GLOBAL ENVIRONMENTAL MONITORING WITH THE EOS MULTI-ANGLE IMAGING SPECTRORADIOMETER (MISR)

D. J. Diner, C. J. Bruegge, J. V. Martonchik, G. W. Bothwell, L. E. Hovland, and K. L. Jones

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California USA 91109

ABSTRACT

The MISR instrument will provide a unique opportunity for studying the ecology and climate of the Earth through the acquisition of systematic, global multi-angle imagery in reflected sunlight. MISR employs nine cameras: A nadir camera and two banks of four cameras each pointed forward and aftward along the spacecraft ground track to image the Earth at ±30.7, ±45.6, ±60.0, and ±72.5°. Radiometrically calibrated images at each angle will be obtained in four spectral bands centered at 440, 550, 670, and 860 nm. MISR will take image data in two different spatial resolution modes: Local Mode, in which selected targets are observed with 240-m spatial sampling, and Global Mode, where the entire sunlit Earth is observed continuously with 1.92-km sampling. The instrument is capable of acquiring global coverage every nine days.

Keywords: Earth Observing System, imaging, bidirectional reflectance

1. INTRODUCTION

The Multi-angle Imaging SpectroRadiometer (MISR) instrument has been selected for flight as part of the NASA Earth Observing System mission. Launch of the first polar platform, designated EOS-A1, is scheduled for late 1998. MISR will be designed and built by the Jet Propulsion Laboratory (JPL). The MISR instrument concept uses state-of-the-art technology in a novel fashion to acquire multispectral images of the angular reflectance signatures of terrestrial scenes on a systematic and routine basis. The global database obtained with MISR will present opportunities for research on the climatic effects of natural and human-induced environmental changes in atmospheric aerosol content, cloud amount, distribution, and type, and surface characteristics. A Science Investigation Team has been established to assist in the development of the instrument and its data processing algorithms for generation of geophysical data products, and to perform analyses on the returned data (see Table 1).

2. INSTRUMENT AND MEASUREMENT CONCEPT

MISR is a charge-coupled-device (CCD)-based pushbroom imager that will observe the Earth at nine discrete view angles. The optical design approach consists of nine f/5.5 refractive cameras. In addition to a nadir-viewing camera, there are symmetric forward- and aftward-viewing camera banks which will acquire observations at ±30.7, ±45.6, ±60.0, and ±72.5° relative to the local vertical at the Earth's surface. This strategy provides observations in two azimuthal planes relative to solar illumination. Each of the nine cameras is electrically identical to the others and consists of a common focal plane structure coupled to a unique telescope assembly. This configuration represents an update to earlier instrument descriptions [1,2].

Table 1. MISR Science Investigation Team

Name and Institution	Role
David Diner *(JPL)*	Principal Investigator
Thomas Ackerman *(Penn. State)*	Aerosol climatic effects
Carol Bruegge *(JPL)*	Calibration Scientist
Roger Davies *(McGill Univ.)*	Cloud climatic effects
Siegfried Gerstl *(Los Alamos)*	Surface bidirec. reflectance
Howard Gordon *(Univ. Miami)*	Ocean studies
John Martonchik *(JPL)*	Data Scientist
Peter Muller *(U. Coll. London)*	Stereo-photogrammetry
Piers Sellers *(GSFC)*	Land climatology

It takes seven minutes of flight time for MISR to observe any given region at all nine view angles. The allocation of a separate camera to each view direction results in continuous multi-angle imagery of the entire globe. Global coverage is possible in nine days. Unique features of the MISR optical design include passive focus adjustment in response to temperature variations, polarization compensation, and radiation resistance. The design also enables matching of crosstrack footprint dimensions at all of the off-nadir view angles. Each of the off-nadir cameras has a unique focal length and field of view and is designed to image a 408 km ground swath onto a 1696-element detector array such that each 18 μm detector element maps to a 240 m ground pixel. The nadir camera design is a replicate of the 30.7° camera. This results in a pixel spacing of 210 m and a swath width of 356 km for the nadir view. Consequently, there are only four unique optical designs in the instrument. The slightly higher resolution in the nadir view is beneficial to the ground data processing, in which the nadir imagery is used as a reference for registering the images from the other cameras.

MISR will observe in two resolution modes, designated Global Mode (GM) and Local Mode (LM). GM data are generated on-board by averaging data from eight adjacent pixels and eight successive lines, yielding images with a crosstrack pixel footprint and spacing of 1.92 km (1.68 km for the nadir camera). This is the nominal imaging mode of MISR, and will have a data rate of 287 kbps. To accomplish more detailed investigations using LM, selected 300-km-long regions will be imaged with 240 m pixel spacing and crosstrack resolution (210 m at nadir) by inhibiting the on-board averaging for each of the cameras in succession, beginning with the most forward-viewing one, according to a pre-defined time sequence. The data rate in this mode is 2.54 Mbps. A standard network of Local Mode scenes will be established by the MISR Science Team.

The basic MISR camera detector is envisioned to be a front-side illuminated CCD. The device consists of four line arrays all on the same chip. The center-to-center spacing between the line arrays is 100 μm. The line arrays consist of an image area 1696 pixels long, a serial transfer register, and an output stage. The pixel active area is 18 μm square. The pixels are contiguous in the crosstrack direction, and the full well is expected to exceed 750,000 electrons/pixel. A four-strip color filter is laminated on the CCD structure so that each of the four rows of pixels is filtered to a different wavelength. MISR imagery will be acquired in these four spectral bands: 440, 550, 670, and 860 nm. The bands are chosen for their utility in vegetation, radiation, and aerosol studies. The integration time within the line-repeat interval is variable from 0.1 msec to 35.6 msec, permitting the equalization of radiometric performance between spectral bands. The repeat time between line acquisitions is 35.6 msec, resulting in 240-m spacing between successive lines in the downtrack direction.

There is one analog-to-digital converter (ADC) per CCD output, or 36 required for the entire instrument. The ADCs are envisioned to be 16-bit devices. The 14 most significant bits are used to linearly encode the observed signals; these 14-bit words will then be put through a square-root look-up table to generate 12-bit output words. The large full well capacity and low noise characteristics of the CCD detectors used in the MISR cameras and square-root digitization to 12-bit resolution insure that high signal-to-noise ratios will be obtained.

MISR radiometric calibration goals include 3% absolute accuracy at the maximum signal level for a uniform scene observed by the instrument, 1% camera-to-camera relative uncertainty, 0.5% uncertainty in relative spectral signature, and 0.5% uncertainty from pixel-to-pixel within a given camera. Although achieving a highly accurate post-launch radiometric calibration is inherently difficult, redundant techniques will be employed in order to reduce systematic errors. A key hardware component of the MISR instrument is a pair of deployable diffuse panels made from a material which has a high, near-lambertian reflectance. A polytetrafluoroethylene-based compound such as Spectralon SRS-99, manufactured by Labsphere, Inc., is envisioned for the MISR diffuse panel material. Our plan is to deploy the panels over the poles on a monthly basis. Over the North pole, one of the plates will swing forward to reflect diffuse sunlight into the fields-of-view of the forward-looking cameras. Over the South pole, the other plate will swing aft for calibration of the aftward-looking cameras. The nadir camera will view both panels, providing a link between the two sets of observations.

The diffuse calibration targets and selected uniform targets on the Earth's surface will also be monitored by two types of diodes: radiation-resistant diodes and QED (Quantum Efficient Detector) self-calibrating diodes. The radiation-resistant photodiodes will be packaged in clusters of four, each diode in the cluster filtered to a MISR spectral band. Five such clusters will be used; four of these will be stationary and oriented to view the nadir, and positioned to view different spatial locations of the diffuse panels. The fifth will be mechanized on a goniometric arm to monitor the angular reflectance properties of the panels. The QEDs consist of three silicon inversion-layer photodiodes arranged so that light reflected from one diode is absorbed by another diode. The output of each diode is summed in parallel resulting in close to 100% quantum efficiency. Four nadir-viewing QEDs, each filtered to one of the MISR spectral bandpasses, will be used. Monitoring of the responsivities of all of the diodes as a function of time will be performed through the use of semi-annual ground calibrations, using large, homogeneous targets such as White Sands, New Mexico. These ground validation field campaigns are key to the long-term maintenance of the MISR radiometric calibration.

A diagram of the MISR instrument conceptual design is shown in Figure 1. It consists of an optical bench and an enclosure structure. The optical bench supports the nine pushbroom cameras and the calibration hardware. The enclosure structure seals the cameras from contaminants, provides radiation surfaces for passive heat dissipation, and structurally supports the electronic boxes required to run the MISR instrument. The overall dimensions of the enclosure are 50" (length) x 27" (width) x 32.5" (depth). Cooling of the instrument is provided using side and nadir-facing radiator panels. The estimated instrument mass is 85 kg, and it is expected to use about 70 W of power.

3. SCIENCE OBJECTIVES

MISR imagery will be used to address several scientific objectives. First, MISR multi-angle radiance data will enable global estimates of aerosol amounts and optical properties necessary to study the effect of these atmospheric particulates on the solar radiation budget. In the case of sufficiently optically thick smoke plumes, stereophotogrammetry will be used to estimate plume-top elevations. Because the net radiative effect of aerosols, i.e., whether they heat or cool the surface, depends on their optical properties and the albedo of the underlying surface, a systematic, global monitoring program is needed to collect data on aerosol opacity, single scattering albedo, size distribution, and surface albedo. Retrieval of these parameters is a key objective of the MISR investigation. Martonchik et al. [3] described how multi-angle imagery could be used to perform such retrievals over land when the aerosol layer is sufficiently transparent so that surface features could be discerned. Their method uses Fourier analysis of scenes containing surface reflectance contrasts to separate the contribution of diffuse scattering to the top-of-atmosphere radiances. The algorithm compares the shape of the surface reflectance as a function of view angle as retrieved from both direct and total Fourier transformed fields for various power spectrum wavenumbers. The values for the various atmospheric parameters which minimize the residuals from such angular reflectance shape comparisons comprises the best estimate of the aerosol properties. Over oceans, algorithms developed for atmospheric corrections of Nimbus-7 Coastal Zone Color Scan-

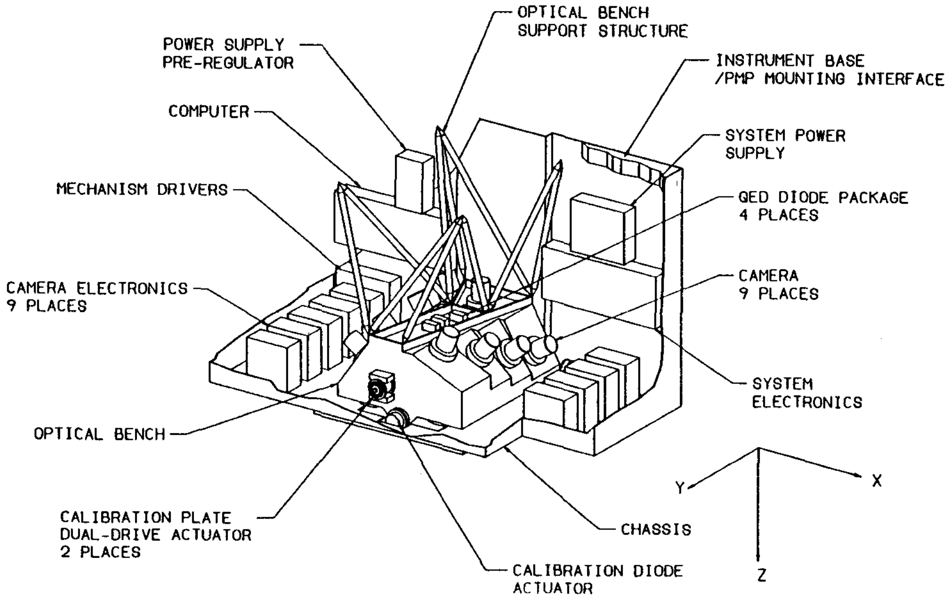

Figure 1. MISR instrument conceptual design

ner (CZCS) imagery will provide the basis for aerosol optical depth retrievals [4]. Extension of this method to multi-angle data will be implemented for the MISR investigation.

A second area of study with MISR concerns the short-wave radiative properties of clouds. There is general agreement that clouds play a major role in governing the Earth's energy balance, and the importance of cloud characteristics in global studies of climate has been well documented. However, current theories and models of the response of the Earth's climate system to, for example, the increase in trace gases, are limited by our present ignorance of the feedback processes associated with changes in cloud amount and cloud properties. Theoretical studies [5] have shown that diffusion of radiation through cloud sides causes the directional reflectances of cumuliform cloud fields to differ markedly from those of stratiform fields, establishing the inadequacies of plane-parallel representations of cloud fields in climate models. Regional studies of the impact of clouds on energy balance require measurements of the radiation budgets as a function of scene type. Our ability to view the same region from different angles both to characterize the scene type and to validate theoretical model predictions has as yet been extremely limited, and a systematic investigation of the role of clouds on climate requires observation of relatively homogeneous local scenes, more or less coincidentally at several different angles. These can be directly integrated to yield the flux. Such observations will be acquired by MISR, enabling direct validation of theoretical angular reflectance models. MISR will also be capable of providing cloud-top height information through stereo-imagery.

A third area of investigation concerns land surface processes, which are important components of the terrestrial climate system. Models describing the interaction of surface and atmospheric processes require the ability to obtain quantitative information on radiation, mass, heat, and momentum fluxes. These fluxes are directly influenced by the spectral, structural, geomorphological, and, in the case of vegetated landscapes, physiological properties of the surface. Retrieval of accurate information about rates of evapotranspiration, photosynthesis, respiration, and radiation absorption at the surface requires estimates of hemispherical albedo, which cannot be accurately estimated from nadir spectral reflectance, thus necessitating the use of multi-angle observations. The use of physical surface models should improve the estimates even further. Radiative transfer modeling of MISR measurements of vegetated surfaces will provide insight into the optical and geometric properties of the scatterers (e.g., leaves) within these media. Many researchers argue that the directional reflectance distribution is diagnostic of canopy structure variables. MISR will provide a global data set on the angular reflectance "signatures" of various classes of surface cover. Determination of surface reflectance and albedo will require correction for the effects of scattering by atmospheric aerosols. Estimates of aerosol optical properties, derived from MISR data, will be used for this purpose, as well as to correct image data acquired by other EOS sensors.

Stereophotogrammetric retrieval of global surface topography with MISR imagery will provide estimates of surface roughness that can be used in sub-grid scale parameterizations of orographic effects in general circulation models. One of the objectives of the MISR experiment is to produce, from a single source, a global digital elevation model (DEM) with guaranteed accuracy and reliability. The expected horizontal resolution of any DEM derived from high resolution MISR data is about 500 m with an estimated height accuracy of 100 m.

Finally, MISR will also contribute to biological studies of the Earth's oceans. The concentration of chlorophyll *a* and its degradation products have been used to estimate the rate of biological productivity in ocean waters. The basis for the phytoplankton pigment abundance determinations is measurement of ocean color in several spectral bands. With the MISR spectral band set, the concentration is estimated by forming the ratio of the water-leaving radiances at 440 and 550 nm. Since MISR does not include bands between 440 and 550 nm, only the low phytoplankton pigment concentration range (0 - 1 mg pigment/m^3) will be available; however, this should be sufficient for most of the tropical oceans.

4. DATA PROCESSING AND PRODUCTS

During each orbit, the nine MISR cameras sequentially image the same area on the Earth. The goal of the MISR systematic photogrammetric image reduction process is to create a set of 36 mutually registered images (nine angles x four spectral bands) for each swath. Additionally, the swaths must be mosaicked into 9-day maps of the entire globe. Throughout the process, it is desired that a 1/4 pixel accuracy, or better, be maintained. Since images acquired of the same territory by the nine MISR cameras are obtained from different viewing angles with a large separation, they will contain a strong stereoscopic component. In order to prepare a set of 36 images that appear to be viewed normal to the surface and are also co-registered, the stereoscopic/topographic component must be removed. In order to apply topographic corrections obtained from DEMs, navigational updating is needed to establish the positional correspondence between the images and the DEM. MISR data can be used to create missing DEMs. The current processing plan is to use a series of data reduction options depending on the complexity of the topography (in which case a pixel-by-pixel, as opposed to a widely spaced tiepoint, correction may be needed).

In addition to the basic image data products, several geophysical data products will be produced at the start of mission operations. These are listed in Table 2.

Table 2. "At-launch" data products

Parameters Measured	Estimated Accuracy
Cloud directional reflectances (classified by cloud type)	1% (angle-to-angle)
Spectral planetary albedo	0.02
Surface directional reflectances (classified by surface type)	2% (angle-to-angle)
Spectral surface albedo	0.03
Vegetation index	2%
Aerosol opacity, τ	0.05 ($\tau < 0.5$) 10% ($\tau > 0.5$)
Aerosol size parameter	20%
Ocean phytoplankton pigment concentration	30%
Surface/ cloud/ plume elevations	100 m

A special computing facility, known as the MISR Laboratory for Instrument Support and Science Analysis (MLISSA) will be established at JPL and will be utilized for development and validation of MISR data analysis algorithms, for performing science analysis, for production of high-level specialized data products, and for instrument calibration analysis. Co-investigators not located at JPL will also be involved in algorithm development at their home institutions. Software development for systematic bulk data processing at the MISR active archive will be conducted at the MISR Algorithm Implementation and Certification Laboratory (MAICL), located at JPL. The MAICL will also be the facility for analyzing the quality of standard MISR data products and updating the calibration and other processing parameters.

5. CONCLUSIONS

By monitoring the global environment via multi-angle imagery, MISR will make unique contributions to Earth System Science research. We anticipate many novel and multidisciplinary applications of the data to be returned by this instrument. MISR images and products will be archived at the EOS Data and Information System (EOSDIS) to make them available to the broad scientific community.

6. REFERENCES

[1] Diner, D. J., Martonchik, J. V., Bruegge, C. J., Danielson, E. D., and Kimes, D. S., "Remote sensing of aerosol and surface properties with a Multidirectional Imaging Spectro-Radiometer," *Proceedings of the IGARSS'87 Symposium*, Ann Arbor, Michigan, 1987.

[2] Diner, D. J., Bruegge, C. J., Martonchik, J. V., Ackerman, T. P., Davies, R., Gerstl, S. A. W., Gordon, H. R., Sellers, P. J., Clark, J., Daniels, J. A., Danielson, E. D., Duval, V. G., Klaasen, K. P., Lilienthal, G. W., Nakamoto, D. I., Pagano, R. J., and Reilly, T. H., "MISR: A Multiangle Imaging SpectroRadiometer for geophysical and climatological research from Eos," *IEEE Trans. Geosci. Rem. Sensing*, Vol. **GE-27**, p. 200, 1989.

[3] Martonchik, J. V., Diner, D. J., Danielson, E. D., and Bruegge, C. J., "Application of heterogeneous scene models to retrieval of land surface and atmospheric optical properties from space," *Proceedings of the IGARSS'90 Symposium*, Washington, DC, 1990.

[4] Gordon, H. R., Clark, D. K., Brown, J. W., Brown, O. B., Evans, R. H., and Broenkow, W. W., "Phytoplankton pigment concentrations in the Middle Atlantic Bight: Comparison of ship determinations and CZCS estimates," *Appl. Opt.* Vol. **22**, p. 20, 1983.

[5] Coakley, J. A., and Davies, R., "The effect of cloud sides on reflected solar radiation as deduced from satellite observations," *J. Atmos. Sci.* Vol. **43**, p. 1025, 1986.

7. ACKNOWLEDGMENTS

The authors are grateful to the MISR Science Team and to Eric Danielson, Elmer Floyd, Virginia Ford, Edward Lin, Leslie Lowes, James McGown, Robert West, and Mary White for assistance. This research is being carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.