Title
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ABSTRACT

The circumsolar measurement project is being carried out to provide data to assess the effects of circumsolar radiation on the operation of solar thermal conversion systems using concentrating collectors, especially central receiver systems. Four circumsolar telescopes have been constructed and are providing detailed intensity vs. angle profiles of the solar and circumsolar region, as well as other solar and climatological data. These measurements have been underway for more than one year at several locations. The current program emphasis is on reducing the data and making it available to groups analyzing the performance of central receiver systems. In most highly concentrating solar systems, the size of the receiver is determined by the ray bundle originating from the most distant heliostat. If the bundle size is calculated by using the solar disc, it is clear that some fraction of the circumsolar radiation will fall outside the receiver aperture. The results of this project provide the detailed type of input data for central receiver simulation codes that are necessary for determining these losses, optimizing the receiver or field size, and determining the distribution of stray flux due to circumsolar radiation.

INTRODUCTION

Circumsolar radiation refers to the light that has its apparent origin in the region of the sky around the sun. The term solar aureole is often used to describe easily observable or characteristic occurrences of circumsolar radiation. The phenomenon can easily be observed by using a finger or nearby object to block the direct sunlight from entering the eye and examining the light that streams around the occulting object.

Circumsolar radiation is caused by the scattering of light by small particles in the earth's atmosphere. The aerosol particles may be composed of ice crystals or water droplets in thin clouds. They may be dust or sea salt particles, smoke or fumes, photochemical pollutants, sulfuric acid droplets, solid particles with a water mantel, flocks formed of a loose aggregates of smaller particles, or any of a large variety of solid, liquid or heterogeneous materials that are small enough to be air borne. The amount and character of circumsolar radiation vary widely with geographic location, climate, season, time of day and observing wavelength. Some of the more striking cases can be observed in the presence of high, thin cirrus clouds.

Under some circumstances these aerosols can cause a significant fraction of the solar flux to be deviated to angles of several degrees or more. Solar energy conversion techniques using high concentration ratios, such as the central receiver concept, only collect light from the solar disc and a small portion of the circumsolar region. Pyrheliometers, the instruments normally used to estimate the direct solar radiation, typically have a field of view of 5-6^{o}. The pyrheliometer measurement includes a large portion of the circumsolar radiation and thus overestimates the amount of direct sunlight that would be collected by a concentrating system. The detailed angular distribution of the circumsolar radiation is important, as it affects the radiant energy distribution on the surface of the receiver in solar thermal power plants.

In the next section the operation of the telescope is described and sample data are given. The following material includes a discussion of the effect of circumsolar radiation on the losses of a solar power plant, presents 16 standard profiles for use with a simulation program, and describes the reduced data base that will be available to general users.

CIRCUMSOLAR TELESCOPE

The basic instrument was designed and fabricated at LBL and consists of a "scanning telescope" that is mounted on a precision solar tracker. A digital electronics system provides control for the tracking and scanning mechanisms. A photograph of three instruments near completion is shown in Fig. 1. The design has been described in more detail elsewhere.[1] The telescope uses as its basic optical element an off-axis mirror of 7.5 cm-diameter and 1-m focal length. A fused silica window protects the mirror from the environment. The mirror forms an image of the sun and sky around it on a plate to the side of the telescope

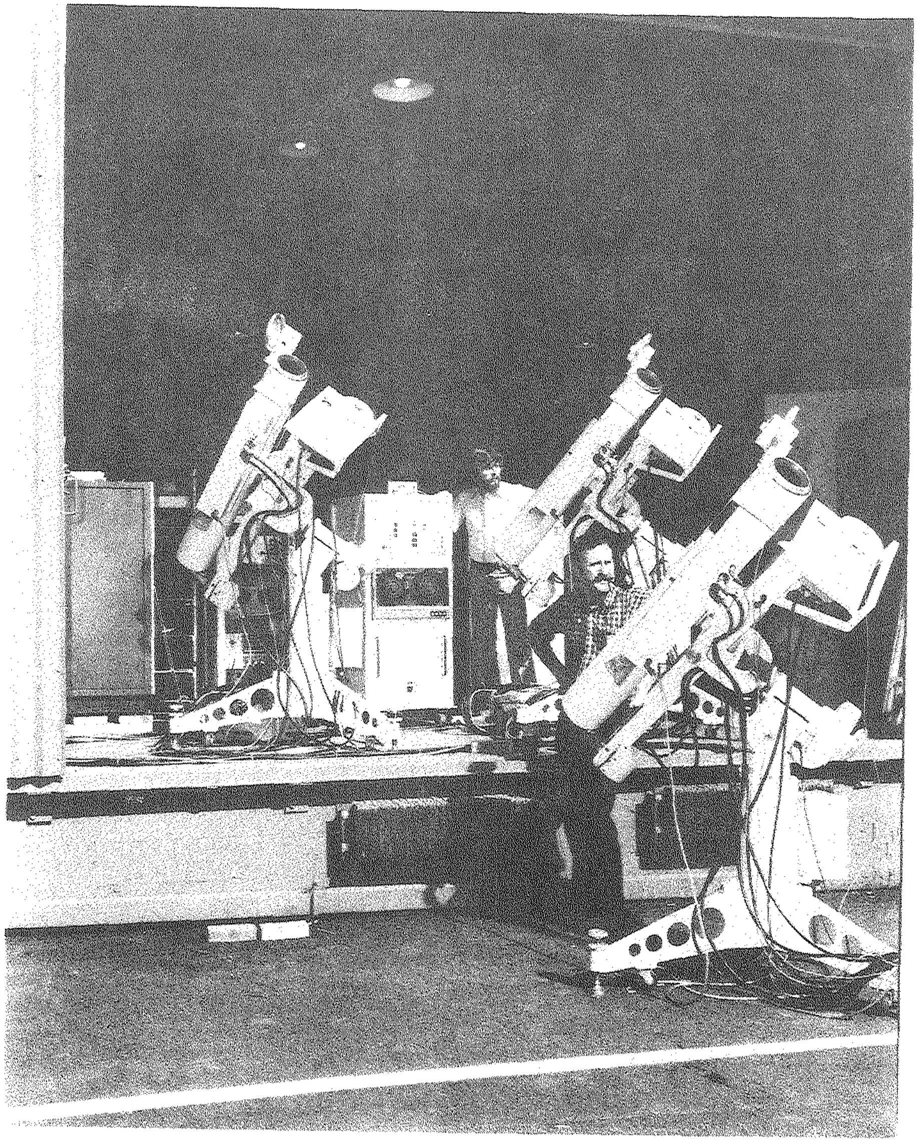

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Fig. 1. The circumsolar telescopes nearing completion.

axis. A small hole in this plate, the detector aperture, defines the angular resolution (1/20 of the solar diameter, and the amount of light passing through the aperture into the detector assembly constitutes the fundamental measurement. In the detector assembly the light is mechanically chopped, optically filtered, and focused onto a pyroelectric (thermal) detector. This type of detector was chosen for its uniform wavelength response in the 0.3 to 2.5 μm region and its wide dynamic range.

The telescope scans through a 6° arc with the sun at the center and measures the brightness of the solar and circumsolar radiation as a function of angle. The instrument scans in declination so that at sunrise and sunset it travels nearly parallel to the horizon and at noon it moves in a vertical plane.

Each 6° scan requires one minute of time. The brightness is digitized every 1.5' or arc. Within 0.5° on either side of the sun an aperture of size 1.5' of arc is used, and outside this region the aperture is increased to 5' or arc. A set of measurements consists of one scan at each of 10 "filter" positions". There are eight optical filters, one open (or "clear") position, and one opaque position. The opaque position is used to monitor the detector noise. The absolute determination of the normally incident flux (within 2.5^{o} of the sun center) is provided by an active cavity radiometer.[2] This device is self-calibrating and has an accuracy of 0.5%. This pyrheliometer is provided with a matched set of filters that rotate synchronously with those on the scanning telescope. Thus the telescopes produce an absolute measurement of the normally incident flux along with the detailed solar profile in eight wavelength bands. Two pyranometers are used, one mounted in the conventional horizontal position, and one tracking the sun.

The telescopes are capable of unattended operation for up to a week, although they typically receive a daily inspection during the work week. During the night the solar trackers run backwards and automatically initiate operation at the beginning of each day. The data is recorded on magnetic tape and processed at the laboratory's computer center.

Four of these circumsolar telescopes have been constructed. Three of them have been making measurements automatically fifteen hours each day for approximately one year at the following locations: Albuquerque, New Mexico (5 MW_{th} test site), Ft. Hood, Texas (planned site for demonstration of a solar total energy system), and China Lake, Ca.

Figure 2 shows a computer-plotted graphical display of a clear filter scan made by SCOPE 1 at Berkeley at 12:50 hours on May 20, 1976. The brightness is integrated from the center to the edge of the sun and from there to the end of the scan to give the intensities of the direct and circumsolar radiation respectively. The ratio of circumsolar to solar radiation is then calculated and is given at the top of the graph (C/S =). The normal incidence measurement provided by the pyrheliometer (NI =) is also indicated. This particular scan is for a slightly hazy day, with a circumsolar to solar ratio of 5.5% and a normal incidence value of 811 W/m^2.

Figures 3 to 6 display the time dependence of various parameters of the solar radiation for two separate days. These measurements were taken by SCOPE 2 which is located at Albuquerque, New Mexico. The total losses that would be experienced by a highly concentrating collector due to circumsolar radiation can be calculated by integrating the product of the normal incident radiation and the circumsolar to solar ratio. If the collector system fills the receiver with the solar disc, the total integrated losses for the day in Fig. 3 and 4 would be equal to 1.2%. Figures 5 and 6 illustrate a day that probably had a blue sky slightly

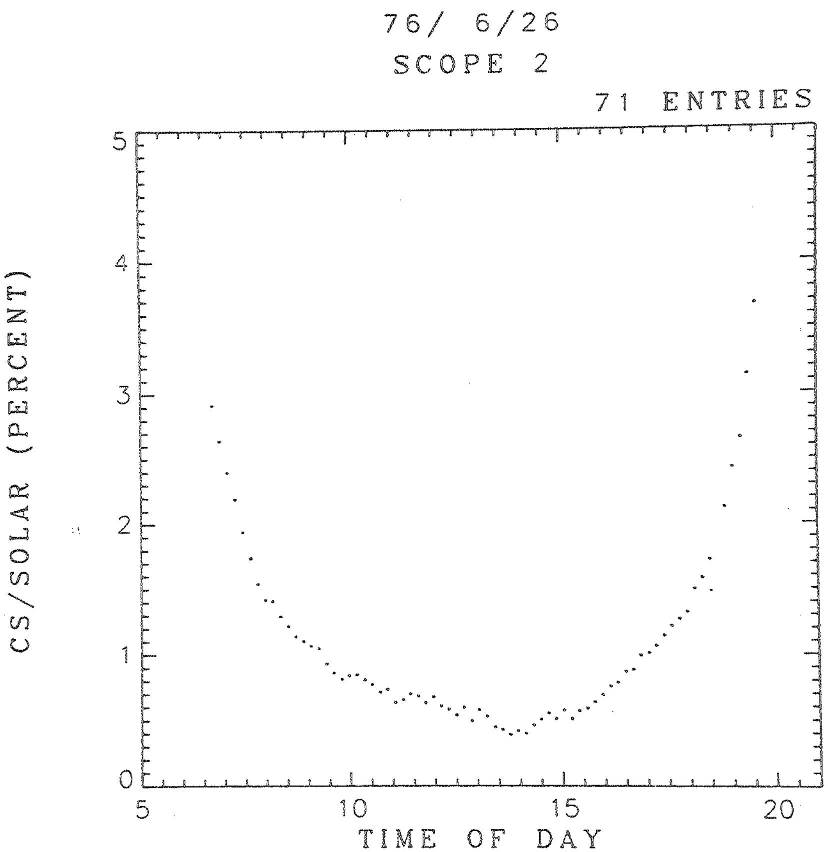

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Fig. 4. Illustrating the ratio of circumsolar to solar radiation for the same day as in Fig. 3.

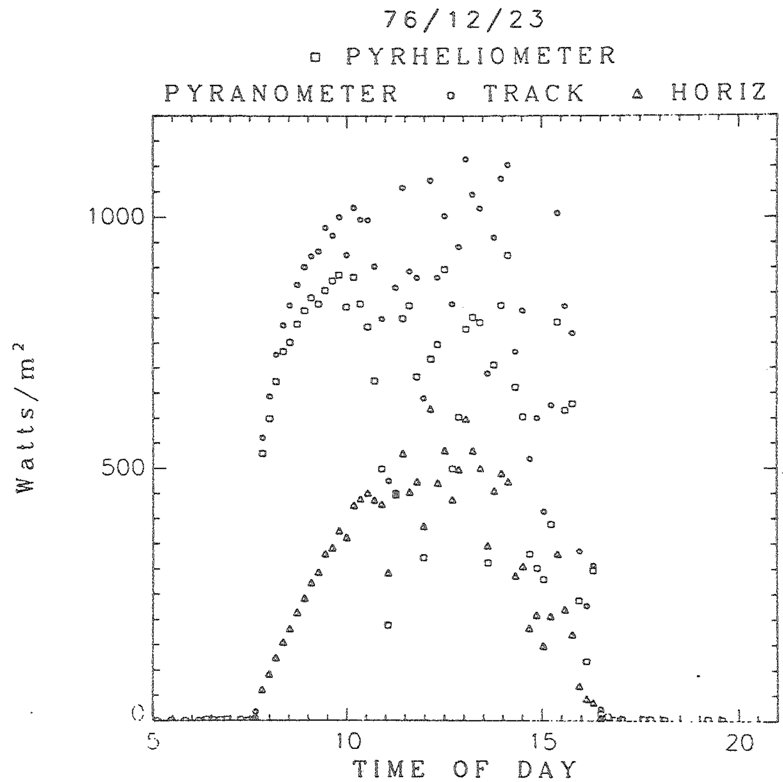

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Fig. 5. The time dependence of various parameters of the solar radiation on December 23, 1976 in Albuquerque, New Mexico showing the normal incidence readings from the pyrheliometer (□), and the total radiation readings from the horizontal pyranometer (Δ) and from the sun tracking pyranometer (O).

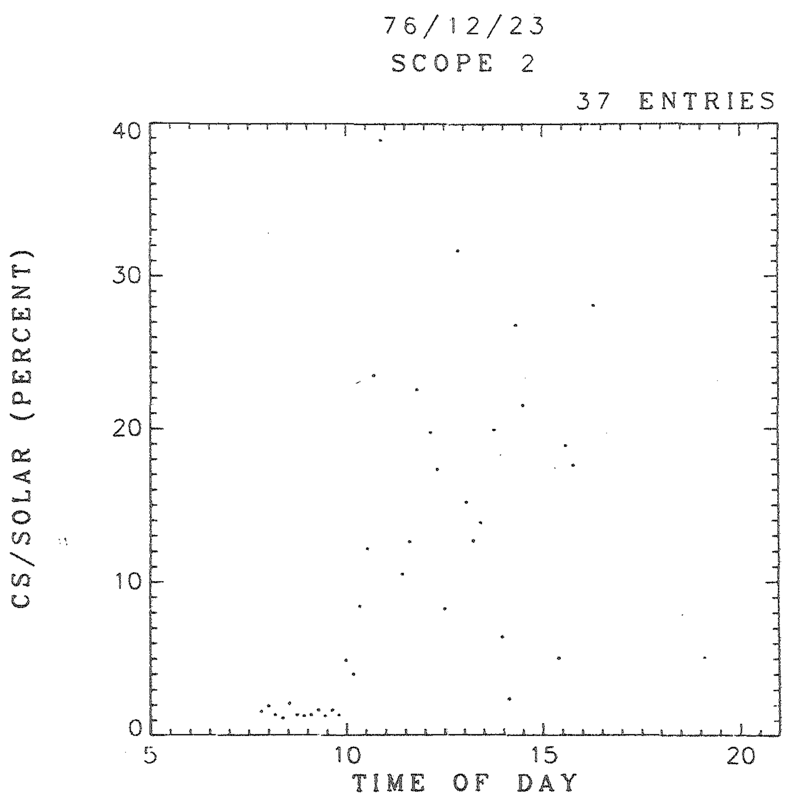

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Fig. 6. Illustrating the ratio of circumsolar to solar radiation for the same day as in Fig. 5.

whitened by cirrostratus cover. (Note the difference in scale for the circumsolar graphs in Figs. 4 and 6). The normal incidence readings are moderately high throughout the day. The circumsolar to solar ratio is low early in the morning but from 10 a.m. onward its average is very high (many points are above the top of the graph). The pyrheliometer data indicates sufficient flux for plant operation most of the day but the integrated amount of circumsolar radiation for the whole day is calculated to be over 17%. Thus the errors in utilizing pyrheliometer data for this kind of day would be considerable.

It is anticipated that solar power plants will be operated whenever the solar input exceeds the radiative losses from the receiver. In order to accurately assess the effects of circumsolar radiation for a given location and type of collector, it is necessary to determine the potential losses by an optical simulation procedure combined with a knowledge of circumsolar radiation throughout the year for various viewing apertures and minimum thresholds of normally incident flux. In the next section two sets of data are presented to determine the impact of circumsolar radiation on various solar collection systems.

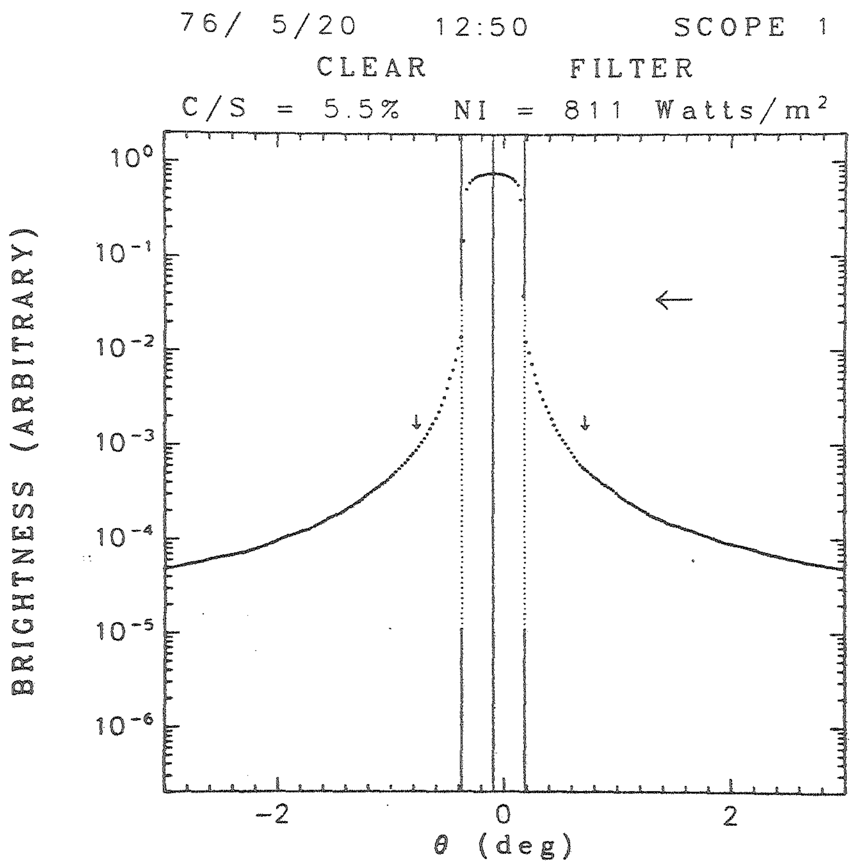

Fig. 2. Computer-plotted graphical display of a clear filter scan made by SCOPE 1 at Berkeley at 1250 hours on May 20, 1976. The dots are the individual scan digitizations. The scan started at +3, as indicated by the large horizontal arrow, crossed the sun near 0^{o}, and ended at -3^{o}. The small vertical arrows indicate the angles where the aperture was switched from 5' of arc to 1.5' of arc, and then back again.

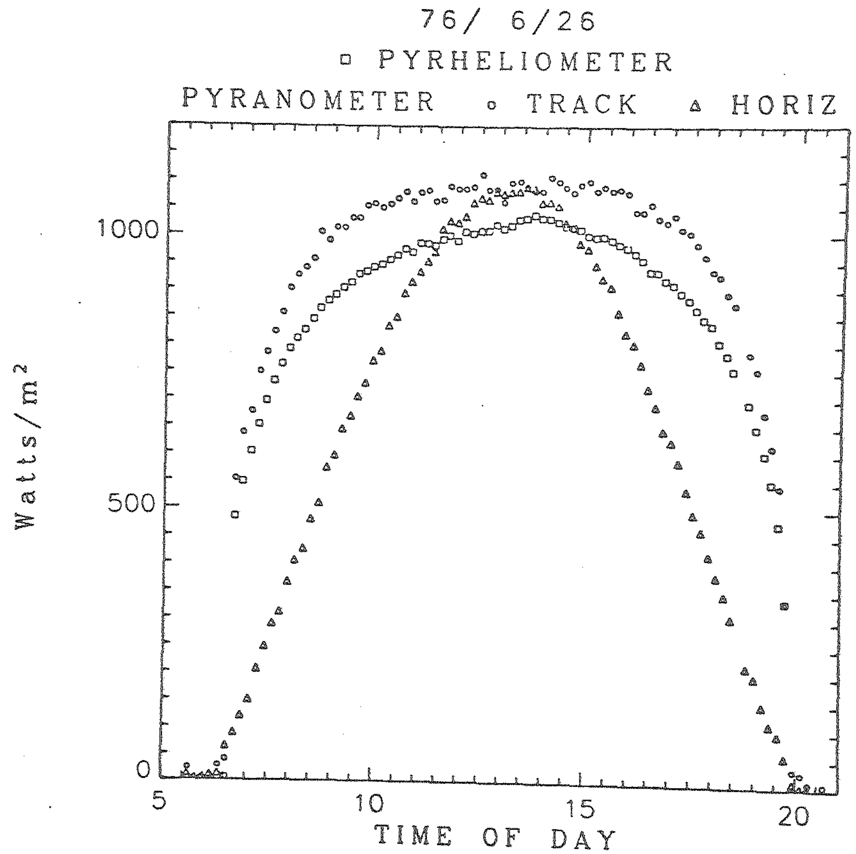

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Fig. 3. The time dependence of various parameters of the solar radiation on June 26, 1976 in Albuquerque, New Mexico showing the normal incidence readings from the pyrheliometer (□), and the total radiation readings from the horizontal pyranometer (Δ) and from the sun tracking pyranometer (O).

DETERMINING LOSSES DUE TO CIRCUMSOLAR RADIATION

There are several ways to estimate the effect of circumsolar radiation on a concentrating solar collector. The least ambiguous method is to use measured radial intensity profiles of the sun in conjunction with an optical simulation code. By using the code with and without the circumsolar component, the fractional energy loss from the system due to that particular profile can be determined. If this is done for a variety of profiles with varying ratios of circumsolar to solar radiation, and the frequency of occurrence and corresponding normal incident flux is known, the overall effect can be determined. This procedure is being carried out for several large heliostat fields with the set of profiles shown in Figure 7 and 8. The profiles are plotted in two sets of 8; one set is selected from data taken at Albuquerque, New Mexico and the second set from Ft. Hood, Texas. The corresponding ratios of circumsolar to solar-plus-circumsolar, values of normal incident flux, and times of occurrences are given in table I. The values of circumsolar radiation for these profiles vary over a considerable range. It should be pointed out that these profiles are meant to represent the range of possible profiles; they do not occur with equal frequencies nor do they typically have comparable

Table I
Selected Circumsolar Profiles

C/(C+S)(%)	NI(W/m^2)	STD Time	Date-site*
0.8	953	11:56	76/8/7-A
1.0	714	9:54	76/8/25-FH
2.7	918	11:29	76/11/20-FH
2.9	794	15:10	76/11/22-FH
3.5	948	11:19	76/12/14-A
5.7	747	15:59	76/12/29-FH
8.9	802	9:39	77/1/25-A
10.6	781	14:32	76/12/29-FH
14.6	802	12:57	76/12/14-A
20.4	639	11:06	77/1/25-A
29.4	468	10:14	76/12/14-A
40.0	347	14:11	76/12/29-FH
47.1	291	10:12	77/1/25-A
52.6	298	10:56	76/12/29-FH
58.7	87	13:17	76/12/29-FH
69.2	85	13:06	77/1/25-A

*Site code, A for Albuquerque, New Mexico, FH for Ft. Hood, Texas

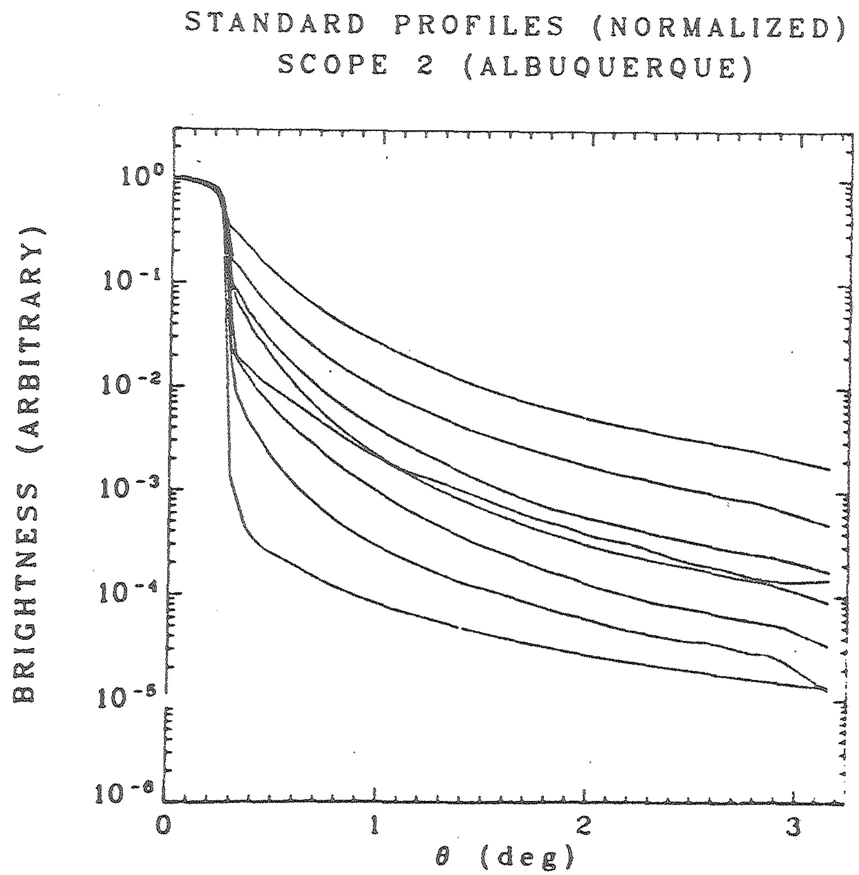

Fig. 7.
Standard solar and circumsolar profiles, selected from Albuquerque, New Mexico.

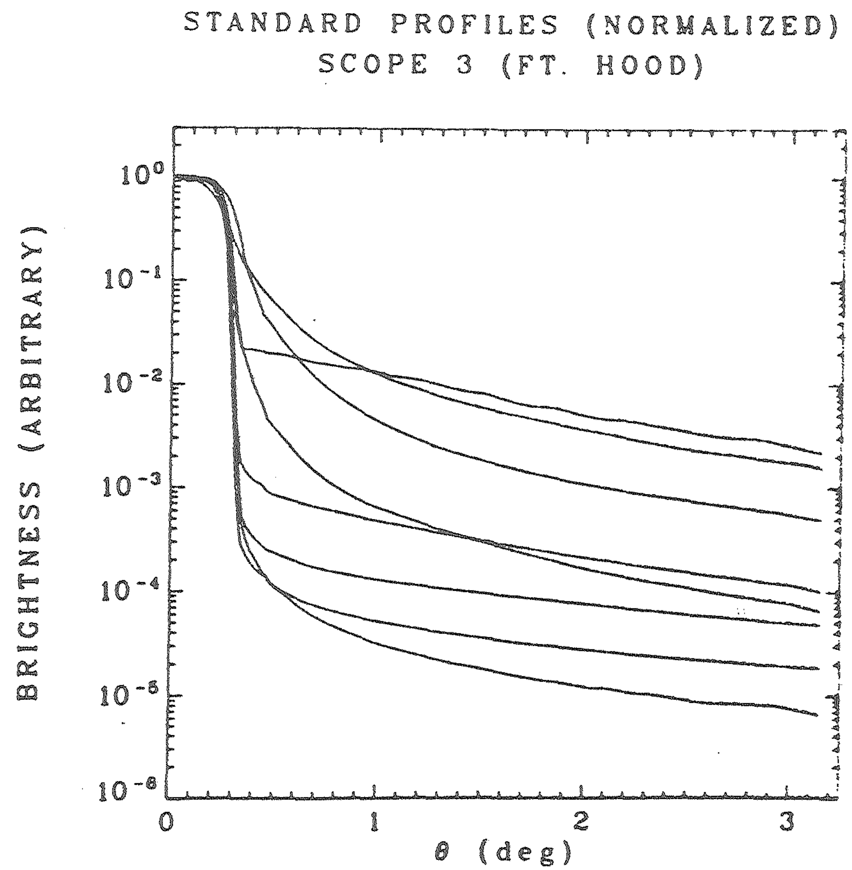

Fig. 8.
Standard solar and circumsolar profiles, selected from Ft. Hood, Texas.

values of normally incident flux.*

The approach discussed above is useful in determining the sensitivity of a solar power plant to the effects of circumsolar radiation. In order to determine the actual monthly losses that would be experienced over the course of a year, measurements must be performed at that site for the corresponding period of time. Once these measurements are in hand, the losses can be determined by sorting all the profiles that occur at that site into one of the 16 standard types. If the fractional energy loss corresponding to each of the 16 profiles known, the measured profile can be weighted with the corresponding value of normal incident flux. These losses then can be tallied and compared to the total plant output for the desired period of time.

The original data base for the telescopes represents a very large amount of data. To put the data into a more manageable form a reduced data base has been generated that contains a subset of the original data. This includes the white light profiles, the pyrheliometer and pyranometer data, the spectral pyrheliometer data, certain indicative information including date, time, solar angle, etc., and some derived data, including true normal incident flux, circumsolar to solar ratio, pyrheliometer errors, etc. This reduced data base is produced in the form of one magnetic tape per year per telescope and will be available to interested users in the future.

*Detailed numerical values for these profiles are available from LBL on computer punch cards.

CONCLUSION

The LBL circumsolar telescopes have completed over one year of nearly continuous measurements at several locations. The resulting set of measurements represents one of the most intensive and extensive characterizations of the effect of the atmosphere on the solar intensity profile. In order to evaluate the effect of circumsolar radiation on solar energy collection systems, the data are being treated in a number of ways. A sensitivity analysis of large central receiver systems, utilizing a selected set of intensity profiles will indicate whether a substantial fraction of the circumsolar radiation is lost from the plant. Since plant performance estimates are based on pyrheliometer measurements that include the circumsolar component it is likely that available normal incidence data should be corrected, or more accurate measurements performed. The amount of the correction will depend on location and season as well as plant design, but the available data from the circumsolar telescopes indicate the errors are from a few percent to nearly ten percent. Since it is not yet clear how to extrapolate the data to new locations, long term measurements of the circumsolar radiation are still necessary to determine the magnitude and seasonal variations of the effect at locations with substantially different climatic conditions than those already explored.

ACKNOWLEDGEMENTS

The able assistance of Stephen Kanzler in many parts of this project is gratefully acknowledged. We also thank all the people, too many to mention, who have cooperated in setting up and running the telescopes at their respective locations.

REFERENCES

(1) Donald Grether, Jerry Nelson, and Michael Wahlig, Measurement of Circumsolar Radiation, Proceedings of the Society of Photo-optical Instrumentation Engineers, 68, 41, (1975).

(2) R. C. Willson, Active Cavity Radiometer, Appl. Opt. 12, 810 (1973).