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# OCEAN OBSERVATIONS WITH EOS/MODIS:

## Algorithm Development and Post Launch Studies

Howard R. Gordon
University of Miami
Department of Physics
Coral Gables, FL 33124

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## 1. Atmospheric Correction Algorithm Development

### a. Task Objectives:

During CY 1994 there are five objectives under this task:

(i) Investigate the effects of stratospheric aerosol on the proposed correction algorithm, and investigate the use of the 1380 nm MODIS band to remove the stratospheric aerosol perturbation.

(ii) Investigate the effect of vertical structure in aerosol concentration and type on the behavior of the proposed correction algorithm.

(iii) Investigate the effects of polarization on the accuracy of the algorithm.

(iv) Improve the accuracy and speed of the existing algorithm.

(v) Investigate removal of the $O_2$ "A" absorption band at 762 nm from the 765 nm SeaWiFS band so the latter can be used in atmospheric correction of SeaWiFS. The importance of this to MODIS is that SeaWiFS data will be used extensively to test and improve the MODIS algorithm. Thus it is essential that the $O_2$ absorption be adequately dealt with for SeaWiFS. [This work is funded mostly from sources other than MODIS; however, by virtue of its importance and the fact that some MODIS funding (and use of the TMCF) was involved, it is included in this report.]

### b. Work Accomplished:

(i) We have completed the addition of a third layer to our radiative transfer code to include stratospheric aerosols. A literature search was carried out and three stratospheric aerosol models were selected representing a background stratospheric aerosol, a fresh volcanic aerosol, and an aged volcanic aerosol. Computations of the optical properties of the aerosol were carried out and radiative transfer simulations have been started. The third layer in the model contains the stratospheric aerosol. To simulate the radiance observed in the 1380 nm band we use a single layer in our code and omit the Fresnel-reflecting sea surface. This in effect assumes that all of the photons that penetrate through the stratospheric aerosol are absorbed by water vapor in the free troposphere. In the absence of an accurate code that can carry out line-by-line multiple scattering computations in the water vapor band we are forced to make this simplifying assumption. We have developed a line-by-line code for other purposes (see item (v) below) and will investigate the possibility of adapting it to this water vapor band.

The stratospheric aerosol contributes to the reflectance at all of the MODIS ocean bands. As much as possible of this contribution should be removed from the visible and NIR bands before applying the atmospheric correction. The analysis of our initial computations is being carried out in the following manner. It is assumed that the reflectance at 1380 nm is totally from the stratospheric aerosol. The atmospheric correction algorithm, as presently implemented, is then operated in four ways. First, the reflectances at 765 and 865 are used in the algorithm as usual, i.e., no attention is paid to the fact that a stratospheric aerosol may be present, and the error in the atmospheric correction at 443 nm is determined. Second, the stratospheric aerosol is incorporated into the algorithm by simply subtracting the reflectance at 1380 nm from those at 443, 765, and 865, inserting the latter two into the correction algorithm and determining the error in the correction. Third, it is assumed that the spectral variation of the optical thickness of the stratospheric aerosol is known (either from an instrument like SAGE or from measurements from the surface) and the reflectance at 1380 nm is scaled by the ratio of the stratospheric optical depth at the given wavelength to that at (or in the case of surface measurements, near) 1380 nm. The scaled reflectances are then subtracted from the reflectances of the other bands, which are then inserted into the correction algorithm and the error in the correction at 443 nm determined. Fourth, it is assumed that measurements of the scattering phase function at each wavelength along with the spectral variation of the optical depth are available for the stratospheric aerosol. The reflectance at 1380 nm is then scaled by the ratio of the single-scattered stratospheric aerosol reflectances at 1380 and the other wavelengths, and the scaled reflectances are subtracted from the reflectances in the visible and NIR, which are then used in the correction algorithm. The preliminary results for a case where 25% of the aerosol optical thickness is from the stratosphere suggest that some, and sometimes significant, improvement is possible with the third and fourth procedure. The second procedure does not seem to appreciably reduce the error over the first procedure, which can result in reflectance errors as large as +0.005 for a total aerosol optical thickness of only 0.2 at 865 nm.

(ii) A Monte Carlo code employing a 50-layer atmosphere has been developed to carry out this investigation. To realistically treat the aerosol in the code, we divide the atmosphere into four broad regions: (1) the marine boundary layer from the surface to 2 km, where the aerosol concentration is independent of altitude; (2) the free troposphere, where the aerosol concentrations varies in proportion to $\exp[-z/h]$, where $z$ is the altitude (2-12 km) and $h$ (the scale height) is 2 km; (3) the background stratosphere (12-30 km), where the aerosol concentration is also exponential with a scale height of 5 km; and (4) a volcanic region (20-25 km) within the stratosphere which can contain a uniformly mixed volcanic aerosol. The optical properties of each of the four regions can be characterized by individual aerosol models, and any of the regions can be free of aerosols if desired.

The models for the two lower regions are taken from Shettle and Fenn.[1] Briefly, based on size distribution and composition measurements they developed two models with log-normal size distributions called the Tropospheric (to model the aerosol in the free troposphere — few large particles) and the Oceanic (to model the aerosol produced by sea spray — few small particles). They combined these to form the Maritime model to represent the aerosol in the marine boundary layer. In terms of total aerosol number per unit volume the Maritime model consists of 99% Tropospheric and 1% Oceanic. Gordon and Wang[2] added a Coastal model (99.5% Tropospheric and 0.5% Oceanic) to provide a description of the aerosol that might be more representative of the boundary layer near the coast.

For the two upper regions we use a model for the background stratosphere from the WMO[3] and for the volcanic aerosol from King et al.[4] Both models assume a 75% solution of $H_2SO_4$. We have also included a volcanic ash model[3] to represent fresh volcanic aerosol. The size distributions in these regions are modified gamma distributions.

The code contains provision for a wind-roughened sea surface with a surface slope distribution governed by the Cox an Munk[5] probability density function. As described below in (v), it is also possible to carry out line-by-line multiple scattering computations within absorption bands. Our comparisons of simulations using this code on problems also solvable with our existing successive order of scattering codes suggest that reflectances can be computed with an error $\lesssim \pm 0.1\%$. The

Monte Carlo code will be used to carry out our investigation of the effects of vertical structure, and when polarization is added will be used to create the most realistic MODIS pseudo data for atmospheric correction thus far. We envisage that it will be a testbed for the performance and further development of MODIS algorithm.

In our initial exercising of the code we compared its output with that of the three-layer code with the same vertical structure., i.e., the same mix of aerosol and Rayleigh scattering in each region and the same aerosol model in each region. The two codes agreed to better than 0.1%. When all of the aerosol was placed in the lower layer as is the case for the preparation of our atmospheric correction lookup tables, differences up to 1% were observed at 443 nm between the 50-layer and the two-layer codes. These observations lead us to believe that the lookup tables that we have produced — based on over 33,000 radiative transfer simulations — will not be satisfactory for atmospheric correction if there is a significant aerosol concentration in the free troposphere.

(iii) We have yet to add polarization to the simulation code described in the previous section.

(iv) In the implementation of our correction algorithm, extensive lookup tables are required for each aerosol model we employ. These give radiances for the various viewing directions and solar positions. The viewing and solar azimuths are incorporated via a Fourier transform (series). [For a complete description, see the MODIS water-leaving radiance ATBD.] We have started to investigate the use of azimuthal interpolation in place of the Fourier transform. This will increase the size of the tables; however, it may increase the speed. Also, originally the radiances for eight aerosol optical depths were fit to a simple linear expression in optical depth. We found that the fit was greatly improved by using a quadratic expression in place of the linear. In the implementation using the Fourier transform, this increases the size of the lookup tables by 50%.

(v) To simulate radiative transfer in the $O_2$ absorption, we modified our code so that line-by-line computations could be carried out. What we wish to learn is the influence of the $O_2$ absorption on the radiance or the reflectance leaving the top of the atmosphere (TOA) in a band extending from 745 to 785 nm (SeaWiFS band 7). Specifically, since the proposed SeaWiFS/MODIS algorithm ignores the $O_2$ absorption, our goal is to be able to estimate what the TOA radiance would be in the absence of the absorption band.

The $O_2$ A band extends from about 759 to 770 nm and consists of 286 individual absorption lines[6] with appreciable strengths. Because of the strong variation of the absorption coefficient with wavelength, the absorption over a band containing several lines will not be an exponential function of the path length. Thus, it is not possible to assign a single mean absorption coefficient to the entire $O_2$ A band. Furthermore, since the individual spectral lines are pressure and temperature broadened, even at discrete wavelengths, i.e., bands with width $\ll$ the width of the individual spectral lines, the absorption coefficient will be dependent on altitude in the atmosphere. Thus, a complete treatment of the radiative transfer in this absorption band requires an atmosphere consisting of several layers in which the absorption coefficient is a very strong function of frequency.

It is possible to understand qualitatively the effect of the $O_2$ A band on the radiance exiting the top of the atmosphere by examining single scattering. First, we assume that the atmosphere is free of aerosols, i.e., we only have Rayleigh scattering and the scattering coefficient will vary with altitude in proportion to the pressure in the same manner as the $O_2$ abundance. For a given viewing geometry we define the air mass $M$ as

$$M \equiv \frac{1}{\cos\theta_v} + \frac{1}{\cos\theta_0},$$

where $\theta_0$ is the solar zenith angle and $\theta_v$ is the viewing angle, i.e., the angle between the surface normal and the direction of propagating of the radiance exiting the TOA. In the single scattering approximation, photons scattering from molecules at any altitude will have traversed a path of length proportional to $M$ upon exiting the atmosphere. Thus, we expect the *decrease* in radiance exiting the atmosphere to be a function of $M$; albeit *not* an exponential function. In the case of multiple scattering the path of the photon is no longer proportional to $M$ so a similar argument does not apply; however, since the Rayleigh optical thickness is small (0.0255) at 765 nm , for the most part, multiple Rayleigh scattering will be negligible and the radiance decrease will still depend on $M$ in much the same manner as for single scattering.

The addition of aerosols causes two complications: the aerosol concentration is a strong and variable function of altitude; and the aerosol concentration is usually sufficiently high that multiple scattering is significant. The influence of the vertical profile of aerosol concentration is easy to understand in the single scattering approximation. Typically, over the oceans most of the aerosol is in the marine boundary layer which is 1-2 km thick. The aerosol component of the TOA radiance at 765 nm with a high concentration of aerosol in the boundary layer will be significantly larger than the molecular-scattering component. This radiance will have had to travel through most of the atmosphere (twice) before reaching the TOA. The total path is proportional to $M$, so we expect that the radiance decrease will be larger than in the case of an aerosol-free atmosphere (because more of the detected photons will have had to travel farther in the atmosphere) and a function of the air mass. In contrast, if there is a high concentration of aerosol in the stratosphere, e.g., following a major volcanic eruption, a fraction of the TOA radiance will have scattered from the stratosphere and not have traveled through a significant portion of the atmosphere. In this case, for the same aerosol concentration in the marine boundary layer, the fractional decrease in the radiance due to the $O_2$ absorption will be less.

We are presently operating the code with the goal of providing a means of dealing with the effects of the $O_2$ absorption in a rational manner.

### c. Data/Analysis/Interpretation:

See item **b** above.

### d. Anticipated Future Actions:

(i) We will continue our analysis of the existing simulations from the three-layer code to try to understand how to utilize the 1380 nm MODIS band to eliminate the influence of stratospheric aerosol. New simulations will be carried out for a variety of stratospheric aerosol types. We will investigate the addition of a line-by-line treatment of water vapor to our MODIS simulation code to provide simulations in the 1380 nm band for understanding the depth to which this band can "see" into the free troposphere as a function of the water vapor concentration and profile.

(ii) We will exercise our 50-layer MODIS simulation code to provide a better understanding of the influence of the aerosol's vertical profile (in concentration and in type) on the reflectance at the top of the atmosphere. In this way we will determine the required inputs into the three-layer radiative transfer code for the preparation of atmospheric correction lookup tables.

(iii) We will begin work on the addition of polarization to our MODIS simulation radiative transfer code. Our goal is to have a validated code during this calendar year.

(iv) We will supply R. Evans with a new set of lookup tables and access subroutines to see the effect of azimuthal interpolation (as opposed to Fourier transformation) on the operation of the SeaWiFS — the MODIS prototype — atmospheric correction code.

(v) We will continue studying the influence of the $O_2$ absorption on the operation of the SeaWiFS atmospheric correction algorithm. We expect to complete the study during this calendar year.

**e. Problems/Corrective Actions:**

(i) None.

(ii) Our initial simulations using the MODIS simulation code suggests that a single set of lookup tables based on an assumed simple vertical profile for the aerosol will not be sufficient to process the data. For example, African dust carried over the Tropical Atlantic is not in the boundary layer as assumed in the lookup tables; a separate set of tables must be used to deal with such situations. Similar problems arise from the presence of strongly absorbing aerosols, which are not in the basic set of models utilized in the present tables, and the presence of volcanic aerosol in the stratosphere, which are absent as well. Thus, the inescapable conclusion is that the lookup tables will have to be regenerated many times using different assumptions in order to be prepared to deal with most of the scenarios known to exist.

Regeneration of the lookup tables is a formidable task. The individual simulations require approximately 10 minutes on the DEC 3000/400. Thus, 33,000 simulations would require approximately 5500 hours, or approximately 230 days (7.5 months). Utilizing the four existing CPU's on a 24-hour basis would reduce the computation time to about 2 months. This is unacceptable for many reasons. First if the computers are being used for routine lookup table generation no other research can be carried out. Next, the lookup tables will have to be regenerated many times not just once, so the computers would rarely be available for other aspects of the algorithm development. Finally, after launch of SeaWiFS and processing of the initial data is complete, we will be required to generate the necessary new sets of tables in a very timely manner, i.e., 1-2 weeks not several months. We can meet this need with two DEC Sable 2100 systems, one of which we propose to procure with calendar year 1994 funding and one with 1995 funding.

The DEC Sable 2100 system has four processors each of which is approximately twice as fast as the DEC 3000/400 CPU. Thus, with one Sable 2100 a single set of lookup tables could be generated in one month and with two Sables the generation time would be two weeks. We plan regular CPU upgrades of the Sables, so by the launch of MODIS the speed should be considerably faster which will allow us to respond to unforseen events in a timely manner.

Under this plan the four existing DEC 3000/400 work stations will always be available for basic algorithm studies, as will the Sables, when not generating tables. The Sables will form the backbone of the Team Member's Computing Facility to be used for post-launch MODIS products.

(iii) None.

(iv) None.

(v) None.

**f. Publications:**

H.R. Gordon and M. Wang,"Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm." *Applied Optics*, **33**, 443—452 (1994).

K. Ding and H.R. Gordon, "Atmospheric correction of ocean color sensors: Effect of earth curvature." *Applied Optics* (Accepted).

## 2. Whitecap Correction Algorithm.

### a. Task Objectives:

As described in our last Semi-Annual Report, financial constraints prevent our carrying out a whitecap study of the scope originally proposed. Since our recent analysis suggested that it is neither possible nor important to have a precise prediction of the reflectance increase of the ocean due to whitecaps, i.e., errors of the order of 0.002–0.004 can be tolerated, we considered abandoning our experimental whitecap program completely. However, to assure acceptance of an atmospheric correction that utilizes the whitecap removal procedure as one component, we believed that some validation of the whitecap algorithm was necessary. Thus, we decided to limit our effort to trying to collect sufficient whitecap data to validate in a coarse manner the correction model that we developed based on a survey of the literature.

### b. Work Accomplished:

A requisite part of our reduced effort is development of a radiometer that can be used in a simple manner to measure the whitecap reflectance from a ship. We considered several alternatives from a video camera located high on the ship to a radiometer near the surface. We settled on a downward looking, narrow field-of-view, three-band radiometer operated on a long boom from the ship. The radiometer would record the reflectance of a spot of the order of 10 cm in diameter on the sea surface in a continuous manner. It will be boresighted with a video camera so interference from other sources, e.g., sun glitter, can be eliminated from the data. The radiometer will record open water and water covered by foam resulting from whitecaps in various stages of their lifetime. The background return from the clear water will provide the whitecap-free reflectance. The average reflectance *above* the background will provide the *average* reflectance *enhancement* of the ocean due to whitecaps. A self contained meteorology package will determine the speed of the ship relative to the air. A GPS unit will provide the speed of the ship. From the two we can determine the true wind speed. Thus we should be able to obtain the reflectance increase as a function of the wind speed for algorithm validation.

We have requested permission from NASA to obtain the required data acquisition system, meterological package, and GPS. And will start procurement and assembly when permission is granted. Our goal is to have a completed system during the present calendar year.

**c. Data/Analysis/Interpretation:** None.

**d. Anticipated Future Actions:** See item b.

**e. Problems/Corrective Actions:** See item a.

**f. Publications:**

A paper " Influence of whitecaps on atmospheric correction of ocean color sensors," by H.R. Gordon and M. Wang has been revised and resubmitted to *Applied Optics*.

## 3. In-water Radiance Distribution.

**a. Task Objectives:**

Acquire radiance data at sea.

**b. Work Accomplished:**

Radiance camera is now basically complete.

**c. Data/Analysis/Interpretation:** None.

**d. Anticipated Future Actions:**

Acquire data at sea at the earliest opportunity. This will most likely be a cruise scheduled by Dennis Clark in November 1994.

**e. Problems/Corrective Actions:** None.

**f. Publications:** None.

## 4. Residual Instrument Polarization.

**a. Task Objectives:** None.

## 5. Direct Sun Glint Correction.

**a. Task Objectives:** None.

## 6. Prelaunch Atmospheric Correction Validation.

**a. Task Objectives:**

The objectives of this task are two fold. First, we need to demonstrate that our atmospheric correction scheme will work to the required accuracy. To effect this we will apply the algorithm to compute the sky radiance in the blue from measurements in the near infrared. We should be able to do this to about the same accuracy as looking downward from space. Second, we need to study the properties of aerosols over the ocean, in particular the aerosol phase function and its spectral variation, in order to verify the applicability of the aerosol models on which we are basing the atmospheric correction. Since we will be able to test the algorithm with SeaWiFS data, we believe that the second task is the more important.

To effect these requires instrumentation for measuring the sky radiance and the optical thickness of the atmosphere. Such instrumentation is available in our laboratory and has been modified to operate with the relevant MODIS spectral bands. Our near-term objective is to learn how to invert sky radiance to obtain aerosol optical properties, to carry out such inversions, and to study the variation of the phase function with wavelength .

**b. Work Accomplished:**

We planned and executed a field trip to Key West, FL in April to obtain sky radiance and other aerosol data. Key West is a small island and was chosen to simulate as much as possible measurements made from a ship, i.e., to reduce the perturbation by the land as much as possible.

The planned measurements included (1) aerosol optical thickness as a function of wavelength in nine bands from 380 to 1026 nm, (2) sky radiance using the full-sky camera at 560, 671, and 860 nm, and (3) sky radiance at selected positions using a hand-held radiometer at 558, 669, and 866 nm. The weather was less than ideal and only one day was sufficiently clear to yield data worth trying to analyze.

**c. Data/Analysis/Interpretation:** Nothing concrete yet.

**d. Anticipated Future Actions:**

We are beginning the analysis of the one day of useful sky imagery obtained at Key West for the aerosol optical properties. To retrieve the aerosol properties, a nearly perfectly cloud-free sky is required. We hope this analysis will allow us to identify the significant experimental and computational problems involved in the retrieval process and to begin to address them.

We are continuing our design of a solar aureole camera and hope to be able to request permission from NASA to build it during this calendar year.

Because of the importance to atmospheric correction of obtaining columnar aerosol data over the oceans, we have decided to operate a site for acquisition of such data over the water near South Florida. Thus, we have requested permission to purchase a CIMEL Electronique, Automatic Sun Tracking Photometer, a Vitel Inc. GOES Data Transmitter with accessories, and a set of Solar Power Panels. We will fabricate these items together as an automated sky scanning radiometer system (ASSR). The major component of the ASSR is the CIMEL radiometer. This radiometer is a one-of-a-kind instrument which automatically carries out spectral sky radiance measurements in specific planes relative to the sun, along with direct solar irradiance measurements. When equipped with solar panels for power, it can accomplish this in an unattended mode, and thus be used in remote locations. The CIMEL radiometer is equipped with an interface for a Vitel GOES data link, which allows the measurements to be transmitted from the remote field station to the laboratory. Several instruments identical to that requested are presently being used successfully by GSFC personnel (Kaufman and Holben) to perform aerosol studies over remote land areas, e.g., Central

Brazil. As such, a complete software system has been developed by them for data reduction and analysis. By duplicating their instrumentation we save the cost of developing the data system and analysis software.

**e. Problems/Corrective Actions:** None.

**f. Publications:** None.

## 7. Detached Coccolith Algorithm and Post Launch Studies.

**a. Task Objectives:**

The algorithm for retrieval of the detached coccolith concentration from the coccolithophorid *E. Huxleii* is described in detail in our ATBD. The key is the backscattering coefficient of the detached coccoliths. These have been measured for *E. Huxleii* and a few measurements have been made for other species. It is found that the coccolith-specific backscattering coefficient has a strong dependence on species; however, the calcite-specific backscattering coefficient shows much less species dependence. We need to quantify this relationship further. There is also a relationship between the growth phase of the cells and the rate of detachment of the coccoliths which needs to be further quantified. With this in mind, the objectives of our coccolith studies are, under conditions of controlled growth of coccolithophores (using chemostats), to define the effect of growth rate on:

(i) the rate at which coccoliths are produced;

(ii) on the morphology of coccoliths;

(iii) the rate that coccoliths detach from cells (this is also related to turbulence conditions, so our chemostats have carefully controlled mixing with quantifiable shear and turbulence); and

(iv) optical properties of coccoliths (such as the calcite-specific backscatter coefficient).

Finally, we will perform shipboard measurements of suspended calcite and associated optical backscatter as validation of the laboratory measurements.

A thorough understanding of these growth-related properties will provide the basis for a generic suspended calcite algorithm. As with algorithms for chlorophyll, and primary productivity, the natural variance between growth related parameters and optical properties needs to be understood before the accuracy of the algorithm can be determined.

**b. Work Accomplished:**

MODIS-sponsored research has only just begun on this work and we have no progress to report.

**c. Data/Analysis/Interpretation:** None.

**d. Anticipated Future Actions:**

Experiments are currently under way to examine objectives (i)-(iv) using a chemostat with controlled turbulence ("Turbulostat"). These experiments will be ongoing through the Fall.

**e. Problems/Corrective Actions:** None

**f. Publications:** None

## 8. Other Developments.

The PI and other personnel on the project devoted virtually all of their effort on the project in January and February toward revising the Algorithm Theoretical Basis Document (ATBD) for normalized water leaving radiance. The ABTD's for Normalized water-leaving radiance (along with aerosol products) and detached coccoliths were delivered to M. King on February 28, 1994. The algorithms were subjected to a standup peer review on May 10, 1994.

## 9. References.

[1] E. P. Shettle and R. W. Fenn, *Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties* (Air Force Geophysics Laboratory, Hanscomb AFB, MA 01731, AFGL-TR-79-0214, 1979).

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[3] WCP–112, *A preliminary cloudless standard atmosphere for radiation computation* (World Meteorological Organization, WMO/TD–No. 24, Geneva).

[4] M. D. King, Harshvardhan and A. Arking, "A Model of the Radiative Properties of the El Chichón Stratospheric Aerosol Layer," Journal of Climate and Applied Meteorology **23**, 1121–1137 (1984).

[5] C. Cox and W. Munk, "Measurements of the Roughness of the Sea Surface from Photographs of the Sun's Glitter," Jour. Opt. Soc. of Am. **44**, 838–850 (1954).

[6] L. S. Rothman, R. R. Gamache, A. Barbe, A. Goldman, J. R. Gillis, L. R. Brown, R. A. Toth, J. -M. Flaud and C. Camy-Peyret, "AFGL atmospheric absorption line parameters compilation: 1982 edition," Applied Optics **22**, 2247–2256 (1983).