INTERNATIONAL ENERGY AGENCY
SOLAR HEATING AND COOLING PROGRAM
TASK 9F. Work item 9f1.

# USING PYRANOMETERS IN TESTS OF SOLAR ENERGY CONVERTERS:

## Step-by-step instructions.

by

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Cover Photo: Flat plate collector located at the Solar Energy Test Facility, Queen's University, Kingston, Ontario, Canada (Photo by D.I. Wardle).

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## Abstract

This report offers a step-by-step guide to the measurement of global solar radiation for the purpose of determining the efficiency of flat plate solar collectors. It provides persons testing the efficiency of collectors with a straightforward set of procedures to simplify the task of measuring solar irradiance without jeopardizing the accuracy of those measurements. Comprehensive instructions are provided for each stage of the procedure, including where to obtain instrument responsivities and how to install and operate pyranometers and their data acquisition systems. Appendices provide information on the World Meteorological Organization (WMO) solar radiation centres, the addresses of instrument manufacturers and the appropriate algorithms that may be required.

It is assumed that the individual using this manual has some technical expertise in collector installation and operations, but is not necessarily familiar with the measurement of solar radiation.

This report represents a collaboration between radiation scientists from North America and Europe working under the auspices of the International Energy Agency (IEA) Solar Heating and Cooling Program Task 9, Solar Radiation and Pyranometry Studies.

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## Context

A number of recent developments in pyranometry can be directly linked to the need to test solar energy conversion systems accurately under outdoor field conditions. Twenty years ago, experts working in the field of solar engineering discovered that radiation measurements could be wrong by as much as 10% when pyranometers were used under what appeared to be reasonable conditions. The causes of these large errors are now understood, partly because of research and development work accomplished under the auspices of the IEA Solar Heating and Cooling Programme. Knowing and taking advantage of these results reduces the uncertainty in the measurements of solar irradiance to the order of 10-20 $Wm^{-2}$ RMS (1 - 2% of full scale) for 10-minute mean values. The instructions presented in this manual are intended to help solar collector researchers take advantage of these developments without devoting excessive time and effort to the study of pyranometry. The user of these guidelines will avoid serious errors and can probably achieve measurement accuracies approaching the best that are currently possible. The instructions can also be used to determine how much effort will be required for different levels of accuracy. This information may be of use when a work plan for any particular collector testing project is being made.

A typical application would be the testing of flat solar energy converters or flat arrays of converters such as thermal collectors or photovoltaic (PV) modules, for which the available solar power is expressed by the irradiance. The test compares the output from the converter with the radiation energy available to it during some specified interval, usually between 10 minutes and one hour (one-minute and shorter intervals are sometimes used). The result, called *efficiency,* is the ratio of these energies. The comparison should be repeated enough times to establish the behaviour of the system under a variety of atmospheric conditions and its overall reliability. The duration of the test can vary between a few hours and several months. The measurement difficulties associated with the tilting of flat converters into their normal operating position are addressed in these instructions.

These instructions have been developed by a group of scientists who have worked extensively on the characterization of pyranometers and methods of radiation measurements. To ensure that this experience was set forth in a straightforward manner, and that the solar engineering aspects of the document were correct, these instructions were discussed and/or tested by solar collector experts at three major solar converter research facilities in three countries. The comments provided the authors from these institutions have been incorporated into this document.

The target audience is assumed to have backgrounds in physics, engineering or equivalents, but with experience in solar energy research and development. Brief explanations are included in the main text with the instructions, while more detailed information is provided in a number of appendices. It is intended that individual readers judge from the main text which, if any, of the appendices they need to consult.

## 1. Instrument choice

1.1 Choose the pyranometer to be used for the test. It should not be of the Black and White type because these instruments are excessively sensitive to the tilt of the instrument (up to 8%). Types based on silicon photodiodes are not suitable because of spectral effects. Temperature compensated models are preferable. Appendix 2 gives some types that are suitable.

1.2 Identify a laboratory, preferably in your own country, where pyranometers are regularly calibrated. Appendix 4 lists institutes accredited by the World Meteorological Organization as Regional Radiation Centres. If the country in which the work is being done does not have a Regional Radiation Centre, the National Radiation Centre can be found from the closest Regional Radiation Centre. Appendix 4 also lists radiation laboratories, excluding manufacturers of pyranometers, which have participated in IEA radiation measuring work. These should be excellent providers of calibration services or advice.

1.3 Ask the scientist or engineer in charge of the radiation laboratory to confirm that:

i) the pyranometer is suitable for use in a collector test,
ii) the laboratory can and will calibrate your pyranometer,
iii) the calibration is traceable to the World Radiometric Reference,
iv) the setting of the bubble level on the pyranometer can be tested in the laboratory or guaranteed accurate to within 0.3 degrees or better.

Find another instrument and/or another radiation laboratory if not satisfied with the answers.

## 2. Calibration strategy

2.1 Obtain an estimate of the length of time required by the radiation laboratory to make the calibration of the instrument. A quote on the cost of the calibration and what it will provide should be obtained before the instrument is sent to the calibration facility. A typical charge for a calibration is 10 - 15% of the purchase price. Based on this information, choose your calibration strategy: i.e., whether to have a calibration before or after the test. Although pyranometers are not normally calibrated more frequently than once per year, pre- and post- test calibrations are advantageous if time and budget permit.

2.2 Find out what conditions the calibration is valid for and whether a modification is recommended for your type of use. These modifications may be either to the instrument (e.g. a thermistor for temperature measurement) or to the responsivity equation. The laboratory should be able to provide assistance in implementing any modifications that they suggest, but an extra charge may apply.

*The calibration given by many radiation laboratories is a responsivity suitable for meteorological use in temperate latitudes and with the instrument in a horizontal position.*

## 3. Installation

3.1 Read the note *Location and orientation of the pyranometer* (Appendix 5) which addresses the need for homogeneous (uniform) radiation over the collector surface and the need to align the pyranometer within 0.5 degrees.

3.2 Ensure that the objects in the field of view of the collector are either (i) distant or (ii) uniform to make the radiation at the collector surface homogeneous by either:

3.2.1a Mounting the collector at the edge of -a roof so that the distance of the nearest part of the ground, as seen by the collector, is at least five times greater than the largest linear dimension (width or height) of the collector (Figures 1 and 2).

or

3.2.l b Finding, or making, a flat area with a uniform surface (grass or concrete) which is large enough to include an area of dimensions 10m x 10m for a collector with gross dimensions of 1 m x 1 m, which would be located at the middle of the north side of the square (or the south side if the installation is in the southern hemisphere). For collectors of other dimensions, the area should be approximately ten times the gross linear dimensions of the collector. Raising the collector so that its lower edge is at least 1.0 m above the ground (see Figure 3) is also advisable.

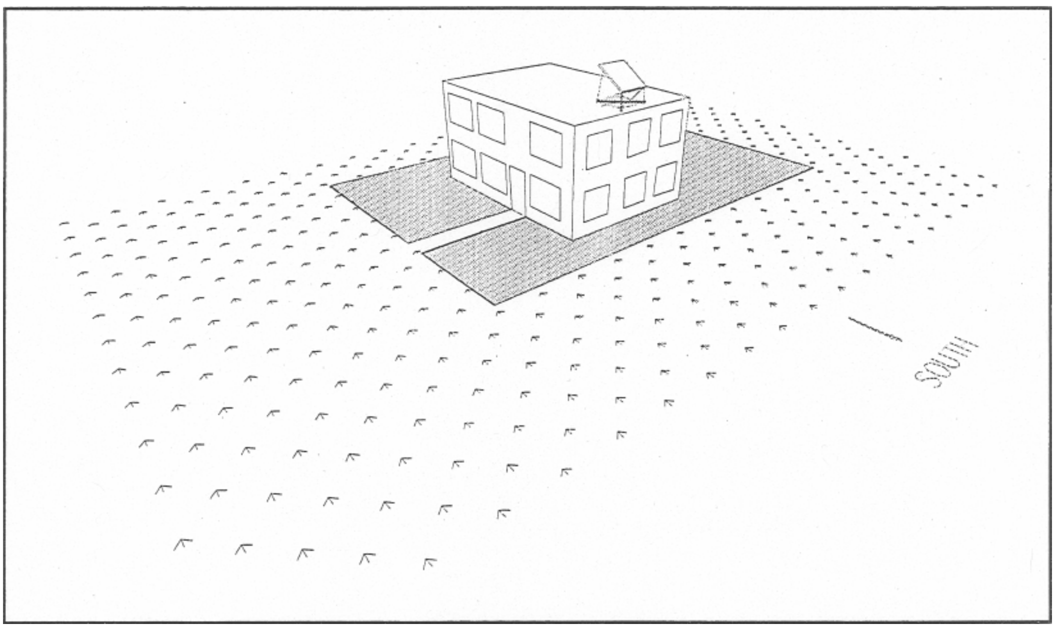


**Figure 1** Ideal location. The collector is at the edge of the roof, with no objects in the field of view. It receives homogenous (uniform) radiation over the collector surface. The major drawback of this location is that access to the front of the collector may be difficult and safety problems could arise.

3.2.2 If several collectors are to be tested simultaneously, they can be deployed side-by-side so that their surfaces are essentially coplanar. This reduces the required ground area.

3.2.3 If several collectors are to be tested simultaneously, it is recommended that each collector be equipped with its own pyranometer.

3.2.4 If only one pyranometer is available to monitor the incoming irradiance for several collectors, it should be mounted independently. The task of ensuring uniform radiation

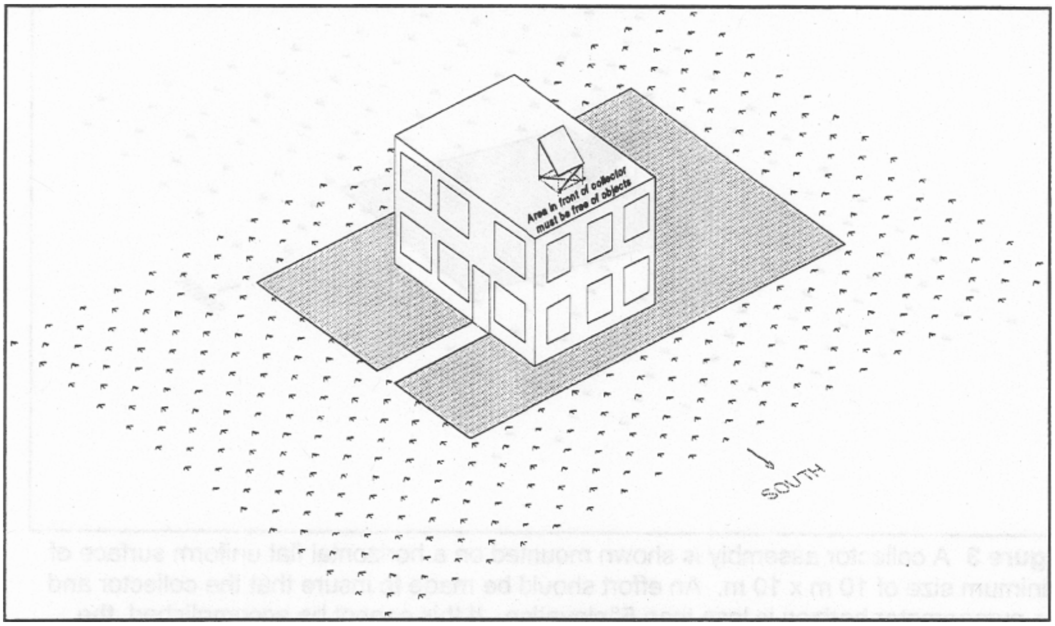


**Figure 2** Alternate location. A more practical and safer location for a collector assembly on the roof of a building, which still takes advantage of the height of the building, is back from the edge of the roof. The immediate foreground must be uniform. There cannot be any vents or similar features in front of the collector.

over the collector(s) and pyranometer is then not trivial. To assure better uniformity over the entire array of equipment, the size of the flat area on which the collectors are deployed should allow every collector and the pyranometer to be at least 12 m from the south edge and at least 6m from the east and west edges. This is 40% larger than what would follow logically from that shown in Figure 3 when extended to multiple collectors each having their own pyranometer. Aligning the collectors and pyranometer is discussed in paragraph 3.5.4 and in Appendix 6.

3.3 Decide whether to mount your pyranometer in a ventilated housing. The main advantage of using a ventilated housing is to keep the pyranometer free from frost, ice, snow and rain. Also, it probably improves the signal quality, especially during calm conditions. An expert from a national or regional radiation laboratory may be consulted about what type, if any, ventilation system to use. Most ventilators either attach to the pyranometer so that the mounting is unchanged or envelop the pyranometer and are mounted using three levelling screws. Figure 9b in Appendix 6 shows a pyranometer in a ventilated housing.

3.4 Choose where to place the pyranometer. The instrument should be in approximately the same plane as the collector and as close to it as possible. The middle of the top edge of the collector (location A in Figure 4) is a good place unless the pyranometer is made inaccessible for inspection and cleaning. Close to one of the side edges of the collector (location B in Figure 4) is a reasonable alternative.

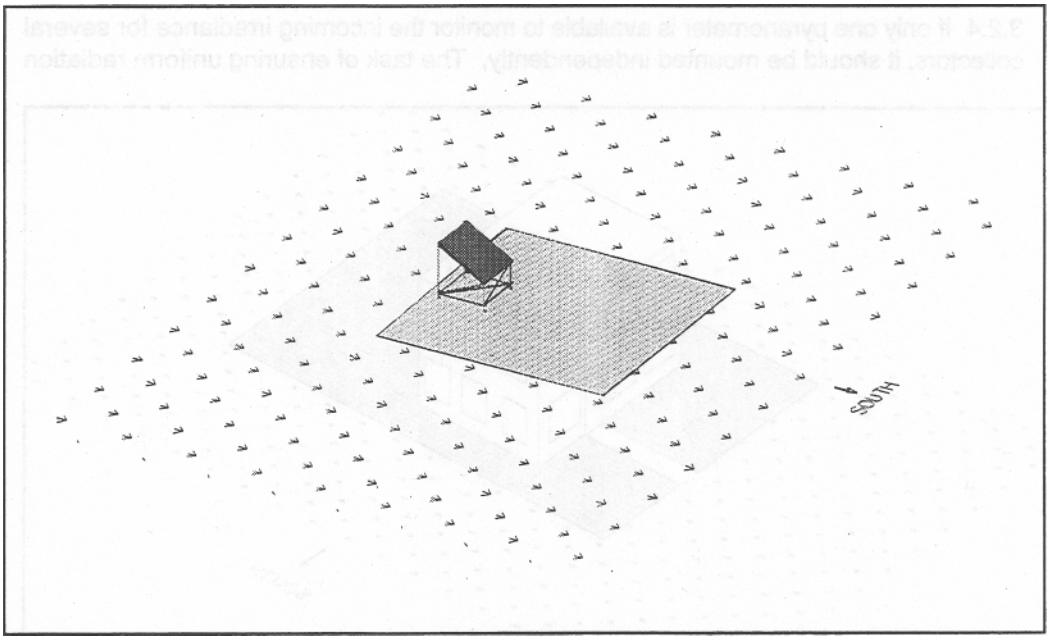


**Figure 3** A collector assembly is shown mounted on a horizontal flat uniform surface of minimum size of 10 m x 10 m. An effort should be made to insure that the collector and the pyranometer horizon is less than 5°elevation. If this cannot be accomplished, the actual horizon should be documented and its influence considered on the overall results of the test. This problem is often encountered in urbanized or mountainous locales.

3.5 Decide how to mount the pyranometer so that it can be aligned with an accuracy of ±0.5 degrees. This important task can be accomplished by a capable technologist, but might require considerable thought and effort. The instrument mounting must be rigid and should take advantage of the three levelling screws and bubble level with which most pyranometers are equipped. The following suggestions are among the simplest and most reliable solutions. Either:

3.5.1 Construct a rigid rectangular frame that can be tilted about an axis along one of its edges. Fix the collector to the frame and adjust either the attachments of the frame to the ground or those between the collector and the frame so that the collector surface is horizontal. Next, fix the pyranometer to the frame and use its levelling screws so that its axis is vertical. Finally, tilt the frame so that the collector is at the orientation required for the test.

or

3.5.2 Attach the pyranometer to an edge of the collector in a way that allows its adjustment screws to be used. Place the collector on the ground and put various spacers under its edges so that the surface is horizontal. Adjust the pyranometer so that

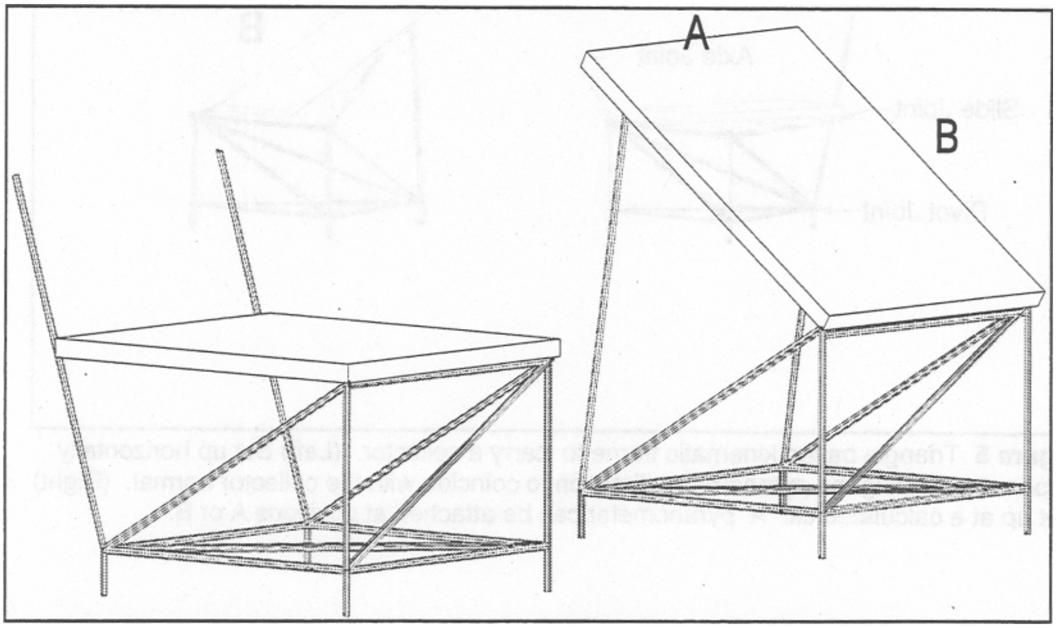


**Figure 4** Rectangular frame to carry a collector. (Left) Set up horizontally to permit adjusting the pyranometer angle to coincide with the collector normal. (Right) Set up at a calculated angle. A pyranometer may be attached at position A or B.

its axis is vertical and lock it in position. Now mount the collector in the desired location and orientation.

3.5.3 Both methods are the same in principle: making the adjustment while the collector and pyranometer are horizontal and then tilting them both while maintaining their rigid connection. While the alignment of the pyranometer to the collector needs to be accurate to within ±0.5 degrees, knowing the actual orientation of the complete system so precisely may not be necessary.

3.5.4 When several collectors are served by a single pyranometer, each collector must be aligned in precisely the same orientation. Even slight differences between the orientation of collectors could result in significant discrepancies in collector efficiency. Therefore, the collectors should be adjustable when in the tilted position, which is not necessary when individual pyranometers are attached to each collector. Consult Appendix 6 *Separate pyranometer mounting* for a suggested method of achieving the required alignment.

3.5.5 Two simple types of metal frame collector mountings, capable of the required adjustments, are illustrated. The more conventional rectangular frame (Figure 4) is easier to construct than the triangular-based structure (Figure 5). The latter, however, especially if its front two feet were adjustable, is easier to operate. This is because the tilt is controlled by just one length rather than by two and the distortion of the collector out of its plane would be impossible. Figure 6 provides details of the labelled mounting brackets of Figure 5.

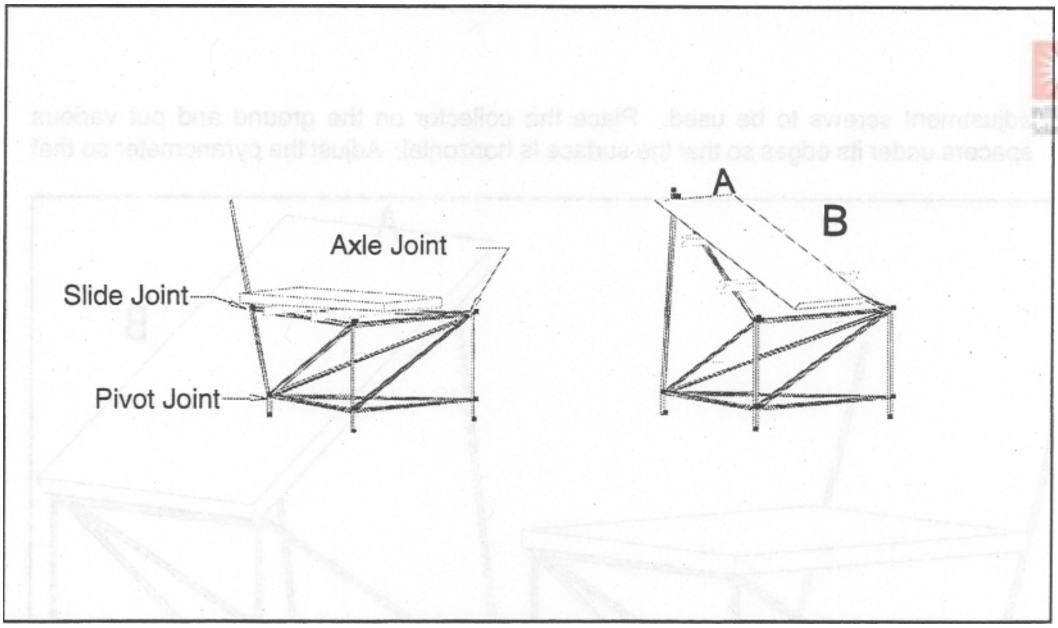


**Figure 5** Triangle based kinematic frame to carry a collector. (Left) Set up horizontally to permit adjusting the pyranometer direction to coincide with the collector normal. (Right) Set up at a calculated tilt. A pyranometer can be attached at positions A or B.

3.6 Check the orientation of a pyranometer. The method described here applies to orientations tilted roughly southward by roughly the latitude angle. In this orientation, the sun would shine directly down on the pyranometer on one day in spring and one day in fall. This method would work during a week on either side of these days.

This procedure requires a transparent tube of about 6 cm internal diameter and 20 cm in length (Figure 8). One end is fitted with a circular metal plate with three 1 mm diameter holes - one is at the centre and the others, which are not essential, are about 8mm away from the centre. An opaque plate, its centre marked with a cross, is mounted about 5cm up from the base of the tube. Three sectors are removed from the base of the tube leaving three 'feet' so that it can be placed on the pyranometer positively. It is assumed that this surface of the pyranometer is either at right angles to its central radiometric direction or that its orientation to the radiometric central direction is known.

When the tube is held against the pyranometer, the spots of sunlight passing through the holes move across the opaque lower plate. The precise time when they pass the tilted line of the cross can be recorded and the corresponding solar azimuth and elevation calculated using the algorithm in Appendix 7. The time can be determined within about 60 seconds, which is equivalent to approximately 0.25 degrees in the azimuth. A tube like this is also useful because an inclinometer can be put on the top edge to measure the pyranometer tilt.

3.7 It is recommended that the pyranometer be mounted so that the electric cable leaving it points downhill to prevent water accumulating in the connector.

3.8 Make the electrical connections between the pyranometer and the data acquisition system. The best electrical cable is one where one or more pairs of multistrand conductors are wrapped separately in conducting foil (shielded pairs). Insulation on the cable should be able to withstand the climatic conditions associated with the test.

Electrical wire manufacturers or distributors can provide information on the proper cable type, including insulation, for the particular tests being performed.

3.9 If the pyranometer is not temperature compensated, its temperature should be monitored

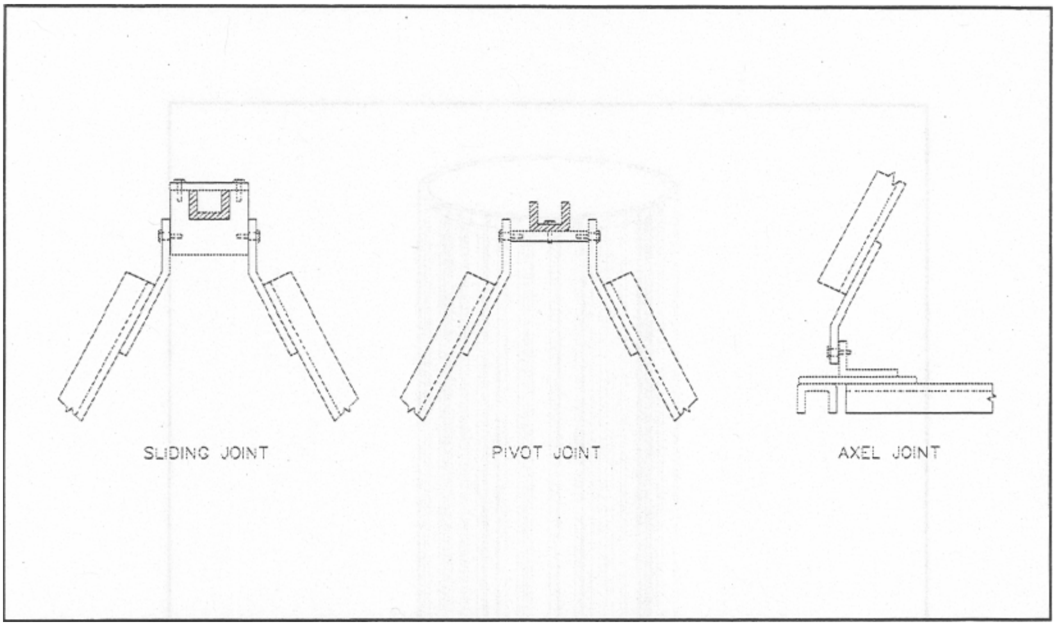


**Figure 6** Details of triangular kinematic frame to carry a collector.

to an accuracy of approximately 2.0 K. A convenient way to do this is to mount a thermistor onto the base of the pyranometer and connect it to the data acquisition system, which would record the resistance. It should be noted that for some data acquisition systems a separate bridge circuit may need to be constructed so that resistance measurements can be made.

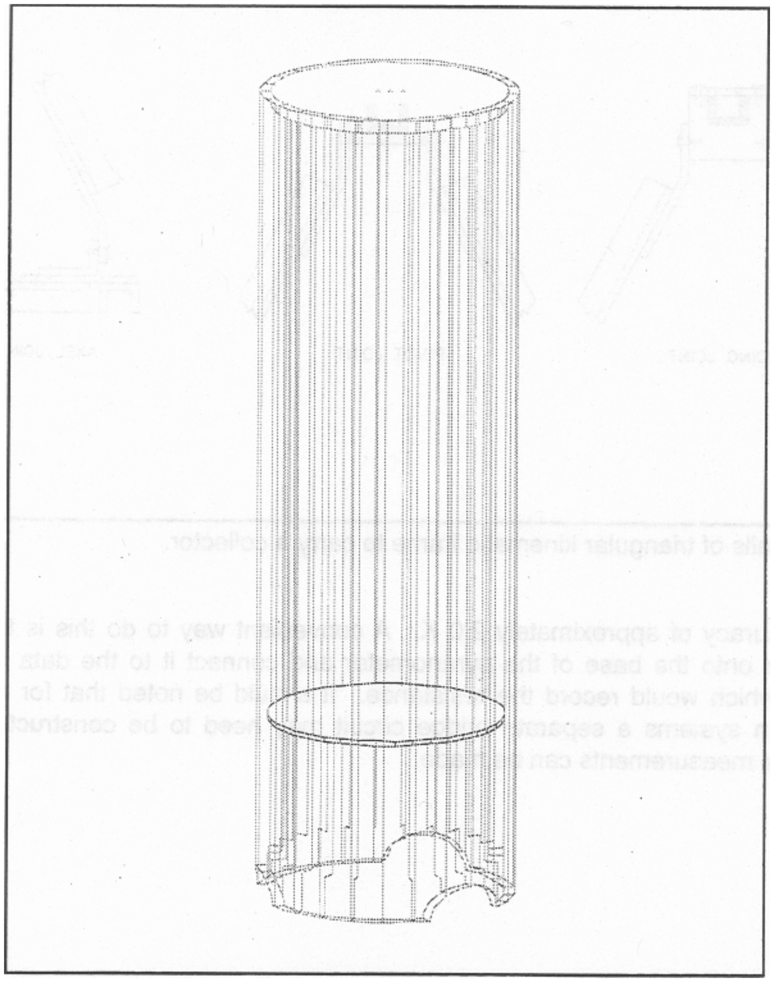

**Figure 7** Transparent tube with sun holes for checking orientation of pyranometer tilted towards the south. The tube is to be held by hand against the pyranometer.

## 4. Data acquisition

4.1 Appendices 8 and 9 provide comprehensive advice on the procurement and installation of data acquisition systems. Individual requirements governing the selection of a system will vary but must consider the following criteria: required accuracy; frequency of measurements; physical robustness of the equipment and accessibility of the recorded data.

4.1.1 Accuracy. A measurement uncertainty of less than 5 μV in 10-minute mean voltage data is ideal. For accuracies better than or equal to this, a data acquisition unit's contribution to the overall uncertainty in radiation measurement can be considered insignificant. An acceptable uncertainty specification, however, could be as large as either 15 μV or 0.3% of the signal. This is approximately equivalent to 2 W $m^{-2}$.

4.1.2 Measurement frequency. In operation, a typical data acquisition system makes measurements on several input channels in sequence. The average signals from many repeated sequences rather than individual samples are recorded. Two time parameters describe this process: (a) the recording interval, which is also the duration of the averaging, and (b) the sampling interval, which is the period between successive measurements on any single input.

a) The recording interval might be set at whatever value is required for the overall test, i.e., 10 minutes, 1 hour etc. However, longer-term averages can easily be computed from short-term data and better quality control can be applied (see later) to the radiation data if it is more frequent. Consequently it is suggested that the recording interval be set at one minute. The only negative aspect of a one-minute interval is the increased data volume, which is unlikely to be significant.

b) Ideally, the sampling interval should be less than half the pyranometer response time. This could be as short as one second for some instruments. However, because radiation changes are not particularly rapid, a two-second interval is satisfactory. A five-second sampling rate is acceptable if the converter test is being done on time averages of ten minutes or greater.

The sampling duration of an individual measurement is also important. This is often set to coincide with the power line AC cycle (e.g., 50 Hz or 60 Hz) so that the measurement has the very desirable feature of being insensitive to power line frequency noise.

4.1.3 Environmental robustness of the equipment and accessibility of the recorded data. Having a data system that functions in all environmental conditions is convenient. However, the design and/or operation of outdoor robust systems usually involves some sacrifice in measurement frequency and/or data availability and/or accuracy. One should be able to examine, anytime, both the instantaneous measurements and the data acquired during the preceding few hours. If the test is to continue for more than one day, being able to calculate the results daily is important so that if a fault should develop in the equipment it can be recognized promptly and corrected. These features can be programmed into a data acquisition system of the type in which a computer controls all the actions of multiplexing, measurement and storage. Such systems are not usually robust and need to be inside a building. Thus the researcher may be faced with the choice between an ideal system and the compromises caused by logistics, accuracy, convenience and costs.

4.2 If the data acquisition system does not meet the general requirements for accuracy and measurement frequency or the requirements for robustness or data accessibility, try to obtain a more suitable system. If this is impossible, and the problem is the voltage measurement uncertainty of the system, estimate its contribution to the irradiance measurement errors and decide whether the error is tolerable. To calculate this, an approximate value of the pyranometer responsivity is needed (refer to Appendix 2). These instruments and many other instruments have a manufacturer's original responsivity on the body of the instrument.

4.3 Similar difficulties may also be faced with respect to sampling frequency, a fixed sampling time and easy accessibility to the recorded measurements. Many small data acquisition systems have fixed sampling functions to increase simplicity and reduce cost. These should be carefully considered before obtaining such a system for collector efficiency testing.

## 5. Electrical Tests

5.1 Test the pyranometer input to the data acquisition system.

5.1.1 Measure the electrical zero. This test should be done near the location where the pyranometer is to be placed to ensure that the cabling is free from induced signals. Disconnect the pyranometer and replace it with a resistor of about the same value as the pyranometer resistance (Appendix 2). Check that the voltage reading is zero to the accuracy specified for the data acquisition system. If not, determine whether the output is due to a fault in the system by performing the same zero test with the resistor attached directly to the input terminal of the unit. Servicing by authorized personnel is required if the data acquisition unit fails. If the unit does require servicing it is also a good opportunity to have the unit calibrated; a procedure that should be repeated every two years. If the problem is not found in the data acquisition unit, it must be assumed that local conditions are causing electrical interference. The cabling should be rerouted and the test repeated. Interference can be reduced by keeping signal cables *away* from power cables. It is good practice to avoid parallel routing and to intersect all cables at 90 degrees whenever possible.

5.1.2 Measure the lead resistance. Short the resistor and measure the resistance of the leads as seen by the data acquisition system (a bridge circuit may have to be built for this test depending upon the capabilities of the system). The resistance should be less than 10 ohms. If the resistance is satisfactory, the resistor (and bridge) can be removed from the circuit and the pyranometer returned. If the value is excessive, determine if this is a result of the length of the cabling. This can be accomplished by calculating the overall resistance of the cable by either measuring a short length of similar cable or obtaining the specification of resistance per unit length from the manufacturer. Once the unit length is obtained, an approximate value of the entire length can be calculated. If the resistance can be attributed to the length of the cable one can account for the commensurate loss in voltage when the measurement is converted into engineering units. If the resistance is greater than indicated by the length of the cable, it is caused by a fault within the cable. This must then be repaired or replaced.

5.1.3 Test the complete system. Measure the resistance of the pyranometer as installed with the data acquisition system and check that it is approximately within the manufacturer's specification. This has to be done at night or with the dome covered unless the resistance measurement is in the offset compensation mode in which case it would be unaffected by the pyranometer signal voltage.

## 6. Operation and data quality control

6.1 Clean the pyranometer with lint-free tissue and an alcohol-based cleaning fluid before each day's set of measurements. If the experiment is to be run continuously the cleaning of the pyranometers should be before sunrise. If this is impractical, the instruments should be cleaned as early in the morning as possible and the time and duration of servicing noted in an appropriate logbook.

6.2 Measure the signal from the pyranometer at night. The output voltage when divided by the pyranometer responsivity should be equivalent to between 0 and -5 $Wm^{-2}$. This measurement should be repeated on several nights throughout the test period.

6.3 Consider programming the system so that:

i) it reports any irradiance values outside the range $-6 < E < 1050$ $Wm^{-2}$. On partially cloudy days, instantaneous measurements of greater than 1300 $Wm^{-2}$ can be recorded, but cannot be sustained. The program should not be designed to delete any data automatically.

ii) it produces a daily graphical record of the irradiance on a resolution of one minute. A graph with this resolution can reveal intermittent faults such as measurement dropouts or shadowing of the sensor by birds or animals that cannot be found in data based upon longer averaging periods. This procedure is strongly recommended.

6.4 Maintain a logbook in which the sky condition and any other relevant information are recorded. This can be either written or computerized. The advantage of the latter method is its ability to co-locate the human observations with the test data. The advantage of having all of this information in the same format may justify any increase in the cost, and/or the complexity of the system. Caution should be used, however, when designing such a system so that it does not intimidate the observer. A clear well-written notebook is superior to a computerized format that is not used.

## 7. Data evaluation

7.1 Compute the radiation according to the following algorithm:

$$E = (V_S - V_0)/R$$

where:

E is the required mean irradiance in $Wm^{-2}$

$V_S$ is the signal in µV

$V_0$ is the night signal in µV. The average of measurements made between approximately one hour after sunset and approximately one hour before sunrise over several nights throughout the evaluation period should provide a value that is sufficiently accurate for the test. This value is normally small in magnitude and negative. For long term testing or increased accuracy, the nighttime offset can be calculated for a given day based upon two one-hour average values obtained about one hour before sunrise and about one hour after sunset.

R is the responsivity of the pyranometer in $\mu V\ W^{-1}\ m^2$. This value is given by the radiation laboratory that calibrated the instrument.

A factor describing the change of responsivity with temperature must also be introduced in the algorithm for instruments that are not temperature-compensated. This factor is often included as part of the calibration.

## 8. Measurement uncertainty

8.1 The use of a high quality pyranometer and a calibrated data acquisition system that has a resolution of approximately 10 times greater than the accuracy required in the measured signal should give an overall uncertainty in the order of 15 to 20 Wm $^{-2}$ rms over a 10-minute averaging period when these instructions are followed. The contributions of systematic and random errors are approximately equal in this range. These uncertainties apply to full-scale measurements (1000 Wm $^{-2}$).

8.2 Uncertainty depends on the amount and distribution of the irradiance and on the integration time. This dependency is not severe, however, except for low solar elevation angles during clear periods. For solar elevations greater than 20°, pyranometer uncertainty approximates a square root dependence on irradiance (i.e., 7.5-10 Wm $^{-2}$ at 250 Wm $^{-2}$). Percentage error is not quoted because of this non-linearity. For hourly data and for minute data, the uncertainties are very roughly 75% and 150% respectively of the values for 10-minute data. If the pyranometer is not one of the best types but merely one of good ones listed in Appendix 2, the uncertainty could be as much as 30 Wm $^{-2}$. During periods of direct beam irradiation at low solar elevations, a knowledge of the directional response of the instrument is required. This can be obtained as part of the calibration from many radiation laboratories.

8.2 These measures of uncertainty apply to the irradiance at the pyranometer and do not include effects caused by misalignment between the pyranometer and the tilted collector surface or to a non-uniform (heterogeneous) distribution of radiation over the surface. These effects raise the maximum uncertainty to the range 20-25 Wm $^{-2}$ for the best instruments and approximately 35 Wm $^{-2}$ for the worst case "good" pyranometer.

In summary, using the best equipment and carefully following the instructions should give an uncertainty of less than 20-25 Wm $^{-2}$ rms in 10-minute mean measurements of the solar irradiance incident on the tilted collector surface.

## Acknowledgements

The authors would like to thank Dr. Björn Karlsson of the Swedish State Power Board at Ä rvkarleby, Professor Stephen Harrison of Queen's University, Kingston, Canada and Mr. Matthias Rommel of the Fraunhofer-Institut für Solare Energiesysteme, Freiburg, Germany for their contributions to refining these instructions. Mr. Tom Grajnar was instrumental in reading the early drafts of the manual and commenting on Professor Harrison's implementation of the original instructions. Mr. E. Vala drafted the figures.

# Appendices

## Appendix 1. Mailing Addresses of Authors

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## Appendix 2. Thermal pyranometers

| Instrument[1] | Thermal Compensation[2] | Negligible Directionality[3] | Negligible sensitivity to tilt[4] | Negligible non-linearity[5] | Typical responsivity ($\mu V\ W^{-1}m^2$) | Typical resistance (ohms) |
|---|---|---|---|---|---|---|
| Kipp & Zonen CM21 | yes | yes | yes | yes | 10 | 65 |
| Kipp & Zonen CM10/11 | yes | yes intermediate | yes | yes | 5 | 1200 |
| Kipp & Zonen CM5/6 | no | intermediate | no | intermediate | 12 | 10 |
| Eppley PSP | yes | intermediate | yes | yes | 10 | 600 |
| Eko MS801 | yes | yes intermediate | unknown | yes | 9 | 250 |
| Swissteco SS25 | no | intermediate | yes | yes | 15 | 110 |
| Middleton EP07 | yes | intermediate | yes | yes | 12 | 10 |

Notes:

1 Several new instruments are now on the market, but have not been tested. These include new instruments by Eko, Middleton and Swissteco. A new company, Yankee Environmental Systems Inc. also produces pyranometers.

2 Thermal compensation indicates whether or not the instrument is equipped with a circuit which removes the temperature dependence effects of the thermopile.

3 Negligible directionality: Yes, indicates a directional error of less than 10 $Wm^{-2}$ (based upon a normal incident beam flux of 1000 $Wm^{-2}$) for all angles above a solar elevation of 70°. Intermediate indicates an error of up to 20 $Wm^{-2}$. The instruments of some manufacturers vary between these values. This illustrates the importance of having individual instruments tested if low uncertainty is important.

4 Negligible sensitivity to tilt. Yes, indicates less than a 0.5 % change in the responsivity of the instrument from the horizontal to a 90° angle. Intermediate indicates the change in responsivity is less than 1%. The responsivity of some instruments, such as the CM5/6, can vary by as much as 3% between the horizontal and vertical position

5 Negligible non-linearity: Yes indicates that non-linearity effects are less than ±1.0% over the range 0 - 1000 $Wm^{-2}$. Intermediate non-linearity indicates an effect of ±2.0% over the range 0 to 1000 $Wm^{-2}$.

## Appendix 3. Pyranometer Manufacturers

**EKO Instruments Trading Co., Ltd.**
21-8, Hatagaya 1-chome
Shibuyaku
Tokyo, 151
Japan

Telephone: 81-3-3469-4511
Facsimile: 81-3-3469-4593

**Eppley Laboratory, Inc.**
12 Sheffield Avenue
Newport, Rhode Island 02840
United States of America

Telephone: (401) 847-1020
Facsimile: (401) 847-1031

**Kipp and Zonen Delft BV**
Mercuriusweg 1
P.O. Box 507
NL 2600 AM Delft
The Netherlands

Telephone: 015-561 000
Facsimile: 015-620 351

**Carter-Scott Manufacturing Pty. Ltd.**
(Middleton)
22 Ailsa Street
Box Hill
Victoria 3128
Australia

Telephone: (61-3) 9899 4266
Facsimile: (61-3) 9899 4277

**Philipp Schenk GmbH Wien & Co KG**
Jedleseer Straße 59
A-1210 Wien
Austria

Telephone: 022 2/3851 31-0
Facsimile: 022 2/3812 28 12

**Swissteco Instruments**
Stegweg, Eichenwies
Ch-9463 Oberriet SG
Switzerland

Telephone: 071-782 717

**Yankee Environmental Systems, Inc.**
P.O Box 746
Montague Industrial Park
101 Industrial Boulevard
Turners Falls, MA 01376
United States of America

Telephone: (413) 863-0200
Facsimile: (413)863-0255

## Appendix 4. Resource centres for radiation measurement

### World Meteorological Organization Regional Radiation Centres

#### Region I

Mr. Ali Bekkouche
Chef, Centre radiométrique régionaux
Office National de la Météorologie
B. P. 7022 Sedikkia
Oran
Algérie

Dr. Richid Kensari
Centre radiométrique régionaux
Chef de Service
31 rue Taieb M'Hiri
2026 Sidi Bou Said
Tunisie

Regional Radiation Centre Khartoum
C/O Meteorological Department
P.O. Box 574
Khartoum
Sudan

Regional Radiation Centre Lagos
C/O Headquarters
Meteorological Department
Private Mail Bag 12542
Lagos
Nigeria

Mr. Darwish Mohamed Ahmed
Director of the Regional Radiation
Centre
The Egyptian Meteorological Authority
P.O. Box 11784
Cairo
Egypt

Centre radiométrique régionaux
Kinshasa
C/O Agence national de Météoroligie et
de
Télédétection par satellite
(METTELSAT)
B. P. 4715 Kin. II
Kinshasa
Zaire

#### Region II

Dr. V. Desikan
Director of the Regional Radiation
Centre
Instruments Division
Meteorological Office
Pune 411 005
India

Mr. Masanori Shiraki
Director of the Regional Radiation
Centre
Observations Division
Observations Department
Japan Meteorological Agency (JMA)
1-3-4, Otemachi, Chiyoda-ku
Tokyo 100
Japan

**Region III**

Mayor Gustavo Ruben Talamoni
Director, Centro Radiometrico Regional
Servicio Meteorologico Nacional
25 de Mayo 658
1002 Buenos Aires
Argentina

Sr. Jorge Carreno Campos
Subjefe Subdepartamento Climatologia
Centro Radiometrico Regional
Direccion Meteorologica de Chile
Casilla 717
Santiago
Chile

**Region IV**

Mr. D. Nelson
NOAA
CMDL R/E/CG1
325 Broadway
Boulder, CO 80303
USA

Dr. Igancio Galindo
Centro Radiometrico Regional
Centro Universitario de Investigaciones
en
Ciencias de la Tierra
Universidad de Colima
25 de Julio No. 965
Villas San Sebastian Colima
Colima
Mexico

Dr. L.J. Bruce McArthur
Head of the Regional Radiation Centre
Experimental Studies Division
Atmsopheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4
Canada

**Region V**

Dr. Bruce Forgan
Regional Radiation Centre
Supervisor Laboratory and Radiation (SRLR)
Bureau of Meteorology
GPO Box 1289 K
Melbourne, Vic. 3001
Australia

## Region VI

Centre radiométrique régionaux Uccle
do Institut royal météorologique de Belgique
3 av. Circulaire
B-1180 Bruxelles
Belgium

Dr Klaus Dehne
Director, Regional Radiation Centre
Meteorologisches Observatorium Potsdam
Deutscher Wetterdienst
Postfach 600552
D-14405 Potsdam
Germany

Regional Radiation Centre St. Petersburg
ROSCOMHYDROMET
Main Geophysical Observatory
7, Karyshev Street
194081 St. Petersburg
Russian Federation

Dr. Claus Frölich
Director of the World Radiation Centre Davos
Physikalisch-Meteorlogisches Observatorium Davos
Dorfsrasse 33
CH-7260 Davos Dorf
Switzerland

Mr. Jean Olivieri
Centre radiométrique régionaux
Chemin de L'Hermitage
Hameau de Serres
F-84200 Carpentras
France

Regional Radiation Centre Budapest
c/o Inst. for Atmospheric Physics
P.O. Box 39
H-1675 Budapest
Republic of Hungary

Dr. Lars Dahigren
Chief, Regional Radiation Centre
Swedish Meteorological and Hydrological Institute
Folksborgsvägen 1
S-601 76 Norrkoping
Sweden

Regional Radiation Center Bracknell
c/o UK Meteorological Office
Met. O(OP)
London Road
Bracknell, Bershire RG12 2SZ
United Kingdom

NOTE: If there is not a Regional Radiation Center in the country, please contact one of the above centres to obtain the address of a certified national or private laboratory where calibrations can be obtained.

## IEA Participating Laboratories
(not otherwise listed)

C.V. Wells
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
U.S.A.

L. Leidquist
Swedish National Testing Institute
S-50115 Borås
Sweden

## Appendix 5. Location and orientation of the pyranometer

The pyranometer must be mounted so that it receives the same radiation as the collector surface. This is not difficult when the surface is horizontal. The pyranometer can be put near the collector and, if there are no close objects in the field of view, both will receive the same radiation. The three levelling screws and the spirit level that are installed on most pyranometer models can then be used to make the radiometric axis vertical (i.e. so that it measures horizontal irradiance). This adjustment can be made quite easily to an accuracy of ±0.25 degrees.

When the surface is tilted, however, which is usually the case, two potential problems exist.

The first problem occurs because the collector and pyranometer receive radiation not only from the sky but also from the ground. This reflected radiation can account for as much as 25% of the total energy incident on the collector. If the ground is not uniform over distances many times the dimensions of the collector, the radiation over the surface of the collector itself will not be uniform and the average intensity may be different from a pyranometer placed close to its edge.

The second problem is that setting the orientation of the pyranometer so that it coincides with that of the collector area may be difficult. Slight mis-alignments between the collector and the pyranometer could result in significant errors in the calculation of collector efficiency. This problem is most apparent on clear days when a large fraction of the total irradiance is coming from the solar beam directly. For example, an error in alignment of 0.5 degrees can cause a measurement error of up to 9 $Wm^{-2}$. This maximum error occurs when beam radiation at maximum strength (1000 $Wm^{-2}$) strikes the pyranometer at 90 degree incidence (glancing incidence). Even if measurements are limited to incidence angles less than 45 degrees, which may be appropriate for collector tests, the 0.5 degree error can cause a discrepancy of 6 $Wm^{-2}$. For this reason, it is suggested that careful attention be paid to achieving an alignment accuracy better than 1.0 degrees. A target ±0.5 degrees is recommended.

## Appendix 6. Separate pyranometer mounting

The orientation of the collector surface must be determined before mounting a pyranometer separate from the collector. If the mounting is of the type shown in Figures 4 & 5, the tilt can be easily calculated from the dimensions of the structure. Tilt can also be measured to an accuracy of about ±0.5 degrees with a good inclinometer (Figure 8). When using an inclinometer it is best to take pairs of readings with the instrument pointed alternately up and down the slope.

The azimuth can be determined by observing when the direct beam solar radiation grazes the surface of the collector either in the morning or afternoon or, preferably, both. An algorithm written in BASIC which computes the solar azimuth and elevation to an accuracy of 0.1 degrees is given in Appendix 7.

The azimuth can also be measured very effectively by sighting a theodolite horizontally along the surface of the collector. Surveying techniques can also be used to measure the tilt but the improved accuracy does not warrant the extra effort.

When several collectors are being monitored by one pyranometer, they must be aligned so that they are all co-planar. This has to be done by successive measurement and adjustment.

Figure 9 is an example of a mounting for a pyranometer at a fixed pre-calculated tilt. It comprises:

- a metal post which is assumed to be within a few degrees of vertical and set, in this example, in concrete. In areas where frost is present, the base of the vertical post must be installed to a depth greater than any frost penetration. Similar caution must be used in areas where the near-surface soil conditions are unstable due to soil water content or organic material.
- a capping plate which can be rotated around the post and then clamped at the desired azimuth,
- a base plate mounted on the capping plate with three screws which can be adjusted to make the base plate horizontal.
- another plate to which the pyranometer is mounted so that it is horizontal when this plate is horizontal.

The pyranometer plate and the base plate (detail in Figure 9b) are attached by two side plates machined accurately to the correct tilt angle.

The adjustments on this mounting are both made using bubble level indicators to achieve horizontal orientations which can easily be done to an accuracy ±0.25 degrees. These achieve the required tilt. The azimuth can be tested similarly to the collector surfaces by observing when the sun grazes equally on both side plates. If these two side plates are approximately 20cm long, the measurement accuracy of this method would be approximately ±0.2 degrees. Each time the azimuth is adjusted by rotating the capping plate, the base plate would probably need to be made horizontal levelled, but the pyranometer feet would not require any readjustment.

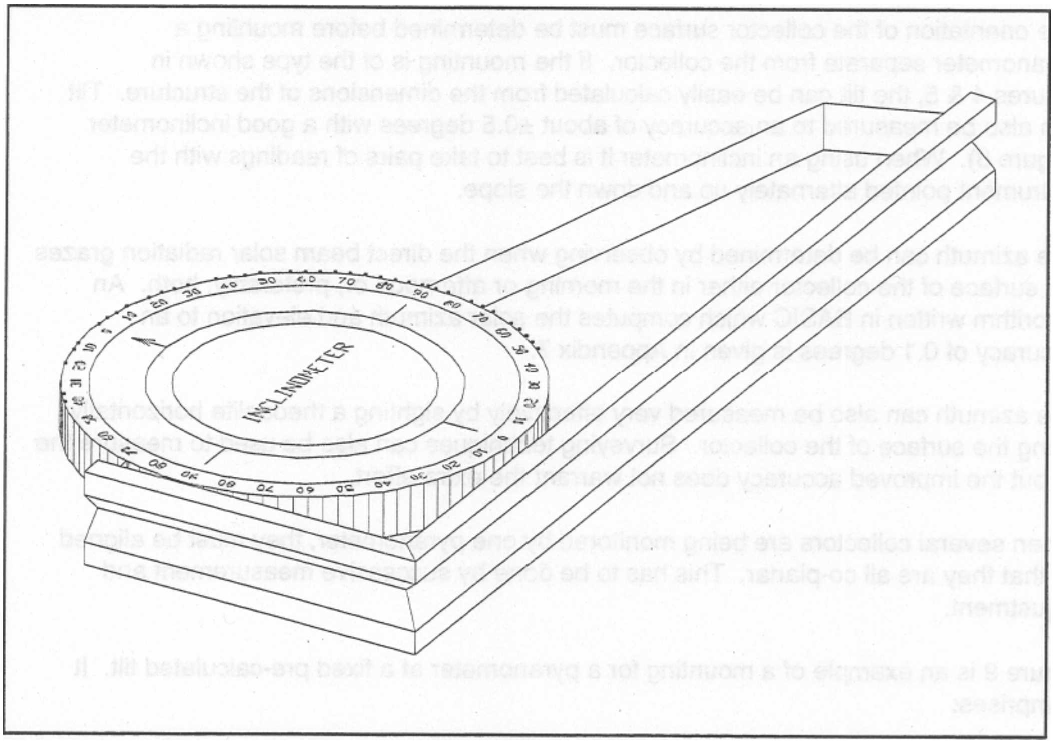
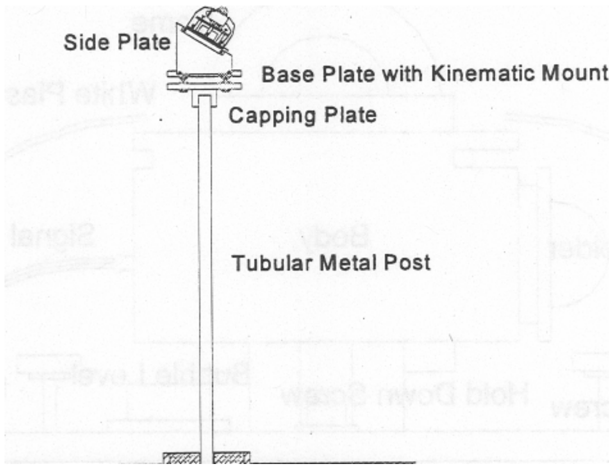



**Figure 8** A precision-made inclinometer with a machined and grooved base can provide a measure of tilt to better than ±0.5 degrees. The instrument should be made of metal with a long reference base and a large diameter dial.

Pyranometer in ventilated housing (see figure 9b for detail)




*iii* base

- * O'< r ',//j/\^ Frost Me

**Figure 9a** A separate mounting for a pyranometer at a specified tilt. The pyranometer is enclosed in a ventilated housing (Figure 9b for detail).

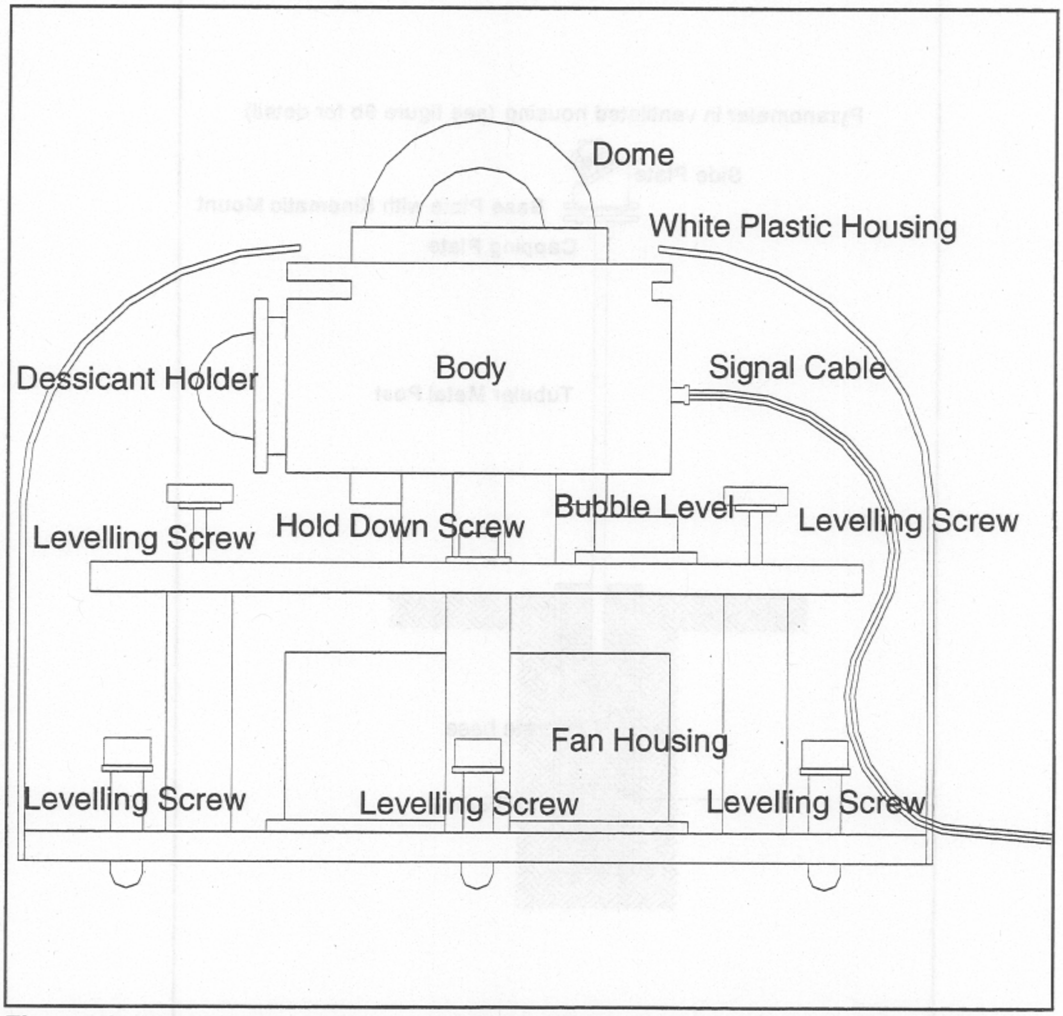



**Figure 9b** Detailed view of a Kipp and Zonen CM11 pyranometer in an AES ventilated housing.

## Appendix 7. Algorithms in BASIC for the calculation of solar azimuth and elevation

Two algorithms are provided for the calculation of astronomical parameters. The first subroutine is based upon the publication of Michalsky (1988) and uses the approximation formulae found in the Astronomical Almanac. The second subroutine is based upon formulae provided by the Royal Greenwich Observatory. Both algorithms give similar results when compared with values published in the Nautical Almanac (Figure 10). The first subroutine is slightly more accurate than the second, but is significantly more complicated. Both provide far greater accuarcy than required for testing simple solar collection systems.

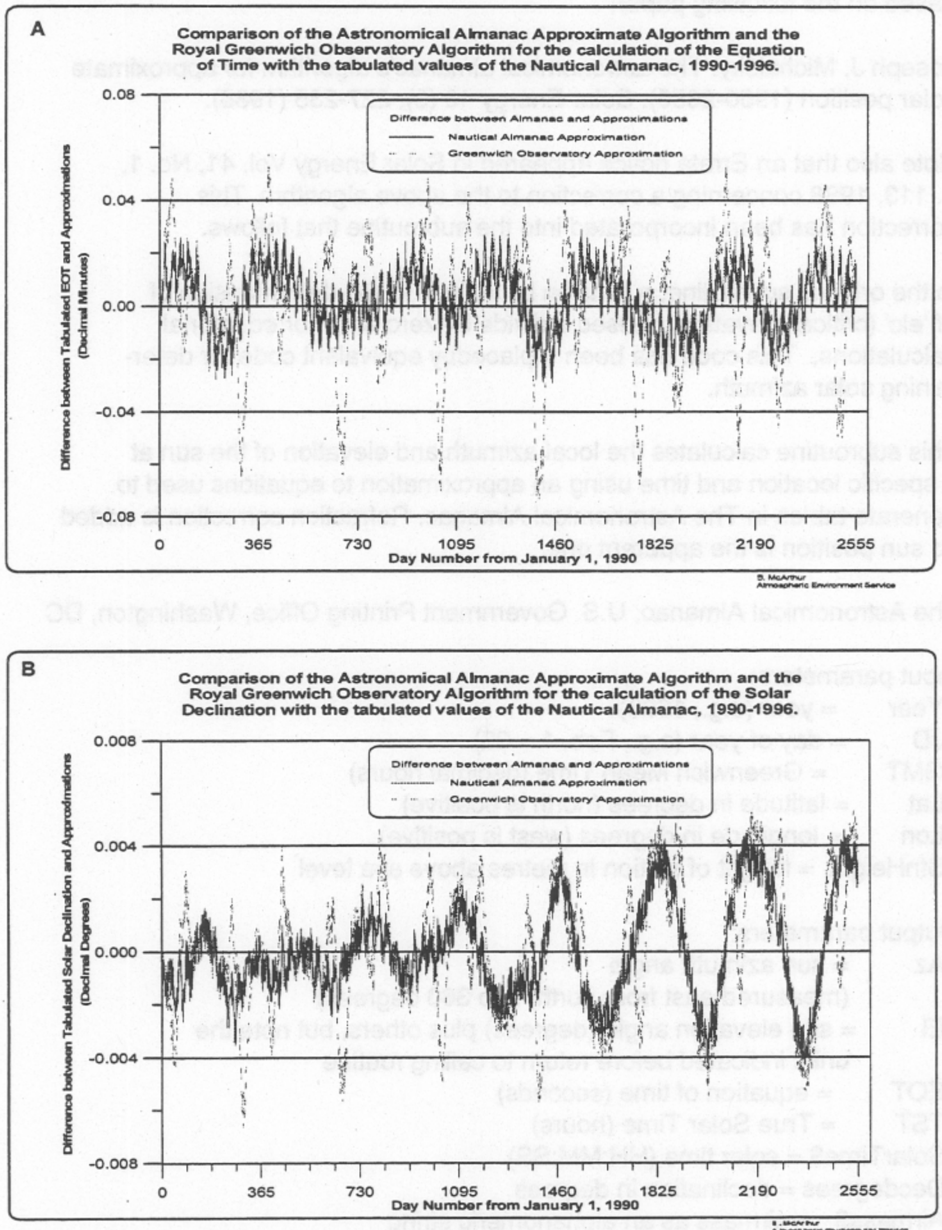



**Figure 10** Comparison of approximations derived from the Astronomical Almanac and the Greenwich Observatory against published values from the Nautical Almanac. (A) Equation of Time, (B) Solar Declination.

Subroutine One: Equations based upon the paper of Michalsky (1988) and the approximate equations given in the Astronomical Almanac.

Note: Subroutine call is to be a single line
SUB AstroAlm (year, jd, GMT, Lat, Lon, StnHeight, Az, El, EOT, SolarTime$, Decdegrees, Airmass$, HaDegrees)

```
'
'====================================================================================
' The following subroutine calculates the approximate solar position and is
' based on the following paper:

' Joseph J. Michalsky: The astronomical almanac's algorithm for approximate
' solar position (1950-2050). Solar Energy 40 (3), 227-235 (1988).

' Note also that an Errata notice appeared in Solar Energy Vol. 41, No. 1,
' p. 113, 1988 concerning a correction to the above algorithm. This
' correction has been incorporated into the subroutine that follows.

' In the original subroutine, a division by latitude in the determination of
' of 'elc' (critical elevation) caused a divide by zero error for equatorial
' calculations.  This code has been replacedby equivalent code for deter-
' mining solar azimuth.

' This subroutine calculates the local azimuth and elevation of the sun at
' a specific location and time using an approximation to equations used to
' generate tables in The Astronomical Almanac. Refraction correction is added
' so sun position is the apparent one.

' The Astronomical Almanac, U.S. Government Printing Office, Washington, DC

' Input parameters:
'   Year        = year (e.g., 1986)
'   JD          = day of year (e.g., Feb. 1 = 32)
'   GMT         = Greenwich Mean Time (decimal hours)
'   Lat         = latitude in degrees (north is positive)
'   Lon         = longitude in degrees (west is positive)
'   StnHeight  = height of station in metres above sea level

' Output parameters:
'   Az          = sun azimuth angle
'                 (measured east from north, 0 to 360 degrees)
'   El          = sun elevation angle (degrees) plus others, but note the
'                 units indicated before return to calling routine
'   EOT         = equation of time (seconds)
'   TST         = True Solar Time (hours)
'   SolarTime$ = solar time (HH:MM:SS)
'   Decdegrees = declination in degrees
'   Airmass$   = airmass as an alphanumeric string
'
' Notes: 1) The algorithm included in the above-mentioned paper was written
'           in Fortran and has been translated into QuickBasic V4.5.
```

```
'     2) Since QuickBasic V4.5 does not contain the arcsin function, the
'        following substitute relationship is used:
'        arcsin(x) = ATN(X / SQR(1 - X ^ 2))
'        where ATN is the arctangent.
'     3) The MOD (modulus) function provided by QuickBasic V4.5 is not
'        used since it does not yield the same result as the modulus
'        function in Fortran. For example:
'        in QuickBasic V4.5  19 MOD 6.7 = 5.0 (decimal portion truncated)
'        in Fortran          19 MOD 6.7 = 5.6
'        As a result, the Fortran modulus function has been rewritten
'        using the equivalent:
'        MOD(X,Y) = X (MOD Y) = X - INT(X / Y) * Y
'        The INT function in Fortran is identical to that in QuickBasic;
'        they both return the sign of x times the greatest integer
'        <= ABS(x).
'==========================================================================

' Work with real double precision variables and define some constants,
' including one to change between degrees and radians.
  DEFDBL A-Z

  Zero = 0#
  Point02 = .02#
  PointFifteen = .15#
  One = 1#
  Two = 2#
  Four = 4#
  Ten = 10#
  Twelve = 12#
  Fifteen = 15#
  Twentyfour = 24#
  Sixty = 60#
  Ninety = 90#
  Ninetyplus = 93.885#
  OneEighty = 180#
  TwoForty = 240#
  ThreeSixty = 360#
  ThreeSixtyFive = 365#
  FiveOneFiveFourFive = 51545#
  TwopointFour = 2400000#:  '2.4D6

  pi = Four * ATN(One)
  TwoPi = Two * pi
  Rad = pi / OneEighty

  basedate = 1949#
  baseday = 32916.5#
  stdPress = 1013.25#

' Constants for solar time/location equations
  C1 = 280.463# :'This constant varies by +/- 0.004 per year, but does not change the final values
```

```
greatly
  C2 = .9856474#
  C3 = 357.528#
  C4 = .9856003#
  C5 = 1.915#
  C6 = 23.44#
  C7 = .0000004#
  C8 = 6.697375#
  C9 = .0657098242#

' Constants for refraction equation
  EC1 = -.56#
  EC2 = 3.51561#
  EC3 = .1594#
  EC4 = .0196#
  EC5 = .00002#
  EC6 = .505#
  EC7 = .0845#

' Constant for the determination of pressure from station height
  HC1 = .0001184#

' Constant for the calculation of airmass
  AC1 = -1.253#

' Get the current julian date (actually add 2,400,000 for JD).
  Delta = year - basedate
  Leap = INT(Delta / 4)
  JulianDy = baseday + Delta * ThreeSixtyFive + Leap + jd + GMT / Twentyfour

' First number is mid. 0 jan 1949 minus 2.4e6; Leap = Leap days since 1949.

' Calculate ecliptic coordinates.
  Time = JulianDy - FiveOneFiveFourFive
' 51545.0 + 2.4e6 = noon 1 jan 2000.

' Force mean longitude between 0 and 360 degrees.
  MnLon = C1 + C2 * Time
  MnLon = MnLon - INT(MnLon / ThreeSixty) * ThreeSixty
  IF MnLon < 0 THEN MnLon = MnLon + ThreeSixty

' Mean anomaly in radians between 0 and 2*Pi
  MnAnom = C3 + C4 * Time
  MnAnom = MnAnom - INT(MnAnom / ThreeSixty) * ThreeSixty
  IF MnAnom < 0 THEN MnAnom = MnAnom + ThreeSixty
  MnAnom = MnAnom * Rad

' Compute ecliptic longitude and obliquity of ecliptic in radians.
  EcLon = MnLon + C5 * SIN(MnAnom) + Point02 * SIN(Two * MnAnom)
  EcLon = EcLon - INT(EcLon / ThreeSixty) * ThreeSixty
  IF EcLon < 0 THEN EcLon = EcLon + ThreeSixty
  OblqEc = C6 - C7 * Time
```

```
  EcLon = EcLon * Rad
  OblqEc = OblqEc * Rad

' Calculate right ascension and declination.
  Num = COS(OblqEc) * SIN(EcLon)
  Den = COS(EcLon)
  Ra = ATN(Num / Den)
  IF Den < 0 THEN
    Ra = Ra + pi
  ELSEIF Num < 0 THEN
    Ra = Ra + TwoPi
  END IF

' Declination in radians.
  Dec = SIN(OblqEc) * SIN(EcLon)
  Dec = ATN(Dec / SQR(One - Dec * Dec))
'  Declination in degrees
  Decdegrees = Dec / pi * OneEighty

' Calculate Greenwich mean sidereal time in hours.
  GMST = C8 + C9 * Time + GMT
' GMT not changed to sidereal since 'time' includes the fractional day.
  GMST = GMST - INT(GMST / Twentyfour) * Twentyfour
  IF GMST < 0 THEN GMST = GMST + Twentyfour

' Calculate local mean sidereal time in radians.
  LMST = GMST - Lon / Fifteen
  LMST = LMST - INT(LMST / Twentyfour) * Twentyfour
  IF LMST < 0 THEN LMST = LMST + Twentyfour
  LMST = LMST * Fifteen * Rad

' Calculate hour angle in radians between -Pi and Pi.
  Ha = LMST - Ra
  IF Ha < -pi THEN Ha = Ha + TwoPi
  IF Ha > pi THEN Ha = Ha - TwoPi
' Hour angle in degrees, 0 North
  HaDegrees = Ha / Rad + OneEighty
' Local Apparent Time or True Solar Time in hours.
  TST = (Twelve + Ha / pi * Twelve)

' Change latitude to radians.
  Lat = Lat * Rad
' Calculate azimuth and elevation.

  El = SIN(Dec) * SIN(Lat) + COS(Dec) * COS(Lat) * COS(Ha)
  El = ATN(El / SQR(One - El * El))

'Determination of azimuth angle based upon TST
 IF TST = Twelve THEN
    Az = pi
 ELSE
    cosaz = (SIN(Dec) * COS(Lat) - COS(Dec) * SIN(Lat) * COS(Ha)) / COS(El)
```

```
    Az = -ATN(cosaz / SQR(One - cosaz * cosaz)) + pi / Two
    IF TST > Twelve THEN Az = TwoPi - Az
  END IF

' Calculate refraction correction for US standard atmosphere. Need to have
' El  in degrees before calculating correction.
  El = El / Rad
  IF El > EC1 THEN
    Refrac = EC2 * (EC3 + EC4 * El + EC5 * El * El)
    Refrac = Refrac / (One + EC6 * El + EC7 * El * El)
  ELSE
    Refrac = -EC1
  END IF
' Note that 3.51561 = 1013.2 mb/288.2 K which is the ratio of the pressure
' and temperature of the US standard atmosphere.
  El = El + Refrac
' Elevation in degrees.

' Convert Az and Lat to degrees before returning.
  Az = Az / Rad
  Lat = Lat / Rad
' MnLon in degrees, GMST in hours, JD in days if 2.4e6 added;
' MnAnom, EcLon, OblqEc, Ra, Dec, LMST, and Ha in radians.

' Calculate the equation of time.
' EOT output in seconds.
  Radegrees = Ra / Rad
' Test for phase change between MnLon and Ra
  IF (MnLon - Radegrees) > OneEighty THEN Radegrees = Radegrees + ThreeSixty
  EOT = (MnLon - Radegrees) * TwoForty
' Format True Solar Time HH:MM:SS.
  SHr = INT(TST)
  SMn = INT((TST - SHr) * Sixty)
  SSc = INT(((TST - SHr) * Sixty - SMn) * Sixty) + One
  IF SSc = Sixty THEN SMn = SMn + One: SSc = Zero
  IF SMn = Sixty THEN SHr = SHr + One: SMn = Zero
  IF SHr = Twentyfour THEN SHr = Zero
  IF SHr < Zero THEN SHr = Twentyfour + SHr
  IF SMn < Zero THEN SMn = Sixty + SMn
  IF SSc < Zero THEN SSc = Sixty + SSc
  SolarHr$ = RIGHT$(STR$(SHr), 2)
  IF ABS(SHr) < Ten THEN SolarHr$ = "0" + RIGHT$(STR$(SHr), 1)
  SolarMn$ = RIGHT$(STR$(SMn), 2)
  IF ABS(SMn) < Ten THEN SolarMn$ = "0" + RIGHT$(STR$(SMn), 1)
  SolarSc$ = RIGHT$(STR$(SSc), 2)
  IF ABS(SSc) < Ten THEN SolarSc$ = "0" + RIGHT$(STR$(SSc), 1)
  SolarTime$ = SolarHr$ + ":" + SolarMn$ + ":" + SolarSc$

' Solar zenith angle in degrees.
  Zenith = (Ninety - El)

' Station pressure in millibars.
```

```
  StnPress = stdPress * EXP(-HC1 * StnHeight)

' Calculate the relative optical air mass.
  IF (Ninetyplus - Zenith) < Zero THEN
    Airmass$ = "Undefined because sun below horizon"
  ELSE
' Airmass calculation of Kasten (1966)
    Airmass = StnPress / stdPress * (COS(Zenith * Rad) + PointFifteen * (Ninetyplus - Zenith) ^
AC1) ^ -One
    Airmass$ = STR$(Airmass)
  END IF

END SUB
```

Subroutine Two: Equations provided by the Royal Greenwich Observatory.

```
'Note: Subroutine call is to be a single line
SUB Greenwich (Year, JulianDay, CUTTime, Latitude, Longitude, AtmPressure,EqnOfTime,
Azimuth, Elevation,Declination, HourAngle)
'
================================================================================

'Equations provided by the Greenwich Observatory for the approximation of the Equation of time
and
'the solar declination.  From these values, the location of the sun can be determind.

' REQUIRED PARAMETERS.
' Year = year (YYYY)
' JulianDay = julian day (DDD)
' CUTTime = Coordinated Universal Time (seconds)
' Latitude = latitude (degrees)
' Longitude = longitude (degrees)
' AtmPressure = atmospheric pressure (millibars)

' CALCULATED PARAMETERS.
' EqnOfTime = equation of time (seconds)
' Declination = declination (radians)
' HourAngle = hour angle (radians)
' Azimuth = azimuth (degrees)
' Elevation = elevation (degrees)
' Sl = sin(elevation)
' Cl = cos(elevation)
' Sz = sin(azimuth)
' Cz  = cos(azimuth)

' ===============================================================================

DEFDBL A-Z

'Defined constants
Zero = 0#
Point0157 = .0157#
Point4 = .4#
Point4336 = .4336#
PointFive = .5#
One = 1#
Two = 2#
Three = 3#
Four = 4#
EightyNine = 89#
Ninety = 90#
OneEighty = 180#
TwoForty = 240#
stdPress = 1013.25#

' Solar ephemeris constants
pi = Four * ATN(One)
TwoPi = Two * pi
```

```
Cc = pi / 180#
C1 = 279.457# * Cc
C2 = .985647# * Cc
C3 = -102.5#
C4 = -.142#
C5 = -429.8#
C6 = .033#
C7 = 596.5#
C8 = -2#
C9 = 4.2#
Ca = 19.3#
Cb = -12.8#
SecondsPerDay = 86400#
DaysperYear = 365.251#
NineteenSixtyFive = 1965

' EQUATION OF TIME.
DaysSince1965 = INT((Year - NineteenSixtyFive) * DaysperYear) + JulianDay
DaysSince1965 = DaysSince1965 + CUTTime / SecondsPerDay
Lx = C1 + C2 * DaysSince1965
DaysSince1965 = DaysSince1965 / DaysperYear
EqnOfTime = (C3 + C4 * DaysSince1965) * SIN(Lx)
EqnOfTime = EqnOfTime + (C5 + C6 * DaysSince1965) * COS(Lx)
EqnOfTime = EqnOfTime + C7 * SIN(Two * Lx) + C8 * COS(Two * Lx)
EqnOfTime = EqnOfTime + C9 * SIN(Three * Lx) + Ca * COS(Three * Lx)
EqnOfTime = EqnOfTime + Cb * SIN(Four * Lx)

' DECLINATION.
Declination = ATN(Point4336 * SIN(Lx - Cc * EqnOfTime / TwoForty))
Declination = Declination / pi * OneEighty

' HOUR ANGLE.
HourAngle = TwoPi * (CUTTime + EqnOfTime) / SecondsPerDay
HourAngle = HourAngle - Cc * Longitude
HourAngle = HourAngle / Cc

' ELEVATION.
Sl = SIN(Cc * Latitude) * SIN(Declination)
Sl = Sl - COS(HourAngle) * COS(Cc * Latitude) * COS(Declination)
Cl = SQR(1 - Sl * Sl)
Elevation = (ATN(Sl / Cl)) / Cc

' ATMOSPHERIC REFRACTION.
RefractionCorr = Elevation
IF RefractionCorr < -PointFive THEN RefractionCorr = -PointFive
IF RefractionCorr > EightyNine THEN RefractionCorr = EightyNine
RefractionCorr = TAN(Cc * (Point4 + RefractionCorr + Three / (RefractionCorr + Two)))
RefractionCorr = Point0157 / RefractionCorr
RefractionCorr = AtmPressure * RefractionCorr / stdPress
' ELEVATION CORRECTED FOR REFRACTION
Elevation = Elevation + RefractionCorr

'AZIMUTH
Sz = SIN(HourAngle) * COS(Declination) / Cl
```

```
Cz = One - Sz * Sz: Azimuth = Ninety
IF Cz > 0 THEN
  Cz = SQR(Cz)
  Azimuth = ABS(ATN(Sz / Cz) / Cc)
END IF
IF SIN(Declination) < SIN(Cc * Latitude) * Sl THEN Azimuth = OneEighty - Azimuth
IF Sz < Zero THEN Azimuth = ThreeSixty - Azimuth

END SUB
```

## Appendix 8. Notes on the technology of data acquisition

The manual recording of data is not a practical option for monitoring solar radiation, except under exceptional circumstances and for very short durations. Therefore, automated data acquisition systems are a necessity for most applications. These vary significantly in their sophistication.

Integrating recorders, which some pyranometer manufacturers market, represent the lowst level of sophistication. These record the average or integrated value over a pre-set interval of one or more input signals. The output is usually a series of numbers printed on a paper tape. These recorders could be used in a converter test. Their disadvantage compared with more sophisticated systems is that the data must be transcribed and that operation at a high data rate is impractical which limits the quality control. Another disadvantage is that the radiation integrators have to be synchronized with the acquisition of the thermal data from the converter.

The data acquisition systems designed for operating and recording data from automated laboratory equipment are generally suitable for radiation measurement and collector testing. These systems have many input channels that are switched sequentially (multiplexed) into a single voltage measuring unit. The multiplexing is accomplished either by magnet operated relay contacts or by semiconductor switches. The relay multiplexing is better for radiation measurement because the relays contribute very little noise (1-2 µV) but some relay equipped systems are slow. The semiconductor multiplexing systems are much faster but the noise or offset voltage may be greater than the 15 pV acceptable level.

The individual parts of the data acquisition system that comprise the multiplexer, the analog-to-digital converter that does the measurement, the voltage measurement unit, the recording system and the controlling computer may be all combined into one unit or they may all be separate units connected, for example, by a GPIB instrument bus. Both arrangements have their advantages. The combined system is more compact and programming may be easier. A system with a separate computer may allow easier analysis of the data that could be done on the same computer.

## Appendix 9. Companies supplying data acquisition systems that can be used for solar radiation monitoring (Partial listing only)

Hewlett Packard
(offices throughout the world)
Intercontinental Headquarters:

3495 Deer Creek Road
Palo Alto, CA 94304
United States of America

-bench and laboratory test and measurement equipment

Keithley
Test Instrumentation Group
Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, OH 44139
USA

-bench and laboratory test and measurement equipment

Fluke
(offices throughout the world)
Corporate Headquarters:

John Fluke Manufacturing Co., Inc.
P.O. Box 9090
Everett, WA 98206-9901
USA

-bench and laboratory test and measurement equipment

Campbell Scientific, Inc.
P.O. Box 551
Logan, UT 84321
USA

-field and remote location data acquistion equipment

Climatronics Corporation
140 Wilbur Place
Bohemia, NY 11716
USA

-field and remote location data acquistion equipment

An increasing number of companies are now producing excellent data acquistion plug-in boards for PC compatible computers. Depending on the shielding of the board against noise generated by the computer and the accuracy required by the user, these provide a low-cost alternative to stand-alone data acquisition systems.

Three companies that produce 16-bit or higher resolution shielded boards are:

American Advantech Corporation
750 East Arques Avenue
Sunnyvale, CA 94086
USA

Data Translation Inc.
100 Locke Drive
Marlboro, MA 01752-1192
USA

Intelligent Instrumentation, Inc.
6550 S. Bay Colony Drive
MS 130
Tuscon, AZ 85706
USA

National Instruments
6504 Bridge Point Parkway
Austin, TX, 78730-5039
USA
(Boards for both PC and Macintosh)