INVESTIGATION INTO ERRORS ASSOCIATED WITH UPWARD-FACING PYRANOMETERS FITTED TO THE MRF HERCULES

BY

J S FOOT, P HIGNETT * AND C G KILSBY

* NOW AT METEOROLOGICAL RESEARCH UNIT
RAF CARDINGTON
BEDFORDSHIRE, U K.

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1. Introduction

An Eppley PSP pyranometer was first installed on the Hercules in 1977 (Cluley 1978) and an installation allowing for two upward and two downward facing pyranometers was in use until late 1985. They have been used successfully to measure total and diffuse radiative fluxes in 2 wavelength bands, using clear and red domes, in a range of conditions from clear to cloudy and at altitudes from 200 to 30,000 feet. However, it has become clear that although the pyranometers' performance is acceptable for many purposes, the absolute accuracy of the pyranometers as they have been used until now has been uncertain.

Measured downward radiative fluxes at high level in cloud-free conditions were systematically lower than fluxes estimated by a radiative transfer model (in some instances by up to ten per cent). This work describes an investigation into some of the errors associated with the upward-facing pyranometers and methods of correcting them.

Pyranometers are known to suffer from a number of error inducing effects. Chief amongst these are sensitivity to the angle of incidence of the solar beam (the cos-Θ effect), dependence on the azimuthal angle of the solar beam and sensitivity to instrument temperature. Other effects such as linearity and dependence on tilt angle will not be discussed here since they are believed to be negligible for Eppley PSP instruments (Nast 1983, Andersson et al 1981).

2. Instrument Background

The MRF pyranometers are calibrated at Met O 16c by comparison with a transfer standard pyranometer in an integrating hemisphere. The transfer standard is compared with a secondary standard pyrheliometer and the sensitivity of the "standard"* MRF clear dome instrument (Eppley No. 14393)

*standard in this context means the most widely used in upward facing position.

has only varied by 0.7% over the last 6 years.

When the instruments are irradiated by a direct source, such as the sun, then in order to derive the flux through a horizontal surface the attitude of the plane of the sensor must be known and a correction applied. This is done by determining the pitch and roll of the aircraft using the INS, adding the pitch and roll "offsets" of the instrument relative to the INS platform, and combining the resultant pitch and roll with the sun's relative azimuth and zenith in a formula implemented in the processing program Hercrad (Cluley (1978) formula is only an approximation).

The pitch and roll offsets have been measured on a number of occasions. One method is to fly the aircraft on a series of straight and level runs on a number of different headings and carry out a multiple regression on the measurements (program S.STRMULT at MRF). Another method is to measure the offsets directly on the ground, using a clinometer placed on the guard plate in conjunction with the INS. This assumes the radiative and physical axes are coincident. Table 1 shows some values derived by these methods, and it can be seen that similar results are obtained using both methods, with little difference between instruments No 14312 and No 14393.

Table 1

Date	Flight No	Offsets (deg) Pitch	Roll	Instrument	Comments
		-2.8	0.6	14393	In use in Hercrad
16.6.77	H197	-2.3	0.5	14393	
20.9.77	H223	-1.5	1.0	14393	
15.7.80	H397	-2.7	0.6	14312	
31.8.83	H607	-2.8	0.8	14393	12 runs
16.11.83	Ground	-3.2	0.5	14393	Clinometer
10.9.85	H745	-3.2	1.0	14393	Clear
		-2.5	1.0	14285	Red

Total flux measurements have often been taken flying towards the sun and it can be seen that an error in the determination of pitch of 0.5^{o} would lead to an error of 1% in the flux at a zenith angle of 50^{o}.

A facility exists in Hercrad for applying a temperature sensitivity correction, but this has not been in widespread use. The standard clear dome is temperature compensated only to -20°C; later instruments are compensated to -40°C and temperature sensitivities supplied by Eppley show sensitivities better than 1% within this range. However for the standard instrument operating below -20°C (temperatures of -30°C or lower are common at FL250 or higher) an error of 1-2% can occur. A determination of temperature sensitivity to -40°C has been carried out (Cluley 1978) and data exist for other Eppleys (Andersson et al 1981) (see Figure 6). Further tests on temperature sensitivity are to be undertaken.

3. Aircraft Data

a) High level runs

To assess the accuracy of the upward facing pyranometers all available measurements made at 25,000 feet in cloud free conditions were collated and compared with model fluxes. The model fluxes are from runs of the short wave model of Slingo and Schrecker (1982) using standard atmospheres (McClatchey 1962) selected according to the time of year of the flight. The seasonal variation of the solar constant is taken into account, and the model was adjusted for the spectral transmission of the clear and red domes. Each model run was carried out at the solar zenith of the aircraft measurement and can be considered to have a relative accuracy of better than ½%. A plot of the ratio of aircraft to model fluxes against cosine of solar zenith is shown in Fig. 1. The aircraft fluxes have been corrected in Hercrad for pitch and roll but nothing else.

Despite the scatter the plot shows a dependence on cosine of zenith although the range of zeniths observed in these latitudes is somewhat limited. Fluxes from three instruments are included and measurements at zeniths over 70° are excluded. The majority of fluxes are from the standard clear dome instrument no. 14393, but eight values from another clear dome, no. 14312, are shown including H582 which was measured at 18,000 feet in the Caribbean. The red dome values (No 24285) are generally worse than the corresponding clear dome values. The under estimate of the fluxes apparent in Fig. 1 cannot be accounted for by simply increasing the absorber amounts (water vapour and ozone) above the aircraft. The necessary increases are typically an order of magnitude, which is physically very unrealistic. The obvious cause of the zenith dependence is a cos-Θ error, since the alternative is a linearity error, and this is known to be negligible. The data used in the plot are given in the appendix.

b) Radiative profiles

Another effect has been observed on a number of flights where a series of runs at different heights was conducted to form a radiative profile. The effect is shown well by H747 (Fig. 2) and appears to be a combination of a cos-Θ effect and another unknown factor (Kilsby (1986)). The aircraft fluxes in Fig. 2 have been corrected to a single zenith angle corresponding to the model profile shown alongside. It can be seen that the aircraft fluxes diverge on the upward profile. Flights H654, H655 and H747 all show this effect and were carried out in considerable amounts of haze and smoke. H707 (Fig. 3), H666 and H749 on the other hand do not show the effect but were flown over low cloud.

This suggests that the upper domes become contaminated by aerosol but this theory is difficult to accept for a number of reasons. Theoretically the collision efficiency of aerosol particles on the domes is very low, and contaminated domes have not been observed.

The clear dome fluxes from H728 (Fig. 4) show little divergence, yet this flight was conducted in heavy haze, with numerous fly impacts and dust deposits present on various parts of the aircraft after landing.

4. Laboratory Measurements

To explain the discrepancy at high level, a large cos-Θ error is required and it was decided to carry out some sensitivity measurements in the lab. Some subsidiary tests were also conducted to investigate azimuth responses and the effect of various kinds of damage to the domes.

a) Cosine response

The pyranometer was clamped with the thermopile in a vertical plane and the thermopile aligned centrally with a rotary table. The fore and aft direction of the pyranometer was aligned horizontally so that the tests would imitate the effect of flying along the sun's azimuth. The rotary table was fixed to an optical bench and a 12V 20W quartz halogen lamp with reflector was fixed at a distance of about 60cm from the thermopile. When measured with a small photodiode the lamp's beam was constant to better than 3% over the area of the thermopile. When the instrument had been in position in the dark overnight, a dark signal was measured which was subsequently subtracted from the readings. The outer dome of the pyranometer was ventilated by a small fan thoughout the measurements.

The lamp was operated to give an equivalent flux of around $900Wm^{-2}$ and its output proved to be stable to better than 1% during a measurement run. To eliminate any error due to variation of irradiation and asymmetry of the pyranometer with respect to the beam, readings at a particular angle were taken by measuring the signal at that angle on both sides of the central position, interspersed with readings at the central position.

This procedure was followed for 4 instruments - the standard clear dome (No. 14393, H124) a second clear dome (No. 14312, H125) and the 2 red domes (No. 24285, H394 and No. 24284, H392). Changing domes had little effect, but the 2 instruments were consistently different. Several runs at various angular intervals between 0 and 85 degrees were made and the resultant sensitivity data form fairly consistent sets. Typical standard deviations in the data were 0.2% sensitivity at 30^{o}, 0.4% at 60^{o} and 1.5% at 75^{o}. Cubic equations were fitted to the data and are given below.

Instrument		Equation
H124	$S = 1 - 1.05 \times 10^{-3}\Theta + 2.70 \times 10^{-5}\Theta^2 - 3.62 \times 10^{-7}\Theta^3$	(1)
H394	$S = 1 - 7.04 \times 10^{-4}\Theta + 1.09 \times 10^{-5}\Theta^2 - 2.25 \times 10^{-7}\Theta^3$	(2)
H125	$S = 1 - 5.12 \times 10^{-4}\Theta + 1.56 \times 10^{-5}\Theta^2 - 2.26 \times 10^{-7}\Theta^3$	(3)
H392	$S - 1 - 6.88 \times 10^{-4}\Theta + 1.24 \times 10^{-5}\Theta^2 - 1.64 \times 10^{-7}\Theta^3$	(4)

S = sensitivity, and Θ is zenith angle in degrees.

The cosine error is similar in shape to that measured by Nast (1983), Andersson et al (1981) and Ambrosetti et al (1984), but is of somewhat greater magnitude (see Fig. 5).

b) Azimuth effects

With the pyranometer facing upwards, and the lamp raised to imitate various zenith angles, rotation of the table gives a measurement of azimuth response. However any instrumental effect was negligible compared with the levelling errors.

The clear dome on No. 14393 appears to be damaged on its leading side by abrasion, and to test if this affected the response the pyranometer was clamped as above, but with the internal o-ring removed to allow rotation of the dome relative to the thermopile. This rotation had only a very small effect on the signal, even at zeniths over 75 degrees where errors amounted to less than 1%.

c) Red dome discoloration

One of the downward facing red domes had been in prolonged contact with water and become visibly discolored. To test the effect on instrument response a pyranometer was subjected to continuous stable irradiation while 3 red domes were interchanged. These domes were; a brand new dome, the discolored dome and a dome which had been used on the upper pyranometer. This test was carried out at zeniths of 0 and 50^{o}, but the only significant effect was at $\Theta = 0^{o}$ when the discolored dome transmitted 3% less than the others.

5. Application of corrections

a) Cosine and temperature corrections

The results of applying the cosine corrections to Fig. 1 can be seen in Fig. 7. The zenith dependence is almost entirely removed but the values are still consistently less than unity. Fig. 8 shows the result of applying a temperature correction based on the measurements of Andersson et al (1981), which is similar in magnitude to that measured for No 14393 and is as follows;

$$\text{Sensitivity} - = .99 + 3.0 \times 10^{-4}T - 7.0 \times 10^{-7}T^2 + 2.22 \times 10^{-7}T^3 \qquad \text{Eqn (5)}$$

T in degrees Celsius.

The combination of these two corrections is adequate to bring the majority of the clear dome measurements to within 2% of their modelled value. The red dome values are still rather low.

The remaining scatter may be due to a number of factors;

- deviation of the model atmosphere from the real atmosphere.
- inaccuracies in determining the pitch and roll of the instrument.
- possible contamination by cloud.
- absolute accuracy of calibration, only of order 2%.

When the corrections are applied to radiative profiles the results are more ambiguous. Certain flights reproduce the model results well (Fig. 3), but others still exhibit a divergence from the model through the flight (Figs. 2, 4). The cause of this divergence remains to be identified. This behaviour was not observed in earlier clear air flights, see Kitchen and Squires (1984).

b) Recommendations for future application

It has become obvious that to use pyranometers on aircraft to devise accurate fluxes and flux profiles, the instruments' individual characteristics must be known with some certainty.

(i) Firstly an absolute calibration is required and although the present system of calibration with a diffuse source is non-ideal for an instrument used to measure predominantly direct radiation a practical alternative method is not available.

(ii) The individual instruments' thermopile orientations must be known accurately, and this involves precise knowledge ($\pm 0.1^{\circ}$) of the pitch and roll offsets. This will be determined for each instrument in the new (1986) pyranometer fit. The better method of the two outlined in section 3 appears to be in-flight measurement and multiple regression since the other method does not measure the orientation of the thermopile, but only the guard-plate.

(iii) Corrections to the measurements due to orientation, cosine error and temperature sensitivity should be applied in a point by point fashion in the initial processing stage. The cosine correction should be based on measurements for the individual instrument (eg. those in Eqns 1 to 4). The correction for temperature sensitivity should be applied to those instruments operating outside their compensated range, and in the absence of any accurate individual characteristics, the relation given in Eqn 5 should be used.

References

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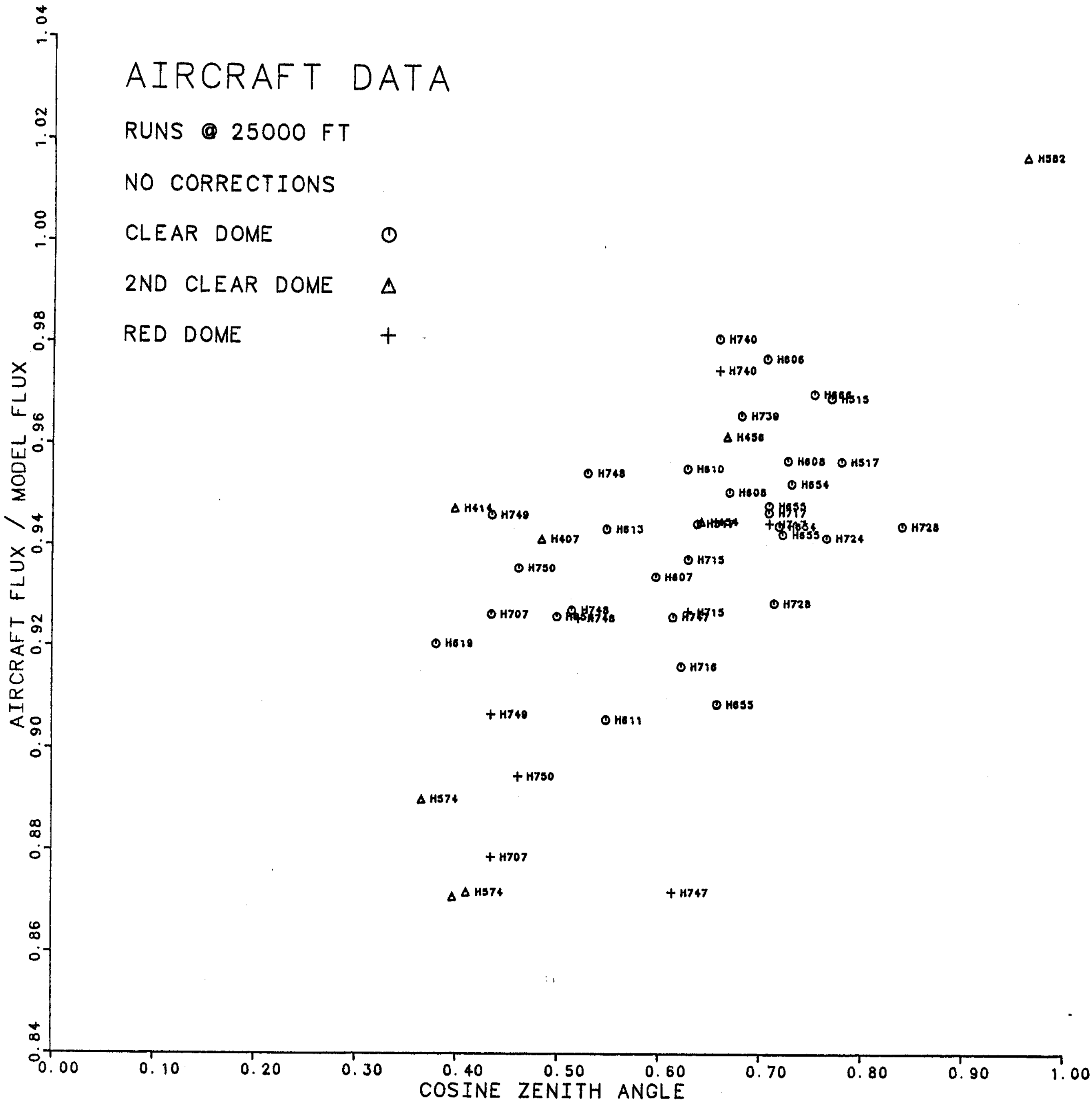


Figure 1

Ratio of aircraft to model fluxes at high level. No corrections.

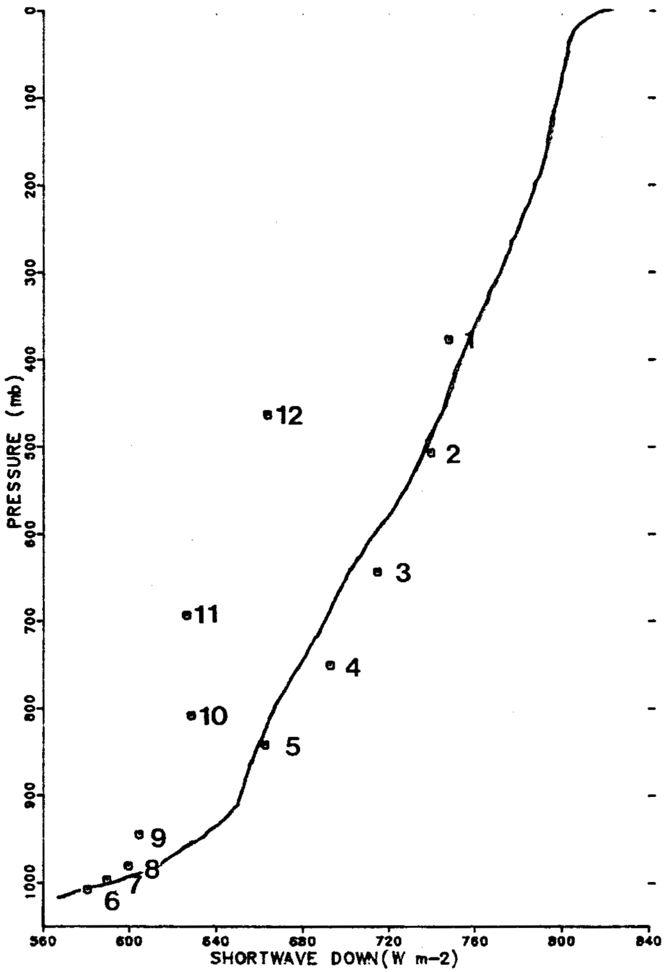


Figure 2
H747

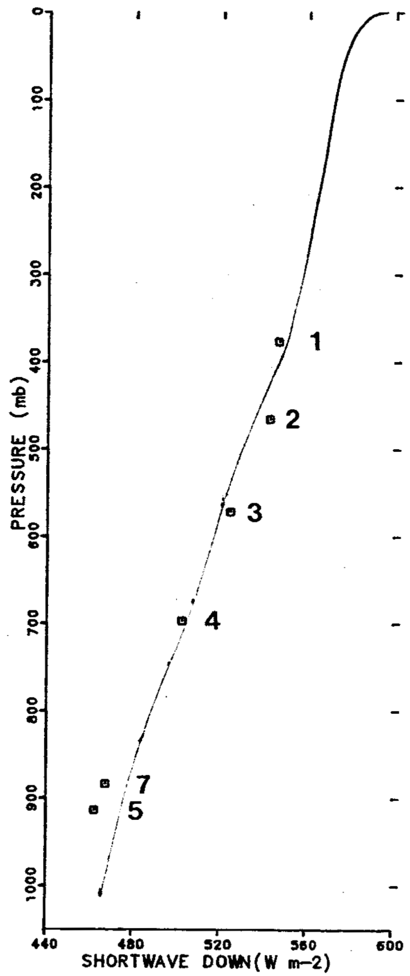


Figure 3
H707

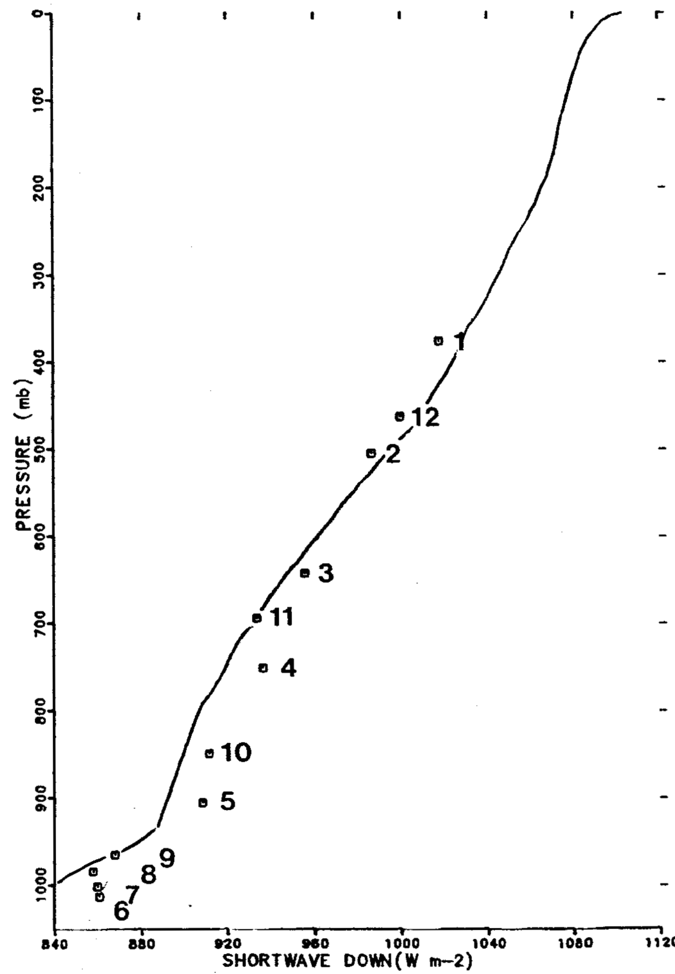
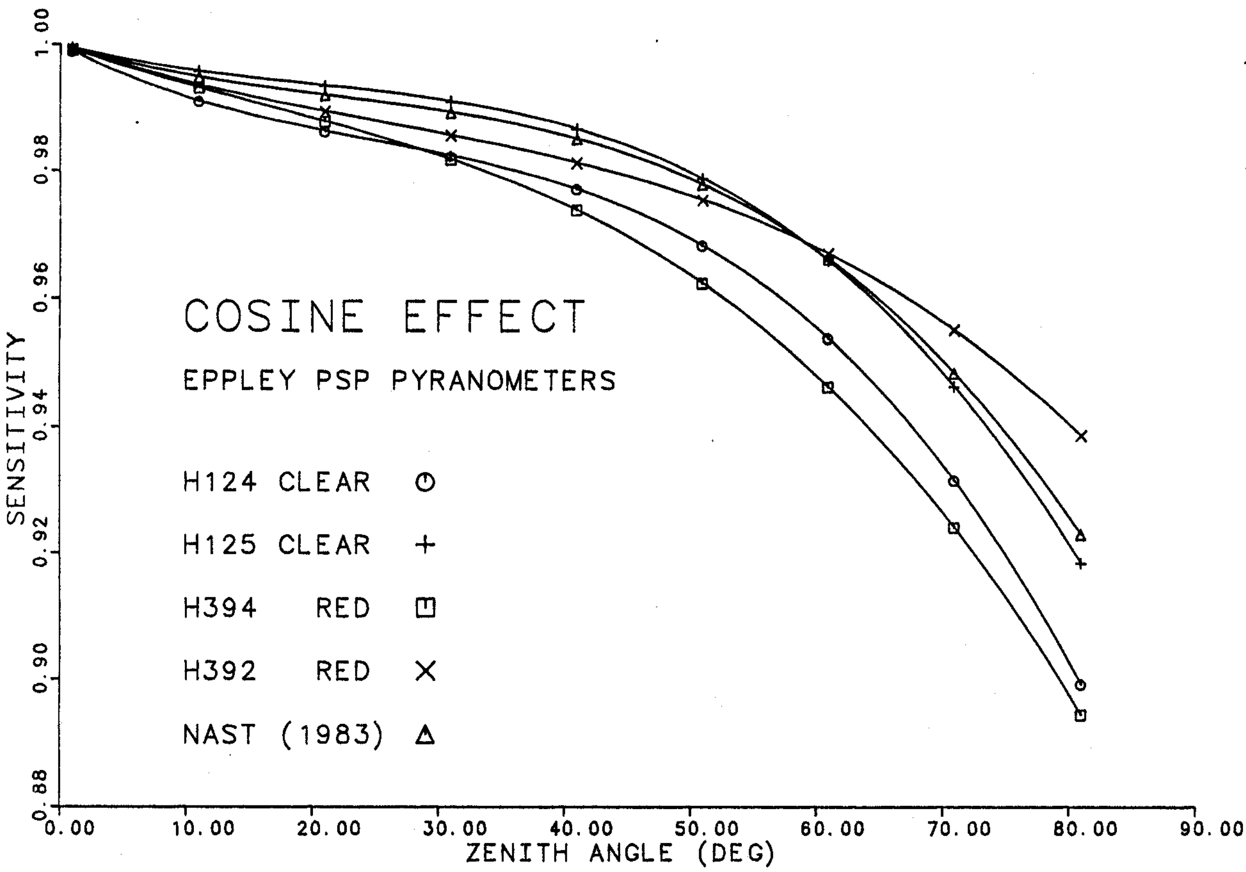


Figure 4
H728

Downward radiative flux profiles. Measurements are referred to in chronological order - each run 3 minutes long. All profiles are corrected to noon, and the model run for that zenith. Measurements are also corrected for temperature and cosine errors.

Figure 5. Cosine effect. Curves are cubic lines of best fit to experimental points.



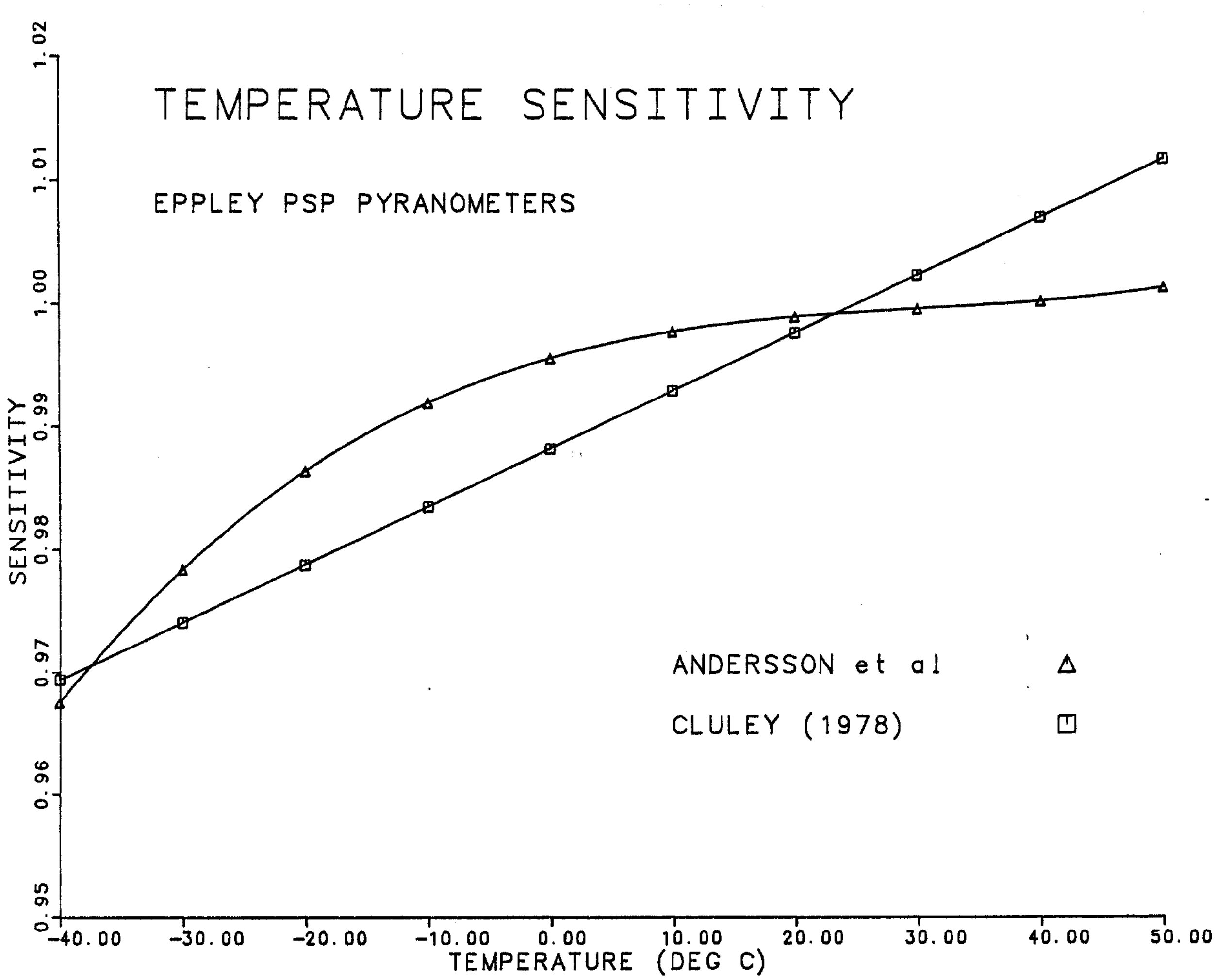


Figure 6. Temperature sensitivity. Andersson's measurements have been extrapolated beyond - 25^{o}C with a cubic fit.

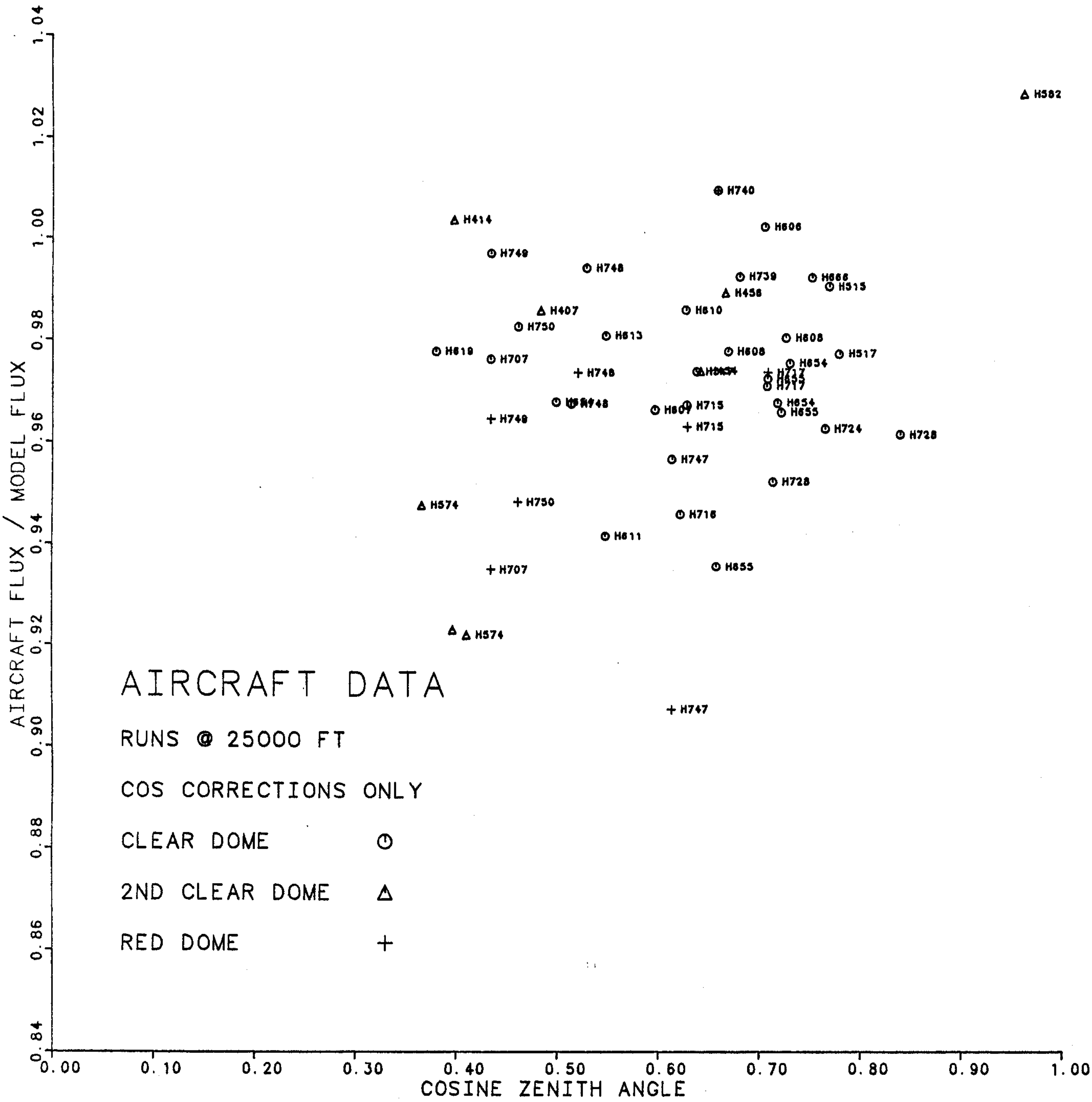


Figure 7

Ratios of aircraft to model fluxes after correction for the measured cosine errors.

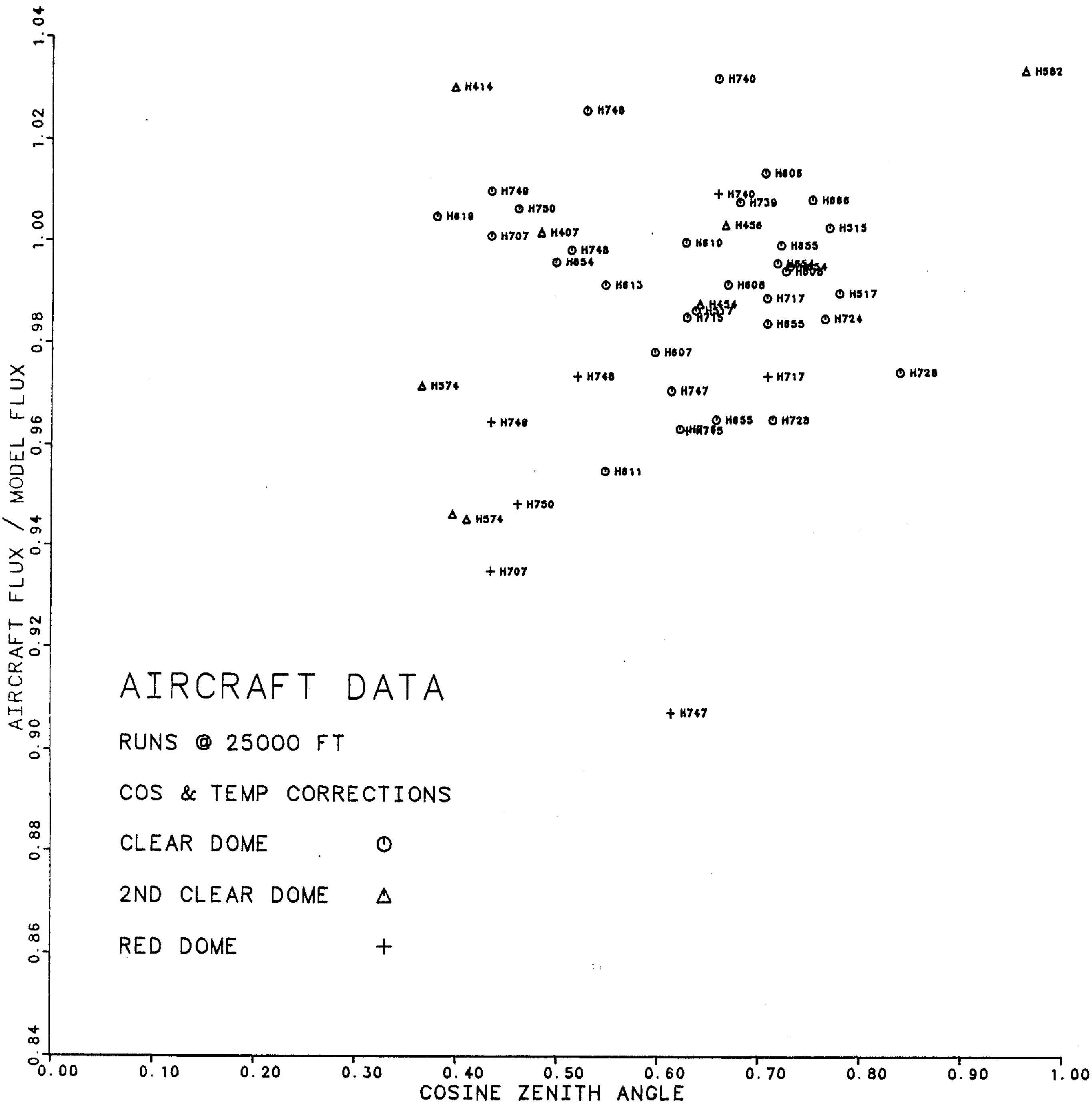


Figure 8

Ratios of aircraft to model fluxes after correction for cosine errors and temperature sensitivity.