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Publication Date
1976-08-01

Presented at the International Solar Energy
Society Meeting, Winnipeg, Canada,
August 16 - 20, 1976

LBL-5292
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August 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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RESULTS FROM CIRCUMSOLAR RADIATION MEASUREMENTS

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Circumsolar radiation results from small-angle scattering of direct sunlight from atmospheric aerosols with dimensions on the order of, or greater than the wavelength of light. We have developed an instrument to provide measurements of circumsolar radiation as a function of angular distance from the sun and wavelength, for various atmospheric conditions, geographic locations, and times of year. These measurements are necessary to predict accurately the performance of solar thermal conversion systems using focusing collectors, and to determine whether pyrheliometer data are adequate for estimating this performance. Sample data are presented for two geographic locations. This project is supported by ERDA.

Atmospheric constituents with dimensions on the order of or greater than the wavelength of light, such as dust, ice crystals, and photochemically produced particulates, scatter direct sunlight preferentially through small angles. This scattering results in circumsolar radiation; to an observer on the ground the scattered light appears to come from "around the sun".

Solar energy conversion techniques utilizing high concentration ratios, such as the Central Receiver concept, essentially collect only the direct sunlight. Pyrheliometers, the instruments normally used to estimate the direct solar radiation, typically have a field of view of 5-6°. 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. As is shown below, when the atmosphere is free of constituents such as dust, ice crystals, etc., then the overestimate is negligible. There are atmospheric conditions, however, for which the circumsolar radiation is a sizable fraction of the direct sunlight: then the over estimate of the pyrheliometer becomes significant. The detailed angular distribution of the circumsolar radiation is also an important feature of these measurements, as it affects the radiant energy distribution on the surface of the receiver in solar thermal power plants. We have developed and built four similar instruments to measure the circumsolar radiation as well as other properties of sunlight, as part of the ERDA Solar Thermal Conversion program. The measurement will be used in performance calculations of solar power plants, and to determine under what

what conditions pyrheliometer data are adequate for estimating this performance.

The basic instrument is a "scanning telescope" mounted on a precision solar tracker. The design has been described in detail elsewhere.[1] Briefly, the instrument 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 scan takes one minute of time, with a digitization of the brightness every 1.5' of arc. Within .5° on either side of the sun, an aperture of size 1.5' of arc is used. Outside this region (i.e., in the region of relatively low circumsolar levels) the aperture is increased to 5' of arc in order to increase the signal level by roughly a factor of ten. A set of measurements consists of one scan at each of ten "filter positions". There are eight optical filters that divide the solar spectrum into eight bands of roughly equal energy content, one open (or "clear") position, and one opaque position. The latter is used to monitor the detector noise. An Active Cavity Radiometer[2] (a type of pyrheliometer) provides an absolute calibration for the telescope as well as the usual normal incidence measurement. Two pyranometers are used, one mounted in the conventional horizontal position, and one tracking the sun.

A protable, prototype instrument (SCOPE 1) has been making measurements at Berkeley for some time and is scheduled to do so at a variety of geographical locations. Three additional "fixed-site" telescopes have been constructed; one is near the 5 megawatt (thermal) solar test facility, Albuquerque, N.M. (SCOPE 2); a second is at the site of a total energy system pilot plant, Ft. Hood, Texas. The third, currently located at China Lake, Ca., will be located at the site of a 10 megawatt (electric) Central Receiver pilot plant. These latter telescopes are capable of unattended operation for up to a week, although they typically receive a daily inspection during the work week. The instruments will withstand most weather conditions. 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.

Figure 1 is a computer-plotted graphical display for a scan using the clear filter from measurements made on SCOPE 1 at Berkeley at 13.13 hours on June 1, 1976. The dots are the individual scan digitizations. As indicated by the large, horizontal arrow, the scan started at +3, crossed the sun near 0°, and ended at -3°. 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. The computer code proceeds as follows. A search is made for the peak brightness point of the sun. (This peak point is close to, but not always exactly at, the center of the sun). The two "edges" of the sun are then empirically defined as the angles at which the brightness is down by a factor of 30 from the peak. These edges are indicated on the graph by the two vertical, dotted lines. The center of the sun is then taken as the angle midway between the two

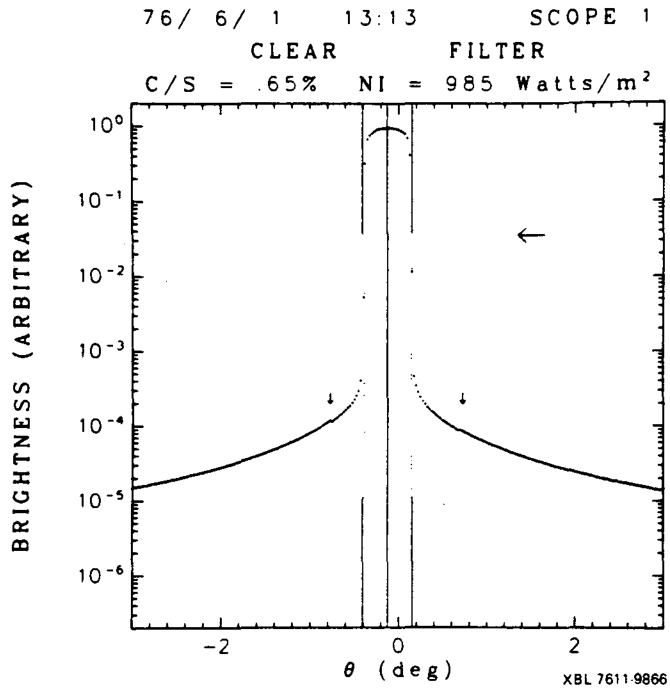

Figure 1. Sample scan with low circumsolar level.

edges, and is indicated by the solid vertical line. An effective radius is then defined as the true radius of the sun (approximately 16' of arc; the exact value is calculated for the specific date, as it varies over the year due to the varying earth-sun distance) plus the radius of the detector aperture (0.8' of arc). The effective radii are indicated by the solid vertical lines at the top and bottom of the graph, and are nearly coincident with the edges of the sun. The brightness is then integrated from the center of the sun to the effective radius to give the intensity of the direct solar radiation (in arbitrary units), and integrated from the effective radius to the end of the scan to give the intensity of the circumsolar radiation. The ratio of circumsolar to solar radiation is then calculated and is given at the top of the graph (C/S =). Also indicated is the normal incidence measurement provided by the pyrheliometer (NI =). This particular scan is for a clear day, with a circumsolar to solar ratio of only .65%, and a normal incidence value of 985 watts/meter squared.

Figure 2 shows two examples of scans with higher levels of circumsolar radiation. The normal incidence values are reduced but probably still within the operating range of a solar power plant

Figure 3 displays various parameters of the solar radiation as a function of time of day in hours for SCOPE 2, located in Albuquerque. The upper graph shows the normal incidence reading of the pyrheliometer

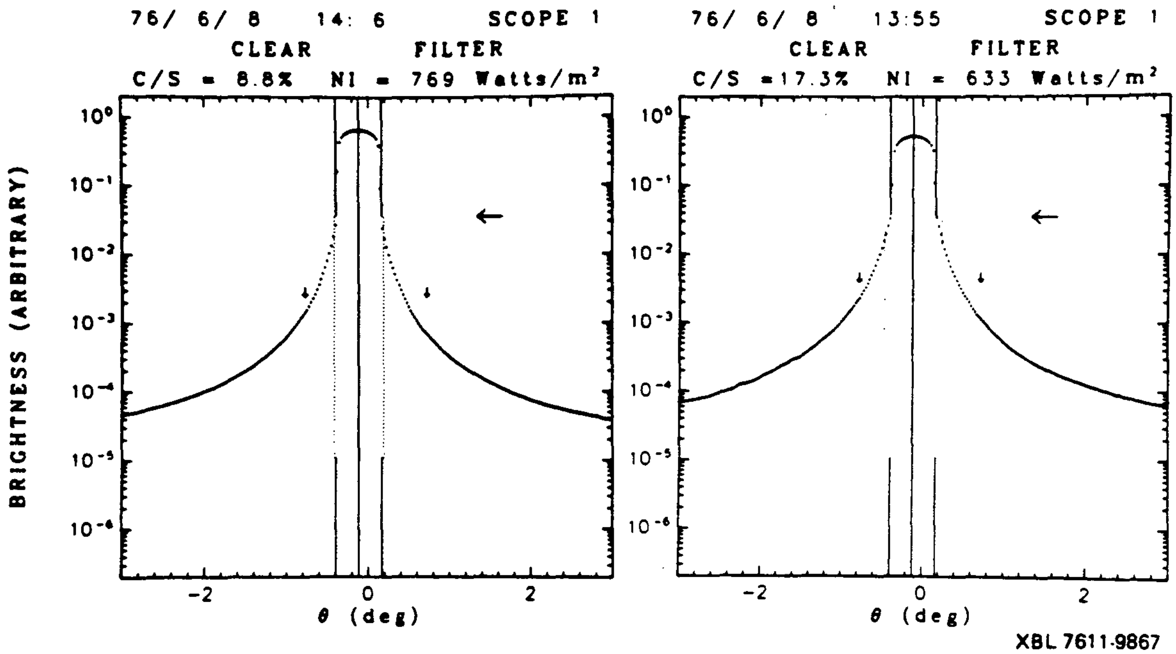

Figure 2. Sample scans with relatively high circumsolar levels.

(squares), and the total radiation readings of the horizontal pyranometer (triangles) and the sun-tracking pyranometer (circles). The bottom graph is the ratio of circumsolar to direct solar radiation for the same day. The data are typical of a clear day in Albuquerque around the summer solstice in 1976 (the only time of the year for which we currently have data from Albuquerque). The normal incidence radiation rises to slightly over 1000 watts/meter^2. The reading from the tracking pyranometer is, of course, higher. Because of the cosine factor, the horizontal reading is lower except around solar noon when it rises to nearly the value of the tracking pyranometer, as would be expected for a date so close to the summer solstice. The ratio of circumsolar to direct solar radiation (C/S) rises to around 4% for the high air-mass values at the beginning and end of the day. If we consider that part of the day when the normal incidence value is $\geq$ 75% of its peak value, then the C/S ratio is always less than about 2%, and is as low as about 0.5% around solar noon. The circumsolar radiation would be considered to be of negligible importance to solar thermal conversion on such days.

Figure 4 displays data similar to that shown in Figure 3, but for a portion of a hazy day at Berkeley (SCOPE 1). (Note the difference in scale for the circumsolar graph between Figures 3 and 4.) The ratio of circumsolar to solar radiation is essentially always above 4%, with

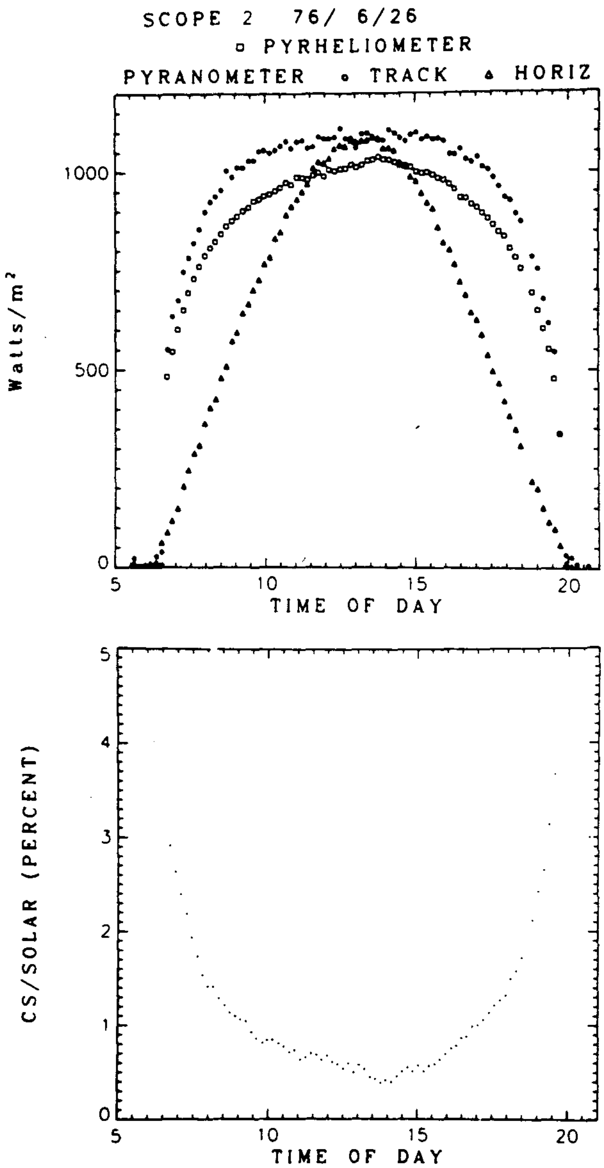

Figure 3. Clear day at Albuquerque

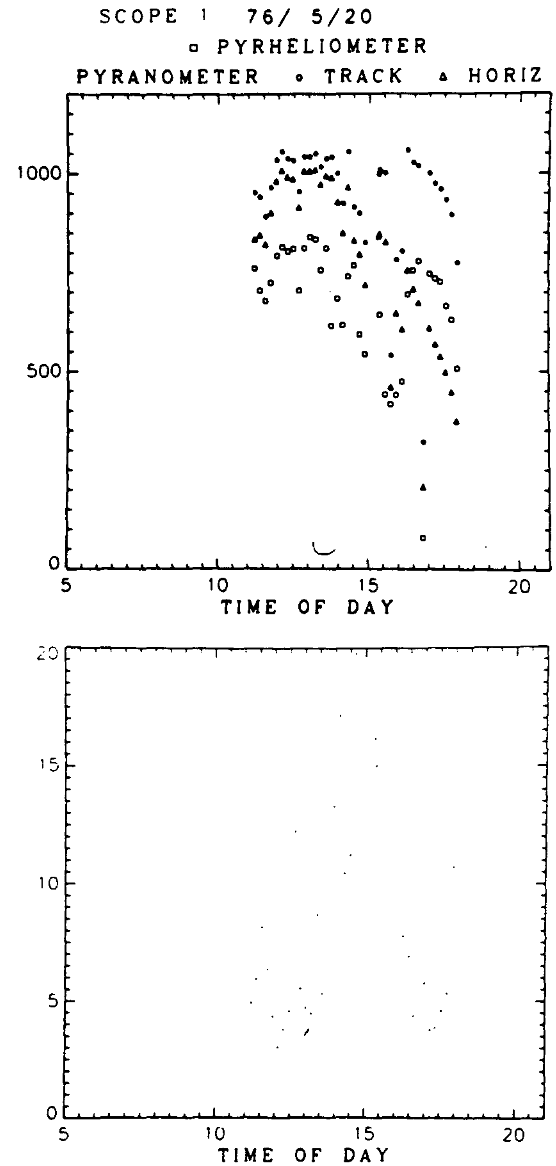

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Figure 4. Hazy day at Berkeley.

excursions to 10% or more. The normal incidence values show considerable fluctuations, but average about 75% of what would be expected for a clear day. As would be expected for high levels of diffuse radiation, the pyranometers give considerably higher readings than the pyrheliometer.

So far, the data obtained at Berkeley and Albuquerque indicate that for clear days, the circumsolar radiation is of negligible importance for solar thermal conversion processes using focusing collectors. There are, however, atmospheric conditions for which the circumsolar levels are non-negligible. Data from the various geographic locations (Albuquerque, Ft. Hood, China Lake, etc.) and for the different seasons of the year will continue to be accumulated and analyzed. This analysis will yield statistical distributions as to the frequency of various levels of circumsolar radiation at the various locations.

The excellent engineering and technical support of the Special Projects group at LBL has been vital to the success of this project. The able assistance of Stephen Kanzler in coping with the day-to-day problems of the project is gratefully acknowledged. We also thank the people at Albuquerque, Ft. Hood and China Lake, too many to mention, who have cooperated in setting-up and running the telescopes at their respective locations.

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

3. R. C. Willson, "Active Carity Radiometer", Appl. Opt. 12, 810 (1973).