PHOTOMETRIC MEASUREMENTS OF SOLAR IRRADIANCE VARIATIONS DUE TO SUNSPOTS

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ABSTRACT

A new telescope and photometer have been constructed which can obtain photometric images of the entire solar disk with a linear diode array and using Earth’s rotation to scan the image. Observations of sunspot irradiance variations have been made with this system beginning in the spring of 1985. We here describe the data collection system and report on irradiance variations measured in 1985 June, July, and October. The measured sunspot irradiance variations are compared to digital spectroheliograms of individual sunspots obtained at higher resolution with the San Fernando Observatory 28 cm vacuum telescope and vacuum spectroheliograph. A comparison also is made to area measurements published in the Solar Geophysical Data Bulletin which have served in most previous attempts to model the sunspot contribution to irradiance fluctuations. The sums of sunspot deficits measured with the new system are compared to daily averages of the total irradiance measured with the ACRIM on SMM. We find that the differences may be accounted for by irradiance contributions from active region faculae and plage.

Subject headings: instruments—Sun: general—Sun: sunspots

1. INTRODUCTION

Measurements of the solar irradiance have been made from space by the Nimbus 7 and the Solar Maximum Mission (SMM) satellites since 1979 and 1980, respectively (Hickey and Alton 1984; Willson et al. 1981; Willson 1984). Most of the short-term variation in the total irradiance has been attributed to the passage of sunspot groups across the visible disk of the Sun. The effect of the sunspots has been modeled, taking into account their expected mean contrast and position on the disk (Eddy, Hoyt, and Gilliland 1982; Foukal and Lean 1986; Hudson et al. 1982; Hudson 1987, 1988; Hoyt, Eddy, and Chapman (1987). Chapman and Meyer (1986) published photometrically determined coefficients for model sunspot deficits that agreed very closely with those calculated in Willson et al. (1981). It has been unclear, however, just how accurate are the sunspot areas upon which these previous analyses have been based. Eddy (1984) found that different observatories agreed on spot areas to about 9%. Chapman and Groisman (1984) compared sunspot areas from digitized photographs with published reports and found good agreement if the edge of the sunspot is defined as approximately —15% contrast with respect to the quiet Sun. Several large sunspots deviated from the regression line significantly, their reported areas being about 15% less than predicted by the regression line. The photometric sunspot index (PSI) given by equation (2) often is used to represent the sunspot contribution to the irradiance deficit. The PSI is based on published estimates of sunspot area and disk position, determined by sunspot drawings, and an assumed mean sunspot contrast. Clearly, one would prefer to have objective measurements of sunspot area and photometric deficit. Accurate measurement of sunspot deficits will permit checking on the long-term effects of faculae and also of the photospheric network, which appears to be important on the time scale of the activity cycle (Lean and Foukal 1988; Livingston, Wallace, and White 1988; Schatten 1988).

In this paper we describe a new photometric telescope that has been constructed for the purpose of obtaining photometric sunspot areas and deficits on a daily basis. We have analyzed data from this Cartesian full disk telescope (CFDT) particularly for the interval 1985 June 4—17 because of the availability, for purposes of comparison and calibration, of overlapping sunspot area and irradiance deficit data from high-resolution, digital spectroheliograms made with the San Fernando Observatory (SFO) 28 cm vacuum solar telescope and vacuum spectroheliograph (SHG) on 1985 June 7, 8, 11, and 14 as listed in Table 1. Also available are sunspot areas, by active region, published in NOAA’s Solar Geophysical Data Bulletin (SGD), as are full disk, bolometric irradiance variations observed by the active cavity radiometer irradiance monitor (ACRIM) aboard the (repaired) Solar Maximum Mission (SMM) satellite.

We wish to compare the CFDT sunspot area and deficit measurements for particular active regions with those of the 28 cm system, and the CFDT area measurements with those published in the SGD in order to calibrate the CFDT data for use in determining the physical origin of solar irradiance fluctuations observed by ACRIM. Finally, we compare our CFDT deficit measurements, for all sunspots detected on the disk on a particular day, with ACRIM irradiance fluctuations and find that the differences can be explained in terms of the expected positive contribution to the solar irradiance of active region facular areas. Section II describes the instrument and the form of the data. Section III presents the data for sunspots observed during the early part of 1985 June, along with results from observations during the same period obtained with the 28 cm vacuum telescope and spectroheliograph. Section IV presents and discusses the results, which are summarized in § V.

II. THE CARTESIAN FULL DISK TELESCOPE

The Cartesian full disk telescope (CFDT) is a one-piece telescope and photometer. It obtains a Cartesian format “picture” of the Sun and surrounding sky, with square pixels aligned north-south, east-west. The aperture is 2.5 cm (1 inch) with...
To obtain an image of the Sun, the CFDT first is positioned to the west of the Sun by moving the solar tracking spar. The scanning of the solar image begins when the spar tracking motor is stopped, Earth's rotation causing the CFDT linear diode array to scan the image while the computer digitizes the data and stores them on magnetic tape. The electronic read-out rate is adjusted each day to correspond to the Sun’s changing declination so that the Sun moves by exactly 1 pixel while one line of data is read out. The period between successive read-outs of a line of the image is $317.7 \text{ ms} \times \cos(\text{solar declination})$. This period is determined by the focal length of the telescope (101.6 cm) and the size of the diodes ($25 \mu\text{m} \times 25 \mu\text{m}$). An image of the entire Sun with surrounding sky has $512 \times 512$ pixels and requires about 3 minutes to complete. Each diode corresponds approximately to a square $5''$ on a side on the sky. The dark response of the diodes is measured each day. The bright response of the diodes is measured by moving the telescope across the center of the imaged disk in a north-south direction along the length of the array. This scan provides an average brightness for each diode that is very nearly constant, consisting of an average brightness along a diameter of the solar disk and including some of the sky to the north and south of the Sun. This calibration scan is carried out every week or 10 days during good sky conditions. Since 1986 July, one image normally has been obtained in the red at $\lambda = 672.3 \text{ nm}$ and one in the violet at $\lambda = 392.0 \text{ nm}$, both with a bandpass of 10 nm. In 1985 the red wavelength was $\lambda = 677.8 \text{ nm}$ with a 3.0 nm bandpass. Beginning in 1988 April, an image has been obtained at $\lambda = 393.4 \text{ nm}$ with a bandpass of 1 nm.

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More than two images are obtained on a given day if necessary.

Beginning in 1986, transparency is monitored by a silicon photodiode viewing the sun and the nearby sky through a Schott VG-14 green filter. This signal is differentiated with that of a second diode that is in a light-tight cylinder next to the active diode. This difference signal is digitized at the end of each line of the image and recorded on magnetic tape. Thus each image of the Sun has 512 records in the east-west direction with each record containing 513 data words, 512 of which are image pixels along the north-south direction and the 513th of which is the integrated solar brightness just discussed, and taken to be a measure of relative sky transparency. The electronic noise in the integrated solar brightness signal is less than $\pm 1$ bit. The range of the analog to digital converter is 12 bits.

III. DATA ANALYSIS

The raw images from the CFDT are corrected for the individual variations in the dark signal and the relative gain of each individual diode using the daily "dark" calibrations and the approximately weekly "telescope" calibrations described in the previous section. This procedure is carried out with the Cyber 170/750 mainframe computer on the California State University, Northridge (CSUN) campus using the MAGNET program. The software package for obtaining sunspot areas and irradiance deficits is called the Full Disk Analysis Program (FDAP). This program also can be used to obtain sunspot areas from digitized photographs (Chapman and Groisman 1984). The CFDT images are transformed from intensity to contrast maps by dividing out quiet Sun limb-darkening curves obtained from the images themselves. The limb-darkening for each image is determined from three adjacent scans through the solar disk center in the geocentric north-south direction and three scans in the east-west direction. These six scans are folded about the disk center and averaged to obtain the quiet Sun limb-darkening curve. The intensity of each pixel of the image is then divided by the quiet Sun intensity at the corresponding position, thus forming a contrast image of the Sun. Figure 2 (Plate 16) is a photographic representation of such a contrast image made on 1985 June 12. The contrast of the display has been strongly exaggerated.

If the empirical limb-darkening curve is not numerically smoothed, then concentric rings appear in the contrast image due to incomplete averaging of quiet Sun intensity structures. Since such rings have a contrast of only 1% or 2% they do not interfere significantly with the identification of sunspot pixels or with the calculation of sunspot irradiance deficits. A more serious problem occurs when sunspots lie within the six scans used to determine the quiet Sun limb-darkening. In this case a function of the form (Aller 1963)

\[ I(\mu) = A + B\mu + C[1 - \mu \ln(1 + 1/\mu)] \tag{1} \]

is used to smooth out the rings. Here $\mu$ is the cosine of the heliocentric angle between the pixel and the direction of the line of sight ($\mu = 0$ at the limb, 1 at disk center). The extreme limb exhibits some brightening in this situation, however. For the present paper smoothing was needed only for data acquired on 1985 June 11.

Once the contrast image has been constructed, it is searched for sunspot pixels, which are defined to be those with a contrast at 677.8 or 672.3 nm which is at least 8.5% below the quiet Sun. This same contrast criterion was found to locate the edge of a typical sunspot observed at 626.4 nm in digital spectroheliograms obtained with the SFO 28 cm vacuum solar telescope and vacuum SHG at a pixel spacing of 0.94 (Chapman et al. 1984; Lawrence et al. 1985). This contrast is found where the intensity has its steepest descent at the outer edge of the penumbra. This criterion should be relatively insensitive to seeing variations since it occurs at a location where the second derivative of the intensity is small, a condition often used to define the position of the solar limb under variable seeing conditions. Changing the contrast criterion led only to small changes in the measured irradiance deficit.

The fraction of pixels on the disk meeting or exceeding the contrast criterion is the projected sunspot area expressed as a fraction of the disk. This is converted to corrected area expressed as a fraction of the solar hemisphere by weighting each sunspot pixel by its corresponding value of $2\mu^{-1}$. Irradiance deficit is determined by weighting each sunspot pixel by its intensity deficit relative to the local quiet Sun and then dividing the weighted sum by the summed intensity of an extrapolated full disk, quiet Sun image. We also calculate the so-called photometric sunspot index or PSI (Willson et al. 1981), which is an estimate of the sunspot contribution to solar irradiance fluctuations based on their area, center-limb position, and a mean sunspot contrast. All of these measured areas and deficits may be assigned to specific active regions on the solar disk, or not, depending upon the desired application.

The accuracy of the data reduction program has been checked by creating a mathematical image with artificial sunspots of known area and deficit and then analyzing the image with FDAP. In all cases, corresponding to spots of different sizes and positions on the disk, FDAP produced the correct deficits and areas within 1 pixel. Of course, the analysis of real sunspots may entail additional systematic errors.

IV. PRESENTATION OF RESULTS

Because the high-resolution, photometric, SHG measurements of sunspot areas and irradiance deficits would seem to be the most precise and objective, we first compare the CFDT measurements to these. Figure 3 shows a linear regression of the CFDT-corrected, hemispheric, areas of NOAA active regions 4662 (including 4660 and 4665) and 4663 on 1985 June 7, 8, 11, and 14 on the corresponding SHG-corrected areas. The data used are presented in Table 1. The regression line is

\[ \text{Area}_{\text{CFDT}} = (0.97 \pm 0.13) \times \text{Area}_{\text{SHG}} - (24 \pm 31) \]

Corrected areas are given in parts per million (ppm) of the solar hemisphere. The CFDT areas are seen to be in fairly good agreement with those from the SHG, though the CFDT areas appear to show a negative offset of about $-24$ ppm, corresponding to about 5 CFDT pixels. The slope of the regression line is indistinguishable from unity. Finally, the correlation coefficient for the linear regression is $r = 0.97$. Even for a number of data points as small as $n = 8$, this gives a significance level $p < 0.001$.

Figure 4 shows a linear regression of the CFDT sunspot irradiance deficits versus the SHG deficits for the same active regions and days as above. The regression line is

\[ \text{Deficit}_{\text{CFDT}} = (0.91 \pm 0.12) \times \text{Deficit}_{\text{SHG}} - (2 \pm 12) \]

where the deficits are in units of ppm of the solar irradiance. The intercept of this line is indistinguishable from zero. The CFDT deficit seems, marginally, to be about 10% less than the SHG deficit, and we shall adopt a 10% correction when comparing the CFDT deficits to the ACRIM measurements below.
Fig. 2.—TV display of a CFDL image of the contrast of solar features for 1985 June 12. The image has been smoothed with the function given in eq. (1) to remove low-contrast structure in the quiet photosphere. The fit has caused some brightening near the limb. This brightened zone was not used in calculating sunspot deficits.

Chapman et al. (see 343, 549).
Fig. 3.—Hemispherical areas for sunspot groups in 1985 June measured by the CFDT vs. those measured by the 28 cm vacuum telescope and vacuum spectroheliograph (SHG). The slope is near unity with an offset of approximately $-30$ ppm.

For this regression the correlation coefficient is $r = 0.995$, and the level of significance is $p < 0.001$.

We have found for the 28 cm vacuum telescope and SHG system that the deficit corrections for scattered light and monochromaticity are approximately equal but opposite at a wavelength of 626.4 nm (Lawrence et al. 1985). The main stray light effect arises from differential scattering of light on the scale of sunspots versus the scale of the solar disk; it is primarily governed by the sunspot-disk geometry rather than the detailed form of the stray light spread function. Thus we have assumed that the rough cancellation of the bolometric and stray light effects holds also for the CFDT at 672.3 nm.

We next compare our CFDT-corrected area measurements to those published in the SGD. For each day during the 1985 June 4–17 interval for which we have CFDT data we have averaged all reported areas given by each observing station for each active region. These areas, along with those from the CFDT, are shown in Figure 5. The centers of the boxes represent the average SGD area, and the half-height of each box represents the standard deviation of the mean of the results from the observing stations. The circles represent the CFDT area averaged for two images at 678 nm. The difference between any two images on the same day is typically only 1 pixel corresponding to about 6 millionths of a hemisphere. Thus the size of each circle indicates approximately the random error in the CFDT areas. It can be seen that for NOAA active region 4663 the sunspot areas found by FDAP are in close agreement with those from the SGD. However, for

Fig. 4.—Sunspot deficits measured by the CFDT vs. those measured by the 28 cm vacuum telescope and SHG for data of 1985 June. The CFDT deficits systematically are 9%–10% lower than those from the SHG.
NOAA region 4662 the CFDT areas are significantly greater than the SGD areas, while for NOAA region 4660 the CFDT areas are significantly smaller than the SGD areas. Internal error in the CFDT results is about 5 millionths of a hemisphere.

No apparent discrepancy exists among the measurements of the various SGD reporting stations. The typical internal error in the CFDT results is about 5 millionths of a hemisphere.

It is instructive to attempt to account for these discrepancies. On June 4, it turns out, the sunspots which later comprise regions of 4660 and 4662 are just appearing around the east limb. On this day the SGD assigns all of the spots to region 4660, accounting for the large excess area for this region in the SGD. Confusion on this point seems to have continued into June 5, and we attribute the excess area of region 4660 in the SGD to this cause. If one examines the details of the SGD area reports for region 4660 on June 8 and 9, one finds that one of the five stations reports areas much greater than do the others (170 ppm vs. 40 ± 4 on June 8 and 240 ppm vs. 42 ± 7 on June 9). If the apparently discrepant observations are dropped, then the SGD areas for region 4660 on June 8 and 9 are in much closer agreement with the CFDT areas. On the other hand, no obvious explanation for the persistent deficit of the SGD corrected areas relative to the CFDT areas for region 4662 presents itself. We can only speculate that this may represent some systematic effect, perhaps related to active region morphology.

The results presented in Figure 5 may alternatively be regarded as a series of independent observations, by both the SGD and CFDT methods, of active region sunspot areas. In Figure 6 we plot a total of 87 such SGD measurements for 1985 June, July, and October versus the corresponding CFDT measurements. In this plot the vertical error bars are the standard deviation of the mean of the SGD observing station results. The full width of the horizontal error bars represent the difference, if any, between the two CFDT measurements, normally from images made a few minutes apart. The solid line represents the linear regression of the SGD measurements on the CFDT measurements: (\( \text{Area}_{\text{SGD}} = (0.86 \pm 0.04) \times \text{Area}_{\text{CFDT}} + (17 \pm 10) \)). Implicit in this regression is the assumption that the CFDT data are the more error free and that they should, therefore, serve as the independent variable. In any case, the CFDT measurements are usually more internally consistent. The dashed line represents the ideal correlation \( \text{SGD} = \text{CFDT} \). The correlation coefficient for these data is \( r = 0.91 \), and with \( n = 87 \) points the level of significance is \( p < 0.001 \). It is instructive to consider the somewhat discrepant point at about \( \text{CFDT} = 100, \text{SGD} = 400 \), represented by a solid circle. This point represents a large region (600–800 ppm on earlier days) on the day it is disappearing around the west limb. Typically the CFDT data are taken quite late on a given UT day, several hours later than the average of the SGD observations, which are more distributed in time. Thus, at the time of the CFDT observation, more of the region had been occulted by the limb than at the average time of the SGD observations, and the CFDT is correspondingly smaller. A gathering of points also is noticeable along the lower portion of the vertical (SGD) axis. The CFDT apparently does not detect very small sunspot areas (cf. the comparison between CFDT and SHG observations). The SGD areas for these points are somewhat exaggerated. Not all of the SGD stations have reported areas for these small spots either. We, on the other hand, have averaged only reported (i.e., nonzero) SGD areas for plotting points in Figure 6. As discussed above, other possibly discrepant points have no obvious explanation.

We point out, finally, that a regression of SGD sunspot areas on those from digitized photographs processed by FDAP (Chapman and Groisman 1984) gave excellent agreement when the range included much larger sunspots up to 1500 ppm.

In Figure 7 we plot the PSI calculated with CFDT measured sunspot areas, versus the CFDT directly measured sunspot irradiance deficit (DEF) for active regions observed in 1985 June, July, and October. The PSI is given by

\[
\text{PSI} = C_s A_s \mu (3 \mu + 2) ,
\]

where \( C_s = -0.164 \) and \( A_s \) is the sunspot area in ppm of the solar hemisphere (Chapman and Meyer 1986). As can be seen in the figure, the 86 data points show a strong linear correlation with regression \( -\text{PSI} = (1.52 \pm 0.03)(-\text{DEF}) + (4 \pm 3) \). The correlation coefficient is 0.985. For those sunspots in 1985 June that also were observed by the vacuum SHG, we found that the regression slope was only \( 1.27 \pm 0.07 \) for 15 data points, whereas for all July spot groups the slope was \( 1.63 \pm 0.02 \) for 37 data points. Part of this difference may be due to instrumental changes in the placement of filters in the CFDT in July. Some of the difference, however, may be caused by differences in the morphology of the July sunspots compared to those in June. The sunspots in July developed quite rapidly on the disk and the dominant group, NOAA 4671/4672, was complex with extensive penumbral areas. We might thus expect that its overall contrast would be less than the average contrast value used in the PSI formula. In this case the calculated PSI deficit would appear greater than the actual deficit. The data points for this region are shown as solid squares in Figure 7. When these data points are excluded, the regression becomes \( -\text{PSI} = (1.34 \pm 0.04)(-\text{DEF}) + (11 \pm 3) \) for 58 data points.
Figure 8 shows the ACRIM signal compared to the total, full disk sunspot deficit measured directly by the CFDT. The CFDT irradiance measurements have been increased by 10%, as discussed above, due to calibration with the higher resolution 28 cm vacuum telescope and SHG data (Laico 1987). The ACRIM fluctuations (solid circles) are shown in ppm relative to an assumed quiet Sun irradiance of 1367.03 W m$^{-2}$ (Willson et al. 1986). This value was determined from the average value of the ACRIM signal during the first half of 1986, at or near the solar minimum (R. C. Willson 1988, private communication). The ACRIM point for June 8, connected by dashed lines, was based on an incomplete daily data set (Hudson 1988), and it is contrary to the evolutionary trend of the sunspot areas on adjacent days. We shall assume that this data point is incorrect. The open circles give the total spot deficit from the CFDT.

We interpret the difference between the ACRIM signal and the CFDT spot deficit as arising from faculae in the active region plages and the network. We have computed a facular signal from published calcium plage areas and a photometric

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**Fig. 6.—**Hemispherical sunspot areas published in the SGD vs. those measured by the CFDT for 1985 June, July, and October. The CFDT data have not been corrected for the bias revealed when compared to the SHG data. This graph shows that the SGD underestimates the sunspot area by about 14%. When corrected for the loss of signal suggested by the comparison to the SHG the SGD underestimates the sunspot area by about 22%.

**Fig. 7.—**Plot of the photometric sunspot index (PSI), as given by eq. (2) vs. the CFDT measured sunspot deficit during 1985 June, July, and October. The solid squares represent data points from NOAA region 4671/2, which was large and complex, with extensive penumbral area, and hence a possibly exaggerated PSI value (see text).
facular index (PFI) formula (Chapman and Meyer 1986). The PFI is given by

\[ \text{PFI} = C_p A_p (3 \mu + 2) \mu (1/\mu - a), \]

where \( C_p = 0.019, A_p \) is the published calcium plage area in millionths of the solar hemisphere, and the parameter \( a = 0.8 \) has been determined from facular contrasts at the center of the solar disk (Lawrence, Chapman, and Herzog 1988). The value of \( C_p \) comes from monochromatic photometry although the functional form of PFI is based on a gray atmosphere. If we apply the 10% correction to the CFDT sunspot deficit as discussed in the comparison to the resolution improvement from CFDT SHG data, we find a mean difference between the ACIRM irradiance fluctuations and the CFDT full-disk sunspot deficits of 800 millionths. We find that this mean value of the difference can be accounted for by equation (3) with the values of the parameters cited above and with published plage areas from the Solar Geophysical Data Bulletin.

V. SUMMARY AND CONCLUSIONS

We have presented solar irradiance variations caused by sunspots measured by a new telescope and photometer system. This system, which is easy for students to use, is able to measure the sunspot component of irradiance variations with a precision of approximately \( \pm 10-20 \) millionths of the mean solar irradiance. We find that the sunspot areas from the CFDT are highly correlated with areas published in the Solar Geophysical Data Bulletin, although the SGD areas appear systematically to be smaller by about 14%. When the CFDT areas are calibrated with the SHG areas, as discussed in § III, the SGD areas are smaller than those of the CFDT by about 22%. We find that the deficits measured by the CFDT are well correlated with the PSI values calculated using the digital sunspot areas and disk positions determined by the CFDT although the PSI gives an irradiance fluctuation somewhat greater than the photometrically determined deficit. The CFDT sunspot deficits determined for 1985 June, when compared to the SMM/ACRIM fluctuations, suggest a substantial irradiance contribution from faculae and active region plage.

We believe that an accurate determination of the sunspot signal in the fluctuations of solar irradiance can only be achieved by long term photometric observations of the kind described here.

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