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Technical Progress Report

Completion of Spectral Rotating Shadowband Radiometers and Analysis of ARM Spectral Short-Wave Data

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SUMMARY

Our ARM goal is to help improve both longwave and shortwave models used in GCMs by providing improved radiometric shortwave data. These data can be used directly to test shortwave model predictions. As will be described below, they can also provide inferred values for trace species and cloud properties that are useful for shortwave and longwave modeling.

Our current ARM research program includes tasks related to the study of shortwave radiation transfer through cloudy and clear skies. One task involves the acquisition and archival of new radiation and meteorological data. Another is the continued development of a moderate spectral resolution rotating shadowband spectroradiometer. The analysis tasks include

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retrieval of column aerosol, ozone, and water vapor. The inference of cloud cover and optical properties of clouds is another goal of this research effort.

At the Atmospheric Sciences Research Center (ASRC) in Albany, New York, we are acquiring downwelling shortwave, including direct and diffuse irradiance, at six wavelengths, plus downwelling longwave, upwelling and downwelling broadband shortwave, and aerosol optical depth that we combine with National Weather Service surface and upper air data as a model test data set for ARM researchers.

The major objective of our program has been to develop two spectral versions of the rotating shadowband radiometer (RSR). The multi-filter rotating shadowband radiometer (MFRSR) contains six filtered, narrow-passband detectors, and one unfiltered silicon detector that serves as a surrogate total shortwave sensor. The MFRSR was completed in the first phase of this program and is operational at the Southern Great Plains clouds and radiation testbed (CART) site. It has been selected as the core instrument of the ARM Solar & Infrared Observing System (SIROS) complement of instruments that is being sited at each of some twenty extended facilities within CART. The rotating shadowband spectroradiometer (RSS) contains a 256-channel diode array that spans the wavelengths 350-1050 nm with resolution varying between 0.6 nm and 8 nm. The prototype of the RSS has acquired data on the roof of the ASRC at the State University of New York in Albany, but is still undergoing shakedown at this point. A first-rate calibration facility for these instruments is being developed at the ASRC to characterize cosine response, to determine absolute spectral calibration, and to characterize spectral response. This facility is nearly operational.

With some of the instrument development complete we are devoting more effort to analysis of the MFRSR data. Progress was made on several fronts this year, resulting in conference papers and submissions to refereed journals. Data from the ASRC roof has been used to develop corrections of the MFRSR shortwave sensor. SGP data has been used to develop and validate a retrieval technique for total column water vapor. Total column ozone has been estimated using MFRSR data, but validation at the SGP was not possible for lack of a suitable ozone column standard. Some progress has been made on cloud cover detection, but it is not yet implemented as a routine classification and reporting procedure.

PROGRESS TO DATE

ASRC Data Acquisition

A small fraction (~10%) of the ARM funding is used to acquire a high quality data set in Albany on the roof of the ASRC in cooperation with the International Daylighting Measurements Program, which cost shares the operational expenses. The station acquires a data set useful to shortwave radiation modeling efforts within the ARM community. It allows a venue for the testing of hardware and firmware changes to the MFRSR. It has enabled us to develop algorithms to improve the accuracy of shortwave irradiance measurements made by the MFRSR.

Using current technology, total shortwave irradiance is best measured as the sum of the direct horizontal irradiance component (obtained by multiplying the direct normal irradiance obtained with a tracking pyrheliometer by the cosine of the solar-zenith angle) and the diffuse horizontal irradiance (obtained by a pyranometer equipped with a tracking disk that blocks the direct radiation from the sun). We have used this technique to collect a top quality shortwave data set since July 1991. Shortwave is measured as described with an Eppley NIP pyrheliometer and an Eppley PSP pyranometer, which are both WMO first-class instruments. Furthermore, the calibration of both of these sensors is tied to our absolute cavity radiometer, which agrees with the world reference standard instruments to about 0.3%. Additionally, we measure downwelling longwave with an Eppley PIR pyrgeometer, upwelling shortwave with a Eppley PSP, and aerosol optical depth is measured whenever there is a clear view of the sun for a least 30 minutes.

The group headed by W.-C. Wang has used these data sets to exercise existing GCM radiation codes with typical clear-sky differences of 60 W/m^2. Adding our aerosol measurements has improved the agreement to about 30 W/m^2, but significant differences still exists. As we develop automated retrieval techniques, we will provide total column water vapor and ozone from an MFRSR that is acquiring concurrent data as part of the Quantitative Links program. These ancillary measurements can further specify the condition of the clear atmosphere and should help reduce the difference between the clear sky shortwave data base and the Wang et al. model.

Chuan Zhou has completed his master's degree using data acquired concurrently from first-class thermopile instruments and an MFRSR. His goal was to correct the response of the silicon cell detector to better match the response of first-class thermopile instruments (Zhou and Michalsky 1994). He found that temperature control of the detector and cosine response corrections as implemented in the MFRSR, even before spectral correction, significantly improved the response compared with other silicon detectors. For example, Michalsky et al. (1991) found the root-mean-square difference between direct irradiance measured with a thermopile pyrheliometer and a commercial silicon cell radiometer was around 40 W/m^2. This same rms difference was 16 W/m^2 for the MFRSR to thermopile direct irradiance comparison. He found dramatic improvements in diffuse horizontal irradiance, as well. After spectral correction, global and diffuse horizontal irradiances improved by 20% and 15%, respectively. He further found that a significant fraction of the remaining rms difference could be attributed to the differences in time responses of the two fundamental detectors. Thermopiles have a time response five orders of magnitude slower than silicon photovoltaic detectors.

Instrument Development Overview

The MFRSR has been selected by the ARM program for the extended network, and will log the data from the SIROS instrument suite at these sites. The SIROS instruments and mode of operation is very similar to the nine Department of Energy Quantitative Links installations, and so this extramural experiment to ARM has served as a very effective testbed for the technology as it is being deployed by ARM.

The other instrument that we have developed uses a prism spectrometer and a charge-coupled device (CCD) photodiode array to measure 256 wavelength intervals from 350 to 1050 nm. This instrument is intended for deployment at the central sites. It is at the advanced prototype stage, and preliminary performance results are discussed.

Both of these instruments require careful laboratory calibrations to aid development and as a necessary part of field measurements. Consequently, development of calibration techniques has been a necessary component of our work to date, and will continue to receive major emphasis in our future research.

Rotating Shadowband Radiometry

The basic geometry of a computer-controlled RSR can be seen in Fig. 1. The shadowing band is a strip of metal formed into a circular arc. The mechanical structure that holds the band is aligned in such a way that the band may be positioned by a microprocessor-controlled stepping motor to block the sun on command at all times of the year; consequently, when the instrument is installed at a site, no further mechanical adjustment is necessary.

At each measurement interval the microprocessor computes the solar position using an approximation for the solar ephemeris. The measurement sequence starts with a measurement made while the band is at the nadir; this is the total horizontal irradiance. The band is then rotated to make three measurements in sequence: the middle one blocks the sun and the other two block strips of sky 9° to either side. These side measurements permit a first-order correction for the "excess sky" blocked by the band when the sun-blocking measurement is made; the average of these two side measurements is subtracted from the total horizontal measurement; this correction is then added to the sun-blocked measurement to determine the diffuse horizontal irradiance. Finally, the diffuse component of the irradiance can be subtracted from the total horizontal to produce the direct horizontal component. Division by the cosine of the solar-zenith angle then produces the direct beam flux.

The microprocessor accumulates the data from the shadowband measurements, as well as ancillary measurements from other instruments if desired; this capability is exploited by the SIROS system where the MFRSR acts as the "data logger" for the other instruments.

In the MFRSR the entire detector consists of the diffuser-integrator that illuminates an internal hexagonal close-packed array of up to seven photodiodes with interference filters. The interior of the detector assembly is thermally insulated, and has a thermostatic electrical heater (25 Watt maximum) that holds the temperature of the internal detector assembly at a setpoint chosen between 40 to 45°C. The MFRSR instruments built for both ARM and the Quantitative Links experiments have six filtered detectors with nominal 10 nm FWHM bandwidths at wavelengths of 415, 500, 610, 665, 862, and 940 nm and an unfiltered silicon photodiode.

Rotating Shadowband Spectroradiometer (RSS)

We are developing a higher spectral resolution instrument consisting of a prism spectrometer

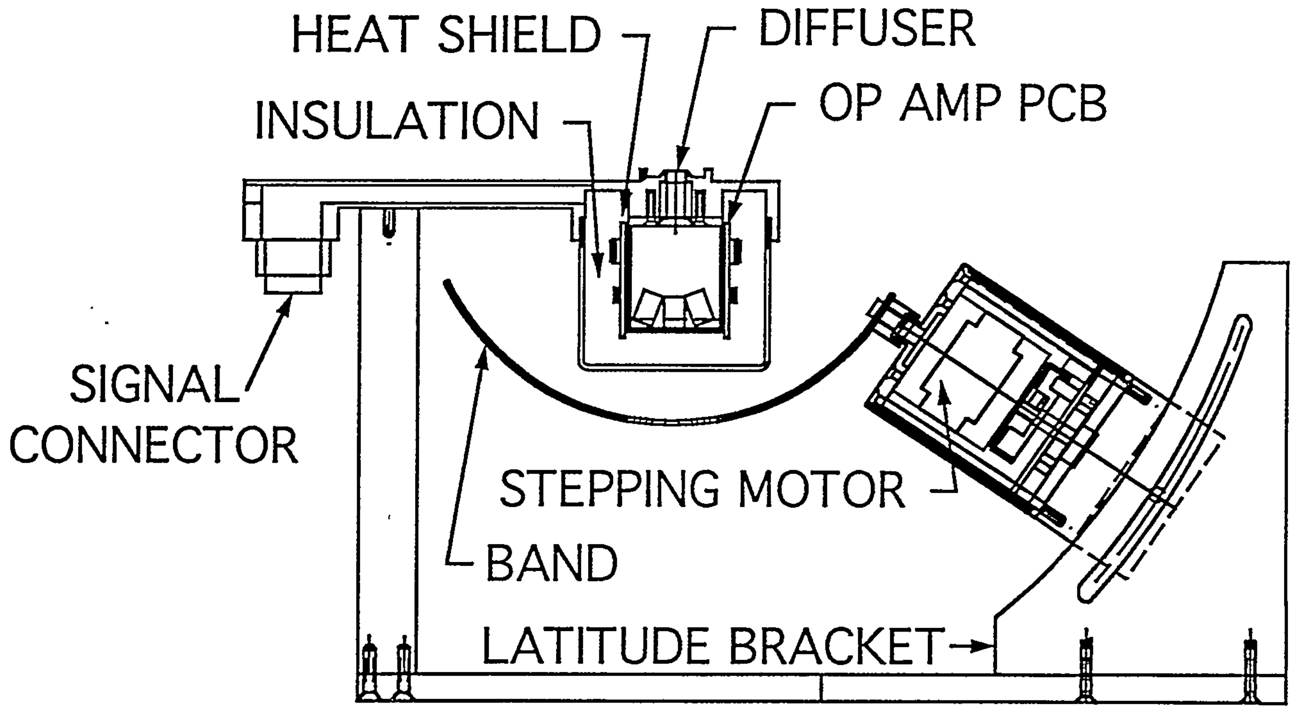

Fig. 1. Geometry of the multi-filter rotating shadowband radiometer.

coupled to a CCD array (see Fig. 2). This instrument is intended for the central facility of each CART. This instrument is unusual for modern spectrometer design in being a prism instrument using all-quartz optics. The advantage of this design is that the optics are inexpensive and extremely durable and stable. The non-linear dispersion is useful in solar applications where higher resolution is desirable at the shorter wavelengths. The nominal wavelength range is 350 to 1050 nm with a corresponding spectral resolution per pixel of 0.6 nm at 350 nm and 8 nm at 1050 nm (see Harrison et al. (1994) for more details).

Two versions of the RSS have been built. The current version is an advanced prototype of what we hope to deploy at the CART sites. Measurements of the total horizontal spectral irradiance, based on a rudimentary calibration, have produced spectra that are plausible according to measured and theoretical spectra.

Our post-doctoral fellow, who had primary responsible for completing the development of the RSS, has left the ASRC. Our plans for the completion of this instrument and its operation in the ARM program are an important part of our future efforts and are discussed below.

Calibration

Radiometric calibration of our spectral instruments requires the development of three test platforms. All will eventually be computer controlled by the software Labview®. The first of these platforms is completed, and we have purchased the components and written major pieces of the software for the other two. We expect to have these three measurement devices operational in the next few months.

Cosine response: Most radiation instruments, either broadband or spectral, commercial or custom, measure total radiation arriving from a hemisphere. These devices are expected to have Lambertian responses, i.e., their response decreases as the cosine of the angle of incidence. No device has this ideal "cosine response." It is important to understand the extent to which each radiometer varies from this ideal, especially so for the RSR class of instruments.

The total and diffuse horizontal irradiances measured by a RSR are no more sensitive to Lambertian-receiver error than conventional radiometers. However, an RSR calculates the direct component by differencing the total and diffuse horizontal irradiances, and so the direct normal is linearly sensitive to the cosine response mismatch. Consequently, it is imperative to achieve the best possible approximation to the ideal Lambertian response and to measure and correct residuals.

We have constructed a cosine-response test bench that consists of a rotating platform precisely oriented by a computer-controlled stepping motor (Michalsky et al. 1992). This facility automates the many measurements needed to characterize the angular response of a detector. We measure the detector's response in four cardinal directions. Corrections can be made to field measurements using angle-weighted interpolations for other azimuths and elevations as described by Harrison et al. (1994). This instrument is Labview® controlled.

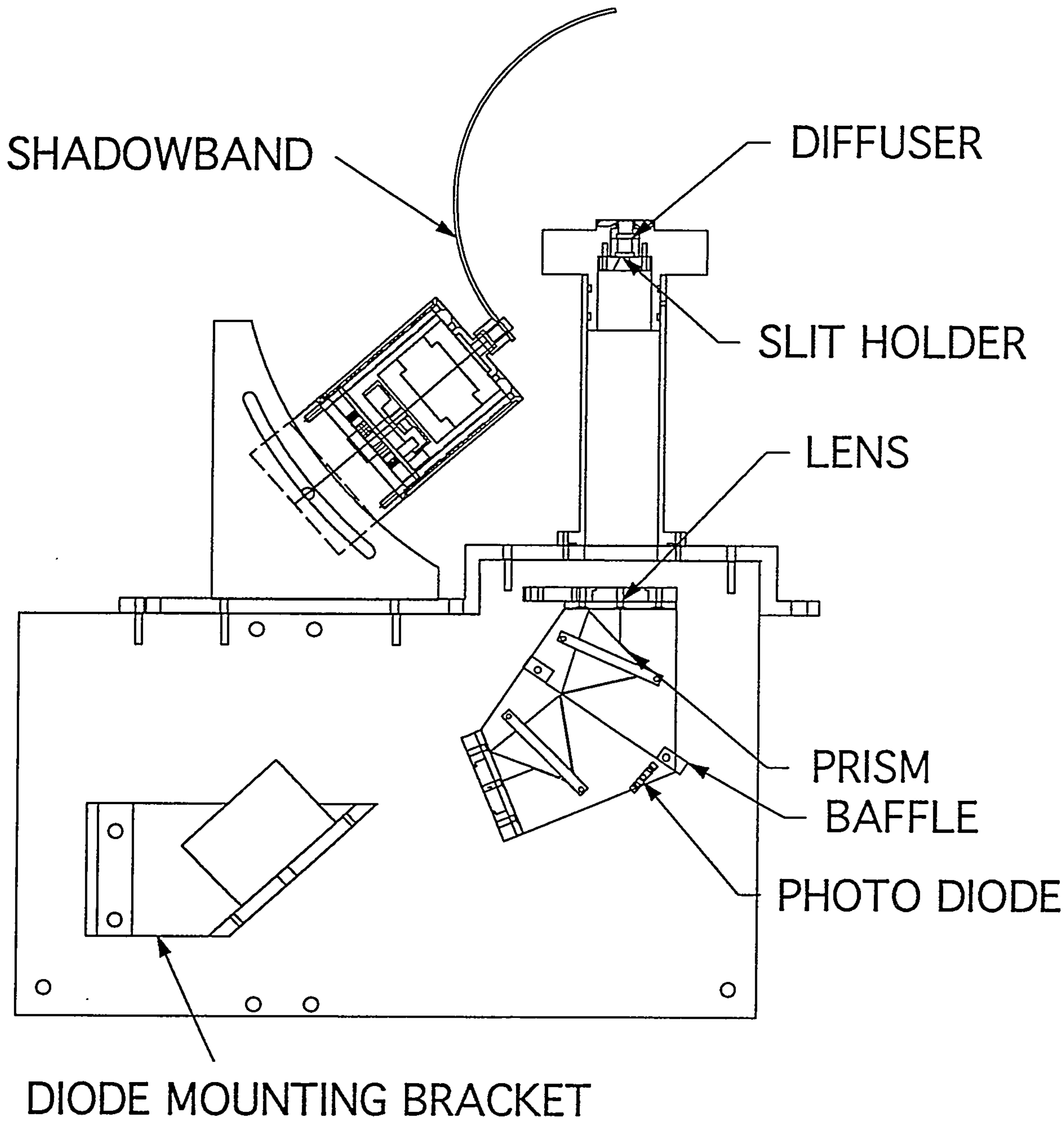

Fig. 2. Schematic of the rotating shadowband spectroradiometer.

Slit function: We define the response of each detector with respect to wavelength as the slit function. For the MFRSR we need to understand how the instrument responds as it is used, therefore, we need to measure the response with the filtered detector in the MFRSR receiver, not before it goes into the receiver. According to the National Institute of Standards and Technology guidelines on optical radiation calibration we should use a monochromator whose spectral width is 40 times narrower than that of the device to be characterized. For our 10-nm FWHM filters this implies 0.25 nm resolution from a monochromator, which is marginally practical.

However, the RSS has a spectral resolution of 0.6 nm per pixel at 350 nm and 8 nm at 1050 nm. It is impractical to use 1/40th the spectral resolution to map the slit functions for this instrument. Instead, we will use the same passband from the monochromator as is used for the MFRSR calibrations, and apply spectral deconvolution techniques to model the CCD array response from the known slit function of the monochromator and lamp output.

We have purchased an Acton® 1-meter scanning monochromator whose grating position and, hence, wavelength will be controlled by the Labview® software. We have written the module for this control function.

Absolute calibration: NIST offers a calibrated quartz-halogen, tungsten filament, 1000-watt lamp that provides a known spectral irradiance over the 350-1050 nm range with better than 1% (1 σ) accuracy. Our calibration is achieved by carefully positioning the MFRSR head at the prescribed distance from the lamp that is powered by a carefully controlled current source. This is no simple task, but we are using a commercial source for the positioning equipment and power supply. We convolve the slit function with the lamp output to assign the effective wavelength and spectral irradiance for our calibration constant. The power supply that controls the lamp and the voltmeter that reads the output of the detectors are controlled by Labview® modules that have already been written and tested.

For field absolute calibration with an approximate accuracy of 4% we use a LI-COR 1800-02 Optical Radiation Calibrator (LI-COR 1990).

Algorithm Development

The MFRSR instruments deployed in the extended facilities log all basic radiometric measurements that must be handled in the ARM environment. Consequently, algorithm development to automate as much of the acquisition and processing as possible is very important. In addition to the algorithms needed to operate the instruments and telemeter these data, we have developed the codes needed to handle the calibration processing, and a variety of correction algorithms that improve data accuracy. We believe that the bulk of these basic efforts are complete and hope that we can focus to a much greater degree on new algorithms to extract useful information from these radiometric data.

Optical Depth Retrieval

The analysis of direct beam extinction measurements by the technique of Langley regression is the principal source of data for changes in atmospheric opacity due to changing aerosol burdens (Volz 1969, Flowers et al. 1969, Shaw et al. 1973, King et al. 1978, Guzzi et al. 1985). Recent studies conducted within ARM by the aerosol working group emphasize the need for accurate routine measurements of aerosol optical depths as a function of wavelength. These are directly retrieved from MFRSR data by Langley regression using an objective and automated method of analysis to keep up with the substantially increased data flow, and to provide assurance that the results are not being biased by an analyst's preference.

We use an algorithm (Harrison and Michalsky 1994) that objectively selects data points from a continuous time series and performs the needed regression. The retrieval of the extraterrestrial irradiance (I_o) via Langley regression is of particular utility for the MFRSR, because the automated shadowband technique guarantees that the calibration coefficient is identical for the three components, and so the observations of I_o (suitably corrected for the sun-earth distance) provide a long-term calibration for the instrument.

Water Vapor Retrieval

Reagan et al. (1987) proposed a technique to retrieve total column water vapor using continuum and water-band pair measurements. The unique aspect of this technique compared to earlier procedures was that it was self calibrating. In other words, it did not depend on some other measurement made side-by-side for calibration. This modified Langley technique was further developed by Bruegge et al. (1992) who used the assessable radiative transfer code LOWTRAN (Kneizys et al. 1989) to calculate water vapor transmission needed to apply the methodology. In a paper recently submitted to the *Journal of Geophysical Research-Atmospheres*, we further modified the technique by using the higher resolution code MODTRAN2 (Berk et al. 1989) to calculated transmission in the water band. We extended our microwave radiometer comparison of retrieved water vapor columns over a complete year of measurements made at the SGP CART site. This comparison for a large range in water vapor column (0.25-4.25 cm) is especially valuable in validating the technique. We hope to develop a "user-friendly" algorithm to routinely retrieve water vapor column from the data stream.

Ozone Retrieval

To retrieve water vapor, it is necessary to estimate the aerosol component of the optical depth in the water band. To estimate aerosol optical depth, we used the methodology of King and Byrne (1976) to perturb the climatological ozone correction for aerosol optical depth in the Chappuis band until a least squares fit of the natural log of optical depth to a quadratic function of the natural log of the wavelength yielded a minimum rms error. This led to a new estimate of ozone. Since no ozone column measurement is made at the SGP site, we compared our results to the nearest Dobson station at the same latitude. The Nashville and SGP seasonal data were both below climatological values with the Nashville data somewhat lower than SGP. These results are consistent with those data reported for the continental US by Komhyr et al. (1994).

Commercialization of the Rotating Shadowband Radiometers

The single channel and multiple channel versions of this instrument are getting considerable attention, largely as a result of exposure through the ARM program. Since the instrument was developed by the Pacific Northwest Laboratory and the State University of New York, these two institutions have entered into an agreement to license the technology to a commercial vendor. Yankee Environmental Systems, Inc. was selected from among three interested companies. They have delivered the first commercial MFRSRs this year.

PROPOSED RESEARCH

The goal of every measurement made in the CART environment should be to achieve state-of-the-art accuracy. Better yet, the ARM program provides us the opportunity to push the state-of-the-art in radiation measurements. By making good observations and better measurements with improved algorithms for inverting and interpolating the data, the ARM community will constrain the process and synoptic models and finally the GCM models that is the primary objective of the ARM program.

We wish to stress this improvement in measurement, especially through improved calibration, and improvements in inversion and interpolation in this phase of our program. To this end we want to work with radiation models and modelers in the instantaneous radiative flux measurement strategy group and the modelers in the four dimensional data assimilation measurement strategy group.

Radiation Code Test Data Sets (Albany Data Acquisition)

We want to continue to operate the ASRC radiation site. This activity requires less than 10% of our total budget request, but contributes substantially to our ARM goals. In effect, the activity is subsidized through our participation in the IDMP, which is funded by NREL. Data sets collected and assembled at this site are used to test the radiation codes used in the ASRC modeling group's GCM (W.-C. Wang group). We expect this activity to continue because we have a different climate than the SGP site. These data can continue to serve as an all-season data set for tests of improvements made to GCM radiation models. Data from the Albany site have enabled us to develop and test algorithms to improve the shortwave measurement made with the MFRSR. One possibility is that some linear combination of the filtered measurements may allow us to improve the retrieval of shortwave direct normal and diffuse horizontal irradiances. Should this be found true, then we can substitute a filtered channel for the unfiltered broadband channel in future versions of the MFRSR.

The Rotating Shadowband Spectroradiometer (Completion)

The advanced prototype of this instrument has been machined and assembled and briefly tested in the laboratory and outdoors. Our post-doctoral fellow, who was charged with getting this instrument operational, has left the ASRC. We are nevertheless committed to finishing and testing this instrument at the ASRC in the next year using a combination of scientists' and technicians' time. Following a rigorous calibration process at the ASRC we would like to deploy it at the SGP CART facility during part of the second and all of the third years of the grant.

The test results are very encouraging with the spectral resolution and instrument sensitivity very close to design values. This instrument will provide moderate spectral resolution measurements of direct, diffuse, and global irradiance in the 350-1050 nm range with very high time resolution. The 256 channels will generate aerosol optical depth at an order of magnitude more wavelengths than filter instruments provide. Water vapor and ozone retrieval accuracy should improve, and nitrogen dioxide retrievals should be possible.

Calibration (MFRSR and RSS)

We have completed the cosine response test bench interface with Labview® already. We expect to complete the absolute calibration and spectral response test benches and interfaces by the end of the current calendar year.

Algorithm Development

Aerosol, Water Vapor, and Ozone

At this point we feel that we have developed effective ways to retrieve total column aerosol as a function of wavelength and total column water vapor. We are working towards producing an aerosol optical depth product for the CART site that could be simply retrieved by others. This would likely report aerosol optical depth whenever there was a cloud-free view of the sun for thirty to sixty minutes. A thirty to sixty-minute time series should allow us to make that determination.

We have not yet incorporated water vapor retrievals as a routine data reduction procedure. We expect some effort to go into making this a production routine rather than the awkward, interactive procedure it is now.

Ozone retrievals certainly seem plausible, but on-site comparisons to a total column ozone standard have not been made. We have potential opportunities to compare ozone column retrievals at NOAA-Boulder, the National Institute for Standards and Technology in Gaithersburg, Maryland, and at the SGP site. We expect to do some comparisons of ozone in this next year.

Clouds

Clouds have the single most important influence on shortwave radiation. We have just begun to investigate ways (1) to compare with other methods for discerning cloud cover, (2) to derive physical and optical properties such as mean cloud particle size and cloud optical depth, and (3) to report cloud observations that may be of use to others.

Cloudiness is observed by ground-based observers at weather stations throughout the world. It is reported as fraction of the sky covered by clouds. To the extent that a spatial and temporal correlation exists, i.e., cloud cover in the solar direction as a function of time represents the spatial distribution of clouds, we can use the MFRSR to specify cloud fraction. This will not hold on the synoptic scale, but may hold over the immediate CART site, where Instantaneous Radiative Flux experiments could use this information. This hypothesis will be tested against all-sky images and human observations.

Sunshine fraction is another indication of cloud transmission and is defined as the time that the direct beam irradiance exceeds 120 W/m^2 divided by the total time of daylight. This is a better predictor of total horizontal irradiance than cloud cover (Norris 1968), because thin transparent clouds pass a large fraction of sunlight incident on them. Calculation of sunshine fraction is straightforward.

Solar energy researchers use a parameter that they refer to as the clearness index (sometimes cloudiness index) defined as the ratio of measured total horizontal irradiance to extraterrestrial horizontal irradiance (Iqbal 1983). This parameterization has the advantage of normalizing, at least to a large degree, the differences caused by the sun elevation as a function of time of day and time of year.

Developing a means of measuring and reporting cloud cover is not meant to replace methods such as imaging or standard reporting at the central site, but we want to use these procedures at the extended facilities where standard cloud observations and imaging are not emplaced.

Most clouds that we will study will not contain particles small enough, nor clouds thin enough that we can use direct irradiance extinction measurements to discern particle size. We may, however, be able to infer effective particle radius. With surface albedo measurements and measured total horizontal irradiance as input to simple two-stream radiative transfer models, we should be able to calculate cloud optical depth. Given the liquid water path as measured by microwave radiometers we can then use the relationship

$$\tau_{cloud} = \frac{3*W}{2*\varrho*r_e},$$

to solve for the effective cloud particle radius r_e, where τ_{cloud} is cloud optical depth, W is liquid water path, and ρ is water density.

We have the opportunity with the MFRSR to use a technique that is very sensitive to cloud cover and to aerosol loading. The ratio of direct normal to diffuse horizontal irradiance is very sensitive to cloud cover, especially for thin or even subvisual clouds. For thin clouds the direct is reduced and the diffuse is increased because of increased scattering. Thus, the ratio of direct to diffuse is doubly impacted. The LBLRTM group has had difficulty selecting very clear sky conditions for model and infrared data comparisons. We have made some attempt to identify very clear conditions for days they have selected. It appears that this is a viable technique, which we are now trying to incorporate into their data stream in cooperation with the PNL data team.

Other

Five of the six filters in the MFRSR may be used to study aerosol. King et al. (1978) provide an algorithm for inverting aerosol optical depth as a function of wavelength to obtain approximate column-averaged size distributions. Generally they find suitable size distributions for aerosol with radii in the 0.1 to 4 micrometer range. We have applied this algorithm to derived stratospheric aerosol optical depths with reasonable results (Michalsky et al. 1990), and expect to investigate seasonal and long-term size distribution behavior at the SGP site using the MFRSR data base. An interesting comparison to make with this data base of sizes will be to the standard aerosol size distributions used in the popular MODTRAN atmospheric transmission code.

The MFRSR measures direct and diffuse radiation simultaneously in five filters. King and Herman (1979) show that this ratio for clear skies is quite sensitive to ground albedo once the optical depth and size distribution are calculated using the techniques described above. A determination of ground albedo in this way is an averaged effective albedo for the location of the measurements. We intend to pursue the development of this method and to compare our derived results with 60-m tower and aircraft albedo measurements when available.

One of the more popular shortwave spectral irradiance codes is the Air Force Phillips Laboratory's MODTRAN code. We will compare our MFRSR and RSS measurements with spectra generated with this code, where the specifications of the atmospheric conditions for the code are taking from measurements at the CART facilities. We expect to collaborate with other ARM investigators in this and other shortwave code comparisons.

PERSONNEL

Chuan Zhou will receive his masters degree in atmospheric science this summer. For his thesis he studied a methodology for improving the agreement between the MFRSR unfiltered silicon sensor measurements and first-class thermopile measurements of total and diffuse horizontal and direct normal irradiance. The silicon detects radiation non-uniformly in the 300-1100 nm range and not at all beyond 1100 nm. Shortwave is usually considered all radiation in the 300-3000 nm range, which thermopile sensors detect with a near-uniform response. As reported above the MFRSR temperature control and cosine response corrections improve the rms error significantly; Chuan's spectral corrections further improve the total and diffuse horizontal irradiances by about 20% and 15%, respectively; and time response differences in the detector technologies account for another 20-40% of the error depending on the solar component in question. Consequently, one standard deviation repeatability with the

MFRSR shortwave silicon detector is better than 10 W/m^2 in each component. He will continue toward his Ph.D., but a thesis topic has not yet been selected.

Mostafa Beik, a post-doctoral fellow from the University of Wyoming, worked almost exclusively on development of the rotating shadowband radiometer. His two-and-one half year appointment ended this spring.

PUBLICATIONS AND PRESENTATIONS

Two papers were published since the last annual report.

Michalsky, J.J., R. Perez, R. Seals, and P. Ineichen. Degradation of Solar Concentrator Performance in the Aftermath of Mount Pinatubo. *Solar Energy* **52**: 205-213 (1994).

Michalsky, J.J., R. Perez, R. Seals, and P. Ineichen. Mount Pinatubo and Solar Power Plants. *Solar Today* **7**: 21-22 (July/August 1993).

Two papers that were reported as submitted to Applied Optics in the last annual report have been accepted for publication in 1994. No firm publication date has been set.

"Automated Multi-Filter Rotating Shadowband Radiometer: An Instrument for Optical Depth and Radiation Measurements" by L. Harrison, J. Michalsky, and J. Berndt is in press with *Applied Optics.*

"Objective Algorithms for the Retrieval of Optical Depths from Ground-Based Measurements" by L. Harrison and J. Michalsky is in press with *Applied Optics.*

Two papers have been submitted for publication since the last annual report.

"Cosine Response Characteristics of Radiometric and Photometric Sensors" by JJ Michalsky, LC Harrison, and WE Berkheiser III was submitted to *Solar Energy.*

"A Comparison of Sun Photometer Derivations of Total Column Water Vapor and Ozone to Standard Measures of Same at the Southern Great Plains Atmospheric Radiation Measurement Site" by JJ Michalsky, JC Liljegren, and LC Harrison was submitted to the *Journal of Geophysical Review-Atmospheres.*

Six papers have been presented since the last annual report, including the first four that have appeared in published proceedings.

Michalsky, J.J., R. Perez, R. Seals, and P. Ineichen. "Concentration System Performance Degradation in the Aftermath of Mount Pinatubo" in Proceedings of the 1993 American Solar Energy Society Annual Conference, S.M. Burley and M.E. Arden (eds). American Solar Energy Society, Boulder, Colorado (22-28 April 1993 in Washington, DC), pp. 495-500.

Laulainen, N. S., N. R. Larson, J. J. Michalsky, and L. C. Harrison. "Aerosol Optical Depth Derived From Solar Radiometry Observations at Northern Mid-Latitude Sites." American Meteorological Society 74th Annual Meeting, Nashville, Tennessee, January 23-28, 1994.

Michalsky, J.J., L.C. Harrison, and J.C. Liljegren. "Water Vapor from Sunradiometry in Comparison with Microwave and Balloon-Sonde Measurements at the Southern Great Plains ARM Site." American Meteorological Society 74th Annual Meeting, Nashville, Tennessee, January 23-28, 1994.

Zhou, Chuan and Joseph Michalsky. "Spectral Correction of Silicon Photodiode Solar Radiation Detectors" in Proceedings of the 1994 American Solar Energy Society Annual Conference, S. Burley, M.E. Arden, R. Campbell-Howe, and B. Wilkins-Crowder (eds). American Solar Energy Society, Boulder, Colorado (27-30 June 1994 in San Jose, California), pp. 393-397.

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Michalsky, Joseph. "Mount Pinatubo Aerosol Loading at Mid-Northern Latitudes" in Impact of Volcanism on Climate--Gordon Research Conference (26-30 July 1993 in Henniker, New Hampshire).

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