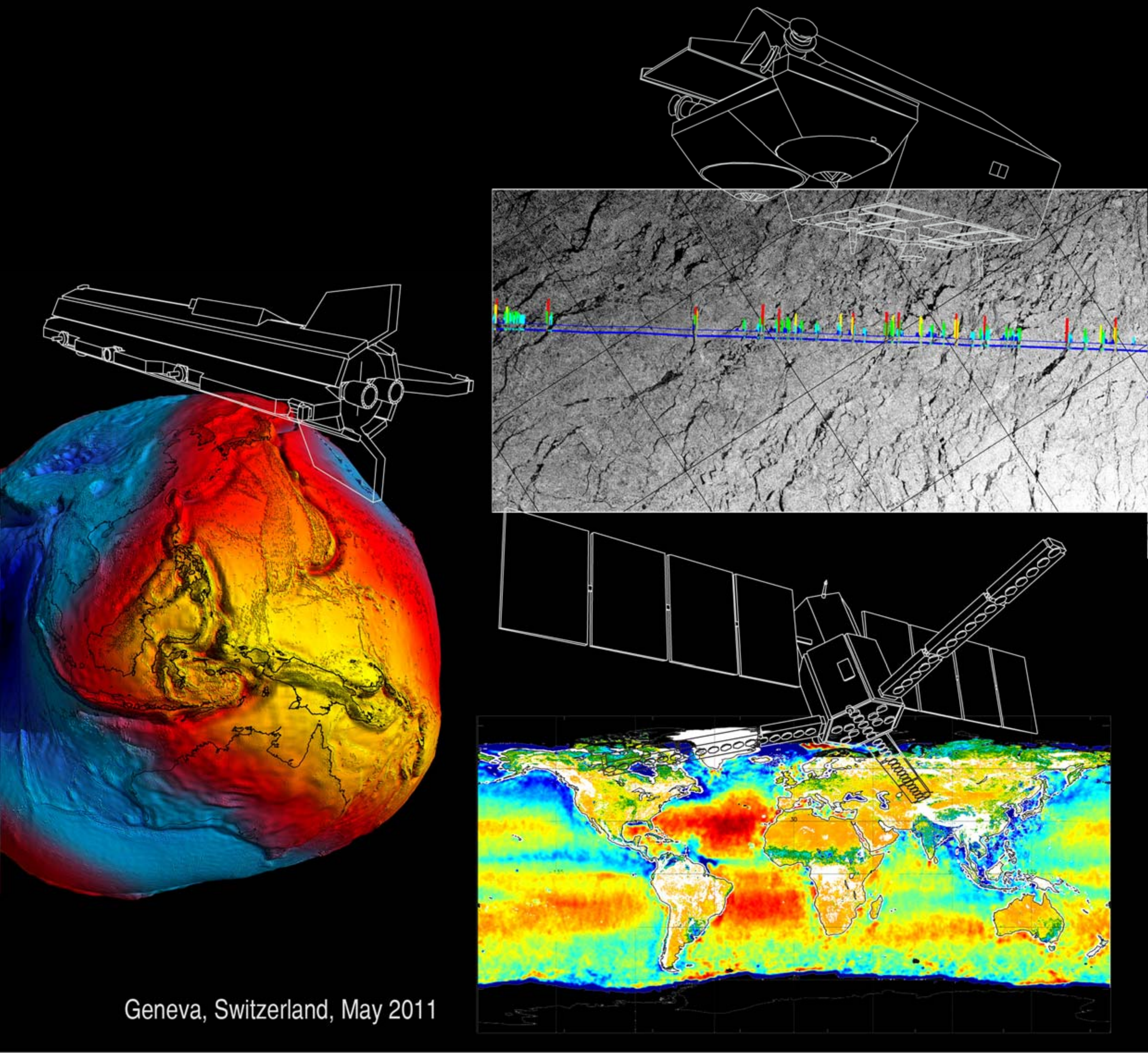
The European Space Agency Earth Observation Envelope Programme

Science Review Report 2011



Geneva, Switzerland, May 2011

The European Space Agency Earth Observation Envelope Programme

Science Review Report 2011

Assessment of the Science Benefits
of the European Space Agency's
Earth Observation Envelope Programme (EOEP)

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Executive Summary

The changing Earth system poses significant short- and long-term scientific challenges and opportunities for Earth observations, especially those from the unique vantage point of space. To understand the changes in the Earth system and its major domains (i.e. atmosphere, oceans, continents, cryosphere, and biosphere), and the complex interactions among them requires sustained and international commitment, to which Europe can respond through the EOEP. The Earth Explorer missions are offering new observational capabilities to explore and understand the Earth system, as a complement to the Earth Watch missions (such as "legacy" missions for ERS and Envisat). These missions are now fulfilling the ESA Living Planet strategic objectives and they are considered as a major component of the global Earth observing system.

The EOEP has evolved very successfully during the past decade in developing, launching and operating these state-of-technology space-based Earth observing satellites. The EOEP has emerged as a sustained technology programme at very high innovation level and it has produced substantial scientific output with significant impact on our understanding of the Earth's complex system and its natural behaviour. The ongoing success of the Programme has put ESA at the forefront of global Earth observation programmes worldwide. Continuing leadership in the EO space sector is expected from ESA on behalf of Europe for the future.

ESA has taken full advantage of rapidly emerging computing, information and telecommunication technologies to receive, process, archive and distribute vast amounts of observations and information resulting from these missions to enable world-class and leading-edge scientific exploration and discoveries of the complex Earth system and its changing climate. Thousands of scientific and technical publications, which describe findings and discoveries based on ESA missions, are published in the open literature (over 1000 peer reviewed publications in the last 4 years). In addition, observations and resulting information from these missions are made available to large numbers of decision makers through public private partnerships, as well as to an impressive number of international government and non-government organizations. Such innovative use of EOEP observations (including those of ERS and Envisat) and information has extended the benefits of EOEP well beyond the scientific community to European and global citizens.

Scientists are an integral part of the end-to-end process of mission definition, technology development, mission formulation development, implementation and exploitation phases of EOEP. Scientific excellence and technological innovations together with a competent ESA team have led to a world-class programme that is now supported by a vibrant community of European experts. The best indicators of EOEP success during the latest period are: 1) successful launch and operation of three Earth Explorer missions, with five additional missions in different phases of development; 2) record turn-around time (few months after launch) and delivery of high quality observations from Earth Explorers and Earth Watch missions to scientists and other users; 3) large numbers of users who are able to access, analyze and publish scientific and technical papers and to make informed decisions for management of natural resources, risks associated with natural hazards, climate change and environmental stewardship; 4) record numbers of very high quality scientific and technical

publications in prestigious journals; 5) greater involvement and partnerships with international organizations, programmes and scientists; and 6) major efforts in education, training and capacity development, and communication and public outreach to convey the benefits and excitement of the Programme throughout Europe and world-wide; 7) strong scientific ownership of the missions throughout the mission lifetime. ESA has also enabled significant progress in promoting greater use of observations from multiple sensors/satellites (Earth Explorers, Envisat, ERS) in conjunction with Earth/Climate System models to demonstrate the benefits of the synergy among these satellites together with those of its international partners (e.g. JAXA, NASA).

ESA has developed a comprehensive approach to integrating science, technology and exploitation in EOEP, which are fundamental to its success. The Programme has managed to stay abreast of ongoing rapid changes taking place in all aspects that affect its development and implementation, namely rapidly evolving scientific focus and associated requirements, as well as very fast evolving technology. The 'Envelope' concept, which provides flexibility and agility in the implementation of the EOEP, is of key importance to address the highly challenging science goals while producing high scientific quality results. The EOEP has excelled in all aspects of the Programme, which can be maintained only with sufficient and sustained investment in the next phase. The solid foundation built by the EOEP during the past decade is capable of carrying out this successful legacy into the next phase of EOEP. In particular, the Programme and its impressive network of scientists, technology experts, engineers and national and international organizations and value added sector cannot be maintained without sustained financial commitment and support during next decade. We would like to convey the following points to the ESA Programme Board for Earth Observation and Council Members:

- The changing Earth poses enormous long-term scientific challenges requiring a long term international programmatic commitment, to which the EOEP is the appropriate ESA response,
- EOEP has put Europe at the forefront of Earth Observation Science and Technology,
- EOEP's comprehensive scope – science, technology, satellite development, exploitation and application development – is fundamental to this success,
- The "Envelope" concept of the Programme – ensuring flexibility, the ability to address highly-challenging science goals in parallel, and high scientific output – is of key importance,
- ESA has developed successfully a Europe-wide network of expertise and has accumulated significant scientific, technological and engineering capabilities over time, and
- EOEP has enabled the successful extension and development of operational EO for the Eumetsat and GMES programmes.

Considering these major and unique strengths, we believe that ESA is very well positioned to execute the next phase of EOEP successfully. The EOEP continued success in the future and its achievements can be maintained only by sustained financial investment by European Member States. ***The Panel recommends that the EOEP-4 should be funded at a sufficient level in the next decade, optimally greater than the last period, to enable ESA to implement the recommendations of this***

report and to ensure European leadership of an exciting and vibrant programme in Earth Observation. This will also contribute directly to maintaining and utilizing a strong EO industrial base at the forefront of global Earth observations science, engineering and technology.

Introduction

The "Living Planet" Strategic Objectives

The European Space Agency (ESA) Delegates requested an independent scientific assessment of the Earth Observation Envelope Programme (EOEP) in preparation for the ESA Ministerial Council planned for end of 2012 when a proposal for the fourth period of the EOEP will be presented for the Members subscription. The Programme that is subject of this review was formally approved in 1999 and its third period (EOEP-3) was initiated in 2008, as a follow up to the EOEP-2. The Programme Board of Earth Observation (PB-EO) approved the Executive's plan for this review.

Composition of the Review Panel

The review Panel appointed by ESA consisted of 8 members, including the Chair. They represented a wide range of scientific and technical disciplines and expertise, including the Chair of the Earth Science Advisory Committee (ESAC), see Table 1 below.

NAME	AFFILIATION	COUNTRY
Dr. Ghassem R. Asrar	World Meteorological Organisation (WMO)	Switzerland
Dr. Richard Biancale	CNES-GRGS	France
Dr. Bruno Carli	IFAC-CNR	Italy
Dr. Alan O'Neill	National Centre for Earth Observation University of Reading	United Kingdom
Dr. Helmut Rott	University of Innsbruck	Austria
Dr. Michael Schaepman	University of Zurich	Switzerland
Dr. Z. (Bob) Su	International Institute for Geo-Information Science & Earth Observation	The Netherlands
Dr. Martin Visbeck	Leibniz-Institut für Meereswissenschaften (IFM-GEOMAR)	Germany

Table 1: Members of the EOEP Scientific Review Panel.

Evaluation Process

ESA established this independent Scientific Review Panel to assess how well the Programme is providing scientific value for money, by developing detailed answers to a set of questions identified in Annex I. The Panel discussed the review guidelines and its charge by ESA and they agreed on the major themes for the reporting by the ESA team. They also converged rapidly in developing the major strategic questions to be answered by the ESA team in reporting on the major Programme elements (see Annex I). The Panel conducted two telephone consultations with support from ESA before their meeting on 30-31 March 2011 at ESTEC. Prior to and in between these consultations, ESA made available several documents to help the Panel members in preparing for the review meetings, see Annex II.

We also requested that ESA should conduct a self-analysis of the Strengths, Weaknesses, Opportunities and Threats (SWOT) in the EOEP to be discussed in a session focused on overall assessment of the Programme and its major elements.

The EOEP is considered as a major contribution to the implementation of the Living Planet Strategy with the following prime objectives of the:

- pursuit of scientific knowledge,
- enhancement of quality of life,
- development of an independent capability for Europe, and
- promotion of a European industry of innovation and value added services.

The Panel also considered these strategic objectives during their deliberation and assessment. In the subsequent sections we will present an in depth analysis and assessment of the major components of the EOEP from the science perspective. The first section focuses on a general overview of EOEP and its evolution and performance, especially during the past decade. The second section is focused on the role of science in the preparatory activities followed by a section on the role of science in mission implementation phase. The fourth section of the report is focused on how science requirements guide the development of the ground segment and mission operation, and is followed by a section devoted to the exploitation of the observations by scientists and other users. In each of these sections we provide an overall analysis and assessment based on the information and presentations provided by ESA followed by some findings and recommendation specific to the section. The last two sections of the report contain the results of the SWOT analysis provided by ESA and an overall summary and list of the Panel findings and recommendations.

Structure, Mission Selection Procedure, and Evolution of EOEP

The EOEP continues to accomplish the science, technology and overall strategic objectives of the Living Planet Programme (LPP). The scientific priorities and requirements that were developed for LPP in an ongoing dialogue with European scientists, and ESA international partners, continue to guide the evolution and implementation of EOEP. We believe that EOEP is making great progress towards its science objective of providing highly innovative space-based observations of the atmosphere, oceans, cryosphere, solid earth and terrestrial ecosystems from recently launched Earth Explorer and legacy missions such as ERS and Envisat. These observations are enabling European scientists to explore and understand less understood aspects of the Earth's natural system. ESA has successfully developed a European network of Earth system scientists, technology experts, engineers and remote sensing experts to assist in implementation of EOEP. This network of scientists and technology experts in partnership with the aerospace industry are key to ESA’s ability to develop and execute the next phase of EOEP. Thus, sustained investment and nurturing of this network is key to European leadership in space-based Earth observations in future decades.

The open solicitation together with rigorous experts review and evaluation processes that ESA has put in place for definition, selection and implementation of EOEP has served very well both ESA and the European scientific and technical community by identifying the most innovative ideas and technologies and developing them to the point that they enable successful missions. For example, the two-step process in mission selection, definition and implementation, has allowed ESA to reduce the associated technology risks for these missions prior to final selection and development. All involved in this process (i.e. ESA, scientists, technology experts, industry) are gaining significant experience as a result of every Earth Explorer mission because of the unique challenges they offer.

We specifically take note of the great progress that ESA has made during the past decade in developing and launching successfully three Earth Explorer missions, each containing a variety of highly advanced and the first of-their-kind technologies to achieve the ambitious and exciting scientific objectives of these missions and in preparing 5 more Earth Explorer missions to be launched in the coming years. Table 2 provides the highlights of some of the impressive EOEP accomplishments for all major elements of the Programme, especially during the past decade. The ground segment and mission operations element of the Programme have used effectively the advances in computer, information and telecommunication technologies to support in a timely and effective manner the missions science objectives and enable the data user element of the Programme. The data user element also excelled at serving the scientific community as its primary customer. It has expanded significantly the user base to include a wide range of non-traditional users of ESA observations including national and international government and non-government organizations, as well as the private sector. Some operational research centres such as the European Centre for Medium-Range Weather Forecasts (ECMWF) are developing test beds for some potential future operational service capabilities (e.g. soil moisture, ocean surface salinity, etc.). We offer the following findings and recommendations based on the assessment of the evolution of the EOEP during the past decade.

We found ESA's approach of consulting broadly, and in a sustained manner, with the scientific community in establishing its science strategy and priorities to have been very effective and sound. This process has served very well both ESA and the European science community resulting in a significant growth in this community, especially during the EOEP-3 period. ***The Panel recommends that ESA should take advantage of its effective working relationship with the scientific community to review and update periodically its "Changing Earth" Strategy and related scientific and technical plans. Identifying an optimum period for a regular update of these plans can be a part of the consultation process, under the guidance of ESAC.***

The balance between risk and innovation in the Earth Explorer Programme requires continued strategic thinking and planning in the future, especially in the light of the rapidly evolving science requirements and the changing European national and other international space-based Earth observation programmes. This particularly applies, as far as the timing of the calls and the subsequent selection of the missions is concerned. ***The Panel recommends that ESA should continue to ensure in its future calls that scientific balance is sought between missions planned and flying and those to be selected in EOEP-4. In this regard, ESA should continue to give careful consideration to missions of national and international partners, as it has in the past. Specific consideration should be also given to proposed mission concepts that serve complimentary scientific objectives of more than one discipline.***

We found the principles of open and un-restricted access to EOEP observations and information are serving ESA and the European community very well. This has put the European EO Programme in the top tier of World leaders as a provider of Earth observations from space. ***The Panel recommends that the principles of an open and un-restricted access to EOEP observations should be re-enforced during the EOEP-4 period and eventually be turned into an ESA-wide data and information sharing policy. In particular, the Panel strongly supports ESA efforts in securing free and unrestricted data access from all future GMES Sentinels for use in support of the Living Planet Programme strategic objectives.***

We found that the major distinction between the "Core" and "Opportunity" missions is rapidly disappearing, especially in overall duration for mission life cycle development. ***The Panel recommends that ESA should review and refine existing definitions of science and programme criteria for the Core and Opportunity missions on the basis of its experience during the past periods of the EOEP, in time for the EOEP-4 solicitation and implementation.***

Preparatory Activities	Implementation	GS Activities and Operations	Exploitation	Some Examples of EOEP Achievements
x	x			Of the many enabling and development technology activities initiated under the EOEP, more than fifty have resulted in leading edge technology solutions being brought to high Technology Readiness Level in preparatory activities or within project implementation. Most of these have already been implemented or will be launched in the coming decade, including: - ultra-sensitive accelerometers, - drag compensation by ion propulsion, - detectors for all optical spectral bands, - high spectral resolution receivers for lidars, - components for high-performance radiometers, down to sub-millimetre wavelengths - interferometric and synthetic-aperture altimeters and radiometers, - microwave sources with kW -level power,
		x	x	Since the start of EOEP-3 in 2008: More than ***2200 new exploitation projects*** using ESA EO data were started: 1300 via fast data access, 700 via category-1 projects, and 200 via Earth Explorer AOs, (in addition to the about 3000 projects registered during EOEP-1 and -2).
		x	x	ESA PIs made more than ***1000 scientific peer-reviewed publications*** in international journals reporting new results from ESA EO missions data: of these 75%+ concern mainly ERS and Envisat data, and 25% mainly Earth Explorers.
	x	x	x	More than ***1200 EO scientists*** attended the ***ESA Living Planet Symposium*** in Bergen in June 2010, to make ***1000+ presentations*** on results from ESA Missions – some 20% more than the Montreux symposium only four years previously
x	x	x	x	ESA organized ***17 thematic*** *workshops* attended by ***5000+ scientists*** and resulting in ***3600+ papers*** on EO science and applications based on data from ESA missions.
			x	ESA issued ***13 special publications*** dedicated to new scientific results that PIs have derived from ERS and Envisat data.
x	x	x	x	More than ***800 PhD and post-doctoral students*** attended ESA advanced EO training courses and summer schools, with in-depth lectures and hands-on sessions given by ESA PIs, Earth Explorer lead scientists, and invited world-leading researchers, who all voluntarily contributed in their own time.
		x	x	More than ***6000 users worldwide*** registered, downloaded and are regularly using the ESA open-source toolboxes for their research.
x	(x)	x		More than ***380 public sector and international research organizations***, engaged with ESA, first to establish authoritative user requirements for new applications of EO, and subsequently to assess, validate, and promote wide use of the innovative products developed jointly by ***200+ specialist companies and research institutes*** of ESA Member States.

			x	A suite of more than ***10 Global EO Products***, made freely and openly on-line access, were widely exploited by global research communities, with as many as ***50,000 downloads*** of Globcover 2009 and ***100,000 downloads*** of the ATSR world fire Atlas and more than ***600 citations*** in multi-disciplinary scientific publications.
			x	More that 75 specialist value-adding companies introduced innovative and competitive EO-based services, using state-of-art data and methods, in ***100+ service trials conducted with 200+ mainly private sector clients***, including large, multi-national corporations.
		x	x	Based on the scientific achievements enabled by EOEP and its predecessor programmes, scientists and industry in ESA member states are now (via the ESA Climate Change Initiative) responding to the highly challenging requirements, for consistent long-term climate-quality records of ***more than half of the 45 Essential Climate Variables*** required by the Global Climate Observing System to support the work of UNFCCC and IPCC.
x	x	x	x	More than **450 EO web stories** were published on the ESA web portal, resulting in a very wide pick-up in international press and media such as New York Times, BBC, Le Monde, El Pais, La Stampa, and Frankfurter Allgemeine Zeitung
	x	x	x	In the area of Education/Training & Scientific Community Building, some example for the GOCE mission over the last decade are: - 37 PhD Students in ESA Member States - 5 ESA Postdoctoral Fellows – of which 4 internal/external and 1 Young Graduate Trainees. 3 still involved with GOCE on-orbit calibration and data processing. - 4 dedicated International GOCE User Workshops: 2001, 2004, 2006, 2011 and one GOCE dedicated Summer School.

Table 2: Some examples of EOEP accomplishments for the major components of the Programme.

1. Role of Science in EOEP Preparatory Activities

In this section, we provide an analysis and assessment of the role of science in the following three interconnected parts of the Programme:

1. Earth Observation Preparatory Activities,
2. Instrument Pre-Development, and
3. Earth Watch Definition Activities.

We focus on the role of science in preparatory activities for Earth Explorers and Earth Watch (1), instrument pre-development for user-driven candidates for Earth Explorer and Earth Watch type missions (2), as well as the definition of Earth Watch type missions and the preparation of dedicated programme proposals for optional Earth Watch type programmes (3).

The Earth Observation Preparatory Activities (1) consist mainly of pre-phase A and phase A activities for new missions. These include the establishment of scientific objectives through consultation with the scientific community and the derivation of mission and system requirements, as well as complementing support of science and market evaluation activities. They further include instrument, satellite system and mission feasibility or concept studies and critical technology development and evaluation. Finally they include the establishment of instrument pre-development requirements for cost and risk reduction, the identification of co-operation possibilities, and the support of scientific and campaign activities.

The Instrument Pre-Development (2) for identified and agreed user-driven candidates for Earth Explorer and Earth Watch type missions comprises activities to develop and test all critical instrument elements, to a sufficient level to demonstrate overall performance against coherently defined requirements. Such pre-development entails the early design and manufacturing of a breadboard version of the space instrument or of a downscaled version of the instrument but still representative of the technology, assembly and verification requirements of the full instrument.

The Earth Watch Definition Activities (3) element of the Programme brings together all aspects of preparation of Earth Watch type programmes. The Earth Watch element includes operational systems developed in partnership with Eumetsat, the European Community and other public and private stakeholders. It covers the classical industrial phase A/B1 studies involving identified partners prepared to contribute to the mission as well as additional activities necessary to define such a programme, e.g. architecture and impact studies.

1.1 Assessment

The EOEP preparatory activities have been carried out successfully based on an effective trade-off between science and technology. We found that the scientific requirements and scientists play an important role in this process. The main challenge of the Programme is to keep the pace with continual changing scientific requirements, rapid technology advancement, and increased complexity of (partly synergistic) observations. In particular moving away from a singular systems approach towards more holistic Earth system observations, analysis and modelling continue to pose significant challenges on preparing EO missions in the future. The Panel notes with great appreciation that the Programme has succeeded in responding to these accelerating changes so far. ESA has succeeded in developing world-leading missions with demonstrated societal benefit and impact. The level of fitness for the future of the EOEP preparatory activities can be judged as very high.

1.2 Technical requirements definition

Within the EOEP preparatory activities, technical requirements emerge from scientific requirements. These scientific requirements stem from either mission proposals, fostered through ESAC recommendations, the preparatory work of the Mission Advisory Groups (MAGs) and finally through general technology advancement and market observations (e.g. including a view on data/product distribution). The technology preparation activities within EOEP are generally limited due to resource limitations. The mission-specific technology preparatory activities have substantially increased in quality and focus within the reporting period and as compared to EOEP-2, though this compensates the resource limitations only in part.

In view of an increasing number of mission proposals being submitted, appropriate emphasis should be given to maturing and promising technologies for Earth Explorers. This emphasis should be made in consultation with ESAC. A future goal would be to ensure that adequate resources are made available to reach the required technology readiness level for Earth Explorer mission approval. A firm commitment can then be taken at the end of Phase B1; with further major mission design changes being avoided. In order to further minimize risk, contingency planning should take place early on in the preparatory phase, e.g. with the definition of requirements and thresholds. Trade-space options should be fully exploited during the preparatory phase and should not be carried into the implementation phase. Enough preparatory activities should be undertaken to avoid technical trade-offs in the implementation phase of the Earth Explorers, thus preventing additional risks and resource demands by introducing new technical solutions at the late stage of the project.

1.3 Science – Technical risks assessment and trade off

A suite of studies and feedback mechanisms between scientists and ESA staff are used in risk assessment and trade-off analysis during the EOEP preparatory activities. They have all substantially decreased development risks. The missions launched so far clearly demonstrate that proper risk assessment has been performed and trade-offs were made to the benefit of the missions. Feedback mechanisms that were put in place are fully used to the benefit of the scientific users, to preserve the mission's scientific goals, while maintaining a balanced financial approach for mission implementation. This is judged as being of utmost importance for a *science* driven programme and has been pursued and supported by ESA with greatest care.

The Programme also fosters the development of instruments to be flown on other, third party missions (within the Earth Watch component), or accepts Earth Explorer missions with external instrument contributions (e.g. EarthCARE). This approach is very beneficial when striving towards a more complete observational approach of many components of the system Earth. The Programme has successfully pursued such an external instrument inclusion, without compromising on its own strategic goals. However, mission selection criteria must be stringent to the point that they secure the external contributions, and preparatory support must be granted for these contributions to reach the necessary degree of maturity to avoid the potential risk to mission success. An improved and timely use of end-to-end simulators at the very early stages of the mission preparation will strongly support both mission concept and technology maturity assessment.

Parallel studies for Earth Explorer missions pre-development are fostering (industrial) competition and provide detailed feedback on maturity of science requirements as well as technical implementation capabilities. Feedback mechanisms from MAGs are put in place and ensure no dilution of science requirements without reference to various technical approaches. However, funding and associated activities in the definition phases of the Programme are highly distributed among different mission candidates, which may result in some complexity and external constraints in priority setting and decision making (e.g. 6 parallel studies for EE-7 extended Phase A). Process efficiency is required in order to avoid missed opportunities (correlation cost / implementation time, benchmarking for efficiency). In all cases, a potential speeding up of this process should not compromise science value or benefits. The MAG may be involved further in trade-off discussions. Additional advantage in this context can be taken of ESAC to engage proactively to support and foster informed decisions.

The EOEP preparatory activities have also substantially invested in a steadily evolving and strong campaign effort, allowing testing technology and science requirements under realistic conditions. The Panel sees a substantial benefit when using sub-orbital demonstrators to reduce risk during the preparatory phases for missions. Further, optimal use can be made of campaigns and sub-orbital platforms for mission definition and for mitigating development risks. In particular integrating in-situ with sub-orbital platforms allows fore more complete observational approaches and therefore allows better management of the risk from predevelopment to end-user data readiness, ensuring that data are provided in a very timely fashion. The Panel strongly encourages ESA to investigate how to integrate coherently these approaches into its programme, by utilizing the variety of existing scientific instruments and activities.

1.4 Management of Science requirements in technology selection and development

The EOEP preparatory activities have emerged to be a flexible and science driven framework, delivering world-class and cost-effective mission designs with a wide variety of observational approaches. The EOEP preparatory activities deliver exceptional value for money, as evident by some of the achievements listed in Table 2. The rigorous and diligent implementation approach chosen ensures the final delivery of top quality scientific data. In addition, well-implemented feedback mechanisms with the scientific community ensure a transparent trade-off approach of scientific requirements, mission specifications and expected mission performance. Preparatory activities are flexible and robust such that they ensure delivery of science goals despite potential worst-case scenarios (e.g., time to mission for CryoSat-2).

The EOEP preparatory activities have incorporated a rigorous feedback mechanism with the scientific community, in essence allowing science feedback during requirement definition and also during consolidation phases. A distinct advantage is the fact that ESA specialists act as moderators between science requirements and technical capabilities of industry, allowing scientists to take and maintain an independent position throughout the definition phases. The preparatory activities in combination with scientific support can provide extensive guidance to technology, algorithms, product development and data processing. This support and guidance leads to concept consolidation via robust trade-offs using alternative approaches.

Risk analysis and mitigation planning is best done by having comprehensive mission preparatory phases and resource allocation might have to be revisited given the sustained submission of high quality mission proposals. Increased funding for the preparatory activities should be envisaged to allow for algorithm development, modelling approaches retrieval methods, and access to end-to-end simulators – potentially under a more detailed guidance of ESAC emphasizing scientific significance.

The EOEP preparatory activities include complementing measures such as impact studies, simulation of data using end-to-end mission simulators, and campaigns, resulting in an improved understanding of scientific needs. In fact, the early engagement of scientists in the mission development phase enables other scientists to be ready for future data use, reducing the time to data utilization substantially. These feedback mechanisms are further complemented by ESA organized workshops, international workshops, or co-sponsoring international events. Regular feedback is also obtained through supporting studies.

As observations of the system Earth evolve to support several aspects of the Earth system science, preparatory activities would substantially benefit from using synergistic approaches. For example, evaluation and analysis of complementary coverage and formation flying with other missions and instruments of opportunity under partner agreements can be performed in the mission preparatory phase. The role of the ESAC within this part of the Programme is to guide specific preparatory activities, in particular advise on recommended missions, which have resulted in improved concepts, often selected later. In addition, entirely new mission ideas and concepts have emerged through this process. This is leading to an increasing amount of recommended missions with very high scientific value. From this process, strong ESAC guidance is desirable on prioritizing mission concepts to be pursued within the preparatory activities.

The EOEP preparatory activities have fed, in certain cases, into operational mission concepts. Selected measurement techniques as used in Earth Explorer missions have reached a maturity level such that they can now be considered for use in Earth Watch (notably GMES Sentinels) missions. Such activities have led to concerted technology development leading to robust systems that can accommodate operational requirements (e.g. multi-spectral and radar measurements on GMES Sentinels, advanced SAR/interferometric altimeters).

The EOEP preparatory activities are also attractive because regular calls for new missions or measurement concepts provide a long-term opportunity for scientific involvement. A sustained high interest of the Earth Observation community is evident through an increasing number of competitive proposals to open calls. The openness of the calls for new missions has had a positive impact on the mission support activities. In addition, these activities foster and encourage scientists to take part in ESA programmes at early mission concept stage, and to stay involved even after non-selection of concepts.

A continued challenge is to sustain high quality provision of mature techniques and measurements in response to changing science requirements. The full chain of mission selection, preparation and implementation is a trade-off between costs, time-to-mission, quality, and evolving science requirements. Improved governance and transparency of the process, articulating in particular the constraints and programmatic limitations faced by the EOEP, will improve the understanding and therefore patience of the science community for time-to-mission. Also preparatory activities will necessarily come to an end, but there is an emerging need to sustain the scientific community during mission implementation. The continuity of the scientific activities between end of preparatory activities and data availability relies on fostering connections to national, international (e.g. EEA), or EU research programmes (e.g. EC FP7/8/9) to sustain their interest.

We offer the following findings and recommendation based on our evaluation of this element of the Programme.

We found the added risk due to technology innovations in later phases of the Programme is the primary reason for prolonged development life-cycle time and increased cost. This has had some adverse impact on the current selection procedure and may have consequences on the EOEP at large. We therefore endorse the ESA approach that selection of future Earth Explorer candidate missions for implementation should be made only after successful completion of Phase B1, in order to minimize the risks of technology innovation to life-cycle time and cost in EOEP-4. ***The Panel recommends that ESA should maintain technology development in the mission definition and preparation phase up to and including Phase B1, and that selection of mission for implementation should occur after Phase B1, when the level of technological maturity is high enough to ensure mission success.***

We discussed the frequency of calls for mission concepts in EOEP and the number of mission concepts retained for the down-selection process. We also explored the ESA scientific and technical capacity to adequately support thorough evaluation of the mission concepts and guiding their development during the mission definition phase. We believe an active dialogue between ESA and the European science community on this topic to explore the merits and de-merits of possible options will be highly beneficial to both sides in preparation for the EOEP-4. ***The Panel recommends that ESA should assess the trade-off between the number of calls for mission concepts and the number of missions considered for down-selection, on the basis of experience it has gained from the past EOEP periods. ESA should consult with the science/user community under the guidance of ESAC to determine the best strategy for the EOEP-4. In this context ESA should devise a strategy to maintain the requisite number of alternative mission concepts during the early phases of the Programme.***

We found that ESA has done a superb job in developing and using very effectively a wide range of capabilities such as end-to-end mission simulators, calibration/validation tools, sub-orbital capabilities, and in-situ observing networks to understand and mitigate risks of new technologies, to develop and validate scientific algorithms, and to prepare the scientific user communities for use of observations from future missions. ***The Panel recommends that capabilities such as end-to-end mission simulators, calibration/validation tools, sub-orbital capabilities, and in-situ observing networks be further strengthened and used effectively in all phases of the EOEP-4. Investments in these capabilities have served ESA and its mission very well and we believe they will be even more critical to mission success with respect to multi-sensor/mission development, operation and exploitation in the future.***

2. Role of Science in Earth Explorer Mission Implementation

2.1 Overview of Earth Explorer Implementation from a Scientific Perspective

The implementation of Earth Explorer missions is based on the primacy of science in the mission objectives definition and implementation. Earth Explorers have remained at the forefront of what is technologically possible, developing and employing novel and challenging instruments and concepts. For example, the GOCE instrument has accelerometers that are 100 times more sensitive than previously flown, with the spacecraft employing novel drag-free control technology based on an ion propulsion system. The role of science in mission implementation is assured by the following means:

- At mission selection, the scientific requirements as documented in the Mission Requirements Document (MRD) are fixed and put under configuration control by ESA.
- The MRD is the basis for implementation of the space and ground segments of the mission (i.e. level 1 and level 2 data processing).
- The MRD is translated into technical requirements for industry in Systems Requirement Documents (SRDs), ensuring that the science needs are traceable as the technical drivers.
- The Mission Advisory Group (MAG) maintains the MRD and safeguards compliance of SRD to the observation requirements.
- Industrial procurement and implementation in Phases B2/C/D are done according to well-established standards and ISO9001 certified procedures.
- Industry conformance to SRD requirements is ensured by legally binding compliance statements, and any non-conformance during industrial implementation by a formal Request for Waiver mechanism.
- If MRD requirements would be impacted by acceptance of a waiver, the MAG is consulted for a decision or for a mitigation approach.
- An End-to-End simulator and performance tools are used to assess any scientific impact of potential technical changes, as a part of review and evaluation of option(s) to be considered.
- Error budgets are used to trace impact on science of any system non-compliance.

Regular milestone project reviews allow monitoring of and compliance with system requirements. The excellent in orbit performance of the Earth Explorers launched so far demonstrate the effectiveness of these processes in this respect.

The commissioning phase is planned to allow verification of satellite compliance to SRD requirements, and the verification of Level 0/1b data processing. Various types of field and aircraft campaigns are performed during implementation and in-orbit commissioning of the missions to ensure that scientific objectives and goals are met. Such campaigns are of fundamental importance to meeting science goals by: providing independent and complementary observations for calibration and validation; testing of retrieval algorithms, and identification of complementary measurements; and for generation of simulated data for verification of prototype data processing. Independent calibration and validation of retrieved products at the end of the processing chain is vital to determine the error characteristics of the products and, in particular, to correct any identified biases. The EOEP has an excellent record of ensuring that missions are supported as necessary by these activities.

Some exciting highlights for science of the Earth Explorer mission implementation have been:

- GOCE has been successfully developed and launched, delivering spectacular, high-quality L1b scientific data, giving a first-ever tensor representation of gravity gradients.
- SMOS has been successfully developed and launched. The mission includes a number of technological "firsts" of importance for science (e.g. an L-band synthetic aperture radiometer). SMOS is delivering near-surface soil moisture and ocean salinity data.
- CryoSat-2 was re-developed quickly (within 3.5 years) and launched successfully. It is delivering excellent quality L1b data.

2.2 Assessment

2.2.1 Implementation of the missions from science perspective

The EOEP has demonstrated a clear drive to improve algorithms and the quality of data products during the development phase of a mission. The MAG provides the scientific advice to guide the supporting studies and field campaigns that are used to determine modes of mission operation and to improve retrieval methods. European expertise in scientific data processing has been harnessed via the concept of distributed scientific data processing. Frequent international user workshops have been hosted to provide status reports and to solicit scientific feedback and advice. Close ties and interaction with international science programmes during the implementation phase should focus on getting the users ready to use the new data quickly after launch.

Some examples of scientific improvements during Earth Explorer implementation have been:

- For GOCE, improved characterisation of instrument performance and error budget allowed L1-L2 data processing methods to be refined, with further improvements being developed by combining along-track gradiometer data with satellite-to-satellite tracking data.
- For SWARM, an improved "comprehensive inversion" solution for the constellation has been developed, making optimal use of the opportunities afforded by a constellation of satellites.
- For ADM-Aeolus, studies have been undertaken to assess the benefit of using the data in numerical weather prediction, and to optimise data assimilation algorithms in readiness for operational use of the data.

- For EarthCARE, assimilation algorithms have been developed at ECMWF to assimilate cloud radar observations into a weather forecasting model, and demonstrating improvements over model forecasts produced without the data.

The investments made in these activities pay great dividends. They prepare the mission science team and the scientific community at large to take full advantage of the new capabilities offered by each Earth Explorer mission as early as possible after successful launch and in-orbit operation. Sustained support for such activities in the next phase of the EOEP will further enhance the use of observations from each mission, and when applicable multiple missions together.

2.2.2 Use of scientific advice during implementation

The EOEP has a good record of acting on scientific advice it receives during mission implementation. The MAG has been engaged to resolve implementation issues such as specification of campaigns and to initiate supporting studies.

Some examples of actions stemming from scientific advice during implementation phase of EOEP-3 have been:

- For SWARM, the MAG rejected a proposed removal of an accelerometer to reduce mass, and proposed an alternative scheme to reduce mass involving a different initial orbit. Scientific needs were preserved and a beneficial flexibility introduced to respond to the level of solar activity.
- For EarthCARE, MAG members were involved in advising on de-scoping options for the ATLID instrument, which allowed a risk mitigation strategy to be approved by the Programme Board for Earth Observation (PB-EO). The MAG was consulted to confirm the scientific importance of use of ultraviolet wavelengths, and ESA therefore abandoned the idea of a switch to the less technologically challenging green wavelengths.
- For ADM-Aeolus, a MAG recommendation was adopted to undertake ground-based and airborne campaigns to improve algorithm development for wind speed and aerosol products.
- For GOCE and CryoSat-2, a MAG recommendation was adopted to combine spaceborne, airborne and in-situ measurements in preparation for combining GOCE and CryoSat data for sea-ice thickness mapping and to determine Arctic ocean currents and tides.

2.2.3 Safeguarding scientific requirements during mission implementation

There is good evidence that scientific requirements have been protected when technical and engineering issues have been encountered during mission implementation. Some examples of this include:

- For GOCE, the MAG was consulted to ensure that breakthrough science could still be achieved despite the removal of a Field Emission Electric Propulsion system.
- For EarthCARE, a request by the PB-EO for an independent assessment was undertaken quickly and diligently. The views of the Science Panel were given

prominence during the assessment. In reaffirming the scientific value of the mission, the Science Panel concluded that the scientific requirements of the mission had been rigorously applied. In determining possible descoping options for risk mitigation, the impact on the science was to the forefront of considerations, and satisfactory options were presented to the PB-EO.
- For EarthCARE, the development of an end-to-end simulator has been an important step to safeguard scientific requirements in the face of technical and programmatic risks. The simulator provided important quantitative information on possible descoping options during the EarthCARE independent assessment.

The key role of scientists during implementation is to verify compliance with mission requirements during both space- and ground-segment implementation. Scientists are involved in risk assessment and in trade-off analysis, but it is less clear that their involvement in programmatic and financial issues, if required, is always early enough. Scientists and MAGs are not explicitly involved in programmatic and financial deliberations and decisions. Potentially more seriously for timely resolution of problems is the fact that there is no direct interaction between scientists (including the MAG) and industry (industry works directly to the SRD). The danger with this approach is that there may be a greater risk of cost overruns and of more difficult scientific choices if communication is perfunctory rather than regular and routine. EOEP can benefit greatly from an end-to-end analysis of science-technical-cost during mission implementation period so that the cost and schedule implications of achieving the last few percentages of requirements are weighed against potential mission delays and adverse impacts on the entire EOEP.

2.2.4 Maintenance of mission requirements during mission implementation

There are sound and transparent procedures for defining, documenting and managing instrument and scientific requirements for Earth Explorer missions:

- The Mission Scientist is the custodian of the scientific and mission requirements, and
- QMS/ISO 9001 procedures are followed to update mission requirements in a traceable and open manner.

Clear evidence of sound practice in this regard emerged during the Independent Assessment of the EarthCARE mission. The EarthCARE review process revealed that the major cause of the challenges that this mission has encountered is due to changes to the mission specification in response to technical problems (i.e. technology development) and not due to changes in mission science requirements.

We found that the needs of science are given high priority during mission implementation and that communication with the scientific community, notably the advice of MAG, is actively sought and is extensive (e.g. through numerous workshops). There is good traceability and transparency in decision-making, and there is a very well documented and managed process for keeping the mission science requirements under configuration control. There are some areas of opportunity to enhance the mission implementation phase and to expedite the science delivery as data become available. To ensure the availability of high-quality data, calibration/

validation should be maintained throughout the mission lifetime, including period of mission extension. This is essential for reliable long-term detection of trends in measured variables.

Level 2 data should continue to be the standard data product produced by a mission. Formation of international consortia for level 2 product generation has been innovative and effective. Higher-level products – e.g. 3D gridded products and multi-mission synthesized products produced by data assimilation– are of considerable interest to the scientific community. ESA should therefore determine whether there is a need to stimulate the provision of such products by either commissioning dedicated activities or national activities are adequate.

The good practice of ensuring coherence of the scientific community through regular workshops during the implementation phase should be reinforced. Further efforts should be made to develop and make available algorithms and tools (e.g. data simulators and prototype retrieval algorithms) to accelerate scientific discoveries with Earth Explorer data. There should be a coherent and well-communicated plan to achieve this.

While there has been good interaction between MAGs and technical and programmatic elements of missions, there appears to be scope for improvement in decision making to prevent science needs from being compromised by technical problems or cost increases during mission development phase. Greater involvement of MAGs in end-to-end mission analysis allows in-depth assessment of the impact of science requirements, and determining whether there are cost and schedule efficiencies, or risk mitigation/reduction to be gained. Similarly, early involvement of the Earth Science Advisory Committee (ESAC) in cases where problems are encountered, especially during the mission implementation phase, could help in developing solutions to avoid loss of major capabilities or the entire mission.

Maintaining close links to international science programmes will help to get broader community involvement prior to launch and data delivery, and will ensure greater visibility support for ESA missions in the future. We offer the following findings and recommendations based on our assessment of this element of the Programme.

We envision that the complexity and interdisciplinary nature of future scientific challenges will require even more innovative technologies and observational methodologies in the next decade. Scientific challenges at the intersection of biological, physical and chemical aspects of the atmosphere, ocean, biosphere, cryosphere, and terrestrial ecosystems will require observations from multiple instruments/platforms and a variety of orbits to capture, characterize and understand the complex Earth system processes towards the ultimate goal of developing the predictive capabilities to project the future course of change. Such complex scientific challenges require long-term and high quality observational records that may span across multiple decades. In this context the Panel recognises the great potential of data from GMES to enable major scientific advances. ***The Panel recommends that ESA should explore and exploit innovative implementation strategies such as different vantage points, virtual constellations, longer duration missions and synergy between Earth Explorer class missions and international and Earth Watch systems***

(notably GMES Sentinels) to address the scientific challenges of the Living Planet Programme.

We have identified a need for a new class of small Earth Explorer experiments of opportunity to meet the rapidly emerging scientific opportunities by taking advantage of national and international partnerships with research, environmental and meteorological organisations. This class of experiments should provide greater flexibility and agility to EOEP for responding to fast emerging scientific, strategic and international partnership challenges and opportunities**. *The Panel recommends that ESA should develop a small Earth Explorer class of science driven missions of opportunity as a part of the EOEP-4. This new class of experiments should be smaller in size and cost significantly less than the current Earth Explorer classes of missions. They could be implemented either in a dedicated mode, not necessarily in synchrony with the Earth Explorer solicitation, by ESA or as experiments of opportunity for space or sub-orbital platforms in partnership with the national or international organisations.***

We found that ESA and the Mission Advisory Groups can benefit further from the scientific and technical expertise available to them through the ESAC and international partner programmes such as the International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), Global Climate Observing System (GCOS) and Global Earth Observing System of Systems (GEOSS). ***The Panel recommends that ESAC should continue to provide its strong leadership in the advisory function to the ESA Executive, and facilitate greater partnership with the international observations and research coordination programmes.***

3. Role of Science in Ground Segment Development and Mission Operations

The EOEP mission operations and ground segment component has been instrumental in delivering its science goals. An effective ground segment has enabled major contributions to international Earth Science initiatives and it has fostered European scientific excellence and legacy in the international arena (e.g. in the International Polar Year and the Dragon programme). The ground segment has also ensured access to 20+ years continuous high-quality EO data for science and applications advances by providing timely access to ESA observations by taking advantage of exceeding sensor performance and extension of mission lifetimes (e.g. ERS-2 and Envisat).

3.1 System definition, design, development and operation

The EOEP mission operations and ground segment have responded pro-actively to users requirements by gathering feedback from scientists to orient programme implementation. The Programme also solicits user assessments to improve mission operations, data quality and applications utility. By supporting the Cal/Val activities and participation in national and international research programmes, the Programme ensures greater use of the EOEP data and benefits from the expertise and capabilities of these networks in fulfilling the Programme's scientific objectives. Sustained support for these efforts from early phase of mission definition and development through mission operation and exploitation has benefited greatly both ESA and the community. For example, provision of simulated observations for the scientific preparation of ground segment aspects of missions and active involvement of scientific consortia has been key to early science return from the missions. The EOEP mission operations and ground segment have laid the foundation for future programmes (viz. GMES, CCI) by sharing lessons learned and best practices from science and applications exploitation into future missions definition. Thus, involvement of scientists in these activities from early stages through all mission phases has proven to be very fruitful. It has helped in understanding technical aspects of new measurement techniques and allowed the science teams to better appreciate the limits in scientific interpretation of the observations. It is also important for preparing the scientific community for processing and using these observations, taking into account full technical subtleties of the observation technologies being used.

The ESA flexibility in mission operations meets advantageously scientific requirements to extend mission results or to broaden the science objectives. Given the nominal Earth Explorers mission duration vs. maximum possible lifetime, ESA needs to be prepared to support operation extension until the major mission scientific goals are reached (e.g. GOCE). ESA needs to maintain flexibility in its mission plan for supporting the scientific community requests for extension of mission operations. The approach to mission extension has to be made clear and ground rules need to be communicated clearly. Based on the experience from all pre-EOEP missions that have been extended, such extensions have provided good science value for money. In cases when lifetime of mission has proven to be longer than planned, the possibility of mission extensions should be taken into consideration at the outset, in combination with the long-term observation requirements. ESA should anticipate longer than planned lifetime for the future Earth Explorer missions and be prepared to receive, evaluate and grant meritorious requests for such extensions. Both nominal and maximum mission duration should be considered in design, development and operation of future ground segment and mission operation systems.

3.2 Software engineering and data analysis

Continued support of the scientific and other user communities for data analysis and availability of analysis and visualization tools is very important for proper and wide use of EO data. Thus, ESA needs to encourage where possible open source development and interoperability. This is particularly important for access to and analysis of large data sets. For Cal/Val phases access to raw data by science teams should be facilitated with evolving requirements for ground segment activities. Integration of Cal/Val activities in data analysis is essential to achieve best science return. Data processing technology should advance with increasing data volumes and new scientific insights. Since these tasks are normally the responsibility of proposing scientific teams, ESA has to make sure that teams have the capacity to deliver level 2 products. The creation of data processing consortium is a possible option for organizing the community involved in data processing steps.

The improved data access during EOEP-3 period has resulted in ever increasing demand for science exploitation with greater science return. ESA has made significant progress in dissemination of data but ESA needs to strive continuously to simplify, expand and accelerate access to ESA EO science data. The trend in increasing data volume, need for greater access to multiple data sets, and increasing number of users all point towards greater needs for processing, re-processing and distribution of the EOEP well into the future. We are fortunate to have access to significant advancements in computational power, data storage and telecommunication technologies, which can be used to meet the EOEP needs. ESA investments in adopting and tailoring these capabilities to meet its scientific and technical needs are key to its continued success into the future.

Data assimilation techniques can greatly enhance near-real-time (NRT) scientific exploitation of future EOEP data and ESA should take full account of evolution of these capabilities for all future Earth Explorers and complimentary missions. Expanding the benefit of multi-mission environments in terms of data fusion and data assimilation systems should be considered by ESA in the future.

There is a significant opportunity for more science return by exploiting data freely available from future operational missions to meet its science/mission objectives. ESA needs to support the science community to exploit data from operational missions following ERS & Envisat, meteorological satellites and Third Party Missions, as applicable to its mission/science objectives. In this respect, the Panel strongly supports ESA efforts in securing free and unrestricted data access from all future GMES Sentinels.

Many opportunities exist in synergy with complementary research programmes (e.g. FP7, FP8, national research programmes) to capitalize on EOEP results. Most national and international research programmes need to constantly align their programmes with emerging scientific challenges and observational capabilities, ESA is encouraged to seek synergies with related research programmes to maximise impact of EOEP results. There are considerable opportunities to increase cooperation with international partners on sensors/missions. While ESA needs to enhance its own leadership role in key Earth system observations, it needs to foster enhanced scientific cooperation on EO with key players worldwide in order to increase the science return of ESA missions.

ESA needs to consider emerging requirements for interoperability as communities' transition to a data rich environment (processes running off-line in a dedicated computing environment, e.g. for re-processing). It needs to take advantage of emerging technologies and existing networks (including DDS/internet via satellite) to broaden ESA's outreach for the EOEP internationally (e.g. use of the most adaptive dissemination technique). ESA also needs to take full advantage of advances in information technology, e.g. by contemplating availability of maps/images for outreach reasons through Internet by vehicles such as popular internet platforms.

3.3 Ease of access and latency

We noted significant progress in data access during EOEP-3 period, but further improvements are needed for free and open access to Earth Explorer data, which is of high importance to ensuring a wider involvement of scientific community. Open and unrestricted data policy together with easy data access is of paramount importance. In order to deliver high quality data to users in a timely manner, the science teams should be directly involved in the development, maintenance and upgrade of the required algorithms and software codes. ESA needs to develop a mechanism to ensure that when the industrial teams cannot guarantee the continuity of competence and the fast response to unexpected problems, the science teams are engaged timely. A combination of system engineering and management experience offered by industry and innovations in research and development offered by scientific community is required for long-term mission success.

Turnaround time for delivery of products to users has significantly advanced and improved, specifically with the higher-level products through investment in the Ground Segment infrastructure. Additional improvement to facilitate further access to Earth Explorer data is desirable recognizing the tremendous advances made in EOEP-3. Data latency has also improved but needs to be continued for future missions. Requirements to NRT products for specific missions need to be considered by ESA in the early phases of a mission, taking into account scientific value, algorithm maturity and feasibility.

The uncertainty about availability and access to science data at the end of Earth Explorer missions' life poses constant threats to their stewardship and long-term use. Access to these observations together with those from complementary missions offer high impact science return. Therefore, ESA needs to facilitate both long-term stewardship of Earth Explorer data and access to the data from relevant non-ESA missions to guarantee the continuity of relevant observation information to meet its LPP mission/science objectives. The scientific impact would decline if Cal/Val/QA activities were reduced after nominal mission lifetimes. ESA needs to ensure that data quality excellence is maintained throughout mission lifetimes, and mission operation extensions.

In recent years, there have been significant improvements in making data products available to and accessible by the scientific user community through the use of web access. There remains, however, an external perception that access to ESA Earth Observation data is difficult and slow. A commonly cited example is the apparently greater utilization of observations from the NASA missions by the scientific community as compared with that of the ESA missions. There is also concern among some element of the scientific community that ESA has a more bureaucratic process for granting access to the data by requiring outline project proposals than some other space agencies, which do not have such requirement. If such a requirement continued, for some scientists it detracts somewhat from the significant progress that ESA has made in supporting access to data from its Earth Explorer missions. Timely availability and wide accessibility of data from Earth Explorer missions must be a very high priority, and costs of achieving this should be factored fully into mission planning and costing. It would be a false economy to do otherwise. ESA should continue to explain and promote its efforts to serve the needs of the scientific community, and its rapidly evolving diverse community of users.

Most of such perception is due to the past policy of ESA for access to observations from its missions. For example, MODIS data is used widely for research and operational purposes, despite the fact that MERIS observations have greater spatial and spectral resolution. The Panel found that ESA policy for free and unrestricted access to its Earth Explorer missions to be highly beneficial, and is a significant step towards addressing the concerns of the scientific community.

We offer the following findings and recommendations based on the assessment of this element of the Programme.

The quality of observations and information provided by ESA during the last decade improved significantly and this together with ESA' policies for un-restricted access to its Earth observations in turn resulted in significantly greater number of users and applications of these observations by the scientific community and a wide range of non-traditional users in value-added industry and governmental and non-governmental institutions. We believe that this strength in increased diversity of users and their needs for Earth observations and information will continue to grow during EOEP-4. ***The Panel recommends that ESA should continue to invest in the ground segment part of its programme by developing and making available to users the necessary analysis, processing and visualization tools to accommodate the increasing demand for the observations and to avoid potential log-jams that may be created due to transfer of large amounts of data by these users from ESA to their local sites. ESA should also ensure continued high quality observations resulting from its mission extension periods, maintaining its high standard of calibration and validation during the entire life of missions***.

We discussed the challenge that ESA faces in financial trade-off between extending the operation of on orbit mission versus development of new Earth Explorer missions. Recognizing the success of the current trend for Earth Explorer missions to last longer than planned and the urgent need for continued access to such observations for addressing high priority science questions, we believe this trend will continue into the future and ESA will be asked to consider extending the operation of the current and future Earth Explorer missions. This is an excellent indicator of mission success. ***The Panel recommends that ESA should develop a clear set of guidelines for mission operation extensions based on a consultation with the scientific community, under the guidance of ESAC. ESA should establish a formal process for submission, evaluation and selection of mission operation extension proposals based on these guidelines and ESA formal selection/approval process. This requires that ESA establish also a dedicated budget line with sufficient resources for funding successful proposals as a part of the EOEP-4.***

We discussed the Long Term Data Preservation in support of long-term scientific exploitation and concluded that ESA needs to develop a strategy to secure future access to all ESA EO science data, algorithms and meta-data in support of its mission/science objectives. The long-term data preservation and greater access to EOEP observations should be secured as an essential activity under ESA's responsibility. ***The Panel recommends that ESA should put in place sufficient means for data processing and reprocessing, long-term archiving and distributing for Level 1 and 2 datasets, and should ensure easy and greater access by the scientific community. ESA should also consider stimulating the provision of higher-level data products because of considerable interest by scientists and other users who do not have the ability to produce such products. This will help to enhance further the user base for ESA Earth observations.***

4. Role of Science in Exploitation and Applications

The exploitation activities within the EOEP cover a wide range of elements in support of science, communication and applications that are also complemented by a dedicated initiative in support of market development for EO-based products and services. The main elements are:

1. Support to PIs, including maintenance of the investigator portal, the development and provision of special software for ESA Earth observation missions as well as open source multi-mission toolboxes for data analysis. The organization of thematic and mission-related workshops and of advanced training courses, leading specific initiatives for international cooperation outreach, and the support of targeted research and development projects.
2. Data User Element (DUE): Development of advanced techniques and generation of innovative EO-based products for science applications, serving scientific organizations as end users, with active involvement of major scientific institutions and international research programmes.
3. Support to Science Element (STSE): Development of innovative mission concepts and advanced EO-based products addressing specific urgent topics in Earth system science, in response to particular needs of major international scientific programmes.
4. Value-adding Element (VAE): to support the development of new, marketable EO-based products and services by the European and Canadian value-added industry.

These activities of EOEP in support of science and market development are primarily founded on exploitation of ERS, Envisat, and Earth Explorer data, but include also missions of partner space agencies, in particular where synergy with ESA missions offers new opportunities. In addition to serving the scientific community in Europe and world wide, EOEP plays an important role in strengthening the European and Canadian value-adding industry by supporting projects that develop and deliver high-quality EO-based products for the scientific community and for application demonstration.

4.1 Assessment

4.1.1 Scientific excellence and innovation

The Panel recognizes the outstanding success of the EOEP in providing the basis for major significant advancements in Earth system science. ERS, Envisat and the Earth Explorer missions have acquired unique and systematic observations of highest quality on key parameters of all major components of Earth system that are addressed in the science strategy of ESA’s Living Planet Programme. These include the solid Earth, atmosphere, terrestrial bio-and geosphere, oceans, and cryosphere. The scientific achievements of these missions span all main fields of Earth science, including solid Earth geophysics and geodynamics, geodesy, atmospheric physics and chemistry, meteorology, terrestrial and marine ecology, oceanography, hydrology, glaciology, and climate-change.

Highly innovative techniques implemented in the ESA missions and the high quality of the delivered EO products have been fundamental for the many success stories of the European and international scientific community. More than 2200 new exploitation projects, using ESA EO data, have started since the beginning of EOEP-3 in 2008, adding to the about 3000 projects registered during EOEP-1 and EOEP-2. Results from ESA EO mission data were reported in more than 1000 scientific peer-reviewed publications in international journals in the last 4 years. About 75% of these publications refer primarily to ERS and Envisat data, and 25% to Earth Explorers. Whereas ESA EOEP provides key input for these research activities by delivering the database, it should be pointed out that the research work is largely funded by external sources and only to a small part within EOEP.

4.1.2 Scientific outreach and user involvement

The Panel acknowledges the high quality and great success of the activities accomplished so far in the EOEP in support of individual scientific users, scientific organizations, and major international research programmes. Taking into account the recommendations of the EOEP-2 science review, the user involvement and science support were further strengthened in EOEP-3 through special initiatives. These activities have been remarkably successful in bridging the gap between the Earth observations specialists and the Earth system science at large, and thus gaining new user communities in addition to providing solid support to established users.

DUE has been expanded in EOEP-3, continuing previous successful applications. The GlobSeries projects have delivered various multi-year global data sets on key Earth system parameters for global change research, involving a total of about 400 national and international institutions and organizations as end users. In these projects scientific end users have been fully integrated, guiding the definition of requirements of satellite products and assessing the performance and usefulness for scientific applications. These projects are serving the global change community with customized high quality products on important climate and environmental variables, and strengthen as well the capabilities of the European EO value-adding industry by developing high-level techniques for generating advanced EO products. Most of the DUE projects have been completed by now, producing valuable demonstration products. It remains a challenge to sustain these efforts, but there seems no clear mechanism here. The Panel feels that a long-term strategy for data exploitation needs to be developed by ESA in order to ensure the continuity of data products, as well as the development of new products.

A similar user driven approach has been adopted for the STSE programme, which addresses important scientific questions, based on intensive consultations with the international scientific community. This is done by seeking advice and guidance by major international research programmes such as WCRP, GEWEX, IGBP, etc., starting with consultation workshops to identify the scientific needs. European and international agencies and programmes, as end users of both DUE and STSE projects, greatly appreciate the selected approach in developing and delivering customized EO products, confirming the high value of the selected approach.

Important and successful tools for outreach and coordination with EO investigators and the science community at large include the maintenance of Web-based PI portals, the organization of dedicated thematic workshops and of the Living Planet Symposia, as well as the organization of special sessions in major international symposia. The *Living Planet Symposium* in Bergen in June 2010 attracted more than *1200 EO scientists* who presented scientific results based on ESA provided Earth observations. During EOEP-3 ESA sponsored 17 thematic workshops, attracting EO specialists from all over the world. These workshops have become cornerstones for presenting and discussing advanced EO technologies, and for providing guidance for future developments. The Panel noted that ESA has taken on board the recommendations from these workshops on technical issues, data provision, and technical support to further enhancing user support, provision of additional training material and courses, and conducting dedicated campaigns.

4.1.3 Education, training and capacity development

The Panel commends the wide range of activities undertaken by ESA in the field of Earth Observation education, training and capacity building. The scope of these activities ranges from Earth Observation education for schools up to high level training in state-of-the-art EO data processing and analysis for young scientists and new scientific users, and includes also more general outreach activities on methods and applications of EO data.

The Panel noted with appreciation the ESA efforts in outreach to the international scientific community through dedicated initiatives such as the TIGER, which greatly enhanced the utilization of EO data by African scientists, and the DRAGON Programme in cooperation with the Ministry of Science and Technology of the P.R. of China. This initial success, based on a rather modest investment of resources, could be also strengthened by allocating adequate funds to cooperation with Africa, Asia, and Latin America. The limited capacity to support scientists of developing countries, e.g. Africa, has impeded ESA's ability to foster science-based and societally relevant applications of EO data in these countries. If ESA intends to promote greater use of its observations in these countries, ESA needs to develop the necessary mechanisms and means to facilitate access and exploitation of its data by scientists from developing countries.

Education and training activities, performed within EOEP, are closely linked to the scientific exploitation of the ESA Earth observations mission. The Panel acknowledges the significant rise in advanced EO training courses and tutorials during EOEP-3 with record attendance in 2010. These training courses, together with the ESA EO summer school on Earth System Monitoring and Modelling, are an important step for the future advance of scientific Earth Observation, as young scientists are attracted to the use of EO techniques and products in order to solve important questions in Earth system science. For promoting the worldwide use of ESA EO data, joint training courses with partners in Africa, Asia and Latin America, as well as special training sessions at scientific conferences have been organized. Feedback from the participants of the various training courses has been very positive, highlighting in particular the quality of the training material and the importance of practical parts for exploiting ESA EO data. A very positive new initiative is also the Changing Earth Science Network as part of STSE, in which young post-doctoral scientists are performing innovative projects on scientific utilization of data from ESA missions, helping to solve scientific challenges of the Living Planet Programme.

A very important basis for promoting the use of EO data and attracting new users are the software tools, ranging from special software for reading and displaying data of ESA mission to open-source multi-mission toolboxes. These software tools have been further expanded within EOEP-3, offering enhanced capabilities for analysing multi-mission data of solid Earth, atmosphere, oceans, land surfaces, biosphere and cryosphere, including the data of the three Earth Explorer missions in space.

4.1.4 Innovative products for EO market

The Panel recognizes the importance of new, focussed developments in EO data analysis techniques and the demonstration of innovative service capabilities for opening up new market opportunities. The Value Adding Element (VAE) component of EOEP-3 serves these needs, building on the results and achievements of its precursor EOMD (Earth Observation Market Development). VAE has been quite successful in conducting specific service trials in collaboration with key users. More than 150 new users have been attracted to these prototype services, two thirds of which are from the private sector including several global players, one third are national and international organizations and bodies. In support of new developments and in expanding the market, the VAE activities strengthen the European and Canadian value-adding industry. Beyond serving individual end users and user groups, it is expected that several of the innovative products and services developed in VAE will be integrated into GMES Core or Downstream Services.

4.1.5 Summary and Outlook on Scientific Exploitation

The Panel acknowledges the outstanding scientific success of EOEP. The number of scientific users has increased remarkably, exploiting the ESA observation data in many innovative projects, leading to an impressive number of high-level publications. Many world-class publications in Earth system science are based on data delivered by ESA EO missions. It should be pointed out that ESA EOEP provides key input for these research activities by delivering an excellent data base, whereas the research work is largely funded by external sources and not structural to EOEP.

Scientific training, outreach and promotion have been further strengthened in EOEP-3. This is greatly appreciated, as concluded from feedbacks by the user community. Training courses, thematic workshops and symposia organized by ESA, are an important requisite for the very positive development of scientific exploitation of ESA missions, being additionally supported by the development of toolboxes and software for the analysis of ESA and multi-mission EO data. The Panel emphasizes these successful activities should be further strengthened by developing a secure and sustained framework for the EOEP in science communication, public outreach, training, and education. In this context, particular attention should also be paid to increasing the support for scientists of developing countries, which so far has been limited by the rather modest amount of dedicated resources.

STSE and DUE projects have a significant share in the success of the exploitation of EO data from the ESA missions regarding science applications, and VAE in enhancing the commercial market. The direct involvement of the Earth science community in STSE and DUE projects as end users, including representatives of major international research programmes, is the right approach to optimize the performance and quality of the EO-based products. This approach should be further pursued, addressing on one hand the development of innovative products for specific open scientific questions (STSE), and on the other hand developing in DUE the basis for routine generation of climate-change variables as pre-cursor for production of ECVs in the Climate Change Initiative (CCI). The Panel recognizes the challenge in sustaining these efforts, and emphasizes the need for defining a clear mechanism for consolidating future DUE and STSE activities.

Many pressing questions in Climate Change and Earth System Science require high quality observations over extended time periods. This stresses the importance of data continuity, sensor calibration, and sensor inter-calibration. In addition to the exploitation of important open scientific questions by the Earth Explorer missions, multi-mission exploitation is important. This option should be further exploited, taking into account also operational missions and links to missions of partner agencies.

As long-term records are particularly important for climate change research, it is essential to make data of operational missions, such as the Sentinels, freely available to the scientific community. Integration of dedicated data from Earth Explorer missions, in synergy with long-term space and in situ based climate observations into advanced Earth system models is a most promising approach for characterizing and predicting the evolution of the climate system, responding to urgent societal needs. In order to achieve these goals it is necessary that EOEP adopt an active long-term strategy for science support. The Panel Members believe that the current limited capacity of EOEP to support data exploitation may jeopardize science goals. ESA needs to maintain pro-active support to scientific exploitation and innovative applications. A long-term strategy for data exploitation needs to be developed in order to ensure the continuity of data products, as well as the development of new products. This will help to extend the benefits of the EOEP to the rapidly expanding user base for the EOEP and realize greater impact of EOEP on its mission/science objectives in the future.

We offer the following findings and recommendations based on our assessment of this element of the Programme.

We found that the current limited capacity of EOEP to support data exploitation may jeopardize EOEP long-term science goals. ESA needs to maintain pro-active support to scientific exploitation and innovative applications. We also recognize the importance of integrating data from Earth Explorer missions, in synergy with long-term space observations from Earth Watch (notably GMES Sentinels), meteorological and third party missions into advanced Earth system models. This is a very promising approach for characterizing and predicting the evolution of the Earth/climate system, in response to urgent societal needs. ***The Panel recommends that ESA should develop a long-term strategy for data analysis and exploitation from EOEP and Sentinels missions as a complement to the CCI, in order to ensure the continuity of currently accepted/expected data products, as well as the development of new products. This plan should integrate and strengthen the EOEP-4 and its components such as STSE, DUE and VAE into a coherent framework directly responding to the needs of the scientific and end- user community. This will help to***

extend the benefits of the EOEP to its rapidly expanding user base and to realize greater impact of EOEP on ESA mission/science objectives in the future.

Scientific training, outreach and communication are very important in demonstrating and conveying the benefits and impacts of EOEP scientific, technical and practical applications to the European Member States and the global community. ***The Panel recommends that ESA should further strengthen this successful line of activity based on training courses, thematic workshops, symposia, and ease of access to freely available software tool. ESA should also establish a routine framework for the science promotion, outreach, education, training, and science communication in EOEP-4. In this context, the support for participation of scientists of developing countries should also be considered.***

5. The ESA Self-Analysis of EOEP Strengths, Weaknesses, Opportunities and Threats (SWOT)

The Panel requested that ESA should complete a self-assessment of Strengths, Weaknesses, Opportunities and Threats (SWOT) for the EOEP based on the experience it has gained and lessons learned during the past decade. We believed this process to be useful to the ESA team in preparing for the definition and implementation of EOEP-4. Some Panel Members' prior experience with this type of analysis has proven that such a self-assessment not only encourages critical thinking, it also motivates the entire ESA team to examine all components of the Programme and their inter-relationship and possible dependencies. In complex programmes such as EOEP very often surprises arise as a result of interdependencies at the interface of different programme elements. If they are identified and managed proactively, significant risks that can lead to schedule and cost complications can be avoided to the benefit of the entire Programme.

The first order feedback that the Panel Members received from the ESA team during the presentation and discussion of the results of this SWOT analysis was quite positive. We believe the ESA team did an excellent job in identifying the major Programme strengths to be reinforced, some weaknesses to be fixed, and some opportunities to be realized in the future. We present below the outcome of the SWOT analysis as it was presented to the Panel without any major change, which reflects well on the thoroughness of the ESA team in this process. The recognition of any weaknesses and threats should not be viewed negatively, but as a means to further improve an already very successful programme. We believe that taking note of and addressing them will undoubtedly benefit the Programme in its next phase.

5.1 Strengths

Preparatory Activities & Implementation Phase

- **Flexible Science-driven framework delivers world-class, cost-effective missions**
  - Comparatively, **exceptional scientific value for money**
  - **Rigorous and diligent implementation** guarantees top quality scientific data
  - Programme flexibility ensures **delivery of science goals despite setbacks** (CryoSat)

- **Strong engagement of scientific community**
  - **Science community empowered** by involvement in requirements definition and consolidation
  - Extensive **guidance to technology, algorithms, product development and data processing**
  - Support to concept consolidation via **robust trade-offs** of alternative approaches
  - **Vital understanding** developed from impact studies, simulation of data products, campaigns

  - Engagement in mission development phase acts as **catalyst for science user readiness**
  - Feedback via International User Workshops and **added-value via supporting studies**

- **ESAC guidance triggers specific preparatory activity**
  - Advice on commended missions **fosters improved mission concepts** (often selected later)
  - Ideas leading to **entirely new mission concepts**

- **Evolving operational mission concepts**
  - EE-proven EO techniques feed into operational meteorological and GMES missions
  - **Concerted technology development leads to robust instruments and operational readiness**

- **Regular Calls for new missions provide a long-term perspective**
  - **Sustained high interest of EO community**: increasing number of competitive proposals to Calls
  - **Encourages scientists to reply** even at early stage of concepts, or after non-selection

Mission Operations, Ground Segment & Exploitation Phase

- **Delivers its science goals**
  - Major contribution to international **Earth Science initiatives**
  - Foster **European scientific excellence** & international collaboration
  - Ensures access to **20+years continuous high-quality** EO data for science and applications
  - Enables scientific advances by **exceeding sensor performance & extending mission lifetimes**

- **Builds the EO community and engages with other stakeholders**
  - Fosters **growth of EO science community**, develops and matures new EO methods
  - Fosters emergence and growth of **advanced EO disciplines**
  - Provides a seamless conduit from EO **science to applications** development
  - Prepares **scientifically sound methods** for a competitive value-adding industry
  - Engages **new user communities** into EO
  - Prepares **next generation** of EO scientists

- **Responds pro-actively to data users requirements**
  - Gathers scientists **feedback to orient programme** implementation
  - Solicits **user assessments to improve** mission operations, data quality and applications utility
  - Leverages **support for Cal/Val and EO research** in national programmes

- **Lays the foundation for future programmes (viz. GMES, CCI)**
  - Feeds lessons from science & applications exploitation into **future missions definition**

- **Extensively communicates and promotes EO science achievements**
  - Expands **public awareness of benefits** of EO science, technology and applications

5.2 Weaknesses

Preparatory Activities & Implementation Phase

- **Limits in technology preparation** – due to decreased resources
  - Appropriate emphasis on maturing promising technologies for EE proposals to future AOs
  - Ensure adequate resources to reach necessary TRL for EE mission approval

- Need to reinforce treatment of missions selected with **external contributions**
  - Make selection criteria more stringent & establish commitment to required preparatory support

- Selection, Preparation and Implementation **not as agile as the Science Community may like**
  - Better inform science community of constraints and programmatic limitations faced by ESA

- **Reliance on National initiatives** to sustain scientific user community during implementation
  - Foster connections to National and EU (e.g. ESF, FP8/9) research programmes to sustain interest

Mission Operations, Ground Segment & Exploitation Phase

- Nominal **EE mission lifetimes are short** with reference to achieving best science return
  - Plan the capacity to extend lifetimes of future Earth Explorer missions

- **Science dilemma**: New EE missions versus extending existing missions
  - Strive to achieve maximum possible scientific return from all 'Earth Explorers 'in orbit'

- **Limited capacity** to support scientists of developing countries – e.g. Africa
  - Facilitate exploitation of ESA data by scientists from developing countries

- Strong **dependence on external programmes** for Cal/Val and exploitation
  - Work with external programme authorities to promote & maintain these activities in future

5.3 Opportunities

Preparatory Activities & Implementation Phase

- **Reduced technical and scientific risk** achieved by more systematic preparatory activities
  - Accumulate know how in a systematic approach to preparatory tools and study analyses

- Mitigation of risk of **technical challenges encountered during Implementation**
  - Mission approval only after EE candidate matured to Ph B1 (per new Implementation Policy)

- Benefits from **Tech/Science knowledge transfer** from parallel international missions
  - Develop interagency links to benefit from synergies; e.g. GOCE-GRACE, SMOS-Aquarius.

- **Strong international cooperation** leads to enhanced scientific exploitation
  - Encourage broader international engagement in MAGs and Campaigns, as appropriate
  - Enhance cooperation by joint pre-development of sensors and missions with ESAC guidance

- **Maintaining core science teams** by strengthened ties with National research programmes
  - Establish National Project offices for EE missions as model to enhance sustained support
  - Foster community engagement thanks to pre-launch campaigns that prepare for exploitation

- **Improved feedbacks** from later phases of current Earth Explorers
  - Take full benefit of lessons learned in prep of future EE and operational missions

Mission Operations, Ground Segment & Exploitation Phase

- **Constantly improved Data Access** can 'explode' future exploitation & science return
  - Strive to continuously simplify, expand and accelerate access to ESA EO science data

- **Data Assimilation techniques** can greatly enhance NRT scientific exploitation of future EEs
  - Take full account of evolution of these capabilities for all future EE missions

- More science by exploiting **data freely available from future operational** missions

  - Support science community to exploit data from operational missions following ERS & Envisat

- Synergy with **complementary research programmes** (FP8, national) to capitalize EOEP results
  - Seek synergies with related research programmes to maximise impact of EOEP results

- Increase **cooperation with international partners** on sensors/missions
  - Foster enhanced scientific cooperation on EO with key players worldwide

5.4 Threats

Preparatory Activities & Implementation Phase

- **Criticality of mission preparation** to achieve stringent science goals
  - Programme encourages "extremely challenging", by nature high risk missions
  - Large number of candidates dilutes preparation efforts
  - Limitations to technology developments, science studies and end-to-end assessments amplify risk
  - Tendency of optimism in technical risk assessment in the face of high-priority science
    - Requisite preparation for achieving required TRL prior to down-select or approval

- **EO under non-EOP Programmes** undermine rigorous science-driven EOEP selection process
  - Stronger effort to preserve EO in EOP Directorate with support of Member States

- **Potentially increasing commitments to other programmes** vs. EOEP
  - Prioritise EOEP with support of Science Community through Member States

- **Science Conflict** between new missions and mission extensions
  - Maintain rigorous process for approval of mission extension

- **Non-secured prelaunch commitments** to National support to Cal/ Val activities
  - Issue AOs early and secure critical efforts via M/S dialogue and support contracts

Mission Operations, Ground Segment & Exploitation Phase

- **Uncertainty** about follow-on science data after EE missions
  - Facilitate future access and scientific exploitation of data from relevant non-ESA missions

- **Scientific impact would decline** if Cal/Val/QA reduced after nominal mission lifetimes
  - Ensure data quality excellence is maintained throughout mission lifetimes and extensions

- **Inadequate** ESA effort to support data exploitation would jeopardize science goals
  - Maintain pro-active EOEP support to scientific exploitation and innovative applications

- **Long Term Data Preservation** to support long-term scientific exploitation is not ensured
  - Act now to secure future access to all ESA EO science data, algorithms & meta-data

6. EOEP Science: Overall Assessment and Recommendations

The EOEP has evolved successfully by developing, launching and operating a series of exciting and cutting edge space-based Earth observing satellites. The Programme uses a unique combination of advanced remote sensing and information technologies to achieve substantial scientific understanding of major components of the Earth's complex system and its natural behaviour. ESA has taken full advantage of rapidly emerging computing, information and telecommunication technologies to receive, process, archive and distribute vast amounts of observations and information resulting from these missions to enable world-class and leading-edge scientific exploration and discoveries of the complex Earth system and its changing climate. Thousands of scientific and technical publications, which describe findings and discoveries based on ESA missions, are published in the open literature. The scientific benefits and the observations resulting from EOEP now extend beyond the scientific community to a wide range of decision makers in public policy, environmental and natural resources managers, natural disaster risk managers, educators, to name just a few of non-traditional users. Such innovative use of EOEP observations and information has extended the benefits of the Programme well beyond the scientific community to the European and global citizens. The ongoing success of the EOEP has put ESA at the forefront of global Earth observation programmes worldwide. To maintain this leadership in the space sector on behalf of Europe, ESA should continue to build on the strong foundation it has established for EOEP in the past. The recommendations that we have provided in each section of this report are intended to assist ESA to maintain the strong base it has built and to grow EOEP in the future to be even more successful. We summarise all of our recommendations in this section of the report to convey their inter-related nature and the need for a balanced approach to their implementation across the entire Programme.

1. Considering the EOEP major and unique strengths, we believe that ESA is very well positioned to execute the next phase of EOEP successfully. The EOEP continued success in the future and its achievements can be maintained only by sustained financial investment by European Member States. ***The Panel recommends that the EOEP-4 should be funded at a sufficient level in the next decade, optimally greater than the last period, to enable ESA to implement the recommendations of this report and to ensure European leadership of an exciting and vibrant programme in Earth Observation. This will also contribute directly to maintaining and utilizing a strong EO industrial base at the forefront of global Earth observations science, engineering and technology.***

2. We found ESA's approach of consulting broadly, and in a sustained manner, with the scientific community in establishing its science strategy and priorities to have been very effective and sound. This process has served very well both ESA and the European science community resulting in a significant growth in this community, especially during the EOEP-3 period. ***The Panel recommends that ESA should take advantage of its effective working relationship with the scientific community to review and update periodically its "Changing Earth" Strategy and related scientific and technical plans. Identifying an optimum period for a regular update of these plans can be a part of the consultation process, under the guidance of ESAC.***

3. The balance between risk and innovation in the Earth Explorer Programme requires continued strategic thinking and planning in the future, especially in the light of the rapidly evolving science requirements and the changing European national and other international space-based Earth observation programmes. This particularly applies, as far as the timing of the calls and the subsequent selection of the missions is concerned. ***The Panel recommends that ESA should continue to ensure in its future calls that scientific balance is sought between missions planned and flying and those to be selected in EOEP-4. In this regard, ESA should continue to give careful consideration to missions of national and international partners, as it has in the past. Specific consideration should be also given to proposed mission concepts that serve complimentary scientific objectives of more than one discipline.***

4. We found the principles of open and un-restricted access to EOEP observations and information are serving ESA and the European community very well. This has put the European EO Programme in the top tier of World leaders as a provider of Earth observations from space. ***The Panel recommends that the principles of an open and un-restricted access to EOEP observations should be re-enforced during the EOEP-4 period and eventually be turned into an ESA-wide data and information sharing policy. In particular, the Panel strongly supports ESA efforts in securing free and unrestricted data access from all future GMES Sentinels for use in support of the Living Planet Programme strategic objectives.***

5. We found that the major distinction between the “Core“ and “Opportunity” missions is rapidly disappearing, especially in overall duration for mission life cycle development. ***The Panel recommends that ESA should review and refine existing definitions of science and programme criteria for the Core and Opportunity missions on the basis of its experience during the past periods of the EOEP, in time for the EOEP-4 solicitation and implementation.***

6. We found the added risk due to technology innovations in later phases of the Programme is the primary reason for prolonged development life-cycle time and increased cost. This has had some adverse impact on the current selection procedure and may have consequences on the EOEP at large. We therefore endorse the ESA approach that selection of future Earth Explorer candidate missions for implementation should be made only after successful completion of Phase B1, in order to minimize the risks of technology innovation to life-cycle time and cost in EOEP-4. ***The Panel recommends that ESA should maintain technology development in the mission definition and preparation phase up to and including Phase B1, and that selection of mission for implementation should occur after Phase B1, when the level of technological maturity is high enough to ensure mission success.***

7. We discussed the frequency of calls for mission concepts in EOEP and the number of mission concepts retained for the down-selection process. We also explored the ESA scientific and technical capacity to adequately support thorough evaluation of the mission concepts and guiding their development during the mission definition phase. We believe an active dialogue between ESA and the European science community on this topic to explore the merits and de-merits of possible options will be highly beneficial to both sides in preparation for the EOEP-4. ***The Panel recommends that ESA should assess the trade-off between the number of***

calls for mission concepts and the number of missions considered for down-selection, on the basis of experience it has gained from the past EOEP periods. ESA should consult with the science/user community under the guidance of ESAC to determine the best strategy for the EOEP-4. In this context ESA should devise a strategy to maintain the requisite number of alternative mission concepts during the early phases of the Programme.

8. We found that ESA has done a superb job in developing and using very effectively a wide range of capabilities such as end-to-end mission simulators, calibration/validation tools, sub-orbital capabilities, and in-situ observing networks to understand and mitigate risks of new technologies, to develop and validate scientific algorithms, and also to prepare the scientific user communities for use of observations from future missions. ***The Panel recommends that capabilities such as end-to-end mission simulators, calibration/validation tools, sub-orbital capabilities, and in-situ observing networks be further strengthened and used effectively in all phases of the EOEP-4. Investments in these capabilities have served ESA and its mission very well and we believe they will be even more critical to mission success with respect to multi-sensor/mission development, operation and exploitation in the future.***

9. We envision that the complexity and interdisciplinary nature of future scientific challenges will require even more innovative technologies and observational methodologies in the next decade. Scientific challenges at the intersection of biological, physical and chemical aspects of the atmosphere, ocean, biosphere, cryosphere, and terrestrial ecosystems will require observations from multiple instruments/platforms and a variety of orbits to capture, characterize and understand the complex Earth system processes towards the ultimate goal of developing the predictive capabilities to project the future course of change. Such complex scientific challenges require long-term and high quality observational records that may span across multiple decades. In this context the Panel recognises the great potential of data from GMES to enable major scientific advances. ***The Panel recommends that ESA should explore and exploit innovative implementation strategies such as different vantage points, virtual constellations, longer duration missions and synergy between Earth Explorer class missions and international and Earth Watch systems (notably GMES Sentinels) to address the scientific challenges of the Living Planet Programme.***

10. We have identified a need for a new class of small Earth Explorer experiments of opportunity to meet the rapidly emerging scientific opportunities by taking advantage of national and international partnerships with research, environmental and meteorological organisations. This class of experiments should provide greater flexibility and agility to EOEP for responding to fast emerging scientific, strategic and international partnership challenges and opportunities***. The Panel recommends that ESA should develop a small Earth Explorer class of science driven missions of opportunity as a part of the EOEP-4. This new class of experiments should be smaller in size and cost significantly less than the current Earth Explorer classes of missions. They could be implemented either in a dedicated mode, not necessarily in synchrony with the Earth Explorer solicitation, by ESA or as experiments of opportunity for space or sub-orbital platforms in partnership with the national or international organisations.***

11. We found that ESA and the Mission Advisory Groups can benefit further from the scientific and technical expertise available to them through the ESAC and international partner programmes such as the International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), Global Climate Observing System (GCOS) and Global Earth Observing System of Systems (GEOSS). ***The Panel recommends that ESAC should continue to provide its strong leadership in the advisory function to the ESA Executive, and facilitate greater partnership with the international observations and research coordination programmes.***

12. The quality of observations and information provided by ESA during the last decade improved significantly and this together with ESA' policies for un-restricted access to its Earth observations in turn resulted in significantly greater number of users and applications of these observations by the scientific community and a wide range of non-traditional users in value-added industry and governmental and non-governmental institutions. We believe that this strength in increased diversity of users and their needs for Earth observations and information will continue to grow during EOEP-4. ***The Panel recommends that ESA should continue to invest in the ground segment part of its programme by developing and making available to users the necessary analysis, processing and visualization tools to accommodate the increasing demand for the observations and to avoid potential log-jams that may be created due to transfer of large amounts of data by these users from ESA to their local sites. ESA should also ensure continued high quality observations resulting from its mission extension periods, maintaining its high standard of calibration and validation during the entire life of missions***.

13. We discussed the challenge that ESA faces in financial trade-off between extending the operation of on orbit mission versus development of new Earth Explorer missions. Recognizing the success of the current trend for Earth Explorer missions to last longer than planned and the urgent need for continued access to such observations for addressing high priority science questions, we believe this trend will continue into the future and ESA will be asked to consider extending the operation of the current and future Earth Explorer missions. This is an excellent indicator of mission success. ***The Panel recommends that ESA should develop a clear set of guidelines for mission operation extensions based on a consultation with the scientific community, under the guidance of ESAC. ESA should establish a formal process for submission, evaluation and selection of mission operation extension proposals based on these guidelines and ESA formal selection/approval process. This requires that ESA establish also a dedicated budget line with sufficient resources for funding successful proposals as a part of the EOEP-4.***

14. We discussed the Long Term Data Preservation in support of long-term scientific exploitation and concluded that ESA needs to develop a strategy to secure future access to all ESA EO science data, algorithms and meta-data in support of its mission/science objectives. The long-term data preservation and greater access to EOEP observations should be secured as an essential activity under ESA's responsibility. ***The Panel recommends that ESA should put in place sufficient means for data processing and reprocessing, long term archiving and distributing for Level 1 and 2 datasets, and for easy and greater access by the scientific community. ESA should also consider stimulating the provision of higher-level data products because of considerable interest by scientists and other users who do not have the ability to produce such products. This will help to enhance further the user base for ESA Earth observations.***

15. We found that the current limited capacity of EOEP to support data exploitation may jeopardize EOEP long-term science goals. ESA needs to maintain pro-active support to scientific exploitation and innovative applications. We also recognize the importance of integrating data from Earth Explorer missions, in synergy with long-term space observations from Earth Watch (notably GMES Sentinels), meteorological and third party missions into advanced Earth system models. This is a very promising approach for characterizing and predicting the evolution of the Earth/climate system, in response to urgent societal needs. ***The Panel recommends that ESA should develop a long-term strategy for data analysis and exploitation as a complement to the CCI, in order to ensure the continuity of currently accepted/expected data products, as well as the development of new products. This plan should integrate and strengthen the EOEP-4 and its components such as STSE, DUE and VAE into a coherent framework directly responding to the needs of the scientific and end- user community. This will help to extend the benefits of the EOEP to its rapidly expanding user base and realize greater impact of EOEP on its mission/science objectives in the future.***

16. Scientific training, outreach and communication are very important in demonstrating and conveying the benefits and impacts of EOEP scientific, technical and practical applications to the European Member States and the global community. ***The Panel recommends that ESA should further strengthen this successful line of activity based on training courses, thematic workshops, symposia, and ease of access to freely available software tool. ESA should also establish a routine framework for the science promotion, outreach, education, training, and science communication in EOEP-4. In this context, the support for participation of scientists of developing countries should also be considered.***

Annex I: Scientific aspects of the EOEP and selected questions addressed in this review.

1. Preparatory Activities	**Earth Explorer Selection Preparation (Phase 0, A, B1) (EE-1 to EE-8) and Earth Watch Definition**	- Mission selection - Preparatory scientific activities (studies and campaigns) - Establishment of scientific and mission requirements Scientific activities for commended but not selected Earth Explorer candidates	- How are science requirements used in identifying and selecting high priority missions? - Have the right missions been chosen? - Has work on non-selected missions proven scientifically useful? Has it resulted in further activities and/or refined concepts? - Is the User Science Community well involved during mission preparation? - What is the role of international partners and programmes in definition of scientific requirements? - Have the right scientific support activities (structure/campaigns) been initiated? - Have international scientific activities in the field been taken into account? - Is the integrity of the science and mission requirements maintained? - How have complementing and feasibility studies supported (and strengthened) the mission selection process? - How adequate were feasibility studies for the evolution and progress of the Programme?

2. Earth Explorer Implementation	**Earth Explorer Development, Launch and Early Operations (Phase B2/C/D/E1)** **(GOCE, SMOS, CryoSat, ADM, EarthCARE, SWARM)**	- Maintenance of mission requirements - Trade-off between scientific requirements and mission concepts/technical solutions - Scientific Cal/Val activities - Development of scientific products - Exploitation of Third Party missions	- Have the missions from a scientific point of view been well implemented? - Has scientific advice (from SAGs and MAGs) been duly taken into account during implementation? - Have mission requirements been safeguarded? What are the role of scientists and science requirements in mission development, cost, schedule and risk assessment and trade-off analysis? - Are the instrument/mission scientific requirements defined clearly, documented and managed consistently by the Programme and Project Scientists and Managers (i.e. are they under management configuration control)?
3. Ground Segment Activities and Operations (Phase E2)	**Earth Explorer Exploitation (Phase E2)** **(GOCE, SMOS, CryoSat)**	- Mission achievements against mission requirements and mission objectives - Data availability and accessibility - Validation of geo-bio physical scientific products - Development of higher level data products - Development of scientific applications - Feed-back loop to preparation of next programme period or into Earth Watch programme - Demonstration of potential operational applications	- Do the missions provide high quality scientific output? - How are scientific requirements used in definition, design, development and operation of the ground segment? - Have science and mission requirements been fulfilled? - Are the data available and accessible? - Is the data quality (including Cal/val) adequate (including higher level products)? How is the algorithms theoretical basis and maturity their development evaluated throughout the mission development and

			operation? How is data use and usefulness by individual scientists, the scientific projects and programmes evaluated? - How are calibration, validation and data quality certification managed throughout the life-time of the missions? - How have feedback mechanisms with the user community resulted in improved data and/or algorithm quality?
4. Exploitation	**Scientific Results and Innovation**	- Scientific achievements and results - New enhanced methods and algorithms - New data sets - Demonstration of ESA data value for science and applications - Fostering ESA data use by the scientific community - Feed-back loop of results into new scientific and also operational programmes	- To what extent have the scientific objectives of the Programme elements been fulfilled? - Has the Programme delivered new scientific results? - Have the Programme elements delivered innovative methods and enhanced products? - Has the EOEP provided the basis for initiating new activities in ESA and been useful as input to external, national and/or international programmes/activities? - How are the lessons learned from individual projects are captured into the programme level definitions, development and evolution? - How are scientific accomplishments and impact evaluated by the Project and Programme?
	Engagement of Earth Science	- Involvement of PIs - Usage by national and international	- Do the science data usage and user feed back indicate

	User Communities and Cooperation with International Science Programmes	entities - Feedback from International Research Programmes and ESAC - Cooperation of Science data Users in the international context - Communication of scientific achievements	'Customer satisfaction'? - Are the mission products of value to the global Earth Observation Science Community? Do they foster collaboration in the International context? - Are the scientific results and achievements adequately communicated - How have international programmes responded to existing and upcoming products (and missions) developed within EOEP?
	Training and Capacity Building	- Involvement of the international community in training and teaching activities - Organisation of courses, workshops, training events - Provision of s/w tools, training- and information material	- Are the training and capacity building activities commensurate to the Programme - Is the Training programme and its elements adequate in the international context? - Can educational curricula (schools/universities) be effectively addressed? - How are the science education, communication and outreach activities defined, and how their effectiveness is evaluated?

Annex II: The EOEP Documents made available to the Science Panel Members for this review.

EOEP Programme Proposal and Declaration:

- PB-EO(2005)53 Rev 2
- Decl_EOEP_ESAC(2009)103 - Declaration covering the Earth Observation Envelope Programme

EOEP History and Strategy:

- ESA-SP-1227 "The Science and Research Elements of ESA's Living Planet Programme" - This document presents the initial plans for the Earth Explorers and LPP implementation aspects.
- ESA-SP-1234 "Introducing the "Living Planet Programme" - This describes ESA's EO strategy back 1999
- ESA-SP-1304 "The Changing Earth" - This presents the currently valid strategy and challenges for the LPP

EOEP Science Review 2005:

- 2005 Final report by Review Panel
- PBEO(2005)23 - Scientific review of the EOEP as presented to PB-EO
- PBEO(2006)24 - Implementation of recommendations from the EOEP science review
- PBEO(2006)95 - Status of implementation of recommendations from the EOEP science review

Earth Explorer Brochures:

- BR-236 - ADM-Aeolus - ESA's Wind Mission
- BR-276 - CryoSat - ESA's Ice Mission
- BR-285 - GOCE - ESA's Gravity Mission
- BR-288- SMOS - ESA's Water Mission
- SP1311 - ADM-Aeolus Science Report
- SP1272 - CryoSat Science Report
- ESA-Bulletin SP133 - GOCE pages
- ESA-Bulletin SP137 - SMOS pages
- ESA-Bulletin SP141 - CryoSat pages:

Living Planet Symposium Bergen 2010:

- User Satisfaction Survey: EO User Services Customer Satisfaction Measurement
  Management Report
  ESA EO User Services Customer Satisfaction Survey 2010
  ESA EO Long Term Data Preservation Survey 2010
  ESA EO User Services Vision beyond 2015
- LP Symposium Abstracts

STSE:

- The Changing Earth Science Network - Supporting the next Generation of European Scientists
- Support to Science Element (STSE) Report 2008-2010

VAE:

- Start of VAE activities - Innovation and Growth for EO Services

DUE:

- Data User Element - DUE-DUP Directory 2000-2007
- DUE Summary

'Technology' folder:

- ESA's Technology End-to-End process - This IPC document describes the E-2-E process and the involved entities and defines the framework of technology coordination within ESA.
- Draft ESA Technology Strategy - ESA's Technology Strategy and Long Term Plan identifies the overall Agency objectives concerning technology. Such objectives aim at developing the enabling technologies for the missions presented in the ESA Long-Term Plan. Cross-sectorial objectives, including innovation, industrial competitiveness and non-dependence are also identified in the Long-Term Plan.
- EO Technology Challenges and Plans - The Earth Observation Technology Challenge and Plan starts from the identification of the New Scientific Challenges for ESA's Living Planet Programme. The Earth Science challenges have been analysed in order to identify the required new Earth Observation methods and techniques. The related technology challenges and requirements have been collected and are outlined in this document.
- Earth Observation part of TRP workplan of 2011 to 2013 - The Earth Observation Part of the TRP workplan 2011-2013 presents the selection of TRP activities for 2011-13 in compliance with the programmatic needs expressed in the EO Technology Challenge and Plans document.

Additional information available on-line at:

Scientific Exploitation of ESA and Third Party Missions (toolboxes, workshops, symposia, advanced training events)

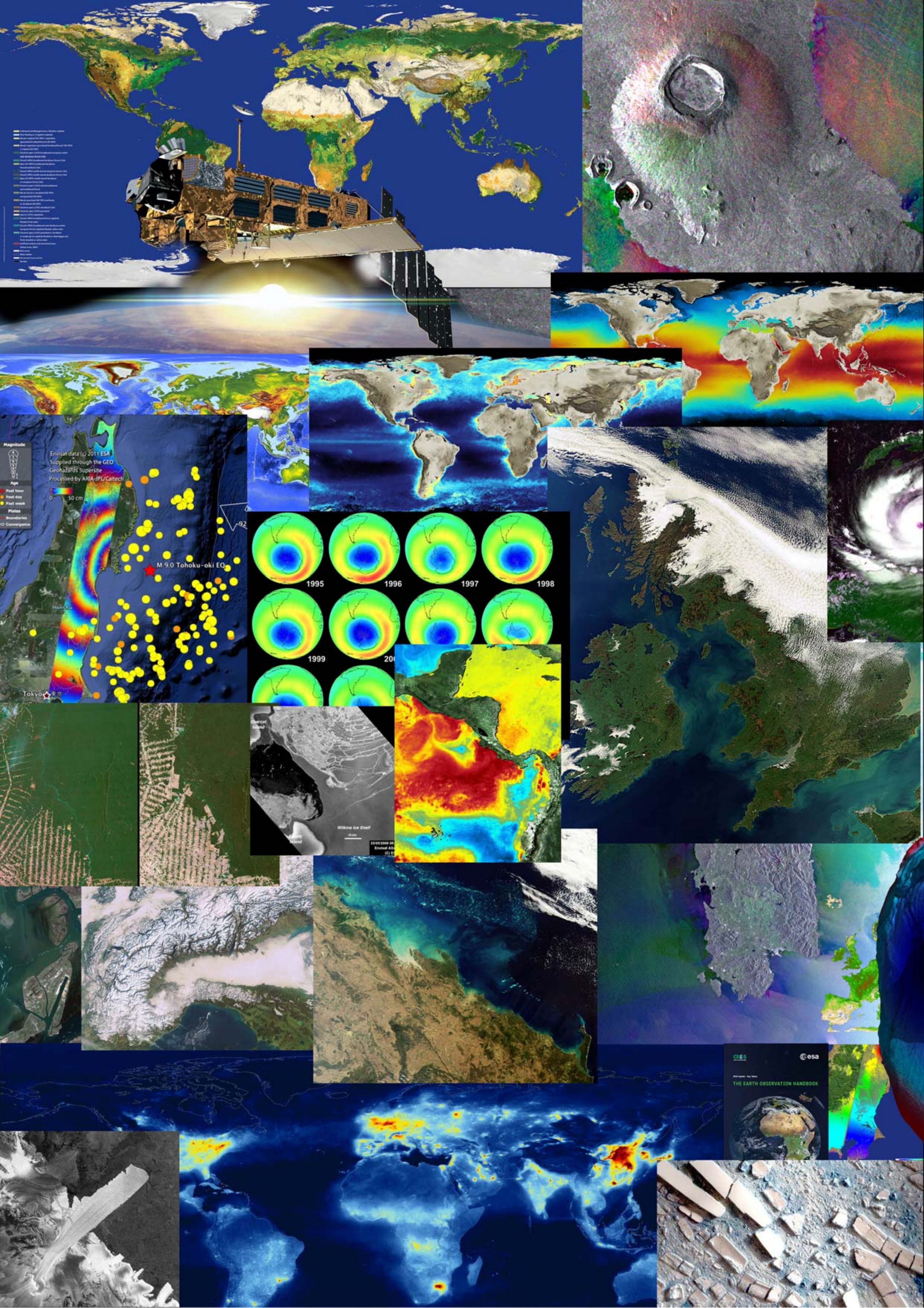
http://eopi.esa.int/esa/esa

DUE

http://due.esrin.esa.int/index.php

VAE

http://www.eomd.esa.int/index.asp


Magnitude
Age
Past hour
Past day
Past week
Plates
Boundaries
Convergence
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Supplied through the GEO
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THE EARTH OBSERVATION HANDBOOK