

Correcting Global Shortwave Irradiance Measurements for Platform Tilt

R. Michael Reynolds
RMR Company, Brookhaven NY 11719 USA

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Abstract

This technical memo describes an algorithm for correcting shipboard measurements of hemispheric solar irradiance, as measured by a pyranometer, for variations in mean tilt of the platform. Such errors are most apparent in conditions of high insolation, almost clear skies, when solar zenith angles are from 20 to 60°. During research maneuvers when the ship makes many turns, the tilt errors show up as jumps in the measured irradiance that correlate with the ship heading changes. Ship list, a steady sideways tilt, can result from wind forcing, ballast arrangement, and strong ocean currents. A ship can list typically by 2° which leads to a 4° tilt change if the ship reversed direction. In heavy weather the list can exceed five degrees. It is difficult to mount a sensor exactly level on a ship. At sea the ship motion makes reading a level gauge difficult, and in port the ship often takes on fuel or cargo and changes its angles after the instrument has been installed.

To achieve the best accuracies, the pitch, roll, and heading *of the sensor* should be measured as part of the data set. If the the mean platform pitch and roll are known, one can compute the solar zenith angle relative to the instrument. However, this information is vital but not sufficient to properly correct the measurement. Information on the relative contributions of the direct beam irradiance and the diffuse irradiance are required. In this paper we use a clear-sky irradiance model developed by Iqbal to provide a ratio of diffuse to direct-beam irradiance. This completes the equation set and allows for correction. The PRP (Portable Radiation Package), developed by Brookhaven National Laboratory, and in use by several institutes world wide, measures platform pitch and roll as part of its measurement suite. The PRP is aligned properly on a ship so the ship gyro/GPS heading measurements provide measure of the instrument heading. Examples, using PRP data, are provided here of the effectiveness of the correction method.

Finally, the same clear-sky model and coordinate transform equations are used to evaluate the effect of a mean tilt on the net daily shortwave flux. It is this term that is important to a climatic energy budget. It is found that the absolute worst case error in the daily insolation is 4 W m⁻² per degree of tilt. We expect under normal conditions of cloudiness, different ship locations, and different headings the errors would be considerably less. Nevertheless, the high-quality, low-uncertainty instrument packages of the future will need to include pitch, roll, and heading in their data set.

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1 Introduction

Measurements of solar irradiance are fundamental to a complete set of oceanic energy flux estimates. Many authors have expressed the importance of low uncertainties, on the order of a few W m^{-2} , in all the flux terms including shortwave solar downward flux [1]. In an energy balance of the tropical western Pacific Ocean the overall mean shortwave flux was more than 200 W m^{-2} while the net flux balance came to only 18 W m^{-2} into the ocean.

The downward hemispheric solar irradiance, S , the insolation, is given by

$$S = N \cos \zeta + D \quad (1)$$

where N is the irradiance contribution by the direct beam of the sun, ζ is the solar zenith angle, measured from zero when the sun is directly overhead, and D is the diffuse irradiance contribution, also called the “sky” irradiance.

A standard pyranometer, such as the PSP (Precision Spectral Pyranometer) made by the Eppley Laboratories, provides a measure of the integrated irradiance, S , and as such is sensitive to the angle of tilt. Bubble levels are provided so the instruments can be set to near level as part of the installation procedure.

When the same sorts of measurements are made from ships at sea, or in the extreme, from buoys, the tilt of the sensor becomes a major concern. A study of the effects of platform motion [2] found that the largest errors in the mean insolation measurement came from a mean tilt. Rocking motions from waves made only a small contribution to the overall uncertainty. The time constant of the sensor is several seconds which makes an effective low-pass filter to the wave effects, and for most solar zenith angles, the signal output for small rocking angles is linear and sums to near zero. These effects are especially true when one is concerned with instruments on ships where the rocking is much smaller than a buoy.

As an example, tilt measurements for a large research vessel, the R/V *Mirai* (length=129 m, gross weight = 8672 tons) are shown in Figure 1 as it passed near Typhoon Bebinca, Tropical Storm 0616, off the coast of Japan. At the beginning and end of the cruise, when the ship was in harbor, the pitch and roll measurements were near zero. The pitch and roll measurements are taken at a 3-sec rate and the mean and standard deviations are computed over a two-minute time period. During the storm, mean winds of about 18 m s^{-1} blew directly against the starboard side of the ship causing a mean negative roll of up to -3° .

The solar radiation during storms is minimal, so we don't expect large errors at these times. Probably the biggest source of tilt error is improper installation or a shift of the equipment during the voyage. Then a significant tilt will be present even during clear days with high radiation which can lead to large cumulative errors.

This memorandum describes the scale of the problem and the overall importance of this error to climate change data sets. It introduces an effective method for reducing the mean tilt errors as long as the platform tilt is properly measured, then uses this technique to evaluate the magnitude of the tilt error to climate data sets. In this paper, when we refer to "platform" we refer to the actual radiometer which might be different than the structure or the ship on which it is mounted.

2 Theory

We refer to two different coordinate systems here. The local plane coordinate system has the $+x$ axis pointing East, the $+y$ axis pointing North, and the $+z$ coordinate pointing vertically upwards. The instrument-based coordinate system requires a North reference on the instrument and based on that, the $[x, y, z]$ axes point to relative East, relative North, and vertically normal to the instrument's x, y plane, following the right-hand rule.

The solar azimuth angle in the two coordinate systems are θ and θ_R for the level and relative coordinate systems. Likewise, the solar zenith angle for the two systems is ζ and ζ_R respectively.

The platform (instrument) attitude is defined by its pitch angle (North reference upward), α_P , the roll (positive for left side, or port upwards), α_R , and the heading, α_H . Note here that α_H is the compass angle towards which the North reference of the radiometer points. If the radiometer is lined up with the ship, then the heading read by the ship's navigation system can be used directly for α_H . Otherwise a correction will be required. Note here that α_P and α_R are measured at the instrument and not in some other location. As mentioned above, the actual installation of the pyranometer, often on a pole in an exposed location or on a foremast on the ship's bow, is difficult and prone to alignment problems.

The PRP (Portable Radiation Package) [3] integrates a PIR (Precision Infrared Radiometer) for Longwave flux, a PSP (Precision Spectral Pyranometer) for shortwave flux, a six-channel FRSR (Fast-Rotating Shadowband Radiometer) for solar spectral information and aerosol optical depth, and a pitch-roll-compass sensor all on the same plate. The flux-gate compass is usually too contaminated by the steel ship to be of much use. Instead we align the instrument with the ship and use the ship's heading as a good surrogate for instrument heading. In this paper we will use data from the PRP data set.

Equation 1 gives the insolation on a level plane and is the actual insolation. The radiometer produces an output voltage that is linearly proportional to the total irradiance from a hemisphere centered on the relative coordinate system. The actual instrument is usually

not level and hence it measures a relative irradiance given by

$$S_R = N \cos \zeta_R + D_R \quad (2)$$

where ζ_R is the solar zenith angle relative to the instrument coordinate system and D_R is the diffuse irradiance from the relative hemisphere.

The attitude angles ($\alpha_P, \alpha_R, \alpha_H$) and the actual solar azimuth and zenith angles, (θ, ζ), from an ephemeris that uses geographic location and time, are all combined to compute the relative solar angles:

$$\{\theta_R, \zeta_R\} = f(\alpha_P, \alpha_R, \alpha_H, \theta, \zeta) \quad (3)$$

Relationship 3 is solved using three two-dimension coordinate transformations. The matrix transform technique is well known and is discussed in many textbooks on matrix algebra.

Thus, by having a complete measure of the attitude of the radiometer in space we compute the relative solar zenith angle. At this point the only quantities we have are S_R , ζ_R , and ζ . We would like to correct our measurement by an algorithm, $S_R \rightarrow S_C \approx S$, where S_C is the corrected irradiance and is our best approximation for S .

By combining equations 1 and 2 and after assuming $D_R \approx D$, we can derive a relationship

$$S = S_R \frac{\cos \zeta + K}{\cos \zeta_R + K} \quad (4)$$

where $K = D/N$, the ratio of diffuse to direct-beam irradiance.

In order to make tilt corrections we need to have some information on N and D , and more importantly on their ratio. We have explored two methods. One, described below, makes use of a clear sky radiation model. The second method makes use of the shadowband radiometer that is part of the PRP (Portable Radiation Package). The FRSR measures N and D in six spectral bands. Because the PRP is not common on research ships or volunteer observing ships, we will consider the more simple and less expensive method using the clear-sky model.

3 An algorithm for tilt error correction

A useful algorithm is available for computing the clear sky solar irradiance for any location on and for different atmospheric conditions. The algorithm, by Iqbal [4], requires five input parameters that are used to approximate the atmospheric transmittance and scattering for a cloud free sky: (a) integrated water vapor in g cm^{-2} which can vary from 1 in dry temperate situations to 5 in the tropical oceans, (b) surface barometric pressure in hPa, (c) aerosol optical depth at 380 nm which can be of the order 0.05 to as much as 1.0, (d) aerosol optical depth at 500 nm which can be of the same range as the 380 nm AOD, and (e) the ozone-layer thickness in cm(NTP) which has a typical value of 0.3 cm. The

Iqbal algorithm produces the clear-sky direct beam and diffuse irradiance, N_c and D_c which can be used to compute the theoretical clear-sky irradiance from equation 1.

For this example we will use data collected on the R/V Southern Surveyor during the TWP-ICE experiment off of the north Australian coast. The measured solar irradiance for this day is shown in Figure 2. All data were averaged onto a two-minute interval with the sample time designating the center of the averaging period. The ship measurement strategy was to sail at $1\text{-}2\text{ m s}^{-1}$ into the wind for three hours the return to the central location as quickly as possible and repeat the cycle. Winds were from easterly so the ship track was pretty much North and South, which is favorable for observing effects of tilt. Further, the deployment $\alpha_P = 2.0^\circ$ and $\alpha_R = 1.8^\circ$ were constant during this day. During this time period and at this location, the sun was nearly directly overhead at noon so $2 \leq \zeta \leq 90^\circ$ which was ideal for testing the correction algorithm.

Using Matlab analysis routines the ratio D/N was computed from the Iqbal model for each time and measured S_R was corrected according to equation 4. The corrected insolation is shown as the red solar curve in the figure.

[MORE EXAMPLES HERE??]

4 Is correction important?

The need for the lowest possible measurement uncertainties has been stressed has been stressed by many authors. Each of the flux components need to be estimated with uncertainties of just a few W m^{-2} . Therefore if we are looking at tilt-generated insolation errors in the tens of W m^{-2} , it would seem that correction is desirable. However, in general the net flux used in climate research is a daily average or longer, which includes a considerable amount of nighttime irradiance (mean = uncertainty = 0 W m^{-2}). Tilt errors are strongest at $\zeta \approx 45^\circ$ where the slope of the cosine curve is strongest.

In the example in Figure 2, the mean daily insolation is obtained by integrating under the curve. For the uncorrected case the mean daily insolation is 320.6 W m^{-2} and for the corrected curve it is 322.4 W m^{-2} . Thus, while the corrected solar curve is aesthetically more pleasing, the net result for flux averages is well within uncertainty requirements. So we wonder, from the point of view of a long-term climate average, if small tilt errors small enough to ignore.

We have used the same analysis package to explore the importance of tilt errors. A measured insolation is computed for perfectly clear skies, using the Iqbal method and for given fixed values of pitch, roll, heading, latitude, longitude, and for particular days. If the sensor tilt is constant and towards the East or West, the mean daily error is very small since individual errors in the mornings cancel out errors of the opposite sign in the afternoon. A worst case of tilt error was found to be a situation of a sensor located at $+22^\circ\text{N}$ latitude on winter solstice, with a heading of $+90^\circ$, i.e. to the East, and a roll angle

of -4° , i.e. away from the solar path. In this situation error is cumulative throughout the day. If the tilt magnitude is a constant 4° , the measured mean insolation for the day is 210.3 W m^{-2} , compared to the true clear sky mean of 229.1 W m^{-2} .

As a rule of thumb then the absolute worst case error in daily insolation measurements from a tilting sensor is 4 W m^{-2} per degree of tilt. Of course if one adds in cloudiness, other days of the year, and random headings, the cumulative insolation error for a site is within the limits of uncertainty to be useful for climate purposes.

Of course, when a cruise provides the pitch, roll, and heading of the instrument as well as the geographic position and a good time base, it seems reasonable to use equation 4 and make the correction. However, it is doubtful if many insolation data sets have such a comprehensive suite of support measurements. However, for best quality these should be added to future climate quality observations on ships or buoys.

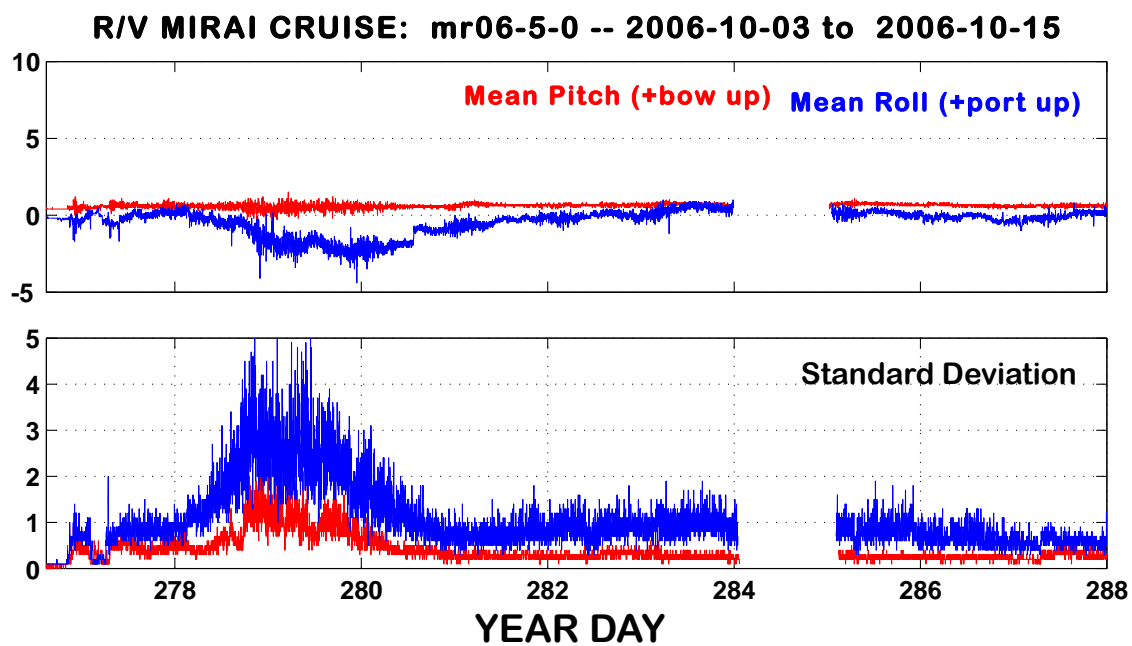


Figure 1: Response of the R/V Mirai to Typhoon Beninca, Tropical Storm 0616, off the coast of Japan on 8 October 2006.

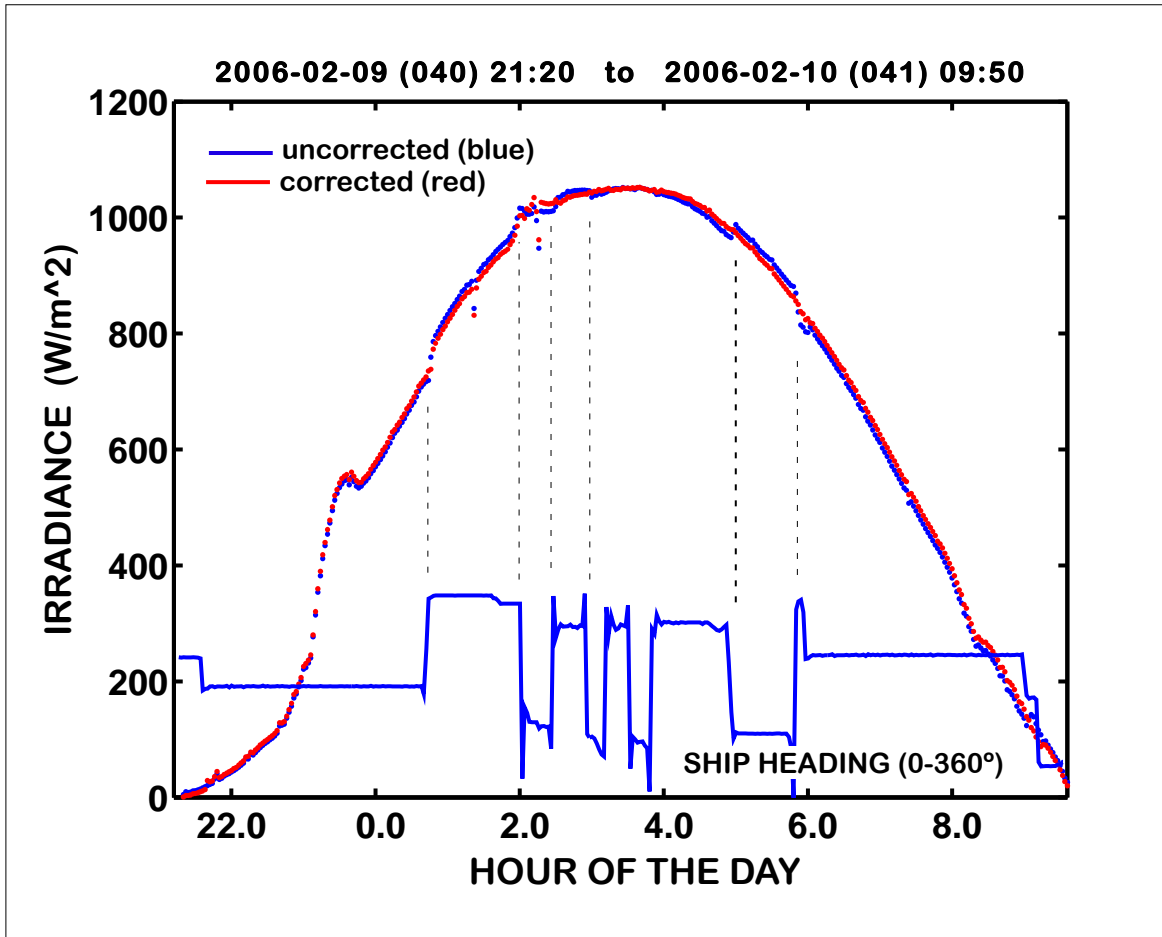


Figure 2: A sunny day during the TWP-ICE cruise off the coast of Darwin in January 2006. The ship made regular trackline reversals throughout the cruise. The instrument pitch angle was $+1.8^\circ$ and the roll angle was $+2.0^\circ$. These angles were related to the mounting of the instrument and not necessarily related to listing of the ship. The noon solar zenith angle was about 2° so changes at noon were negligible. However, at mid-morning and mid-afternoon the jumps in irradiance were quite apparent. The mean insolation for the uncorrected curve is 320.6 W m^{-2} and for the corrected curve is 322.4 W m^{-2} .

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