Jet Propulsion Laboratory
California Institute of Technology

MISR Multi-angle Imaging Spectro-Radiometer

March 3, 1998

MISR-SDFM#181

TO: Dave Diner
FROM: Bill Ledeboer
CC: Wedad Abdou, Carol Bruegge, Jim Conel, Ralph Kahn, John Martonchik
LOCATION: /data/validation/doc/memo/sdfm181_AlgorithmAccuracy.fm
SUBJECT: MISR Product Accuracy Document

This memo contains inputs supplied by Wedad Abdou, Carol Bruegge, Jim Conel and Ralph Kahn in response to Yoram Kaufman's e-mail regarding "documentation of accuracy of the algorithms" dated February 7. In keeping with Yoram's instructions and the limited time available to prepare this material, this document contains a first draft, in Yoram's suggested format, of a document describing the accuracy of a few of the MISR products.

Portions of the following products are described:

1. Level 2 Aerosol Product (Kahn)
2. Level 1B1 Radiometric Product (Bruegge)
3. Validation Aerosol Product (Conel)
4. Validation Surface Product (Conel, Abdou)

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PRODUCT NAME: Level 2 Aerosol Product PRODUCT NUMBER: MIS 05

Coverage: Global
Spatial/Temporal Characteristics: 9-day global coverage; 17.6 km resolution
Science team contacts:

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SHORT DESCRIPTION:

The MISR Aerosol Product will contain retrievals of aerosol optical depth, and best-fitting aerosol type(s), over deep water, dense dark vegetation, and heterogeneous land. For all retrievals, we simulate MISR radiances for climatologically common mixes of aerosol types, and derive the optical depth and constraints on particle type based on best fits to these simulations. Fitting criteria between the simulations and the measurements are based on the statistical chi-squared formalism, which takes instrument calibration uncertainty into account. (For further details, see: Martonchik et al., 1998).

Optimal conditions for derivation from the EOS data:
Dark water; Dense dark vegetated surfaces; and Heterogeneous land; all cloud-free

Non-optimal conditions:
Very low latitudes, where the range of scattering angles seen by MISR is limited.

Other caveats:
For retrievals, we assume aerosols are uniform in optical depth and physical properties over a 17.6 km region at the surface, growing to ~ 100 km along-track at the tropopause. Over deep water, we assume the surface is black at red and near-ir wavelengths (672 nm and 866 nm), except for sun glint and whitecaps. Over dense dark vegetation, we assume a uniform surface albedo (the value of which is retrieved) and a shape for the BRDF (which is not retrieved). No MISR aerosol retrievals are performed: When detectable cloud or fog is present; Over low-contrast bright surfaces; For sun-glint contaminated regions; Over topographically complex or cloud-shadowed regions; (For details, see: Martonchik et al., 1998).

PHYSICAL QUANTITY:

Aerosol Optical Depth at 557 nm and Particle Type over Deep Water

Theoretical accuracy:
Using theoretical simulations, we have assessed the sensitivity of the algorithm to characteristics of pure particles having a wide range of sizes, shapes, and compositions, over deep water. As best we can tell prior to launch, we can retrieve column optical depth from measurements over calm ocean, for all but the darkest particles, with typical size distributions and compositions, to an accuracy of at least 0.05 or 10%, whichever is larger, even if the particle properties are poorly known. MISR should be able to distinguish spherical from non-spherical particles, to separate two to four compositional groups according to indices of refraction, and to identify three to four dis-

tinct size groups between 0.1 and 2.0 microns characteristic radius at most latitudes. (see: Kahn et al., 1997; 1998).

Pre-launch verification:

We hope to acquire data from the AirMISR instrument to test the accuracy of the algorithm over ocean, either pre-launch, or in the early post-launch timeframe.

Post-launch verification:

The MISR Science Data Validation Plan (Conel et al., 1996) describes a series of field experiments, including instrumentation, data analysis, and scheduling. The list of sites includes Monterey Bay, where aerosol spectral optical depth, particle size, surface BRDF and other quantities will be measured over deep water, both from the ground, and from AirMISR. Estimates of particle heterogeneity over a 17.6 km MISR sampling site will be made using multiple surface instruments during the field experiment.

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3. Kahn, R., P. Banerjee, D. McDonald, and D. Diner, "Sensitivity of Multiangle imaging to Aerosol Optical Depth, and to Pure-Particle Size Distribution and Composition Over Ocean ", J. Geophys. Res., submitted, 1998.

4. Martonchik, J.V., D.J. Diner, R. Kahn, M.M. Verstraete, B. Pinty, H.R. Gordon, and T.P. Ackerman, Techniques for the Retrieval of aerosol properties over land ocean using multiangle data, IEEE Trans. Geosci. Remt. Sensing, in press, 1998.

Coverage: Global

Spatial/Temporal Characteristics: 9-day global coverage; same spatial resolution as that transmitted by the camera (275 m to 1.1 m depending on commanded on-board pixel averaging mode)

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SHORT DESCRIPTION

The MISR Radiometric Product is derived by scaling the Level 1A Product digital number (DN) values to derive incident radiances in units of W m^{-2} sr^{-1} μm^{-1}. These radiances are band-weighted by a spectral response function unique for each of the four MISR spectral response bands. In addition, image sharpening is conducted on each scene. This makes use of measured point-spread function response (PSF) values in a one-dimensional maximum likelihood deconvolution algorithm. This PSF deconvolution process eliminates the effects of MISR filter-to-detector scatter that otherwise would blur targets which are of small spatial extend and surrounded by a contrasting background.

Optimal conditions for derivation from the EOS data:

Equivalent top-of-atmosphere reflectances should be greater than 3% for optimum accuracy.

Non-optimal conditions:

Data quality flags will report when conditions are less than optimal. These conditions include having one or more saturated pixels within a given channel, or having a small dark target surrounded by a very bright extensive background.

Other caveats:

Saturation levels are dependent on view-angle within a given channel. At the edge-of-field the saturation levels can be as large as 1.5 in equivalent reflectance. On-axis views range from 1.0 to 1.2, depending on camera and band. Details are described in Ref. 6 (Bruegge, et. al.; 1998).

PHYSICAL QUANTITY:

Band-weighted Spectral Radiances [W m^{-2} sr^{-1} μm^{-1}]

Theoretical accuracy:

The MISR radiometric calibration requirements includes a specification of ±3% (at 1σ confidence level) absolute uncertainty in the radiance product, at full-scale illumination. Other requirements are listed in the table below.

MISR radiometric calibration requirements

Feature	Specification
Absolute	±3% at ρ_{eq}=100%; ±6% at ρ_{eq}=5%
Relative at ρ_{eq}=100%	±0.5% pixel-pixel (within channel) ; ±1% band-band and camera-camera
Stability at ρ_{eq}=100%	0.5% during a month short-term; 2% per year long-term
SNR (unaveraged pixels)	700 at ρ_{eq}=100%; 100 at ρ_{eq}=2%
Polarization sensitivity	Radiometric error <±1% with respect to unpolarized input

Pre-launch verification:

During radiometric calibration the relationship between an incident radiance field and camera digital output is established. The illumination is achieved using an “ideal” target that emits or reflects unpolarized light, is spatially and angularly uniform, and lacks spectral features such as absorption lines. For preflight calibration, MISR made use of a large integrating sphere to provide this source. Through regression of the sphere exitance against the camera output the radiometric gain coefficients are determined, and the instrument is thereby radiometrically calibrated.

The sphere output is placed on a radiometric scale by measurements made with detector standards. (MISR is unique among the EOS-AM instruments, in that the radiometric scale is determined preflight and on-orbit using detector standards.) In order to achieve the highest radiometric accuracy, two types of laboratory detector standards are used (Ref 6. Bruegge, et. al.; 1998). A QED-200 (made of United Detector Technology inversion layer diodes) is used to measure sphere output for the blue and green MISR spectral bands, Bands 1 and 2; and a QED-150 (made of Hamamatsu p-on-n photodiodes) is used for the red and near-infrared channels, Bands 3 and 4. Each detector is nearly 100% in internal quantum efficiency, for the wavelength regions at which they are operated. Each is made of three silicon photodiodes, mounted in a light-trap configuration so as to collect the light reflected at each air/ detector interface. These standards are used with filters of the same spectral bandpass design as the flight cameras, and with a known field-of-view, established by use of a precision aperture tube. Traceability to Système International (SI) units is established through the measurement protocols of current, apertures, and aperture distances. JPL maintains working standards of voltage, resistance, and length which are traceable to the National Institute of Standards and Technology (NIST) or other international standards that are recognized by NIST. The filter transmittance for the standards are measured by a dual-beam spectrometer, also requiring certification. The quantum efficiency and reflectance losses of the standards are assumed to be unity and zero respectively, per design of the trap devices.

Planning for the calibration and characterization of the instrument evolved in parallel with the instrument design itself. Peer support was provided through semi-annual meetings of the EOS calibration working group, consisting of representatives from the instrument development teams, universities, and the national standards laboratory. Peer reviews of each of the proposed instrument test programs were held. Equally important were the round-robin experiments. One experiment of this nature involved transporting several travelling radiometer standards, maintained by a variety of institutions, to the JPL calibration laboratory (Ref, 7, Bruegge, et. al.; 1993). These were used along side the MISR standards, to cross-compare the measured output of the integrating sphere. In this way the radiometric scale defined for MISR was verified. A second round-robin experiment circulated diffuse-reflectance targets among EOS-affiliated institutions. These were measured for bi-directional reflectance factor (BRF), and a comparison of results was made (Ref. 11, Johnson, et. al.; 1998). Validation of these measurements is important, in that they are used for the on-orbit calibration of MISR using both the On-Board Calibrator and vicarious calibration (Ref. 12, Thome, et. al.; 1998) methodologies.

Post-launch verification:

MISR’s radiometric response is to be updated post-launch using multiple methodologies. It is believed that systematic errors are thereby reduced. An on-board calibrator makes use of deployable Spectralon diffuse-reference panels. These are solar-illuminated at the North and South Poles. On-board detector standards have ben custom built, in-order to minimize the size of the photodiodes (Ref. 4, Bruegge, et. al.; 1993). Monthly calibration exercises will reestablish the radiometric response.

In addition, results of vicarious calibration experiments will be folded into the response analysis. These experiments will involve characterizing a uniform surface for both reflectance and atmospheric properties. Radiances are then predicted using a radiative-transfer code, and ratioed to coincident DN readings from the MISR on-orbit instrument.

Another radiance-based vicarious calibration techniques will make use of AirMISR (Ref. 10, Diner, et. al., 1998) underflights to provide a transfer calibration.

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13. R.M. Woodhouse, C.J. Bruegge, B.J. Gaitley, G. Saghri, and N. Chrien, "Multi-angle Imaging SpectroRadiometer (MISR) Ancillary Radiometric Product (ARP)," Earth Observing System II, Proc. SPIE **3117**, San Diego, July 1997.

Coverage: Local
Spatial/Temporal Characteristics: ~20 km; daily measurements at network sites, seasonal measurements at selected field campaign sites
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SHORT DESCRIPTION:

This discussion provides estimates of accuracy of ground-based retrieval of total optical depth using solar radiometers for validation of both MISR products and retrieval algorithms in both pre and post-launch time frames. Subsequently this discussion will be expanded to include errors for other column equivalent parameters derived from local observations, including aerosol optical depth, ozone optical depth, particle size distribution, aerosol complex refractive index, phase function and single scattering albedo.

Total average and instantaneous spectral optical depths (10 channels, 380- 1030 nm, $\delta\lambda \approx$ 10 nm) are derived by the Langley method. The principal source of uncertainty in retrieval is instrument calibration, i.e., determination of the so-called zero airmass radiometer response V_0, discussed below. Aerosol component is subsequently obtained by adjustments for Rayleigh scattering (pressure measurement), NO_2 absorption (neglected or use of standard value), ozone absorption., and possibly water vapor absorption in some circumstances. In retrieval process, algorithm of Flittner et al (1993) is used for simultaneous retrieval of aerosol and ozone optical depths from residual (total - Rayleigh) optical depth. The Flittner algorithm makes no assumption about aerosol optical depth variation with wavelength and takes a standard absorption wavelength profile in ozone Chappuis band from MODTRAN III data base. A smoothness constraint is implemented in the form of minimizing the second derivative on aerosol optical depth variation with wavelength. Flittner algorithm is expected to improves in performance compared to other retrieval schemes based on Junge distribution wherever the actual or simulated distributions depart from a simple Junge model in the 400-1000 nm region.

Other Caveats:

Ground-based observations usually neglect diffuse component present in solar aureole in angular field of view of radiometers, but which in some circumstances (for example thick smoke, clouds) may contribute heavily to or dominate observed irradiance. Magnitude and influence of the diffuse component is discussed by Shaw (1976) who gives a maximum relative error in optical depth determination of 0.025 for moderate turbidity and airmasses less than about 6. Optimal conditions for comparison with MISR EOS data include clear (cloud free) skies that are so describable for the period of a MISR observation (e.g., about 7 minutes per site). Sampling for strict comparison is equal to line of sight path to sun at any given time. Inferences to larger areas are obtained by averages of network observations (where available) or averages obtained from time series at single stations, where the sampling time t of fluctuations present is great enough to cover a distance X = U t where U is a measure of the average horizontal wind speed, and X is ~ 17 km.

PHYSICAL QUANTITY:

Total Optical Depth

Theoretical Accuracy:

Resolution of digital recording of ground-based radiometer response (Reagan automated instruments) is 1 part in 2^{16} (~1/66000), with actual instrument noise from photodiode and opt-amp sources about one-eighth of this (Ehsani, 1992). From error propagation, with this level of uncertainty in radiometer output, the standard error of determination of V_0 is $O(10^{-5}\text{-}10^{-6})$ and the standard error of optical depth determination is of $O(10^{-6})$.

In practice the limit on instrument calibration is best established by multiple local determination of V_0 on clear stable days and/or at high altitude observing sites. Studies of this problem (Bruegge, *et al.*, 1994) indicate relative determinations of V_O to a few percent, and total optical depth retrievals to 0.02. Recently, Erxleben and Reagan (1997) have applied wavelet filtering techniques to improve V_0 determinations for Reagan solar radiometers. These indicate reductions in uncertainty of *V0* to *O*(1%) or less, leading to optical depth determinations of this order of uncertainty.

Pre-launch verification:

Field campaigns consisting of simultaneous aircraft overflights (with ASAS) and ground-based observations have been carried out at BOREAS (northern mid-continent) 1994 and 1996, SCAR C (biomass smoke) 1994, Monterey Bay (marine aerosol) 1995. ASAS sensor calibration 1995

Post-launch verification:

(no observations yet)

REFERENCES:

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PRODUCT NAME: MISR Validation Surface Product PRODUCT NUMBER: N/A

Coverage: Local
Spatial/Temporal Characteristics: Sampling at MISR pixel resolution (250 m in Local Mode) of selected field campaign sites
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SHORT DESCRIPTION:

A preliminary estimate of accuracy of ground-based retrieval of the bidirectional reflectance function (BRF) from directional sky and ground radiance measurements is given here. Observations are assumed available with the Portable Apparatus for Rapid Acquisition of Bidirectional Observation of the Land and Atmosphere (PARABOLA, Model III). This instrument is used as basis for validation of MISR algorithms and products, e.g., surface bidirectional reflectance factor (BRF) and other closely-related parameters that can be derived from it (*e.g.*, hemispherical directional reflectance factor, HDRF, bihemispherical reflectance, BHR, etc.). See MISR ATBD JPL Document 11401. The three principal error sources for retrieval of BRF from ground-based observations are: (1) instrument noise, (2) errors in total optical depth retrieval constraining the direct solar spectral irradiance incident at the surface, (3) algorithm errors.

The BRF describes reflectance of light at the surface into the upward hemisphere given that the incident radiation consists only of a beam that is perfectly collimated. In nature the reflected radiance in any upward direction consists of: (1) direct solar radiation reflected at the surface into the direction of observation, (2) diffuse skylight diffusely reflected into the direction of observation. Extraction of the BRF from the surface-reflected radiance under natural conditions requires observations of the direct solar and diffuse sky radiances over the upward hemisphere and the surface reflected radiance at all angles of view from the surface, both as functions of solar zenith angle. PARABOLA provides the required observations of incident and reflected radiance over upward and downward hemispheres respectively.

The retrieval process has been described by Martonchik (1994). The surface reflectance boundary condition is written as a two-dimensional Fredholm integral equation of the second kind. The dependent variable corresponds to the surface-reflected radiance, the inhomogeneous term to the reflected direct radiance and the integral term to the diffuse sky radiance contribution. The method of solution for BRF factor is iterative, assuming as a first approximation that the diffuse light term is zero. The first approximation solution for the BRF thus obtained is used to form a second approximation by including the diffuse light reflected term and the first approximation BRF. The BRF is updated and the iteration continued until differences between calculated and measured surface-leaving radiance distributions fall below one percent. Improvements in the accuracy of retrieval of the BRF in this fashion did not depend upon choice of 0.5% as opposed to one percent for the convergence criterion.

Other caveats:

(1) Spatially inhomogeneous surface reflectance. Natural targets are inhomogeneous, and the resulting variations in reflectance properties at the scale of PARABOLA observations must be averaged spatially, either by occupying multiple sites, or by binning pixels from any one site. This problem is under study. (2) Scaling to larger areas. The typical PARABOLA footprint for an instrument height of two meters and 80 degree view angle from the horizontal, is 22 meters in diameter. The scaling to 1.1 km must involve AirMISR, whose nadir pixel size is 7 m and footprint size~9 km. (3) The simulation of algorithm error sources described below assumes a homogeneous target. ((4) Possible uncertainties in the solar irradiance are not considered. (5) As with Reagan solar radiometers PARABOLA instrumental noise is considered negligible compared to other sources. (6) errors in total optical depth retrieval we believe can be constrained to $O(1\%)$ by application of noise filter techniques to our solar radiometer observations.

PHYSICAL QUANTITY:

Bidirectional reflectance factor (BRF)

Theoretical accuracy:

(1) A principal error source in determination of BRF is described as algorithm error. Simulations were performed using the three-parameter BRF model of Rahman-Pinty-Verstraete (RPV, 1993) according to the iterative retrieval scheme described above. To estimate algorithmic error, the data and optical depth for these simulations are considered perfectly measured. (a) Algorithm errors: Generally the errors in retrieved BRF are very large when either the sun incidence or view angles are greater than 80°. For angles at 75° the error is 3% and falls to less than 1% for sun angles less than 75° (b) Round-off numerical errors: no impact. (c) Total optical depth errors: Optical depth errors of 10% lead to increases in retrieval error by factor of five. Methods to limit errors in absolute optical depth retrieved values are described under MISR ground-based algorithms Practical uncertainties. Further study of sky turbidity, view angle dependencies for PARABOLA-based BRF retrievals are under way.

(2) Radiometric calibration errors. The dynamic range of PARABOLA measurements is 10^{20}. The lower part of the range is calibrated by measurements with an integrating sphere. The standard errors of least squares fits of such observations are wavelength dependent. For example at 550 nm these errors imply an uncertainty of $O(1\%)$ in the radiance recovery. Neglect of diffuse light altogether in the error tally leads to an error in BRF determination proportional to the radiance error. Where the diffuse light component itself is, say, 10% of the illumination, this gives a systematic overestimate of the BRF by about 10%. Calibration of PARABOLA III in the direct solar irradiance range has yet to be carried out.

Pre-launch verification:

Field campaigns consisting of simultaneous aircraft overflights (with ASAS) and ground-based observations have been carried out at BOREAS (dense dark vegetation canopies of conifer and aspen), 1994 and 1996. ASAS sensor calibration at Ivanpah Playa, CA, 1995.

Post-launch verification:

(no observations yet)

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