SEMI-ANNUAL REPORT

(for January – June 1998)

Contract Number NAS5–31363

OCEAN OBSERVATIONS WITH EOS/MODIS:

Algorithm Development and Post Launch Studies

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Semi-Annual Report (1 January – 30 June 1998) NAS5–31363

Preamble

As in earlier reports, we will continue to break our effort into six distinct units:

- Atmospheric Correction Algorithm Development
- Whitecap Correction Algorithm
- In-water Radiance Distribution
- Residual Instrument Polarization
- Pre-launch/Post-launch Atmospheric Correction Validation
- Detached Coccolith Algorithm and Post-launch Studies

This separation has been logical thus far; however, as launch of AM-1 approaches, it must be recognized that many of these activities will shift emphasis from algorithm development to validation. For example, the second, third, and fifth bullets will become almost totally validation-focussed activities in the post-launch era, providing the core of our experimental validation effort. Work under the first bullet will continue into the post-launch time frame, driven in part by algorithm deficiencies revealed as a result of validation activities. We will continue to use this format for CY98.

Abstract

Significant accomplishments made during the present reporting period:

- We completed approximately 200,000 separate radiative transfer simulations to be used in the preparation of look up tables for our improved "spectral matching" algorithm.

- We participated in the SeaWiFS Initialization Cruise (MOCE-4). All instrumentation performed well and an excellent data set was obtained.

1. Atmospheric Correction Algorithm Development.

a. Task Objectives:

During CY 1998 there are seven objectives under this task. Objectives (i) and (ii) below are considered to be the most critical. If the work planned under objective (i) is successful, a module that enables the algorithm to distinguish between weakly- and strongly-absorbing aerosols will be included in the atmospheric correction algorithm.

(i) We will continue the study of the "spectral matching" algorithm. The initial realization of the algorithm will be to provide a flag that will signal the probable presence of absorbing aerosols, and indicate that the quality of the derived products cannot be assured. Later realizations will provide an atmospheric correction in the presence of absorbing aerosols.

(ii) We need to test the basic implementation of the MODIS atmospheric correction algorithm with actual ocean color imagery. We will do this with SeaWiFS imagery.

(iii) We must implement our strategy for adding the cirrus cloud correction into the existing atmospheric correction algorithm. Specific issues include (1) the phase function to be used for the cirrus clouds, (2) the details of making two passes through the correction algorithm, and (3) preparation of the required tables. These issues will be addressed as time permits in CY 1998.

(iv) The basic correction algorithm yields the product of the diffuse transmittance and the water-leaving reflectance. However, we have shown that the transmittance depends on the angular distribution of the reflectance only when the pigment concentration is very low and then only in the blue. We need to develop a model to include the effects of the subsurface BRDF for low-pigment waters in the blue.

(v) We need to study the efficacy of the present atmospheric correction algorithm for removal of the aerosol effect from the measurement of the fluorescence line height.

(vi) We need to examine methods for efficiently including earth-curvature effects into the atmospheric correction algorithm. This will most likely be a modification of the look-up tables for the top-of-the-atmosphere contribution from Rayleigh scattering.

(vii) We will examine the necessity of implementing out-of-band corrections to MODIS.

b. Work Accomplished:

(i) We consider this task to be one of our most important atmospheric correction activities of 1998 [the other is item **(ii)** above: testing MODIS algorithms with SeaWiFS imagery], and as such, the major part of our effort on atmospheric correction will be focussed on it. During the first quarter, we began carrying out the necessary radiative transfer simulations required to prepare the look up tables (LUTs) for operation of the spectral matching algorithm described in the Appendix to the July-December 1997 Semi-Annual Report. In this algorithm, power-law size distributions are utilized. This allows us to use straightforward interpolation to size distributions and particle compositions (index of refraction) that are not part of the candidate set. We also interpolate on the real and imaginary parts of the complex refractive index. Thus, a complete spectrum of models can be generated from a relatively small candidate set. We then use standard optimization techniques to find the best fitting set of parameters.

Thus far approximately 200,000 separate radiative transfer simulations have been completed. This effort consumed much of our and R. Evans' computer resources during the first quarter. The LUTs resulting from these simulations can also be used in the standard atmospheric correction algorithm if desired. Experience with these computations convinced us that we needed more computational resources. Procurement is underway for a DEC AlphaServer 4100.

In addition, we found in the examination of the data acquired during the SeaWiFS Initialization Cruise (MOCE-4) that additional models were required for the existing algorithm. These are the "Oceanic" models of Shettle and 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)]. We have completed all of the radiative transfer simulations required to generate LUTs for these models, and they will be incorporated into the MODIS code.

(ii) We are acquiring SeaWiFS imagery on a regular basis and, with R. Evans, prepared an end-to-end test of the performance of the MODIS algorithm in its present state. To effect this we have created a set of SeaWiFS-specific LUTs, but in a format required by the MODIS code. Evans' group has reformated SeaWiFS imagery into the MODIS format and thus we can test the MODIS codes using SeaWIFS-simulated MODIS data. Thus far the tests have been successful, i.e., MODIS code running SeaWiFS data in the MODIS format reproduced well the SeaWiFS code processing SeaWiFS data.

(iii) None. In the light of the success of our spectral-matching algorithm, we may have to make significant modifications in our original strategy. This task has been put on hold to free resources for examination of task (i). The issues will be addressed during CY 1998 with the goal of having a complete implementation strategy ready during CY 1999.

(iv) No work was carried out on this task.

(v) No work was carried out on this task.

(vi) No work was carried out on this task.

(vii) We have recently received the MODIS relative spectral response (RSR) functions from MCST. These are being incorporated into the algorithms following the procedures described by Gordon (1995) ["Remote sensing of ocean color: a methodology for dealing with broad spectral bands and significant out-of-band response", Applied Optics, 34 8363-8374 (1995)].

c. Data/Analysis/Interpretation: See item **b** above.

d. Anticipated Future Actions:

(i) We will continue preparations to test the new spectral matching algorithm using SeaWiFS imagery. We expect to have successfully processed SeaWiFS imagery using this algorithm by the end of the summer.

(ii) We shall continue testing the present algorithm with SeaWiFS imagery until MODIS imagery becomes available.

(iii) None. The cirrus cloud issue in the presence of our "spectral matching" method needs to be explored. We will resolve the "spectral matching" questions first.

(iv) An ocean BRDF model is being tested by comparison with experimental data obtained at the MOBY site and during MOCE-4. This testing will continue for the rest of CY 1998. (See **5** below).

(v) None.

(vi) None.

(vii) We will (1) prepare new LUTs for the Rayleigh scattering component, (2) provide a set of Ozone absorption coefficients, (3) provide a set of weighted extraterrestrial solar irradiances, and (4) derive the functions needed to incorporate the out-of-band influence on the aerosol component of the atmospheric correction algorithm. This will be completed during the next reporting period.

f. Publications:

R. Chomko and H.R. Gordon, Atmospheric correction of ocean color imagery: Use of the Junge power-law aerosol size distribution with variable refractive index to handle aerosol absorption, *Applied Optics*, (Accepted).

2. Whitecap Correction Algorithm (with K.J. Voss).

As the basic objectives of the experimental portion of this task has been realized (acquiring whitecap radiometric data at sea), experimental work is being suspended until the validation phase, except insofar as the radiometer is being operated at sea when it is sufficiently important to do so, e.g., the SeaWiFS Initialization Cruise (MOCE-4). Our goal is to maintain experience in operating and maintaining the instrumentation in preparation for the validation phase of the contract. In addition, we need to reanalyze the Tropical Pacific whitecap data because of the surprisingly low reflectance increase due to whitecaps that we measured there. This is a unique data set (our most important), as it was acquired in the trade winds with moderately high winds (8-12 m/s) and practically unlimited fetch and duration. This will better bound the limits of oceanic whitecap reflectance.

a. Near-term Objectives:

Operate the radiometer at sea to maintain experience in preparation for the validation phase. Reanalyze data acquired during the Tropical Pacific cruise.

b. Task Progress:

A strategy has been developed that we believe will improve the analysis of the whitecap data. The radiometer was operated during the MOCE-4 cruise in support of SeaWiFS initialization whenever whitecaps were present (four of seventeen stations).

c. Data/Analysis/Interpretation: See item **b** above.

d. Anticipated Future Actions:

We will begin the reanalysis of the Tropical Pacific data with the goal of submitting a revised manuscript on whitecap reflectance by the end of the summer.

e. Publications:

K.D. Moore, K.J. Voss, and H.R. Gordon, Spectral reflectance of whitecaps: Instrumentation, calibration, and performance in coastal waters, *Jour. Atmos. Ocean. Tech.*,**15**, 496-509 (1998).

3. In-water Radiance Distribution (with K.J. Voss).

a. Task Objectives:

The main objective in this task is to obtain upwelling radiance distribution data at sea for a variety of solar zenith angles to understand how the water-leaving radiance varies with viewing angle and sun angle. In the near term, the objective was to collect radiance distributions during the SeaWiFS Initialization Cruise (MOCE-4)

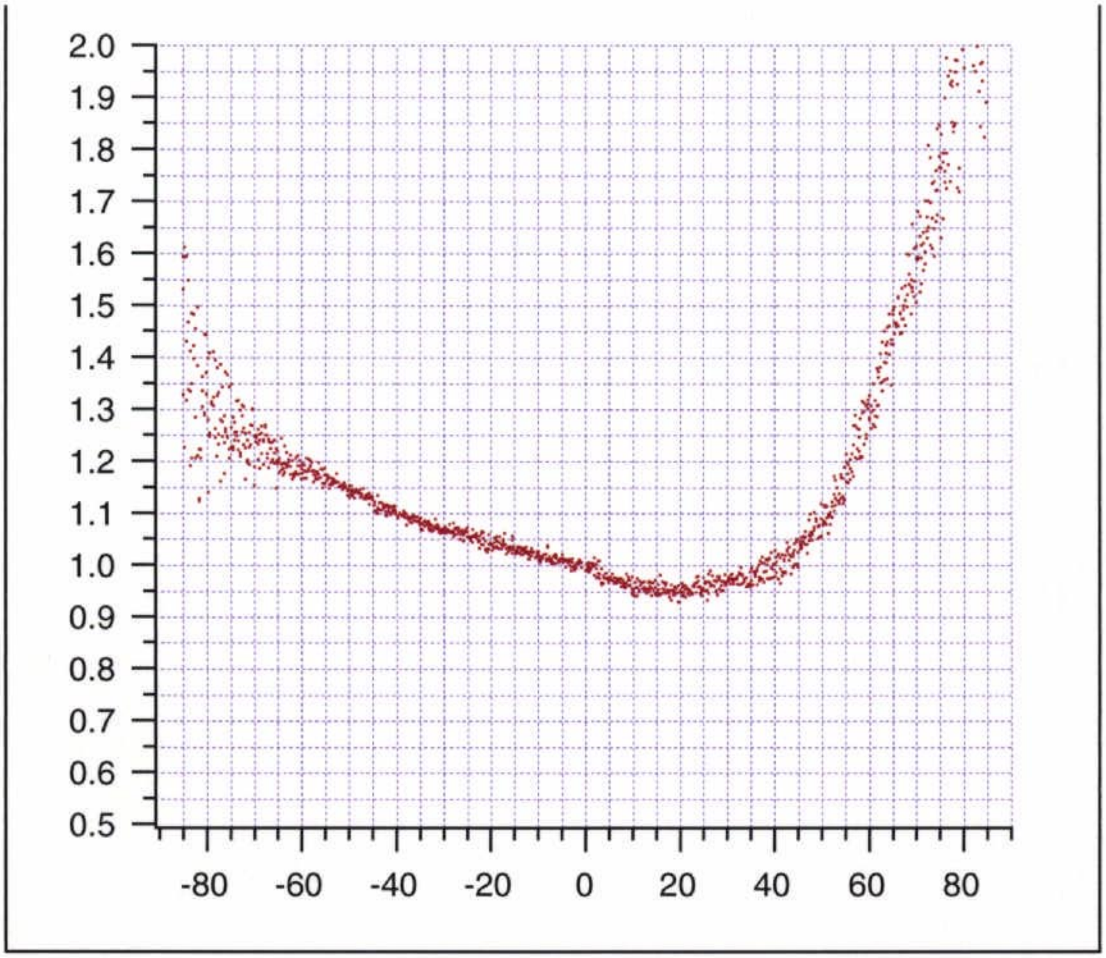
b. Work accomplished:

Data were acquired during the July 1997 Hawaii cruise with this instrument. We have reduced this data to radiometric quantities and are now working with the data. During this cruise we had an opportunity to take an extensive data set during one afternoon (July 23), in which data were acquired with sun angles varying from approximately 40°to 85°. This will give us a good data set to evaluate the effect of sun angle on the upwelling radiance distribution at the MOBY site.

Data were also acquired simultaneously with SeaWiFS overpasses at ~3/4 of the MOCE-4 cruise stations.

c. Data/Analysis/Interpretation:

Because of its importance, we suspended work on the July data in favor of the MOCE-4 data. These data have now been reduced. Since both the sun angle and water pigment concentration were essentially constant ($\approx$ 37° and 0.1 mg/m^3, respectively) during the cruise we decided to average the data obtained at each wavelength to reduce the influence of wave-induced "noise" in the measurements. The resulting radiance distributions (BRDFs) normalized to unity are provided in the figures on the next four pages for the wavelengths 440, 490, 550, and 670 nm, respectively. In each figure, the image at the bottom is a polar plot of the normalized radiance distribution, and the graph at the top represents the normalized radiance distribution in the principal plane, with the steep portion of the curve in the direction of the sun. The line across the first figure near the perpendicular plane is the approximate position of the SeaWiFS scan on the BRDF. In contrast, the MODIS scan would pass through the center of the plot. Notice that differences as large as 10% can occur between the nadir radiance and the radiance in the direction of viewing. In the last figure, the strong minimum in the principal plane opposite the sun is the shadow of the radiometer itself. This is used to locate the position of the sun in each set of images for the averaging process.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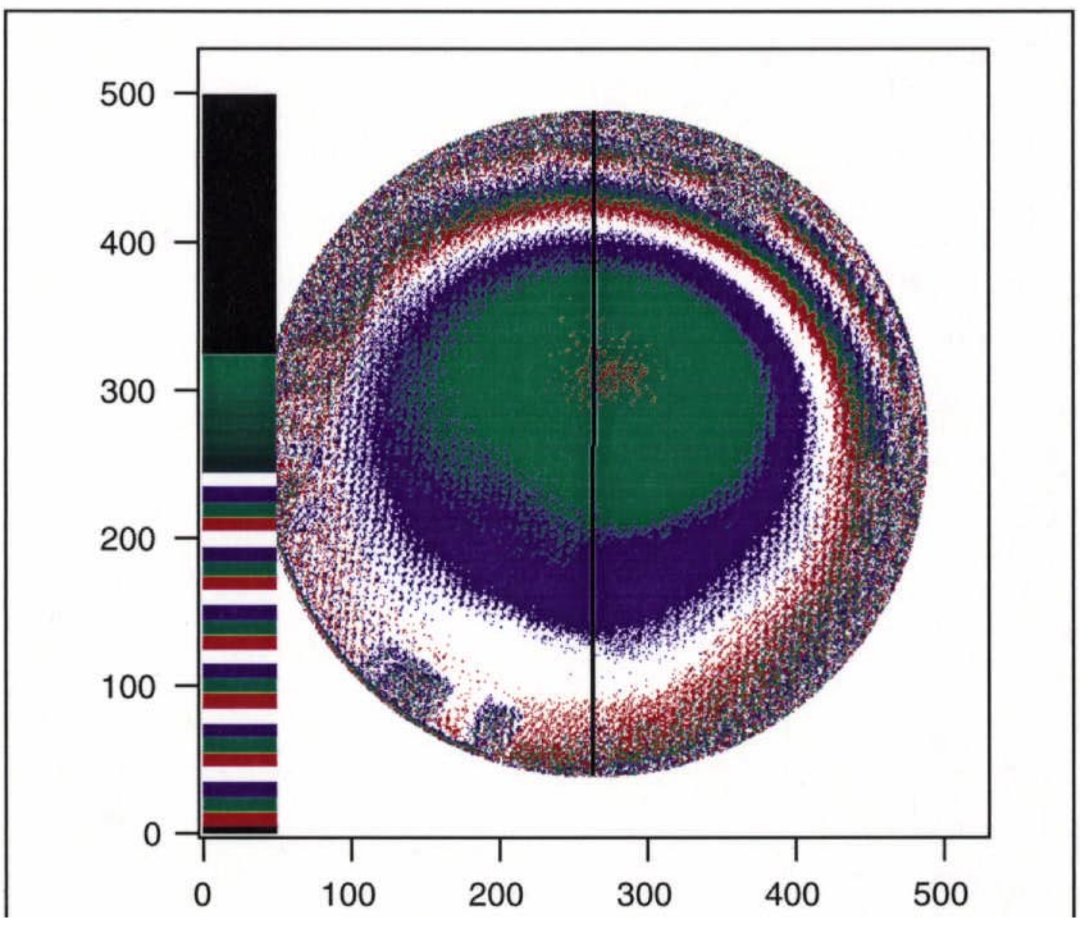
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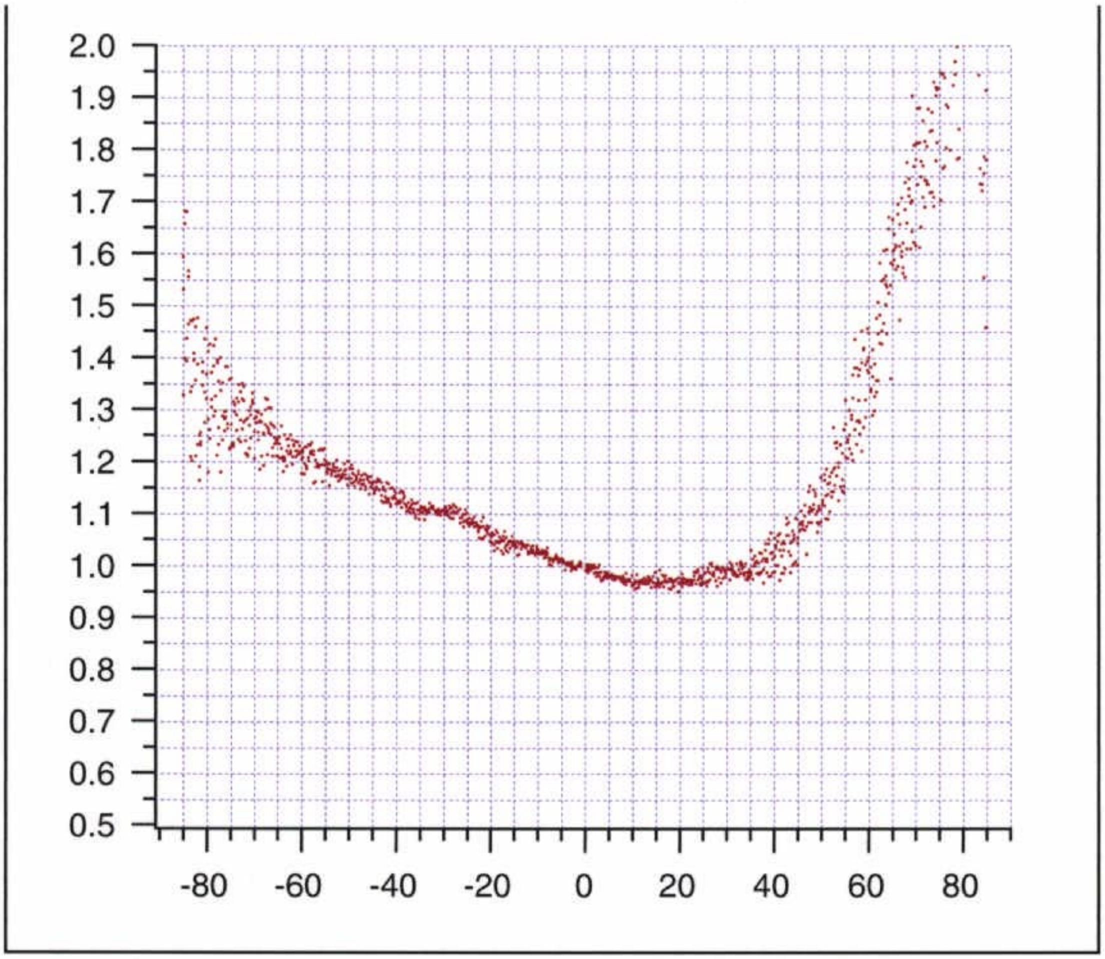

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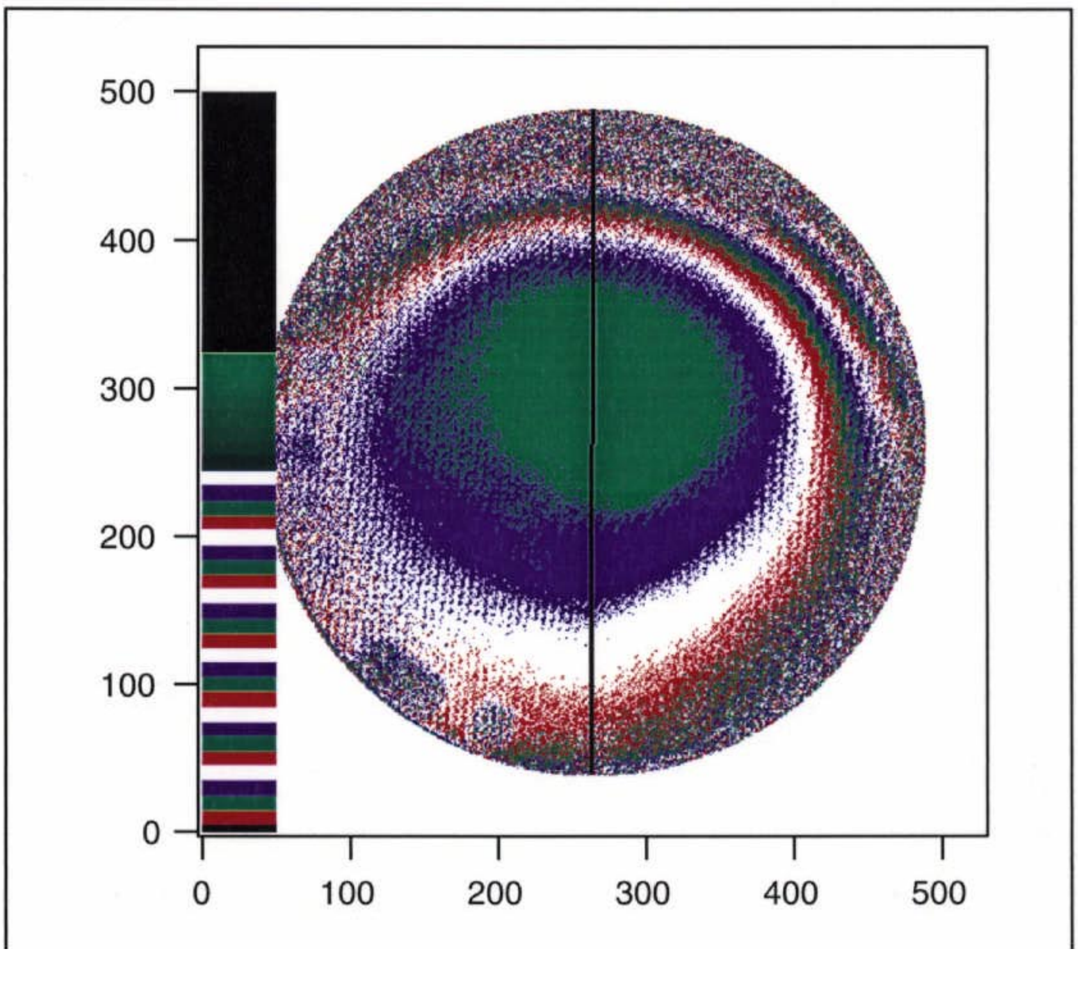

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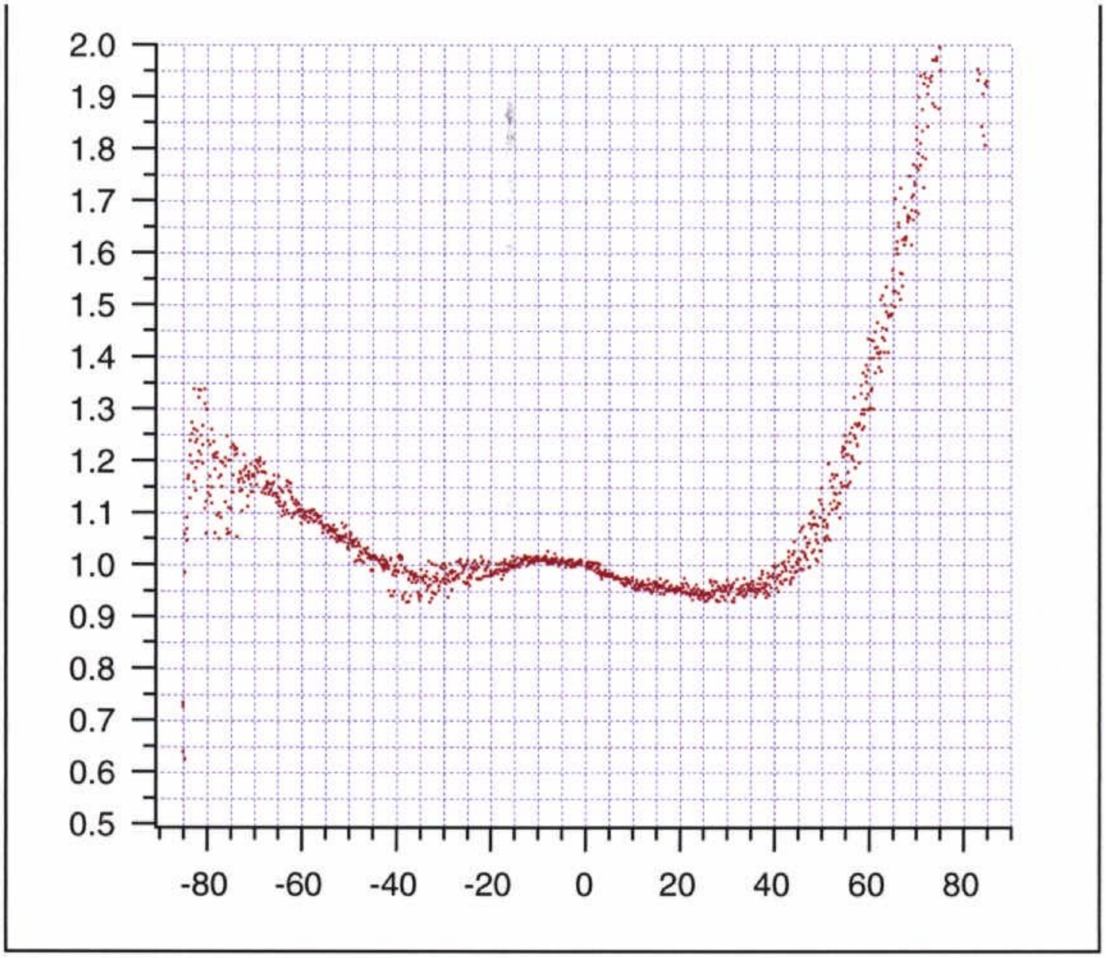

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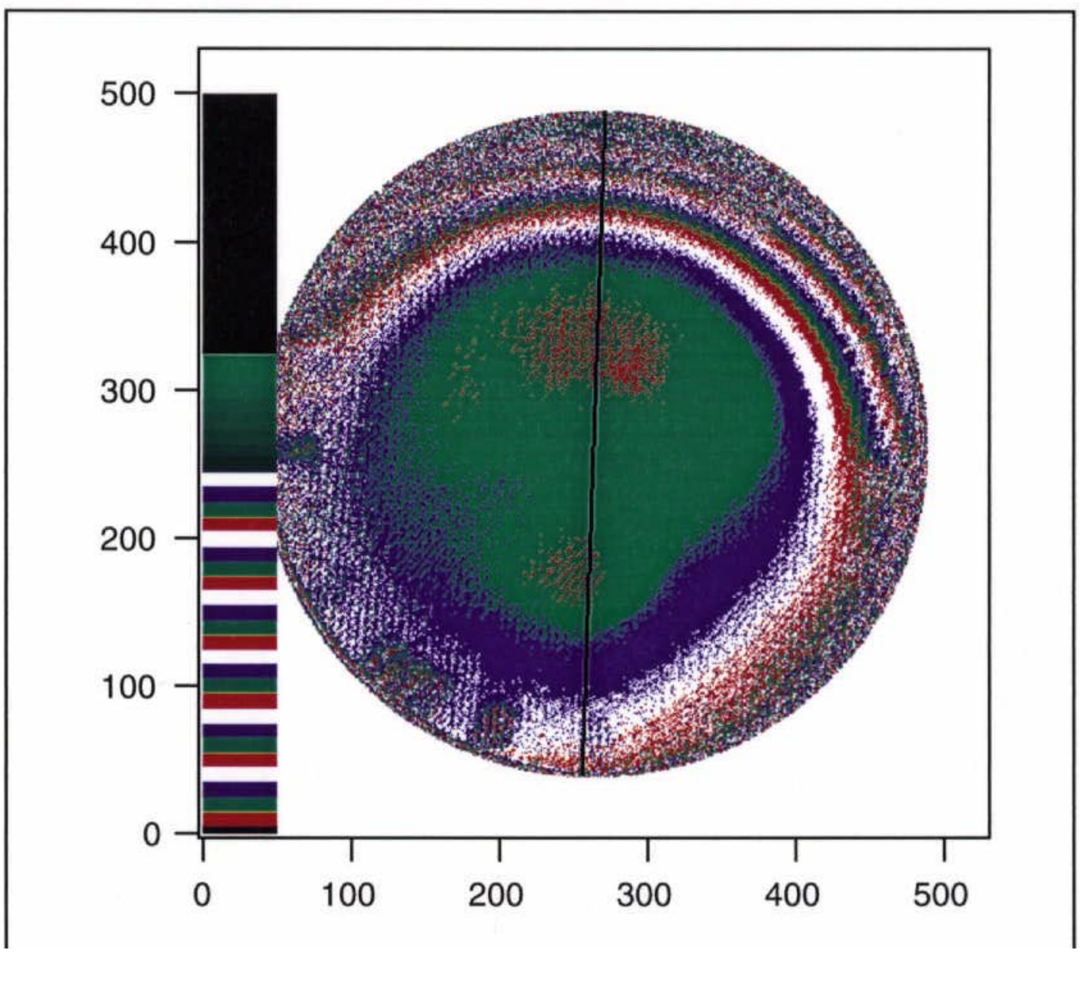

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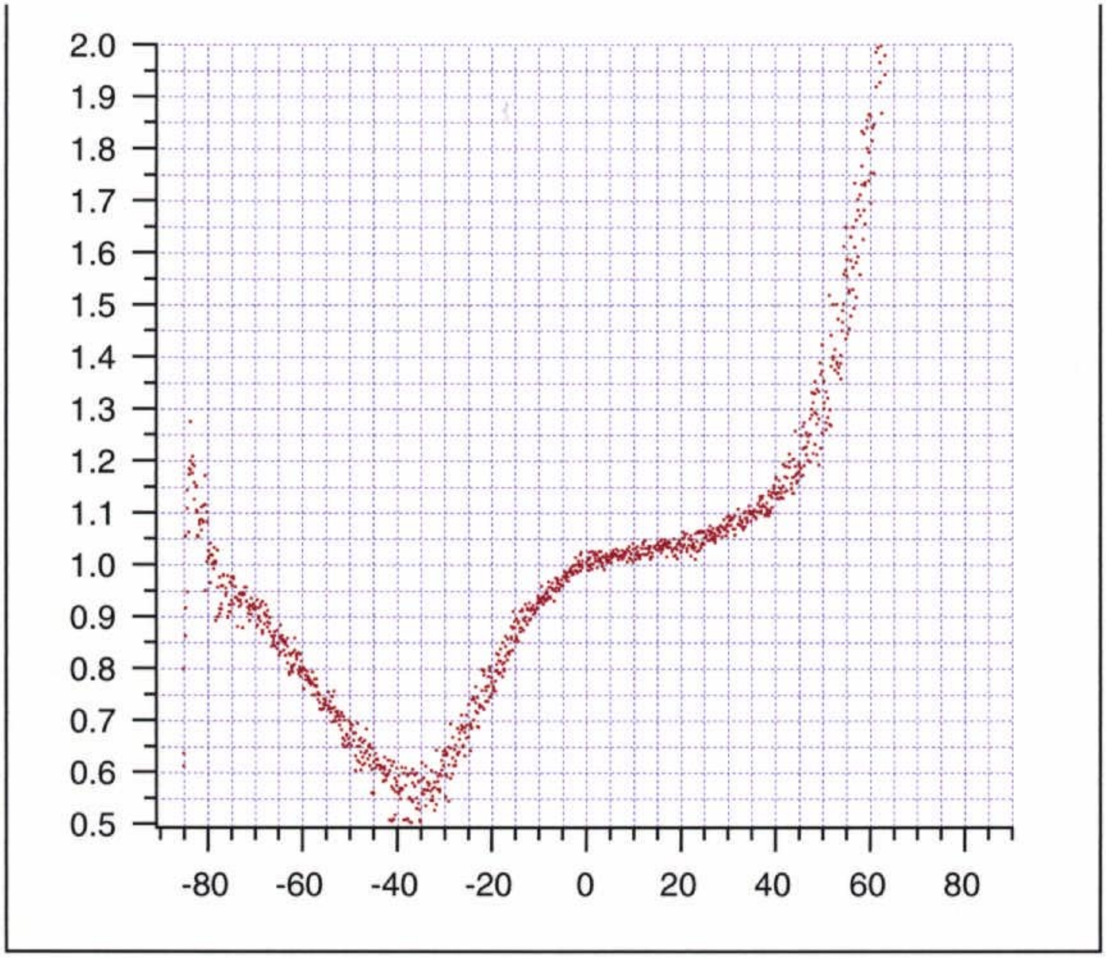
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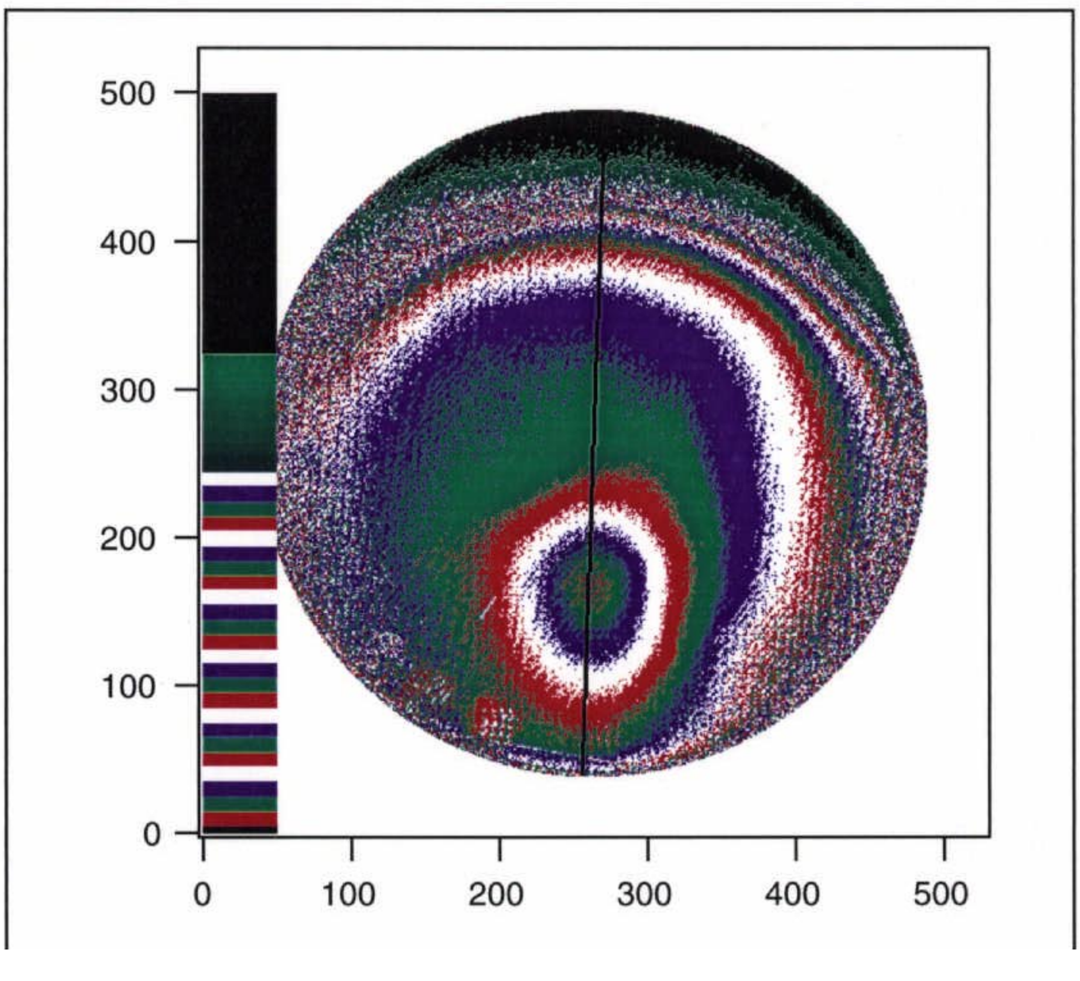
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We are now comparing the radiance distribution with theoretical models including both elastic and inelastic (Raman) scattering. In addition we will be comparing our measurements with the f/Q model of Morel (which is being used in other models in the community).

d. Anticipated future actions:

We will be continuing our data analysis. We will be participating in INDOEX during January and February of 1999, as well as the MODIS initalization cruise.

e. Problems/Corrective actions: None.

f. Publications: None.

4. Residual Instrument Polarization.

The basic question here is: if the MODIS responds to the state of polarization state of the incident radiance, given the polarization-sensitivity characteristics of the sensor, how much will this degrade the performance of the algorithm for atmospheric correction, and how can we correct for these effects?

a. Task Objectives:

Add a module to perform the correction for residual instrument polarization.

b. Work Accomplished:

A module was added to perform the correction for residual instrument polarization.

c. Data/Analysis/Interpretation: None.

d. Anticipated Future Actions:

Although this task is now basically complete. All that remains is incorporating the SBRS/MCST polarization-sensitivity data into the module.

e. Problems/Corrective Actions: None

f. Publications: None.

5. Pre-launch/Post-launch Atmospheric Correction Validation (with K.J. Voss).

a. Task Objectives:

The long-term objectives of this task are four-fold:

(i) First, we need to study aerosol optical properties over the oceans to assess the applicability of the aerosol models used in the atmospheric correction algorithm. Effecting this required obtaining long-term time series of the aerosol optical properties in typical maritime environments. This was achieved using a CIMEL sun/sky radiometer. This radiometer is identical to those used in the AERONET Network (in which we are a participant).

(ii) Second, we must be able to measure the aerosol optical properties from a ship during the initialization/calibration/validation cruises. The CIMEL-type instrumentation could not be used (due to the motion of the ship) for this purpose. The required instrumentation consisted of an all-sky camera (which can measure the entire sky radiance, with the exception of the solar aureole region) from a moving ship, an aureole camera (specifically designed for ship use) and a hand-held sun photometer.

In the case of strongly-absorbing aerosols, we have shown that knowledge of the aerosol vertical structure is critical. Thus, we need to be able to measure the vertical distribution of aerosols during validation exercises as well as to build a climatology of the vertical distribution of absorbing aerosols. This is accomplished with a LIDAR system, which we have modified for ship operations. This LIDAR will also be used to detect the presence (or absence) of thin cirrus during the initialization/calibration/validation cruises.

(iii) The third objective was to determine how accurately the radiance at the top of the atmosphere can be determined based on measurements of sky radiance and aerosol optical thickness at the sea surface. This required a critical examination of the effect of radiative transfer on "vicarious" calibration exercises.

(iv) The forth objective is to utilize data from other sensors that have achieved orbit (OCTS, POLDER, SeaWiFS ...) to validate and fine-tune the correction algorithm.

b. Work Accomplished:

(i) We have been operating the CIMEL instrument in the Dry Tortugas continuously during most of 1998. It has been working well, however the temperature sensor appears to have failed. We have extracted specific days of the data set, believed to be dust, marine aerosol, or nonseasalt sulfate aerosols. On these days we are running our inversions method to compare with that used by Nakajima (i.e., used in the Aeronet Network). This work is continuing.

(ii) Aureole and sky camera data acquired during the July Hawaii cruise were reduced during this period. These data are being analyzed, specifically for several locations while the cruise went near the volcanic plume to look at the retrieved size distribution of particulates in the plume. The aureole and sky cameras were also operated during the MOCE-4 cruise, and these data are in the process of being reduced (actually, they are reduced and need only be combined to provide the entire sky radiance distribution).

We also deployed the LIDAR during the MOCE-4 campaign, and it performed flawlessly. The figure on the next page provides a low resolution trace of the lidar signal ($\propto$ attenuated backscatter) for the entire time period of the experiment. Note the presence of a few cirrus clouds near 14 km about 1/3 of the way into the experiment. One purpose of the LIDAR is to screen thin cirrus from the analysis. We have performed inversions on the days of the SeaWiFS satellite overpasses.

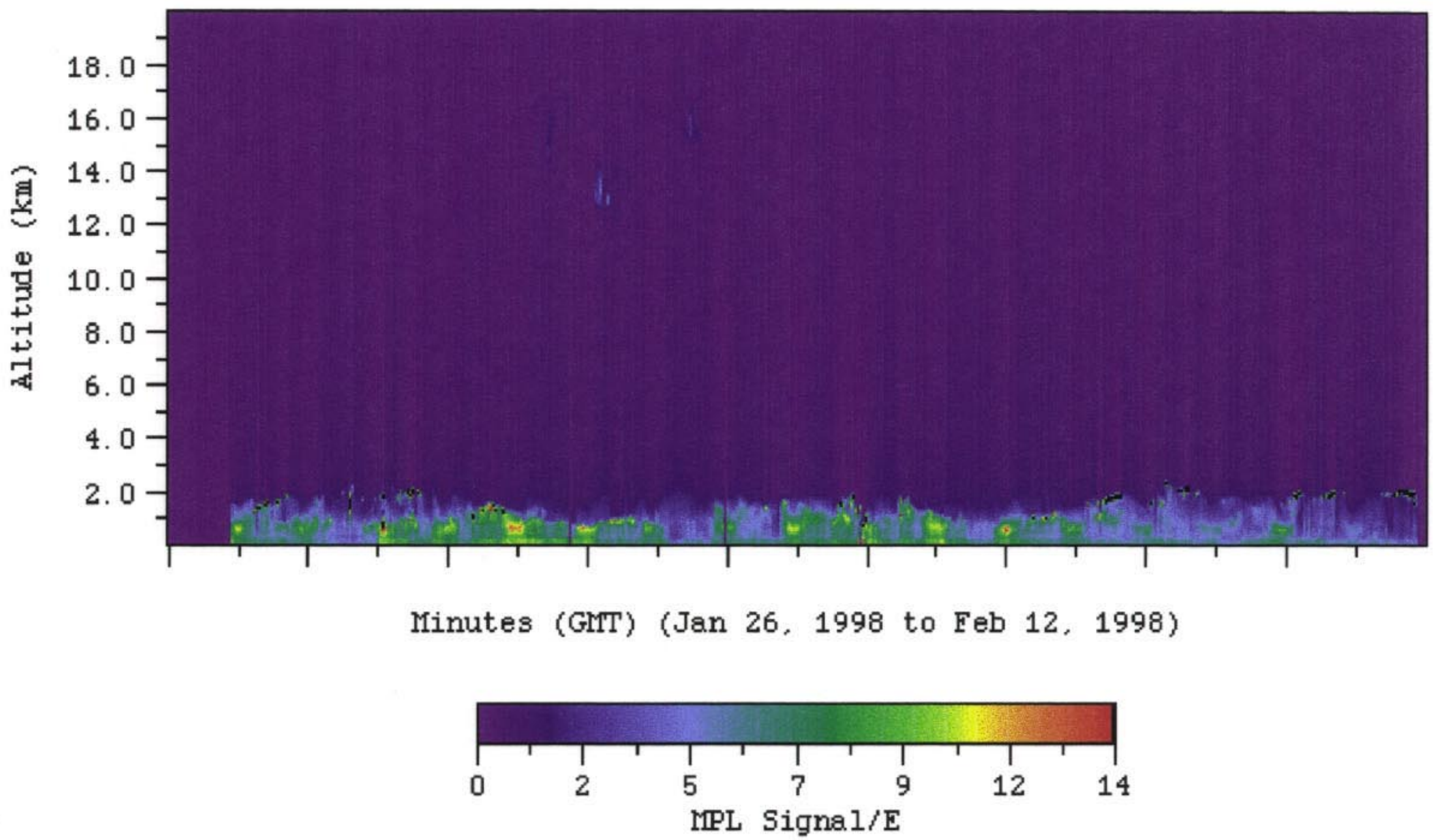
(iii) The theoretical aspects of this work have been completed. The next phase is to use surface measurements to predict top-of-atmosphere radiance.

(iv) We have prepared a duplicate version of the MODIS algorithm code to use the SeaWiFS spectral bands. This is being used to test the MODIS code with SeaWiFS data. (See Section **1-ii**.)

c. Data/Analysis/Interpretation:

(i) and (ii) We had anticipated acquiring data from the Dry Tortugas simultaneous with a SeaWiFS overpass near the winter solstice; however, there was so little clear weather during that time that no simultaneous data were obtained. The El Niño that produced unusually clear weather for MOCE-4 off Hawaii, essentially prevented any useful data for initialization from the Dry Tortugas.

A detailed report of our analysis thus far is presented in Appendix 1. E.J. Welton's Ph.D. Dissertation. Dr. Welton is now a postdoc on the project.



- MOCE-4 MPL data from Jan 26 to Feb 12, 1998. The signals have been divided by the output energy, E.
- Each major and minor tickmark, at 0000 GMT (1400 HST), separates the days.

d. Anticipated Future Actions:

(i) We will continue to keep the CIMEL operation in the Dry Tortugas, including the monthly maintenance checks. We will also try to correct the temperature problem with input from the Goddard group. In addition we will replace some cables that were discovered to be marginal on the last maintenance trip. If the instrument temperature readings are not fixed by these, we will replace the instrument when one becomes available.

We will continuing our work inverting the CIMEL data to determine the aerosol phase function.

(ii) The aureole and sky camera are being recalibrated in anticipation of another cruise in January-February. We will also continue with the data reduction for these instruments.

Future use of the ACE-2 MPL data (see July–December 1998 Semiannual Report) is currently being planned. The data will also be the focus of at least two papers. The first will describe the MPL ACE-2 system and the problems and resulting calibration procedures used to correct the data. The second paper will involve other ACE-2 participants and will focus on closure analysis. Much of the subject matter to be published in these papers is described in Appendix 1.

We plan to use the MPL and aureole camera during INDOEX in January-February of 1999, and MODIS initialization cruise.

e. Problems/corrective actions: None.

f. Publications:

H. Yang and H.R. Gordon, Retrieval of the Columnar Aerosol Phase Function and Single Scattering Albedo from Sky Radiance over Land: Simulations, *Applied Optics*, **37**, 978–997 (1998).

H.R. Gordon, In-orbit calibration strategy of ocean color sensors, *Remote Sensing of Environment*, **63**, 265–278 (1998).

6. Detached Coccolith Algorithm and Post Launch Studies (W.M. Balch).

a. Task Objectives:

Our MODIS work during involves understanding all aspects of the influence of suspended calcium carbonate particles on inherent optical properties in the sea. Work during this reporting period focused on several areas: processing cell count, atomic absorption, particulate organic carbon, and scattering data from MODIS pre-launch cruises in the Gulf of Maine, preparation and submission of three MODIS-related manuscripts, another MODIS pre-launch cruise to the Gulf of Maine to examine in situ properties of calcite particles, and analysis calcite optical properties from the Arabian Sea.

The algorithm for retrieval of the detached coccolith concentration from the coccolithophorid, E. huxleyi is described in detail in our ATBD. The key is quantification of the backscattering coefficient of the detached coccoliths. Our earlier studies focused on laboratory cultures to understand factors affecting the calcite-specific backscattering coefficient. A thorough understanding of the relationship between calcite abundance and light scattering, in situ, 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. To this end, the objectives of our coccolith studies during this reporting period have been:

(1) acquire optical field data on the distribution and abundance of coccolithophores in the Gulf of Maine,

(2) process data from recent cruises, and

(3) publish earlier results from our remote sensing work done with the CalCOFI data set, flow cytometry experiments, optical experiments with coccoliths, and Gulf of Maine pre-launch cruises.

For perspective on the directions of our work, we provide an overview of our previous activities:

> Jan-June 1995: Research focus – chemostat cultures (in which algal growth rate was precisely controlled) and we examined how the optical properties of these calcifying algae changed as a function of growth.

July-Dec 1995: Research focus – shipboard measurements of suspended calcite and estimates of optical backscattering as validation of the laboratory measurements. We participated on two month-long cruises to the Arabian Sea, measuring coccolithophore abundance, production, and optical properties.

Jan-June 1996: Research focus – field calcite distributions, during two Gulf of Maine cruises, one in March and one in June.

July-Dec 1996: Research focus – participated on another cruise to the Gulf of Maine and processed samples from the Gulf of Maine.

Jan-June 1997: Research focus – continued processing samples from our previous cruises, upgraded our laser light scattering photometer used in all of the calcite scattering measurements, performed another pre-launch cruise on calcite particle optics in the Gulf of Maine, and analyzed our results from the MODIS-funded flow cytometer work.

July-December 1997 Research focus – continued building our data base on calcite-dependent scattering with a cruise to the Gulf of Maine in November 1997. Work was also performed on processing the data from the June 1997 cruise. The results from the flow cytometer work were submitted for publication.

b. Work Accomplished, January-June 1998:

(1) Our flow cytometer manuscript submitted to J. Geophysical Research in the last quarter of 1997 has been accepted for publication in the MODIS special issue of JGR. A copy is attached as Appendix 2.

(2) Continued microscope cell/coccolith counts for samples from the Gulf of Maine. We processed count data from June 1997, and are completing enumeration of the last November 1997 samples. (This is in order to make room for the June 1998 samples which will be collected in June.)

(3) During the past two years, we have amassed a huge amount of data on calcite distributions in the Gulf of Maine. Merging of all the various types of data was becoming time consuming, so we generated new software to automate the process. We are now completely caught-up in the merging of the optical and chemical data and have written new software to process upcoming shipboard above-water reflectance measurements.

(4) We participated with the University of Miami MODIS group (headed by Dr. Robert Evans) to verify final algorithm output prior to launch.

(5) We have finished all data analyses for the Arabian Sea measurements and are halfway through the first of two manuscripts.

(6) We went to sea in June 1998 on another MODIS pre-launch cruise in the Gulf of Maine. The cruise loaded on 25 May, and finished 12 June, 1998.

(7) A manuscript covering the March, June and November 1996 Gulf of Maine cruises is completed and is awaiting final editorial changes.

(8) We have upgraded our underway system for MODIS pre- and post-launch cruises which will be done on a ship of opportunity, the M/V Scotian Prince which runs between Portland, Maine and Yarmouth, Nova Scotia.

(9) The paper on coccolith optics with Ken Voss and Katherine Kilpatrick, should appear in print shortly in *Limnology and Oceanography.* The paper deals with a laboratory comparison of volume scattering instruments, using the coccolithophore, *Emiliania huxleyi*, and how to model the optical properties.

c. Data/Analysis/Interpretation:

<u>Arabian Sea Results</u>:

The results of our Arabian Sea expeditions (continuous along-track scattering measurements of calcium carbonate) are now completed, and we are halfway through the first manuscript on distributions of coccoliths, and the optical consequences. Following these manuscripts, we will begin analysis and publication of the Gulf of Maine optical results from the previous four cruises.

<u>Cruise Results</u>:

Examination of the November 1997 cruise results, showed that calcite-dependent backscattering was quite high in the Gulf of Maine. This cruise was the first late Fall cruise in the Gulf of Maine, where calcium carbonate optical properties were quantified. Calcite scattering commonly accounted for 10-20% of total backscattering. Interestingly, even with the low light conditions, coccolithophores were still remarkably abundant in the Gulf of Maine. We formerly interpreted strong coccolith influence on particle optics as a "summer-only" issue but it now can be clearly considered a year-round phenomenon. Since we collected AC-9 data of absorption and attenuation (which by difference gave us scattering), then we have been processing the data to calculate $\widetilde{b_b}$ or the backscattering probability (b_b/b) and how this varies with the standing stock of chlorophyll and calcium carbonate.

Given the future plan for more Gulf of Maine cruises, as well as our SIMBIOS activities, we have written new software to merge the various data sets into one file that can be submitted to NASA's SeaBass data archive. The software (which performs vicarious calibrations, offset corrections, plus calculating "derived quantities" has now been through 3 sets of revisions to streamline it and make it more efficient. This software will considerably reduce the time currently required to quality control the numbers and produce hydrographic plots of the inherent optical properties (a, b, c, b_b, calcite-dependent backscattering, $\widetilde{b_b}$, temperature, salinity, and fluorescence).

d. Anticipated Future Actions:

Work in the next reporting period will address several areas:

(1) Completion of the suspended calcite analyses from the Gulf of Maine cruise series.

(2) Final pre-publication formatting of JGR manuscript on coccolith scattering properties.

(3) Continued microscope cell/coccolith counts for latest samples from the Gulf of Maine.

e. Problems/Corrective Actions: None

f. Publications:

Voss, K., W. M. Balch, and K. A. Kilpatrick. Scattering and attenuation properties of *Emiliania huxleyi* cells and their detached coccoliths. *Limnol. Oceanogr.* (In press).

Balch, W. M. and B. Bowler. Sea surface temperature gradients, baroclinicity, and vegetation gradients in the sea. *J. Plank. Res.*, **19**, 1829-1858 (1998).

Balch, William M., David T. Drapeau, Terry L. Cucci, and Robert D. Vaillancourt, Katherine A. Kilpatrick, Jennifer J. Fritz. Optical Backscattering by Calcifying Algae. *J. Geophys. Res.* (Accepted).

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7. Other Activities.

The PI participated in the MOCEAN meeting at GSFC (June 8 and 9) and the MODIS Science Team Meeting (June 24-26, 1998).

Presented poster at AGU/Ocean sciences meeting: "Upwelling in-water radiance distribution measurements near the MOBY site in Hawaii," K. J. Voss, D. K. Clark and C. Trees, AGU/Ocean Science Meeting, San Diego, Ca. February, 1998.