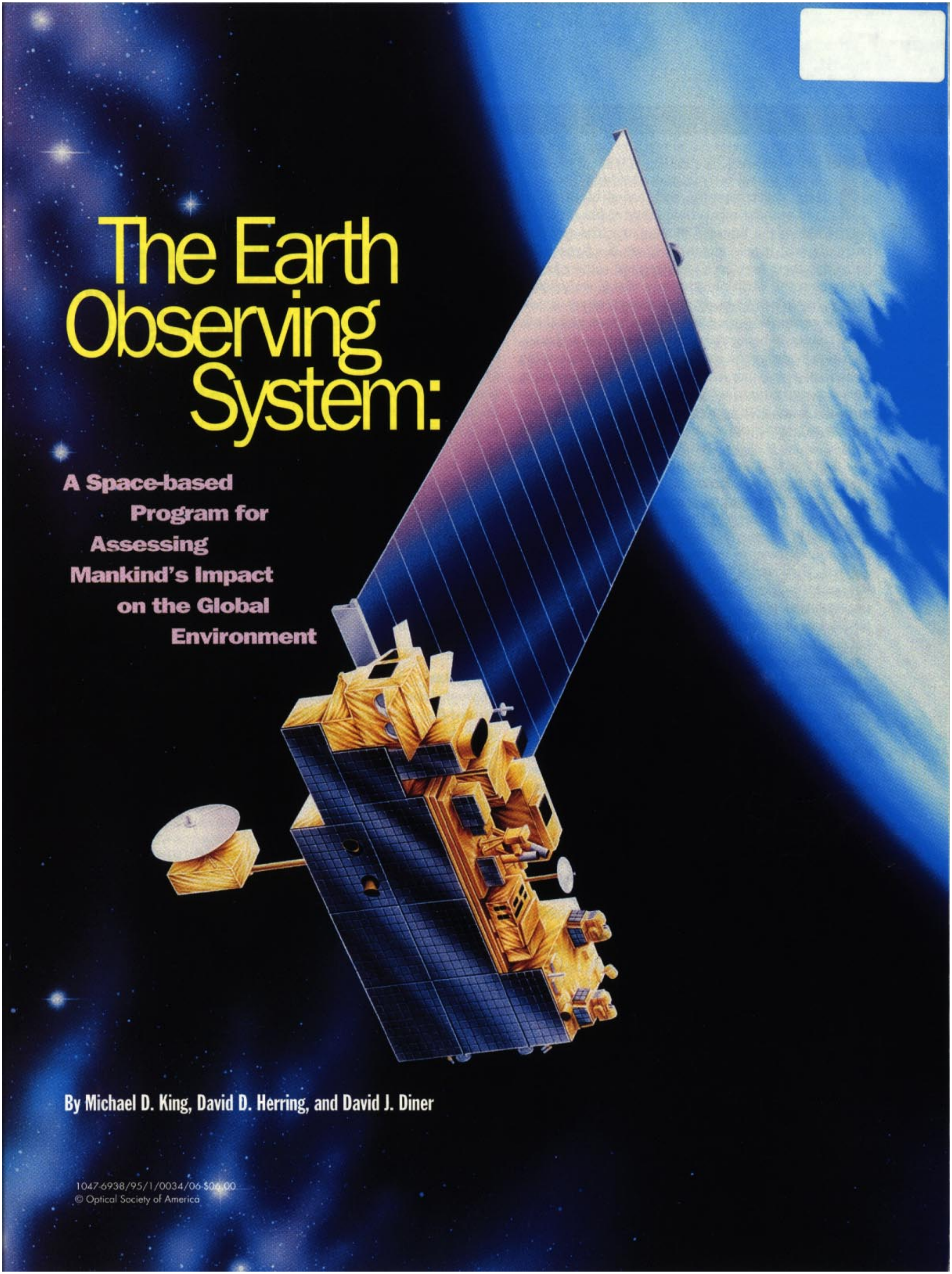

The Earth Observing System:

A Space-based Program for Assessing Mankind's Impact on the Global Environment

By Michael D. King, David D. Herring, and David J. Diner

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These days, we frequently hear or read news about global warming, ozone depletion, acid rain, desertification, and loss of biodiversity, and wonder what the quality of life on Earth will be like in the future. Unfortunately, too few data currently exist to provide an adequate description. We know that there have been warming and cooling trends throughout the Earth's history, and that global climate change has arisen from natural causes. However, now there is compelling scientific evidence that global climate change is being accelerated by human activities. Through widespread activities related to increasing urbanization—such as deforestation and biomass burning, or industrial and automobile emissions—mankind is conducting an uncontrolled experiment on the Earth's environment without knowing what the consequences will be. Decades ago, scientists began raising critical questions concerning global climate change in hopes of differentiating human-induced climate change from natural fluctuations. In 1988, scientists from the Intergovernmental Panel on Climate Change (IPCC) met in hopes of bringing their questions and concerns to the forefront of the Earth science agenda. Two years later, the U.S. Global Change Research Program (USGCRP) identified key areas of uncertainty in global climate change. In the early 1980s, NASA began planning the Earth Observing System (EOS), the primary initiative in its Mission to Planet Earth to provide scientists with the tools needed to meet the goals set forth by the USGCRP and IPCC—to develop a better understanding of our planet with which to assist policymakers worldwide to protect and manage our environment and natural resources more effectively and efficiently.

EOS consists of three components[1,2]: a space-based observing system comprised of a series of satellite sensors by which scientists can monitor the Earth, a Data and Information System (EOSDIS) enabling researchers worldwide to access the satellite data, and an interdisciplinary scientific research program to interpret the satellite data. The objectives of EOS[1] are to:

- Establish an integrated, sustained, and comprehensive program to observe the Earth on a global scale;
- Conduct focused and exploratory studies to improve understanding of the physical, chemical, biological, and social processes that influence the Earth's climate;
- Develop models of the Earth system to integrate and predict climate changes; and
- Assess impacts of natural events and human activities on the Earth's climate.

The first EOS spacecraft, EOS AM-1 (Fig. 1), will launch in 1998. "AM-1" means that the satellite will fly in a sun-synchronous polar orbit, descending southward across the equator at 10:30 a.m. In 2000, EOS PM-1 will be launched into a sun-synchronous polar orbit ascending northward across the equator at 1:30 p.m. Six years after AM-1, EOS AM-2 will launch, followed by EOS PM-2, and so on. Other EOS satellites include Radar Altimetry (launches in 1999), EOS Chemistry (launches in 2002), and Laser Altimetry (launches in 2003). Additionally, there are a number of EOS sensors on flights of opportunity, including international spacecraft; *e.g.*, SeaWinds, which will fly aboard Japan's ADEOS II satellite in 1999. Overall, the EOS Program will provide a 15-year global dataset of many atmospheric, terrestrial, and oceanic properties.

> **"The goal is to construct models of the Earth's global dynamics"**

EOS AM-1 will carry a payload of five unique, highly sophisticated sensors for measuring Earth's features and processes: the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Clouds and the Earth's Radiant Energy System (CERES), and the Measurement of Pollution in the Troposphere (MOPITT). The focus of this article is on EOS AM-1, with particular emphasis on MODIS and MISR.

Background

Through observation and measurement, scientists have learned that atmospheric constituents—such as clouds, gases, and aerosols (stratified hazes and dust layers)—profoundly affect the Earth's land and oceans; and as changes occur on the land and in the oceans, they in turn profoundly affect the atmosphere.[3] Scientists conclude that the relationship between land, oceans, and atmosphere is cyclical and tightly interwoven. So, to better understand natural global climate change, as well as mankind's role in accelerating these changes, scientists must study the Earth as a whole integrated and interacting ecosystem. The goal is to construct models of the Earth's global dynamics—atmospheric, oceanic, and terrestrial—and predict changes before they occur.

Before scientists can begin to understand and accurately model global dynamics, they need information in the form of data. To differentiate short-term trends from long-term, as well as to distinguish regional phenomena from global, these data must be collected every day for a long period of time (at least 15 years) and should represent every region of the Earth's lands, oceans, and atmosphere. Satellite sensors serve as an effective means for collecting these needed data, primarily by remote sensing of certain key attributes of the electromagnetic radiation reflected and emitted by the Earth.

Our planet is continually bathed in electromagnetic radiation from the Sun, which directly or indirectly

Figure 1 (Left). An artist's rendering of the EOS AM-1 Platform. The first in a series of EOS satellites, AM-1 will launch in 1998 carrying a payload of five unique, highly specialized Earth sensors.

drives most of the Earth's surface dynamics. Solar radiation entering the atmosphere is either reflected back into space, absorbed by suspended particles (such as aerosols or clouds), or transmitted to the Earth's surface, where again it is either reflected, absorbed, or transmitted. Depending on their chemical composition, all objects reflect, absorb, or transmit radiant energy characteristically in certain bands of the electromagnetic spectrum. For example, in the visible spectrum, the pigments in certain species of phytoplankton preferentially absorb red and blue light and reflect green. Using satellite-based measurements to infer the abundance of these organisms quantitatively is challenging because the intervening atmosphere influences the characteristics of the observed signal. Therefore, it will be necessary to measure characteristics of the atmosphere, in addition to those on the Earth's surface, so that scientists may infer the conditions of both.[4]

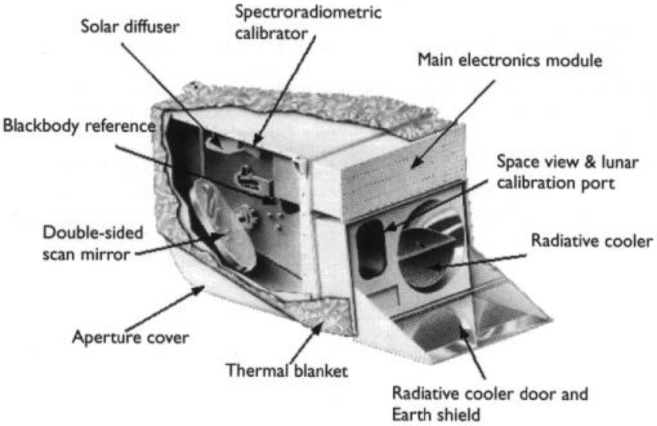

Figure 2. A cutaway view of the MODIS instrument illustrating some of its essential components for calibration. MODIS will have unprecedented capabilities to characterize instrument performance while in orbit.

The instruments that will fly aboard EOS spacecraft are well-designed to take measurements in seven key areas of scientific uncertainty related to global change[1,2]:

1. Sources and sinks of greenhouse gases, which affect predictions of their future concentrations and global warming;
2. Clouds and the Earth's radiation balance, which strongly influence the magnitude of climate change;
3. Oceans, which are the heat engine of global climate and influence the timing and patterns of climate change;
4. Land surface hydrology, which affects regional climate and water availability for agricultural and industrial development;
5. Polar ice sheets, which affect predictions of global sea level;
6. Ecological dynamics, such as vegetation patterns, biological diversity, and carbon cycling, which are affected by and affect climate change; and
7. Volcanoes, which can add materials to the atmosphere that cause short-term climate change.

Moderate resolution imaging spectroradiometer

Currently being developed by Hughes Santa Barbara Research Center, MODIS will be a key instrument on each of the EOS AM and PM satellites (see Fig. 2). MODIS' objective is to provide a comprehensive series of global observations of the Earth's land, oceans, and atmosphere in the visible and infrared regions of the spectrum in 36 spectral bands ranging from 0.405 to 14.385 μm. Here, the word "comprehensive" refers to the wide spectral range and spatial coverage, as well as the continuous coverage MODIS will provide over time. With its swath width of 2,330 km, MODIS will view the entire surface of the Earth every 1 to 2 days.

Additionally, MODIS is "comprehensive" in that it will continue to take measurements in spectral regions that have been and are currently being measured by other satellite sensors, or "heritage instruments." Subsequently, MODIS will extend data sets taken by such instruments as the Advanced Very High Resolution Radiometer (AVHRR), used for meteorology and monitoring sea surface temperature, sea ice, and vegetation; and the Coastal Zone Color Scanner (CZCS), used to monitor oceanic biomass and ocean circulation patterns.[4,5] However, it should be noted that MODIS will meet or exceed the capabilities of all of its heritage instruments. "Comprehensive" also refers to the unified nature of MODIS' observations, necessary for multidisciplinary studies of land, ocean, and atmospheric processes and their interactions. In short, MODIS will be a central tool on the EOS satellites for conducting global change research. MODIS data will be used by all other EOS AM-1 instrument teams to complement their respective science data products.

Onboard calibration

Technologically, MODIS will break new ground in onboard calibration. No other spectroradiometer has been able to measure the spectral location of its bands while in orbit. MODIS will have this capability, as well as the unprecedented capability to measure band-to-band registration while in orbit. Until now, scientists have had to assume that pre-launch, band-to-band registration remains the same after launch, and that the spectral purity of bands remains unchanged for the life of the mission. There is some evidence that there have been in-orbit spectral changes in heritage satellite sensors. If an in-orbit spectral shift should occur in MODIS, it will be measured and characterized.[6] Moreover, in addition to using the sun and moon as shortwave calibration sources and an internal blackbody as a longwave calibration source, MODIS will continually monitor any degradation of the solar diffuser that allows it to look directly at the sun (see Fig. 3).[6]

Improved science capabilities

Although MODIS will not contain revolutionary new optics technology, it does stretch current state-of-the-art to new limits for new scientific applications. MODIS contains a cross-track scanning mirror and a set of linear detector arrays with spectral interference filters located in four focal planes.[6] The challenge has

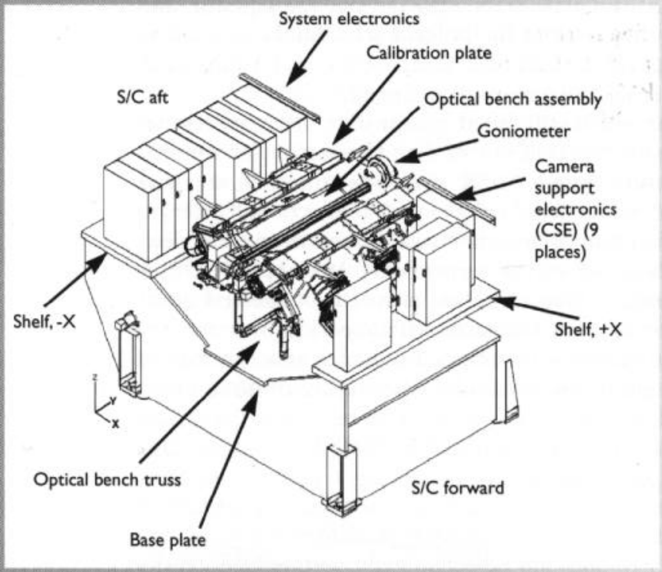

Figure 4. Layout of the MISR instrument illustrating the primary support structure, base plate, and optical bench, which holds the nine cameras. The primary support structure attaches to the EOS AM-1 spacecraft, and the base plate maintains rigid support for the optical bench.

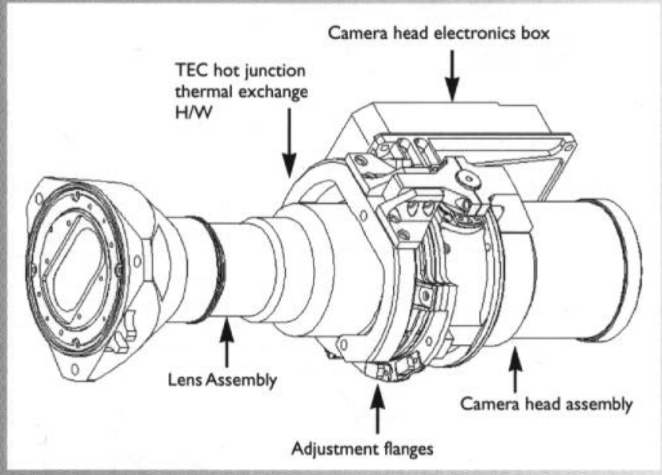

Figure 5. Example of an MISR charge coupled device (CCD) camera. Each camera contains a refractive f/5.5 telecentric lens and has its own power supply and serial data interfaces.

as their optical properties at each scene.[8] Clouds and aerosols both play a major role in climate. Over land, MISR's multi-angle views will enable scientists to study the impact of land processes on climate. For vegetated terrain in particular, MISR data will enable scientists to study vegetation reflectance relative to canopy structure. Here, MISR will particularly complement MODIS—its multi-angle observations will help scientists interpret directional vegetation indices acquired by MODIS.[8] MISR's multi-angle imagery will help scientists classify land vegetation worldwide, as well as derive photosynthesis and transpiration rates.

Detector-based calibration

MISR uses detector-based calibration techniques, both pre-flight and in-flight to achieve a radiometric scale. Detector standards are more accurate than conventional source standards, and are used at national standards labs such as NIST (U.S.) and NPL (U.K.). MISR is the first spaceborne instrument to introduce high quantum efficiency (HQE) diode technology as part of in-flight calibration, which is expected to reduce calibration uncertainties by a factor of two from conventional methods.

The HQE diodes used as part of MISR's on-board calibrator (OBC) are silicon detectors with high internal quantum efficiency. Three of these diodes are packaged in a "light trapping" configuration, such that light that is reflected (*i.e.*, undetected) by the first diode illuminates the second diode, where it has another opportunity for capture; light reflected there hits the third diode and is then reflected back to the second and first diodes for a total of five opportunities for capture. The output from the three diodes is summed together, giving the entire device a near-100% quantum efficiency. MISR uses four such packages, each optimized for one of the MISR spectral bands. The diode filters have the same spectral characteristics as the filters used for the camera CCDs.

In addition to the HQE devices, highly radiation-resistant PIN photodiodes are used as part of the MISR OBC as a secondary detector standard. This standard typically exhibits higher environmental stability relative to the HQEs. However, environmental testing has demonstrated a higher level of charged particle radiation resistance for the HQEs used for MISR Bands 1-3 than previously expected, which should enable full reliance on these devices throughout the mission. Several sets of PIN diodes are mounted on the MISR optical bench, and one set is mounted on a mechanized goniometer to obtain bidirectional reflectance measurements of the calibration panels.

Spectralon diffuse panels

MISR incorporates two deployable diffusely-reflecting panels for calibration of the cameras. In evaluating materials to be used for these panels, considerations including Lambertian reflectance (which is important because the cameras view each panel from different angles), spatial uniformity, high hemispherical reflectance, low contamination, effects of static charge build-up, and mechanical robustness were taken into account. The material chosen for the panels is Spectralon, a form of sintered polytetrafluoroethylene. MISR has provided for the flight qualification of this material. Because of MISR's reliance on detector-based calibration as described above, it is not necessary for the panel reflectance to remain invariant throughout the EOS mission. Studies involving exposure of Spectralon to UV radiation in vacuum, however, indicate that the material's reflectance at the MISR wavelengths is stable to better than 2% in the blue with even better performance at the longer wavelengths. To achieve this stability, special cleaning and handling methods have been developed to ensure against contamination by photoactive hydrocarbons.

EOS data and information System

The EOS Data and Information System (EOSDIS) is one of the most exciting features of the EOS Program—users will not need in-depth knowledge of remote sensing technology to use EOS data. Each instrument science team will be responsible for the quality of its data products. EOSDIS will receive, process, store, and render these data available internationally to the Earth science community, as well as policymakers, resource planners, and commercial users.[9] It is estimated that EOS AM-1 alone will collect 1 to 2 terabytes of data per week. To make these data easily accessible to its diverse users, EOSDIS will use advanced technology for data management, compression, and distribution. Although EOSDIS will be geographically distributed throughout the U.S., users will access the system with a single computer interface, so it will appear to them as a single entity. Users will connect to EOSDIS using any one of several Internet networks, including the NASA Science Internet and the National Research and Education Network, currently under development.[10] The idea is to make accessible calibrated, validated global data products and encourage the international Earth science community to perform the analyses.

Anyone interested in learning more about EOS, or browsing sample remote sensing images, should refer to the EOS Project Science Office Home Page available via Mosaic on the World Wide Web. The URL (Uniform Resource Locator) is `http://spso.gsfc.nasa.gov/spso_homepage.html`

The big picture

In scope and complexity, EOS is an awesome endeavor. It involves the synergistic union of researchers from a broad range of scientific disciplines working together to, for the first time ever, understand the Earth as a whole, integrated system. EOS AM-1 employs the internationally distributed science and technical teams of five highly specialized instruments working together, in complementary fashion, to collect what will become the largest dataset in history. The goal is to construct models of the Earth's global dynamics—atmospheric, oceanic, and land surface—enabling scientists to predict climate changes before they occur. Scientists also hope to differentiate between natural and human-induced climate change. Ultimately, EOS will assist policymakers worldwide in making sound decisions concerning the protection and management of our environment and resources.

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