Solar irradiance measurements from the Danish Galathea 3 Expedition

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Abstract

The Danish Galathea 3 Expedition completed an eight month journey of exploration and discovery on April 25th, 2007, having set sail from Copenhagen on August 11th, 2006. SolData Instruments was privi-ledged to be selected to contribute an "optics table" with pyranometers, ultraviolet, lux, sky luminance, PAR and other optical radiation detectors. These instruments recorded data continuously during the 100.000 kilometer voyage of the Royal Danish Navy vessel Vædderen. The voyage provided global solar irradiance and other data as far north as the Arctic Circle near Greenland and as far south as Antarctica. The data collected was analyzed to validate a solar irradiance model described in this paper. A unique opportunity was also provided to check the perfor-mance of SolData photovoltaic pyranometers against data from a Kipp-Zonen CM11 instrument. In addition to optical radiation, ionizing radiation and atmospheric pressure were also measured, and some interesting aspects of these measurements will also be mentioned.

1. EQUIPMENT

The data logger used was a CR10X from Cambridge Scientific which provided half a dozen analog input channels and a number of digital inputs. The data logger, power suppliers etc. were mounted inside the hydrographics laboratory container and connected to a PC with data logger control software. A ca. 20 meter long cable connected the data logger to the instruments on the optics table mounted on top of the laboratory container.

The three pyranometers were used for mutual control and calibration. Other light detectors measured illum-inance (lux) and sky luminance (candela per square meter) and UVB (ultraviolet intensity units UVI).

A PAR (photosynthetically active radiation) detector was also connected to our data logger. An atmo-spheric pressure sensor inside the laboratory and the ionizing radiation detector were also in use.

2. DATA COLLECTION

Our data was recorded in the same fashion as is standard practice for the Danish Met Office: 10 minute averages are recorded every 10 minutes. In the case of the GM counter the total number of counts during each 10 minute interval was recorded. All data records were date and time stamped with the UTC time. An e-mail was sent by a technician on board weekly with data from Monday through

Figure 1: *The The Royal Danish Navy vessel Vædderen served as instrument platform for the SolData optics table during the 100.000 kilometer, eight month round the world voyage of exploration and scientific research. It was conducted under the auspices of the Danish Galathea 3 Expedition. Previous Galathea expeditions sailed from Denmark in 1845 and 1950.*

Figure 2: *The optics table was an aluminum frame firmly fastened to the aft port side of the vessel near the rail. The sky luminance sensor (at right) points towards the horizon with an elevation angle of about 10 degrees. The two SolData photovoltaic pyranometers are visible at the left rear behind the Kipp-Zonen CM 11.*

Sunday. The raw data were then transferred in a block to an Excel spreadsheet for calibration, unit conversions, graphics and other data analysis. This database was updated weekly throughout the duration of the voyage. It is currently available to all at the internet address: **www.soldata.dk**

There were an average of 20-30 research scientists and graduate students continuously engaged in their own projects, and many additional data (acidity, salinity, sea surface temperature, CO_2 content, dissolved oxygen, etc.) were collected throughout the voyage. The expedition database is accessible via the Galathea 3 Expedition home page.

3. SOLAR GLOBAL IRRADIANCE

Clear weather predominated during the Galathea Expedition. Many days were "perfect" clear days as can be seen in Figure 3 which shows data from the harbor of Accra, Ghana, collected in October 2006. Data from the optics table have yielded the clear day global irradiance on a horizontal surface for a wide range of geographic locations and atmospheric conditions.

Fine, clear days are ideal for testing radiation models which aim to predict the global solar irradiance on the horizontal as a function of the time of day, location on the earth's surface and the solar declination angle. This knowledge is valuable in connection with the design of solar energy systems, photovoltaic and thermal, as well as for use in agriculture and in computations of the energy balance of the earth in climate modelling. Consider now the following equation describing the *global irradiance*, i.e. the sum of the direct solar irradiance striking the surface and the diffuse irradiance from the sky and from clouds.

$$I_G = I_0 \, F_J \, a^L \sin V + I_F$$

The first term takes the *direct irradiance* into account, and the second corresponds to the *diffuse irradiance* from the sky and from clouds. Note that the direct irradiance term contains *the solar constant* $I_0 = 1367 \ \mathrm{W/m^2}$ multiplied by three factors:

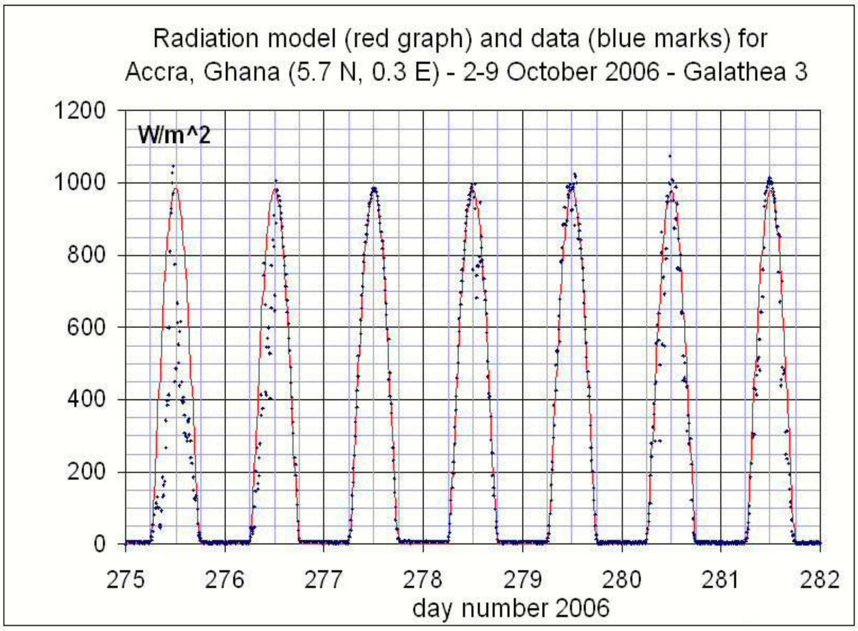

Figure 3: *The Galathea Expedition provided a unique opportunity to measure global solar irradiance over a wide range of locations, solar elevation angles and temperatures. The data shown was measured using a SolData 80spc pyranometer. It was continuously checked against a second 80spc and with a Kipp-Zonen CM-11 pyranometer. Sunny days were by far the predominant weather type during the 8 month 100.000 kilometer voyage.*

F_J accounts for the yearly *variation in the earth-sun distance*. The sun is nearest the earth around January 3rd. (This partly explains why winters in the Northern Hemisphere are somewhat milder that at corresponding latitudes in the Southern Hemisphere.) The following formula can be used to estimate F_J, where the "day number" can be found from an almanac or calendar:

$$F_J = 1 + 0.033 \cdot \cos(360\,(day - 3)/360)$$

The factor a^L accounts for the *attenuation* (absorption plus scattering) of the direct solar irradiance during its passage through the atmosphere, where L is the air mass.

Finally the factor *sin V* takes the *geometry* of the situation into account for a solar elevation angle V. The solar elevation angle can be computed with knowledge of the latitude, the solar declination angle and the local time. The equation required is widely available in the solar energy design literature [1].

The air mass L through which the direct rays of the sun must pass depends of course on the solar elevation angle above the horizon. For angles $V > 25^0$ a simple drawing will reveal that the air mass $L = 1/\sin V$, for in this case it is reasonable to assume that the earth is a flat surface, and the atmosphere is a thin, flat layer above it. The curvature of the earth can be ignored. For example, if the angle $V = 30^0$, then $L = 1/\sin 30^0 = 2$ air masses. However, for angles below 25^0 it becomes necessary to take the curvature of the earth and temperature gradients in the atmosphere into consideration, and the connection between the air mass and the solar elevation angle becomes more complex. Fritz Kasten and Andrew Young have developed a good, practical formula for use with small solar elevation angles [2]:

$$L = \frac{1{,}002432\ \sin^2 V + 0{,}148386\ \sin V + 0{,}0096467}{\sin^3 V + 0{,}149864\ \sin^2 V + 0{,}0102963\ \sin V + 0{,}000303978}$$

Young's equation is not only valid for small angles; it works fine for angles up to and including 90^0, for the above relationship asymptotically approaches *1/sin V* for angles above 25^0. For example, if the angle $V = 90^0$ is entered into the above equation, one finds $L = 1{,}00$ as one should when the sun is at the zenith. Equation (3) has been used in the calculations of solar irradiance in this paper.

The term I_F in the irradiance equation accounts for the diffuse irradiance on the horizontal surface due to scattering from the sky and from clouds. In previous work we have demonstrated how the diffuse irradiance depends upon atmospheric turbidity [3]. The *Linke turbidity factor* is a good measure of atmospheric clarity, being equal to unity for a "perfectly clear" Rayleigh atmosphere with no aerosol, about 3 for a typical day and around 8 for an exceptionally hazy atmosphere. The precise definitions can be viewed in the reference cited at www.soldata.dk under the heading "Download documents".

The model calculations (red graph) shown in Figure 3 are based on the radiation model just described. The model has been implemented in *Excel*. The input data required are: *latitude* and *longitude* of the location of interest, UTC and the *day of the year* - this permits calculation of F_J; the *solar declination angle*, time and declination permit computation of the solar elevation angle V; the *air mass L* follows from Young's formula when V is known.

The only "adjustable" parameter in the irradiance equation is the attenuation factor a. Fine tuning a in the *Excel* spreadsheet permits the radiation model to be fitted closely to the observed data. This fitting process can be carried out for entire blocks of data or for selected time intervals to reveal the best value of the atmospheric attenuation during the period of interest.

4. CONCLUSIONS

The Danish Galathea 3 Expedition offered a unique opportunity to perform world wide global radiation measurements using several different pyranometers. The instruments should good agreement under a wide range of temperatures and solar elevation angles. A simple clear day irradiance model for global solar irradiance on a horizontal surface was developed for use with the data. The model permitted investigtation of the attenuation factor a in many different locations and atmospheric conditions. The model yields best agreement between observations and the model in Arctic regions for values of a in the range from 0.8 to 0.9, while a value between 0.7 and 0.8 often yields best agreement in the tropics.

REFERENCES

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