SERI/TP-215-1509
UC Category: 62e

A High-Intensity Flux Mapper for Concentrating Solar Collectors

T. W. Cannon
H. W. Gaul

February 1982

Presented at the Solar Thermal Test Facilities Users' Association Workshop on High Intensity Solar Flux Measuring Techniques
Albuquerque, New Mexico
26 October 1981

Prepared Under Task No. 1093.00
WPA No. 116-81

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $ 4.00

NOTICE

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T. W. Cannon
Solar Energy Research Institute
1617 Cole Blvd.
Golden, Colorado 80401
U.S.A.

H. W. Gaul*
Solar Innovations, Inc.
P.O. Box 1175
Boulder, Colorado 80306
U.S.A.

Introduction

A high-intensity flux mapper has been developed at the Solar Energy Research Institute for use at its ACRES (Advanced Component Research) facility. This instrument provides an accurate description of the two-dimensional distribution of flux at the focal plane of concentrating solar collectors where the flux density may be as high as 1000 suns.

During the concept phase, a constraint was placed upon the system to gather the data within a relatively short time span (<1 sec.). This constraint existed because the collector tracking system would update the collector's position on roughly a 15 second period; motion of the focussed image between updates precluded a long duration scan by the flux mapper. Several design concepts were considered, including the scanning calorimeter bar employed at the Sandia Central Receiver Test Facility (CRTF) and the Georgia Tech Advanced Components Test Facility. The scanning bar did not meet the time constraints for data acquisition.

*Formerly with the Solar Energy Research Institute

In addition to calorimeters, thermopiles and light sensing diode arrays with and without fiberoptic coupling were considered. These were rejected because of the high cost and excessive heating at the focus. Finally, a video system with ceramic scatter plate target was selected as the best alternative, meeting the criteria of rapid scan and sufficiently accurate measurements for dish alignment, testing and evaluation. A similar system is used at the CRTF for evaluation of heliostats as described by Thalhammer[1] and Phipps[2]; however, their Beam Characterization System (BCS) is designed for flux levels on the order of only ten suns.

Description

The flux mapper consists of a ceramic scatter plate, video camera with silicon diode array image tube (vidicon), 75 mm focal-length lens with appropriate filters, video frame store, television monitors, disk drive, magnetic tape drive and minicomputer. The camera and scatter plate are shown installed on an Omnium-G parabolic solar collector, Fig. 1, at the ACRES facility.

A ten-inch diameter alumina plate, located at the parabolic collector's focus, provided a light scattering surface for visualization of the focussed flux[+]. Optical properties of the plate were measured by Masterson and Bohn[3]. It was determined to have a solar reflectance of 77 percent and standard deviation from perfect cosine (Lambertain) scattering of 0.86 percent over the angles of interest. The video camera, positioned near the vertex of the collector, about four meters from the scatter plate, is focussed on the plate. To obtain a non-saturated video signal, two neutral density dye

[+]The alumina disk was provided by Coors Porcelain Company and is a developmental product carying company code PS441. It is a very porous material that has extremely high tolerance to thermal shock.

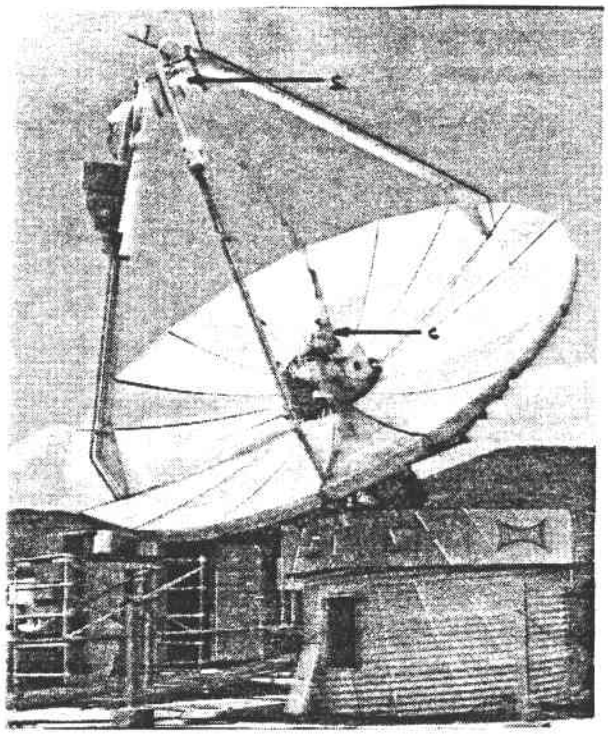

Fig. 1 Omnium-G point focus collector with scatter plate S and video camera C in position for flux mapping

filters, ND3 and ND4, were attached to the camera's lens by a special filter holder. The camera was usually mounted in an environmental chamber which provided heating or ventilation as needed. A Cohu 4415 camera with RCA 4532 silicon diode array vidicon was used. This type of vidicon was chosen because its target is relatively burn proof and the vidicon has a linear response to light level of over three orders magnitude. On the other hand, the camera electronics, as manufactured, did not have linear response, but contained automatic gain and clipping circuits used to optimize picture appearance. Modifications made at SERI included disabling black clipping, white clipping, automatic gain control and gamma control functions. In addition, composit video signal voltages were adjusted to give a useable range of almost 1600 mV, with linear response to light level over two orders of magnitude.

The data acquisition and processing components are shown schematically in Fig 2. The video frame store is a Colorado Video model 274A. It contains analog-to-digital circuitry to digitize a video field in real time (16.7 msec per field) on command from the computer. Data is stored within the unit's 256 x 256 byte memory for processing by the computer or for storage on the magnetic tape or disk for future processing by the LSI-11 or CDC Cyber 7600 mainframe computer.

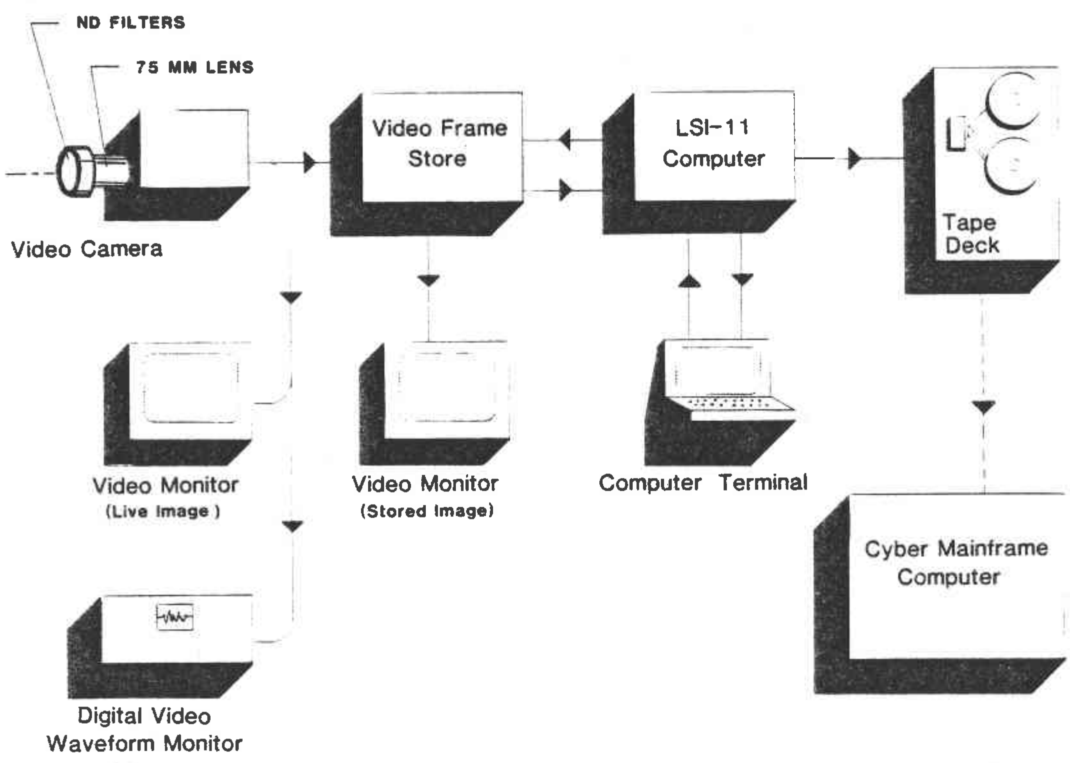

Fig. 2 Schematic of flux mapper data acquisition system.

The LSI-11 minicomputer is used to control the data acquisition and storage as well as to generate contours of equal intensity, determine total and average flux, to locate centroids of user defined areas and to expand the dynamic range of the image up to the total (256_{10}) word size of the frame store's memory. Data from the frame store can be transferred to the LSI-11 computer's memory in about eight seconds. The digital video waveform monitor is used to set video levels for calibration of the frame store and for monitoring the signal to assure that the video level does not reach saturation during data acquisition.

Dye filters were used because metallized filters were found to have objectionable internal reflections. The combination of ND3 and ND4 filters was found necessary because of the high flux levels.

Calibration

The best approach to calibration is to have a radiometer located somewhere within the focussed spot being viewed by the camera. A radiometer reading is taken simultaneously with each video frame. This calibration point, together with the previously measured system response, determines calibration for the entire flux map. This technique is used with the Sandia BCS.

Lacking a radiometer for measuring high flux levels, calibration was made by focussing the sun directly onto the vidicon target. Since the sun is about two-orders of magnitude brighter than the brightest portion of the scatter plate image, it was necessary to add an additional ND1 filter for the calibration. The camera was mounted, together with a normal incidence pyrheliometer (NIP), on an Eppley tracker for tracking the sun during the calibration.

The radiant exitance, M_e, of the sun is 6.41×10^3 watts cm^{-2} corresponding to an effective black-body temperature of 5800K.[4] An equivalent observed exitance, M_{eq}, can be determined as $M_{eq} = \frac{E_e}{E_{eo}} M_e$, where E_e is the solar irradiance measured at the camera's location by the NIP, E_{eo} is the extraterrestrial (AMO) irradiance[4], 0.1388 watts cm^{-2}, giving $M_{eq} = 4.62 \times 10^4 \times E_o$ watts cm^{-2} as the exitance observed by the camera. The camera's response

Z(in digitized brightness levels, 0-255) to exitance M_{eq} was determined from solar irradiance measurements to be $Z = a\ M_{eq} + b$, where $a = 3.57 \times 10^{-2}$ cm^2 $watt^{-1}$ and b = 15, the Z level with no radiation present.+

With corrections for target reflectivity (77 percent), camera aperture, ND filter factor, and frame-store gain differences between calibration and experimental cases, the final response of the camera is

$$Z = 2.74 \times E + 15$$

where E is the irradiance at the scatter plate in watts cm^{-2}.

Example Flux Map

Measurements of the focussed flux were made on the south Omnium-G collector on 30 September 1981. Fig. 3a shows the focussed spot and Fig. 3b a flux map obtained from this data. Total spatially-integrated flux within the contoured area is about 6.6 kW, giving a total optical efficiency of about 31 percent, based on theoretical total collected energy by the 6-meter diameter dish at the concurrently measured direct normal irradiance of 755 watts m^{-2}.

The efficiency is not representative of the performance of a normal Omnium-G as the petals were not properly alligned and the (Alzac) reflective surfaces had been allowed to badly oxidize; effects of the misalignment are easily visualized from the assymetry of the contours in Fig. 3b. Prior measurements using calorimetric and heat of fusion methods gave optical efficiencies from 21 to 37 percent over a 10 cm receiver aperture depending on

+The calibration was performed under clear sky conditions using a 5.7° field-of-view pyrheliometer. Z values corresponding to the pyrheliometer readings are averaged over a square area just circumscribed by the sun's image. Because of limb darkening and atmospheric effects, the entire solar disk should be used.

the alignment and condition of the petals, as reported by Bohn and Gaul[5] and Bohn[6].

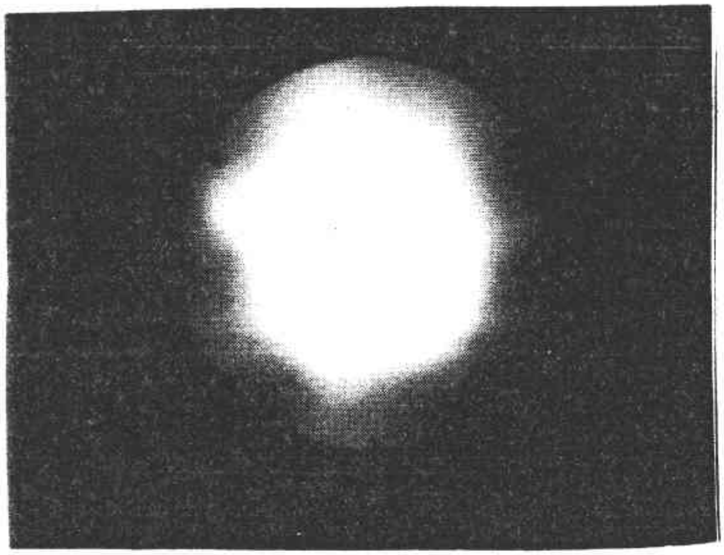

Fig. 3a. Video image of focussed energy from Omnium-G collector. Scatter plate is 10 inches diameter

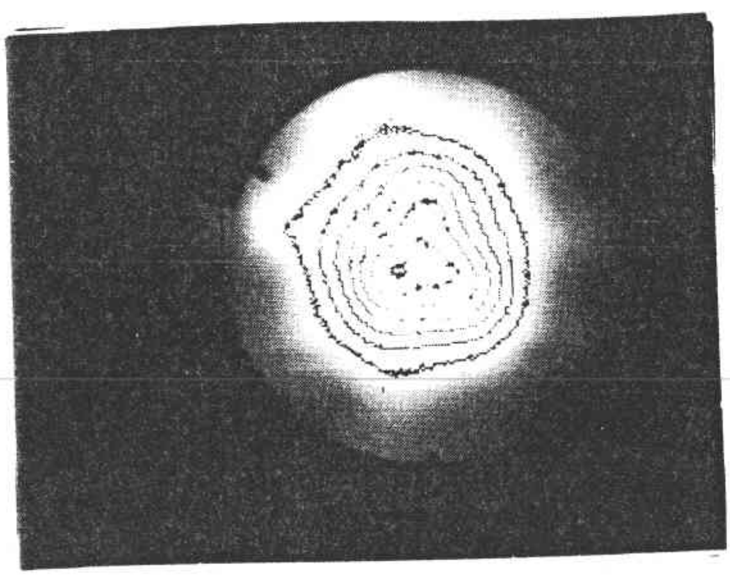

Fig. 3b. Contours of 2.5, 7.5, 12.5, 17.5, 22.5, 27.5, and 32.5 watts cm^{-2}. Contour lines are generated by LSI-11 computer program and superimposed by the computer on the image of Fig. 3a.

Further Comments and Conclusions

Geometric distortion of the camera system was measured by taking images of a black aluminum plate having holes of very uniform diameter drilled on precise centers in a two-dimensional matrix. Computer analysis of the images of these holes shows ±5 percent random geometrical error.

The light-intensity calibration is estimated to be accurate to about ±7 percent using the solar calibration method. Errors here are due to pyrheliometer error (±1 percent), random scatter in the camera calibration data, spectral mismatch between pyrheliometer and silicon vidicon and the ND1 filter calibration. Use of an accurate radiometer taking simultaneous readings of irradiance at the scatter plate for real-time calibration would minimize these errors.

Drift in the response of the video frame store circuitry has been noted. Care must be taken to minimize drift error by measuring and recording total dark field (lens cap on) and reference bright field (camera looking into integrating sphere with consistent brightness) before and after each run. These black and the white files of video data are used to correct for slope and offset of each pixel's response.

Absolute accuracy of mechanically scanning radiometric instruments scanning the flux field may be higher than that of the present flux mapper but they are more difficult to operate, requiring considerable flexible wiring and coolant piping; some of their accuracy advantage is lost if the incident irradiance changes or if the focussed pattern moves during the scan. Furthermore, the components of an expensive scanning system or detector arrays at the focus may be subject to thermal damage, especially if loss of coolant occurs. The present method is fast, relatively inexpensive and easy to facilitate, requiring only the mounting of the scatter plate and camera on the collector system. Operation is then largely automatic, being handled by the control computer. By storing a frame of data, changing petal alignment, and then comparing the successive frames, effects of allignment changes are easily evaluated; the collector may be easily fine tuned for optimum efficiency for a given receiver aperture. The flux pattern information is easily assimulated from the video images; this information is readily enhanced by expanding the dynamic range of the images and/or superimposing contour lines on the image. Numerical analysis of data on any portion or portions of the flux field is obtained by computer processing of the stored images.

In addition to the configuration described above, the flux mapper has been configured with a wide angle lens system to map the diffuse component of luminance from the entire sky, as described by Cannon and Dwyer.[7] The wide angle configuration should make the system applicable to radiant flux mapping of collector troughs.

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Acknowledgements

Our thanks to Mr. David King and others at Sandia CRTF for providing information on the Beam Characterization System (BCS) which was useful in early decisions on approach and hardware; to Drs. Keith Masterson and Mark Bohn and Mr. Mike Lang for helpful interaction and for obtaining and calibrating the scatter plate; to Mr. David Jack of Coors Porcelain Co. for providing the alumina plate; to Mr. John Houkal and Ms. Nancy Birkenheuer for writing the computer programs; to Mr. Harlan Weber and Mr. Karl Danninger for technical assistance and to Ms. Judi Rich for typing this manuscript. This program was supported under DOE Contract EG-77-C-01-4042.