NOTES AND CORRESPONDENCE

A Technique to Account for the Misalignment of Pyranometers Installed on Aircraft

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ABSTRACT

Misalignment of pyranometers used for airborne measurements can lead to serious errors in the determination of downwelling radiation flux. The magnitude of these errors depends strongly on the elevation angle of the sun. This note presents an iterative numerical procedure for determining the angles of misalignment of upward-facing pyranometers. Deviations in pitch and roll of the instrument with respect to the aircraft's inertial navigation system (INS) must be added to the pitch and roll angles measured by the INS before the radiometric data are corrected for the attitude of the aircraft. For successful determination of the two angles of deviation, a calibration flight must be performed in which the aircraft flies in at least three directions at the same altitude under clear skies and above any haze.

1. Introduction

Airborne radiometer measurements for studying the radiation budget and the extinction of incoming solar irradiance use UV radiometers, pyranometers, and pyrgeometers. The results of the measurements and the conclusions drawn from them are very dependent on the quality of the data used. Interpreting data from radiometers used on aircraft is not a simple task, because most devices of these types are designed for ground-based operations where the instruments can be installed on stable, leveled platforms. The techniques discussed in this paper are important for all airborne upward-looking radiometers operating in the solar spectrum.

Airborne radiometric observations have been carried out by many researchers over the last three decades. Robinson (1966) determined aerosol absorption from airborne radiation measurements. Foot et al. (1985) and Kilsby (1986) investigated radiative properties using broadband pyranometers on a Hercules C-130 aircraft. Cluley and Cowley (1980) presented explicit corrections of radiation data for aircraft attitude. Bannehr (1990) retrieved aerosol bulk properties from spectral airborne radiation measurements in South Australia. He applied the correction as derived by Cluley and Cowley (1980) to the radiation data and addressed the importance of accurate installation of the instruments on aircraft. Generally it is assumed that the pyranometers are perfectly aligned with the aircraft references axes so that only the attitude correction is required. A recent paper by Saunders et al. (1992) mentions the need of correcting for misalignment between pyranometers and aircraft reference axes.

In the present investigation we found that, in addition to performing the calibrations and attitude corrections as accurately as possible so that uncertainties are minimized, it is important to know the precise angles between the instruments and the inertial navigation system (INS) reference axes. The INS provides the attitude angles of pitch, roll, and heading of the aircraft, which are the input parameters for the attitude correction of the radiometer data. The misalignment angles between the pyranometer and the INS reference axes are specified as delta pitch and delta roll angles. The magnitude of the error in the global irradiance that arises from the radiometer misalignment depends on the atmospheric loading and, more strongly, on the solar elevation angle. It is larger at lower solar altitudes. Thus, proper alignment is especially important for research flights carried out during wintertime or at high latitudes. At 20° solar altitude, for instance, the error in the global irradiance caused by a misalignment of ±2° in the pitch and roll angles might be as large as ±12%. Since there is currently no practical technique available to position the pyranometer accurately with respect to the INS, an iterative numerical procedure was employed to determine the unknown delta pitch and delta roll angles from suitable calibration flight data.

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To illustrate the importance of knowing the angle between an upward-facing radiometer and the inertial navigation system, we performed radiative transfer calculations, assuming clear sky conditions (i.e., assuming no diffuse irradiance). Table 1 shows the percentage error in measured global irradiance for different solar altitudes and an error in pyranometer reference angle of ±2°.

Figure 1 illustrates an observed time series of the error in attitude-corrected global irradiance data that arises if the angle between the radiometer and the INS reference axes is in error by ±2°.

2. Observations

Modified versions of Eppley Laboratories pyranometers are installed on the Sabreliner research aircraft of the National Center for Atmospheric Research (NCAR). The alignment of the short-wavelength instrument with respect to the inertial navigation system is done using an inclinometer. The accuracy achievable by this technique is slightly better than ±2°. To account for the remaining difference between the axes of the pyranometer and the INS, a flight pattern (calibration flight) was chosen where the aircraft heading changed from 302° to 333° and then to 69° with a mean flight altitude in the lower stratosphere of 11 870 m. Any such calibration flight must be above any atmospheric turbidity. The flight was performed on 2 February 1989 northeast of the United States during the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) project. No clouds were in the vicinity of the observations. The data were collected at a rate of 5 Hz and averaged over 1 s, so that 1 s is equivalent to one sample in the following figures. The total duration of the calibration flight was 15 min. It was subdivided into sections A, B, and C, each with a different heading. The data for sections A and B include 350 samples each. Section C includes 200 samples before the aircraft descended to a different altitude. Data taken during turns for heading changes were rejected from the data processing. Figure 2 shows the time series of the global irradiance as it was measured during the calibration flight without attitude correction. During this time, the solar altitude changed from 20.6° to 17.3°. We recall that a misalignment of ±2° can produce an uncertainty of up to ±12% at this solar altitude. The time series shows no trend caused by the declining sun. One indication of misalignment is the sudden change in the global irradiance at the boundary between sections B and C, at sample 700 in the time series.

TABLE 1. Percentage error in global irradiance caused by a misalignment of the pyranometer of 2°.

Solar altitude (°)	Error (±%)
10	26
30	7
50	3
70	1
90	—

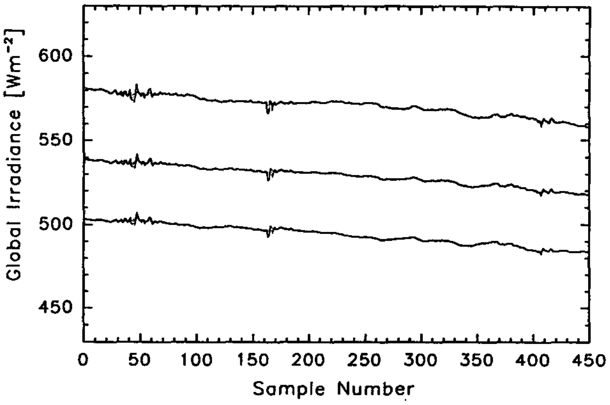

FIG. 1. The effect of misalignments of a pyranometer at a mean solar altitude of 20.0°. The data are attitude corrected. For the top time series, we assume that the delta pitch and delta roll angles are +2° and −2°. The middle time series assumes that the pyranometer is accurately aligned (delta pitch and delta roll are zero). The bottom time series assumes that the delta pitch and roll angles are −2° and +2°. The trend in the data is caused by the declining sun.

3. Accounting for misalignment

The idea of retrieving the delta pitch and delta roll angles of the radiometer from the data is based on the fact that the global irradiance incident on the sensor of the radiometer under clear skies and at a fixed altitude is approximately constant. It is independent of the direction in which the aircraft flies. Only trends caused by changing solar altitude are expected. When the instrument is not properly aligned, sudden changes in both the uncorrected and corrected global irradiance signal will occur when the aircraft changes heading (Fig.

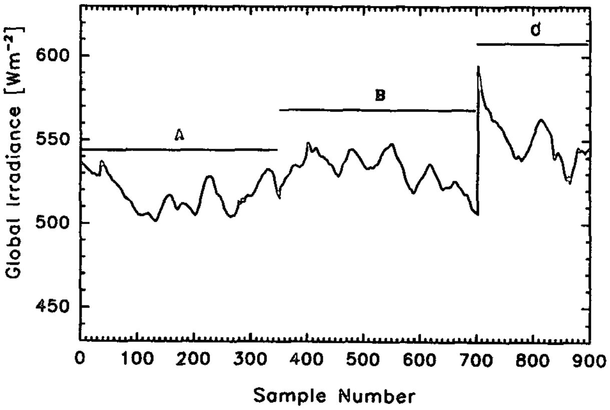

FIG. 2. Time series of global irradiance without attitude correction. The three bars in the upper part of the graph show the subdivided sections A, B, and C of the calibration flight. The data were taken at high altitude under clear skies.

2). Of course the radiometer dome must be clean for such a measurement, especially in the direction of the direct solar incidence.

The retrieval method uses the equation that corrects the direct-beam radiometer data for deviation from level flight. Note that the correction factor applies to only the direct (not diffuse) component of the total irradiance. The correction equation can be written as

$$F = \frac{\sin\theta_s}{\cos\theta_s \sin\alpha \sin(\phi - h) - \cos\theta_s \sin\beta \times \cos\alpha \cos(\phi - h) + \sin\theta_s \cos\beta \cos\alpha}, \qquad (1)$$

where F is a correction factor (the direct signal must be multiplied by this quantity), θ_s is the solar altitude, α is the roll angle of the aircraft (positive for left wing up), β is the pitch angle (positive for nose up), h is the aircraft heading, and ϕ is the azimuthal angle of the sun.

The following five steps summarize how the delta pitch and delta roll angles are retrieved. To begin the procedure, we assume no installation error: that is, delta pitch, $\Delta p = 0$, and delta roll, $\Delta r = 0$.

1) The correction factor F for each sample is derived from the observed quantities (solar altitude and azimuth, as well as pitch, roll, and heading of the aircraft) and assumed values for delta pitch and delta roll. Delta pitch and roll are held constant for each iteration for the entire calibration flight; F is then applied to the data to produce a corrected dataset.

2) The corrected time series is low-pass filtered to determine any trends caused by changing solar altitude. This has the same effect as fitting a linear sloping function to the data. The filtered data trend is stored temporarily.

3) Then the low-pass-filtered time series is subtracted from the unfiltered time series to obtain a series of higher-frequency residuals with zero mean.

4) The standard deviation of the residual time series is determined. The delta pitch angle is found by searching iteratively for the minimum standard deviation of the residual time series, while keeping the delta roll angle constant.

5) Using the retrieved Δp as a new input parameter, a better estimate of Δr is then determined iteratively (i.e., $\beta_{\text{new}} = \beta_{\text{old}} + \Delta p$). Steps 1–5 are repeated until $|\Delta p_n - \Delta p_{n-1}|$ and $|\Delta r_n - \Delta r_{n-1}|$ (where n is the iteration number) are less than 0.01°.

A few comments may help clarify the retrieval procedure. The procedure searches for a minimum of the standard deviation as a two-dimensional function of the variables delta pitch and delta roll, starting from the origin. It is reasonable to expect, and is confirmed by our experience, that this function is well behaved near (0, 0). We do not give details of the minimization procedure in steps 4 and 5, because each researcher has a preferred algorithm. Essentially, one calculates a numerical derivative of the standard deviation function by assuming a step in delta pitch, for example, and uses the derivative to set the direction of the next assumed step until the derivative changes sign, indicating that the minimum of the function in the plane of constant delta roll is near. The same procedure is then applied to delta roll. In practice, the convergence is very rapid.

The removal of a linear trend from the data in steps 2 and 3 is used instead of just a simpler high-pass filter because it is important to retain the offsets in the trends as seen in the first two time series in Fig. 3, for example. Much of the contribution to the standard deviation comes from these offsets.

The delta pitch and delta roll angles retrieved by the numerical procedure for the example chosen were $\Delta p = 0.48°$ and $\Delta r = 0.08°$. By adding these values to the recorded INS pitch and roll angles, the pyranometer is aligned with respect to the INS. Unless the instrument is repositioned on the aircraft or the INS is disturbed, the values for Δp and Δr remain constant.

The result of the procedure is shown in Fig. 3. The top time series shows the corrected global irradiance for the whole calibration flight according to (1), assuming the pyranometer delta pitch angle of +2° and delta roll angle of −2°. The time series in the middle of Fig. 3 illustrates the same data but with assumed delta pitch and roll angles of −2° and +2°. The erratic changes in both time series from one flight direction to another indicate that the assumed values are incorrect. The lower time series shows the corrected global irradiance, incorporating the delta pitch and delta roll angles retrieved by the method previously outlined. The latter time series is smooth and contains no discontinuities at boundaries between the three flight segments. Furthermore, the trend caused by changing solar altitude is obvious in the dataset after the proper correction is applied.

We have chosen to compare in Fig. 3 the results of the fitting procedure with time series having delta pitch and delta roll approximately equal to the uncertainty in instrument alignment. This comparison indicates the magnitude of gains expected in typical cases. Comparison with a time series having delta pitch and roll equal zero is not particularly illustrative of the usefulness of the technique for correcting for misalignment. As it turns out, fitted values for delta pitch and roll in the example are fortuitously close to zero, but this is not a typical situation.

This procedure for determining delta pitch and roll is essentially a geometrical correction for the radiometer installation. The proper application of the attitude correction (1) in the presence of diffuse radiation is an important, separate issue not addressed in this note. An estimate of the direct to diffuse ratio is needed before applying the correction (1) operationally.

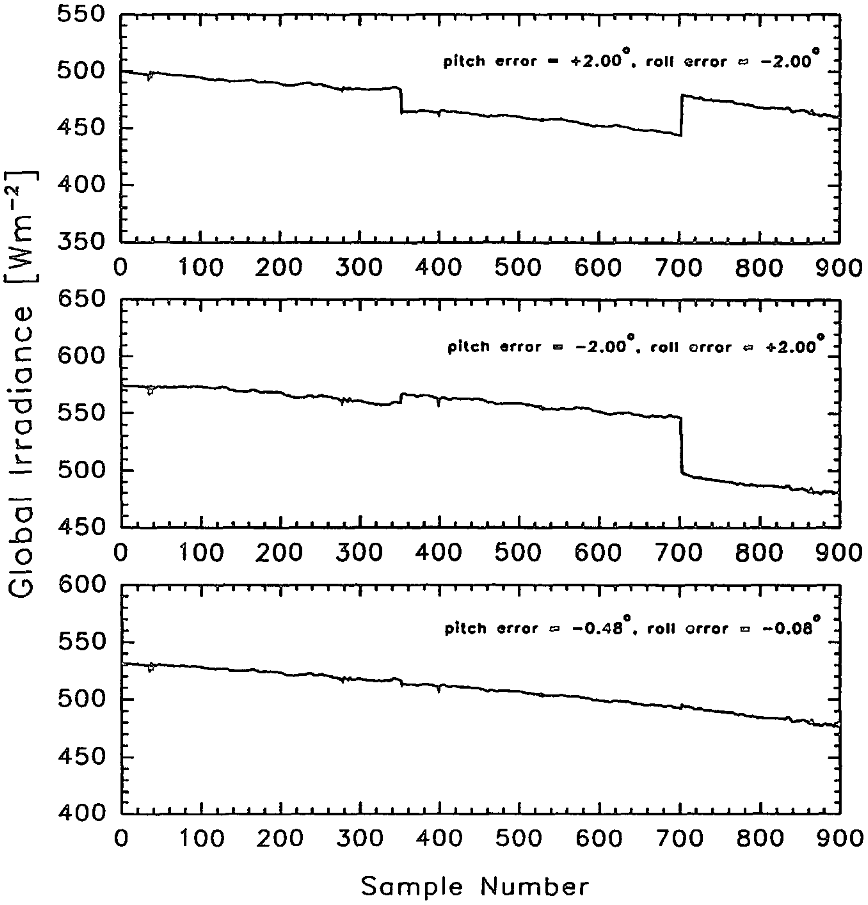

FIG. 3. Time series of global irradiance for the calibration flight for different delta pitch and delta roll angles. The data were taken at high altitude under clear skies.

4. Summary

As radiative transfer calculations have indicated, it is important to have the pyranometer that measures downwelling radiation accurately referenced to the inertial navigation system, especially at low solar altitudes. An alignment error of only ±2° leads to an error in the global irradiance of ±12% at 20° solar elevation. Since sufficiently accurate adjustment of the radiometer is a cumbersome task, we have developed a technique to derive the residual delta pitch and delta roll angles from the data. For the successful determination of the two angles, however, data on at least three different headings at one altitude under clear skies above atmospheric turbidity are required.

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