Ascribing societal benefit to applied remote sensing data products: an examination of methodologies based on the Multi-angle Imaging SpectroRadiometer experience

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Abstract. This paper describes and illustrates frameworks for societal benefits associated with data products from the Multi-angle Imaging SpectroRadiometer (MISR), one of five instruments launched into polar orbit aboard NASA's Terra spacecraft in December 1999. The objective of framing and illustrating benefits is impelled by the January, 2007, U.S. National Research Council's seminal decadal survey of U.S. Earth science. The survey urges that all missions explicitly identify potential societal benefits in mission planning and operation. In this paper, our retrospective look at MISR offers approaches which mission planning for future instruments could operationalize. "Societal benefit" generally refers to practical applications of data and data products beyond their intrinsic science merit. The paper demonstrates how societal benefit frameworks work, highlights some of these benefits in the case of MISR, and seeks to provide useful guidance for benefit descriptions in future multi-angle and other Earth observation research programs.

Keywords: applied remote sensing, multi-angle imaging, spectroradiometer, societal benefit, economics, Earth observations.

1 INTRODUCTION AND BACKGROUND

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 US Earth science. The inherent purpose of Earth science data has traditionally been assumed as enhancing basic theoretical and observational scientific understanding of Earth processes and their interrelationships, baseline measures of these systems, and how they may be changing over time. However, the recent and seminal decadal survey of US Earth science [1] finds that even if Earth observation data are intended first and foremost for science research, consideration of how additional benefits might accrue from these data is essential in informing public understanding of and willingness to invest in this information.

The survey, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," was commissioned by the Office of Earth Science of the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the United States Geological Survey (USGS) to establish a community vision and consensus on priorities for Earth and environmental sciences and

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applications extending into the next decade and beyond. In establishing "prioritization criteria" for choosing Earth science missions, the survey includes "Contribution to applications and policy making (societal benefits)." The survey (p. ES-1) repeatedly emphasizes the need for Earth scientists to enter into a "new social contract," in which "The scientific community must focus on meeting the demands of society explicitly, in addition to satisfying its curiosity about how the Earth system works."

The survey's emphasis on applications of Earth science for broad social benefit is impelled by over a decade of exhortations for government agencies, including the National Aeronautics and Space Administration (NASA), to demonstrate a full range of their value to the public. As directed by the 1993 National Performance Review, ensuing legislation in the 1993 Government Performance and Results Act, and continuing to the present in the President's Management Agenda, NASA ([2,3]) has been seeking to explore and document the role of Earth science data in contributing to resource management and public policy decisions. NASA intentionally distinguishes this focus from exclusively scientific study or commercial applications of the data. 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.

In addition to NASA's efforts, the Climate Change Science and Climate Change Technology program strategies, both established in 2002 as part of a US government, cabinet-level structure to oversee public investment in climate change science and technology, emphasize the desirability of using climate-related Earth observations 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]. 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, p. 7].

Prior to the decadal survey, a series of studies by committees of experts convened by the NRC's Space Studies Board (SSB), the same board that oversaw the survey itself, has also supported a focus broader than – but including—science merit as an objective of U.S. Earth observations. These studies include a 1995 report that acknowledges that "the scientific merit and benefits of an initiative are primary considerations in setting priorities for scientific initiatives" but immediately adds that

> "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" [7, p. 16].

Three subsequent studies recommend steps to better realize Earth science information benefits [8-10].

While this push towards linking Earth science with its social benefits is large and growing, the studies offer virtually no guidance for how to describe and demonstrate this link. This article begins to fill this gap by describing frameworks for and illustrations of how to characterize this link. The examples draw from experiences with data products from the Multi-angle Imaging SpectroRadiometer (MISR), one of five instruments launched into polar orbit aboard NASA's Terra spacecraft in December 1999.

Before proceeding, a caveat is in order about a study of societal benefits associated with currently orbiting instruments such as MISR. The reports cited above argue 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 (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 co-investigators are not expressly directed towards identifying or demonstrating such benefits. Despite these constraints, retrospective study has shown benefits for society resulting from many data products. For instance, NOAA produces studies of the economic value of weather data [11]; NASA has identified relationships between some Earth science data products and national resource and environmental management and public policy decisions [12, 13]; see also [14] and the special combined issue of *Earth Observation Magazine* 11(8) August 2002 and 12(2) March/April 2003). Other researchers have modeled and measured the economic value of weather and in a few cases, other Earth science data [15-26].

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 applications of MISR data products to a range of societal issues and were 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, program managers, other decisionmakers, and the science community. For example, designs for two instruments derived from MISR are currently being developed. The Multiangle SpectroPolarimetric Imager (MSPI) extends the MISR spectral range, doubles the image swath to achieve more rapid global coverage, and adds high-accuracy polarimetry to improve the accuracy and availability of global aerosol characteristics for climate and air quality studies [27]. MSPI is a potential candidate sensor for the Aerosol-Cloud-Ecosytem (ACE) mission endorsed by the Earth Science decadal survey [1]. The Cloud Motion Vector Camera (CMCV) is a simplified instrument focused on global wind retrievals for weather forecasting. Should these instruments fly on future Earth orbiting satellites, operational application of their data will substantially benefit from MISR heritage [28].

The remainder of the paper proceeds as follows. Section 2 discusses two frameworks for describing societal benefits from Earth-observing satellite instruments.[1]

[1] To be complete, a third method is a standard "value of information" (VOI) framework from which has come a very large theoretical and applied literature [29-33]. 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 observations data products (for instance, 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).

One is a framework developed by NASA's Earth science applications office and now widely adopted by other agencies. The other framework has been advanced by the Department of Energy (DoE) as a means of describing benefits from investment in energy research and development. 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. Each topic listed below– air quality, carbon management, and aviation safety – is from NASA's list of potential national resources to which the agency's Earth science may be applicable [34].

> Air quality: new means of observing air pollutants, sources, and transport vectors—here, Earth science may enable more detailed and synergistic measurement of air pollutants, their dispersion, and other attributes of air quality.
>
> 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 implement 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 enable increased 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 framework includes these kinds of improvements but in addition, allows for some additional future (that is, not yet realized) benefits.

2.1 The National Aeronautics and Space Administration Earth Science (NASA/ES) framework: a specific Earth science data product approach

In 2002, NASA formulated a conceptual framework in the form of a flow chart to characterize the link between NASA Earth science data and their potential contribution to resource management and public policy. The framework begins with Earth observations that are 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." Examples and further discussion are at http://www.public.hq.nasa.gov/earth-sun/applications/benchmark2.htm (accessed July 2007).

In this framework, decision support tools (DSTs) are typically computer-based models assessing such phenomena as resource supply, the status of real-time events (for example, forest fires, flooding), or relationships among environmental conditions and other scientific metrics (for instance, water-borne disease vectors and epidemiological data). Examples include the National Energy Modeling System (NEMS) used by the U.S. Department of Energy to describe and forecast energy markets and the Community Multiscale Air Quality (CMAQ) modeling system of the U.S. Environmental Protection Agency. The decision support tools are an element of the broader decision making context that may include not just computer tools but 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. In some cases, formal modeling is not 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 is (implicitly or explicitly) standard for some teams, and has been a requirement for some instruments, including MISR (see Fig. 1). The NASA/ES framework takes the wiring diagram several steps further into the arena of actually applying the data to decision making.

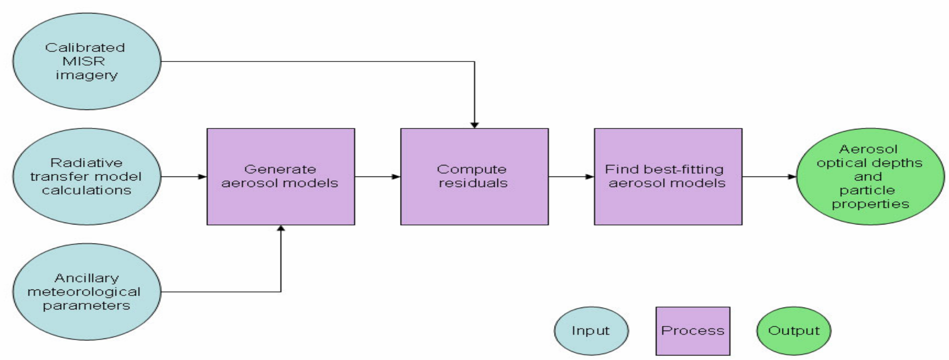

Fig. 1. Wiring Diagram Illustration Source: Adapted from MISR Level 2 Aerosol Retrieval Algorithm Theoretical Basis, JPL D-11400, Rev. E, 10 April 2001.

NASA has funded external research to use this approach to identify some examples of the role of Earth observations data in informing energy and health policy [14]. As noted earlier, the US 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.

2.2 The National Research Council framework for the U.S. Department of Energy (NRC/DoE)

A widely cited study by the NRC for the U.S. Department of Energy (DoE) develops a conceptual framework for identifying the benefits of taxpayer investment in two decades' of basic and applied energy-efficiency R&D [35]. The 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.

Table 1 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 – for example, will renewable energy R&D be federally subsidized? "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 favorable at present for commercialization. For instance, a variety of federal, state, and local policies influence adoption 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. The study comments (p. 17) "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." Energy R&D, like NASA R&D, is often justified on the basis of spin-offs. However, a dominant refrain in benefits research cautions against reliance on spin-offs to justify investment.

Table 1. Matrix for assessing benefits (Original figure includes "and costs" in each row and column heading). Source: Ref. 35.

	Realized benefits	Options benefits	Knowledge benefits
Economic benefits			
Environmental benefits			
Security benefits			

The study considers investments during 1978 to 1999 in seventeen R&D projects to enhance energy efficiency. Realized benefits included projects such as 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).

3 ILLUSTRATIONS OF POTENTIAL MISR SOCIETAL BENEFITS

Before casting MISR benefits within these frameworks, a fuller description of the sensor is useful. MISR provides continuous multiangle imagery of the sunlit Earth [36,37, and the MISR web site at http://www-misr.jpl.nasa.gov]. The instrument contains nine pushbroom cameras; one view points vertically downward (nadir), and the other eight are symmetrical views at 26º, 46º, 60º, and 70° forward and backward of nadir. Images at each angle are obtained in four spectral bands centered at 446, 558, 672, and 866 nm. The swath width of the MISR imaging data is 400 km, providing contiguous zonal coverage between ±82º latitude in 9 days at the equator and 2 days at the poles. It takes 7 minutes for any particular scene to be observed at all nine viewing angles. In its global observing mode, data from the red band of all of MISR's off-nadir cameras, and in the four bands of the nadir camera, are acquired at 275-m spatial resolution; all other channels are averaged on-board to 1.1-km resolution to conserve data rate.

Ground data processing maps MISR radiances to a Space Oblique Mercator (SOM) projection, which geolocates and co-registers the data from all instrument channels. Radiometry has been validated using multiple methodologies and stability is maintained with bimonthly activations of the on-board calibrator (OBC) [38]. To maintain high geometric data quality, image geolocation and camera co-registration errors have been carefully monitored and refined during the mission [39]. Because each point is imaged nine times over a 7-minute interval, and Terra is in a repeating orbit, the time dimension is sampled on scales from minutes to years. In addition to the basic Level 1 georectified radiance products, standard Level 2 (geophysical) products include cloud masks and classifiers, stereoscopic cloud and aerosol plume heights, top-of-atmosphere and surface albedos and bidirectional reflectances, parameters related to vegetation structure, and aerosol optical depths and particle properties over both ocean and land. Many of these parameters are spatially and temporally aggregated to create global maps (known as Level 3 products).

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 [39], and therefore provides information directly relevant to the three example applications areas noted in Section 2. Both the NASA/ES and NRC/DoE frameworks are useful as a means of organizing these results to illustrate the societal benefits of these types of data products, and to provide a paradigm for explicitly aiming to achieve such benefits as part of the plans for a future mission.

3.1 MISR in the NASA/ ES benefit framework

MISR observations, and those from future instruments derived from MISR heritage, are relevant to a variety of the societal benefit themes identified in national-level policy documents including the Strategic Plan for the US Integrated Earth Observation System and the NASA Earth Science Applications Plan [5,12,13]. Among the themes in these documents, MISR-like data contribute to improving weather forecasting, addressing climate variability and change, supporting global land observations, assisting in measurement of water supply, and air quality. These 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 the current MISR experiment, 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); the greater aerosol retrieval accuracy and scope of a successor instrument such MSPI (discussed above in section 1), combined with a profiling lidar [27], will make the application of such data even more relevant in the future. Research has shown that MISR data are in statistical agreement with measurements that the US Environmental Protection Agency takes at ground-based stations.[2] 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.

3.2 MISR in the NRC/DoE benefit framework

Societal benefits as categorized in the NRC/DoE framework [35] represent another perspective on the contribution by MISR and its prospective successors. Table 2 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), open doors to future opportunities, such as through proof-of-concept ("options benefits"), and offer new knowledge about the familiar or processes that are poorly understood ("knowledge benefits"). The usefulness of the NRC/DoE approach for characterizing contributions of Earth science data products is highlighted by the MISR examples shown in Table 2.

3.3 Institutional factors limiting MISR in these benefit frameworks

Some of the design attributes of the MISR program limit fuller realization of MISR's potential societal benefits. It is notable that these deliberate design attributes differ from other attributes that unexpectedly can confer benefit. For instance, a review of MISR accomplishments has noted, "the newness of the measurement approach has resulted in MISR data being used in many applications beyond those anticipated pre-launch" [55]. However, because an instrument like MISR has never before flown in space, a large portion of the program budget has been dedicated to preserving the scientific integrity of the basic (Level 1) data products (calibrated and georectified multiangle, multispectral radiances) by ensuring high radiometric and geometric accuracy [38,39] and applying other quality controls.

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[2]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 $PM_{2.5}$ (near-surface particulate matter with diameters less than 2.5 microns) concentrations derived entirely independently of *in situ* data yet exhibiting unbiased agreement (slope = 1.0, intercept negligible) with EPA surface measurements [40,41]. GEOS-CHEM is described at http://www-as.harvard.edu/chemistry/trop/geos/geos_overview.html (accessed February 2006).

Table 2. Illustrative Contributions of Multiangle Measurements (MISR) to Societal Benefit Themes using the NRC/DoE Framework.			
Benefits Themes	REALIZED BENEFITS *Demonstrated potential for assisting in evaluating or improving models*	OPTIONS BENEFITS *Opportunities with future multiangle sensors to influence decisionmaking*	KNOWLEDGE BENEFITS *New knowledge about the familiar or processes we don't understand*
Climate	Clouds: MISR cloud-top height (CTH) 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/decadal climate change detection (see [42] for additional discussion of this benefit theme).	Clouds: A future MISR spin-off sensor would continue the unique height/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 a trend may not continue and any offset may not be sustainable indefinitely [43]. 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; distinguish "blue" ice regions thought to be indicators of changes in ice sheet ablation and accumulation patterns from spectrally similar active glacier crevasses; distinguish different types of first-year sea ice, and to some extent, multi-year ice from first year ice, to help understand the interaction between ice formation and melting, climate, and ocean processes [44-46].

Environ-ment	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, and has also been used in conjunction with other data and a multiscale model to map plume dispersal from the September 11, 2001 World Trade Center attack and to estimate human exposure [47].	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 ±5 $\mu g/m^3$ uncertainty potentially enables routine evaluation of NAAQS $PM_{2.5}$ attainment (15 $\mu g/m^3$ and 65 $\mu g/m^3$, respectively, for annual and 24-hour time intervals) from satellite.	Aerosols: Discrimination between spherical and randomly oriented nonspherical particles has been demonstrated with MISR, providing improved natural vs. anthropogenic source attribution [48,49].
Weather	Clouds: Geometrically-derived cloud-top heights can be used to assess performance of hurricane simulation models.	Clouds: Acquisition of stereo cloud heights and cloud-tracked winds with broader swath width and reduced data latency than MISR will provide daily, global height-resolved winds with accuracies commensurate with radiosondes (±3 m/s).	
Resource Manage-ment		Biosphere: Multiangle imagery potentially improves accuracy of above-ground biomass inventories, particularly when acquired globally in conjunction with lidar canopy heights as training input [50-52].	

Natural Hazards	Seismic events: Detection of deep ocean waves and motion of near-shore breakers from the 12/26/2004 Indian Ocean tsunami provide one-of-a-kind data for calibrating wave propagation models at high resolution [53].	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 1/26/2001 Gujarat (India) Earthquake—was detected by MISR far from the epicenter and in remote areas inaccessible to ground teams [54].

3.3.1 An "experimental" instrument

The MISR instrument was designed as an experiment to explore how remote sensing using moderately high resolution multiangle imaging data can provide new or improve the quality of existing geophysical products compared with products derived by 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, for example, in the sense of providing data routinely as a basis for 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 co-registration and calibration. These steps require a host of quality controls to which new data are subject before data sets and data products become publicly available or publicly accepted.[3] As many technology issues are now solved, e.g., the ability to generate accurately co-registered multiangle data automatically on a global basis [39], and to derive geophysical parameters with algorithms that had been untested prior to launch [57], future missions will be in a position to capitalize on this experience and dedicate resources to operational concerns. Ongoing advances in computing power and network capabilities will contribute substantially to making this possible.

3.3.2 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

[3] 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 "back-casting" or retrospective analysis of data. For example, as noted in table 2, MISR investigators have studied how pollution levels from aerosols have varied over past years using the MISR aerosol data product. In analysis of anomalies in aerosol measurements over greater India during the winters of 2001 - 2004. it was observed that pollution levels were unusually high over the northern Indian state of Bihar. At that location, meteorology, topography, and aerosol sources combine to concentrate airborne particles. Although high levels of pollution in parts of India have been observed for several decades, the accurate spatial distribution permitted by MISR and elucidation of factors establishing Bihar as a region of high aerosol concentration are new information [56]. The study drew much media attention in India and elsewhere.

coverage since 1972 (Landsat) and 1979 (AVHRR). The relatively longer experience of working with data from these instruments offers 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. Successor instruments to MISR, if and when flown, will similarly have new attributes but the degree of heritage will be significantly greater, and community familiarity with the data will start with a much greater level of maturity. This is exemplified by the observed trends in MISR data usage: from 2000 to 2006, the number of unique customers for MISR data products increased from 48 to 1273, and the distributed data volume increased from 1.3 TB (terabytes)/year to 186 TB/year [58].

3.3.3 Concerns about continuity and longevity of the record of data

Given the experimental nature of MISR, at the current time no successor to MISR is yet manifested on an approved mission, although as noted above, new sensors making use of the MISR legacy are in development. As a consequence, some 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, some researchers have expressed skepticism regarding the utility of MISR products for the study of decade-scale climate change without a guarantee of a data record having the requisite duration. As a result of NASA’s Senior Review of Terra [55] and other Earth science satellite missions, Terra operations were continued beyond the nominal mission duration and the instrument payload has now acquired a continued 7-year data record. Terra contains sufficient fuel for another 7 years of orbital maneuvers, and MISR performance continues to be excellent with high stability [37-39].

3.3.4 Incompatibility of instrument attributes with operational applications

MISR resources have been largely dedicated to pursuing scientific questions and proving the concept of MISR technology rather than to anticipated operational use. This focus caused a major portion of MISR funding to be weighted toward accurate instrument calibration as well as research associated with developing and testing new algorithms for using the data and data products. Pioneering advances in retrieval of geophysical parameters such as aerosol optical depth over land [59] and tropospheric wind velocities [60], among others, have now been demonstrated, yet the 400-km wide swath and the associated 9-day global coverage time limit the usefulness of such data for assimilation into forecast models. These design attributes were predicated on scientific, engineering, and cost/benefit judgment at the time of instrument development; nonetheless, they make it problematic to evaluate MISR within the context of operational applications (which demand a different set of sensor characteristics). Having now demonstrated the viability and accuracy of MISR geophysical retrievals, a wider swath is planned for future instruments; MSPI, for example, is being designed to provide 1-4 day global coverage, and a constellation of CMVCs can cover the Earth in less than 1 day.

3.3.5 Data latency

For certain applications, particularly forecasting, a short interval (i.e., a few hours at most) is required between acquiring data, processing them into "final products," and sending the products to the communities that use them. For example, these processes require mechanisms to transmit data from the instrument to ground stations, and then to transfer data from ground stations to processing facilities. None of these mechanisms is in place for MISR. It generally takes 24 hours after acquiring raw MISR data for the data to be processed into radiometrically and geometrically calibrated and georeferenced data products. An additional 24 hours is typically required to make the next level of useful products for many communities. Plans for future sensors and the associated downlink capabilities have the goal of turning raw instrument data into geophysical products within a few orbits of acquisition, i.e., within about 3 hours.

3.3.6 Software interface and format incompatibilities

Off-the-shelf software is typically designed for data that are expected to be routinely available over time compared with data from newer or specialized instruments. Software developers may be reluctant to modify or create software to accommodate 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 a new and experimental instrument such as MISR.

For example, in the early (pre-launch) days of MISR product development, externally imposed data volume constraints led to the adoption of certain non-conventional data formats and approaches that required special software tools to interpret. As these constraints were relaxed somewhat after launch, and the impact of early design decisions on data usability became more apparent, data formats and ordering interfaces were revised accordingly. Doubling of the distributed data volume between 2005 and 2006, and greater than 50% increase in the number of unique customers during that same time period, is a likely consequence of the availability of a simplified data format, a revised data product ordering and customization tool, and the accumulated effect of outreach efforts by the MISR project at the Jet Propulsion Laboratory and the data distributors at the NASA Langley Atmospheric Sciences Data Center. Furthermore, modern information technology approaches are making great strides in improving data interoperability, which is the ability to process and exchange data from multiple platforms. For example, NASA is funding development of the Aerosol Measurement and Processing System (AMAPS), which uses "grid" technology combined with special Python programming language data structures to access, manipulate and analyze large volumes of aerosol data (including but not limited to MISR) stored in diverse, remote locations [61]. Such a system is one step toward the vision outlined in the PARAGON (Progressive Aerosol Retrieval and Assimilation Global Observing Network) concept [62,63], which includes a recommendation to use advanced grid, massively parallel, and other high-performance computing and cyber infrastructure initiatives (e.g. [64]) to create an aerosol "virtual observatory" that will enhance climate and environmental research.

3.3.7 Additional perspective on these limits

The opportunities – and challenges – of using Earth observation data for practical applications were the topic of a set of three NRC/SSB studies during 2001 - 2003. One of the studies [8, pp.12-13] optimistically points out "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." But the report continues by describing at length the challenges in pursuing these applications. These challenges offer a reprise to 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

The societal benefit frameworks and examples drawn from MISR data products illustrate approaches to linking application of Earth observations and their science, thus offering guidance for implementing one of the NRC survey's key recommendations for the coming decades. Next steps might be community discussion of the differences between frameworks and a search for an approach to combine the "best" attributes of both methods. From the perspective of the NASA/ES decision support model, practical applications inform decisions about managing natural resources or public policy implementation. The NASA/ES model has the support of NASA's Earth science division, the US climate change research program, and international organizations such as the GEOSS and the WMO's water research program. Applying this framework to MISR emphasizes the resource management and policy contribution of moderate resolution multiangle data and requires collecting information from resource managers, identifying the decision support tools and systems they use, and identifying the public policies that such data 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). The NRC/DoE model has support from an external constituency (having been adopted by the Department of Energy). Particular advantages of this approach for Earth observations 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 preserves the option of opening new doors to useful information (once, say, existing decision support software – the focus of the NASA/ES approach – are revised, if necessary, to accommodate the new data product).

Generalizing beyond application to MISR, a combination of the two frameworks described in this paper may be useful as a template for characterizing benefits associated with Earth observations. The specificity of the NASA/ES view towards use (by way of decision support tools) and outcome (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 observations 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, etc.)

Regardless of any benefit-related approach ultimately taken, 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 figure 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. The decadal survey acknowledges the value of incentives, emphasizing (p. 5-5) the "need for devising professional rewards for those who develop and sustain applications and societal benefits." In addition, 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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References

[1] National Research Council, Space Studies Board, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, National Academies Press, Washington, DC (2007).

[2] National Aeronautics and Space Administration, Earth Science Enterprise, *NASA's Earth Science Data Resources*, NP-2003-11-587-GSFC, NASA, Washington, DC (2003).

[3] National Aeronautics and Space Administration, Earth Science Enterprise, *Earth Observation Satellites Version 1.2*, NP-2003-07-313-HQ, NASA, Washington, DC (2004).

[4] Climate Change Science Program, Subcommittee on Global Change Research, *Strategic Plan for the US Climate Change Science Program*, Executive Office of the President, Washington, DC (2003)

[5] Group on Earth Observation Data Utilization Subgroup, *Report of the Subgroup on Data Utilization*, GEO4DOC 4.1(3) (2004), http://www.earthobservationsummit.gov

[6] World Meteorological Organization, *The World Climate Research Program: Strategy for 2005-2015* (2005), www.gewex.org/SSG-18_WCRP-COPES.pdf
[7] National Research Council, Space Studies Board, *Setting Priorities for Space Research: An Experiment in Methodology*, National Academies Press, Washington, DC (1995).
[8] National Research Council, Space Studies Board, *Transforming Remote Sensing Data into Information and Applications*, National Academies Press, Washington, DC (2001).
[9] National Research Council, Space Studies Board, *Toward New Partnerships in Remote Sensing – Government, the Private Sector, and Earth Science Research,* National Academies Press, Washington, DC (2002).
[10] National Research Council, Space Studies Board, *Using Remote Sensing in State and Local Government – Information for Management and Decision Making*, National Academies Press, Washington, DC (2003).
[11] National Oceanic and Atmospheric Administration, *Economic Statistics 2005* NOAA, Washington, DC (2005), http://www.publicaffairs.noaa.gov/pdf/economic-statistics2005.pdf
[12] National Aeronautics and Space Administration, Earth Science Enterprise, *The View from Space: NASA Earth Observations Serving Society*, NP-2003-11-589-GSFC, NASA, Washington, DC (2003).
[13] National Aeronautics and Space Administration, *NASA Earth Observations Serving Society*, NP-2005-7-705-GSFC, NASA, Washington, DC (2005).
[14] M. K. Macauley and F. M. Vukovich, "Earth science remote sensing data: the contribution to natural resources policymaking," *Resources for the Future* Discussion Paper **05-35**, Resources for the Future, Washington, DC (2005).
[15] R. M. Adams, K. J. Bryant, B. A. Mccarl, D. M. Legler, J. O'Brien, A. Solow, and R. Weiher, "Value of improved long-range weather information," *Contemp. Econ. Pol.* **13**(3), 10-19 (1995) [doi: 10.1111/j.1465-7287.1995.tb00720.x].
[16] B. A. Babcock, "The value of weather information in market equilibrium," *Am. J. Agr. Econ* **72**(1), 63-72 (1990). [doi:10.2307/1243145].
[17] D. F. Bradford and H. H. Kelejian, "The value of information for crop forecasting in a market system," *Bell J. Econ* **9**, 123-144 (1977) [doi:10.2307/3003].
[18] W. E. Easterling and J. W. Mjelde, "The importance of seasonal climate prediction lead time in agricultural decision making," *Agr. Forest Meteorol.* **40**, 37-50 (1987) [doi: 10.1016/0168-1923(87)90053-0].
[19] L. B. Lave, "The value of better weather information to the raisin industry," *Econometrica* **31**(1-2), 151-164 (1987) [doi: 10.2307/1910954].
[20] R. R. Nelson and S. G. Winter, "A case study in the economics of information and coordination: the weather forecasting system," *Q. J. Econ.* **78**(3), 420-441 (1964) [doi: 10.2307/1879475].
[21] A. S. Pfaff, "What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data," *J. Environ. Econ. Manag.* **37**(1), 26-43 (1999) [doi: 10.1006/jeem.1998.1056].
[22] R. A. Pielke, Jr., "Usable information for policy: an appraisal of the U.S. global change research program," *Pol. Sci.* **28**(1), 39-77 (1995) [doi: 10.1007/BF01000820].
[23] R. Roll, "Orange juice and weather," *Am. Econ. Rev*. **74**(5), 861-880 (1984).
[24] S. T. Sonka, J. W. Mjelde, P. J. Lam, S. E. Hollinger, and B. L. Dixon, "Valuing climate forecast information," *J. Appl. Meteorol.* **26**(9), 1080-1091 (1987) [doi: 10.1175/1520-0450(1987)026<1080:VCFI>2.0.CO;2].

[25] T. J. Teisberg and R. F. Weiher, "Valuation of geomagnetic storm forecasts: an estimate of the net economic benefits of a satellite warning system," *J. Pol. Anal. Manag.* **19**(2), 329-334 (2000) [doi: 10.1002/(SICI)1520-6688(200021)19:2<329::AID-PAM9>3.0.CO;2-P].

[26] R. A. Williamson, H. R. Hertzfeld, J. Cordes, and J. M. Logsdon, "The socioeconomic benefits of Earth science and applications research: reducing the risks and costs of natural disasters in the USA," *Space Pol.* **18**, 57-65 (2002) [doi: 10.1016/S0265-9646(01)00057-1].

[27] D. J. Diner, S. W. Boland, E. S. Davis, R. A. Kahn, C. A. Hostetler, R. A. Ferrare, J. W. Hair, B. Cairns, and O. Torres, "Future mission concept for 3-D remote sensing of aerosols from low Earth orbit," in *Proc. IEEE Aerospace Conf.,* (2007) [doi: 10.1109/AERO.2007.352709].

[28] D. J. Diner, J. T. Booth, E. S. Davis, V. Jovanovic, S. A. Macenka, C. Moroney, and R. Davies, "Future mission concept for operational retrieval of cloud-top heights and cloud motion wind vectors," *Proc. IEEE Aerospace Conf.*, (2007) [doi: 10.1109/AERO.2007.352712]

[29] W. D. Nordhaus, "The value of information," *Policy Aspects of Climate Forecasting*, R. Krasnow, Ed., *Proc. Resources for the Future*, pp. 129-134 (1986).

[30] J. Hirshleifer and J. G. Riley, "The analytics of uncertainty and information – an expository survey," *J. Econ. Lit.* **17**(4), 1375-1421 (1979).

[31] M. K. Macauley and M. A. Toman, "Providing Earth observation data from space: economics and institutions," *Am. Econ. Rev.* **81**(2), 38-41 (1991).

[32] M. K. Macauley, "Some dimensions of the value of weather information: general principles and a taxonomy of empirical approaches," in *Report of the Workshop on the Social and Economic Impacts of Weather*, R. A. Pielke, Ed., National Center for Atmospheric Research, Boulder, CO (1997).

[33] M. K. Macauley, "The Value of information: a background paper on measuring the contribution of Earth science applications to national initiatives," Resources for the Future Discussion Paper 05-26, Resources for the Future, Washington, DC (2005).

[34] National Aeronautics and Space Administration, Office of Earth Science, "National Applications Program: program strategy status," NASA, Washington, DC (2002).

[35] National Research Council, *Energy Research at DOE: Was it Worth It?* National Academies Press, Washington, DC (2001).

[36] D. J. Diner, J. C. Beckert, T. H. Reilly, C. J. Bruegge, J. E. Conel, R. Kahn, J. V. Martonchik, T. P. Ackerman, R. Davies, S. A. W. Gerstl, H. R. Gordon, J-P. Muller, R. Myneni, R. J. Sellers, B. Pinty, and M. M. Verstraete, "Multi-angle Imaging SpectroRadiometer (MISR) description and experiment overview," *IEEE Trans. Geosci. Rem. Sens.* **36**, 1072-1087 (1998) [doi:10.1109/36.700992].

[37] D. J. Diner, J. C. Beckert, G. W. Bothwell, and J. I. Rodriguez. "Performance of the MISR instrument during its first 20 months in Earth orbit," *IEEE Trans. Geosci. Rem. Sens.* **40**, 1449-1466 (2002) [doi: 10.1109/TGRS.2002.801584].

[38] C. J. Bruegge, D. J. Diner, R. A. Kahn, N. Chrien, M. C. Helmlinger, B. J. Gaitley and W. A. Abdou, "The MISR radiometric calibration process," *Rem. Sens. Environ.* **107**, 2-11 (2007) [doi: 10.1016/j.rse.2006.07.024].

[39] V. Jovanovic, C. Moroney, and D. Nelson "Multi-angle geometric processing for globally geo-located and co-registered MISR image data," *Rem. Sens. Environ*. **107**, 22-32 (2007) [doi: 10.1016/j.rse.2006.08.013].

[40] Y. Liu, R. J. Park, D. J. Jacob, Q. Li, V. Kilaru, and J. A. Sarnat "Mapping annual mean ground-level $PM_{2.5}$ concentrations using Multiangle Imaging SpectroRadiometer aerosol optical thickness over the contiguous United States," *J. Geophys. Res.* **109**, D22206 (2004) [doi: 10.1029/2004JD005025].
[41] Y. Liu, J. A. Sarnat, V. Kilaru, D. J. Jacob, and P. Koutrakis "Estimating ground-level $PM_{2.5}$ in the eastern United States using satellite remote sensing," *Environ. Sci. Tech.* **39**, 3269-3278 (2005) [doi: 10.1021/es049352m].
[42] G. Ohring, B. Wielicki, R. Spencer, W. Emery, and R. Datla (eds.), *Satellite Instrument Calibration for Measuring Global Climate Change*, report NISTIR 7047 from a workshop sponsored by the National Institute of Standards and Technology, the National Polar Orbiting Environmental Satellite System/Integrated Program Office, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration, College Park, MD, 12-14 November 2002 (2004), http://physics.nist.gov/Divisions/Div844/publications/NISTIR7047/nistir7047.pdf
[43] R. Davies, "Interannual differences in cloud albedo and cloud height measured by MISR," *Eos Trans. AGU* **86**(52), Fall Meeting Suppl., Abstract A54D-03 (2005).
[44] A. W. Nolin, F. M. Fetterer, and T. A. Scambos, "Surface roughness characterizations of sea ice and ice sheets: case studies with MISR data," *IEEE Trans. Geosci. Rem. Sens.* **40**(7), 1605-1615 (2002) [doi: 10.1109/TGRS.2002.801581].
[45] A. W. Nolin and M. C. Payne, "Classification of glacier zones in western Greenland using albedo and surface roughness from the Multi-angle Imaging SpectroRadiometer (MISR)," *Rem. Sens. Environ*. **107**, 264-275 (2007) [doi: 10.1016/j.rse.2006.11.004].
[46] J. C. Stroeve and A. W. Nolin, "New methods to infer snow albedo from the MISR instrument with applications to the Greenland Ice Sheet," *IEEE Trans. Geosci. Rem. Sens.* **40**, 1616-1625 (2002) [doi: 10.1109/TGRS.2002 .801144].
[47] G. Stenchikov, N. Lahoti, P. J. Lioy, P. G. Georgopoulos, D. J. Diner, and R. Kahn, "Multiscale plume transport from collapse of the World Trade Center on September 11, 2001," *Environ. Fluid Mechan*. **6**(5), 425-450 (2006) [doi: 10.1007/s10652-006-9001-8].
[48] R. Kahn, "The box," *Air and Space* September, 14-15 (1998).
[49] O. V. Kalishnikova, R. Kahn, I. N. Sokolik, and W.-H. Li. "The ability of multi-angle remote sensing observations to identify and distinguish mineral dust types: part 1: optical models and retrievals of optically thick plumes," *J. Geophys. Res.* **110**(D18), D18S14 (2005) [doi:10.1029/2004JD004550].
[50] D. S. Kimes, K. J. Ranson, G. Sun, and J. B. Blair, "Predicting lidar measured forest vertical structure from multi-angle spectral data," *Rem. Sens. Environ*. **100**, 503-511 (2006) [doi: 10.1016/j.rse.2005.11.004].
[51] M. Chopping, L. Su, A. Laliberte, A. Rango, D. P. C. Peters, and J. V. Martonchik, "Mapping woody plant cover in desert grasslands using canopy reflectance modeling and MISR data. *Geophys. Res. Lett.* **33**, L17402 (2006) [doi: 10.1029/2006GL027148].
[52] M. Chopping, G. Moisen, L. Su, A. Laliberte, A. Rango, J. V. Martonchik, and D. P. C. Peters "Large area mapping of southwestern forest crown cover, canopy height, and biomass using MISR," *Rem. Sens. Environ*. (accepted, 2007).
[53] M. J. Garay, and D. J. Diner "Multi-angle Imaging SpectroRadiometer (MISR) time-lapse imagery of tsunami waves from the 26 December 2004 Sumatra–

Andaman earthquake," *Rem. Sens. Environ*. **107**, 256-263 (2007) [doi: 10.1016/j.rse.2006.10.022].
[54] B. Pinty, N. Gobron, M. M. Verstraete, F. Mélin, J.-L. Widlowski, Y. Govaerts, D. J. Diner, E. Fielding, D. L. Nelson, R. Madariaga, and M. P. Tuttle, "Observing earthquake-related dewatering using MISR/Terra satellite data," *Eos Trans. A G U.* **84**, 37-43 (2003) [doi:10.1029/2003EO050001].
[55] K. J. Ranson, S. T. Tsay, V. V. Salomonson, B. A. Wielicki, H. Tsu, J. R. Drummond, D. J. Diner, M. J. Abrams, and J. C. Gille, "Terra Senior Review Proposal," submitted to Senior Review 2005 of the Mission Operations and Data Analysis Program for the Earth Science Operating Missions (2005).
[56] L. Di Girolamo, T. C. Bond, D. Bramer, D. J. Diner, F. Fettinger, R. A. Kahn, J. V. Martonchik, M. V. Ramana, V. Ramanathan, and P. J. Rasch, "Analysis of Multi-angle Imaging SpectroRadiometer (MISR) aerosol optical depths over Greater India during Winter 2001-2004," *Geophy. Res. Lett.* **31**, L23115 (2004) [doi:10.1029/2004GL021273].
[57] D. J. Diner, B. H. Braswell, R. Davies, N. Gobron, J. Hu, Y. Jin, R. A. Kahn, Y. Knyazikhin, N. Loeb, J. Muller, A. W. Nolin, B. Pinty, C. B. Schaaf, G. Seiz, and J. Stroeve, "The Value of Multiangle Measurements for Retrieving Structurally and Radiatively Consistent Properties of Clouds, Aerosols, and Surfaces," *Rem. Sens. Environ.* **97**, 495-518 (2005) [doi: 10.1016/j.rse.2005.06.006].
[58] N. Ritchey, "NASA Langley Atmospheric Sciences Data Center user services report," presented at the MISR Science Team Meeting, Pasadena, CA (December 6, 2006).
[59] R. Kahn, B. Gaitley, J. Martonchik, D. Diner, K. Crean, and B. Holben, "MISR global aerosol optical depth validation based on two years of coincident AERONET observations," *J. Geophys. Res*. *– Atmospheres* **110**, D10S04 (2005) [doi: 10.1029/2004JD004706].
[60] R. Davies, Á. Horváth, C. Moroney, B. Zhang, and Y. Zhu, "Cloud motion vectors from MISR using sub-pixel enhancements," *Rem. Sens. Environ*. **107**, 194-199 (2007) [doi: 10.1016/j.rse.2006.09.023].
[61] A. Braverman, O. Kalashnikova, J. Penner, L. Xu, C. Chuang, B. Wilson, B. Rheingans, and D. Cordner, "Constraining IMPACT biomass-burning source model predictions with level 2 satellite data using the AMAPS Distributed Science Network," *Eos Trans. AGU* **87**, Fall Meet. Suppl., Abstract A31F-06 (2006).
[62] D. J. Diner, R. T. Menzies, R. A. Kahn, T. L. Anderson, J. Bosenberg, R. J. Charlson, B. N. Holben, C. A. Hostetler, M. A. Miller, J. A. Ogren, G. L. Stephens, O. Torres, B. A. Wielicki, P. J. Rasch, L. D. Travis, and W. D. Collins, "Using the PARAGON framework to establish an accurate, consistent, and cohesive long-term aerosol record," *Bull. Amer. Meteor. Soc*. **85**(10), 1535-1548 (2004) [doi:10.1175/BAMS-85-10-1535].
[63] T. P. Ackerman, A. J. Braverman, D. J. Diner. T. L. Anderson, R. A. Kahn, J. V. Martonchik, J. E. Penner, P. J. Rasch, B. A. Wielicki, and B. Yu, "Integrating and interpreting aerosol observations and models within the PARAGON framework," *Bull. Amer. Meteor. Soc*. **85**, 1523–1533 (2004).
[64] I. Foster, "The grid: A new infrastructure for 21st century science," *Phys. Today* **55**, 42–47 (2002) [doi:10.1063/1.1461327].

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