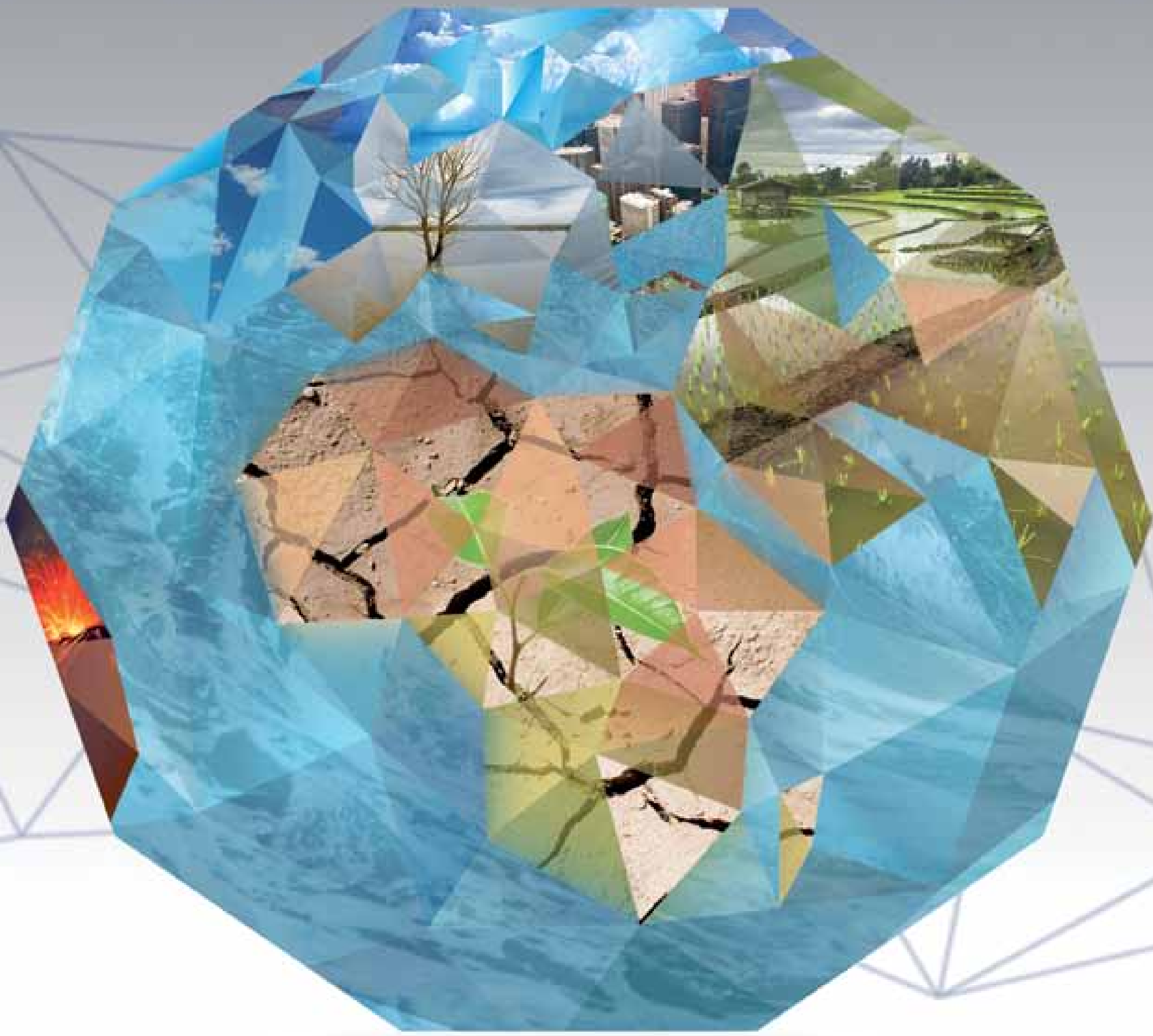

→ EARTH OBSERVATION SCIENCE STRATEGY FOR ESA

A New Era for Scientific Advances and Societal Benefits

SP-1329/1
February 2015

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European Space Agency

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Contributory Writing Team:
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Foreword

Thanks to the ERS and Envisat workhorse satellites and the series of ongoing and planned Earth Explorer missions, our scientific understanding of Earth has come a long way in recent decades. While science continues to reap the benefits of these missions, we are now in a new era where Earth observation also plays a pivotal role in environmental management systems to benefit society at large and everyday life.

The launch of the first Sentinel mission for Europe's environmental monitoring Copernicus programme signalled a new beginning for operational monitoring. Accordingly, ESA's new Earth observation science strategy takes a holistic approach that responds to both scientific and societal challenges.

Developing new and integrated observing systems, ensuring sustained observations and capabilities to fill gaps in current observing systems, building on well-established international cooperation and taking advantage of the major technological advances in computing capabilities, modelling and data handling not only advances knowledge, but also has cross-cutting impacts.

The value of Earth observation is increasingly recognised beyond the traditional fields. Today's paradigm shift towards open access to data, big data and exascale computing, collaborative approaches and analyses, as well as new ways of visualising and communicating data mean that Earth observation is at society's fingertips. In essence, as these rapidly evolving technologies become more commonplace and improvements in the ways in which data can be exploited and transformed into knowledge, the better we can address environmental, scientific and societal challenges, adapt to change and improve our way of life. In turn, new knowledge feeds back into new challenges, thereby continuing the process.

Volker Liebig
Director of Earth Observation Programmes

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→ EARTH OBSERVATION SCIENCE STRATEGY FOR ESA

1. Science and Technical Innovation Allied to New and Sustained Observing Systems

With the recent successes of ESA's Earth Observation Envelope Programme (EOEP), through the realisation of highly successful Earth Explorers, the launch of the first in the series of operational Sentinel satellites for Copernicus, and with the rapidly increasing power of technologies for data processing, analysis and dissemination, Europe has entered a new era in the development and exploitation of Earth observing satellites.

We now have the potential to build on and further develop the advances made in the scientific understanding of our complex planet. Moreover, we have reached the point where significant scientific and societal benefits are beginning to flow from these advances and breakthroughs. The key links in the chain are now in place to allow us to address major issues we face in responding to our changing environment and climate.

ESA's new Earth Observation Science Strategy aims to cover all areas of science to which Earth observation (EO) missions from space can make a vital contribution. The overarching goal is to challenge ESA and the scientific community to strive for major advances in knowledge along with the technological capabilities that are needed to respond to the ever-increasing societal needs associated with risks and opportunities in our changing global environment (Fig. 1.1).

The strategy sets out key goals for scientific activities along the entire chain from fundamental knowledge to societal benefits. All the links in the chain are critical, but continued advances in scientific knowledge and technological innovation are the anchor point that secures the whole.

The strategic science goals identified in this strategy are tailored to ESA's role as a science enabling organisation. The strategy identifies the areas

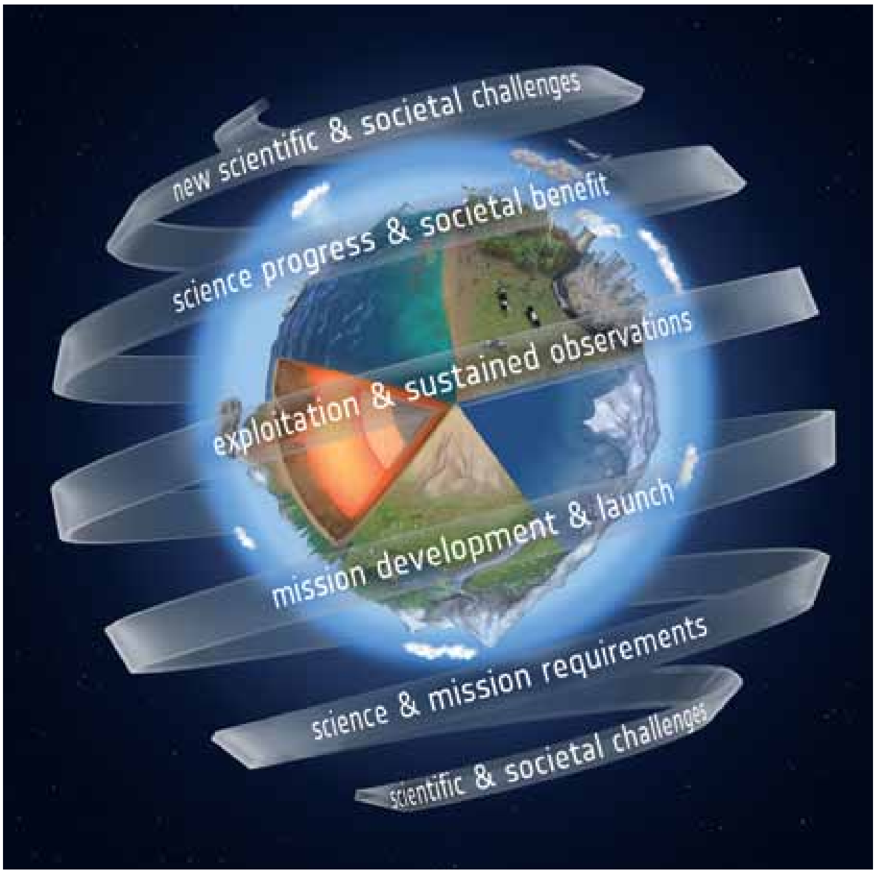

Figure 1.1. An upward spiral of innovation is needed to advance science and to respond to societal issues involving global change. Greater capabilities offer new opportunities to respond to scientific and societal challenges, thus continuing the upward spiral of innovation.

of science that ESA needs to be responsive to along the value chain from innovative missions through excellent science to societal benefits. Full implementation of this strategy will in many cases involve strong partnerships with other organisations, funding agencies and national programmes.

The specific scientific challenges involved in increasing knowledge and capabilities in the Earth science disciplines are identified in the accompanying volume, *ESA's Living Planet Programme: Scientific Achievements and Future Challenges – Scientific Context of the Earth Observation Science Strategy for ESA* (ESA, 2015). Progress in addressing these challenges will provide the foundation for the multidisciplinary science that is needed to realise societal benefits from scientific progress.

2. Context

ESA's previous scientific challenges for Earth observation from space were described in *The Changing Earth: New Scientific Challenges for ESA's Living Planet Programme* (ESA, 2006). The Living Planet programme comprises scientific and research elements, and aspects designed to support the delivery of data for use in operational services. ESA plays a key role in the coordination and progressive integration of Europe-wide Earth observation activities.

Since the publication of *The Changing Earth*, ESA and other international space agencies have launched a range of Earth observation satellites, which continue to further our knowledge and understanding of the planet. Satellites make accurate global observations and measurements, giving a whole-Earth perspective in a matter of hours. Through these observations, the evolution of our planet can be followed on timescales from just tens of minutes to decades, and even longer with follow-on missions. Observing Earth with satellites has demonstrated clearly the extent of change, with strong evidence derived from the scientific findings that humans are significantly affecting the environment and the climate (Fig. 2.1).

The demand for scientific and technological progress continues to grow in order to respond to the global issues of climate and environmental change, and to help meet the needs and aspirations of Earth's growing human population. Satellites are widely recognised as playing a critical – in fact, essential – role in implementing an effective 'Earth management system'. To ensure that the value of Earth observation both for fundamental science and for society can be fully exploited and further enhanced, it is time to revise the science strategy for ESA's Living Planet Programme.

This science strategy for ESA was developed by ESA's Earth Science Advisory Committee. A team of external scientific experts provided written contributions. Members of the wider scientific community were consulted during the preparation of the strategy, notably at ESA's Living Planet Symposium in Edinburgh, Scotland, in September 2013. The committee also took into account the recommendations made in the ESA Earth Observation Envelope Programme Science Review in May 2011.

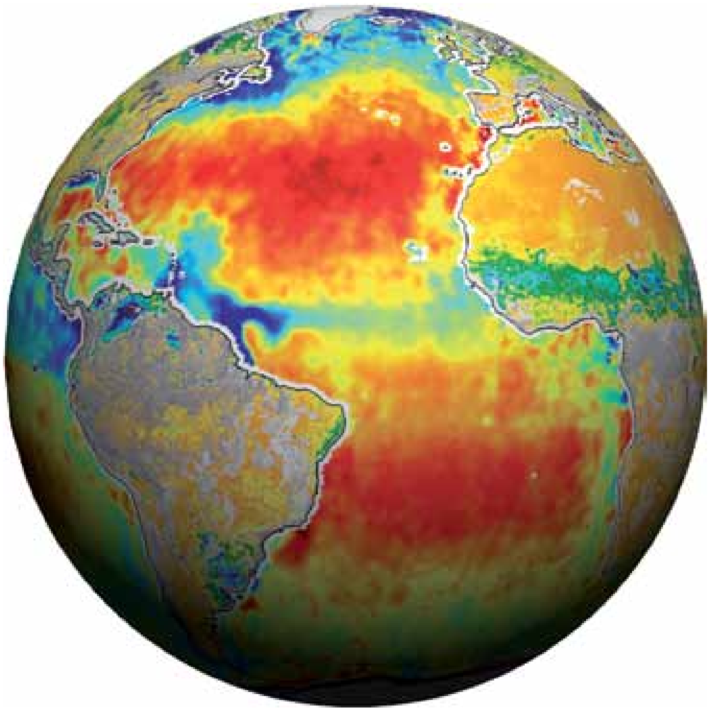

Figure 2.1. Global soil moisture and surface ocean salinity derived from SMOS satellite measurements. A global perspective is needed to address global issues. Earth observation satellites offer unique vantage points for viewing our planet globally, frequently, uniformly and in a timely manner. Satellites can make consistent measurements of even the most remote places with high revisit times, and data can be delivered to users in near-real time. (ESA/CNES/CESBIO/IFREMER/BEC/ICM)

3. Earth Observation for Society: Scientific Challenges for Earth Observation in a Changing World

The growing global population, through increasing consumption, emissions and pollution, is causing significant environmental changes that are having knock-on effects on the Earth system balance. There are persistent and observable natural changes, such as increasing urbanisation and the demand for food, water and energy, which owing to their continuity can be extrapolated into the coming decades. In addition, rapid technological advances are transforming our society.

Global trends that are significantly affecting the environment and our demands upon it (Fig. 3.1) include:

Climate change

In its Fifth Assessment Report the Intergovernmental Panel for Climate Change (IPCC, 2013) affirmed that human activities are significantly influencing Earth's climate and environment. The report highlighted the following major impacts:

- Changes in precipitation, declining seasonal snow cover and retreating mountain glaciers are altering hydrological systems and are affecting water resources in terms of quantity and quality in many regions.

- Sea-level rise will have considerable impacts on populations in coastal and island regions.

- Ocean acidification is increasing, with potentially dramatic effects on many organisms.

- Shifts are occurring in the geographic ranges, seasonal activities, migration patterns, abundances and interactions of many terrestrial, freshwater and marine species.

- Increasing climate-related extremes, such as heatwaves, droughts, floods, cyclones and wildfires, are revealing the significant vulnerability and exposure of ecosystems and human systems to climate variability.

- Climate-related hazards such as reduced crop yields and damage to property will affect many people directly, especially the poor. There are also indirect effects such as increased food prices and food insecurity.

Food and water

The vast majority of water resources are used for food production and is the main reason for increasing regional water scarcity. Food and water issues are therefore inseparable. It is estimated that global agriculture will have to more than double its production over the next 40 years. The goal is to use water more efficiently, reduce soil erosion and degradation, minimise the use of energy and resources such as fertilisers and pesticides, while maximising crop yields under uncertain natural and economic conditions.

Natural resources and energy

Society and industry need a wide range of natural resources with energy being one of the most important. To help find, exploit and secure traditional and new sources of energy while minimising environmental impacts is a major challenge of the 21st century.

Figure 3.1. Global trends will result in huge pressures on the Earth system, presenting new challenges to society. Earth observation from space will deliver global and timely information needed to help society respond to these challenges. Rapid developments in information and communication technologies will revolutionise our ability to exploit this information to the full.

Disasters

Society will become more vulnerable to natural and manmade disasters. Climate-related hazards (storms, floods and droughts) are expected to increase. Hazards become disasters when rare events such as earthquakes, tsunamis, volcanic eruptions, storms, floods and droughts exceed the coping capacity of the affected system. Consequently, improved knowledge of how systems respond to disasters is essential for improving their resilience and capacity to cope.

Health and pollution

The health of the human population could greatly benefit from operational Earth observation systems, especially those focusing on monitoring and reducing pollution of the air, water, soil and land. Documentation of the impacts of pollution is needed, as well as information on the success of mitigation measures.

Biodiversity

As the biosphere has evolved over the past 2.5 billion years, the composition of species has changed enormously, as species have continually adapted to and influenced various environmental conditions. The advent of human activity, particularly through agriculture and industrial production, largely changed the feedback mechanisms and interactions. Today, in order to ensure the functioning of the biosphere, its elements must be protected and the human impacts managed sustainably.

Concerns about the impacts of these changes have led to a large and growing body of international organisations and agreements that focus on restoring, protecting and sustaining healthy systems. Data, information and knowledge are needed to design and implement adaptive approaches to sustainable development that maintain the capacity of the environment and ecosystems to support the services valued by society.

Observations provide the foundation of scientific knowledge to understand and protect biodiversity and ecosystem services, and to help mitigate and adapt to environmental and climate change. Modern science relies on observations and numerical models to capture, understand and predict variations and trends across scales in both space and time. Earth observation satellites are uniquely placed to deliver global information on the state of the planet and the environment, even in the most remote and difficult to access regions. They ensure global coverage with adequate spatial and temporal resolution and continuity to capture both natural changes as well as the footprint of human activities.

Complementing and enhancing the value of *in situ* observations, Earth observation from space is critical to address the significant problem of under-sampling. Satellite observations are repetitive and homogeneous, so that time-varying phenomena can be distinguished. Satellites are able to provide synoptic observations of spatial distributions from local to global scales, and long-term time series of changes in these distributions as well as short-term temporal variability. Moreover, satellites provide nearly simultaneous and near-realtime observations of many different variables, allowing the state of the whole system to be assessed, and interrelations within the system to be identified.

Long-term observations of individual Earth system variables and parameters have an intrinsic value for understanding long-term processes. However, addressing current and future challenges, and filling gaps in our current observing capabilities, will often demand an evolution from individual observations towards integrated observing systems (Fig. 3.2). Scientific applications linked to societal needs will drive the design of these observing systems. Integrated observing systems can incorporate data in a multidisciplinary fashion (e.g. geophysical and ecological observations and models) in order to study and understand processes, validate theories and constrain simulations and forecasts with numerical model simulations. In order to capture the important phenomena and processes, integrated observing systems must provide information on a wide range of scales: spatially, from local to global phenomena; and temporally, from seconds to hours to decades and longer.

Figure 3.2. ESA is involved in partnerships with international scientific programmes, regulatory bodies, space agencies and coordination activities to respond to global challenges. ESA provides the core competences in space technologies and the data needed to address these challenges.

Technological trends such as cloud computing, big data, data sharing and open data distribution, as well as global connectivity, are fundamentally changing our ability to access, synthesise, visualise and disseminate information on the Earth system. The increasing power of high-performance computing is allowing Earth system models to be run at much higher spatial and temporal resolutions, making further demands on observations to evaluate their performance.

4. The Strategic Response: Towards Earth Science for Society

The Earth system behaves as a single, highly coupled system comprising physical, chemical and biological components and processes, on which humanity is now having significant effects. There are complex interactions and feedbacks between the components that cross traditional disciplinary boundaries of study, and take place over a wide range of spatial and temporal scales. Even in the absence of external forcing, the Earth system exhibits considerable natural variability, which needs to be understood and distinguished from human-induced trends.

The societal challenges we face require a strategic, sustained scientific response. The Earth Observation Science Strategy for ESA identifies the following key elements as the foundation for this response:

— Ground-breaking exploratory missions integrated into flexible observing systems for Earth system science.

— Sustained observations to understand and attribute trends beyond the expected variability.

— International cooperation to provide an integrated, optimised Earth observing system that can fill gaps in observational needs and build new capabilities in a cost-effective way.

— Translational science to synthesise and adapt the data streams from individual instruments and satellites into knowledge.

— Wide communication and dialogue with individuals beyond the scientific sector to help explain the value, opportunities and inspiration provided by Earth observation from space.

Stringent, transparent processes must continue to be applied to mission preparation, selection and implementation by drawing on impartial advice from advisory bodies, such as the Earth Science Advisory Committee, Mission Advisory Groups and Science Advisory Groups. This will ensure feedback and translation of scientific requirements from the proposal to implementation stages, and will increase the interest of different scientific and user groups.

4.1 From Ground-breaking Individual Missions to Integrated, Flexible Observing Systems

Excellent science and technological innovation through exploratory missions are the foundations on which the whole of this science strategy is based. ESA's Earth observation missions have led to major scientific advances and have laid the foundation for operational systems such as Copernicus. Today's major scientific questions require an Earth system science approach, which requires a range of observations that generally exceeds what individual missions can offer. The significant next step is therefore to go beyond the deployment of individual missions to the construction of an integrated observing system (Fig. 4.1). Such a system would comprise an optimised constellation of satellites measuring different parameters, along with enhanced networks of *in situ* data as well as airborne data.

An Earth system science approach is needed to understand and predict environmental changes and to understand fundamental science issues. This approach is not restricted to a single, uniquely defined methodology, but

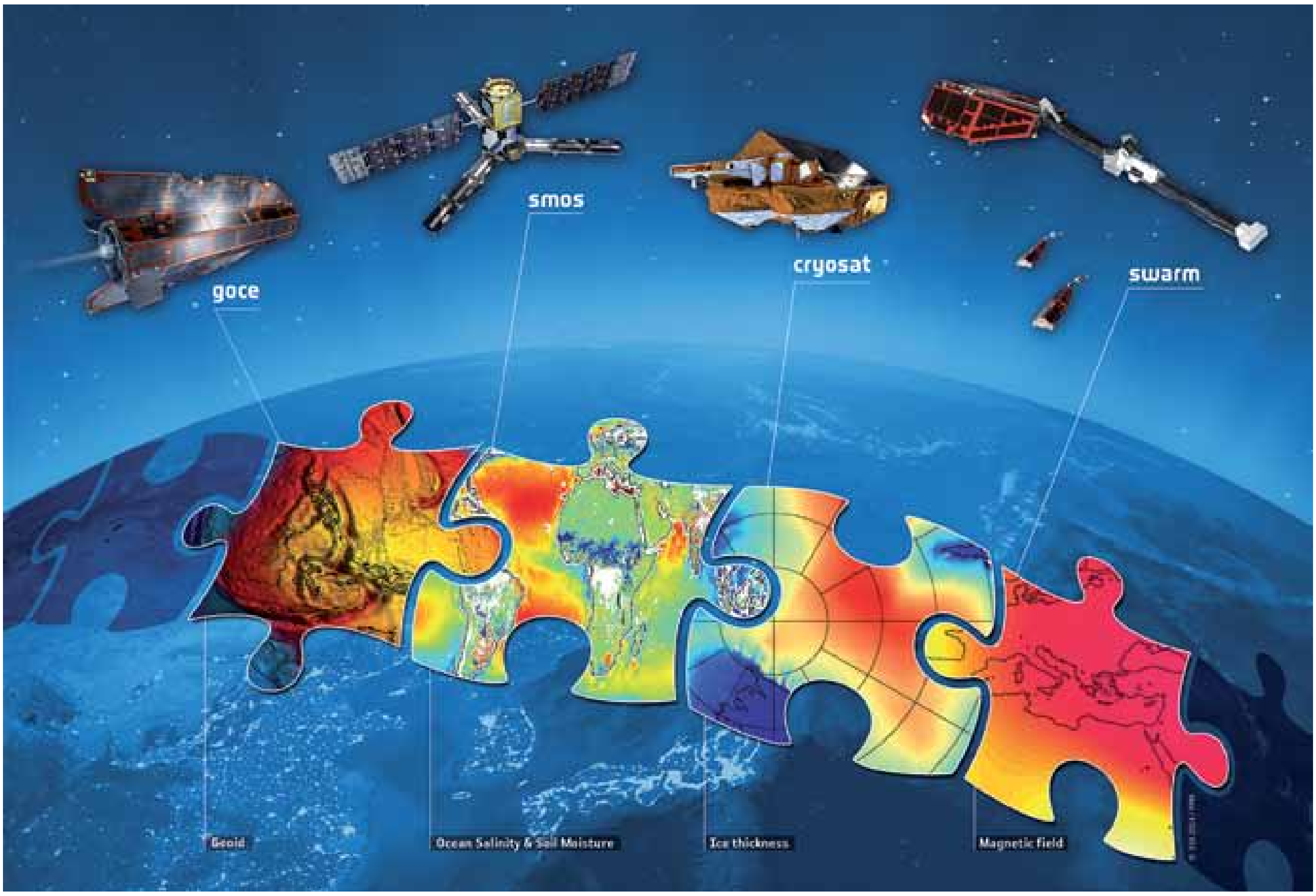

Figure 4.1. The interlocking of datasets from different satellites. An integrated observing system provides scientists with unique insights into the workings of the different components of the Earth system (ocean, atmosphere, land, cryosphere, solid Earth, the biosphere) and how they interact. Our ability to understand and model the Earth system, and forecast its evolution, depends critically on the synthesis of all these sources of data.

embraces and synthesises a range of complementary methods, including detailed studies of individual Earth system components (atmosphere, oceans, land, solid Earth, the cryosphere and the biosphere), analyses of the couplings and interactions between components, and a more holistic approach involving, for example, quantification of cycles – flows of energy and mass transport through the whole Earth system. Finally, attribution of cause–effect relationships is required, allowing human-induced effects to be distinguished from natural variability.

The recognition of the need for Earth system models for climate and environmental predictions, involving the well-matched integration of model and *in situ* components, needs to be mirrored in the development of an integrated Earth observing system. Without such a system, the observational foundations of Earth system science would be severely diminished, in particular our ability to test the reliability of models as tools for prediction and risk assessment. Without such a system, our ability to provide the suite of diverse observations almost invariably needed to respond to the major societal issues we face would also be severely impaired.

The complementarity of satellites and satellite-borne instruments must be planned and carefully designed in order to maximise measurement synergies. Flexible satellite mission concepts will also be essential for optimal, cost-effective solutions. Concerted efforts will be needed to develop and integrate *in situ* networks and airborne systems in order to improve measurement accuracy and spatial/temporal sampling, as well as to extend the range of types of measurement.

The techniques of data assimilation, which combine observational and model data to maximise information and to set initial conditions for forecasts, will have to be extended considerably. At present, the usual approach to data assimilation is to assimilate observations of one Earth system component into a model of that component only. Such methods need to be extended to assimilate simultaneously and consistently observations of multiple Earth system components into multicomponent Earth system models.

By observing system simulation experiments, such a capability could provide valuable quantitative information on the benefits of different design options for an integrated Earth observation system. The strategic use of this design technique would also accelerate the implementation of model improvements, and would prepare modelling and software systems, as well as the scientific community, for the rapid exploitation of data as soon as they are available online.

Strategic Science Goals

— ESA must continue to fulfil its crucial role in developing and deploying cutting-edge exploratory missions in order to address new scientific questions that emerge to fill knowledge gaps in response to societal issues.

— The complexity of the Earth system and the scientific challenges of the 21st century demand an integrated and flexible observing system, designed and planned to exploit synergies between different satellites and instruments. An end-to-end, 'systems engineering' approach is needed to take advantage of improved models and data assimilation methods to optimise design through observing system simulation experiments, so that the value of a mission can be better quantified before launch.

— Flexibility in the kind of missions developed and deployed for cost-effective and responsive solutions to consolidated requirements is essential. This may involve relaxing any sharp distinctions between different classes of Explorer-type missions, as well as supporting the deployment of entirely different types of mission (e.g. small satellites).

— Calls for new missions will stress the dual importance of scientific innovation and societal impact. Mission selection criteria will include the need to respond to this science strategy, where this dual importance is emphasised.

— The nature of the calls will be adapted according to circumstances and opportunities. In order to respond to societal issues in a timely manner, some calls will be targeted at specific areas of science. At other times, calls for ideas of a more open kind will be encouraged to allow for novel, possibly one-off missions, which may not necessarily have an immediate societal impact, but which represent an important developmental step in this direction.

— To achieve greater responsiveness to scientific opportunities and societal needs, the development of missions from concept to deployment must be accelerated as far as possible. The time span from concept to deployment has to be kept streamlined.

— Earth system science requires the integration of diverse data streams, as is invariably needed in order to address societal problems. Improving *in situ* observational networks, and the infrastructure for data processing and dissemination, is therefore vitally important, taking advantage of developments such as cloud computing for efficient data processing.

— Delivering science data in near-real time, where needed, to allow weather and ocean forecasting agencies and other organisations to incorporate data, at least passively, into their operational systems, and thereby provide rapid feedback on data quality. Rapid data delivery will also offer greater opportunities for applications when information is time critical, such as in connection with natural hazards.

4.2 Building on Innovative Exploratory Missions to Develop Sustained Observing Systems

All components of the Earth system vary on a range of spatial and temporal scales. For example, cloud formation processes in the atmosphere can occur over minutes, variations in the masses of ice sheets may be seen over centuries, while many geodynamic processes take place on time scales of millions of years. Of particular interest is the detection and attribution of trends that, from a human and practical perspective, can be considered to be systematic changes, over a decade or more. The notion of a trend depends on the time perspective; an apparent trend over a decade, say, may switch sign when seen in a longer time record. Decadal and longer trends induced by human activities – notably fossil fuel burning, land-use change and greenhouse gas emissions – are major concerns today.

In order to detect, understand and attribute the causes of long-term trends in the Earth system, and to distinguish such trends from short-term variability, sustained observations from space are essential, along with ancillary ground-based data. These have to be based on sustained observations of every component of the Earth system. For instance, in global change science and its applications (e.g. the management and protection of terrestrial, coastal and marine ecosystems), attributing heat waves, storm surges or droughts as features of regional and global climate change would not be possible without the climate norms derived from long-term observations.

Sustained observations are also essential if scientific capabilities in Earth observation are to make the transition to practical applications. Without the security of sustained observations, potential end users are likely to be reluctant to invest time and money in building infrastructure and developing markets. Experience shows that many valuable applications have been found for data from satellite missions lasting five to ten years, but, without security of data supply, these applications are difficult to scale up into transformative activities that could bring about major beneficial changes in society and the economy.

The idea that a novel instrument technology can lead to scientific advances and then to hugely transformative applications now needs to be broadened to the science and derived services relevant to the whole Earth system. With its heritage of innovative technology and science in ESA's Earth Observation Programme, the European Copernicus Programme offers great potential for the subsequent deployment of operational missions, with Europe in a world-leading position.

The vision for the coming decades can be of a virtuous upward spiral from innovative science and satellite missions designed to increase scientific knowledge in response to societal issues, through to their operational deployment in an Earth observing system of continually increasing capability. To effect this transition from technical and scientific innovation, key Earth observation programme elements will need to be in place. These include satellite missions that push out the boundaries of scientific and technological capabilities as the drivers of innovation, a programme that adapts and prepares the new observational capabilities for operational deployment, including research and development for new scientific applications, and a programme to build, with increased international collaboration, a truly integrated and optimised satellite Earth observing system.

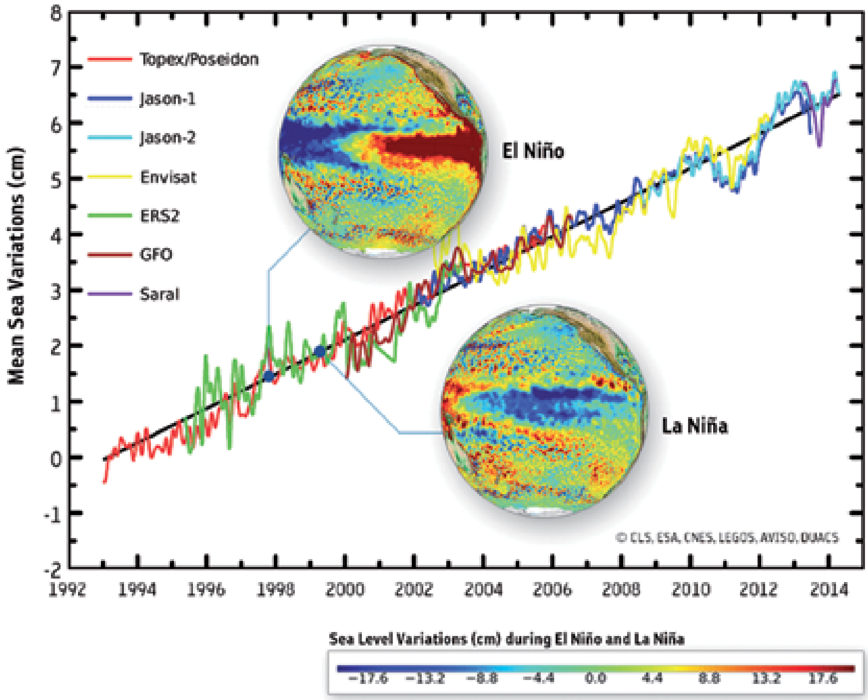

Figure 4.2. Global trend in mean sea level as derived from a series of altimeters on various satellites. Sustained observations are essential to understand the processes that can lead to long-term trends in the Earth system and to discriminate between long-term trends induced by human activities and shorter-term natural variability (e.g. El Niño, La Niña). Sustained observations are also vital to turn scientific advances into sustainable services for the benefit of society. (CNES, ESA, LEGOS, CLS)

Because of the relatively limited lifetime of any individual satellite, sustained observations of the various quantities required by Earth system science and applications have to be derived by piecing together datasets from a series of satellites deployed in sequence (with sufficient overlaps to allow the inter-calibration of sensors). This piecing together of short time series into longer ones is a considerable challenge, since it is essential that the series can be matched up, i.e. that errors (especially biases) in individual time series are removed (see Fig. 4.2).

Such was the motivation of ESA's Climate Change Initiative, which is designed to produce carefully calibrated, long time series of Essential Climate Variables. To achieve this, a concerted of data reprocessing effort is needed, involving scientists from many disciplines. There needs to be an ongoing, coordinated activity to continue data reprocessing as improvements in processing algorithms are developed by the scientific community and as new satellite datasets come along, which need to be harmonised with those of past missions. The need for long time series also highlights the importance of strengthening *in situ* networks across the globe. Besides their value as independent, complementary observations, *in situ* networks also enable accurate calibration and validation of satellite data products.

Long-term, carefully calibrated and documented datasets of the Earth system derived from Earth observation satellites will become a legacy of the highest importance for science, policy makers and society. It is essential that such data are preserved for posterity.

Strategic Science Goals

— Careful consideration has to be given to the extension of all successful missions and mission capabilities where there is a clear need. Such extensions need to be prioritised scientifically against alternative opportunities given potential programmatic constraints. They must also be considered in a wider international context of data provision by other space agencies. A stringent process for reviewing mission extensions is essential, informed both by the scientific benefits and by their wider (actual or potential) societal benefits.

Careful consideration is needed of how a mission could transition, if appropriate, from scientific advances and benefits into sustained operational capabilities of societal value.

— A vibrant and innovative observing system development programme needs to be in place to take the technological innovations derived from the more exploratory classes of missions, and transition them into systems ready for operational deployment. These operational systems will also be expected to enable research and development of new scientific applications. The Earth Watch component of ESA's Living Planet Programme (or its programmatic equivalent) needs to be reinvigorated if the science-to-society aspirations of this science strategy are to be realised to a significant degree.

— A well-coordinated programme needs to be in place for data reprocessing to implement scientific algorithmic improvements and to harmonise time series from different satellite instruments – the programmatic extension of ESA's Climate Change Initiative. Such reprocessing of data on individual variables will draw maximum benefit from relevant information derived from analysing and reprocessing other variables. As data improvements are delivered from the science community into operational delivery systems, a fast, repeating feedback loop from the identification of problems with data to improved algorithms, feeding into new operational processing, is essential. It is also essential that such data are preserved for posterity.

— The creation of high-quality, comprehensive metadata to enable all users to judge the fitness of datasets for their particular uses. Besides the essential characterisation of errors that should accompany all datasets as a matter of routine, there should be additional complementary metadata that give a wider perspective on the value of the data for particular uses (e.g. significant events in data processing; the experience of use of the data by others). Without such information, the datasets will be of limited value, especially after a significant time has passed since the observations were made.

— Increasingly, the methods of data assimilation currently used in so-called global reanalyses of atmospheric data, for example, should be brought to bear in the wider Earth system context. Besides the synthesis of individual variables from different data sources that data assimilation affords, it will be possible to estimate additional quantities that are not directly measured, such as fluxes, which are important in an Earth system context. This should be done in full knowledge that model shortcomings will have to be overcome iteratively before the resulting datasets can be used reliably (e.g. to identify and attribute trends). Achieving this overall vision will require, in the long term, a harmonised, self-consistent, four-dimensional (spacetime) digital rendition of the whole Earth system.

— Close links between the observational and modelling communities are needed to ensure that new variables to be observed are well linked into Earth system models, and vice versa. In addition, while striving for a coherent set of harmonised observations for the Earth system, priorities need to be elaborated, in order to ensure the timely provision of input data for models.

4.3 Integration with International Assets and Observing Systems: International Cooperation to Provide and Support a Coherent Range of Mission Concepts

An integrated, comprehensive and continually improving Earth observation system in space, along with advanced technologies for data processing, synthesis and dissemination, would provide the vital infrastructure that is needed to allow science to respond to environmental and climate challenges and opportunities. A term for such a system has already been coined – the Global Earth Observation System of Systems (GEOSS).

There is now a pressing scientific and societal need for such a GEOSS. In recent decades important steps have been taken in the development of such a system as more and more satellites have been deployed. Individual space agencies around the world have, to a large extent, pursued their own agendas, although there have been some good examples of international cooperation in the Earth observation sector.

No single space agency has the resources or capacity to deliver the required infrastructure at the required pace. Increased international collaboration and coordination is essential to bring this about. The broad picture should be one of collaboration extending from the development of novel observation concepts to the joint creation of a globally integrated, 'systems engineered', optimised observing system that is sustained and continually enhanced as new technological capabilities, developed in experimental programmes, are fed into it. Scientific and technical innovation must remain key drivers for this ongoing enhancement.

Coordination mechanisms for an internationally evolving Earth observation system in space are already in place, through the Committee on Earth Observation Satellites (CEOS). The CEOS concept of virtual constellations (Fig. 4.3) would help promote the integration of global Earth observation systems along geophysical themes (e.g. atmospheric composition; sea-surface temperatures). International collaboration should include the sharing of resources for system calibration and data validation, the development of data handling and dissemination technologies, and agreement on data protocols. Rapid and open access to publicly funded Earth observation data from space will be essential for effective collaboration.

Figure 4.3. The construction of a virtual constellation of satellites from different space agencies. International collaboration is needed for the cost-effective and optimal design of a global integrated observing system. Such a system could involve virtual constellations, as illustrated here, or formation flying and convoys. International collaboration should extend to open access to data (from publicly funded satellite missions and projects at least), data sharing, data quality assessment and interoperable data processing systems.

Strategic Science Goals

- Increasing international collaboration to achieve stronger coordination of the overall Earth observation system, leading to more effective overall use of resources; higher scientific and societal impact and return on individual missions; and avoiding, or considering carefully the merits of, stand-alone or duplicative missions.

- Fostering the integration of global assets through the mutual provision of platform space for instruments and exchange of payloads.

- Increasing the use of thematic or virtual constellations, comprising carefully coordinated contributions from different space agencies, with consideration of observation synergies already at the mission planning stage.

- Increasing implementation of formation flying and convoys, with multi-agency contributions, to satisfy the scientific need for contemporaneous observations of different elements of the Earth system.

- Increasing international coordination and prioritisation of satellite deployments to avoid data gaps in key observations.

- Broadening, through international collaboration, the spectrum and range of missions to form part of the GEOSS.

- Ensuring greater integration and interoperability of data processing assets, with free and open access to publicly funded satellite data, and minimising any hurdles to data access.

- Promoting international coordination on data standards, measurement traceability and metadata, and the integration of data portals to achieve, in effect, a worldwide web of well-documented, easily accessible Earth observation data.

4.4 Realising a Fully Integrated System for Translational Science

While Earth observation data from satellites have great potential value for society and the economy, fully realising this potential presents a challenge in itself. With the possible exception of simple photographic (optical) imagery from space, Earth observation data may not be of immediate use to non-expert users. There are often significant gaps to be filled in the value chain between satellite measurements and desired applications (Fig. 4.4).

Such data gaps can arise for a number of reasons. The satellite measurement is often not a direct measurement of a quantity of interest (e.g. radiance is measured rather than temperature). The spacetime sampling and resolution of the measurement may need to be adapted for an application not originally envisaged. A particular data stream may need to be blended with other data streams, including model data, to provide usable information. Finally, the information may need to be tailored, and often reduced, to feed into decision-making tools used by potential end users.

Scientific knowledge and expertise are central to the necessary conversion of ‘raw data’ into applicable, tailored information. Without the involvement of trained scientists, the compromises that are often needed to distil complex information down, for example, to simple decision choices cannot be done with any confidence. Translational science is the technical channel of

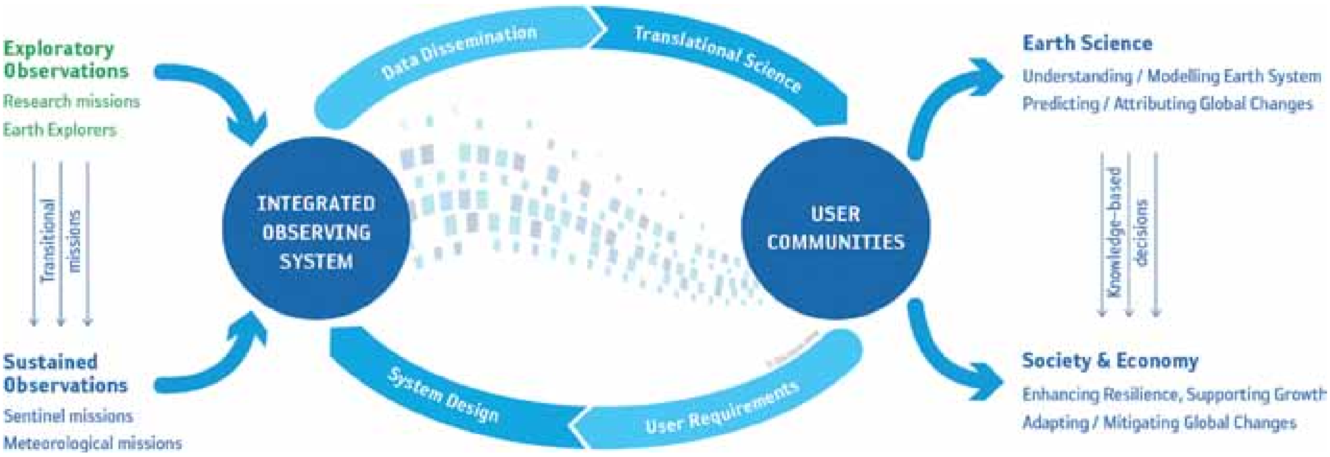

Figure 4.4. The value chain from the data gathered by an integrated observing system and their synthesis into actionable information to support a wide variety of user communities. The integration of these key elements – data dissemination, translational science, user requirements and system design – into a seamless and coherent system would maximise the scientific and societal benefits of the data. The design criteria for new Earth observation missions will need to be flexible, and the time from concept to deployment will need to be speeded up as far as possible, as will the transition from exploratory to sustained observations.

communication between the scientific users of Earth observation data and users in the world of economic and societal applications.

Translational science needs a dedicated effort on the part of scientists to work closely and routinely with nontechnical end users. It would benefit from increasing numbers of people who are professionally motivated to sit at this interface between the basic science and practical applications, and who are recognised and rewarded for this important role. ESA can play an essential part in nurturing and supporting the development of this class of scientists, and in developing science translational activities in a precompetitive (from a commercial point of view) arena of open innovation.

Strategic Science Goals

— Sustaining a vibrant and proactive programme of science translational activities to pull science and technical innovation in Earth observation through to societal and commercial applications, with ESA as the recognised institutional connector between scientists and the outside world.

— Drawing on the experience gained thereby to challenge and steer science and technology in new directions, feeding back into proposals for new missions and enhancements in data handling capabilities.

— Building capacity by fostering partnerships between skilled Earth observation scientists and nonexpert decision makers and commercial partners.

— Maintaining and advocating an open data policy for open innovation and knowledge transfer, and minimising as far as possible any impediments to data access.

— Achieving major advances in adaptable data handling (e.g. cloud computing) tools, and in the interoperability of these tools as far as is practicable.

— Building sophisticated data visualisation tools to convey the power and potential of Earth observation in applied settings, and to stimulate imaginative designs of new applications.

— Accelerating the timely delivery of data from satellites to scientists and end users for the desired application; in some cases this will involve delivery in near-real time.

— Ensuring that the basic measurement data are supplemented routinely and consistently with essential metadata, allowing 'science translators' and end users to judge whether the data are fit for a particular purpose (metadata to include essential error characteristics, as well as commentary data describing other characteristics of the data and experience of its use by others).

— Developing observations based on new science and technologies to fill observational gaps.

4.5 Wider Communication: Data and Science Outreach, Communication and Citizen Engagement

The delivery of the benefits to society of advances in Earth observation science and technology necessitates, as another key link in the chain, a much more sophisticated approach to communication. Efforts must be made to move away from a 'science and society' approach, where the two stay largely separate, to a more 'science in society' approach, where they are much more fully integrated. This integration requires that the use of Earth observation from space be broadened to those areas that currently do not utilise Earth observation data. It needs to be driven by a mix of Earth observation scientists, natural and social scientists and communication specialists.

Traditional forms of communication by science and technology agencies have often been asymmetrical: audiences are invited to listen to what agencies want them to hear. The modern movement in science communication is that it should be a two-way dialogue – to engage rather than just to inform. This involves not only tailoring information to a target audience, but setting it in a context with which the audience can clearly identify. ESA needs to be in the vanguard of this movement.

For ESA, the benefits of adopting a more sophisticated approach to communication include: building a better public understanding of the benefits of investing in innovative science and technology at the start of the value chain; enhancing ESA's reputation and international prominence for its central role in developing Earth observation satellite and data-handling infrastructures; breaking down the language and cultural barriers between physical and social scientists; ensuring the participation of wider sections of society and commerce in driving innovation forward, and in sharing the pleasures and benefits of doing so; and providing inspiration for young people to study science, technology, engineering and mathematics as a prelude to entering the challenging, exciting and widely beneficial world of Earth observation from space.

Free and open access to diverse interrelated datasets, beyond those of Earth observation, is an integral part of modern communication. Rapid innovations in digital technologies (e.g. social media, mobile devices, smartphones), digital networks (the internet, the Web of Knowledge, the Internet of Things) and computing power and architecture (the cloud, big data, exascale computing) are transforming the ways we communicate, access and exploit data (Fig. 4.5).

Teams of Earth observation scientists and applications specialists around the world can now access a wide range of open data across disciplines, and can combine and remotely process them on the cloud to tackle the kind of complex, multidisciplinary problems that simply could not be addressed even a few years ago. This revolution is creating a new sector in society, that of the 'citizen scientist'. This sector, with its diverse and multi-talented membership, is becoming a significant force in driving forward this revolution. ESA needs to be fully engaged with these revolutionary developments.

Figure 4.5. Communicating advances in science and technology must be an integral part of the science-to-society value chain, and not just an afterthought. The complexities of environmental and climate change need a well-informed community of decision makers and citizens to understand the nature and importance of the actions that must be taken. Science communication must be a two-way dialogue, involving professional communicators, and making use of modern technology to involve citizens.

Strategic Science Goals

— Making a concerted effort to raise the scope and level of sophistication of ESA's communication activities by bringing together groups of Earth observation scientists, social scientists and communication specialists.

— Creating new and imaginative forums for two-way interactions between these groups of people along with target audiences in commerce, government and society.

— Increasing the exploitation of modern digital technologies and communication networks, such as the web, to engage citizens in new ways, and to inspire them to participate in the exciting and worthwhile endeavour of deriving benefits of Earth observation from space.

— Using free and open access to data, including those of operational missions, and powerful data processing tools such as the cloud to broaden the participation and interconnectedness of people who could benefit from the use of Earth observation data.

— Drawing the 'citizen scientist' much more into this collective endeavour, as a particularly effective way of communicating the benefits of Earth observation, in leading novelty in its use, and inspiring young people to get involved and to take up careers in the field.

5. Summary and Way Forward

The overarching objective of this Earth Observation Science Strategy is to challenge ESA and the science community to enhance their already crucial roles in delivering the benefits of Earth observation from space to science and society. The environment, climate and resource issues faced by society today are enormous, as are the opportunities now available in Earth observation to respond to them. The discipline-based scientific challenges identified in ESA's Living Planet Programme: Scientific Achievements and Future Challenges: The Scientific Context of the Earth Observation Science Strategy for ESA (ESA, 2015) are indicative of the scientific advances that will be needed in a rapidly changing world.

The key messages of this science strategy are:

— Continuing innovation in exploratory satellite missions is the essential starting point of the delivery and value chains. Scientific and societal issues demand, in addition, an Earth system science approach, which necessitates an integrated Earth observation capability in an optimally designed end-to-end system. Future missions must promote the dual benefits to science and society, and maintain innovation through a mix of responsive, targeted calls as well as open calls. The speed of deployment and the flexibility of mission concepts (avoiding rigidity in mission classes) will be very important.

— From the starting point of innovative missions, both scientific and societal needs demand sustained observations and technologies for filling gaps in the current observing systems and capabilities, as well as diligence in ensuring data quality and in data preservation. The evolution of appropriate missions into operational Earth system monitoring must be carefully planned in the future. A programme to develop transitional missions will be needed to effect this transfer.

— There should be a concerted and proactive international collaboration to optimise the development of a global, integrated Earth observation system, leading to more effective overall use of resources and avoiding data gaps in key observations. This could be achieved by making use of formation flying, mission constellations in space and ensuring the interoperability of space and ground segments.

— An essential link in the science-to-society value chain is translational science to adapt data and scientific capabilities to specific end-user applications. Such knowledge and capability transfers work both ways. Experience gained from responding to societal needs stimulates new ideas for science and new missions. The enhancement of data handling capabilities, an open data policy and easier access to data are necessary adjuncts.

— It is necessary to raise the scope and level of sophistication of ESA's wider communication activities, including forging stronger links between Earth observation scientists, social scientists and communication specialists, as well as exploiting modern digital technologies and communication networks and providing opportunities for wider access to free and open data. Modern technology allows citizens to participate in the challenge and benefits of exploiting Earth observation, as well as in driving innovation.

ESA must continue to fulfil its critically important role as a knowledgeable agency to provide the essential infrastructure for and to nurture the scientific community. This role must be undertaken in close partnership with national and international agencies, and with funding bodies, to deliver the crucial benefits of Earth observation from space for science and society.

→ APPENDICES

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Acronyms

CEOS	Committee on Earth Observation Satellites
ESA	European Space Agency
ESAC	Earth Science Advisory Committee
EOEP	Earth Observation Envelope Programme
GEOSS	Global Earth Observation System of Systems
IPCC	Intergovernmental Panel on Climate Change
SMOS	Soil Moisture and Ocean Salinity

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