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Solar Spectral Measurements and Modeling

Richard E. Bird
Roland L. Hulstrom

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Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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PREPARED UNDER TASK NO. 3623.01

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PREFACE

This report documents work performed by the Solar Energy Research Institute (SERI) Renewable Resource Assessment Branch for the U.S. Department of Energy under Task No. 3623.01. It describes a solar spectroradiometer, built under contract with SERI by the Baird Corporation, and its outdoor measurements of global, direct, and diffuse spectra. It presents modeled spectra from a rigorous radiative transfer code together with a brief description of the code and comparisons with results from two other codes as well as a preliminary comparison between measured and modeled data. We would like to thank J. V. Dave and IBM for providing extensive data sets on magnetic tape. We acknowledge the fine work by Herman Eldering and Arthur Kliman of the Baird Corporation in building the spectroradiometer; and finally, we are grateful for the many years of development of the BRITE Monte Carlo Code by Radiation Research Associates.

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SOLAR ENERGY RESEARCH INSTITUTE

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SUMMARY

Objective:

This report presents the status of spectral measurement and modeling capabilities of the Renewable Resource Assessment Branch at the Solar Energy Research Institute (SERI). It describes a new instrument that was specifically developed to routinely measure solar spectra. In addition, it illustrates several global, direct, and diffuse solar spectra produced by this instrument and also discusses spectral modeling capabilities.

Discussion:

For ease in making accurate solar spectral measurements, SERI has directed the development of a unique solar spectroradiometer. A computer controls the instrument and provides data reduction and analysis. A complete spectrum from 300-2500 nm can be recorded in 2 minutes, 25 seconds.

As a parallel effort to the development of the spectroradiometer, SERI has implemented a rigorous radiative transfer code for producing modeled solar spectra and for detailed radiation studies. The code uses Monte Carlo techniques to solve the equation of radiative transfer. This paper compares data from this code and two other codes and makes a preliminary comparison between modeled and experimental data.

Conclusions:

SERI has directed the development of an extremely versatile and advanced instrument with some unique features to measure terrestrial solar spectra. Spectral measurements have been made with this instrument that appear to be of very high quality. SERI has implemented a rigorous computer code that can produce solar spectra and perform detailed spectral studies. Initial indications are that the modeled spectra will agree to within ±8% of real spectra under the same atmospheric conditions. These measurement and modeling capabilities have already proven to be extremely important to several solar applications (especially photovoltaics, materials, and biomass research). In the future, SERI will compare measured and modeled data in more detail. In addition, standard solar spectra for various regions inside the United States will be produced with the spectroradiometer. SERI will continue to perform detailed studies with the radiative transfer code.

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SECTION 1.0

INTRODUCTION

For many years the solar community has recognized the need for accurate terrestrial solar spectra. Probably the greatest use of spectral data up to this time has been in extraterrestrial applications of photovoltaics for power on satellites. Terrestrial spectra were needed to calibrate and test these solar cells. As the solar industry has grown, many new applications of solar spectra have arisen. For example, the emergence of new materials for photovoltaic applications with very different spectral response characteristics has resulted in the need for spectral standards that represent different climatic conditions. It is possible to foresee photovoltaic cells with a spectral response that is tailored for a particular location. Research into biomass and new materials for solar applications also requires good solar spectra. Finally, we have felt that there is a lack of good spectral data for use in verifying spectral models of solar radiation. Many rigorous radiative transfer codes have been formulated over the years, but as far as we can determine, none of them has been properly verified with spectral data. Although many research facilities have measured solar spectra [1-9], these have not been used for model verification. One serious limitation of several existing spectra is that adequate measurements of meteorological conditions do not accompany them.

It is hoped that this work will result in a better understanding of the solar spectrum and the phenomena that affect it. Spectral modeling of solar radiation will surely be put on a firmer basis by comparison with measurements; and finally, the results of this work are expected to be of tremendous use to several solar technologies.

SECTION 2.0

DESCRIPTION OF SPECTRORADIOMETER

The Solar Energy Research Institute (SERI) solar spectroradiometer was designed and developed over approximately an 18-month period beginning in early 1979. This instrument measures the solar spectrum and records the results on plotter paper, magnetic tape, or printed output. Three modes of measurement are available: global, direct normal, and diffuse.

The complete system, except for the diffuse module, is shown in Fig. 2-1. From left to right in this figure, there is a 9-track tape recorder, and an x-y plotter with a calibration lamp power supply in an instrument rack. Next, a computer terminal/printer. The small cabinet to the right of this houses a PDP 11VO3-L computer and an RX02 floppy disk system. The cart at the far right carries the tracking base, the spectroradiometer head, the direct normal module, the calibration module, and the tracker power supply. Most of these units are on wheels, and the cart can be leveled and stabilized with four screw jacks. Figure 2-2 shows the diffuse module mounted on the system. A side view of the inside of the spectroradiometer head is shown in Fig. 2-3, and an end view of one of the monochromator assemblies is shown in Fig. 2-4. Each monochromator assembly is mounted on a keyed base plate that allows it to be removed as a separate unit.

In tracing sunlight through the system, one begins at the top plate shown in Fig. 2-3. The main input port to an integrating sphere is flush with the top of this plate, and a specially designed hemispherical chopper over this port permits a 180° field-of-view (FOV). The light reflects around inside of the integrating sphere, which is coated with $BaSO_4$. The light then leaves the integrating sphere through the sphere coupling sleeves and enters the entrance slit to each monochromator. The exit ports of the integrating sphere are situated such that direct sunlight never illuminates either of them. The two grating monochromators, one visible and one infrared, are of a crossed Czerny-Turner design with entrance and exit slits in line. After passing through the monochromators, the light passes through the exit slit on through order separating filters controlled by the computer, and onto the cooled detectors. The visible channel contains a 9-stage gallium arsenide photomultiplier, and the infrared channel contains a thin film lead sulfide detector. Both detectors are maintained at a temperature that is approximately 40°C below the ambient temperature.

Some unique features of this system are:

- Continuous dynamic spectral calibration.
- Continuous wavelength calibration.
- Continuous monitoring with a broadband silicon detector.
- A full 180° FOV with excellent cosine response.

Some of these features are implemented through the chopping mechanism. Each chop cycle consists of four segments. The first segment is a dark measurement, the second is a sun measurement, the third is a wavelength calibration measurement on a mercury lamp and a laser diode, and the fourth segment is a secondary reference lamp measurement. Sixteen measurements are made during each segment to improve the signal-to-noise ratio. A broadband silicon detector records data from the sphere continuously during the sun measurement segment to detect any changes in sun intensity during a run.

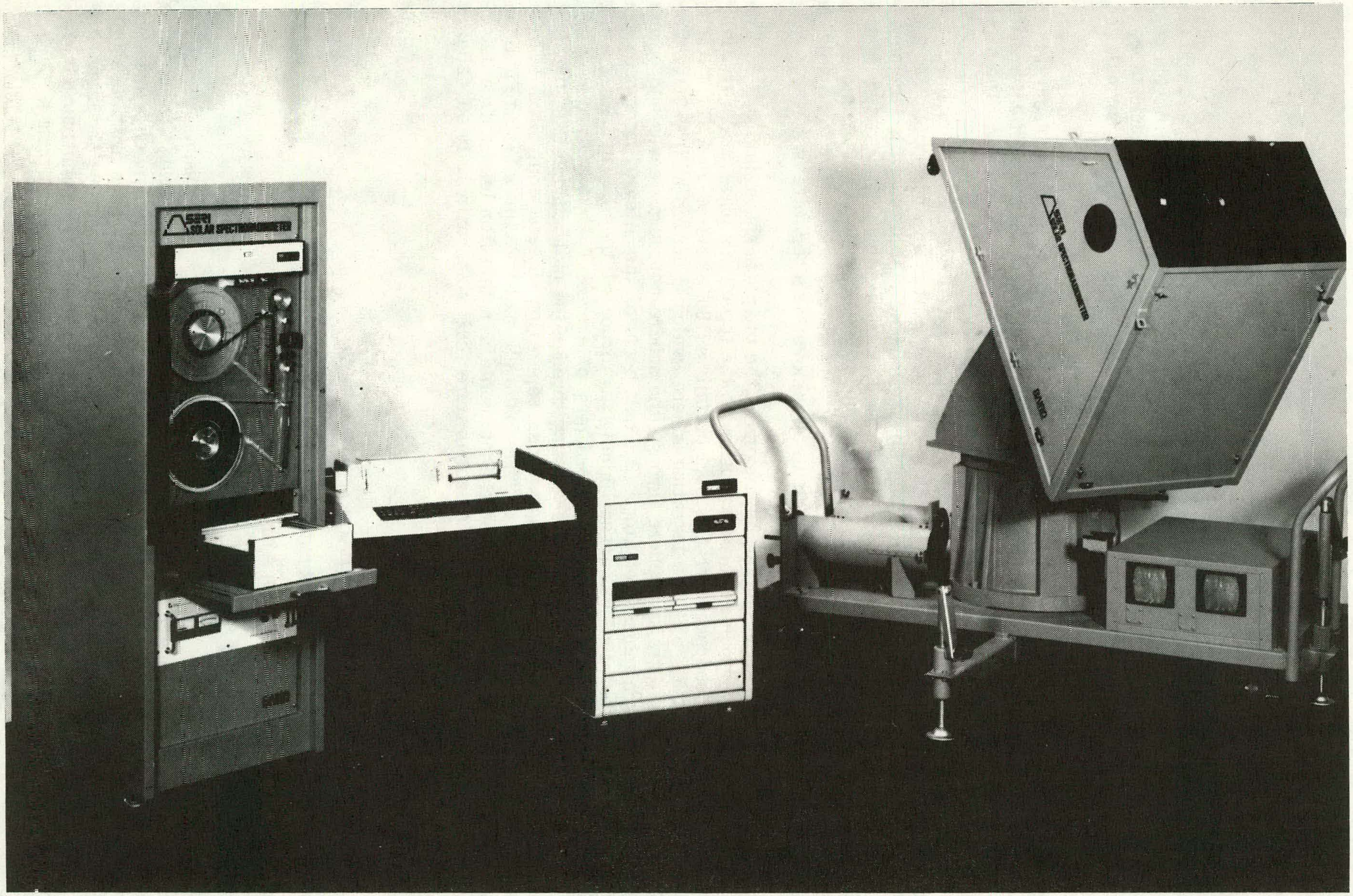

Figure 2-1. Complete Spectroradiometer System

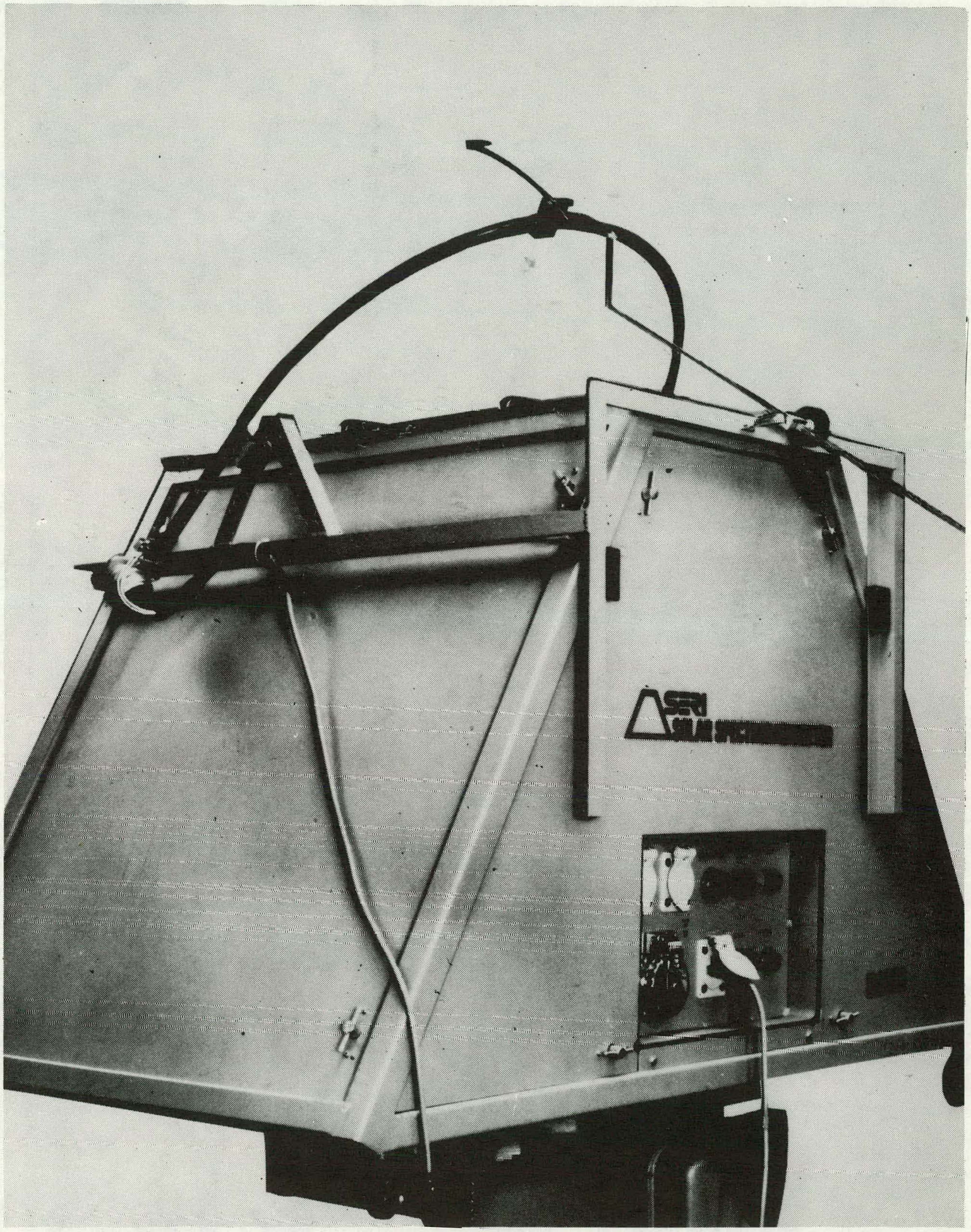

Figure 2-2. Spectroradiometer Head with Diffuse Module Mounted

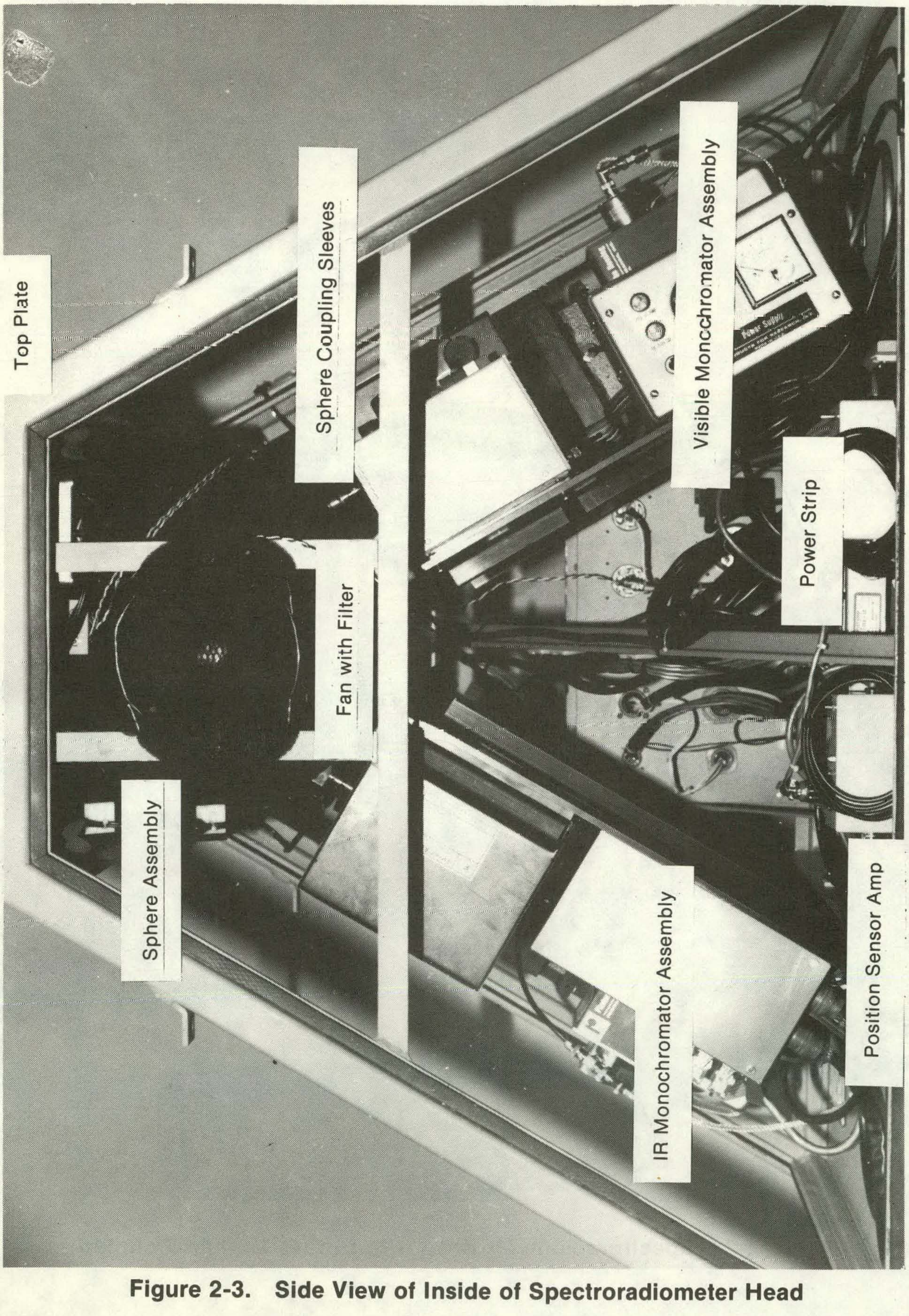

Figure 2-3. Side View of Inside of Spectroradiometer Head

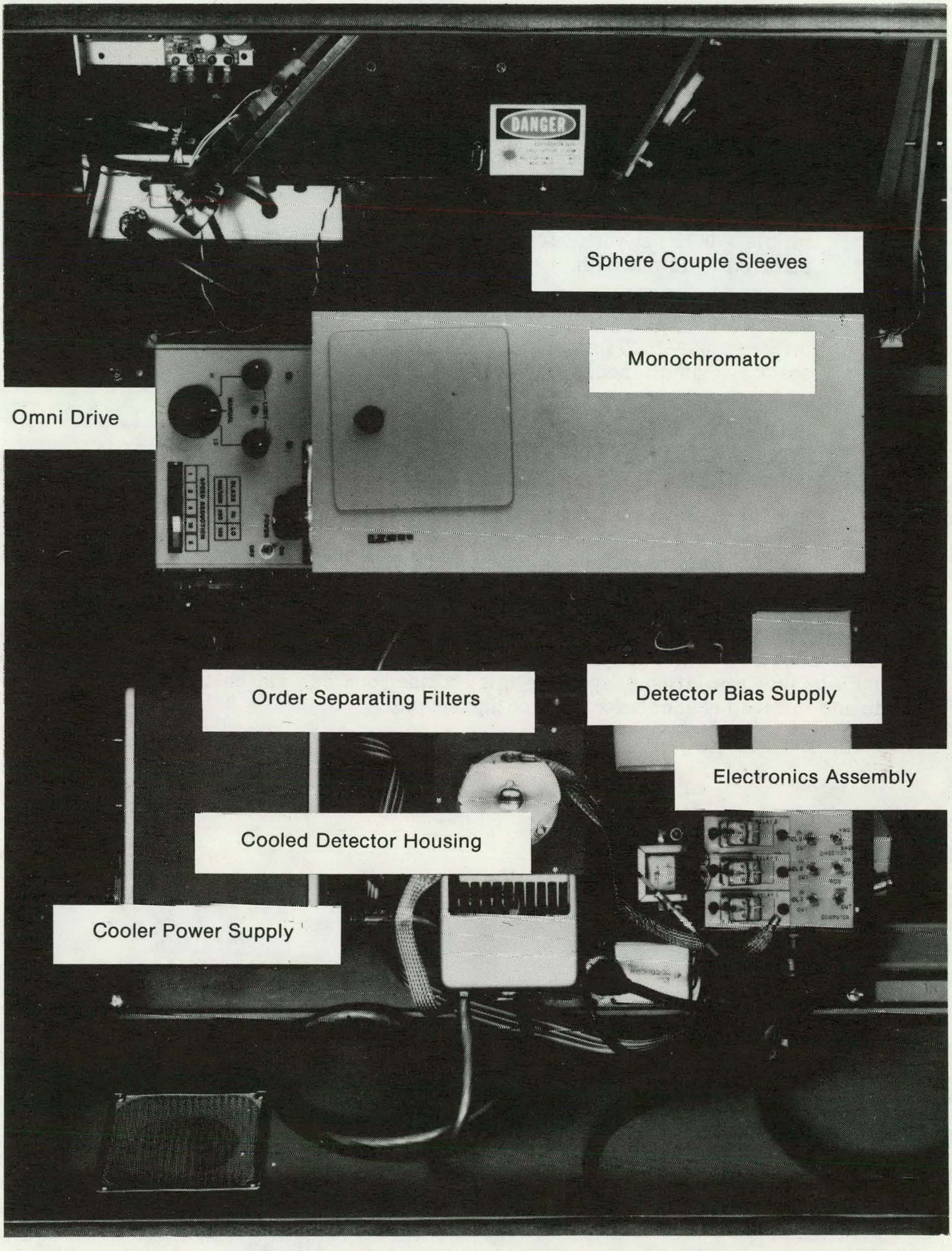

Figure 2-4. End View of Spectroradiometer Head Showing Infrared Monochromator Assembly

Some of the performance characteristics of the system are:

- Spectral Range
  visible 300-880 nm
  infrared 700-2500 nm
- Absolute irradiance calibration of ±5%
- Wavelength calibration accuracy of better than 0.05 nm rms
- Resolution
  visible 0.75 nm with 100 μm entrance and exit slits
  infrared 12 nm with 1500μm entrance and exit slits
- Scan time
  visible 280-900 nm in 1 min and 40 s
  infrared 660-2550 nm in 2 min and 25 s
  scans are simultaneous
- Tracking
  better than 0.02° accuracy
  ± 190° azimuth
  0° to 95° elevation
- Cosine Response
  0° to 75°-1.5% to +0.7%
  75° to 90°-2.9% to +3.6%

Most of the system is run from the computer keyboard and is under automatic control of the computer. A large amount of computer software was developed to aid in operation and data reduction. An example of this software is a smoothing routine that allows one to simulate less resolution. By using this routine, one can match the resolution of the visible and infrared channels for one continuous plot.

SECTION 3.0

RESULTS OF SPECTRAL MEASUREMENTS

This section presents spectra that represent data that have been taken with the spectroradiometer.

Figure 3-1 is a sample of direct normal insolation data taken at Golden, Colo., on 21 October 1980. The data in Fig. 3-1 are unsmoothed (high resolution) results taken with the visible channel of the spectroradiometer at different air mass (AM) values during the day. To illustrate what the fine structure looks like, high resolution data are plotted on expanded scales in Figs. 3-2 and 3-3, which were taken from direct normal data gathered in Bedford, Mass., on 18 July 1980 at 13:27 local standard time. Several Fraunhofer lines are labeled in Fig. 3-2 as they were found in a table. In Fig. 3-3, the most prominent features are oxygen absorption appearing near 760 nm and water vapor absorption appearing around 720 nm. In these expanded figures, each fine histogram structure represents one chop cycle where 16 data samples were taken. A more complete plot of

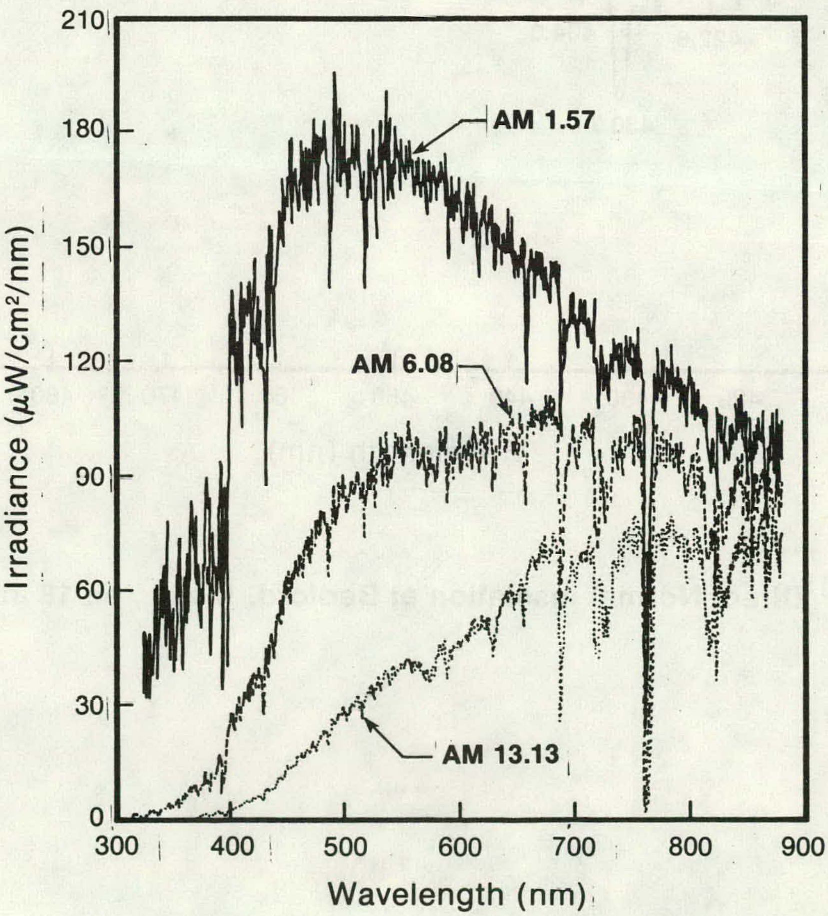

Figure 3-1. Direct Normal Insolation at Golden, Colo., on 21 October 1980

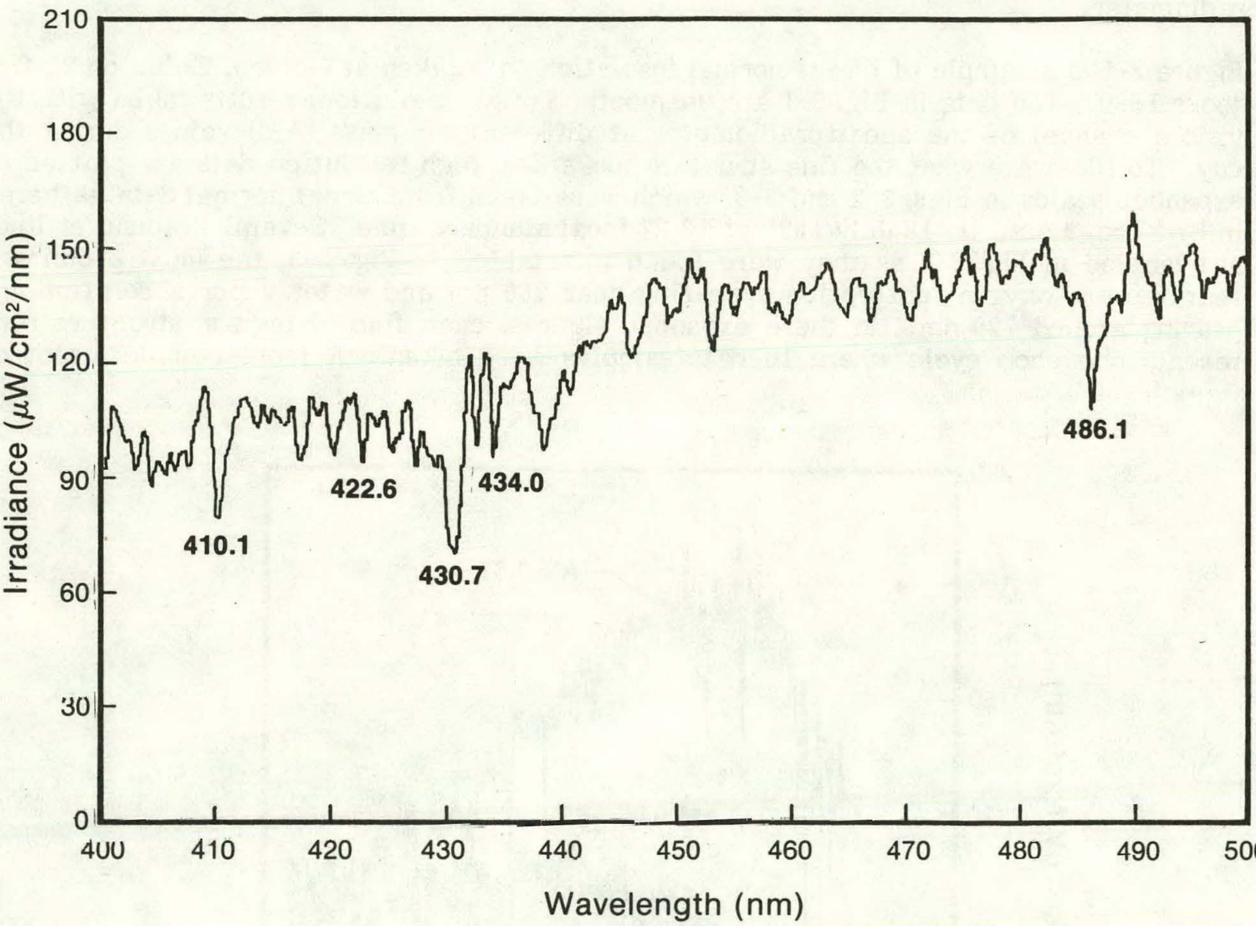

Figure 3-2. Direct Normal Insolation at Bedford, Mass., on 18 July 1980

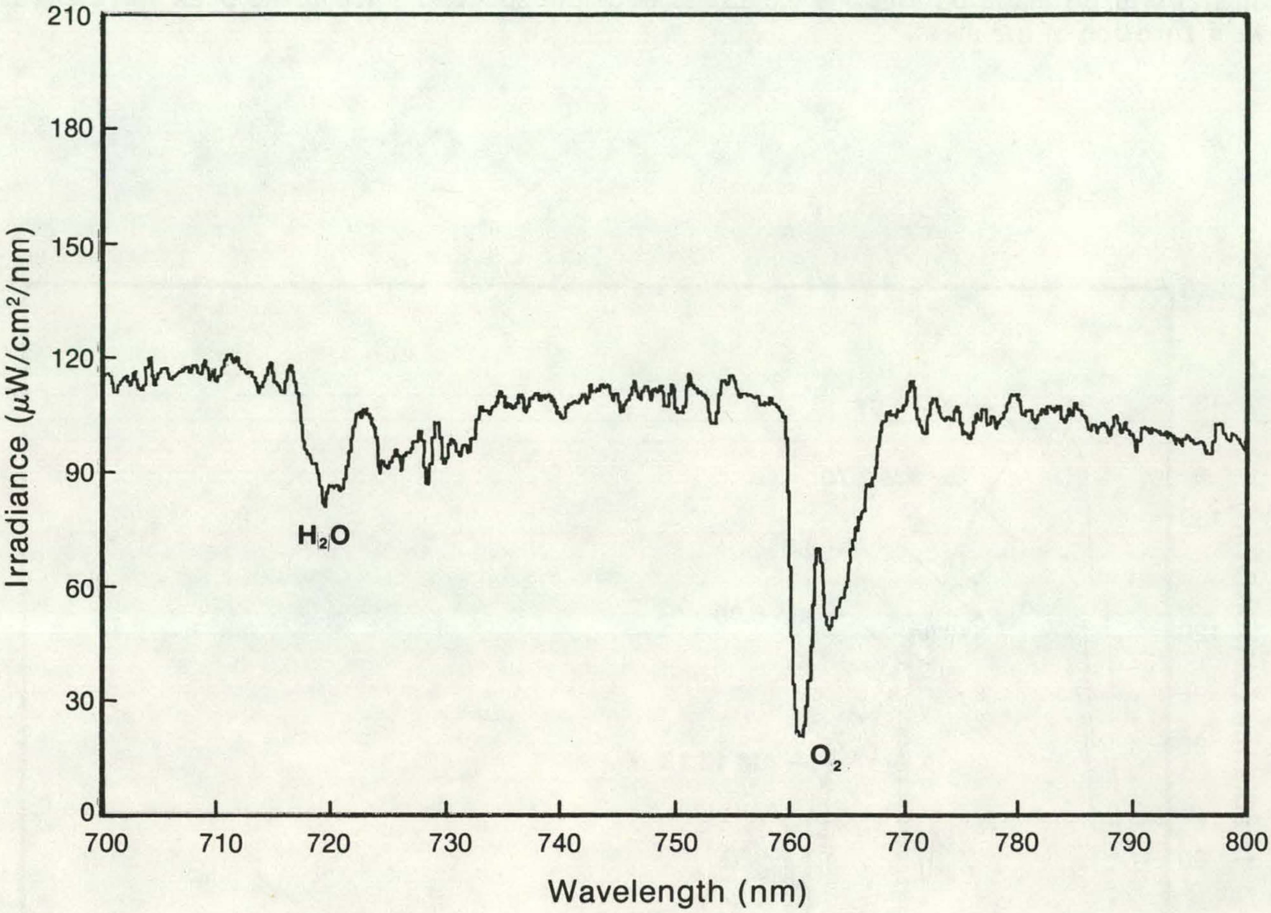

Figure 3-3. Direct Normal Insolation at Bedford, Mass., on 18 July 1980

direct normal data taken on 21 October 1980 at Golden, Colo. is shown in Fig. 3-4. The visible portion of the data in Fig. 3-4 has been smoothed to match the resolution of the infrared channel. The resolution is approximately 10 nm throughout the spectrum in this figure. These data were taken on an extremely clear day with no clouds visible. The turbidity was measured with a Volz sun photometer at 500-nm wavelength to range between 0.04 and 0.05 during the morning when these data were taken in Golden. No further comments will be made on Fig. 3-4 except to note the spectral shift in the peak wavelength as a function of air mass.

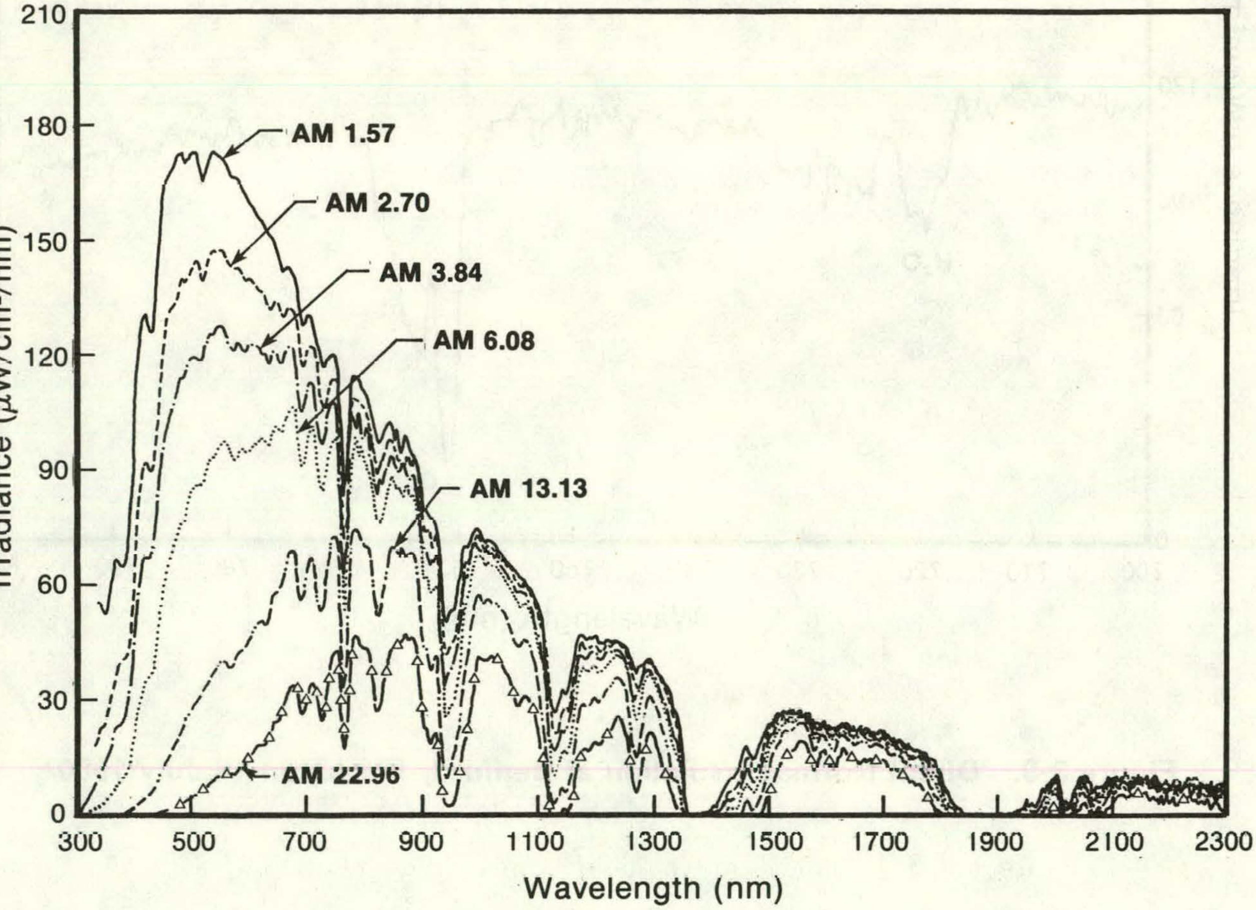

Figure 3-4. Direct Normal Insolation at Golden, Colo., on 21 October 1980

The global and diffuse horizontal data shown in Fig. 3-5 were taken on another very clear day in Golden, Colo. As is noted in the figure, the turbidity (τ) in a vertical column was measured to be 0.054 at 500-nm wavelength. Because of the clearness of the atmosphere and the altitude (1.7 km), the diffuse component is very small. It should be remembered that a large cosine effect is evident here, because of the data being measured from a horizontal surface. This reduces the magnitude of the spectrum.

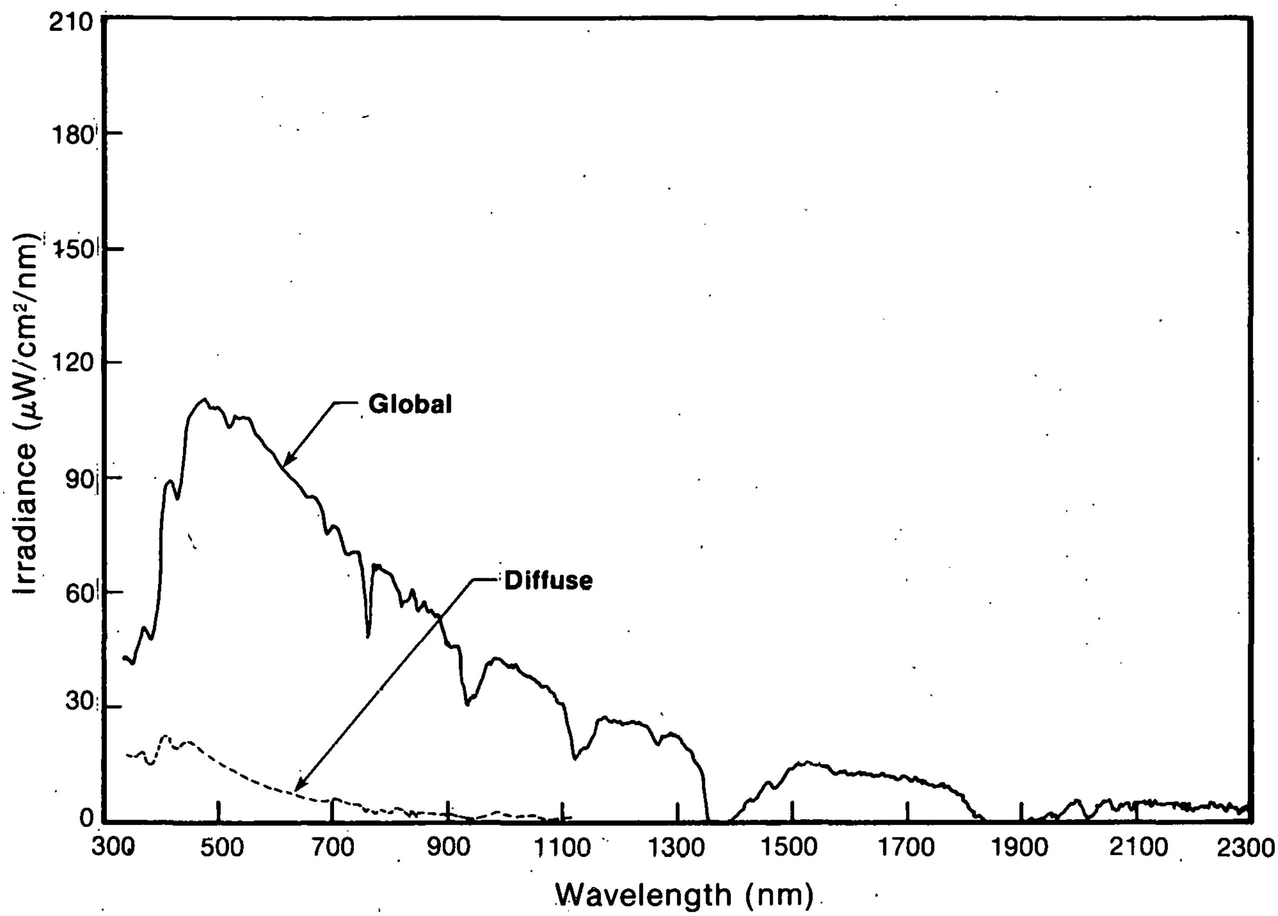

Figure 3-5. Horizontal Insolation at Golden, Colo. on 24 October 1980
AM = 1.73, τ(.5) = 0.054

Another set of spectra collected on 24 October 1980 at Golden, Colo., within a 20-min period is shown in Fig. 3-6. This illustration shows the different spectra that a tracking flat plate, a tracking concentrator, and a horizontal flat plate would see. The diffuse normal is the difference between the global normal and direct normal curves. Only the visible portion of the direct normal data is shown.

To illustrate the effect from changes in turbidity, data taken within a four-day period at Bedford, Mass., are shown in Fig. 3-7. The turbidity was not measured on 7 July 1980, but it is suspected that the value was near 0.2 since this value was reached on other days. These spectra illustrate the importance of measuring meteorological parameters such as turbidity when detailed analysis is being performed.

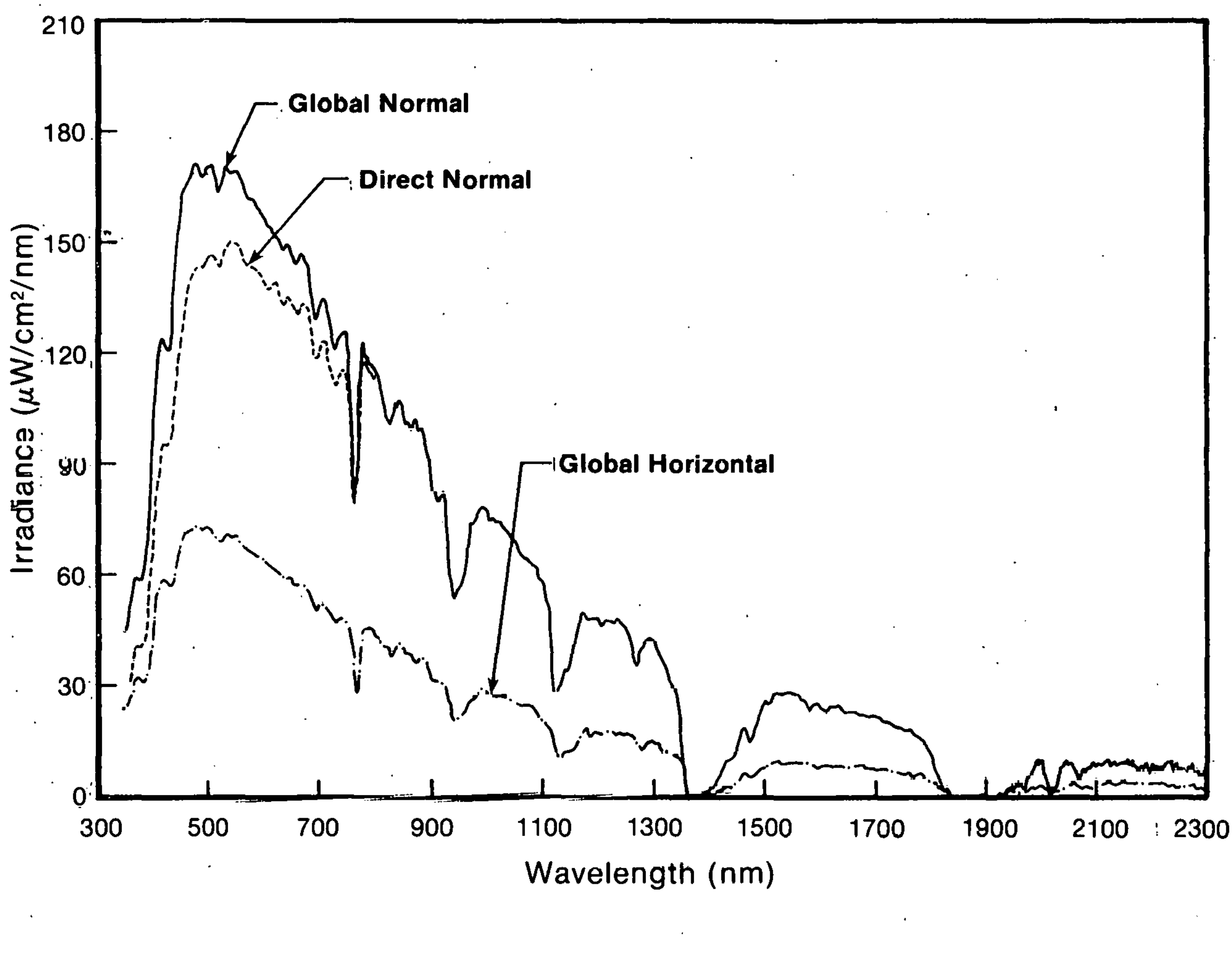

Figure 3-6. Insolation at Golden, Colo., on 24 October 1980
AM = 2.5, $\tau(.5) = 0.037$

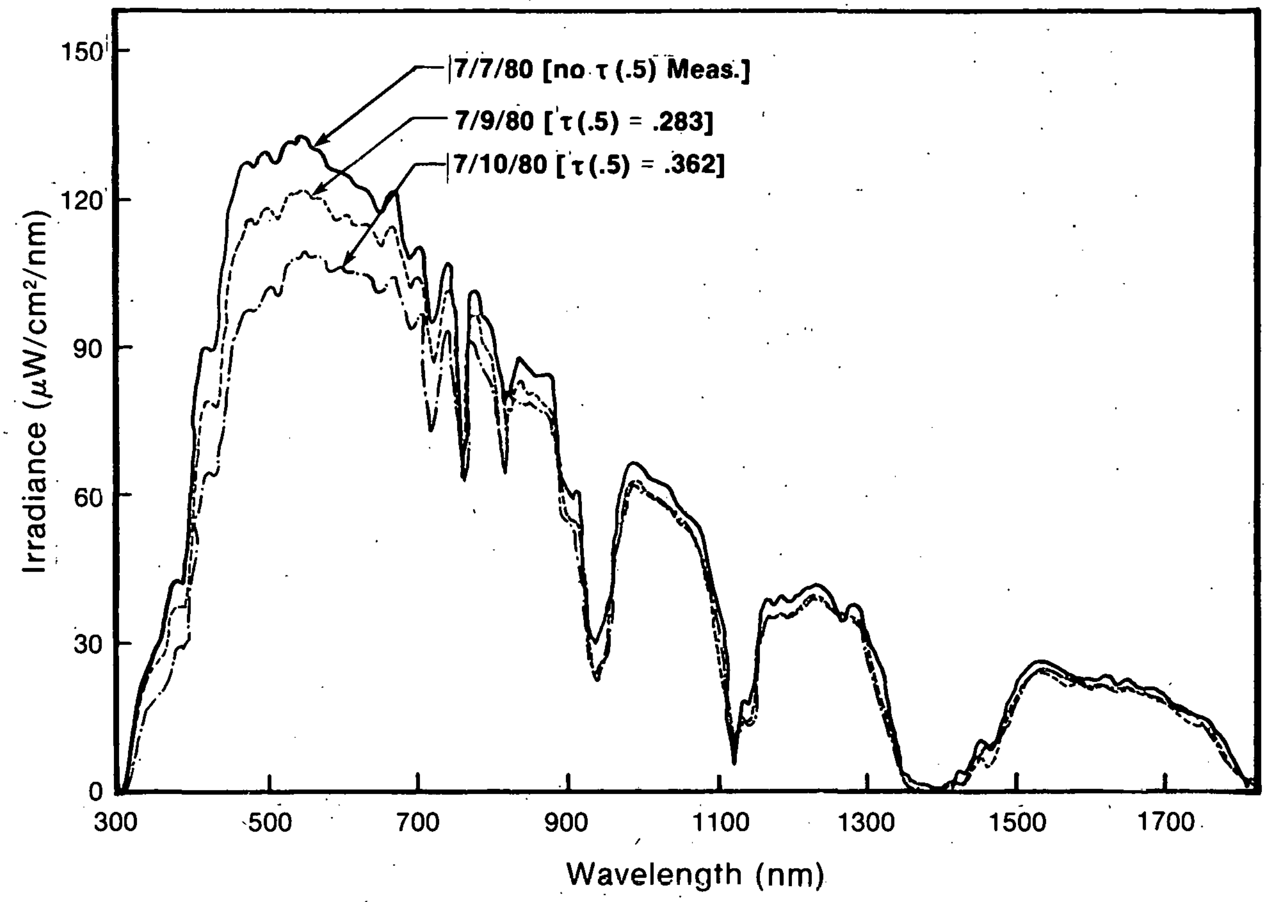

Figure 3-7. Direct Normal Insolation at Bedford, Mass.
Air Mass = 1.29

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SECTION 4.0

SPECTRAL MODELING AND COMPARISONS

Many different methods of solving the radiative transfer equation have been used in the past. The method that was initially chosen at SERI uses Monte Carlo techniques. The Monte Carlo method is the only one that can be used to solve some radiative transfer problems, but it is generally considered to require more storage and computer time than most of the deterministic methods. SERI is likely to obtain a deterministic code also.

The illustration in Fig. 4-1 portrays some of the characteristics of the Monte Carlo code, which traces photons through both absorption and scattering events. It statically samples properties of the medium to determine scattering angles and pathlengths. The atmospheric medium can be divided into many layers that are non-homogeneous in the vertical dimension and homogeneous in the horizontal. The density of atmospheric constituents is defined at the boundary of each layer. Photons can scatter in the atmosphere, from the ground, or from both. For further details on this approach, see Ref. 10.

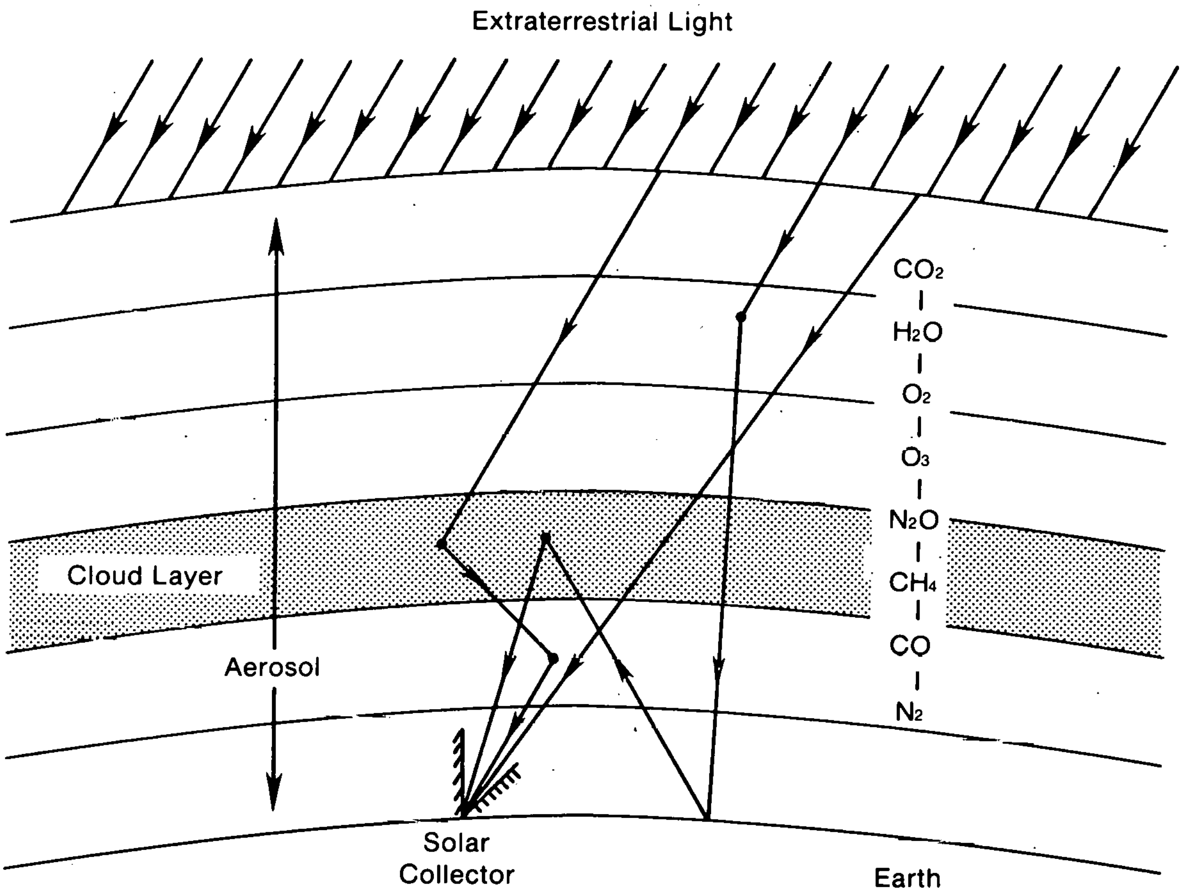

Figure 4-1. Atmospheric Structure for the Monte Carlo Insolation Model

The direct portion of the Monte Carlo code is deterministic. A comparison between results from the direct portion of the code and a direct code called SOLTRAN 4 [11] is shown in Fig. 4-2. In general, the two codes agree very well, but there are some slight differences that can usually be attributed to different molecular absorption data used in the two codes, or to the number of wavelengths at which calculations were made. The Monte Carlo code uses a newer data base than SOLTRAN 4 uses.

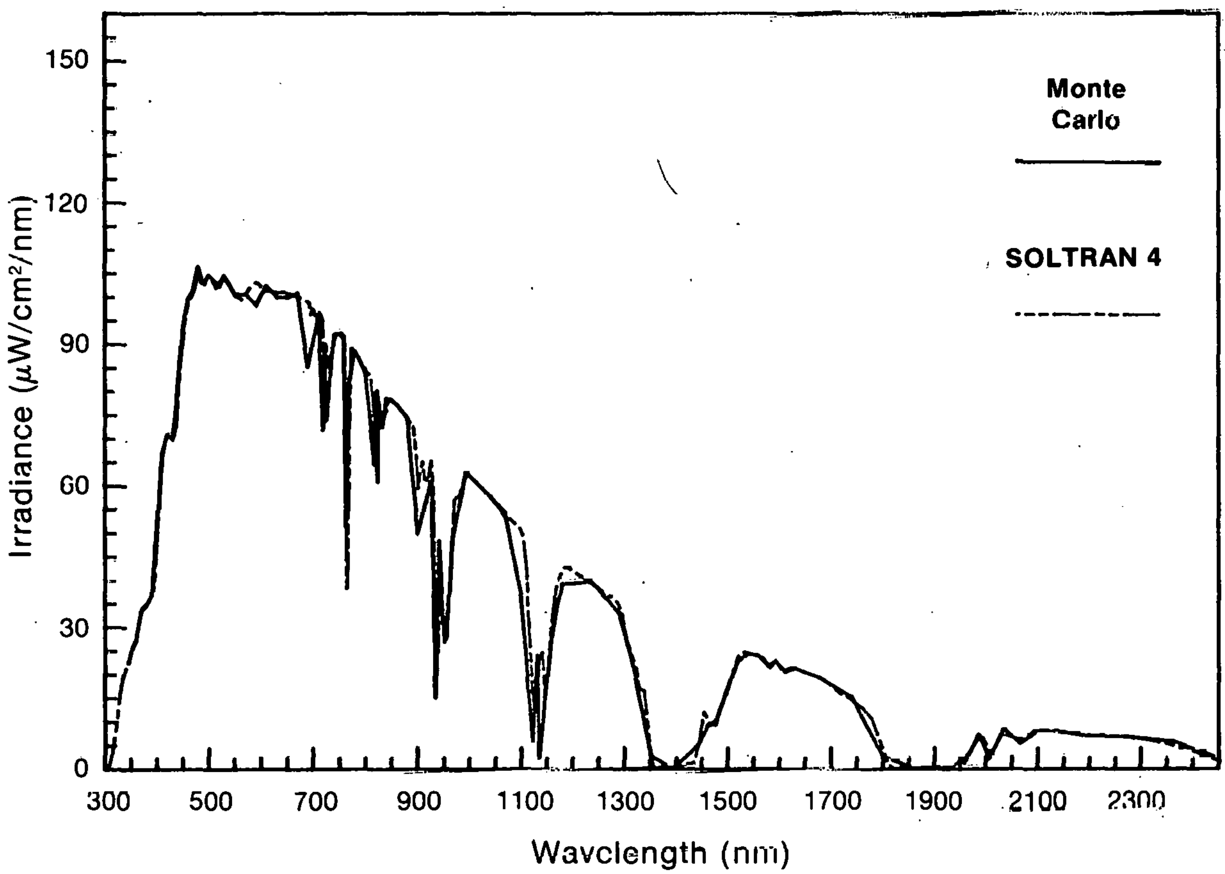

Figure 4-2. Direct Normal Insolation for a U.S. Standard Atmosphere
(23 km visibility rural aerosol, AM = 1.5)

A comparison between results from the Monte Carlo code and the Spherical Harmonics code of Dave [12] is shown in Figs. 4-3, 4-4 and 4-5. The global horizontal results for the two codes shown in Fig. 4-3 agree very well. Many of the differences are due to a different data base for molecular absorption. The Spherical Harmonics code uses the same data base as SOLTRAN 4. However, some of the differences are shown in Figs. 4-4 and 4-5 to be due to methods used. Some of the variations between the diffuse horizontal results of the two codes are probably caused by statistical fluctuations in the Monte Carlo results. The diffuse results shown in Fig. 4-4 are included in the global results shown in Fig. 4-3. Figure 4-5 is for an increased ground albedo and a larger zenith angle than Fig. 4-4.

It appears that the diffuse components from the two codes agree to within approximately ±15% of each other. Since the diffuse component is normally less than 20% of the total global radiation, the global radiation from the two models agrees to within ±5% at all spectral points.

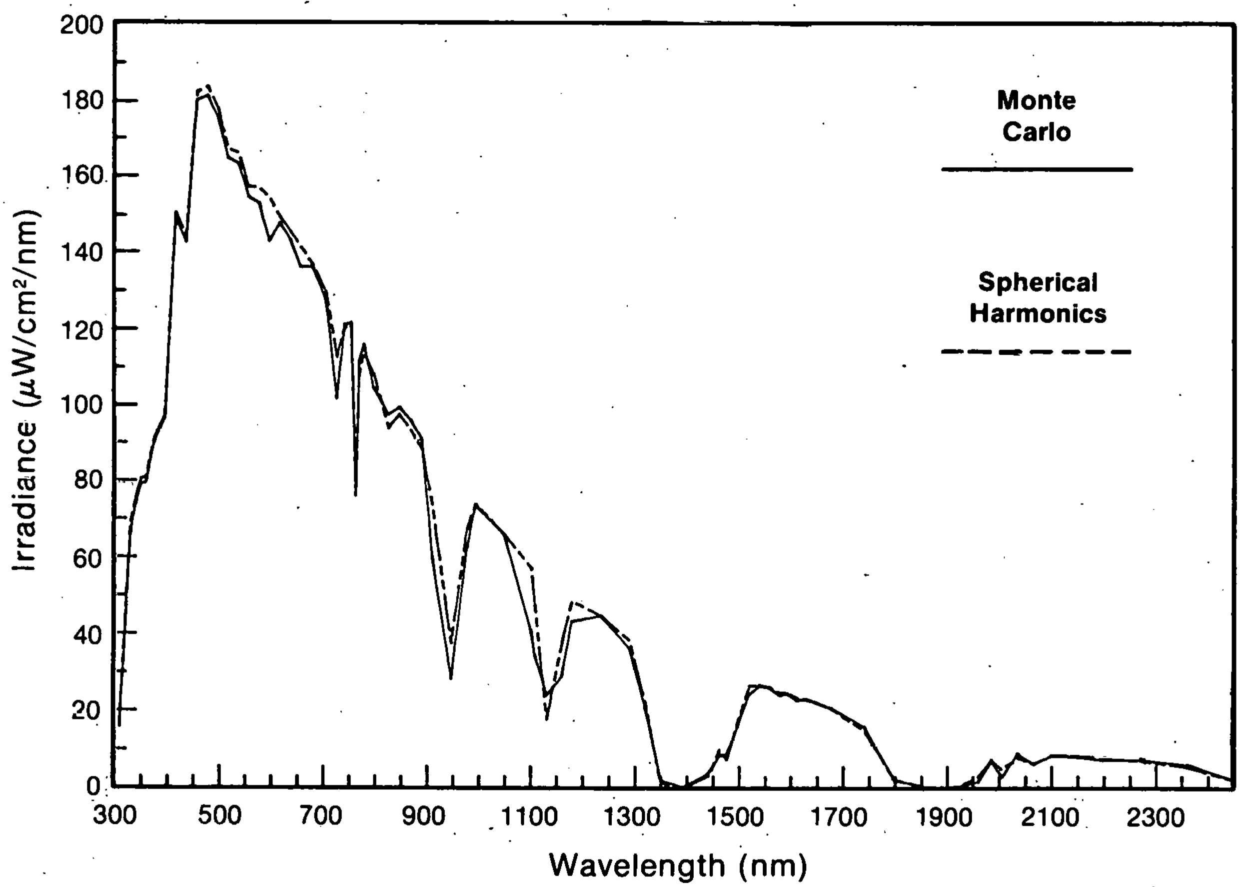

Figure 4-3. Global Horizontal Insolation for Dave Model 3
(Albedo = 0.0, AM = 1)

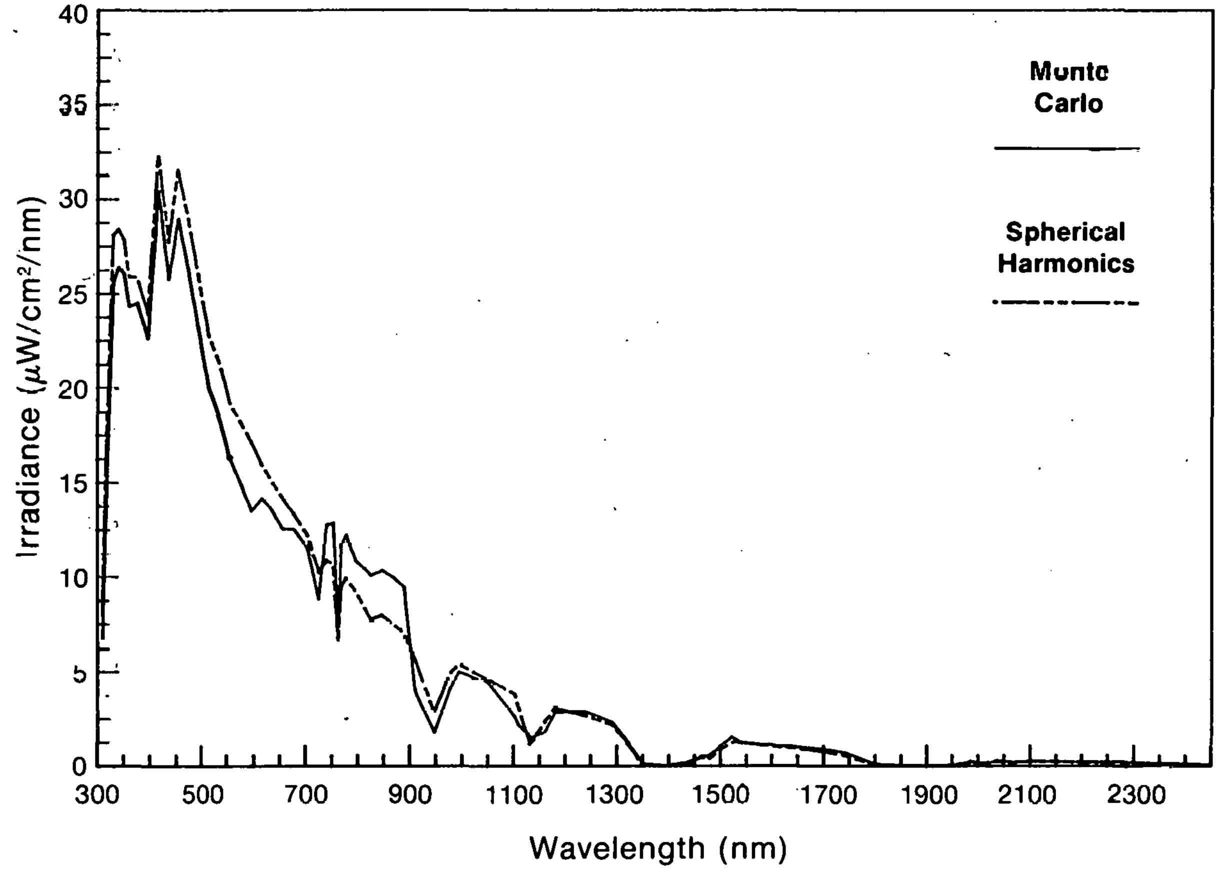

Figure 4-4. Diffuse Horizontal Insolation for Dave Model 3
(Albedo = 0.0, Angle = 0.0)

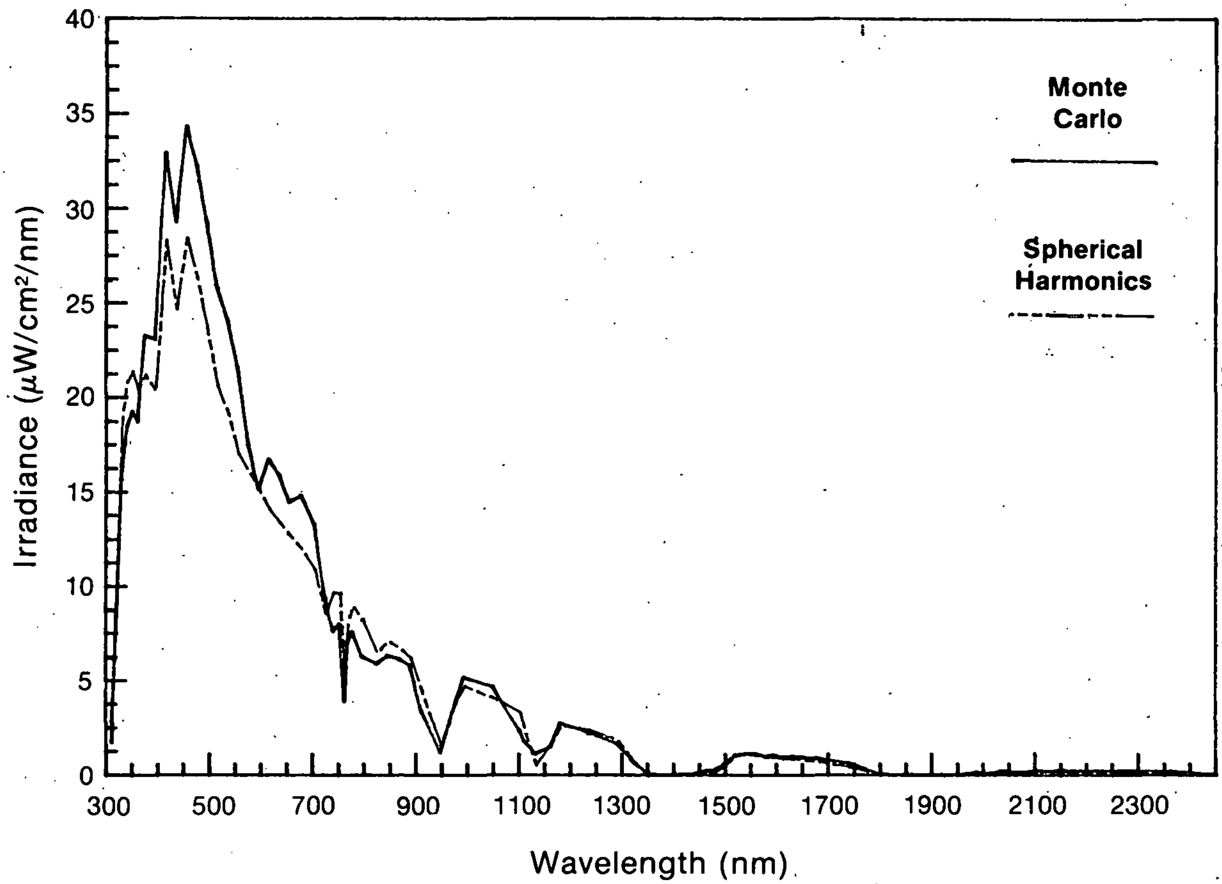

Figure 4-5. Diffuse Horizontal Insolation for Dave Model 3
(Albedo = 0.2, Angle = 60)

Finally, we compared modeled and experimental data. Because SERI cannot yet measure meteorological parameters as accurately as we believe to be necessary, a detailed comparison that included diffuse radiation was not undertaken with the Monte Carlo code. Instead, a very simple calculation using the SOLTRAN 4 code was made for direct normal insolation. A turbidity of 0.28 at 500-nm wavelength and an air mass of 1.29 that were measured at the time of the experimental measurement were used in the SOLTRAN 4 code. No attempt was made to match exactly the water vapor amount in the model with that at the time of measurement. Instead, a standard atmosphere (the midlatitude summer model) with 2.93 cm of precipitable water vapor and 0.31 cm of ozone was selected as approximating conditions in Bedford, Mass., in July of 1980. The results of this comparison are shown in Fig. 4-6. There are differences in the results, but they are still

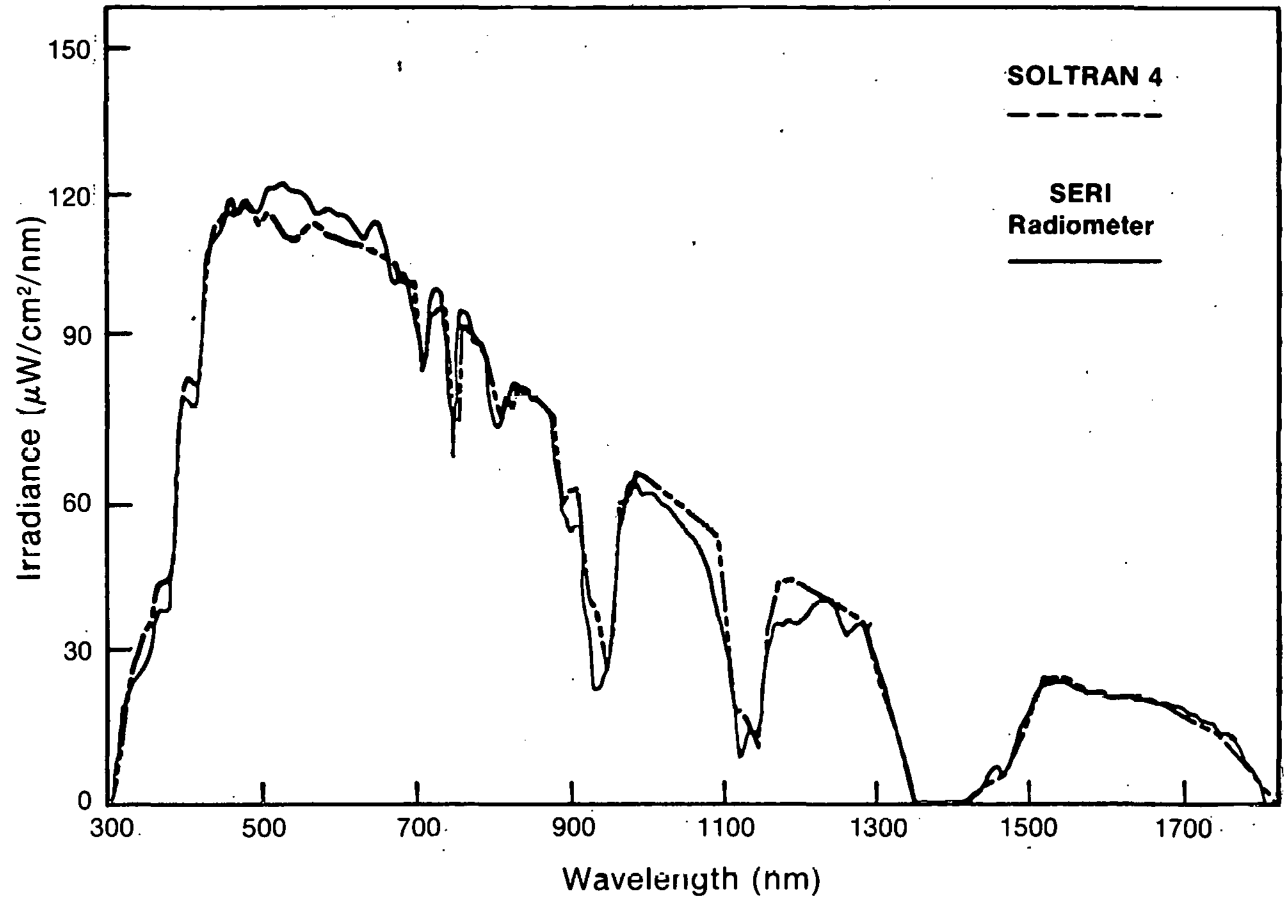

Figure 4-6. Direct Normal Insolation at Bedford, Mass. [AM = 1.29, τ(.5) = .28]

in remarkable agreement, especially considering that circumsolar radiation is included in the 6° FOV of the spectroradiometer measurement, and none is included in the modeled data. This circumsolar component has been shown by one of the authors to add approximately 1% to the broadband spectrum, and it is concentrated in the visible region of the spectrum where the greatest discrepancy occurs. It should be noted that there are slight differences since the resolution of the modeled data is not constant throughout the spectrum.

SECTION 5.0

CONCLUSION

We have described a new instrument for measuring terrestrial solar spectra quickly and accurately. The paper includes many examples of global, direct, and diffuse spectra that were measured in Bedford, Mass., and Golden, Colo. These data illustrate the effects of air mass, turbidity, and tracking or nontracking instruments.

We have presented the results from a rigorous radiative transfer code, together with comparisons with other codes and one set of measured data. We expect agreement between all of these to fall between 3%-8% at almost all points in the spectrum.

In the future, we will perform a more detailed comparison between measurement and theory, including accurate measurements of meteorological parameters at the time of the experiment. In addition, the spectroradiometer will be used to measure spectra under varying climatic conditions and different locations to produce representative spectra for use by the solar community.

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SECTION 6.0

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16. Abstract (Limit: 200 words)

This paper describes a newly developed spectroradiometer for routine measurement of the solar spectra. This instrument measures the solar spectrum between 300 and 2500 nm in less than 2.5 min, with 0.7-nm resolution in the visible and 10-nm resolution in the infrared. Many examples of global, direct, and diffuse spectra are illustrated for Beford, Mass. and Golden, Colo. The report presents the effects of air mass, turbidity, and sun tracking on the spectrum and discusses radiative transfer modeling capabilities and comparisons between models and between models and experiment.

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