# A PROGRAM OF PHOTOMETRIC MEASUREMENTS OF SOLAR IRRADIANCE FLUCTUATIONS FROM GROUND-BASED OBSERVATIONS

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## ABSTRACT

Photometric observations of the sun have been carried out at the San Fernando Observatory since early 1985. Since 1986, observations have been obtained at two wavelengths in order to separately measure the contributions of sunspots and bright facular to solar irradiance variations. We believe that the contributions of sunspots can be measured to an accuracy of about ± 30 ppm. The effect of faculae is much less certain, with uncertainties in the range of ± 300 ppm. The larger uncertainty for faculae reflects both the greater difficulty in measuring the facular area, due to their lower contrast compared to sunspots, and the greater uncertainty in their contrast variation with viewing angle on the solar disk. Recent results from two separate photometric telescopes will be compared with bolometric observations from the ACRIM that was on board the Solar Max satellite.

## INTRODUCTION

High precision, two-dimensional photometric mapping of solar active regions was begun in 1982, partly in response to the accurate, space-based measurements of the total solar irradiance. In the summer of 1982, observations were carried out using a single linear diode array with the San Fernando Observatory 61/28 cm vacuum telescopes and vacuum spectroheliograph. Beginning in 1983, two linear diode arrays were operated, obtaining simultaneous photometric images in nearby wavelengths. These data have a pixel spacing of 0.94 arc-sec. Normally, data were obtained only for 512 x 512 pixel regions centered on specific active regions or predicted returns of active regions (Lawrence et al[1]). Occasionally, the disk of the sun was scanned in four swaths, each having a height of 512 pixels and a width of 2200. Only a small part of the north and south poles were not scanned (Lawrence and Chapman[2]).

To reduce the volume of data, to greatly simplify the observational procedure, and to make the observations less prone to bad weather, two new telescope/photometer systems were developed in 1984-1986. One of these systems, called the Cartesian Full Disk Telescope (CFDT) is designed to scan the full solar disk in about three minutes with a pixel spacing of 5 arc-sec. The CFDT produces a photometric image of the sun in one of several wavelengths with each pixel digitized to an accuracy of 12 bits. Since the sun's image is scanned by the earth's rotation, the image has virtually no distortion. The other photometric system is the Rotating Full Disk Photometer (RFDP). This system has a telescope with an aperture of 7.5 cm and a photometer that rotates about the disk center, producing an image with the disk center at pixel 1 and the solar limb near pixel 420. Due to limits on data rate, the data are averaged in real-time, 2 x 2, and written on magnetic tape. The effective pixel spacing is about 5 arc-sec. The time to acquire a complete image is approximately 2½ minutes. These two photometric instruments are complementary to each other in that they obtain photometric solar images that are, on the one hand undistorted near the disk center and, on the other hand, undistorted near the solar limb. These photometric systems are used by undergraduate and graduate students on a daily basis. In addition, full disk photographs are obtained, as a back-up, in H$\alpha$ and in a 3840Å filter. In this report, we describe some of the preliminary results of these observations and some plans for the near future.

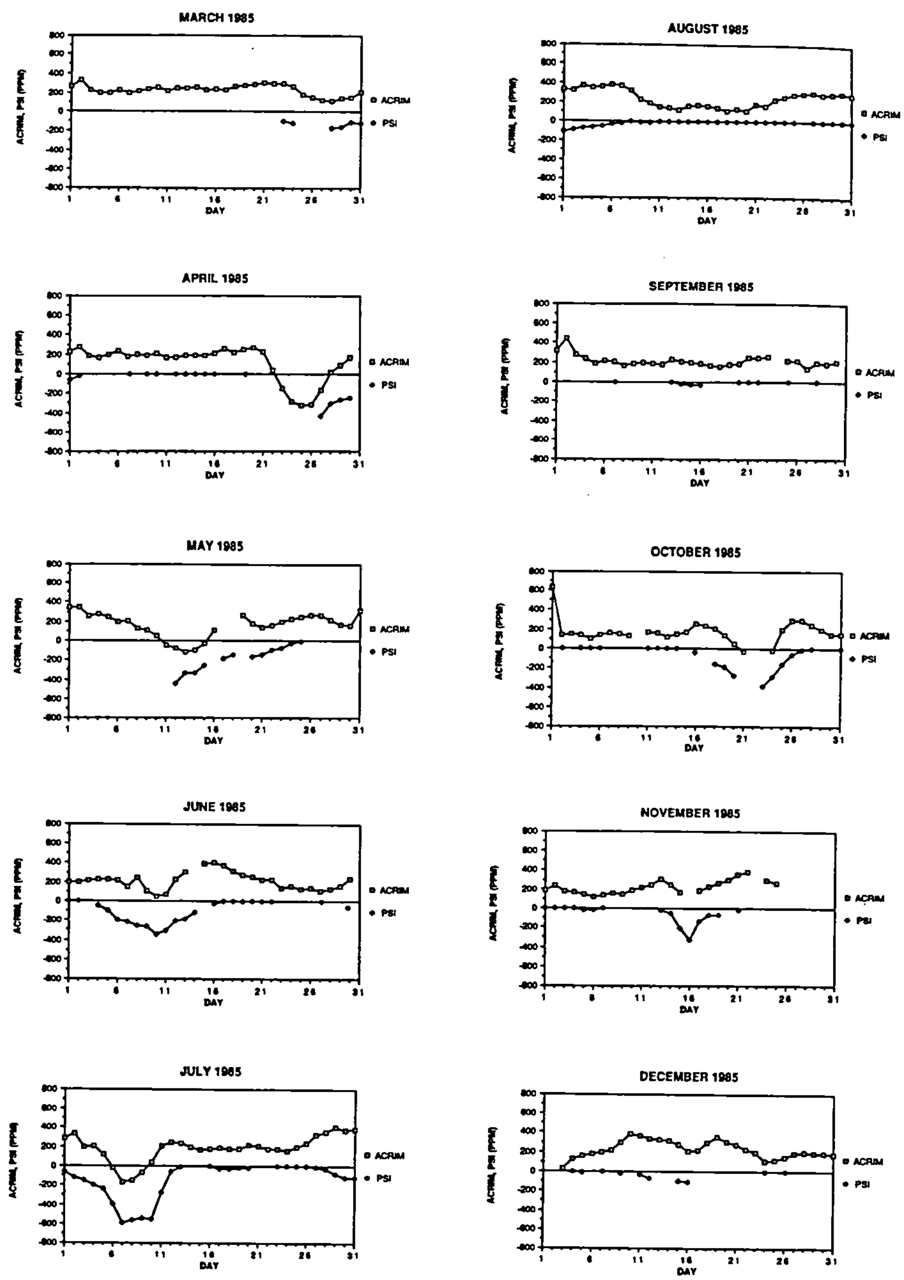


Fig. 1 Digital PSI determined from the CFDT during 1985 compared to the fluctuation in the ACRIM signal relative to 1367 W/m$^2$. The time difference between the ACRIM signal and the San Fernando Observatory PSI has not been removed.

## SYNOPTIC FULL-DISK PHOTOMETRY

The CFDT began routine observations using a red filter in the spring of 1985 (Chapman et al.[3]). Analysis of these data has resulted in a determination of sunspot irradiance deficits and areas (in units of millionths of a hemisphere) for 1985 (Chapman and Davis[4] and Davis[5]). Beginning in 1986, an intermediate band filter at 3920Å was added. This filter, with a bandpass of 100Å, was intended to detect faculae. In 1988, a 10Å narrow band filter was added at a wavelength of 3934Å. This filter was intended to detect faculae more effectively than the 3920Å filter. We present here some results for part of the summer of 1988, as well as for most of the year 1985.

The RFDP was constructed and installed with the help of a NASA grant during 1984 and 1985. This photometer is fed by a 15 cm aperture achromat, stopped down to 7.5 cm, with a focal length of 229 cm. The data are obtained at a wavelength of 5319Å with a bandpass of 100Å. The pointing of the RFDP is controlled by a separate guider. Because of the limitations in data storage rate, pixels are averaged, 2 x 2, to 5 arc-sec, before being written to magnetic tape. Thus, each image corresponds to 1320 records, each with a length of 256 pixels.

At the end of each record of a photometric image, an accurate measurement of the sky transparency is recorded. These data can be used later to remove the effect of changes in sky transparency that occur during the solar observation. These "exposure meter" observations are obtained at a wavelength of 0.53μm.

## RECENT RESULTS

The observations from the CFDT for the year 1985 have been processed (Chapman and Davis[4] and Davis[5]). The Photometric Sunspot Index (PSI) is compared with fluctuations in the ACRIM signal in Fig. 1. The Photometric Sunspot Index is defined in Chapman and Meyer,[6] based on the form first discussed in Willson et al.[7] In our work, the corrected sunspot area is determined from the CFDT red image after removing the quiet sun limb darkening. This results in a smoothed contrast map that is searched for pixels that have a negative contrast that exceeds -8.5 percent. This criterion was

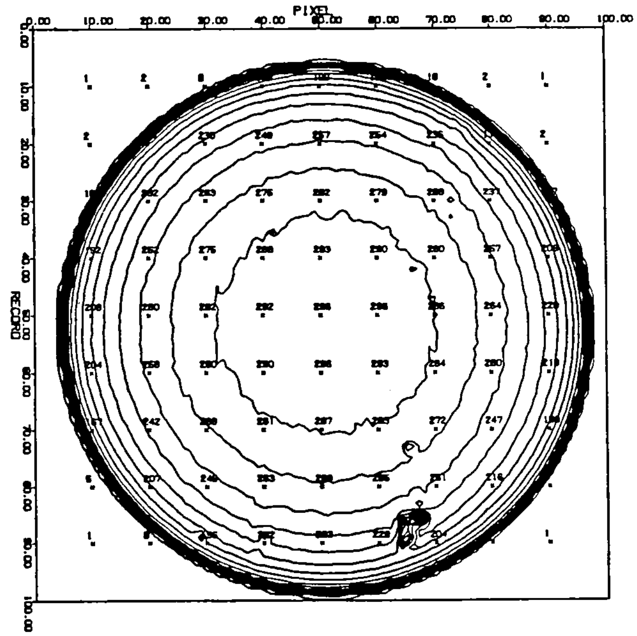


Fig. 2 A contour plot of the whole solar disk from the CFDT for 27 June 1988. Each pixel in this plot represents 20 arc-sec.

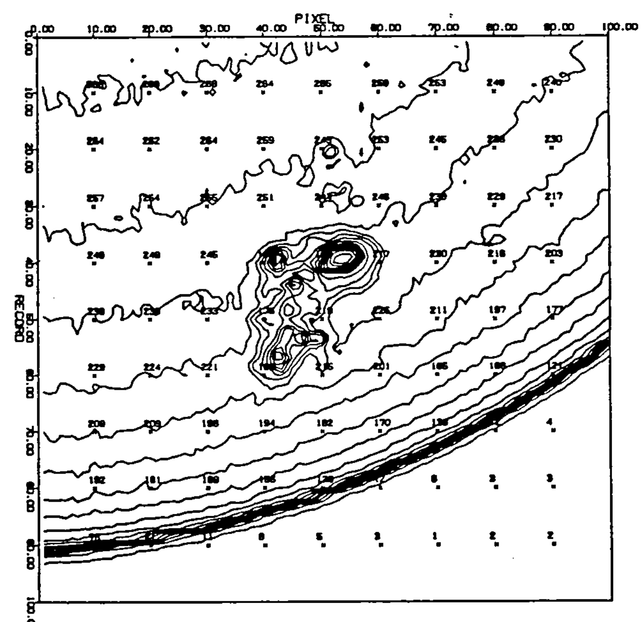


Fig. 3 A contour plot of the active region at the SE limb, from the image in Fig. 2, but at the full resolution, 5 arc-sec per pixel of the CFDT.

determined by an examination of several sunspot images obtained with one arc-sec pixels using the 28 cm vacuum telescope and vacuum spectroheliograph. This same criterion is used to define a sunspot in the higher resolution RFDP data. We will see that there is a systematically smaller sunspot area from CFDT data compared with RFDP data that is probably due to the lower spatial resolution of the CFDT optical system (Chapman et al.[3] and Herzog et al.[8]). A small adjustment in the contrast criterion for CFDT sunspots can bring these two systems into very close agreement. Corrected sunspot areas can also be determined from the CFDT K-line images by changing the sunspot contrast criterion from -8.5% to -9.6% (Wilson[9,10]).

The Rotating Full Disk Photometer (RFDP) has a 7.5 cm objective and a 2.5 arc-sec pixel at the detector. Although the data are co-added, 2 x 2, in order to reduce the data rate, one expects to have larger sunspot signals from this system. This appears to be the case.

The appearance of the sun as seen by these two instruments is shown in Figs. 2-3. Fig. 2 shows the full disk seen by the CFDT at 6723Å. In order to plot the full disk on one plot, the data have been averaged 4 x 4. Fig. 3 shows a sunspot group from the same day at the full resolution of the CFDT, approximately 5 arc-sec per pixel. Fig. 4 shows the same sunspot group as seen by the RFDP at a scale of 5 arc-sec per pixel. These data are most useful in studying active regions near the limb. An increasing geometric distortion that increases toward the disk center can be removed. Except for some distortion, the sunspot images in Figs. 3 and 4 look quite similar.

Fig. 5 shows the relation of corrected sunspot areas, in parts per million of the solar hemisphere, from the RFDP compared with sunspot areas published in the Solar Geophysical Bulletin. These data cover the time period from 9 May to 22 August 1988 (Herzog et al.[8]). Although the correlation coefficient is high, r = 0.97, there is a significant difference from unity in the slope of the relation. The published areas appear to underestimate the corrected area of sunspots, as measured by the RFDP, by approximately 30 ± 2 percent (one sigma error).

The effects of bright faculae are determined by searching a "flattened" K-line image for pixels

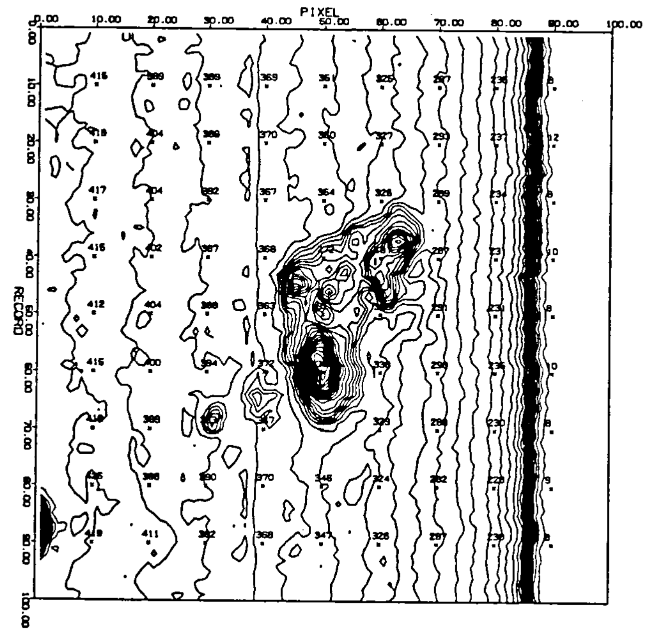


Fig. 4 A contour plot of the active region shown in Fig. 3 from the RFDP. The pixel size is nearly the same as for the CFDT.

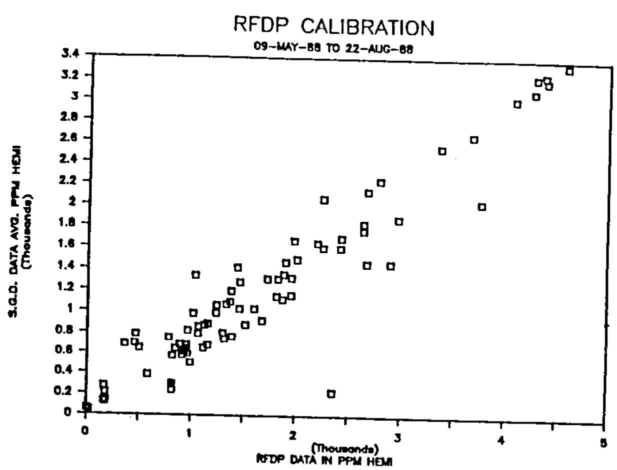


Fig. 5 A plot of corrected sunspot areas, in ppm, of the solar hemisphere determined from the RFDP and compared with those published in the SGD Bulletin. The values in the SGD represent averages from each station reporting.

brighter than some criterion, usually 4% (about 2.5 sigma), and calculating a Photometric Facular Index (PFI), a measure of the irradiance excess caused by faculae.

The standard deviation in the Photometric Facular Index has been determined for several days when from 3 to 6 images have been obtained in the K-line filter. An analysis of these data suggests that the standard deviation in the PFI is about 200 millionths of the mean solar irradiance. If the mean solar irradiance is approximately 1367 W/m$^2$, then this photometric uncertainty corresponds to 0.27 W/m$^2$. This standard deviation includes noise from the possible evolution of active regions.

A preliminary analysis for 25 days between 10 June and 23 July 1988 shows that the CFDT and the RFDP corrected sunspot areas are highly correlated with a correlation coefficient of 0.990. The slope is not unity and it appears that the larger aperture RFDP obtains sunspot areas that are 9 percent larger than those from the CFDT. There may be a 200 millionth zero point offset, although its value is not statistically significant (1 sigma). The analysis of more data will help to clarify this point (Herzog et al.[8]).

An analysis of ACRIM data and sunspot and facular photometry for a two-week period in June and July of 1988 shows that ground-based photometry can correlate with the spacecraft data with a multiple correlation coefficient of about 0.98 for 21 data points. The quiet sun irradiance, determined from these regressions, is approximately 1367.0 W/m$^2$. The details will be contained in a forthcoming paper (Chapman et al.[11]). The largest source of systematic noise appears to be the time difference between the ground-based data and the daily values of irradiance available from the ACRIM group. A good fit to the ACRIM data is obtained using the Photometric Irradiance Fluctuation (PIF) (see Chapman et al.[3] for further discussion of the PIF) to represent the sunspot signal but with a coefficient of 1.062. Basically, the PIF measures the photometric deficit of sunspot pixels relative to the mean solar irradiance. The facular signal used was based on the function given in Schatten et al.,[12] although the function given by Foukal[13] gave nearly as good a fit. The Schatten et al.-function required a coefficient of 2.035. The squared partial regression coefficients for the CFDT signal and the Schatten et al.-signal were 0.96 and 0.69, respectively.

In summary, the ground-based program described here appears to be able to match accurate space-based radiometry to within approximately 0.2 W/m$^2$, or in the range of 100 to 200 parts per million, at least for the two-week interval described above. With further refinements in the image processing and improved averaging of the space-based data, this noise can be further reduced. Extending such an analysis over a longer time base should lead to some interesting improvements in our understanding of the sun.

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