Precision Insolation Measurement Under Field Conditions

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A solar energy instrumentation project was started at Goldstone to support the DSN energy conservation project. The objective is to help provide an adequate technological foundation for supporting a solar energy based facilities design at Goldstone. The lack of historical records of insolation for the Goldstone area required that a program of instrumentation development and solar data recording be started as quickly as possible. Prior NASA-supported work at the Jet Propulsion Laboratory had resulted in the development of a primary absolute cavity radiometer (PACRAD), which was recently accepted as an international standard of irradiance. This report discusses the development of an all-weather, field-worthy solar radiometer based on the PACRAD, and describes its calibration stability over a two-year period in the field.

I. Introduction

A solar energy instrumentation project was started at Goldstone to support the DSN energy conservation project. The objective is to help provide an adequate technological foundation for supporting a solar energy based facilities design at Goldstone. The lack of accurate historical records of insolation (Ref. 1) for the Goldstone area required that a program of instrumentation development and solar data recording be started as quickly as possible.

At the time the solar energy instrumentation project (which has been described elsewhere (Refs. 2 and 3) was started in 1973, no high-precision, field-worthy instrument was available for unattended insolation survey work. Prior NASA-supported work under a different program at the Jet Propulsion Laboratory (JPL) had resulted in the development of a primary absolute cavity radiometer (PACRAD), which was recently accepted as an international standard of irradiance. This report discusses the development of an all-weather, field-worthy solar radiometer based on the PACRAD, and describes its calibration stability over a two-year period in the field. This work was completed by 1 October 1976.

II. An Absolute Calibration Standard

In the mid-1960s, an anomaly in the equilibrium temperature of spacecraft in flight, from that which was predicted from solar simulation testing, encouraged instrumentation engineers at JPL to investigate the validity of irradiance measurements with respect to the absolute scale of energy. Instruments that were used to measure synthesized solar irradiance were scaled to agree with the International Pyrheliometric Scale (I.P.S.). This scale was recommended by the International Radiation Conference in Davos, Switzerland, in 1956 and referred to the Ångstrom Pyrheliometer maintained at the World Radiation Center in Davos. Although the Ångstrom instrument was originally intended to represent the absolute scale of units, it has been used only in a relative reference capacity to achieve agreement of radiometric measurements made throughout the world.

In the later 1960s a standard absolute cavity radiometer was developed for solar simulated irradiance measurement (Ref. 4). This instrument is a primary standard since its calibration depends only on dimensions, arrangement of components, and electrical measurements. Sensor absorptivity was enhanced by using a cavity receptor that greatly decreased the measurement uncertainty over previously built instruments. Proof of measurement accuracy has been ascertained experimentally by its use in the determination of the Stephan-Boltzmann constant, and verified by the accuracy with which spacecraft equilibrium temperatures may now be determined prior to flight (Ref. 4).

Modification of the standard absolute cavity radiometer with a view limiting aperture provided an instrument for measuring direct normal incidence solar irradiance (Ref. 5). This instrument, the primary absolute cavity radiometer (PACRAD) was compared with the Ångstrom I.P.S. in Davos and found to give readings in the order of two percent higher. The same instrument, the PACRAD III, was used in International Pyrheliometric Comparisons (I.P.C.) at Davos in 1970 and 1975 (Ref. 6). Because of its extreme stability and the agreement with similar cavity type instruments, it was recommended and accepted as an international reference for the absolute scale of units. The PACRAD has a windowless black cavity receptor mounted in a massive heatsink, and has equal sensitivity to ultraviolet, visible, and infrared radiation. The incoming radiation is absorbed and converted into heat that flows through a metallic thermal resistor to the massive heatsink to produce a temperature difference of about one Kelvin. This difference is measured by a thermopile. A totally enclosed electric heater winding serves as a source of cavity heating accurately equivalent to radiation heating, and provides a built-in means of calibration. There is no temperature to control or measure. By measuring the voltage and current to the heater, a known amount of equivalent power is applied to the cavity. Thermopile output is measured to give an accurate calibration of the radiometer. The design, which includes a compensating cavity and thermal resistor, minimizes all unwanted heat transfers. The view-limiting aperture is normally set to 5-deg total angle, but can be opened to a maximum of 15-deg total angle or greater, depending on the desired use. The PACRAD has been described in detail elsewhere (Ref. 5), and is shown in Fig. 1.

III. An All-Weather, Field-Worthy Radiometer

The PACRAD III, and other copies of it that have recently been built, are primary standards of reference. They are used in intercomparisons for absolute calibrations and are not suitable for extended field operations. Further instrument development work began in 1973 in response to the requirements of a solar energy based facility design study at the Goldstone Deep Space Communications Complex (GDSCC), as described above (Refs. 3 and 7). The lack of precision historical insolation data clearly pointed to the need for an accurate and stable field instrument. The result of this instrument research was the development of an all-weather, field-worthy version of the PACRAD. This field instrument, designated the Kendall Radiometer System Mark 3, is identical to the PACRAD except for a modification to ensure all-weather operation.

The Mark 3 radiometer has a flat quartz window to seal the cavity aperture and is dry nitrogen filled to avoid dew formation on the glass. The instrument is mounted on a continuously tracking mount and the view angle has been opened to 15 deg to permit reasonable tracking errors. The quartz window adds approximately 7-percent attenuation that is not present in the PACRAD, but this has been compensated for. Two Mark 3 radiometers have been in service side by side at GDSCC for over two years and are continuing to provide data that are within plus and minus one percent of the absolute value. The Mark 3 radiometers, both with and without their quartz windows, were extensively calibrated against the PACRAD II prior to installation in the field. Figures 2 and 3 are photographs of the Kendall Radiometer System Mark 3.

IV. Stability Analysis of the Mark 3 Systems

Two Mark 3 systems and several commercial pyranometers were installed at GDSCC in mid-1974. The objectives are to initiate and operate a solar (and meteorological, including wind) measurement program at GDSCC using high-precision instrumentation and to archive the data on magnetic tape (Ref. 3). Further objectives are to combine these data into a mathematical model of solar energy for the GDSCC (Mojave Desert) area (Ref. 7), and to test the long-term stability and accuracy of the Kendall Radiometer System Mark 3.

Normal incidence pyrheliometer data from the Mark 3 systems have been collected on magnetic tape for approximately two years. During this time the Mark 3s were operated continuously and were subjected to ambient temperatures ranging from $-7.5^\circ C$ to $48^\circ C$, and rain, snow, wind, and dust. Declination settings were manually adjusted approximately once per week, at which times the quartz windows were cleaned, if necessary.

On 28 April 1976 one of the GDSCC Mark 3 systems (serial number 6) was taken to the Table Mountain (TM) facility for calibration against an absolute standard. The TM facility has been used since 1923 as an optical calibration and operational site because of its high altitude and stable and clear atmosphere. The absolute reference standard was a commercially built instrument* equivalent to the PACRAD. The outputs from the Mark 3 serial number 6 and the absolute instrument were fed into an automatic data acquisition system that recorded one simultaneous data set every 30 seconds. Several data sets of measurements and calibrations, of varying lengths up to 20 minutes, were recorded around solar noon. Zero calibration runs were made by covering the instruments with shielded black bodies, and the data system was calibrated by electrically short-circuiting the output terminals of the instruments. The details of the calibration method have been described elsewhere (Ref. 5). Data from the initial settings show that the two instruments' outputs differ by less than 0.5 percent. The Mark 3 system recorded the higher output. This might be explained by the differing view angles of the two instruments – 15 deg and 5 deg. The Mark 3's 15-deg view angle may have detected some additional circumsolar radiation that was not in the 5-deg view angle. Circumsolar radiation was not separately measured.

After the calibrations at the TM station were complete, the calibration factor of the Mark 3 serial number 6 was adjusted to coincide with the absolute instrument. It was then returned to the GDSCC station, where it agreed with the second Mark 3 (serial number 1) within 0.5 percent.

On 16 September 1976 a standard calibration instrument, the PACRAD II, was taken to the GDSCC station. Both Mark 3 radiometers (serial numbers 1 and 6) were calibrated against the PACRAD in good weather using the same techniques as described above. The results of these intercomparisons showed that both Mark 3 instruments were within 0.5 percent of the PACRAD II.

*Built by Technical Measurements Inc., under license from the California Institute of Technology.

Both the absolute calibration standards used in these intercomparisons are continually compared with the PACRAD, which was present at Davos in 1970 and 1975; they are, therefore, both traceable to IPC IV (1975). Two Kendall Radiometer Systems Mark 3 have therefore demonstrated stability of calibration to 0.5 percent for over two years in the field.

V. Data Bank

The data from the two Mark 3 pyrheliometers and several commercial pyranometers, together with conventional ground-level meteorological data, are fed into a data acquisition system for recording on magnetic tape. One data set is recorded every two minutes, the value of the parameters being the average over two minutes. This data bank is therefore accumulating insolation records typical of the Mojave Desert area and calibrated to the International Standard.

VI. Conclusions

The Mark 3 Kendall Radiometer System is an all-weather insolation radiometer that has demonstrated extraordinary stability in severe environments over an extended period of time. The instrument may therefore be considered a transfer standard as well as a field-worthy radiometer of unique precision and accuracy. A simple improvement to the tracking system would eliminate the need for weekly manual declination adjustments. Experience with these instruments has shown that the 15-deg view angle could be reduced considerably without compromising the tracking accuracy.

References

1. Durrenberger, R. W., and Brazel, A. J., "Need for a Better Solar Radiation Data Base," *Science,* Vol. 193, 17 Sept. 1976, pp. 1154-1155.

2. Reid, M. S., Gardner, R. A., and Parham, O. B., "Goldstone Solar Energy Instrumentation Project: Description, Instrumentation, and Preliminary Results," in *The Deep Space Network Progress Report 42-26,* pp. 133-144, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1975.

3. Reid, M. S., and Gardner, R. A., "A Versatile Data Acquisition System for Goldstone," in *The Deep Space Network Progress Report 42-30,* pp. 132-143, Jet Propulsion Laboratory, Pasadena, Calif., Dec. 15, 1975.

4. Kendall, J. M., Sr., and Berdahl, C. M., "Two Black-body Radiometers of High Accuracy," *Applied Optics,* Vol. 9, No. 5, May 1970.

5. Kendall, J. M., Sr., *Primary Absolute Cavity Radiometer,* Technical Report 32-1396, Jet Propulsion Laboratory, Pasadena, Calif., July 1969.

6. Frolich, C., "The Third International Comparisons of Pyrheliometers and a Comparison of Radiometric Scales," *Solar Energy,* Vol. 14, No. 2, 1973, pp. 157-166.

7. Hamilton, C. L., and Reid, M. S., "Toward a Mathematical Model of Solar Radiation for Engineering Analysis of Solar Energy Systems," in *The Deep Space Network Progress Report 42-34,* pp. 147-151, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1976.

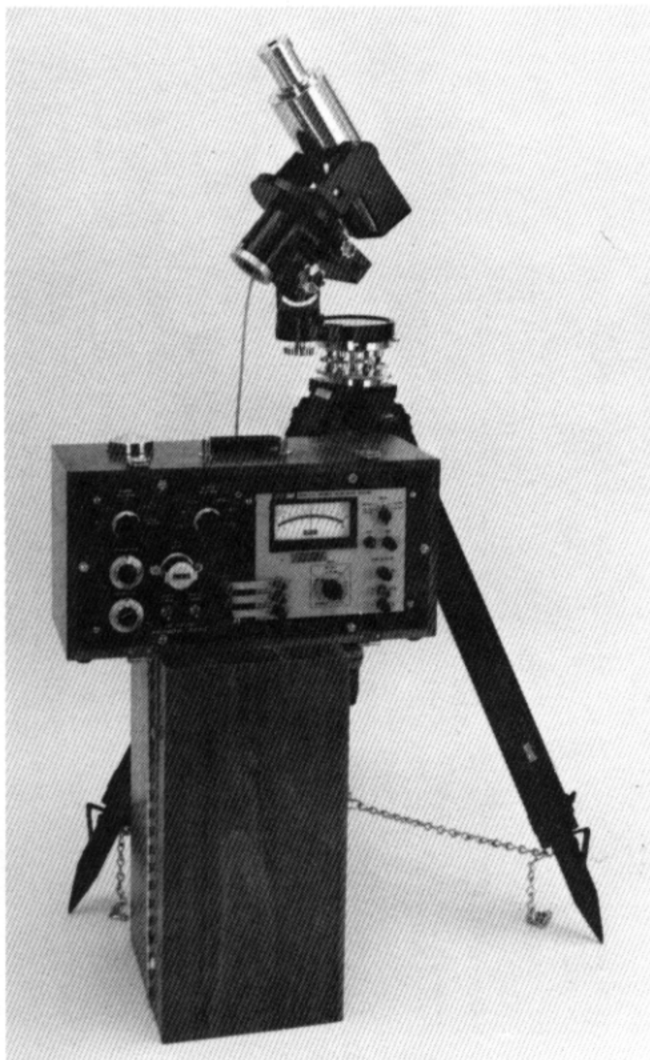

Fig. 1. Primary absolute cavity radiometer

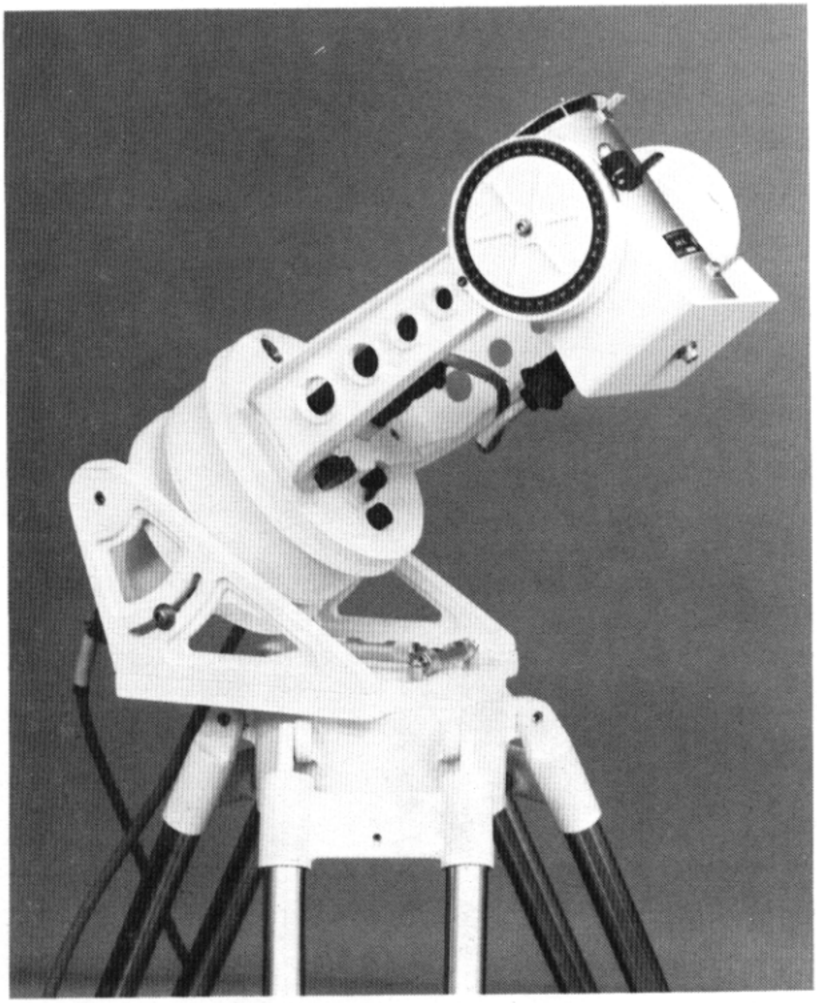

Fig. 2. Kendall Radiometer System Mark 3, closeup view

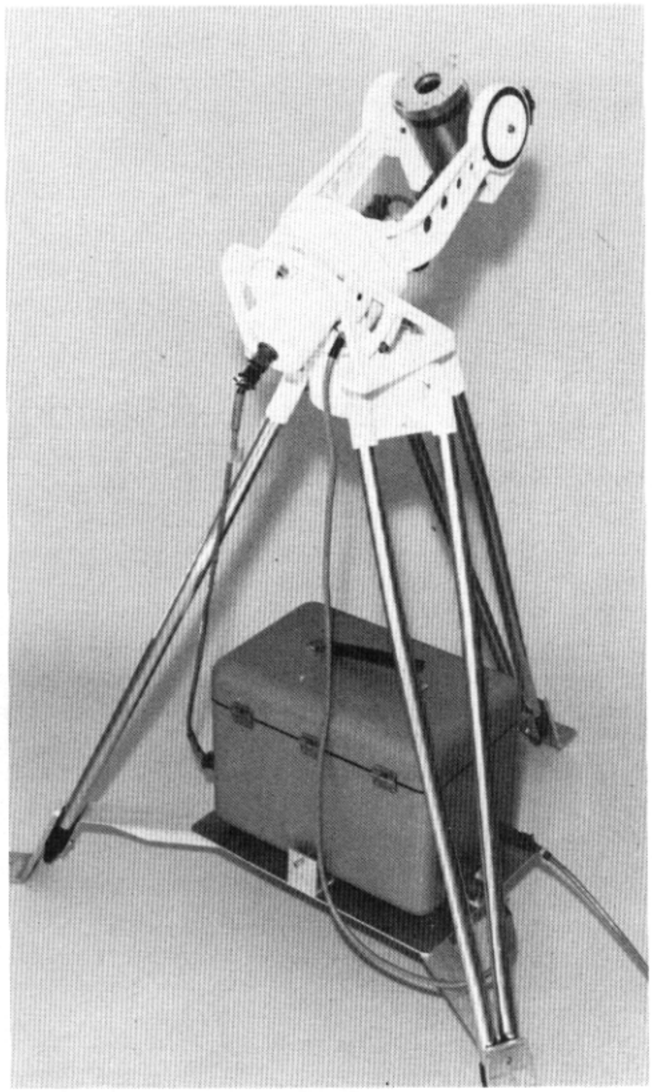

Fig. 3. Kendall Radiometer System Mark 3, overall view