CALIBRATION AND CHARACTERIZATION OF MODIS IMAGERS ON 15-YEAR EOS MISSION

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ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) instruments for National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS) satellites for the international MPE (Mission-to-Planet-Earth) program will provide 36 spectral images of the Earth every two days for fifteen years. These data will be acquired starting in 1998 from Sun-synchronous polar orbits. Land-related data products include: surface reflectance, spectral albedo, emissivity, snow cover, surface temperature, land cover type, vegetation/soil indices, evapotranspiration, net primary productivity and photosynthesis and respiration. These products will be input for regional and global models of climate, hydrology and biogeochemistry.

The MODIS instruments are being built by SBRC (Santa Barbara Research Center). On-board calibrators include the Spectral Radiometric Calibration Assembly (SRCA), a solar diffuser and associated solar diffuser stability monitor, a black body and a view of space. The required redundant approaches to calibration represent the most significant commitment to calibration in an Earth Science satellite instrument to date. In addition, the MODIS calibration and characterization efforts will include scene-derived characterizations, passive and direct lunar observations, nighttime imagery and scene-dependent radiometric and spatial inversion algorithms. Vicarious field observations for instrument verification and calibration, as well as product validation, are designed to assure the success of the MPE global change program.

The primary function of the MODIS calibration algorithm is to convert uncalibrated raw (Level-0) data into spectrally, geometrically and radiometrically calibrated and characterized geolocated (Level-1) data. The Level-1 calibration product is designed to characterize, and potentially reduce, any systematic errors by taking advantage of the inherently high 12-bit sensitivity, precision, accuracy and stability of the MODIS instruments.

MODIS INSTRUMENTS ON EOS PLATFORMS

MODIS (Moderate Resolution Imaging Spectroradiometer) instruments for NASA's EOS (Earth Observing System) satellites for the international Mission-to-Planet-Earth (MPE) are designed to provide the scientific community and the public with 36 different spectral images of the whole Earth every two days for a period of fifteen years. This objective is to be reached by launching an EOS-AM platform, as well as an EOS-PM platform, with both being replaced in orbit every five years. The first, EOS-AM1, is scheduled for launch in 1998; EOS-PM1 is scheduled for launch in 2000.

Each EOS-AM and EOS-PM platform will have a MODIS instrument on it. Some of the scientifically significant MODIS instrument requirements are listed in Table 1. Most of these requirements are from the NASA/GSFC (Goddard Space Flight Center) MODIS specification (Weber, 1992). Some are derived or platform requirements. The geometric, spectral and radiometric requirements for MODIS were developed by scientists largely from the heritage of previous satellite missions (Barnes, 1986; Salomonson et al., 1989; King, 1991; and Salomonson and Barker, 1992). These previous missions included the following sensors and satellites (Manual of Remote Sensing, 1983):

6-band/1 Km CZCS (Coastal Zone Color Scanner) on Nimbus-7,

4-band/80m MSS (Multispectral Scanner) on Landsat-1/2/3/4/5 (1972-present), 7-band/30m-120m TM (Thematic Mapper) on Landsat-4/5 (1982-present),

5-band/1 Km AVHRR (Advanced Very High Resolution Radiometer) on NOAA-1-11 (1978-present), and

20-band/~15Km HIRS (High Resolution Infrared Sounder) on Nimbus 6 and NOAA-7.

Some of the scientific reasons for the exact spectral locations from 0.41 to 14.4 µm of the thirty six 250-1000m bands on the MODIS instruments are given in Table 2a (Reflective Solar Bands 1-19 & 26) and in Table 2b (Emissive Thermal Bands 20-25 & 27-36). Table 3a and Table 3b provide additional information on dynamic range and performance specifications. The development of the spectral requirements for these MODIS bands has included considerations such as the avoidance of Fraunhofer lines in the solar irradiance spectrum, avoidance of atmospheric absorption lines and inclusion of key features in target spectra (Barker et al., 1993).

The sensor requirements were chosen for observing at-satellite radiances, cloud properties, atmospheric constituents, surface-leaving radiances and surface reflectance for inferring the type and state of various surfaces, and temperatures of the cloud, land and ocean surfaces. These requirements have been factored into the choice of the ground instantaneous field-of-view (GIFOV), spectral tolerances on center wavelength and band width, unsaturated radiometric dynamic range and the signal-to-noise ratios that led to the derived 12-bit radiometric sensitivity for MODIS bands. The scientific requirement for monitoring anthropogenic and natural environmental change on a global scale with optical instruments led to the requirement for nearly daily coverage, which requires an along-scan ground field-of-view (GFOV) swath of 2300 Km for platforms in Sun-synchronous orbit.

The actual design of MODIS was derived from NASA's functional requirements by the MODIS contractor, Hughes Santa Barbara Research Center (SBRC). The layout of the detectors on the four focal planes is shown in Figure 1.

MODIS CALIBRATION AND DATA PRE-PROCESSING

The experience of Earth Scientists assembling multi-year data sets of satellite imagery for change detection, e. g. using AVHRR imagery to produce NDVI (Normalized Difference Vegetation Index) maps from even a single instrument, has led to the placing of a high requirement on the MODIS instruments being well calibrated and characterized over their entire operational lifetimes. Glint-free global coverage of the oceans has required that the non-tilting MODIS instruments be on both the AM and PM platforms. Therefore, imagery from the sensors on these two platforms must be mergible into a single calibrated data set on a daily basis. In addition, the imagery collected from all six MODIS instruments in the EOS/MPE mission must be mergible into a single 15-year data set. Finally, MODIS data must be sufficiently well calibrated and characterized to be comparable to other EOS and non-EOS instruments in order to realize synergistic benefits of simultaneous observations and to extend the historical record for modeling long term global change.

Given the importance and difficulty of the calibration task, the MODIS Science Team has assumed that there will be multiple approaches, some of them discipline specific, to accomplish the required level of precision, accuracy and verification of the characterization and calibration, including both sensor-dependent and sensor-independent methodologies. The MODIS Science Team Leader, Vince Salomonson, has set up a separate organizational entity at Goddard Space Flight Center (GSFC), namely the MODIS Characterization Support Team (MCST), headed by John Barker. MCST has been assigned the primary responsibility for collecting input from these various sources, including the instrument vendor, SBRC, and for integrating the approaches where appropriate. In particular, MCST is to provide a single official Level-1 calibration/characterization algorithm. The calibration algorithm developed by MCST, and the changes made to it over time, are peer reviewed by the MODIS Calibration Review Team chaired by Phil Slater (U. AZ), who is also a member of the MODIS Science Team, with final approval coming from the Science Team and the Team Leader. The geolocation and spatial resampling algorithms will be developed by the MODIS Science Data Support Team (SDST) at GSFC with input from MCST. SDST is headed by Ed Masuoka, with consulting from Al Fleig (U. MD). These geolocation and resampling algorithms are subject to review by MCST and the MODIS Science Team. SDST receives the calibration algorithm from MCST and integrates it with the MODIS product algorithms provided by the Team Members. SDST then provides the integrated software to the GSFC Distributed Active Archive Center (DAAC) at the ECS/ESDIS (EOS Core System of the Earth Science Data and Information System) ground processing facility. It is anticipated that there will be the potential for value-added characterization and calibration as a result of on-orbit observations, in addition to the hardware related calibration algorithms supplied by the vendor. As each of these algorithms and characterizations are developed, MCST intends to produce and maintain through the GSFC/DAAC/DADS an electronically accessible "MODIS Science Calibration Handbook" containing and/or referencing the information the working scientist needs to know about the instrument in order to use MODIS imagery.

The primary function of the calibration algorithm is to convert uncalibrated (Level-0) data into spatially unresampled but radiometrically calibrated (Level-1) data. An illustrative flow diagram for generation of this MODIS Level-1 Calibration and Characterization Product output is shown in Figure 2. EDOS (Earth Data Operations System) transmits the raw Level-0 imagery and accompanying ancillary data from the satellite as relayed to the White Sands, NM receiving station, and then to the West Virginia EDOS Relay/Packaging Station, and finally to the ECS. ECS provides these data to the GSFC/DAAC PGS (Product Generation System) for the production of the Level-1A uncalibrated MODIS imagery and the Level-1B calibrated imagery. The MCST-developed output of the standard Level-1 production process includes browse products/algorithms, and metadata files such as quality assessment products, modeled performance characteristics as a function of time, and calibration site imagery for the GSFC/DAAC DADS (Data Archive and Distribution System) databases. The Level-1 output can be used directly for production of MODIS products or be called up for access by scientists and other users at a later time through the DAAC IMC (Information Management Center). The ECS ICC/EOC (Instrument Control Center of the EOS Operations Center) also receives all the Level-1 output data for comparison with its summary of the condition of the MODIS detector channels based on analysis of all the raw Level-0 input. Error and quality assessment (QA) information on the characterization and calibration is generated automatically by the PGS from MCST-supplied algorithms; additional QA information may be appended through human intervention to the metadata files at a later time from PGS, ICC/EOC or MCST.

The functional calibration requirements on the instrument are explicitly stated in the GSFC MODIS specifications (Weber, 1992), or derived from them by SBRC (Table 4). The MODIS instrument has been designed by SBRC to meet the functional and derived calibration requirements. In particular, the on-board calibrators (OBCs; Barker and Young, 1993) and sensor-based methods consist of the SRCA (Spectral Radiometric Calibration Assembly), the Solar Diffuser (SD) Plate and associated Solar Diffuser Stability Monitor (SDSM), Blackbody (BB), and a view of space and the Moon (Figure 1).

SRCA: The SRCA is a 1/4 aperture calibration instrument on MODIS that provides for the first time on an Earth Science satellite an active on-orbit method that can characterize spectral ($0.4 \leq \lambda_c \leq 2.0$ µm) and spatial (all bands) changes in the instrument performance characteristics, in addition to providing both a pre-launch to on-orbit traceable absolute radiometric transfer standard for the solar diffuser ($0.4 \leq \lambda_c \leq 2.2$ µm) and a within-orbit radiometric calibration mechanism. The SRCA provides observations to verify the radiometric and stability requirements for time scales of the order of minutes to weeks and to years for spectral and spatial changes.

SD/SDSM: The solar diffuser is designed to provide two ranges of radiances that differ by a factor of ten to cover the dynamic range of all the reflective bands whenever the SD door is open when passing over the North Pole. Since degradation of the full aperture diffuser plate is perceived to be a major concern, even with a pure Teflon-type diffuser, the SDSM is an instrument designed to alternately look at the Sun and the SD to provide a calibration of the SD. Given the presumed known irradiance from the Sun, the solar diffuser provides for radiometric calibration to meet the 2 % precision requirement on a time scale of days to a few years, depending on the stability of the SDSM.

BB: The full-aperture blackbody is an aluminum plate with V-grooves cut at 25^o half angles. The plate will be painted with a specular black paint to provide a high effective emissivity (≥ 0.992). The blackbody will be allowed to float thermally and its temperature will be monitored to an accuracy of 0.1 K. The SRCA provides observations to calibrate the emissive bands, in order to meet the radiometric requirements for the full five year+ mission of each MODIS instrument.

Space View: Space is viewed once per scan by all the bands through the space port. For the emissive bands, this will provide the second temperature calibration point for a linear calibration, as required with the BB. In addition, the possibility of a lunar radiometric calibration of the reflective bands on a time scale of 2-5 years is provided by the fact that the Moon passes through the view of the space port two to six times per year at approximately 2/3rds of full Moon. Even with the necessary spectral model of lunar reflectance of solar irradiance with time and viewing geometry over the full lunar cycle, this infrequent viewing of a partial Moon is probably not sufficient for radiometric calibration of the 1000 m MODIS bands without additional direct observations of the full Moon with near horizon viewing.

The required redundant approaches to calibration and the on-board MODIS calibration mechanisms represent the most significant committment to calibration in an Earth Science satellite instrument to date.

In addition to the on-board sources, the MODIS calibration efforts will include study of scene-based calibration processes, direct lunar observations, night-time imagery, and scene-dependent spectral, radiometric and spatial inversion algorithms. The routine scene-based methodologies include a modified version of histogram equalization for homogeneous targets and a radiometric rectification procedure using cloud-free daylight satellite observations of calibration sites on the ground. The histogram equalization procedure provides an at-launch within-orbit de-striping method for within-band relative radiometric calibration. The radiometric rectification procedure (Hall et al., 1991) will require on-orbit verification of the slowly varying and predictable radiometric properties of perhaps 10-100 calibration sites per orbit, which may take several years and iterative removal of the atmosphere. Because of the stability of the atmosphere-free lunar surface and the knowability of solar irradiance, direct near-horizon viewing of the Moon at near zero phase on a semi-monthly or monthly basis potentially provides the best chance of multi-year and cross-instrument calibration during the 15-year MODIS/EOS mission. Furthermore, the known spherical shape and sharp radiometric edge of the Moon provides an independent means of measuring changes in the spatial MTF (Modulation Transfer Function) of the MODIS bands as function of time in orbit. Observations at night throughout the life-time of the mission will be used to provide the basis for corrections for systematic errors such as coherent noise. For enhanced radiometry at the cost of reduced spatial resolution, scene-dependent MTF-inversion algorithms will be examined. With the SRCA spectral information it may be possible to provide spectral calibration for those investigators who would use a coarse spectral correction based on masking and known target spectra. Finally, traditional methods of aircraft (Abel et al., 1993) and ground observations(Slater et al., 1990) of targets at the time of satellite overpass will be used to verify the radiometric methodologies. While none of these target- or scene-based sensor-independent methodologies offers the same short-term potential for enhanced precision and accuracy of the routine and repeated on-orbit use of the OBCs, they do substantially lower the risk of mission failure, due to OBC failure, by providing independent approaches to radiometric calibration.

The MODIS Level-1 calibration and characterization product (flow chart in Figure 2) is intended to be as accurate and stable as possible. While there will be adjustments in the calibration algorithm during the 3-6 month check out and on-orbit optimization phase, and in the early phases of operation, it is anticipated that a few months of observations will be sufficient to identify the best methodologies for each band and that changes in the algorithm itself will be less and less frequent with time in orbit. MODIS imagery will be made available to users without hold-up, while changes in calibration methodology are made. The initial algorithm will depend heavily on the vendor supplied instrument-based calibration algorithm. Other methods will be used on a band-by-band basis to the extent that they improve the calibration precision and accuracy. Fitting parameters for the algorithm will be calculated as a moving multi-orbit average. Calibration databases will be maintained and linked by pointer files in such a way that a user will have access to a quantitative measure of any difference between the calibration applied to a scene on a given date and the best current estimate of a calibration if it were reapplied with the benefit of the increased trending and modeling. It is the intention to have all significant information on the state of the instrument and the calibration, including independent calibration information from validation and verification experiments, available to users as an integral part of the ECS/DADS metadata information. One of the objectives of the MODIS math models is to take advantage of the inherently high precision and stability of the MODIS instrument to reduce the effect of systematic errors over time. The long-term objective for MODIS calibration is to provide "value-added" calibration capability from both empirical and predictive models based on in-orbit measurement of the model fitting parameters and observations of several instruments over periods of years.

Field observations are a part of both national and international efforts to assure the success of the MPE global change program. One international group in which these efforts are being coordinated is the Calibration and Validation Working Group (CVWG) of the Infrared and Visible Optical Sensors (IVOS) subgroup of the Committee on Earth Observation Satellites (CEOS). IVOS recommends that CEOS member agencies support the identification, characterization, and maintenance of ground test sites and their associated databases for the verification of on-board calibration systems, the in-orbit calibration, and subsequent cross-calibration of instruments. Another group which is known as the Calibration Test Site and Cross-Calibration Effort is the EOS Cal/Val Panel. MODIS team members are responsible for validating both the MODIS calibration and the MODIS data products. In pre-launch studies such as the one on MODIS spectral requirements (Barker et al., 1993) the MODIS scientists are working with MCST to develop sensitivity curves quantitatively relating product accuracy to errors in calibration and characterization.

MODIS UTILITY MASK GENERATION

One of the standard MODIS products will be a generic utility mask product. It will be developed by MCST in collaboration with members of the MODIS Science Team. The utility masks associated with this product will be produced as part of the Level-1 calibration process, therefore, they will be available, if desired, for use in the production of any other Level-2 or higher data products. Initially, this generic masking product will be three 8-Byte Level-1B images, one for each of the different 250, 500 and 1000 m MODIS spatial resolutions. The bits in these image masks will contain 1-bit binary or 3-bit fractional information on each pixel. The information will characterize the instrument, data and scene, as needed for generation of standard MODIS products. Instrument characteristics will include masks for dead and noisy channels, replaced data channels, and pixels which observe the same area on the ground as at least one other pixel in an adjacent scan. Data characteristics will include outliers, which might represent data drops in transmission or processing. Finally, a few masks will allow users access to masks which indicate the "definite" presence or absence of clouds, snow/ice, water, land, glint, shadow, spatial center/edge, and day/night terminator lines. There will be different discipline-dependent masks for some of these classes. For some cases, there will be mixture information on the pixel. There will be different algorithms for daytime and nighttime imagery. This standard masking product will be available for all MODIS datasets (Table 6). Some of the science team members will chose to develop their own masks as necessary for their specific products.

Cloud detection algorithm development efforts in the science community (Chou 1986) have evolved two categories of approaches: those using statistical methods and those using fixed thresholding. Statistical methods can respond to mixture pixels containing varying proportions of cloud and can respond to changes in cloud and background characteristics due to changing location and time. Threshold methods are less complex and can be tailored to work well on limited data. Rossow et. al. (1985) conducted an extensive comparison of six cloud algorithms and found that all performed similarly but none could be considered optimum. MCST is developing an approach to the masking utility algorithm which is statistically based and uses a multi-band texture pure pixel extraction step prior to clustering and classification of the mask categories. Both spectral and spatial clustering are used with database labeling of mask categories. The masking algorithm is being developed in the context of the needs of the MODIS science community. For example, the MODIS utility mask is used as input to land-related data products (Figure 3), which include: surface reflectance, spectral albedo, emissivity, snow cover, surface temperature, land cover type, vegetation/soil indices, evapotranspiration, net primary productivity and photosynthesis and respiration. These products will be input for regional and global models of climate, hydrology and biogeochemistry.

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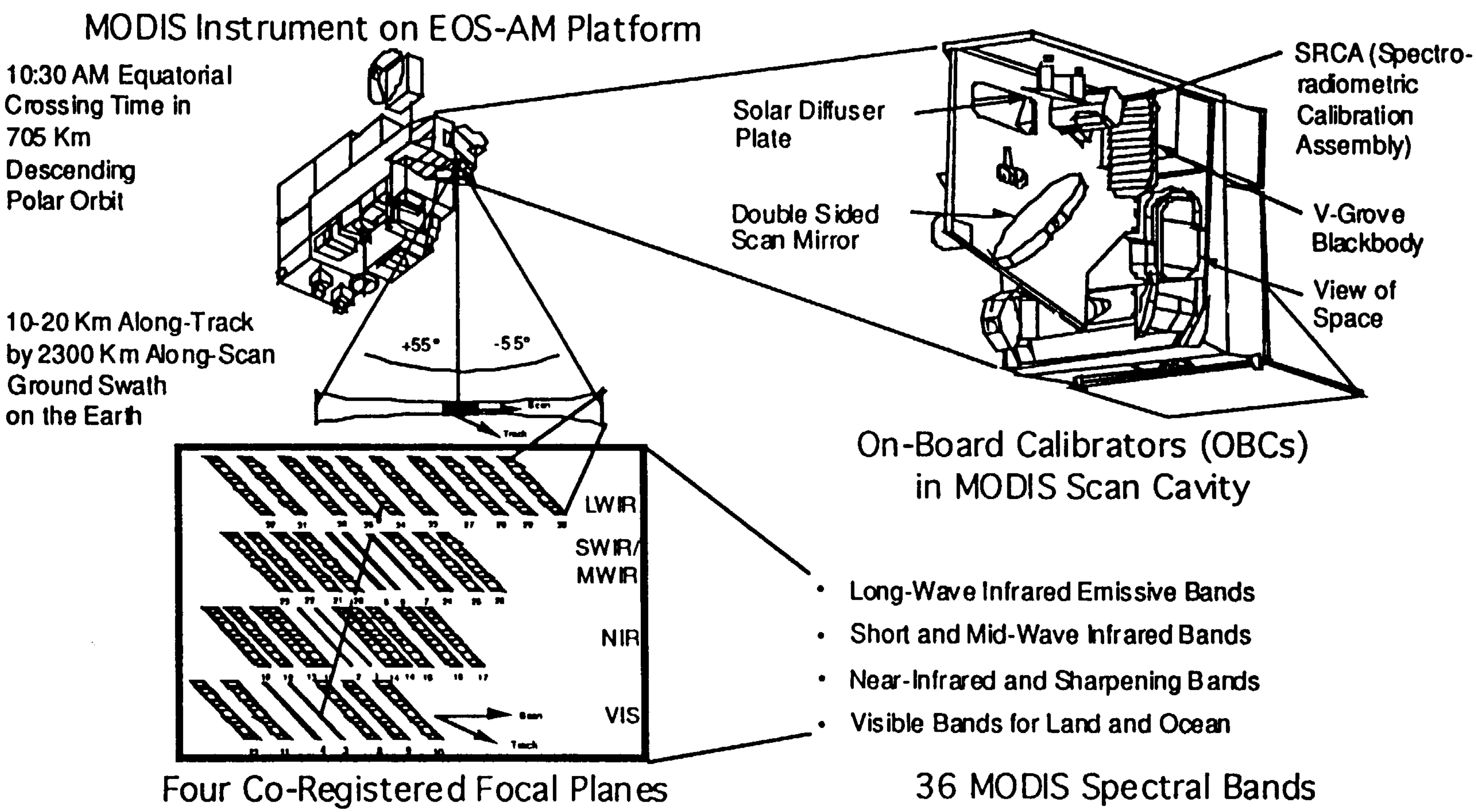
MODIS Instrument on EOS-AM Platform
10:30 AM Equatorial Crossing Time in 705 Km Descending Polar Orbit
10-20 Km Along-Track by 2300 Km Along-Scan Ground Swath on the Earth
+55°
-55°
Solar Diffuser Plate
Double Sided Scan Mirror
SRCA (Spectro-radiometric Calibration Assembly)
V-Grove Blackbody
View of Space
On-Board Calibrators (OBCs) in MODIS Scan Cavity
LWIR
SWIR/MWIR
NIR
VIS
Four Co-Registered Focal Planes
• Long-Wave Infrared Emissive Bands
• Short and Mid-Wave Infrared Bands
• Near-Infrared and Sharpening Bands
• Visible Bands for Land and Ocean
36 MODIS Spectral Bands

Figure 1

MODIS Level-1 Calibration/Characterization Products

Illustrative Flow Diagram

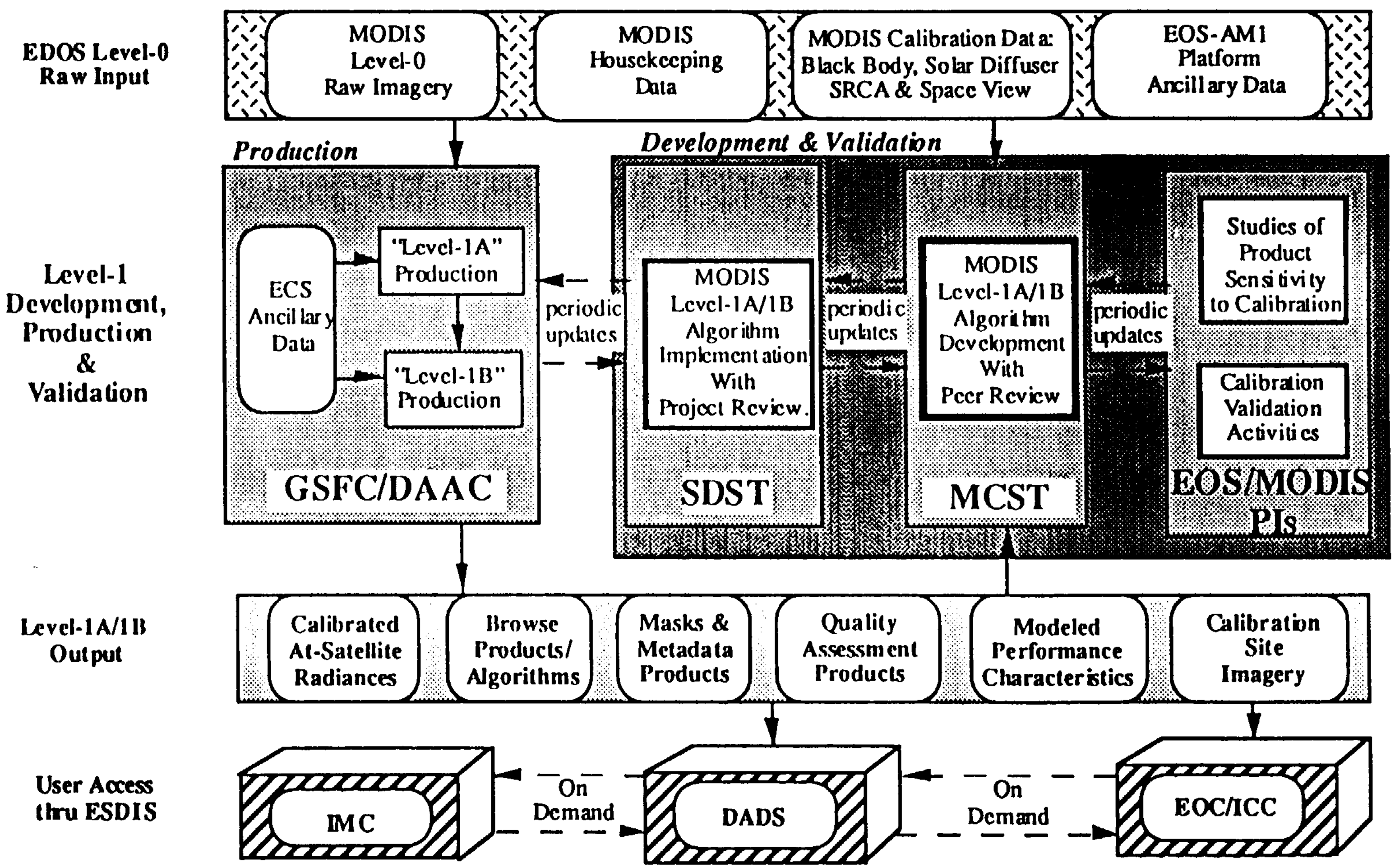

Figure 2

Simplified Land Data Products Interrelations

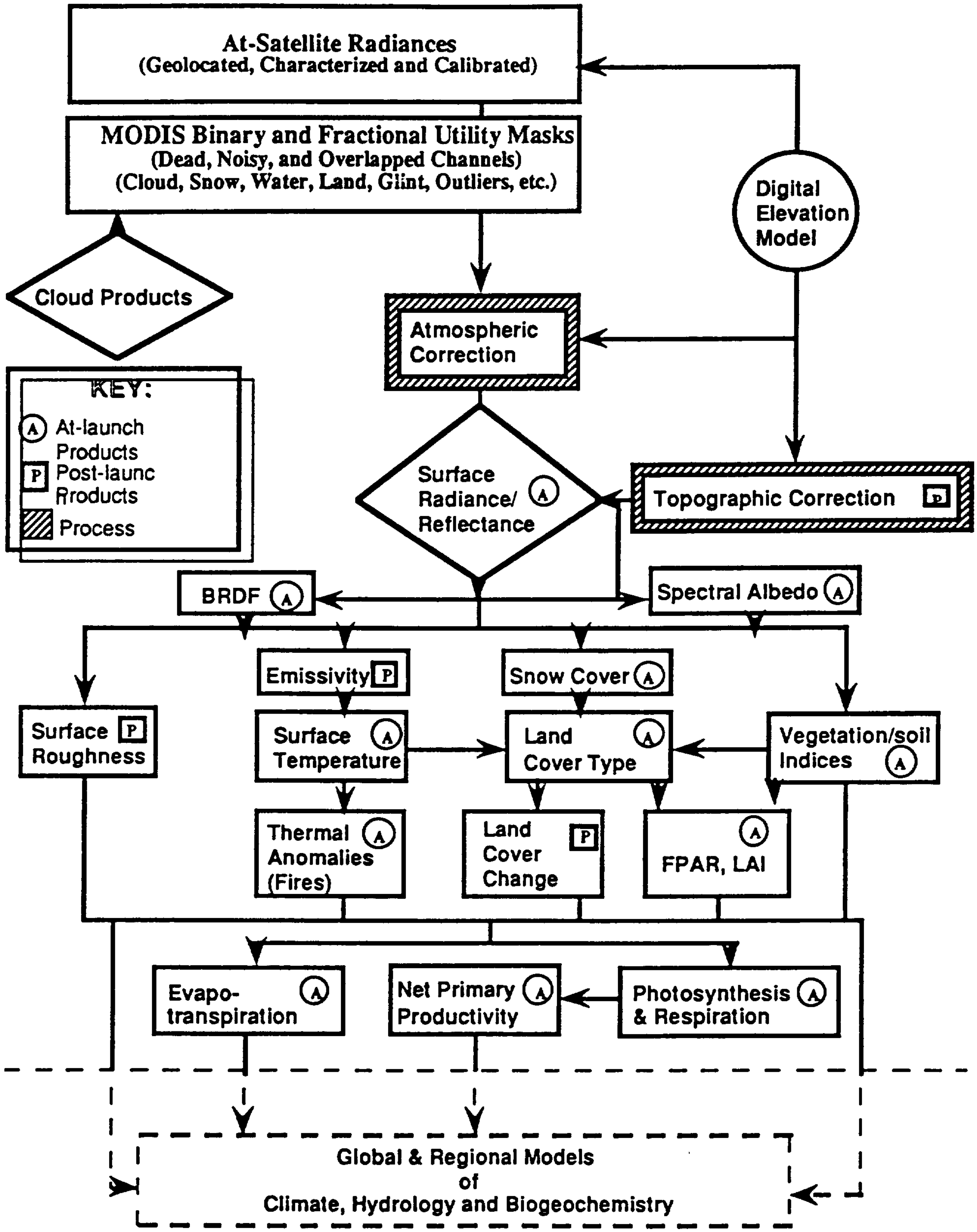

Figure 3

Table 1
MODIS Instrument Requirements

Parameter	Symbol	Requirement
Equatorial Crossing Time	t	10:30 AM Descending EOS-AM Orbit Platforms 1:30 PM Ascending EOS-PM Orbit Platforms
Platform Altitude	H	705 Km
Number of Spectral Bands	N	36 from 0.41 to 14.4 μm
Ground Swath	GFOV	2330 Km Along-Scan by 10-20 Km Along-Track
Angular Swath	FOV	$\pm$ 55°Along-Scan by 14 milliradians Along-Track
Ground Resolution	GIFOV	Band-Dependent 250m, 500m and 1000m @Nadir Band-Dep. 375m, 750m and 1500m at $\pm$ 45° Band-Dep. 500m, 1000m and 2000m at $\pm$ 55°
Angular Resolution	IFOV	0.354 mr, 0.709 mr, 1.418 mr (all $\pm$ 6%)
Band-to-Band Registration	BBR	< 0.1 IFOV goal, < 0.2 IFOV Requirement (3σ)
Quantization	n	12 Bit (to meet Signal-to-Noise (SNR) Spec)
Modulation Transfer Function	MTF	0.3 at Nyquist Frequency
Polarization Factor Insensitivity	PF	< 2%, 0.41 to 2.2 μm
Volume (Length x Width x Height)	V = l x w x h	< 1 x 1.6 x 1 m
Mass	M	< 250 Kg
Power	P	< 225 W average, < 275 W peak
Operating/Duty Cycle	OC	100%
Data Rates (with overhead)	DR	< 11 Mbps (Day Mode) < 3 Mbps (Night Mode)
Pointability Angle of Optical Axis	PA	$\pm$ 20° from Horizon (Full Phase of Moon)
Absolute Radiometric Accuracy	AL	$\pm$ 5% (1σ) ≤3 μm, $\pm$ 1% (1σ) > 3 μm
On-Orbit Reflectance Precision	PR	$\pm$ 2% (1σ) ≤ 3 μm relative to the Sun

Table 2a

Band N	Ground Resolution GIFOV [m]	FWHM Band Pass* Lower Bandpass λMin [nm]	Upper Bandpass λMax [nm]	Primary Scientific Purpose
1	250	620	670	Vegetation Chlorophyll Absorption Land Cover Transformations Cloud/Edge Detection/Masks
2	250	841	876	Cloud/Vegetation/Water/Edge Detection Land Cover Transformations/Masks
3	500	459	479	Soil & Vegetation Differences
4	500	545	565	Green Vegetation
5	500	1230	1250	Leaf & Canopy Properties
6	500	1628	1652	Snow & Cloud Differences/Masks
7	500	2105	2155	Land & Cloud Properties
8	1000	405	420	Water Color (Chlorophyll/Pigments/Sediments) Atmospheric Scattering/Cloud Mask
9	1000	438	448	Water Color
10	1000	483	493	Water Color
11	1000	526	536	Water Color
12	1000	546	556	Sediments
13	1000	662	672	Sediments, Atmosphere
14	1000	673	683	Chlorophyll Fluorescence
15	1000	743	753	Aerosol Properties
16	1000	862	877	Aerosol and Atmospheric Properties
17	1000	890	920	Water Vapor/Atmospheric Properties
18	1000	931	941	Water Vapor/Atmospheric Properties
19	1000	915	965	Water Vapor/Atmospheric Properties
26	1000	1360	1390	Cirrus Cloud/Cloud Mask

* FWHM (Full Width at Half Maximum) = λMax-λMin, where $\lambda Max=\lambda_c+(BW/2)$ and $\lambda Min=\lambda_c-(BW/2)$

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

Table 2b

Band N	Ground Resolution GIFOV [m]	FWHM Band Pass* Lower Bandpass λMin [nm]	Upper Bandpass λMax [nm]	Primary Scientific Purpose
20	1000	3660	3840	Sea Surface Temperature
21	1000	3931	3987	Forest Fires / Volcanoes
22	1000	3929	3989	Cloud
23	1000	4020	4080	Cloud / Surface Temperature/Cloud Mask
24	1000	4433	4498	Cloud / Surface Temperature/Cloud Mask
25	1000	4482	4549	Tropical Temperature / Cloud Fraction
26	Moved to Table 2a			
27	1000	6535	6895	Tropical Temperature / Cloud Fraction
28	1000	7175	7475	Mid-Tropical Humidity
29	1000	8400	8700	Upper-Tropical Humidity
30	1000	9580	9880	Surface Temperature/Cloud Mask
31	1000	10780	11280	Total Ozone
32	1000	11770	12270	Cloud / Surface Temperature
33	1000	13185	13485	Cloud / Surface Temperature
34	1000	13485	13785	Cloud Height & Fraction
35	1000	13785	14085	Cloud Height & Fraction
36	1000	14085	14385	Cloud Height & Fraction

* FWHM (Full Width at Half Maximum) = λMax-λMin, where $\lambda Max=\lambda_c+(BW/2)$ and $\lambda Min=\lambda_c-(BW/2)$

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

Table 3a

Band N	Ground Resolution GIFOV [m]	Center Wave-length λ [nm]	Center Wavelength Tolerance TCW [nm,1σ]	Band Width Δλ [nm]	Band Width Tolerance TBW [nm,1σ]	Max Spectral Radiance LMax [W/m^2-µm)]	Noise Equiv. Spectral Radiance NEdL [W/m^2-µm)]	Signal to Noise Ratio SNR [unitless]	Max Reflectance * RMax [unitless]
1	250	645	4	50	4.0	685	0.169	128	1.43
2	250	858	2.2	35	4.3	285	0.123	201	0.96
3	500	469	4	20	2.8	593	0.145	243	1.01
4	500	555	4	20	3.3	518	0.127	228	0.93
5	500	1240	5	20	7.4	110	0.073	74	0.78
6	500	1640	7	** 25	9.8	70	0.027	275	1.02
7	500	2130	8	50	12.8	22	0.009	110	0.81
8	1000	412	2	15	1.5	175	0.051	880	0.33
9	1000	443	1.1	10	1.6	133	0.050	838	0.23
10	1000	488	1.2	10	1.7	101	0.040	802	0.18
11	1000	531	2	10	1.9	82	0.037	754	0.14
12	1000	551	5	10	1.4	64	0.028	750	0.12
13	1000	667	[+1, -2]	10	1.7	32	0.010	910	0.08
14	1000	678	1	10	1.7	31	0.008	1087	0.07
15	1000	748	2	10	1.9	26	0.017	586	0.07
16	1000	869	5	15	4.3	16	0.012	516	0.06
17	1000	905	2.3	30	5.4	185	0.060	167	0.67
18	1000	936	2.3	10	5.6	256	0.063	57	1.00
19	1000	940	2.4	50	5.6	189	0.060	250	0.74
26	1000	1375	6	30	8.0	** 90	0.040	150	1.00

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

* Used to derive MODIS Specification.
** Band Width = 24.6 and Max Spectral Radiance = 89.9 as stated in MODIS Specification.

Table 3b

N	Ground Resolution GIFOV [m]	Center Wavelength λ [nm]	CW Tolerance TCW [nm,1σ]	Band-width Δλ [nm]	BW Tolerance TBW [nm,1σ]	Max. Spectral Radiance LMAXλ [W/m^2-μm)]	Noise Equivalent Spectral Radiance NEdL [W/m^2-μm)]	Maximum Temperature * TMax [K]
20	1000	3750	19	180	22.5	1.71	0.001	335
21	1000	3959	20	59.4	23.8	86.00	0.150	500
22	1000	3959	20	59.4	23.8	1.89	0.002	328
23	1000	4050	20	60.8	24.3	2.16	0.002	328
24	1000	4465	22	65	26.8	0.34	0.002	264
25	1000	4515	22	67	27.1	0.88	0.006	285
26	Moved to Table 3a							
27	1000	6715	34	360	40.3	3.21	0.011	271
28	1000	7325	37	300	44.0	4.46	0.017	275
29	1000	8550	43	300	51.3	14.54	0.009	324
30	1000	9730	49	300	58.4	6.34	0.022	275
31	1000	11030	55	500	66.2	13.25	0.007	324
31-hi	1000	11030		500		29.08	0.247	400
32	1000	12020	60	500	72.1	12.10	0.006	324
32-hi	1000	12020		500		25.07	0.198	400
33	1000	13335	67	300	80	6.56	0.018	285
34	1000	13635	68	300	81.8	5.02	0.016	268
35	1000	13935	70	300	83.6	4.42	0.014	261
36	1000	14235	71	300	85.4	2.96	0.015	238

Note: The high range of nonlinear Bands 31 & 32 is 324K to 400K.

Ref: NASA/GSFC/EOS Document: MODIS-N Spec.,as amended to 12/23/92, Ref#422-20-02, Greenbelt, MD 20771

*Used to derive MODIS Specification.

Table 4
MODIS Calibration Requirements

Parameter	Requirement	Predicted Pre-launch	Predicted On-Orbit
Radiometric Calibration	**%(+/-1σ)**	**%(+/-1σ)**	
Below 3000nm	5.0	4.0	3.0
Above 3000nm	1.0	1.0	1.0
Reflectance	2.0	4.0	2.0
Spectral Band-to-Band Stability Full Scale	0.5	0.5	0.5
Half Scale	1.0	1.0	
Spectral Characterization (Knowledge)	**nm**		
Center Wavelength Pre-launch On-Orbit	0.5 1.0	0.5	1.0
Geometric Characterization	**IFOV**		
Band-to-Band Registration Required Goal	0.2 0.1	0.1	0.15

Table 5
On-Orbit MODIS Calibration and Characterization

Specification	Calibrator	Duration	Frequency
Radiometric			
Below 3.0 μm 5% Absolute Reflectance 2% relative to Sun	SRCA All Lamps 1-2 Lamps SD & SDSM	75 min 10-100% 3 min at NP	5-10 /Week Within Orbit1 100/Week
	SV of Moon Image Moon Vicarious	1 orbit Minutes	2-6/Year 1-2/Month 1-5/Year
Above 3.0 μm 1.0% Absolute	BB & SV BB@315	100% 100 min	Every Scan 1-10/year
Spectral			
Center Wavelength ±1.0nm Band-to-Band Stability 0.5% Full Scale 1.0% Half Scale	SRCA	75 min	1-5/month
Geometric			
Band-to-Band Registration 0.2 IFOV MTF 0.3 @Nyquist	SRCA Reticles	75 min	2-6/year

Table 6
Three 8-Byte MODIS Level-1B Utility Masks for 250, 500 and 1000 m Bands of Instrument Channel, Data, and Scene Usefulness

Illustrative 1-bit Binary Masks

•Replaced Dead Channels	•Unreplaced Noisy Channels
•Overlapped with Adjacent Scan	•No Overlapped Ground Pixels
•Opaque Clouds	•Transparent Clouds
•Calculated Cloud Shadow	•Radiometric Outlier
•Pure Pixels	•Mixed Pixel (Mixels)
•Land	•Water
•Calculated Potential Glint	•Actual Observed Glint

Illustrative 3-bit Fractional Masks

- Pixel Area on Ground
- Water Fraction
- Opaque Cloud Fraction
- Snow/Ice Fraction
- Solar Irradiance at Top of Atmosphere
- Modular Transfer Function (MTF) Significance on Radiometry
- Size of Corrected (or Uncorrected) Systematic Errors