1 of 1

Technical Progress Report
Development of Rotating Shadowband Spectral
Radiometers and GCM Radiation Code Test Data Sets
in Support of ARM

Work Performed for:
Environmental Sciences Division
Office of Health and Environmental Research
Office of Energy Research
U.S. Department of Energy
Grant No. DE-FG02-90ER61072

Co-Principal Investigators:
Joseph Michalsky and Lee Harrison
Atmospheric Sciences Research Center
University at Albany
State University of New York

3rd Award Period
September 15, 1992 to October 31, 1993

Report Date:
April 30, 1993

SUMMARY

Our ARM goal is to help improve both longwave and shortwave models 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 aerosol and cloud properties that are useful for longwave modeling efforts as well.

Our current ARM research program includes three tasks all related to the study of shortwave radiation transfer through clouds and aerosol. Two of the tasks involve the assembly of archived and new radiation and meteorological data sets; the third and dominant task has been the development and use of new shortwave radiometric sensors.

Archived data from Golden, Colorado, and Albany, New York, were combined with National Weather Service ground and upper air data for testing radiation models for the era when the Earth Radiation Budget Experiment (ERBE) was operational. These data do not include optimum surface radiation measurements; consequently we are acquiring downwelling shortwave, including direct and diffuse irradiance, plus downwelling longwave, upwelling shortwave, and aerosol optical depth, at our own institution, as an additional dataset for ARM modelers.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *clz*

The major objective of our program, however, has been to develop two spectral versions of the rotating shadowband radiometer (RSR). The RSR technique permits a single sensor at each wavelength to acquire the total horizontal, diffuse horizontal, and direct normal spectral irradiance, thus eliminating the uncertainty associated with intercomparisons of solar component measurements made with separate sensors. 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 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 MFRSR is complete and operational at the Southern Great Plains and Tropical Western Pacific clouds and radiation testbed (CART) sites. It has been selected as the core instrument of the ARM Solar & Infrared Observing System (SIROS) complement of instruments that will be emplaced at each extended facility within CART. The prototype of the RSS is acquiring data on the roof of the Atmospheric Sciences Research Center (ASRC) at the State University of New York in Albany.

PROGRESS TO DATE

Radiation Code Test Data Sets

Solar data have been collected at a number of sites in the United States to support the development of practical solar energy devices [NREL (1992) contains references to some of the best U.S. data sets]. Total and diffuse horizontal and direct normal shortwave irradiance data from the ASRC in Albany, New York, and the Solar Energy Research Institute [now National Renewable Energy Laboratory (NREL)] in Golden, Colorado, were combined with surface and upper air data from the Albany County Airport and Stapleton International Airport, respectively, to produce a data set for the testing of radiation algorithms contained in global climate models. The data set included one month of data representative of each season of the year for Albany and one winter and one summer month of data for Golden. These data coincided with the Earth Radiation Budget Experiments (no longer operating).

These archived surface radiation measurements contain only shortwave irradiances, and were not made as accurately as is now possible. Using current technology, total shortwave irradiance is best measured as the sum of the direct horizontal component (obtained by multiplying the direct normal obtained with a tracking pyrheliometer by the cosine of the solar-zenith angle) and the diffuse horizontal (obtained by a pyranometer equipped with a tracking disk that blocks the radiation from the solar position). We have used this technique to collect an improved data set since July 1991. Shortwave is measured as described with an Eppley NIP pyrheliometer and an Eppley PSP pyranometer. Additionally, we measure downwelling longwave with an Eppley PIR pyrgeometer, upwelling shortwave with a Eppley PSP, and aerosol optical depth is measured on clear days at a wavelength of 555 nm.

Both data sets are available to all the ARM modelers. 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 watts/m². As the techniques are developed, we will provide total column water vapor and ozone from a 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 significant difference between this new clear sky shortwave data base and the Wang et al. model.

Instrument Development Overview

We are developing two related instruments for use in the ARM program. Both share the improved Lambertian receivers developed as part of our work to date, and use an automated rotating shadowband technique to make spectrally resolved measurements of the direct normal, total horizontal, and diffuse horizontal irradiances. These parameters of the sky-radiance function are measured using the same detector (for a given wavelength), eliminating the difficulties inherent in comparing these data when measured by independent detectors.

The first of these instruments, the multi-filter rotating shadowband radiometer (MFRSR), uses independent filter/photodiode detectors behind a common Lambertian diffuser to measure at seven wavelengths. These instruments have been in use by the ARM program since June 1992, and instruments are currently deployed and operating at the central facility of the Southern Great Plains (SGP) CART site, and at Kavieng and Nauru in the tropical western Pacific in conjunction with PROBE. Nine MFRSR instruments are currently deployed as part of the United States Department of Energy Quantitative Links measurement program. This instrument, and tests to demonstrate its level of performance, are discussed in Harrison et al. (1993).

The MFRSR has been selected by the ARM program for the extended network, and will form the core of the SIROS suite at these sites. The SIROS complement of instruments and mode of operation is very similar to the Quantitative Links installations, and so this extramural experiment is serving as a very effective testbed for the technology as it will be deployed by ARM. A first batch of 25 of these MFRSRs were built for ARM at PNL in 1992 and 1993 to serve in the extended facilities for the SGP CART site. The installation of these instruments is expected to commence in early summer of 1993. A second batch of 25 MFRSRs is currently under construction at PNL to support ARM installations elsewhere and demand by related programs.

The other instrument that we have developed uses a prism spectrograph 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 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 receive major emphasis in our future research effort.

Automated Rotating Shadowband Radiometry

The basic geometry of a computer-controlled RSR can be seen in figure 1. The shadowing band is a strip of metal formed into a circular arc that lies along a celestial meridian (the face of the Lambertian detector is the center of this arc). It can be precisely rotated (0.4°) around the polar axis by a stepping-motor that is in turn controlled by a microprocessor. This band blocks a strip of sky with an umbral angle of 3.27° , more than sufficient to block the solar disk. The mechanism permits a simple mechanical adjustment for the latitude. This adjustment, together with the azimuth alignment to the earth's pole, is done when the instrument is installed at a site, and no further mechanical adjustment is necessary.

The operation of the instrument is controlled by its self-contained microprocessor. At each measurement interval it 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 (available from the ephemeris calculation) then produces the direct beam flux on a normal surface. The entire measurement sequence is completed in less than ten seconds and is normally programmed to occur four times per minute.

Figure 1: RSR Geometry

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. The instrument stores and telemeters data, and has a battery-backup so that operation continues through power outages.

The RSR has several advantages over the traditional alternative of using two detectors: one fixed to measure the total horizontal irradiance and one mounted on a tracking mechanism to measure the direct normal component. The RSR is simpler, less expensive, and more robust. Further, the three irradiance components are derived from a single optical detector, greatly reducing intercalibration worries about both absolute sensitivity and spectral passband, and guaranteeing that the measurements are synchronous. These features improve the utility of calibration via Langley extrapolation (discussed below), since the measurements of the diffuse and total horizontal irradiances are calibrated as well.

The Multi-Filter Rotating Shadowband Radiometer

Figure 2 shows the design of our multi-filter detector assembly for the MFRSR. The exterior, except for the optical inlet, is black-anodized aluminum. The optical inlet is a protruding diffuser surrounded by a raised blocking ring (with a drain hole not shown). The diffuser is made of Spectralon™, an optical plastic manufactured by Labsphere¹. The thin-walled external "button" acts as a transmission diffuser, and the thick internal sidewalls form a partial integrating

¹ Labsphere Inc. North Sutton, NH

cavity. Two diaphragms of frosted WG-280 glass² act as transmission diffusers to increase the randomization of the photon trajectories. The geometry of the protruding diffuser, the sidewall blocking rings, and integrating cavity were arrived at by extensive empirical optimization ('cut-and-try') using the automated test facility described in our section on calibration.

Figure 2: Multi-Filter Detector Cross-Section (*not to scale*)

The entire detector consists of the diffuser-integrator described above that illuminates an internal hexagonal close-packed array of seven photodiodes with interference filters. These diodes are mounted to the interior of a five-sided cubic printed circuit board that provides a separate transimpedance amplifier (zero-bias current-to-voltage amplifier) for each of the photodiodes. The photodiodes are operated in the photovoltaic (rather than photoconductive) mode to reduce noise and increase sensitivity and stability. Transimpedance amplifiers are implemented using individual commutating-auto-zero (i.e., "chopper stabilized") devices to reduce variations in input offset and bias current.

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 35°C to 45°C. Temperature stabilization is necessary to improve the accuracy in several ways. Both the passband and transmission of interference filters are sensitive to temperature, although these effects are most pronounced with passbands that are significantly narrower than those we employ. More importantly the photodiodes exhibit changes in sensitivity with temperature, and the bias currents of the amplifiers are temperature sensitive as well. Finally the elevated and stable temperature improves long-term stability of the interference filters by eliminating temperature-cycle induced mechanical fatigue of the dielectric lamina (that have differing expansion coefficients), and by guaranteeing a low internal humidity³. An important operational side benefit of this temperature control is that the heat loss keeps the detector ice-free in all but the worst icing conditions.

² Schott Glaswerke, Mainz, Germany

³ Provision is made for an additional dessicator for environments that are warm and humid.

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. All the filtered passbands except 940 nm (a water vapor band) are chosen to permit Langley analysis for the direct determination of optical depth. The wavelengths were chosen to span a useful range for flux calculations, and to permit the maximum information about the aerosol to be retrieved via inversions such as those described by King et al. (1978), King and Herman (1979), and Shaw (1979). An additional goal is the estimation of column ozone from Chappuis band absorption.

The Rotating Shadowband Spectroradiometer (RSS)

We are also working on a higher spectral resolution instrument consisting of a prism spectrograph coupled to a CCD array. 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 the solar application where higher resolution is desirable at the shorter wavelengths.

Neither flint achromats nor flint dispersing prisms can be employed if observations below 400 nm are to be made. Consequently careful optical trade-off studies were necessary to arrive at an acceptable design. A solution was found that is very straightforward to construct; it uses only simple plano-convex lenses, and coma and spherical aberrations are controlled by making the f -number of the system ≈ 7 . Chromatic aberration "controls itself" because the prism material is identical to that of the lenses, and the lenses *are not* chromatically corrected. The result is that the entire effect of chromatic aberration manifests itself as a planar tilt in the focal surface of the dispersed spectrum, which can be readily accommodated by tilting the detector.

The nominal wavelength range is 350 to 1050 nm, although this can be adjusted by changing the focal length of the final lens, and repositioning the detector array. The detector is a 256 element linear charge-coupled device (CCD) silicon photodiode array manufactured by Hamamatsu. The corresponding spectral resolution per pixel is 0.6 nm at 350 nm and 8 nm at 1050 nm.

We are starting to operate the RSS. Our wavelength calibrations are done using standard low pressure gas discharge lamps. Our selection of lamps allow us to find spectral lines over most of the spectral range covered by the instrument. These lines provide sufficient data to map the geometric passbands of all remaining pixels using a least-squares fitting process and the known refractive index of fused silica as a function of wavelength.

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. The first of these is completed and the other two are under development. Our plan is to have all three platforms under computer control. Much of this development effort will carry into the next grant period, but should be completed within the first year of the new term.

Cosine response: Most of our 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 a 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.

However, once this has been achieved then measurements of both the total horizontal and diffuse horizontal irradiances can be improved by bootstrap corrections as described by Harrison et al. (1993), yielding better measurements than possible by conventional techniques that depend on independent instruments to measure the separate components. This is possible because the shadowband technique guarantees that all three components share an identical calibration coefficient.

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 as it will be oriented for field measurements. Corrections can then be made to field measurements using angle-weighted interpolations for other azimuths and elevations as described by Harrison et al. (1993).

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, 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 must use essentially 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.

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% (1σ) 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 will use 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.

Currently, we do not measure the slit function of either instrument, but we do provide an absolute calibration of approximate 4% accuracy using the LI-COR 1800-02 Optical Radiation Calibrator (LI-COR 1990). Once these instruments are deployed for field use we use the sun-earth-distance-corrected intercept from the Langley analysis on clear stable days to check the stability of our calibrations.

Algorithm Development

The MFRSR instruments deployed in the extended facilities will 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 have also interacted with the ARM data-processing team to help identify and correct programming mistakes that have affected data outputs. These efforts are necessary to support the ARM infrastructure, but have been very time consuming during our first grant cycle. We believe that the bulk of these basic efforts are nearly complete and hope that over the next three years we can focus to a much greater degree on new algorithms to extract useful information from these radiometric data. However we have already accomplished a major goal, the objective retrieval of optical depths from the data by a completely automated algorithm.

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 can be directly retrieved from MFRSR data by Langley regression, but an objective and automated method of analysis is needed both to keep up with the substantially increased data flow, and to provide assurance that the results are not being biased (either by site, or over time) by change of analyst, or subtle changes of the analyst's preference.

Optical depth retrieval via Langley regression is complicated by cloud transits and other time-varying interferences. We have developed an algorithm (Harrison and Michalsky, 1993) that objectively selects data points from a continuous time series and performs the needed regression. The performance of this algorithm is compared by "double blind" tests with analysis done subjectively, and these results demonstrate the effectiveness of this method. The retrieval of the extraterrestrial irradiance (I_0) 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_0 (suitably corrected for the sun-earth distance) provide a long-term calibration for the instrument.

ARM Related Activities

In this section we summarize our activities that contribute to the ARM program, but were not formally a part of our original proposed effort. We cooperate with several Department of Energy laboratories and programs, and a few of these will be discussed briefly. Harrison's Department of Agriculture program to develop high-resolution ultraviolet spectrometers will result in the siting of the first instrument at the SGP CART central facility. Our commercialization of the MFRSR is also discussed.

International Daylighting Measurements Program: Sponsored by the International Illumination Commission and the International Energy Agency, observations began worldwide in 1991 to improve models of daylight availability and skylight distribution based on the more frequent measurements of solar shortwave. The ASRC serves as a general class site. ARM cooperated with this program by providing the solar shortwave measurements. In turn we obtain the visible wavelength aerosol optical depth for GCM radiation code testing.

Quantitative Links: We participate in the Department of Energy's Quantitative Links (QL) program as a joint effort with the Pacific Northwest Laboratory. The QL program's ultimate goal is to establish unequivocal evidence of the link between atmospheric composition change and climate change. Our contribution to this has been to establish a small network of stations anchored by MFRSRs that acquire spectral radiometry, temperature, humidity, precipitation, downwelling infrared and upwelling shortwave. The goal is to acquire a quality data base that

will allow us to establish interannual and seasonal variability in cloud cover, with emphasis on cirrus, and aerosol loading in the troposphere in order to search for real long-term trends in these parameters.

SIROS: The QL network served as the testing platform for the MFRSRs, allowing ARM to make several improvements in their field unit, and it has, in effect, led to a better design of the solar and infrared observing system (SIROS). The SIROS measures all spectral and broadband radiation at an extended facility and has as its main component a re-engineered RSR data acquisition system (DAS). The new SIROS includes 32 channels of data acquisition. This is sixteen more than the original. These extra channels will allow the MFRSR to run its normal irradiance measurement sequence, and provide enough additional data acquisition capability to acquire data from all primary radiometers at the facility. There are several channels provided to handle low voltage output radiometers and there are reference voltage sources on the board to provide excitation for the thermistors in the pyrgeometers.

High-Resolution UV Spectroradiometers, and the UV - Biosphere Monitoring Program: We are also involved in the development of improved instruments for measuring UV-B surface irradiance. This work is being supported by the U.S. Dept. of Agriculture's UV - Biosphere Monitoring Program, but is related to ARM both because the first of the instruments will be deployed at the SGP site, and because there are very substantial synergies between these two programs.

These new instruments combine a dual Ebert grating monochromator developed by Research Support Instruments (RSI), and both Lambertian (cosine response) optics and detector and signal processing technologies developed by us using our facilities and insights gained from our ARM work. These instruments use dual-threshold single-photon counting to improve the absolute accuracy and extend the minimum detection limits. The instruments will operate remotely and telemeter data; the computer control and data-handling techniques are derived from the RSR.

These instruments are capable of operating over the wavelength range 280 to 400 nm, covering both the UV-B and UV-A regions. The instruments achieve a spectral passband of 0.3 nm, and a reproducibility of wavelength determination of 0.02 nm. The instrument has an internal self-calibrator for wavelength. Because the instrument counts individual photons, accuracy is limited only by calibration accuracy and Poisson statistics.

Two of these instruments are complete, and are undergoing "shakedown" testing at the ASRC. The instruments will be calibrated and characterized by the NIST before deployment. The SGP CART site has been selected for the first deployment site. The presence of this instrument will augment ARM measurements, and provide accurate column ozone determinations via the Dobson technique. Subsequent sites have not been selected, though regional siting criteria have been established. It is expected that the Biosphere Monitoring Program will ultimately operate 6 to 10 instruments dispersed across the U.S.

Cooperation with Oak Ridge National Laboratories : As part of the ARM Instrument Development Program, ORNL has proposed to develop a scanning radiometer capable of direct solar measurements, but also solar aureole measurements and all-sky radiance measurements. This instrument would be capable of producing low resolution, but very accurate, sky radiance maps that would complement the all-sky imagers being built for ARM. We have provided advice and reviews of the ORNL activity for ARM management.

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 within 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. Three interested companies have been identified, and negotiations are nearly complete to have one of these begin commercial manufacture of single and multi-channel instruments.

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 the opportunity to push the state-of-the-art for these 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 are the primary objective of the ARM program.

We wish to stress this improvement in measurement and in inversion and interpolation in this next three-year 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 have been used to test the radiation codes used in the ASRC modeling group's GCM (W.-C. Wang group). We expect this activity to continue, but at a reduced level now that the SGP CART site is on line. These data can continue to serve as an all-season data set for initial tests of improvements made to GCM models. Data from the Albany site will enable us to develop and test algorithms to improve the shortwave measurement made with the MFRSR. Since the extended facilities will not have direct beam measurements other than the MFRSR, it is important to improve this measurement as much as possible.

The Rotating Shadowband Spectroradiometer (Completion)

The second prototype of this instrument has been machined and assembled and is undergoing tests in the laboratory and outside. It will not be completely tested and automated during the current grant period. We would like to finish this instrument and thoroughly test it at the ASRC. Following a rigorous calibration process at the ASRC we would like to deploy it at the SGP CART facility during the next grant period.

The test results are very encouraging with the spectral resolution and instrument sensitivity very close to design values. This instrument will provide reasonably high 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 perhaps, nitrogen dioxide retrievals will be possible.

Calibration (MFRSR and RSS)

The goal of 1% measurements of shortwave irradiance will not be achieved without substantial effort in calibration. In the "Progress to Date" section we discussed the various calibration efforts that we will make to achieve this improvement. Only the cosine response measurement bench is operational at this time. We are proceeding with purchases and design and assembly of

the slit function measurement station and NIST absolute calibration facility, but these will not be complete until the next grant period. It is our intention to automate all three benches with a common control computer and data acquisition system.

Algorithm Development

It is important to understand, especially for clear-sky conditions, the effects to shortwave radiation caused by aerosol, water vapor, and ozone. Clouds, of course, are the single most important influence on shortwave radiation. We wish to spend about half of the effort during the next grant period developing and applying algorithms to determine and study the behavior and influence of these atmospheric attenuators.

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. One interesting comparison to make with this data base of sizes will be to the standard aerosol size distributions used in the popular LOWTRAN 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 tower albedo measurements and aircraft albedo measurements when available.

Water Vapor: The MFRSR contains two near-infrared filters, one reasonably free of molecular absorption lines at 862 nm and one in the center of the strong water band at 940 nm. Reagan et al. (1987), among others, have devised a water vapor retrieval technique using the 940-nm water vapor channel of their radiometer assuming a square root dependence of the transmission on water vapor column abundance. However, we intend to use the procedure followed by Bruegge et al. (1992) to extract water vapor from direct irradiance measurements. The optical depth at 862 nm is used to estimate the aerosol component at 940 nm. We will use the LOWTRAN model (or MODTRAN) and the measured response of the 940-nm filter as a function of wavelength to calculate a water vapor optical depth as a function of water vapor column. As part of the ARM program we have the opportunity to compare our derived values with other measurements including microwave radiometers and infrared interferometers and radiosondes to improve this retrieval. This will be unprecedented to the extent that other derivations of water vapor from sun radiometry have not had the opportunity for extended comparisons that are afforded by the CART environment.

Ozone: The weak, broad Chappuis ozone band is centered near 600 nm. The MFRSR has a filter near this wavelength at 610 nm expressly for estimating ozone column optical depth. The 500 and 665 nm filters sample the wings of this ozone absorption band. The 415 and 862 filters are not affected by ozone. One approach that we will use for this estimate was developed by King and Byrne (1976) and uses optical depths at several wavelengths both within and to the long and short wavelength sides of the Chappuis band. After removing the Rayleigh scattering contribution to optical depth, the wavelength bands have either an aerosol contribution only or both ozone and aerosol. By making reasonable assumptions about the expected analytical behavior of aerosol extinction as a function of wavelength, different amounts of ozone optical

depth may be added or subtracted until the desired functional form is realized in a least squares sense.

A simpler method, employed by LeBaron and Michalsky (1988), uses a linear extrapolation from two wavelengths short of the ozone peak to predict aerosol extinction at the ozone peak. The difference in optical depth from this estimate is used to estimate the total column ozone. The apparent advantage of this simple method over the King and Byrne (1976) method was its insensitivity to the volcanic aerosol perturbation through the El Chichon epoch. More development and testing is required to assess the best approach to use in the ozone retrieval from visible wavelengths. Ozone measurements will be made at the ARM site using infrared interferometers and ultraviolet spectrometers. These provide a unique opportunity to compare measurements and improve our retrieval. Using visible ozone retrieval methods, we do not expect to rival state-of-the-art accuracy for ozone abundance, but rather intend to provide a better estimate for our aerosol retrievals than simply using climatological ozone values, as is the current procedure.

Cloud Cover: Cloudiness is observed by ground-based observers at weather stations throughout the world. It is reported as fraction of the sky covered by clouds in eighths, tenths or a percentage. 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 for 100s of km, but may hold over the immediate CART site, where Instantaneous Radiative Flux experiments are being conducted. This hypothesis can be tested using the other observations of cloud cover at the site, e.g., the all-sky imagers and human observations. Data are recorded every minute by the MFRSR. Cloud cover in this case will be defined as the number of minutes with zero direct in the interval of interest divided by the total number of minutes in the interval.

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. We can easily calculate sunshine fraction in a manner similar to cloud cover above. These are traditional methods for reporting cloudiness.

Solar energy researchers use a parameter that they refer to as the clearness index (sometimes cloudiness index) defined as the ratio of measured global 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.

We have the opportunity with the MFRSR to use a technique that should be very sensitive to cloud cover and to aerosol loading. The top of Fig. 4 illustrates the nearly perfect clear day of 30 September 1992 for the SGP site. The light line, which is the direct irradiance plot, does not indicate any change except for the effect of transmission changes with solar elevation. The ratio of direct to diffuse irradiance, however, shows a subtle but clear asymmetry between morning and afternoon. In the bottom of Fig. 4 the noticeable "noise" in the afternoon irradiance signal is significantly amplified in the direct-to-diffuse signal, which additionally shows a noon-centered dip that is not apparent in the irradiance plot.

We propose developing a cloud-type and optical thickness identification tool using these and other parameters. This could be developed through comparisons with the all-sky imagers and human observations that are made at the central facility. Once developed and validated for the

central site, it may be applied for this purpose at the extended facilities where the standard cloud observations will not be made.

Fig. 4. Comparison of direct irradiance sensitivity to clouds and direct-to-diffuse sensitivity to clouds.

Spectral Shortwave Model Intercomparisons

One of the more popular shortwave spectral irradiance codes is the Air Force Phillips Laboratory's LOWTRAN code. We will compare our MFRSR and RSS measurements with spectra generated with this code and MODTRAN, where the specifications of the atmospheric conditions for the code are taken from measurements at the CART facilities. We will

collaborate with other ARM investigators in this intercomparison (see Clough proposal). As shortwave spectral codes are considered by the ARM community, they will be tested against our data either by us or in collaboration with other investigators.

PERSONNEL

Chuan Zhou should receive his masters degree in atmospheric science during the summer or fall of 1993. His thesis work is the development of a two-channel MFRSR containing a silicon photodiode and a germanium photodiode. The silicon detects radiation in the 300-1100 nm range and the germanium detects radiation in the 800-1800 nm range. These two sensors cover the most important portion of the shortwave solar, and as such should provide a better determination of total shortwave than the single measurement made with silicon, which is the current situation. He will derive a methodology for calibrating the sensor output for direct normal and total and diffuse horizontal against the shortwave data set collected for radiation code testing on the roof of the ASRC.

Mostafa Beik received his Ph.D. from the University of Wyoming in electrical engineering. His education included considerable work in optics. In his post-doctoral position at the ASRC he has worked almost exclusively on development of the rotating shadowband radiometer. He has given two poster talks on the RSS at professional meetings and has given talks at the ASRC on his ultraviolet sensor calibration work and on the RSS development. His two-year appointment will end in the summer or fall of 1993.

PUBLICATIONS AND PRESENTATIONS

Six papers have been presented at conferences and two have been submitted to refereed journals. These are listed and briefly summarized below. Four of the presented papers appear in the published proceedings. In addition to these we have been presented papers at the 1991 and 1993 ARM Conferences in Denver and Norman and at two ARM workshops in Oak Ridge and Richland.

"Multi-Spectral Automated Rotating Shadowband Radiometry in the Atmospheric Radiation Measurement (ARM) Program" by L. Harrison in Proceedings of the Biennial Congress of the International Solar Energy Society, Denver, Colorado, 19-23 August 1991. This paper describes early designs of the two spectral versions of the rotating shadowband radiometer that are being developed as part of our ARM program.

"Mount Pinatubo Stratospheric Aerosol Perturbation Measured by Northern Mid-Latitude Solar Photometers" by N.R. Larson, E.W. Kleckner, J.J. Michalsky, L.C. Harrison, and D. Nelson at the 1992 Spring Meeting of the American Geophysical Union, Montreal, Canada, 12-16 May 1992. This paper describes the early effects of the Philippine volcano on the stratosphere at three North American sites using ground-based radiometry. Separation of volcanic aerosol from total column aerosol is explained. The data cover the first nine months following Pinatubo's eruption.

"Cosine Response Characteristics of Radiometric and Photometric Sensors" by J.J. Michalsky, L.C. Harrison, and W.E. Berkheiser III in Proceedings of the 1992 Annual Conference of the American Solar Energy Society, Cocoa Beach, Florida, 15-18 June 1992. This paper describes an apparatus developed at the ASRC for the measurement of the cosine response of Lambertian receivers. It includes tests of several commercial instruments that are commonly used in solar energy and atmospheric science programs, including the ARM CART.

"Evolution of Mount Pinatubo Stratospheric Aerosols Above Washington State as Measured by Ground-Based Solar Photometers" by N.R. Larson and J.J. Michalsky at the 1992 Fall Meeting of the American Geophysical Union, San Francisco, California, 7-11 December 1992. This paper describes the maximum perturbation of the stratosphere by this volcano as measured at five wavelengths. It derives aerosol size as a function of time before and after this maximum.

"Automated Multi-Filter Rotating Shadowband Radiometer: An Instrument for Optical Depth and Radiation Measurements" by L. Harrison, J. Michalsky, and J. Berndt has been submitted to Applied Optics. It gives a detailed description of the radiometer including arguments regarding the improved accuracy one can achieve in total and diffuse horizontal radiometry using such a scheme. The accuracy of the direct is compared to a direct normal measurement made with a tracking instrument using the same filter set.

"Objective Algorithms for the Retrieval of Optical Depths from Ground-Based Measurements" by L. Harrison and J. Michalsky has been submitted to Applied Optics. This paper explains our procedure for automating data selection for Langley analysis of optical depths from narrow filter radiometry. Comparisons are made to optical depth and extraterrestrial irradiances obtained using conventional subjective analysis techniques.

"The Automated Rotating Shadowband Spectroradiometer" by L. Harrison, M. Beik, and J. Michalsky in the Optical Remote Sensing of the Atmosphere 1993 Technical Digest of the Optical Society of America, Salt Lake City, Utah, 8-12 March 1993. This paper provides an overview of the optical and mechanical design of this 256-channel spectral instrument, and includes a discussion of the calibration and preliminary results.

"Time-Dependent Behavior of Mount Pinatubo Aerosol" by J.J. Michalsky and N.R. Larson in Optical Remote Sensing of the Atmosphere 1993 Technical Digest of the Optical Society of America, Salt Lake City, Utah, 8-12 March 1993. This paper discusses the effects of this volcano on the mid-northern latitude stratosphere as observed at three sites. It finds the results to be within the error limits of each other. It also finds the time evolution to be identical to that of El Chichon except for a scale factor of about 40% with Mount Pinatubo having the larger effect.

OTHER

The ARM program is addressing the highest priority item on the Committee on Earth and Environmental Sciences agenda with regard to the climate change program. The emphasis is on improved global climate models for better prediction of cloud feedback resulting from trace gas increases. We feel that ARM is taking a correct approach. In our opinion it is often the case that field programs are too short lived to either develop the statistics to understand the phenomena they are trying to study or too short to sample all of the phenomena of a climatological domain. ARM in sampling major climatological regimes and doing it over a sufficient period is on the right track in our opinion.

The present federal support of the radiation group at the ASRC includes 11% from NSF, 38% from USDA, and 28% from DOE grants and 23% from contracts through DOE's laboratories PNL and NREL.

REFERENCES

Bruegge, C.J., J.E. Conel, R.O. Green, J.S. Margolis, R.G. Holm, and G. Toon (1992). *Water Vapor Column Abundance Retrievals During FIFE*. J. Geophys. Res. **97**: 18759-18768.

Flowers, E.C., R.A. McCormick, and K.R. Kurfis (1969). *Atmospheric Turbidity over the United States, 1961 -1966*. J. Appl. Met. **8**: 955-962

Guzzi, R., G.C. Maracci, R. Rizzi, and A. Sicardi (1985). *Spectroradiometer for Ground-Based Measurements Related to Remote Sensing in the Visible from a Satellite*. Appl. Opt. **24**: 2859-2863

Harrison, L. and J. Michalsky (1993). *Objective Algorithms for the Retrieval of Optical Depths from Ground-Based Measurements* (submitted to Appl. Opt.).

Harrison, L., J. Michalsky, and J. Berndt (1993). *Automated Multi-Filter Rotating Shadowband Radiometer: An Instrument for Optical Depth and Radiation Measurements* (submitted to Appl. Opt.).

Iqbal, Muhammed (1983) *An Introduction to Solar Radiation*, Academic Press, Toronto
ISBN 0-12-373750-4

King, M.D. and D.M. Byrne (1976). *A Method for Inferring Total Column Ozone from the Spectral Variation of Total Optical Depth Obtained with a Solar Radiometer*. J. Atmos. Sci. **33**: 2242-2251.

King, M.D., D.M. Byrne, B.M. Herman, and J.A. Reagan (1978). *Aerosol Size Distributions Obtained by Inversion of Spectral Optical Depth Measurements*. J. Atmos Sci **35**: 2153-2167.

King, M.D. and B.M. Herman (1979). *Determination of the Ground Albedo and the Index of Absorption of Atmospheric Particles by Remote Sensing, Part 1: Theory*. J. Atmos Sci **36**: 163-173.

LeBaron, B.A. and J. J. Michalsky (1989). *Ozone Measurement Using the Chappuis Band in the Visible Spectral Region* in Proceedings of the International Radiation Symposium, (eds. J. Lenoble and J.-F. Geleyn). A. Deepak Publishing, Hampton, Virginia.

LI-COR, inc. *1800-02 Optical Radiation Calibrator Instruction Manual*. Lincoln, Nebraska (October 1990).

Michalsky, J.J., L.C. Harrison and W.E. Berkheiser III (1992). *Cosine Response Characteristics of Radiometric and Photometric Sensors* in Proceedings of the 1992 Annual Conference of the American Solar Energy Society. Cocoa Beach, Florida.

Michalsky, J.J., E.W. Pearson, and B.A. LeBaron (1990). *Assessment of the Impact of Volcanic Eruptions on the Northern Hemisphere's Aerosol Burden During the Last Decade*. J. Geophy. Res. **95**: 5677-5688.

National Renewable Energy Laboratory. *Interim Solar radiation Data Manual*, NREL/TP-463-5176. November 1992.

Norris, D.J. (1968). *Correlation of Solar Radiation and Clouds*. Solar Energy **12**: 107-112.

Reagan, J.A., K. Thome, B. Herman, and R. Gall (1987). *Water Vapor Measurements in the 0.94 Micron Band: Calibration, Measurements and Data Applications* in Proceedings of the International Geosciences Remote Sensing Symposium, IEEE 87CH 2434-9, 63-67.

Shaw, G.E. (1979). *Inversion of Optical Scattering and Spectral Extinction Measurements to Recover Aerosol Size Spectra*. Appl. Opt. **18**: 988-993.

Shaw, G.E., J.A. Reagan, and B.M. Herman (1973). *Investigations of Atmospheric Extinction Using Direct Solar Radiation Measurements Made with a Multiple Wavelength Radiometer*. J. Appl. Meteor. 12: 374-380.

Volz, F.E. (1969). *Some Results of Turbidity Networks*. Tellus 21: 625-630.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**DATE
FILMED**

12 / 30 / 93

END