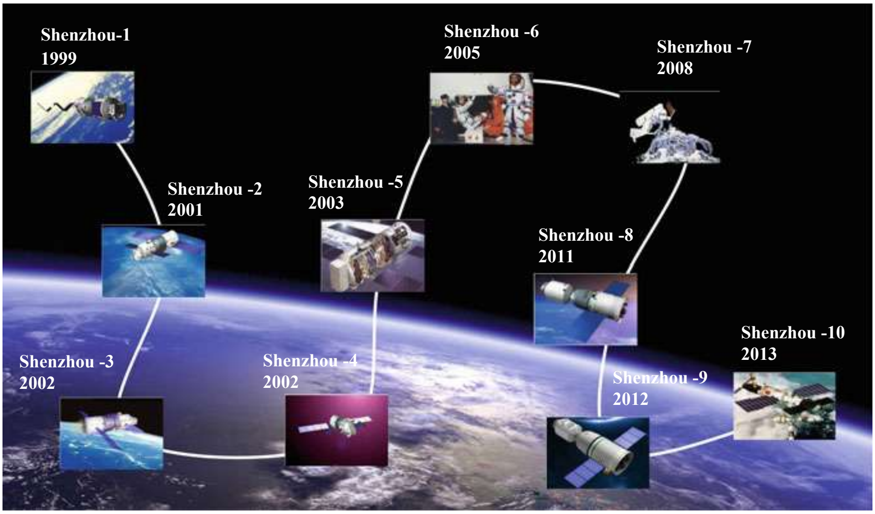

Fig. 3.9 Roadmap of the Shenzhou spacecraft program

indicate a 60-satellite orbital constellation capable of a 30-min update. From 2030, the Jilin constellation will have 138 satellites in orbit, forming a 24-h, all-weather, full-spectrum acquisition segment with the capability of observing any arbitrary point on the globe with a 10-min revisit capability, providing the world's highest spatial and temporal resolution space information products.

The Beijing-2 remote sensing satellite constellation comprises three identical optical EO satellites, which makes it possible to target any place on Earth once per day. The constellation provides less than 1-m high-resolution imagery products with a 23.4-km swath. The constellation was launched on July 10, 2015 from the Dhawan Space Centre in Sriharikota, India. The space and ground segments were designed to efficiently deliver timely information. The satellites were developed by the UK-headquartered Surrey Satellite Technology Ltd. (SSTL), which is the world's leading small satellite company and part of the Airbus Group. The Twenty First Century Aerospace Technology Company (21AT) will manage the satellites' operation, which includes observation and control, data reception and production, and related services. The satellites will provide the best combination of spatial resolution and temporal resolution to stimulate monitoring applications such as urban planning and intelligent management at a very high resolution. The main parameters of the constellation are shown in Table 3.15.

The SuperView-1 01 and 02 satellites were launched by one rocket on December 28, 2016, and two better performing satellites will be launched in the future to comprise four 0.5-m resolution satellites phased 90° from each other on the same orbit to provide services to global clients.

The Lishui-1 satellites, developed by the privately owned Zhejiang Lishui Electronic Technology Co Ltd, are commercial remote sensing satellites that were

Table 3.15 Parameters of the Beijing-2 satellite constellation

Feature	Parameter
Number of satellites	3
Satellite orbit	Sun-synchronous orbit Altitude: 651 km LTAN: 10:30
GSD	<1 m PAN <4 m MS
Bands	B/G/R/NIR
Swath width	23.4 km
MTF	PAN: 10% MS: 20%
Signal-to-noise	>100
Off-pointing capacity	±45°
Revisit	1 day
Lifetime	7 years

launched by an LM-11 solid-fuel rocket from the Jiuquan Satellite Launch Center in northwest China on November 10, 2016. The company plans to build a constellation of up to 80 to 120 commercial satellites to obtain images of the Earth and data to serve business purposes.

3.2.4 Other Land Observation Satellites

3.2.4.1 Japan's Satellites

In 1992, Japan's first Earth resource satellite, JERS-1, was launched into orbit. It carried next-generation SAR and optical sensors with a ground resolution of 18 m. During satellite operation, SAR transmits more than 1,500 microwave pulse signals per second to the surface and receives signals reflected from the ground with the same antenna. The optical sensor is composed of a VNIR radiometer and a shortwave infrared radiometer, and Earth observation is carried out in eight wavebands. Japan's Advanced Earth Observation Satellite (ADEOS), launched on August 17, 1996, was a next-generation large-scale Earth observation satellite that followed Japan's marine observation satellite, MOS, and Japan's Earth resource satellite, JERS-1.

On January 24, 2006, the Japan Space Agency launched the ALOS-1 satellite. ALOS-1 used advanced land observation technologies to obtain flexible, higher resolution Earth observation data that could be applied to mapping, regional observation, disaster monitoring, resource surveys, technical development, and other fields. The basic parameters of the ALOS-1 satellite are shown in Table 3.16.

The JAXA completed operation of ALOS-1 on May 12, 2011. The technologies acquired from ALOS-1 operation were succeeded by the second Advanced Land Observing Satellite (ALOS-2). The PALSAR-2 on board ALOS-2 is an L-band SAR

Table 3.16 ALOS-1 characteristics

Parameter	Value
Launch date	2006.01.24
Type of orbit	Sun-synchronous orbit
Repetition period (d)	46
Altitude (km)	691.65
Inclination (°)	98.16
Attitude control precision (°)	2.0×10^{-4} (in coordination with ground control point)
Positioning accuracy (m)	1.0
Data rate (Mbps)	240 (via data relay satellites)
Onboard data storage	Solid-state data recorder (90 GB)

sensor, a microwave sensor that emits L-band radio waves and receives their reflection from the ground to acquire information. The PALSAR-2 has three modes: (1) Spotlight mode—the most detailed observation mode with 1 by 3 m resolution (25 km observation width); (2) Strip Map mode—a high-resolution mode with the choice of 3, 6 or 10 m resolution (observation widths of 50 or 70 km); and (3) ScanSAR mode—a broad area observation mode with observation widths of 350 or 490 km and resolution of 100 or 60 m, respectively.

3.2.4.2 India's Satellites

Resourcesat is part of the Indian remote sensing satellite system. The first of the Resourcesat satellites, Resourcesat-01, was launched on October 17, 2003. This series is used for disaster forecasting, agriculture, water resources, forest and environment monitoring, infrastructure development, geological exploration, and mapping services.

The second satellite of this series, Resourcesat-02, was the 18th remote sensing satellite designed and developed by ISRO (Fig. 3.10). With a total mass of 1,206 kg, Resourcesat-02 adopts three-axis stabilization technology and was designed to work for five years. Its sensors and related subsystems were jointly developed by the ISRO Satellite Center (ISAC) and the Space Application Center (SAC). The Indian National Remote Sensing Center (NRSC) is responsible for receiving and preprocessing the satellite's image data as well as for production and distribution of products. Resourcesat-02 enhanced the Earth observation capability of the country's remote sensing satellite system to better serve India's economic development and national defense.

Resourcesat-02 replaced Resourcesat-01 after a series of on-orbit tests, and expanded ISRO's remote sensing data services. The Resourcesat-02 satellite's payload includes: linear imaging self-scanning sensors (LISS-3 and LISS-4), an

Fig. 3.10 The Resourcesat-02 satellite

advanced wide field-of-view sensor (AWIFS), three high-resolution multispectral cameras, and a marine automatic identification system (AIS). LISS-4 has a spatial resolution of 5.8 m and scanning width of 70 km, can work in the VNIR spectral range, and can obtain cross-track stereo images (Goward et al. 2012).

3.2.4.3 Russia's Satellites

The Resurs-F series of satellites are tasked with monitoring crop growth, ice cover, landforms, and other features. They also undertake scientific research missions. For example, the two Resurs-F1 satellites launched in May and July 1989 were passive atmospheric research satellites, 70 mm in diameter and 78 kg in mass, that were used to study the density of the upper atmosphere. The two satellites also carried scientific instruments from other countries for scientific experiments.

The first Resurs-F satellite was launched on September 5, 1979 from the Plesetsk Launch Site using an SL-4 rocket. The satellite was 7 m long, 2.4 m in diameter, 6,300 kg in mass and was composed of three compartments. The central part of the satellite was a 2.3-m diameter sphere that housed the imaging system, electronic control system, and recovery system. One side was connected to the 3 m long and 2 m wide propulsion module via a fixing mechanism that unlocked when the retarding rocket was ignited. The other side was 1.9 m long and the propulsion unit occupied up to 1.0 m. The propulsion unit was used for orbital adjustment and was cast off when the return capsule re-entered the atmosphere. The remaining 0.9 m of space was

Fig. 3.11 The Resurs-F1 satellite

used to carry additional releasable secondary payloads of up to 30 kg or more. These secondary payloads could be placed inside or outside the return capsule and carried back to the ground. An overview of the Resurs-F1 satellite is shown in Fig. 3.11.

The imaging system on board the Resurs-F1 satellite included an SA-20M long-focus wide imaging system with a KFA-1000 camera and an SA-34 wide mapping and imaging system with a KATE-200 camera. Compared with Resurs-F1, the Resurs-F2 satellite's biggest improvement is the addition of two solar panels, which extended its service life to nearly one month. The first Resurs-F2 satellite, also known as Cosmos-1906, was launched into space in 1987. However, the launch was unsuccessful and the satellite was destroyed in orbit. Resurs-F2 satellites are operating in 170–240 km low Earth orbits and near-polar circular orbits with an orbital inclination of 82.3°. An outline of the Resurs-F2 satellite is shown in Fig. 3.12.

The Resurs-F2's imaging system is significantly different than that of Resurs-F1 and includes a KFA-1000 camera and a high-resolution MK-4 mapping camera. Equipped with a passive remote sensor, the MK-4 camera can record images on three separate pieces of film and perform imaging in any three of the following six spectral bands: 0.63–0.69 μm, 0.81–0.90 μm, 0.52–0.57 μm, 0.46–0.51 μm, 0.58–0.80 μm, and 0.40–0.70 μm. The camera's focal length is 300 m, the spatial resolution is greater than 10 m, the panchromatic spectral resolution is 8 m, and the ground width is 120–180 km. One scan can generate 2,700 images and the image size is 180 $\times$ 180 mm with an overlap ratio of 60%. The satellite can be used for mapping, environmental monitoring, and geographic surveys.

The Resurs-O series of satellites were mainly used in geology, cartography, fire detection, ice detection, hydrology, and agriculture. They were designed and manufactured by the then National Institute of Electronics in the former Soviet Union.

Fig. 3.12 The Resurs-F2 satellite

3.3 Ocean Observation Satellites

Ocean satellites are the best tools for understanding Earth's oceans, and can be economically used for real-time, synchronous, and continuous monitoring of large areas. At present, ocean satellites are the primary means of marine environment monitoring, making their development a necessity. Ocean satellites can enhance scientists' capability for marine environment and disaster monitoring, forecasting, and early warning, and can provide efficient services for marine resource surveying, development, and management. These satellites can conduct global surveys of fisheries, scientifically estimate fishery potential, and provide a basis for the development of fishery policies. Furthermore, they can effectively and affordably measure the marine gravity field to provide an understanding of submarine tectonics and oil and gas reserves, and assist in developing offshore oil fields.

3.3.1 US Ocean Observation Satellites

3.3.1.1 Development Stages of US Ocean Satellites

The development of US ocean satellites has experienced four stages (Dong 2012): (1) preparation stage (before 1978); (2) experiment stage (1978–1985); (3) application research stage (1985–1999), and (4) comprehensive oceanographic observation stage (1999–present).

(1) Preparation stage

The first US meteorological satellite, TIROS-I, was launched by NASA in April 1960, followed by TIROS-II, which started sea surface temperature observation. In 1961, the United States began to implement the Mercury Program, making it possible for astronauts to observe the ocean from a high altitude. In 1969, NASA began to promote a marine observation plan; in 1975, GOES-3 was equipped with an altimeter for measuring the distance from the satellite to the sea surface. In 1973, the Skylab space station confirmed the potential of visible and infrared remote sensing in continuous Earth observation.

(2) Experiment stage

In this stage, marine remote sensors were mainly installed on US ocean satellites such as Seasat, Nimbus-7, TIROS-N, and GEOS. The main marine elements inversed in this stage included sea surface temperature, ocean color, and sea ice. In 1981, NOAA satellites began using the multichannel sea surface temperature (MCSST) algorithm to forecast sea surface temperature.

(3) Application research stage

The main ocean satellites launched in this stage were equipped with a variety of microwave monitoring instruments, infrared radiometers and ocean color imagers to monitor the sea surface, submarine topography, sea waves, sea wind, ocean currents, marine pollution, primary oceanic productivity, and other factors. In 1985, the United States launched an ocean topography satellite called Geosat, which was mainly used to measure significant wave height, wind velocity and meso-scale oceanic features. Over the years, Geosat provided a wide range of altimeter data. Other meteorological satellites were also involved in marine observation. For instance, NOAA meteorological satellites were used for sea surface temperature inversion, sea condition monitoring, and sea pollution research. In 1987, the SeaWiFS Working Group of NASA and the Earth Observation Satellite Company (EOSAT) jointly proposed a systematic plan for spaceborne wide-field-of-view marine observation. In August 1997, the United States launched an ocean satellite, SeaSTAR, (also called OrbView-2), which was later included in the EOS program as the first ocean color satellite of the program. Subsequently, the United States developed the navy remote ocean sensing system (NPOSS) and, in cooperation with France, NASA developed TOPEX/Poseidon for observing ocean topography.

(4) Comprehensive oceanographic observation stage

According to the research objectives of the EOS and ESE, the period from 1999 to the present is the comprehensive oceanographic observation stage in the development of ocean remote sensing. The first satellite of the next-generation international Earth observation satellite system, Terra (EOS-AM1), was launched on December 18, 1999, marking the beginning of a new era of human observation of Earth. The second polar-orbiting environmental remote sensing satellite, Aqua (EOS-PM1), was launched on May 4, 2002. Both Terra and Aqua are equipped with a Moderate Resolution Imaging Spectroradiometer (MODIS) that has 36 wavebands ranging from visible to thermal infrared light, nine of which can be used for ocean color remote sensing. Compared with SeaWiFS, MODIS is more advanced and is known as the third-generation ocean color (and meteorological element) sensor (DeVisser 2013). The Jason program was proposed to meet the requirements for establishing a global marine observation system and the demands of oceanic and climatological research. The Jason-2 ocean altimetry satellite (also used for accurate determination of ocean topography) was jointly developed by the Centre National d'Etudes Spatiales (CNES), EUMETSAT, NASA, and NOAA and launched on June 20, 2008. As a follow-up to TOPEX/Poseidon and Jason-1, it is an important observation platform for global oceanographic studies.

3.3.1.2 Typical US Ocean Satellite Systems

(1) Seasat-1

Launched on June 27, 1978, Seasat-1 operated on orbit for 105 days and stopped working on October 10, 1978, due to an electrical system fault. It was launched to demonstrate global monitoring technologies including the observation of oceanic dynamics and satellite orbit characteristics and to provide oceanographic data for the development and application of an operational ocean dynamics monitoring system.

Seasat-1 was the first ocean satellite to use synthetic aperture radar (SAR) for ocean observation by means of remote sensing (Fig. 3.13). Its purpose was to prove the feasibility of using satellites to monitor global oceanic phenomena and help determine the requirements of ocean remote sensing satellite systems. The goal was to collect data about ocean surface wind, sea surface temperature, atmospheric water, sea ice characteristics, ocean topography, and similar parameters. Seasat-1 could cover 95% of the world in a 36-h observation cycle.

(2) OrbView-2

Also called SeaStar, OrbView-2 was launched into a 705 km sun-synchronous orbit on August 1, 1997. The mass of the parent capsule was 155 kg, the mass of the instruments was 45.4 kg, and that of the satellite was 317 kg. The outer dimensions of the satellite were $1.15 \times 0.96 \times 1.6$ m, and the solar wing plate had a span of 3.5 m when unfolded (Fig. 3.14).

Fig. 3.13 Seasat-1

The satellite carried only one remote sensing instrument, SeaWiFS, which could monitor ocean color, generate multispectral images of the land and sea surface, and analyze the impacts of ocean color changes on the global environment, atmosphere, carbon cycle, and other ecological cycles. SeaWiFS consisted of optical remote sensors and an electronic module, and the satellite covered the global ocean area once every two days.

OrbView-2 was the world's first satellite that could generate color images of the Earth every day. The imager had eight spectral segments, six of which were visible and two of which were near infrared. With a spatial resolution of 1.1 km and a 2,800 km scanning width, OrbView-2 data could be used in the fishing industry, agriculture, scientific research, and environmental monitoring.

(3) Jason-1

As an ocean satellite, Jason-1 is used to study the relationship between the ocean and the atmosphere, monitor global ocean circulation, improve global weather prediction and forecasting, and monitor El Niño, ocean eddies, and other events (Chander et al. 2012). With a total weight of 500 kg and payload of 120 kg, Jason-1 was launched on December 7, 2001 (Fig. 3.15). It was the world's first satellite to use the French Alcatel PROTEUS multifunctional microplatform and carried five scientific instruments: one dual-frequency solid-state spaceborne radar altimeter (Poseidon-2), which was the main payload of Jason-1, one triple-channel microwave radiometer (JMR) used to measure atmospheric water vapor content and provide water vapor correction for the radar altimeter, and three other instruments for accurate orbit determination that comprise one Doppler orbitography by radio positioning integrated by satellite

Fig. 3.14 OrbView-2

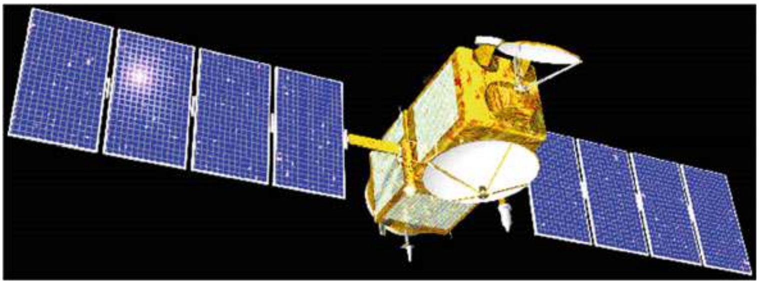

Fig. 3.15 Jason-1 ocean satellite

(DORIS), one laser retro reflector array (LRA), and one turbo rogue space receiver (TRSR).

As the main payload of the Jason-1 satellite, Poseidon-2 was developed by the CNES as an improved model of the Poseidon-1 radar altimeter. In addition to inheriting all the advantages of its predecessor, Poseidon-2 used dual-frequency technology, with working frequencies of 13.575 GHz (Ku-band) and 5.3 GHz (C-band). Compared to other radar altimeters, Poseidon-2 was smaller in volume and lighter weight and had more efficient power consumption. It is mainly used to measure sea surface height, wind velocity, significant wave height, and ionospheric corrections. The main technical parameters of the Poseidon-2 radar altimeter are shown in Table 3.17.

Table 3.17 Main technical parameters of the Poseidon-2 radar altimeter

Satellite feature	Parameter
Operating frequency (GHz)	13.575 (Ku), 5.3 (C)
Pulse repetition frequency (PRF) (Hz)	2,060
Pulse duration (μs)	105
Bandwidth (MHz)	320
Antenna diameter (m)	1.2
Antenna wave width (°)	1.28 (Ku), 3.4 (C)
Power (W)	7

3.3.2 European Ocean Observation Satellites

The successful launch of the first meteorological satellite, Meteosat, in 1977 marked the beginning of the implementation of the European Earth Observation Program (EOP). The main task of Meteosat was to monitor the atmosphere over Europe and Africa. Implementation of the ERS missions in the early 1990s marked the EOP's entry into a new stage. The launch of an ENVISAT satellite in 2002 sped up the pace of EOP implementation. The ESA proposed the Living Planet Programme (LPP) in 1998. Compared with the ERS and ENVISAT missions, the LPP used smaller satellites, was less costly and had better defined targets.

3.3.2.1 ERS-1/2

The ERS-1/2 satellites operated on a near-polar sun-synchronous orbit, with an average orbital altitude of 785 km and an orbital inclination of 98.50°. The local time when the satellite moved from north to south across the equator was 10:30 AM. The ERS-1 launch involved a number of adjustments to the orbital altitude instruments. The three months after launch, the satellite used a three-day period for trial operation at an orbital altitude of 785 km (reference orbit). The orbital adjustment period of the sun-synchronous satellite was 3–176 days, and the main working period was 35 days. The average orbital altitude for the three-day period was 785 km, the orbital altitude above the equator was 909 km, and the satellite circled Earth 43 times. The main parameters of ERS-1/2 are shown in Table 3.18.

The satellite platform carried the following seven instruments (Fig. 3.16): (1) an active microwave instrument (AMI) with an SAR that had a 100-km mapping swath; (2) a wind scatterometer that used three groups of antennas to measure the direction and velocity of sea surface winds; (3) a radar altimeter that was used to accurately measure sea surface topography and elevation, wave height, sea surface wind velocity, and characteristics of sea ice; (4) an orbit-tracking scanning radiometer and microwave sounder; (5) a precision ranging velocimeter that was used to accurately measure the satellite position, orbital characteristics, and the position of fixed ground stations; (6) a laser reflector that used laser beams emitted from the

Table 3.18 ERS-1/2 parameters

Satellite parameter	Value
Weight (kg)	2,400
Total length (m)	11.8
Solar cell array	Area: 11.7×2.4 m^2; power: 1.8 KW; service life: 2 years
SAR antenna (m)	10×1
Scatterometer antenna (m^2)	Anterio-posterior direction: 3.6×0.25; middle direction: 2.3×0.35
Radar altimeter antenna diameter (m)	1.2
Communication frequency band	S-band
Orbit	800 km sun-synchronous orbit
Orbital period (d)	35

Fig. 3.16 ERS-1

ground station to measure the satellite orbit and position; and (7) an onboard data processing system.

3.3.2.2 ENVISAT Satellite

Launched on March 1, 2002, ENVISAT was a polar-orbiting Earth observation satellite and the largest Earth observation satellite built (Fig. 3.17). ENVISAT had ten

Fig. 3.17 ENVISAT satellite

Table 3.19 The working modes and characteristics of the ASAR sensor on the ENVISAT satellite

Feature	Image	Alternating Polarization	Wide Swath	Global Monitoring	Wave
Imaging swath width (km)	Max. 100	Max. 100	Approx. 400	Appr. 400	5
Downlink data rate (Mbps)	100	100	100	0.9	0.9
Polarization mode	VV or HH	VV/HH or VV/VH or HH/HV	VV or HH	VV or HH	VV or HH
Resolution (m)	30	30	150	1,000	10

instruments that constituted an observation system that captured lithosphere, hydrosphere, atmosphere, biosphere, and ice layer information.

At the time, the ASAR on board ENVISAT was the world's most advanced spaceborne SAR sensor with new features including multipolarization, multiple modes, and multiple incident angles. The ground resolution of data reached 25 m, and the widest coverage was 400 km. The multipolarization SAR imaging system could acquire copolarization and cross-polarization information of ground objects and more accurately detect features of a target. The five working modes and characteristics of the ENVISAT satellite's ASAR sensor are listed in Table 3.19.

3.3.2.3 The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)

The GOCE was a satellite that adopted new technologies to map the Earth's gravitational field (Fig. 3.18). The GOCE was launched on March 17, 2009 (Metzler and Pail 2005). The satellite started scientific observation activities on September 30, 2009 and carried out its functions during its service life. In October 2010, the first batch of GOCE satellite data was released freely to scientific researchers and noncommercial users across the world, opening up a new historical period for Earth gravity field research.

The GOCE moved on a low, nearly-circular, twilight sun-synchronous orbit. The orbital plane's eccentricity was less than 0.001 and its inclination was 96.7°, leaving a nonobservable area with a spherical radius of approximately 6.7° in the northern and southern polar regions. The satellite's working time was twenty months, including three months of commissioning and calibration followed by a period of scientific measurement and period of dormancy. Due to its energy supply, trial operation, gradiometer calibration, orbital adjustment and other reasons, the time period for scientific observation was only twelve months. Once the satellite's working time period had expired, it was decided to extend the GOCE's operational period based on the working state of all systems and the quality of data products obtained. The original plan was to extend the mission by ten months and increase the observation tasks accordingly (Floberghagen et al. 2011).

The goal of the GOCE mission was to provide a high-precision, high-resolution static Earth gravity model (Bouman et al. 2009). Such models can be obtained based

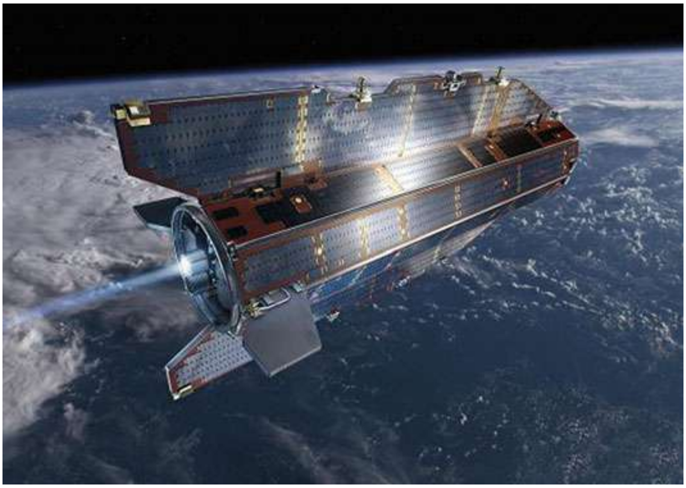

Fig. 3.18 GOCE

on the gravity gradient and GPS tracking data. The specific goals were to: determine global gravity anomalies with a precision of 1 mGal, determine the global geoid with a precision of 1–2 cm, and fulfil these goals with a spatial resolution above 100 km (half-wavelength) (Visser 2010; Gooding et al. 2007).

3.3.3 *China's Ocean Observation Satellites*

China's first independently developed ocean satellite, HY-1A, was launched on May 15, 2002. As an experimental satellite, HY-1A was used to monitor ocean color and temperature. HY-1B was launched on April 11, 2007, and was positioned for operation on September 3. HY-1B was the successor to HY-1A, with a design life of three years, and its technical indicators and functions were superior to those of HY-1A. The HY-2A satellite was launched on August 16, 2011. As a marine dynamic environment satellite, HY-2 worked to detect the sea surface wind field, temperature field, sea surface height, wave field, and flow field. It adopted the platform of the ZY-1 satellite. A roadmap of ocean satellite development is shown in Fig. 3.19.

(1) HY-1A

The ten-band Chinese ocean color and temperature scanner (COCTS) was used to detect ocean color environmental factors (concentration of chlorophyll, content of suspended sediments, and presence of soluble organic matter) and temperature field. The satellite had a nadir ground resolution of 1,100 m, 1,024 pixels per line,

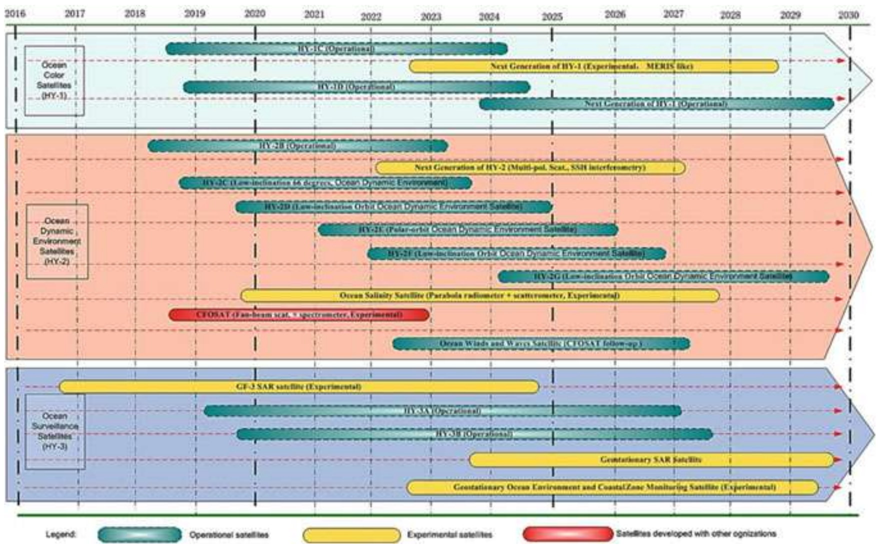

Fig. 3.19 Roadmap of ocean satellite development

Table 3.20 Ocean color and temperature scanner parameters

Parameter	Value
Spectral range (μm)	B1: 0.402–0.422, B2: 0.433–0.453 B3: 0.480–0.500, B4: 0.510–0.530 B5: 0.555–0.575, B6: 0.660–0.680 B7: 0.740–0.760, B8: 0.845–0.885 B9: 10.30–11.40, B10: 11.40–12.50
Band-center wavelength shift (nm)	≤2(B1-B8)
Nadir ground resolution (m)	≤1100
Number of pixels per line	1664
Quantization level (bit)	10
Radiometric precision	Visible light: Infrared: ±1 K (when the onboard calibration accuracy is 300 K)

a quantization level of 10 bits, and a radiometric precision of 10% of the visible light. The four-band CCD imager was used to monitor coastal zone dynamics to obtain relatively high-resolution images of land-sea interaction areas. The imager had a nadir ground resolution of 250 m, 2,048 pixels per line, and ≤5% degrees of polarization.

(2) HY-1B

As the successor of HY-1A, the HY-1B ocean satellite was launched on April 11, 2007, and had a design life of three years. Its payload parameters are shown in Table 3.20 (National Satellite Ocean Application Service 2007, 2011). HY-1B monitors the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, and their coastal zones to detect chlorophyll, suspended sediments, soluble organic matter, and sea surface temperature.

(3) HY-2A

The HY-2A ocean satellite was China's first marine dynamic environment satellite to integrate active and passive microwave remote sensors and is capable of high-precision orbital measurement and determination, and all-weather, 24-h global detection. Its mission is to monitor and investigate marine environments and obtain dynamic ocean environment parameters including sea surface wind, wave height, ocean current, and sea surface temperature. HY-2A also provides data for the pre-warning and forecasting of disastrous sea conditions, and offers supportive services for the prevention and mitigation of marine disasters, protection of marine rights and interests, development of marine resources, protection of the marine environment, marine scientific research, and national defense. HY-2A was launched at 06:57 on August 16, 2011 from the Taiyuan Satellite Launch Center using a CZ-4B rocket.

The satellite is equipped with a scanning microwave radiometer, a radar altimeter, a microwave scatterometer, a calibrated microwave radiometer, DORIS, dual-frequency GPS, and a laser range finder. The parameters of the radar altimeter are shown in Table 3.21.

Table 3.21 Technical parameters of the HY-2 radar altimeter

Parameter	Value
Operating frequency (GHz)	13.58, 5.25
Pulse limited footprint (km)	≤2
Altitude measurement precision (cm)	<4
Effective wave height measurement range (m)	0.5–20

3.3.4 Other Ocean Observation Satellites

In addition to the United States and the ESA, Russia, Japan, Canada, and India have launched various ocean satellites into space. Generally, modern ocean satellites have an accurately determined sun-synchronous orbit, use a variety of remote sensors for measurement, and adopt a comprehensive remote sensing platform.

3.3.4.1 Japan's Satellites

On February 19, 1987, Japan launched its first ocean observation satellite, MOS-1, on an N-l rocket from the Tanegashima Space Center (Fig. 3.20).

MOS-1 was loaded with two optical remote sensors: a multispectral electronic self-scanning radiometer (MESSR) and a visible thermal infrared radiometer (VTIR). Other payloads included a microwave scanning radiometer (MSR), a data collection system (DCS), and a visible thermal infrared repeater. The MESSR is an electronic scanning optical observation remote sensor that uses a CCD to capture land and ocean information. Wavelengths ranging from visible light to near infrared are divided into four spectral bands (see Table 3.22). On board the satellite were two identical devices

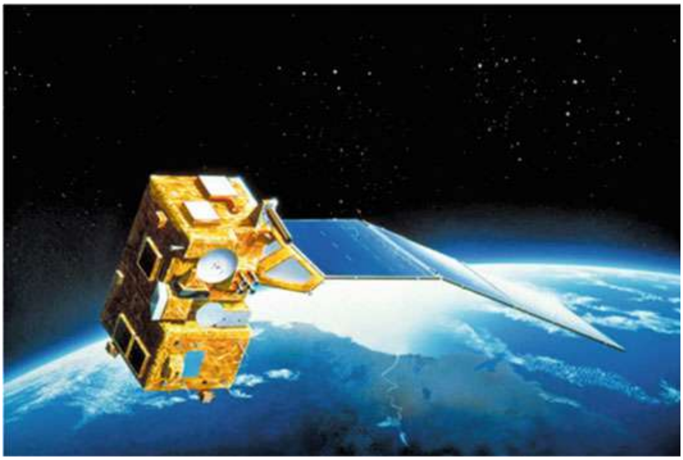

Fig. 3.20 MOS-1

Table 3.22 MOS-1 sensor characteristics

	MESSR	VTIR		MSR
Observation purpose	Ocean color, land use, etc.	Sea surface temperature, etc.		Water vapor, ice, snow, etc.
Observed wavelength (μm)	0.51–0.59	0.5–0.7	6–7	
	0.61–0.69			
	0.72–0.80		10.5–11.5	
	0.80–1.1		11.5–12.5	
Instantaneous field of view (km)	0.05	0.9	2.7	32, 23
Radio wave resolution	39–15 dB	55 dB	0.5 K	<1.5 K
Observation width (km)	100	1500		317
Scanning mode	Electronic scanning	Mechanical scanning		Mechanical scanning

with a land observation width of 100 km, coordinated coverage of 185 km, and ground resolution of 50 m.

3.3.4.2 India's Satellites

OceanSat-1 was launched for the study of marine physics and marine biology on May 26, 1999 using a PSLV-C2 rocket (Dash et al. 2012). It was equipped with an ocean color monitor (OCM) and a multifrequency scanning microwave radiometer (MSMR) (Fig. 3.21). The OCM was used to collect data and worked at 402–422 nm, 433–453 nm, 480–500 nm, 500–520 nm, 545–565 nm, 660–689 nm, 745–785 nm, and 845–885 nm with a spatial resolution of 360 m and width of 1,420 km.

OceanSat-2 was launched on September 23, 2009 using a PSLV-C14 rocket. It functions on a circular near-polar sun-synchronous orbit 720 km above Earth, and continuously provides effective IRS-P4 services (Gohil et al. 2013; Sathiyamoorthy et al. 2012). The observation data from OceanSat-2 are applied to new areas of ocean research such as tornado trajectory prediction, coastal area mapping, and atmospheric research. The OCM and ROSA provide several geophysical parameters such as suspended sediment, yellow matter, phytoplankton, sea surface temperature (SST), sea wind, sea conditions, significant wave height, and atmospheric profiles derived from GPS radio occultation.

Fig. 3.21 OceanSat-1

3.3.4.3 Russia's Satellites

Since 1979, the Soviet Union/Russian Federation has launched a series of ocean color satellites known as the Okean-O1 series of satellites for marine and polar ice observation (Fig. 3.22). Twelve Okean-O1 satellites were launched (including one launch failure) by the end of August 1995 and four satellites were launched between May 1988 and October 1994, referred to as Okean-1 to Okean-4. The satellite payloads included an X-band side-looking radar with 350/1,500 m resolution and 1,380/1,930 km scanning width, and a microwave radiometer with an 8 mm working

Fig. 3.22 Okean-O1 Satellite

frequency and a 550 km scanning width. The Okean-O1 series of satellites functioned at an orbital altitude of 650 km and an inclination of 82.5°. Each satellite weighed 1.95 t and had a design life ranging from six months to a year. In 1999, Russia launched a new type of ocean satellite, Okean-O, whose design life and weight were increased to three years and 6.5 t, respectively. The Okean-O series of satellites adopted a sun-synchronous orbit with an altitude and inclination of 670 km and 98°, respectively. Each satellite was equipped with nine remote sensors, leading to improved optical resolution (25–200 m for visible light and 100–600 m for infrared).

3.3.4.4 Canada's Satellites

RADARSAT is a joint research project conducted by Canada (Canadian Space Agency/Canada Centre for Remote Sensing) and the United States (NASA). The radar is designed to provide detailed information for sea ice, land ice, and climate studies, and the radar images can be used in fields such as oceanography, agriculture, forestry, hydrology, geology, and geography and to provide real-time ice surveillance of the Arctic ocean.

RADARSAT-1 was launched by Canada on November 4, 1995 (Fig. 3.23). Satellite-borne SAR is an active remote sensing device. Because it actively emits electromagnetic waves to obtain information, it can penetrate clouds and fog and overcome night barriers and is capable of all-weather, 24-h observation. It can observe the surface on a regular basis and obtain real-time observation data. The SAR on board RADARSAT-1 was a C-band multiangle sensor with an HH polarization mode and

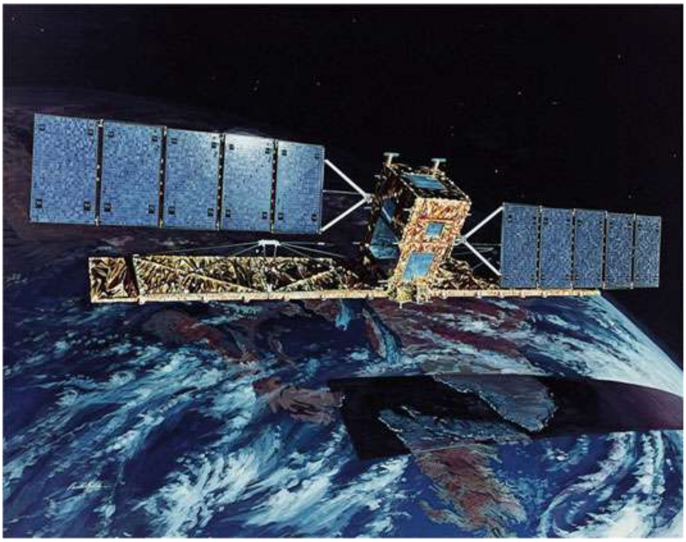

Fig. 3.23 RADARSAT-1

seven working modes used for coastal zone observation, sea ice monitoring, topographic surveys, and other uses.

RADARSAT-2 was launched in December 2007 as Canada's next-generation commercial radar satellite offering powerful technical advancements for mapping in Canada and around the world. This satellite is a follow-up to RADARSAT-1. It has the same orbit and is separated by half an orbit period (~50 min) from RADARSAT-1 (in terms of the ground track, this represents ~12 days of separation). RADARSAT-2 is a C-band imaging radar system, with a nominal imaging swath from 20 to 500 km, incidence angles from 10° to 60°, and fully polarimetric imaging capability; it is an indispensable tool for managing natural resources and monitoring the environment in the twenty-first century. It fills a wide variety of roles, including in sea ice mapping and ship routing, iceberg detection, agricultural crop monitoring, marine surveillance for ship and pollution detection, terrestrial defense surveillance and target identification, geological mapping, land use mapping, wetlands mapping, and topographic mapping.

3.4 Meteorological Observation Satellites

Meteorological satellites have become an indispensable part of the basic and strategic resources for national economic and social development in countries across the world. As the problems of environmental pollution, resource shortages, and natural disasters become increasingly worse, the role of meteorological satellites in weather forecasting, environmental monitoring, and disaster mitigation and prevention has become more important than ever.

3.4.1 US Meteorological Observation Satellites

Since the launch of its first meteorological satellite in April 1960, the United States has developed two series of meteorological satellites: geostationary meteorological satellites and polar-orbiting meteorological satellites. The former is the Geostationary Operational Environmental Satellite (GOES) series and the latter comprises NOAA satellites in the Defense Meteorological Satellite Program (DMSP).

3.4.1.1 The DMSP Satellite System

DMSP satellites operate on sun-synchronous orbits. Some of the orbital parameters are listed in Table 3.23.

The DMSP satellite series adopts a double-satellite operation system. One satellite operates on a 06:00 AM orbit and the other on a 10:30 AM orbit, both with a repeat observation cycle of twelve hours and seven payloads, which are shown in Table 3.24.

Table 3.23 Orbits of the current DMSP system satellites

Satellite code	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch time	Orbiting direction
DMSP 5D 3/F14	833	101	98.7	20:29	Clockwise
DMSP 5D 3/F15	833	101	98.9	20:29	Clockwise
DMSP 5D 3/F16	833	101	98.9	21:32	Clockwise
DMSP 5D 3/F17	850	101	98.7	17:31	Clockwise
DMSP 5D 3/F18	850	101	98.7	17:31	Clockwise

Table 3.24 Payloads of the DMSP system satellites in orbit

Satellite code	Payloads
DMSP 5D 3/F14	OLS, SSB/X-2, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F15	OLS, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F16	OLS, SSI/ES-3, SSJ/5, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F17	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F18	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI

The DMSP satellite series uses two data transmission modes: direct reading mode and storage mode. The former can transmit data to the ground station in real time and the latter transmits the data stored in the satellite-borne magnetic tape unit to the ground station when the satellite is flying over it. These ground stations include the Fairchild Air Force Base in the state of Washington, the Loring Air Force Base in Maine, and the Ka'ena Point Satellite Tracking Station in Hawaii. Then, the ground stations transmit the data, via relay satellites, to the Air Force Global Weather Center (AFG-WC) at the Offutt Air Force Base in Nebraska and the Fleet Numerical Oceanographic Center (FNOC) in Monterey, California.

3.4.1.2 The NOAA Satellite System (POES)

Satellites of the Polar-orbiting Operational Environmental Satellite (POES) system operate on sun-synchronous orbits. The NOAA satellite system adopts a double-satellite operation system. The local time of the orbit descending node of one of the satellites is in the morning, and that of the other is in the afternoon. Currently, the POES system satellites carry six kinds of payloads, which are shown in Table 3.25.

Table 3.25 Payloads of the POES system satellites

Satellite	Payloads
NOAA- K	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA)
NOAA- L	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- M	AMSU-A, AMSU-B, ARGOS, AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N	AMSU-A, ARGOS, AVHRR/3, HIRS/4, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N'	A-DCS4, ARGOS, AVHRR/3, HIRS/4, LRIT, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)

In these payloads, AVHRR/3 is used to detect clouds, and cloud-top, sea surface and land surface temperatures. Its channel characteristics are shown in Table 3.26.

HIRS/3 is used to sound the vertical profiles of atmospheric temperature and humidity on cloudless or partly cloudy days. With a quantization level of 13 bits, the instrument has 20 channels and a resolution of 17.4 km.

AMSU consists of AMSU-A and AMSU-B. AMSU can sound temperature and humidity on cloudy days, sound precipitation on the land and sea, recognize sea ice and determine its scope, and sound soil moisture to a certain degree.

SEM is used to measure solar protons, alpha particles, electron flux density, the energy spectrum, and the total particle energy distribution in the satellite orbit to study the satellite's physical environment in space, predict proton events, and ensure the safe operation of spacecraft working in orbit.

ERBS is used to observe incident solar shortwave radiation, solar shortwave radiation reflected to outer space, and longwave radiation transmitted from the Earth-atmosphere system. SBUV is used to measure the total amount and vertical distribution of ozone. The instrument detects the 160–400 nm band and measures two aspects: the ultraviolet backscatter of the atmosphere in the O_3 absorption band and the ultraviolet radiation of the Sun.

Table 3.26 Channel characteristics and applications of AVHRR/3

Channel	Wavelength (μm)	Resolution (km)	Typical application
1	0.58–0.68	1.09	Daytime cloud imaging
2	0.725–1.00	1.09	Ice and snow monitoring
3A	1.58–1.64	1.09	Aerosol, snow, and ice monitoring
3B	3.55–3.93	1.09	Fire and nighttime cloud imaging
4	10.30–11.30	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing
5	11.50–12.50	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing

Table 3.27 Payloads of third-generation GOES satellites in orbit

Satellite code	Payloads
GOES-12	DCS (NOAA), GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI, WEFAX
GOES-13	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI
GOES-14	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder
GOES-15	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI

3.4.1.3 The GOES Satellite System

The United States is now using the third generation of geostationary meteorological satellites. These satellites adopt a three-axis stabilization mode and a satellite-borne vertical sounder, and the imager can perform sounding separately at the same time. There are four main kinds of payloads. The orbital information and payloads of the Geostationary Operational Environmental Satellite (GOES) satellites currently in operation are shown in Table 3.27.

3.4.2 European Meteorological Observation Satellites

The European meteorological satellite program began in 1972. The initial goals of the program were to meet European countries' need for weather analysis and forecasting and meet the demand for global atmospheric monitoring and research in accordance with the WMO's World Weather Watch (WWW) program and the Global Atmospheric Research Program (GARP).

3.4.2.1 Typical Geostationary Meteorological Satellites of Europe

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) has launched ten Meteosat satellites since the first geostationary meteorological Meteosat satellite was launched in November 1977. The European geostationary meteorological satellites are the Meteosat series of satellites launched by EUMETSAT; Meteosat-7 belongs to the first generation (Fig. 3.24) and Meteosat-8, Meteosat-9 and Meteosat-10 belong to the second generation.

The main instrument installed on the first generation of Meteosat operational satellites is a three-channel imager, MVIRI. The parameters of each channel are listed in Table 3.28. The satellites' main tasks are to (1) provide 48 full-disk images of Earth daily; (2) transmit near-real time digital and analog images to primary data user stations and secondary data user stations; (3) relay image data transmitted from

Fig. 3.24 First-generation Meteosat system

Table 3.28 Features of first-generation Meteosat operational satellites

Channel	Spectrum (μm)	Pixel × scan line
Visible (VIS)	0.5–0.9	5000 × 5000
Infrared (IR)	10.5–12.5	2500 × 2500
Water vapor (WV)	5.7–7.1	2500 × 2500

other meteorological satellites; (4) collect data transmitted from the data acquisition platform; (5) send meteorological products to users; and (6) perform meteorological data distribution (MDD), which is mainly intended to improve the transmission of African meteorological data.

The second-generation Meteosat satellites entered Phase A (system design phase) before 1993 and entered Phase B (sample satellite development phase) soon after. Phase C was developed as the launch and implementation phase, and Phase D was the postlaunch application and improvement phase.

MSG is a spin-stabilized satellite (Fig. 3.25), similar to the first generation of meteorological satellites. Its design was improved in many aspects. For instance, the satellite-borne radiometer SEVIRI has much higher performance, the spectral channels were increased from three to twelve, the resolution was greatly improved (1 km in the wideband high-resolution visible light channel), and the scanning time was halved from thirty minutes to fifteen minutes. The data transmission system was also improved, making data transmission and broadcast much faster (3.2 Mbps and 1 Mbps, respectively).

Fig. 3.25 MSG satellite

3.4.2.2 Polar-Orbiting Meteorological Satellite System

The European Union's polar-orbiting meteorological satellite system, MetOp, and EUMETSAT teams are working closely together to develop a European polar-orbiting meteorological satellite system and launch the MetOp series of satellites which, starting in 2002, began replacing older meteorological satellites (TIROS series) launched earlier by NOAA. Satellites owned and operated by EUMETSAT will be part of an American-European three-satellite operating system, in which one US satellite will appear at dawn, MetOp will appear in the morning and another US satellite will appear in the early afternoon.

MetOp is being designed to carry instruments provided by the ESA, EUMETSAT, NOAA, and CNES. These satellites have a larger carrying capacity, improved payload, and better performance than the NOAA system. The MetOp series consists of three satellites; the first, MetOp-A (Fig. 3.26), was launched on October 19, 2006, with a design life of five years and the second, MetOp-B (Fig. 3.27), was launched on September 1, 2012.

The EUMETSAT polar-orbiting satellite system is an integral part of the global observing system (GOS) that is designed to provide long-term global observation

Fig. 3.26 MetOp-A

Fig. 3.27 MetOp-B

data in conjunction with NOAA satellites. The operational instruments on board the EUMETSAT polar-orbiting system are designed to be the same as those on board NOAA satellites to ensure the consistency of observation data. The first one or two satellites are large-capacity, nonoperational polar-orbiting platforms (EPOP/POEM), and subsequent satellites are smaller MetOp satellites.

3.4.3 *China's Meteorological Observation Satellites*

China's polar-orbiting meteorological satellites (FY-1 and FY-3 satellite series) are also referred to as sun-synchronous orbiting meteorological satellites, those whose orbital plane is usually 98°–99° from the equatorial plane and whose orbit crosses the north and south poles. Geostationary meteorological satellites (FY-2 satellite series) move at the same speed as Earth's rotation at an altitude of 36,000 km above the equator. Information on the FY satellite series is shown in Fig. 3.28 (National Satellite Meteorological Center, China Meteorological Administration 2013a).

3.4.3.1 Polar-Orbiting Satellites

(1) *FY-1A/1B*

FY-1A was launched on September 7, 1988, as an experimental meteorological satellite. Although it only worked in orbit for 39 days due to a control system failure, the successful launch of FY-1A was considered a milestone in China's development of meteorological satellites. The satellite was equipped with an infrared and visible light scanning radiometer, a data collection system, a space environment detector, and other instruments. Technical parameters of the multispectral infrared and visible light scanning radiometer are shown in Table 3.29 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

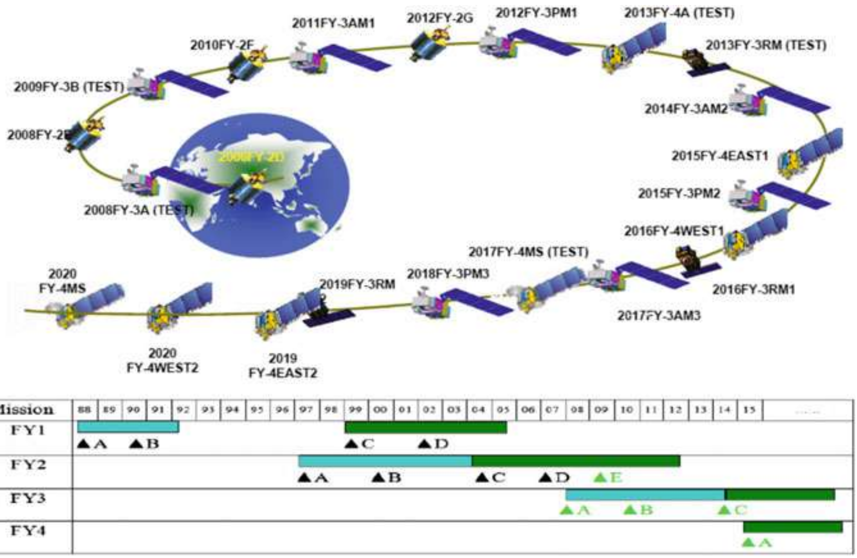

Fig. 3.28 FY satellite series (CMA)

Table 3.29 Technical parameters of FY-1A's visible and infrared scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.725–1.1, 0.48–0.53, 0.53–0.58, and 10.5–12.5
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

The FY-1B satellite was successfully launched on September 3, 1990. As China's second experimental meteorological satellite, FY-1B was an improvement over FY-1A. Compared with FY-1A, FY-1B's attitude control system was improved and its visible cloud images were clearer. The performance of the satellite's sensors and the main functions of the satellite were similar to those of the United States' third-generation polar-orbit meteorological satellites. The satellite's performance was at a level similar to that of commercial applications, its visible channel image quality was high, and its signal-to-noise ratio was above the design requirement. However, the satellite's system lacked reliability.

(2) *FY-1C*

FY-1C was successfully launched from the Taiyuan Satellite Launch Centre on May 10, 1999. Compared with FY-1A/B, the FY-1C satellite had significantly improved performance, with increased detection channels and accuracy. Its design life was two years. A series of technical measures were taken that led to improvements in the product quality, adaptability to space environments, and system reliability. FY-1C functioned stably in orbit until June 24, 2004, when the reception of FY-1C cloud images ceased.

The satellite was equipped with a space particle composition detector and a multichannel visible infrared scanning radiometer (MVISR). The number of MVISR channels for FY-1C was increased from five (FY-1A) to ten, and included four visible light channels, one shortwave infrared channel, and two longwave infrared channels. Table 3.30 lists the wavelength and use of each channel. The field of view was 1.2 microradians, the nadir resolution was 1.1 km, and the scanning speed was six scan lines per second, with each line containing 20,480 pixel points. The calibration

Table 3.30 Technical parameters of FY-1C's multispectral infrared and visible scanning radiometer

Channel no.	Wavelength (μm)	Main purpose
1	0.58–0.68	Daytime clouds, ice, snow, vegetation
2	0.84–0.89	Daytime clouds, vegetation, water
3	3.55–3.93	Heat sources, nighttime clouds
4	10.3–11.3	Sea surface temperature, day/nighttime clouds
5	11.5–12.5	Sea surface temperature, day/nighttime clouds
6	1.58–1.64	Soil moisture, ice and snow recognition
7	0.43–0.48	Ocean color
8	0.48–0.53	Ocean color
9	0.53–0.58	Ocean color
10	0.90–0.965	Water vapor

accuracy of the visible and near infrared channels reached 10%, and the infrared radiometric calibration accuracy reached 1 K, as technically required. The spatial resolution of the HRPT and GDPT images was greater than 1.1 km and 4 km, respectively. The Chinese high-resolution picture transmission (CHRPT) had a frequency of 1,700 MHz, a bit rate of 1.3308 Mbps, and real-time reception from anywhere in the world. The delay picture transmission (DPT) had a frequency of 1,708 MHz and a bit rate of 1.3308 Mbps and was divided into two types: GDPT and LDPT (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) *FY-1D*

Design of the FY-1D flight model began in 2000 based on FY-1C technology and previous experience. Fourteen technical improvements were made that led to improved stability. The 950 kg satellite was launched from the Taiyuan Satellite Launch Center on May 15, 2002, using an LM-4B rocket. FY-1D functioned normally for ten years, exceeding its design life and completing all tasks. It is no longer in operation.

FY-1D's main onboard sensor was a multichannel visible infrared scanning radiometer (MVISR), whose main technical parameters are listed in Table 3.31. Data were transmitted using two methods: HRPT and DPT. The HRPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,700.4 MHz. The DPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,708.46 MHz. Global meteorological data could be acquired through four channels (Channels 1, 2, 4 and 5), with a spatial resolution of 3.3 km (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(4) *FY-3A*

The FY-3 satellites (FY-3) were China's second-generation polar-orbiting meteorological satellites used for weather forecasting, climate prediction, and environmental monitoring. The FY-3 series comprised two satellites: FY-3A and FY-3B. The satellites were used to conduct 3D atmospheric detection, greatly improved China's ability

Table 3.31 Technical parameters of FY-1D's multispectral infrared and visible scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.84–0.89, 3.55–3.93, 10.3–11.3, 11.5–12.5, 1.58–1.64, 0.43–0.46, 0.48–0.53, 0.53–0.58, and 0.900–0.965
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

to acquire global information and further enhanced its cloud area and surface feature remote sensing capabilities. These features enabled the country to obtain global, all-weather, three-dimensional, quantitative, multispectral data on atmospheric, land surface, and sea surface characteristics.

FY-3A was the first FY-3 meteorological satellite launched using an LM-4C rocket from the Taiyuan Satellite Launch Center at 11:02 on May 27, 2008. Although it was developed based on the FY-1 meteorological satellites, FY-3A was substantially superior in both technology and function. The satellite was capable of three-dimensional atmospheric detection, greatly improving the capability for global information acquisition and cloud area and surface feature remote sensing.

(5) *FY-3B*

FY-3B is the second satellite in the FY-3 meteorological satellite series. It was launched from the Taiyuan Satellite Launch Center in the early morning of November 5, 2010, using an LM-4C rocket. FY-3B is China's first afternoon-orbit meteorological satellite, making it the first polar-orbiting meteorological satellite to conduct observations at this time. FY-3B is useful for accurate monitoring and numerical forecasting of rainstorms in southern China that usually occur in the afternoon. Working in conjunction, FY-3B and FY-3A increased the global scan frequency from twice a day to four times a day. Thus, China's ability to monitor disastrous weather events such as typhoons and thunderstorms was enhanced markedly. The satellite had a design life of three years but is still operating in orbit.

FY-3B is equipped with eleven advanced remote sensing instruments and 99 spectral detection channels, five of which have a resolution of 250 m. FY-3B is similar to FY-3A in terms of the satellite platform, payload configuration, and main performance parameters. However, as the first next-generation, polar-orbiting meteorological satellite, FY-3A showed weak operation of some onboard instruments. FY-3B was developed by meteorological satellite experts based on their experience acquired from the development of the FY-3A satellite. As a result, FY-3B demonstrated improved performance for the infrared spectrometer, microwave radiation imager, and solar backscatter ultraviolet sounder.

(6) *FY-3C/3D*

FY-3C is a sun-synchronous orbit satellite launched on September 23, 2013 by the carrier rocket Chinese Long March 4C from the Taiyuan Satellite Launch Center in Shanxi province. The FY-3C orbital satellite joins its predecessors FY-3A and FY-3B. It replaced FY-3A to operate, after undergoing tests, in a morning orbit with FY-2B, which is in an afternoon orbit, to provide temporal resolution of global observation data of up to six hours.

The FY-3C missions primarily include Earth surface imaging and atmospheric sounding, and its observational data will be used in weather forecasting, and in monitoring of natural disasters and ecological and environmental factors. Compared with FY-3A and FY-3B, the payload on board FY-3C features 12 sensing instruments, including a visible infrared radiometer, a microwave scanning radiometer, a microwave temperature sounder (MWTS), a microwave humidity sounder (MWHS), a microwave imager, and a medium resolution imaging spectrometer. It also includes a UV-O-zone sounder, a total O-zone UV detector, a solar radiation and Earth radiation detector, space environmental monitoring suits, and GNSS occultation detectors.

FY-3D was launched on November 14, 2017 as China's fourth second-generation polar-orbiting meteorological satellite and will replace the orbiting FY-3B satellite. The satellite is designed to provide weather forecasts in medium- and long-range numerical weather prediction (NWP) models, enabling high-impact weather forecasting up to a week in advance, and alleviate the impacts of natural disasters on the economy and society and improve livelihood.

Equipped with greenhouse gas probing capacity, FY-3D was also developed to help tackle climate change, in addition to serving ecological, civilization, and construction needs and the 'Belt and Road' initiative. FY-3D features ten instruments, including a microwave temperature sounder (MWTS), a microwave humidity sounder (MHTS), a microwave radiation imager (MWRI), a space environment monitor (SEM), and a global navigation satellite system occultation sounder (GNOS).

3.4.3.2 Geostationary Orbit Satellites

(1) *FY-2A/2B*

The FY-2A satellite was the first experimental satellite in China's first-generation geostationary meteorological satellite series, FY-2, and was launched on June 10, 1997. FY-2A had a three-channel scanning radiometer and a design life of three years at a stable spinning altitude. The satellite began to have issues after working for three months and then worked intermittently, only operating for six to eight hours each day. Ultimately, FY-2A failed to meet the requirements for commercial meteorological services.

The main payload of FY-2A was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.32 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

The FY-2B satellite was the second experimental satellite in China's first-generation geostationary meteorological satellite FY-2 series. FY-2B was launched on June 25, 2000 from the Xichang Satellite Launch Center using an LM-3 rocket. The first original cloud image was received on July 6. FY-2B only had a three-channel scanning radiometer and a design life of three years in a stable spinning altitude. It functioned in orbit for less than eight months before a problem occurred with one of the components on board the satellite; from then onward, the signals it sent back were too weak to receive. Ultimately, FY-2B failed to meet the requirements for commercial meteorological services. However, FY-2B's operation provided valuable experience for the development of subsequent FY-2 meteorological satellites.

The technical parameters of the FY-2B and FY-2A satellites were identical. The cloud images sent from FY-2B played an important role in monitoring typhoons and marine weather, forecasting rainstorms, preventing floods, analyzing the weather system above the Qinghai-Tibetan Plateau, providing meteorological support for aviation, and predicting climate change.

(2) *FY-2C/2D/2E/2F/2G/2H*

FY-2C was the first commercial-use satellite in the FY-2 meteorological satellite series. After a successful launch on October 19, 2004, FY-2C was positioned at an altitude of 36,000 km above the equator at 105° east longitude on October 24.

Table 3.32 Technical parameters of FY-2A's visible and infrared light spin-scan radiometer (VISSR)

Channel	Visible light	Infrared	Water vapor
Wavelength (μm)	0.55–1.05	10.5–12.5	6.2–7.6
Resolution (km)	1.25	5	5
Field of view (μrad)	35	140	140
Scan line	2,500 × 4	2,500	2,500
Detector	Si-photo-diode	HgCdTe	HgCdTe
Noise resolution	S/N = 6.5 (Albedo = 2.5%) S/N = 43 (Albedo = 95%)	NEDT = 0.5–0.65 k (300°K)	NEDT = 1 K (300°K)
Quantitative byte (bit)	6	8	8
Scanning step	140 μrad (N-S scanning)		

FY-2C occupied FY-2B's former position to monitor weather conditions in the Asia Pacific Region. Four days after it was positioned, adjustments were made to the ground application system to technically coordinate it with the satellite. The satellite's service monitoring, data transmission, and forwarding channels were opened, and the scanning radiometer was switched on. FY-2C could observe changes in sea surface temperature, and one of its channels was designed for measuring 3.5–4 μm light waves to observe high-temperature heat sources on the ground. It was possible to use spectral channels to observe ground heat sources to promptly discover forest fires in remote and desolate places, monitor their situation, and predict their development trends.

FY-2D was the fourth satellite in the FY-2 meteorological satellite series. FY-2D was also the country's second application-oriented geostationary-orbiting meteorological satellite. It was launched using an LM-3A rocket at 08:53 on December 8, 2006. After 1,421 s of flying, it successfully separated from the rocket, entering into a large elliptical transfer orbit with a perigee altitude of 202 km, apogee altitude of 36,525 km, and inclination of 24.97°. At 01:24 on December 9, the apogee engine was ignited for orbital transfer, and secondary separation was successfully completed. After four batches of orbit trimming, the satellite was positioned at an altitude of 36,000 km above the equator at 86.5° E longitude at 17:00 on December 13. It is currently no longer in operation.

On December 23, 2008, and January 13, 2012, China's third and fourth service-oriented geostationary meteorological satellites, FY-2E and FY-2F, respectively, were launched from the Xichang Satellite Launch Center using LM-3A rockets. The two satellites were of great significance for the continuous and stable operation of China's geostationary meteorological satellite observation services. FY-2F boasted flexible capability for scanning specific regions with a high temporal resolution and could monitor disastrous weather conditions such as typhoons and severe convections. FY-2F played an important role in China's meteorological disaster monitoring, early warning, prevention, and mitigation. The space environment monitor continuously monitored solar X-rays and the flow of high-energy protons, electrons, and heavy particles, and the data were used for space weather monitoring, forecasting, and early warning services.

The geostationary meteorological satellites FY-2C, FY-2D, FY-2E, and FY-2F working in orbit formed a "double-satellite observation with mutual backup" service pattern. These satellites helped modernize China's comprehensive meteorological observation system. During flood season, the double-satellite observation mode allowed for spinning the satellite, enabling it to provide a cloud picture every fifteen minutes. This intensified observation mode played a key role in monitoring disastrous weather systems such as typhoons, rainstorms, thunderstorms, and small- and medium-scale local convective systems. The FY-2 meteorological satellite series played a crucial role in combating heavy rain, freezing snow, and other extreme weather events. The satellites also provided assistance in the Wenchuan earthquake relief operations and in providing meteorological services for the Beijing Olympics and Paralympics.

The FY-2G satellite was launched on December 31, 2014 from the Xichang Satellite Launch Center. Based on the technology of FY-2 F satellite, the FY-2G satellite was improved by reducing infrared stray radiation, uplifting the observation frequency for the blackbody, and improving the telemetry resolution of optical components. These improvements increase the retrieval accuracy of FY-2G satellite quantitative products and enhance the quantitative application of satellite data products.

FY-2H was launched on June 5, 2018. It is positioned over the Indian Ocean and has realized the sustained observation of one-third of the Earth's territories from Oceania to central Africa. It can provide favorable observation perspectives and custom-made high-frequency subregional observation for countries and regions such as western Asia, central Asia, Africa, and Europe. Equipped with a scanning radiometer and a space environment monitor, FY-2H can supply data for dozens of remote sensing products such as cloud images, clear sky atmospheric radiation, sand and dust, and cloud motion wind (CMW) for weather prediction, disaster warning, and environmental monitoring, enriching the data sources for global NWP models.

The main payload of FY-2C/2D/2E/2F was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.33 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) *FY-4A*

FY-4A was launched on December 11, 2016, as the first Chinese second-generation geostationary meteorological satellite. FY-4A is China's first quantitative remote sensing satellite with a three-axis stabilization structure on a geostationary orbit. Four new instruments are on board the latest independently developed weather satellite, namely, an advanced geosynchronous radiation imager (AGRI), a geosynchronous interferometric infrared sounder (GIIRS), a lightning mapping imager (LMI) and a space environment package (SEP).

FY-4A is the first satellite in China that can capture lightning. The onboard Lightning Mapping Imager enables this function. It is the first geostationary optical remote sensing instrument in China and has filled the gap in terms of lightning observation and satellite-borne detection. FY-4A can detect lightning over China and neighboring areas and take 500 lightning pictures per second. By real-time and consecutive observation of lightning, it can aid in observation and tracking of severe convective weather and provide early warning for lightning disasters.

Table 3.33 Technical parameters of the radiometer on board FY-2C/2D/2E/2F

Channel	Waveband (μm)	Resolution (km)
Visible light	0.55–0.90	1.25
Infrared 1	10.3–11.3	5
Infrared 2	11.5–12.5	5
Infrared 3	6.3–7.6	5
Infrared 4	3.5–4.0	5

3.4.4 Other Meteorological Observation Satellites

3.4.4.1 Japan's Satellites

Since Japan launched its first geostationary meteorological satellite, GMS-1, in 1977, it has put five geostationary meteorological satellites into orbit. The GMS-4 satellite is positioned at 140°E above the equator and is equipped with visible and infrared scanning radiometers that observe a fourth of Earth to monitor cloud distribution, height and dynamics. The satellite can obtain information about winds below and above clouds, and detect sea surface temperature distribution.

Similar to other GMS satellites, GMS-5 is a spin-stabilized satellite. Its total mass is 756 kg, the design life is five years, and the main onboard instrument is a visible and infrared light spin-scan radiometer (VISSR). The VISSR was significantly improved by building upon the radiometer on board GMS-4. One 6.5–7 µm WV channel was added to observe water vapor radiation in the middle layer of the troposphere. The original 10.5–12.5 µm infrared window area was split into a 10.5–11.5 µm channel and an 11.5–12.5 µm channel to observe radiation from Earth's surface and the atmosphere. The nadir spatial resolution of GMS-5 is 1.25 km for the visible light channel and 5 km for the WV channel. The main parameters of the VISSR on board GMS-5 is listed in Table 3.34.

After GMS-5 was launched, Japan suspended the development of single-function meteorological satellite systems. The Japan Meteorological Agency and Japan Civil Aviation Administration jointly developed a new large, multifunctional, integrated satellite system called MTSAT. MTSAT-1, the first satellite of this system, was scheduled to be launched on November 15, 1999. However, the launch was unsuccessful due a fault with the rocket and both the satellite and rocket were destroyed. Japan manufactured another MTSAT satellite named MTSAT-1R (Kim et al. 2011). The satellite was not launched until February 26, 2005 due to the time required to remove the fault and improve the rocket. The satellite began to broadcast images two to three months after launch. It was followed by MTSAT-2, which was launched on December 26, 2006 (Fig. 3.29). The MTSAT satellites are equipped with VISSR, cloud image broadcasting, DCS, aviation communication, and other subsystems mainly used for meteorological exploration and aviation communication and are the largest geostationary satellites with meteorological sounding functions (Crespi et al. 2012).

Table 3.34 VISSR parameters of the GMS-5 satellite (Huang et al. 2004)

Channel	Wavelength (µm)	Quantization level (bit)	Spatial resolution (nadir) (km)
Visible light	0.55–0.90	8	1.25
Water Vapor (WV)	6.5–7.0	8	5
Infrared window area	10.5–11.5	8	5
Infrared window area	11.5–12.5	8	5

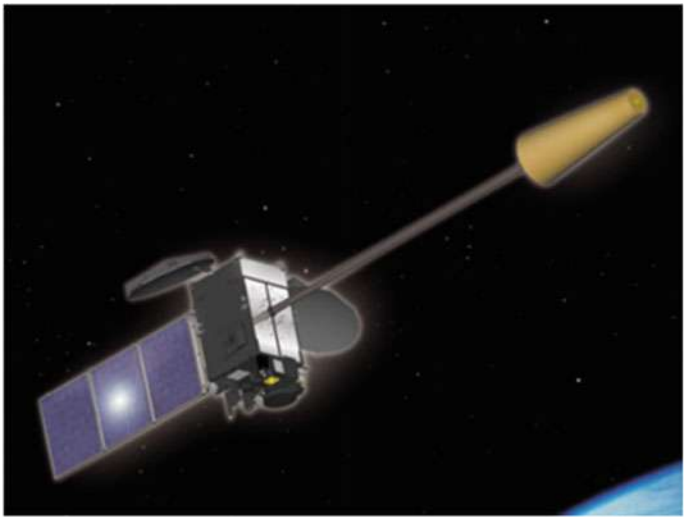

Fig. 3.29 The MTSAT-2 satellite

3.4.4.2 India's Satellites

INSAT is a multiagent multitarget satellite system and is one of the largest satellite systems in Asia. The INSAT satellite system has played an increasingly important role in the Indian aerospace industry with the continuous development and improvement of the INSAT-1, INSAT-2, and INSAT-3 series of satellites.

INSAT provides services such as domestic long-distance communication, meteorological and Earth observation data relay, augmented television receiver national direct satellite broadcasting, TV education, rural communications, meteorology, and disaster alarms.

The first-generation INSAT satellites, the INSAT-1 series, were manufactured by Ford Motor Co. in the United States and comprised four satellites: INSAT-1A, INSAT-1B, INSAT-1G, and INSAT-1D. The second-generation INSAT satellites, INSAT-2, were independently developed by India to meet the needs of the 1990s. The INSAT-2 series consisted of five satellites: INSAT-2A, INSAT-2B, INSAT-2C, INSAT-2D, and INSAT-2E. In addition to normal C-band transponders, the INSAT-2 satellites also adopted the high-frequency section of the C-band, or the extended C-band. The third-generation INSAT satellites, INSAT-3, were also made by the Indian Space Research Organization (IRSO) and comprise five satellites: INSAT-3A, INSAT-3B, INSAT-3C, INSAT-3DR, and INSAT-3DS.

INSAT-3A is a multipurpose satellite launched on April 10, 2003 using an Ariane rocket. The satellite is fixed at 93.50° E and has the following payloads (Fig. 3.30). Of the twelve C-band transponders, nine provide coverage that extends from the Middle East to southeast Asia with an EIRP of 38 dBW, and three provide coverage of India with an EIRP of 36 dBW. The six extended C-band transponders provide

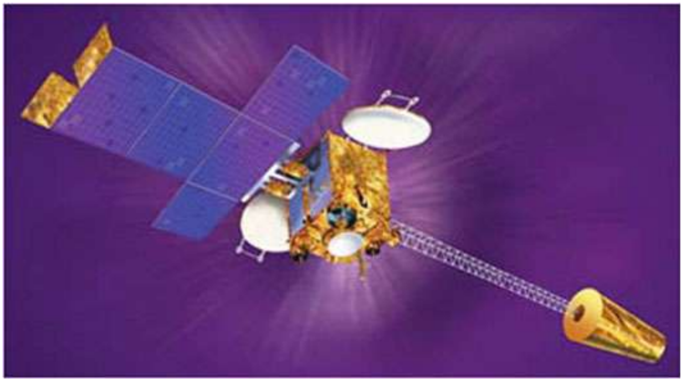

Fig. 3.30 The INSAT-3A satellite

Indian coverage, with an EIRP of 36 dBW. The six Ku-band transponders also provide coverage of India, with an EIRP of 48 dBW. The one very high-resolution radiometer (VHRR) can perform imaging in the visible light channel (0.55–0.75 μm), thermal infrared channel (10.5–12.5 μm), and water vapor channel (5.7–7.1 μm) with ground resolutions of 2 × 2 km, 8 × 8 km, and 8 × 8 km, respectively. The CCD camera has a ground resolution of 1 × 1 km in the visible (0.63–0.69 μm), near infrared (0.77–0.86 μm), and SWIR (1.55–1.70 μm) channels.

3.4.4.3 Russia's Satellites

(1) *Russia's polar-orbiting meteorological satellites*

The "Meteor" series of polar-orbiting meteorological satellites was developed by the Soviet Union/Russian Federation and has gone through four generations. Most of the previous three generations of satellites do not function in sun-synchronous orbit. However, the fourth-generation of satellites is known to work in a sun-synchronous orbit.

As early as 1962–1969, the Soviet Union had launched more than 20 COSMOS satellites for meteorological observation. In March 1969, it launched its first-generation polar-orbiting meteorological satellite: Meteor-1. The first generation consisted of 31 satellites (Meteor-1-31) launched from 1969 to 1981, most of which had an orbital inclination of 81.2°. The second generation (Meteor-2) comprised 24 satellites launched after 1975. In most cases, two or three satellites were simultaneously operating on orbit, with an orbital inclination of 82.0° and orbital altitude of 950 km. The third-generation (Meteor-3) polar-orbiting meteorological satellites were launched in 1984. The third generation was composed of eight satellites, which had an orbital inclination of 82° and orbital altitude of 1,200 km.

Meteor-3 M N1, the first satellite of the fourth generation of Russian meteorological satellites, (the Meteor-3 M series) was launched on December 10, 2001 (Fig. 3.31).

Major changes in the Meteor-3 M series of satellites include: 99.6° orbital inclination, 1,024 km sun-synchronous orbit, and a broadcast data format that is compatible with NOAA's high-resolution picture transmission (HRPT).

(2) *Russia's geostationary orbit meteorological satellites*

Russia's first geostationary orbit meteorological satellite (GOMS) was successfully launched in November 1994. It is a three-axis stabilized satellite positioned at 76°E. A problem occurred with the attitude control after launch, but the satellite resumed working after some remedial measures were taken. Unfortunately, its scanning radiometer's visible light channel has been unable to acquire any images due to an optical design error; thus, the satellite can only capture infrared images.

On January 20, 2011, Russia launched the geostationary hydrological and meteorological satellite Elektro-L from the Baikonur Launch Center in Kazakhstan (Fig. 3.32). Fixed at a position 36,000 km above Earth, the satellite is used to monitor climate change in Russia's Asian region. The visible light and infrared photographic devices installed on the satellite can capture 1-km and 4-km resolution ground images, respectively. Under normal circumstances, the satellite takes a photo once every 30 min. The shooting frequency can be increased to once every 10–15 min in the event of a natural disaster. The satellite is also responsible for forwarding and exchanging weather information as well as receiving and forwarding signals from the international search and rescue satellite COSPAS-SARSAT. GOMS has a life span of ten years and the data distribution mode is HRPT/LRPT. Its mission is to observe

Fig. 3.31 The Meteor-3 M satellite

Fig. 3.32 The Electro-L satellite

Earth's surface and atmosphere, perform solar-geophysical measurement, and support the data collection system and COSPAS-SARSAT services. The satellite's main payload is an optical imaging radiometer, MSU-GS, which provides imaging data in three VNIR channels and seven infrared channels. Its nadir spatial resolution (sampling distance) is approximately 1 km (for visible light) and 4 km (for VNIR and infrared), with a new Earth image provided once every 30 min.

3.5 Trends in Remote Sensing for Digital Earth

Looking back on the past five decades of spaceborne remote sensing, every step along the way has been based on the national backgrounds and political and economic conditions of each country. During this period of development, the purpose of Earth observation shifted from single-field surveying toward serving the demands of the overall development of human society (Guo 2014). Since entering the period of globalization, remote sensing technologies have developed into a complete system (Guo et al. 2013), which will provide more abundant data for Digital Earth.

Countries and regions with leading Earth observation technologies, such as the United States and Europe, have formulated Earth observation plans for long-term development. In 2013, the United States and European organizations were expected to launch 34 Earth observation satellites, and India and China planned to launch 25 and 26 satellites, respectively. Russia, Japan, and Canada also had plans for over ten launch missions (Fig. 3.33). Russia will remain a major contributor to satellite launches in Europe, but European organizations will launch significantly more, and there will be a greater emphasis on cooperation and coordination between European

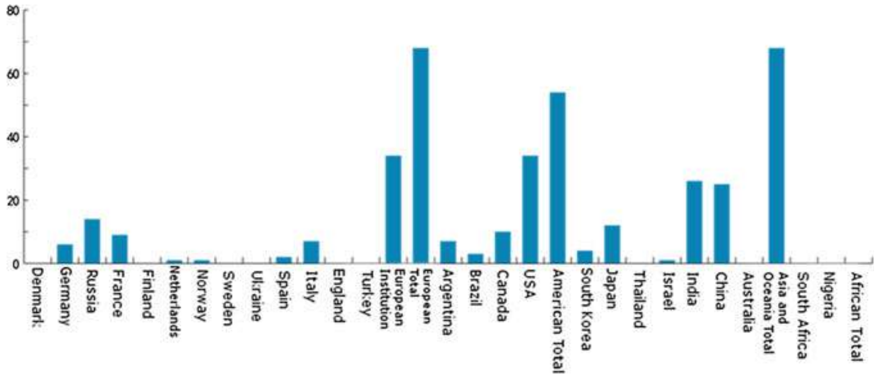

Fig. 3.33 Global launch plans for Earth observation satellites by 2035

countries. In America, the United States will remain a leading force, and Canada will occupy a secondary role. In Asia, the existing trend will continue, with China, India, Japan, and South Korea continuing to be major contributors. Currently, no African countries have plans to launch new satellites.

All of the aforementioned satellite programs have clearly defined services. For example, the United States' Earth observation program for 2016–2020 focuses on measuring global ozone conditions and other relevant gases (GACM program), atmospheric pollution monitoring (3D-Winds), geological disasters (LIST), weather forecasts (PATH), and water resource utilization (GRACE-II/SCLP) (Neeck et al. 2008). The European GMES program covers the six service fields of land, ocean, emergency management, security, atmosphere, and climate change (Veefkind et al. 2012). In addition, Russia, Japan, India, and some other countries have issued strategic plans for Earth observation, forming systems with their own characteristics. The Russian Federal Space Agency (Roscosmos) intends to form a satellite system consisting of geostationary meteorological satellites (Elektro series), polar-orbiting meteorological satellites (METEOR series), and resource/environment satellites (KANOPUS-V and Resurs-P series) by 2020. The Japan Aerospace Exploration Agency (JAXA) proposed the GOSAT program for greenhouse gas monitoring and the GCOM program for global change monitoring in addition to its ongoing efforts to build the ALOS program of high spatial resolution satellites carrying L-band SAR and hyperspectral sensors. Additionally, JAXA has plans to continue with its navigation experiment satellite program (QZS). The Indian Space Research Organization (ISRO) and the Indian National Remote Sensing Agency (NRSA) aim to improve the spatial resolution of the Resourcesat series and develop SAR-carrying satellites and environment satellites (Environment Sat) of their own (RISAT series).

In addition, some companies such as DigitalGlobe are planning to deploy new high-resolution satellites and trying to enter the microsatellite field. The planned satellites have also been extended from optical to meteorological and radar satellites. However, at present, there are few companies in the commercial satellite market; for example, DigitalGlobe provides high-resolution optical images, and the European

Airbus Defence and Space division can provide high-resolution optical and radar data. China is also planning a series of microsatellites for commercial service. Shenzhen-1 is its first microsatellite constellation and will realize 0.5 m resolution with a revisit period of less than 1 day. Furthermore, the Zhuhai-1, Beijing-1 and Beijing-2 microsatellites will be launched successively and networked. These commercial microsatellites aim to provide real time information for Digital Earth.

Future Earth satellite observation programs will focus on program continuity, development potential, and the capacity for comprehensive and coordinated applications. Therefore, long-term observation programs will be proposed and the development of aircraft-carried and satellite-carried sensors will continue with improved coordination. Relevant Earth observation programs will emphasize the coordinated use of Earth observation platforms and data to better meet the requirements of various fields that may benefit from observation efforts, as well as the nuanced strategic goals of countries and regions (Guo 2018).

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Chapter 4
Satellite Navigation for Digital Earth

Chuang Shi and Na Wei

Abstract Global navigation satellite systems (GNSSs) have been widely used in navigation, positioning, and timing. China's BeiDou Navigation Satellite System (BDS) would reach full operational capability with 24 Medium Earth Orbit (MEO), 3 Geosynchronous Equatorial Orbit (GEO) and 3 Inclined Geosynchronous Satellite Orbit (IGSO) satellites by 2020 and would be an important technology for the construction of Digital Earth. This chapter overviews the system structure, signals and service performance of BDS, Global Positioning System (GPS), Navigatsionnaya Sputnikovaya Sistema (GLONASS) and Galileo Navigation Satellite System (Galileo) system. Using a single GNSS, positions with an error of ~ 10 m can be obtained. To enhance the positioning accuracy, various differential techniques have been developed, and GNSS augmentation systems have been established. The typical augmentation systems, e.g., the Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), the global differential GPS (GDGPS) system, are introduced in detail. The applications of GNSS technology and augmentation systems for space-time geodetic datum, high-precision positioning and location-based services (LBS) are summarized, providing a reference for GNSS engineers and users.

Keywords BDS · GNSS augmentation systems · High-precision positioning · Real-time · LBS

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4.1 Introduction

The concept of Digital Earth was proposed by former US vice president Al Gore in 1998. At the 6th International Symposium on Digital Earth in Beijing, Digital Earth was defined as an integral part of other advanced technologies, including earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, and grid computation. Satellite navigation and positioning technology can provide precise position and time information, which are key elements of the Digital Earth.

In satellite navigation and positioning technology, the radio signals transmitted by navigation satellites are received by the user terminal. By measuring the time delay of the signal propagated from the navigation satellite to the receiver, navigation, positioning and timing services can be realized. Compared with conventional navigation and positioning techniques, satellite navigation and positioning technology can provide precise three-dimensional positions, velocity and time for users. It is an all-weather, all-time and globally available technology. Great progress has been made in recent decades, and many countries and consortia have established their own global navigation satellite systems. Global satellite navigation and positioning technology has been widely applied in navigation for vehicles, offshore ships, aero craft and aerospace vehicles and in the fields of geodesy, oil exploration, precision agriculture, precise time transfer, and earth and atmospheric sciences.

4.2 Global Navigation Satellite System

Before the advent of man-made satellites, navigation and positioning mainly depended on ground-based radio navigation systems that were developed during the Second World War such as LORAN and Decca Navigator, shown in Fig. 4.1. On October 4th 1957, the former Soviet Union (Union of Soviet Socialist Republics, or USSR) launched the first man-made satellite. Based on the Doppler shift of the radio signal, Dr. Guier and Dr. Wiffenbach from Johns Hopkins University successfully calculated the orbit of the satellite. This laid the foundation for the scientific idea of navigation and positioning with the use of man-made satellites. In 1958, the US military began to develop the first (generation) satellite navigation and positioning system in the world—the Transit navigation satellite system (TRANSIT), which was formally put into military use in 1964. The USSR also began to establish the CICADA system in 1965, and the first CICADA satellite was launched in 1967. Using the Doppler shift method, the first-generation satellite positioning system needed long-term observations to realize navigation and positioning, and the positioning accuracy was also unsatisfactory. To overcome these limitations, the joint development of a new generation satellite navigation system—the Global Positioning System (GPS)—by the US army, navy and air force was formally approved

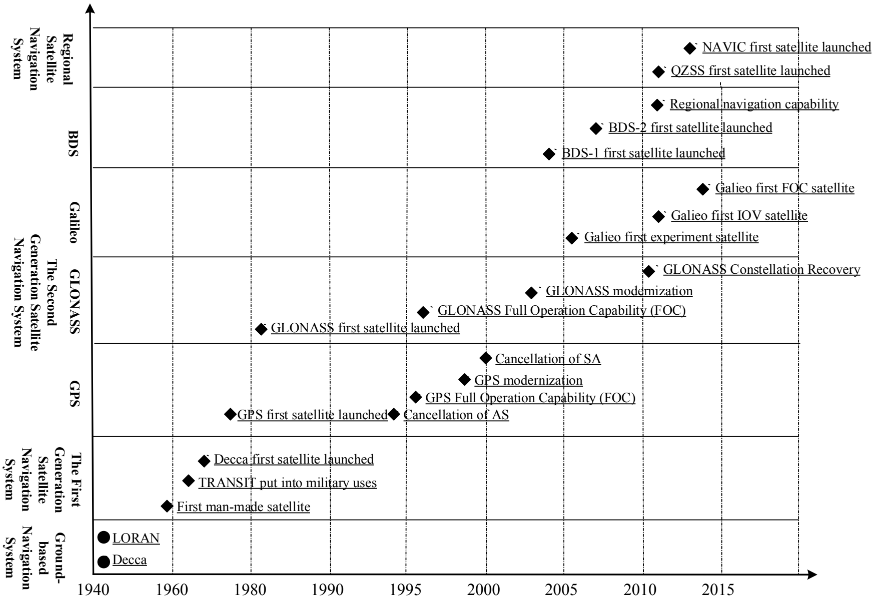

Fig. 4.1 Overview of the development of satellite navigation systems from the 20th century

by the United States Department of Defense (DoD), opening a new chapter for the development of satellite navigation systems.

The satellite navigation system was initially designed for military requirements. With the end of the Cold War, the growing demand for civil and commercial navigation became increasingly strong. Many countries in the world began to develop independent global navigation satellite systems (GNSSs), including the GPS developed by the US, the Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) developed by Russia, the Galileo Navigation Satellite System (Galileo) established by the European Union (EU), and the BeiDou Navigation Satellite System (BDS) developed by China. Since the technical reserve and capital investment required for the GNSS development is rather large, some countries began to develop regional navigation satellite systems (RNSS) to meet the navigation and positioning demands in their own territory and the surrounding areas, for example, the Quasi-Zenith Satellite System (QZSS) of Japan and the Navigation with Indian Constellation (NAVIC) of India.

GNSSs have evolved from a single GPS constellation to multiple GNSS constellations. In the coming decades, the number of navigation satellites in orbit may increase to several hundreds. Therefore, the integration of multifrequency and multisystem GNSS data, compatibility of GNSS signals and interoperability between different GNSSs are the most important development directions.

Satellite navigation systems consist of three components: the space segment, the control segment (CS) and the user segment. The space segment comprises a constellation of navigation satellites that continuously broadcast ranging code and navigation message to users, and receive various information and commands from a ground monitoring system. The design of the navigation satellite constellation should ensure that four satellites are visible by any user at any time for positioning. The CS includes master control stations (MCSs), uplink stations and monitoring stations. The ground monitoring stations track navigation satellites and the MCSs collect observation data and calculate satellite orbit and clock errors, which are forecasted and formatted into navigation messages and uploaded to the navigation satellites through the uplink stations. The ground CS can also send various commands to the satellites through uplink stations for satellite orbit maneuver, atomic clock adjustment, fault recovery, or initiation of spare parts. The geometric distance between the navigation satellite and the receiver can be measured by the user with a GNSS receiver, and parameters such as the three-dimensional position, velocity and receiver clock errors can be obtained according to the satellite's location in space described by the ephemeris. As the main functions of these segments are similar for different satellite navigation systems, we ignore the common details in the following sections and introduce the unique features of each GNSS.

4.2.1 BDS

BDS, formerly known as COMPASS, is an independent global satellite navigation system developed and operated by China. As the third mature satellite navigation system after GPS and GLONASS, BDS provides high-quality positioning, velocity measurement, timing and short message services for global users. BDS has evolved from active positioning to passive positioning. A global passive positioning system will be established by 2020 (http://www.beidou.gov.cn).

Development of the BeiDou Navigation Satellite Demonstration System (BDS-1) was initiated in 1994. Two geosynchronous equatorial orbit (GEO) satellites were launched in 2000, and the regional double-satellite positioning system was established and put into operation. Based on the active-positioning scheme, positioning, timing, wide-area differential and short message communication services were provided for users in China. With the third GEO satellite launch in 2003, the system performance was further enhanced.

Development of the regional BeiDou Navigation Satellite System (BDS-2) began in 2004. As a passive-positioning system, BDS-2 can provide positioning, timing, wide-area differential and short message communication services for users in the Asia-Pacific region. By the end of 2012, the deployment goal of a regional satellite navigation system was accomplished, with a constellation of 5 GEO satellites, 5 inclined geosynchronous satellite orbit (IGSO) satellites and 4 medium earth orbit (MEO) satellites. On December 27th, 2012, it was officially declared that the BDS could provide regional positioning and navigation services with positioning accuracy of 10 m. China became the third country in the world with an independent satellite navigation system.

In a third step, the global BeiDou Navigation Satellite System (BDS-3) should be completed in 2020, with a constellation of 30 satellites (3GEO + 3IGSO + 24MEO). Both the GEO and IGSO satellites operate in orbits at an altitude of 35,786 km (BDS-ICD 2013). The inclination of the IGSO orbital plane is 55°. The altitude of the MEO satellites is 21,528 km, and the inclination is 55°, with a satellite orbit period of 12 h and 53 min.

BDS-3 has entered into a new era of global deployment with the introduction of new functions such as intersatellite links, and global search and rescue. The technical scheme of BDS-3 is fully forward compatible with that of BDS-2 and realizes performance improvement and service extension. By the end of 2018, the BDS-3 'basic system' comprising of 18 MEO and one GEO satellites was completed to provide services for users in China and neighboring countries along the Belt and Road. In-orbit validation has shown that the positioning accuracy is 10 m globally and 5 m in the Asia-Pacific area. By 2020, BDS-3 will be fully completed to provide global services and an integrated positioning navigation and timing (PNT) system should be set up by 2035.

The code division multiple access (CDMA) signal system is used by the BDS and the carrier signal is broadcasted at B1, B2 and B3 frequencies in L band. B1I and B3I were maintained and inherited from BDS-2, and a new open signal B1C was added and the B2 signal was also upgraded into the newly designed B2a signal, which replaces the original B2I signal and greatly improves the signal performance of BDS-3. The compatibility and interoperability with other GNSSs were also taken into account. A domestically developed high-precision rubidium and hydrogen atomic clock with better stability and smaller drift rate was equipped on the BDS-3 satellites, leading to significant improvement in the performance of the onboard time and frequency standards.

The intersatellite links in the Ka frequency band are equipped for the BDS-3 constellation, and two-way intersatellite precise ranging and communication is realized through use of phased-array antenna and other intersatellite link equipment. Mutual ranging and timing through intersatellite links allow for obtaining more measurements from multiple satellites to improve the observation geometry for autonomous orbit determination. The intersatellite measurement information can also be used to calculate and correct satellite orbit and clock errors for satellite-satellite-ground integrated precise orbit determination, improving the accuracy of satellite orbit determination and time synchronization. Both open and authorized services are provided by BDS-3. The open service provides free services for global users with a positioning accuracy of 10 m, velocity measurement accuracy of 0.2 m/s and timing accuracy of 10 ns. The authorized service provides authorized users with high-precision and reliable measurement of position, velocity and time, communication services, and system integrity information.

The basic BDS observations include pseudorange and carrier phase measurements. The pseudorange measurement is calculated by multiplying the speed of light with the transmission time of the GNSS ranging code from the satellite to the receiver, which comes from the correlation operation of the ranging code generated by the receiver clock with that generated by the satellite clock. The pseudorange reflects the distance between the satellite antenna phase center at the time when the GNSS signal is transmitted by the satellite and the receiver antenna phase center when the signal arrives. Its accuracy therefore depends on the code correlation accuracy. Currently, the noise of the pseudorange measurement is approximately 1%–1‰ of the code width.

The carrier phase measurement refers to the measurement of the navigation signal received from the satellite relative to the carrier phase generated by the receiver (the beat frequency phase) at the time of reception. Once the receiver is powered on, the fractional part of the beat frequency phase is measured and the changes in the integer number of carriers are counted. However, the initial integer number of carriers between the receiver and the satellite cannot be measured. Taking a complete carrier as one cycle, the unknown number of integer cycles is called the ambiguity. The initial measurements of the carrier phase include the correct fractional part and an arbitrary integer number of cycles at the starting epoch. At present, the accuracy of the carrier phase measurement recorded by electronic devices is better than 1% of the wavelength; that is, the carrier phase measurement accuracy is millimeter level.

Compared with the other existing GNSSs, the BDS has the following features: first, the space segment of the BDS is a hybrid constellation comprised of satellites in three kinds of orbits, and the anti-jamming and anti-spoofing capability is better due to more satellites in higher orbits, especially for the low latitude regions; second, the BDS is the first GNSS with signals broadcasted at three frequencies in the full constellation, which could improve service accuracy with a multifrequency combination signals; third, navigation and communication are innovatively integrated in the BDS, so that it can implement five major functions including providing real-time navigation and positioning, precise timing and short message communication services. The service performance of BDS are summarized in Table 4.1.

Table 4.1 Overview of BDS service performance

	BDS-1	BDS-2 (regional)	BDS-3 (global)
Service coverage	China and neighboring areas	Longitude: 84°–160° E, Latitude: 55° S–55° N	Global
Positioning accuracy	<20 m	Horizontal 25 m, Elevation 30 m	<10 m (three-dimensional)
Velocity accuracy	/	0.2 m/s	<0.2 m/s
Timing accuracy	100 ns for one-way, 20 ns for two-way	50 ns	20 ns

4.2.2 GPS

The GPS space segment consists of a constellation of 24 satellites, 21 operational satellites and 3 spare satellites, shown in Fig. 4.2. Four satellites are equally spaced in each of the six orbital planes with an orbit inclination of 55°. The difference between the ascending nodes of each orbital plane is 60° and the difference in the argument of latitude for satellites in the same orbital planes is 30°. This ensures that at least four GPS satellites can be visible at any time and any location around the world. The average orbital altitude of the GPS satellites is approximately 20,200 km, and their orbital period is approximately 11 h 58 min 2 s. For more information about GPS, please refer to http://www.gps.gov/.

The first GPS satellite was launched in 1978, and the constellation of 24 MEO satellites was completed in 1994. Based on the launch time, the GPS satellites can be divided into six different types, namely, BLOCK I, BLOCK II/IIA, BLOCK IIR, BLOCK IIR-M, BLOCK IIF and GPS III satellites. The CDMA modulation is also adopted for GPS satellites to broadcast carrier signal in the L1 band (1575.42 MHz) and L2 band (1227.60 MHz). The open civil C/A code is modulated on carrier L1, and the encrypted P(Y) code for military uses is modulated on carrier L2 (ICD-GPS-200J 2018).

To further expand the GPS civil market and better serve military demands, the GPS modernization program was promoted by the US government. As shown in Table 4.2, the modernization of the GPS navigation signal and satellite constellation includes:

(1) Broadcasting a new civil navigation signal and new military code (M code). The second civil pseudorange code L2C was introduced on BLOCK IIR-M satellites in 2005, and the third carrier frequency L5 (1176.45 MHz) was added on

Fig. 4.2 Constellation of the GPS system (*source* http://www.gps.gov/multimedia/images/constellation.jpg)

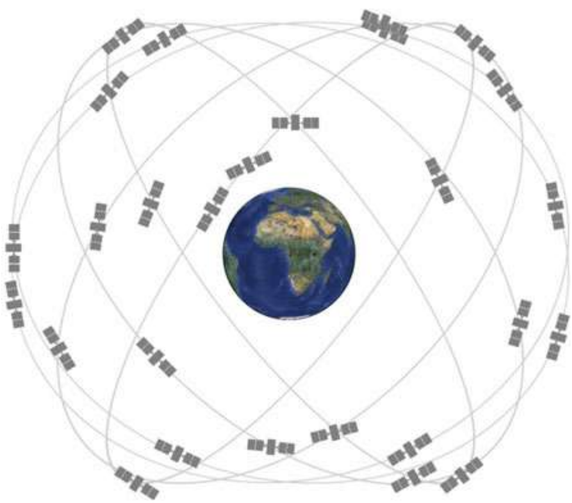

Table 4.2 GPS satellite constellation and navigation signal modernization

	BLOCK I	BLOCK II/IIA	BLOCK IIR	BLOCK IIR-M	BLOCK IIF	GPS III
Civil code	C/A	C/A	C/A	L2C added	L5 added	L1C added
Military code	P(Y)	P(Y)	P(Y)	M code added		
Designed lifetime	4.5 years	7.5 years	7.5 years	7.5 years	12 years	15 years
Launch time	1978–1985	1990–1997	1997–2004	2005–2009	2010–2016	2016–present
	No SA ability				L5 added	No SA ability
						With laser prism reflector

(*source* http://www.gps.gov/)

BLOCK IIF satellites in 2010. In 2016, the GPS III satellites began to broadcast three GPS carrier frequencies (L1, L2 and L5) with four civil navigation codes (C/A, L2C, L5 and L1C), among which the L2C was mainly designed for commercial applications. L5 was developed to meet the demands of navigation users in the field of safety-of-life-related transportation and other high-precision applications, and L1C was designed for compatibility and interoperability between GPS and other GNSSs.

(2) Launching the new generation GPS III satellites to gradually replace the earlier satellites. The GPS III satellites were no longer able to implement the Selective Availability (SA) policy and a laser prism reflector was carried onboard to separate the satellite orbit and clock errors. The lifespan of the GPS satellites was also extended.

Until 2016, the GPS ground control segment consisted of one MCS, one backup MCS, 15 globally distributed monitoring stations, 11 uplink stations and the auxiliary communication network, shown in Fig. 4.3. Its MCS was located in Colorado, US. The ground control segment upgrade was included in the GPS modernization program and consisted of the following main aspects: (1) the Legacy Accuracy Improvement Initiative (L-AII) plan completed in 2008; ten GPS monitoring stations that belonged to the National Geospatial-Intelligence Agency (NGA) were added to the ground monitoring network to improve the forecasting accuracy of the GPS broadcast ephemeris; (2) the Architecture Evolution Plan (AEP) for MCS IT upgrade and the Launch and early orbit, Anomaly resolution, and Disposal Operations (LADO) plan for monitoring out-of-operation satellites in 2007; and (3) the Next Generation Operational Control System (OCX) plan implemented in 2010.

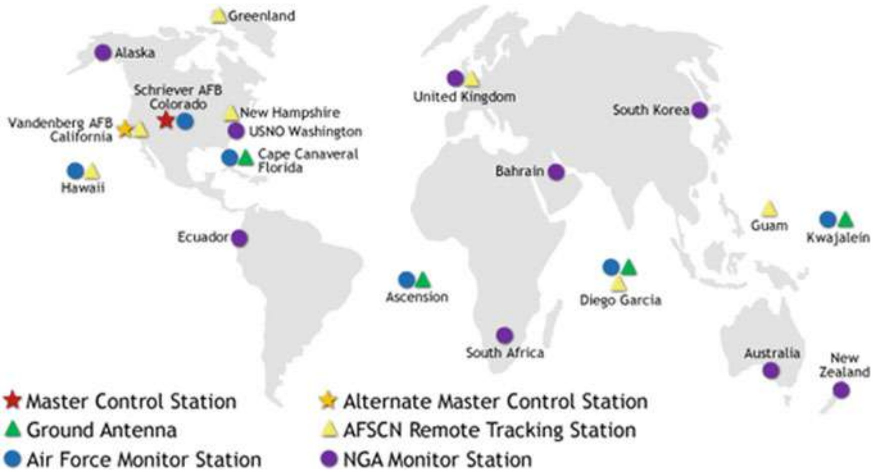

Fig. 4.3 GPS ground control segment (*source* http://www.gps.gov/multimedia/images/GPS-control-segment-map.pdf)

The major function of the GPS user segment, including GPS receivers and handheld terminals, is to track GPS satellites and compute the three-dimensional positioning, velocity and time for users. Users can receive two types of GPS positioning services: standard positioning service (SPS) and precise positioning service (PPS), shown in Table 4.3. SPS is free for all users. The positioning and timing services are obtained with C/A code on L1 and the broadcast ephemeris. PPS is aimed at serving the military and authorized users, and the positioning and timing services are obtained using the ranging code modulated on both L1 and L2 (Grimes 2007).

4.2.3 GLONASS

GLONASS was developed by the USSR in 1976 and is now operated by Russia. With the first GLONASS satellite launched on October 12, 1982, the full constellation was completed and was put into operation at the beginning of 1996. However, due to the short satellite lifespan of only 2–3 years on average and the lack of adequate funding to launch supplementary satellites after the economic recession, there were only six operational GLONASS satellites on orbit in 2011, which severely impacts the normal use of GLONASS. With the recovery of the Russian economy, the GLONASS modernization program was initiated. At the end of 2011, the full 24-satellite constellation was restored for independent navigation and positioning capability.

The space segment of GLONASS consists of 21 operational satellites and 3 backup satellites, which are evenly distributed over three orbital planes with an inclination of 64.8°. The longitude of the ascending node of each plane differs by 120° from

Table 4.3 Performance of GPS SPS and PPS

	Service performance		SPS	PPS	
	Coverage		Global (civil)	Global (authorized)	
Signal in space	Accuracy			Single frequency	Double frequency
	Ranging accuracy			5.9 m	6.3 m
	Accuracy of ranging rate			0.006 m/s	0.006 m/s
	Accuracy of ranging acceleration			0.002 m/s^2	0.002 m/s^2
	Accuracy of timing			40 ns	40 ns
	Integrity (95%) SIS URE	Alarm threshold	150 m	150 m	
		Warning threshold	8 s	8 s	
		Integrity risk	1×10^{-5}/h	1×10^{-5}/h	
	Continuity risk		SIS: 0.0002/h	SIS: 0.0002/h	
	Single slot availability		0.957	0.957	
Performance indicators	Accuracy (95%)		Horizontal: 9 m Vertical: 15 m		
	PDOP availability		Global average: PDOP $\leq$ 6 (98%) Worst case: PDOP $\leq$ 6 (88%)	Global average: PDOP $\leq$ 6 (98%) Worst case: PDOP $\leq$ 6 (88%)	
	Accuracy availability		Horizontal: 17 m Vertical: 37 m		

plane to plane. In each orbit plane, there are 8 satellites separated by 45° in argument of latitude (ICD-GLONASS 2008). At an altitude of 19,100 km, the orbital period is 11 h 15 min and 44 s. In September 2016, the number of operational satellites in orbit was increased to 27, 24 of which are GLONASS-M and GLONASS-K1 satellites with full operational capability. For more information about GLONASS, please refer to https://www.glonass-iac.ru/.

Frequency division multiple access (FDMA) modulation is used by GLONASS; thus, different satellites are distinguished by different frequencies. The frequencies of the civil signals G1 and G2 broadcasted by GLONASS satellites are as follows:

$$\begin{cases} G1: f_{K1} = 1602\,\text{MHz} + 0.5626\,\text{MHz} \times K \\ G2: f_{K2} = 1246\,\text{MHz} + 0.4375\,\text{MHz} \times K \end{cases} \quad (4.1)$$

where $K = -7, \ldots 0.6$ is the frequency number of each satellite. For any satellite, $f_{K1}/f_{K2} = 9/7$. The frequencies of carriers G1 and G2 for military use are different than those for civil use. Pseudo-random-noise code is modulated on the carrier signal and is the same for each set of frequencies. Similar to GPS, the civil code C/A was initially modulated only on carrier G1 whereas the military code P was modulated on both carriers G1 and G2. Later, the C/A code was also modulated on carrier G2 of GLONASS-M satellites. In contrast to GPS, the GLONASS P code is not encrypted.

The original intention to adopt the FDMA system in GLONASS was to enhance the anti-jamming capability. However, this strategy prevented the promotion of commercialization of GLONASS. To improve the compatibility and interoperability with other GNSSs, GLONASS began to broadcast the CDMA signal. For example, the first GLONASS-K1 satellite launched in 2011 broadcasted FDMA signals in the G1 and G2 bands and the new CDMA signal in the G3 band (1202.025 MHz), marking the first step of GLONASS signal modernization. In the future, the development of GLONASS CDMA signals will mainly focus on the G1 and G2 bands. As an improved version of GLONASS-K1, the GLONASS-K2 satellite could broadcast civil FDMA ranging code in G1 and G2 as well as the civil CDMA ranging code in G1, G2 and G3. GLONASS constellation modernization also includes stability and performance improvement of the onboard atomic clock, satellite lifespan extension, and introduction of intersatellite laser ranging (shown in Table 4.4).

The GLONASS system control center (SCC) is located in Krasnoznamensk, Moscow. The GLONASS time reference is maintained by the central clock (CC-M) in Schelkovo. Five telemetry, tracking and command (TT&C) centers are evenly

Table 4.4 GLONASS constellation modernization (*source* https://www.glonass-iac.ru/en/guide/)

		GLONASS	GLONASS-M	GLONASS-K1	GLONASS-K2
Civil signal		G1OF	G1OF/G2OF	G1OF/G2OF G3OC	G1OF/G2OF G1OC/G2OC G3OC
Military signal		G1SF/G2SF	G1SF/G2SF	G1SF/G2SF	G1SF/G2SF G1SC/G2SC
Designed lifetime		3.5 years	7 years	10 years	10 years
Launch time		1982–2005	2003–2016	2011–2018	2017~
Clock stability		5×10^{-13} $\sim 1 \times 10^{-13}$	1×10^{-13} $\sim 5 \times 10^{-14}$	1×10^{-13} $\sim 5 \times 10^{-14}$	1×10^{-14} $\sim 5 \times 10^{-15}$
Modulation mode		FDMA	FDMA	FDMA/CDMA	FDMA/CDMA
Intersatellite links:	RF	–	+	+	+
	Laser	–	–	–	+

Note 'O' is the open signal, 'S' is the precision signal, 'F' is FDMA and 'C' is CDMA

Table 4.5 Overview of GLONASS service performance

Performance indicator			Performance specification
Signal-in-space	Ranging error for any satellite		18 m
	Ranging velocity error for any satellite		0.02 m/s
	Ranging acceleration error for any satellite		0.007 m/s^2
	RMS ranging error for all satellites		6 m
Service	Coverage		From the earth's surface to an altitude of 2000 km
	Positioning accuracy (95%)	Horizontal	5 m (global average) 12 m (global average)
		Vertical	9 m (global average) 25 m (global average)
	Timing accuracy		$\leq$700 ns
	Availability (95%)	Horizontal	12 m (global average $\geq$ 99%, worst case $\geq$ 90%)
		Vertical	25 m (global average $\geq$ 99%, worst case $\geq$ 90%)
	Reliability	Fault rate	$\leq$3 times/year
		Reliability	99.97%

distributed in Saint Petersburg, Schelkovo, Yenisseisk, Komsomolsk and Ussuriysk in Russia. Although the GLONASS TT&C stations are not distributed worldwide, a high-accuracy broadcast ephemeris can be generated by the ground control segment because the longitudinal span of the Russian territory is large. In addition, some TT&C stations are also equipped with a laser station (LS) and other Monitoring and measuring stations (MS). The service performance of GLONASS system are summarized in Table 4.5.

4.2.4 Galileo

Galileo was developed in a collaboration between the European Union and the European Space Agency (ESA). Galileo is the first global navigation satellite system designed for civil uses. The space segment of Galileo consists of 24 operational satellites and 6 spare satellites, which will be positioned on three orbital planes with an inclination of 56°, and the ascending nodes on the equator are separated by 120°. The orbital altitude is 23,222 km, and the orbital period is approximately 14 h (ICD-Galileo 2008).

The development of Galileo can be divided into three phases: the development system testbed, in-orbit validation (IOV) and full operational capability (FOC). During the development system testbed phase, two experimental satellites, GIOVE-A and

GIOVE-B, were launched in 2005 and 2008, respectively (known as the Galileo In-Orbit Validation Element, GIOVE). Later, four Galileo-IOV satellites were launched in 2011 and 2012. In 2014, the Galileo-FOC satellites began to be launched.

The ground control segment of Galileo comprises two parts: the ground mission segment (GMS) and the ground control segment (GCS). The GMS is mainly responsible for processing observations to generate broadcast ephemeris. One ground control center (GCC) is located in Fucino, Italy, and is mainly responsible for monitoring the satellite constellation along with the GCC in Oberpfaffenhofen, Germany. These two GCCs are responsible for coordination and control of the TT&C stations, several uplink stations (ULS) and the Galileo sensor stations (GSSs) distributed worldwide, to maintain routine operation of the control segment. Galileo attaches great importance to system augmentation and integrity, which helps ensure the positioning accuracy and reliability in the fields of aviation and other safety-of-life applications.

Galileo makes use of the CDMA system to broadcast carrier signals on four frequencies: E1, E5a, E5b and E6. Five types of services are provided by Galileo for users: the free open service (OS) similar to GPS SPS, the safety-of-life service (SoLS), the commercial service (CS), the public regulated service (PRS) and the search and rescue (SAR) service. Signal E1 supports OS/CS/SoL/PRS services, E6 supports CS/PRS services, E5a supports OS services, and E5b supports OS/CS/SoL services. The service performance of Galileo system are summarized in Table 4.6.

With the modernization of GPS and GLONASS and the deployment of BDS and Galileo, the GNSS constellations has developed from approximately 30 GPS

Table 4.6 Overview of Galileo service performance

Satellite self-standing service			OS	CS	SoLS	PRS
Service	Coverage		Global	Global	Global	Global
	Positioning (95%)	Single frequency	Horizontal: 15 m Vertical: 35 m		–	Horizontal: 15 m Vertical: 35 m
		Double frequency	Horizontal: 4 m Vertical: 8 m		Horizontal: 4 m Vertical: 8 m	Horizontal: 6.5 m Vertical: 12 m
		Timing	30 ns		30 ns	30 ns
	Integrity	Alarm threshold	–		Horizontal: 12 m Vertical: 20 m	Horizontal: 20 m Vertical: 35 m
		Alarm time			6 s	10 s
		Integrity risk			3.5×10^{-7}/150 s	3.5×10^{-7}/150 s
	Continuity		–	–	1×10^{-5}/15 s	1×10^{-5}/15 s
	Availability	Available accuracy	99.8%	99.5%	99.8%	99.5%
		Available integrity	–	–	99.5%	99.5%

Table 4.7 Summary of BDS/GPS/GLONASS/Galileo system

	GPS	GLONASS	Galileo	BDS
First Launch	1978-02-22	1982-10-12	2005-12-28	2017-11-05
FOC	1995-07-17	1996-01-18	/	/
Service type	Military/civil	Military/civil	Commercial/open	Military/civil
No. of designed satellites	24	24	30	30
No. of orbital planes	6	3	3	3 (MEO)
Orbital inclination	55°	64.8°	56°	55° (MEO)
Orbital altitude	20,200	19,100	23,222	21,528 (MEO)
Orbital period	11 h 58 m	11 h 15 m	14 h 04 m	12 h 53 m (MEO)
Coordinate system	WGS84	PZ-90	GTRF	BDCS
Time system	GPST	UTC(SU)	GST	BDT
Modulation mode	CDMA	FDMA	CDMA	CDMA
Frequencies	L1:1575.42 L2:1227.60 L5:1176.45	G1:1602.00 G2:1246.00 G3:TBD	E1:1575.42 E5a:1176.45 E5b:1207.14 E6:1278.75	B1:1575.42 B2:1176.45 B3:1268.52

satellites in the early stage to more than 100 GNSS satellites in September 2016, summarized in Table 4.7. RNSSs such as QZSS and NAVIC are also under development. As shown in Fig. 4.4, the global coverage and availability of satellite navigation system signals have been improved.

In addition, the frequencies and types of GNSS satellite signals are becoming increasingly abundant (as shown in Table 4.7). For example, the second civil ranging code L2C and the third frequency L5 have been gradually provided by modernized GPS satellites. In the future, GLONASS will simultaneously broadcast FDMA, CDMA, as well as the third frequency signal G3. BDS provides signals in three frequencies of the full constellation and Galileo could broadcast carrier signals on four frequencies and 10 ranging codes. There are over 75 types of measurements (Gurtner and Estey 2013). To meet the ever-growing demand for GNSS civil applications, the third frequency signals L5 and G3 that are used for safety-of-life applications were designed by GPS and GLONASS, respectively; as a civil GNSS, Galileo gave high priority to aviation, safety-of-life and SAR applications at the beginning of its development.

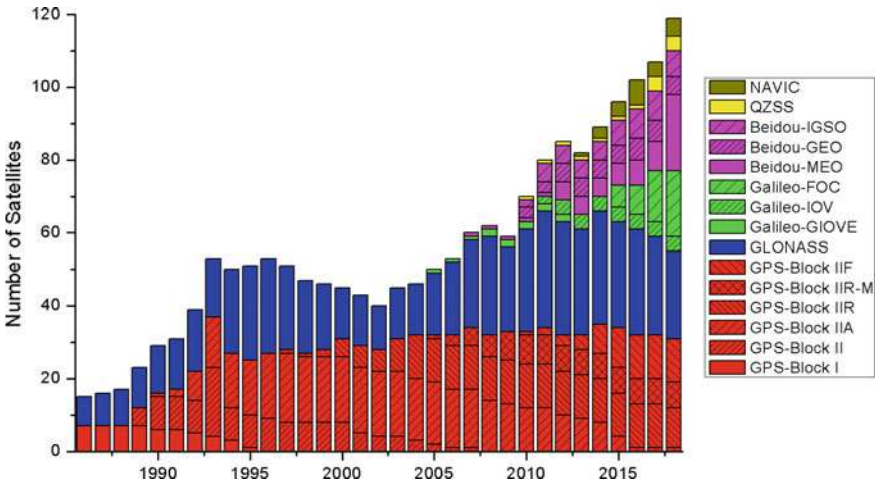

Fig. 4.4 The number of in-orbit satellites in GNSSs and RNSSs

4.3 GNSS Augmentation Systems

As described in Sect. 4.2, the accuracy of GNSS is rather limited and cannot meet the required positioning accuracy, time latency, reliability and integrity needs of higher-level users. The GNSS differential positioning technique and GNSS augmentation system strategy address this issue. In GNSS differential positioning, the observations of GNSS reference stations are used to model the error sources such as the ionospheric, tropospheric, satellite orbit and clock errors. These errors are then mitigated from the observation of users in real-time or post-processed mode to improve the accuracy and reliability of positioning. To meet the demands of different users, several different kinds of GNSS high-accuracy and real-time positioning systems have gradually been developed, including the wide-area differential augmentation system, the global/wide-area precise positioning system, the local area differential augmentation system and the local area precise positioning system (summarized in Table 4.8).

4.3.1 Wide-Area Differential Augmentation System

In the wide-area differential augmentation system, GNSS satellites are monitored with a ground tracking network and the raw observations are transferred to the master control center through communication links. The master control center models the errors of the GNSS raw observations and divides the errors into satellite orbit, clock, and ionospheric errors, which are formatted and broadcasted to users in the service region through communication links. The positioning accuracy can be improved by

Table 4.8 Overview of GNSS augmentation systems

	Reference station	Processing principle	Broadcast link	Broadcast format	Performance	Typical systems
Wide-area differential technique	Ranges of several thousand kilometers with several dozen reference stations	Differencing in the state domain, with corrections generated for orbit and clock errors, grid ionospheric VTEC values based on pseudorange measurements (assisted by the carrier phase)	GEO satellites or radio beacons	RTCA	Single-frequency pseudorange differential positioning, Precision: 3 m without initialization	WAAS EGNOS MSAS GAGAN SDCM
Global precise positioning technique	~100 globally reference stations	Differencing in the state domain, with corrections generated for orbit and clock errors based on carrier phase measurements	GEO satellites or through the Internet	SOC or User-defined protocol	Double-frequency carrier phase differential positioning, Precision: decimeter-level with initialization of approximately 20 min	GDGPS StarFire OmniStar SeaSTAR Veripos RTX
Local-area differential technique	Range of a few tens of kilometers with several reference stations	Differencing in the observation domain, with pseudorange corrections generated based on pseudorange measurements (assisted by the carrier phase)	U/VHF data link	RTCA or RTCM	Single-frequency pseudorange differential positioning Precision: submeter level without initialization	LAAS
Local-area precise positioning technique	Range of a few tens of kilometers with several reference stations and can be extended to larger regions with several thousand reference stations	Differencing in the observation domain, with regional error correction parameters generated in VRS, FKP, MAC and other processing modes based on carrier phase measurements. Users in the region can apply for such correction information	GPRS/CDMA communication link broadcasting	RTCM	Double-frequency carrier phase differential positioning Precision: centimeter level with an initialization of approximately 1–2 min	CORS

using the wide-area differential corrections. With uniform precision over broad coverage, the positioning accuracy of the wide-area differential augmentation system is independent of the distance between the user and the reference station. Several wide-area differential augmentation systems have been established worldwide, e.g., the Wide Area Augmentation System (WAAS) of the Federal Aviation Administration (FAA), the European Geostationary Navigation Overlay Service (EGNOS), the Multi-functional Satellite Augmentation System (MSAS) of Japan, the GPS-Aided Geo Augmented Navigation (GAGAN) of India and the System Differential and Correction Monitoring (SDCM) of Russia.

4.3.1.1 WAAS

The GPS SPS could not meet the higher accuracy, integrity, continuity and availability demands of users in aviation and other fields. As a result, the FAA initiated the WAAS program. As a satellite-based augmentation system (SBAS) to serve North America, WAAS is aimed at providing GPS differential correction information through GEO satellites to augment the GPS SPS. In addition to applications in the field of aviation, the WAAS has also been widely applied to support PNT services.

As illustrated in Fig. 4.5, the WAAS currently consists of 3 wide-area master stations (WMS), 38 wide-area reference stations (WRS), 4 Ground Uplink Stations and

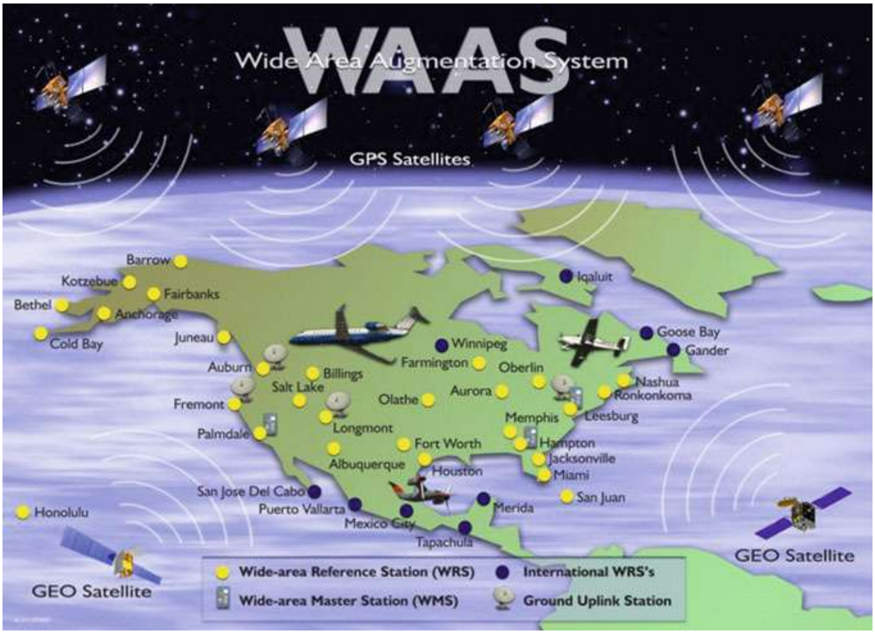

Fig. 4.5 Diagram of WAAS (*source* http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/)

GEO satellites. The WMS is responsible for calculating the differential corrections and monitoring the system integrity. The WAAS data processing center receives real-time GPS observations from the WRS and computes differential correction vectors using the RTG (Real Time GIPSY) software package developed by the JPL based on GIPSY-OASIS. The corrections include the satellite orbit error, satellite clock error and the ionospheric error. Since these differential corrections are expressed as vectors, the precision of positioning within the areas covered by the wide-area differential system is equivalent, in contrast to the local-area differential system. The corrections are uploaded to GEO satellites through uplink stations and broadcast to users in RTCA format to improve positioning accuracy. The nominal positioning accuracy of WAAS (with 95% reliability) is better than 7.6 m in the horizontal and vertical directions. The horizontal and vertical positioning accuracy of WAAS are better than 1.0 m and 1.5 m, respectively, in most regions adjacent to the US, Canada and Alaska.

4.3.1.2 EGNOS

EGNOS is a joint program of the European Space Agency (ESA), the EU and the European Aviation Safety Agency (EASA). The working principle of EGNOS is similar to that of WAAS. The difference is that EGNOS broadcasts differential corrections and integrity information for GPS as well as the differential corrections for GLONASS. The EGNOS differential correction information is calculated using software developed from BAHN, the ESA-owned precise positioning and orbit determination software, and broadcasted by GEO satellites through the L band. The EU is considering extending the broadcast coverage from the EU to other regions, including countries neighboring the EU and Africa.

The EGNOS ground network consists of 39 ranging integrity monitoring stations (RIMSs), 4 mission control centers (MCCs) and 6 navigation land earth stations (NLESs). The 4 MCCs are located in Torrejon, Spain, Gatwick, England, Langen, Germany, and Ciampino, Italy. EGNOS presently provides three types of service: (1) free open service since October 2009, with positioning accuracy of 1–2 m; (2) safety-of-life service since March 2011, with positioning accuracy of 1 m; and (3) data access service since July 2012, with positioning accuracy better than 1 m.

4.3.1.3 MSAS

MSAS was jointly developed by the Japan Civil Aviation Bureau (JCAB) and Japan's Ministry of Land, Infrastructure and Transport, mainly to provide communication and navigation services for Japanese aviation users. MSAS covers all flight service areas of Japan, and can broadcast meteorological information to mobile users in the Asia-Pacific region. The space segment of MSAS consists of two multifunctional transport satellites (MTSats), which are second generation Himawari satellites, the geostationary meteorological and environmental survey satellite developed by Japan.

The two MTSats are positioned at 140° E and 145° E. The Ku and L bands are the two frequencies; the Ku band is mainly used to broadcast high-speed communication information and meteorological data. Similar to the GPS L1 frequency, the L band is mainly used for navigation services. The working principle of MSAS is similar as those of WAAS and EGNOS, and the RTG software authorized by JPL is used for data processing. From its initial operation in September 2007, MSAS remarkably improved the navigation service performance for Japanese airports located on remote islands and met the precision demand for the nonprecision approach specified by the International Civil Aviation Organization (ICAO).

4.3.1.4 GAGAN

The GAGAN system was jointly developed by the Indian Space Research Organization (ISRO) and the Airports Authority of India (AAI). The space segment of GAGAN consists of two GEO satellites positioned over the Indian Ocean. Two bands are applied in GAGAN: the C band is used for TT&C application and the L band is used to broadcast navigation information. The frequency of the L band is identical to that of the GPS L1 (1575.42 MHz) and L5 (1176.45 MHz); thus, GAGAN is compatible and interoperable with GPS. The GAGAN signal covers the whole Indian continent, providing users with GPS signals and differential corrections to improve the GPS positioning accuracy and reliability for Indian airports and other aviation applications. The key technique and core algorithm of GAGAN is also based on technical support from the JPL. The ground segment of GAGAN consists of a master station located in Bangalore, an uplink station and eight reference stations located in Delhi, Bangalore, Ahmedabad, Calcutta, Jammu, Port Blair, Guwahati and Thiruvananthapuram.

4.3.1.5 SDCM

Serving as the GLONASS satellite navigation augmentation system, Russia began developing the SDCM system in 2002 with an aim of providing differential augmentation information for GLONASS and other GNSSs. The space segment of SDCM consists of three GEO satellites, also called the Russian civil data relay (Luch/Loutch) satellites. The three satellites are known as Luch-5A, Luch-5B and Luch-5, located at 167° E, 16° W and 16° W, respectively.

4.3.2 Global Differential Precise Positioning System

The global differential precise positioning technique was developed from the wide-area differential GNSS and the precise point positioning technique. In global differential positioning systems, the GNSS pseudorange and carrier phase observations are collected by globally distributed GNSS dual-frequency monitoring stations and transferred to data processing centers through a real-time data transmission network to calculate the real-time precise satellite orbit, clock error and ionospheric corrections. Using the corrections, a user could realize decimeter to centimeter level precise positioning around the world. The wide-area differential augmentation system mainly serves navigation users with the pseudorange observations whereas the global precise positioning system mainly targets positioning users with the carrier phase observations. Well-known established representative global differential precise positioning systems include the global differential GPS (GDGPS) system applied for satellite orbit determination, scientific research and high-end commercial services, the StarFire system developed by NavCom, OmniSTAR and SeaStar by Fugro, CenterPoint RTX by Trimble and Veripos by Subsea7.

4.3.2.1 GDGPS

GDGPS is the global precise positioning system developed by the National Aeronautics and Space Administration (NASA) of the United States. As shown in Fig. 4.6, the ground monitoring network of the GDGPS consists of more than 200 real-time monitoring stations all over the world. These monitoring stations transmit real-time data to the GDGPS processing center at 1 Hz frequency. Among the tracking stations, over 75 monitoring stations belong to the JPL. They are evenly distributed worldwide and equipped with three-frequency receivers. The time latency of the GDGPS from receiving observations to generating and broadcasting real-time differential correction products is approximately 5 s. The real-time differential correction products can be broadcasted in a variety of ways, including through the Internet, a VPN, T1, frame relay, modem and satellite broadcasting.

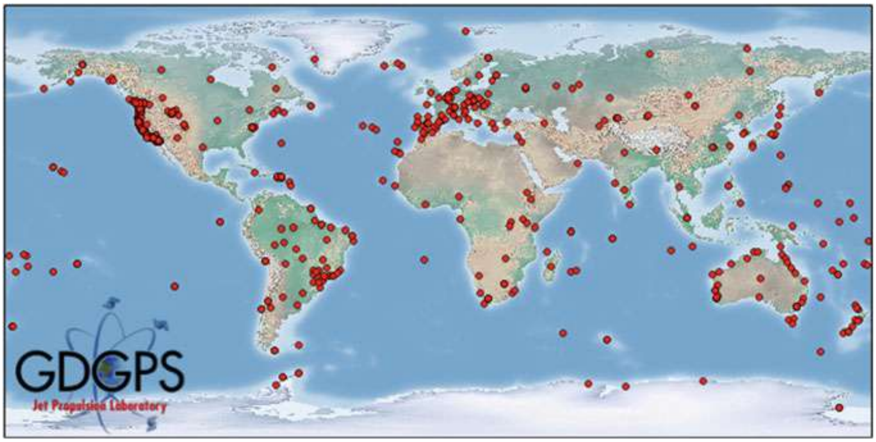

Fig. 4.6 The real-time tracking network of the GDGPS (*source* http://www.gdgps.net/)

The JPL-developed RTG software is adopted in the GDGPS, with the state-square approach proposed by the JPL as its core algorithm. Based on the real-time dual-frequency GPS observation data collected by GDGPS monitoring stations worldwide, precise satellite orbit and clock errors are determined and compared with relevant parameters in the GPS broadcast ephemeris to generate differential corrections. The corrections are broadcasted to users for precise point positioning. The GDGPS can provide decimeter-level positioning and subnanosecond-level time transfer for dual-frequency GPS receivers over the globe. Compared with traditional differential positioning services, the positioning accuracy has been improved by one order of magnitude. The single-frequency users can also use the global ionospheric TEC maps provided by the GDGPS to implement ionospheric correction and improve positioning accuracy.

4.3.2.2 StarFire

In the early stage, StarFire was designed to provide independent wide-area differential augmentation services for precision agriculture in North America, South America, Europe and Australia. The early StarFire system was similar to WAAS and EGNOS, except that StarFire users must be equipped with high-quality dual-frequency GPS receivers to eliminate ionospheric delay, and should adopt the wide area correction transform (WCT) technique that was developed on the basis of NavCom.

In 2001, an agreement was reached between NavCom and NASA/JPL to upgrade StarFire into a global dual-frequency GPS precise positioning system based on the RTG technique. Continuous real-time positioning services with subdecimeter accuracy can be accessed anywhere and anytime around the world. In addition to the RTG technique, StarFire can access observation data from the NASA/JPL global monitoring network to augment the StarFire ground monitoring network. In addition, StarFire makes use of the International Maritime Satellite (INMARSAT) to broadcast differential signals to global users through the L band. StarFire users equipped with L band communication receivers can track and observe GPS satellites and receive the differential correction signals broadcasted by INMARSAT.

RTG/RTK is a new real-time differential positioning mode recently launched by NavCom. The disadvantage of a relatively long initialization time in RTG can be overcome by using RTK. If lock-lose or communication interruption of data links occur during RTK, real-time positioning services can be continuously provided by the RTG with centimeter-level positioning accuracy. After restoring the signal tracking and data link communication in RTK, the positioning result of the RTG can be used as the initial value for rapid searching and integer ambiguity resolution. The disadvantage is that at least two RTG/RTK combined dual-frequency receivers are required on the user side for real-time positioning.

4.3.2.3 OminiSTAR/SeaStar

OmniSTAR and SeaStar are real-time global differential systems developed by the Fugro company. OmniSTAR is mainly used in land and aviation applications and SeaStar was established to meet the demands for high kinematic positioning in marine applications. OmniSTAR currently provides four types of differential GPS positioning services with different accuracies, VBS, HP, XP and G2, among which the G2 service can support both GPS and GLONASS. OmniSTAR has been widely applied in agriculture, GIS, aviation, surveying and mapping, asset tracking and monitoring and, thus, occupies a considerable market share in differential GPS services.

SeaStar primarily serves the offshore oil and gas exploitation industry to meet the demands for submeter and decimeter-level kinematic positioning with high accuracy and reliability under special circumstances. It can provide G2, XP2, SGG and standard L1 services for GPS and GLONASS, as well as XP service for GPS. The latest G4 service simultaneously supports GPS, GLONASS, BeiDou and Galileo.

4.3.2.4 CenterPoint RTX

CenterPoint RTX (Real-Time eXtended) is a global real-time differential system developed by the US company Trimble. It provides worldwide precise positioning services with a horizontal accuracy better than 4 cm for GPS, GLONASS and QZSS. Using the corrections broadcasted by the L-band satellite, the initialization time needed for positioning is less than 5 min.

4.3.2.5 Veripos

Established by the Subsea7 company, Veripos consists of more than 80 reference stations all over the world. The two control centers of Veripos are located in Aberdeen, Britain and Singapore. The Veripos Apex, Veripos Apex^2, Veripos Ultra and Veripos Ultra^2 can provide services with a positioning accuracy better than 10 cm, and Veripos Standard and Veripos Standard^2 can provide a positioning accuracy better than 1 m. The latest Veripos Apex^5 can provide augmentation services for GPS/GLONASS/Galileo/BDS/QZSS with a horizontal positioning accuracy better than 5 cm (within a 95% confidence level).

4.3.3 Local Area Differential Augmentation System

The local area augmentation system (LAAS) at airports is a typical local area differential augmentation system. Based on GPS real-time differential corrections, LAAS was established as an all-weather precision approach and landing system. It consists of reference stations, a central processing station and airborne equipment. GPS satellites are continuously tracked by several reference stations located around the airport, and the central processing station receives the GPS observations to generate pseudorange differential corrections and integrity and precision approach and landing data, which are encoded and broadcasted to the airplane through VHF data links. Based on the GPS observations, differential corrections and integrity information broadcasted by LAAS, the airborne equipment can improve the navigation accuracy, integrity, continuity and availability to realize precision approach category I (CAT I) along a specified path. The ultimate goal of an LAAS is to provide CAT II and CAT III.

4.3.4 Local Area Precise Positioning System

In the local area precise positioning system, several GNSS reference stations are established in a certain region (district, city or country) and high-accuracy positioning service is provided to users within its coverage by taking advantage of differential corrections through a wired/wireless real-time data communication link. The local area precise positioning system can be categorized into two operational modes, single reference station mode and multiple reference stations mode. In single reference station mode, a reference station directly broadcasts high-precision carrier phase measurements to users at the rover station. The rover station receives the measurements and realizes precise positioning based on the differential positioning technique. The positioning accuracy of single reference station mode is at the centimeter level, which can meet the demands of applications within a small area.

The continuously operating reference station (CORS) system is a local area precise positioning system operated in the multiple reference station mode. CORS consists of continuously operating GNSS reference stations, which are interconnected by computer, data communication and the Internet. The observation data (carrier phase and pseudorange) at CORS reference stations are transmitted to the data processing center through the communication link in real-time. The data from the reference network are then uniformly processed to calculate and model the real-time corrections for various GNSS errors within the region, such as the satellite orbit/clock error an ionospheric and tropospheric error. The corresponding observation data and GNSS error model are broadcasted by the data processing center to users at the rover station for high-accuracy positioning. Many countries have established their own CORS systems at the national level, including the US, Germany, England, Australia, Japan, and Canada. Brief introductions to the US CORS and EPN in Europe are provided as representative examples.

4.3.4.1 US CORS

The establishment of CORS in the US was led by the National Geodetic Survey (NGS). More than 200 agencies and organizations have been involved in this program. The three largest CORS networks include the national CORS network, the operational CORS network and the California CORS network. In 2015, the US CORS consisted of more than 2000 reference stations. Most of the stations are distributed in American. However, several stations are located in Canada, Mexico, Central America and North America. The US CORS provides users with coordinates under the International Terrestrial Reference Frame (ITRF) and the 1983 North American Datum (NAD83), as well as raw observations and satellite orbit products. Real-time differential positioning service is also available in some areas, e.g., the San Diego real-time network.

4.3.4.2 EPN in Europe

The EUREF permanent network (EPN) in Europe is a cooperative regional continuously operating network established by the European Commission of the IAG. The EPN was composed of 250 permanent reference stations in 2016. The workflow of the EPN is as follows: the reference stations are divided into several subnetworks with independent system operation centers. Several system operation centers constitute a regional data center, and the data from regional data centers are gathered into the European regional center, which transfers the data products to the IGS data center, regional data centers and various kinds of users. The EPN provides users with centimeter-level coordinates and velocity in ITRF and EUREF, as well as zenith tropospheric products for the reference stations. In addition, the EPN can be applied to monitor crustal deformation, sea level changes, and in numerical weather prediction (NWP).

GNSS augmentation systems have achieved significant developments in the aspects of the accuracy, integrity, coverage and differential mode. The positioning accuracy of GNSS augmentation systems has improved from meter-level, as for WAAS, EGNOS and MSAS, to real-time decimeter-level and post-processed centimeter-level, e.g. StarFire and OmniStar. The GNSS augmentation system has been extended from regional coverage to seamless global coverage. The early GNSS augmentation systems provided users with correction based on one differential approach whereas the current system can provide users with high-precision positioning with corrections derived from multiple differential approaches. As an effective supplement to GNSS, the GNSS augmentation systems have greatly improved the GNSS SPS performance to meet the ever-growing demands for integrity, continuity and availability of navigation systems. They also benefit many other applications such as navigation, aviation, maritime, industry, and precision agriculture.

4.4 Applications in Digital Earth Case Studies

GNSSs have been widely applied in navigation for vehicles, offshore ships, aero craft and aerospace vehicles, geodesy, oil exploitation, precision agriculture, precise time transfer, Earth and atmospheric sciences, and many other fields. Its applications in the establishment of space-time geodetic datum, high-precision positioning and location-based services are introduced below.

4.4.1 Terrestrial Reference System

As a result of inexpensive GNSS receivers, densely distributed tracking stations and the high accuracy performance, GNSSs have played an important role in the establishment and maintenance of geodetic datum. The location and movement of a point on the Earth's surface must be expressed in a terrestrial reference system (TRS) attached to the Earth (also called the Earth-centered Earth-fixed system). The origin of the TRS is usually defined as the center of mass of the Earth, the Z axis is aligned with the international reference pole, the X axis is coincident with the Greenwich zero meridian, and the Y axis is orthogonal to the Z and X axes in the right-handed sense. As an ideal realization of the TRS, the TRF is comprised of a set of stations distributed on the Earth's surface with precisely known coordinates. The TRF is of great importance for geodesy, geophysics and space research. GNSS is an important data source to establish and maintain the TRF.

The widely used ITRF was established based on space-geodetic observations including GNSS, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and Doppler orbit determination and radio positioning integrated on satellite (DORIS). As a realization of the International Terrestrial Reference System (ITRS), the ITRF can provide datum definitions (including origin, orientation and scale) for other global and regional TRS. Since 1988, more than ten versions of the ITRF have been released by the IERS, the latest version of which is the ITRF2014 released on January 2016 (Altamimi et al. 2016).

Different TRFs are adopted by different GNSSs. They include the World Geodetic System 1984 (WGS84) for GPS, Parametry Zemli 1990 (PZ-90) for GLONASS, Galileo terrestrial reference frame (GTRF) for Galileo and the BeiDou coordinate system (BDCS) for BDS. Most of the TRFs are aligned to the ITRF. The positioning results based on GNSS broadcast ephemeris are expressed in the corresponding TRF. As the TRF for GPS broadcast ephemeris, WGS84 has been refined several times by the US DoD, resulting in WGS84 (G730), WGS84 (G873), WGS84 (G1150), WGS84 (G1674) and WGS84 (G1762). PZ-90 is the TRF for GLONASS broadcast ephemeris. Successive versions of PZ-90, PZ-90.02 and PZ-90.11, have been released (Zueva et al 2014). GTRF is the TRF for the Galileo broadcast ephemeris, and GTRF07v01, GTRF08v01, GTRF09v01 and GTRF14v01 have been released (Gendt et al. 2011).

To unify the positioning results expressed in different TRFs, a 7-parameter Helmert transformation should be applied:

$$\begin{pmatrix} X_2 \\ Y_2 \\ Z_2 \end{pmatrix} = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} + D \cdot R_1(\alpha_1) \cdot R_2(\alpha_2) \cdot R_3(\alpha_3) \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} \tag{4.2}$$

where T_1, T_2, T_3 are the translation parameters for the X, Y and Z axes, respectively, D is the scale factor, and $\alpha_1, \alpha_2, \alpha_3$ denote the Euler angles of rotation for the X, Y and Z axes. $R_i(\alpha_i)$ indicates the rotation matrix constituted by the rotation angles α_i for axis i, which can be expressed as:

$$\begin{aligned} R_1(\alpha_1) &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha_1) & -\sin(\alpha_1) \\ 0 & \sin(\alpha_1) & \cos(\alpha_1) \end{pmatrix} \\ R_2(\alpha_2) &= \begin{pmatrix} \cos(\alpha_2) & 0 & \sin(\alpha_2) 0 \\ 0 & 1 & 0 \\ -\sin(\alpha_2) & 0 & \cos(\alpha_2) \end{pmatrix} \\ R_3(\alpha_3) &= \begin{pmatrix} \cos(\alpha_3) & -\sin(\alpha_3) & 0 \\ \sin(\alpha_3) & \cos(\alpha_3) & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{aligned} \tag{4.3}$$

For the transformation parameters between different ITRF versions, please refer to Table 4.1 in the IERS Conventions (2010). The transformation parameters between ITRF2008 and WGS84, PZ-90, and GTRF versions are shown in Table 4.9. The definitions of the transformation parameters are the same as in Eq. (4.3).

4.4.2 Time System

Three types of time systems are commonly used. Their time scale are based on the Earth's rotation, e.g., the universal time (UT), the revolution of the Earth around the sun, and the electron transition frequency of atoms, e.g., the International Atomic Time (TAI). Coordinated Universal Time (UTC) uses the SI second of atomic time as its fundamental unit and is kept in time with the UT.

Atomic time is a time system based on the electromagnetic oscillation generated by the atomic transition inside substances. The Standard International (SI) second is defined as the time that elapses during 9,192,631,770 cycles of the radiation produced by the transition between two levels of the cesium 133 atom. The International Atomic Time (TAI) is the time system determined by the SI second, with the same origin as UT2 on 0 h 0 m 0 s, January 1, 1958. As a continuous and uniform time scale, TAI

Table 4.9 Transformation parameters between WGS84, PZ-90, GTRF and ITRF2008 (*source* http://www.unoosa.org/oosa/en/ourwork/icg/resources/Regl-ref.html)

From	To	T_1 (mm)	T_2 (mm)	T_3 (mm)	D (ppb)	R_1 (mas)	R_2 (mas)	R_3 (mas)	Epoch
WGS84 (G1674)	ITRF2008	0	0	0	0	0	0	0	2005.0
PZ-90.11	ITRF2008	−3 ±2	−1 ±2	0 ±2	0 ±0.3	0.019 ±0.072	−0.042 ±0.073	0.002 ±0.090	2010.0
WGS84 (G1150)	PZ-90.02	360 ±100	−80 ±100	−180 ±100	0	0	0	0	2002.0
GTRF09v01	ITRF2008	2.0	0.9	4.7	−0.94	0.00	0.00	0.00	2000.0
Rate		−0.3	0.0	0.0	0.00	0.00	0.00	0.00	

is maintained by the Bureau International des Poids et Mesures (BIPM) using the atomic clocks of 400 national laboratories worldwide.

Universal Time (UT) is defined as the hour angle of mean sun relative to the Greenwich meridian plus 12 h. UT can be divided into three types. UT0 is directly determined from astronomical observations. Correcting the Earth's polar motion from UT0 yields UT1 whereas UT2 is obtained by correcting the seasonal variations of the Earth's rotation from UT1. UT1 defines the orientation of the average Greenwich meridian with respect to the mean equinox and thus represents the real rotation of the Earth. Since UT1 has a tendency of long-term slowdown, the difference between UT and the atomic time will grow increasingly larger. To avoid such an inconvenience, Coordinated Universal Time (UTC) has been adopted since 1972 based on the second length of TAI. It is a uniform but discontinuous time scale, and the difference between UTC and UT1, which is known as the leap second, is maintained within 0.9 s. The leap second with respect to UT1 is released by the IERS, and the relationship between TAI, UTC and leap seconds can be described as

$$TAI = UTC + leap \tag{4.4}$$

GNSSs are also an important technology to establish and maintain time systems. The GNSS time system is atomic time, in which the TAI second length is used and maintained jointly by high-accuracy atomic clocks onboard the GNSS satellites and implemented in the ground system. With an origin at 00:00 on January 1, 1980, the GPS Time (GPST) is adopted for GPS system. To ensure uniform continuity, there is no leap second in GPST and the constant difference between TAI and GPST is maintained as 19 s.

GLONASS makes use of GLONASS Time (GLONASST), which is synchronized to the UTC (SU) of Russia but biased by 3 h to match the local time zone of Moscow: GLONASST = UTC (SU) + 3 h. Unlike GPST, there are leap seconds in GLONASST.

Galileo adopts the Galileo System Time (GST) with an origin at 00:00 on August 22, 1999 (UTC time). The difference between GST and UTC at the starting epoch is 13 s and there is no leap second to maintain the uniform continuity of GST.

BDS makes use of BeiDou Time (BDT) with an origin at 00:00 on August 22, 1999 (UTC time). The difference between BDT and TAI at the origin moment is 33 s. BDT is counted with the week number (WN) and seconds of week (SOW). Similar to GST, no leap second is adopted to maintain uniform continuity of BDT. BDT is steered to UTC (NTSC).

The transformations between GPST, GLONASST, BDT, GST and UTC are as follows:

$$\begin{cases} UTC - GPST &= 19s - leap + C_0 \\ UTC - GLONASST &= C_1 \\ UCT - BDT &= 33s - leap + C_2 \\ UTC - GST &= 19s - leap + C_3 \end{cases} \tag{4.5}$$

where *leap* is the leap second of UTC with respect to TAI, as shown in Eq. (4.4); C_0, C_1, C_2, C_3 are the daily deviation values of GPST, GLONASST, BDT and GST relative to UTC, respectively, provided by the BIPM. The accuracies of C_0 and C_1 are approximately 10 ns and several hundreds of ns, respectively (ftp://ftp2.bipm.org/pub/tai/other-products/utcgnss/utc-gnss).

High-accuracy UTC time can be obtained through GNSS data. The GNSS common-view technique has been used by the BIPM for many years as one of its main techniques for international time transfer. It has the advantages of low equipment cost, high accuracy and convenient operation. In this technique, the time difference between two clocks, A and B, is determined by simultaneous observation of a third clock on a GNSS satellite. Each station observes the time difference between its clock and the GNSS time plus a propagation delay, which can be largely removed by using one-way GNSS time transfer procedures. By exchanging data files and performing a subtraction, the time difference between the two receiving stations is obtained.

The GNSS timing technique has been widely applied to time and frequency synchronization in the communication, finance and power industries in China. In the communication field, time synchronization for the whole communication network is realized through installation of GNSS timing terminals, so the billing time can be ensured to be consistent and accurate. For the frequency synchronization networks of China mobile, China telecom and China Unicom, the first-level reference clock and part of the second-level/third-level/micro-synchronization-node clock are equipped with a built-in GNSS reception module and external GNSS receivers. The time synchronization networks are also equipped with dual-mode GNSS timing receivers.

In the power industry, time and frequency synchronization for the substation network can be provided by GNSS timing. The time systems from power transmission network to power computer network in the Chinese power industries mainly use GPS as the master clock for timing and synchronization. On December 1, 2017, the 'Technical specification of time synchronization system and equipment for smart substation' (GB/T 33591-2017) became officially effective, in which the BDS is adopted as the main technique for time synchronization. By the end of 2017, there were nearly 900 sets of dispatching automation master station systems (in 11 categories) that could receive BDS signals in the domestic power grid control network, and more than 15,000 sets of GPS timing equipment have been updated to be compatible with the BDS.

4.4.3 High-Precision Positioning

The accuracy of single-point positioning based on broadcast ephemeris is only 10 m and is influenced by the unmodeled errors and noise of the pseudo-ranges. It cannot meet the requirements of many applications and limits the use of GNSSs. Differential GNSS techniques were developed to improve the positioning accuracy to decimeter-level. DGNSS/RTK and precise point positioning (PPP) are two commonly used high-precision differential positioning methods. The basic principle uses one or more reference stations with precisely known positions to model the observation errors, including the ionospheric and tropospheric delay and satellite clock and orbit errors to improve the accuracy and reliability of positioning for users.

The high-precision GNSS positioning algorithm was developed from the single-station pseudorange differential approach and carrier phase differential approach into a real-time carrier phase differential approach based on multiple reference stations (network RTK), PPP, and PPP with fixed ambiguity resolution (PPP-AR), improving the resolution accuracy and extending the application modes. The differential algorithms can be categorized into location differential, pseudorange differential and carrier phase differential techniques according to the differential observations adopted. The differential algorithms can also be classified as single-station differential, local area differential, wide area differential, or global real-time high-precision PPP based on the effective range of the differential corrections. They can be categorized into satellite-based and ground-based differential augmentation based on the type of broadcast link. Finally, the differential algorithms can be categorized into the state space representation (SSR) differential method and the observation space representation (OSR) differential method according to the differential model algorithm and parameters.

The PPP (SSR) and the network RTK (OSR) are the two major techniques in high-precision GNSS positioning services. The network RTK method, also known as the RTK method with multiple reference stations, usually needs more than three GNSS CORS stations within a certain region. Taking one or several stations as the reference stations, the distance dependent errors are modeled as regional OSR corrections. The differential corrections are provided to the rover stations in real time for precise positioning. The network RTK method can be classified into four types, including the virtual reference station (VRS) method, the master auxiliary concept (MAC) method, the Flächen Korrektur parameter (FKP) method or the combined bias interpolation (CBI) method, according to the OSR differential corrections used.

The VRS method is the most widely used network RTK technique at present. A virtual reference station is established near the rover station. Observation of the virtual reference station is generated using the real observation of the surrounding reference stations plus the regional error corrections. By receiving the observations of the virtual reference station, users can realize high-accuracy real-time positioning with the single-station RTK method. In the MAC method, corrections from the reference network can be divided into two categories: corrections closely correlated with the carrier frequency, e.g., the ionospheric delay, and corrections independent of the carrier frequency, e.g., the orbit error, tropospheric error, and multipath effect. The integer ambiguity of the reference network is initially fixed to ensure a uniform integer ambiguity reference for all the reference stations. The correction difference between the auxiliary station and the master station is calculated and broadcasted to the rover station. The principle of the FKP method is to estimate nondifferential parameters for each reference station in real time and generate the network solution. The spatial correlation error of the ionosphere and the geometric signal inside the network is then described with regional parameters. Based on these parameters and locations, the rover station computes the error corrections and realizes precise positioning.

The FKP method has been widely applied in Germany, the Netherlands and other European countries. The CBI method does not distinguish ionospheric delay from tropospheric delay and other types of errors when calculating the corrections of the reference stations. The corrections for each reference station are not broadcasted to the users. Instead, the observation data of all the reference stations are gathered to select, calculate and broadcast the comprehensive error corrections to the user.

For specific regional users, the accuracy of network RTK can achieve centimeter-level. However, due to the spatial restriction of OSR differential correction methods, the distance between reference stations in network RTK can generally be no more than 70 km. Therefore, it would be very costly to establish a wide-area real-time service system to serve a large number of users using the network RTK method. The PPP technique based on the wide-area (global) tracking network can realize high-accuracy positioning with only a few reference stations in a wide area. It could effectively overcome the disadvantages of network RTK. However, although PPP could provide positioning service with the same accuracy all over the world, it has the disadvantages of slightly lower positioning accuracy and relatively longer initialization time than network RTK.

Based on precise satellite orbit and clock error data, the PPP method could realize decimeter-level to millimeter-level positioning accuracy using carrier phase and pseudorange observations collected by a single GNSS receiver. Only the high-precision satellite orbit and clock errors are needed to obtain high-precision positioning for any station at any location and the positioning error is homogenous worldwide. Thus, PPP has been widely used in crustal deformation monitoring, precise orbit determination, precise timing, earthquake/tsunami monitoring and warning, and many other fields. As an extension of the standard PPP technique, PPP-AR can obtain ambiguity-fixed coordinates through restoring the integer characteristics of the nondifferential ambiguity. Its accuracy is equivalent to that of RTK.

In China, the first-generation BDS augmentation system was formally approved on April 28th, 1998, with the goal of providing GPS wide-area differential and integrity service for users based on BDS-1. It aims to improve the GPS accuracy and reduce the risk of using GPS. The first-generation BDS augmentation system (the first phase of construction) was completed and began trial operation in 2003. During this period, the augmentation system operated stably and provided real-time GPS differential correction and integrity service for various users in the service region. The positioning accuracy and integrity warning capability were basically in accordance with the design indicator requirements. In recent years, research and development of a wide-area real-time precise positioning prototype system in China and the neighboring areas have been carried out with the support of the national 863 program. As a key project in the field of Earth observation and Navigation Technique under the National High-tech Research and Development Program (863 program) in 2007, the 'wide-area and real-time precise positioning technique and prototype system' was jointly undertaken by the China Satellite Communications Corporation (China Satcom), China Center for Resources Satellite Data and Application, and Wuhan

University. Based on the wide-area differential and PPP technique, the satellite navigation augmentation service is realized with a positioning accuracy of better than 1 m for land, ocean and air transport in China.

The construction of CORS around world has entered into a new era. A provincial-level CORS system in Jiangsu and Guangdong provinces has been established in China. CORS systems have also been established in various large- and medium-sized cities, e.g., Beijing, Shanghai, Tianjin, Chongqing, Nanjing, Guangzhou, Shenzhen, Wuhan, Kunming, Jinan, Qingdao, Suzhou, Changzhou, Hefei, Dongguan, and Zibo. There are more than 2200 CORS stations in China. CORS systems may be upgraded to install BDS receivers. High-precision surveying can be conducted through these CORS systems with high efficiency and less man-power than traditional technology such as a total station. The CORS system is currently a vital part of surveying and mapping activities around the world, including urban planning, land surveying and mapping, cadastral management, urban and rural construction, and mining surveying.

The differential GNSS technique can support cadastral surveying to establish property boundaries, which is of great importance for fiscal policies such as land taxation. In the different construction stages of a building or civil engineering project (such as a highway, motorway, bridge, underground tunnel, railway, reservoir or embankment), GNSS positioning can be used to automatically control the construction equipment. GNSSs are also used to define specific location points of interest for cartographic, environmental and urban planning purposes. GNSSs play an important role in measurement and calculation at each stage of mine exploitation, including safety checks. GNSSs are used to monitor critical infrastructure and the natural environment to prevent major disasters and promptly intervene in case of emergency. GNSSs can support a wide range of activities in marine surveying, such as seabed exploration, tide and current estimation and offshore surveying.

4.4.4 Location-Based Service

Location-based service (LBS) systems work independently or cooperate with mobile terminals to provide real-time and post-processed positioning and timing service for various users through different communication networks. LBS relies on GNSS and augmentation systems to provide uniform space-time datum. Other assisted navigation and positioning techniques are also incorporated to improve the anti-jamming capability and availability of LBS. Through communication networks, e.g., the internet and mobile internet, LBS can provide users with positions, attitude, velocity and time synchronization services.

The workflow of a typical LBS system can be designed as follows: the GNSS wide-area augmentation system receives a real-time data stream from various GNSS tracking networks, generates the wide-area and regional satellite navigation augmentation signals, and provides them to the authorized public users through broadcasting systems controlled by a service provider. GNSSs are ‘outdoor’ positioning techniques, as the GNSS signal is affected by strong attenuation and multipath caused by complex indoor environments. In severe environments, the GNSS signals cannot be captured. Thus, the location of users inside a building should be determined by an indoor positioning system using WIFI, Bluetooth, INS, magnetic fields, and virtual beacons. The information integration platform receives the satellite navigation augmentation signals and merges them with geographical data to provide users with comprehensive location-based value-added service through LBS providers. As an integration of social networks, cloud computing and the mobile internet, LBS could become the core element of a series of significant applications, e.g., intelligent transportation systems (ITS), precise agriculture, intelligence manufacturing and smart cities. GNSS-enabled LBS applications are mainly supported by smartphones.

ITS refers to efforts to add information and communications technology to transport infrastructure and vehicles in an effort to manage factors that are typically at odds with each other, such as vehicles, loads, and routes, to improve safety and reduce vehicle wear, transportation times, and fuel consumption. GNSSs play an important role in ITS applications such as traffic control and parking guidance by providing accurate and reliable positioning. The low-cost high-precision GNSS receiver has a big potential market in ITS. The low-cost GNSS receiver can also be integrated with an inertial navigation system (INS) to develop an autonomous navigation system for general aviation (GA). General aviation is the term used to describe all aviation except government and scheduled-airline use.

The accuracy of GNSS SPS is only approximately 10 m. It cannot tell users the optimal lane to get to their destination, especially in dense urban environments such as multilane roads and highways. With the aid of an LBS system, lane-level navigation and positioning with meter-level accuracy can be realized. It will become the standard configuration for passenger vehicles and freight vehicles with hazardous chemicals in the future. The consortium within the EU-funded InLane project is working on the fusion between computer vision and GNSS technologies to achieve the required level of positioning that allows for the safe operation of autonomous vehicles (https://www.gsa.europa.eu/market/market-report).

The embedment of GNSS terminals in bicycle-sharing systems can result in more accurate and reliable positioning for better user experiences, especially in complex scenarios. The positioning accuracy can be improved from 50-100 m to approximately 3 m. The GNSS terminals can also support orderly parking. Currently, approximately half of the bicycle-sharing systems in China are equipped with GPS terminals. High-precision BDS positioning has also been adopted in driver training. It can automatically record the trail of the wheel at the centimeter level. Many driving test centers in China promote this technique.

The premise of precision agriculture is to adapt field operations to local variations in crop and soil conditions using state-of-the-art technology combined with knowledge-intensive field management. The positioning system is a part of precise equipment that consists of a differential global positioning system (DGPS) receiver, a radar velocity sensor, a wheel velocity sensor and an electronic compass. Precision positioning helps complete field applications faster and more productively, accurately, safely and comfortably, with less operator fatigue. GNSS is used in agriculture in a few key areas. As crops are harvested, a GNSS receiver connected to a yield monitor sensor records a coordinate along with the yield data. This data is combined and analyzed to create a map of how well different areas of the field are producing. When spreading fertilizer or planting, equipment operators have traditionally used markers such as foam or other visual aids to mark where they've been to try to avoid overlap. The assistance of GPS and onboard guidance systems such as a light bar, can further reduce overlap.

For many years, the leading technology for precision agriculture was GPS L1 receivers providing submeter precision. That precision can meet the requirements of applications at the submeter level, such as applying chemicals, field mapping and aerial spraying. However, high-precision applications such as auto-steer need centimeter precision. Historically, Hemisphere GPS (formerly CSI), Trimble Navigation, OmniSTAR, and smaller designers and system integrators have been the GNSS technology providers for precision agriculture. The world-wide agriculture market is booming. Auto-steer and other high-precision GNSS applications in agriculture have contributed to increased production capacity.

The GNSS navigation function in smart phones can record the wheel path and personal interests as well as the behaviors of pedestrians and drivers, providing large amount of social activity information. It should be regarded as an important source of big data on human activities and interests. In the future, with the application of high-accuracy navigation based on smart phones and the implementation of integrated indoor and outdoor location services, this big data will provide more abundant information. A 2013 Nature paper noted that the owner of a cellphone can be specified (with 95% probability) by analyzing the big data of the cellphone location tracks in a city with approximately 1,500 thousand people. LBS systems could also support applications such as geomarketing and advertising, fraud management and location-based billing, which require authentication of the position to protect app users.

LBS applications for healthcare are increasing. Healthcare needs are driving the diversification of wearables. For example, a GNSS-enabled haptic shoe allows for visually impaired users to set a destination in a smartphone app. The soles guide the user to the destination by vibrating in the front, back, or sides. Visually-impaired people or wheelchair users rely on a seamless navigation experience between outdoor and indoor environments. They need more high-precision horizontal and vertical position information (https://www.gsa.europa.eu/market/market-report).

In summary, there is a huge navigation and LBS market. The navigation and LBS network will also promote the development of industries such as national security, social security, energy conservation and emission reduction, disaster relief and mitigation, traffic and transportation, the IoT, resource investigation, and precision agriculture.

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Chapter 5
Geospatial Information Infrastructures

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Abstract Geospatial information infrastructures (GIIs) provide the technological, semantic, organizational and legal structure that allow for the discovery, sharing, and use of geospatial information (GI). In this chapter, we introduce the overall concept and surrounding notions such as geographic information systems (GIS) and spatial data infrastructures (SDI). We outline the history of GIIs in terms of the organizational and technological developments as well as the current state-of-art, and reflect on some of the central challenges and possible future trajectories. We focus on the tension between increased needs for standardization and the ever-accelerating technological changes. We conclude that GIIs evolved as a strong underpinning contribution to implementation of the Digital Earth vision. In the future, these infrastructures are challenged to become flexible and robust enough to absorb and embrace technological transformations and the accompanying societal and organizational implications. With this contribution, we present the reader a comprehensive overview of the field and a solid basis for reflections about future developments.

Keywords Geospatial information · Infrastructure · Spatial data · Public sector · Government

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5.1 Introduction

Geospatial information (GI), i.e., information including a relationship to the Earth (Worboys and Duckham 2004), is a foundational ingredient for any Digital Earth application. Examples include information about land parcels, transport networks and administrative boundaries, vehicles, microplastics, fine particles, mobile devices and people. With GI, we can build digital replicas of our planet and use them to exchange knowledge, monitor the state of the Earth, simulate possible future scenarios or assess possible impacts of decision making. Although also other terms (such as 'geographic' or 'spatial') are used in scientific and other literature to refer to the same or similar concepts, we use 'geospatial' in this chapter. Furthermore, we speak of 'information' as (possibly processed) data in a context that allows for interpretation and meaningful use.

The technological, semantic, organizational and legal structure that allows for the discovery, sharing, and use of GI is called geospatial information infrastructure (GII) (Yang et al. 2010; Granell et al. 2014). With its core functionalities, a GII can be considered the backbone for Digital Earth. GIIs are essential to facilitate the information flow that is required to implement any past, present and future version of the Digital Earth vision—the knowledge sharing platform as initially envisaged by Gore (1998), a global tool for multidisciplinary research as outlined by Goodchild and colleagues (2012), or the world laboratory to support codesign, cocreation and codelivery that was suggested by Schade and Granell (2014).

Emerging from an initially highly technical concept, GIIs have a relatively long history and are well researched, including their close relationships with geographic information systems (GIS) (Worboys and Duckham 2004) and spatial data infrastructure (SDI) as enabling technologies (Masser 2005; Yang et al. 2010). Prominent examples of these enabling technologies include the spatial data infrastructure for Australia and New Zealand (ANZLIC 2019), the United States of America-US National Spatial Data Infrastructure (NSDI 2019), the Infrastructure for Spatial Information in the European Community [(INSPIRE 2019), see also Chap. 20], OpenStreetMap [(OSM 2019a), see also Chap. 18], and Google Maps (Google 2019).

By nature, GIIs undergo a continuous evolution that is primarily driven by the increasing pace of technological advancements and the inherent digital transformation of our societies (Castells and Cardoso 2005; Gimpel and Röglinger 2015). Similar to other information handling tools, GIIs face continuous challenges caused by the speed of technological progress that sometimes conflicts with the heaviness inhering in most governance structures. For example, the implementation of heavily governed GIIs bears a risk to continually run behind technological solutions (Schade and Smits 2012; Tsinaraki and Schade 2016). We have witnessed a shift from public sector (alone) to more collaborative approaches to the provision and operation of GI and related services, which increasingly involve the private sector (smeSpire 2014; Sjoukema et al. 2017). Whereas public sector information (e.g., about cadastral parcels or protected sites) continues to play an important role, increasing amounts of spatial data are produced, owned and provided by the private sector. Examples include street (navigation) data and satellite imagery, and 'standard' products such as Google Earth, Google Maps, Bing, and spatial data from GPS providers such as Here and TomTom.

In this situation, we face two opposing forces: traditional standardization processes and frequent technological disruption. Heavily standardized large infrastructures and platforms to support Digital Earth may have been a necessity a few years ago (Granell et al. 2016), when large amounts of GI were not easily accessible and data transformation used to be a process that was run on large computing machines for a long time before harmonized information could be provided to users. During that time, it was affordable to invest in traditional standard-based infrastructures and in educational programs that provided specialized training to develop, maintain and use such infrastructures (Masser 2005; Vandenbroucke and Vancauwenberghe 2016). However, is this still affordable today—in an era of fast digital transformation when disruptive technologies are about to become a new norm? Or will microservice-based architectures (Dragoni et al. 2017) to build smaller, more manageable platforms beat monolithic, big, layered architectures? How must the development of standards change to fit these new dynamics? What roles will the private sector play in this new set-up?

The question of whether Digital Earth will follow the traditional standardization approach, an alternative approach that completely embraces vivid digital transformation or anything in between has strong implications on the definition of the conceptual architecture of the GII with Digital Earth. Hence, we are at a controversial point in GII and Digital Earth history. This chapter outlines how we arrived at this point, explains the current situation in more detail, provides a critical reflection, and outlines a few future trajectories. We hope that this contribution to the Manual of Digital Earth aids in understanding the importance and evolution of GIIs and provides food for thought for those that will develop and use GIIs to implement the Digital Earth vision.

The remainder of this chapter is structured as follows. The next section introduces the history of GIIs during the different phases of organizational and technological development (Sect. 5.2). Next, we outline the current situation in respect to GII development, education and use (Sect. 5.3). We focus on the evolving relationship between GIIs and Digital Earth and important recent movements such as Open Science. In Sect. 5.4, we discuss changes and the challenges that GIIs face today. The most important implications for the Digital Earth vision are highlighted. In Sect. 5.5, we close the chapter with a brief conclusion and an outlook on the future of GIIs in support of Digital Earth. For details about GI analysis and processing, we refer the reader to Chap. 6. Matters of GI visualization are discussed in Chap. 7.

5.2 A Brief History of Geospatial Information Infrastructures

GIIs are not a new concept, and have evolved over a series of generations, each characterized by changing purposes, available technologies, and the main stakeholders involved in their design, implementation and use. Instead of describing these generations in detail, which has been done elsewhere (Rajabifard et al. 2002; Yang et al. 2010), we highlight fundamental milestones in the history of GII. We also highlight evolutions of the technical architectures used to implement GIIs over the past few decades.

5.2.1 Geospatial Information Infrastructure Milestones

In the history of GIIs worldwide, a series of milestones have been essential for the evolution of GIIs into their current form—most of which relate to actions of government, i.e., policy updates. Notably, these milestones differ in nature, for example, by administrative dimension, research purpose or geographic extent. However, they give a sensible impression of aspects that have framed the evolution of GIIs up to today.

As a first milestone, the EU initiated the CORINE program in 1985 with the aim of describing the status of the environment in Europe. This program was the first large-scale effort in Europe to collect spatial data covering the European territory according to agreed specifications in view of supporting different policies. It delivered its first pan-European land cover data set in 1990, with updates in 2000, 2006 and 2012. The second milestone dates back more than thirty years to the establishment of the Australian Land Information Council (ALIC) in January 1986. ALIC was the result of an agreement between the Australian Prime Minister and the heads of the state governments to coordinate the collection and transfer of land-related information between the different levels of government and to promote the use of that information in decision making (ANZLIC 1992). One year later, a third milestone occurred in May 1987 with the publication of the Report of the British Government Committee of Enquiry on Handling Geographic Information chaired by Lord Chorley (Coppock 1987). This report, also known as the Chorley report, set the scene for much of the subsequent discussion about GIIs in the UK and in other parts of the world. While the report reflected the committee's enthusiasm for the new technology: "the biggest step forward in the handling of geographic information since the invention of the map" (para 1.7), it also expressed their concern that information technology must be regarded as "a necessary, though not sufficient condition for the take up of geographic information systems to increase rapidly" (para 1.22). A fourth important milestone in the late 1980s was the release of the first issue of the International Journal of Geographic Information Systems, also in 1987. The journal, renamed the International Journal of Geographic Information Science in 1997, was the first scholarly journal devoted to GI.

The fifth milestone occurred in 1990 when the United States Office of Management and Budget (OMB) established an interagency Federal Geographic Data Committee (FGDC) to coordinate the "development, use, sharing, and dissemination of surveying, mapping, and related spatial data." The main objectives of a national GII were "encouraging the development and implementation of standards, exchange formats, specifications, procedures, and guidelines, promoting technology development, transfer, and exchange; and promoting interaction with other existing Federal coordinating mechanisms that have an interest in the generation, collection, use and transfer of spatial data…" (OMB 1990, pp. 6–7). These ideas were subsequently developed and extended by the United States National Research Council's Mapping Science Committee in their report 'Toward a coordinated spatial data infrastructure for the nation' (National Research Council et al. 1993). This report, which can be seen as a sixth milestone in the history of GIIs, recommended that effective national policies, strategies, and organizational structures be established at the federal level for integration of national geospatial data collection, use and distribution. A seventh milestone is the outcome of an enquiry by the Directorate-General XIII (now DG Connect) of the European Commission (EC), which found that there was a strong Europe-wide demand for an organization that would further the interests of the European GI community. As a result, the first regional level multidisciplinary SDI organization in the world was set up in 1993. The vision of the European Umbrella Organisation for Geographic Information (EUROGI) was not to "replace existing organisations but catalyse effective cooperation between existing national, international, and discipline-oriented bodies to bring added value in the areas of Strategy, Coordination, and Services" (Burrough et al. 1993).

An eighth milestone that marks a turning point in the evolution of the SDI concept came in the following year with the publication of Executive Order 12906 signed by President Bill Clinton, entitled "Coordinating Geographic Data Acquisition and Access: the National Spatial Data Infrastructure" (Executive Office of the President 1994). This described the main tasks to be carried out and defined time limits for each of the initial stages of the national spatial data infrastructure. These included the establishment of a national geospatial data clearing house and the creation of a national digital geospatial data framework. (Here, we understand data clearing houses as "internet-based components that intend to facilitate access to spatial data, by establishing a centralized site from which data from several sources can be found, and by providing complementary services, including searching, viewing, transferring, and ordering spatial data" (Davis 2009). The Executive Order gave the FGDC the task of coordinating the Federal government's development of the National Spatial Data Infrastructure. As the Executive Order also required each member agency of that committee to hold a policy-level position in their organization, it significantly raised the political visibility of geospatial data collection, management and use among US institutions and internationally. The organization of the first Global Spatial Data Infrastructure (GSDI) Conference in Bonn, Germany, in September 1996 was another—ninth—milestone in the 90s. The conference brought together representatives from the public and private sectors and academia for the first time to discuss matters relating to NSDIs at the global level. Shortly after, in 1998, the Baveno Manifesto set a fundamental milestone for European space policy. It led to the establishment of the Global Monitoring for Environmental Security (GMES) program, which was formally established in 2010 (Regulation (EU) No 911/2010), and followed by the Copernicus program in 2014 (Regulation (EU) No 377/2014).

After 2000, the evolution of GIIs worldwide continued, and several milestones can be highlighted. One was the establishment of the intergovernmental Group on Earth Observations in February 2005 to implement a global Earth observation system of systems (GEOSS) to integrate observing systems and share data by connecting existing infrastructures using common standards. In 2018, there were more than 400 million open data resources in GEOSS from more than 150 national and regional providers such as NASA and ESA, international organizations such as the World Meteorological Organization (WMO) and commercial sector groups such as Digital Globe (Nativi et al. 2013). Another—eleventh—milestone was the launch of the first scholarly journal in the GII field in 2006. The International Journal of SDI Research is a peer-reviewed journal that is operated by the Joint Research Centre of the European Commission, which aims to further the scientific endeavor underpinning the development, implementation and use of Spatial Data Infrastructures. Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 established an Infrastructure for Spatial Information in the European Community (INSPIRE, see Chap. 20 for more details) can be seen as a twelfth milestone in the evolution of GIIs. The INSPIRE Directive aimed to establish a spatial data infrastructure to improve the sharing and interoperability of geospatial data in support of environmental policies and policies that might have an impact on the environment (Directive 2007/2/EC of the European Parliament and the EU Council) and was the second multinational GII initiative that sought to make harmonized high-quality GI readily available. INSPIRE stresses the principles of data sharing and cross-border usage of the data. The year 2011 marked a key event that initiated the deep involvement of the private sector: the first Geospatial World Forum "Technology for people and Earth" (Geospatial World 2011). This global conference gathers diverse stakeholders to present and discuss the pathways of the geospatial industry. In addition, the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) was established in July 2011 (ECOSOC Resolution 2011/24) as the official United Nations consultative mechanism on global GI management. Its primary objectives are to provide a forum for coordination and dialogue among Member States of the United Nations (UN) and between member states and relevant international organizations and to propose work plans that promote global frameworks, common principles, policies, guidelines and standards for the interoperability and interchangeability of geospatial data and services. Not long ago, (23 June 2015) the first Sentinel (satellite developed for the Copernicus program delivering open Earth Observation) was launched. This milestone initiated the launch of a set of sister satellites that deliver high-resolution images and contribute strongly to a new era of GI provision worldwide.

Table 5.1 provides an overview of the fifteen milestones discussed in this section. They are mostly institutional, legal and policy-related. Notably, the milestones cover different regions (e.g., Europe, North America and Australia), administrative levels (e.g., national, regional and global) and sectors (e.g., academic and cross-sectoral initiatives). They reflect the breadth and diversity of GII initiatives since the 1980s. This demonstrates how GIIs took a leading role in promoting and enabling open data publishing, possibly as the most common theme across the globe. These developments took place in support of the Open Movement, Open Science, Open GIScience, and citizen science, which we explore in more detail later in this chapter (in Sect. 5.3).

Table 5.1 Geographical information infrastructure milestones

Year	Milestone
1985	The European Union (EU) launched the CORINE land cover program as the first large-scale effort to collect spatial data covering the European territory
1986	The Australian Land Information Council began coordinating the collection and transfer of land-related information between the different levels of government
1987	Report of the Committee of Enquiry into Handling Geographic Information, chaired by Lord Chorley
1987	Launch of the International Journal of Geographic Information Systems
1990	The US Federal Geographic Data Committee was created to coordinate the development, use, sharing and dissemination of surveying mapping and related geospatial data
1993	US Mapping Science Committee report on 'Toward a coordinated spatial data infrastructure for the nation'
1993	Establishment of the European Umbrella Organisation for Geographic Information (EUROGI) as the first regional-level multidisciplinary SDI organization
1994	Executive Order 12906 'Coordinating geographic data acquisition and access: the National Spatial Data Infrastructure'
1996	First Global Spatial Data Infrastructure conference in Bonn, Germany
2005	Establishment of the intergovernmental Group on Earth Observations in February 2005 to implement a Global Earth Observation System of Systems (GEOSS)
2006	Launch of the International Journal of Spatial Data Infrastructure Research
2007	Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)
2011	The first Geospatial World Forum 'Technology for people and Earth' took place
2011	The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) was established
2015	Launch of Sentinel-2, the first of a series of Copernicus satellites delivering open and high-resolution GI

5.2.2 Architectural Evolutions in Geospatial Information Infrastructure Development

Alongside these milestones, we have witnessed an evolution of GII architectures and technological solutions, following the increased sophistication of technology and growth in user requirements. We summarize the central developments, concentrating primarily on GII. Another chapter of this manual addresses the irruption of sensors, sensor networks and the Internet of Things (IoT, see also Chap. 11). For developments and implications of machine learning, deep learning, and artificial intelligence, we refer the interested reader to Chap. 10.

GI has been used for many decades in different application fields (Longley et al. 2011). In the eighties, GIS technology started to spread globally. Prior to the development of SDIs, which only expanded at a broader scale in the nineties, geospatial data assets were created, managed and used by individual organizations using standalone GIS. In 1987, Specialized software companies such as ESRI brought GIS software to the market that could run on personal computers. Others, such as Intergraph, did the same, and academic and even public sector parties developed software for using geospatial data for particular purposes. Examples include ILWIS (2019) and GRASS (2019).

However, in this period, most efforts were focused on the collection and maintenance of data, as well as its use within the organization. Big data collection efforts started taking place. For example, in Europe the need for data that are standardized, well-documented, high-quality and available for the broader community became apparent. Therefore, the Coordination of Information on the Environment—CORINE program was initiated by the EU. This and similar initiatives elsewhere in the world, e.g., in the US through the FGDC, revealed the need to work more systematically in several technical aspects: documentation (metadata), data harmonization, access mechanisms and standards (Nebert 2004). These technological developments occurred in parallel with the organizational and institutional developments described in the previous section.

Originally, the focus was on exchange formats and particularly on the transformation—where required—from one format to another. In practice, for a long time de facto standards were used a lot. One good example is the shapefile format developed by ESRI that was (and still is) used to transfer geospatial data from one organization to the other (ESRI 1998). In the nineties, data exchange between organizations, although often on an ad hoc basis, became more and more important to avoid duplication of data sets and to share resources more efficiently. With this increased exchange, good documentation became paramount (Danko 2005). From the early nineties, organizations explored ways of documenting data in a standard manner. The first standard used by many was the FGDC metadata standard, which was initiated by President Clinton by executive order 12906 (1994) and became official in 1998 (FGDC 1998). This standard was used a lot, even in Europe. Work on an international metadata standard also began in the nineties but saw only light in 2003 with the adoption and publication of the International Organization for Standardization (ISO) standard

19115 in 2003 (ISO 2003). Since then, thousands of organizations have documented their geospatial data sets according to this standard.

To make potential interested parties aware of the existence of geospatial data resources, the publish-find-bind paradigm was defined as a key concept for SDIs (van Oosterom 2005). The idea is to 'publish' geospatial data resources by documenting and putting them in a catalogue, then make them 'discoverable' by a search mechanism and 'accessible' through a binding mechanism, which means that they can be integrated in a user application (e.g., a web-viewer, a desktop GIS or other application). In addition to the metadata, access mechanisms were designed and developed and became a key component of the technical parts of an SDI (Zhao and Di 2011). The Open Geospatial Consortium (OGC), which was established in 1994, brought together different academic, private and public sector parties and soon focused on the standardization of interfaces for accessing geospatial data resources (OGC 2019). They developed several web service interfaces to perform basic jobs such as 'discovery' (CSW—Catalogue Services for the Web), 'viewing' (WMS—Web Mapping Services—a first version of the standard was released in 2000), and 'downloading' (WFS—Web Feature Services). These OGC standards were meant to adhere to Service-Oriented architecture (SOA), an architectural style aimed at designing applications based on a collection of best practices, principles, interfaces, and patterns related to the central concept of a service (Papazoglou and van den Heuvel 2007). In SOA, services are the basic computing unit to support development and composition of larger, more complex services, which can be used to create flexible, ad hoc, dynamic applications. The main design principle behind SOA is that a service is a standards-based, loosely coupled unit composed of a service interface and a service implementation. Previous examples of OGC service specifications were designed to comply with these SOA principles to publish, find and use geospatial data. Most of the commercial software companies, as well as the Free and Open Source Software for Geospatial (FOSS4G) community—with a major push in 2006 with the establishment of the Open Source Geospatial Foundation (OSGeo)—developed tools and platforms to create such services and build portals for users to find and access data (Tait 2005; Maguire and Longley 2005).

In addition to the efforts to document GI and make it more discoverable and accessible, many efforts were made to better harmonize them for use in cross-border and cross-sector settings. The ISO Technical Committee 211 (ISO/TC211) was created in 1994 to look into the standards for Geographic Information and Geomatics. There was a large effort to develop the so-called ISO 19100 series of standards that, in addition to the already mentioned metadata standard, comprise a series of standards describing how to model our world (ISO 2002). The series includes a reference model, the definition of spatial and temporal schema, rules for application schema, and a methodology for cataloguing spatial features. In 2001, preparations began to design and implement INSPIRE, the Infrastructure for Spatial Information in Europe (INSPIRE 2019). In addition to the key idea of improving GI sharing (policy challenge), another objective was to improve spatial data interoperability through the design of data specifications for 34 themes (technical and organizational challenges). The ISO 19100 series of standards served as a basis for this huge effort. The resulting portfolio of standardized data sets serves cross-border applications in the context of environmental policy making/monitoring and other sectors. The process of harmonization is still ongoing at the time of writing.

In parallel with these more formal developments, stimulated by the public sector, developments in the private sector soon influenced SDIs and were ultimately (at least partially) integrated. In 1998, US Vice President Al Gore coined the term Digital Earth in view of global challenges such as climate change (Gore 1998). In 2001, a small software company called Keyhole Inc. launched and developed the Keyhole Earth viewer for looking at our globe from a global, bird's-eye view. The technical solution, aimed primarily at the defense sector, looked at geospatial data from a 3D perspective. A few years later, in 2004, Google acquired the small company and launched the still very popular product Google Earth based on the KML standard. More SDI developments embraced these new developments and aimed to integrate data from these commercial products into SDIs and applications. This whole process ended with the adoption of KML (originally keyhole markup language) by the OGC as a community standard.

In support of the development of SDIs, specific software developments emerged. Traditional GIS desktop software such as ArcGIS from ESRI was extended with server and mobile software, and the FOSS4G communities developed specific products that became very popular, such as GeoNetwork (to create geoportals and catalogue services), GeoServer, Degree and others (to set up all kinds of web services), and open source systems for data management such as POSTGIS (Steiniger and Bocher 2009; Brovelli et al. 2017). In addition to open standards and open software, open data became a new paradigm with important initiatives that are still very popular. In 2004, there was a global effort from the geospatial community to develop and maintain a network of streets (OSM), which was a joint effort of thousands of volunteers to provide and include data into an open data product (Haklay and Weber 2008). These volunteered geographic information (VGI) efforts became also part of the maintenance procedures of commercial products such as those from TomTom (formerly Tele Atlas) and Here (formerly NavTeq). The idea of citizens contributing to data and information gathering has now become widespread and is termed crowdsourcing [(Capineri et al. 2016), see also Chap. 18 for more details]. From the SDI perspective, which often focuses on authoritative data coming from government, these initiatives and the resulting geospatial data resources are considered complementary. The concept of GIS-based (open) data portals for smart city projects has also taken hold in recent years (ESRI 2019a).

These developments (see Table 5.2) led to a vibrant geospatial community and many GIIs that are interconnected (Vandenbroucke et al. 2009) and rich in content and quality, and new developments started to influence the way of working and the methods of providing data to user communities. Although the geospatial world has always worked somewhat in isolation, the developments in the general ICT world led to increased interest in joining forces. In 2006, Tim Berners-Lee coined the concept of Linked Data to combine the huge amounts of data available on the web (Berners-Lee 2006). In the geospatial world, this led to the idea of the geosemantic web. In 2014, the OGC and W3C started several joint initiatives including the Spatial Data

Table 5.2 Timeline of relevant technological developments

Year	Technological development
1982	First release of GRASS as open source software, managed by the US Army Corps of Engineers
1985	First release of ILWIS as closed, proprietary software developed by a university, ITC in the context of a land use zoning and watershed management project in Sumatra; the release as open source software followed in 2002
1987	First release of pcARC/INFO (ESRI), available on personal computers
1992	Introduction of the shapefile format by ESRI, which became a de facto standard format for exchanging geospatial data
1994	The Open Geospatial Consortium (OGC) is established and starts work with 8 members (currently more than 500)
1994	ISO/TC 211 is created as one of the technical committees of the International Organisation for Standardisation (ISO) responsible for the field of Geographic Information
1998	The FGDC metadata standard (US) becomes official
1998	The term Digital Earth is coined by former US Vice President Al Gore, describing a virtual georeferenced representation of the Earth
1998	Publication of the specifications of the shapefile format, which became open at that stage
2000	First version of the Web Mapping Service (WMS) interface standard released by OGC
2001	Keyhole Inc., the developers of Google Earth (originally called Keyhole Earth Viewer) and the KML format, is established
2002	The development of quantum GIS (QGIS) began, released as open source in 2009
2003	ISO 19115 Geographic Information—Metadata standard is adopted by the participating countries
2004	Publication of the SDI Cookbook by the Global Spatial Data Infrastructure Association (GSDI)
2004	Keyhole Inc. is acquired by Google
2004	OSM launched
2006	Linked Data as a concept, method and technique was coined by Tim Berners-Lee within the W3C as part of the semantic web project
2006	Founding of the open source geospatial foundation OSGeo, with currently more than 30000 volunteers, and the first FOSS4G International Conference in Lausanne, Switzerland
2007	The term volunteered geographic information (VGI) was coined by Michael Goodchild
2008	INSPIRE metadata regulation adopted as Implementing Rule 2007/2/EC
2010	INSPIRE regulation regarding interoperability of spatial data sets and services adopted as Implementing Rule 1089/2010
2014	The DCAT metadata standard for data resources of W3C is released
2014	Establishment of the Spatial Data on the Web Working Group focused specifically on the intersection of issues facing OGC and W3C members
2015	OGC adopts KML as a community standard
2015	GeoDCAT-AP, an implementation allowing for data exchange between geoportals and open data portals, was adopted by the EU ISA program

on Web Working Group to examine and test new ways of publishing and linking data (W3C 2015). One of the tangible results of this closer collaboration was the effort to exchange metadata between geoportals and (open) data portals through a more generic and broadly used DCAT standard (W3C 2014). More of these developments are expected to take place—and will continue to emerge faster and faster. This poses particular challenges to standardization processes, which should keep pace with these evolutions. In the next sections, we describe ongoing and new developments, for example, the changing power relationship from the public to the private sector and challenges posed by the trending platformization of society (van Dijck et al. 2018).

5.3 Geospatial Information Infrastructures Today

Leaving the past behind, several important developments and aspects of the current situation of GIIs are important to mention. We consider the following items worth highlighting in the context of Digital Earth: the mainstreaming of GI and the proliferation of GIIs, especially on the web; the contribution of GII developments to the opening of data and science as a whole; and the growth of knowledge exchange and learning networks across the globe.

5.3.1 The Evolution of Geospatial Information on the Web

In parallel to the organizational milestones described in Sect. 5.2, the technical foundations of GIIs were developed and standardized, mostly through bodies such as the OGC and ISO (see Sect. 5.2.2). Along with this development, the proliferation of slippy web maps and map-based mobile applications has led to the establishment of a separate branch of GII that primarily addresses end-user needs by, for example, providing directions to get from one place to another or offering extensive geocoding capabilities (“where is the closest coffee shop?”). The widespread adoption of these new services that were no longer just providing GI for a group of professional users was driven by the introduction of Google Maps in 2005 as well as the introduction of touch-screen smart phones with built-in GPS through the first iPhone in 2007.

Shortly after the introduction of Google Maps, the first reverse-engineered map mashups appeared and demonstrated how Google’s JavaScript-based maps could be combined with GIs from other sources (such as crime data on ChicagoCrime.org or real estate offerings on housingmaps.com). The subsequent release of a public Application Programming Interface (API) for Google Maps that allowed for any web developer to embed a map in their web pages triggered the development of open source alternatives such as OpenLayers (OpenLayers 2019), which is still under active development today as an OSGeo project. OpenLayers is notable in this context because it bridges the worlds of consumer-oriented GI and GIIs targeted at professional use cases by allowing the combination of data from OGC-based web services with tiles and file formats such as KML. Esri released its JavaScript API to facilitate the creation of web apps from traditional GIS datasets (ESRI 2019b). Together with other, more recent examples such as Leaflet (Leaflet 2019), a 'grass-roots' standard emerged for the URL scheme of map tiles for slippy maps (OSM 2019b). This URL scheme enabled any web mapping framework to consume and display the tiles from any of the increasing number of servers that can produce them (GeoServer, MapServer and TileStache are a few examples)—a de facto standardization process that was successfully completed without the involvement of any of the abovementioned standardization bodies.

A third aspect that explains today's GII landscape is the development and widespread adoption of open data (Open Data Barometer 2015; Gurstein 2011; Kitchin 2014). This includes thematic open data sets available for direct download via web portals (ESRI 2019c) and the free provisioning of governmental data, which was previously made available for a (sometimes substantial) fee—if at all. The proliferation of open government data (OGD) has been complemented by the development of user-generated data sources, dubbed volunteered geographic information (VGI, Goodchild 2007) in the context of GI. OGD aims to make data originally produced for professional users available to a broader public, and VGI can be seen as a grass-roots movement producing its own collection of non-authoritative datasets. The VGI project with the most profound impact is OSM. OSM started as a free, bottom-up alternative to the then-prohibitively expensive data produced by the UK's Ordnance Survey, and has since become the largest collection of freely available GI. At the time of writing of this chapter, the OSM database consisted of close to 5 billion mapped nodes (points), collected by almost 5 million registered users (OSM 2019c). Its significance for development in the field today lies in the provisioning of a free, global, and in many areas extremely detailed collection of GI and in the number of innovative companies that have entered the market with products based on OSM. They continuously contribute to the OSM dataset and have developed open source tools around it for mapping, quality checking, and the use and processing of OSM data.

A notable recent development that emerged from this OSM ecosystem is the trend towards using vector tiles instead of prerendered image tiles. The improved support for rendering vector data in modern web browsers has enabled this switch. Vector tiles have several advantages over image tiles, such as adaptable styling, maps that look sharp independent of screen resolution, and opportunities for interaction with the actual individual map features (interactive labels or clickable features, for example), with smaller data volumes to transfer between the server and client.

As these examples show, the collection, distribution, and analysis of GI has evolved from a field that used to require expensive equipment and extensive professional training to activities that are carried out by users (and contributors) with highly diverse backgrounds and different levels of education. The ubiquity of devices capable of both producing and consuming GI, in combination with an ever-growing amount of free-to-use GI and powerful free and open source software solutions has led to a somewhat chaotic landscape of practices, standards and conventions for the data and processes involved. The involvement of a broader public in these processes also means that organizations such as OGC or ISO that primarily focus on the professional use of GI are addressing a decreasing share of the actual GI user base. An increasing number of users and producers of GI do not work for government agencies, conduct commercial mapping efforts, or develop software for GI web services. Instead, they may be working in data science or data visualization (Bostock et al. 2011), may be open data advocates or citizen scientists, or may do research in areas such as economics, ecology, or the humanities.

New companies that deal with GI at the core of their business that do not consider themselves GIS companies have established new ways of dealing with GI, without taking the time to go through time-consuming standardization processes. The long list of prominent examples of these companies includes Mapbox, Carto, Uber, booking.com, Trip Advisor, Google and Facebook. Many of the relatively new internet platforms contain GI and thereby initiated a shift to the traditional organizational structures (van Dijck et al. 2018).

Arguably, with this industrial production and use of GI, large companies set the de facto standards—as far as standards are relevant for their internal workings. To some extent, these developments have been acknowledged by the World Wide Web Consortium (W3C) in some efforts that have traditionally been exclusive to the OGC, most notably the Spatial Data on the Web Working (W3C 2015) and Interest Groups (W3C 2017) and the best practices documents produced in this context (W3C 2019). The formation of these groups leverages the opportunity to involve a much broader group of users in the discussion around how GI should be shared on the web, and their discussions and outputs clearly show that the integration of GI from different sources is a semantic issue at its core (Kuhn 2005). This semantic interoperability and its role for the future of GII in the context of Digital Earth is discussed in detail in Sect. 5.4.2. The following section describes how GII is a prime example of the openness that has become the new normal in many fields of science, technology, and business.

5.3.2 Geospatial Information Infrastructures Champion Openness

As presented earlier, today's GII landscape is shaped by the influence, development and widespread adoption of open data (see also above). The notion of 'openness' has long been part of GIIs, especially due to the long-term leading role of the public sector (Schade et al. 2015). A foundational role of GIIs has been, and still is, to enable the discovery and sharing of spatially referenced data. As described in Sect. 5.2, SDIs were essentially designed and developed to support the generation, management and processing of GI, as key vehicles to make data openly accessible to a broader community. However, as a social construction, the understanding and interpretation of openness is far from static; it is dynamic and changes as the tandem technology-society evolves. Thus, the interpretation of 'open' (data, tools, etc.) reflects the changes in society and necessarily adapts to the new uses and needs of people. In addition, the value of open data is under scrutiny (Craglia and Shanley 2015) and an increasing number of commercial companies produce and host GI.

To better understand how the current discussion about openness affects GIIs and to better speculate future scenarios, we provide two brief stories, paraphrasing the way Arribas-Bel and Reades (2018) examine the evolution between geography and computers. First, we take a brief historical perspective to determine what openness meant in the origins of (governmental) GIIs. Next, we look at the new 'open' trends and growing forces that are currently emerging, mostly outside of GIIs, which we argue are important for GIIs (and Digital Earth) to pay close attention to. Both stories allow for us to reflect and speculate on the need for a convergent point in the future, where GIIs can embrace and continuously adapt to evolving notions of openness and to the resulting societal changes and economic implications.

The first story goes back to the reasons that motivated the need to establish GIIs. Since the outset, GIIs in the form of hierarchical visions on SDI (Rajabifard et al. 2003) or networked visions (Tulloch and Harvey 2008; Vandenbroucke et al. 2009) contained relatively restricted themes and types of resources owned by the public sector. The underlying motto was "collected once, shared multiple times", so each GII node was managed homogeneously its own spatially referenced data. Data sharing was feasible through these infrastructure nodes because data discovery, access, and delivery were affordable through well-known standardization practices (see Sects. 5.2.2 and 5.3.1). Standardized data models and service interfaces characterized the data sharing capabilities of these government-led GIIs, although only a small group of specialized, tech-savvy users benefitted from them. At that time, the concept of openness was tightly coupled to the idea of sharing. The democratization of data sharing through GIIs was a great leap to facilitate transnational and multidisciplinary projects because the problems of discovery, access and redundancy of GI were significantly alleviated by standardized and unified mechanisms. Most recently, this led to the offerings of location enabled e-Services using web-based application programming interfaces (APIs) built upon SDIs. One example of this is the development of an application for citizens called Spotbooking to apply for, process and maintain uses of public spaces within a town or city (Spotbooking 2019).

In addition to past studies to find synergies bridging geospatial research data with public sector information and open data initiatives, other relevant open trends/movements enable knowledge/data collection, creation and dissemination and mostly operate outside GIIs (Schade et al. 2015). We do not list the multitude of open trends and their technological infrastructure here but highlight a few examples to underline the evolving meaning of openness from data sharing to dynamic processes for knowledge production and dissemination. One example is the European Open Science Cloud (EOSC 2019), a cloud for research data in Europe that supports the ongoing transitions in how research is performed and how knowledge is shared. As a second example, the IoT infrastructure generates a vast amount of spatiotemporal data streams at a finer granularity, which undoubtedly represent valuable sources of data (i.e., 'things' observe the environment by collecting data) and analytical computation (i.e., 'things' act by processing gathered data) for Digital Earth and GIIs. Granell et al. feature the promising bridges and synergies between the IoT and Digital Earth application scenarios in Chap. 11, but a true convergence of the two infrastructures is still in its infancy. As a third example, the relationship between Digital Earth and citizen science is outlined in detail in this book by Brovelli and others (Chap. 18).

Fast-forwarding to the present, openness has become a more prominent concept than ever. It has been transformed and extended to all aspects of people's daily lives (Price 2013). Contrary to the common perception of openness in the first example, which was practically restricted to 'sharing' data, today's vision of openness takes multiple and varied forms (Sui 2014). Openness permeates many facets of today's culture, society, government, science and education, leading to a series of (old and new) 'open terms' such as open culture, open cities (Domingo et al. 2013; Degbelo et al. 2016), open movement (Lee et al. 2015), open government (Lathrop and Ruma 2010; Goldsmith and Kleiman 2017), open software (Aksulu and Wade 2010), open hardware (Powell 2012), open science, open research, open laboratories (Nosek et al. 2015), open innovation (Schade and Granell 2014; Mathieu and Aubrecht 2018), and open education (Bonk et al. 2015). In contrast, as analyzed below, daily (geospatial) information still flows to platforms that are not defined as open and are owned by the above-mentioned companies. Offering services free of charge but in exchange for personal (user-generated) data has become a popular business model.

We argue that peoples' perception of openness is dramatically influenced by the irruption, rapid adoption, and new uses and appropriations of technology. Digital transformations brought changes in the proliferation of new data sources, the consolidation of novel ways of producing and consuming data, and in the demography of users. The cost of creating GI anywhere, at any time, from anyone, about anything (aka 4-A technology) drastically decreased. However, the cost for current GIIs to consume, integrate and make sense of 4A-generated data is still considerable—especially when considering the direct and indirect costs for the provision and application of 4-A-generated data for a rich portfolio of use cases and stakeholders (Johnson et al. 2017). The scale, frequency, and granularity of the data being generated and gathered today were simply unimaginable when the foundations of GIIs were designed many years ago. The motto "collected once, shared multiple times" is no longer a fundamental truth that drives GIIs because anyone can collect data on the same phenomenon, in the same place, from multiple perspectives, which was previously technically infeasible. In fact, we unconsciously create such GIs all the time. As a result, more and more data sources are available for a single phenomenon, requiring additional analytical approaches and interoperability arrangements to integrate these data sources and offer a comprehensive picture about the phenomenon in question (Huang et al. 2018). Thus, data in traditional (governmental) GIIs provide one perspective of a phenomenon (mobility, pollution, demography, etc.). Other perspectives of that phenomenon are provided by data that are collected via other infrastructures. This does not fully address the concept of openness. Openness means sharing data about a phenomenon for small groups of experts, enabling and promoting comprehensible views of phenomena taken from disparate sources, and making them accessible and understandable to various user groups. What characteristics do modern GIIs need to fully exploit 4A-generated data? What does this imply in terms of interoperability? And how does this impact current approaches to openness?

While common sense tells us that the way to solve the growing complexity of today's social challenges and underlying research problems is through multidisciplinary collaboration at all levels including technical infrastructures, access to data, and participation in the creation and dissemination of knowledge, the reality is that the diversity of 'open' trends is understandable considering the diversity of actors that have different objectives and needs and are affected differently by a constantly changing technological landscape. It appears that each actor (citizens, NGOs, scientists, private companies, government, etc.) has a different understanding of the meaning and application of the notion of openness. All of them are entirely legitimate given the contexts in which each of the different stakeholders operate.

Regardless of any controversy about the future meaning of openness, it is clear that 'open' cannot be considered a static feature of data or of GII, but should be considered under the lens of recent trends and critiques as a dynamic process for the production, creation and dissemination of knowledge, which is subject to improvements and optimizations over time. The reconceptualization of openness as a dynamic process is vital to enable convergent points and bridges among emerging movements and GIIs—which still operate rather disconnectedly—to make sense of the vast amounts of collected data to solve the pressing issues facing the Earth today. We can rephrase the previous questions: What characteristics would define such dynamic processes in GIIs to exploit 4A-generated data?

Leading GIS scientists recently reflected on the current limitations of the field and called for an entirely new brand of geospatial algorithms and techniques to analyze and process these new forms of data (Jiang 2015; Miller and Goodchild 2015; Li et al. 2016). Lü et al. (2019) magnificently summarize this perception in one sentence: "a successful past [of GII] does not guarantee a bright future" (pp 347). The historical view of GII reported in this chapter is indisputably a story of success. Nevertheless, new driving forces and trends such as open movements and open information infrastructures—along with the datafication and platformization of society—have had and will have significant impacts on the future success of GIIs, so GIIs should carefully consider them to explore alliances and actively integrate and process new forms of information sources.

5.3.3 Capacity Building and Learning for Geospatial Information Infrastructures

Although appropriate technologies and policies to enable data access and data sharing are crucial in the development of GIIs, it also requires education and capacity building to ensure the necessary knowledge, skills and competencies are available

(Craglia et al. 2008). Complementing more general frameworks on the development of digital skills (van Deursen and van Dijk 2014), the need for collaboration between government, businesses and academics in the development of an appropriate knowledge infrastructure has been reflected in national and regional GII strategies and actions (Vancauwenberghe and Vandenbroucke 2016). In the past 20 years, various education and training initiatives on GII and related topics have been developed and implemented by higher education institutions, public administrations and businesses. Throughout the years, the focus has broadly shifted from raising awareness of the potential of GI, to capacity building for the implementation of different GII components to skills and knowledge related to the use and integration of GII data and services in decision making, service delivery and product development processes. GII education and training also must be dynamic and change in response to new technological and policy-related developments. The key challenge in successful GII education and training is to ensure that it addresses the needs of GII professional developers and users. Demand-driven GII education and training requires insight in and agreement on what professionals in the domain of GII should know and be able to do (Vandenbroucke and Vancauwenberghe 2016). Studies investigating the demand for GII capacity building have been undertaken at organizational, national and cross-national levels. A European-wide study on the workforce demand in the domain of GISandT showed that, despite differences in the tasks they perform, employees and representatives from the different sectors including public administration, private sector and academia have strongly similar views on the skills and knowledge areas they consider the most relevant (Wallentin et al. 2014). The European GI community identified a shift in focus from map making and local database handling towards online and mobile technologies based on SDIs with a massive amount of—open—data to be integrated. This is a clear indication that the importance of capacity building for GII will increase in the near future.

A valuable approach in the identification of the specific knowledge and skills that professionals need to master for career success in their field is the development of a comprehensive inventory of the knowledge domain. To provide such an inventory for the GISandT domain, in 2006 the University Consortium of Geographic Information Science (UCGIS) developed the Geographic Information Science and Technology Body of Knowledge (GISandT BoK) (DiBiase et al. 2006). The main intended use of the GISandT BoK was to support the development and assessment of GISandT curricula, but the document also serves other purposes such as for professional accreditation or screening of employees. The 2006 version of the Body of Knowledge included more than 330 topics organized into seventy-three units and ten knowledge areas. Notably, the concept of 'spatial data infrastructure' was included twice, in two different knowledge areas: once in the knowledge area of geospatial data (as a topic under the 'Metadata, standards and infrastructures' unit) and once in the organizational and institutional aspects knowledge area (as a topic under the Institutional and interinstitutional aspects unit). This reflects the need for training and education on the technological and organizational (or institutional) aspects of SDI. In addition to the concept of spatial data infrastructure, the Body of Knowledge contains other concepts that are linked or relevant to the development of SDIs and

GIIs, spread across different knowledge areas and units. This demonstrates the relevance and importance of GIIs as a field and the need for an ontology-based approach to the field, where different types of relationships between concepts can be identified (Vandenbroucke and Vancauwenberghe 2016).

To reflect and address recent trends, developments and challenges in the GISandT domain, continuous revision and updating of the Body of Knowledge are required. Initiatives to revise and update the Body of Knowledge have been undertaken and are ongoing in Europe and the United States (Vandenbroucke and Vancauwenberghe 2016). In addition to the topics covered and defined learning objectives, another key aspect in the design and implementation of GII training and education is the teaching and learning activities applied to help students achieve these objectives. GII education has evolved from traditional 'teacher-centric' teaching styles to more 'learner-centric' methods and approaches. With the availability of online—open—education resources by organizations and institutions such as the EuroSDR (EduServ program), the University of Salzburg (UNIGIS program), the Geographical Information System International Group (GISIG) and recently the European Commission (Geospatial Knowledge Base (GKB) Training Platform), the GI/GII community has a strong tradition of e-learning activities. Collaboration between higher education institutions and other stakeholders to design and deliver GI and GII education has taken place for many years. In many cases, this collaboration is often organized in a rather traditional manner, through internships at public or private organizations, the provision of data and tools for educational purposes, and the organization of study visits and excursions to private or public organizations in the GISandT domain (Vancauwenberghe and Vandenbroucke 2016). Recently, several universities started experimenting with more case-based approaches in which students and teachers closely collaborate with practitioners on real-life case studies. The concept of academic SDIs for research and for education can be viewed in the context of adopting more innovative teaching and learning methods (Coetzee et al. 2017). Students could actively contribute to the development and implementation of various SDI components and use the infrastructure to share the results of their efforts with other students, teachers and researchers. In addition, GIIs play a role in the cocreation of knowledge and thereby in lifelong learning (Foresman et al. 2014), and through their fundamental contribution to the Digital Earth vision, GIIs can enable living labs, i.e., user-driven approaches to innovation (Schade and Granell 2014).

5.4 Recent Challenges and Potential for Improvement

Given the situation today—as indicated in the introduction to this chapter—we face a series of challenges. These challenges primarily emerge from the pace of technological change, including more frequent technological disruptions than in the past, and the (to some extent heavy-headed) standardization applied to GIIs. We note the challenges caused by what we call the 'big data' phenomenon (Tsinaraki and Schade 2016) and by the mainstreaming of GI, which introduced new users with new needs as well as new providers of GII. Given these current changes and challenges, we emphasize two implications for GIIs and their future evolution.

5.4.1 Strengthened Role of Semantics

The insight that semantic heterogeneity is a key factor that interferes with the effective use and analysis of GI from different sources is by no means new, nor are the solutions based on semantic web technologies to address the corresponding challenges (Kuhn 2005; Lutz and Klien 2007; Lutz et al. 2009). However, although academic research noted these issues quite early on in the establishment of SDIs, in practice, most efforts have been focused on achieving the underlying technical and syntactic interoperability. This focus is understandable, as semantic interoperability only becomes an issue when the technical and syntactical issues are largely solved. This stage in the development of GII appears to have been reached, since the role of geospatial semantics has been strengthened considerably and is now an issue that practitioners deal with in implementation of open data platforms and geospatial web services.

Arguably, this development was not solely driven by questions about the semantics of geospatial data at hand. Rather, the need for approaches that let us add information about the semantics of entities (geospatial features, in our case), particularly their types and properties, has been recognized in many other fields. These include generic examples such as the publication of structured data on the web (Schema.org is the most prominent example) or specialized application domains (such as biology or history), and closely related research fields such as the sensor web and the Internet of Things. The common need for structured data with clearly defined semantics across those domains has led to efforts in a number of different directions, including research on the theoretical underpinnings of semantic reasoning (Noy 2004; Wang et al. 2004), development of specifications [RDF(S) (Staab et al. 2002), OWL (McGuinness and Van Harmelen 2004), OWL2 (Hitzler et al. 2009; Motik et al. 2009), query languages [SPARQL (Harris et al. 2013), GeoSPARQL (Battle and Kolas 2012)], implementation of the triple stores (Rohloff et al. 2007) and query engines (Broekstra et al. 2002; Carroll et al. 2004). In combination, these efforts have led to a more widespread adoption of approaches that focus on the semantics of geospatial data (Stock et al. 2011), and semantics is now front and center in best practice recommendations for publishing spatial data (W3C 2019).

The W3C's Spatial Data on the Web Best Practices discusses how to best semantically annotate geospatial data—, i.e., using shared vocabularies—and recommends full-fledged adoption of Linked Data principles. A more widespread adoption of these best practices will imply a paradigm shift (Kuhn et al. 2014) towards a radically distributed approach to the publication of GI. Linked Data are currently treated as a byproduct in the publication of GI, e.g., when government agencies such as the UK's Ordinance Survey are starting to offer their GI as Linked Data or when universities convert OSM data to Linked Data. These are valuable efforts—a little semantics goes a long way (Hendler 2009)—but the data that is being published is still the output of an extract-transform-load (ETL) process on top of an original data source such as a relational spatial database. Furthermore, the provision of GI as Linked Data only adds another data offering with the potential use for data integration. Actual success cases remain rare.

The opportunities and challenges of making Linked Data the original data format based on which all changes are made and from which other formats can be derived can currently be observed in the Wikidata effort (Vrandečić and Krötzsch 2014). After the immense success of DBpedia (Auer et al. 2007)—a Linked Data product generated via ETL from the structured information in Wikipedia—the potential of turning this process around by making the produced structured data the actual data underlying all language editions of Wikipedia has been recognized. This approach now allows for an editor to update information in Wikidata—such as the population number for a country after a new census, or the publication of the latest book by a given author—and that information can automatically be reused across all Wikipedia.

GI still has a way to go in making a semantics-based approach its primary format for data management and publication, and thus become part of an ever-growing distributed knowledge graph. Conceived as part of the infrastructure driving Digital Earth, this goal appears attractive, particularly because of its potential to further normalize the use GI across a wider range of disciplines. However, a number of challenges must be addressed before this vision can be put into practice, including the development and implementation of standardized handling of GI in triple stores, interfaces to access geospatial Linked Data directly from GI 'front ends' such as traditional GIS, web-based and mobile mapping applications, as well as capacity building, particularly in the form of educating students in the underlying technology stack so that they can help with these developments after graduation. These challenges highlight the fact that geospatial semantics will remain an essential and dedicated research area for the foreseeable future, helping users make sensible use of GI and turn it into actionable knowledge. Finally, in the context of Linked Data, (geo)spatial information is definitely special because spatial (and particularly spatiotemporal) data can be used as an integrator to help build connections between originally disparate data sources.

5.4.2 Is Spatial Still Special?

There are several slogans related to GI, including "spatial is special". Although one might argue that GI is only more complex than many kinds of (nonspatial) information, at least in the past, geospatial informatics filled a niche role with comparably few specialists working on the topic. As far as mainstream computing was concerned, the spatial-temporal components of GI were restricted to a pair of coordinates (a point) and a date-time stamp. Today, the spatiotemporal characteristics of GI have made it popular for data integration tasks, where location is an obvious commonality between many separately collected data sources (Tsinaraki and Schade 2016). In combination with the recent trend towards platformization of society and wider use of remotely sensed images, online maps, sensors (see also Chap. 11), as well as people's location and tracks, one might argue that the time when (geo)spatial has been special has come to an end. However, although the collection of GI has become much easier (and hence gone mainstream), pitfalls in analysis (spatial autocorrelation, projections, etc.) remain. Related special challenges surface, especially when standard approaches for handling big data are directly applied to GI. Many of the common "divide and conquer" approaches applied to big data analysis tasks fail because of the spatial relationships between chunks of data. As argued in Sect. 5.4.1, semantics is highly important. Using colocation as the only element for data integration can easily lead to the senseless combined processing of data from completely different and potentially conflicting contexts.

The mainstreaming of location information has direct implications for the evolution of GII, as with the future conceptualization of GIS and SDIs. In the past, these notions were a research and application field in their own right, and they now appear to be much more integrated into the wider fields of computer science and data science (Cadell 2018). With a narrow view, this could be seen as a thread to the communities and associations that formed around these concepts (the introduction to this chapter provided some examples of these). Conversely, the mainstreaming of GI provides immense opportunities such as the increasing market for companies specializing in GI and many new job opportunities for GI experts.

From a government perspective, GIIs became more relevant—and geospatial data less special—through the use of data in this infrastructure for the provision of spatially enabled e-government services to citizens, businesses and other societal actors (Vancauwenberghe and van Loenen 2018). Geospatial data that became increasingly available were used to improve existing e-services and provide novel services. Such spatially enabled e-services now exist in many policy areas (i.e., environment, agriculture, transport) and at different levels of government (i.e., local, regional, national). They evolved from more simple information and contact services to more advanced transaction services. These spatially enabled transaction services refer to the use of geospatial data in the electronic intake and handling of requests and applications of rights, benefits and obligations. Because these transaction services demand multiple two-way interactions between governments and citizens/businesses, they are more complex than information or contact services, which are mostly one-way services. This increased complexity applies to both technological and organizational aspects, since the delivery of these e-services requires a strong alignment and possible integration of GIIs with e-government developments. Initiatives to enable this integration have been taken at organizational, national and regional levels—especially in Europe (Vancauwenberghe and van Loenen 2018).

In the private sector, we have observed manifold developments. First, the traditional partnerships with the public sector evolved into collaborations in which governmental bodies such as mapping agencies still own and provide authoritative content (such as cadaster information, protected sites, and utilities), and the industry offers solutions for data hosting, access, and cost recovery. The data and information access services (DIAS) for the European Space program Copernicus is a particularly impressive example (Copernicus 2019). In each of these five different implementations, the public-sector GII is coupled with data from commercial satellites to provide additional value. Second, there are an increasing number of companies building upon GIIs. Especially for technologies such as web-based APIs, as in the example of Spotbooking, GI has become more accessible and value-added services and applications have been created. Due to the abovementioned platformization, large internet firms create many GIs and host them in their infrastructures, and they are only occasionally linked to existing public-sector GIIs. GI has clearly moved into the mainstream information infrastructures. Lastly, many GI projects today rely on data provided by companies such as Google, DigitalGlobe, Waze, Here, and Esri. Examples include geospatial data about commercial demographics and personal mobility.

In the context of Digital Earth, these developments are all good news. In every conceptualization of the Digital Earth vision—and in any future evolution thereof—GI and GIIs will remain fundamental building blocks. As increasing related expertise becomes available and the mainstreaming trend of GI continues, GI can provide the capacity that is required for improving Digital Earth applications and enlarging implementations of the Digital Earth vision across the globe. The transition from mainstreamed GI to GIIs that are readily available to developers and implementers of the Digital Earth vision is the logical next step and an area for further research and organizational improvements. The interplay between and the changes in power relationships between society, research, industry and the public sector deserve dedicated attention.

5.5 Conclusion and Outlook

This chapter situated GIIs in the wider context of the Digital Earth vision and introduced GIIs as a major enabling element for Digital Earth implementation. The past and present of GIIs was outlined along with a subjective view of today's major challenges concerning the status of GII development and use, and possible future directions. Notably, this view might be biased towards academia and governments, but we have highlighted emerging developments from the private sector as a disruptive driving force that quickly emerged over the past decade.

This chapter demonstrates that GIIs have come a long way and evolved as a strong underpinning contribution for implementation of the Digital Earth vision. Whereas we witnessed a dispersion of efforts in the early days, we illustrated how GIIs evolved and coordinated efforts emerged in different national and international contexts. The increasing pace of technological changes poses new challenges to the continuation and further convergence of these efforts because new actors with different backgrounds and expectations enter the discussion. We see a particular need to continue and strengthen the role of semantics in GII development and implementation to ensure that the provided information can be used appropriately. We also recognize the changing power relationship from the public to the private sector, with a disrupting effect on traditional data owners (especially mapping agencies). These changes will significantly affect the role of the public sector in geospatial data management and provision.

Lastly, we underlined the needs for further evolution of GIIs so that they become flexible and robust enough to absorb and embrace technological transformations and the accompanying societal and organizational implications. These required capacities for addressing technological and organizational issues, and training of present and future generations of GII developers and GII users. As a prominent example, we highlighted the relationships to movements to open up data and the access to knowledge. GIIs—which were in the forefront of open data sharing in the past—must react to changing conditions, provide bridges to other existing infrastructures to absorb new data sources, and contribute to the development of new standards for collaboration. The next generation of GIIs should provide management and processing capacities for classical GI, and must be able to input and handle novel information sources. In this way, they will continue to fuel innovation for the future of Digital Earth. Chapters 6, 9 and 10 provide additional insight into analytical aspects and issues related to big data. For details about the economic value of Digital Earth, we refer the reader to Chap. 19.

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Chapter 6
Geospatial Information Processing Technologies

Zhenlong Li, Zhipeng Gui, Barbara Hofer, Yan Li, Simon Scheider and Shashi Shekhar

Abstract The increasing availability of geospatial data offers great opportunities for advancing scientific discovery and practices in society. Effective and efficient processing of geospatial data is essential for a wide range of Digital Earth applications such as climate change, natural hazard prediction and mitigation, and public health. However, the massive volume, heterogeneous, and distributed nature of global geospatial data pose challenges in geospatial information processing and computing. This chapter introduces three technologies for geospatial data processing: high-performance computing, online geoprocessing, and distributed geoprocessing, with each technology addressing one aspect of the challenges. The fundamental concepts, principles, and key techniques of the three technologies are elaborated in detail, followed by examples of applications and research directions in the context of Digital Earth. Lastly, a Digital Earth reference framework called discrete global grid system (DGGS) is discussed.

Keywords Geospatial big data · High-performance computing · Online geoprocessing · Distributed geoprocessing · Discrete global grid system

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6.1 Introduction

With the advancement of sensor and computing technologies, massive volumes of geospatial data are being produced at an increasingly faster speed from a variety of geo-sensors (e.g., in situ and remote sensors) and model simulations (e.g., climate models) with increasing spatial, temporal, and spectral resolutions. For example, satellite sensors are collecting petabytes data daily. Climate model simulations by Intergovernmental Panel on Climate Change scientists produce hundreds of petabytes of climate data (Schnase et al. 2017). In addition to these traditional data sources, geospatial data collected from ubiquitous location-based sensors and billions of human sensors (Goodchild 2007) are becoming more dynamic, heterogeneous, unstructured, and noisy.

These massive volumes of geospatial data offer great opportunities for advancing scientific discovery and practices in society, which could benefit a wide range of applications of Digital Earth such as climate change, natural hazard prediction and mitigation, and public health. In this sense, efficiently and effectively retrieving information and deriving knowledge from the massive geospatial datasets have become critical functions of Digital Earth. The questions that can be (or should be) addressed with Digital Earth include, for example, how to investigate and identify unknown and complex patterns from the large trajectory data of a city to better understand human mobility patterns (e.g., Hu et al. 2019a, b), how to rapidly collect and process heterogeneous and distributed hazard datasets during a hurricane to support decision making (e.g., Martin et al. 2017; Huang et al. 2018), how to synthesize huge datasets to quickly identify the spatial relationships between two climate variables (e.g., Li et al. 2019), and how to find spatial and temporal patterns of human activities during disasters in massive datasets that are notoriously "dirty" and biased population samples (e.g., Twitter data) in a scalable environment (e.g., Li et al. 2018).

Geospatial information computing refers to the computational tasks of making sense of geospatial data. Such tasks mainly include but are not limited to geospatial data storage, management, processing, analysis, and mining. Addressing the above questions poses great challenges for geospatial information computing. First, the volume of the geospatial data at the global scale (e.g., at the petabyte-scale) exceeds the capacity of traditional computing technologies and analytical tools designed for the desktop era. The velocity of data acquisition (e.g., terabytes of satellite images a day and tens of thousands of geotagged tweets a minute) pushes the limits of traditional data storage and computing techniques. Second, geospatial data are inherently heterogeneous. They are collected from different sources (e.g., Earth observations, social media), abstracted with different data models (e.g., raster, vector, array-based), encoded with different data formats (e.g., geodatabase, NetCDF), and have different space and time resolutions. This heterogeneity requires interoperability and standards among the data processing tools or spatial analysis functions. For example, producing timely decision support often requires combining multiple data sources with multiple tools. Moreover, with the involvement of multiple tools and datasets in the problem-solving process, data provenance, analysis transparency, and result reproducibility become increasingly important. Third, global geospatial data are often physically distributed. They are collected by distributed sensors and stored at data servers all over the world. Moving data from one location such as local server to another such as cloud for processing becomes problematic due to the high volume, high velocity, and necessity of real-time decision making.

A variety of processing and computing technologies have been developed or adapted to tackle these challenges. Figure 6.1 depicts a geospatial information computing framework of Digital Earth, highlighting three types of popular technologies in geospatial information computing: high-performance computing (HPC, Sect. 6.2), online geospatial information processing (or online geoprocessing, Sect. 6.3), and distributed geospatial information processing (or distributed geoprocessing, Sect. 6.4). HPC aims to tackle the large-volume challenge by solving data- and computing-intensive problems in parallel using multiple or many processing units (e.g., GPU, CPU, computers). Online geoprocessing comprises techniques that allow

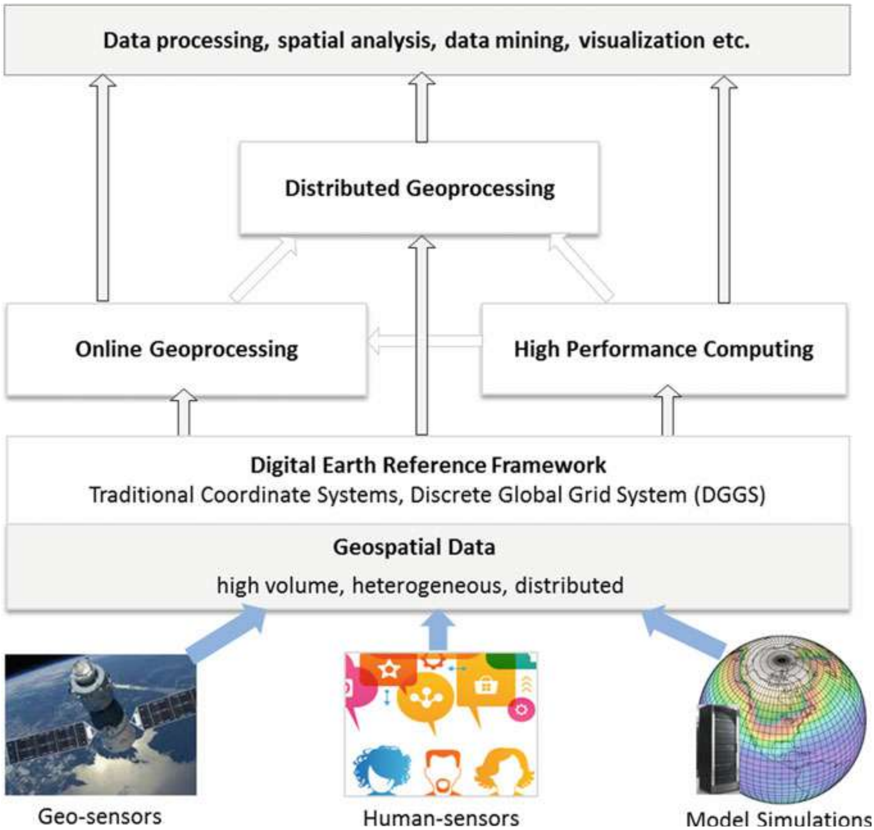

Fig. 6.1 Geospatial information computing framework of Digital Earth composed of high-performance computing, online geoprocessing, and distributed geoprocessing

for performing data processing and spatial analysis tasks on the web using geospatial web services (e.g., OGC web services) or web APIs (e.g., RESTful). Through standardization, these services and APIs are essential for addressing the heterogeneity challenges of geospatial data. Distributed geoprocessing refers to processing geospatial data and information in a distributed computing environment. By chaining a set of distributed data processing services into an executable workflow, the datasets and analysis steps involved in a task are documented, which improves the reproducibility of the analysis.

The following three sections start with a brief introduction and definition of a technology followed by its key principles, techniques, and examples of applications that support Digital Earth. Research challenges and future directions are discussed at the end of each section. A summary of the three technologies and a discussion of the discrete global grid system (DGGS) are provided in the last section. This chapter is not intended to be comprehensive or cover all aspects and technologies of geospatial information computing. The three selected technologies are described to provide the readers with a sense of geoinformation processing and how it is applied to support Digital Earth.

6.2 High-Performance Computing

6.2.1 The Concept of High-Performance Computing: What and Why

HPC aims to solve complex computational problems using supercomputers and parallel processing techniques. Since commodity clusters revolutionized HPC twenty years ago, a price-performance standard has become dominant, which includes inexpensive, high-performance x86 processors, functional accelerators (e.g., Intel Xeon Phi or NVidia Tesla), and open source Linux software and associated toolkits. It has been widely used in various applications such as weather forecasting, nuclear test simulation, and molecular dynamics simulation.

The growing availability of spatial datasets, in the form of GPS vehicle trajectories, social media check-ins, earth observation imagery, and sensor readings pose serious challenges for researchers and tool users in geo-related fields. The currently available computational technology constrains researchers and users in geo-related fields in two ways. First, the size of problems that can be addressed using the currently available methods is limited. Additionally, new problems, patterns, research, and decisions that may be discovered from geospatial big data cannot be found using existing tools. The 3 "V" s of big geospatial data (volume, variety, and velocity) impose new requirements for computational technology for geospatial information processing, for example, large, cheap, and reliable storage for large amounts of data, as well as scalable algorithms to process data in real time. Due to its computational capability, HPC is well suited for geospatial information processing of geospatial big data. A highly integrated and reliable software infrastructure ecosystem based on HPC will facilitate geo-related applications in two ways. First, it will scale up the data volume and data granularity of data management, mining, and analysis, which has not been possible in the desktop era using the currently available methods. Furthermore, it will inspire and enable new discoveries with novel big-data-oriented methods that are not implementable in the current desktop software.

In the following, we describe HPC platforms frequently used in geospatial information processing, and look at how HPC is applied in spatial database management systems and spatial data mining.

6.2.2 High-Performance Computing Platforms

Since HPC was introduced in the 1960s, parallelism has been introduced into the systems. In parallelization, a computational task is divided into several, often very similar, subtasks that can be processed in parallel and the results are combined upon completion. The direct computational time savings of HPC systems results from the execution of multiple processing elements at the same time to solve a problem. The process of dividing a computational task is called decomposition. Task interaction necessitates communication between processing elements, and thus increasing granularity does not always result in faster computation. There are three major sources of overhead in parallel systems: interprocess interaction, idling, and excess computation. Interprocess interaction is the time spent communicating data between processing elements, which is usually the most significant source. Idling occurs when processing elements stop execution due to load imbalance, synchronization, or the presence of serial components in a program. Excess computation represents the extra time cost of adopting a parallel algorithm based on a poorer but easily parallelizable algorithm rather than the fastest known sequential algorithm that is difficult or impossible to parallelize.

To facilitate the parallelism of HPC systems, the architecture of HPC systems dictates the use of special programming techniques. Commonly used HPC platforms for large-scale processing of spatial data include the Message Passing Interface (MPI), Open Multi-Processing (OpenMP), Unified Parallel C (UPC), general-purpose computing on graphics processing units (GPGPU), Apache Hadoop, and Apache Spark. These platforms can be roughly classified according to the level at which the hardware supports parallelism.

OpenMP, MPI, and UPC support parallelism on central processing units (CPUs). OpenMP is an API that supports multi-platform shared memory parallel programming in C/C++ and Fortran; MPI is the most commonly used standardized and portable message-passing standard, which is designed to function on a wide variety of parallel computing architectures. There are several well-tested and efficient implementations of MPI for users programming in C/C++ and Fortran. They can work cooperatively in a computer cluster such that OpenMP is used for parallel data processing within individual computers while MPI is used for message passing between computers. UPC extends the C programming language to present a single shared, partitioned address space to the programmer, where each variable may be directly read and written by any processor but is physically possessed by a single processor.

The GPGPU platform performs computations that are traditionally conducted by CPUs using graphic processing units (GPUs). Architecturally, a CPU is composed of a few cores that can handle complex tasks whereas a GPU is composed of hundreds of cores for simple tasks, so a GPU can dwarf the calculation rate of many CPUs if the computational task can be decomposed to simple subtasks that can be handled by a GPU's core. The GPGPU is programmed using programming models such as CUDA or OpenCL.

Due to the popularity of commodity computer clusters, the MapReduce programming model was introduced to maintain their reliability. Apache Hadoop, which is a collection of open-source software utilities based on the MapReduce programming model, can automatically handle hardware failures that are assumed to be common. Apache Spark was developed in response to limitations in the MapReduce model, which forces a linear dataflow structure to read and write from disk. Instead of a hard drive disk, Apache Spark functions on distributed shared memory. Figure 6.2 illustrates how HPC platforms support both spatial database management systems and spatial data mining.

The abovementioned HPC platforms facilitate the realization of several HPC applications such as cloud computing, newly emerging edge computing (Shi et al. 2016) and fog computing (Bonomi et al. 2012). Cloud computing is the on-demand availability of computational resources such as data storage and computing power without direct active management by the users. It emphasizes the accessibility to HPC over the Internet ("the cloud"). As the cost of computers and sensors continuously decrease and the computational power of small-footprint devices (such as

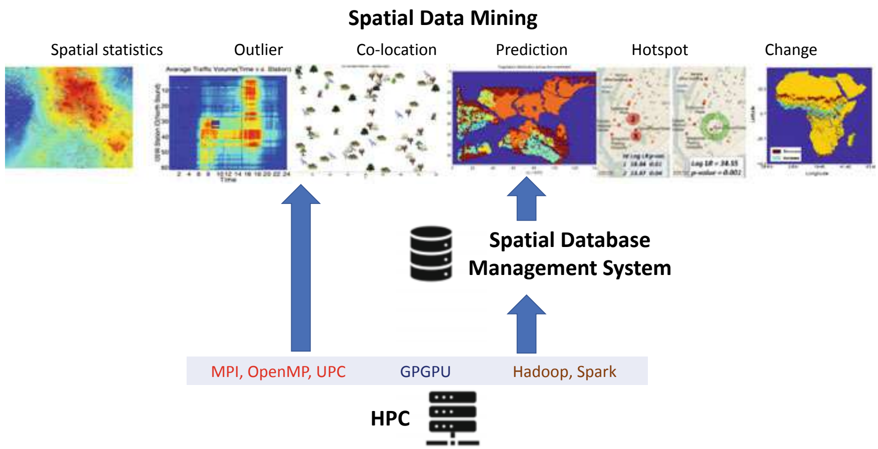

Fig. 6.2 HPC for spatial database management systems and spatial data mining

gateways and sensor hubs) increase, the concepts of edge computing and fog computing include more processing elements such as end devices in the Internet of Things in the computer clusters.

6.2.3 Spatial Database Management Systems and Spatial Data Mining

A database management system (DBMS) is a computerized system for defining, creating, querying, updating, and managing a database. It provides persistence across failures, concurrency control, and scalability to search queries of datasets that do not fit inside the main memories of computers. Spatial DBMSs are software modules that can work with an underlying DBMS; they were developed to handle spatial queries that cannot be handled by a traditional DBMS, for example, listing the names of all employees living within one kilometer of a company (Shekhar and Chawla 2003). Spatial DBMSs are an essential component of spatial data storage and management for geospatial information processing.

Spatial data mining is the process of quantifying and discovering interesting, previously unknown, potentially useful pattern families from large spatial datasets such as maps, trajectories, and remote sensing images (Shekhar et al. 2015). Compared with traditional data mining, spatial data mining has three special challenges. First, objects in space exhibit spatial dependence at nearby locations as well as distant locations. The spatial dependence at nearby locations is called the spatial autocorrelation effect. It is also known as Tobler's first law of geography: "Everything is related to everything else, but near things are more related than distant things." For example, people tend to cluster together with others that share similar characteristics, occupation, and background. Examples of long-range spatial dependence, i.e., spatial tele-coupling, include El Niño and La Niña effects on the climate system. A second challenge is that spatial data is embedded in a continuous space whereas classical datasets are often discrete. Third, spatial heterogeneity and temporal nonstationarity make it difficult to find a global law that is valid across an entire space and for all time. In other words, spatial context matters. Consequently, classical data mining algorithms often perform poorly when applied to spatial data sets and thus more powerful methods such as spatial statistics and spatial data mining are needed.

Spatial statistics (Cressie and Wikle 2015) provides theories (e.g., spatial point process, geostatistics, and lattice statistics), models (e.g., spatial autoregression model), and methods (e.g., Kriging) for spatial data mining. Spatial data mining focuses on five pattern families, namely, outliers, colocations and tele-couplings, location prediction, hotspots, and spatiotemporal change. A spatial outlier is defined as a spatially referenced object whose nonspatial attribute values are inconsistent with those of other objects in its spatial neighborhood (Shekhar et al. 2003). Contrary to global outliers, whose nonspatial attributes are compared with the remainder of the dataset, the attributes of spatial outliers are compared with a local subset of data around their footprints. For example, a road intersection where the vehicle speed is much higher than in other intersections nearby is a spatial outlier although it may not be a global outlier compared with other intersections in the city.

Spatial colocations represent subsets of spatial event types whose instances are often located in close geographic proximity (Huang et al. 2004). For example, the Nile crocodile and the Egyptian plover are frequently colocated, which indicates their symbiotic relationship. Other common colocation patterns include the colocation of the fast food restaurants McDonald's, Burger King, and KFC; the colocation of shopping malls with movie theaters; and the colocation of bars and drunk driving. Spatial tele-coupling represents interactions across distant locations. For example, the El Niño weather pattern (warming of the Pacific Ocean) affects the weather thousands of miles away in the midwestern and eastern United States.

Location prediction aims to learn a model to infer the location of a spatial phenomenon from maps of other spatial features. Examples include learning land-cover classification maps, predicting yearly crop yield, and predicting habitats for endangered species. Classical data mining techniques yield weak prediction models as they do not capture the spatial autocorrelation and heterogeneity in spatial datasets. Ignoring spatial autocorrelation often results in salt-and-pepper noise, i.e., locations whose predicted land-cover class is very different from the predicted land-cover classes of its neighboring locations. Such problems are significantly reduced by spatial autocorrelation-aware location prediction methods such as spatial autoregression, Markov random field-based Bayesian classifiers, and spatial decision trees (Jiang et al. 2015). Spatial heterogeneity, which prevents single-learner methods (e.g., neural networks and random forests) from accurately learning a global model is considered by spatial ensemble methods as well as Gaussian multiple instance learning methods (Jiang et al. 2017).

Spatial hotspots represent spatial regions where the concentration of objects inside the region is significantly higher than that outside. Hotspot analysis is widely used in public health and public safety to identify hotspots of disease and crime, respectively. False positives and true negatives carry high costs in such settings. Incorrectly labeling a neighborhood a disease or crime hotspot may lead to stigmatization and significant economic loss, and missing true hotspots of disease may lead to preventable mortalities and disease burden.

Spatiotemporal change may be defined in several ways. It may be a change in a statistical parameter, where the data are assumed to follow a distribution and the change is a shift of this distribution. It may be a change in actual value, where the change is defined as the difference between a data value and its spatiotemporal neighborhood. It may also refer to a change in models fitted to data, where the change is defined as a change in the models fitted to the data. Studies have been conducted to find more scalable algorithms for biomass monitoring using Gaussian process learning (Chandola and Vatsavai 2011).

There are many other interesting, useful and nontrivial patterns of interest in spatial data mining. For example, emerging hotspot detection aims to detect disease outbreak well before an outbreak results in a large number of cases. Interested readers are referred to papers on spatial data mining (Shekhar et al. 2011, 2015) and parallel computing algorithms for GIS (Healey et al. 1997; Shekhar et al. 1996, 1998; Zhao et al. 2016) for additional details.

6.2.4 Applications Supporting Digital Earth

Spatial database management systems using HPC have been studied extensively. Since Hadoop was introduced and its ability to handle big data in computer clusters was demonstrated, researchers and savvy tool users have taken advantage of it in various ways. Some tools and studies use Hadoop as a black box for operations on data, such as GIS tools for Hadoop, a package composed of programming libraries and an add-on toolbox of ArcGIS desktop (ESRI 2018), and Hadoop-GIS, a scalable spatial data warehousing system (Aji et al. 2013). Spatial Hadoop adds native support for spatial data by supporting a set of spatial index structures and developing spatial functions that interact directly with Hadoop base code (Yao et al. 2017). Impala, a distributed SQL query engine for Hadoop, has also been extended for spatial data (Eldawy et al. 2015). Apache Spark's core in-memory data abstraction, called a resilient distributed dataset (RDD), outperforms MapReduce-based approaches. Inefficient handling of interactive operations, the performance bottleneck of Hadoop-based tools, is addressed by GeoSpark, which adds support for spatial data and operations to Spark (Yu et al. 2015). GCMF, an end-to-end software system on GPGPU, illustrates the potential of GPGPU as a platform for geospatial information processing, as it can handle spatial joins over non-indexed polygonal datasets containing more than 600,000 polygons on a single GPU within 8 s (Aghajarian et al. 2016).

HPC is also applied in spatial data mining. Examples of HPC for spatial statistics include parallelizing the computation of statistical measures (e.g., Moran's I and Getis-Ord) using MPI and OpenMP (Wang et al. 2008; Kazar et al. 2004). Parallelization of the interpolation method has also been studied. Parallelized Kriging has been implemented on both MPI and GPGPU (Pesquer et al. 2011; de Ravé et al. 2014). Hadoop and Spark have also been leveraged as platforms to implement Kriging and inverse distance-weighted interpolation algorithms (Xu et al. 2015; Rizki et al. 2017). Parameter estimation for many spatial statistical models (e.g., spatial autoregression and space-time kernel density estimation) relies on matrix operations and may benefit from parallel formulations of linear algebra algorithms. A parallelization of wavelet transform, which can locate frequency outliers, has been implemented on MPI to scale up outlier detection algorithms (Barua and Alhajj 2007). Both GPU-based and OpenMP-based parallel algorithms have been explored for spatial prediction and classification (Gandhi et al. 2006; Rey et al. 2013). Researchers are investigating the use of GPUs as a platform for computing likelihood ratios as well as Ripley's K function (Pang et al. 2013; Tang et al. 2015). GPU-based methods have also been introduced to accelerate the computation of change detection (Prasad et al. 2013, 2015).

6.2.5 Research Challenges and Future Directions

HPC is essential for handling today's growing volumes of spatial data and the ever-increasing size and complexity of geospatial information processing problems. In addition to the existing methods and tools, further study in two focus areas is necessary to take full advantage of HPC for geospatial information processing.

The first focus of study is the parallelization of the currently available methods for HPC. The ubiquitous existence of spatial autocorrelation makes parallelization not applicable for most geo-related algorithms because the dependence between data partitions requires task interaction, which increases the difficulty of parallelizing serial algorithms in spatial database and spatial data mining functions. Additionally, the load balancing between processing elements is complicated when dealing with sparse data structures for which the pattern of interaction among data elements is data-dependent and highly irregular. Spatial networks (e.g., road networks) are an example of these data structures.

The second focus of study is utilization of geospatial big data to discover novel problems, patterns, research, and decisions. For example, most current research in spatial data mining uses Euclidean space, which often assumes isotropic properties and symmetric neighborhoods. However, the distribution of many spatial phenomena is strongly affected by the underlying network space, such as rivers and road networks. Some cutting-edge research has been conducted to generalize spatial analysis and data mining methods to the network space, such as network spatial interpolation (Kriging), network point density estimation, and linear hotspot detection (Okabe and Sugihara 2012). However, more research is needed in the network space. For example, in addition to the shortest paths, simple paths or irregular subgraphs are potential candidates for study in linear hotspot detection problems to discover interesting patterns.

In addition to the network space, the curved surface of the Earth is rarely considered in the currently available spatial database and data mining functions. For example, Chap. 2 discusses extending spatial indexing based on a space-filling curve and coordinate system to the curved surface. However, another family of spatial indexing, R-tree, which is the default spatial indexing supported by major DBMSs such as Oracle, MySQL, and PostGIS, only works in Euclidean space. Additionally, the definition of distance on the curved surface of the Earth is different from that in the Euclidean space, which affects the discovery of spatial patterns such as outliers, hotspots, and colocation.

Spatial heterogeneity is another topic to be explored. Spatial heterogeneity refers to the uneven distribution of spatial phenomena within an area. Most of the existing methods focus on the discovery rules or patterns valid for the whole dataset. However, the belief that spatial context matters is a major theme in geographic thought (Miller and Goodchild 2015). Different rules or patterns may exist in various places. If a pattern is infrequent relative to the size of the whole dataset, it may be missed if the entire dataset is analyzed. Such localized patterns are easier to find in smaller subsets of the data, around their spatial footprints. Identifying these patterns is challenging due to the need to enumerate all relevant footprints that may include an exponential number of data partitions (e.g., subgraphs of a road network). Examples of research on this topic include the spatial ensemble classification method (Jiang et al. 2017) and study of local colocation pattern detection (Li and Shekhar 2018).

Both the abovementioned future research directions pose new challenges for the computational capacity of currently available systems and tools. A highly integrated and reliable infrastructure ecosystem of HPC is required for geospatial information processing because most existing approaches focus on parallelization of specific tasks. Such an infrastructure can be utilized to speed up data management, mining, and analysis projects with scale and data granularity that were previously not possible, and enable new discoveries and ways of planning and decision making with novel big-data-oriented tools that are unavailable in the standard software.

6.3 Online Geospatial Information Processing

6.3.1 Web Service-Based Online Geoprocessing

Online geoprocessing refers to the use of spatial analysis functionality (such as buffer, interpolation and filtering operations) on the web to generate the desired output by applying a requested operation or chains of operations on input data. For the client-server interaction to work, clients and servers must be able to exchange requests and responses, for example, in the form of standardized web services. The standardization body in the geoinformatics sector is the Open Geospatial Consortium (OGC) (http://www.opengeospatial.org/standards/owc). OGC standards are aimed to provide syntactically interoperable services to facilitate integration, exchange and reuse of observations, data and geocomputational functions. Current applications of online geocomputation in the context of Digital Earth demonstrate the benefits of this standards-based technology. Some examples of such applications as well as challenges for advancing online geoprocessing for Digital Earth applications are discussed in Sect. 6.3.3. The alternative to standardized web services is application programming interfaces (API) and data formats such as JSON—the JavaScript Object Notation, which are increasingly popular (Scheider and Ballatore 2018). However, the plethora of available APIs limits the reusability of services that is with standardized approaches.

OGC service specifications cover services for raster or vector data, sensor observations, processing services, catalog services, and mapping services. The principle behind these services is that the interfaces are standardized, which means that resources can be requested following a set of defined parameters via the hypertext transfer protocol (HTTP). The requests are processed by a server and a response is sent back to the requesting user or service; the responses are generally encoded in XML (eXtensible Markup Language). Providers of web services can register their services in catalogs such that clients can discover and use these services. This publish-find-bind principle is fundamental in service-oriented architectures (SOAs) that realize the principle of integrating resources from distributed sources. Service-oriented architectures are commonly used in the context of spatial data infrastructures and (open) data initiatives, for example, GEOSS (http://www.geoportal.org).

According to Yue et al. (2015) such web services have the potential to become *intelligent,* i.e., easing the *automated* discovery and composition of data and processing services to generate the required information at the right time. To realize this vision, a move from the currently supported syntactic interoperability towards *semantic interoperability* is a core requirement (Yue et al. 2015). This section discusses the state-of-the-art of online geoprocessing in the context of Digital Earth as well as current lines of research related to semantics of geocomputational functions and spatial data. The objectives of this section are reflected in its structure: Sect. 6.3.2 introduces the principles of two geoprocessing services—the web processing service (WPS) and the web coverage processing service (WCPS). Section 6.3.3 discusses the state-of-the-art by reviewing successful applications of geoprocessing technology. Some current research trends and future directions to realize intelligent online geoprocessing are discussed in Sect. 6.3.4.

6.3.2 Web (Coverage) Processing Services

The key technologies for web service-based online processing are web processing services (WPSs) and web coverage processing services (WCPSs). As their names suggest, WCPSs provide processing functionality for coverages and is related to the web coverage service (WCS) standard; WPS provide general processing functionality for geospatial data. Both of these services follow the overall design principle of interoperable OGC web services and are briefly introduced below.

WPSs are currently available in version 2.0. A WPS must support the GetCapabilities, DescribeProcess and Execute requests, which are sent to the server using the HTTP GET or POST methods or the simple object access protocol (SOAP) (http://cite.opengeospatial.org/pub/cite/files/edu/processing/basic-index.html). The responses of the GetCapabilities and DescribeProcess requests contain information on parameter values required for an Execute request. These pieces of information cover the input, parameters and output of processes. Input and output data, which are either complex or literal data, are specified with a description and information on mimeType (e.g., "text/xml"), encoding (e.g., "UTF-8") and schema (e.g., "http://schemas.opengis.net/gml/3.2.1/feature.xsd"). It is possible to specify the data types of literal data as well as allowed values. WPS can be executed in synchronous or asynchronous modes; asynchronous execution is preferred for calculations that take longer.

The nature of WPS is generic as the kind of calculation a processing service provides is not specified. The generic nature of WPS is said to be one reason for its slow uptake, as it is difficult for clients to deal with the variety of outputs generated by different WPSs (Jones et al. 2012). The process implementations are hidden from the users; the information provided on the processes includes their input, output and parameters as well as a title, description, identifier and additional optional metadata. To reuse processes, it is essential to have information on what a process does and the datasets it can be applied to. Thus, process profiles have been revised and modified to describe the meaning of operations and their inputs and outputs in the WPS 2.0 standard (Müller 2015).

The web coverage processing service is an extension of the WCS standard with an explicit focus on the processing of coverages, i.e., multidimensional raster data; it has been available since 2008. The current WCS 2.1 version supports the GetCapabilities, DescribeCoverage and GetCoverage requests. These requests are extended for the ProcessCoverage request in WCPS. Filter mechanisms that restrict the spatial or temporal extent of the processed data are a core requirement for interaction with multidimensional coverages. The WCPS provides a specific syntax, which is somewhat similar to the structured query language SQL, for formulating queries of temporal and spatial subsets of data (Baumann 2010). WCS and WCPS can handle a multitude of different formats of data encodings that are relevant in the context of image data; these include NetCDF, GeoTiff, JPEG, and GRIB2. A tutorial on WCS and its extensions is available on Zenodo (Wagemann 2016).

Although WCPS was specifically designed for coverage data, its reuse across applications is hindered by diverging definitions of data models and the heterogeneity of data formats (Wagemann et al. 2018).

6.3.3 Online Geoprocessing Applications in the Context of Digital Earth

This section presents three recent examples of application of online geoprocessing. These applications were published in a related special issue aimed at promoting online geoprocessing technology for Digital Earth applications (Hofer et al. 2018). The applications demonstrate the use of web processing services and web coverage processing services as extensions of existing infrastructures in a variety of contexts. They derive relevant and timely information from (big) data in efficient and reusable manner, which serves the objectives of Digital Earth.

Wiemann et al. (2018) focus on the assessment of water body quality based on the integration of data available in SDIs to date; the data types considered are feature objects and raster data. Their work introduced a new concept of geoprocessing patterns that suggest the application of processing functionality based on input data selected by the user of the application. The motivation behind this development is to assist users in deriving information from data. Their information system supports determination of river sinuosity as an indicator of the ecological quality of rivers, assessment of real estate values potentially affected by floods, and the discovery of observations made along rivers.

Stasch et al. (2018) present the semiautomatic processing of sensor observations in the context of water dam monitoring. An existing infrastructure makes sensor observations such as water levels and GPS measurements of dam structure available and the objective of their work is to statistically analyze the observations and use them as model inputs. Their motivation to use WPS is related to the possible reuse of services and flexibility regarding the integration of sensor observations from other sources in the final decision making. The coupling of sensor observation services (SOSs) with WPS is not a standard use case. Therefore, Stasch et al. (2018) discuss various approaches of coupling SOSs and WPS and selected a tight coupling approach in which a processing service can directly request observations from an SOS, which reduces overhead in communication. The authors also developed a REST API for WPS to reduce the required parsing of extensive XML files and ease client development; they provided the specification of a REST binding, which is lacking in the current WPS 2.0 standard.

Wagemann et al. (2018) present examples of the application of web coverage processing services in the context of big Earth data. They show how online geoprocessing supports the derivation of value-added products from data collections and how this technology transforms workflows. They state that server-side data processing can overcome issues using different solutions for data access and can minimize the amount of data transported on the web (Wagemann et al. 2018). They described examples of the application of WCPS in the domains of ocean science, Earth observation, climate science and planetary science; all of the examples use the rasdaman server technology. One of the presented applications for marine sciences provides a visual interface where a coverage of interest such as monthly values of chlorophyll concentration that were derived from ocean color satellite data can be specified (http://earthserver.pml.ac.uk/www). The provided coverage data can be compared with in situ measurements via a match-up tool. The match-up is calculated on the server and the users are presented with the results without having to download the chlorophyll data to their machines. The provider of this service must offer the required computing resources and the limitation of requests to a certain data volume is a known issue (Wagemann et al. 2018).

6.3.4 Research Challenges and Future Directions

Online geoprocessing technology has been improved over the last decade and the applications demonstrate its usability in real-world use cases. The potential of standardized web services lies in the flexible integration and reuse of services and computational power from different providers. However, in addition to the costs of service provision to potential clients, the *complexity* and *opacity* of geoprocessing workflows seem to hinder their mass usage. This is indicated by the fact that mapping services and data services are much more widely spread than processing services (Lopez-Pellicer et al. 2012). The reasons for this are manifold and relate to the variety of data models and formats, which limits the applicability of existing processing services (Wagemann et al. 2018), lacking descriptions of processing services such as those approached with WPS process profiles (Müller 2015) and the required transfer of potentially large data from a data provider to a service provider.

Assuming that geoprocessing services are available for reuse across applications, the most relevant current challenges concern the *opacity* of service, data and tool interfaces, and the corresponding lack of clarity about when a geocomputational service is potentially useful. Applying a geocomputational function is a matter of analytic purpose as well as of the properties of the data sources used. The latter goes well beyond data types and necessarily involves background knowledge about the semantics of spatial data (Hofer et al. 2017; Scheider et al. 2016). Thus, it was recognized early in the field of geocomputation that, in addition to syntactic interoperability (i.e., the matching of formats and data types), *semantic interoperability* must be taken into account (Ouksel and Sheth 1999; Bishr 1998). Since then, many attempts have been made to incorporate semantics into service descriptions, e.g., in the form of Datalog rules and types that restrict the application of geocomputational functions (Fitzner et al. 2011; Klien et al. 2006). The technology evolved as a particular (service-oriented) strand of the semantic web, starting in 2000 (Lara et al. 2004) and resulting in standards such as the semantic markup for web services (OWL-S) (https://www.w3.org/Submission/OWL-S/) and web service modeling language (WSML) (http://www.wsmo.org/).

Researchers of semantic web services have shown that service descriptions and Semantic Web technology can be effectively combined and that abstracting from particular implementations of geocomputational functions remains very difficult (Treiblmayr et al. 2012). Which aspects of such a function are mere technicalities? Which aspects are essential and thus should be represented on the semantic level of the service and data? More generally, what does a reusable representation that is valid across implementation specific details look like (Hofer et al. 2017)? The lack of a good answer to these questions in semantic web service research, e.g., in terms of a *reusable service ontology,* may be the reason why semantic web processing services have become less of a focus in research today. Drawing a line between semantic and syntactic interoperability is not straightforward, and different and incompatible "ontological" views on the world must be acknowledged (Scheider and Kuhn 2015). The need to infuse and reuse such flexible semantics in the age of big data has not lessened and is more urgent than ever (Janowicz et al. 2014; Scheider et al. 2017).

We currently lack *reusable representations* of the different views that make geoprocessing operations and data sources useful for a specific purpose. We also lack *neat theories* that tell us which concepts and aspects should be retained to describe data and geocomputational functions from the practical viewpoint of data analysis. Ontology design patterns have been proposed as a means to create such representations (Gangemi and Presutti 2009) and have recently gained popularity. Furthermore, it is an open question how geocomputational functions relate to the *purposes of analysis*. Finally, we need *computational methods* that allow for us to *infuse* the needed background knowledge into service and data descriptions to enable *publishing* and *exploiting* it.

Current research on semantic issues in geoprocessing tackles these challenges to support spatial analyses. We summarize three main lines of research that have evolved in recent years that may be promising for progress on a *semantically interoperable* Digital Earth:

6.3.4.1 Service Metadata, Computational Core Concepts, Linked Data and Automated Typing

In the current web processing service standards, to reuse a service it is necessary to describe the capabilities of the service and the service parameters (including data sources) in terms of metadata. However, the current metadata standards do not specify how to do this. It remains unclear which language and concepts should be used in these descriptions; it is also unclear how these concepts can be shared across communities of practice and how they can be automatically added without manual intervention. Regarding the first problem, several recent investigations attempted to identify a necessary and sufficient set of "core" concepts of spatial information (Kuhn 2012; Kuhn and Ballatore 2015; Scheider et al. 2016), which remain to be tested in diverse practical analytical settings. Regarding the second problem, linked open data (LOD) provides a way to remove the distinction between metadata and data, enabling us to publish, share and query data and its descriptions at the same time (Kuhn et al. 2014). Similarly, Brauner (2015) investigated the possibilities of describing and reusing geooperators with linked data tags on the web, and Hofer et al. (2017) discussed how such geooperator descriptions can be used for workflow development. Regarding the third problem, it has long been recognized that semantic labeling is a central automation task for the semantic web, as users tend to avoid the extra manual work involved. For this purpose, it has been suggested that the provenance information contained in workflows can be used to add semantic labels to the nodes in such a workflow (Alper et al. 2014). For the geospatial domain, it was demonstrated that the information contained in GIS workflows can be used to enrich geodata as well as GIS tools with important semantic types by traversing such a workflow, and share this information as linked data (Scheider and Ballatore 2018). Furthermore, certain semantic concepts such as the distinction between extensive and intensive attributes, which is central for geocomputation and cartography, can be automatically added as labels using machine learning classifiers (Scheider and Huisjes 2019).

6.3.4.2 From Service Chaining to Automated Workflow Composition

Automated service chaining has been a scientific goal and research topic since the start of the development of semantic web services (Rao and Su 2005). Ontologies are used to describe the restrictions on input and output types, which can be exploited by service chaining algorithms to suggest syntactically valid workflows. This idea has also been adopted for the geospatial domain (Yue et al. 2007), where the ontological concepts were mainly based on geodata types. However, in the wider area of workflow composition (Gil 2007; Naujokat et al. 2012), finding efficient composition algorithms is not the issue, finding the relevant semantic constraints that render the problem tractable is. Once such constraints are found, it is much easier to devise an algorithm that makes service composition computable for practical purpose, and it becomes possible to filter out syntactically valid but *nonmeaningful* workflows that are currently clogging the workflow composition flows (Lamprecht 2013). Thus, similar to the metadata challenge discussed above, scientific progress largely depends on whether we will be able to devise a set of reusable valid semantic concepts for both geocomputation and geodata. In the future, it would be valuable to measure the effectiveness of spatial semantic concepts in reducing computational time and increasing accuracy in automated GIS workflow composition.

6.3.4.3 From Geocomputation to (Indirect) Question Answering

Since the application of geocomputational tools and the chaining of services require lots of background knowledge and GIS skills, their usage is currently restricted to GIS experts. However, those with little or no technical expertise in this area would benefit most, as well as those with a *relevant spatial question* about Digital Earth. How can Digital Earth technology help such users answer their questions? Question-based spatial computation was proposed as a research topic by Vahedi et al. (2016) and Gao and Goodchild (2013). The question-answering (QA) computational technique has been investigated during the last two decades from the information retrieval perspective (Lin 2002). Standard QA technology parses a natural language question and matches it with answers available in a database or the web. Recently, linked data-based data cubes were proposed as a way to realize question answering on a web scale (Höffner et al. 2016). However, question answering for geocomputation and analysis requires handling questions that *do not yet have an answer* but could be answered using appropriate tools and data. The latter problem was therefore termed *indirect question answering* by Scheider et al. (2017). A semantically informed retrieval portal that can answer such questions should be able expand a data query in a way that encompasses data sets that do not directly answer a given query but can be made to do so via appropriate analysis steps. For this purpose, geocomputational tools and datasets need to be described by the questions they answer, so that they can match the questions posed by a user. A recent first step in developing such a system for a set of common GIS tools was made based on SPARQL query matching (Scheider et al. 2019), following the idea of query matching for service descriptions proposed by Fitzner et al. (2011). However, similar to the previous two computational challenges, the kinds of questions and the matching language and technology are dependent on our theories of spatial (interrogative) concepts used to formulate these questions. In the future, we should investigate what kinds of spatial questions are relevant and how they can be formally captured in terms of core concepts. For related work, refer to the ERC-funded project QuAnGIS: Question-based analysis of geographic information with semantic queries (https://questionbasedanalysis.com).

6.4 Distributed Geospatial Information Processing

6.4.1 The Concept of Distributed Geospatial Information Processing: What and Why

Distributed geospatial information processing (DGIP) (Yang et al. 2008; Friis-Christensen et al. 2009) refers to geospatial information processing (geoprocessing for short) in a distributed computing environment (DCE). With the development of the Internet and world wide web, architecture modes of software have changed dramatically. Decentralization and cross-domain collaboration under a loosely coupled and dynamically changed DCE has become an emerging trend. Adoption of service-oriented architecture (SOA) and cloud computing is a promising and prevalent solution for modern enterprises to enhance and rebuild their cyberinfrastructure. Using these technologies, it is more agile and much easier to build cooperation networks and adjust cross-enterprise business workflows dynamically.

Following this trend, geographical information systems (GISystems) are also experiencing an evolution from traditional stand-alone toolkits to web service-based ecosystems (Gong et al. 2012), e.g., the geospatial service web (GSW). The GSW is a conceptual framework for a loosely coupled geospatial collaboration network through which the end users can share and exchange geospatial resources and conduct geoprocessing online by using distributed geographical information services (GIServices). In the GSW, everything is encapsulated as a service (XaaS), as shown in Fig. 6.3, including computing resources (CPU, memory, storage and network, etc.), geospatial data, models, algorithms and knowledge. The wide adoption of the enabling technologies such as web services, SOA and cloud computing make such a distributed geospatial collaboration network possible but there are also challenges. One of the major challenges is how to guarantee the reliability of geoprocessing in a mutable DCE (Gong et al. 2012; Wu et al. 2015). Traditionally, geoprocessing is conducted on a single machine with a stand-alone GISystem toolkit installed. Since the functional components of a GISystem are tightly coupled, it is relatively easy to capture and handle geoprocessing exceptions and ensure the whole geoprocessing process, e.g., a workflow synthesized with coordinate transformation, buffering and overlay operations. In comparison, in a DCE, it is complicated to define, coordinate and guarantee such a process due to the complexities in data transmission, workflow control and exception handling.

Therefore, DGIP has become a research hotspot as well as an application trend (Yang et al. 2008; Wu et al. 2014; Jiang et al. 2017). In this section, we introduce the basic concept and key techniques of DGIP, and demonstrate its applications in Digital Earth. Finally, we discuss the technical challenges and future directions.

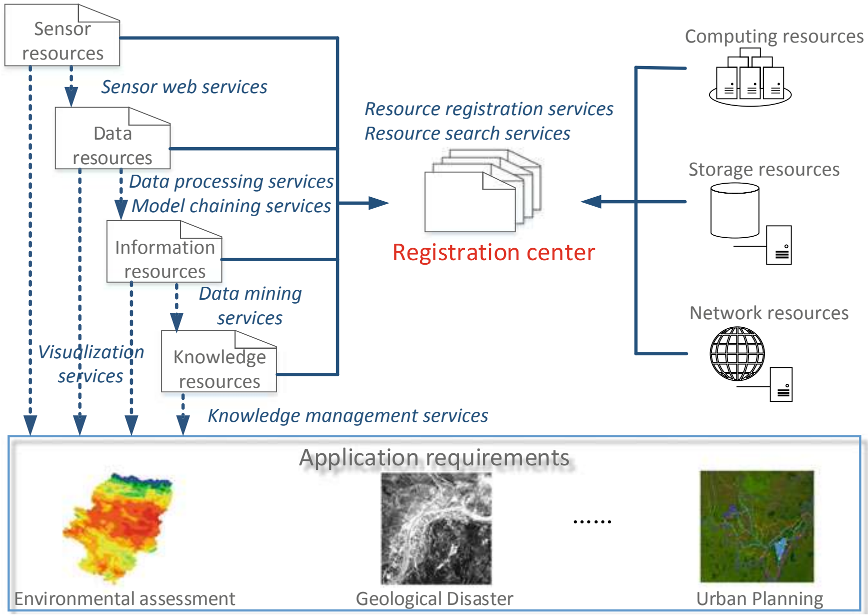

Fig. 6.3 The Conceptual framework of the geospatial service web (Gong et al. 2012)

6.4.2 Fundamental Concepts and Techniques

6.4.2.1 Collaboration Mode (Orchestration vs. Choreography)

For a distributed workflow to operate appropriately, the coordination and controlling mechanism is critical. In an SOA context, there are two basic collaboration modes (Peltz 2003), choreography and orchestration, based on the control flow patterns and how messages are exchanged, as illustrated in Fig. 6.4.

Web service orchestration (WSO) employs a centralized approach for service composition. A workflow is represented by a centralized coordinator that coordinates the interaction among different services. The coordinator or so-called composite service is responsible for invoking service partners, manipulating and dispatch messages. The relationships between the participating services are maintained by the coordinator. Since WSO adopts a hierarchical requester and responder model, it is process-centralized and the cooperation among participating services is weakened. The participating services do not need to know about each other in collaboration. In WSO, the status maintenance and error handling are relatively easier since it can be monitored and controlled by the coordinator. When an exception occurs, the coordinator can trigger exception handling or a compensation mechanism before the workflow progresses into the next step.

In comparison, web service choreography (WSC) adopts a decentralized peer-to-peer model. There is no a centralized compose service acting as the coordinator to

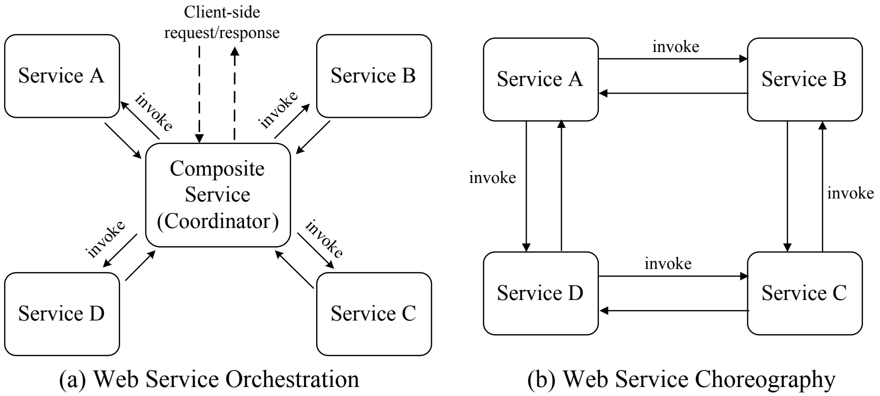

Fig. 6.4 Architectures of web service orchestration and web service choreography

control participating services, which makes it much more loosely coupled. The whole workflow is defined by exchanging messages, rules of interaction and agreements between services. Each participating service knows when and how to interact with each other, as well as whom to interact with, i.e., it is self-described and highly autonomous. One side effect is that it is difficult to detect errors in a timely manner and conduct exception handling from the workflow perspective. However, it can avoid the performance bottleneck problem for the coordinator in message exchange and data transmission.

In summary, the WSC describes the interactions between multiple services from a global view whereas WSO defines control from one party's perspective, and the control logic of the interactions between services is explicitly modeled in the composite service (Peltz 2003). Therefore, WSO is generally an intraorganization workflow modeling solution whereas WSC is more suitable for interorganizational or cross-domain workflow modeling when it is difficult to set up a centralized coordinator across the boundary of management.

Learning from service composition in the IT domain, the geospatial domain proposed the concept of a geospatial service chain, which is defined as a model for combining services in a dependent series to achieve larger tasks for supporting DGIP. According to the definition of international standard ISO 19119 (2002), there are three types of architecture patterns to implement a service chain, as illustrated in Fig. 6.5, by giving different controlling authorities to clients (Alameh 2003; ISO 19119 2002), i.e., user-defined chaining, workflow-managed chaining and aggregated chaining.

- In user-defined (transparent) chaining, the client defines and controls the entire workflow. In this case, the client discovers and evaluates the fitness of available services by querying a catalog service, which gives most freedom to the client to make the control decision and ask for workflow modeling knowledge.
- In workflow-managed (translucent) chaining, the workflow management service controls the service chain and the client is aware of the participating services. In

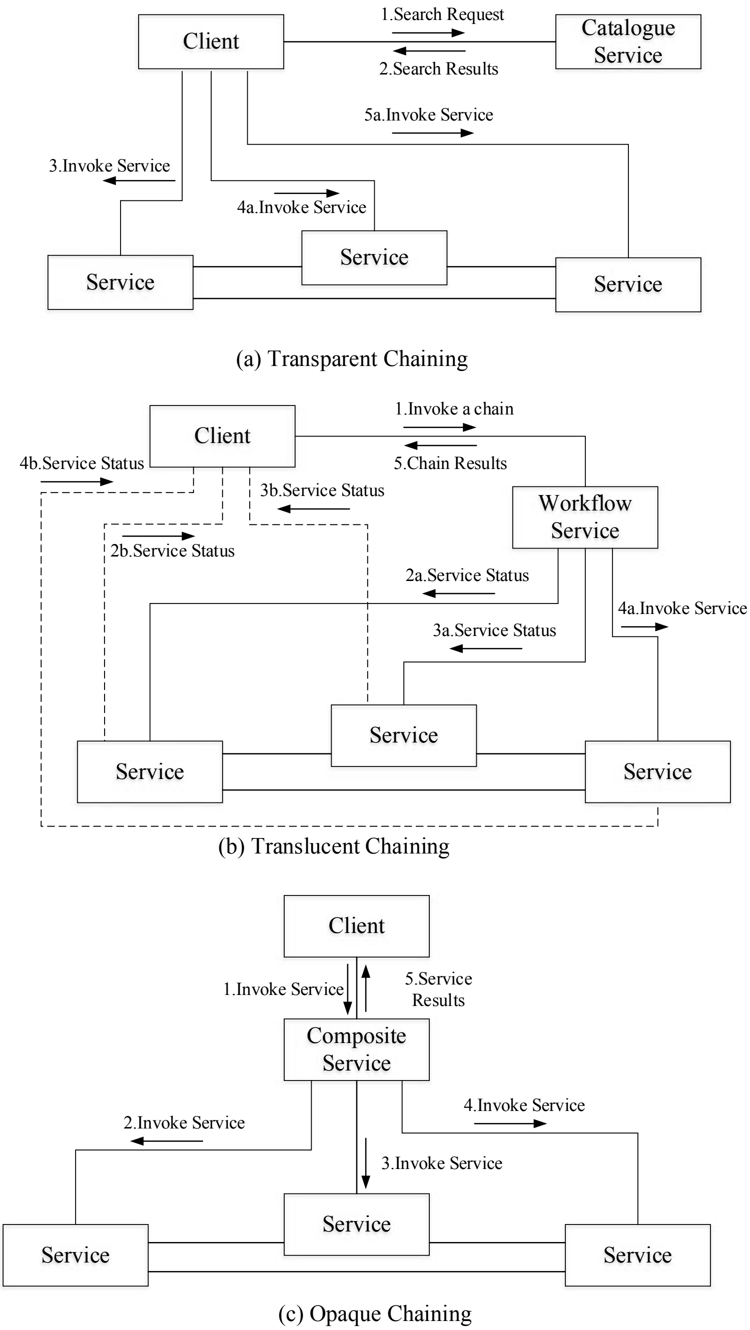

Fig. 6.5 Three architecture patterns for geospatial service chains defined in ISO 19119

this mode, the client can check the execution status of individual participating services, and the workload on workflow control is reduced.

- In aggregated service (opaque) chaining, the client invokes a compose service without awareness of the individual participating services. The compose service manages all the details of chain execution.

Although ISO 19119 gives the architecture patterns of service chaining, there is no de facto domain-specific standard on modeling language. The modeling languages of web service composition introduced in the next section use service chain modeling as a reference.

6.4.2.2 Workflow Modeling Language

A formalized model description language is desired to allow for a service chain be understood and shared among heterogeneous systems. Computer-aided business process management (BPM) has been widely used in modern enterprises for decades. Due to the variety of the backend IT enabling technologies and application scenarios, there are hundreds of workflow languages developed by different communities. These languages have different capabilities for flow rule expression (Aalst et al. 2003). In general, the languages can be classified into industrial specifications and academic models (Beek et al. 2007).

Industrial workflow specifications are model languages that target a certain technique implementation, and are widely supported by companies and standardization organizations. Web services business process execution language (WS-BPEL) and web service choreography description language (WSCDL) are two workflow standards specialized for web service composition. There are many open-source and commercial toolkits for reliable workflow modeling and execution management based on these specifications. However, these specifications are usually mixed with lower-level techniques such as XML encoding, XQuery, SOAP, WSDL and WS-addressing. These technical details increase the learning curve for users that lack or have little background knowledge of programming and web service standards. Workflow Management Coalition (WfMC) created an XML-based process definition language (XPDL) to store and exchange workflow models defined by different modeling language that is independent of concrete implementation techniques. XPDL is considered one of the best solutions to formally describe workflow diagrams defined using business process modeling notation (BPMN).

Academic workflow models express abstract process structures and rules that are not bound by a concrete runtime environment, lower-level implementation details and protocols (Beek et al. 2007; Gui et al. 2008), e.g., automata and process algebras. Directed graph and mathematical notations are widely used for workflow description, e.g., Petri nets (Hamadi and Benatallah 2003). Academic workflow models can express abstract process knowledge and have strict mathematical logics for process validation. However, these models are less used in industrial environments, and software to support workflow modeling and runtime management is lacking.

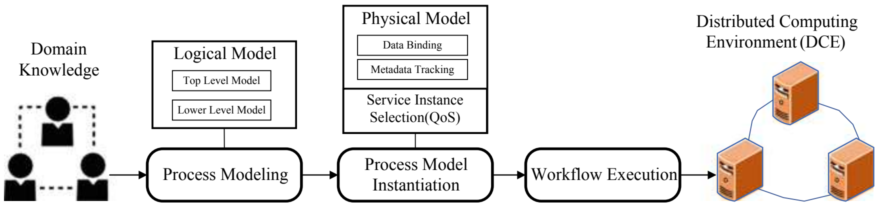

Fig. 6.6 A multistage geospatial service chaining process

In terms of geospatial service chaining, there is no well-accepted model language and domain-specific modeling methods should be developed. The European Space Agency (ESA) adopted WS-BEPL and established a service partner network to support global collaboration on earth observation. WS-BPEL is a de facto and widely used standard of the Organization for the Advancement of Structured Information Standards (OASIS) derived from the combination of IBM's Web Services Flow Language (WSFL) and Microsoft's notation language for business process design (XLANG). However, the lower-level technique details in WS-BPEL may be beyond the expertise of domain experts without web service knowledge. WS-BPEL adopts static binding to specify service partners and communication rules in advance and makes it difficult to adopt a dynamic and mutable environment. Therefore, a multistage geospatial service chaining method is highly desired to separate abstract geoprocessing workflow knowledge and lower-level implementation details, and make service partner binding dynamic, as illustrated in Fig. 6.6.

As shown in Fig. 6.6, Di et al. (2006) divided geospatial service chaining process into three steps, geoprocessing modeling, geoprocessing model instantiation and workflow execution. In the processing modeling stage, geoscience domain experts use a logical model language to depict abstract geoprocessing workflows based on process knowledge. In the process model instantiation stage, the logical model is mapped into a physical model that binds with implementation details. The data sources of the input data and service instances of participating services are specified during instantiation. Then, the physical model can be deployed into a workflow engine for workflow execution and runtime management.

6.4.3 Application Supporting Digital Earth

6.4.3.1 Development of Geospatial Workflow Modeling Languages and Tools

Based on the concept of multistage geospatial service chaining, various model languages have been proposed and modeling platforms have been developed. Chen et al. (2009) defined a geospatial abstract information model (AIM) language to describe logical models, which can be considered a new virtual geospatial product for process knowledge sharing and reuse. A logical model has a directed graph expression as well as an XML presentation that can be instantiated and translated into an executable WS-BPEL model for reliable execution management. By adopting such technologies, Di (2004) developed GeoBrain, a geospatial knowledge building system based on web service technologies, to automate data discovery and facilitate geoprocessing workflow modeling. Gui et al. (2008) also proposed an abstract geospatial service chain model language, DDBASCM, by combining data-dependency directed graph and block structures. In DDBASCM, the data flow is represented using a directed graph structure, and the control flow and aggregated service are depicted as block structures by learning from the concept of a transition-bordered set in Petri Net. Based on DDBASCM and WS-BPEL, a geospatial web service chain visual modeling and execution platform called GeoChaining was developed, which integrates catalog-based geospatial resource searching, service chain visual modeling, execution status monitoring and data visualization (Wu et al. 2011, 2014). Sun et al. (2012) developed a task-oriented geoprocessing system called GeoPWTManager to design, execute, monitor and visualize the workflow. In GeoPWTManager, the entire modeling and execution process is ensured by the collaboration of three components, i.e., a task designer, a task executor and a task monitor. Based on GeoPWTManager, GeoJModelBuilder, an open source geoprocessing workflow tool, was developed by leveraging open standard, sensor web, geoprocessing service and OpenMI-compliant models (Jiang et al. 2017).

Although implementation technologies are continuously evolving and new tools will be developed, the demand for development of a domain-specific workflow modeling language that can explicitly describe the terminologies and geoprocessing knowledge in the geospatial domain is still high. Cloud-based services that integrate online resource discovery, visualization, automatic/semiautomatic modeling, model sharing and reuse will be a trend to facilitate DGIP workflow modeling and execution management.

6.4.3.2 Digital Earth Applications

Geospatial service chaining provides an agile and loosely coupled approach to arrange the cooperation of dispersed GIServices to achieve DGIP. Based on the aforementioned technologies and platforms, DGIP-supported earth science applications have been developed. For example, the ESA created a net primary productivity (NPP) workflow in its online collaboration platform, Service Support Environment (SSE), for repeatable estimates of the net flux of carbon over user-specified AOI areas using SPOT vegetation S10 data. There are also more than 30 DGIP workflow-based applications provided by 23 service partners from 10 countries, including for oil spill detection, fire risk, Kyoto protocol verification, desert locusts, land use, snow cover, tidal currents, and multiple catalog access. In GeoBrain, many DGIP workflow models have been developed based on the proposed logical modeling language. A landslide susceptibility model (Chen et al. 2009) that integrates terrain slope and aspect analysis services as well as landslide susceptibility analysis services has been used to analyze landslide susceptibility in California, USA. GeoChaining (Wu et al. 2014) also provides workflow models by integrating third-party developed GIServices such as OpenRS (Guo et al. 2010) and GIServices developed by encapsulating the open-source GIS tool GRASS (https://grass.osgeo.org). A flood analysis model was developed to analyze flooding in the Boyang Lake area using remote sensing data before a flood, during flooding and after flooding. By developing web-based human-computer interaction interfaces using Rich Internet Application (RIA) technologies, workflow models involving human participation have also been developed in GeoSquare for educational and research purposes (Wu et al. 2015; Yang et al. 2016), including remote sensing image geometrical rectification and classification. Through integration with NASA world wind, GeoJModelBuilder (Jiang et al. 2017) also provides many hydrological models such as for water turbidity, watershed runoff, and drainage extraction.

In addition to applications comprised of geospatial service chaining, there are other forms of DGIP. For example, volunteer computing (VC) is a type of distributed computing that incorporates volunteered computing resources from individual persons and organizations. The VC usually adopts middleware architecture containing a client program that is installed and running on volunteer computers. VC has been successfully applied to many scientific research projects such as SETI@home (https://setiathome.berkeley.edu) and Folding@home(https://foldingathome.org). In the earth science domain, NASA launched a VC project named Climate@home to create a virtual supercomputer to model global climate research. This project utilizes worldwide computing resources to establish accuracy models for climate change prediction (Li et al. 2013).

Various applications have been developed, and the potential application scenarios are unlimited. As more GIServices for geoprocessing and big data analysis are developed using cloud computing and VC technologies, more interdisciplinary applications in earth science and social science will be developed.

6.4.4 Research Challenges and Future Directions

6.4.4.1 Communication Mechanism and Code Migration

Optimized network communication is critical for efficient and reliable DGIP because it relies on network communication for data transmission and service collaboration. The simple object access protocol (SOAP) is a widely used messaging protocol for exchanging information and conducting remote procedure calls (RPCs) in DCE using multiple lower-level transportation protocols such as HTTP, SMTP and TCP. SOAP is extensible to support functions such as security, message routing and reliability by compositing with web service specifications. SOAP supports multiple message exchange patterns (MEPs) such as one-way messages, request/respond mode and asynchronous messages. However, SOAP is not efficient in encoding due to its XML-based hierarchical envelope structure, for example, when transmitting vector data represented in GML or a raster image formatted using base64 binary encoding. As a result, SOAP message transmission optimization technologies have been developed. Binary data code can be sent as multipart MIME documents in SOAP attachments, and XML-binary Optimized Packages (XOP) provide a reliable approach to refer external data in the SOAP messaging, as proposed in SOAP standard version 1.2.

The development of HTTP Representational State Transfer (RESTful) (Fielding 2000) brings new challenges for DGIP. The RESTful architecture style has been widely adopted in web application development (Pautasso et al. 2008). OGC GIService standards use RESTful APIs as the major interoperating approach. Considering this trend, service composition technologies and tools should support RESTful services. Compared with SOAP, RESTful is lightweight and stateless, but the security, routing and reliable message transmission are weakened. Therefore, making DGIP reliable and secure has become critically important. Robust flow control, exception handling and compensation mechanisms must be developed for both the workflow engine and the participating services.

Communication issues have also inspired new ideas and research directions. Geoprocessing usually involves a large data volume and intensive geo-computation. The intensive data transmission increases the workload of the network infrastructure, as well as those of the participating services and workflow coordinator, and makes time efficiency a troublesome issue. To improve the user experience for DGIP, an asynchronous execution status-tracking method has been developed (Wu et al. 2014). Version 2.0 of the OGC web processing service (WPS) standard officially supports asynchronous execution of geoprocessing by the conjunction of *GetStatus* and *GetResult* operations. The *GetStatus* operation provides status information of a processing job for query, and *GetResult* allows for the client to query the result of a processing job. Through an asynchronous mechanism, a geoprocessing workflow engine can actively and instantly push the latest execution status of dispersed services to clients. Data transmission may also introduce data security risks, especially for classified or sensitive data. As the volume of software programs may be much smaller than the data volume, researchers proposed the idea of code migration. However, it is not easy to migrate code in heterogeneous systems due to the complex dependency of software packages. VC provides an alternative solution by installing a specified client to set up a unified runtime environment, e.g., BOINC (https://boinc.berkeley.edu). This problem is eliminated in a clustered computing environment because the computing nodes are equipped with the same operating system and distributed computing framework and thus the code can be migrated smoothly. For example, the high-performance frameworks introduced in Sect. 6.2, e.g., Apache Hadoop and Spark, migrate codes to computing nodes according to the locality of the dataset in the distributed file system to avoid IO overhead and optimize computing performance.

6.4.4.2 Quality-Aware Service Chain Instantiation

As global providers deliver more GIServices with similar functions but diverse quality, it has become challenging to select appropriate service instances from similar service candidates. To enable quality-aware service chain instantiation, quality evaluation methods and mathematical planning methods must be developed (Hu et al. 2019b). Quality evaluation assesses the fitness of individual participating services or aggregated services according to user quality requirements, and mathematical planning assists the service instance selection for each individual participating service by considering the overall quality of the service chain.

Multiple quality dimensions such as time efficiency and reliability must be leveraged to evaluate the quality of a participating service. Operations research methods such as multiple attribute decision making (MADM) and the analytic hierarchy process (AHP) provide solutions for quality dimension integration (Zeng et al. 2003). However, the control-flow and data-flow structures must be considered to determine the aggregated quality of a service chain (Jaeger et al. 2004).

In terms of service chaining, quality metrics have different aggregation behaviors under different flow structures (Aalst et al. 2003). For example, the total response time of a service chain with a sequential control-flow structure is the sum of the response times of all the participating services, and the total reliability is calculated by multiplying the availability of all the participating services. Quality computation can be more complicated in service chains with nested flow structures. If only the quality status of participating services is considered and the workflow structure is ignored, then the overall optimization of a service chain cannot be guaranteed (Jaeger et al. 2004; Gui et al. 2009; Hu et al. 2019a, b), especially when multiple quality metrics must be balanced.

To support quality-aware geospatial service chain instantiation, sophisticated GIS-ervice selection methods must be developed. Mathematical programming approaches such as Linear Programming (LP) can be used in service chains (Zeng et al. 2003; Gui et al. 2009) with a limited number of participating services. When the scale of the service chain increases, these methods become less efficient due the computing complexity. Furthermore, LP can only provide one optimized solution in the planning stage, which may not be optimal when one of the quality metrics slightly changes, since service runtime and network environments are typically mutable. Evolutionary methods (Canfora et al. 2005) such as genetic algorithms and swarm intelligent algorithms provide strong search capabilities and robustness in dynamic situations (Jula et al. 2014) and can be applied for geospatial service chain optimization. Considering the nature of complex flow structures and high dimensions of the quality metrics of a geospatial service chain, more research on quality evaluation and GIService selection must be conducted.

6.4.4.3 Semantic-Aided Automatic Service Chaining

With the development of artificial intelligence (AI) and semantic web technologies, automatic service chaining has been a research hotspot for many years and is still evolving. The goal of automatic service chaining is to make the computer capable of discovering web service resources and automatically building the service chain according to the requirements and constraints of the end user. In contrast to quality-aware service chain instantiation, there is no logical model available in advance for automatic service chaining. Thus, the computer must build the logical chain and instantiate it upon domain knowledge and the timeliness of the service resources, i.e., whether the service instance or data provider is available or not. To achieve this goal, a formal description of knowledge is required. The development of semantic web, ontology web language (OWL) and domain ontologies facilitates GIService semantic markups. For example, ontology-based description languages and rule languages are used for semantic discovery and geospatial service chaining (Lutz and Klien 2006; Yue et al. 2009), including semantic markup for web services (OWL-S), web service modeling ontology (WSMO), description logics (DL) and first-order logic (FOL). GeoBrain provides a web-based semiautomatic chaining environment by allowing for end-users to participate in human-computer interaction during the backwards reasoning (Di 2004; Han et al. 2011). The degree of suitability for candidate workflows is calculated by using the semantic similarity to support semiautomatic chaining (Hobona et al. 2007).

Semantic-aided chaining approaches have been developed and verified in laboratory environments; however, more research must be conducted to make them feasible in real-world applications. Currently, semantic markups for describing content, functions or prerequisites lack in most online-accessible geospatial resources. In addition, spatial data infrastructures (SDIs) and geoportals such as GEOSS clearinghouse, Data.gov, and INSPIRE do not provide semantic-aware discovery functions. The challenges include determining how to provide a semantic-enabled metadata Registry Information Model (RIM) for GIService semantic description, retrieval and validation (Qi et al. 2016; Zhang et al. 2017). W3C semantic standards such as the resource description framework (RDF) and OWL-S provide promising solutions for describing domain knowledge, enabling intelligent and efficient service discovery. However, these semantic languages must be linked with existing metadata standards in global SDIs (Gui et al. 2013). From the chain modeling perspective, AI reasoning technologies require further development to enable automatic and intelligent chaining. The rapid development of knowledge graph and mining technologies may provide a potential solution, which has been widely adopted in domain knowledge modeling and reasoning (Lin et al. 2015). Furthermore, to conduct DGIP-supported geoscience data analysis using heterogeneous Earth observation and socioeconomic data, we need to establish and advocate for standardization of the Discrete Global Grid System (DGGS) (Mahdavi-Amiri et al. 2015). It is critically important to promote heterogeneous earth science data fusion and interoperability, and the related standards and data models should be integrated into global SDIs (Purss et al. 2017).

6.5 Discussion and Conclusion

Geospatial information processing and computing technologies are essential for Digital Earth, as they enable various Digital Earth applications by turning geospatial data into information and knowledge. By identifying the challenges of geospatial data manipulation in the big data era, including massive *volume*, *heterogeneous*, and *distributed*, this chapter introduced three population technologies for geospatial data processing: high-performance computing, online geoprocessing, and distributed geoprocessing. Each of the three technologies focuses on addressing a specific challenge, though there are some overlaps. High-performance computing primarily deals with the *volume* challenge by solving data- and computing-intensive problems in parallel. Online geoprocessing tackles the *heterogeneous* challenge through standardized and interoperable geospatial web services and web APIs. Distributed geoprocessing addresses the *distributed* challenge by processing geospatial data and information in a distributed computing environment. The fundamental concepts, principles, and key techniques of the three technologies were elaborated in detail. Application examples in the context of Digital Earth were also provided to demonstrate how each technology has been used to support geospatial information processing. Although the three technologies are relatively mature and have a broad range of applications, research challenges have been identified and future research directions are envisioned for each technology to better support Digital Earth.

For high-performance computing (Sect. 6.2), one research challenge and direction is to continue the efforts to parallelize existing serial algorithms in spatial database and spatial data mining functions considering the dependence and interactions between data and problem partitions. Another direction is to develop new parallel algorithms to mine geospatial big data in the network space instead of in Euclidean space, as many spatial processes and interactions often occur in the network space. The third direction is to explore new and efficient computing methods to identify patterns from massive volumes of geospatial data considering the spatial heterogeneity. For online geoprocessing (Sect. 6.3), the main challenge is the lack of opacity in the services, data, and tool interfaces. This hinders the interoperability among the diverse services and creates a challenge when a problem needs to be solved by processing multi-sourced data using different services and tools. One promising solution is to incorporate semantics into web services to increase the interoperability among heterogeneous resources. In semantic web service research, three research directions are envisioned to achieve a semantically interoperable and intelligent Digital Earth: linked data and automated typing, automated workflow composition, and question answering. For distributed geoprocessing (Sect. 6.4), one challenge arises from reliability and security concerns. More efforts are needed to ensure a reliable and secure distributed computing environment considering aspects of the flow control, exception handling, compensation mechanism, and quality-aware service chains. The large volumes of geospatial data also lead to challenges in moving distributed data to the processing tools/services. Although moving code to data (code migration) is a promising solution, further research is needed to migrate code among the heterogeneous systems due to the complex dependency of software packages. In addition, more efforts are needed to move semantic-aided automatic service chaining techniques from the laboratory environment to real-world applications.

Lastly, the Digital Earth reference framework (Fig. 6.1) aims to integrate heterogeneous data sources with a harmonious high-level data model of the Earth so that data can be handled seamlessly with different tools, protocols, technologies. Currently, most of the tools use the framework of traditional coordinate systems such as the geographic coordinate system based on the continuous latitude and longitude or the projected coordinate system that projects the curved Earth surface to a flat surface. Although the traditional coordinate systems have been successful, another reference framework called the discrete global grid system (DGGS, see Chap. 2 *Digital Earth Platforms* for more details) is considered better for data associated with the curved heterogeneous surface of the Earth (Sabeur et al. 2019). We believe that the DGGS will play an increasingly important role in geospatial information processing in the big data era because (1) the DGGS provides a single and relatively simple framework for the seamless integration of heterogeneous distributed global geospatial data from different sources and domains; (2) the DGGS works with high-performance computing to handle big data extremely well because data managed with the DGGS is already decomposed into discrete domains and can be processed in parallel; and (3) by providing a single framework, the DGGS benefits interoperability among different tools and geoprocessing technologies and is a promising solution to build a semantically interoperable Digital Earth. However, most available analysis tools are designed to work with the traditional reference framework. Thus, more efforts are needed to design and develop storage mechanisms, spatiotemporal indexes, computing algorithms, and big data computing platforms that are compatible with the DGGS framework.

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Chapter 7
Geospatial Information Visualization and Extended Reality Displays

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Abstract In this chapter, we review and summarize the current state of the art in geovisualization and extended reality (i.e., virtual, augmented and mixed reality), covering a wide range of approaches to these subjects in domains that are related to geographic information science. We introduce the relationship between geovisualization, extended reality and Digital Earth, provide some fundamental definitions of related terms, and discuss the introduced topics from a human-centric perspective. We describe related research areas including geovisual analytics and movement visualization, both of which have attracted wide interest from multidisciplinary communities in recent years. The last few sections describe the current progress in the

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use of immersive technologies and introduce the spectrum of terminology on virtual, augmented and mixed reality, as well as proposed research concepts in geographic information science and beyond. We finish with an overview of "dashboards", which are used in visual analytics as well as in various immersive technologies. We believe the chapter covers important aspects of visualizing and interacting with current and future Digital Earth applications.

Keywords Visualization · Geovisualization · User-centric design · Cognition · Perception · Visual analytics · Maps · Temporal visualization · Immersive technologies · Virtual reality · Augmented reality · Mixed reality · Extended reality

7.1 Introduction

A future, fully functional Digital Earth is essentially what we understand as a (geo)virtual reality environment today: A multisensory simulation of the Earth *as-is* and how it *could be*, so we can explore it holistically, with its past, present, and future made available to us in any simulated form we wish (Gore 1998; Grossner et al. 2008). The concept of Digital Earth can be associated with the emergence of the (recently popularized) concept of a 'digital twin', conceptualized as a digital replica of a physical entity. Although several researchers have expressed skepticism about the appropriateness and precision of the term 'digital twin' in recent publications (Batty 2018; Tomko and Winter 2019), it appears that the broad usage of the term refers to a reasonably rigorous *attempt* to digitally replicate real-world objects and phenomena with the highest fidelity possible. Such efforts currently exist for objects at microscales, such as a wind turbines, engines, and bridges; but they are also envisioned for humans and other living beings. A digital twin for an entire city is more ambitious and requires information on the interoperability and connectivity of every object. A true 'all containing' Digital Earth is still unrealized and is more challenging to construct. However, as Al Gore (1998) noted in his original proposal for a Digital Earth in 1998, **making sense** of the information a Digital Earth contains is even more difficult than its construction. A key capability that supports sensemaking is the ability to **visualize geospatial information**. There are countless ways to visualize geospatial information. For thousands of years, humankind has used maps to understand the environment and find our way home. Today, there are many visual methods for depicting real, simulated, or fictional geospatial 'worlds'.

This chapter provides an overview of key aspects of visualizing geospatial information, including the basic definitions and organization of visualization-related knowledge in the context of a future Digital Earth. As understanding related human factors is necessary for any successful implementation of a visualization within the Digital Earth framework, we include a section on cognition, perception, and user-centered approaches to (geo)visualization. Because we also typically pose and answer analytical questions when we visualize information, we provide an overview of visual analytics; paying special attention to visualizing and analyzing temporal phenomena including movement because a Digital Earth would be clearly incomplete if it only comprises static snapshots of phenomena. After this examination of broader visualization-related concepts, because we conceptualize Digital Earth as a virtual environment, we pay special attention to how augmented (AR), mixed (MR), and virtual reality (VR) environments can be used to enable a Digital Earth in the section titled "Immersive Technologies—From Augmented to Virtual Reality". The Digital Earth framework is relevant to many application areas, and one of the foremost uses of the framework is in the domain of urban science. This is unsurprising given that 55 percent of the population now live in urban areas, with the proportion expected to increase to two-thirds of the population by 2050 (United Nations Population Division 2018). Urban environments are complex, and their management requires many decisions whose effects can cause changes in other parts of the urban environment, making it important for decision makers to consider these potential consequences. One way of providing decision makers with an overview of urban environments is through dashboards. Therefore, we feature "dashboards" and discuss the current efforts to understand how they fit within the construct of Digital Earth. We finish the chapter with a few concluding remarks and future directions.

7.2 Visualizing Geospatial Information: An Overview

Cartography is the process by which geospatial information has been typically visualized (especially in the pre-computer era), and the science and art of cartography remain relevant in the digital era. Cartographic visualizations are (traditionally) designed to facilitate **communication** between the mapmaker and map users. As a new approach to making sense of geospatial information in the digital era, specifically in the development of digital tools that help map readers interact with this information, the concept of **geovisualization** emerged (MacEachren 1994; Çöltekin et al. 2017, 2018) and widened our understanding of how maps could help make sense of a Digital Earth when used in an **exploratory** manner in addition to their role in communication. Thus, geovisualization is conceived as a process rather than a product, although the term is also commonly used to refer to any visual display that features geospatial information (maps, images, 3D models, etc.). In the geovisualization process, the emphasis is on information exploration and sensemaking, where scientists and other experts design and use "visual geospatial displays to explore data, and through that exploration to generate hypotheses, develop problem solutions and construct knowledge" (Kraak 2003a, p. 390) about a geographic location or geographic phenomenon. How these displays (and associated analytical tools) could be designed and used became a focus of scientific research within the International Cartographic Association's (ICA) *Commission on Visualization and Virtual Environments*, whose leaders described the term geovisualization as the "theory, methods and tools for visual exploration, analysis, synthesis, and presentation of geospatial data" (MacEachren and Kraak 2001, p. 3). Designing tools to support visualizing the geospatial information contained in a Digital Earth requires thinking about the data, representation of those data, and how users interact with those representations. Importantly, it requires the design of visual displays of geospatial information that can combine heterogeneous data from any source at a range of spatiotemporal scales (Nöllenburg 2007). To facilitate the ability to think spatially and infer spatiotemporal knowledge from a visualization, the visualization must also be usable, support users' tasks and needs, and enable users to interact with the data (Fuhrmann et al. 2005). Visualizations of geospatial data connect people, maps, and processes, "leading to enlightenment, thought, decision making and information satisfaction" (Dykes et al. 2005a, p. 4). Below, we describe three key areas of knowledge that support the design of visualizations with the goal of helping users make sense of the information that a Digital Earth contains. The **data** that are available for incorporation in a Digital Earth are increasingly heterogeneous and more massive than before. These complex, large datasets include both spatial and aspatial data, all of which must be combined, 'hybridized' (i.e., synthesized in meaningful ways), and **represented** within a visualization environment. Users expect to be able to visualize complex spatiotemporal phenomena to analyze and understand spatiotemporal dynamics and systems. To support them in this, considering **user interaction** and interfaces is necessary to develop and incorporate intuitive and innovative ways to explore visual displays. This is especially relevant to virtual and augmented reality, to facilitate exploration of data and experiencing spaces 'without hassle'.

Data A key goal of geovisualization is "to support and advance the individual and collective knowledge of locations, distribution and interactions in space and time" (Dykes et al. 2005b, p. 702). This remains a challenge due to increases in the diversity and quantity of data, users, and available visualization techniques and technologies (Griffin and Fabrikant 2012). The age of the data deluge (Bell et al. 2009) resulted in the generation of large quantities of spatial data (vector databases, maps, imagery, 3D models, numeric models, point clouds, etc.), as well as aspatial data (texts, stories, web data, photographs, etc.) that can be spatialized (Skupin and Buttenfield 1997). The 'covisualization' of those data together, such as in *multiple coordinated views* (or *linked* views, see Roberts 2007), is difficult due to their heterogeneity. This heterogeneity can be in the data's source, scale, content, precision, dimension, and/or temporality. The *visual integration* of such heterogeneous data requires the careful design of graphical representations to preserve the legibility of the data (Hoarau and Christophe 2017).

7.2.1 Representation

Bertin's seminal work (1967/1983) provides a conceptual framework, the visual variables, that allows for us to consider the graphical representation of geospatial information at a fundamental level (although it is important to note that Bertin's propositions were not evidence-based, it was rather based on intuition and qualitative reasoning). Originally, Bertin proposed seven variables: position, size, shape, color value, color hue, orientation, and texture. Later work extended Bertin's framework to include dynamic variables such as movement, duration, frequency, order, rate of change, synchronization, (Carpendale 2003; DiBiase et al. 1992; MacEachren 1995) and variables for 3D displays such as perspective height (Slocum et al. 2008), camera position, and camera orientation (Rautenbach et al. 2015). Visual variables remain relevant as a core concept of visualization research and have generated renewed interest in digital-era research questions, including in fields beyond geovisualization (e.g., Mellado et al. 2017). Notably, the information visualization community has also embraced Bertin's visual variables (e.g., Spence 2007). Visual complexity is a major challenge in designing representations of geospatial data, and innovative measures and analysis methods have been proposed to address this problem (Fairbairn 2006; Li and Huang 2002; MacEachren 1982; Schnur et al. 2010, 2018; Touya et al. 2016). Digital Earth's 'big data' challenges these efforts, stretching the capacity of existing tools to handle and process such datasets as well as the capacity of visualization users to read, understand, and analyze them (Li et al. 2016). One application area that is particularly afflicted by visual complexity is research on the urban and social dynamics that drive spatiotemporal dynamics in cities (Brasebin et al. 2018; Ruas et al. 2011). Developing approaches to represent spatiotemporal phenomena has been a long-standing challenge and many options have been investigated over the years (Andrienko and Andrienko 2006). Despite some progress, many questions remain (see the "Visualizing Movement" section). Some potential solutions such as using abstraction and schematization when visualizing urban datasets in Digital Earth can be found in the fields of data and information visualization (Hurter et al. 2018).

Another key aspect of visual representation design for geospatial data in Digital Earth applications involves how to deal with uncertainty. Uncertainty, such as that related to data of past or present states of a location or models of potential future states, remains difficult to represent in visual displays, and this is a major challenge for geovisualization designers. Which visual variables might aid in representing uncertainty? This question has been explored and tested to some degree (e.g., MacEachren et al. 2012; Slocum et al. 2003; Viard et al. 2011), although the majority of research has focused on developing new visualization methods rather than testing their efficacy (Kinkeldey et al. 2014). There are still no commonly accepted strategies for visualizing uncertainty that are widely applied. MacEachren (2015) suggests that this is because data uncertainty is only one source of uncertainty that affects reasoning and decision making and argues that taking a visual analytics approach (see the "Geovisual Analytics" section) might be more productive than a communication approach. Hullman (2016) notes the difficulty of evaluating the role of uncertainty in decision making as a major barrier to developing empirically validated techniques to represent uncertainty.

7.2.2 User Interaction and Interfaces

Since geovisualization environments are expected to provide tools and interaction modalities that support data exploration, user interaction and interface design are important topics for geovisualization. The visual display is an interface for the information, so users need effective ways to interact with geovisualization environments. Interaction modalities in geovisualization environments are ideally optimized or customizable for the amount of data, display modes, complexity of spaces or phenomena, and diversity of users (e.g., Hoarau and Christophe 2017). Interaction tools and modalities are a core interest in human-computer interaction (e.g., Çöltekin et al. 2017) and, in connection with visualization, they are often investigated with concepts explored in the information visualization domain (Hurter 2015; van Wijk and Nuij 2003), among others. Interaction and how it is designed are especially relevant for virtual and augmented reality approaches to visualization (see the "Immersive Technologies—From Augmented to Virtual Reality" section). Some form of interaction is required for most modern 2D displays, and it has a very important role in supporting exploration tasks, but seamless interaction is a necessity in a virtual or augmented world. Without it, the immersiveness of the visualization—a critical aspect of both VR and AR—is negatively affected. One approach that is notably at the intersection of representation design and user interaction design is a set of methods that are (interactively) nonuniform or space-variant. An example is displays in which the resolution or level of detail varies across the display in real time according to a predefined criterion. The best known among these nonuniform display types are the focus + context and fisheye displays (dating back to the early 1990s, e.g., see Robertson and Mackinlay 1993). Both the focus + context and fisheye displays combine an overview at the periphery with detail at the center, varying the level of detail and/or scale across a single display. A variation on the focus + context display has been named "context-adaptive lenses" (Pindat et al. 2012). Conceptually related to these approaches, in gaze-contingent displays (GCDs), the level of detail (and other selected visual variables) is adapted across the display space based on where the user is looking. This approach draws on perceptual models of the visual field, mimicking the human visual system. GCDs were proposed as early as the 1970s (see, e.g., Just and Carpenter 1976) and have continued to attract research interest over time as the technology developed (e.g., Bektas et al. 2015; Duchowski and Çöltekin 2007; Duchowski and McCormick 1995). For more discussion of "interactive lenses" in visualization, see the recent review by Tominski et al. (2017). Various other space-variant visualization approaches have been proposed in which, rather than varying the scale or level of detail, the levels of realism or generalization are varied across the display to support focus + context interactions with the data. These approaches aim to smoothly navigate between data and its representation at one scale (e.g., Hoarau and Christophe 2017), between different levels of generalization across scales (e.g., Dumont et al. 2018), or between different rendering styles (Boér et al. 2013; Semmo and Döllner 2014; Semmo et al. 2012). Mixed levels of realism have been proposed for regular maps used for data exploration purposes (Jenny et al. 2012) as well as for VR. In VR, egocentric-view-VR representations with selective photorealism (a mix of abstract and photorealistic representations) have been tested in the context of route learning, memory, and aging and have been shown to benefit users (Lokka et al. 2018; Lokka and Çöltekin 2019).

Decisions on how to combine data to design representations and user interactions should be informed by our understanding of how visualization users process visual information and combine it with their existing knowledge about the location or phenomenon to make sense of what they see. Thus, building effective visualizations of geospatial information for a Digital Earth requires an understanding of its **users**, their capabilities and their constraints, which we describe in the next section.

7.3 Understanding Users: Cognition, Perception, and User-Centered Design Approaches for Visualization

A primary way that humans make sense of the world—the real world, an "augmented world" with additional information overlaid, or a virtual word (such as a simulation)—is by making sense of what we see. Because vision is so important to human sense-making, visualizations are major facilitators of that process and provide important support for cognition. When effectively designed, visualizations enable us to externalize some of the cognitive burden to something we can (re)utilize through our visual perception (Hegarty 2011; Scaife and Rogers 1996). However, our ability to *see* something—in the sense of *understanding* it—is bounded by our perceptual and cognitive limits. Thus, any visualizations we design to help work with and understand geospatial information must be developed with the end user in mind, taking a **user-centered design (UCD)** approach (Gabbard et al. 1999; Huang et al. 2012; Jerald 2015; Lloyd and Dykes 2011; Robinson et al. 2005). A UCD approach is useful for understanding perceptual and cognitive limits and for adapting the displays to these limits. It also helps to evaluate the strengths of new methods of interacting with visualizations (Roth et al. 2017). For example, a user-centered approach has been used to demonstrate that an embodied data axis aids in making sense of multivariate data (Cordeil et al. 2017). Similarly, UCD was useful in determining which simulated city environments lead to the greatest sense of immersion to support participatory design processes for smart cities (Dupont et al. 2016), assuming that immersion has a positive effect in this context.

7.3.1 Making Visualizations Work for Digital Earth Users

7.3.1.1 Managing Information

As briefly noted earlier, a key benefit—and a key challenge—for visualization in the Digital Earth era is related to the amount of data that is at our fingertips (Çöltekin and Keith 2011). With so much available data, how can we make sense of it all? What we need is the right information in the right place at the right time for the decisions we are trying to make or the activities we are trying to support. Thus, understanding the context in which information and visualizations of information are going to be used (Griffin et al. 2017)—what data, by whom, for what purpose, on what device—is fundamental to designing appropriate and effective visualizations. For example, ubiquitous sensor networks and continuous imaging of the Earth's surface allow for us to collect real-time or near real-time spatial information on fires and resources available to fight fires, and firefighters would benefit from improved situation awareness (Weichelt et al. 2018). However, which information should we show them, and how should it be shown? Are there environmental factors that affect what information they can perceive and understand from an AR system that visualizes important fire-related attributes (locations of active burns, wind speed and direction) and firefighting parameters (locations of teammates and equipment, locations of members of the public at risk)? How much information is too much to process and use effectively at a potentially chaotic scene?

A great strength of visualization is its ability to abstract: to remove detail and to reveal the essence. In that vein, realism as a display principle has been called "naive realism" because realistic displays sometimes impair user performance but users still prefer them (e.g., Lokka et al. 2018; Smallman and John 2005). The questions of how much abstraction is needed (Boér et al. 2013; Çöltekin et al. 2015) and what level of realism should be employed (Brasebin et al. 2018; Ruas et al. 2011) do not have clear-cut answers. In some cases, we need to follow the "Goldilocks principle" because too much or too little realism is suboptimal. As Lokka and Çöltekin (2019) demonstrated, if there is too much realism, we may miss important details because we cannot hold all the details in our memory whereas if there is too little, we may find it difficult to learn environments because there are too few 'anchors' for the human memory to link new knowledge of the environment. These issues of how to abstract data and how it can be effectively visualized for end users are growing in the era of big data and Digital Earth.

7.3.1.2 Individual and Group Differences

Nearly two decades ago, Slocum et al. (2001) identified individual and group differences as a research priority among the many "cognitive and usability issues in geovisualization" (as the paper was also titled). There was evidence prior to their

2001 paper and has been additional evidence since then that humans process information in a range of ways. Such differences are often based on expertise or experience (e.g., Griffin 2004; Çöltekin et al. 2010; Ooms et al. 2015) or spatial abilities (e.g., Liben and Downs 1993; Hegarty and Waller 2005), and are sometimes based on age (Liben and Downs 1993; Lokka et al. 2018), gender (Newcombe et al. 1983); culture (Perkins 2008), confidence and attitudes (e.g., Biland and Çöltekin 2017), or anxiety (Thoresen et al. 2016), among other factors. For brevity, we do not expand on the root causes of these differences, as this would require a careful treatment of the "nature vs. nurture" debate. We know that many of the shortcomings people experience can be remedied to different degrees based on interventions and/or training. For example, spatial abilities, as measured in standardized tests, can be enhanced by training (Uttal et al. 2013), and expertise/experience and education affect the ways that people process information (usually in improved ways, but these forms of knowledge can also introduce biases). Many of the above factors could be considered cognitive factors and might be correlated in several ways. A key principle arising from the awareness that individuals process information differently and that their capacities to do so can vary (whatever the reason) is that the "*designer is not the user*" (Richter et al. 2015, p. 4). A student of geovisualization (we include experts in this definition) is a self-selected individual who was likely interested in visual information. With the addition of education to this interest, it is very likely that a design that a geovisualization expert finds easy-to-use (or "user friendly", a term that is used liberally by many in the technology sector) will not be easy-to-use or user friendly for an inexperienced user or a younger/older user.

7.3.1.3 Accessibility

Related to the individual and group differences as described above, another key consideration is populations with special needs. As in any information display, visualization and interaction in a geovisualization software environment should ideally be designed with accessibility in mind. For example, visually impaired people can benefit from multimedia augmentation on maps and other types of visuospatial displays (Brock et al. 2015; Albouys-Perrois et al. 2018). Another accessibility issue linked to (partial) visual impairment that is widely studied in geovisualization is color vision impairment. This is because color is (very) often used to encode important information and color deficiency is relatively common, with up to eight percent of the world's population experiencing some degree of impairment (e.g., Brychtová and Çöltekin 2017a). Because it is one of the more dominant visual variables (Garlandini and Fabrikant 2009), cartography and geovisualization research has contributed to color research for many decades (Brewer 1994; Brychtová and Çöltekin 2015; Christophe 2011; Harrower and Brewer 2003). Two of the most popular color-related applications in use by software designers were developed by cartography/geovisualization researchers: ColorBrewer (Harrower and Brewer 2003) for designing/selecting color palettes and ColorOracle (Jenny and Kelso 2007) for simulating color blindness. Color is a complex and multifaceted phenomenon even for those who are not affected by color vision impairment. For example, there are perceptual thresholds for color discrimination that affect everyone (e.g., Brychtová and Çöltekin 2015, 2017b), and how colors are used and organized contributes to the complexity of maps (e.g., Çöltekin et al. 2016a, b). Color-related research in geographic information science also includes examination of the efficacy of color palettes to represent geophysical phenomena (Spekat and Kreienkamp 2007; Thyng et al. 2016) or natural color maps (Patterson and Kelso 2004). We include color in the above discussion because it is one of the strongest visual variables. However, color is not the only visual variable of interest to geovisualization researchers. Many other visual variables have been examined and assessed in user studies. For example, the effects of size (Garlandini and Fabrikant 2009), position, line thickness, directionality, color coding (Monmonier 2018; Brügger et al. 2017), shading, and texture (Biland and Çöltekin 2017; Çöltekin and Biland 2018) on map reading efficiency have been examined.

It is not possible to provide an in-depth review of all the user studies in the geovisualization domain within the scope of this chapter. However, it is worth noting that if a design maximizes accessibility, the users benefit and the (consequently) improved usability of visuospatial displays enables other professionally diverse groups to access and create their own visualizations: for example, city planners, meteorologists (e.g., Helbig et al. 2014) and ecoinformatics experts (e.g., Pettit et al. 2010), all of which are support systems of a 'full' future Digital Earth.

7.4 Geovisual Analytics

The science of analytical reasoning with spatial information using interactive visual interfaces is referred to as **geovisual analytics** (Andrienko et al. 2007; Robinson 2017). This area of GIScience emerged alongside the development of **visual analytics**, which grew out of the computer science and information visualization communities (Thomas and Cook 2005). A key distinction of geovisual analytics from its predecessor field of geovisualization is its focus on support for analytical reasoning and the application of computational methods to discover interesting patterns from massive spatial datasets. A primary aim of geovisualization is to support data exploration. Geovisual analytics aims to go beyond data exploration to support complex reasoning processes and pursues this aim by coupling computational methods with interactive visualization techniques. In addition to the development of new technical approaches and analytical methods, the science of geovisual analytics also includes research aimed at understanding how people reason with, synthesize, and interact with geographic information to inform the design of future systems. Progress in this field has been demonstrated on each of these fronts, and future work is needed to address the new opportunities and challenges presented by the big data era and meeting the vision proposed for Digital Earth.

7.4.1 Progress in Geovisual Analytics

Early progress in geovisual analytics included work to define the key research challenges for the field. Andrienko et al. (2007) called for decision making support using space-time data, computational pattern analysis, and interactive visualizations. This work embodied a shift from the simpler goal of supporting data exploration in geovisualization toward new approaches in geovisual analytics that could influence or direct decision making in complex problem domains. Whereas the goal in geovisualization may have been to prompt the development of new hypotheses, the goal in geovisual analytics has become to prompt decisions and actions. To accomplish this goal, GIScience researchers began to leverage knowledge from intelligence analysis and related domains in which reasoning with uncertain information is required to make decisions (Heuer 1999; Pirolli and Card 2005). Simultaneously, there were efforts to modify and create new computational methods to identify patterns in large, complex data sources. These methods were coupled to visual interfaces to support interactive engagement with users. For example, Chen et al. (2008) combined the SaTScan space-time cluster detection method with an interactive map interface to help epidemiologists understand the sensitivity of the SaTScan approach to model parameter changes and make better decisions about when to act on clusters that have been detected. Geovisual analytics have been applied in a wide range of domain contexts, usually targeting data sources and problem areas that are difficult to approach without leveraging a combination of computational, visual, and interactive techniques. Domains of interest have included social media analytics (Chae et al. 2012; Kisilevich et al. 2010), crisis management (MacEachren et al. 2011; Tomaszewski and MacEachren 2012), and movement data analysis (Andrienko et al. 2011; Demšar and Virrantaus 2010). The following section on "Visualizing Movement" includes a deeper treatment of the approaches to (and challenges of) using visual analytics for dynamic phenomena.

A concurrent thread of geovisual analytics research has focused on the design and evaluation of geovisual analytics tools. In addition to the development of new computational and visual techniques, progress must also be made in understanding how geovisual analytics systems aid (or hinder) the analytical reasoning process in real-world decision making contexts (Çöltekin et al. 2015). Approaches to evaluating geovisual analytics include perceptual studies (Çöltekin et al. 2010), usability research (Kveladze et al. 2015), and in-depth case study evaluations of expert use (Lloyd and Dykes 2011). Additionally, new geovisual analytics approaches have been developed to support such evaluations (Andrienko et al. 2012; Demšar and Çöltekin 2017), as methods such as eye tracking are capable of creating very large space-time datasets that require combined computational and interactive visual analysis to be made sense of.

7.4.2 *Big Data, Digital Earth, and Geovisual Analytics*

The next frontier for geovisual analytics is to address the challenges posed by the rise of big spatial data. **Big data** are often characterized by a set of so-called *V's*, corresponding to the challenges associated with volume, velocity, variety, and veracity, among others (Gandomi and Haider 2015; Laney 2001). Broadly, geovisual analytics approaches to handling big spatial data need to address problems associated with analysis, representation, and interaction (Robinson et al. 2017), similar to the challenges faced by geovisualization designers. New computational methods are needed to support real-time analysis of big spatial data sources. Representations must be developed to render the components and characteristics of big spatial data through visual interfaces (Çöltekin et al. 2017). We also need to know more about how to design interactive tools that make sense to end users to manipulate and learn from big spatial data (Griffin et al. 2017; Roth et al. 2017).

The core elements behind the vision for Digital Earth assume that big spatial data will exist for every corner of our planet, in ways that support interconnected problem solving (Goodchild et al. 2012). Even if this vision is achieved (challenging as that may seem), supporting the analytical goals of Digital Earth will require the development of new geovisual analytics tools and techniques. Major issues facing humanity today regarding sustainable global development and mitigating the impacts of climate change necessarily involve the fusion of many different spatiotemporal data sources, the integration of predictive models and pattern recognition techniques, and the translation of as much complexity as is possible into visual, interactive interfaces to support sensemaking and communication.

7.5 Visualizing Movement

One of the most complex design issues in visualization is how to deal with dynamic phenomena. Movement is an inherent part of most natural and human processes, including weather, geomorphological processes, human and animal mobility, transport, and trade. We may also be interested in the movement of more abstract phenomena such as ideas or language. Although movement is a complex spatiotemporal phenomenon, it is often depicted on static maps, emphasizing *geographical* aspects of movement. In the context of visualization, "Digital Earth" implies use of a globe metaphor, where movement data is displayed on a globe that can be spun and zoomed (see Fig. 7.1). In this section, we review *map-based* representations of movement that can be used within a 3D globe-based immersive environment. Visual representations that do not emphasize geographical location (e.g., origin-destination matrices and various timeline-based representations) are less amenable to being used within a global immersive environment, though they may have a supporting role as multiple coordinated views.

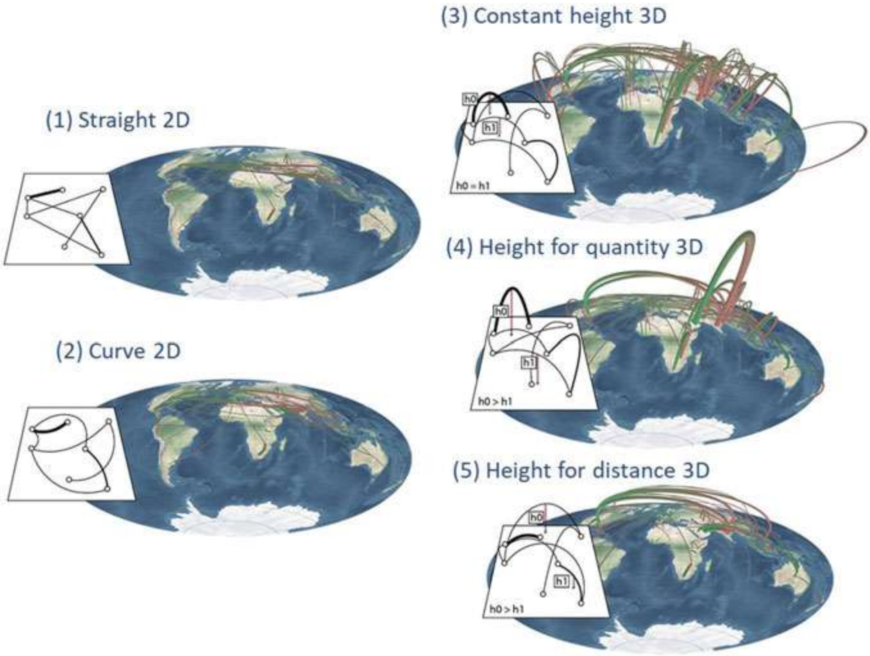

Fig. 7.1 Approaches to visualizing flows in a 3D immersive environment that were investigated by Yang et al. (2019). Figure is modified based on Yang et al. (2019) with permission from the original authors

Note that most techniques for visualizing movement on the Earth's surface were developed as *2D* representations. However, many of these representations can be placed on the surface of a 3D globe and we can identify where the 3D environment may offer benefits and disadvantages. Notably, one disadvantage is that 3D environments often result in occlusion, and this occlusion is only partially addressed through interaction (Borkin et al. 2011; Dall'Acqua et al. 2013). Below, we begin by visually depicting *individual* journeys and progressively review *aggregated* movement data representations, which are more scalable and can synthesize and reveal general movement patterns (the individual trajectories cannot).

7.5.1 Trajectory Maps: The Individual Journey

Individual journeys can be expressed as **trajectories** that represent the geometrical paths (routes) of objects through time as a set of timestamped positions. For example, if we were interested in migrating birds, GPS loggers attached to individual birds could produce trajectories (see Fig. 7.2 for an example). These may help understand the route taken, stop-overs, timing, and interactions between individuals. The detail

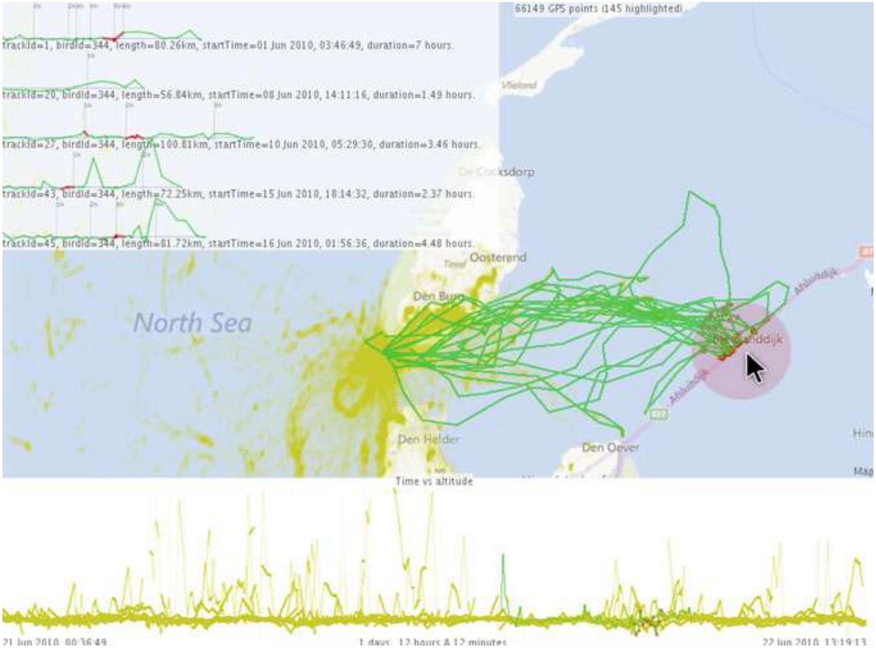

Fig. 7.2 A (green) subset of bird tracked trajectories filtered on the spatial region on the map indicated by the red circle linked to the mouse pointer. These trajectories are identified in green on the timeline below (time vs altitude), indicating when the journeys occurred, with five of the journeys shown at the top left (time vs distance, with hourly isochrones). Figure is modified, based on Slingsby and van Loon (2016) with permission from the original authors

with which the geometrical path is captured depends on the temporal resolution of the sampled locations. Trajectories can also be reconstructed by stringing together locations from other sensors, for example, from multiple cameras with automatic license plate recognition or from a set of georeferenced tweets from a single user. One aspect of trajectories that is often overlooked is how they are **segmented**, that is, where they start and stop over the course of the journey. For tracked animals, algorithms that segment trajectories based on position or time intervals during which where there is little movement are common (e.g., Buchin et al. 2011). In the example above (Fig. 7.2), the nest location was used to segment trajectories into foraging trips.

Trajectory maps depict individual movement by showing the geometrical traces of individual journeys on a map. Where there are few trajectories, trajectory maps can clearly illustrate specific journeys and facilitate visual comparison within an individual's journeys or between journeys undertaken by different individuals. An excellent book by Cheshire and Umberti (2017) uses a whole range of static visualization methods to illustrate the movements of various types of animals, including trajectory maps. As well as presenting movement traces, trajectory maps can be a useful precursor to more substantial and directed analyses (Borkin et al. 2011; Dall'Acqua et al. 2013).

Map-based representations emphasize the **geometry** of the path, and it can be difficult to use maps to determine **temporal** aspects of the trajectory, including direction and speed. One option is to use **animation**, which only displays the parts of trajectories that are within a moving temporal window. Although animation may be effective when presented as part of an existing narrative, it can be difficult to detect trends as it is hard to remember what came before (Robertson et al. 2008). Various user studies have investigated animation and its efficiency and effectiveness for spatiotemporal tasks, with mixed results. The current understanding is that animations can introduce too much cognitive load if the task requires comparisons, thus, animations must be used cautiously (Robertson et al. 2008; Russo et al. 2013; Tversky et al. 2002). So-called **small multiples** (a series of snapshots, see Tufte 1983) can be better than animations for some tasks. Another option that is similar to small multiples in the sense that all of the presented information is visible at all times or is easily on demand is the use of **multiple coordinated views** (briefly introduced above). With multiple coordinated views, a temporal representation of the movement is interactively linked to the map. When the mouse is "brushed" over parts of the trajectory on the map, corresponding parts on the timeline are identified and vice versa (as shown in Fig. 7.2). **Brushing** along the timeline has a similar effect as animation but is more flexible. Although trajectory maps can be good to represent relevant individual instances of journeys, they **do not scale well** to situations where there are more than a few trajectories. The effect of over plotting with multiple crossing lines often obscures patterns. Making trajectories **semitransparent** can help to some degree, as it emphasizes common sections of routes by de-emphasizing those that are less commonly used. Modifying the color hue—and/or other visual variables or symbols—can help **identify individuals** or **categories of journeys** (which might include the purpose of the journey or mode of transport). Hue typically does not facilitate distinguishing more than approximately ten individuals or categories, but **labels** and **tooltips** can provide such context. Sequential color schemes can indicate continuous numerical data along trajectories such as **speed** or **height** above the ground. Arrows or tapered lines can help show the direction of movement. To simplify displays, one can also attempt to simplify the underlying data rather than tweak the display design. Common approaches include **filtering trajectories** by various criteria, **considering only origin-destination pairs**, or **spatiotemporal aggregation** (we elaborate on these approaches below). Trajectory maps can also be shown in a **3D environment**. **Space-time cubes** (Hägerstrand 1970) are a form of 3D trajectory map (Andrienko et al. 2003; Kapler and Wright 2004; Kraak 2003b) where the *x*- and *y*-axes represent geographical coordinates and the ***z*-axis represents the progression of time** (see Fig. 7.3 for an example). As with trajectory maps, space-time cubes can indicate spatiotemporal aspects of small numbers of journeys. However, when more trajectories are added, the occluding effects can be even more severe than in 2D. Interactive rotation and zooming of the cube, highlighting trajectories, and interactive filtering can address the problematic effects of such occlusion but do not scale well to many trajectories.

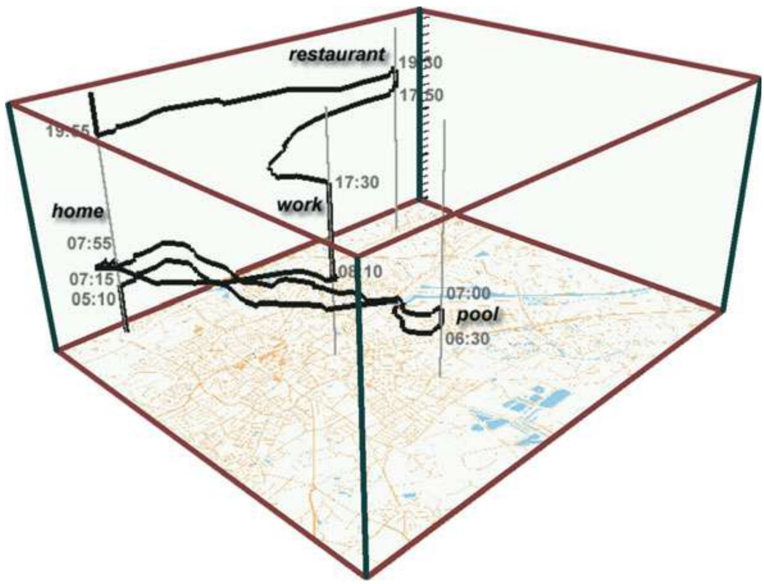

Fig. 7.3 A Space-Time Cube, showing a journey in which a person visits a pool, home, work, a restaurant and home. Figure based on Kraak (2008) with permission from the original author

In 3D representations, the ***z*-axis can also be used for nontemporal data**, which may create a conflict. Where trajectories define movement in 3D space, the z-axis can be used to represent a third spatial dimension, that is, it can be used to depict the **height above the ground**. There are also many opportunities to depict other characteristics of trajectories along the z-axis, as illustrated by the "trajectory wall" (Tominski et al. 2012) shown in Fig. 7.4.

Because the above approaches do not scale well when there are many trajectories, we must consider simplifying the data and display, such as by **filtering** the data. Notably, filtering serves *two* purposes. The first addresses the fact that trajectory maps do not scale well in situations in which there are more than a few trajectories. The second is to **identify multiple trajectories or groups of trajectories for comparison**. Tobler (1987) suggested **subsetting** and **thresholding** to reduce the number of trajectories on a single map. This involves filtering on the basis of characteristics of trajectories, such as using geographical (see Fig. 7.5 below) and temporal windows (see Fig. 7.7) through which trajectories can pass or filtering the trajectory's length, importance, or category. These are now routinely facilitated using interactive methods that support visual exploratory data analysis. Identifying multiple trajectories or groups of trajectories for comparison includes choosing representative trajectories for a set of people or different times of the day or different days of the week. This identification of trajectories may be manually achieved as part of an exploratory analysis or geovisualization approach and can be assisted by

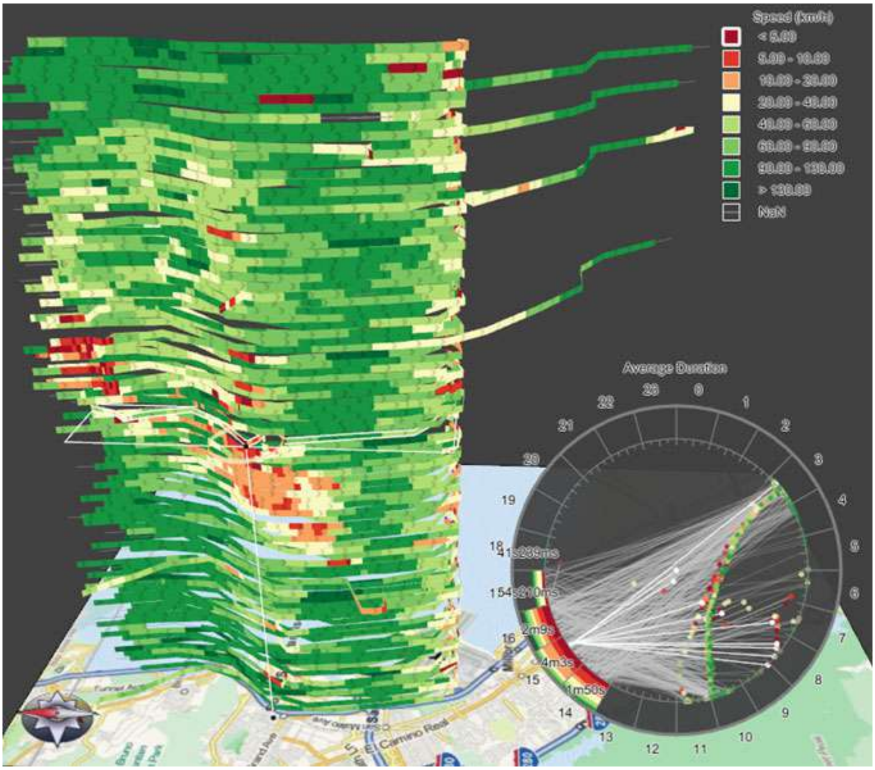

Fig. 7.4 "Trajectory wall" in which multiple (and sometimes time-varying) attributes are displayed vertically along a trajectory, based on Tominski et al. (2012), with permission from the original authors

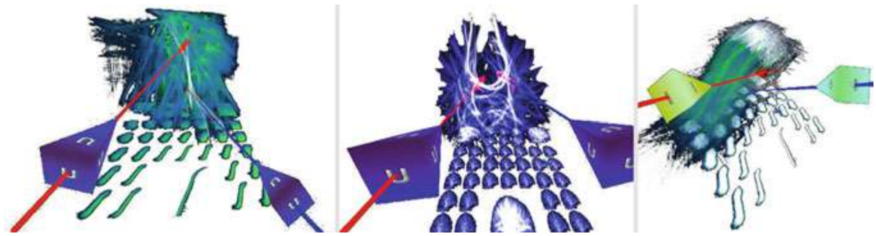

Fig. 7.5 Hurter et al.'s (2018) interactions in a 3D immersive environment to explore and filter a huge set of trajectories. Figure based on Hurter et al. (2018), with permission from the original authors

statistical and data mining techniques in a geovisual analytics approach. For example, "K-means" clustering can be used to group trajectories into "clusters" (based on a chosen metric of trajectory similarity) and representative trajectories can be compared (Andrienko and Andrienko 2011). Visualization techniques that facilitate such comparisons are simply **switching between** displaying trajectories or groups of trajectories by using interactive brushing, **superpositioning** (where trajectories are displayed on the same map), or **juxtaposition**, where maps of groups of trajectories are displayed side-by-side using small multiples (Tufte 1983).

In summary, trajectory maps are good for showing detailed examples of journeys but do not scale well to more than a few trajectories. Characteristics of these individual trajectories can be explored through multiple coordinated views with brushing. Trajectories are often displayed in maps in 2D, but 3D space-time cubes are also common. Overplotting many trajectories with semitransparent lines can help indicate parts of routes that are commonly taken, and a selected trajectory can be highlighted using a visual variable if there is a reason to emphasize a particular trajectory. In addition, trajectories can be filtered, grouped, and visually compared. For higher-level pattern identification, it is helpful to perform some aggregation, as discussed in the next section.

7.5.2 Flow Maps: Aggregated Flows Between Places

Flow maps depict movement between locations or regions. Unlike trajectory maps, they typically do not represent the route or path taken. This is suitable for cases in which there are **origin-destination pairs**; for example, county-country migrations (Fig. 7.6) and public bike hire journeys taken between pairs of bike docking stations (Fig. 7.7).

Tobler's (1987) early flow maps connected locations with **straight lines**. However, **curved lines** help reduce the undesirable occluding effects of line crossings. Jenny et al. (2018) provide a comprehensive set of guidelines for designing flow maps. Wood et al. (2011) also used curved lines to distinguish and visually separate flow in either direction, using asymmetry in the curve to indicate direction (Fig. 7.7). Yang et al. (2019) provide specific guidance for designing flow maps on (**3D**) digital **globes**. They recommend taking advantage of the *z*-axis to design flows with **3D curvature** to help reduce clutter and make the maps more readable and provide evidence-based advice for displaying flows on 3D globes.

A characteristic of flow data is that it is usually **aggregated**, with the number of flows between origin-destination pairs reported. This is facilitated by the fact that there are often a finite number of spatial units (origins and destinations), as is the case for bike docking stations or country-country migration data. This makes them more scalable but, as shown in Fig. 7.6 (Wood et al. 2011), flow maps can have clutter and occlusion issues similar to those observed in trajectory maps. These can be partially addressed by filtering as in trajectory maps, but because flows are usually already aggregated, filtering by geographical area is likely to reduce such

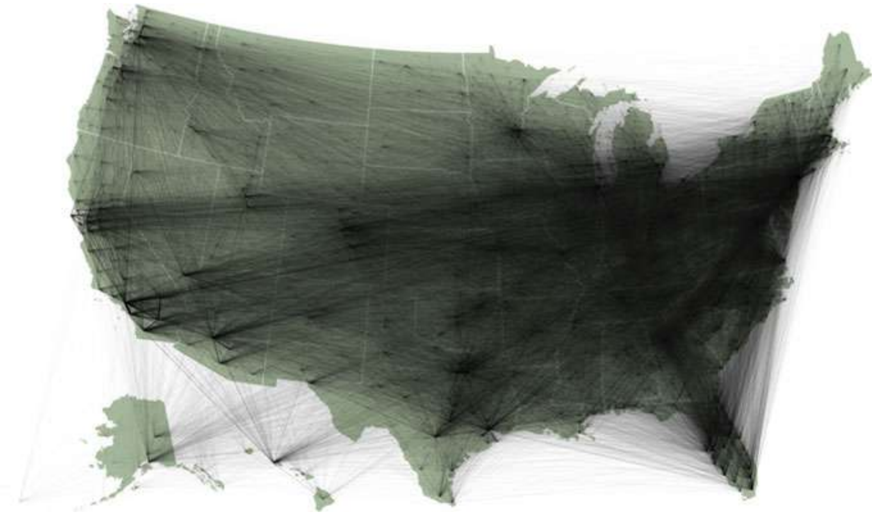

Fig. 7.6 20,000 county-county US migration vectors (3% random sample) between 2012 and 2016, rendered with transparency and anti-aliasing to show 'occlusion density'. Figure based on Wood et al. (2011), redrawn by Jo Wood using data from https://vega.github.io/vega-lite/data/us-10m.json and https://gicentre.github.io/data/usCountyMigration2012_16.csv

Fig. 7.7 As in Fig. 7.6, but clutter is reduced by filtering county-county flows to and from Ohio (orange and purple, respectively), where line thickness is proportional to volume and curved lines allow directions to be distinguished and reduce occlusion. Produced by Jo Wood using data from https://vega.github.io/vega-lite/data/us-10m.json and https://gicentre.github.io/data/usCountyMigration2012_16.csv

clutter more effectively to make patterns visible and interpretable (Andrienko and Andrienko 2011) [see the geographical filtering in the green trajectories shown in Fig. 7.2]. There are other ways to reduce clutter and provide more interpretable visual representations of movements, for example, by employing **spatial aggregation** or applying **edge bundling.**

7.5.2.1 Spatial Aggregation of Flows

Spatial aggregation reduces the geographical precision of movement but benefits visualization. In Fig. 7.6, although the US county-county migration data is already aggregated by county pair, further aggregating the state-state migration would produce a more interpretable graphic. However, this additional aggregation is at the expense of being able to resolve differences within states. In this example, we suggested aggregating the input data by pairs of **existing defined regions** (counties and states), but the data can also be aggregated into pairs of **data-driven irregular tessellations** (e.g., Voronoi polygons, Fig. 7.8) or **regular tessellations** (e.g., grid cells). **Flows can also be generated from full trajectory data** (see the above section) by aggregating the start and end points to spatial units, provided they have meaningful start and end points. When performing spatial aggregation, it is typical to disaggregate by temporal unit (e.g., year) and/or by categorical attribute (e.g., gender). This enables comparison of temporal and other attributes, for example, using small multiples as described in the previous section (e.g., Fig. 7.7 could be arranged in small multiples by the hour of the day).

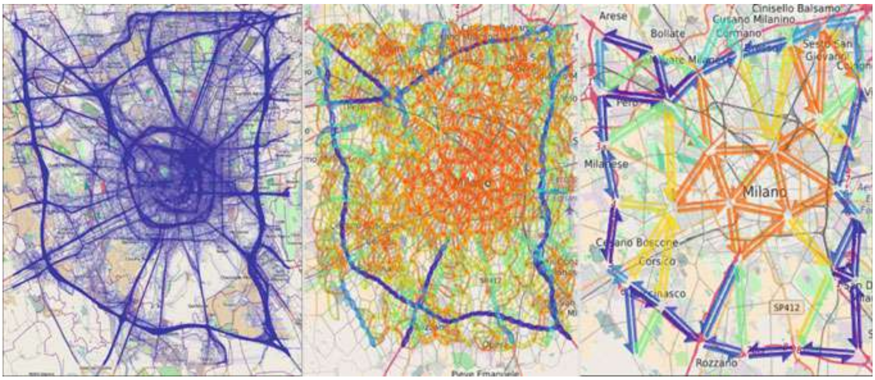

Fig. 7.8 Aggregating flows into data-driven Voronoi polygons. **Left**: Car journey trajectory data, using transparency to reduce clutter and occlusion. **Middle and right**: Aggregated flows into data-driven Voronoi polygons of different scales. Figure based on Andrienko and Andrienko (2011) with permission from the original authors

7.5.2.2 Edge Bundling of Flows

Edge bundling is a class of techniques designed to layout flows in interpretable ways, by 'bundling' parts of different flows that go in different directions (see the example in Fig. 7.9). Bundling techniques are used to reduce occlusion and convey the underlying movement structure (Holten and van Wijk 2009; Fig. 7.10). Jenny et al. (2017) provide an algorithm to facilitate this. For cases with a specific origin or destination of interest, Buchin et al. (2011) suggest an algorithm that aggregates flows into a tree-like representation that clarifies the flow structure (Fig. 7.11).

7.5.3 Origin-Destination (OD) Maps

OD maps (Wood et al. 2011) are also an important tool. They aggregate flows into a relatively small number of spatial units based on existing units (e.g., states) or those that result from a Voronoi- or grid-based tessellation. OD maps are effectively small

Fig. 7.9 Examples of origin-destination maps that are subsetted on a single origin and where an aggregated tree layout simplifies the visual complex complexity of flows to multiple destinations (Buchin et al. 2011). Figure based on Buchin et al. (2011), with permission from the original authors

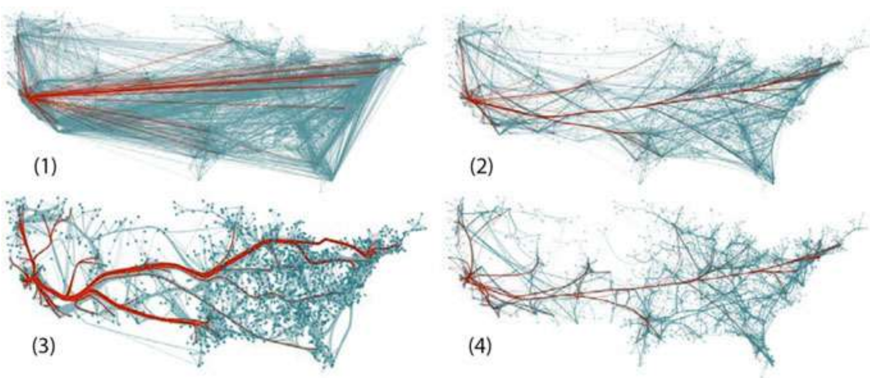

Fig. 7.10 US migration graph (9780 aggregated origin-destination pairs), in which (a) simply uses straight lines and the others are *bundled* using various algorithms (Holten and Van Wijk 2009). Figure based on Holten and Van Wijk (2009) with permission from the original authors

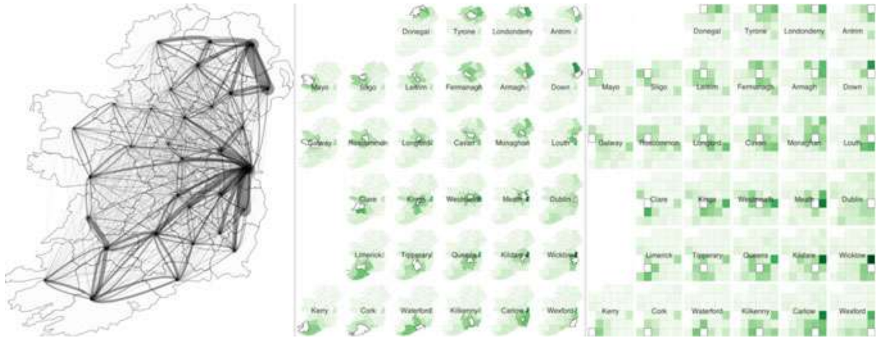

Fig. 7.11 Internal migration in Ireland. **Left**: a flow map, where line thickness indicates flow. **Middle**: spatially-arranged small-multiples of destination maps. **Right**: OD maps with the same grid-based layouts at both levels of the hierarchy. Based on Kelly et al. (2013) with permission from the original authors

multiple destination maps. Cases with irregular spatial units should be organized in a grid layout that preserves as much of the geographical 'truth' as possible. The center of the labels typically indicates the origin (e.g., of migrants or another phenomenon), and the maps show the destinations from each origin (Fig. 7.9). Flow maps aid in visually understanding the structure of movement between places (Jenny et al. 2017). Below, we disregard the connection between the origin and destination and simply consider the density of movement.

7.5.4 In-Flow, Out-Flow and Density of Moving Objects

This section concerns movement for which we **do not have the connection between origin and destination**. This includes situations in which we only have data on the **outflow** (but do not know where the flow goes), **inflow** (but do not know where the flow originates from), or the **density of moving objects**. This can be expressed as a single value describing the movement for each spatial unit, for example, the out-migration flow from each county. As described above, the spatial units used may be derived from existing units (e.g., states) or Voronoi/grid-based tessellations. These values can be displayed as **choropleth maps**, in which regions are represented as tessellating polygons on a map and a suitable color scale is used to indicate in- or out-movement or the density of moving objects.

When performing spatial aggregation, the data in each spatial unit can be disaggregated by temporal unit or by category. Figure 7.12 provides a visual representation of this, where the density of delivery vehicles is aggregated to 1-km grid squares and the vehicles in each grid square are disaggregated into densities for five vehicle types, the days of the week, and 24 h of the day. Many environmental datasets that describe

Fig. 7.12 Represents the density of moving vehicles in London, by grid square, day of week, hour of day and vehicle type, using a logarithmic colour scale. Figure based on Slingsby et al. (2010) with permission from the original authors

the movement of water or air masses do not have a meaningful concept of individual journeys. These datasets usually summarize movement as **vectors depicting the flow magnitude and direction** within grid cells. Visual representations of these movements usually take the form of **regular arrays of arrows on maps** (Fig. 7.13). Here, vectors represent a summary of 'movement' within grid cells. These can be explored using some of the methods described above, including filtering, temporal animation, and small multiples. Doing so may result in multiple vectors per grid cell, which provides an opportunity to symbolize multiple variables as glyphs (Slingsby 2018), for example, for climatic data (Wickham et al. 2012) or a rose diagram at origin or destination locations. In spatial tessellations, the problem of overlapping places is not as common. However, the on-screen size of spatial units must be large enough for the symbolization to be interpreted.

In summary, movement data exists in different forms and can often be transformed. This section provided an overview of map-based representations for three different levels of precision for movement data. The reviewed approaches can be used with digital globes, or a future Digital Earth with virtual dashboards through which one can integrate analytical operations within an AR or VR system. Hurter et al. (2018) show how interactions in a 3D immersive environment (see the "Immersive Technologies—From Augmented to Virtual Reality" section) can enable the exploration of large numbers of individual 3D trajectories. Next, we review the current state of the art in immersive technologies.

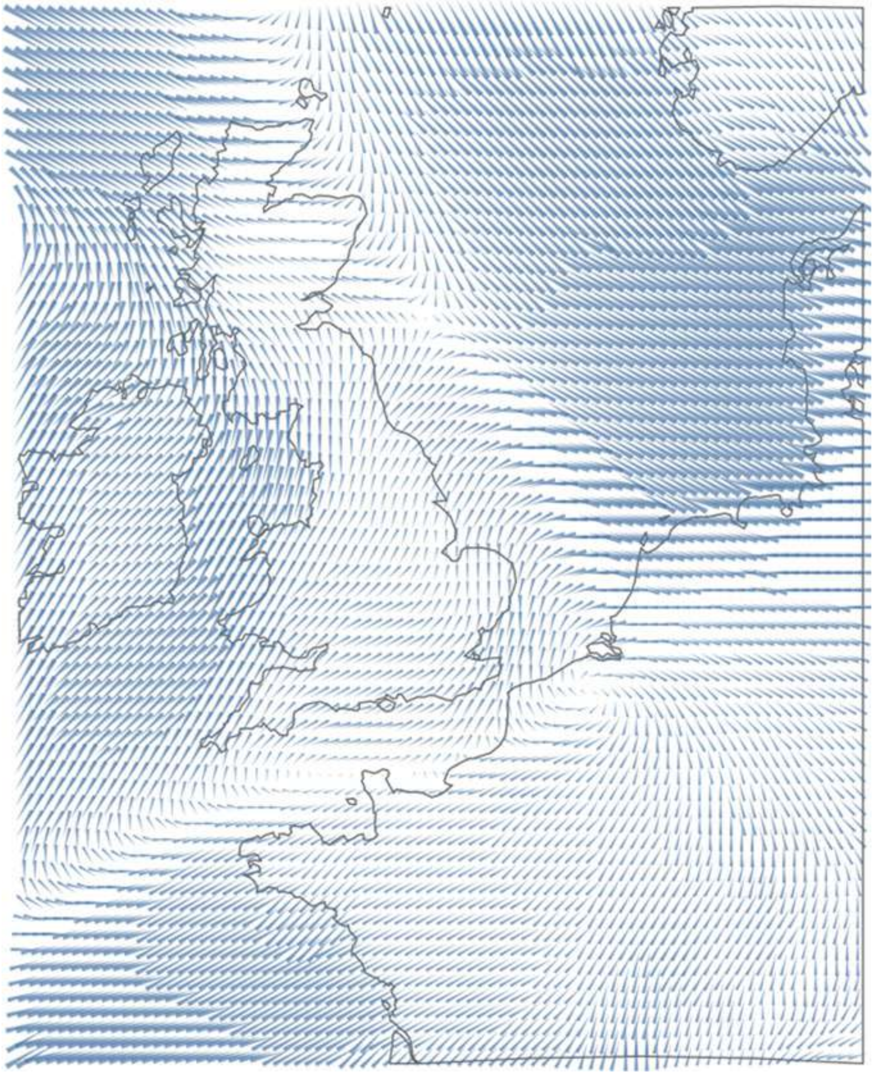

Fig. 7.13 A wind field map, in which arrows indicate wind direction (arrow orientation towards the thin end) and strength (arrow length) for grid squares. It indicates aggregated movement per grid cell. Based on https://github.com/gicentre/litvis/blob/master/examples/windVectors.md with the original author's permission and data from http://www.remss.com/measurements/ccmp/

7.6 Immersive Technologies—From Augmented to Virtual Reality

In the virtual and augmented reality (VR and AR) domains, there is almost "visible" excitement, both in academia (off and on for over 30 years) and in the private sector (more recently). A 2016 Goldman Sachs analysis predicted that VR and AR would be an 80 billion dollar industry by 2025 (reported on CNBC: https://www.cnbc.com/2016/01/14/virtual-reality-could-become-an-80b-industry-goldman.html). Arguably, geospatial sciences will not be the same once immersive technologies such as **augmented (AR)**, **mixed (MR)**, and **virtual reality (VR)** have been incorporated into all areas of everyday life. In this chapter, we use the shorthand **xR** to refer to all immersive technologies and use the individual acronyms (AR/MR/VR) to refer to specific technologies. A closely related term that has recently been gaining momentum is **immersive analytics**, described as a blend of visual analytics, augmented reality, and human-computer interaction (Marriott et al. 2018), which draws on knowledge and experience from several fields described in this chapter to develop visualizations of geospatial information that support thinking. We do not elaborate on immersive analytics; see, e.g., Billinghurst et al. (2018) and Yang et al. (2019). Current technologies for xR hold promise for the future, despite being strongly "gadget"-dependent and somewhat cumbersome and 'involved' to set up (i.e., they require *some* technical skill and dedication). Thus, it remains to be seen whether these immersive experiences will become commonplace. We describe and elaborate on these display technologies below. We begin by outlining several concepts that are important for xR technology use.

7.6.1 Essential Concepts for Immersive Technologies

Concepts characterizing immersive technologies and their definitions are sometimes subject to debate. This is mainly because their development involves multiple disciplines. Because there have been parallel developments in different communities, similar concepts might be named using different terms. The related technology also evolves quickly, and a newer/improved version of a concept/approach/method/tool typically gets a new name to distinguish it from the older versions or because technology actors want to "brand" their innovative approach, or there is a scientific paradigm shift and a new name is needed even though it was based on an older concept. As in many other interdisciplinary and fast-evolving scientific disciplines, there is considerable discussion and occasional confusion about terminology. This process of "maturing" terminology is not unique to immersive technologies. One of the first taxonomies that provided an overview of all xR technologies, and perhaps the most influential one, was proposed by Milgram and Kishino (1994), who used the concept of a continuum from reality to virtuality (see Fig. 7.14).

Fig. 7.14 Shown are examples from projects in ChoroPhronesis that demonstrate the reality-virtuality continuum proposed by Milgram and Kishino (1994). Figure designed by Mark Simpson

Their original definitions are more nuanced than this continuum and are challenging to apply in a fast-developing technology field. Nonetheless, it is useful to revisit some of their main distinctions for a conceptual organization of the terms in xR.

A confusing, yet central, term is **immersion** (see the "Virtual Reality" subsection below). Currently, the commonsense understanding of immersion is different than its rather narrow focus in the technical VR literature. For example, Slater (2009) distinguishes immersion from **presence**, with the former indicating a physical characteristic of the medium itself for the different senses involved. Presence is reserved for the psychological state produced in response to an immersive experience. To illustrate a simple example, Fig. 7.15 shows three experimental setups that were used in a recent study on how different levels of immersion influence the feeling of being present in a remote meeting (Oprean et al. 2018).

In this study, Oprean et al. (2018) compared a standard desktop setting (the lowest level of immersion) with a three-monitor setup (medium level of immersion) and an immersive headset (the Oculus Rift, DK2). One can "order" these technologies along a spectrum of immersiveness (as in Fig. 7.16), which helps in designing experiments to test whether or not feeling physically immersed affects aspects of thinking or collaboration (e.g., on the subjective feeling of team membership). Another key concept for immersive technologies, and a research topic in itself, is **interaction** (also discussed in the "Visualizing Geospatial Information" section). Interaction is important for any form of immersive technology because the classical "keyboard and mouse" approach does not work well (or at all) when the user is standing and/or moving. Interaction, along with immersion, is one of the four "I" terms proposed as the defining elements of VR; the other two are information intensity and intelligence of objects, as proposed by MacEachren et al. (1999a) in the 1990s. We elaborate on the four "I"s and other relevant considerations in the Virtual Reality section because they are discussed most often in the context of VR, and are relevant for other forms

Fig. 7.15 Different levels of immersion, with immersiveness increasing from top to bottom. Increased immersion is supported by a combination of an increased field of view and the use of an egocentrically fixed rather than an allocentrically fixed reference frame. Based on Oprean et al. (2017) with the original author's permission

of xR. In addition to Milgram and Kishino's (1994) continuum, there are many other ways to organize and compare immersive technologies. For example, a recent take on levels of realism and immersion is shown Fig. 7.16. This example extends the immersiveness spectrum by considering where visualization designs are located on an additional continuum: abstraction-realism.

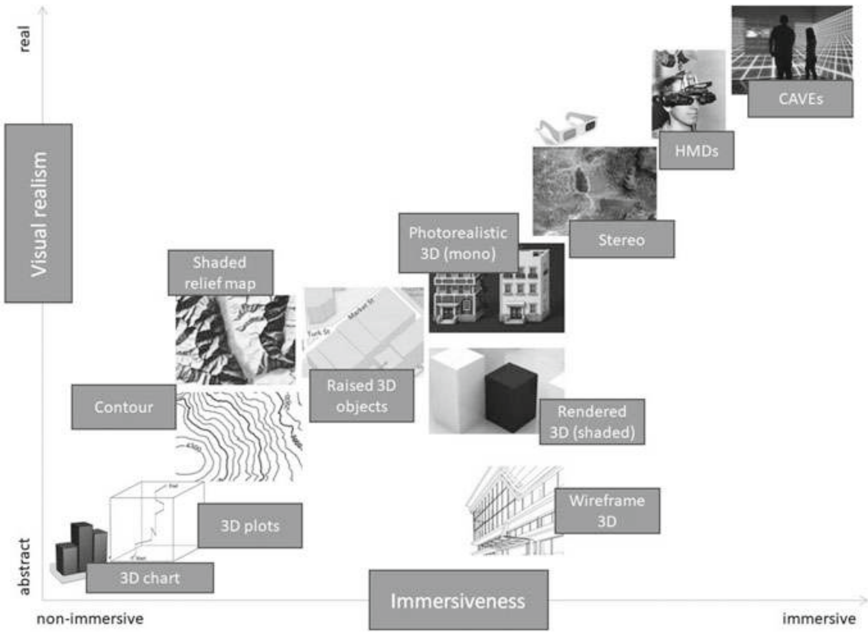

Fig. 7.16 Extending the immersiveness spectrum by also considering where specific visualization designs are located on an additional continuum: abstraction-realism. Figure by Çöltekin et al. (2016a, b), CC-BY-3.0

7.6.2 Augmented Reality

In Milgram and Kishino's (1994) model, the first step from reality toward *virtuality* is **augmented reality (AR)**. Augmented reality allows for the user to view virtual objects superimposed onto a real-world view (Azuma 1997). Technological advancements have allowed for augmented reality to evolve from bulky head-mounted displays (HMDs) in the 1960s to smartphone applications today (some examples are featured below), and through specialized (though still experimental) glasses such as Google Glass or Epson Moverio (Arth and Schmalstieg 2011). Although technology has truly advanced since the early—bulky and rather impractical—HMDs, there are still challenges in the adoption of augmented reality for dedicated geospatial applications in everyday life. These challenges are often technical, such as latency and the inaccuracy of sensors when using smartphones, and result in inaccuracies in registration of features and depth ambiguity (Arth and Schmalstieg 2011; Chi et al. 2013; Gotow et al. 2010). There are also design issues that should be considered and, ideally, user-evaluated when developing and designing a "geospatial" AR application (Arth and Schmalstieg 2011; Cooper 2011; Kounavis et al. 2012; Kourouthanassis et al. 2015; Kurkovsky et al. 2012; Olsson 2012; Tsai et al. 2016; Vert et al. 2014).

Akçayır and Akçayır (2017) and Wu et al. (2013) reviewed the current state of AR in education. They concluded that AR provides a unique learning environment because it combines digital and physical objects, an insight relevant to students and scientists who are learning about geographical systems. An example of AR in education and research is the "augmented reality sandbox" (https://arsandbox.ucdavis.edu) that has been widely used, for example, in an urban/landscape design experiment (Afrooz et al. 2018). A similar application is the "tangible landscape" (https://tangible-landscape.github.io) (Petrasova et al. 2015). Both of these applications superimpose an elevation color map, topographic contour lines, and simulated water on a physical sand model that can be physically (re)shaped by the user. A tourism-related science and education example is the "SwissARena", which superimposes a 3D model on top of topographic maps of Switzerland (Wüest and Nebiker 2018), enabling smartphone and tablet users to visit museums and other public spaces through an augmented experience. Motivated by a fundamental (rather than an applied) question, Carrera and Bermejo Asensio (2017) tested whether the use of AR improves participants' (spatial) orientation skills when interpreting landscapes. They found a significant improvement in participants' orientation skills when using a 3D AR application. However, some pedagogical questions (e.g., how should AR be used to complement the learning objectives; what is the gap between teaching and learning?) and other usability gaps (e.g., it was difficult to use at first, unsuitable for large classes, cognitive overload, expensive technology, and inadequate teacher ability to use the technology) identified by Akçayır and Akçayır (2017) and Wu et al. (2013) regarding the use of AR in teaching need to be addressed. Given that early research suggests that AR might aid in developing spatial skills, its potential in education (especially in science education) appears to be reasonably high. Furthermore, there appear to be several benefits of using AR in research. For example, it has been suggested that AR is an excellent tool for collaborative work among researchers (Jacquinod et al. 2016). At the time of this writing, there are no *common* examples of these types of applications in use, but there have been various experimental implementations of AR in research and scientific visualization (e.g., Devaux et al. 2018). Thus, most of the present excitement about AR seems to be based on belief and intuition, which can be correct but may also mislead.

7.6.3 Mixed Reality

As conceptualized in the Milgram and Kishino (1994) model (Fig. 7.15), the term Mixed Reality (MR)—sometimes referred to as Hybrid Reality—applies to everything in between the real world and a virtual world. Therefore, the term *includes* AR, and the issues described above about AR also apply to MR. MR also includes **augmented virtuality** (AV). AV refers to virtual environments that are designed so that physical objects still play a role. Of the two subcategories of MR (AR and AV), AR is more developed at this point in time. Nonetheless, AV is relevant in a number of VR scenarios. For example, when we want haptic feedback, we give users suits or gloves. It is also relevant when we want to interact with the virtual world using any kind of hardware. Using hardware to drive interaction is the current state of the art; that is, although there are an increasing number of gesture tracking methods that map functions onto the body's natural movements, several of the controls are physical objects, such as remote controls, often referred to as "wands", or small trackable objects attached to the viewers called "lights". Any combination (hybrid) environments of physical and virtual objects can be considered a form of MR. We do not expound on MR in this chapter, and any information presented in the AR section above and most of the information in the VR section below is relevant to MR.

7.7 Virtual Reality

How should we define virtual reality? There is no consensus on the "minimum requirements" of VR, though it is understood that an ideal VR system provides humans experiences that are indistinguishable from an experience that could be real. Ideally, a VR should stimulate *all* senses. That is, a virtual apple you eat should look, smell, and taste real, and when you bite, the touch and sounds should be just right. Current VR technologies are not there yet. The sense of vision (and the associated visualizations) has been investigated a great deal and audio research has made convincing progress, but we have a long way to go in terms of simulating smells, tastes, and touch. There are no hard and fast rules for "minimum requirements" for a display to qualify as VR, but there have been various attempts to systematically characterize and distinguish VR from other types of displays (see Fig. 7.16). Among these, Sherman and Craig (2003) list four criteria: *a virtual world* (graphics), *immersion*, *interactivity*, and *sensory feedback*. They distinguish interaction and sensory feedback in the sense that interaction occurs when there is an *intentional* user request whereas sensory feedback is embedded at the system level and is fed to the user based on tracking the user's body. In the cartographic literature, a similar categorization was proposed even earlier by MacEachren et al. (1999b) in which they describe the *Four 'I's*, adding *intelligence of objects* to Heim's (1998) original three 'I's: *immersion, interactivity, information intensity.* The *Four 'I's* and Sherman and Craig's criteria have clear overlaps in immersion and interactivity, and links between a "virtual world" and "information intensity" and between "sensory feedback" and "intelligence of objects" can be drawn. Notably, some authors make a distinction between *virtual reality* and *virtual environments*: the term virtual reality does not exactly refer to mimicking reality (but an experience that feels real to the user). Nonetheless, because the word *reality* can invoke such an impression, the term **virtual environment** emerged. The term originated because one can also show fictional (or planned) environments using a visualization environment, and thus, the term "environment" more effectively encapsulates the range of things one can do in such a visualization environment. Below, we give a brief history of VR in domains that are directly related to Digital Earth and elaborate on what was once described as a "virtual geographic environment" (VGE).

7.7.1 Virtual Geographic Environments

An extension of earlier conceptualizations of 'virtual geography' (e.g., Batty 1997; MacEachren et al. 1999a), the term VGE was formally proposed at the beginning of the 21st century (attributed to Lin and Gong 2001) around the same time as the seminal book by Fisher and Unwin (2001). Since its beginnings, the VGE concept and accompanying tools have significantly evolved. A modern description of a VGE is a digital geographic environment "generated by computers and related technologies that users can use to experience and recognize complex geographic systems and further conduct comprehensive geographic analyses, through equipped functions, including multichannel human-computer interactions (HCIs), distributed geographic modeling and simulations, and network geo-collaborations" (Chen and Lin 2018, p. 329). Since their conception, VGEs have attracted considerable attention in the geographic information science research community over the last few decades (e.g., Goodchild 2009; Huang et al. 2018; Jia et al. 2015; Konecny 2011; Liang et al. 2015; Mekni 2010; Priestnall et al. 2012; Rink et al. 2018; Shen et al. 2018; Torrens 2015; Zhang et al. 2018; Zheng et al. 2017). Much like the "digital twin" idea, and well-aligned with the Digital Earth concept, VGEs often aim to mirror real-world geographic environments in virtual ones. Such a mirrored virtual geographic environment also goes *beyond* reality, as it ideally enables its user to visually perceive invisible or difficult-to-see phenomena in the real world, and explore them inside the virtual world (e.g., looking at forests at different scales, examining historical time periods, seeing under the ocean's surface). As it can incorporate advanced analytic capabilities, a VGE can be superior to the real world for analysts. In an ideal VGE, one can view, explore, experience and analyze complex geographic phenomena. VGEs are not 'just' 3D GIS environments, but there are strong similarities between VGEs and *immersive analytics* approaches. A VGE can embed all the tools of a GIS, but a key point of a VGE is that they are meant to provide realistic experiences, as well as simulated ones that are difficult to distinguish from real-world experiences. A VGE would not be ideal if *only* analytics are needed, as 2D plans combined with plots may better facilitate the analyst's goals. The combination of a traditional GIS and the power of immersive visualization environments offers novel ways to combine human cognitive abilities with what machines have to offer (Chen and Lin 2018; Lin et al. 2013a).

7.7.2 Foundational Structures of VGEs

Lin et al. (2013b) designed a conceptual framework that includes four VGE subenvironments: *data*, *modeling and simulation*, *interaction*, and *collaborative* spaces. They posit that a geographic *database* and a geographic *model* are core necessities for VGEs to support visualization, simulation, and collaboration. Below, we briefly elaborate on the four VGE subenvironments (Lin et al. 2013b).

7.7.2.1 Data Space

The "data space" is conceptualized as the first step in the pipeline of creating a VGE. This is where data are organized, manipulated, and visualized to prepare the digital infrastructure necessary for a VGE. One can also design this environment so that users can "walk" in their data and examine it for patterns and anomalies (as in immersive analytics). The data is ideally comprehensive (i.e., "information intensity" is desirable), such that semantic information, location information, geometric information, attribute information, feature spatiotemporal/qualitative relationships and their evolution processes are considered and organized to form virtual geographic scenarios with a range of visualization possibilities (e.g., standard VR displays, holograms, or other xR modes) and thus support the construction of VGEs (Lü et al. 2019).

7.7.2.2 Modeling and Simulation Space

Models and simulations, as the abstraction and expression of geographical phenomena and processes, are important means for modern geographic research (Lin et al. 2015). With the rapid development of networks, cloud/edge computing, and other modern technologies, modeling and simulation capabilities allow for a large range of exploration and experimentation types (e.g., Wen et al. 2013, 2017; Yue et al. 2016). VGEs can also integrate such technologies. Chen et al. (2015) and Chen and Lin (2018) propose that doing so would provide new modes for geographic problem solving and exploration, and potentially help users understand the Digital Earth.

7.7.2.3 Interaction Space

In general, interaction is what shifts a user from being a passive 'consumer' of information and makes them active producers of new information (see the "Geovisualization" section earlier in this chapter). In VGEs, interaction requires a different way of thinking than for desktop setups because the aspiration is to create experiences that are comparable to those in the real world (i.e., mouse-and-keyboard type interactions do not work well in VGEs). Thus, there have been considerable efforts to track a user's hands, head, limbs, and eyes to model natural interaction. Interaction tools play an important role in information transmission between the VGE and its users (Batty et al. 2017; Voinov et al. 2018).

7.7.2.4 Collaboration Space

In addition to the interaction between a human and a machine, it is important to consider the interactions between humans, ideally, as it occurs in the real world (or improving upon real-world collaboration). At present, there is an increasing demand for collaborative work, especially when solving complex problems. Complex geographic problem solving may require participants from different domains, and collaboration-support tools such as VGEs might help them communicate with each other. There are many examples of collaborative research based on VGEs (e.g., Chen et al. 2012; Li et al. 2015; Xu et al. 2011; Zhu et al. 2015). If the four subenvironments are well-designed, VGEs could become effective scientific tools and advance geography research: simulations in a VGE could be systematically and comprehensively explored to deepen scientists' understanding of complex systems such as human-environment interactions. Virtual scenarios corresponding to real-world scenarios with unified spatiotemporal frameworks can be employed to support integration of human and environmental resources. With Digital Earth infrastructure and modern technological developments, geographical problems at multiple scales can be solved and related virtual scenarios can be developed for deep mining and visual analysis (e.g., Lin et al. 2013b; Fig. 7.17). Importantly, VGEs can support collaborative exploration beyond reality. Working with virtual scenarios, users can communicate and conduct collaborative research free from the constraints of physical space (and in some cases, time).

This chapter so far has focused on theoretical constructs and examples of geographical visualization that can be used to represent and provide insights into our Earth system. However, it is also important to consider how such visualizations can

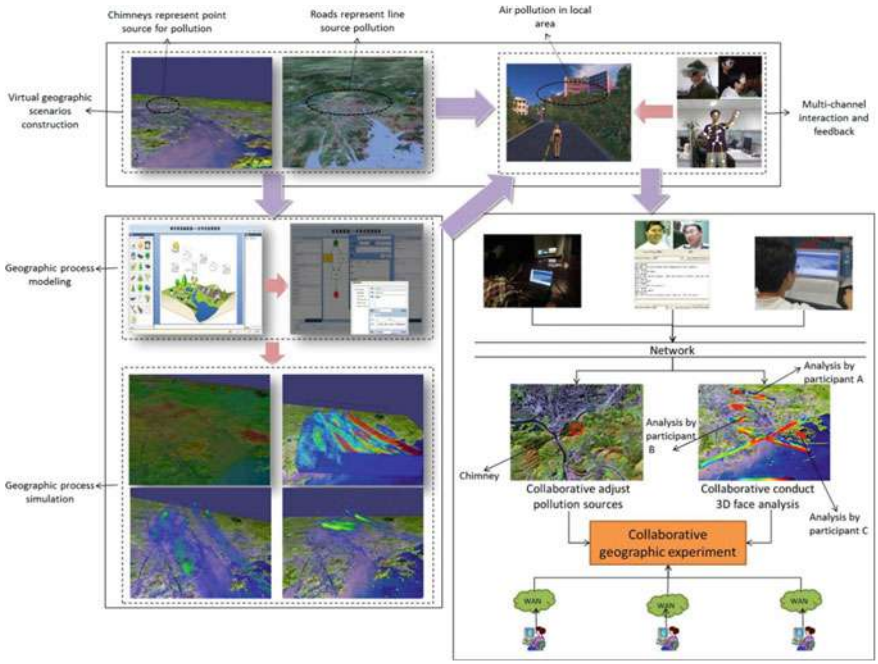

Fig. 7.17 A VGE example built for air pollution analysis (Lin et al. 2013a). Figure by Lin et al. (2013a). CC BY-NC-SA 3.0

be presented to policy and decision-makers to plan for a more sustainable future. The next section outlines a number of platforms for engaging such end users with packaged geographical information, known as *dashboards*.

7.8 Dashboards

A true Digital Earth describes Earth and all its systems, including ecosystems, climate/atmospheric systems, water systems, and social systems. Our planet faces a number of great challenges including climate change, food security, an aging population, and rapid urbanization. As policy-makers, planners, and communities grapple with how to address these critical problems, they benefit from digital tools to monitor the performance of our management of these systems using specific indicators. With the rise of big data and **open data**, a number of **dashboards** are being developed to support these challenges, enabled by geographical visualization technologies and solutions (Geertman et al. 2017). Dashboards can be defined as "graphic user interfaces which comprise a combination of information and geographical visualization methods for creating metrics, benchmarks, and indicators to assist in monitoring and decision-making" (Pettit and Leao 2017).

One can think of dashboards as installations that can provide key indicators of the performance of a particular Earth system, powered through the construct of Digital Earth. In 2016, the United Nations launched 17 Sustainable Development Goals to guide policy and funding priorities until 2030. Each of these goals include a number of indicators that can be quantified and reported within a Digital Earth dashboard, as illustrated, for example, such as in SDG Index and Dashboards (https://dashboards.sdgindex.org/#/) (Sachs et al. 2018).

For illustrative purposes, we focus on one SDG 11—Sustainable Cities and Communities, as there are a number of city dashboard initiatives that aim to provide citizens and visitors access to a rich tapestry of open data feeds. Data in these feeds are typically aggregated and presented to the user online and can include, for example, data on traffic congestion, public transport performance, air quality, weather data, social media streams, and news feeds. Users can interact with the data and perform visual analyses via different/multiple views, which might include graphs, charts, and maps. Examples include the London Dashboard (Gray et al. 2016) and the Sydney Dashboard (Pettit et al. 2017a), illustrated in Fig. 7.18.

There are also advanced dashboard platforms that support data-driven policy and decisions through analytics. For cities, there has been an increase in the number of city analytics dashboard platforms such as the Australian Urban Research Infrastructure Network (AURIN) workbench (Pettit et al. 2017b). The AURIN workbench provides users with access to over 3,500 datasets through an online portal. This portal provides data and includes more than 100 spatial-statistical tools (Sinnott et al. 2015). The AURIN workbench (Fig. 7.19) enables users to visualize census data and a number of other spatial datasets, including the results of statistical analyses through multiple coordinated (i.e., linked) views. Thus, it enables geovisual analytics as the user

Fig. 7.18 City of Sydney Dashboard. Figure provided by Chris Pettit

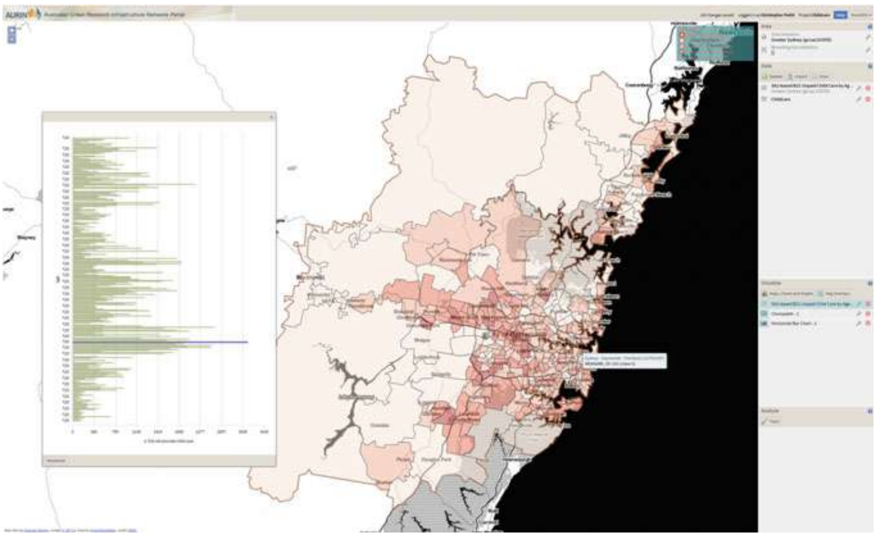

Fig. 7.19 The AURIN Workbench provides a rich geovisual analytics experience. Figure provided by Chris Pettit

can *brush* between maps, graphs, charts, and scatterplots to explore the various dimensions of a city (Widjaja et al. 2014). In an era of smart cities, big data, and city analytics, an increasing number of geographical visualization platforms include both data and simulations to benchmark the performance of urban systems.

Dashboard views of the performance of Earth systems such as urban systems have a number of pros and cons. Dashboards can potentially provide the best available data on the performance of an urban system or natural asset so that decisions can account for multiple dimensions, including sustainability, resilience, productivity, and liv-ability. Dashboards are also a window into the democratization of data and provide greater transparency and accountability in policy- and decision-making. However, there are a number of challenges in developing and applying dashboards; without good quality indicators and benchmarks, the utility of such digital presentations of performance can be questionable. Traditionally, dashboards have provided a unidirectional flow of information to their users. However, with the emergence of digital twins, there may be an opportunity for a true bidirectional flow of data between dashboards, their users and Earth systems.

7.9 Conclusions

Our understanding of the vision of Digital Earth is that it is a fully functional virtual reality system. To achieve such a system, we need to master every aspect of relevant technology and design and keep the users in mind. Visualization is an interdisciplinary topic with relevance in many areas of life in the digital era, especially given that there is much more data to analyze and understand than ever before. Because the Earth is being observed, measured, probed, listened to, and recorded using dozens of different sensors, including people (Goodchild 2007), the data we need to build a Digital Earth is now available (at least for parts of the Earth). Now, the challenge is to organize these data at a global scale following cartographic principles so that we can make sense of it. Herein lies the strength of visualization. By visualizing the data in multiple ways, we can create, recreate, and predict experiences, observe patterns, and detect anomalies. Recreating a chat with an old neighbor in our childhood living room 30 years later (e.g., instead of looking at a photo album) is no longer a crazy thought; we might be recording enough data to be able to do such things soon. The possibilities are endless. However, as inspiring as this may be, one must understand how to "do it right"; that is, we have much to learn before we will know what exactly we should show, when and to whom. In this chapter, we provided an overview of the current state of the art of topics related to visualization in the context of Digital Earth. We hope this chapter provided some insights into our current broad understanding of this challenge.

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The Way Forward

We have an unparalleled opportunity to turn a flood of raw data into understandable information about our society and out planet. This data will include not only high-resolution satellite imagery of the planet, digital maps, and economic, social, and demographic information. If we are successful, it will have broad societal and commercial benefits in areas such as education, decision-making for a sustainable future, land-use planning, agricultural, and crisis management.

The Digital Earth project could allow us to respond to manmade or natural disasters—or to collaborate on the long-term environmental challenges we face.

A Digital Earth could provide a mechanism for users to navigate and search for geospatial information—and for producers to publish it. The Digital Earth would be composed of both the "user interface"—a browsable, 3D version of the planet available at various levels of resolution, a rapidly growing universe of networked geospatial information, and the mechanisms for integrating and displaying information from multiple sources.

A comparison with the World Wide Web is constructive. [In fact, it might build on several key Web and Internet standards.] Like the Web, the Digital Earth would organically evolve over time, as technology improves and the information available expands. Rather than being maintained by a single organization, it would be composed of both publically available information and commercial products and services from thousands of different organizations. Just as interoperability was the key for the Web, the ability to discover and display data contained in different formats would be essential.

I believe that the way to spark the development of a Digital Earth is to sponsor a testbed, with participation from government, industry, and academia. This testbed would focus on a few applications, such as education and the environment, as well as the tough technical issues associated with interoperability, and policy issues such as privacy. As prototypes became available, it would also be possible to interact with the Digital Earth in multiple places around the country with access to high-speed networks, and get a more limited level of access over the Internet.

Clearly, the Digital Earth will not happen overnight.

In the first stage, we should focus on integrating the data from multiple sources that we already have. We should also connect our leading children's museums and science museums to high-speed networks such as the Next Generation Internet so that children can explore our planet. University researchers would be encouraged to partner with local schools and museums to enrich the Digital Earth project—possibly by concentrating on local geospatial information.

Next, we should endeavor to develop a digital map of the world at 1 meter resolution.

In the long run, we should seek to put the full range of data about our planet and our history at our fingertips.

In the months ahead, I intend to challenge experts in government, industry, academia, and non-profit organizations to help develop a strategy for realizing this vision. Working together, we can help solve many of the most pressing problems facing our society, inspiring our children to learn more about the world around them, and accelerate the growth of a multi-billion dollar industry.

Appendix F
1999 Beijing Declaration on Digital Earth and 2009 Beijing Declaration on Digital Earth

Beijing Declaration on Digital Earth

December 2, 1999

We, some 500 scientists, engineers, educators, managers and industrial entrepreneurs from 20 countries and regions assembled here in the historical city of Beijing, attending the first International Symposium on Digital Earth being organized by the Chinese Academy of Sciences with co-sponsorship of 19 organizations and institutions from November 29, 1999 to December 2, 1999, recognize that humankind, while entering into the new millennium, still faces great challenges such as rapid population growth, environmental degradation, and natural resource depletion which continue to threaten global sustainable development;

Noting that global development in the 20th century has been characterized by rapid advancements in science and technology which have made significant contributions to economic growth and social wellbeing and that the new century will be an era of information and space technologies supporting the global knowledge economy;

Recalling the statement by Al Gore, Vice President of the United States of America, on *Digital Earth: Understanding Our Planet in the 21st Century*—and the statement by Jiang Zemin, President of the People's Republic of China, on Digital Earth regarding trends of social, economic, scientific and technological development;

Realizing the decisions made at UNCED and Agenda 21, recommendations made by UNISPACE III and the Vienna Declaration on Space and Human Development, which address, among other things, the importance of the Integrated Global Observing Strategy, the Global Spatial Data Infrastructure, geographic information systems, global navigation and positioning systems, geo-spatial information infrastructures and modeling of dynamic processes;

Understanding that Digital Earth, addressing the social, economic, cultural, institutional, scientific, educational, and technical challenges, allows humankind to visualize the Earth, and all places within it, to access information about it and to understand and influence the social, economic and environmental issues that affect their lives in their neighborhoods, their nations and the planet Earth;

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Recommend that Digital Earth be promoted by scientific, educational and technological communities, industry, governments, as well as regional and international organizations;

Recommend also that while implementing the Digital Earth, priority be given to solving problems in environmental protection, disaster management, natural resource conservation, and sustainable economic and social development as well as improving the quality of life of the humankind;

Recommend further that Digital Earth be created in a way that also contributes to the exploration of, and scientific research on, global issues and the Earth system;

Declare the importance of Digital Earth in achieving global sustainable development;

Call for adequate investments and strong support in scientific research and development, education and training, capacity building as well as information and technology infrastructures, with emphasis, inter alia, on global systematic observation and modeling, communication networks, database development, and issues associated with interoperability of geo-spatial data;

Further call for close cooperation and collaboration between governments, public and private sectors, non-governmental organizations, and international organizations and institutions, so as to ensure equity in distribution of benefits derived from the use of Digital Earth in developed and developing economies;

Agree that, as a follow-up to the first International Symposium on Digital Earth held in Beijing, the International Symposium on Digital Earth should continue to be organized by interested countries or organizations biannually, on a rotational basis.

Beijing Declaration on Digital Earth
September 12, 2009

We scientists, engineers, educators, entrepreneurs, managers, administrators and representatives of civil societies from more than forty countries, international organizations and NGOs, once again, have assembled here, in the historic city of Beijing, to attend the Sixth International Symposium on Digital Earth, organized by the International Society for Digital Earth and the Chinese Academy of Sciences, with co-sponsorship of sixteen Chinese Government Departments, Institutions and international organizations, being held from September 9–12, 2009.

Noting

That Significant global-scale developments on Digital Earth science and technology have been made over the past ten years, and parallel advances in space information technology, communication network technology, high-performance computing, and Earth System Science have resulted in the rise of a Digital Earth data-sharing platform for public and commercial purposes, so that now Digital Earth is accessible by hundreds of millions, thus changing both the production and lifestyle of mankind;

Recognizing

The contributions to Digital Earth made by the host countries of the previous International Symposia on Digital Earth since November 1999, including China, Canada, the Czech Republic, Japan and the USA, and by the host countries of the previous Summit Conferences on Digital Earth, including New Zealand and Germany, for the success of the meetings as well as further promotion of Digital Earth;

Further, that the establishment of the International Society for Digital Earth and the accomplishments of its Executive Committee, the launch of the International Journal on Digital Earth, and its global contribution to cooperation and data exchange;

That the themes of the previous seven meetings: Moving towards Digital Earth, Beyond Information Infrastructure, Information Resources for Global Sustainability, Digital Earth as Global Commons, Bring Digital Earth down to Earth, Digital Earth and Sustainability, Digital Earth and Global Change, and Digital Earth in Action, have laid out a panoramic scenario for the future growth of Digital Earth;

That Digital Earth will be asked to bear increased responsibilities in the years to come, in the face of the problems of sustainable development;

Further Recognizing

That Digital Earth should play a strategic and sustainable role in addressing such challenges to human society as natural resource depletion, food and water insecurity, energy shortages, environmental degradation, natural disasters response, population explosion, and, in particular, global climate change;

That the purpose and mission of the World Information Summit of 2007, the Global Earth Observation System Conference of 2007, and the upcoming United Nations Climate Change Conference of 2009, and that Digital Earth is committed to continued close cooperation with other scientific disciplines;

Realizing

That Digital Earth is an integral part of other advanced technologies including: earth observation, geo-information systems, global positioning systems, communication networks, sensor webs, electromagnetic identifiers, virtual reality, grid computation, etc. It is seen as a global strategic contributor to scientific and technological developments, and will be a catalyst in finding solutions to international scientific and societal issues;

We Recommend

(a) That Digital Earth expand its role in accelerating information transfer from theoretical discussions to applications using the emerging spatial data infrastructures worldwide, in particular, in all fields related to global climate change, natural disaster prevention and response, new energy-source development, agricultural and food security, and urban planning and management;
(b) Further, that every effort be undertaken to increase the capacity for information resource-sharing and the transformation of raw data to practical information and applications, and developed and developing countries accelerate their programs to assist less-developed countries to enable them to close the digital gap and enable information sharing;

(c) Also, that in constructing the Digital Earth system, efforts must be made to take full advantage of next-generation technologies, including: earth observation, networking, database searching, navigation, and cloud computing to increase service to the public and decrease costs;
(d) Further, that the International Society for Digital Earth periodically take the lead in coordinating global scientific research, consultations and popular science promotion to promote the development of Digital Earth;
(e) Expanding cooperation and collaboration between the International Society for Digital Earth and the international community, in particular with inter-governmental organizations, and international non-governmental organizations;
(f) Extending cooperation and integration with Government Departments, the international Scientific and Educational community, businesses and companies engaged in the establishment of Digital Earth;

We Call for

Support from planners and decision-makers at all levels in developing plans, policies, regulations, standards and criteria related to Digital Earth, and appropriate investments in scientific research, technology development, education, and popular promotion of the benefits of Digital Earth.