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MEASUREMENT OF CIRCUMSOLAR RADIATION*

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Abstract

An instrument system has been developed to measure the flux of energy from the sun and the circumsolar region (the small-angle region around the sun) as a function of angle, wavelength, and atmospheric conditions. The measurements are necessary to accurately predict the performance of solar thermal conversion systems using focusing collectors, and to determine whether pyrheliometer data are adequate for estimating this performance. The instrument system consists of a "scanning telescope", several conventional solar instruments, and a digital electronics control and recording system. The telescope makes a scan of ±3°, passing through the center of the sun. The angular resolution is approximately 1.5 minutes of arc from the center of the sun out to two solar radii, and 5 minutes from there out to 3°. The background caused by direct solar light scattering within the telescope itself has been reduced to less than 1% of the intensity of the circumsolar radiation. Spectral dependence of the radiation is determined using filters. A measurement program using this telescope will be carried out at various locations in the West and Southwest. Additional instruments are being constructed for deployment for the accumulation of data at potential sites for future solar power plants.

Introduction

Solar thermal conversion, one of the solar energy technologies currently under active development, involves the collection of solar energy in the form of heat, or thermal energy, followed by the use of conventional technology (such as steam turbogenerators) for the conversion of the thermal energy to mechanical and then electrical energy. Most proposed systems would use mirrors or lenses to concentrate the solar radiation upon a receiver element, thereby achieving high temperature operation and thermal-to-electrical conversion efficiencies comparable to those of conventional nuclear or fossil-fuel plants.

The leading candidate for the first pilot plant is the Central Receiver concept, wherein a field of heliostats (mirrors mounted on sun-tracking mechanisms) reflects the incident sunlight onto an elevated receiver atop a tower that is located somewhere between the center and the southern edge of the mirror field. In such systems the solar radiation impinging upon the receiver has been concentrated by a factor of up to 1000 times that falling upon the individual mirrors in the field. Clearly, the energy density distribution of this intense, concentrated radiation over the surface of the receiver is a critical design factor, both for the integrity of the materials used for the receiver, and for the performance (operating temperature) of the solar collection system. The energy distribution on the receiver surface is determined by a number of factors, including the quality of the mirror surface, the accuracy of the tracking system, and the energy distribution of the sunlight incident upon the mirrors. The main purpose of this project is the determination of this last factor; specifically, the absolute magnitude and the distribution (spatial and spectral) of the solar radiation incident upon a solar collector field.

Calculations of the expected system performance of ground-based focusing collectors have heretofore assumed that the solar flux is contained within the 1/2° angle subtended by the sun. This assumption would be justified if the only atmospheric effect were absorption of the sunlight. However, such is not the case. The sunlight is also scattered by molecules (Rayleigh Scattering), and by suspended particulates and aerosols (Mie Scattering). While the molecular scattering is nearly isotropic, the particulates and aerosols scatter the sunlight predominately through small angles, resulting in circumsolar radiation (also referred to as the solar aureole). Pyrheliometers, the standard instruments used to measure the "direct" solar flux, typically have a 6° field of view. Thus circumsolar radiation is included in the measurement of the pyrheliometers, overestimating the amount of energy that would be collected by focusing devices.

Therefore, the objectives of this project can be summarized as follows:

1. to measure the magnitude and angular distribution of the solar and circumsolar radiation with sufficient resolution and accuracy that the measurements may usefully be applied to performance calculations of solar thermal conversion systems.

2. to measure the amount of circumsolar radiation between the edge of the sun's disk and a 3° radius circle, and thus test the adequacy of existing pyrheliometers as measurers of the direct solar flux.

The first phase of meeting these objectives required the development of an instrument system capable of making these measurements. The system consists of a specially designed "scanning telescope" to make the measurements as a function of angle and wavelength, some commercially available auxiliary equipment, and an electronics control and recording system. This paper will deal mainly with the design and performance of this instrument.

*Work done under the auspices of the Energy Research and Development Administration.

Scanning Telescope

Design Criteria

Specific design criteria were formulated to achieve the two objectives stated above.

Angular Intervals and Resolution. Focusing collector systems are expected to collect light from a region including the sun's disk (32' diameter) and a peripheral region defined by allowed tracking errors and optical aberrations, typically a few minutes of arc in extent. Pyrheliometers, in contrast, measure only the total radiation within a field of view of 5-6°. To study the radiation pattern within this field with sufficient angular resolution, it was specified that this telescope should encompass the full 6° interval, and should have a basic angular resolution of 1/10 the sun's diameter (3') for measurements made on and near the solar disk. Once one is sufficiently far from the sun's edge (∿30' from the center of the sun) the radiation levels are changing much more slowly than near the edge, and a reduced angular resolution of 10' was considered adequate.

Measurable Levels of Circumsolar Radiation. The criterion adopted here was that the circumsolar radiation from the edge of the sun out to 3° from the center be measurable when its integrated intensity is 1% or more of that coming from the sun's disk. This criterion sets limits on the amount of direct sunlight that can be scattered from the optical and non-optical elements of the instrument; the direct sunlight scattered within the instrument itself must be of such a low intensity that it does not mask the light scattered by the atmosphere at the level indicated above.

Wavelength Dependence. Essentially all of the solar radiation available at the earth's surface is between .3 microns (3000A°) and 2.5 microns. Many focusing collectors would absorb essentially all light in this interval, and pyrheliometers have a nearly uniform wavelength response. Consequently the circumsolar instrument was required to have an approximately uniform response within the .3-2.5 micron interval. This requirement placed constraints upon the optics and the type of detector. Detectors with wavelength-sensitive responses, such as photomultiplier tubes, silicon cells or photographic film, are inadequate, and more uniformly sensitive devices such as thermopiles or pyroelectric detectors must be used, in spite of their generally lower overall sensitivity.

Measurements as a function of wavelength are especially important for collector schemes that employ selective absorption. From theoretical considerations the circumsolar radiation was expected to have a fairly smooth wavelength dependence, varying as the inverse of the wavelength. Additionally, any practical solar collector must use a significant fraction of the sun's light and thus absorb over a sizable portion of the spectrum. Thus relatively broad band measurements were judged adequate. Another consideration is that each band be wide enough to transmit light at a level significantly greater than the noise level of the detector in both the circumsolar instrument and the pyrheliometer. Accordingly, eight pass bands, each transmitting about 1/8 of the solar spectrum, were selected.

Time Interval Between Measurements. From the above discussion of Wavelength Dependence, a set of data includes one wavelength independent measurement and eight wavelength dependent ones. [Each measurement comprises a scan across the entire 6°.] In addition, a measurement was added in which no light is transmitted to the detector. The "opaque" measurement provides a measure of the noise level of the detector plus its electronics. A time interval of ten minutes between repeat measurements was deemed satisfactory, allowing one minute for each of the ten individual measurements.

Calibration. The final result of a measurement will be values of the direct solar and circumsolar radiation as a function of angle in absolute units (e.g., watts/m^2-degree or watts/m^2-degree-nm). However, the circumsolar instrument itself need not give absolute readings if simultaneous measurements are made with a pyrheliometer. That is, the circumsolar instrument can be calibrated by equating the integral of the circumsolar measurement (over the field of view of the pyrheliometer) to the reading of the pyrheliometer. For calibration of each wavelength-dependent measurement, the pyrheliometer must be provided with a filter identical to that used in the circumsolar instrument.

Control and Data Recording System. The system was required to be capable of unattended operation during the course of a day, with the data recorded on magnetic tape for subsequent computer processing.

Basic Telescope Design

The basic telescope design is shown in Figure 1. An off-axis spherical mirror of 7.5 cm diameter and 1 meter focal length forms an image of the sun plus adjacent sky on a plate off to the side of the incoming light. A fused silica window with a slightly larger diameter than the mirror protects the mirror from the environment. The plate in the focal plane of the mirror contains a small hole, the detector aperture, which defines the angular resolution. The amount of light passing through the detector aperture into the detector assembly (to be described in detail below) constitutes the fundamental measurement. The measurement as a function of angle is made by rotating the entire telescope barrel about the y axis from -3° thru the center of the sun to +3°.

To assure an angular resolution of 1/10 the diameter of the sun, the telescope was designed for a resolution of 1/20 of the diameter; i.e., 1.6 minutes of arc. A one-meter focal length was selected as a reasonable scale for the telescope, to allow for portability. This resolution and focal length combine to require a .046 cm diameter for the detector aperture. The combination of angular resolution and range of wavelengths to be included sets a minimum size of approximately 5.6 cm for the main optical element in order to avoid being diffraction limited.

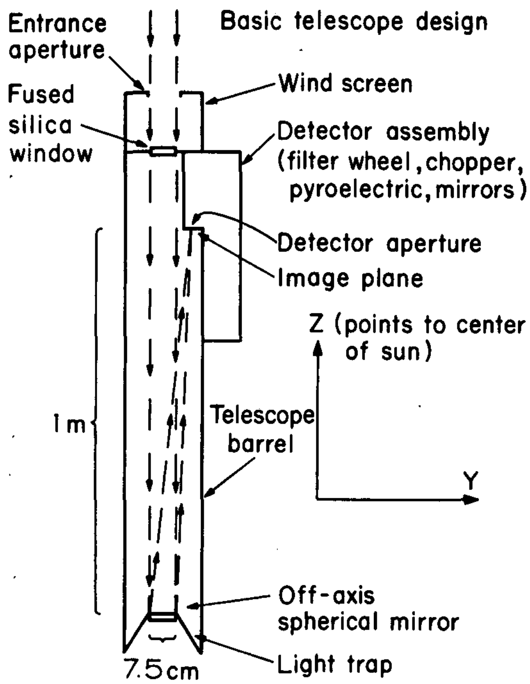

Figure 1. Basic Telescope Design

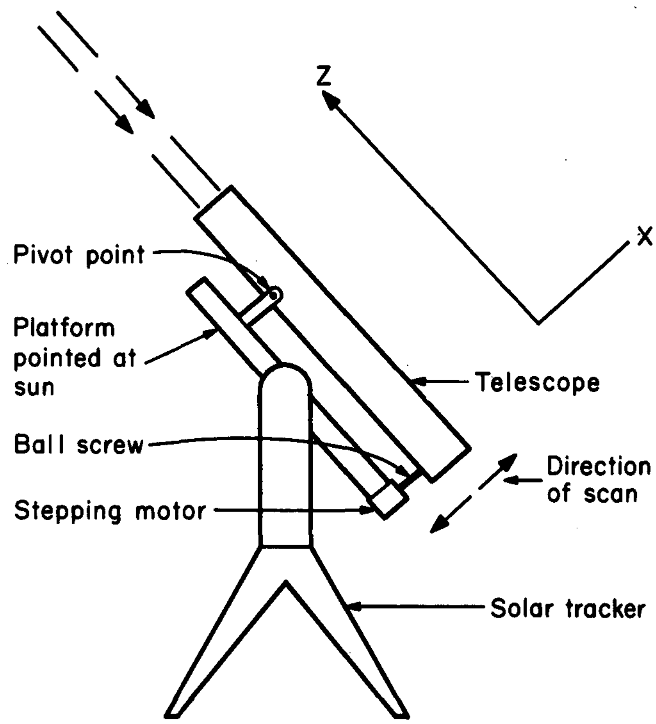

Figure 2. Schematic of Telescope Mounted on Solar Tracker

A simple lens of the desired focal length ($\sim$1 meter) and diameter (>5.6 cm) has chromatic aberrations much larger than the desired angular resolution. A color corrected compound lens would require at least two materials of high transmission over the full wavelength region of 0.3 to 2.5 microns, but different indices of refraction. Such a lens is difficult, if not impossible, to construct and would, of course, lose some of the desired low optical scattering properties of a simple lens.

A telescope with one or more mirrors avoids the difficulties associated with the lens. Of primary concern is the criterion on measurable levels of circumsolar radiation. Much of the design work was devoted to reducing the amount of direct sunlight that would be scattered into the detector from the mirror(s) and other optical or non-optical elements of the telescope. Referring to Figure 1, a 7.5 cm diameter mirror (somewhat larger than the 5.6 cm minimum established by diffraction considerations) was chosen to match the sensitivity of the detector.

For a mirror of a given focal length and diameter, the aberrations at the detector aperture are determined by the tilt of the mirror or, correspondingly, by the displacement (along the y-axis) of the aperture from the optical axis. To insure that no portion of the sun's image hits the window, the displacement must be greater than 4 cm (radius of the mirror plus radius of the sun's image). Mechanical considerations of the detector assembly increased this distance to 6 cm. A ray trace program was then used to determine the aberrations for both a spherical and a parabolic mirror. For a "best focus" (determined by slight variations of the image plane from the nominal focal length), all parallel rays hitting the spherical mirror are contained within a circle of diameter .005 cm at the aperture, a factor of 9 smaller than the diameter of the aperture. The parabolic mirror had somewhat smaller aberrations, but the spherical mirror was selected since it is more than adequate and considerably cheaper.

To make the angular measurements, the entire telescope is rotated about the y-axis. The direct sunlight entering the telescope at oblique angles is prevented from striking the sides of the barrel at grazing incidence by having the diameter of the barrel three times that of the mirror, as indicated in Figure 1. This oblique light hits the base of the telescope and is largely absorbed in a cone-shaped light trap. This trap, together with all other components of the inside of the telescope barrel, is painted flat-black with 3-M Velvet Black.

The scanning motion is illustrated in Figure 2. A solar tracker keeps a platform pointed at the center of the sun. The telescope is rotated about a pivot point on the platform by a stepping motor driving a ball screw. Each scan is a 6° arc with the sun at the center. At the beginning of the scan, 3° from the center of the sun, the detector aperture is "large", about three times the diameter ($\sim$10 times the area) of the "small" aperture discussed above. At about two solar radii from the center of the sun, the aperture is switched (using a solenoid-driven linear actuator) to the small one. After the sun has been crossed, the aperture is switched back to the large one for the remainder of the scan. The purpose of the aperture switch is to increase the amount of light incident upon the detector in the region of low circumsolar light levels and, in effect, extend the dynamic range of the detector by an order of magnitude. The two aperture holes of diameter .46 mm and 1.4 mm (subtending angles of about 1.6' and 5' of arc) were electro-formed in a .08 mm thick stainless steel plate, producing accurate round holes that minimize scattering from the sides of the holes.

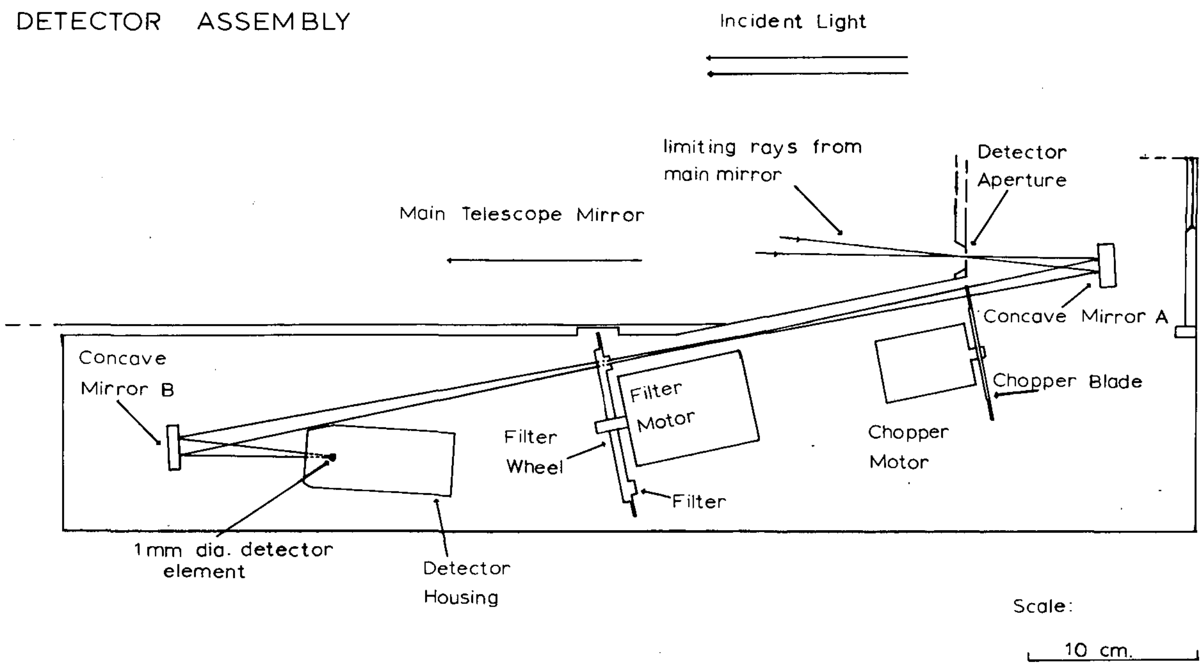

Figure 3. Detector Assembly

The complete 6° scan takes one minute of time. A measurement of the light level is taken every 1.5' of arc, which is one measurement every .25 seconds of time. There are, then, a total of 240 measurements per scan.

Detector Assembly

The principal components of the detector assembly are shown in Figure 3. Light from the main telescope mirror (not shown) passes thru the detector aperture, is reflected from mirror A, optically chopped, filtered, and reflected from mirror B onto the detector.

The telescope performance requirements dictated that the detector have a fairly flat wavelength response, a dynamic range between 10^5 and 10^6, and a time response fast enough to accommodate the telescope scanning speed.

The detector selected is a pyroelectric device manufactured by Laser Precision Corp. The complete device consists of a kT-4110 detector module, a kTH-111 preamplifier and a .85 x 10^9 - ohm load module. The three modules are combined in one physical unit and constitute the "detector housing" in Figure 3. The preamp transforms the detector from a high-impedance current source to a low impedance voltage source. The load module determines the voltage responsivity (ratio of output voltage to input light level) as well as the time response.

The detector has as its sensitive element a 1 mm diameter crystal of pyroelectric material with a nearly uniform wavelength response to incident light. For optimal performance, the crystal should be illuminated uniformly over its surface area at or near normal incidence. The detector is an AC device and requires that the incident light be optically chopped. The chopper is a three-bladed disk mounted on a synchronous motor. The motor is driven at 32 Hz, producing a chopped frequency of 96 Hz.

The design requirements for the optics in the detector assembly are that the diverging beam from the detector aperture must be refocused to a 1 mm diameter spot size to match the detector, this spot size must be essentially independent of the aperture size, and the light path between aperture and detector must be of sufficient length to accommodate the chopper and filter wheels. These requirements proved rather troublesome and could not be satisfied with an optical system containing a single mirror or lens. As a result, the two mirror system shown in Figure 3 was adopted. Although not strictly necessary, it was convenient to have two mirrors of the same focal length. The first design specification for this two mirror system was that the main telescope mirror be focused onto the detector element. Changing the size of the aperture is then like varying the f-stop on a camera. The second specification was that the final focus of the detector aperture be at infinity. This rendered any possible difference in image spot size on the detector (due to the different aperture sizes) essentially independent of the position of the detector along the optical axis. The mirrors are used at sufficiently small angles of reflection that aberrations are minor. This optical design was checked by detailed ray tracing calculations, and the final optical parameters were selected to minimize the effect of aberrations on the spot size at the detector. Each of the two small mirrors is 2.5 cm in diameter and has a 6.9 cm focal length.

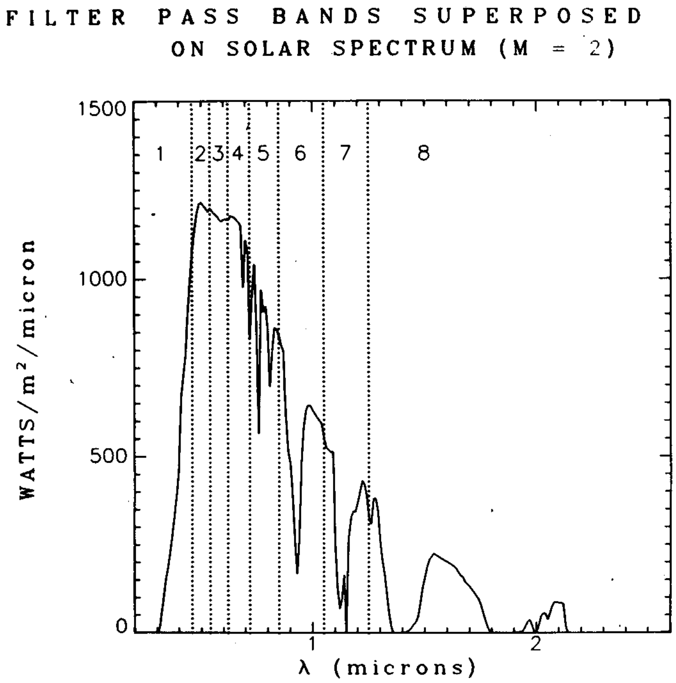

Figure 4. Filter Pass Bands Superposed on the Solar Spectrum for Air Mass = 2.

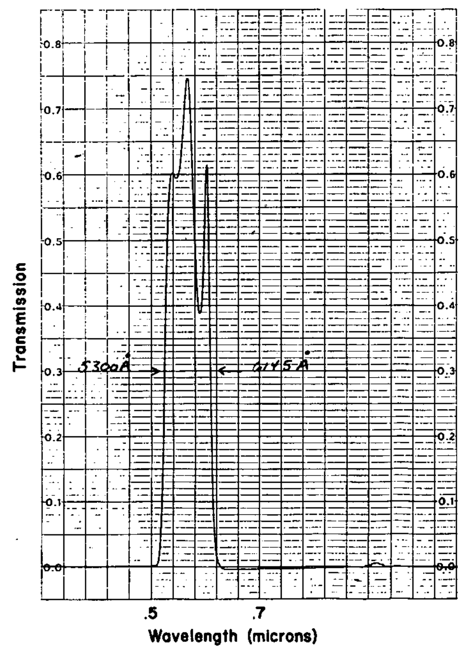

Figure 5. Example of a Filter Transmission Curve

The wavelength dependence of the circumsolar radiation is determined by use of a set of filters placed between the aperture and the detector. These filters are mounted on a wheel turned by a stepper motor.

The eight filter pass bands were determined by dividing the solar spectrum into eight intervals of approximately equal energy contents. The resulting bands are shown in Figure 4 superposed on the solar spectrum for air mass = 2. A given band was specified by a cuton and a cutoff wavelength, defined as the half-peak-power wavelengths. The transmission curve for one of the filters is shown in Figure 5.

The filters had to satisfy several requirements. The transmission in the pass band had to be greater than 50%. The filters had to be blocked outside the band from .3 microns to 2.5 microns, such that the total amount of out-of-band light transmitted is less than 1% of the light transmitted within the band. The filters had to be made in matched pairs: a small one (20 mm diameter) for the filter wheel in the detector assembly, and a large one (38 mm diameter) for the pyrheliometer filter wheel (see below). The filters were supplied by Spectra-Optics.

Auxiliary Equipment

Pyrheliometer

The pyrheliometer provides the absolute calibration for the scanning telescope, and also provides the usual "normal incidence" measurement. The instrument acquired is a Radiometrics Active Cavity Radiometer. It is self-calibrated in electrical units and has an accuracy of 0.5% at a light intensity of one solar constant. The operation of the instrument is described in detail in the literature.[1] A brief description is given here of those aspects particularly important to the use of the instrument in this project.

The Radiometer is basically a collimator with a black body cavity as the detector. By the use of a chopper blade, the cavity is alternately exposed to and shielded from the direct sunlight. The cavity is maintained at constant temperature by a resistive heating element that requires relatively less (more) current when the cavity is exposed to (shielded from) the sun. The voltage across the resistive element constitutes the output signal. The intensity I of the normal incidence radiation is given by

$$I = K\,(V_C^2 - V_O^2)\ \text{milliwatts/cm}^2$$

where

K = instrument constant that depends primarily on the heater resistance and area of the cavity aperture.

V_C = Chopper-Closed voltage

V_O = Chopper-Open voltage

In this instrument system, the chopping is provided by a combination filter wheel and chopper. The wheel has 20 positions: 10 measurement positions corresponding to chopper-open, alternating with 10 opaque positions corresponding to chopper-closed.* At the beginning of each scan of the telescope, the filter wheel will be rotated to a measurement position. Near the middle of a one minute scan, when the telescope is pointing close to the sun, the radiometer output will be recorded and the filter wheel rotated to the adjacent opaque position. At the end of a scan the output will again be recorded and the wheel rotated to the next measurement position to begin the next scan.

Pyranometers

Two pyranometers will make 180° measurements while the telescope is in operation. One will be mounted horizontally in the usual way. The second will be mounted on the telescope platform so that it is always normal to the direct solar radiation. Two Eppley PSP's (Precision Spectral Pyranometers) were acquired. During the operation of the telescope, the pyranometer outputs will be recorded at the end of each 1-minute scan.

Solar Tracker

The scanning telescope was designed so that the scan motion is relative to a platform pointed at the center of the sun by a solar tracker. In addition, the platform supports the pyrheliometer and one pyranometer. The tracker was purchased from Carson Astronomical Instruments, Inc. The requirements on the tracker were that it be portable, capable of tracking the sun to within 1/2 of an arc minute, and able to support at least 50 Kg of instruments.

The Carson tracker is an equatorial mount type with a polar and a declination axis. The polar axis is clock driven in right ascension at mean solar time. A "solar guider" mounted on the telescope platform provides the required tracking accuracy. For both the polar and declination axes the guider drives a correction motor so as to balance the outputs of two photodiodes that are located behind a narrow slit. An additional photodiode, a "sun sensor", disables the guider when clouds obscure the sun. The tracker then reverts to the clock motor.

Alignment of the tracker at a given geographical location requires that it be adjusted for latitude and true north. Following Harrison,[2] an extremely simple but very effective north finding device was constructed and attached to the tracker.

Integrated Instrument

Operating Configuration

The scanning telescope is shown in Figure 6. From a comparison with Figure 2, one can identify the solar tracker, the telescope barrel, the telescope platform that the tracker keeps pointed at the sun, and the stepping motor and ball screw mechanism. The rack attached to the front of the telescope platform holds the solar guider (the cylindrical object at the bottom of the rack), the chopper wheel for the pyrheliometer, and the pyranometer (which was not in place when this photograph was taken). The pyrheliometer chopper wheel shown is the one normally supplied with the instrument; it has since been replaced with the combined chopper/filter wheel. The pyrheliometer is mounted inside the telescope platform. Its entrance aperture can be seen directly below the front end of the telescope barrel.

Control System Electronics

The electronics control system is illustrated in Figure 7. The master controller exercises control over the basic scan motion of the telescope, the synchronous rectifier and integrator for the pyroelectric detector, the aperture switch and filter wheel in the detector assembly, the combination filter/chopper wheel for the pyrheliometer, and the recording of data on magnetic tape.

The box in Figure 7 labeled Multiplexer A/D refers to a Datel 16-channel multiplexer with a 12 bit analog-to-digital converter. At present only four of the channels are used for the pyroelectric detector (or, more correctly, the log amplifier output), the pyrheliometer, and the two pyranometers.** A tape interface designed at LBL transmits the A/D output to the Kennedy tape recorder.

A digital clock (not shown) provides timing signals for the system. The clock has a digital display in hours-minutes-seconds, and thumbwheel switches for the date and for flags indicating the running conditions. This digital information is recorded on the tape at the end of each scan of the telescope.

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*One "measurement position" is itself opaque but is included as a simple method of keeping this filter wheel in step with the one in the scanning telescope.

**The remaining channels are available for recording other solar instruments or meteorological parameters such as the temperature or wind velocity.

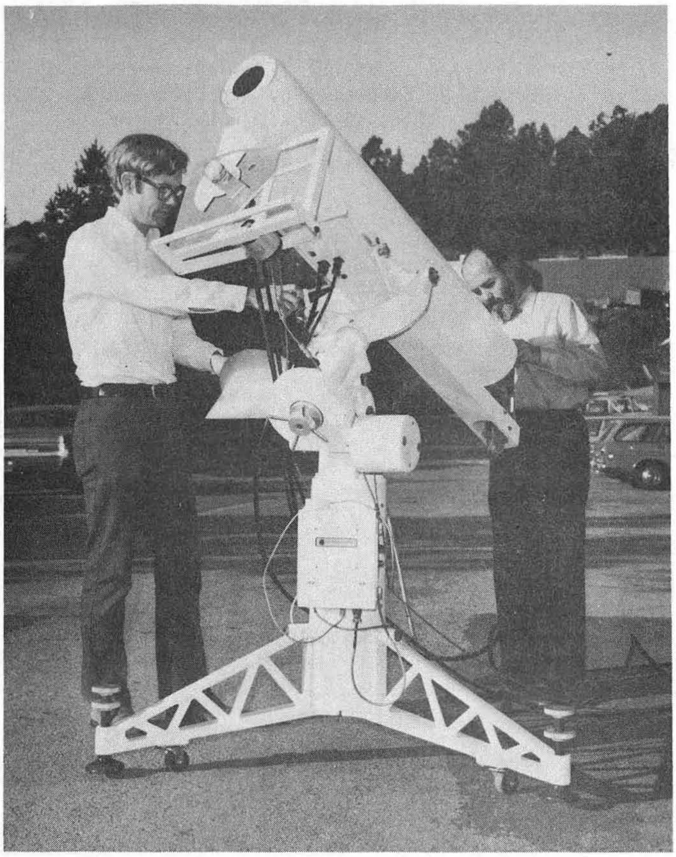


Figure 6. Photograph of Scanning Telescope

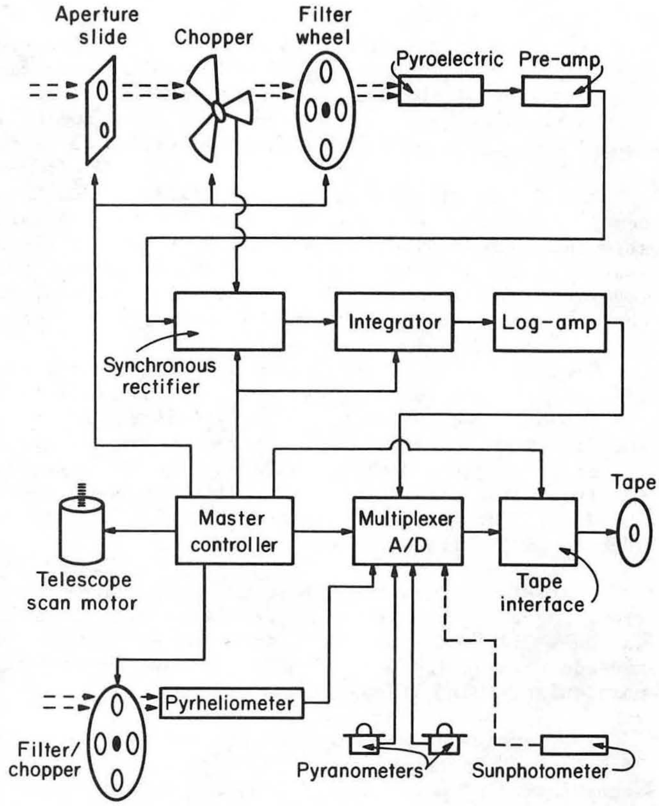


Figure 7. Block Diagram of Control System Electronics

To realize the desired dynamic range of 10^5 to 10^6, an electronics circuit had to be developed that would accomplish the necessary narrow-band filtering (the pyroelectric detector is a source of broad-band noise), without sacrificing the necessary dynamic range or time response. The filtering is carried out by the synchronous rectifier and the integrator (see Fig. 7). The synchronous rectifier is driven by the output of an optical switch, which is, in turn, activated by the blades of the chopper wheel. The chopper blades are precision machined, and the physical position of the optical switch is adjusted to give maximum rectification of the pyroelectric signal (after it has passed through a pre-amplifier). The Integrator part of the circuit integrates the signal over 22 chopper pulses, effectively integrating to zero, on the average, most frequencies other than that of the chopper. The integrator output feeds into a log-amplifier that converts the 10^6 dynamic range to a voltage level between +10 volts and -10 volts, which is then processed by the analog-to-digital converter.

The normal sequence of operations is as follows: Starting at one limit of the scan, the master controller drives the telescope scan motor at a uniform rate, until the other limit is reached after scanning 6° of arc. During the scan, the Integrator is read out and reset every 24 chopper pulses (0.25 second), corresponding to every 1.5' of arc. At the beginning of the scan, the aperture slide is in the "large aperture" position. The slide is switched to the "small aperture" position when the scan reaches two solar radii ($\sim$30') from the center of the sun, and is switched back to the "large aperture" position after passing through the sun and reaching the two-solar-radii mark on the other side of the sun. Pyrheliometer readings are taken at the same time the apertures are switched. At the end of the scan, data from all the peripheral devices are recorded, including the pyrheliometer, pyranometers, clock, and thumbwheel switch positions. The two filter wheels are then rotated to the next filter position, and the next scan is started.

Several checks are built into the logic to test for failure modes, including checks that the proper number of stepper motor pulses were used between the -3° and +3° limits of the telescope scan, that the proper aperture hole is in place, and that the two filter wheels are in step with each other.

Manual control switches are available to start the automatic scan in the correct initial state, and to override the automatic controls for manual slewing and positioning of the telescope.

Results

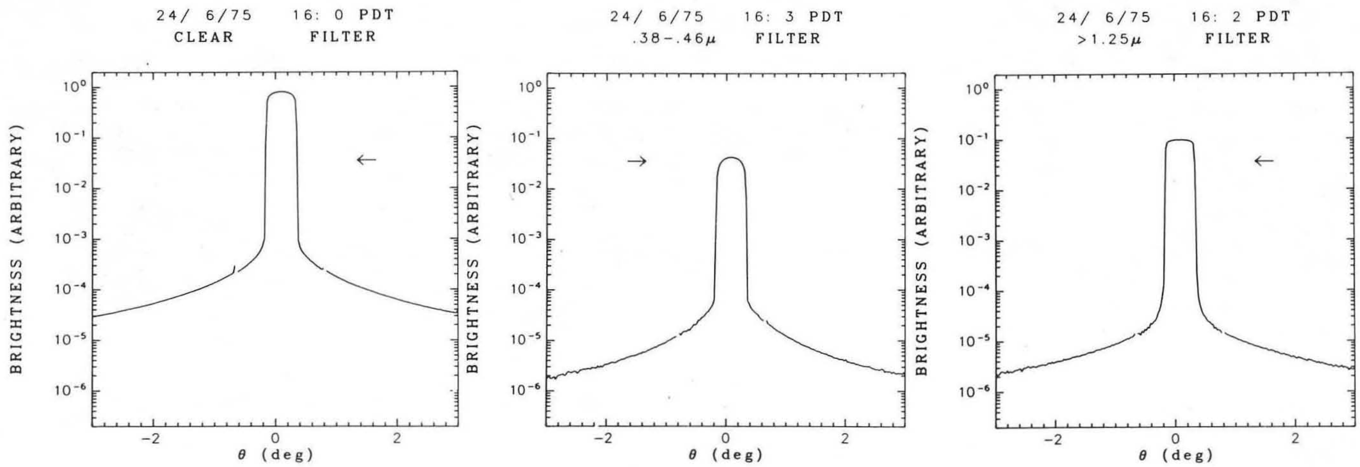
The measurements of the solar and circumsolar radiation are displayed in Figure 8 for some typical scans on a fairly clear day. The individual measurement points have been connected by straight lines. The direction of the scan is indicated by the arrow. The two discontinuities (located, roughly, one solar radius from each edge of the sun) correspond to the points where the aperture is switched from the large one to the small one (used when measuring on or near the sun) and then back to the large one.

For the no filter case (Figure 8a), the smoothness of the line connecting the measurement points demonstrates that the signals are well above the random component of the noise from the detector and associated electronics. The sharp falloff at the edge of the sun indicates both the sharpness of the solar image and the ability of the detector and electronics to respond to the abrupt change in brightness at the edge of the solar disk. For this particular scan, the amount of circumsolar radiation from the edge of the sun's disk out to 3° from the center is 1.9% of that coming from the sun.

Figures 8b and 8c show scans made for the filters passing the shortest wavelengths and longest wavelengths, respectively, of the eight optical filters used. The reduction in overall intensity is such that the random noise component is now visible. The average component of the noise (obtained once per cycle of the filter wheel from the measurement using the opaque filter) has been subtracted off. Note that for the filter passing the shortest wavelengths, the intensity of the sun's disk decreases towards the edge of the sun (so-called limb darkening), while for the longest wavelengths the intensity is nearly constant across the disk. For these two filters the values for the circumsolar radiation are 2.6% and 1.1%, respectively, of that coming from the sun.

The measurements shown here have been taken during the final debugging stages of the telescope operation. On the clearest day to date that measurements have been taken, the amount of circumsolar radiation was only 0.28% of that coming from the solar disk. This low value demonstrated that the instrument had exceeded its design criterion (of 1%) by a comfortable margin. Measurements have not yet been made under particularly hazy or smoggy conditions.

The next stage will include the use of this instrument to carry out extensive measurements at a series of locations in the West and Southwest, plus the fabrication of three additional instruments for the accumulation of solar and circumsolar data at potential sites for future solar thermal conversion plants.



(a) No Filter (b) Filter for Short Wavelength End of Solar Spectrum (c) Filter for Long Wavelength End of Solar Spectrum.

Figure 8. Examples of Telescope Scan Measurements

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

2. Harrison, P. L., "A Device For Finding True North," Solar Energy 15, 303 (1974).

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