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I. Task Objectives

The Moderate Resolution Imaging Spectroradiometer (MODIS) being developed for the Earth Observing System (EOS) is well suited to the global monitoring of atmospheric properties from space. Among the atmospheric properties to be examined using MODIS observations, clouds are especially important, since they are a strong modulator of the shortwave and longwave components of the earth's radiation budget. A knowledge of cloud properties (such as optical depth and effective radius) and their variation in space and time, which are our task objectives, is also crucial to studies of global climate change. In addition, with the use of related airborne instrumentation, such as the Cloud Absorption Radiometer (CAR) and MODIS Airborne Simulator (MAS) in intensive field experiments (see below), various types of surface and cloud properties can be derived from the measured bidirectional reflectivities. Therefore, the primary task objective is to extend and expand our algorithm for retrieving the optical thickness and effective radius of clouds from radiation measurements to be obtained from MODIS. The secondary objective is to obtain an enhanced knowledge of surface angular and spectral properties that can be inferred from airborne directional radiance measurements.

II. Work Accomplished

a. MODIS-related Instrumental Research

Michael King spent time examining the spectral bandpass filter specifications of MODIS and the performance characteristics of MAS, a newly developed MODIS Airborne Simulator that flew on the NASA ER-2 aircraft during the Atlantic Stratocumulus Transition Experiment (ASTEX), based in the Azores during June 1992. He reconfigured MAS for incorporation of 50 channels, including the C02 slicing channels in the thermal infrared and numerous visible channels, not previously incorporated in the November FIRE cirrus configuration. Also, considerable work was expended in cleaning and replacing numerous mechanical and optical elements and in upgrading the electronic gain switching circuit of the CAR, which flew on the University of Washington's C-131A research aircraft during ASTEX and the Lead Experiment (LEADEX), conducted in the Beau fort, _ Sea, Alaska during April 1992.

b. MODIS-related Algorithm Study

In the area of cloud property retrievals, much effort has been expended by Si-Chee Tsay to convert our research data analysis code for determining cloud optical thickness and effective particle radius into a more professional code for data processing of MAS and subsequently MODIS data. This code has now successfully been run on the Cray YMP (it was originally developed for and executed on the IBM 3081). Effort is continuing to extend our cloud retrieval program so that it is more capable of managing the data input/output from multiple instruments (MCR, CAR, MAS, Landsat, AVHRR) and in averaging pixels at different sampling frequencies. Si-Chee Tsay has also spent time assembling radiation and microphysical data to incorporate in a radiative transfer model to simulate the scattered radiation field observed from the Kuwait oil fire smoke by the CAR. This study will contribute to a better understanding of the relationship between microphysical and radiative properties of particulate clouds.

In addition, on the surface property studies, much effort has been devoted to searching for a suitable algorithm (e.g., Hapke's, Pinty-Verstraete's model or one of our own) to characterize the bidirectional reflectance pattern of our measurements (e.g., desert sand and smoke from the Kuwait oil fires; snow and sea ice surfaces from LEADEX; and ocean with sun glint from ASTEX and the Persian Gulf) of the angular distribution of surface reflectivity obtained from the CAR. Following discussions between Michael King and Bernard Pint-y on surface reflectance properties, Si-Chee Tsay has begun preparing a paper tentatively entitled "Observational and theoretical studies on bidirectional reflectance. Part I. Various types of surface (by S. C. Tsay and M. D. King)."

c. *MODIS-related Field Experiments*

1. LEADEX Experiment

Between April 4 and 20, Michael King and Si-Chee Tsay participated in the airborne portion of the LEADEX, conducted over sea ice in the Beaufort Sea, Alaska. They participated as part of the University of Washington C-131A research team, which was based in Prudhoe Bay. The objectives of this project were to measure (i) the extent of the plumes from the leads and the fluxes of sensible heat, water vapor, droplets, ice crystals, and chemicals from leads; (ii) the spatial distribution and fractional coverage of leads, and the effects of leads on upwelling longwave infrared radiation, surface temperature, lidar backscatter; (iii) the extent and composition of arctic haze and to identify possible sources of arctic haze; and (iv) the radiative properties of arctic haze, stratus clouds and various types of snow/ ice surfaces, open water, and leads by CAR.

In the early part of April the sea ice was quite extensive with no significant leads, whereas later in the month leads started to form quite rapidly. This experiment'-involved 8 research flights over sea ice, leads, and snow fields, with some flights conducted in optically thick ice crystal clouds formed in the cold temperatures of the high Arctic following the formation of leads and open water. Among the CAR measurements obtained on these flights were measurements of the bidirectional reflection function of snow, one-year and multiple-year sea ice under clear and cloudy sky conditions at discrete wavelengths between 0.5 and 2.3 pm. Measurements, for the first time from CAR, were also acquired of the bidirectional reflection function of optically thick ice clouds and the spectral absorption of solar radiation by these thick ice crystal clouds (within the diffusion domain). Some statistics of lead distributions, within a particular domain area, maybe obtained from the CAR albedo measurement at nadir direction. Preliminary inspection of the data suggests that the reflectance pattern of the sea ice was generally quite isotropic (Larnbertian) with very little limb brightening even at 1.6 and 2.2 µm. Furthermore, there were unexpected differences in the reflectance characteristics of sea ice at 1.22 and 1.27 µm, presumably due to differences in the refractive index of ice at these nearly identical wavelengths.

2. *ASTEX Experiment*

Michael King, Tom Arnold and Si-Chee Tsay participated in the ASTEX, based in the Azores, Portugal, between May 29 and July 1, 1992. During this experiment Michael King was the flight scientist for the NASA ER-2 aircraft for 3 weeks (based on the Island of Terceira, Azores) and co-principal investigator of the University of Washington C-131A aircraft (based on the Island of Santa Maria, Azores) for an additional week. Si-Chee Tsay was with the University of Washington C-131A aircraft for the whole period of time. This experiment was an international airborne campaign involving three U. S., two French and one British research aircraft, the purpose of which was to validate satellite remote sensing estimates of cloud properties, to determine the fraction of solar radiation reflected, absorbed and transmitted by the clouds, to obtain a comprehensive data set of cloud properties that can be used to improve predictions of greenhouse warming effects, and to measure the concentration of chemicals emitted by organisms living in the ocean. The principal instruments of interest to this research group and to MODIS consist of the MAS on the ER-2 and the CAR on the University of Washington C-131A, in addition to in situ microphysical measurements to be used for validation of remote sensing estimates.

Many cloud climatological regimes were encountered during this month-long experiment, thereby providing a very useful data set for further study. Specific observations that were obtained include: (i) many optically thick stratocumulus clouds, with coincident microphysics and solar radiation measurements; (ii) broken clouds, including shadows and sunglint at 3.73 µm; (iii) sharp cloud transitions between small droplet continental clouds and large droplet maritime clouds; (iv) high resolution images that should enable cloud edge effects to be examined, both in the visible and near-infrared wavelength regions; (v) multilayer clouds, including thin to thick cirrus clouds overlying boundary layer marine stratocumulus; (vi) numerous overflights of the ground sites on Santa Maria Island, Azores, Porto Sante, Madeira Islands, and the French ship Le Suroit; and

(vii) directional scattering pattern, both the sea surface (clear and cloudy sky) and cloud decks (homogeneous and broken conditions) as a function of solar zenith and viewing azimuthal angles.

In addition, this experiment enabled the same calibration equipment from Goddard Space Flight Center to be used to calibrate several instruments on the ER-2 as well as the CAR, flown on the University of Washington C-131A.

d. MODIS-related Services

Michael King was appointed Deputy Science Team Leader on January 23, 1992. Subsequently he chaired the twice-monthly MODIS Technical Team meeting, and regularly attended weekly MODIS Administrative Support Team meetings and monthly meetings with Team Leader Vince Salomonson. He attended and actively participated in several meetings and workshops to plan a Smoke, Clouds and Radiation (SCAR) field experiment in Brazil (expected 1993-1995).

III. Data/Analysis/Interpretation

a. Data Processing

Following the transit flight from Ames Research Center (ARC) to Ellington Field, Johnson Space Center (JSC), Houston on November 12, the ER-2 conducted 10 research flights during the 3.5 week FIRE cirrus experiment, during which time the MAS worked extremely well. Continuous monitoring of the instrument performance was performed by Ken Brown (GSFC instrument manager), Tom Arnold and Liam Gumley (GSFC contractors), Pat Grant and Don Smyrl (ARC contractors), Paul Menzel (MODIS Science Team member, NOAA), Chris Moeller (Univ. of Wisconsin), and Michael King (MODIS Science Team member, GSFC). In addition, GSFC supported the calibration of the spectrometer in the field by sending 2 calibration experts along with an integrating hemisphere, small integrating sphere, and monochromator (John Cooper and Reginald Gallimore, GSFC contractors). Subsequent to this field campaign, Liam Gumley has processed some of the data into level 1-B netCDF files for subsequent data analysis.

Tom Arnold developed a method for determining the calibration coefficients of the FIRE-Cirrus MAS visible channels which accounts for the change in instrument temperature at the aircraft flight altitude. Using data from the February cold chamber tests at Ames, an expression for each channel was derived to convert the raw counts recorded in flight at cold temperatures to ‘equivalent’ counts at room temperature. This allows the calibration coefficients derived on the ground to be applied to the in-flight data, thereby leading to better estimates of the absolute intensity level of the radiation measurements. The CAR integrating hemisphere calibration data obtained during March 1992 was also entered and-uploaded to the IBM mainframe by Tom Arnold. Data were processed through program CALBRATE to obtain valid calibration coefficients for the LEADEX and ASTEX missions.

Michael King decided on the wavelength specifications and bandpasses of MAS for the subsequent ASTEX deployment (only 11 of the available 50 channels can be recorded at the present time). Ward Meyer prepared a purchase request to acquire a new CY8500 Exabyte tape drive for the MAS quick view system, which arrived in time for the engineering test flight at Ames Research Center during the week of May 20. Most calibration data taken during the ASTEX mission has been decoded from exabyte tapes by Tom Arnold and run through CALBRATE (updated to run on a Macintosh from the previous IBM mainframe version). Processing is not yet complete, pending the availability of final hemisphere calibration data from John Cooper.

b. Analysis and Interpretation

Tom Arnold has downloaded some of the flight lines from the November 1991 FIRE cirrus flights, and has displayed images of selected spectral channels on his Macintosh computer and printed them out for a data notebook of quick-look products. Program AVGCNTS using the netCDF Fortran interface was written and run on the Climate and Radiation Branch SGI computer (Climate) to read the calibration files, average the data and dump the results to data files. Then, using a Macintosh Spyglass program (FORMAT), sample images can be displayed and printed. Figures 1 and 2 illustrate MAS imagery data for Flight Line #8 on 5 December 1991 at wavelengths of 0.67 and 1.64 µm (Figure 1), and 8.80 and 11.95 µm (Figure 2). These data were obtained over marine stratocumulus clouds in the Gulf of Mexico, in which some parts of the scene contained a second, overlying cirrus cloud layer. This is especially evident in the upper right-hand portion of the images, in which the cirrus clouds are cold (black at 8.80 and 11.95 µm) in Figure 2, with correspondingly little effect in the visible and near-infrared channels (Figure 1). The primary indication in Figure 1 that there is some overlying cirrus cloud is the loss of detail in the underlying marine stratocumulus cloud. The bottom portion of the image was open water with low reflectance in the visible (black in Figure 1) but relatively warm (white in Figure 2), relative to the clouds in the upper 2/3 of the scene.

Michael King presented these images at 2 different meetings in Colorado in February (FIRE Science Team Meeting and the NCAR Research Aviation Facility Fleet Workshop). Considerable interest was expressed in these images, as they showed considerable detail both in the visible and thermal infrared of cirrus clouds overlying lower stratiform clouds over the Gulf of Mexico. Many scientists have contacted Michael King to obtain copies of these data for their algorithm work and subsequent analysis. Documentation on the data access, format, and availability y of MAS data prepared by Liam Gumley has been distributed to, - all members of the cloud retrieval group of the CERES Science Team (Bruce Wielicki, Pat Minnis, Jim Coakley, Larry Stowe, Ron Welch). We anticipate analyzing and presenting MAS data for the ASTEX in a similar way when the data are available.

Figure 3 illustrates the bidirectional reflectance function of the smoke layer from the Kuwait oil fires as a function of zenith and azimuth angles at two wavelengths (0.75 and 1.64 µm) obtained from CAR measurements. These images show, among other things, an enhanced backscattering in the antisolar direction (glory, located at $\theta = 39°$, $\phi = 180°$) and in the rainbow (oilbow) direction, near nadir in these figures. Presently, we are in the process of decoding the gain switch setting in the CAR data stream. We anticipate analyze and presenting CAR data for the LEADEX and ASTEX experiments, as well as our previous measurements obtained under a wide variety of conditions in a similar way when the data are available. In addition to the rainbow and glory features previously noted, the reflectance measurements in the forward scattering direction ($\phi = 0°$) are nearly the same at both wavelengths, in contrast to the backscattering plane where the smoke was about 50% brighter at 0.75 than at 1.64 µm (cf. Figure 4). We are in the process of studying this case, which will contribute to a better understanding of the relationship between microphysical and radiative properties of particulate clouds.

IV. Anticipated Future Actions

a. Continue to be involved in planning the Smoke, Clouds and Radiation Experiment in Brazil (with Yoram Kaufman and key members of the MODIS land/atmosphere discipline groups) and to interact with key NASA Headquarters program managers (Janetos, Suttles, Wickland);

b. Continue to analyze the bidirectional reflectance measurements obtained in LEADEX and ASTEX (as well as previous missions). This research will likely contribute two papers that are tentatively entitled “Observational and theoretical studies of bidirectional reflectivity. Part I. Various types of surfaces; Part II. Water and ice clouds” by S. C. Tsay and M. D. King;

c. Continue to analyze CAR data generated during the Kuwait oil fire experiment. This case study of the scattering pattern produced by oil drizzle droplets will contribute to a research paper that is tentatively entitled “Simulation of directional and spectral reflectance of the Kuwait oil fire smoke” by S. C. Tsay and M. D. King;

d. Re-examine more carefully (better instrumentation and field plans) the retrieval of cloud optical and microphysical properties by using data gathered from the MAS and C-131A in situ data during the ASTEX. Results of some interesting cases will likely contribute to a research paper.

V. Problems/Corrective Actions

No problems that we are aware of at this time.

VI. Publications

1. King, M. D., Y. J. Kaufman, W. P. Menzel and D. Tanre, 1992: Remote sensing of cloud, aerosol, and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS). *IEEE Trans. Geosci. Remote Sens.*, 30, 2-27.

2. Harshvardhan, and M. D. King, 1992: Comparative accuracy of diffuse radiative properties computed using selected multiple scattering approximations.

3. King, M. D., 1992: Directional and spectral reflectance of the Kuwait oil-fire smoke. *J. Geophys. Res.*, in press.

4. Nakajima, T. and M. D. King, 1992: Asymptotic theory for optically thick layers: Application to the discrete ordinates method. *Appl. Opt.*, in press.

5. King, M. D., L. F. Radke and P. V. Hobbs, 1992: Optical properties of marine stratocumulus clouds modified by ships. *J. Geopkys. Res.*, in press.

6. King, M. D., 1992: Radiative properties of clouds. *Aerosol-Cloud-Climate Interactions, P.* V. Hobbs, Ed., Academic Press, in press.

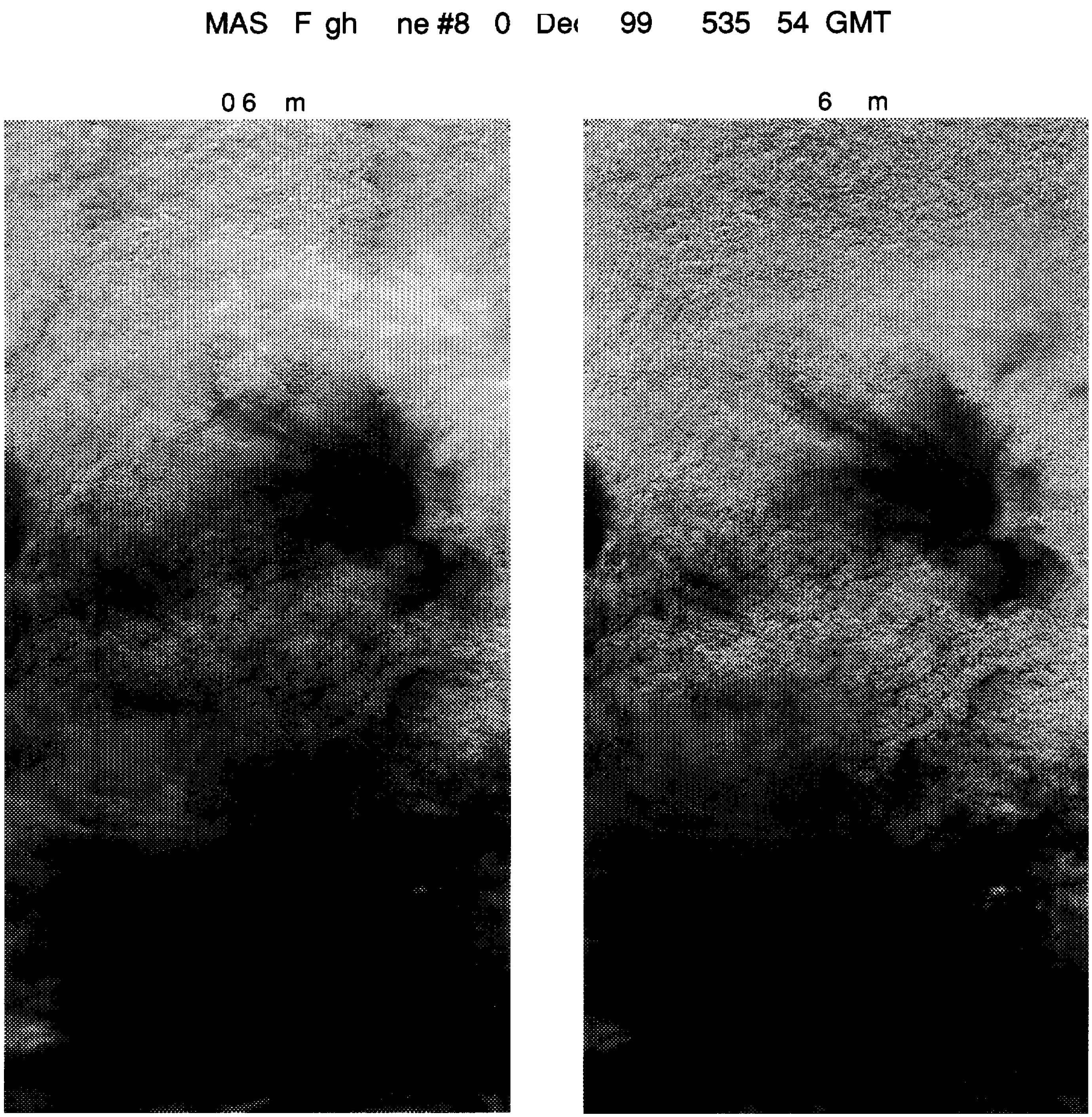

Figure 1

MAS - Flight Line #8 05 Dec. 1991 1535-1541 GMT

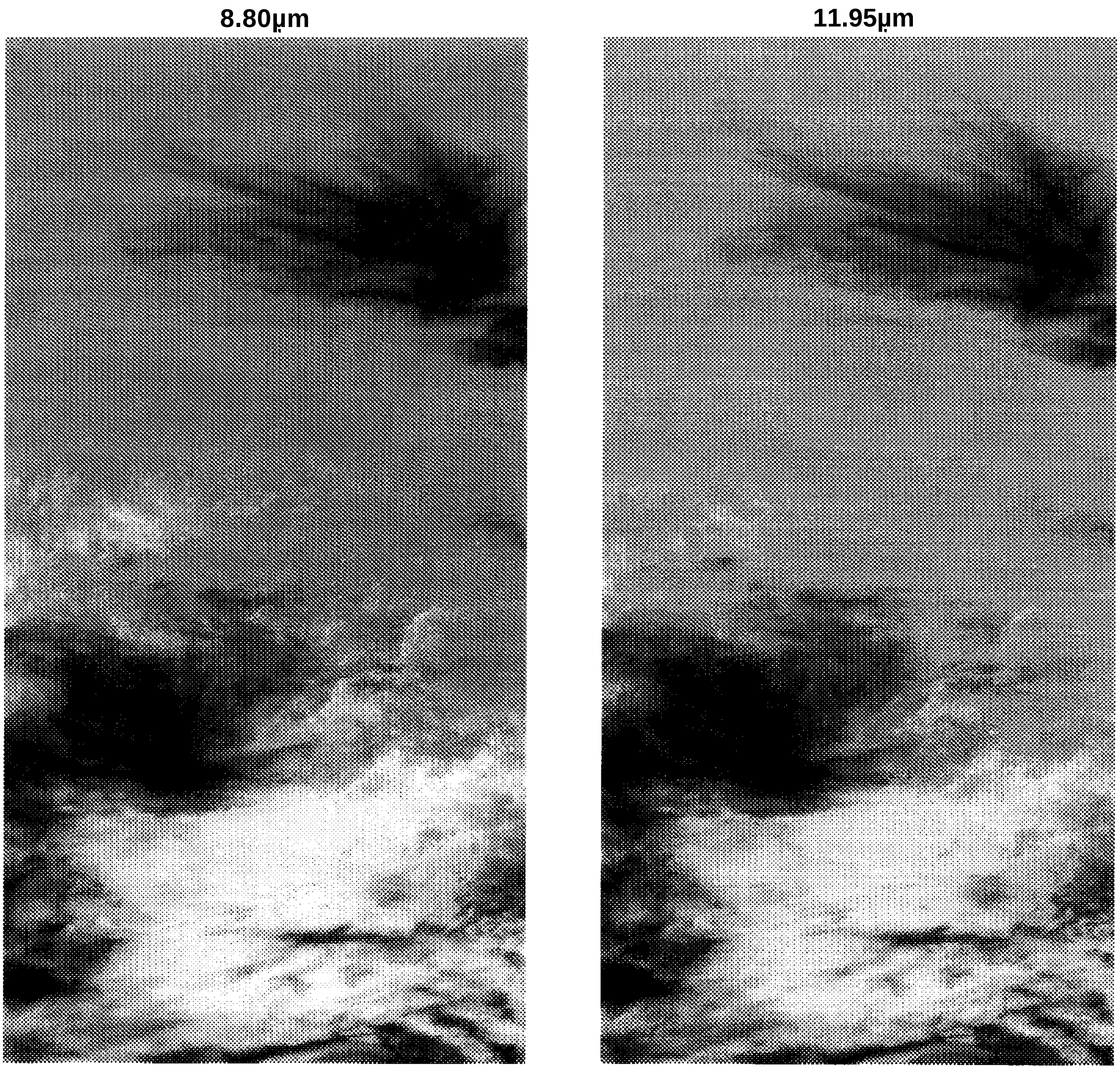

Figure 2

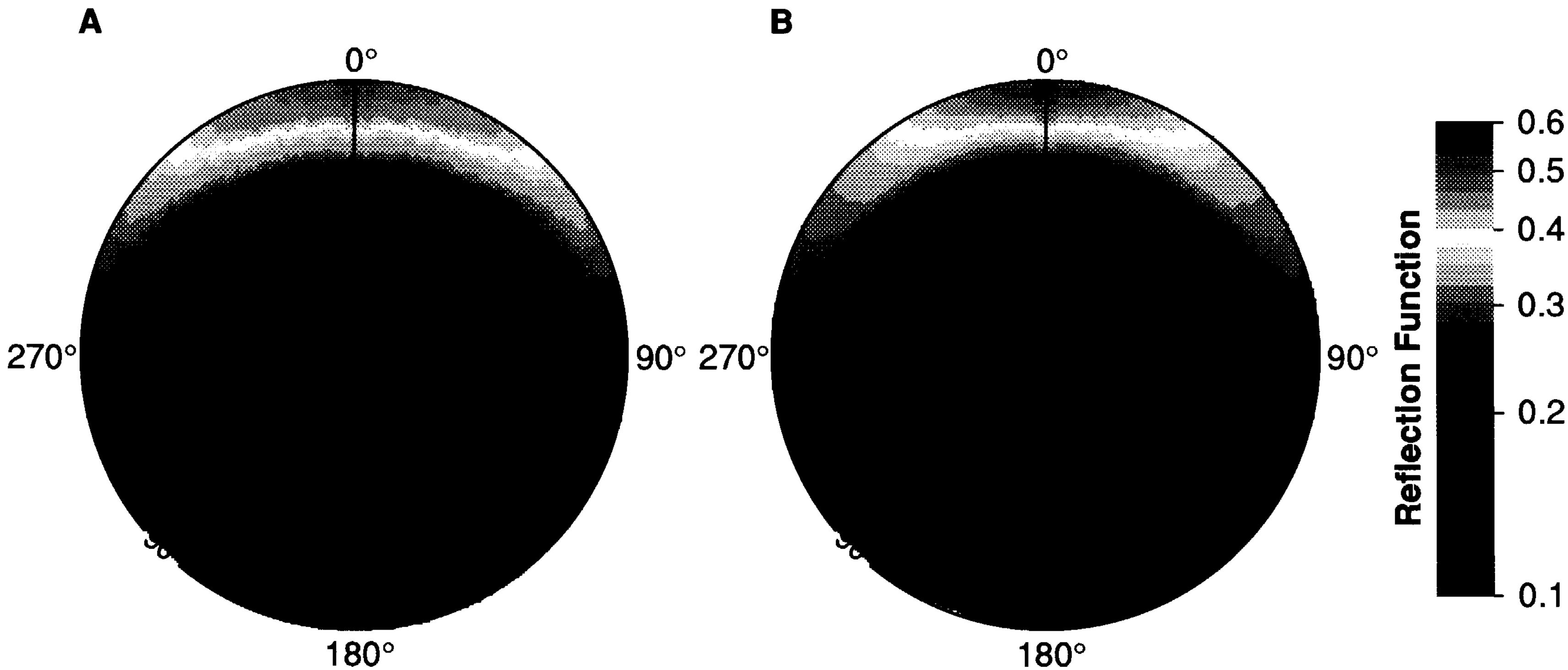
A
B
0°
90°
180°
270°
0°
90°
180°
270°
Reflection Function
0.6
0.5
0.4
0.3
0.2
0.1

Figure 3

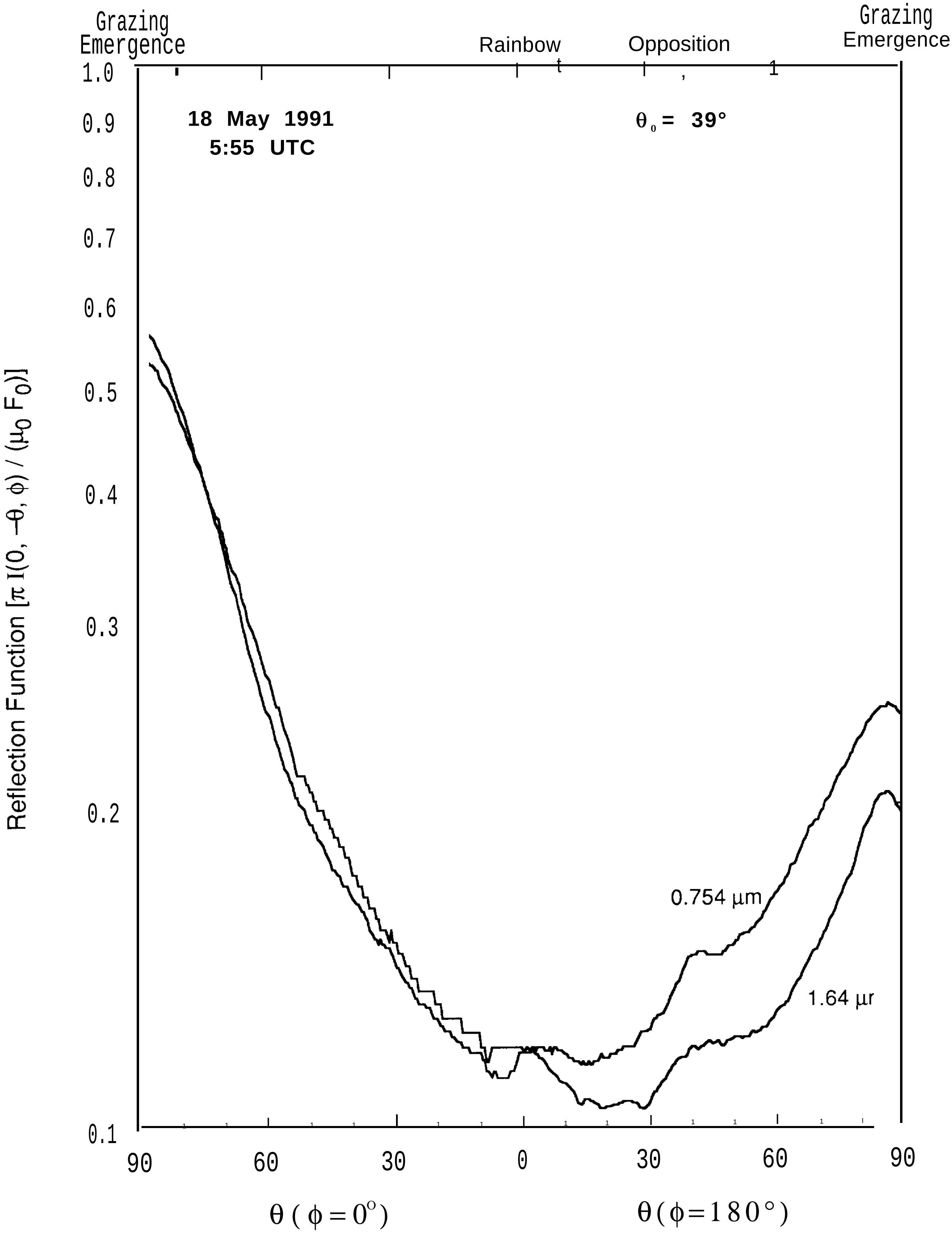
Grazing Emergence
Rainbow
Opposition
Grazing Emergence
18 May 1991
5:55 UTC
θ₀ = 39°
0.754 µm
1.64 µr
Reflection Function [π I(0, −θ, φ) / (µ0 F0)]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
90
60
30
0
30
60
90
θ (φ = 0°)
θ(φ=180°)

Figure 4