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Ascribing Societal Benefit to Environmental Observations of Earth from Space

*The Multiangle Imaging
SpectroRadiometer (MISR)*

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Abstract

At the request of managers at the National Aeronautics and Space Administration, this paper describes frameworks for and illustrates societal benefits associated with Earth observations from an experimental satellite known as the Multiangle Imaging SpectroRadiometer (MISR). MISR is a unique camera that images Earth's atmosphere and other characteristics simultaneously from nine angles. This multiangle perspective enhances our ability to measure and monitor dimensions of climate, weather, air quality, natural hazards, and the biosphere. "Societal benefit" in this paper generally refers to practical applications of data and data products beyond their intrinsic science merit. The paper has two objectives: to demonstrate how several societal benefit frameworks work, and to highlight some of these benefits in the case of MISR. Such consideration of practical benefits is timely, as their realization is becoming a prominent objective of future space remote sensing activities. At least four groups of experts recommend that societal benefit serve as a heavily weighted criterion for prioritizing Earth science research opportunities. The National Academy of Sciences' forthcoming decadal survey for U.S. Earth science applications from space, the U.S. Climate Change Research Program, the framework for the international Global Earth Observing System of Systems (GEOSS), and the new world water program of the World Meteorological Organization (WMO) all argue that societal benefit should be a determining factor in selecting the next Earth-observing spacecraft missions and instruments. If these recommendations are implemented, the frameworks and illustrations below may prove useful in guiding benefit descriptions in future space-derived Earth observation programs.

Key Words: societal benefits, resource and environmental management, Earth observations, Earth science

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Molly K. Macauley*

1. Rationale

Ascribing societal benefit to data collected by space-based Earth science instruments—that is, practical applications of data and data products beyond their intrinsic science merit—has taken on heightened prominence in the present decade of budget reductions for U.S. Earth science. Some 73 Earth science satellites currently operate under national government auspices; as of 2005, the U.S. National Aeronautics and Space Administration (NASA) alone was flying some 80 instruments on 18 spacecraft and providing more than 1,800 science data products.¹ The inherent purpose of Earth science data has traditionally been to enhance basic theoretical and observational scientific understanding of Earth processes. Even if it is argued that Earth observation data are intended first and foremost for science research, consideration of how additional benefits might accrue from Earth science data products is useful—even critical—in informing public understanding of investment in these services.

In response to legislated mandates, NASA has been seeking to explore and document the role of Earth science data in contributing to resource management and public policy decisions.² NASA intentionally distinguishes this focus from exclusively scientific study or commercial applications of the data.³ In addition to NASA's efforts, the Climate Change Science and Climate Change Technology program strategies, both established in 2002 as part of a U.S. cabinet-level

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¹ Birk (2005).

² These mandates include the 1993 National Performance Review, ensuing legislation in the 1993 Government Performance and Results Act, and the current President's Management Agenda. See also NASA (2003a, 2004).

³ The focus has also been distinguished from previous studies that seek to monetize the value of Earth science by estimating, for example, the savings to various industries (electric utilities, commercial aviation) enabled by Earth science information.

structure to oversee public investment in climate change science and technology, emphasize the desirability of using climate-related Earth observation data in practical resource management and public policy decisions.⁴ Similarly, the framework for the Global Earth Observing System of Systems (GEOSS), initiated during the 2003 Earth Observation Summit convening the G-8 heads of state, is an international plan for coordination of the world's Earth observation networks based in part on pragmatic applications of data.⁵ Most recently, the 2005 World Meteorological Organization's plan for the world climate research program during 2005–2015 is oriented in “a new direction, towards an increasing range of practical applications of direct relevance, benefit and value to society.”⁶

A series of studies by committees of experts convened by the National Research Council's (NRC) Space Studies Board, a long-time adviser to NASA, has also supported a focus that goes beyond science merit as an objective of U.S. Earth observations. These studies include a 1995 report, *Setting Priorities for Space Research: An Experiment in Methodology*,⁷ that acknowledges, “[T]he scientific merit and benefits of an initiative are primary considerations in setting priorities for scientific initiatives,” but immediately adds,

with the increasing emphasis on contributions by federally funded research to national goals, it is ever more important that scientists be able to describe and justify the benefits of initiatives to the public and their representatives.... While contributions to enhanced understanding may be emphasized by scientists, the task group believes that scientists will benefit if they analyze the full range of potential benefits and are mindful of their importance to others.

Three subsequent studies, *Transforming Remote Sensing Data into Information and Applications* (NRC 2001), *Toward New Partnerships in Remote Sensing—Government, the Private Sector, and Earth Science Research* (NRC 2002), and *Using Remote Sensing in State and Local Government—Information for Management and Decision Making* (NRC 2003), recommend steps to better realize Earth science information benefits.⁸

⁴ Climate Change Science Program (2003).

⁵ Group on Earth Observation Data Utilization Subgroup (2004).

⁶ World Meteorological Organization (2005, 7).

⁷ NRC (1995, 16).

⁸ NRC (2001, 2002, 2003).

The most recent call for identifying, pursuing, and realizing societal benefits appears in the “Urgent Needs” report. In 2004, NASA’s Office of Earth Science, the National Oceanic and Atmospheric Administration (NOAA), and later, the U.S. Geological Survey, asked the Space Studies Board to conduct a major “decadal survey” to establish a community vision and consensus on priorities for Earth and environmental sciences and applications extending into the next decade and beyond. In response to large budget cuts forecast in the NASA budget for Earth science, the Space Studies Board issued an interim report in summer 2005, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*.⁹ The report has come to be referred to as the “Urgent Needs” report and was the basis for congressional testimony that summer during contentious deliberations on the Earth sciences budget and priorities within NASA.

The “Urgent Needs” report is significant in its emphasis on societal benefit and the role it should play in determining the next decade of Earth science. The significance arises from the exhaustive collaboration and consensus anticipated in the decadal survey itself. The survey involves more than 60 experts serving as committee members (Committee on Earth Science and Applications from Space) and report authors; the project also provides for contributions by Earth science researchers throughout the nation.¹⁰

In the executive summary, the interim report points out,

The Committee on Earth Science and Applications from Space affirms the imperative of a robust Earth observation and research program to address such profound issues as the sustainability of human life on Earth and to provide specific benefits to society. Achieving these benefits further requires that the observation and science program be closely linked to decision support structures that translate knowledge into practical information matched to and cognizant of society’s needs. The tragic aftermath of the 2004 Asian tsunami, which was detected by *in situ* and space-based sensors that were not coupled to an appropriate warning system in the affected areas of the Indian Ocean, illustrates the consequences of a break in the chain from observations to the practical application of knowledge. (NRC 2005a, 2)

⁹ NRC (2005a).

¹⁰ The widespread community participation anticipated in the final report is not represented in “Urgent Needs,” since this interim report was initiated as an immediate response to budget forecasts.

In the first chapter, titled “Science for the Benefit of Society,” the report further states,

The increase in knowledge produced over the last decade by Earth scientists is itself a tremendous societal benefit with clear public policy implications.... And the experience in applying that knowledge lays a solid foundation for more systematically selecting new missions that address not only important scientific issues but also critical societal needs. *A fundamental challenge for the coming decade is to ensure that established societal needs help guide scientific priorities more effectively, and that emerging scientific knowledge is actively applied to obtain societal benefits.* New observations, analyses, better interpretive understanding, enhanced predictive models, broadened community participation, and improved means for information dissemination are all needed. If we meet this challenge, we will begin to realize the full economic and security benefits of Earth science. (NRC 2005a, 11; italics in original text)

Just prior to the “Urgent Needs” report, NASA asked NRC to review several strategic roadmaps that the agency was developing, including one for Earth science. Like the decadal survey, the roadmaps are forward looking. The NRC report on the roadmaps, *Review of Goals and Plans for NASA’s Space and Earth Sciences*, states,

Although the roadmap is titled “Exploring our Planet for the Benefit of Society,” the applications component of the roadmap is inadequately developed. The NRC decadal survey interim report states, “a central responsibility for the coming decade is to ensure that established societal needs help guide scientific priorities more effectively and that emerging scientific knowledge is actively applied to obtain societal benefits.” There are several pressing societal issues, such as global food and water security, biodiversity loss, and pollution in coastal zones, that will be exacerbated over the coming decades and that can be informed by NASA science and observations. The applications “lines of inquiry” of the roadmap have yet to be developed, and they need to be closely coupled to both the science and the planned measurements, driven by societal needs, and developed in close communication with the stakeholders. *The panel recommends that as part of long-term planning, NASA develop the applications aspects of its Earth sciences program to greater degree than was done in the roadmap and strengthen the linkage between the science and applications program components.* (NRC 2005b, 28; italics in original text)

Taken together, these statements represent momentum toward consensus to accord high priority to societal applications in planning future Earth science. This background provides context and rationale for describing the societal benefits of data from MISR and applying lessons learned to the formulation of future missions that build upon MISR.

Before proceeding, a caveat is in order about a study of societal benefits associated with currently orbiting instruments such as MISR. The studies cited above are generally arguing for prospective incorporation of societal benefits into setting priorities for future Earth science activities. Arguably, existing missions were undertaken without societal benefit as an explicit objective (although some may argue that such benefits are tacitly understood as likely spin-offs from the missions). Typically, the funding or performance requirements of principal or coinvestigators are not expressly directed toward identifying or demonstrating such benefits. Despite these constraints, retrospective study has shown benefits for society resulting from many data products.¹¹ Some observers may suggest that realization of these benefits has been serendipitous and the result of an unplanned coincidence of investigators interested in and motivated to pursue use of the data beyond their scientific import. In fairness, then, to this retrospective look at MISR, the terms under which societal benefits flow from its data are not those of explicit goals or funding. In fact, as described in the next section, several attributes of MISR—for example, it is an experimental instrument competing with the incumbent advantages of existing and legacy instruments—limit realization of social benefits.

The next sections of this paper highlight some applications identified by the MISR science team for illustrative purposes. These applications are organized in two frameworks, both of which have a heritage in the policy community. If societal benefits are indeed to figure prominently in future Earth science, then the role of this paper in exploring how benefits associated with an instrument such as MISR can be defined and described may be helpful to developers of future instruments capitalizing on experience with MISR, program managers, other decisionmakers, and perhaps the science community itself.

The remainder of the paper proceeds as follows. Section 2 discusses two frameworks for describing societal benefits from MISR. One was developed by NASA's Earth science applications office and is now widely adopted by other agencies. The other has been advanced by the Department of Energy (DoE) as a means of describing benefits from investment in energy

¹¹ For instance, NOAA produces studies of the economic value of weather data (NOAA 2005); NASA has identified relationships between some Earth science data products and national resource and environmental management and public policy decisions (NASA 2003b, 2005; Macauley and Vukovich 2005; see also the special combined issue of *Earth Observation Magazine* 11(8) August 2002 and 12(2) March/April 2003); and other researchers have modeled and measured the economic value of weather and in a few cases, other Earth science data (e.g., see Adams 1995; Babcock 1990; Bradford and Kelejian 1977; Easterling and Mjelde 1987; Lave 1963; Nelson and Winter 1964; Pfaff 1999; Pielke 1995; Roll 1984; Sonka et al. 1987; Teisberg and Weiher 2000; and Williamson et al. 2002).

research and development.¹² The DoE approach, although not yet applied to Earth science, has an attractive set of placeholders for the “knowledge” and “options” benefits that may be ascribed to research or science activities, in addition to their more direct societal benefits. Section 3 uses these frameworks to describe some applications of MISR data products. Section 4 offers conclusions.

2. Frameworks for Describing Societal Benefits

A few examples suggest the range of practical applications that may be associated with Earth observations. The following topics—energy forecasting, carbon management, and aviation safety—come from NASA’s list of potential national resources to which the agency’s Earth science may be applicable (NASA 2002):

Energy forecasting: the presence of solar thermal or geothermal resources compared with their absence. In this application, a possible contribution of Earth science is an improved toolkit with which to assess the likely quantities of these resources and more accurately map their spatial distribution for the purpose of using and managing global energy resources.

Carbon management: improved modeling and measurement of the carbon cycle compared with current understanding of the cycle. Here, Earth science may provide improvements that are sufficiently adequate to enable policymakers to design an effective carbon management regime (e.g., carbon control or carbon trading).

Aviation safety: improvements in weather forecasting or detection of volcanic eruptions. Earth science may enhance the efficiency and safety of air travel.

One of the frameworks discussed in this section is based on a flow chart relating the collection of data to the ultimate attainment of these kinds of improvements. The other

¹² To be complete, a third method is a standard “value of information” (VOI) framework, which has generated a very large theoretical and applied literature. These models are grounded in Bayesian probability. They use an expected value approach for imputing gains or losses attributable to actions taken or not taken in response to the information. In other words, VOI methods are essentially the outcome of choice in uncertain situations. These models require quantitative data not typically available for many Earth observation data products (e.g., the monetary value of output in affected industries, the cost to decisionmakers to use the data, the probability that decisionmakers in these industries use the data products, the uncertainty the decisionmakers assign to the data, and in large-scale econometric studies, dozens if not more observations—over time, over space, or across industries—on each of these variables). Valuing information is discussed in Nordhaus (1986) and Hirschleifer and Reilly (1979). Valuing Earth science information is discussed in Macauley and Toman (1991) and Macauley (1997, 2005).

framework includes these kinds of improvements but also allows for some additional future (that is, not yet realized) benefits.

The NASA Earth Science Framework: A Specific Earth Science Data Product Approach

In 2002, the National Aeronautics and Space Administration formulated a conceptual framework in the form of a flow chart (Figure 1) to characterize the link between NASA Earth science data and their potential contribution to resource management and public policy. Earth observations become inputs into Earth system models that simulate the dynamic processes of land, the atmosphere, and the oceans. These models lead in turn to predictions and forecasts to inform “decision support tools.”

In this framework, decision support tools are typically computer-based models assessing such phenomena as resource supply, the status of real-time events (e.g., forest fires, flooding), or relationships among environmental conditions and other scientific metrics (e.g., water-borne disease vectors and epidemiological data). The decision support tools are an element of the broader decisionmaking context, or “decision support system.” Decision support systems include not just computer tools but also the institutional, managerial, and financial constraints involved in managing resources.

The outcomes in this framework are decisions about managing resources (management of public lands, measurements for air quality and other environmental regulatory compliance) and policy decisions (as promulgated in legislation or regulatory directives) affecting local, state, regional, national, or even international actions. To be sure, and for a variety of reasons, many decisions are not based on data or models: formal modeling may not be appropriate, timely, or feasible for all decisions. But among decisions that are influenced by this information, the flow chart stylistically characterizes a systematic approach for science to be connected to decision processes.

Some Earth science data teams already conceive of at least the initial part of this framework. In particular, a “wiring diagram” that links raw data to a data product (as illustrated in Figure 2) is (implicitly or explicitly) standard for some teams and has been a requirement for

some instruments, including MISR.¹³ The NASA framework takes the wiring diagram several steps further, into actually applying the data to decisionmaking.

NASA has funded external research to use this approach to identify some examples of the role of Earth observation data in informing energy and health policy.¹⁴ As noted earlier, the U.S. Climate Change Science and Climate Change Technology program strategies, the framework for the Global Earth Observing System of Systems (GEOSS), and the World Meteorological Organization's World Climate Research Program for 2005–2015 have all adopted the framework as a means of structuring their societal benefit objectives.

The NRC Framework for the U.S. Department of Energy

A recent study by the National Research Council for the U.S. Department of Energy (DoE) develops a conceptual framework for identifying the benefits of taxpayer investment in two decades' worth of basic and applied R&D on energy efficiency. NRC has recommended, and DoE has agreed to, adoption of this approach to assess retrospectively as well as inform prospectively decisions about federal investment in energy technology. The approach is particularly interesting because of its "knowledge" and "options" categories. The knowledge category allows the benefits of federal investment to include knowledge gained from the R&D in addition to any realized, tangible economic benefits. The options category admits research that opens doors to future possible energy technology.¹⁵

Figure 3 depicts the NRC–DoE framework. The rows define types of public benefits appropriate to the objectives of DoE R&D programs. The columns reflect benefits conditioned by different degrees of uncertainty about whether a given benefit will be obtained. Sources of uncertainty include technological uncertainty and uncertainty about policy and economic conditions that influence success of the R&D. "Realized benefits" are manifested in technologies that become commercially successful. "Options benefits" refer to technologies that are fully developed but for which conditions (policy, economic markets) are not currently favorable for commercialization. For instance, a variety of federal, state, and local policies influence adoption

¹³ "Data products" typically refers to data that have undergone some quality control (validation and verification of accuracy, etc.) and have typically been formatted for use; these steps are among concerns of users of the data (see NRC 2001; Macauley and Vukovich 2005).

¹⁴ See Macauley and Vukovich (2005).

¹⁵ NRC (2001).

of energy-efficient appliances. “Knowledge benefits” are scientific understanding or useful technological concepts that flow from the R&D. These benefits can include the benefit of learning from a “failed” R&D project.¹⁶

The study considers investments during 1978 to 1999 in 17 R&D projects to enhance energy efficiency. Realized benefits included advanced refrigerators and turbines, low-e glass, and electronic ballasts. Options benefits included compact fluorescent lighting and technologies for the next generation of autos (improvements in hybrid or other fuel technologies). Knowledge benefits included some types of gasification technology, advanced batteries for electric vehicles, catalytic converters for diesels, and some types of fuel cells. The knowledge benefits also include an example of a “failed” investment (the Stirling engine for automobiles).

Arguably, the NRC–DoE framework could be considered less applicable to Earth science if the NASA objective in investing in Earth science is not a tangible product (like a refrigerator) but rather an information product. However, the explicit allowance for uncertainty about policy and economic conditions and for knowledge benefits does seem relevant for information products. This approach may be a more appropriate model to apply retrospectively to an experimental project like MISR, as opposed to an instrument intended to be routinely operational or intended as a follow-on to MISR, for which input to a decision support system could be planned in advance.

3. Illustrations of MISR Societal Benefits

MISR data products have demonstrated applicability to a variety of environmental and natural resource concerns. The contributions of MISR largely center on its ability to gather data about the physical structure of the atmosphere and surface at microscopic, landscape, and meso scales. So, for example, MISR characterizes the microphysical properties of aerosols, the structure of the canopy of vegetation, and three-dimensional distributions of clouds and aerosol plumes.¹⁷ Both the NASA Earth science and the NRC–DoE frameworks are useful for organizing these results to illustrate MISR societal benefits.

¹⁶ The study comments, “Knowledge benefits may include unanticipated and not closely related technological spin-offs that are made possible by the research programs. This is probably the broadest and most heterogeneous category of benefits” (17). Energy R&D, like NASA R&D, is often justified on the basis of spinoffs. However, a dominant refrain in benefits research cautions against reliance on spinoffs to justify investment. It is generally cheaper to pursue a new technology directly rather than by way of indirect association with a larger project.

¹⁷ Diner et al. (2005).

MISR in the NASA Earth Science Benefit Framework

MISR observations are relevant to a variety of the societal benefit themes identified in national-level policy documents, including the Strategic Plan for the U.S. Integrated Earth Observation System (Group on Earth Observation Data Utilization 2004) and the NASA Earth Science Applications Plan (NASA 2003b, 2005). MISR furthers several objectives identified in these documents, including weather forecasting, addressing climate variability and change, supporting global land observations, assisting in measurement of water supply, and monitoring air quality. Such contributions primarily take the form of development of new remote sensing approaches that overcome limitations of traditional techniques or that demonstrate improvements in accuracy. In some instances, most notably with regard to air quality, methodologies developed using MISR data can potentially influence existing decision support systems. Although air quality forecasting in close to real-time is not possible with MISR, the high accuracy of MISR aerosol information over land makes it possible to incorporate these data into compliance assessments of the U.S. National Ambient Air Quality Standards (NAAQS). Research has shown that MISR data are in statistical agreement with measurements that the U.S. Environmental Protection Agency takes at ground-based stations.¹⁸ Technology developments undertaken in connection with the MISR project can also help identify those decision support tools and specific policies that would benefit from future multiangle measurement programs.

MISR in the NRC–DoE Benefit Framework

Societal benefits as categorized in the NRC–DoE framework represent another perspective on MISR contributions. Table 1 illustrates this approach. Here, MISR has demonstrated new ways of measuring environmental or climate parameters, which can in their present form be used to reap societal benefits, such as through evaluation or improvement of models (“realized benefits” in the NRC–DoE model); to open doors to future opportunities, such as through proof-of-concept (“options benefits”); and to offer new knowledge about the familiar or processes that are poorly understood (“knowledge benefits”).

¹⁸ Specifically, MISR aerosol optical depths remove biases in the GEOS-CHEM aerosol–chemical transport model (a global 3-D model of atmospheric composition that is also used as part of the Community Multiscale Air Quality (CMAQ) modeling system of the U.S. Environmental Protection Agency), yielding concentrations of PM_{2.5} (near-surface particulate matter with diameters less than 2.5 microns) derived entirely independently of in situ data yet exhibiting unbiased agreement (slope = 1.0, intercept negligible) with EPA surface measurements (Liu et al. 2004, 2005). GEOS-CHEM is described at http://www-as.harvard.edu/chemistry/trop/geos/geos_overview.html (accessed February 2006).

The usefulness of the NRC–DoE approach for characterizing contributions of Earth science data products is highlighted by the MISR examples shown in Table 1. The NRC–DoE approach accommodates these kinds of benefits, which are likely to arise with information products. In contrast, the NASA Earth science approach is less amenable to incorporating such attributes, but it is attractively specific in demanding a demonstration of actual data product to policy links.

Institutional Factors Limiting MISR in Benefit Frameworks

Some of the design attributes of the MISR program limit fuller realization of MISR’s potential societal benefits.¹⁹ It is notable that these deliberate design attributes differ from other attributes that unexpectedly can confer benefit. For instance, a review of MISR has noted, “the newness of the measurement approach has resulted in MISR data being used in many applications beyond those anticipated pre-launch.”²⁰ A possible disadvantage to the newness, however, is that because an instrument like MISR has never before flown in space, a large portion of the program budget has been dedicated to ensuring radiometric and geometric accuracy as well as other quality controls.

An “Experimental” Instrument

The MISR instrument was designed as an experiment to explore how remote sensing using multiangle imaging data can provide new or improve the quality of existing geophysical products compared with products derived from traditional single-view instruments. As a result, the MISR data stream and algorithms are not intended for, nor have they been funded for, operational use—that is, in the sense of providing data routinely as a basis for, say, resource or environmental management. Wholly new data such as those from MISR also involve technical issues, such as determination of appropriate map projections and protocols for coregistration and

¹⁹ Much of this section is from discussions with MISR science investigators, including Larry Di Girolamo, Mark Chopping, Anne Nolin, and Yang Liu.

²⁰ Ranson et al. (2005, 4).

calibration. These steps represent a host of quality controls to which new data are subject before data sets and data products become publicly available or publicly accepted.²¹

The Incumbent Advantage of Existing and Facility Instruments

Another limiting attribute is the “heritage” or “legacy” advantage conferred upon older, existing series of instruments, particularly those characterized by more or less continuously operated missions. Examples of heritage missions include Landsat and the Advanced Very High Resolution Radiometer (AVHRR), which have provided fairly continuous global coverage since 1972 (Landsat) and 1979 (AVHRR). These instruments offer an advantage of familiarity (for instance, with data validation and verification processes and in terms of awareness of inherent shortcomings that may be present in the data). In addition, as noted, the newness of MISR, as well as its experimental purposes, requires a full complement of validation and verification of MISR data compared with the fewer (although still stringent) quality control requirements associated with follow-on legacy instruments. Because the validation and verification processes are time and resource intensive, they limit the opportunity of investigators facing constrained budgets to carry out applications of data beyond the pursuit of science objectives.

Concerns about Continuity and Longevity of Data Records

A disadvantage related to the experimental nature of MISR is that at the current time, no successor to MISR is planned. As a consequence, researchers may be reluctant to invest in the learning curve associated with the new data type in the absence of assurances of a long-term payoff. In other instances, researchers may be skeptical of the utility of MISR products for the study of decade-scale climate change without a guarantee that the data record will have the requisite duration. It may also be disadvantageous to adopt MISR data for air quality measurements, say, of particulate matter, if routine access to these data is not assured.

²¹ Even though near-real-time monitoring of environmental phenomena (such as weather, forest fires, volcanic eruptions) is not possible with MISR data because they are not designed for operational use, some monitoring capability is nonetheless possible based on “backcasting,” or retrospective analysis of data. For example, as noted in Table 1, MISR investigators have studied how pollution levels from aerosols have varied over past years using the MISR aerosol data product. Di Girolamo et al. (2004) analyzed anomalies in aerosol measurements over greater India during the winters of 2001–2004. They observed that pollution levels were unusually high over the northern Indian state of Bihar, where meteorology, topography, and aerosol sources combine to concentrate airborne particles. Although high levels of pollution in parts of India have been observed for decades, the accurate spatial distribution shown by MISR and new details about factors establishing Bihar as a region of high aerosol concentration is new information..

Incompatibility of Instrument Attributes with Operational Applications

Budget constraints contribute to additional limitations. MISR was largely dedicated to pursuing scientific questions and proving the concept of MISR technology rather than to anticipated operational use. This focus caused the preponderance of MISR funding to be weighted toward operating the instrument as well as research associated with developing and testing algorithms for using the data and data products. As an example, the 400-km-wide swath of data collected and the associated nine-day global coverage time limit the usefulness of MISR data for forecasting. These design decisions, while predicated on scientific, engineering, and cost–benefit judgment, make it problematic to evaluate MISR within the context of operational applications, which demand a different set of sensor characteristics.

Data Latency

For certain applications, particularly forecasting, of existing instruments, a short interval (i.e., a few hours at most) elapses between data acquisition, data processing into “final products,” and delivery to the users. That process requires mechanisms to transmit data from the instrument to ground stations and then to transfer the data from ground stations to processing facilities.²² None of these mechanisms are in place for MISR. It generally takes 24 hours after acquiring raw data from MISR for processing the data into radiometrically and geometrically calibrated and georeferenced data products. An additional 24 hours is typically required to create the next level of useful products for many communities.

Possible Lack of Software Interface and Format Compatibility

Off-the-shelf software is typically designed for data that are expected to be routinely available over time. Software developers may be reluctant to modify or create software to accommodate new or specialized instruments deemed experimental. The resulting “lock-in” effect associated with using data from legacy instruments thus limits the compatibility of existing software to import and readily use data from MISR.

²² For example, some existing sensors on spacecraft are able to make use of direct broadcast capability to ground stations in real time. Some sensors are also able to use a data transfer link known as the “bent pipe,” which facilitates rapid movement of data to the ground data-processing center.

Additional Perspective on the Limitations

The opportunities and challenges of using Earth observation data for practical applications were the topic of a set of three NRC Space Studies Board reports during 2001–2003. One of the studies, *Transforming Remote Sensing Data into Information and Applications*, optimistically points out that “advances in computing capabilities and the development and availability of geographic information technologies have given added impetus to the use of remote sensing data in new types of applications.... The intersection of these various technological advances offers the potential for a new period in the application of remote sensing to public policy, governance, and commercial needs” (NRC 2001, 12–13). But the report continues by describing at length the challenges in pursuing these applications. These challenges offer a reprise of those cited by MISR investigators and listed above. The concerns include the failure to fund development of applications; a lack of training and financial resources in the applications communities; problems in communicating between scientists and these communities; the lack of standard data formats, open and accessible protocols, and standard validation and verification information; and the lack of recognition accorded the development of applications among researchers and the journals in which they publish.

4. Conclusions

Whether the rationale for associating societal benefits with Earth observation data products is compelling or whether Earth observations can and should be justified solely on the basis of science merit is outside the scope of this paper. Also outside the scope of this paper is determining a line between “science” that imparts new fundamental understanding or augments or corrects existing understanding (i.e., requiring a rewriting of science textbooks) and “information” that, say, sheds light on climate processes and in turn informs carbon trading policy. Instead, the objective of this paper is to report the momentum that seems to be building within the Earth science community for identifying practical applications of data products and to suggest ways to frame these applications.

Practical applications, like beauty, are defined by the beholder. From one perspective, that of the NASA Earth science decision support model, practical applications inform decisions about managing natural resources or about public policy implementation. The NASA Earth science model has the support of NASA’s Earth science division, the U.S. climate change research program, and international organizations such as the GEOSS and the World Meteorological Organization’s water research program. Applying this framework to MISR emphasizes the resource management and policy contribution of MISR and requires collecting

information from resource managers, identifying the decision support tools and systems they use, and identifying the public policies that MISR may assist in informing. Using this framework prospectively—that is, to characterize future practical applications associated with follow-on multiangle imaging instruments—requires the same information, but in this case, information would be based on ex ante expectations about the usefulness of the data and the existing or augmented ability of decision support tools and systems to accommodate them. In this prospective application, all parties would need to understand the uncertainty associated not only with the science but also with the other benefits that may derive from the instrument.

The NRC–DoE model includes realized practical applications (the original model characterizes tangible technology, such as an energy-efficient light bulb, but an Earth observation data product is arguably a tangible technology as well). This model, having been adopted by the Department of Energy, has support from an external constituency. Particular advantages of this approach for Earth observation data products in general and MISR in particular are the knowledge and options benefits. These kinds of benefits admit the possibility that Earth observations can provide a wholly new or improved information product or one that could open new doors to useful information (once existing decision support software, the focus of the NASA Earth science approach, are revised, if necessary, to accommodate the new data product).

It remains to be seen whether any particular approach to benefit characterization becomes a recommendation of the ongoing NRC decadal survey for space-derived Earth sciences. A combination of the two frameworks described in this paper may be useful. The specificity of the NASA Earth science view toward uses (by way of decision support tools) and outcomes (influencing managers and policymakers) leads naturally to an expression of realized benefits in the NRC–DoE framework. The NRC–DoE model goes a step or two further in allowing the information inherent in Earth observation data to be credited for knowledge and the preserving of options for future benefit: the options category explicitly provides that benefits otherwise realizable may be restricted by external factors, such as limits in off-the-shelf software.

Regardless of any benefit-related approach ultimately taken in the NRC decadal survey, funding for Earth science is likely to continue to be severely constrained, leading to continued pressure on the Earth science community for compelling and credible means for defining, pursuing, realizing, and communicating practical applications. At the same time, financial and other professional rewards are necessary incentives for investigators to consider practical applications and to have the wherewithal to pursue them to a reasonable extent. In addition, these investigators also need to know “how good is good enough”—that is, what level of accuracy is

adequate for practical uses of data compared with scientific research using these data. At some point in the flow from data collection to practical use, actual application of Earth observations rests with associated communities—the decisionmakers and their research and analysis staffs. They, too, need financial, training, and other resources to entertain use of new information. Pursuit of societal benefit using a combination of Earth science researchers and practitioners of natural resource management and policy could result in mutually beneficial and exciting new discoveries beyond those imagined by either community working in isolation.

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Figures and Tables

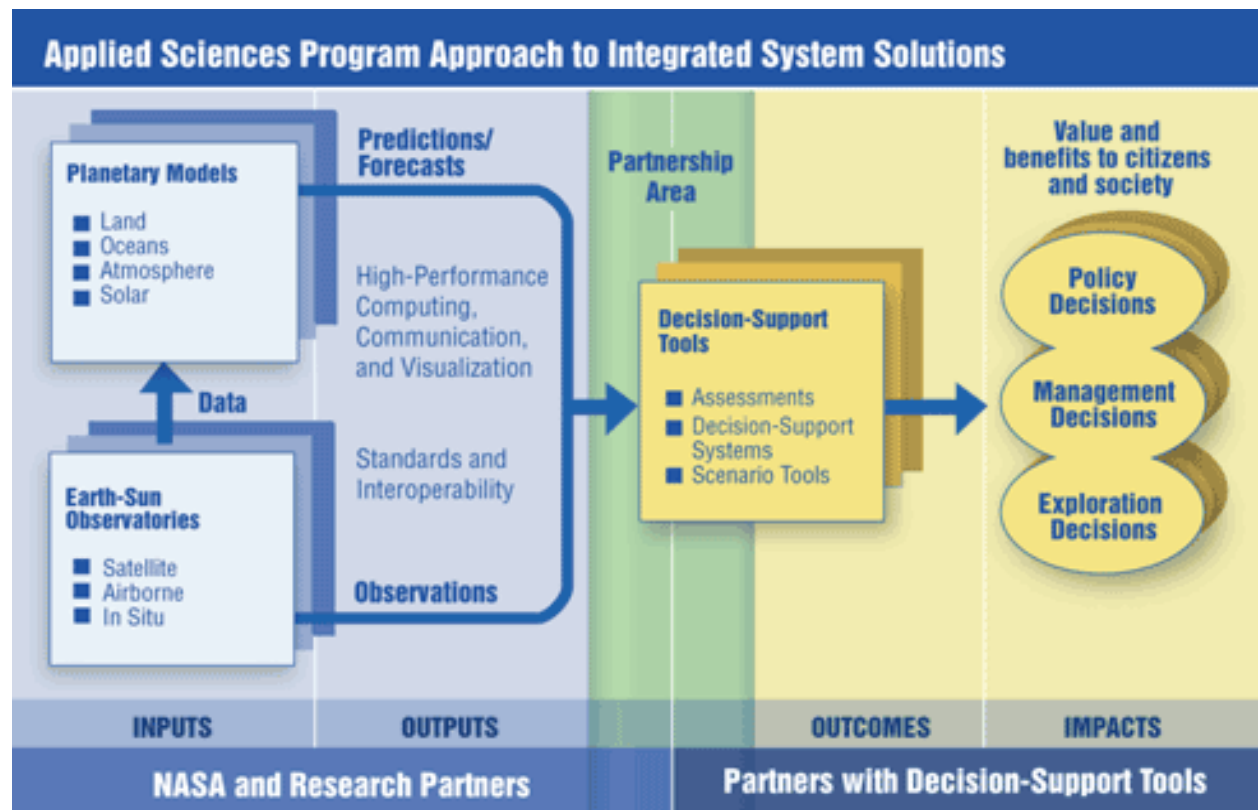


Figure 1. Framework for the Use of Earth Science Data in Policymaking

Source: NASA, The View from Space: NASA Earth Observations Serving Society NP-2003-589-GSFC, 2003, 3.

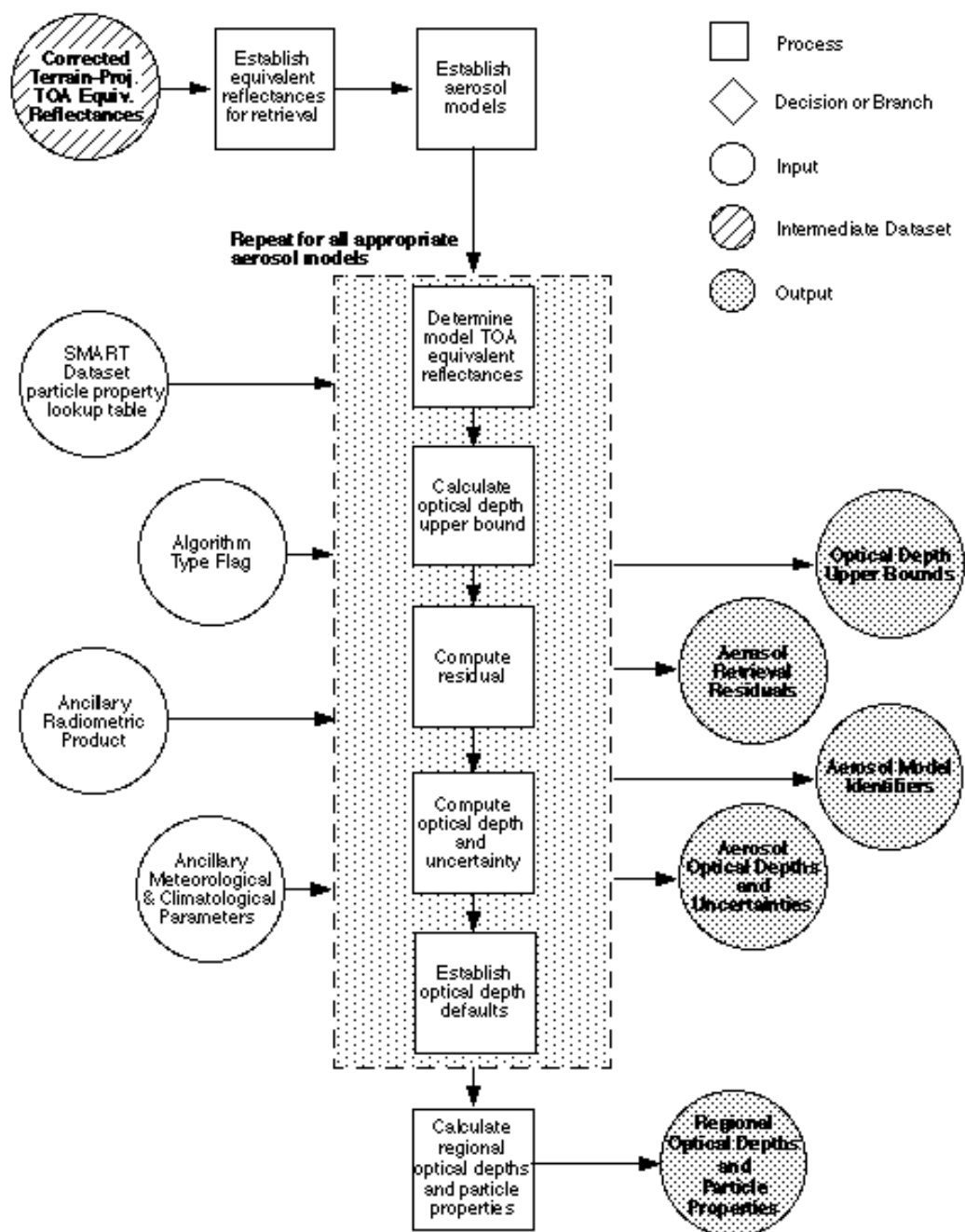


Figure 2. Wiring Diagram Illustration

Source: MISR Level 2 Aerosol Retrieval Algorithm Theoretical Basis, JPL D-11400, Rev. E, April 10, 2001.

	<i>Realized benefits</i>	<i>Options benefits</i>	<i>Knowledge benefits</i>
Economic benefits			
Environmental benefits			
Security benefits			

Figure 3. Matrix for assessing benefits*

Source: NRC (2001).

* Original figure includes “and costs” in each row and column heading.

Table 1. Illustrative Contributions of MISR to Societal Benefit Themes Using the NRC–DoE Framework

Benefits Themes	<i>Realized benefits</i> <i>Demonstrated potential for assisting in evaluating or improving models</i>	<i>Options benefits</i> <i>Opportunities with future multiangle sensors to influence decisionmaking</i>	<i>Knowledge benefits</i> <i>New knowledge about the familiar or processes we don't understand</i>
Climate	Clouds: MISR cloud-top height distributions and pole-to-pole cloud motion wind vectors, derived from a purely geometric (stereophotogrammetric) approach, are insensitive to atmospheric temperature profile, emissivity, and radiometric calibration drifts (in contrast to traditional infrared approaches). Global and temporal averaging yields precision necessary for interannual and decadal climate change detection. ¹	Clouds: A future MISR spinoff sensor would continue the unique height and wind climate data record.	Clouds: The existing multiyear trend of MISR data shows a decrease in effective global cloud height sufficient to offset greenhouse warming; however, such an offset may not be sustainable indefinitely. ² Cryosphere: Simultaneous measurement of ice surface roughness and albedo make it possible to measure relationships among surface melt, ice fracturing, and albedo on rapidly evolving outlet glaciers; to distinguish “blue” ice regions thought to be indicators of changes in ice sheet ablation and accumulation patterns from spectrally similar active glacier crevasses; to distinguish types of first-year sea ice, and to some extent, multiyear ice from first-year ice, and thus help understand the interaction between ice formation and melting, climate, and ocean processes. ³

Environment	<p>Aerosols: Retrieval of optical depths over land, including bright desert and urban source regions, with ± 0.05 uncertainty provides improved source inventories in transport models. Stereoscopic retrieval of plume injection heights from fires, with ± 0.5 km uncertainty, provides transport model initialization data for assessing effect of future fire prevalence on air quality.</p>	<p>Aerosols: Future measurement enhancements through inclusion of ultraviolet, shortwave-infrared, and polarimetric sensing will improve aerosol particle type discrimination, and fusion with lidar will provide vertical resolution and improved accuracy in column optical depth-to-surface PM_{2.5} estimation. Improving on current surface PM_{2.5} accuracy of $\pm 5 \text{ g/m}^3$ uncertainty potentially enables routine evaluation of NAAQS PM_{2.5} attainment (15 g/m^3 and 65 g/m^3, respectively, for annual and 24-hour time intervals) from satellite.</p>	<p>Aerosols: Discrimination between spherical and randomly oriented nonspherical particles has been demonstrated with MISR, providing improved natural versus anthropogenic source attribution.⁴</p>
Weather	<p>Clouds: Geometrically derived cloud-top heights can be used to assess performance of hurricane simulation models.</p>	<p>Clouds: Acquisition of stereo cloud heights and cloud-tracked winds with broader swath width and reduced data latency than MISR (e.g., from NPOESS*) will provide daily, global height-resolved winds with accuracies commensurate with radiosondes ($\pm 3 \text{ m/s}$).</p>	
Resource Management		<p>Biosphere: Multiangle imagery potentially improves accuracy of above-ground biomass inventories, particularly when acquired globally in conjunction with lidar canopy heights as training input.⁵</p>	

Natural Hazards	Seismic events: Detection of deep-ocean waves and motion of near-shore breakers from the December 2004 Indian Ocean tsunami provide one-of-a-kind data for calibrating wave propagation models at high resolution. ⁶	Volcanoes: Acquisition of aerosol plume heights and plume-tracked winds with broader swath width and reduced data latency than MISR could assist in volcano hazard monitoring.	Seismic events: Extensive dewatering—a primary cause of building collapse after the January 2001 Gujarat (India) earthquake—was detected by MISR far from the epicenter and in remote areas inaccessible to ground teams. ⁷
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Notes:

¹ A federally sponsored report on climate observing (Ohring et al. 2004, 25) states, “Independent instrument measurements from space of each key climate variable are required to verify accuracy. This requirement is based on the experience of NIST [National Institute of Standards and Technology] and is a fundamental lesson for climate data. The measurements should be different technological approaches. Cloud amount and layering should be measured both by active lidar and radar as well as passive imagers.” A decadal cloud height stability requirement of 30 m to detect variation attributable to climate change is cited. Current work implies that this level of precision is attainable with MISR.

² Davies (2005).

³ Nolin et al. (2002); Stroeve and Nolin (2002).

⁴ Kahn (1998); Kalishnikova et al. (2004) and references therein.

⁵ Ranson et al. (2005).

⁶ Garay et al. (2005).

⁷ Pinty et al. (2003)

* National Polar Orbiting Environmental Satellite System.