Multi-angle Imaging SpectroRadiometer (MISR) Instrument Description and Experiment Overview

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***Abstract*—The Multi-angle Imaging SpectroRadiometer (MISR) instrument is scheduled for launch aboard the first of the Earth Observing System (EOS) spacecraft, EOS-AM1. MISR will provide global, radiometrically calibrated, georectified, and spatially coregistered imagery at nine discrete viewing angles and four visible/near-infrared spectral bands. Algorithms specifically developed to capitalize on this measurement strategy will be used to retrieve geophysical products for studies of clouds, aerosols, and surface radiation. This paper provides an overview of the as-built instrument characteristics and the application of MISR to remote sensing of the earth.**

***Index Terms*—Earth, remote sensing.**

I. Introduction

THE Multi-angle Imaging SpectroRadiometer (MISR) instrument [1] was delivered by the Jet Propulsion Laboratory (JPL), Pasadena, CA, to the spacecraft contractor, Lockheed Martin Missiles and Space, Valley Forge, PA, on May 26, 1997. This delivery marked one of many major milestones in preparation for launch, which is currently scheduled for late 1998 from Vandenberg Air Force Base, CA.

MISR measurements are designed to improve our understanding of the earth's ecology, environment, and climate. The illumination source for MISR imagery is reflected sunlight. A detailed understanding of how sunlight is scattered in different directions is necessary to determine how changes in the amounts, types, and distribution of clouds, airborne particulates, and surface cover affect our climate. MISR takes the novel approach of imaging the earth in nine different view directions to infer the angular variation of reflected sunlight and the physical characteristics of the observed scenes. MISR's cameras are arranged with one pointing toward the nadir (designated An), one bank of four pointing in the forward direction (Af, Bf, Cf, and Df in order of increasing off-nadir angle), and one bank of four pointing in the aftward direction (Aa, Ba, Ca, and Da). Each of the nine cameras obtains images at four wavelengths (blue, green, red, and near-infrared). Onboard detector-based calibration hardware provides high radiometric accuracy and stability of the data. This observing strategy enables the rigorous use of radiative transfer theory and physically-based models to facilitate the retrieval of cloud, aerosol, and surface properties. Fig. 1 is a rendering of the MISR instrument measurement concept. The EOS-AM1 orbit is near-polar, sun-synchronous, with a 10:30 a.m. equator crossing time on the descending node, and has a 16-day global coverage repeat cycle.

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II. Instrument Overview

A. Architecture

At the heart of the MISR instrument is the optical bench, which holds the cameras at their light-admitting end with the detector end cantilevered into the instrument cavity. The fore-aft cameras are paired in a symmetrical arrangement and set at fixed view angles on the optical bench. In order to acquire images with nominal view angles, relative to the earth's surface, of 0, 26.1, 45.6, 60.0, and 70.5° for An, Af/Aa, Bf/Ba, Cf/Ca, and Df/Da, respectively, each off-nadir camera is oriented at a fore-aft pointing angle that is somewhat smaller than the corresponding view angle to account for earth curvature. This along-track mounting angle is called the boresight angle. The convention used is that a positive (negative) boresight angle points the camera forward (aftward). Additionally, to maximize overlap of the swath seen at all angles, the effect of earth rotation during the 7-min interval between viewing a point on the surface by the Df and Da cameras must be taken into consideration. This is accomplished by incorporating a slight cross-track offset angle into each camera's view direction. For these angles, the convention is that a positive (negative) offset points the camera in the same (opposite) direction as the earth is rotating.

The primary support structure provides kinematic attachment of the instrument to the spacecraft bus and is designed to

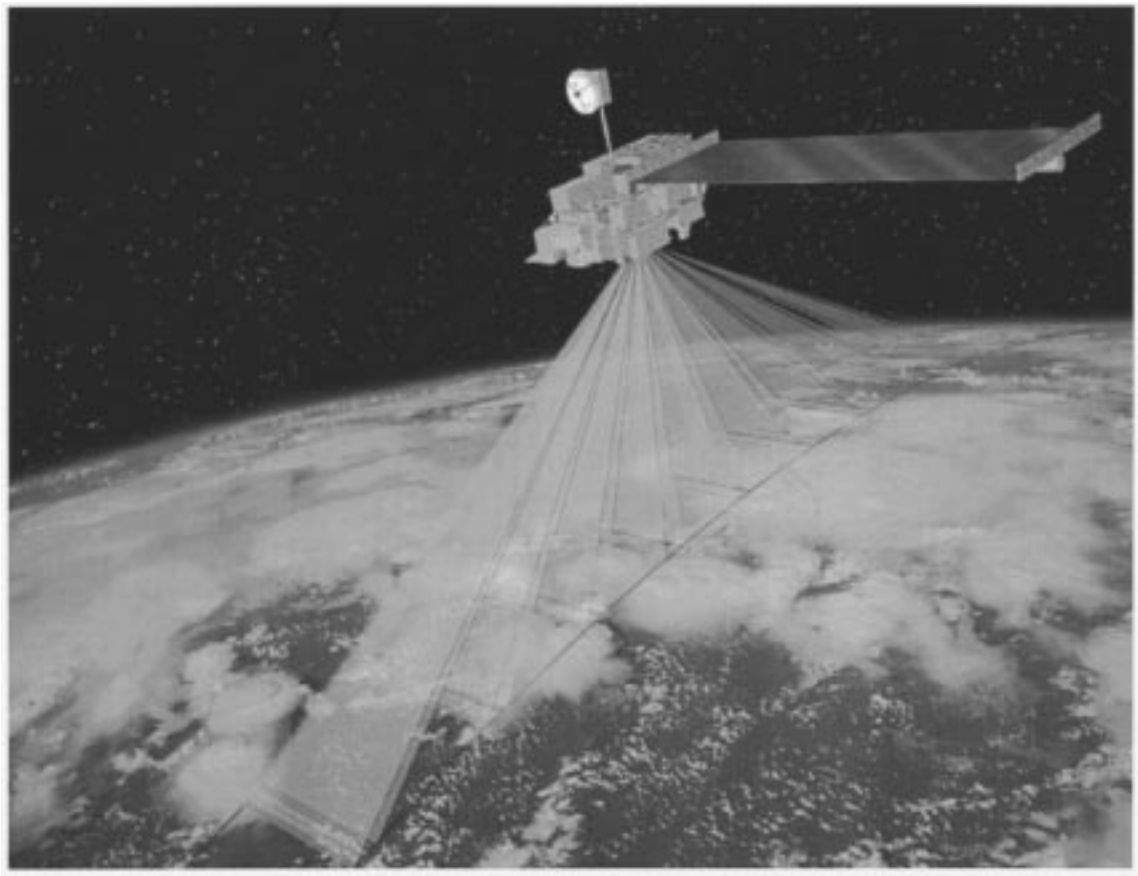

Fig. 1. Measurement approach of the MISR instrument. Nine pushbroom cameras point at discrete angles along the spacecraft ground track, and data in four spectral bands are obtained for each camera. It takes 7 min for a point on the earth to be observed at all nine angles.

maintain rigid support for the optical bench. Connection of the optical bench to the instrument structure is provided through a system of titanium tubular bipods. The instrument enclosure provides a structural mount for the nadir-facing radiators. In addition, it houses the system electronics and flight computers, and incorporates external optical baffles to keep specular glints from neighboring instruments from illuminating MISR's optical calibration surfaces.

A cutaway drawing of the MISR instrument is shown in Fig. 2, and a photograph of the instrument on the end bell of the JPL 10-ft thermal vacuum chamber is shown in Fig. 3. A summary of its specifications and as-built characteristics is shown in Tables I–III. In Table I, the small difference between the as-built power usage and the allocation at delivery has been waived by the EOS-AM1 project office. Camera pointing-angle measurements shown in Table II are relative to the instrument coordinate system. The view angles vary slightly with orbital location and position within each camera's field-of-view; the values in Table II are calculated for the center of the red band field-of-view and the point in the orbit at which the spacecraft is above the equator. Slight modifications to all of the angles shown will occur when the instrument-to-spacecraft pointing is established. In Table III, spectral bandwidths are larger than specification, due to larger than expected out-of-band spectral response as a result of scattering within the spectral filters. Where required, a correction for this response is incorporated into the data-processing algorithms. Further details on the preflight instrument calibration and characterization may be found in [2].

B. Cameras

The MISR lenses are superachromatic, seven-element, refractive f/5.5 telecentric designs. Focal lengths vary with view angle to maintain cross-track sample spacing. A double-plate Lyot depolarizer is incorporated into each of the cameras to render them polarization insensitive. The lenses are mounted in aluminum barrels with some additional materials to accommodate thermally induced dimensional changes of the lenses during flight. Each MISR camera contains a camera head that houses the focal plane structure and to which is attached the driver electronics for the charge-coupled device (CCD) line arrays. The camera heads and electronics are identical for all nine cameras, leading to a modular design in which only the lens barrels are unique.

MISR contains 36 parallel signal chains corresponding to the four spectral bands in each of the nine cameras. Each signal chain contains the output from the 1520 pixels (1504 photoactive plus eight light-shielded plus eight "overclock" samples of the CCD serial register) in each detector array. The detector elements (pixels) measure 21 (cross-track) $\times$ 18 μm (along-track). Each camera focal plane contains four separate line arrays, one for each spectral band. The spacing between the line arrays is 160 μm, causing certain bands to "lead" others in spatial position on the ground

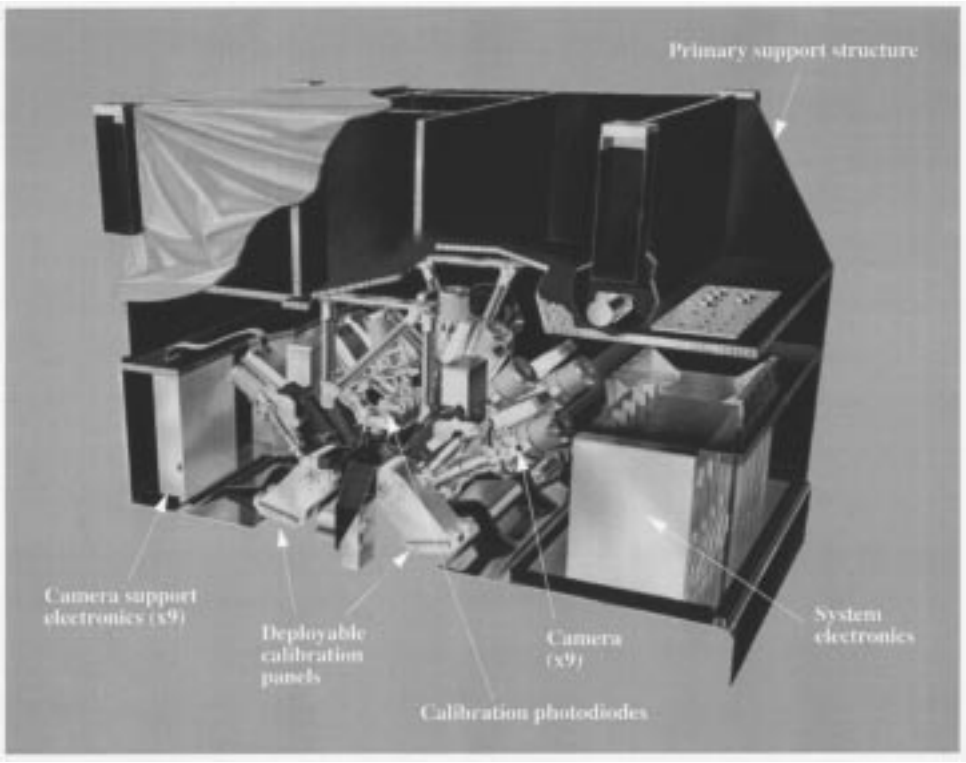

Fig. 2. Artist's rendition of the MISR instrument in cutaway view. The back ends of the nine MISR cameras appear as cylinders. In this orientation, MISR would look down toward the earth.

(see Fig. 1); coregistration of the data is accomplished in ground data processing.

The MISR CCD architecture is based on standard three-phase, three-poly, n-buried channel silicon detector technology. Thinning of the poly gate over the active pixels increases the detectors' quantum efficiency in the blue spectral region. Full well capacity is 10^6 electrons with read noise $<$20 electrons, yielding a large dynamic range for the devices. The signal chains amplify and convert the CCD video into 14-bit digital numbers. To optimize a tradeoff between dark current and radiation sensitivity, the CCD's are operated at -5 °C using a single-stage Thermo-Electric Cooler (TEC) in each focal plane.

A focal plane filter assembly defining the four optical bandpasses is placed about 1.5 mil above the CCD. The camera filters are mosaicked arrays of four separate medium band filters. Masks are placed over the epoxy bond lines between the different filters to prevent white light from leaking to the focal plane. The filters use ion-assisted deposition technology to insure stable and durable coatings that should not shift or degrade with age or environmental stresses.

Electrically, each camera is relatively autonomous, with its own power supply and serial data interfaces. The power supplies are 25-kHz sine wave units, providing high efficiency and low noise performance. The camera digital electronics provide interfaces to the system electronics controlling the camera as well as all of the drive and timing signals to the CCD focal plane, the double correlated signal chain, and the engineering signal conditioning (ESC) circuits. The signal chains are hybrids, and all camera digital circuits reside on field-programmable gate arrays (FPGA's). These technologies provide for high packing densities.

C. Onboard Calibrator

A key component of the MISR On-Board Calibrator (OBC) is a pair of deployable diffuser panels. These are covered with Spectralon, a pure polytetrafluoroethylene (Teflon) polymer resin, which is compressed and sintered. While not in use, the panels are stowed and protected. At approximately monthly intervals, the panels will be deployed for calibration. Over the North Pole, the forward-mounted panel will swing aftward to reflect diffused sunlight into the fields-of-view of the aftward-looking and nadir cameras. Over the South Pole, the aftward-mounted panel will swing forward for calibration of the forward-looking and nadir cameras. The nadir camera will provide a link between the two sets of observations.

The diffuse calibration targets are monitored in-flight by radiation-resistant p, intrinsic, and n-doped (PIN) photodiodes and high quantum efficiency (HQE) diodes. These diodes establish the radiometric scale upon which the instrument calibration is based. The PIN photodiodes are fabricated four to a package, each diode filtered to a different MISR spectral band. Five such packages are used. Two view in the nadir direction, two in the Df and Da camera directions, and one package is mechanized on a goniometric arm to monitor the angular reflectance properties of the panels. The calibration electronics consist of the calibration diode preamplifiers and the ESC circuits associated with the diodes.

The HQE's are in a "trap" configuration, in which three silicon photodiodes are arranged in a package so that light

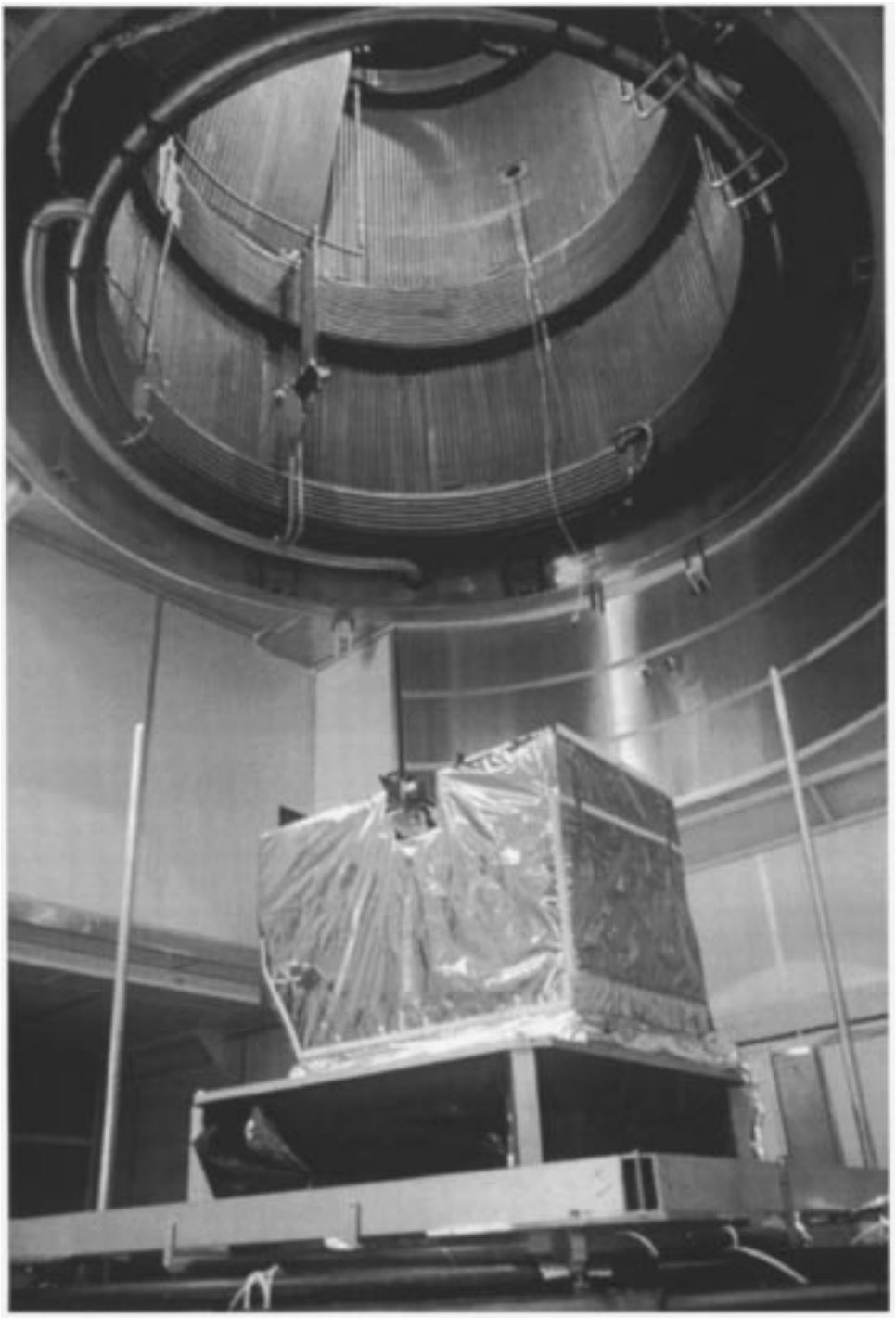

Fig. 3. MISR instrument is shown seated on the end bell of the thermal vacuum chamber in the 10-ft Space Simulator Facility at JPL. Testing within this chamber was used to verify the instrument performance over a range of temperatures.

reflected from one diode is absorbed by another diode. The output of each diode is summed in parallel, resulting in near 100% quantum efficiency. A single spectral filter per package is used, and four such packages provide coverage at the four MISR wavelengths.

The OBC will be used to provide camera response as a function of input radiance, as established by the diode detector standards. Ground data processing of the resulting radiometric transfer curves will be performed on a per-pixel basis to provide the coefficients for an analytic equation relating camera data number to radiance. This radiance scaling will be applied to MISR data routinely, prior to any further data processing. Further information about the MISR calibration program is contained in [3].

D. System Electronics

All MISR system electronics are redundant, having an A side and a B side, to avoid the possibility of a single-point failure. The system electronics consist of power supplies, logic units, which include the firmware to control the instrument

TABLE I
MISR INSTRUMENT SYSTEM REQUIREMENTS AND AS-BUILT SPECIFICATIONS

Parameter	Specification	As-Built
Size	Specified by spacecraft envelope	0.9 m (W) x 0.9 m (H) x 1.3 m (L)
Mass	≤ 157 kg	149 kg
Power	≤ 77 W (worst case orbital average) ≤ 130 W (peak)	83 W (worst case orbital average) 131 W (peak)
Data Rate (orbital average)	≤ 3.8 Mbps	3.3 Mbps
Quantization	Established by signal-to-noise ratio requirements	14 bits linear, compressed by square-root encoding to 12 bits
Spatial Sampling	275 m, 550 m, or 1.1 km (individually commandable for each channel)	As specified
Swath width (minimum overlap at all nine view angles along a line of constant latitude)	360 km	389 km

TABLE II
MISR CAMERA POINTING REQUIREMENTS AND AS-BUILT SPECIFICATIONS

	View angle		Boresight angle		Swath offset angle		Effective focal length (mm)	
Camera	Specification	As-Built	Specification	As-Built	Specification	As-Built	Specification	As-Built
Df	70.5° (forward)	70.3°	58.0 ± 0.2°	57.88°	-2.7 ± 0.2°	-2.62°	123.8 ± 1.9	123.67
Cf	60.0° (forward)	60.2°	51.2 ± 0.2°	51.30°	-2.3 ± 0.2°	-2.22°	95.3 ± 1.4	95.34
Bf	45.6° (forward)	45.7°	40.0 ± 0.2°	40.10°	-1.7 ± 0.2°	-1.71°	73.4 ± 1.1	73.03
Af	26.1° (forward)	26.2°	23.3 ± 0.2°	23.34°	-1.0 ± 0.2°	-1.06°	59.3 ± 0.9	58.90
An	0.0° (nadir)	0.1°	0.0 ± 0.2°	-0.04°	0.0 ± 0.2°	0.04°	59.3 ± 0.9	58.94
Aa	26.1 (aftward)	26.2°	-23.3 ± 0.2°	-23.35°	1.0 ± 0.2°	1.09°	59.3 ± 0.9	59.03
Ba	45.6° (aftward)	45.7°	-40.0 ± 0.2°	-40.06°	1.7 ± 0.2°	1.76°	73.4 ± 0.9	73.00
Ca	60.0° (aftward)	60.2°	-51.2 ± 0.2°	-51.31°	2.3 ± 0.2°	2.24°	95.3 ± 1.4	95.33
Da	70.5° (aftward)	70.6°	-58.0 ± 0.2°	-58.03°	2.7 ± 0.2°	2.69°	123.8 ± 1.9	123.66

TABLE III
MISR RADIOMETRIC AND SPECTRAL REQUIREMENTS AND AS-BUILT SPECIFICATIONS

Parameter	Specification	As-Built
Spectral Bands (solar weighted, measured in-band response)	Blue: 443 ± 2 nm Green: 555 ± 2 nm Red: 670 ± 2 nm NearIR: 865 ± 2 nm	Blue: 446.4 nm Green: 557.5 nm Red: 671.7 nm NearIR: 866.4 nm
Spectral Bandwidths (solar weighted, measured in-band response)	Blue: ≤ 30 nm Green: ≤ 20 nm Red: ≤ 20 nm NearIR: ≤ 60 nm	Blue: 41.9 nm Green: 28.6 nm Red: 21.9 nm NearIR: 39.7 nm
Polarization Sensitivity	≤ 1%	As specified
Absolute Radiometric Uncertainty	≤ 3% of absolute radiance at full signal	2%
Signal-to-Noise Ratio	≥ 700 at full signal at highest spatial resolution	As specified

prior to loading of the flight software, data management units, and 1750A computers, programmed in Ada, with 1553-type interfaces to the spacecraft. The 1553 interface is used for all commanding, instrument housekeeping data transmittal, flight software loading, and memory readout. The system electronics also provide the high-rate data interface as well as camera, power, and mechanism controls. System-wide temperature, voltage, and current measurements are provided by a system ESC circuit. All nine of the camera TEC's are powered by the system power supply and placed in series; however, a diode is placed in parallel with each TEC such that a single failure will not disable the entire string.

As in the cameras, all of the custom digital circuits used in the system electronics reside in FPGA's. These include the logic to enable buffering the CCD data to provide 2 sample $\times$ 2 line, 4 sample $\times$ 4 line, or 1 sample $\times$ 4 line averages, in addition to the configuration in which pixels are sent with no averaging (1 sample $\times$ 1 line). The averaging capability is individually selectable within each of the 36 channels. The system electronics also provide an additional form of data compression by reducing the 14-bit camera outputs to 12 bits through a digital lookup table that square-root encodes the data numbers. Square-root encoding minimizes quantization error at low signal levels at the expense of increased error at high signal levels, where photon noise dominates. Reversal of the square-root encoding takes place during the early stages of ground data processing.

III. Instrument Operations

From the 705-km orbit of the EOS-AM1 spacecraft, the zonal overlap swath width of the MISR imaging data (that is, the swath seen in common by all nine cameras along a line of constant latitude) is designed to be at least 360 km to provide multiangle coverage of an entire latitude circle in 9 days at the equator and 2 days near the poles. The cross-track field-of-view and sample spacing of each pixel is 275 m for all of the off-nadir cameras and 250 m for the nadir camera. Along-track footprints depend on view angle, ranging from 214 m in the nadir to 707 m at the most oblique angle. However, sample spacing in the along-track direction is 275 m in all cameras as a consequence of the 40.8-ms line repeat time of each channel.

There are 14 operational modes of the MISR instrument. Instrument engineering data are always provided over the low-rate 1553 interface. When the instrument is operating under control of the flight software, packetized instrument data, including engineering data, CCD imagery, motor current information, and OBC measurements, are available over the high-rate data interface. A brief description of each mode follows.

1) *Off:* This mode is used during launch or at any time the instrument is dormant. All subsystems are unpowered with all mechanisms closed or stowed.
2) *Survival:* In this mode, the instrument is off with the exception of an A or B string of survival heaters.
3) *Start-up:* When power is first applied to the instrument, it powers up the computer and system electronics on the selected instrument side (A or B). The power supply for the camera support electronics is powered to a standby level.
4) *Safe:* This mode is used in response to conditions that have the potential for jeopardizing the mission. Transition to Safe Mode will cause all calibration panels to stow, the goniometer, cameras, and diodes to turn off and optical bench and instrument replacement heaters to turn on.
5) *Safe-Exit:* This is a transition mode out of Safe Mode that is activated by commanding either the calibration panel or the goniometer to move, or a camera to turn on.
6) *Pre-Memory Load:* The nominal configuration for this mode is for all cameras, TEC's, optical bench heaters, focal plane heaters, and diodes to be off, in preparation for loading the instrument flight software.
7) *Engineering:* This mode provides engineering telemetry over the 1553 low-rate data interface as well as packetized engineering data over the high-rate interface. Nominally, all cameras, diodes, and mechanisms are off and only the system electronics are powered.
8) *Global:* This mode provides continuous operation of the cameras on the day side of the orbit. Global coverage in each instrument channel is provided by commanding the corresponding signal chain to operate continuously in a selected resolution mode. Standard geophysical data products will be generated using Global Mode data. Current plans are to acquire global data sets by operating the red band of all cameras and all bands of the nadir camera in 1 $\times$ 1 (no averaging); the blue band of the C and D cameras in 1 $\times$ 4; and the remaining channels in 4 $\times$ 4 averaging, as required by the geophysical retrieval algorithms [4]–[8].
9) *Local:* This mode provides high-resolution (1 $\times$ 1) images in all four bands of all nine cameras for selected earth targets. This is accomplished by inhibiting pixel averaging in all bands of each of the cameras in sequence, one at a time, beginning with the first camera to acquire the target (Df) and ending with the last camera to view the target (Da). The instrument geometry limits the downtrack length of Local Mode targets to about 300 km.
10) *Calibration North:* This mode is used when the spacecraft is in an orbital position at which the deployed forward-mounted calibration panel is illuminated by the sun. The instrument gathers science data from the An, Aa, Ba, Ca, and Da cameras and all diodes. CCD calibration data will be obtained by cycling each channel through the various averaging configurations during the calibration period. This mode will be used on a monthly basis during routine mission operations, although early in the mission it will be used more frequently.
11) *Calibration South:* This mode is used when the spacecraft is in an orbital position at which the deployed aftward-mounted calibration panel is illuminated by the sun. The instrument gathers science data from the An, Af, Bf, Cf, and Df cameras and all diodes. In other respects, this mode operates in similar fashion to Calibration North.
12) *Calibration Diodes:* This mode enables collection of both camera and diode science data on the day side of the orbit. The goniometer-mounted diodes are on, but the mechanism is not actuated. The cameras remain in the same averaging configuration used for Global Mode.
13) *Calibration Dark:* This mode enables collection of both camera and diode science data on the dark side of the orbit. The goniometer motor is actuated for a portion of the sequence. Each CCD channel is cycled

through all of the averaging configurations to provide an assessment of dark current and the influence of goniometer actuator activity on instrument noise.

14) *Test:* In this mode, the instrument outputs a fixed pattern to the high-rate data interface and shuts off engineering data flow to this interface.

IV. Georectification and Registration

Spatial coregistration of the 36 channels of data from the instrument is an essential requirement of all of the MISR geophysical retrievals. This is accomplished during ground data processing. Instrument-related geometric distortions will be accounted for by extensive geometric camera calibration. The results of preflight and in-flight geometric calibration will be used to construct a camera model, which utilizes the rigid relation between the cameras to describe the instrument pointing in terms of static and dynamic (temperature dependent) parameters.

A. Use of Space-Oblique Mercator (SOM) Map Grid

A common map projection, or grid, for the georectified radiances is established to provide the required coregistration. Space-Oblique Mercator (SOM) is used for this grid because its projection meridian nominally follows the spacecraft ground track and a constant distance scale is preserved along that track, thus minimizing distortion and resampling effects. The map resolution of the projection will also be matched to the horizontal sampling mode of each camera channel. The horizontal datum for each projection is the World Geodetic System 1984 (WGS84) ellipsoid. A separate projection will be established for each of the paths of the 233 repeat orbits of the EOS 16-day cycle. The SOM-gridded images and geophysical data constitute an intermediate step to the earth-based map projections to be used for global mapping at higher processing levels. Two types of SOM projection will be used for MISR data [9].

1) *Terrain Projection:* Certain retrieval algorithms require the radiances from all nine cameras of MISR to be coregistered and projected to the surface terrain. This is achieved by projecting the images to a surface defined by a digital elevation model (DEM) to account for angle-dependent, topographically induced misregistrations. In areas where it is necessary to correct for topography, the position and pointing information contained in the spacecraft ancillary data may not provide sufficiently accurate ground location. The MISR terrain projection algorithm will therefore utilize matching to a set of reference images to supplement the spacecraft navigation data. The reference orbit imagery is to be constructed from relatively cloud-free MISR data collected early in the EOS-AM1 mission.
2) *Ellipsoid Projection:* Other retrieval algorithms require the radiances from all nine cameras of MISR to be projected to a surface defined by the WGS84 ellipsoid. For example, this surface is where camera-to-camera stereo matching will be performed to determine cloud-top altitude. Projection of the imagery from the nine cameras (and individual bands) to a smooth ellipsoid is not as sensitive to viewing geometry as the terrain-projection algorithm. Therefore, the spacecraft attitude and position are used as reported (but improved by the calibrated camera model and static corrections obtained from matching) to determine an intersection with the surface ellipsoid. Then, resampling of the imagery to the SOM projection is performed.

V. Cloud Studies

A. Background

As a result of their large areal extent, high albedo, and variability on many length and time scales, clouds play a major role in governing the earth's energy balance. Models of the response of the earth's climate system, for example, the increase in trace gases, are severely limited by our present ignorance of the feedback processes associated with changes in cloud amount and cloud properties. Deriving from its ability to measure any scene from multiple directions, MISR will improve our ability to model cloud-radiation interaction by taking into account the variable structure of broken cloud fields and will obtain hemispherical fluxes with resolution sufficient to discriminate between cloud-filled and cloud-free scenes. The overall scientific objectives of the MISR cloud retrievals are described next.

1) *Cloud Detection and Screening:* Cloud detection is used to a) determine whether a scene is classified as clear or cloudy for the purpose of choosing the angular integration coefficients that are used in estimating top-of-atmosphere (TOA) albedos, b) calculate regional cloud cover, and c) determine whether a scene is clear enough to perform aerosol and surface retrievals. Applying traditional cloud screening methods to each MISR camera is a challenging problem, given the small number of spectral channels available, none of which are longward of 1 μm. As a result, only a few simple cloud detection observables are constructed from arithmetic operations on the camera radiances. However, MISR affords the opportunity to apply multiangle methods as well, including stereophotogrammetric techniques and angular signature-based approaches.
2) *Cloud Classification:* Cloud classification by MISR will partition clouds into categories distinguished by parameters, such as cloud-top elevation and texture or degree-of-brokenness (e.g., stratiform versus cumuliform). Reliable estimates of cloud-top altitude are required to model the three-dimensional (3-D) field of radiative fluxes that play a critical role in climate feedback. Cloud-top elevation is conventionally retrieved using thermal-infrared brightness temperatures together with temperature-pressure profiles from objective analyses of meteorological data. Stereoscopic observations from satellite provide an independent and wholly geometric means to obtaining this information without assumptions about the relationship between cloud-top radiative temperature and cloud-top pressure [10]–[12]. Recent

experience with automated stereo matching algorithms as applied to AVHRR [13], SPOT [14], and Along-Track Scanning Radiometer (ATSR) [15] suggest that the fore-aft viewing strategy of MISR is a viable means for retrieving cloud height. Once the cloud images are coregistered to the appropriate altitude level, multiangle textural parameters will also be calculated.

3) *Characterization of Cloud Climatic Effects:* Many theoretical studies have established that plane-parallel representations of cloud fields introduce large errors in the parameterization of radiation for climate models [16], [17]. Cloud modeling must consider not only the effects of individual cloud shape, but also interactions such as shadowing and multiple scattering between clouds. Diffusion of radiation through the cloud sides and side illumination causes the angular reflectance of cumuliform cloud fields to differ markedly from those of stratiform fields [18], [19]; therefore, careful scene classification and angular integration schema will be implemented by MISR to obtain accurate estimates of TOA albedo.

B. Retrieval Strategy

Cloud screening involves discriminating between clear and cloudy pixels in an image. Radiance threshold techniques work on a pixel-by-pixel basis, and single or multiple-channel thresholds that are defined are then used to divide clear and cloudy pixels. The observables that are used for MISR data depend on whether the observations are made over water or land. Each observable will be tested by comparing to thresholds derived from time-cumulated statistics over a particular geographical region. The thresholds are a function of view angle, sun angle, relative view-sun azimuth angle, time, and surface type. The result of this process, applied to each camera, is known as the Radiometric Camera-by-Camera Cloud Mask (RCCM).

Stereoscopic detection of clouds (and, if present, volcanic plumes) is based on height retrieval that uses the contrast measured by different cameras and a combination of feature-based and area-based matching techniques [20]. Determining the heights from multiangle views involves detecting disparities (i.e., horizontal spatial offsets in the imagery resulting from the parallax obtained by viewing at different angles). An accurate stereo matching algorithm is used to retrieve velocity and height values for a sparse subset of features in the MISR imagery. By selecting triplets of cameras with unsymmetric and oblique view zenith angles, we are able to separate the heights and velocities in the data reduction. Once the motion field has been derived, the conjugate points of stereo matchers applied to high-resolution data from pairs of cameras are used to retrieve a height field. The results are used to establish a Stereoscopically-Derived Cloud Mask (SDCM).

Detection of high cirrus is also important to MISR. Nadir imagers cannot always detect cirrus clouds due to restricted phase angle coverage. Therefore, the multiangle strategy will be used in a novel way. Di Girolamo and Davies [21] have developed a method known as Band-Differenced Angular Signature (BDAS), which takes advantage of the difference in the Rayleigh signal above high clouds between blue and red or near-infrared wavelengths as a function of angle. High clouds have a unique signature that distinguishes them from clear sky and low-level clouds. Application of this technique generates an additional classifier known as the Angular Signature Cloud Mask (ASCM).

In order to establish a parameter that serves the purpose of providing a classification scheme that incorporates cloud altitudes and serves as a dynamic (i.e., spatially varying) reference altitude for coregistering the multiangle views, a reference level known as the Reflecting Level Reference Altitude (RLRA) is established. The RLRA is derived from the stereoscopic height field. Physically, it corresponds to the main reflecting layer and, depending on atmospheric conditions, will typically be either the tops of bright clouds or the surface. The RLRA is defined over subregions measuring 2.2×2.2 km. For scene classification purposes, the stereoscopic heights used in deriving the RLRA are also used to generate regional altitude-binned cloud fraction metrics. The RLRA is also used as a common reference altitude for projecting the multiangle bidirectional reflectance factors, from which albedos and textural parameters will be derived.

The calculation of directional hemispherical reflectance (DHR), or albedo, involves an angular integration of bidirectional reflectance factors (BRF's) over the upwelling hemisphere. MISR's arrangement of nine cameras provides good coverage in zenith angle; however, the fore-aft views provide sampling at only two azimuth angles for each zenith angle. (Denser coverage in azimuth angle would require binning data acquired on different orbits and, thus, would not represent an instantaneous view of the same scene). Supplemental information to model the azimuthal dependence of BRF is therefore required to obtain the most accurate estimates of albedo. This is accomplished by choosing an azimuthal model (AZM) to facilitate the angular integrations. Selection of the appropriate AZM coefficients depends on solar zenith angle, whether a scene has been classified as clear or cloudy by the cloud detection process and, if cloudy, on an estimate of the cloud phase (liquid or ice), cloud texture, brightness, and altitude (to account for Rayleigh scattering) [22].

The probability of scene heterogeneity increases rapidly with scene size, making the relationship between area-averaged radiance and area-averaged scene properties (e.g., cloud liquid water) progressively more biased [23]. By matching albedos to scene characteristics, especially cloud information, local albedos can be corrected for azimuthal bias more effectively than albedos of larger areas. The local albedos can then be summed over larger areas to produce albedos of more heterogeneous scenes at coarser resolution. Two coarse resolution albedos, defined over regions measuring 35.2×35.2 km and referenced to 30-km altitude, are defined for MISR. We define the "restrictive" albedo to be the one obtained using angular integration of the observed BRF's over the given region only and the "expansive" albedo to be the one obtained using integration over all relevant surrounding regions, that is, all regions influencing the radiative flux leaving the top of the atmosphere in an area

extending to a few hundred kilometers on each side. As a result, the restrictive albedo is the more useful measure of scene-dependent properties, such as column absorption, and is analogous to earlier single-view determinations of the TOA albedo [e.g., the Earth Radiation Budget Experiment (ERBE)], whereas the expansive albedo corresponds to what would be measured by an albedometer at 30-km altitude.

VI. Aerosol Studies

A. Background

Aerosols are solid or liquid airborne particulates of various compositions, frequently found in stratified layers. Generally, they are defined as atmospheric particles with sizes between about 0.1 and 10 μm, though the sizes of condensation nuclei are typically about 0.01 μm. Under normal conditions, most of the atmospheric aerosol resides in the troposphere. Natural sources (e.g., dust storms, desert and soil erosion, biogenic emissions, forest and grassland fires, and sea spray) account for about 90% of this aerosol, with the rest resulting from anthropogenic activity [24]. The background tropospheric aerosol is temporally and spatially variable. The overall objectives of the MISR aerosol retrievals are described below.

1) *Characterization of Aerosol Climatic Effects:* Aerosols are thought to play a direct role in the radiation budget of earth, on regional and hemispheric length scales [29], [30]; however, their net radiative effect, i.e., whether they heat or cool the surface, depends on their optical properties and the albedo of the underlying surface. It is believed that on the global average, aerosols provide a net cooling effect. Northern hemispheric sources are thought to be sufficiently large so that the net radiative effect of anthropogenic sulfate aerosols alone is comparable in size (of order 1–2 W/m^2), though opposite in sign, to the anthropogenic CO_2 radiative forcing [31]. Aerosols may also play an indirect role in the earth's radiation balance, through their effects on clouds [32], with a radiative effect of similar magnitude. MISR global aerosol retrievals will be used to obtain aerosol optical depth and place constraints on aerosol particle types.
2) *Mapping of Aerosol Distribution:* The lifetimes of tropospheric aerosol particles are thought to range from about a week to a little over a month. These include sulfuric acid particles, which form photochemically from SO_2 [25]. Because these lifetimes are short, relative to global atmospheric mixing times, spatial-temporal patterns are often indicative of sources and sinks. For example, particles off the northwest coast of Africa and the east coast of central Asia are generally interpreted as being desert dust, those around Latin America in northern spring as forest fire particles, and those off the east coasts of Japan and North America as industrial particles [26]. However, current satellite retrievals from the Advanced Very High Resolution Radiometer (AVHRR) [27] are otherwise unable to distinguish different particle types or compositions, since they are based on measurements at a single wavelength and angle of view. Their algorithm to convert observed radiance to aerosol optical depth assumes particles of a fixed composition and size. Total Ozone Mapping Spectrometer (TOMS), ultraviolet satellite data detect aerosol presence, but the conversion to quantitative optical properties is sensitive to assumptions about aerosol altitude, and aerosols in the boundary layer (the lowest 1 km of the atmosphere) are not observable [28]. MISR's extensive coverage in both wavelength and view angle provides the means to distinguish different particle types based on their physical and optical properties. This will improve our ability to constrain the underlying sources and, to varying degrees, sinks and lifetimes, that govern their concentration in the troposphere.
3) *Atmospheric Corrections:* The goal of any atmospheric correction scheme is the accurate retrieval of surface reflectance or surface-leaving radiance from TOA radiances. It is well established that scattering and absorption by aerosols are responsible for dramatic modifications of the spectral content of remotely sensed images of the earth's surface, leading to classification errors [33], reduced accuracy of image products, such as vegetation maps [34], and a degradation in the accuracy of quantitative estimates of surface radiative properties. The retrieval of aerosol scattering properties by the MISR algorithm is an essential precursor to retrieval of surface properties using MISR data.

B. Retrieval Strategy

In order to constrain the MISR aerosol retrievals, it is advantageous to make reasonable use of what is known about the types of aerosols that are found in the troposphere. In general, tropospheric aerosols fall into a small number of compositional categories, which include sea spray, sulfate/nitrate, mineral dust, biogenic particles, and urban soot. Approximate size ranges and the proclivity of each particle type to adsorb water under increasing relative humidity are also known. Therefore, the MISR team has chosen an approach in which the physical and chemical (and therefore optical) properties of candidate aerosols are completely prescribed. The advantages of this approach, in contrast to a purely "generic" representation in terms of effective single scattering albedo, effective size distribution, and effective phase function, are that it potentially enables identification of aerosol sources and provides the means of extending aerosol properties retrieved at the MISR wavelengths to other spectral regions, which will be useful for comparisons with other sensors and for model validation. To this end, a review of published aerosol climatologies was performed (including [35]–[38] and many others). Aerosol attributes typical of natural conditions as described in these references (such as compositional and size classes) are adopted in the MISR retrievals. Based on these assumptions, the aerosol amount and specific spatial and temporal distributions are retrieved from the MISR observations.

The MISR aerosol retrieval strategy works as follows. Based on the physical and compositional properties of known

types of aerosols, forward radiative transfer calculations are performed to provide various components of the atmospheric radiation field in the 36 MISR channels. These are stored in a preestablished lookup table, and top-of-atmosphere radiative properties of mixtures of these "pure" aerosols is accomplished during the retrievals using a modified linear mixing theory [39]. The results will be compared with the MISR observations to determine those models that provide good fits to the data and to retrieve aerosol optical depth. Three retrieval pathways, one over water and two over land, are utilized. For each of these retrieval paths, optical depth constraints, such as the maximum allowable optical depth, based on the darkest radiance observed in the scene, are calculated.

Because of the reflectance uniformity of large water bodies (e.g., the ocean) and the fact that deep water bodies have negligible water-leaving radiance at red and near-infrared wavelengths, considerable progress has been made in development of algorithms to retrieve aerosol properties over dark water. Under the assumption of an aerosol model (i.e., specification of particle size distribution, particle shape, and complex refractive index), it is possible to relate observed radiance to aerosol optical depth. Such modeling has been applied to the retrieval of aerosol concentration from Landsat [40], [41] and AVHRR [27], [42]–[44]. However, these techniques can incur systematic biases, due to the inherent assumptions, such as spherical particles of "sulfate" composition, a specific Junge distribution of sizes, and a Lambertian surface of reflectivity 0.015 [45].

Substantial improvements in the retrieval of aerosol over ocean and other dark water bodies are possible with MISR. Multiangle radiances, which are governed strongly by the shape of the aerosol scattering phase functions, provide additional information with which to refine the aerosol model used in the retrieval of optical depth. For example, Kahn *et al.* [46] have shown that MISR data will be capable of distinguishing spherical from unspherical particles, and additional sensitivity studies demonstrate the ability of multiangle data to distinguish among particles with small, medium, and large modal sizes and to provide an estimate of particle absorption [47].

The retrieval of aerosol optical depth over land is less well developed than the dark water case because of the higher brightness and heterogeneity of the land surface. As a consequence, separation of the land-leaving and atmosphere-leaving signals in remotely sensed radiances must be performed to retrieve aerosol properties from the measured signal. The simplest means of determining the atmospheric contribution to the satellite signal is to make an assumption about the surface reflectivity or albedo. Locations where the surface boundary condition is believed to be reasonably well understood are areas covered by dense dark vegetation (DDV). A method based on imaging over DDV has been investigated [48] and forms the basis of the aerosol retrieval over land [49] to be used at single angles of view by the Moderate-Resolution Imaging Spectroradiometer (MODIS), also on the EOS-AM1 platform. MISR extends this approach by assuming a parametric model for the shape of the angular reflectance distribution in the blue and red spectral bands [50]. The functional form is a modification of the Rahman–Pinty–Verstraete model [51], and the absolute reflectance in the two spectral bands, along with aerosol optical depth, are treated as free parameters to be determined during the retrieval process.

Since dense vegetation is found only over a portion of the land surface, other methods are required to extend the aerosol retrieval spatial coverage. Separability of the surface-leaving and atmosphere-leaving signals over terrain with heterogeneous surface reflectance provides the foundation of the third aerosol retrieval pathway. The heterogeneous land algorithm differs from the dark water and DDV retrieval methods in that it does not use the observed radiances directly, but instead uses the presence of spatial contrasts to derive an empirical orthogonal function (EOF) representation of the angular variation of the scene reflectance, which is then used to estimate the scene path radiance (the radiance field reflected from the atmosphere without interacting with the surface) [52]. This is used in turn to determine the best-fitting aerosol models and associated optical depth by comparing the results with the precomputed values contained in the lookup table. Sensitivity studies on both the DDV and EOF methods imply that MISR data will afford unique approaches to retrieving aerosol properties over the land surface.

VII. Surface Studies

A. Background

Land surface processes are important components of the terrestrial climate system [53]. In particular, continents affect the climate system because of the following:

1) their roughness on many length scales, which affects the dissipation of atmospheric kinetic energy through friction and turbulence and modifies the planetary atmospheric flow;
2) their relatively small heat capacity, compared with that of the oceans, which induces a range of dynamic perturbations, from sea-breezes to monsoons;
3) their albedo and, to a lesser extent, emissivity, which are highly variable in space and time and which control the absorption of solar and the emission of thermal radiation, respectively, hence the bulk of the energy available in the climate system;
4) their hosting of most of the biosphere (over 99% by mass), which exerts significant controls on the exchange of heat, moisture, and chemical compounds within the climate system.

Over oceans, roughly the same amount of photosynthesis as is performed by land vegetation occurs as a result of marine phytoplankton, which are the basic link in the ocean food chain. The overall scientific objectives of the MISR surface retrievals are described below.

1) *Surface Radiative Fluxes:* The bulk of the solar energy provided to the troposphere is absorbed at the lower boundary (oceans and continents) and then reemitted to the atmosphere through the fluxes of sensible and latent heat as well as in the form of thermal radiation. Accurate descriptions of the interactions between the surface and the atmosphere require reliable quantitative information

on the fluxes of energy (all forms), mass (including water and CO_2), and momentum, especially over terrestrial areas, where they are closely associated with the rates of evapotranspiration and photosynthesis. Many of these processes and interactions directly affect the reflectance of the surface [54]–[56]. Reflectance measurements, which can be acquired by remote sensing, are therefore particularly useful to describe and predict these surface-atmosphere interactions. Clearly, the usefulness of such measurements is not limited to vegetated areas, as all significant modifications of surface properties, whether due to natural or human-induced causes, tend to affect this property. It is well known that natural surfaces do not behave as Lambertian scatterers but exhibit anisotropic reflectance properties that depend on the characteristics of the surface. Integration of the retrieved directional reflectances over the whole hemisphere of viewing angles defines the hemispherical reflectance (spectral albedo) of the surface.

2) *Land Surface Classification:* The evolution of terrestrial ecosystems is difficult to monitor at the surface, and satellite platforms provide a unique opportunity to carry out extensive surveys with comprehensive spatial coverage and high time resolution. Detection of ecophysiological change on the land surface, resulting from natural processes (canopy succession and species replacement) or anthropogenic activities (e.g., deforestation, acid rain), necessitates accurate, repeatable measurements of the surface that can be used for landscape classification. Hall *et al.* [57] showed how time series of satellite data could be used to monitor ecosystem dynamics over large areas, a task that was not feasible prior to the advent of satellite remote sensing. Although spectral data provide some information on the physiological state of vegetation, inference of the structural properties of the 3-D vegetation stand is also required, and it is difficult to determine canopy architecture and states [e.g., biomass, leaf area index (LAI)] from a single view angle [58], [59]. Multiangle information enables the use of physically based models to infer canopy structure [60].
3) *Biological Productivity:* The productivity of land vegetation is related, among other factors, to the amount of incident photosynthetically active radiation (400–700 nm) absorbed by the photosynthesizing tissue in a canopy, parameterized by the ratio of absorbed-to-incident radiation, FPAR. An accurate specification of FPAR is a crucial factor in the estimation of large-scale productivity and carbon budget models [61]–[63]. Over oceans, the concentration of chlorophyll a and its degradation products (known as phaeopigments) provide an estimate of the rate of biological productivity in the marine environment. The primary instrument for assessing ocean productivity on EOS-AM1 is MODIS. When the satellite passes over the solar equator, some imagery is lost due to sun glint. Because MISR acquires images continuously at several angles, has good SNR at low signal levels, and provides high accuracy aerosol retrievals, ocean color data uncontaminated by sun glitter will be obtained in this region.

B. Retrieval Strategy

Before surface retrievals can be performed within a given region, atmospheric parameters need to be determined by means of an aerosol retrieval. Then, over land, the following sequence of surface retrieval activity is performed on all suitable 1.1-km samples within a region [64]. First, the hemispherical-directional reflectance factors (HDRF's) for all available camera views and the bihemispherical reflectances (BHR's) are determined for the four MISR spectral channels. The HDRF's and BHR's are surface reflectance properties for illumination conditions of the ambient atmosphere (i.e., direct and diffuse sunlight) and are retrieved with a minimum number of assumptions. The HDRF, because it is defined for the actual illumination conditions, is useful for climate modeling and for comparison with field measurements. Using the HDRF's as a starting point, the corresponding BRF's and the DHR's are determined. These quantities are defined for illumination by direct sunlight only and, thus, are more useful for the purpose of determining the physical state of the surface from angular shape information. Their retrieval requires assumption of a model describing the bidirectional reflectance properties of the surface because it is necessary to correct for the diffuse skylight illumination. We use a modified form of an empirically derived, parametric formulation to carry this out [51].

From the spectral BHR's and DHR's the photosynthetically active radiation (PAR)-integrated BHR and DHR are obtained. The PAR band covers the 400–700-nm wavelength range, allowing three of the four MISR channels to be used in the integration. The PAR-integrated BHR and DHR are a measure of the amount of PAR absorbed by the surface (vegetative and nonvegetative) under ambient and direct illumination conditions. Then, a Normalized Difference Vegetation Index (NDVI) derived from red and near-infrared DHR's will be used to distinguish vegetated from nonvegetated terrain. These NDVI values do not depend on view angle and have been corrected for atmospheric effects. Over vegetated land, the green LAI is estimated from a comparison of the retrieved spectral BHR's and DHR's with a lookup table containing results of detailed radiative transfer modeling of the plant canopy biome types. Six biome types are considered: grasses and cereal crops, shrublands, broadleaf crops, savanna, broadleaf forests, and needle forests. All canopy models that pass this comparison test are then put through another discriminator by comparing their directional reflectances to the retrieved BRF's. This process provides a land surface classifier along with an associated LAI. FPAR, the fractional amount of incident PAR absorbed by vegetation canopies only (and not the understory) is then estimated.

Correction for atmospheric scattering over oceans is essential for studies of ocean color because the low reflectance of the ocean surface (away from sun glitter) results in the signal being dominated by Rayleigh and aerosol backscatter. Gordon *et al.* [65] have developed operational atmospheric correction

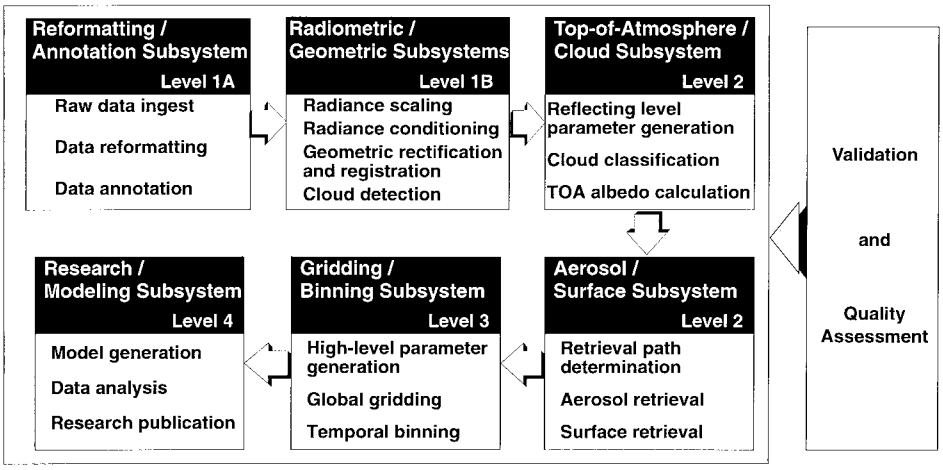

Fig. 4. Conceptual flow of MISR data through the product generation system.

algorithms for use with Coastal Zone Color Scanner (CZCS) imagery. The multiangle coverage of MISR enables further refinement of the aerosol model and the application of rigorous surface retrieval algorithms [64]. The ocean surface retrieval process is performed only for the tropical ocean, which for our purpose is limited to a 600-km wide band centered on the geographic equator. Phytoplankton pigment concentration is estimated at a spatial resolution of 1.1 km, using the retrieved water-leaving radiances in the MISR blue and green bands as inputs to the CZCS bio-optical pigment algorithm. With the MISR spectral band set, chlorophyll pigment concentration is estimated by forming the ratio of the equivalent reflectances in the blue (446 nm) and green (558 nm) bands. Since MISR does not include bands between 446 and 558 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.

VIII. Ground Data System

A. MISR Science Data Processing

The MISR Science Computing Facility (SCF) at JPL and the Distributed Active Archive Center (DAAC) at NASA Langley Research Center, Hampton, VA, represent the primary entities in which the functions of MISR science data processing will be implemented. The DAAC, which is shared with several other EOS instruments, is the facility at which software incorporating MISR science algorithms will operate in a high-volume, real-time mode to produce standard science data products. The generation of science data products can be divided into six subsystems within the product generation system. Each subsystem has at least one primary output product, but may have other secondary output products. It is convenient to conceptualize the processes within these subsystems as occurring in sequence, with the predecessor producing at least one complete product, a portion of which is the primary input for the successor. Each of these subsystems correspond to a processing level of a product generation flow, as shown in Fig. 4. These levels conform generally to the EOS scheme from Level 1 to Level 4. Standard products cannot be generated at the DAAC independently of the rest of the MISR science data system. They are critically dependent on calibration parameters and other lookup data, such as threshold data sets, atmospheric climatologies, aerosol and surface model data sets and the like, which are produced at the SCF. Updates to these data structures occur infrequently compared to the rate of standard product generation and, therefore, fit into the more limited processing capabilities of the SCF. Other essential functions that have activities at the SCF include quality assessment, algorithm and data product validation, software development, and instrument operations.

IX. Conclusions

Some of the ways in which the multiangle viewing strategy of MISR provides unique information about clouds, aerosols, and surfaces are summarized below.

1) *3-D Structure Characterization:* The angular scattering "signature" of complex scenes, such as cloud fields and vegetation canopies, is expected to be diagnostic of their 3-D geometry. The high resolution of the MISR data (275 m–1.1 km) facilitates the classification of unique scene types.
2) *Stereoscopic Height and Wind Retrieval:* The nadir and several of the off-nadir cameras will be used stereophotogrammetrically to estimate cloud-top or plume-top altitudes for the purposes of regional scene classification and for coregistering the multiangle views to a common reference level. Unlike single camera-pair stereo, multicamera disparity measurements obtained at both small and large base-to-height ratios from satellite altitudes enable compensation for the effects of motion due to wind.
3) *Aerosol Composition Identification:* The nine cameras provide coverage in scattering angle, which is the angle between the direction of the sun's rays and the direction to the sensor. The phase function, which is dependent on scattering angle, differs among aerosols of varying compositions and sizes.
4) *Aerosol Optical Depth Retrieval:* The compositional information provided by the scattering phase functions,

coupled with the fact that the oblique MISR viewing angles accentuate the aerosol signal because of the increased optical path length through the atmosphere, enable new methodologies for retrieving aerosol optical depth over land and ocean.

5) *Cirrus Detection and Characterization:* The oblique viewing angles of the cameras at high off-nadir angles, particularly the C and D cameras, accentuate the signal of high thin clouds (cirrus) because of the increased optical path length through the atmosphere. This forms the basis for a novel technique to detect cirrus. The single-scattering phase function of cirrus is not well known, and MISR data will provide new information on cirrus reflective properties.
6) *Scene-Dependent Albedo Determination:* The high spatial resolution, multiangle observations provide a novel methodology for determining the hemispherical albedo at the top-of-atmosphere and surface.
7) *Surface Classification:* The NDVI retrieved from MISR data is independent of view angle and atmospheric conditions and will be used to distinguish vegetated from nonvegetated land. Spectral hemispherical reflectances and BRF's will be used to establish the land biome type. Accurate multiangle aerosol and surface retrievals over ocean will provide assessments of biological productivity in tropical marine environments.

For further information about the MISR experiment, the reader is invited to peruse our World Wide Web site at http://www-misr.jpl.nasa.gov.

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