The measurement of the solar constant from high altitude balloons

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ABSTRACT

The solar constant has been measured by the use of Eppley normal incidence pyrheliometers on three different days at 31 kilometers altitude. After correcting the readings for the remaining 1 % of the atmosphere, and the earth–sun distance, a value of 1.912 gm-cal cm^{-2} min^{-1} has been determined for the solar constant.

Introduction

The solar constant is the rate at which energy is received upon a unit surface normal to the sun's direction in free space at the earth's mean distance from the sun. Up until 1954 its value was considered to lie in the range from 1.89 gm-cal cm^{-2} min^{-1} to 1.95 gm-cal cm^{-2} min^{-1}. This range was the result of measurements made by various investigators at the Smithsonian Institution. Johnson (1954) suggested that on the basis of recent measurements of the spectral intensity of the solar irradiance in the visbile to near ultraviolet region the solar constant should be greater than 1.95 gm-cal cm^{-2} min^{-1} and arrived at a value of 2.00 gm-cal cm^{-2} min^{-1}. Stair & Johnston (1956) after measuring the spectral distribution of the solar irradiance arrived at a value of 2.05 gm-cal cm^{-2} min^{-1}. The major uncertainty in the measurement is due to the corrections that have to be made for the effect of the earth's atmosphere on the radiation. The technique for making the measurement is discussed in detail in the article by Johnson (1954). The major source of uncertainty can be reduced by making the measurement from high altitude where the corrections that have to be applied are small and the quantity of interest can be measured directly rather than through the circuitous technique required for a ground based measurement. While the measurements should ideally be made from a satellite or high altitude rocket it is possible to reduce the uncertainty considerably by making the measurement from high altitude balloons. This article describes the instrumentation developed for making such a measurement and presents the results obtained during three balloon flights.

Instrumentation

In the work recounted here two sorts of pyrheliometers were used. Three specimens of the Eppley 1965 Model of the Ångström compensation pyrheliometer were used as standards for calibrating the flight pyrheliometers in terms of the International (1956) Pyrheliometric Scale. Two of several specimens of a special Eppley Normal Incidence pyrheliometers were used for the flight measurements. These units were special in that the temperature of the instrument was stabilized by the circulation of liquid from a reservoir through the space between the double walls of the collimating tube and a coil in the thermopile housing. In addition for the precision sought in this measurement it was necessary to enclose the pyrheliometers in a thermal enclosure and the fluid was also circulated through coils on the walls of this enclosure. The requirement for the connection of the oriented thermal enclosure with the stationary reservoir and the desire to avoid the use of slip rings in the precise measurements of the pyrheliometer outputs ruled out the use of a pointing system similar to that previously described (Murcray, Murcray & Williams, 1967).

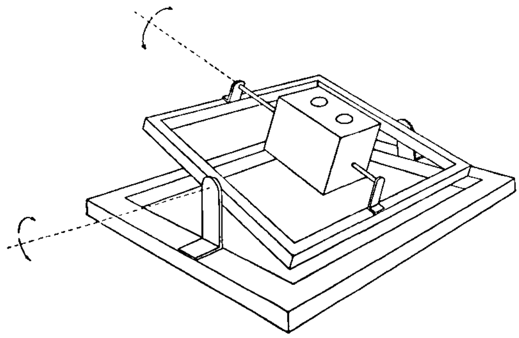

Fig. 1. A schematic illustration of the rotational axes of the pointing system.

Table 1. *Flight details*

	26.6.1967	23.1.1968	22.4.1968
Launch time	0601 MST	0910 MST	0630 MST
Ascent rate	200 m/min	250 m/min	250 m/min
Floating altitude	31 km	31 km	31 km
Termination time	0852 MST	1449 MST	1115 MST
Time at float	22 min	3 hrs 20 min	2 hrs 45 min
Ave. solar elevation	45°	37°	50°

A new system was designed which operated around the two axes shown in Fig. 1 rather than the azimuth and elevation axes. No slip rings are required since the rotation about either axis never exceeds 180°. The data generated by the pyrheliometers as well as the auxiliary information required for the interpretation of the results and monitoring the performance of the various units were recorded by means of an on-board digital magnetic tape recording system. The data were also telemetered by means of an FM/FM telemetry system, this system being used as a backup and also to monitor the overall system performance during the flight on a real time basis.

The outputs of the two pyrheliometers occur as voltages in the 6 millivolt range. The voltage must be amplified until it is in the range suitable for recording (~ 3 volts). In order to achieve the accuracy required it was necessary to accurately determine the voltage gain of the unit throughout the flight and to detect any drift in the zero level. This was accomplished by providing an accurate dc reference voltage. The input to the amplifier was switched from one pyrheliometer to a shorted position, then to the other pyrheliometer, and then to the reference voltage. The switching was accomplished by means of a Leeds & Northrup low noise switch and a geneva gear driven by a 400 cycle synchronous motor.

All units were designed to operate from either 28 vdc or 115 vac 400 cycle power. The 28 vdc was supplied by means of a silver zinc primary battery and the 400 cycle power was derived from the 28 vdc by means of transistorized converters. A gondola constructed of electrical conduit arranged to form a proper configuration was used to protect the various units. The biaxial control system and the pyrheliometers were further protected by shock mounting them to the gondola.

Flight details

The instrumentation was flown for the first time on June 26, 1967, after an extensive ground calibration program. It has been flown three times to date. All flights were launched from Holloman AFB, New Mexico. The balloon vehicle used on all flights was a 2 million ft^3 $1\frac{1}{2}$ mil stratofilm balloon constructed by Winzen Research. All flights were launched successfully and the instrumentation was recovered in excellent condition after each flight. The pertinent flight details for the three flights are given in Table 1.

Results

The instrumentation operated properly and data were obtained on all three flights. A summary of the solar irradiance values obtained with the two pyrheliometers on the three flights are given in Table 2. Examination of the data obtained on the June 26, 1967 flight indicated that as the balloon ascended the value of the solar irradiance as measured by one pyrheliometer (P1) started reading higher than the other unit when the balloon had reached an altitude of 15 km, and the discrepancy between the two units continued to increase as the balloon ascended. It was thought that this

Table 2. *Summary of solar irradiance values*

Date	Time (MST)	Solar elevation angle	Intensity P1	P2
Jun. 26 '67	0844	44.98	1.823	1.807
Jun. 26 '67	0851	46.03	1.826	1.807
Jan. 23 '68	1122	35.95	1.938	1.907
Jan. 23 '68	1200	37.40	1.949	1.908
Jan. 23 '68	1235	37.35	1.952	1.908
Apr. 26 '68	0832	38.63	1.829	1.836
Apr. 26 '68	0905	45.40	1.831	1.839
Apr. 26 '68	0940	52.38	1.834	1.841
Apr. 26 '68	1010	58.03	1.834	1.842

divergence was the result of a lack of ultraviolet response in the lower reading unit. In view of this the latter unit was disassembled and the thermopile was painted with an additional coat of Parsons black. On the second flight the same phenomenon occurred. However on this flight the longer time at float altitude was accompanied by a continual increase in solar irradiance as measured by pyrheliometer P1 in spite of the fact that solar elevation angle was decreasing during the latter part of the flight. Subsequent tests with the units revealed that this pyrheliometer had a slow pressure leak and the gradual decrease in pressure during the flight caused an increase in sensitivity of the unit. (The sensitivity of the units depends on the pressure inside the unit.) Thus on these two flights the lower readings obtained with pyrheliometer P2 are the correct readings. After these two flights a pressure transducer was incorporated into each unit so that the pressure could be monitored to make sure no leaks were present. The units were properly sealed during the April flight. During the April flight the pyrheliometer P1 consistently read about 0.4 % low. This appears to have been due to a slight obscuration on the window of this unit due to dust which got on the unit during launch.

The results presented in Table 2 give the solar irradience as measured during flight. Since the solar constant is defined as the solar irradiance at the mean earth sun distance the above irradiances have to be multiplied by an appropriate correction factor to correct them to the mean earth sun distance. The results obtained when this correction is applied are given in Table 3.

Residual corrections

Although the measurements are made above 99 % of the earth's atmosphere the residual 1 % still removes a significant fraction of the solar radiation. The major effect is in the wavelength region short of 3000 Å and is due mainly to the ozone present above the floating altitude of the balloon. The amount and distribution of ozone is variable; however in the region between 30 km and 40 km the variability is greatly reduced. Since the major portion of the residual absorptions due to ozone arises from the ozone in this region it is possible to estimate the amount of residual absorption due to ozone with reasonably good accuracy without knowing the actual distribution on the dates of the flights. In addition it is also necessary to correct for losses due to scattering. The scattering theory is well developed for the short wavelengths where this is important. Complete correction for scattering requires a knowledge of the aerosol distribution above the floating altitude of the balloon. In most cases the amount of aerosol is small enough so that a correction for it is not necessary. On occasion however it can be important and this is discussed in detail below. In addition to the corrections for residual atmospheric effects it is also necessary to add a small correction to take into account the solar radiation in the infrared region not transmitted by the windows in front of the pyrheliometers. The windows, which are made of thin quartz, cut off sharply at 4.5 μ. Since the 4.3 μ absorption band of CO_2 is still strongly absorbing even at these altitudes the correction has been made

Table 3. *Summary of corrected solar irradiance values*

Date	Time (MST)	Distance correction factor	Corrected intensity P1	P2
Jun. 26 '67	0844	1.0340	1.884	1.867
Jun. 26 '67	0851	1.0340	1.887	1.867
Jan. 23 '68	1122	0.9684	1.877	1.847
Jan. 23 '68	1200	0.9684	1.887	1.848
Jan. 23 '68	1235	0.9684	1.890	1.848
Apr. 26 '68	0832	1.0130	1.853	1.860
Apr. 26 '68	0905	1.0130	1.855	1.863
Apr. 26 '68	0940	1.0130	1.858	1.865
Apr. 26 '68	1010	1.0130	1.858	1.866

on the basis that no radiation beyond 4.0 μ is measured by the pyrheliometers. The corrections to be applied in all three cases are as follows:

Residual atmospheric effects: 0.035 gm-cal cm^{-2} min^{-1}.

Additional radiation not measured by pyrheliometers: 0.017 gm-cal cm^{-2} min^{-1}.

Discussion

On the basis of the corrections discussed above the measured value for the solar constant from the June '67 and April '68 flights is 1.918 gm-cal cm^{-2} min^{-1} and 1.890 gm-cal cm^{-2} min^{-1} from the January '68 flight. The accuracy achieved in the ground calibrations and the consistency achieved during flight lead us to believe that the difference in the two results lies well outside of the range of experimental error. Analysis of the variation in the pyrheliometer readings with altitude during the three flights indicate a significant attenuation due to atmospheric aerosol in the regions from 16 km to 30 km. The aerosol distribution is quite different on the three dates. In particular on the January '68 flight the indications are that the aerosol layer was quite high and the balloon never got above it. This is in agreement with Elterman's (1966) aerosol data obtained using a searchlight technique. The low reading obtained during the January flight appears to be due to the aerosol layer lying higher on this date. Thus the January reading should have an additional correction added to correct for the residual aerosol absorption which would bring it up to the 1.918 gm-cal cm^{-2} min^{-1} value.

The values reported here are based on several hours of very precise measurement of the solar irradiance at altitudes in excess of 31 km. The instruments used in making these measurements have undergone an extensive series of calibrations. These will be reported in detail in a separate article but some features will be mentioned here. The calibrations have been carried out at Mount Evans, Colorado (elevation 3 km), Cloudcroft, New Mexico (elevation 2.8 km) and at Denver, Colorado (elevation 1.6 km) using three different Eppley-Ångström electrical compensated pyrheliometers as standards. The Eppley-Ångström units were calibrated by the Eppley Laboratory against their primary standard to within ± 0.2 % using the 1956 Pyrheliometric Scale. The calibration of the pyrheliometers used for flight have been carried out over a wide temperature range and the results used to determine the temperature dependence of the already internally corrected pyrheliometers. The agreement between the two flight pyrheliometers was within 0.1 % at all times during the ground calibration. The agreement between the two flight units and the Eppley–Ångström units used as standards is more difficult to assess due to the difference in time required to obtain a reading on the different units. However on days when the atmospheric conditions are stable a standard deviation of less than 0.2 % is obtained.

Recently there have been a number of measurements of the solar constant from high altitude balloons and aircraft. Kondratiev (1968) has reported balloon measurements yielding values of from 1.92 to 1.94 gm-cal cm^{-2} min^{-1} as the solar constant. Drummond *et al.* (1968) give a value of 1.95 gm-cal cm^{-2} min^{-1} as measured from high altitude aircraft. The discrepancy between our value and the value given by Drummond *et al.* (1968) lies outside the estimated experimental error of either measurement. The reason for this discrepancy is not immediately evident. Our balloon measure ment and those of Kondratiev (1968) indicate that the aerosol layer between 15 km and 30 km significantly attenuates the solar radiation traversing this region, however, the aircraft measurements were not corrected for aerosol attenuation. In view of this and a comparison of the attenuations given by Elterman (1966) suggests that the residual corrections applied by Drummond *et al.* (1968) should be reexamined. Even at balloon altitudes the aerosol may still be significantly affecting the measurement as the data obtained during the January flight indicate. Elterman's data indicate that on days when the majority of the aerosol lies below 30 km the residual correction should be quite small. Unfortunately however the searchlight technique of aerosol measurement is limited in altitude capability and there may be a higher layer that is not detected by this technique.

It is interesting to compare our measurements of the solar irradiance at 31 km with the measurements reported by Kondratiev *et al.* During the course of 8 balloon flights the solar irradiance measured at this altitude corrected to the mean earth sun distance by this group varied from 1.85–1.88 gm-cal cm^{-2} min^{-1} with a mean value of 1.867 gm-cal cm^{-2} min^{-1}. Our value as measured at altitude with P-2 ranges from 1.865–1.867 gm-cal cm^{-2} min^{-1}. Thus there is very good agreement between the two sets of measurements.

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ИЗМЕРЕНИЕ СОЛНЕЧНОЙ ПОСТОЯННОЙ С ВЫСОТНЫХ БАЛЛОНОВ

При помощи пиргелиометров Эппли с поверхностью датчика, перпендикулярной падающей радиации, на высоте 31 км для трех различных дней была измерена солнечная постоянная. После исправления показаний на остающейся 1% массы атмосферы и на расстояние от Солнца до Земли, значение солнечной постоянной оказалось равным 1,912 кал $см^{-2}$ $мин^{-1}$.