MODIS DATA STUDY
TEAM PRESENTATION

December 8, 1989

AGENDA

1. MODIS Post-Launch Processing Scenario Document

2. Atmospheric Correction for Ocean Products for MODIS

MODIS POST-LAUNCH PROCESSING SCENARIO DOCUMENT

The MODIS Post-Launch Processing Scenario Document, the MODIS Data Study Team's deliverable for November 1989, presents a concept for processing the Moderate Resolution Imaging Spectrometer (MODIS) data and the generation of MODIS data products in the post-launch period. One purpose of this document is to put forward for discussion some initial concepts regarding the selection, development, and refinement of algorithms among MODIS team members for the production of oceanic, terrestrial, and atmospheric-sciences data products after launch, particularly Level-2 and higher, to meet the Earth Observing System (Eos) mission objectives. Additional motivations include the desire to understand the growth of the MODIS processing requirements during the post-launch period beyond those of the initial core data product set. We also wish to illuminate some concepts regarding the calibration and validation of the MODIS measurements, and the anticipated reprocessing of some of the MODIS data sets.

Six issues are considered in this scenario for MODIS data processing: (1) the conversion of science-team-member proposed research and development (R&D) products into new standard products; (2) the identification of new R&D and standard data products by the general science community, including the interdisciplinary investigators; (3) the development of an accurate estimate growth in the processing and storage requirements of the data system; (4) the maintenance of the calibration of the MODIS measurements; (5) the reprocessing requirements; and (6) the initial post-launch and ongoing validation of MODIS data products (which includes the role and requirements of field experiments). As a result of this analysis, the following general requirements may be stated:

1. EosDIS must be sized to accommodate growth in the processing requirements of MODIS over five-year periods.

2. The data management system within EosDIS must be designed to accommodate an increasing number of data products, and possibly an increasing complexity in ancillary data requirements and the corresponding external and internal interfaces.

3. Policies and automated procedures must be developed to efficiently manage the reprocessing of MODIS data products.

4. Adequate capabilities for the transportation and visualization of data sets must be built into EosDIS to permit the science team members to optimally validate their data products.

Atmospheric Correction for Ocean Products for MODIS

Atmospheric correction involves removing the contributions of the atmosphere from the total radiance signal received by the satellite. It must be performed for retrieval of sea surface temperature (SST) and water-leaving radiances. Removal of atmospheric contributions is critical for water-leaving radiance because the atmosphere accounts for about 90% of the signal received at the satellite.

For both SST and water-leaving radiances, the first atmospheric effect that must be removed is clouds. Cloud contamination for both products will be achieved through the MODIS Cloud Identification Utility Algorithm, described elsewhere in this report.

SEA SURFACE TEMPERATURE

Correction of water vapor is required to obtain SST. This algorithm will be applied only to MODIS-N observations, because only this sensor has the thermal infrared bands required for SST determinations.

The atmospheric attenuation due to water vapor is removed by applying expressions of the form $T_s = T_i + C_1 (T_i - T_j) + C_2$, where i and j refer to the MODIS-N bands at 3.75, 11.03, and 12.02 μm. For large satellite zenith angles (greater than 40°), an extra term of the form (sec Z -1) is required for all expressions except for the split-window daytime equation. A residual systematic bias is removed through regressions between matched buoy and satellite data.

WATER-LEAVING RADIANCE

Three atmospheric effects must be removed to obtain water-leaving radiances: 1) Rayleigh radiance, 2) aerosol radiance, and 3) attenuation due to ozone absorption. An additional effect is that of sun glitter, which is properly due to the water, but is important in obtaining accurate water-leaving radiances. Hence it, too is considered part of the atmospheric correction for ocean color products.

Before the atmospheric correction for water-leaving radiance is applied, the following external look-up tables must be available:

o Mean extraterrestrial solar spectral irradiance

- o Spectral Rayleigh optical thickness at standard atmospheric pressure, temperature
- o Fourier coefficients of Rayleigh scattering
- o Fresnel reflectance coefficients for downwelling irradiance and upwelling radiance
- o Seawater index of refraction

Consider also that the following data sets obtained in the Level 1 processing are available:

- o Solar zenith angle
- o Solar azimuth angle
- o Spacecraft zenith angle
- o Spacecraft azimuth angle

Finally, it is necessary to have or compute the following external data sets:

- o Atmospheric surface pressure
- o Surface wind speeds
- o Spectral ozone optical thickness

One may then proceed with the atmospheric correction for water-leaving radiance.

The governing equation for atmospheric correction is

$$L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_g(\lambda) + t(\lambda)L_w(\lambda) \qquad (1)$$

where $L_t(\lambda)$ is the total radiance received by the sensor, $L_r(\lambda)$ is the contribution arising from Rayleigh scattering, $L_a(\lambda)$ is that arising from aerosol scattering, $L_g(\lambda)$ is the contribution from sun glitter (direct sunlight reflecting from the sea surface), and $t(\lambda)L_w(\lambda)$ is the water-leaving radiance $L_w(\lambda)$ diffusely transmitted to the top of the atmosphere $t(\lambda)$. Eqn. 1 is identical to the algorithm used for CZCS atmospheric correction except for the addition of a correction for sun glitter.

Procedure for Atmospheric Correction

<u>Instantaneous Extraterrestrial Irradiance</u>

The procedure for atmospheric correction for MODIS begins with obtaining, from literature values (Neckel and Labs, 1984), the mean extraterrestrial solar irradiance $\underline{F}_o$, which must be weighted for MODIS bandwidths and bandwidth sensitivity. Then the instantaneous extraterrestrial solar irradiance F_o must be computed

$$F_o(\lambda) = \underline{F}_o(\lambda)[1 + e \cos[2\pi(JD-3)/365]]^2 \qquad (2)$$

(Gordon et al., 1983) where e is the eccentricity of the Earth's orbit (= 0.016) and JD is Julian Day.

Cloud Filter

Further processing requires that only cloud-free pixels be identified, so a method for identifying cloudy pixels will be employed. The CZCS uses a threshold radiance value at 750 nm, and it is assumed MODIS will use the same approach. Once the cloud-free pixels have been identified, they must be Earth-located so that solar and spacecraft zenith and azimuth angles may be computed.

Ozone Absorption

With zenith and azimuth angles known, one must next obtain the ozone optical thickness $\tau_{oz}(\lambda)$. Gordon (1989) proposes using GOMR data for ozone optical thickness, but other sources may be available, including MODIS itself. AIRS/AMSU may also provide a source of ozone information.

Next is calculated the instantaneous solar irradiance after reduction by two passes through the ozone layer

$$F_o'(\lambda) = F_o(\lambda) \exp[-\tau_{oz}(\lambda) (1/\cos\theta + 1/\cos\theta_o)] \qquad (3)$$

where θ is the spacecraft zenith angle and θ_o is the solar zenith angle.

Rayleigh Radiances

The contribution to the satellite from Rayleigh scattering must then be removed. This is computed by including multiple scattering effects and polarization (Gordon et al., 1988). On the CZCS this is computed every 8 pixels across a scan line and every 16 scan lines. Values between these points are computed by bi-linear interpolation.

First the Rayleigh optical thickness $\tau_r(\lambda)$ must be computed. Assuming a depolarization factor of 0.031 (Gordon et al., 1988), a "standard" Rayleigh optical thickness $\tau_{ro}(\lambda)$ (at standard atmospheric pressure P_o, 1013.25 mbar) may be computed by

$$\tau_{ro}(\lambda) = 0.008569\lambda^{-4}(1 + 0.0113\lambda^{-2} + 0.00013\lambda^{-4}) \qquad (4)$$

(Hansen and Travis, 1974). $\tau_r(\lambda)$ may then be calculated at any surface pressure P by

$$\tau_r(\lambda) = P/P_o \ \tau_{ro}(\lambda) \qquad (5)$$

The surface atmospheric pressure field at low resolution may be obtained from meteorological data and models from NOAA.

The total intensity of multiple scattered Rayleigh radiance, I, normalized to unit incoming solar irradiance, may then be computed from

$$I(\tau_r(\lambda),\theta,\theta_o,\Delta\phi) = \sum_{m=0,2} I_m(\tau_r(\lambda),\theta,\theta_o) \cos(m\Delta\phi) \quad (6)$$

where I_m are Fourier coefficients of the radiance and $\Delta\phi = \phi-\phi_o$ where ϕ and ϕ_o are the spacecraft and solar azimuth angles, respectively. For the CZCS, the Fourier coefficients I_m are computed in advance for a fixed Rayleigh optical thickness. They are made available for CZCS processing at 40 spacecraft zenith angles and 39 solar zenith angles. Interpolation to other combinations of angles is done by bilinear interpolation. Rayleigh radiance $L_r(\lambda)$ is then $I_o(\lambda)\ F_o'(\lambda)$.

For MODIS, the Fourier coefficients I_m will also be computed in advance. Correction for surface pressure will be made by

$$I = I_o \{[1-\exp(-\tau_r/\cos\theta)]/[1-\exp(-\tau_{ro}/\cos\theta)]\} \quad (7)$$

The normalized Rayleigh radiance intensities I at actual atmospheric temperature and pressure will then be obtained from this Eqn. 7, and multiplied by $F_o'(\lambda)$ to obtain $L_r(\lambda)$.

Correction for Sun Glitter

The tilt capability of MODIS-T drastically reduces the amount of sun glitter contribution to the total radiance. However, minor amounts of sun glitter are commonly present, even on sensors with a tilt capability. These contributions are usually absorbed into the estimation of the aerosol and are corrected along with aerosols. However, at times the sun glitter may be more intense, and a method for removal will facilitate more accurate water-leaving radiance computations. MODIS-N has no tilt capability, and the sun glitter contribution to its total visible radiance signal will dominate at times.

Sun glitter is known to be related to the wind speed. Knowledge of the wind speed enables an estimation of the sea slope probability distribution, which determines the intensity of sun glitter.

Two methods are proposed by Gordon for the removal of sun glitter from MODIS imagery. The first is to obtain surface wind speeds from SCATT-2 to determine the distribution of surface sea slopes according to the Cox and Munk (1954) theory. The glitter radiance can then be determined from the slope distribution and orbital geometry. If SCATT-2 winds are not available, surface wind speeds may be estimated from meteorological models. The second is to obtain glitter radiance from land bands on MODIS-N, and estimate the surface sea slope distribution therefrom. Again the glitter radiance can be estimated from these slopes and orbital geometry.

In either case, one may generate a look-up table relating the solar and spacecraft orbital positions to wind speeds and interpolate to reduce computational time.

The glitter radiance is computed by

$$L_g(\theta,\phi,\theta_o,\phi_o,V,\lambda) = F_{o'}(\lambda)\rho p(\theta,\phi,\theta_o,\phi_o,V)/(4\cos\theta\cos^4\theta_o) \qquad (8)$$

(Viollier et al., 1980) $p(\theta,\phi,\theta_o,\phi_o,V)$ is the probability of seeing sun glitter in the direction θ,ϕ given the sun in position θ_o,ϕ_o as a function of wind speed, and is given by

$$p(\theta,\phi,\theta_o,\phi_o,V) = 1/(\pi\sigma^2)\ \exp(\tan^2\theta_n/r^2) \qquad (9)$$

and θ_n is given by

$$\theta_n = \arccos[\cos\theta+\cos\theta_o/(2\cos\omega)] \qquad (10)$$

and ω may be obtained by

$$\cos 2\omega = \cos\theta\cos\theta_o + \sin\theta\sin\theta_o\cos(\phi-\phi_o) \qquad (11)$$

This correction can only be attempted for weak sun glitter (i.e., at the edges of intense glitter). In areas of intense sun glitter no correction is possible. Determining where this correction can apply may require human intervention since sun glitter patterns are usually determined by visual inspection. However, it may be possible to automate this procedure, and Gordon will run simulations to assess this possibility.

<u>Aerosol Radiances</u>

Correction for aerosol scattering and absorption for MODIS takes advantage of the fact that water is totally absorbing for $\lambda > 660$ nm in Case 1 waters, except near 685 nm where chlorophyll fluoresces. Thus, from Eqn. 1, $L_a(\lambda)$ is known for these wavelengths after Rayleigh radiance and sun glitter removal. $S(\lambda_1,\lambda_2)$ is the ratio of aerosol radiances at two wavelengths

$$S(\lambda_1,\lambda_2) = L_a(\lambda_1)/L_a(\lambda_2) \qquad (12)$$

and may be computed directly at those wavelengths where $L_a(\lambda)$ may be determined directly from Eqn. 1, assuming no sun glitter. $S(\lambda_1,\lambda_2)$ is related to a parameter $\epsilon(\lambda_1,\lambda_2)$ which is essentially the ratio of the aerosol optical thicknesses at these two wavelengths

$$\epsilon(\lambda_1,\lambda_2) = S(\lambda_1,\lambda_2)\ F_o'(\lambda_2)/F_o'\lambda_1) \qquad (13)$$

where $F_{o'}(\lambda)$ is the instantaneous extraterrestrial irradiance corrected for two trips through the ozone layer (Eqn. 3).

The utility of Eqn. 12 is that if ϵ can be determined for all wavelengths, then the aerosol radiances at all wavelengths may be determined by computing S and then multiplying S by the known aerosol radiance at a wavelength where water is totally absorbing (e.g. at 865 nm)

$$La(\lambda_i) = S(\lambda_i, \lambda_{865})\ L_a(\lambda_{865}) \tag{14}$$

Substituting Eqn. 13 into Eqn. 1

$$L_w(\lambda) = [L_t(\lambda) - L_r(\lambda) - L_g(\lambda) - S(\lambda, \lambda_{865}) L_a(\lambda_{865})]/t(\lambda) \tag{15}$$

Gordon (1989) proposes the following approach for determining ϵ for MODIS.

Let λ_o be a MODIS wavelength at which water is always (even in Case 2 waters) totally absorbing; 875 nm on MODIS-T or 865 nm on MODIS-N. For Case 1 waters the water-leaving radiance near 665 nm should be zero, as will the water-leaving radiance at 755 or 750 nm for all waters. At these wavelengths we know ϵ from knowledge of S and Eqn. 13. We seek ϵ at wavelengths for which the water-leaving radiance is non-zero, all the way into the blue at 410 nm. Using an Angstrom approximation, and assuming ϵ represents the ratio of aerosol optical thicknesses at two wavelengths, we assume

$$\epsilon(\lambda_i, \lambda_o) = (\lambda_i/\lambda_o)^{\eta(\lambda i)} \tag{16}$$

where the subscript i refers to 665 nm and 755 (or 750) nm. We generate two $\eta(\lambda_i)$'s using the ratios of $\lambda(665)$ and $\lambda(750)$ to λ_o. The method of extrapolation of these $\eta(\lambda_i)$'s to shorter wavelengths is undetermined, but for the CZCS it was assumed that η of shorter wavelengths was the mean of the η's at higher wavelengths. Thus,

$$\eta(\lambda_i) = (\eta(\lambda_{665}) + \eta(\lambda_{750}))/2 \tag{17}$$

We can now compute $\epsilon(\lambda_i, \lambda_o)$ for i = all wavelengths from Eqn. 16 and then $S(\lambda_i, \lambda_o)$ from Eqn. 13. Since $L_a(865)$ is known, $L_a(\lambda_i)$ is known from Eqn. 13. The important point here is that, unlike the CZCS, the aerosol type (characterized by ϵ) can be determined at each pixel, thus minimizing errors associated with assuming a constant aerosol type in an entire scene. For Case 2 waters, Eqn. 17 cannot be used because $L_w(665)$ is not necessarily zero. In such case, either the η computed using only the 750 band will have to be used, or some other method sought.

Determination of the aerosol radiances is subject to three fundamental assumptions: 1) that the water-leaving radiance is zero for $\lambda > 660$ nm, 2) that the aerosols follow the Angstrom wavelength dependence, and 3) that the aerosol optical thickness is < 0.6. The first of these assumptions is validated by observation, except in the cases of significant suspended sediment, coccolithophores, or chlorophyll fluorescence, for which significant water-leaving radiance between 660 and 690 nm may be present. Usually these waters will be classified as Case 2 and extrapolation of Angstrom exponents will have to be made based on the exponent determined for $\lambda_{750}/\lambda_{865}$ (i.e., assumed spectrally constant). Such waters, however, usually constitute < 10% of the oceanic area. The second assumption, that Angstrom's formulation is valid, may be suspect in some instances, but generally it has been found to be representative for most aerosols. The third assumption, that $\tau_a(\lambda)$ be < 0.6, is usually ensured through the cloud-flagging process, which removes from processing not only cloudy pixels, but also those with large haze concentrations.

Water-Leaving Radiances Computation

All terms in Eqn. 1 are now known except $t(\lambda)$ and $L_w(\lambda)$. The water-leaving radiance will be revealed once $t(\lambda)$, the diffuse atmospheric transmittance is computed. The expression is

$$t(\lambda) = \exp[-(\tau_r(\lambda)/2 + \tau_{oz}(\lambda)]/\cos\theta \qquad (18)$$

where $\tau_r(\lambda)$ is the Rayleigh optical thickness and $\tau_{oz}(\lambda)$ is the ozone optical thickness. Eqn. 1 may now be solved for $L_w(\lambda)$.

The method for computing $L_w(\lambda)$ (i.e., correcting the radiance signal for atmospheric contributions) for MODIS is substantially simpler than for the CZCS. This is because the Near IR bands on MODIS will allow a pixel-by-pixel estimation of aerosol radiance, and avoid the required assumption in the CZCS that the aerosol type does not change substantially over a scene. This pixel-by-pixel aerosol correction will also improve the accuracy of water-leaving radiance from MODIS, which for the CZCS was ≈ 10%, thereby allowing more accurate estimates of pigment concentrations. However, although the MODIS atmospheric correction algorithm is simpler in design, it requires substantially more computations per pixel than the CZCS.