P1.6 **MODIS RADIANCES AND REFLECTANCES FOR EARTH SYSTEM SCIENCE STUDIES AND ENVIRONMENTAL APPLICATIONS**

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## 1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS), a major component of NASA's Earth Observing System (EOS), was designed to provide improved long-term global observations of land, ocean and atmosphere features relative to "heritage sensors". MODIS was launched aboard the Terra satellite on December 18, 1999 (10:30 am equator crossing time, descending node, Sun-synchronous near polar orbit). MODIS with its 2330 km viewing swath width provides almost daily global coverage. It acquires data in 36 high spectral resolution bands between 0.415 and 14.235 microns with spatial resolutions of 250 m (2 bands), 500 m (5 bands), and 1000 m (29 bands). This year a similar instrument will be flown on the EOS-Aqua satellite (1:30 pm equator crossing time, ascending node). This will enable studies of the diurnal variation of rapidly varying systems. The radiance data measured by MODIS with some new channels (never used before for remote sensing from space) provides improved information about the physical structure of the Earth system. Measured raw sensor counts, radiometrically calibrated and geolocated radiances along with derived atmosphere and ocean data are archived (Ahmad et al. 2002) at the NASA Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC). These products and other MODIS derived products archived at other NASA centers are made freely available to the public and scientific community.

The purpose of this presentation is to provide key characteristics of the MODIS radiance and reflectance products (referred to as the Level 1B product) with some examples of applications of the MODIS radiances in detecting human impacts on the earth and its climate and how this data is used in improving the predictions and characterization of natural disasters such as wild fires, volcanoes, floods and drought.

## 2. MODIS Instrument

MODIS, a cross-track scanning radiometer, provides high spectral resolution data from 36 bands with center wavelengths ranging from 0.412 to 14.235 microns (Barnes et al. 1998). MODIS spectral band passes are shown in Table 1. MODIS carries 490 detectors that are aligned in parallel rows on four separate focal planes (Visible, NIR, SWIR/MWIR, and LWIR).

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The number of detectors per band are 10 for 1000 m, 20 for 500 m, and 40 for 250 m spatial resolution bands. In addition, 2 of the 1000 m spatial resolution bands provide measurements for the same scenes at two gains, 13 L and 14L at low gains for measuring bright scenes and 13H and 14H at high gains for measuring dark ocean scenes.

The instrument's 110 degree field of view is swept over the focal planes by the double sided rotating scan mirror. Each mirror rotation provides two scans (one for each mirror side). The scan period is 1.477 sec. During each scan, 5 view sectors (solar diffuser, spectral radiometric calibration assembly, blackbody, space, and earth view) are observed. The 110 degree-wide instrument field of view sweeps out a ground swath approximately 2330 km wide during the 0.451 seconds of earth view. The ground swath (± 55 deg viewing angles relative to nadir) exhibits significant earth curvature effects. The 55 degree scan angle increases to approximately 65 degree due to earth curvature. In addition, ground resolution increases with scan angle. Ground dimensions of a 1 by 1 km nadir pixel increase to 4.8 km along scan and 2km along track at 55 degrees. This increase in the pixel size and the overlap of scan lines increases with scan angle (called bow tie effect).

To ensure better calibrated radiance products MODIS is equipped with four high performance onboard calibrators (OBC).

*Solar Diffuser (SD) & Solar Diffuser Stability Monitor (SDSM)* – these are used for calibration of reflective solar bands. The scan mirror views the illuminated SD when the satellite is near the North Pole. The SDSM is used to monitor degradation of the SD by comparing the solar diffuser reflectance to a direct solar view with a fixed 1.5 % transmission screen. SD and SDSM measurements are made once a week

*Spectral Radiometric Calibration Assembly (SRCA)* operates in 3 modes; radiometric, spectral, and spatial. The SRCA includes a calibrated source (activated by ground command) to be viewed by the rotating scan mirror. The SRCA is used to track changes in the radiometric response of MODIS through launch, to characterize the limits of within-orbit changes in responsivity for the reflective solar bands, to determine center wavelength for these bands, and to track the shifts in earth location for all 36 bands. SRCA radiometric calibrations are performed once a month, spatial calibrations every two months, and spectral calibrations every four months.

*Black Body (BB*) - is viewed by the rotating mirror in each scan. The BB provides dc restoration (a zero radiance level for reflected solar bands) and a known radiance source for calibration of the thermal bands.

*Space View (SV)* - is viewed by the rotating mirror in each scan, thereby providing a second calibration point for the radiometric calibration of the 16 thermal bands. Emissive infrared bands calibration is done on a scan line by scan line basis automatically through BB and SV observations.

A *Lunar View* is also obtained once a month providing an additional standard radiance source. Since the reflectance of the Moon's surface is not expected to change over lifetime of MODIS, this measurement can also be used for tracking degradation of the solar diffuser.

MODIS has the ability to change gain settings for some of the bands, bias voltages of the FPAs and black body temperatures via ground command. MODIS has backup power supplies and electronic components. For better ADC (analog to Digital Conversion) performance, MODIS was switched from one set of components (side-A) to the backup components (side-B) on October 30, 2000. When MODIS experienced over-voltage shutdown on June 15, 2000 due to failure of the B-Side Power supply (assumed to be caused by a high energy radiation event), MODIS operation was successfully switched back to side-A and data collection resumed on July 2, 2001.

**3. MODIS Radiometrically Calibrated and Geolocated (Level 1B) Radiance and Reflectance Products**

To produce accurate radiometrically calibrated and geolocated radiances, an extensive calibration and data processing algorithm called the 'Level-1B Algorithm' has been developed by the MODIS Characterization Support Team (MCST).

The reflective solar bands covering the spectral range 0.4 through 2.3 micron and the emissive infrared bands (3.6-14.4 micron) are calibrated and analyzed with separate techniques. Emissive infrared band calibration is done on a scan line by scan line basis using BB and SV observations. For reflective solar bands, pre-launch calibration values (Guenther et al. 1998) are used. Changes in the calibration are tracked from the SD/SDSM system and algorithms are developed to generate updated calibration coefficients. The MCST team, working closely with the MODIS Science Team, has been developing unique solutions in response to each instrument effect detected.

The Level 1B algorithm developed by the MCST team corrects the raw digital signals measured by each detector for all known instrumental effects such as electronic offsets, non-linearity in the analog-to-digital converters, angular variations of the scan mirror reflectance, changes in the gain caused by variations in the instrument and focal plane temperatures, out-of-band spectral response. These counts are then adjusted for the effects of variations in calibration parameters from detector to detector within each band, so that one pair of calibration terms apply to every detector in each band. Radiances are produced from these corrected counts for all bands. For solar reflective bands, the parameters "reflectance × cosine solar zenith angle" (= π × radiance/ sun earth distance corrected solar irradiance) are also computed.

The corrected counts (effective digital numbers), radiances, and reflectance × cosine solar zenith angle (for reflective solar bands only) are scaled to 16-bit (unsigned integer) representation and are stored as Science Data Set (SDS) data objects of HDF-EOS format. Scale factors and offset values are provided as SDS attributes to convert back to actual data values. Uncertainty indices for each band are also provided as 8-bit (unsigned integer). The following equation may be used to convert stored values back to actual data:

data values = scale factor × (stored numbers – offset)

Based on spatial resolution, the Level 1B algorithm produces three radiance products. Due to the large volume of MODIS data, each file (granule) contains observations of a 5 minute duration (288 files for day and night observations). The standard Level 1B radiance products are:

1**) MODIS Level 1B 250 M Earth View Radiance Data Product (MOD02 QKM)** - contains corrected counts, radiances, reflectance × cosine solar zenith angle, and uncertainty indices for the MODIS Reflective Solar Bands 1 and 2 at 250-m spatial resolution. It also contains geolocation information (latitude and longitude) for *every 4$^{th}$ pixel*.

2) **MODIS Level 1B 500 M Earth View Radiance Data Product (MOD02 HKM)** - contains corrected counts, radiances, reflectance × cosine solar zenith angle and uncertainty indices for the MODIS Reflective Solar Bands 1 and 2 (250 m spatial resolution data aggregated at 500 m spatial resolution), and for Bands 3 to 7 at 500-m spatial resolution. It also contains number of samples used in the aggregation. Geolocation information (latitude and longitude) are included for *alternate pixels*.

3) **MODIS Level 1B 1000 M Earth View Radiance Data Product (MOD021KM) -** contains corrected counts, radiances, reflectance × cosine solar zenith angle, and uncertainty indices for the MODIS Reflective Solar Bands 1 and 2 (250 m spatial resolution data aggregated to 1000 m spatial resolution), Reflective Solar Bands 3 through 7 (500 m spatial resolution data aggregated to 1000-m spatial resolution), and for Reflective Solar Bands 8 through 19 & 26 at 1000 m spatial resolution. Corrected counts, radiances, and uncertainty indices for emissive infrared bands 20

through 25, and 27 through 36 at 1000-m spatial resolution are also included. For emissive infrared bands data is reported for both day and night. For reflective solar bands, 1 through 19 data is reported only for daytime, whereas for reflective solar band 26, data is sent for both day and night. For reflective solar bands the night time files contain missing data indicator or fill-value. Earth view 1km data files contain a subset of geolocation data (latitude, longitude, solar and sensor zenith and azimuth angles, geodetic heights above geoid, slant ranges from spacecraft, geolocation quality flag) *for every fifth pixel*. For aggregated data the numbers of samples used in the aggregation are also included.

The Level 1B algorithm also generates an additional product "**MODIS Level 1B On-Board Calibrator and Engineering Data (MOD02OBC)"** which contains on-board calibrators (SD, SRCA, BB, Space view) observations in raw digital numbers from all MODIS bands at their original resolution, uncertainty indices, and engineering data.

A Level 1A product **"MODIS Geolocation Level 1A Product (MOD03)"** , used in the processing of Level 1B product is also made available which provides geolocation data (latitude, longitude, solar and sensor zenith and azimuth angles, geodetic heights above geoids and other ancillary information) sampled at *1 km pixel resolution*.

Details of the above products and calibration algorithms are available from the MCST web site (http://mcstweb .gsfc.nasa.gov/product.html).

## 4. Data Production Status

The Goddard DAAC has been processing, archiving and distributing MODIS data since February 24, 2000. All MODIS products generated with preliminary calibration algorithms were assigned "beta status". These beta products, not of science quality, but were made available for evaluation purposes only. Calibration and validation efforts continued (Salomonson et al. 2000). By late Fall of 2000, many of the instrument calibration issues were resolved (Salomonson et al. 2001). Many of the data products using improved calibration algorithm were given "provisional status". Beta release is referred as version-1 and provisional release as version-3. There are no version-2 products. The provisional release (version-3) data products show significant improvement over the beta products. These products also compare very well when compared with the coincident ground and aircraft based observations, acquired during several field campaigns (WISC-T2000, PRIDE, Safari-2000, TX-2001) designed for MODIS data validation.

A *consistent year dataset* is being produced by processing one year of data (November 01, 2000 to Oct 31, 2001) using one consistent (improved) calibration algorithm. This dataset should be very useful in studying seasonal changes on regional and global scale. Descriptions of the data products and data availability information are available from the Goddard DAAC web site (http://daac.gsfc.nasa.gov). The derived atmosphere, land, and ocean products at pixel resolution (level-2 swath data) and time and space averaged, globally gridded (level-3 & 4) products are also generated at the Goddard NASA MODIS Adaptive Processing System (MODAPS) using consistent algorithms (Masouka et al. 2001) and archived at different NASA archive centers for distribution.

## 5. Applications

There are 35 to 40 standard data products that are being produced from MODIS radiances. Some of the examples of these products are: cloud and aerosol characteristics, vertical distribution of temperature and humidity, trace gases, land and sea surface temperature, surface emissivity, land cover and primary productivity, snow cover and sea ice concentration, ocean color, sea sediment concentrations, and phytoplankton. These products are being used by scientists from a variety of disciplines, including oceanography, biology, and atmospheric science.

Although almost all key climate and environmental parameters are available as standard MODIS products and are derived from MODIS radiances, the radiometrically corrected and geolocated radiance data (Level 1B product) that are used in deriving the standard products are much in demand by the science user community. These radiances are needed to enhance existing algorithms, to test new algorithms for the retrieval of existing or new parameters, and for developing simulation datasets for characterization of new sensors. The multi-angle spectral radiance and reflectance data is also needed in developing a more realistic Bi-directional Reflectance Distribution Function (BRDF) for the accurate computation of surface albedo, an essential parameter used in the earth radiation budget and climate models.

MODIS data has also been put into operational use for monitoring of environmental disasters by several agencies. Some examples are:

**Drought & Fire** - MODIS can identify the regions of drought, burning, smoke plume, old burned area, in addition to forest clearing and changes in the land cover. After a long period of drought, forest or bush fires are common and spread very quickly endangering the community. A specially chosen MODIS fire band (channel 20 at 3.9 microns) is particularly sensitive to very high temperatures and can spot the burning area through smoke. U.S firefighters and land managers are using MODIS data to combat wildfires. MODIS Land Rapid Response System ( a collaborative effort between NASA, NOAA, the university of Maryland and the USDA Forest service (http://rapidfire.sci.gsfc.nasa.gov) has been developed which provides active fire maps (showing actively burning areas and previously burned areas) for strategic resource allocation when fighting wild fires.

**Flood Monitoring** - hundreds of thousands of people are endangered by flooded rivers. Break down of communications following flooding makes it difficult to assess the true extent of the disaster and where relief efforts are most needed. MODIS capability of accurate discrimination between land and water and its high frequency global coverage provides near real-time monitoring of the flooded area. MODIS data is being used by the Dartmouth Flood Observatory (project funded by NASA) to produce global flood maps (http://www.dartmouth.edu/artsci/geog/floods) in order to provide information about the severity and precise location of flood for aid relief efforts.

**Volcanoes** - in the past many lives have been lost due to volcanic eruptions. During processing of MODIS data at the Goddard DAAC, volcanic eruption alert data (unusually hot spots) are extracted and sent to the University of Hawaii for the prediction and monitoring of volcanic eruptions. MODIS capability of discrimination between volcanic plumes and ordinary clouds makes it valuable for the surveillance of erupting volcanoes (maximum height reached, changes in the extent) for timely overview of affected areas and evacuation. Dispersal of an ash plume can be tracked to provide early warnings for air traffic authorities (http://eos.pgd.hawaii. edu/docs/dpdcloud.html). MODIS radiance values also provide information on the emission characteristics (type and concentrations) which can be used to deduce impact on global climate.

**Toxic Algae Blooms** - toxic algal blooms, sometimes called red tides, have in the past killed huge numbers of fish, shellfish, marine mammals, birds, and can cause skin and respiratory problems in humans. A multi-disciplinary research project ECOHAB: Florida (Ecology and Oceanography of Harmful Algal Blooms) has been designed to study harmful algae (partially funded by NASA). MODIS high frequency and high resolution global coverage data has been found to be more useful when compared to other satellite sensors, in monitoring arrivals of iron rich Saharan desert dusts (which provide an environment for toxic algae blooms) and hence prediction of time and location of the red tides and other toxic algal blooms (http://www.redtide.whoi.edu/hab )

## 6. Data Access

MODIS calibrated radiances and geolocation, atmosphere, and ocean products are archived at the NASA Goddard DAAC (http://daac.gsfc.nasa.gov) and are freely made available to the public and science user community. To facilitate data access, a user friendly web based (http://daac.gsfc.nasa.gov/data/dataset/) search and order system (with simple point & click buttons for selections from the world map and data calendar) has been developed by the NASA Goddard DAAC MODIS Data Support Team (MDST).

The MDST provides expert assistance to the user (modis@daac.gsfc.nasa.gov) in the areas of accessing data products, documentation, browse, and data analysis (Leptoukh et al. 2001). For users convenience, on-demand subsetting is also provided. Several data manipulation, re-projection, subsetting, and visualization tools (http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS /MODIS/software.shtml) developed by MDST (Ouzonov et al. 2001) and by several MODIS science teams have been made available to the Earth science community. These data tools have the capability of displaying and extracting specific parameters and spatial subsets of MODIS data (from large MODIS files in HDF-EOS format) and saving them as binary, ASCII, or image files.
The whole suite of MODIS products (including products from other Terra sensors) can also be searched and ordered from all NASA DAACs and NASA affiliated centers via the NASA EOS Data Gateway (EDG) at http:// eos.nasa.gov/imswelcome.

## 7. Summary

The strengths of MODIS include its global coverage, high radiometric resolution, appropriate dynamic ranges, and accurate calibration in reflective and thermal infrared bands designed for retrievals of atmospheric, land and sea surface properties. Almost 40 higher level science standard products are being produced from MODIS Level 1B radiance data. Even though data validation activities are still in progress, the provisional radiometrically calibrated radiances and reflectances, and derived products (version-3) show very fine details and exceed the expectations when compared to in-situ observations. Almost one year of consistent data processed with an improved calibration algorithm (version-3), will soon be made available to the public and science user community. These high radiometric accuracy measurements can be used by the scientific community to detect subtle signatures of climate change, study regional and global phenomena, and for prediction and characterization of natural disasters such as wild fires, volcanoes, floods and drought. MODIS radiance counts, calibrated radiance and reflectance, geolocation products, and all derived geophysical atmospheric & ocean products are archived at the Goddard DAAC (http://daac.gsfc.nasa.gov). All land products are archived at Earth Resource Observation System (EROS) Data Center (EDC), and snow & ice products are archived at the National Snow and Ice Data Center (NSIDC). MODIS products, ancillary and related data, documents, and data analysis and visualization tools are freely made available to the public and science user community from these data archive centers via NASA EOS Data Gateway (EDG) at http://eos.nasa.gov/imswelcome.

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**Table 1. MODIS Spectral Bands**

| Band | µm | Bandwidth | Use |
|---|---|---|---|
| Reflective Solar Bands ( 250 m spatial resolution) | | | |
| 1 | 0.659 | 0.620 - 0.670 | aerosol, cloud, land |
| 2 | 0.865 | 0.841 - 0.876 | |
| Reflective Solar Bands ( 500 m spatial resolution) | | | |
| 3 | 0.470 | 0.459 - 0.479 | aerosol & cloud optical thickness, cloud phase, cloud effective radius, cloud mask, snow, land |
| 4 | 0.555 | 0.545 - 0.565 | |
| 5 | 1.240 | 1.230 - 1.250 | |
| 6 | 1.640 | 1.628 - 1.652 | |
| 7 | 2.130 | 2.105 - 2.155 | |
| Reflective Solar Bands ( 1 km spatial resolution ) | | | |
| 8 | 0.412 | 0.405 - 0.420 | Ocean color chlorophyll phytoplankton biogeochemistry |
| 9 | 0.443 | 0.438 - 0.448 | |
| 10 | 0.488 | 0.483 - 0.493 | |
| 11 | 0.531 | 0.526 - 0.536 | |
| 12 | 0.551 | 0.546 - 0.556 | sediments, atmosphere |
| 13 | 0.667 | 0.662 - 0.672 | |
| 14 | 0.678 | 0.673 - 0.683 | fluorescence |
| 15 | 0.748 | 0.743 - 0.753 | atmosphere, aerosol |
| 16 | 0.869 | 0.862 - 0.877 | |
| 17 | 0.905 | 0.890 - 0.920 | atmospheric total precipitable water vapor, clouds |
| 18 | 0.936 | 0.931 - 0.941 | |
| 19 | 0.940 | 0.915 - 0.965 | |
| 26 | 1.375 | 1.360 - 1.390 | cirrus cloud |
| MWIR Thermal Emissive Bands (1km spatial resolution) | | | |
| 20 | 3.75 | 3.660 - 3.840 | cloud & surface, temperature, fire& volcano, sea surface temperature |
| 21 | 3.96 | 3.929 - 3.989 | |
| 22 | 3.96 | 3.929 - 3.989 | |
| 23 | 4.05 | 4.020 - 4.080 | |
| 24 | 4.47 | 4.433 - 4.498 | atmospheric temperature profile |
| 25 | 4.52 | 4.482 - 4.549 | |
| LWIR Thermal Emissive Bands(1km spatial resolution) | | | |
| 27 | 6.72 | 6.535 - 6.895 | tropospheric water vapor |
| 28 | 7.33 | 7.175 - 7.475 | |
| 29 | 8.55 | 8.400 - 8.700 | cloud particle radius |
| 30 | 9.73 | 9.580 - 9.880 | total column ozone |
| 31 | 11.03 | 10.780 -11.280 | cloud, surface temperature, fire |
| 32 | 12.02 | 11.770 -12.270 | |
| 33 | 13.34 | 13.185 -13.485 | cloud top height, temperature, pressure, temperature profile |
| 34 | 13.64 | 13.485 -13.785 | |
| 35 | 13.94 | 13.785 -14.085 | |
| 36 | 14.24 | 14.085 -14.385 | |