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Policy for robust space-based earth science, technology and applications

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ABSTRACT

Satellite remote sensing technology has contributed to the transformation of multiple earth science domains, putting space observations at the forefront of innovation in earth science. With new satellite missions being launched every year, new types of earth science data are being incorporated into science models and decision-making systems in a broad array of organizations. Policy guidance can influence the degree to which user needs influence mission design and when, and ensure that satellite missions serve both the scientific and user communities without becoming unfocused and overly expensive. By considering the needs of the user community early on in the mission-design process, agencies can ensure that satellites meet the needs of multiple constituencies. This paper describes the mission development process in NASA and ESA and compares and contrasts the successes and challenges faced by these agencies as they try to balance science and applications within their missions.

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1. Introduction

Satellite remote sensing technology has, over the past six decades, contributed to the transformation of multiple earth science domains. Space-based earth observations have contributed to quantitative understanding of processes and interactions between the land, ocean and atmosphere, as well as enabled real-time monitoring of weather, agriculture, water supplies, snow pack and a myriad of other environmental parameters, enabling a better understanding of important societal benefits. As the number and capability of space-based sensors has expanded, the amount of data available for use in environmental management, decision making and operational modeling environments have also increased. Using satellite remote sensing for practical decision making and action, now involves a broad community individuals, institutions, and organizations both public and private [1]. This broad constituency has led to the perception that earth science missions should be more closely aligned with the needs of the user community [2].

Because user requirements can be poorly aligned with mission characteristics required to obtain scientific observations, technological advances or strategic integration of missions wanted by space agencies, there is a need for a more comprehensive policy on the way the broader user communities influence new science missions. Policy guidance can influence the degree to which user needs influence mission design and when, and ensure that satellite missions serve both the scientific and user communities without becoming unfocused and overly expensive. By understanding and considering the needs of the environmental data and applied research user community early on in the mission-design process, agencies can ensure that satellites meet the needs of multiple constituencies.

This paper examines the experience that the US National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have had in their efforts to increase the integration of user communities into mission development. ESA has begun the Global Monitoring for Environment and Security (GMES)

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program, whose focus is to convert observations into environmental services. With the publication of the 2007 US National Research Council's Earth Science Decadal Survey, NASA has begun working to change its mission development process to incorporate the needs of satellite data users into mission development [3]. The paper describes the mission development process in both space agencies and compares and contrasts the successes and challenges faced by these agencies as they try to balance science and applications within their missions.

1.1. Background

As the scope of data products derived from satellite-derived information has expanded over the past six decades, the incorporation of Earth science products into the mainstream environmental, meteorological and other user communities has increased [4]. This includes the movement of essentially science-produced research products derived from missions into operational observations, such as those that the National Oceanographic and Atmospheric Administration (NOAA) are responsible for providing. Whitney and Leshner define research activities as those that "develop scientific understanding of important processes and/or demonstrate the capabilities of new analysis, modeling techniques, or measurement techniques, typically through acquiring, calibrating, and characterizing a specific set of measurements" [5]. One can consider a spectrum of activities that begin with mission design and end with operational production of measurements that are ingested into algorithms and models to produce data products. Applications of remote sensing are very diverse and include scientific analysis, periodic assessments of land cover, one-time decision making assessments, or operational use in models such as weather prediction [6–9]. Operational activities "routinely and reliably generate specific services and products that meet predefined accuracy, timeliness, and scope/format requirements, as well as disseminating or making them available to a variety of users in the public, private, and academic sectors" [5].

Diverse communities have made efforts to move from an ad hoc approach of integrating scientific data into operational processes to a more systematic and flexible process that is funded by adequate resources. The 'Valley of Death' between research and operations, discussed in a 2003 National Academy of Sciences report, can be bridged with improved supporting infrastructure that links research to operations to the user community of satellite data [3]. Gilruth et al. (2006) describe efforts to develop performance metrics based on results from the US Congress-mandated, NASA-funded Earth Observing Systems (EOS) Data and Information System (EOSDIS) project. This project has worked to provide data and products relevant to global change research to a broad user community. Their paper provides clear examples of the specific benefits and uses of satellite observations in models and in decision-support systems across different US government agencies and private institutions [4]. This effort has raised NASA's profile as a provider of scientific analysis and resulting data product that can be useful for policy and decision-making processes.

In Europe, the Global Monitoring for Environment and Security (GMES) programme focuses on the implementation of a common European space policy, and the need to build environmental monitoring and research capability that will serve all nations in the European Union [10,11]. Like Gilruth et al., Brachet discusses how the implementation of GMES is focused on delivering information and services needed by user, ongoing assessment of how needs are being met, and developing an infrastructure required to provide these services. Metrics and deliverables were at the center of the relationship between users and producers, similar to those seen in EOSDIS [11].

Thus the increase in the use of satellite data beyond the research community and the ever increasing 'pull' or need for earth observations from user communities should affect how missions are designed and implemented [12]. Precipitation, vegetation, sea ice, atmospheric variations, land use and land cover, forest dynamics and many other remote sensing derived environmental variables are regularly used in the public, private and educational sectors [13–16]. As the need for these data expands, the tension between research and operational sensor design and product delivery becomes more acute. This paper examines how national space policy can ensure continual improvement of earth observations, while sustaining measurements in key areas to ensure support of decision makers.

2. Earth science at NASA

As the US civil space agency, NASA has the responsibility of communicating and applying its mission products to all interested US agencies. Thus, by fostering relationships with interested entities, NASA can strengthen the development of Earth science applications. The US National Research Council's (NRC) 2007 earth science decadal survey provided a broad set of new instruments, observations and climate data records [16]. The report addressed the importance of applications and "recommended a suite of satellite missions and complementary activities that serve both scientific and applications objectives for the nation". It stated that identifying and supporting applications of scientific data to obtain societal benefits from NASA missions should play an equal role during the formation and implementation of new missions to that of science and presented a vision for developing new satellite data products that have specific user communities' needs and requirements at the center of mission development. Meeting this objective will require a continual evolution in the way NASA and the earth science community does business. It will need to re-evaluate how it prioritizes, makes decisions and communicates with the user community. NASA must engage with communities of satellite data users early in process of mission development, and sustain the engagement for the entire life of the mission.

The US National Space Policy of 2010 states that one of NASA's goals is to 'improve space-based Earth and solar observation capabilities needed to conduct science, forecast terrestrial and near-Earth space weather, monitor climate and global change, manage natural resources, and support disaster response and recovery.' NASA has assigned the responsibility for defining, planning, and overseeing its space and earth science programs to the Science Mission Directorate (SMD). SMD organizes its work into broad scientific pursuits: conducting scientific exploration of the Earth, Sun, Solar System and Universe, enabled by access to space. SMD develops instruments and spacecraft to support NASA's science goals and sponsors fundamental research and analysis to advance scientific knowledge [17].

NASA's Applied Science Program, located within SMD, works primarily through partnerships with organizations that have established connections to users and decision makers. The program supports applied science research and applications projects to promote innovation in the use of NASA earth science, transition of applied knowledge to public and private organizations, and integration of Earth science in organizations' decision making and services, helping to improve the quality of life and strengthen the economy. The Program leverages investments made in other areas and works within the broader scope of SMD to achieve its goals, competing with science, engineering, financial and strategic interests within and outside the organization.

2.1. Applications of earth science

Despite the existence of a NASA strategy for encouraging earth science applications, it has become clear that greater attention is needed to demonstrate the practical benefits of Earth observations and their applications to society. The 2007 National Academy of Science report, *Earth Science and Applications from Space*, recognized that "although promoting societal benefits and applications from basic research has been emphasized in national science policy discussions for decades, policy and decision makers at federal, state, and local levels also increasingly recognize the value of evidence-based policy making, which draws on scientific findings and understandings". The decadal survey also recognized the need for "a renewal of the national commitment to a program of Earth observations in which attention to securing practical benefits for humankind play[s] an equal role with the quest to acquire new knowledge about the Earth system" [2].

The applicability of earth observations to society can cover a broad range of issues, as recognized by the intergovernmental Group on Earth Observations (GEO) and the US Group on Earth Observations (USGEO). The societal benefit areas identified by GEO, including agriculture, biodiversity, climate, disasters, ecosystems, energy, health, water, and weather, will be served by current and future satellite systems. Part of the aim of GEO is to develop, through its Global Earth Observation System of Systems (GEOSS), a proper system of earth monitoring and to provide information from the technologies to a global range of users. NASA contributes to GEO through its broad program of earth observing missions, both past and future (The European contribution to GEOSS is through GMES.)

2.2. NASA policy on mission development

Although there are many forces compelling greater sensitivity from NASA to the needs of those partners who use its satellite data, NASA policy is currently to focus on continual advances in both science and technology. This policy is critical as it structures how the agency obtains societal benefits from its work. All NASA missions are driven by their science requirements, which determine the sensor design, data resolution and temporal characteristics, accuracy and format [19]. These science requirements can incorporate aspects of users' needs, but only to the point where they can be justified by the overall scientific goals.

The 2007 Decadal Survey generated consensus recommendations from the earth and environmental science and applications communities regarding a systems approach to space-based earth science observations. The survey was to replace NASA mission prioritization, as it contained guidance on which missions to fund, the set of observations needed, and the broader purpose each mission was to serve. NASA and the remote sensing community were urged to 'focus on meeting the demands of society explicitly, in addition to satisfying its curiosity about how the Earth system works' [2]. This will require an engagement with the community of data users who have their own requirements beyond those required by science.

In contrast to the more overtly science-driven earth observation missions of NASA, ESA such missions have a more user-oriented focus. It is to the ESA experience of managing Earth observation missions that we now turn.

3. European Space Agency and earth applications

During the same time Earth observations were becoming important for NASA, ESA was founded. Earth Observation soon became one of its major activities and now makes up 25% of its total budget.

The unified European Space Policy, formalized in the EU–ESA Framework Agreement signed in 2004, laid the basis for the establishment of the GMES program, a joint undertaking between ESA, the European Union and their respective member states. GMES is the result of longstanding cooperation between the two European agencies and aims to ensure autonomous access to reliable, traceable and sustainable information on environment and security [18]. It will also contribute to global climate change monitoring by monitoring essential climate variables (ECVs) under the assumption that space data continuity will be assured beyond 2020. The program uses observation data received from earth observation satellites and from ground- and atmosphere-based sensors which, once assimilated into models, are turned into information services for monitoring the environment and for security-related issues.

In order to accomplish these objectives, the programme has been divided into three components: space, in-situ and services. The space component of GMES is managed by ESA and is currently in its pre-operational stage, serving users with satellite data currently available through the GMES Contributing Missions at national, European and international levels. It will become operational in 2014, once the dedicated space infrastructure, the Sentinel satellites, is in orbit [26,27].

The in-situ component, coordinated by the European Environment Agency (EEA), is composed of atmospheric, airborne and ground-based monitoring data required for validation of GMES services as well as for input to some of these. The services component is based on data from the space and in-situ components. The main users of GMES will be policy makers. GMES should allow them to prepare national, European and international legislation on environmental matters (including climate change) and to monitor the implementation of this legislation.

3.1. ESA earth observation missions

Easy and wide access to satellite data is a key ingredient for a mission's success. GMES is the result of a preparatory program which started with ERS-1 (launched in 1991), ERS-2 (launched in 1995) and Envisat (launched in 2002). These were considered experimental and demonstration missions, combining scientific research objectives and application demonstration capabilities. It also took advantage of several users' programs (DUP: Data User Program, DUE: Data User Elements) funded by ESA member states to explore in detail users' requirements for many thematic applications (forestry, agriculture, marine surveillance, emergencies, sea-ice, etc).

Responding to users' needs, ESA's Living Planet Programme [20] comprises a science and research element [21,22], which includes the Earth Explorer missions (with missions such as GOCE, SMOS, CRYOSAT and SWARM) and an 'Earth Watch' element, designed to facilitate the delivery of Earth observation data for use in operational services. Earth Watch includes the well-established meteorological missions developed with Eumetsat [23,24].

3.1.1. GMES satellite missions

The space component of GMES is composed of satellite missions called Sentinels, specifically developed by ESA for the needs of GMES, and of "GMES Contributing Missions", owned or operated by European national or multinational organizations that are already providing data to GMES. An integrated ground segment ensures access to Sentinels and Contributing Missions data. The Sentinels is a series of five families of satellites comprising the first operational satellites responding to the EU's earth observation needs. Even if GMES is built primarily to serve operational services, there is a large benefit for science users as well. In addition, science will be crucial to advance services and provide critical input to the definition of new observation systems. The Sentinels will start to be launched in 2013 and carry a range of technologies for land, ocean and atmospheric monitoring.

The Contributing Missions are designated existing or planned missions from ESA and its member states, from Eumetsat and from other European and international third party operators that make part of their data available for GMES. These data are available through coordinated data access and dissemination for GMES services.

Unfortunately, GMES has experienced significant challenges in sustaining its funding into the operational phase of its development (post-2013, the planned date of the first satellite launch). The EU and ESA member states have already invested €3.4 billion in the development phase of GMES. The funding of its operational phase is not yet secured. It is part of the EU budget negotiations 2014–2020, which will continue until the end of 2013. The main programmatic challenge is therefore to ensure the program's long-term sustainability.

3.2. ESA and GMES policy on missions

GMES missions being implemented by ESA are prioritized based on those that can be used for societal benefit, which has resulted in the development of the Sentinel sensors [25,26]. The Sentinel missions were selected through a process of studies, workshops and input from the environmental community, focusing on the need for specific environmental monitoring services. The key to providing operational GMES services is to have an appropriate governance and business model structure in place that supports provision of these environmental services [28–35]. The prioritization of user needs over scientific and technological advancement makes the GMES program far more oriented towards providing services than NASA programs. Thus the Sentinel missions, once launched, can be clearly assessed for their societal values since the data resulting will be tied directly to environmental products and services to be used by the community.

4. Policy impact on mission process evolution

The scale of the GMES program is significantly beyond anything being proposed at NASA, but the European experience provides context to NASA's new initiative. GMES has designed its satellite missions with a focus on scientific, government and commercial communities interested in using the satellite data produced. For example, Sentinel 1 was designed to serve organizations and institutions that monitor Arctic sea-ice extent, map sea-ice, conduct surveillance of the marine environment, including of oil-spills and ships (for maritime security), monitor land-surface for motion risks, conduct mapping for forest, water and soil management and support humanitarian aid and crisis situations.

In contrast, NASA's mission selection process focuses entirely on the scientific contribution of a mission, with societal benefits as a secondary consideration. Although NASA has instruments that provide societal benefit, to be selected for funding, new missions require significantly new technology, observational capacity or scientific discoveries, which may preclude them from continuing the data record already established by their mission predecessors. NASA's challenge in this effort is to fuse the scientific objective of future missions with the existing societal and political callings related to climate change.

At NASA, there is no single avenue by which a mission is initiated. An original concept for a mission to obtain scientific data may come from members of the science community who are interested in particular aspects of an Earth science problem; it may come from an individual or group, such as a scientific team working on a particular issue, which knows of an opportunity to provide unique measurements; or it may be requested by NASA Headquarters to fill an identified need. As a project matures, the effort typically goes through the mission phases listed in Table 1, starting with Pre-Phase A formulation through to operations. Formal reviews are typically used as control gates at designated "critical points" of the system life cycle. These reviews determine whether the system development process should continue from one phase to the next, or what modifications may be required.

As of 2011, NASA also started to require an Applications Plan in addition to project plans, mission operations, education and public outreach and others. The Applications Plan details how the mission will engage the broader user community before and after a satellite is launched. This strategy will encourage the mission to have a well-defined contribution to society. Early in the mission development, there is usually selection of a Science Definition Team (SDT) and initiation of SDT meetings to provide oversight of the development of these products, leading up to the Senior Review and commencement of Phase A. The Applications Plan demonstrates how members of the science leadership plan to address applications activities during each phase of the mission (Table 1).

Currently, the potential uses of data products that come out of each missions are not at the center of the actual development process – they are a secondary objective. NASA's focus on high-quality science objectives may marginalize user observations, products and resolutions requirements. Involvement of the community who may use the data products often occurs either during the last year or two before launch of the instrument or after launch. This is very different from the GMES approach, where data users have provided data requirements for each satellite mission designed.

5. Assessing socioeconomic benefits

GMES has been focused on understanding the socioeconomic benefits of its activities for many years. In 2006 it funded a comprehensive study of these benefits by the private agency Price Waterhouse Coopers (PWC) along with collaborative partners [28]. The main objective of this report was to determine the extent of the impact resulting from GMES, and to characterize these benefits with respect to:

- The strategic and political impacts on Europe and its global position;
- The economic and social impacts, including more cost-effective information gathering, more targeted policies that use this information, and improved international agreements that address common environmental threats.

The report provided information on direct or 'micro-level' benefits derived from the construction and operation of the project. It also assessed wider, indirect 'macro-level' benefits from the project, including economic development, cost savings, improved management strategies and others.

A similar study was performed by Booz & Co [21] which, based on a literature review, looked at different funding levels and performed an impact analysis in the areas of climate change, environment and security and industrial development. From both studies a benefit–cost ratio of about ten was derived. This means that for every euro spent by the European tax payer on GMES, a public return of €10 can be expected.

In addition to these economic benefits GMES is expected to provide strategic benefits by providing Europe with better information globally, therefore allowing it to assume a stronger role on the political stage and the global marketplace. GMES policy for use of satellite data, unlike NASA applied sciences, represents a framework for the collection and dissemination of information. It is therefore likely that the significant social and economic benefits

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Table 1
Descriptions of NASA mission phases and applications activities relevant to each phase.

Mission phase	Description	Application activity	Work description
Pre-phase A	Science Working Group (SWG) is established, which establishes level 1 requirements, science goals and prepares a preliminary scientific conception of the mission.	Assessment of the *community of practice*. Description of the intersection of mission requirements and the needs of known applications.	Present the user community to mission team and define the scientific and policy need relevant to Mission Science objectives. Workshop Report, involving the science community, the policy community and the community of practice to create optimal Level 1 requirements, with descriptions of trade-offs and required latencies for applications and optimal societal benefit.
A Preliminary analysis	The project creates a preliminary design and proof of concept specifying instrument design, orbit, altitude, ground data systems and other details. The publication of the preliminary costing plan marks the completion of Phase A.	Website establishment and database of user community individual begins. Application Plan written and posted to website.	Feedback workshop of mission design study. Identification of potential Early Adopters. Data requirements discussed. Mission relevant policies identified. Identification of "important society decisions that will be made with mission science products".
B Definition	The definition phase converts the preliminary plan into a technical solution. Requirements are defined, schedules determined, and teams established around hardware. Science Definition Teams are competed and teams are chosen for each instrument and algorithm; the Science Team Leader is chosen.	Workshop conducted with targeted science communities to communicate key model, observation and applied science opportunities and requirements. Newsletters, articles and other communication strategies to expand the *community of potential*. Applications Working Group established, member of SDT designated as leader.	Early Adopters Identified, Call for Proposals and collaboration with test data. Thematic groups are created and Focus groups are planned.
C/D Design/ development	This phase involves building the hardware and software, testing and verification, and ends with the launch of the satellite.	Annual workshop focused on results from organizations who are early adopters; description and provisions of test and cal/val datasets to the community of practice; conference presentations and papers; newsletters and journal articles on user interaction to expand the community of potential. Interaction with NASA HQ Applied Science prepare funding opportunities.	Early Adopter applied research presented, Mini focus groups feedback loops and articles in thematic journals. Publication of test. Data feedback and results. Large Policy workshop to discuss the decision making process of existing Early Adopter research.
Operations Mission ops and data analysis	This phase includes flying the spacecraft and obtaining the data, processing, and delivering data to the community.	Documenting decision support provided by mission data; newsletter, journal articles, conference presentations of applications of data; community interaction and support of data reprocessing and improvement; calibration/validation of data quality, format, issues.	Selection of Mission Thematic Leaders. (Science and Policy) assigned to Science Team. Work into Applications Phase II-Coordination with Mission Operations and Support. • Documenting decision support provided by mission data through newsletters, journal articles, conference presentations of applications of data; • Community interaction and support of data reprocessing and improvement. • Participation of calibration/ validation of data quality, format, issues; • Evaluating and reporting on verified uses of mission data.

arising from GMES will be generated through the use to which this information is applied.

In 2010 the Earth Science Exploration Directorate at NASA requested a similar study on the value of information of satellite data in natural resource management [4]. The paper describes a general framework for conceptualizing the value of information and illustrates how the framework might be used to value information from earth science data. The NASA Applied Sciences division is motivated to provide quantitative assessment of the success of its programs that focus on providing NASA satellite remote sensing data to decision makers. This is currently a challenge, since all NASA missions are defined by scientific requirements as opposed to user-community requirements. Unlike in GMES, NASA has not made the goal of providing satellite-derived information that has value for societal activities explicit, and therefore it is much more difficult to evaluate the results in a way that is comparable across missions.

A socioeconomic benefits framework that is used in both the NASA and GMES studies seeks to provide information on both the societal and the economic benefits of user-focused programs for earth observation. The framework serves two purposes. The first is provision of a common basis by which to conduct and evaluate studies of the value of earth science information that serves a variety of uses, from improving environmental quality to protecting public health and safety. The second is to better inform decision makers about the value of data and information. Decision makers comprise three communities: consumers and producers of information, public officials whose job is to fund productive investment in data acquisition and information development (including sensors and other hardware, algorithm design and software tools, and a trained labor force), and the public at large [4].

Value of Information (VOI) is essentially an outcome of choice in uncertain situations. Individuals may be willing to pay for information depending on the known degree of and types of uncertainties as well as the level of risk on what is at stake. They may be willing to pay for additional information, or improved information, as long as the expected gain exceeds the cost of the information – inclusive of the distilling and processing of the information to render it useful. Information is only valuable if it is used – even if the decision is to do nothing with the information, it is a decision nonetheless. Thus, if a user community has difficulty in accessing data, understanding its content (because of obscure file formats, for example) or knowing how to use data, its value is reduced [36].

VOI studies have a long and far-ranging history that brings a wealth of examples on which to build approaches for earth science applications. They fall into three types of models: econometric estimation of output or productivity gains resulting from information; hedonic price studies; and contingent valuation surveys. Each of these models sheds light on approaches that might be taken.

GMES spends much more time and effort on assessment of applied projects than NASA. It seeks to involve stakeholders at each stage of the mission process in order to determine requirements for its environmental services, which satellite missions will contribute. GMES projects are assessed by their usefulness, reliability, and affordability, with the goal of conducting a cost–benefit analysis, following a harmonized approach to typify the service costs.

As NASA moves forward with its mission applications activity, it will work towards a common methodology, such as the cost–benefit analysis being implemented by GMES, to evaluate the success of the use of its data in decision making. By integrating stakeholder needs into missions earlier in the process, NASA can improve its ability to evaluate missions' impact on society. A clear, explicit policy will help the agency explore the broad impact of its missions, evaluate the result and ensure continued broad support for its activities.

6. Conclusions

As the world grapples with global environmental change, the need to have access to comprehensive data to document the dynamic of a changing environment over decades will grow. Understanding how these datasets will be used to reduce the impact of a transforming environment through policy, regulation and economic incentives will become increasingly important for scientific agencies' efforts to produce useful data that are both well understood and readily available for user communities.

NASA and ESA have both recognized the enormous value their earth science satellite data products could bring to those who support their programs, beyond improved scientific understanding. With clear policy on how to incorporate applications into satellite missions, NASA and ESA can improve the global datasets available for global environmental monitoring. To do this, both agencies must balance scientific progress with the need for consistent environmental monitoring data that enable accurate measurement of change through time.

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