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WORLD METEOROLOGICAL ORGANIZATION

WORLD CLIMATE RESEARCH PROGRAMME

BASELINE SURFACE RADIATION NETWORK

(BSRN)

OPERATIONS MANUAL

(Version 1.0 – *Reprinted, December 2000*)

L. J. B. McArthur

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Acknowledgements

The efforts required in creating any document far exceed the capabilities of any one person. This manual has been no exception. I would particularly like to thank the World Meteorological Organization for support during the initial drafting of this report and the Atmospheric Environment Service for providing me with the necessary time away from my regular duties to research the manual. The first draft was ably reviewed at the Boulder 1996 meeting of the BSRN. While all the participants at the meeting provided input I would especially like to thank the following individuals who acted as group leaders during that process: Klaus Dehne, Bruce Forgan, Roger Newson, Rolf Philipona and Tom Stoffel. Dr. H. Teunissen, of WMO, did a masterful job in editing the manuscript. Finally, I would like to thank Ellsworth Dutton as manager of the BSRN for his continuous encouragement throughout the production of this work.

A number of individuals have graciously allowed manuscripts to be placed in the annexes for easy access. I would encourage readers, if they use these papers, to reference them directly to the original report or journal.

Preface

Like all aspects of the Baseline Surface Radiation Network, this manual is in its infancy. The ideas contained within may be new to many, but have been applied successfully at various locations throughout the globe. On the one hand this indicates that these concepts should be considered seriously before being rejected, but on the other hand there may be some that are unworkable because of various climatic or operational factors. I would encourage all those using this manual not to reject any procedures without first carefully attempting to put them into operation. There is an anecdote within the meteorological community that must be overcome if the operation of the BSRN is to be successful. The question is asked, “How long does it take for a new instrument to be accepted as operational?” The answer, “One generation of meteorologists.” Let this not be the case within the BSRN!

Some instructions or ideas within the manual may be unclear. If this is the case, I would appreciate having these reported to me as quickly as possible. I believe that everyone who has ever written step-by-step instructions has fallen into the trap of missing a step, or assuming too much. I would encourage scientists and technicians alike who use this manual to also apply “common sense” to the problem to overcome any omissions that I may have made.

Although the WMO allowed me a significant amount of travel and opportunity to observe how various stations were operated, I am sure that excellent ideas have been missed within this first version of the manual, even with the significant help of those who reviewed it at the BSRN meeting in August 1996. Although only one person can place ideas on paper (or its virtual counterparts), the contents of this manual must remain a group effort if we are to build a radiation observing system of which we can be proud in our years of retirement. To this end I encourage new ideas be brought forward and new areas suggested for inclusion in the next revision.

As paper gives way to electronic publications, the idea of editorial revisions has changed substantially over the last few years. Where once the second edition of a book might be expected a decade after the first printing, our expectations have increased to seeing something new on the WEB every day. It is hoped that minor revisions of the manual (clarifications etc.) can be put into place almost immediately and the revision number of the electronic version of the manual altered to reflect any changes. Major revisions (e.g. new sections) will obviously be less frequent, but will come out not only electronically, but also as a new printed manual.

Finally, and again, this manual will improve with the feedback of the users. I urge anyone to contact me with any and all suggestions to improve this manual for the use of all.

Bruce McArthur
Experimental Studies Division
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, CANADA
M3H 5T4

Telephone: 1 416 739 4464
Facsimile: 1 416 739 4281
Email: bruce.mcarthur@ec.gc.ca

CONTENTS

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Baseline Surface Radiation Network
Operations Manual

(Version 1.0)

1.0 Introduction

The determination of a global climatology of the radiation budget at the surface of the Earth is fundamental to understanding the Earth's climate system, climate variability and climate change resulting from human influence. Global estimates of the surface radiation budget cannot be inferred reliably from satellite observations without high accuracy surface-based measurements at various sites in contrasting climatic regions for calibration and validation. Long-term observations of the same accuracy are also required to assess trends within climatic regions. Such measurements are essential in assessing theoretical treatments of radiative transfer in the atmosphere, verifying climate model computations, and for studying trends in surface radiation at scales smaller than normally associated with climatic regions.

In order to meet these requirements, the World Climate Research Programme (WCRP), jointly sponsored by the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO initiated (and is organizing the implementation of) the Baseline Surface Radiation Network (BSRN). The goal of this network is to provide continuous, long-term, frequently sampled, state-of-the-art measurements of surface radiation fluxes adhering to the highest achievable standards of measurement procedures, calibration and accuracy. Many nations have expressed strong interest in participating in the BSRN and a range of stations as diverse as the Arctic, mid-latitude forested and plain areas, high mountain regions, tropical rainforest, desert, tropical islands have been established or are in the process of being installed (Figure 1.1 shows the distribution of existing and planned stations).

Each station, or group of stations, within a given jurisdiction operates under the guidance of a qualified scientist with expertise in the measurement of radiation. Within this structure, some sites have been specifically established for the purpose of making measurements for determining local climate trends and providing accurate ground-truth for satellite observations. Other sites have been observing radiation components for years, but have been enhanced to meet the accuracy and resolution objectives of the BSRN. A number of sites remain part of the BSRN because of their importance with respect to climate or geography although they do not fully conform to the implementation standards at present. Observatories such as these have been encouraged to adopt the standards set forth in the implementation documentation, and repeated in this operations manual, by 1997.

Whether new or in operation for many years, each station has its particular characteristics. The purpose of this manual is, building on the experiences gained, to provide a standardized guide to measurement techniques for all stations involved in the programme. This requires that each station manager adapt the techniques presented in the manual to the station for which they are responsible.

1.1 Overall goals and purpose

The original concept for the BSRN developed from the needs of both the climate change and satellite validation communities. The initial plan for a global network of radiation stations was developed by the WCRP Working Group on Radiative Fluxes (WGRF) in 1989, and

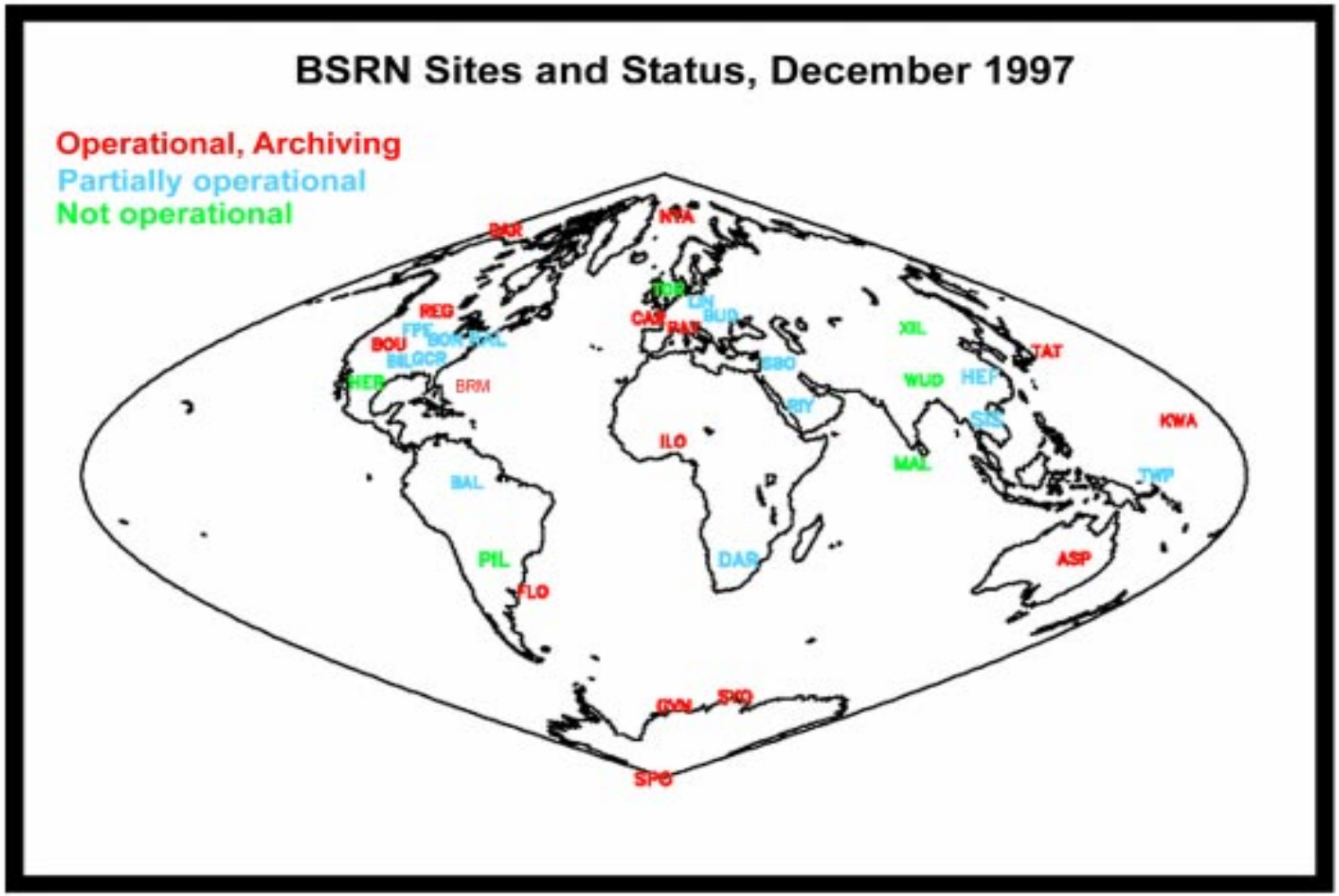

Figure 1.1. Location of Baseline Surface Radiation Stations in operation, partial operation or planned. Table 1.1 provides the names and locations of each of the stations on the map. (Courtesy of E. Dutton, NOAA/CMDL.)

Location of Operating and Planned BSRN Stations					
Symbol	**Station Name**	**Sponsor**	**Latitude**	**Longitude**	**Status**
PIL	Pilar	Argentina	31 S	61 W	Not Operational
ASP	Alice Springs	Australia	23.70 S	133.87 E	Operational
BAL	Balbina	Brazil	2 S	59 W	Not Operational
FLO	Florinopolis	Brazil	27.58 S	48.52 W	Operational
REG	Regina	Canada	50.12 N	104.43 W	Operational
WUD	Wangdaoliang	China	35 N	93 E	Not Operational
TOR	Toravere Observatory	Estonia	58.33 N	26.73 E	Not Operational
CAR	Carpentras	France	44.05 N	5.03 E	Operational
GVN	Georg von Neumayer, Antarctica	Germany	70.39 S	8.15 W	Operational
LIN	Lindenberg	Germany	49.38 N	8.10 E	Partially Operational
NYA	Ny Alesund, Spitsbergen (N)	Germany/Norway	78.56 N	11.56 E	Operational
BUD	Budapest-Lorinc	Hungary	47.50 N	19.05 E	Partially Operational
SBO	Sede Boqer	Israel	30.87 N	34.77 E	Partially Operational
TAT	Tateno	Japan	36.03 N	140.08 E	Operational
SYO	Syowa, Antarctica	Japan	69.00 S	39.35 E	Operational
HEF	Hefei, China	Japan	32 N	117 E	Not Operational
SIS	Si Samrong, Thailand	Japan	17 N	100 E	Not Operational
HER	Hemosillo	Mexico	29 N	111 W	Not Operational
XIL	Xilinhat	Mongolia/United States	47.90 N	109.98 E	Not Operational
ILO	Ilorin	Nigeria/United States	8.32 N	4.34 E	Operational
MAL	Maldives	Maldives/United States	5 N	73 E	Not Operational
RIY	Riyadh	Saudi Arabia	18 N	42 E	Partially Operational
DAR	De Aar	South Africa	30.40 S	24.01 E	Partially Operational
PAY	Payerne	Switzerland	46.82 N	6.95 E	Operational
BAR	Barrow	United States	71.27 N	156.83 W	Operational
BOU	Boulder	United States	40.03 N	105.27 W	Operational
BRM	Bermuda	United States	32.30 N	64.75 W	Operational

Table 1.1 Location, sponsorship, and operational status of BSRN stations (courtesy of E. Dutton, NOAA/CMDL).

Symbol	Station Name	Sponsor	Latitude	Longitude	Status
KWA	Kwajalein, Marshall Islands	United States	8.72 N	167.73 E	Operational
SPO	South Pole, Antarctica	United States	89.98 S	24.48 W	Operational
FPE	Fort Peck	United States	48.30 N	105.12 W	Partially Operational
BON	Bondville	United States	40.05 N	88.37 W	Partially Operational
GCR	Goodwin Creek	United States	34.25 N	89.87 W	Partially Operational
BOS	Boulder SURFRAD	United States	40.12 N	105.23 W	Partially Operational
TWP	Momote, Manus Is. Papua New Guinea	United States	2.06 S	147.43 E	Partially Operational

Table 1.1 Continued.

refined at two workshops on the implementation of the BSRN, the first in Washington, DC, USA in December 1990, and the second in Davos, Switzerland in August 1991. The formal goals and objectives were set down as follows:

- ✶ provide data for calibrating satellite-based estimates of the surface radiation budget (SRB) and radiation transfer through the atmosphere
- ✶ monitor regional trends in radiation fluxes at the surface.

As well as the important contribution to global climate research made by the BSRN, it is emphasized that countries assuming the responsibility of operating a BSRN station will benefit significantly from having a reference surface radiation measurement station, especially in the context of national efforts to exploit environmentally clean renewable energy resources and also, to some extent, in enhancing agricultural production. The measurements from a BSRN station are also a key element in monitoring national and regional climate variations, and in assessing the associated economic implications. In countries where radiation networks already exist, the instrumentation and operational procedures developed for the BSRN can be used to effectively upgrade present measurements and enhance calibration traceability to the World Radiation Centre by using BSRN station instruments and techniques. In summary, BSRN data sets have a wide range of applications beyond climate research.

1.2 Specific objectives and research activities

The specific objectives of the BSRN as found in the Washington, D.C. meeting report, are defined as:

- ✶ to measure the surface radiation components at strategic locations with a demonstrated accuracy and precision sufficient for revealing long-term trends
- ✶ to obtain concurrent measurements of atmospheric constituents such as clouds, water vapour, ozone and aerosols that affect the radiation at the surface and at the top of the atmosphere

- to assure uniform adherence to the highest achievable standards of procedure, accuracy and calibration throughout the network.

The associated activities and research goals are:

- Site characterization: Acquisition of quantitative information on features such as nature of the surface, average cloud cover and type, aerosols, etc., that characterize the site for satellite applications

- Infrared Irradiance Measurements: Advancing state-of-the-art for accurate measurement of downwelling radiance and irradiance measurements to meet Surface Radiation Budget (SRB) measurement standards

- Extended-Surface Reflectance and In Situ Measurements: development of methods for measuring surface reflectance over a larger area (e.g. 20 X 20 km) by using a tower or small aircraft, special aircraft and balloon experiments to collect in situ information to validate the remote sensing measurements

- Atmospheric Inhomogeneities: studies aimed at improving the understanding and measurement of the radiative features of inhomogeneous and broken clouds

- Special Measurements: development of cost-effective instrumentation and methods for measurement of spectral ultraviolet and infrared SRB that will aid the improvement of satellite algorithm design and validation of satellite SRB determinations

- Improvement of Instrumentation: investigations to improve the design and performance of “standardized” instrumentation such as sunphotometers and pyranometers, and incorporate, improve, and develop more sophisticated remote sensing instrumentation to enhance the cloud-observing abilities of the BSRN.

The type of geographical region where such stations would most aid the development and validation of satellite algorithms (Table 1.2) and specific research areas on instrument development and calibration were also proposed at the workshop.

While the objectives and goals have been laid down specifically for climate research, the impact of the BSRN concept is far wider than just this one community. By providing a standard means of measuring radiation to a known accuracy, other programs and countries can implement these ideas with little added effort. Other programs such as the Global Atmosphere Watch (GAW) and the Atmospheric Radiation Measurement (ARM) Program have already implemented ideas presented in the early BSRN documents. Countries presently developing radiation networks or upgrading older networks can also benefit from results of the ongoing research that has been conducted specifically to improve the measurement of solar and terrestrial fluxes using commercially available instrumentation. The quality control procedures outlined later in this manual and the archiving procedures presented elsewhere, can be used with little modification for many other radiation networks. These improvements in measurement techniques, quality assurance and quality control can be used for networks involved in the measurement of solar radiation for such diverse applications as passive and active solar energy utilization and cloud absorption modelling. Moreover, efforts to install networks to observe UVB and ozone could readily build on an established BSRN station designed to operate according to the highest achievable standards.

Site Evaluation Criteria		
Characteristic	Locations Representing	Example Location
Radiation field values	large variability, both synoptic and seasonal scales	Siberia
Satellite algorithm performance	a range of difficulty for set retrievals	Equatorial Indian Ocean Temperate Oceania
Cloud Properties	a range of cloud types	Tropical Pacific
Climate Change	the potentially higher sensitivity of a region to changes in global climate	Antarctic coast, Northern Canada
Satellite Coverage	a range dependence on orbit, viewing angle, overlap regions	Spitzbergen
Unusual atmospheric phenomenon	a range of unusual atmospheric phenomenon (aerosol, clear skies, etc.)	Sahel, Tropical Pacific
Surface Cover	a range of surface cover (e.g. snow, sea ice, ocean, vegetated, desert, etc.)	South Ocean, Ice Island, Equatorial Africa
Climatic Regions	a range of climate regions (polar, tropical, etc.)	Ice Island, Central Australia, Antarctic Coast
Upwelling flux studies	area where upwelling flux studies would be of particular value to validation because of the site qualities and in some cases the existence of SRB measurement facilities	Boulder Tower
Calibration	locations possessing reasonably uniform and high surface reflectance properties for satellite calibrations	Prairie, Amazon Basin

Table 1.2. List of site evaluation criteria based upon a selection of desirable surface/atmospheric characteristics and the results of satellite algorithm performance comparisons.

1.3 Purpose and scope of operations manual

In developing a network such as the BSRN, decisions need to be made on such questions as:

- what equipment should be purchased based upon the estimated accuracy, cost and maintenance requirements?
- where and for how long should the measurements be made?
- how will the instrumentation be maintained at each location?
- how will the data be quality controlled and archived?

In the BSRN, standards of measurement accuracy and archiving have been clearly defined, but the exact manner in which these standards can be achieved is left to national experts responsible for implementing the measurements. This is because there are a number of commercially available instruments capable of performing to the desired accuracy when used properly and because maintenance, quality control and archival are determined to a considerable extent by the circumstances of individual stations and national constraints and station procedures. This manner of developing a network has strengths and weaknesses. Its greatest strengths are the ability of regional experts to operate a station designed especially for the regime in which it exists, and that the operation of each station is closely monitored scientifically. On the other hand, it is more difficult to achieve a high degree of standardization in overall BSRN procedures. For example, the solutions to problems at one station may not be applicable to any other stations because of the dependency on particular

equipment or national requirements. Thus, while each station may be the best possible for any given set of circumstances, the ability to transfer expertise from one station to another is more difficult.

The operations manual for such a network must utilize the strengths and overcome the weaknesses of this multi-national approach. This manual has been developed based partly upon the following general observations:

- The individuals involved in the set-up and operation of each station are experts in the field of radiation measurement. Therefore, these scientists already know a great deal about the best way of implementing the BSRN guidelines. Such individuals often have difficulty accepting ideas other than their own, however. They will find it difficult to accept any form of standardization for the benefit of the network if it is not already part of their site plans.

- National policies or individual experiences dictate what types of instrumentation can be used. This may provide the best equipment for each individual station, but it may limit the ability of some stations to obtain certain instruments. It makes writing a single set of operating instructions for all stations impossible.

- Individual nations have varying levels of commitment to the BSRN with respect to manpower and financing. This is a function of both desire and capability.

- National interests will alter the focus of each station among climate change, satellite validation and experimental research pertaining to the BSRN concept.

- Station directors require freedom to alter portions of the operation manual to optimize on-site use of resources, both human and financial.

These observations are reflected in the contents of the manual in several ways:

- The description of a wide variety of instruments will be found. Often several different types of instruments are capable of measuring a single flux.

- In a number of cases, alternate methods for accomplishing the same task are presented. Not all methods will give the same quality or results, but they are provided in recognition of the fact that some sites do not have the capabilities to carry out various procedures.

- Certain subjects within the operating manual have not been specified in detail because of their dependency on specialized procedures developed or on specific products. An example of this, is the programming repair and calibration of data acquisition systems.

While keeping the above considerations in mind, the manual is intended to be used by three groups of individuals:

- experts who have an established BSRN station

- experts intending to obtain the necessary resources to establish a BSRN station

- technologists involved in the construction and operation of a BSRN station.

For experts, it is hoped that the manual will provide: the necessary information required to obtain resources, the documentation required to support the establishment of a BSRN site,

and the types and manufacturers of instruments being used within the BSRN that meet the guidelines on accuracy. While none of these purposes is fulfilled in an exhaustive manner, most researchers should find the information sufficient.

The use of the manual by well-trained technologists will aid in the establishment and maintenance of a BSRN measuring program in a manner consistent with the goals and purposes of the programme. It is recognized that some of this information will need modification in a variety of ways. The simplest transformation may be into a language appropriate to those operating the site. More significant alterations may include the addition of information on particular data acquisition units or in the forms provided as guidelines for routine maintenance checks. These changes should be made in a consultative manner between the station scientist and those technologists performing the particular tasks under discussion.

The manual contains sections on sampling frequency and accuracy requirements for BSRN stations, the siting of stations, the installation of radiation instruments, solar tracking devices, data acquisition, station maintenance, radiation instrument calibration, and radiation data reduction and quality assurance procedures, as well as a variety of ancillary information in Annexes. However, it must be stated categorically that this operations manual is NOT a primer on the construction and operation of a radiation monitoring site. It is assumed that the station director has previous experience in the operation of radiation instruments. Furthermore, it is assumed that the technologists have at least a minimum of experience in operating data acquisition systems, computers and similar hardware, although not necessarily equipment specific to the measurement of solar and terrestrial radiation. The manual does provide fundamental guidance in assisting station scientists and technologists in meeting the aims, objectives and specifications of the Baseline Surface Radiation Network.

2.0 Sampling Frequency and Accuracy Requirements for BSRN Stations

2.1 Sampling Frequency

2.1.1 Sampling Frequency of Radiation Measurements

The BSRN requires that all radiation variables be sampled at 1 HZ with an averaging time of one minute. The final output for each variable should consist of the one-minute mean, minimum, maximum and standard deviation. This specification is based upon the typical 1/e response time of first class pyranometers and pyrheliometers being approximately 1 second. Although a number of instruments require the measurement of more than one signal for the calculation of a specific radiation element, the archived data will consist only of the mean, minimum, maximum and standard deviation of the radiation element.

The realization of this sampling and averaging rate is difficult when considering the accuracy requirements set out in section 2.2.1. To allow stations time to develop hardware and software to meet this specification, data will be accepted as 2,3,5,6 or 10 minute averages until 1 January 1998 (BSRN Scientific Workshop and Review Meeting, 12-16 September, 1994).

2.1.2 Sampling Frequency of Ancillary Measurements

At stations where the ancillary measurements are under the control of an independent agency, such as a national weather service, the frequency of the various measurements often cannot be altered. The higher the frequency the greater the usefulness of the data, up to the sampling rate of the radiation measurements. BSRN station managers should encourage any independent collection agency to sample and record data following standard WMO procedures at the very minimum.

When automatic data logging is employed to measure such variables as pressure, temperature, humidity, wind speed and wind direction, it is beneficial to provide these data at the same frequency as the radiation data. Because of the importance of the temperature, pressure and humidity data to fully understanding the energy balance of the various radiation instruments and the infrared component of the radiation balance, stations are encouraged to obtain such measurements coincidentally with the radiation measurements whenever possible. At a very minimum, all stations should record air temperature at the same location and at the same sampling frequency as the radiation measurements.

2.2 Accuracy of Measurements

2.2.1 Accuracy of Radiation Measurements

The accuracies of the radiation measurements are set out in previous BSRN documents. These accuracies are based upon available state-of-the-art commercially available equipment. Table 2.1 summarizes the accuracies achievable at present under normal operating procedures and those that are anticipated at BSRN sites within a five-year time frame following the program initiation in 1991.

It is anticipated that to meet these target accuracies, the measurement of each quantity will require a particular methodology of measurement. While these methodologies are not absolute in nature, they will ensure a certain accuracy of

measurement if followed (assuming appropriate on-site maintenance etc.). The BSRN is more concerned with meeting the target measurement accuracies however, than the manner in which they are met. The methodologies associated with these accuracies were first published in WCRP-64, 1991. These have changed little over the last five years and are incorporated into this manual nearly verbatim.

BSRN Measurement Accuracies		
Quantity	Present*	Target**
1. Direct Solar Irradiance		1% or 2 Wm^{-2}
2. Diffuse Radiation	10 Wm^{-2}	4% or 5 Wm^{-2}
3. Global Radiation	15 Wm^{-2}	2% or 5 Wm^{-2}
4. Reflected Shortwave Radiation	15 Wm^{-2}	5%
5. Downwelling Longwave Radiation	30 Wm^{-2}	5% or 10 Wm^{-2}
6. Upwelling Longwave Radiation	30 Wm^{-2}	5% or 10 Wm^{-2}
	* from WCRP-54, Mar 1991	** from WCRP-64, Nov 1991

Table 2.1. Accuracy requirements for the Baseline Surface Radiation Network radiation fluxes. Where values are given in percent and absolute, the latter is the minimum deviation from the “true” value measured by the instrument for any irradiance.

2.2.1.1 Direct Solar Irradiance

The target accuracy for measurement of direct solar irradiance in the BSRN is 1% (or 2 Wm^{-2} as the minimum deviation from the "true" value as reflected in the uncertainty of the World Radiation Reference). For the continuous measurements used in providing the mean value over 1,2,3 or 6 minutes (see section 3.3 - Data acquisition), a normal incidence pyrheliometer (NIP) or similar is recommended. Since the noise level of such an instrument is too high to satisfy BSRN requirements for direct solar irradiance measurements (see paragraphs 2.2, 2.3), an absolute cavity radiometer (ACR) shall be used in parallel to "calibrate" the normal incident pyrheliometer quasi-continuously (every 5-60 minutes if I > 400 Wm^{-2}).

The original requirement assumes the use of windows on both the working pyrheliometer and the ACR. Therefore, it is necessary to ensure that both windows are made of the same material so that differences in spectral absorption will not add uncertainty to the measurements. However, recent advances in the construction of all-weather enclosures have nearly eliminated this problem. It is now recommended that a windowless ACR be used on a continuous basis, with a standard pyrheliometer used to fill in “data gaps” during the time period when the ACR is in calibration mode. The minimum protection recommended to operate a windowless ACR continuously is to house the instrument in a ventilated housing. The opening aperture of the housing should be a minimum of 10 radiometer-opening-aperture diameters distant from the entrance aperture of the enclosed ACR and have a diameter no greater than twice the field of view of the ACR. Care must be taken when ventilating the instrument so that no venturi effects are created that might alter the thermal equilibrium of the instrument. In areas where severe weather conditions are prevalent, systems which include a means of closing the opening aperture are required.

A solar tracker with an accuracy of ±0.10 is needed to accommodate the pyrheliometer, the ACR and, during calibrations, a second ACR. The solar tracker is required to have a four-quadrant sensor for continuously monitoring the pointing (same sampling rate as the pyrheliometer).

The parameters to be monitored are: output of the pyrheliometer thermopile; outputs of the ACR (U,I or thermopile signal for a passive instrument); body temperatures of the pyrheliometer and ACR; output of the four-quadrant sensor. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by the BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.1.2 Diffuse Radiation

BSRN target accuracy is 4% (5 Wm^{-2}). The pyranometer to be used shall be ventilated and have a body temperature sensor. For shading from direct sun, a tracking disk is needed with the same field of view as the ACR (5° full angle from the centre of the detector) and always shading the dome completely.

Parameters to be acquired are: output of pyranometer thermopile; pyranometer body temperature. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.1.3 Global Radiation

BSRN target accuracy is 2% (5 Wm^{-2}). Although the global radiation may be determined as a sum of direct and diffuse irradiance, a direct measurement shall be made with a ventilated pyranometer (same instrument type as for diffuse radiation) in order to provide a basis for quality control and calibration boot-strapping (see Section 7.3 - Calibration procedures).

Parameters to be acquired are: output of pyranometer thermopile; pyranometer body temperature. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.1.4 Reflected Shortwave Radiation

This measurement, required at BSRN stations undertaking the "expanded measurement" programme, shall be performed using the same type of ventilated pyranometer as for diffuse and global radiation. A horizontal shadowband is needed to protect the instrument dome from direct solar radiation at low solar elevation. The angle sustained shall be less than 5° (i.e. covering nadir angles 85° to 90°). The instrument should be mounted on a tower with a minimum height of 30 m to provide a representative measurement of the surrounding area. The actual height of the downfacing centre should be reported to the archive.

Parameters to be acquired are: output of pyranometer thermopile; pyranometer body temperature. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.1.5 Downwelling Longwave Radiation

BSRN target accuracy is 5% or 10 Wm^{-2}, whichever is greater. Downward longwave irradiance shall be measured with a shaded and ventilated pyrgeometer or pyrradiometer (using a shading device as for measurement of diffuse solar irradiance). At present, it

seems that only a “modified PIR" pyrgeometer (Eppley) with three dome temperature sensors at 45° (but without a battery circuit) can meet BSRN requirements, although use of a shaded and ventilated unmodified Eppley pyrgeometer may provide nearly the same quality of measurement. Pyrradiometers have been shown to give results of similar quality under some circumstances, but are not generally recommended for use within the BSRN.

Parameters to be acquired are: outputs of pyrgeometer thermopile; instrument body temperatures; dome temperatures of the pyrgeometer. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.1.6 Upwelling Longwave Radiation

This measurement, required at BSRN stations undertaking the expanded programme, shall be performed with the same type of ventilated pyrgeometer used for observing the downward longwave irradiance. As for measurement of reflected shortwave radiation, a horizontal shadow band is needed to protect the instrument dome from solar radiation at low solar elevation. The angle sustained shall be less than 5° (i.e. covering nadir angles 85° to 90°). The instrument should be mounted on a tower with a minimum height of 30 m to provide a representative measurement of the surrounding area. The actual height of the downfacing centre should be reported to the archive.

Parameters to be acquired are outputs of pyrgeometer thermopile and instrument body temperatures. Only the values associated with the calculated irradiance (mean, maximum, minimum and standard deviation) are required by BSRN archive. All other raw data should be archived at the centre responsible for the measurements.

2.2.2 Accuracy of Meteorological Measurements

The requirement of meteorological observations at or near BSRN sites infers that certain levels of confidence must be placed in the measurements. Most of these observations are made at stations which are part of national observing networks where changing instruments to meet BSRN needs is difficult or even impossible. In such cases it is important for the site scientist to ascertain the accuracy of each measurement from the appropriate experts and provide this information to the BSRN Archive.

Where instrumentation is obtained specifically for the measurement of meteorological variables at a BSRN site, research quality instrumentation should be acquired. Table 2.2 presents a guideline on the uncertainty and resolution for some typical measurement fields. Experts in the appropriate measurement fields familiar with the climatology of the BSRN station should be consulted on specific instruments.

2.3 Accuracy of Data Acquisition Equipment

2.3.1 Time

Time is critical with respect to the frequency of the measurement sequence and the absolute time of the observation. This requires that the clocks for all observations be maintained to within ±1% of the averaging period used for the most frequent measurements. For one minute averages this equates to a time accuracy of 0.6 seconds. Because of the difficulty in manually setting a clock to better than one second, this time accuracy was relaxed to one second at the BSRN Science and Review Workshop (Boulder, Colorado, USA, 12-16 August, 1996).

Typical Meteorological Measurement Field Specifications		
Measurement	Resolution	Uncertainty
Air Temperature	0.1 °C	±0.3 °C
Dew Point Temperature	0.1 °C	±0.5 °C
Soil Temperature	0.1 °C	±0.3 °C
Relative Humidity	1%	±7%
Wind Speed	0.5 ms^{-1}	±5% or ± 2 ms^{-1}
Wind Direction	5°	±10°
Accumulated Precipitation	0.2 mm	greater of ±0.2 mm or ± 2% of total
Precipitation Intensity	0.2 mm h^{-1}	greater of ±0.2 mm h^{-1} or ± 2% of total
Snow Depth	1 mm	greater of ± 10 mm or ±1% of value
Atmospheric Pressure	0.1 hPa	±0.5 hPa

Table 2.2. Recommended measurement requirements for ancillary meteorological variables.

While most PC computer clocks cannot maintain an accuracy of better than one second, several means of maintaining time to within several milliseconds are now available. Two primary methods of maintaining such accuracy are: (1) the time transmitted by the Global Positioning System (GPS) satellites and; (2) through radio frequency time signals sent out by national standards agencies. These signals can either be incorporated directly into more advanced data acquisition systems or set on a daily basis for less advanced systems or externally controlled data acquisition systems such as the Campbell Scientific CR21X. For a PC clock-based data acquisition system the clock can be automatically updated via the serial port with terminate-and-stay-resident software or more directly with card-based timing systems. For a PC with a time gain of 10 seconds per day, the clock would require automatic updating approximate once each hour.

For data acquisition systems with internal time keeping, the same clock correction must be maintained for the relative sampling rate, while the absolute time can be corrected during data processing.

2.3.2 Data Acquisition System Accuracy

The specification for data acquisition system requirements for BSRN radiation measurements is set forth in the report of the WCRP BSRN Implementation Workshop, Davos, Switzerland, 6 - 9 August 1991. At that time the accuracy of the complete system (digital voltmeter (DVM), scanner (multiplexer) and cabling) was set as ±0.01% of the reading or ±1 µV, whichever is greater. If the overall accuracy afforded by the latter value is found to be greater than 10% of the overall accuracy required for the variable being measured (e.g. 1 Wm^{-2} for a instantaneous uncertainty of 10 Wm^{-2}), a high quality pre-amplifier should be used.

Each instrument should be scanned at least once per second with the analog signals

integrated to provide one-second values. On those systems where integration time is programmable, the shortest time period to be used for sampling of radiation signals is one power line cycle (PLC).

While the primary aim of the BSRN is to obtain accurate radiation fluxes, the accuracy of the data acquisition system used in the collection of ancillary data should be commensurate with the general aims of the program. Thus, a data acquisition accuracy greater than 10 times the uncertainty of the ancillary measurement is recommended.

3.0 The BSRN Site

3.1 Geographic Location of Site

3.1.1 General Considerations

In selecting sites for the Baseline Surface Radiation Network, the objective is to choose a site which is representative of a relatively large area (greater than 100 km^2) with common features. The site location should be consistent with the intended purpose for which the observations are being made. For example, a site which is representative of a unique micro-climate within a large region should not be selected as a site for regional climate observations. In order to achieve this goal, it is necessary to select sites which are not influenced by small-scale topographic or man-made features which are unique to the site but not common to the area for which the data are required. Conversely, if the area is mountainous and contains numerous lakes, then the site should be selected to reflect the effect of these features.

Great care must be taken in determining the exact placement of a radiation site so that local influences do not impact the long-term measurement goals of the BSRN. While it is impossible to predict future developments, the selection of the location should proceed only after a careful survey of the area. Before a site is constructed, the local authorities should be consulted to determine future plans for the area. It is wise to know whether or not housing developments, commercial developments or even road allowances are planned for the area. Furthermore, changes in these official plans may also be required before construction of a monitoring laboratory begins. Similarly, BSRN stations should not be built on or near airports or near a single major industrial source because of the possibility of constructing a long data set that reflects changes in airport traffic or air pollution control legislation. In rural areas, care should be taken to ensure that significant land-use changes are not planned. The removal of forests or the change in farming techniques may have significant effects on the albedo and the amount of natural contaminants. Both of these could be significant enough to mask any climate trends that might be global or regional in nature.

While changes in the view of the horizon are less critical if they are small, potential changes should be considered before the location of a site is selected. It must be remembered that in urban areas, unless specific allowances are in place, buildings may tower above the site in years to come where open areas presently exist. Even trees grow over decades and can become a significant obstruction.

Generally, sites on flat land with few obstructions will yield representative data where the terrain is flat and free from obstruction. In forested, mountainous, not built-up areas, moderately sheltered sites which meet the minimum distances from obstructions should be selected because they will yield data which are representative of the particular region. The key to success is to develop a site in an area representative of the surrounding region.

In general, BSRN stations should avoid locations which are:

a) not representative of the surrounding area (approximately 100 km^2 for the local area and 10,000 km^2 for regional representativeness);

b) near areas that will adversely affect the radiation or ancillary measurements because of pollution sources, areas of unnatural reflectance or areas where the micro-climate is altered by irrigation or other human modifications;

c) near major roadways;

d) near airports;

e) where there is excessive human or animal traffic;

f) near vehicle parking areas; and

g) where heat is exhausted by vehicles or buildings.

Conversely, BSRN stations must be located where facilities exist, preferably on a full-time 24 hour basis. Ideally, the site should be co-located with a synoptic station and within 50 km of an upper air station.

3.1.2 Horizon

The ideal site for the measurement of solar and terrestrial radiation for meteorological purposes is one that has a completely flat horizon. The WMO Guide to Meteorological Instruments and Methods of Observation (WMO No. 8) recommends that if possible no obstruction should be present, particularly within the azimuth range of sunrise and sunset over the year (see Annex I for a solar position algorithm). In cases where obstructions do occur, the instrument should be located where these subtend an elevation angle of less than 5° to minimize their affects. The total diffuse radiation received by a surface from elevation angles of less than 5° accounts for only about 1% of the total global radiation. The determination of the change in radiation fluxes with respect to changing climate, and the use of surface measurements to test and ground-truth satellite retrieval algorithms do not require strict adherence to this guideline when distant topography is considered. In the latter case, measurements in areas of complex topography are required to determine the capabilities of the retrievals.

While the distant horizon may be influenced by topography, the local horizon should be as clear as practically possible. A distance of 12 times the height of any object to the location of the sensor will ensure that the elevation of the object is less than 5° above the horizon. The site should be located such that all objects are to the poleward side of the installation and do not interfere with the direct beam radiation at any time during the year. The instruments should be removed, as far as is practical, from any highly reflective objects. Where a site is to be developed in a built-up area, the sensors can be located on the roof of a building to overcome problems with the local horizon.

While antennas and other slender objects should be avoided, their effect is minimal and can be endured if they are less than 1° wide, and do not block the direct beam radiation during any time of the year.

3.1.3 Latitude, Longitude, Elevation

A detailed description of the measurement site and its surroundings is probably one of the most significant pieces of meta-data provided to other researchers. It is of utmost importance to describe the site and its surroundings, not only in terms of latitude, longitude and elevation, but also with respect to the topography and land use surrounding the measurement location. One must consider this description in terms of the pixel size of present-day satellite measurements and the potential for influences on the radiation regime due to multiple scattering.

The first and foremost information required is the geographic coordinates of the site; latitude, longitude and elevation above mean sea level (msl). These normally can be obtained from high-quality topographic maps obtained through the mapping

agencies of national governments. The BSRN archive records this information in a floating point format with three decimal places. This is equivalent to an accuracy of approximately 3.5 seconds of arc, or about 108 metres in latitude and 76 metres in longitude at 45°. To obtain such accuracies a map with a scale of better than 1:100000 is required. The latitude and longitude should be recorded in decimal degrees, North and East positive with the South Pole and 180° W being defined as zero. For example, a station located in the Northern Hemisphere and east of Greenwich, such as Potsdam, Germany (52 N, 13 E) would be encoded 142.000, 193.000, while for a similar latitude, but in the Canadian prairies (52 N, 105 W) the location would be encoded 142.000, 75.000. This is for consistency with the Archive station-to-archive file format.

Elevation can also be read from topographic maps, normally to within 5 metres. More accurate measurements require site surveys. The Archive records the elevation to within 1 metre.

In locations where a site is presently located, this information should be present with the required accuracy.

New developments using Global Positioning System (GPS) technology can provide the site location to within 30 m without correction and to better than 5 m with corrected systems. Elevation can also be accurately determined from GPS. For a new site, this technology may be the easiest and most accurate means of determining its location.

3.1.4 General site description for the Archive

A second aspect of describing the site location is a general description of the surrounding area. The Technical Plan for BSRN Data Management (TPBDM), Version 2.1, defines two fields for the description of each site. The first field is *surface type*, while the second field is *topography type*. These fields are further described in Tables 4.14 and 4.11, respectively, of the TPBDM and are included as elements in logical record four of the station-to-archive file format. The tables are reproduced below as Table 3.1 and Table 3.2 for convenience. The format for each descriptor is I2.

While these tables are useful, they remain limited in fully describing a site because few sites fall easily into any simple set of categories as described. To aid researchers in understanding the overall complexity of the area surrounding a station a more complete description, including topographic maps and photos of the site and its surroundings, is required. A more complete formulation of a site description is described below.

3.2. BSRN Station Information Document

While the Archive information provides a brief description of the site and the site survey provides information on obstructions to the incoming radiative fluxes, if any, a more thorough description is necessary for data users. Both those involved in the determination of climate change over time or the validation of satellite algorithms require detailed information about the site surroundings to determine the quality of the data for their specific needs. For example, individuals studying climate change require not only a knowledge of the general topography, but also details of city growth, changes in land use, farming techniques if in an agricultural area or flight patterns and frequency if near an airport over the time period of the measurements. Similarly, those using the data to obtain vicarious calibrations of satellite-borne instruments require similar knowledge to determine how representative the site is with

respect to its surroundings. To provide this information, a more complete site description is required. The document, as described, has been modelled after a similar one designed for the Commission Internationale de l'Éclairage (CIE) International Daylight Measurement Programme.

Data in relation *topography type*		
Value	*Topographic Feature*	*Population Density*
1	flat	urban
2	flat	rural
3	hilly	urban
4	hilly	rural
5	mountain top	urban
6	mountain top	rural
7	mountain valley	urban
8	mountain valley	rural

Table 3.1. Topography types used in archive site identification.

The description consists of 11 sections broken down into three main areas: General Description, Site Description and Station Description; much of this information is required for the Archive, but it is set up as an information package for prospective data users. A description of the information required to complete the package follows. A blank document is included in Annex A.

3.2.1 General Description

(1) Information on whom the scientific authority is for the site. Postal address, telephone, fax and E-mail if applicable.

(2) The site's location: latitude (N positive 0 - 90), longitude (East/West of Greenwich), Elevation above MSL, Local Time from GMT, Station Topography and Station Surface Type from the archive, and the date of the first data submitted to the archive.

(3) Topographic map showing the land within a 15 km radius. A topographic map with a scale of approximately 1:250000 provides the appropriate resolution. This gives users a sense of the homogeneity of the surrounding areas.

3.2.2 Site Description

(4) Site Surroundings: a written description indicating population centres, population density. If within a large city; whether the city is growing, stagnant or declining in population. Major sources of pollution. Large bodies of water or significant local topographic effects. If the site is located at an educational institution or on the top of

a building.

(5) Climate characteristics: the general climate type (maritime, polar etc.), climatic normals (min/mean/max summer/winter temperatures, mean rainfall etc), significant climatic events (e.g. monsoons, hurricanes, tornadoes)

Data in relation *surface type*		
Value	*Major Surface Type*	*Descriptor*
1	glacier	accumulation area
2	glacier	ablation area
3	iceshelf	-
4	sea ice	-
5	water	river
6	water	ocean
7	water	ocean
8	desert	rock
9	desert	sand
10	desert	gravel
11	concrete	-
12	asphalt	-
13	cultivated	-
14	tundra	-
15	grass	-
16	shrub	-
17	forest	evergreen
18	forest	deciduous
19	forest	mixed
20	rock	-
21	sand	-

Table 3.2 Surface types used in archive site identification

(6) A map of the local area around the station (approximately a 1 - 2 km radius). A recent topographic map or photomap with a scale of 1:50000 provides the necessary resolution.

3.2.3 Station Description

(7) A list of all the radiation fluxes being measured routinely at the station and the types of instruments being used. The type of data acquisition system(s) being used, the sampling rate and the archived outputs. Information on the tracking and shading systems being used in the measurements.

(8) Station map: a detailed map indicating the location of the individual instruments in relation with each other. This map is primarily for the radiation instrumentation locations and need not include the location of the meteorological station or upper air station. Such information would be on the station map if the distances were greater than approximately 20 m.

(9) A horizon view of the global radiation sensor indicating the major obstructions. This would be a figure utilizing the data supplied to the Archive running from North through South to North in a clockwise direction.

(10) Comments on the site. For example, comments would include the instrumentation and data acquisition systems that are used for the meteorological variables. If another individual is the responsible contact for the meteorological portion of the site, the name and address would be included in these comments. A brief description of the method and frequency of calibration of the sensors would be included in this set of comments. If a particular set of research measurements were being made at the site, this should be noted and the name and address of the appropriate contact given. This section can be used by the site manager to advertise anything that makes the particular site special.

(11) Photographs of the station and its surrounds. Up to 4 photographs with appropriate comments. These can convey useful information concerning the instrument set-up and the surrounding horizon if there are significant obstructions. For example, if a tower is found on the site, a photograph may be appropriate to show where the instruments are located, or four pictures of the cardinal points of the compass from the central instrument with a wide-angle camera. In a manner similar to the comments section above, the photographs are to convey information about the station to the data users.

The BSRN Station Description document should be updated regularly. If significant changes occur in the instrumentation, the horizon or the ancillary measurements, corrections should be made immediately. In a manner similar to the horizon survey, the site description should be up-dated every five years.

3.3 Instrument Exposure

To obtain data on the radiative field with respect to the surroundings, it is necessary to map the horizon of the instrument. With few exceptions this actual horizon will be different from the theoretical horizon because of buildings, trees or landforms. In some cases other instruments will create reflecting surfaces from which additional radiation will be incident on the receiver of the sensor of interest.

The archive requires that the elevation be catalogued at 10° intervals beginning at 0° N and ending at 350°. All prominent features are also to be catalogued and inserted as ordered pairs in the increasing sequence of azimuth angles. This accuracy is increased to a 5° interval for the published station description (see below).

The two most common means of accomplishing horizon mapping are by a survey camera, which exposes azimuth and elevation grid lines on the negative, or by theodolite. The advantage of the former is that it also provides evidence of various reflecting surfaces. In cases where a theodolite is used, either panoramic photographs or an all-sky image from the location of the instrument should also be obtained.

Surveys should be carried out before installation of the equipment and then at a minimum once every five years. If significant changes in the horizon occur, they should be documented immediately and a new site survey performed.

If buildings or other objects are in the near field of view, separate surveys should be made from the location of each instrument if they are affected differently.

In cases where the obstructions are highly reflective, a separate measurement of the reflected radiation should be attempted. This is of particular importance if the object is man-made and constant (e.g. a white building). This information should be submitted to the Archive as part of the metadata.

Corrections to the data to eliminate the effect of obstructions (e.g. assuming an isotropic radiance distribution and adding the difference between the actual and the theoretical horizon to the signal) should not be used. In cases where an object blocks the direct beam radiation during all or part of the year, the data during these periods should be appropriately flagged.

3.4. Additional Station Requirements

The installation of the radiation instruments at a given location is dependent on a number of factors beyond the sighting of the instruments (Sec.3.1.1). This section is meant to provide a guide to ensure that these other factors are considered.

3.4.1 Ease of Access

Sensors must be easily accessible for daily maintenance. If the sensors are distant from the workplace of the support personnel, the quality of maintenance will be reduced, particularly following significant weather events. If the pyranometers are located on a building roof, access to the roof must be such that a technician will not be hesitant in inspecting or working on the instruments several times per day if required. If the instruments are mounted above the surface on a pole, a permanent platform or a ladder may be required so that the technician will be able to visually inspect the top of the instrument without difficulty. Safety factors must also be considered if instruments are to be located on towers or on the top of buildings. Human nature is such that instruments that are in areas that are inaccessible or can only be checked at some personal risk will be poorly maintained.

3.4.2 Electrical Power

The instrumentation required for the accurate measurement and storage of radiation fluxes and related meteorological variables requires reliable and stable electrical power over long periods of time. Depending upon the location of the site, to obtain and/or maintain such requirements may require devices as simple as surge protectors or as sophisticated as back-up generators. During the initial design phase of a BSRN station it is crucial to determine the quality of the electrical power available. This can be accomplished by obtaining information on the power supply from the local power authority.

The minimum suggested protection on all crucial equipment (e.g. computers, trackers, line powered data acquisition systems) is an uninteruptable power supply (UPS) capable of maintaining the system during outages caused by electrical storms, increased commercial demand (brownouts) and automatic switching of grid loads due to equipment failures. Most of these outages only require that the system maintain the equipment for less than 10 - 15 minutes; many times for periods of less than one second. Nevertheless surges or failures even of this short duration will cause the resetting and/or failure of equipment with an inherent loss of data.

Within the observatory, the complete power requirements, including design for future expansion, must also be considered. Transformers, fusing and wiring must be capable of bearing the load required to maintain the instrumentation. This problem is of particular concern when (1) individual circuits are overloaded with computing and data acquisition equipment or (2) long line lengths are required to conduct electrical power to distant field sites from a main panel.

3.4.3 Communication

At stations remote from network infrastructures, consideration must be given to transferring information from the observation platform to the laboratory where data analysis is performed. While formerly such data transfer took place by mailing information to the central processing facility, first on paper and later on diskettes, today a plethora of options is available. The intent of this section is to make the user aware of some of the possibilities available to transfer the collected measurements to the platform(s) on which the analyses occur. Expertise on the installation and operation of many of these methods should be available either from within national meteorological services or through private-sector consultants.

For data transport within a complex between two computers, a simple method is through direct serial communication. Using readily-available commercial software a connection between two computers can be accomplished quickly and easily. By replacing the direct serial connection with high speed modems and common carrier analog telephone lines the same software can be used to move data to wherever telephone communications exist. In more technologically advanced regions (e.g. urbanized Europe and North America) by increasing the complexity of the software and purchasing access to a local Internet provider, data can be moved over the Internet from one location to another on a regular schedule. Similarly, the use of file transfer protocol (FTP) services can be implemented for larger data transmission needs. These latter methods of transfer between computers can be operationally advantageous depending upon the charges applied to tele-communication rates.

When more than two computers are required to communicate, a simple Local Area Network (LAN) can be easily established. Using standard protocols (often sold as part of the computer operating system) and inexpensive adapters, several to hundreds of computers can communicate together, sharing resources, at far greater data transfer rates than serial communications. For example, data can be downloaded from a data acquisition system (e.g. Campbell Scientific CR7) using serial protocols (either locally or through remote communication methods) onto a single computer which is part of a network. This computer can then be accessed by many authorized users through a LAN. Data can be downloaded from the computer communicating with the data acquisition system through the network, or users can simply access the data from storage that resides at the site of the observations.

The Wide Area Network is similar in nature to a LAN but is designed to connect geographically distant locations. Within many countries national or regional governments operate WAN's for internal use (e.g. transfer of meteorological data from observing stations to the central forecast office). If these can be accessed to transfer data over long distances, significant operating cost may be saved, albeit at the expense of slower data transfer rates.

More sophisticated means of transferring data from remote locations are through radio frequency and satellite transmissions. An example of the latter method is the United States NASA aerosol optical property network AERONET. In this case a global network of instruments obtains measurements once per hour of aerosol optical properties which is transmitted via satellite for analysis at the Goddard Space Flight Center (GFSC). This method, however, is limited by the amount of data that can be transmitted through existing meteorological satellites.

Whatever means of communication is selected, Stamper (1989)[1] provides an excellent set of criteria on which to base the decision. Each criterion should be considered, even though it may not be significant in the final selection process.

Cost: this includes the price of the medium selected, the installation of the necessary equipment (e.g. cable), software and hardware requirements (e.g. drivers and computer cards) specific to the medium and the ancillary cost of expansion, if and when needed.

Speed (capacity): this is broken into response time (the time required for each individual transaction) and aggregate data rate (the amount of information transmitted per unit time). An example of such is modem communication with a data logger every hour to download mean values of climate variables. The response time is the time it takes the modems to connect, while the aggregate time is the time it takes to download the data. In this case, the more complex the modems the greater the response time in determining speed and compression type, while the aggregate data rate may be of little importance because the amount of data is only several thousand bytes. Conversely, when transferring Mb of data, the aggregate data rate becomes the most important factor.

Availability: Is the medium available when there is a need to utilize it? For example, if using common carrier telephone lines, does one get a 'busy' signal at the times data is to be transferred, or is the telephone system so busy that lines are unavailable (e.g. during special holidays).

Expandability: Can the system be enlarged for increased demand? This can either be an increase in the number of stations using the communication system or in the amount of data being transmitted through the system. An example of the latter would be the upgrading of telephone modems to higher baud rates to handle increased amounts of data transfer over the same time period (increased aggregate data rate).

Errors: All means of data transmission are subject to signal distortion, which can produce errors in the data. To reduce this problem, data communication environments transmit redundant data to detect if such errors have occurred. The more complex the method used for detecting such errors, the slower the data throughput, but the higher the probability that the data will be error free. The number of copies of the data and how long each copy is maintained should in part be correlated to the frequency of data transmission errors. In turn this will dictate part of the overall cost of the system.

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[1] Stamper, D.A., 1989: *Business Data Communications*, 2nd Edition, Benjamin/Cummings Publishing Co. Ltd., Redwood, CA, U.S.A.

Security:	The ease of access by outsiders increases the threat of breaches in security. This can vary from someone accidentally interrupting a data transfer to vandals physically or electronically destroying equipment and data. While it is impossible to have complete defence against loss, the need for security must be balanced against the cost of its implementation.
Distance:	The physical distance between the data collection location and the data archive location will often determine the methods of communication that are available. For example, the only viable solutions for long distances may be common carriers or even satellite communications, while shorter distances (e.g. within a complex of buildings) can utilize hard-wired local area networks.
Environment:	Physical or legal constraints may affect the type of medium that can be used. Local ordinances may prohibit the use of certain types of radio communications or the laying or stringing of cable. Climatic variables, such as wind, temperature, rain and icing conditions also need to be considered when selecting a communication medium. For example, overhead wires in areas where icing is a common problem may not provide a reliable means of communication.
Application:	Peculiarities in particular applications will dictate significant portions of the selection of a media. This is especially true at remote sites where power conservation requires only limited communication access. The slowest portion of the communication chain will also dictate the overall requirements of the entire chain. For example, if communication between a data logger and a computer, through common carrier lines, is constrained by the baud rate at which the data logger can transfer the data to the modem, there is no reason to purchase modems with a higher baud rate.
Maintenance:	All media are subject to failure. The system design should take into account the probability of a failure, the cost of such a failure to the user in money and inconvenience, and the ability of the user to obtain alternate communication media for the duration of the failure. Routine maintenance must also be considered in terms of down time and overall cost of the system.

3.4.4 Security

Depending upon the location, security may be a significant consideration. Security is both for the protection of the site against vandalism and theft, and for the protection against harm of would-be intruders (the concept of being responsible for a thief's well-being while on the victim's property may well be found only in North America).

At a minium the measurement site should be well-fenced against intruders, both human and animal. Further security measures may include alarm systems, security lights (on buildings, but away from the instrumentation) and video camera systems.

In some locales special security should be considered against burrowing and gnawing rodents.

3.5 Site Preparation

The preparation of the site before measurements begin consists of designing the installation to reduce interference of the sensors from buildings and other sensors, ensuring that the instrument platforms are appropriate for the climate and soil conditions, and designing a signal cable grid that is efficient and easy to maintain. While general principles can be applied to each of these aspects of the site, individual stations will require special adaptations to the following procedures.

3.5.1 Instrument siting

Care must be taken so that the instruments do not interfere with each other. Ideally, instruments should be far enough apart that they become insignificant objects in the field of view of adjacent instruments. Space limitations, however, often restrict the distance apart instruments can be placed. To reduce such interference, the instruments should be lined up in a poleward direction with slightly increasing elevation. In cases where the measurement of diffuse radiation and direct radiation are separate, the diffuse and infrared (if shaded) measurement should be the furthest poleward and slightly elevated, while the direct instrument should be closest to the equator and at the lowest height. The global instrument should be centred between these two instruments and higher than the direct instrument. The global, diffuse, and infrared instruments should be at the same height, with only the shade portion of the diffuse apparatus extending above the height of the thermopile of the global instrument. In the case where the direct and diffuse instruments are set on the same tracking platform, the direct beam instrument(s) should not interfere with the horizon of the diffuse instruments.

When locating instruments that measure upwelling fluxes it is important to be able to service these instruments from their poleward direction to reduce ground disturbance that may affect direct reflectance into the sensor from the sun. For example, significant differences in snow albedos can be observed by the internal reflectances associated with footsteps near a downfacing instrument on its solar side.

For meteorological instrumentation, distant horizon problems are minimal but interference between instruments is significant. For the measurements of temperature and pressure, the Stevenson screen (or equivalent) should be at least twice the distance apart from the height of all significant objects. These objects should be located poleward of the measurement site so that shading will not interfere with the instruments within the screen. Precipitation measurements should be at least a distance of 4x the height of any obstruction away from the obstruction. Wind measurements must be at least 10 times the height of an object distant from that object. For example, the 10 metre mast in Figure 3.1[2] is located 200 m away from the 20 metre tall tree. Ideally, the wind mast should be located such that the data affected by the object are from the least frequent wind direction. Where the obstructions are trees, it is good practice to increase these distances, recognizing that vegetation will grow over time.

3.5.2 Instrument platforms

Instrument stands can be as simple as a vertical post holding a single pyranometer or as complex as a raised platform that can hold a large number of individual instruments and

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[2] *AES Guidlines for Co-operative Climatological Autostations, Version 2.0*, Climate Information Branch, Canadian Climate Service, Atmospheric Environment Service, Downsview, Canada, M3H 5T4, 1992. 85 pages.

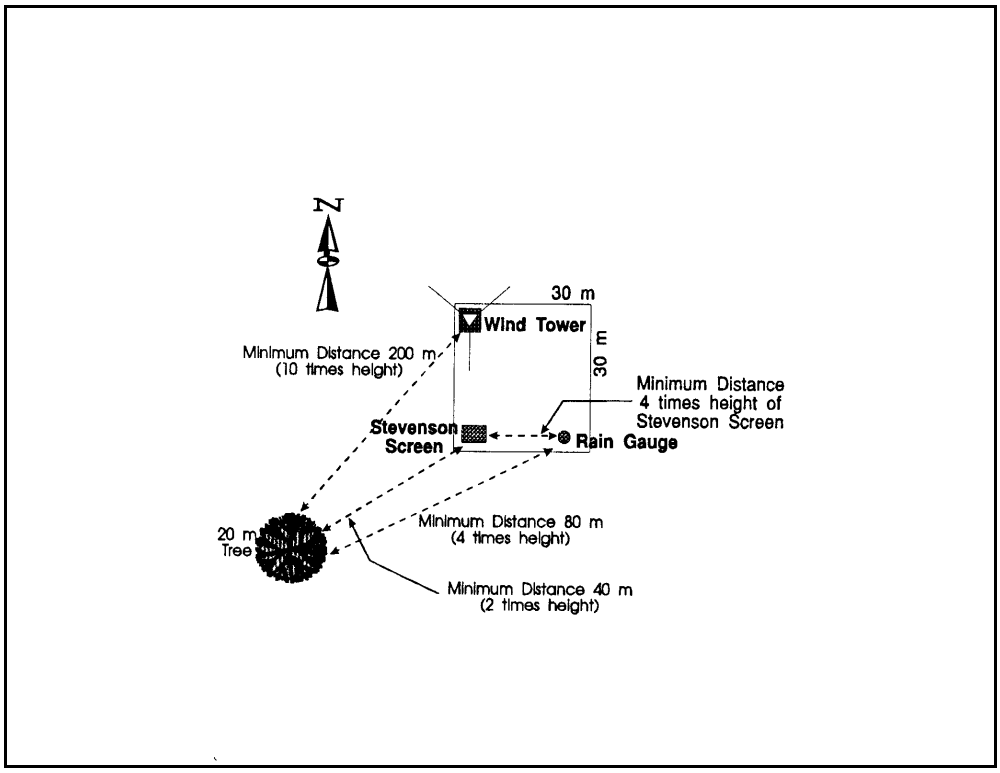

Figure 3.1. Diagram indicating appropriate distances from an obstruction to meteorological instrumentation (from *AES Guidlines for Co-operative Climatological Autostations, Version 2.0*).

trackers. In all cases, the platform must be stable over long periods of time, resisting warping by changes in temperature and humidity, and be immovable in strong wind conditions (to within ±0.05°). In most climates, wooden platforms should not be used because of their tendency to warp with humidity and seasonal changes and because of attack by insects. In temperate climates platforms made of steel or aluminum provide both the necessary stability and durability required for radiation measurements. In hot climates though, these may be inappropriate because of extreme heating (both with respect to expansion and ease of access due to heating). Reinforced concrete, or concrete and steel structures, when expansion is considered, are probably the optimal materials for the construction of stands, whether they be simple posts or complex platforms.

The base of any post or platform must be either firmly attached to a building or dug into the ground. In the latter case, the base of the structure should be anchored at a depth below any material that may be subject to heaving due to frost or water. Local or national building codes where available provide excellent information on both the depth to which posts must be implanted and the means in which this is best accomplished. If further information is required a qualified mechanical or civil engineer familiar with the location should be consulted. Figure 3.2 illustrates a typical post installation for a continental site in well drained soil, while Figure 3.3 illustrates the more complex German platform required to elevate the instruments above the local horizon.

Along with the structural integrity of the platform, the height of the platform above the surface must also be carefully considered. As previously mentioned, in built-up areas up-facing sensors can be located on top of buildings to overcome local horizons. In more rural areas instruments can be located as close as 1.5 m above the surface. In the latter case, consideration must be given for terrain effects such as blowing or accumulating sand or snow. When instruments are placed higher than approximately 1.5 m, a means of accessing the instrument for cleaning must be provided. This can vary from a permanent

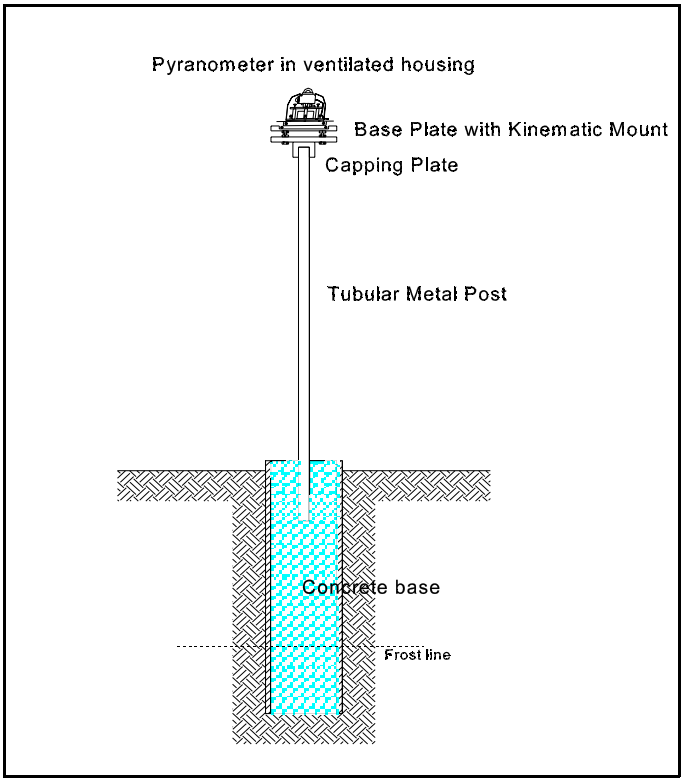

Figure 3.2 Simple post mount in concrete base.

deck structure to a simple step ladder, remembering that the easier the access to the instrument the more likely the instrument will be well maintained.

If the instrument is to be mounted on the roof of a building care must be taken to guarantee that the instrument will not be blown off during high winds. The secure anchoring of the instrument stand should be done in consultation with the building manager or engineer. If possible, a permanent installation with the instrument stand bolted to the building is preferable to the use of stands set on the roof and secured only by heavy weights.

Depending on the site, further measures may be required to ensure the stability of the pyranometer platform during high wind conditions. Extra guy-wires or bracketing may be added to keep the stand from oscillating.

3.5.3 Cables

3.5.3.1 Signal cables

Just as important as determining the best field of view for the instruments is routing the signal cable from the instrument to the data acquisition system. As most surface-based radiometers are thermopile instruments, the maximum signal is usually in-the-order of 10 mV for a 1000 Wm^{-2} flux or 10 $\mu VW^{-1}m^{2}$. Such small signals can be affected easily by large line resistance due to long cable lengths and electrical interference from other sources, particularly AC power lines running parallel to the signal lines. Several suggestions follow to aid in the design of the measurement system.

(1) All signal cables should consist of grounded, shielded pairs. The outer sheathing of

Figure 3.3 BSRN instrument platform at Lindenberg, Germany.

the signal cable should be based upon the climatic regime of the station and the overall EMF to which the cable is to be subjected. It is recommended that cables be made of stranded copper for flexibility.

(2) Cable lengths should be kept as short as practically possible. The overall length of the cable is dependent upon the remoteness of the measurement platform and the type of data acquisition system being used to sample the signal. Types of data acquisition systems are discussed in Section 6.

Where long cables are required and the total resistance of the cable is greater than 10 Ω (approximately 50 m), a pre-amplifier should be placed at the instrument end of the system. Extreme care should be taken with this solution because of the temperature dependency and non-linearity of electronic components.

(3) All cables that run along the ground should be buried to a depth where they will not normally be disturbed by routine maintenance operations. Cables not specifically capable of withstanding burial should be placed in conduits. This increases the overall neatness of the site and reduces the danger of personnel being injured or dislodging the cable from the instrument. When effort is being expended to place cables underground extra capacity for future expansion should be considered.

(4) Signal cables should be run through separate conduits from electrical power cables whenever possible. Cables should cross a right angles to reduce electrical

interference. When such arrangements are impractical, specially shielded cables should be used.

(5) At remote locations, secondary signal processing and serial or satellite communications should be considered to transfer data to a permanent storage device. In the design of such a system, the potential for communication failures must be considered in the overall plan.

Cabling between the instrument and the data acquisition system should be carefully grounded and protected against lightning. Figure 3.4 gives a general illustration on how the grounding and lightning protection should be placed within the instrument/cable/acquisition system configuration.

Whenever a system is wired, care must be taken to accurately map both the physical location of the cables (especially if underground) and the connections running from the instruments through the junction boxes to the data acquisition system.

3.5.3.2 Electrical Cable

Electricity should be available at the location of the sensors, both for the operation of the instruments and for use in the maintenance of the observation platform. Separate circuits for each set of instruments is desirable, but not always practical. Whenever redundant instrumentation is used, it should be operated on separate electrical circuits. All electrical wiring should meet or exceed local electrical codes. The local electrical utility, an electrical engineer or qualified electrician should be able to provide information on local electrical regulations and provide an estimate of the electrical consumption of the site.

Just as in the case of the signal cables, all electrical cables should be either buried or securely fastened to the instrument mounting platforms. Furthermore, for safety, switches or circuit breakers should be installed close to the equipment for easy servicing.

The quality of power supplied to the instruments should be the same as described in 3.4.3.

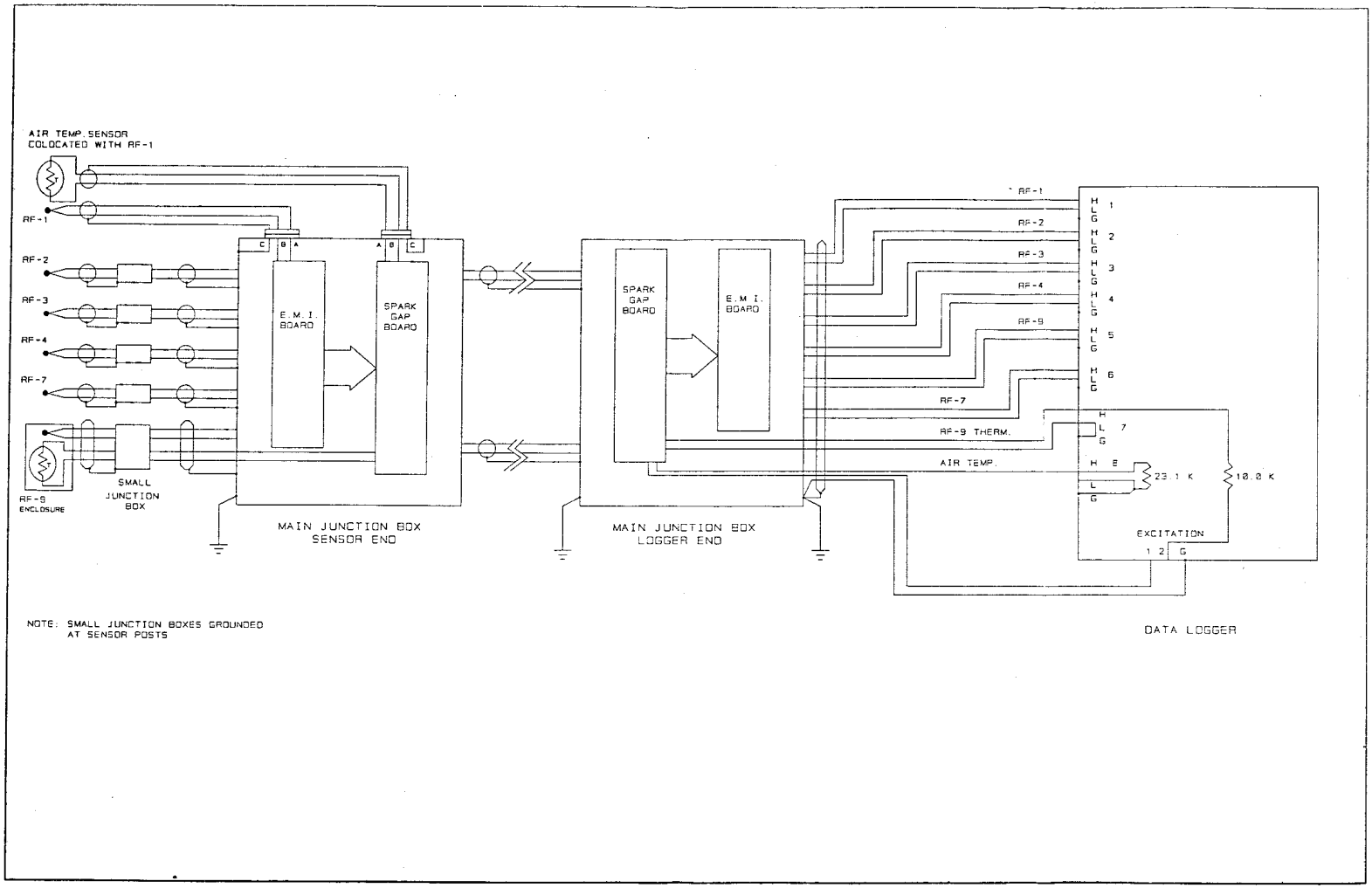

Figure 3.4. Generalized schematic of the interface between radiation sensors (RF) and a data acquisition unit showing lightning protection and cable grounding.

4.0 Installation of Radiation Instruments

4.1 General

The installation of pyranometers, pyrheliometers and pyrgeometers is relatively simple (Annex B provides information on some of the instruments used in the BSRN), but nevertheless requires care and attention to detail.

In all cases, the manufacturer and type of instrument used for the measurement of global radiation should also be used for the measurement of diffuse radiation. It is also recommended that the pyrheliometer used be of the same manufacture as the pyranometers. This is to ensure that the spectral response of the instruments is similar.

A number of documents, including manuals provided by manufacturers, have been published that include information on the installation of these instruments. Documents published by technical agencies include:

Radiation Measurement. International Field Year for the Great Lakes, Technical Manual Series No. 2, National Research Council of Canada, 1972.

Revised Instruction Manual on Radiation Instruments and Measurements. World Climate Research Programme, WCRP Publication Series No. 7, WMO/TD No. 149, 1986.

Meteorological measurements concerning questions of air pollution, Global radiation, direct solar radiation and net total radiation. VDI-Richtlinien, VDI 3786, Part 5, 1986.

Solar Energy - Field Pyranometers - Recommended practice for use. International Standards Organization Technical Report TR9901, 1990.

4.2 Installation of pyranometers and pyrgeometers

4.2.1 Pre-installation Checks and Service

Before installing any pyranometer the instrument should be carefully inspected.

(1) If not provided by the manufacturer, the instrument should be calibrated so that the following information is available:

- (i) the responsivity of the instrument to radiation
- (ii) the linearity of the instrument between 0 and 1500 Wm^{-2}
- (iii) the directional responsivity of the instrument (cosine and azimuthal response of the instrument) for pyranometers
- (iv) the deviation of the temperature compensation circuit of the instrument over the temperature range (-10° to +10° of range) or if not compensated, the required temperature correction of the instrument
- (v) the instrument has been radiometrically levelled. That is, the thermopile is horizontal when the bubble level indicates such (the bubble level should have an accuracy of ±0.1°).

(2) Checks should be made of all wiring to ensure that there are no nicks in the sheathing nor stress on the connections. The wire should be of a variety that will withstand the climatic regime of the area in which the instrument is to be installed.

(3) All O-rings should be lubricated lightly with a very fine grease (e.g. Dow Corning Model 55 O-ring lubricant or Fischer Scientific Cello-Seal C-601).

(4) All threaded parts should be lubricated in a manner similar to the O-rings.

(5) The thermopile should be visually inspected to ensure that the surface is uniform in colour and texture.

(6) The BSRN accuracy guide indicates that the case temperature of the instrument should be monitored. If the instrument is fitted with a thermal measuring device, the wiring should be checked and the reduction algorithm tested at known temperatures. In the case of pyrgeometers, all thermistors should be tested.

(7) The inner and outer domes should be checked for scratches or nicks. If found the domes should be replaced. In the case of pyrgeometers a similar check should be made of the silicon dome. However, if the dome requires replacement due to damage, the instrument must be re-calibrated.

(8) The impedance of the instrument should be checked against the manufacturer's values.

(9) The desiccant should be fully activated. It is recommended that the desiccating material be of the bead type (e.g. Trockenperlen, Kali-chemie AG) and not one which easily powders (e.g. Drierite, Hammond Drierite)

(10) All connectors must be waterproof and should be appropriate for the climatic conditions in which the sensor will be deployed. For example, in marine environments care must be taken against using connectors that are prone to corrode. It is recommended that keyed connectors be used for greater safety in maintaining instrument polarity.

4.2.2 Mechanical Installation

(1) The instrument should be mounted with the direction of the connector facing poleward for fixed platforms and away from the solar disk when mounted on solar tracking devices.

(2) The instrument must be fastened to the platform (or ventilating device (see below)) so that it will not move in inclement weather. The bolts used should be lubricated before assembly for ease of disassembly. Initially, these bolts (normally two or three depending upon the instrument) should be not be tightened until the instrument is levelled according to its bubble level.

Spring loaded bolting devices for mounting the instrument are also an excellent means of guaranteeing the instrument will remain fixed while providing the added ability of levelling the instrument without requiring the bolts being loosened.

(3) The instrument should be levelled using the supplied three levelling feet. By first adjusting the foot closest to the bubble, the instrument should be adjusted until the bubble is centred within the inner circle of the supplied bubble. When completely centred, and radiometrically levelled, the bubble level indicates that the thermopile is

horizontal to within ±0.1° causing an azimuthal variation of ±1% at a solar elevation of 10°.

(4) Carefully tighten the retaining screws so that the instrument is immovable. To do so, gently tighten the bolts alternately until secure. Be careful not to over-tighten.

(5) Place and adjust the radiation shield or ventilated housing cover so that it is parallel to, and level with or below the thermopile surface.

4.2.2.1 Ventilated housing

The recommended procedures for the measurement of global radiation require the use of a ventilated housing to improve the overall accuracy of pyranometer measurements. In some climates, the use of a ventilator also improves the amount of recoverable data by eliminating dew and reducing the number of occurrences of frost and snow on the instrument domes. Measurements in other regions, however, have not shown a significant increase in accuracy or percent data recovered with the use of ventilated housings. As each ventilator adds extra cost and complexity to the installation and maintenance of a station a thorough analysis of its requirement should be made before installation.

In areas where dew, frost or snow is prevalent a ventilator should be used. In areas where natural ventilation is infrequent or variable, a ventilator is recommended. In areas where there is significant radiative cooling during portions of the year, a ventilated housing will instrument reduce zero-offset. In areas where the humidity is high during portions of the year a ventilator will reduce the possibility of water damage and reduce the frequency of desiccant changes.

There are three major types of ventilated housings:

(i) Remote ventilation of the domes by free nozzles (Figure 4.1). These nozzles provide independent airflow from various azimuthal directions around the side of the pyranometer dome. Care must be taken that the nozzles do not extend above a 5° elevation. The temperature of the resulting airstream is a function of the heat dissipated by the ventilator motor and cooling by the Doule-Thompson effect. These are the least popular of the various types of ventilator. Their primary advantage is that they are able to direct a significant flow of air to the zenith of the dome, while the principle disadvantage is that a significant temperature differential may be created between the dome and the body of the instrument. For this reason, these types of ventilators are not recommended.

(ii) Ventilation of the dome where the ventilator motor is situated beside the instrument and the air is forced over the instrument dome via a slit. A modification of this design is to encapsulate the pyranometer completely so that the air flows evenly around the dome. The advantage of this design over (i) is that the blower may be significantly smaller and of lower power. The disadvantage is the reduction in the amount of air reaching the zenith of the dome. The temperature of the instrument in the encapsulated ventilator and the instrument dome will rise slightly above the ambient temperature due to the heating of the air by the blower motor. The body of the instrument in the open housing is not heated, while the dome will be heated slightly above ambient. When wind speeds are high for either design the dome heating effect will be neutralized and the dome temperature will be at ambient. Figure 4.2 illustrates this type of blower as used by the Deutscher Wetterdienst.

Figure 4.1. Directional ventilation of an Eppley Pyrgeometer. (Alice Springs, Australia)

(iii) The most common ventilation system employed encloses the ventilator motor beneath the instrument in a completely enclosed system (Figure 4.3). The power dissipation heats the incoming air by approximately 1 K, which in turn heats the body and dome of the enclosed instrument. The major advantage of such a system is the increased temperature stability of the pyranometer which reduces the zero-offset. Care must be taken to ensure that the ventilator provides enough airflow over the dome's zenith. The disadvantages are similar to (ii).

Heating resistors can be added to both (ii) and (iii) if required during cold weather operations. Care must be taken, however, in that these may also alter the overall response of the instrument.

4.2.3 Mechanical installation of shaded sensors (pyranometers and pyrgeometers)

The general installation of shaded sensors follows the guidelines set out in 4.2.2 but includes the added complexity of aligning the shading device with the instrument. Within the BSRN, shade rings (diffusographs) are not accepted as a means of shading an instrument because

Figure 4.2. Ventilator with motor located beside the instrument as used by Deutscher Wetterdienst.

Figure 4.3 Ventilator with motor located beneath the instrument. Note the extra ventilation holes near the top of the housing used to reduce snow accumulation (Davos, Switzerland).

of the field of view the ring subtends. Two other common devices are presently used within the BSRN.

Figure 4.4 illustrates the synchronous motor shade device employed by the Swiss, while Figure 4.5 illustrates the Australian computer-controlled tracking device where the direct beam is measured from the same tracker using a pyrheliometer. In the former design, the assembly is placed such that the shading arm is placed equatorward with the axis being set at the latitude of the site, the instrument being placed on the fixed horizontal plate. In the latter design, the device tracks the sun in the azimuth so that the same portion of the instrument faces the sun continually. General information on solar tracking devices, including the setup of a synchronous motor equatorial mount, is found in Section 5.

In both cases, the instrument requiring shading must be placed precisely so that the shade of the diffusing disk completely covers the outer dome of the instrument. The general rule presented by the WMO for pyrheliometry is that the ratio between the length and the diameter of the of the opening angle of a pyrheliometer is 10:1. This rule can be used to approximate the geometry of the disk or sphere used to block the irradiance from solar disk. Major (1992)[3] discusses the use of pyrheliometers and shaded pyranometers for the measurement of global radiation with respect to the optimum design of the diffuser. The results indicate that the best equivalence can be expected if the distance between the receiver and the shading disk is chosen so that the slope angle is larger and the opening

[3] Major, G., 1992: Estimation of the error caused by the circumsolar radiation when measuring global radiation as a sum of direct and diffuse radiation. *Solar Energy*, 48(4), 249-252.

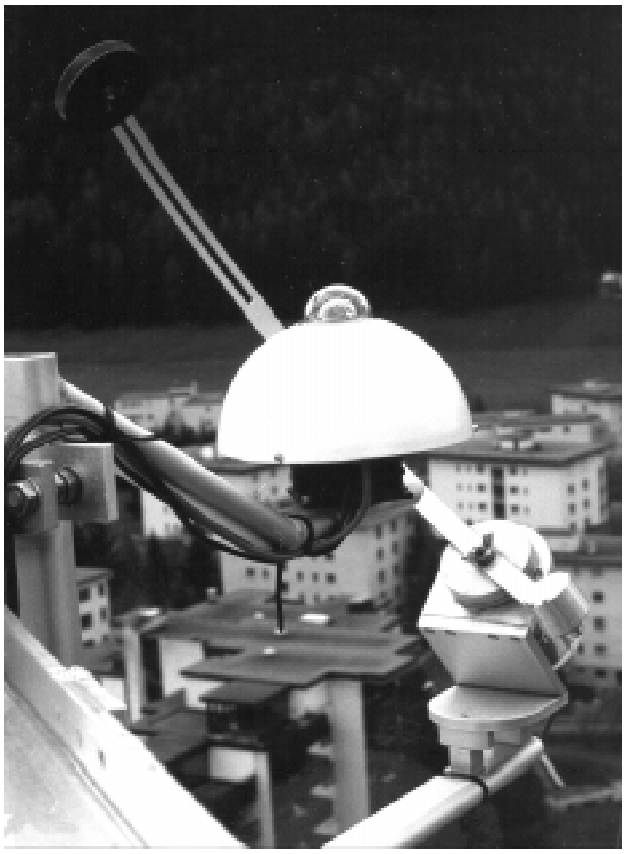

Figure 4.4. Swiss single axis oversize tracking disk (Davos, Switzerland). Note the slot used to adjust the tracking disk with respect to changing solar declination.

angle is less than those of the pyrheliometer in use.

4.2.4 Installation of downfacing sensors (pyranometers and pyrgeometers)

Downfacing sensors should only be installed when the sensor can be located a minimum of 30 m above the surface to increase the representativeness of the field of view.

The tower from which the instrument is to be deployed should be as compact as possible while recognizing the need for individuals to climb the tower to service the instrument. Open towers provide less interference of the radiation flux than solid towers of the same dimension. The further the instruments are mounted away from the tower on booms, the less the tower influences the radiation field. In the worse case scenario of a solid tower of diameter D with a boom of length L measured from the centre of the tower, the fraction of radiation intercepted is $D/2\pi L$.

In all cases the sensors should be installed with the tower poleward of the instruments so that only in the most poleward latitudes will the tower intercept the solar beam.

As in the case of the up-facing sensors, the sensors must be horizontal. To accomplish this, however, is more difficult because the bubble levels attached to the instruments no longer function properly. Two methods are suggested to help overcome the levelling problem.

(1) By assuming that the rotation of the instrument about its horizontal axes is true, the instrument can be levelled in the up-facing position with its own

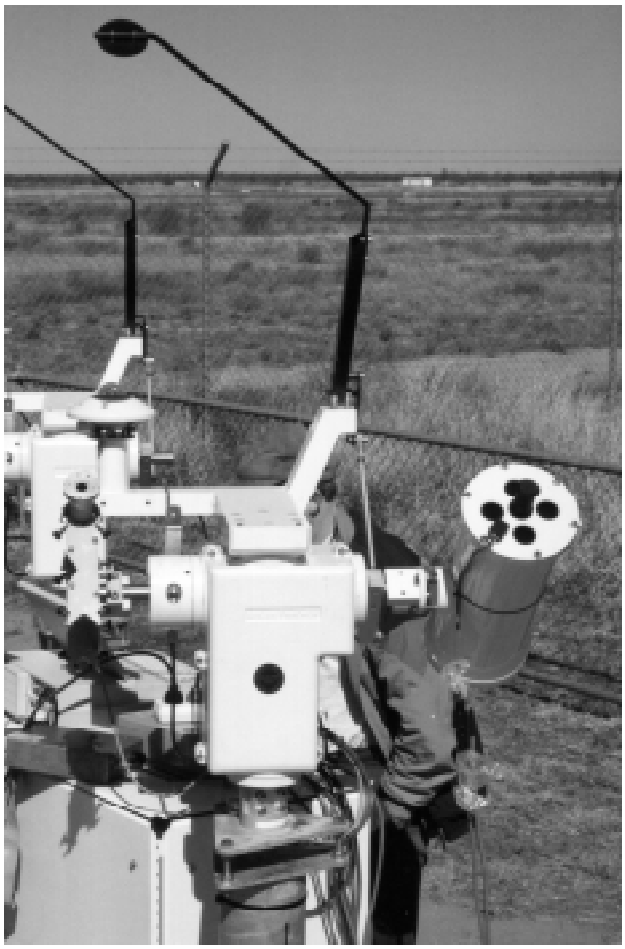

Figure 4.5. Australian active tracker used for both diffuse and direct measurements. This tracker is shading a single pyranometer while pointing a multi-filter sunphotometer. The active eye is located immediately to the left of the main tracker gearbox. A pyrheliometer is mounted on the far left.

bubble level and then rotated 180°.

This method works well if the instrument is on a vertical post attached to the boom extending from the tower. The pyranometer is levelled while the post is vertical in an upright position. The measurement of the angle of the post can be accomplished to within 0.1° using a high quality carpenter's level.

(2) The second procedure requires the construction of a levelling jig. This consists of a flat planed parallel piece of metal attached to a circular ring whose diameter is such that it will sit around the outside dome of the pyranometers to be inverted. The ring must have known parallel ends. The metal flat (which can be reversed, side-to-side) is attached to one end of the ring, while the other end of the ring sits on the ring surrounding the pyranometer outer dome. To improve the performance of this tool, three small 'feet' may extrude from the instrument end of the ring for positive placement on the pyranometer. On the far end of the metal plate an adjustable circular spirit level is attached for the ultimate levelling of the pyranometer (pyrgeometer) to be used in the downfacing position.

The pyranometer is first levelled in its normal position following radiometric levelling of the instrument. The levelling tool is placed on the pyranometer and the adjustable level on the plate set to conform to the instrument bubble level. The plate is then turned over so that the bubble level will be upright when the pyranometer is inverted.

When attaching the pyranometer to its inverted position, spring loaded retaining bolts are required to maintain a constant pressure again which the levelling feet can be adjusted. The level can be set by holding the levelling jig against the instrument and adjusting the levelling feet of the pyranometer in the normal manner.

4.3 Installation of instruments for the measurement of direct beam radiation

4.3.1 General Considerations

The original goal of the BSRN was to use a cavity radiometer with an open entrance aperture for the measurement of direct beam radiation. This was later amended to include the use of a normal incidence pyrheliometer (or more simply pyrheliometer) to fill gaps in the data stream during those time periods when the cavity radiometer was in calibration mode. Further amendments were made to the original concept when concerns about protecting the open cavity radiometer against the elements were brought forward. At present, the ideal configuration for the measurement of direct beam radiation remains the use of an open cavity radiometer with a pyrheliometer to complete the data set. Thus the cavity radiometer is the primary instrument with the pyrheliometer being used by correlating its values during the non-calibration period against the cavity radiometer so that the data set can be completed using the pyrheliometer during the calibration period of the cavity. The actual definition of calibration period depends upon the type of cavity radiometer being used. Lesser alternatives, however, are acceptable. In rank order of preference these are: (1) The use of a pyrheliometer as the primary instrument while an open cavity radiometer is used in tandem at all times weather conditions permit. In this manner, the pyrheliometer is calibrated against the cavity radiometer nearly continuously. (2) same as (1), but with a cavity radiometer with a quartz flat covering the entrance aperture. This cavity in turn is to be calibrated against an open aperture cavity radiometer to account for the effect of the flat. (3) The use of two pyrheliometers measuring on a routine base, with an open aperture cavity radiometer checking the calibration on a periodic basis during high solar radiation conditions.

4.3.2 Pre-installation checks and service

(1) If not provided by the manufacturer, the instrument should be calibrated so that the following information is available:

- (i) the responsivity of the instrument to radiation
- (ii) the linearity of the instrument between 0 and 1500 Wm^{-2}
- (iii) the deviation of the temperature compensation circuit of the instrument over the temperature range (-10° to +10° of the local range in temperature) or if not compensated the required temperature correction of the instrument
- (iv) the opening angle and the slope angle of the instrument

(2) Checks should be made of all wiring to ensure that there are no nicks in the

sheathing nor stress on the connections. The wire should be of a variety that will withstand the climatic regime of the area in which the instrument is to be installed.

(3) The BSRN accuracy guide indicates that the case temperature of the instrument should be monitored. If the instrument is fitted with a thermal measuring device, the wiring should be checked and the reduction algorithm tested at known temperatures. In the case of pyrgeometers, all thermistors should be tested.

(4) The impedance of the instrument should be checked against the manufacturer's values.

(5) Some instruments require desiccant. If so, the desiccant should be fully activated. It is recommended that the desiccating material be of the bead type and not one which easily powders.

(6) All connectors must be waterproof and should be appropriate for the climatic conditions in which the sensor will be deployed. For example, in marine environments care must be taken against using connectors that are prone to corrode. It is recommended that keyed connectors be used for greater safety in maintaining instrument polarity.

4.3.3 Mechanical Installation

The primary obstacle in obtaining quality direct beam radiation measurements is the difficulty in pointing the instrument toward the sun. This is not so much a problem in mounting the sensor as correctly installing and operating the tracking device (Section 5).

The mechanical installation of the pyrheliometer or cavity radiometer must ensure that the instruments are firmly attached to the tracker on which they are to be mounted. Care must be taken that the instrument will not shift position throughout the day as the centre of gravity shifts with respect to the mounting brackets. Figures 5.1 and 5.2 illustrate a typical mountings of pyrheliometers on tracking devices

When installed on a correctly pointing tracker, the combination tracker and instrument should work as an integrated unit with the sight of the instrument acting as the primary sight for the tracker (with the exclusion of trackers with active tracking). In the case where a pyrheliometer and a cavity radiometer are mounted on the same tracker, the pointing of the cavity radiometer should take precedence over the pyrheliometer.

It should be noted in aligning direct beam radiometers, that the sights of the radiometers differ, but are all significantly smaller than the field of view of the instruments. Nominally, pyrheliometers have a field of view of approximately 5°. The sun targets subtend a maximum angle of between 1.4 and 2.0° for the solar dot to be incident on the target. Figure 4.6 illustrates graphically how the pointing accuracy of the major types of pyrheliometers affects their output signal. Two types of model atmosphere are used for the illustration. Further details of this work can be found in Annex C.

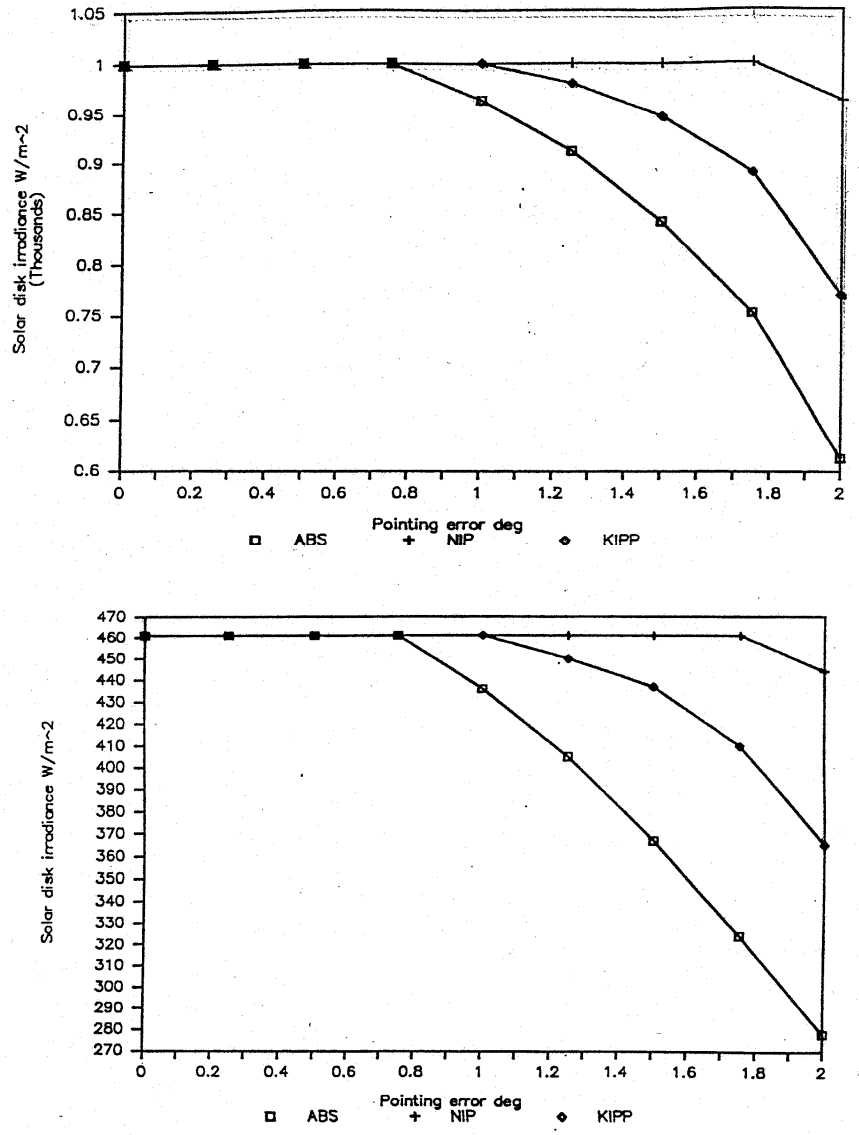

Figure 4.6 The contribution of the solar disk to the irradiance of pyrheliometric sensors depending on the pointing error. Upper graph, case of mountain aerosol and 60° solar elevation. Lower graph, case of background continental aerosol and 20° solar elevation. (Contributed by G. Major)

5.0 Installation of Solar Tracking and Shading Devices

5.1 Introduction

Several types of solar tracking devices exist, from the single-axis synchronous motor tracker to the computer-controlled dual-axis active-sensor tracker. Each type of tracker has advantages and disadvantages which must be balanced by the individual researcher before installing the device of choice. Table 5.1 indicates some of the advantages and disadvantages of some of the more common types of tracker. It goes well beyond the scope of the manual to provide the installation and maintenance instructions for each of these devices. A broad overview, however, is important because of the significance solar tracking plays in the measurement of direct and diffuse radiation.

5.2 General Considerations for Tracking

While each system requires specialized set-up and maintenance procedures, general characteristics are common to all.

The tracker location must be known. The more accurately the location can be determined the easier the setup of the tracker. With modern GPS receiver systems the position of the tracker can be determined (latitude and longitude) to within ±3 m. From a 1:50,000 topographic map the location can be determined to within better than 50 m. Depending upon the size of the installation care should be taken so that the actual location of the tracker is determined and not simply the central location of the BSRN observatory.

In all cases a reliable power supply is necessary. Synchronous trackers not only require a constant power supply, as do the other trackers, but also a constant and accurate electrical frequency if the tracker is to maintain accurate alignment on the solar disk at all times. Changes in power line frequency will alter the speed at which the solar disk is tracked. Most utility companies are required by law to maintain the power line frequency to some stated accuracy within a 24-hour period with a maximum excursion from that stated frequency at any given moment. Stepper-motor-controlled trackers are less susceptible to such changes because of their internal conversion from AC to DC power. The use of UPS systems on synchronous motor trackers is also limited because many inverter systems output frequency as square waves rather than the sinusoidal wave required by the tracker.

The base on which the tracker is to be placed must be stable. While active trackers and some passive trackers are able to correct for a non-level surface, all trackers perform better if they are mounted such that the instrument base is level. Trackers mounted on pedestals should be levelled such that the actual tracker axes are found to be horizontal and perpendicular.

The trackers need to be aligned in the north-south direction. Depending on the type of tracker the accuracy of this alignment varies. Equatorial trackers need to be precisely aligned, while most two-axis passive and active trackers have correction algorithms built into the software to allow alignment to be less precise. Again, however, the greater the accuracy in aligning the tracker, the easier it will be to initiate the operation of the tracker. The easiest manner of obtaining a north-south line is to trace the shadow of a perpendicular object at solar noon.

Types of Solar Pointing Devices Used in the BSRN		
Tracker Type	Advantages	Disadvantages
Synchronous Motor (Equatorial Mount) Figure 5.1	- least expensive - self-contained - very portable (light weight) - easiest maintenance	- single axis requires adjustment for solar declination - pyrheliometer wiring must be untangled every few days - accuracy dependent upon quality of the power line frequency
Two-axis Passive (algorithm controlled) Figure 5.2	- follows solar disk by translating accurate solar position algorithms into stepper motor control functions (using either an internal or external CPU) - usually has larger payload than synchronous motor trackers - does not require untangling of cables - may be able to attach an unshaded pyranometer on the azimuth axis to reduce the azimuth uncertainty	- requires accurate clock for accurate solar tracking - more expensive than equatorial mount - may require a separate computer control system to operate - pointing accuracy and smoothness of position dependent upon stepper motor functions
Two-axis Active (quadrant sensor controlled) Figure 5.3	- similar load capabilities to the two-axis passive tracker - active tracking device overcomes problems with clock accuracy during line-of-sight tracking (added accuracy over algorithm control) - most reliable accurate tracking - may be able to attach an unshaded pyranometer on the azimuth axis to reduce the azimuth uncertainty	- expensive - active tracking eye must be calibrated to ensure proper tracking in complex sky conditions - may require a separate computer control system to operate - requires accurate clock during cloudy conditions to maintain accurate solar tracking - pointing accuracy and smoothness of position dependent upon stepper motor functions

Table 5.1 Advantages and disadvantages of common solar tracking instruments.

Annex D provides the instruction set from Eppley Laboratories on the installation of an equatorial mount. This is provided in order to aid in the general understanding of the requirements of installing a tracking device.

5.3 General Considerations for Shading

The same types of tracker used for pointing direct beam instruments can be used for the shading of pyranometers from the sun.

In the case of the single-axis equatorial mount, the pyranometer is maintained in a stable position, while the shading device rotates about the centre of the thermopile. The equatorial mount is placed pointing poleward with the shaft of the motor at an angle equal to the latitude of the station. The instrument is mounted horizontal at a location where the centre of the thermopile is intersected by a line extending from the motor shaft. By passing the cables for the pyranometer and the ventilated housing through a hollow central shaft tangling of cables is prevented. Figures 5.4 and 4.4 illustrate the German and Swiss designs of this style of shading assembly. In both cases, the shade disk must be manually positioned following the solar declination to ensure that the instruments remain shaded throughout the year. While inexpensive to fabricate, the daily maintenance of these devices is high, similar to that of the equatorial mount used for pyrheliometers.

Two-axis trackers can be used either as a means of shading one or more instruments or as a combination unit where a pyrheliometer is also attached to the tracker. To use the tracker as a platform for both the shading of a pyranometer and the pointing of a pyrheliometer, the elevation drive must be mechanically translated so that it is horizontal and at the same height as the signal transducer of the instrument to be shaded. Figure 4.5 illustrates the construction used by the Bureau of Meteorology, while Figure 5.2 illustrates the method used by Sci-Tec Instruments on their tracker. In both cases, the shade disk(s), or sphere(s), remain at a fixed distance from the instrument sensor via a cantilevering-motion provided by the armature. Once installed, care must be taken so that the elevation drive of the tracker does not rotate completely about its axis or the arms will collide with the body of the tracker. This is accomplished by not allowing the elevation axis to go more than about 5 - 10° below the horizon before programming the tracker to “go to sleep” and/or return to a pre-sunrise position.

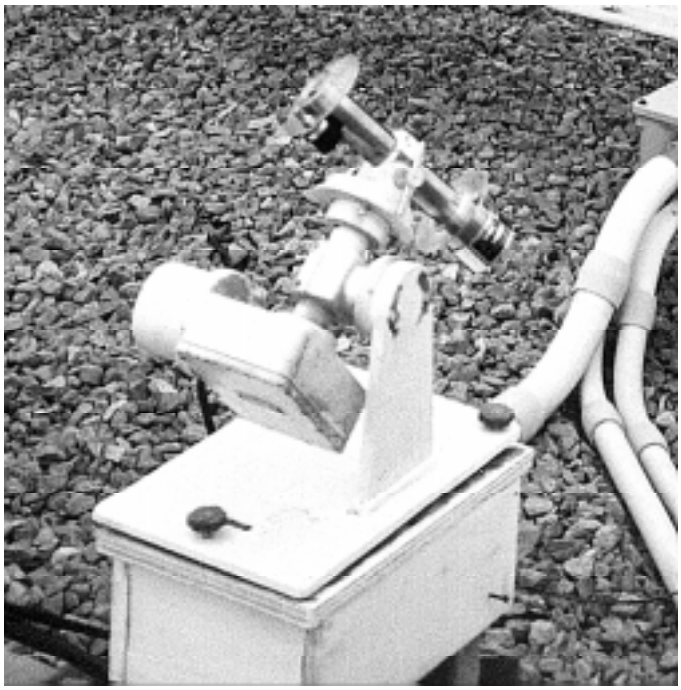

Figure 5.1. Eppley Model ST-1 equatorial mount.
Single axis, syncrhonous motor tracker.

Figure 5.2. Sci-Tec 2 AP passive, computer-controlled two-axis tracker carrying an Eppley NIP (under near arm) and two Eppley PSP pyranometers in Eppley ventilated housings.

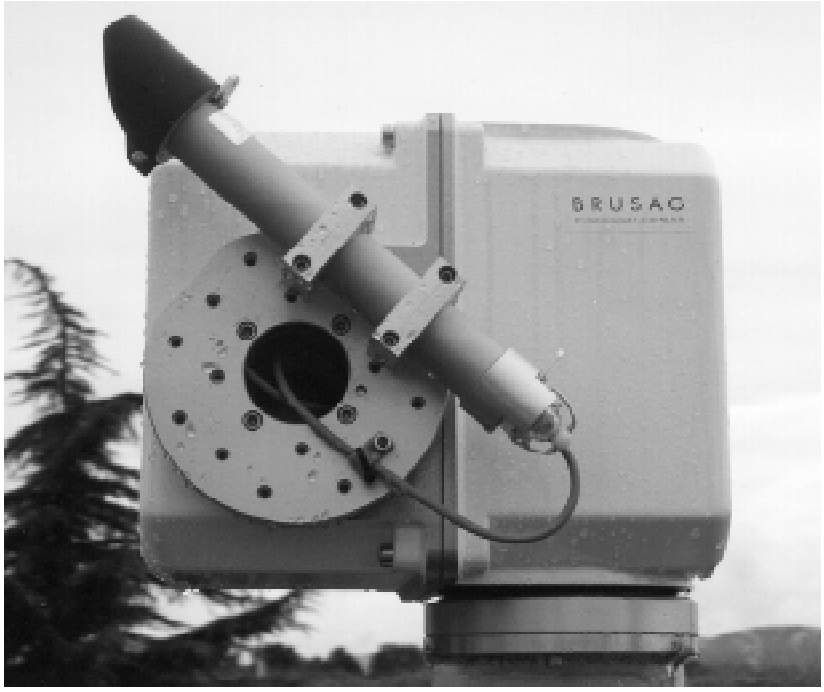

Figure 5.3. Brusag two-axis active tracker. The quadrant sensor is found on the flat of the disk holding the K&Z CH1 pyrheliometer.

Figure 5.4. An one-axis tracker used in shading a pyranometer. Note the use of two fine wires to maintain the stability of the shading disk. (Developed by Deutscher Wetterdienst)

6.0 Data Acquisition

6.1 Introduction

Installing and maintaining the network data acquisition system or systems is crucial if high quality of radiation data is to be consistently sent to the archive. Within this manual *data acquisition system* (DAS) is defined as those electronic devices (including the controlling software) and their connectors, which carry out the process of measuring the signals emanating from the radiation and ancillary measurement devices (transducers).

DAS designed for operating and recording data from automated laboratory equipment are generally suitable for radiation measurement. In general, these systems consist of four components:

(1) the multiplexer, which sequentially switches across a number of input channels, each of which is connected to one of the transducers that are to be measured.

(2) the analog-to-digital converter (ADC), that converts the analog signal (e.g. voltage, resistance) into a digital signal.

(3) the recording system, which may be a combination of internal and external, buffers and permanent storage locations

(4) the controlling computer(s), both internal and external, that handle sending control signals to the muliplexer, the ADC and the storage based upon the user's commands.

These may be all combined into a single unit, may be separate units connected, for example, by a General Purpose Interface Bus (GPIB) instrument bus (e.g. HP, Fluke), or may be on a card that plugs into a PC which is used as the overall control unit. Each of these arrangements has their own advantages. The combined system is more compact and the programming may be easier. A system with a separate computer may allow for easier data analysis by allowing it to be done on the same computer. Those that are totally separate normally have higher accuracies than combined or PC card systems and can be more easily updated if required.

Although the number of data acquisition or data logging products on the commercial market is enormous, many do not meet the exacting specifications required by the BSRN. Annex E lists the names and addresses of companies that can provide systems that will meet the general requirements imposed by the BSRN. The most stringent of these requirements are the accuracy requirement of 1 µV on a 10 mV signal (0.01%) and the need to make 60 measurements per channel per minute. Within the system, the two major components that must be carefully considered with respect to accuracy and timing are the multiplexer and the ADC.

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 15 µV. In either case, settling time is required before the measurement can be made.

In considering the ADC, the type and time of integration, the number of bits of resolution and the linearity must all be considered. High-end, bench-type digital multimeters (DMM) are now capable of 24 bit resolution with accuracies in the order of 10's of ppm under stable

operating conditions. More rugged systems usually consist of either 12 or 16 bit ADC. The former do not provide the resolution, without regard to the accuracy, required for the BSRN, while the latter still may not meet the accuracy requirements. In some cases, where the resolution is fixed to a 5 V scale, but the accuracy is found to be adequate with respect to full scale, the addition of a high quality instrument pre-amplifier at the transducer end of the signal can increase the magnitude of the signal to a level where the DAS can meet the BSRN requirement. In such cases though, the overall accuracy of the system is a linear combination of the uncertainties of both the DAS and the pre-amplifier. (A cautionary note: resolution does not equal accuracy).

Another means of obtaining increased accuracy in systems that otherwise meet the resolution and timing requirements is by calibrating individual data acquisition systems and then correcting for any non-linearities etc. found within the DAS. This process, while possibly saving capital funds, can be labour intensive and requires that the DAS be calibrated under the conditions associated with the measurement regime.

Of secondary importance in the selection of the DAS is its programmability. While the minimum requirement for the DAS is to measure a set of signals with a 0.01% accuracy at 1 Hz, the output to be archived is the one minute mean, minimum, maximum, and the standard deviation. Thus one can store the second data and post process the results or use the features associated with the DAS. In overall storage requirements and operator ease, the programmable DAS is the more attractive option.

6.2 Set-up Considerations

Depending upon the location of the instruments, the accessibility of laboratory space and the overall climatic conditions, the installation of the DAS may be near the instruments (within 5 m) or somewhat distant inside a laboratory. The ideal site would have a completely climate controlled building within a few metres of the instruments (e.g. roof-top measurements with a laboratory below). When this does not occur the decision must be made as to what will provide the higher quality data; the use of a robust data logger near the instruments or increased cable length to reach a bench model DAS.

Having a data system that functions in all environmental conditions eliminates the problems of signal loss along cables and the potential of electrical interference. However, the design and/or operation of outdoor robust systems usually involves some sacrifice in measurement frequency and/or data availability and/or accuracy.

For increased quality control it is recommended that the DAS be one that has the capability of displaying measured data (either in raw or engineering form) in near real time (e.g. within 2 minutes), preferably graphically. The station operator should be able to examine, anytime, both the instantaneous measurements and the data acquired during the preceding few hours or even the last day. With recent developments in serial communications and scientific display software for PC's, this can be easily accomplished with both types of DAS.

Whatever the choice, internally or externally housed, the DAS must be both secure and easily accessible - secure against inadvertent reprogramming or physical harm and accessible for easy maintenance and changes in software or signals. It is highly recommended that a secondary external power supply be used as insurance against loss of primary power. This may include an uninteruptable power supply (which will also reduce the possibility of damage from power surges) for bench and computer-style acquisition systems and a secondary battery or battery charger connected to the main battery of systems developed to operate on DC power.

The operator must consult the manuals provided by the DAS manufacturers for the specific

set-up requirements of the system. When several different products are purchased, it is preferable that they be bought from the same supplier as a package to alleviate the problem of attempting to determine which one of several products is in conflict during the initial installation.

6.3 Standard Practices

(1) Each signal should be connected as a differential input to ensure the greatest measurement accuracy.

(2) The minimum integration time for radiation signals should be one power line cycle to eliminate powerline frequency noise.

(3) Every two years: Calibrate the ADC in an accredited standards laboratory. This is important even if constant voltages and resistance are input into the system on a continuous basis (see below). Check the associated multiplexer for changes in noise levels and settling time and repair or replace as required.

6.4 Suggested Practices

(1) Test the pyranometer input to the data acquisition system.

(i) 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. 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.

(ii) 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.

(iii) 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.

(2) Installation of constant signals

For greater assurance in the reliability of the data, channels should be set aside to be used with known signals in the same range as those signals being measured. For example, on a system where both resistance and voltages are being measured, a fixed resistor and a known voltage should be included as part of the sampling sequence. These provide a means of rapidly flagging any changes in the quality of the measurements. Obviously, in a multiplexed system, the potential exists for scanning problems being missed.

(3) Instrument resistance checks

An easy means of determining a fault in cabling or a sensor which outputs a voltage is testing for changes in the resistance. On programmable systems, it is encouraged to test the resistance of each sensor on a daily basis to determine if any significant changes have occurred in the overall resistance of each channel. While a trained operator may observe changes in a signal associated with a broken wire or instrument, floating channels are not necessarily easy to detect immediately if they are not well defined (e.g. pyrgeometer voltages) or adjacent to a channel with a similar signal.

(4) Programmable flagging

If the system is capable of automatic data quality checks, it should be programmed to set flags when:

(i) any irradiance values fall outside the range $-10 < E < 1200\ Wm^{-2}$. The program should not be designed to delete any data automatically.

(ii) any air temperature value (air, case, dome, etc.) is outside the normal climatological range of the station by greater than ± 10 °C. The program should not be designed to delete any data automatically.

7.0 Maintenance

7.1 Introduction

High quality, consistent on-site maintenance is crucial if accurate long-term records are to be obtained. Not only does the individual have to care for the instruments, they must also carefully document any work that they perform on those instruments. For example, it is not good enough to assume that instruments are cleaned regularly; this activity must be promptly documented. To help in this documentation sample log sheets are reproduced in Annex F. A number of national networks have developed their own methods of documentation and these can be used if they contain the appropriate information for the radiometers. **ALL MAINTENANCE PROCEDURES, VARIATIONS IN INSTRUMENT BEHAVIOUR AND CHANGES IN INSTRUMENTATION MUST BE FULLY DOCUMENTED WITH RESPECT TO ACTIVITY, TIME AND DATE.**

7.2 Daily Maintenance

The minimum daily requirements for maintaining a BSRN radiation station are as follows:

(1) Cleaning:

(i) Active Cavity Radiometers: Radiometers fitted with a protective quartz (or glass) flat should be cleaned using a soft cloth and/or a photographer's airbrush. If any matter is adhering to the flat, either de-ionized water or methyl hydrate (or equivalent) should be used to wet the cloth before cleaning. Care should be taken to ensure that there is no build-up of material along the border of the flat with the flange holding it on the instrument. If there is a frost or ice build up on the flat, the general procedures outlined below should be followed.

For cavity radiometers without protective flats the area around the opening aperture should be inspected and any foreign material brushed away from the opening.

(ii) Pyranometers and Pyrheliometers: The exterior of domes or optical surfaces of each of the instruments must be cleaned at least once, preferably more often as long as it does not interfere with data collection. It is preferable that this cleaning be done before dawn. However, if because of manpower restrictions this can not always be accomplished, the sensors should then be cleaned as early as possible during the day. If possible the instruments should also be cleaned following the occurrence of any forms of precipitation. Each time the instruments are cleaned, the time during which the cleaning took place should be recorded in the site documentation.

All loose dust or particulate matter should be blown gently off (a camera brush is a useful tool) before the dome is wiped. Using a soft lint-free cloth the dome should then be wiped clean. If any matter is adhering to the dome, either de-ionized water or methyl hydrate (or equivalent) should be used to wet the cloth before cleaning the dome. Do not pour the liquid onto the dome directly. Caution must be used so that the dome is not scratched, nor the instrument moved, during this procedure.

In cases where frost or ice have been deposited on the dome, several

methods may be used depending upon the severity. Light deposits can be removed be lightly rubbing the surface using the lint-free cloth as in normal cleaning. Heavier deposits can be removed by using a methyl hydrate solution on the cloth. Where ice build-up cannot be removed with methyl hydrate alone, the observer (depending on weather conditions) can melt the ice by placing his hand on the dome. In severe cases a hand held hair dryer can be used. In the most severe cases the instrument should be removed and brought inside to thaw. It is NEVER appropriate to use any sharp objects to chisel away the ice. In cases where the ice is melted by whatever means, the dome should be cleaned with methyl hydrate and the wiped with a clean lint-free cloth following the operation. The procedure used and the time required should be documented.

While cleaning the dome, an inspection should be made to determine whether there are any scratches or chips since the last cleaning. Such marks are made by scouring of the radiometer dome by sand or by hyrdometeorites such as hail. If the dome is damaged, it should be replaced with one made of the same optical material. The change should be documented and the dome kept for future reference. Although domes do not normally change the overall calibration of the system, the instrument with the new dome should be monitored for any differences, particularly changes in directional responsivity.

(iii) Pyrradiometers: If pyrradiometers are in use at the site for the measurement of all-wave radiation, special care must be taken in cleaning the soft domes. A soft clean cloth or special 'laboratory' style paper tissue must be used to clean the polyethylene domes. If the residue from water droplets or other material has been deposited on the dome the use of de-ionized water as a cleaning agent is recommended. For the removal of frost and ice on the domes the method recommended above should be followed. Further inspection of the domes should determine if the domes are becoming opaque because of incident UV, are cracked, have been pierced (birds are known for pecking at the domes in some regions) or have been creased. If found, the dome should be replaced prior to the normal replacement and the procedure documented.

At the time of cleaning, the air system used to maintain the dome's shape should also be checked and adjusted as appropriate. This air must be dry to maintain the instrument in good working order.

(2) The radiometer should be checked for any condensation on the inside of the outer dome. If this occurs, the outer dome must be removed in a clean, dry location, cleaned and the cause for the leak determined. The most probable cause is poor maintenance of the desiccant (see weekly maintenance). If the desiccant has been changed within a week, the probable cause is a poor 'O' ring seal. A replacement is required. If moisture is found on the inner surface of the inner dome, the instrument should be replaced with a spare instrument and the faulty instrument sent for service.

(3) The colour and the condition of the thermopile should be checked. If the colour is fading or changing, or the thermopile surface appears rough, cracked or weathered, the instrument should be removed from service and replaced with a spare. On newer instruments this occurs rarely.

(4) The level of each instrument (e.g. pyranometers, pyrgeometers, pyrradiometers) that is mounted horizontally should be checked and corrected as necessary. The bubble

of the circular level should be completely within the inner circle. For most instruments, this indicates that the instrument is level to within ±0.1°.

(5) The cabling leading from the instrument to the data acquisition system or junction box should be inspected for wear. Unless the cable is to be replaced, or must be untangled, the instrument should not be disconnected. If work is required on the cable it should be appropriately documented. In cases where a cable is functional, but aging, a time should be set for its replacement during the station semi-annual or annual maintenance (see below).

(6) The ventilator motors should be checked on a daily basis. If the motor is not operating properly the problem should be corrected or the motor replaced. All procedures should be documented, including the start and end time of the work. If knowledge of when the ventilator began to malfunction is known (e.g. lightning strike) this should also be included in the log. On those ventilators where the cover acts as a radiation shield, the top of the cover must be situated below the receiver surface of the radiometer.

(7) The pointing of any instruments should be checked and if necessary corrected. The reasons for possible mis-alignment are somewhat dependent upon the type of tracker being used. The sun must be shining to determine spot alignment for direct beam instruments; however, the checking of clock times and general system failures is independent of weather conditions.

(i) One-axis solar tracker

- the solar declination must be checked and adjusted to align the solar spot with the instrument target.

- as most one-axis trackers use synchronous motors, the power frequency must be monitored to ensure that the tracker is being driven at the correct speed.

- the tracker must be inspected to ensure that no mechanical malfunction has occurred (e.g. slippage in the clutch)

- in the case of one-axis trackers, unless especially equipped, the cables attached to the instruments must be manually unwound each day.

(ii) Two-axis passive solar tracker

Passive trackers use either internal or external computers to calculate the position of the solar disk. Following the initial setup of the system, tracking of the solar spot by the shading disk or the instrument attached to the tracker should not normally vary except when the power is removed from the tracker and/or the computer operating the tracker, or when the time used to calculate the solar position is incorrect.

- check that the clock time used in the calculation of solar position is accurate to better than 15 seconds for tracking of instruments with a 2° field of view or greater. The smaller the FOV, the greater the time accuracy required.

- on days when the solar spot is visible on the target, check tracker alignment. If not aligned follow the procedures below and/or in the manual.

- determine if the power to the tracker has been disrupted either at

the main power panel or within the cabling to and within the tracker.

- for friction-driven drives check for slippage of the drive disks (see tracker operating manual for the proper procedure).

- for gear-driven drives, if slippage occurs check gear alignment or if one or more gears have broken teeth (see tracker operating manual for proper procedures).

- check to ensure that the tracker has not changed its physical position, either in level or location (e.g. the tracker has not been bumped accidentally).

- a tracker mechanical malfunction or software failure can also cause a loss of tracking capability. The operator should refer to the tracker operating manual in such cases.

(iii) Two-axis active solar tracker

An active tracker corrects for small variations in the pointing of a passive system. Such a system requires that the tracker not operate in active mode during periods where the solar signal is below a defined solar irradiance threshold. During such periods, the active tracker should operate in a mode similar to a two-axis passive system. Following the initial setup of the system, tracking of the solar spot by the shading disk or the instrument attached to the tracker should not normally vary except when the power is removed from the tracker and/or the computer operating the tracker.

- clean the active sensing unit on the tracker daily and following occurrences of precipitation.

- check that the clock time used in the calculation of solar position is accurate to better than 15 seconds for tracking of instruments with a 2° field of view or greater. The smaller the FOV, the greater the time accuracy required.

- on days when the solar spot is visible on the target, check tracker alignment. If not aligned follow the procedures below and/or in the manual.

- determine if the power to the tracker has been disrupted either at the main power panel or within the cabling to and within the tracker for a time period greater than what the active sensing unit is capable of correcting.

- check the operation of the active sensing unit. This can be accomplished by covering the active sensor and manually positioning the tracker to within the acceptance limits of the active sensor with the power turned off. By turning on the power to the tracker (ensuring that any computer programs are operating correctly) the active sensor should move the tracker into correct alignment. If this does not occur, technical assistance in further checking the operation of the active sensor is required.

- for friction-driven drives check for slippage of the drive disks (see tracker operating manual for the proper procedure).

- for gear-driven drives, if slippage occurs check gear alignment or if

one or more gears have broken teeth (see tracker operating manual for proper procedures).

- check to ensure that the tracker has not changed its physical position, either in level or location (e.g. the tracker has not been bumped accidentally).

- a tracker mechanical malfunction or software failure can also cause a loss of tracking capability. The operator should refer to the tracker operating manual in such cases.

In all cases, the operator should note the position of the solar spot on the pyrheliometer or cavity radiometer being adjusted before any adjustment is made. Following the adjustment, the new location of the solar spot should be noted. The time required to make the adjustment and the details of what caused the failure to track and its correction should also be documented.

(8) Cavity Radiometers

(i) All-weather instruments: Cavity radiometers housed in enclosures appropriate for continuous use should be checked daily to ensure that any safety features on the housing are operating properly. These might include such items as automatic shutters, rain sensors or fan switches. The manufacturer's operating manual should be consulted. Fans in continuous operation should be checked for proper operation.

(ii) Fair-weather instruments: Instruments operated during fair weather conditions must be checked for proper alignment and correct signal and power connections as part of the set-up procedure. Shutters should be checked to ensure correct operation before measurements begin. Following use, the exterior of the instrument should be wiped down and the entire instrument inspected for any damage, including the lodging of any insects within the instrument cavity. If the instrument is moved into a heated enclosure following the measurement period, care should be taken to avoid moisture condensing in the cavity. Although the transducer coating is not water soluble, over time, chemical constituents within the condensing liquid can cause changes in the absorptance of the coating. Cleaning of the sensor should be done only by qualified personnel.

(9) Shaded Instruments - Diffuse Irradiance, Infrared Irradiance

Each shaded instrument must be checked to ensure that the shading device completely covers the outer dome of the instrument. These checks are similar to those above for the direct beam instruments.

(10) Data acquisition/computer systems

The system collecting the data should be checked to ensure that the it is operational. The operator, in conjunction with the site scientist, should devise appropriate methods to determine that the system is operational. Simply looking at a computer screen is NOT sufficient. Tests should be devised to determine that data are being acquired successfully, that the time stamp is correct and that the system has not malfunctioned since the last check.

Because data are being obtained at 1 second intervals, a correct system time is crucial. Unfortunately, many PC compatible computers have very poor clock systems. Each day the clock offset should be recorded and the time corrected if this

offset is greater than 1 second. If the clock varies by more than 10 seconds per day a new clock should be installed. A system changing at a rate of less than 1 second per month would be ideal (see section 2.3.1).

(11) Where possible, the site operator should have the ability to review the data from the previous day. This information will allow him to detect any significant changes that may have occurred during the day. An example of such a change would be a passive tracker that was not level. During the morning when the observer checks the shading of instruments it would be found correct, but during the afternoon the diffuse flux would increase because of the shading disk moving off the sensor.

7.3 Weekly Maintenance

The minimum weekly requirements for maintaining a BSRN radiation station are as follows (in addition to the daily maintenance):

(1) Check the desiccant in each sensor. Desiccant should normally last several months, but is dependent upon atmospheric water vapour, the quality of radiometer seals, the size of the desiccant chamber and the quality of the desiccant. In drier climates it may be sufficient to check the desiccant on a monthly basis while in areas where monsoon conditions occur, twice weekly inspections should be made during the most humid season. Depending upon the type of sensor and the type of ventilated housing, the shield portion of the ventilator may require removal to check the desiccant. Once checked and replaced if necessary, the shield should be carefully replaced ensuring that the top of the shield is below the level of the instrument receiver surface. Whenever possible, desiccant should be changed during conditions of low relative humidity.

If the desiccant is not a bright blue/purple it should be changed. Desiccant can be recharged by drying. Therefore there is no saving gained by attempting to have the desiccant last for another week. The material removed from any instruments should be saved and re-activated by placing in an oven at a low heat for several hours. The desiccant will return to its original colour when dry. Desiccant should be stored in an air tight container.

(2) If not part of the normal data acquisition program, the resistance of each of the instruments should be checked and recorded. Significant changes in resistance can be used to detect system faults.

(3) If not part of the normal data acquisition program, a reference voltage source and reference resistor should be used to test the stability of the response of the data acquisition system. This should be repeated at various temperatures to determine the effect of temperature changes on the data acquisition system when such systems experience temperature extremes (e.g. data loggers kept in unheated outdoor enclosures).

7.4 Long term maintenance

7.4.1 Monthly Maintenance

The minimum monthly requirements for maintaining a BSRN radiation station are as follows (in addition to the above maintenance schedule):

(1) If pyrradiometers or net pyrradiometers are used for measurements

(i) the polyethylene domes should be replaced. Operators are instructed to check the particular instrument's manual for instructions.

(ii) if the domes are inflated using an air purge system, this system should be checked and lubricated as required. A number of systems contain desiccant which should be checked on a monthly basis.

7.4.2 Semi-annual maintenance

(1) The pyranometers used for the measurement of global and diffuse radiation should be swapped. For more information please see Section 8.3 on calibration.

(2) The pyrgeometer should be replaced for calibration. For details please see Section 8.4 on calibration of pyrgeometers.

(3) Any wiring that has become cracked or brittle should be replaced. Any connectors that have begun to corrode should be replaced.

(4) A careful inspection of all instruments should be made to determine aging. If radiation shields etc. have begun to show signs of aging (brittleness, discolouration etc.) they should be replaced. Pyranometers should be checked for excessive weathering, O-rings checked and lubricated etc.

(5) All-weather housings for cavity radiometers should be cleaned and any internal electrical connections checked and repaired as necessary. All weather-tight seals should be checked, lubricated or replaced as appropriate. Fans motors should be check and lubricated or replaced as necessary. Any other moving parts should be checked and lubricated according to the manufacturer's recommendations.

(6) Some trackers require semi-annual maintenance. Check with the manual provided with the tracking device to determine these requirements.

(7) All seals in weather-tight enclosures should be checked and lubricated or changed if necessary.

7.4.3 Annual maintenance

(1) Calibration of the cavity radiometer (see Section 8.2.1).

(2) All field support assemblies should be checked for level and structural integrity.

(3) All bolts should be loosened, lubricated and tightened. This preventative maintenance is especially important in areas of harsh climate where corrosion may occur.

(4) Fans used in ventilated housings should be lubricated or replaced (depending on the type of system in use).

Ideally, the annual maintenance should take less than one day to complete if a team of workers is present. Although unlikely, it would be best done while the sun is below the horizon.

(5) Calibration of the digital voltmeter (or equivalent) used in the data acquisition system. Because of the complex nature of system testing and calibration (it is not just placing a known source on the input terminals) this procedure should only be done by qualified personnel, either associated with the metrology laboratory of the institution operating the BSRN station or the manufacturer. The calibration should be traceable to a national standards institute.

It is recommended that one or more spare units be obtained so that during a calibration a newly-calibrated spare unit can replace the unit being calibrated.

8.0 Radiometer Calibration

8.1 Introduction

Well defined and documented, systematic procedures must be carefully followed to ensure accurate and reproducible instrument responsivities. Calibrations must be routine, internally consistent and traceable if the BSRN is to provide the quality of data required for the calibration and development of satellite algorithms and the measurement of variations in radiation fluxes that may be responsible for climate change.

The responsivity of each solar radiometer must be traceable to the WMO World Radiometric Reference (WRR) which has an estimated accuracy of better than 0.3% and guarantees the homogeneity of radiation measurements to better than 0.1%. This reference is realized by a group of seven absolute cavity radiometers, the World Standard Group, housed at the World Radiation Centre (WRC), Davos, Switzerland. The WSG is externally monitored at each WMO International Pyrheliometer Comparison (IPC) against regional standard cavity radiometers and internally checked during favourable weather conditions throughout the year. Figure 8.1 illustrates the linkage between the solar radiometers associated with a given BSRN observatory and the WRR.

The calibration of broadband infrared radiometers (pyrgeometers, pyrradiometers and net pyrradiometers) is based upon the Stephan-Boltzmann formula for black-body radiation. While there are many organizations with apparatus to perform this calibration, recent tests have shown that few are characterized well enough currently to provide responsivities of the quality necessary for the BSRN. Only the methodology for the calibration of pyrgeometers will be outlined in the document because other broadband infrared measurement techniques are less advanced at present.

At each observatory, the station scientist is responsible for the overall maintenance and calibration of each instrument and its associated data acquisition system. Depending upon the instrumentation configuration these procedures may differ slightly, but must maintain the overall standard and frequency of calibration set out within the BSRN documentation.

8.2 Pyrheliometer Calibration

8.2.1 Absolute Cavity Radiometer/Pyrheliometer Calibration

Each station requires two cavity radiometers to function to the full mandate of the BSRN. One instrument (working instrument) will be used to continuously monitor the direct beam radiation, while the second (primary instrument) will maintain the radiometric linkage between the WRR and the instruments at the observatory. Ideally, both instruments should have open apertures. In locations where climate does not permit, the working instrument may have a quartz flat as a protective window. In such cases though, an appropriate correction must be determined for the window. This correction must account for the humidity regimes of the locale, as the infrared portion of the spectrum will be most affected by the window.

At a minimum of once every two years, the reference instrument must be compared with either the World Standard Group (WSG) of cavity radiometers or with a cavity radiometer which participates regularly at the International Pyrheliometer Comparisons (IPC). Where practical, the former means of reference is preferable. The performance of all reference instruments must be monitored regularly between IPC's to guard against performance degradation between international comparisons. One means of monitoring performance is

the use of the reference instrument in WMO Regional Pyrheliometer Intercomparisons. It should be cautioned that an instrument's calibration coefficients should not be changed unless a confirmed shift in the instrument properties has occurred.

The reference instrument in turn will be used to monitor the responsivity of the field instrument on an ongoing basis depending upon weather. This procedure should occur at least quarterly, if weather permits. While frequent comparisons between the reference instrument and the field instrument are beneficial, it is not the goal of the procedure to compare the instruments at every favourable opportunity. Therefore, it is not necessary for the reference instrument to remain permanently at the station. At sites where a cavity radiometer is being used continuously, normal incidence pyrheliometers should only be used to fill in data gaps when the cavity radiometer is in calibration mode. The output of these thermopile instruments should be correlated with the output of the cavity radiometer obtained immediately before and after the calibration cycle of the field cavity radiometer.

In the special cases where two thermopile pyrheliometers are used to measure the direct beam radiation at a station, only one cavity radiometer is necessary. In this case, the single instrument will follow the procedures set down by the reference instrument in the preceding paragraphs with the exception that the normal incidence pyrheliometers be compared against the reference instrument as frequently as possible. This latter procedure, while more economical, will not provide the same overall quality of data.

In all cases, the link between the WRR and the BSRN observatory instruments should be through a cavity radiometer.

8.2.2 Detailed procedures

As all shortwave radiation measurements are linked to the output of the working cavity radiometer or working pyrheliometers, great care must be taken to maintain the highest standards in comparing the working instruments with the reference radiometer. This comparison is the prime link between individual BSRN stations and the WRR and thus all other BSRN stations. The following procedures are presented as a means of ensuring that this prime link is maintained with the lowest uncertainty possible.

(1) The reference and field radiometers should be co-located (within metres). If possible, a permanent mount should be constructed on the same optical axis as the field radiometer for the reference radiometer. If this is not possible, extreme care must be taken to ensure the accuracy of the pointing of both instruments during the comparison.

(2) To reduce uncertainty, both instruments should be connected to the same data acquisition system. All measurements should be differential. Extreme care must be taken to eliminate unnecessary noise and ground loops. When a single digital multimeter (or equivalent) cannot be used, a reference voltage and reference resistance should be measured by the different multimeters and any discrepancies corrected. The references used should be of the same magnitude as the signals being measured.

(3) Sampling frequency should be the same as used during normal operations.

(4) Averaging period should be a minimum of 10 minutes and a maximum of 25 minutes. Following each averaging period those instruments operated in a passive mode (e.g. Hickey-Frieden) must be zeroed and calibrated. The minimum time allotted for each of the functions should be one minute.

(5) All calibration activities must be conducted on days in which the cloud cover is less

than 4/8's and the cloud is greater than 15° distant from the solar disk. As a quantitative check of stability, all averaging periods must have a standard deviation of less than 0.1% of the mean solar signal during the averaging period or 0.3 Wm^{-2} (whichever is greater).

(6) The irradiance levels should be between 400 and 1100 Wm^{-2}during the comparison (the maximum value is dependent upon season and latitude).

(7) Any averaging period where the difference between the reference instrument and the field instruments is greater than 1% should be discarded, if that series is greater than 3 standard deviations away from the mean difference.

(8) A minimum of 25 acceptable series must be completed for each comparison.

(9) All changes in the ratio between the reference and the field instrument(s) must be recorded. Changes of less than 0.1%/year (normalized) need not be reported to the archive.

Changes greater than 0.5%/year (normalized) indicate significant drift in one or both of the instruments and remedial action should be taken immediately. If a third cavity radiometer is available, the comparison should be repeated in an attempt to isolate the changes. Once the problem instrument is isolated it should be returned to the manufacturer to identify the cause of the change in responsivity.

(i) If the field cavity radiometer is faulty, the reference instrument should be used as a replacement until the field instrument is returned. At that time, the reference instrument should be compared against the WRR.

(ii) If one of the field pyrheliometers is found to be in need of service, another pyrheliometer of the same manufacture and model should be substituted while it is sent for service.

(iii) If the reference instrument has apparently changed its responsivity, the instrument should be sent to the manufacturer to determine the reason(s) for the change and then compared against the WRR before a new comparison with the field instruments is performed.

The archive should be informed of the problem and its solution once obtained. Large changes of this nature may require re-evaluation of previously obtained data. If expertise is not available to analyse the effects such a change in responsivity may have on previous determinations of the responsivity of other instruments or on the data, contact the BSRN archive for further advice.

8.3 Pyranometer Calibration

The standard procedure for the calibration of pyranometers adopted by the BSRN is that of Forgan (1996)[4]. This method recognizes that the best calibration accounts for the climatic regime in which the pyranometer is located. The following steps provide a brief outline of the procedure.

(1) Two (or four for redundancy) pyranometers are required with approximately equal

[4] Forgan, B. W., 1996: A new method for calibrating reference and field pyranometers, *Journal of Atmospheric and Oceanic Technology*, 13 638 - 645. (Reprinted as Annex G).

sensitivity. The original sensitivities can be determined by the sun/shade technique against a standard radiometer.

(2) One instrument is used as the global instrument, while the second is installed on site as the shaded radiometer. Care must be taken to ensure that the area blocked by the diffuse disk matches the field of view of the cavity radiometer (or working pyrheliometer) being used for the measurement of direct beam radiation.

(3) At about the time of the summer solstice, the two pyranometers are switched during a period of sunny weather.

(4) Using a series of simultaneous equations the sensitivity of the two pyranometers can then be calculated from the data obtained during the several days before and after the instrument swap.

This procedure has several significant advantages over the sun/shade method of pyranometer calibration. Firstly, the procedure does not require the instrument to be removed from service during the calibration procedure with the exception of changing its location, which can be accomplished during darkness. Secondly, it alleviates the potential of thermal shock to the instrument which occurs first when the instrument is exposed to direct beam radiation and then again when the instrument is shaded. The actual extent of such shock has not been measured for all instruments, but may be significant. Thirdly, the pair of instruments being used to measure diffuse and global (the redundant measurement) solar radiation are calibrated simultaneously.

A similar transfer method of calibration can also be undertaken during days where there are periods where the solar line of sight is clear and periods where the sun is covered by cloud. By assuming that the disk subtending the angular extent of the sun removes an insignificant amount of diffuse radiation during overcast conditions, the responsivity of the direct beam radiometer can be transferred using a similar set of simultaneous equations of two variables and two unknowns.

By grouping all the data obtained from either of these procedures, the uncertainty due to the instrument directional responsivity (cosine and azimuth error) becomes inherent in the coefficients over the multitudes of samples that make up the calibration procedure. Conversely, by grouping samples with respect to zenith angle and intensity, the cosine response and the linearity of the instrument can also be determined.

In the calibration procedure, care must be taken to eliminate the zero offset components associated with the net thermal radiation of the sensor and its surroundings. ISO 9060 considers a ventilated first class instrument to be one for which this negative flux is less than $\pm$ 15 Wm^{-2} for a net thermal flux of 200 Wm^{-2}. This offset becomes important when two instruments have significantly different offsets and when the responsivity is transferred from the pyrheliometer to the shaded radiometer. If care is not taken to eliminate the offset, it will be incorporated into the responsivity as an uncertainty in the calibration slope. At large radiation levels the error is minor, however, in the diffuse flux, it can be lead to as much as a 20% underestimation.

Although the zero offset is observed at night it remains part of the pyranometer signal throughout the daylight hours, especially during clear days. Therefore, for the most accurate measurements of solar irradiance, the zero offset of individual pyranometers should be determined by correlating the night time offset with the incoming infrared radiation. Using the Canadian-style ventilating housing it has been found that the relationship for Eppley

PSP's and Kipp and Zonen CM11's is approximately[5]

$$Z = -1.5 + 0.025\ P$$

where Z is the zero offset and P the infrared signal as measured by the pyrgeometer.

8.4 Pyrgeometer Calibration

Absolute calibration of pyrgeometers is difficult because of the complex interaction between the instrument and the incoming signal. This is primarily due to the difficulty in producing an hemispheric interference filter to transmit the broadband infrared signal (approximately 4 - 50 µm) emitted by the atmosphere and/or earth's surface to the thermopile detector. Two complications to be surmounted through characterization and calibration are: (1) The absorptance of solar radiation by the dome causing heating and thus thermal emissions from the dome to the sensor surface. (2) The variation of transmissivity of the dome over the wavelength range. The first is overcome by monitoring the dome temperature and correcting for the increase in signal reaching the thermopile, while the second requires calibrating the instrument in a thermal radiation regime similar to that in which the instrument is to be deployed.

At present no standard method exists for the calibration of pyrgeometers, but most characterizations are accomplished by applying the Stefan-Boltzmann Law to a blackbody calibration source. A recent BSRN-sponsored comparison, however, has shown that significant variations exist between laboratories and that few laboratories have the capability to perform characterizations at different ambient and radiative temperatures. Therefore, to reduce the overall uncertainty between measurements made in various countries using different calibration techniques, the BSRN Scientific Panel recommends that the primary calibration of pyrgeometers be performed at the WRC, or other authorized centres, following the procedures developed by Philipona *et al.* (1995)[6]. While not yet recognized as an absolute calibration, this procdure reduces measurement uncertainty through the inclusion of varying both the cavity and dome temperatures of the pyrgeometer, as well as varying the radiative temperature of the blackbody. All three temperatures are varied respecting the mean annual temperature of the location of the final deployment of the pyrgeometer. In this manner, each instrument is characterized for a specific radiation regime.

To maintain the traceability of pyrgeometer measurements the following procedure has been established:

(1) Each BSRN station requires a minimum of two pyrgeometers, initially calibrated at the WRC. One of these instruments is to be declared a site reference instrument and used only during times of comparison. The other instrument(s) will be classified as the field instrument(s). An initial comparison of the two instruments should be made immediately upon deployment at the station to determine the relationships between the thermistors and thermopiles of the instruments.

(2) Comparisons between instruments should occur a minimum of once every 4 months

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[5] Wardle, D.I. *et al.*, 1996: *Improved measurements of solar irradiance by means of detailed pyranometer chracacterisation*. Solar Heating and Cooling Programme Task 9, International Energy Agency Report IEA-SHCP-9C2, Atmospheric Environment Service, Downsview, Ontario.

[6] Philipona, R., C. Fröhlich, Ch. Betz, 1995: Characterization of pyrgeometers and the accuracy of atmospheric long-wave measurements. *Applied Optics, 34(9), 1598-1605.* (Reprinted as Annex H)

at sites where no significant seasonal variations occur and once each season (nominally every 3 months) at locations with significant change. IT SHOULD NOT BE NECESSARY FOR THE FIELD INSTRUMENTS TO BE TAKEN OUT OF SERVICE DURING THE PERIOD OF THE COMPARISON.

(3) Wherever possible, the instruments being compared should use the same tracking shade device and data acquisition system to reduce systematic biases. Instrument ventilation must be with the same style ventilator. In cases where separate tracking shade devices are used, care must be taken to ensure that both the field and reference instruments are shaded correctly. When the same data acquisition system cannot be used, a comparison between data acquisition systems must be performed. Comparison data should not be collected until the reference instrument has come to thermal equilibrium with its surroundings.

(4) Normal station sampling protocols should be used during the comparison.

(5) The comparison should last a minimum of 2 days and a maximum of 5 days. It is desirable that data be obtained which corresponds to a typical range of irradiances for the period. This may be accomplished by acquiring measurements under a variety of non-precipitating weather conditions during both daylight and nighttime hours.

(6) From the continuous data set collected during the comparison period, only steady-state conditions should be used for the comparison. This can be somewhat arbitrarily defined as those periods where the standard deviations of the thermopile and thermistor signals are less than 0.25% of the magnitude of the respective mean signal for the averaging period.

(7) Analyses should be performed to determine if there are any changes in the following:
   (i) the ratio of a given reference instrument thermistor to the respective field instrument thermistor (dome and body).
   (ii) the ratio of the reference instrument thermopile output to the field instrument thermopile output.
   (iii) the ratio of the calculated irradiance of the reference instrument to the calculated irradiance from the the field instrument.

Note: For typical irradiances, the temperature of the case accounts for between 75 and 100% of the signal for clear to isothermal conditions. The Eppley PIR uses Yellow Springs Instruments (YSI) thermistor YSI 44031 for these measurements. The thermistor is specified to have an interchangeability of ±0.1 °C between 0 °C and 70 °C and is nominally 10 KΩ at 25 °C. The coefficients provided by YSI for the Steinhart and Hart equation are: a = 0.0010295, b = 0.0002391 and c = 1.568e-07. Using these values, the difference between the measured temperature at a given resistance and the calculation at that resistance is no more than 0.02 °C through the temperature range -60 °C to 50 °C. Figure 8.1 illustrates the effect of a positive deviation in the determination of the case temperature on the calculated ‘case flux’ from the correct value. This difference may be due to sampling errors, an incorrect thermistor reading (e.g. the case thermistor is not representing the actual cold junction temperature) or an incorrect thermistor inversion equation. As can be seen, unless the error is greater than approximately 5%, the overall accuracy of the measurement is not greatly effected.

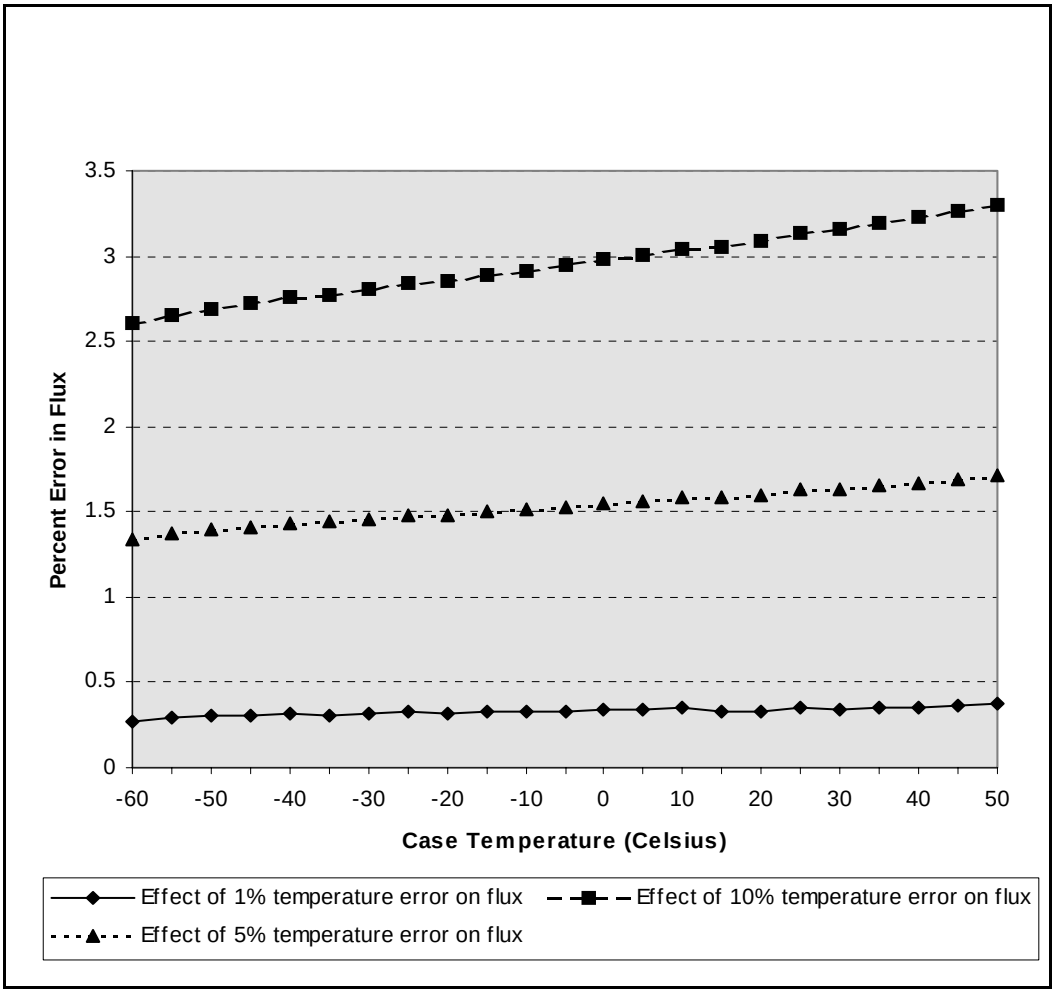

Figure 8.1. Percentage change in longwave flux due to case thermistor errors.

9.0 Radiation Data Reduction and Quality Assurance Procedures

9.1 Introduction

To be certain that the quality of the data obtained is of a high standard, care must be taken from the initial site set-up through the selection of the instrumentation and DAS to the daily maintenance of the radiometers. Once a voltage or resistance measurement is taken, nothing can be done to improve the quality of that measurement. Nevertheless, if quality assessment is performed in near-real-time, any inaccuracies found in the process can be corrected so that future data are of a higher quality. This section will suggest a number of operations that can be performed on the data to aid in the rapid assessment of the measurements.

Although the BSRN Archive has carefully laid out the format required for measurements to be included in the archive, it is recommended that all measurements be kept in their original form (e.g. voltage, resistance, counts etc.), either at the network observatory or the parent institution. Maintaining these data eliminates the need for any back processing of engineering data when new, improved or corrected algorithms need to be applied. Furthermore, unless the instrument can be shown to be malfunctioning or disconnected, data should not be removed from the data stream, but only flagged because of unlikely values. The use of the daily log report of activities associated with the station is crucial when considering the removal of data.

9.2 Standard Data Reduction Procedures

Local quality assurance procedures provide a means of assuring that the data are internally consistent (to some level of uncertainty) within the site. However, to ensure consistency throughout the network, more is required than simply providing calibration traceability; the actual means of reducing the transducer signals to engineering units must have common outcomes. Within the BSRN a large number of instruments are being used in an attempt to measure the same radiative and meteorological variables. The results of these measurements can only be compared if it is known that the differences are not inherited through the algorithms chosen by individual station managers in the conversion of transducer signals to engineering units. In an attempt to overcome this increased uncertainty, the following section sets out a number of protocols to be followed in the data reduction process.

9.2.1 Cavity Radiometer and Pyrheliometer

The reduction of all data from cavity radiometers should be fully compatible with the WRC procedures used in the calculation of the WRR and the conversion of electrical signals to irradiance values used during International Radiation Comparisons and published by the WRC.[7]

For pyrheliometer signals, the conversion should be based upon the assigned responsivity determined through comparison with a cavity radiometer following the subtraction of any zero signal. The responsivity of the instrument should be normalized to the temperature at

[7] For example: International Pyrheliometer Comparisons IPC VII, 24 September to 12 October 1990, Results and Symposium. Working Report No. 162, Swiss Meteorological Institute, Davos and Zurich, March 1991, 91 pages.

which the calibration was obtained if there is greater than a 0.5% change in responsivity over the operating temperature range of the instrument.

$$F = R_T \bullet T(K) \bullet (V - V_Z)$$

Where F is the irradiance in W m^{-2}, R_T is the responsivity of the instrument at a known temperature T in μV $W^{-1}m^2$, T(K) is the ratio of the responsivity of the instrument at temperature K to that at the calibration temperature T, V is the signal in mv under irradiance and V_z is the zero offset voltage.

9.2.2 Pyranometers

Pyranometer signals should be corrected for zero offset before the responsivity factor is applied to the transducer signal. In the same manner as the pyrheliometer, if the responsivity of the instrument changes by greater than 0.5% over the operating temperature range of the instrument, a responsivity correction factor should be applied.

Following Section 7.3 the zero-offset due to thermal emittance should be correlated to the pyrgeometer signal. A second, somewhat less accurate method of determining the offset, is through the linear interpolation of the 30-minute-mean value of the pyranometer signal from before and after astronomical twilight ($\geq 108°$) for the same day.

9.2.3 Pyrgeometers

The pyrgeometer signal should be based upon the calibration constants directly traceable to the WRC blackbody. The flux should be calculated as[8]:

$$E = \frac{U_{emf}}{C}(1 + k_1 \sigma T_B^3) + k_2 \sigma T_B^4 - k_3 \sigma (T_D^4 - T_B^4) - f \Delta T_{S-N}$$

where C, k_1, k_2, k_3 are calibration constants, T_B and T_D are the body and dome temperatures respectively, U_{emf} is the electrical output from the thermopile and $f\Delta T_{S-N}$ is a correction factor for longwave irradiance on unshaded domes. Details are given in Philipona *et al.* (1995).

The thermistor temperatures are calculated using the Steinhart and Hart equation with the standard coefficients provided by the manufacturer:

$$T^{-1} = a + b(LnR) + c(LnR)^3$$

where T is temperature in Kelvins, a,b,c are the standard coefficients provided by the manufacturer and R is the resistance in ohms.

[8] Philipona, R. C. Fröhlich, Ch. Betz, 1995: Characterization of pyrgeometers and the accuracy of atmospheric long-wave radiation instruments. *Applied Optics*, 34(9) 1598-1605.

9.3 Quality Assurance Techniques

9.3.1 General testing procedures

9.3.1.1 Redundancy

Whenever possible it is useful to have more than one instrument measuring the same signal. This not only provides a means of flagging a signal as problematic when the redundant measurements differ, but also provides a back up during those times when an instrument is malfunctioning. It is recognized that having multiple instruments is not always feasible and this is therefore not mandated within the BSRN framework.

9.3.1.2 Visual inspection

The most rapid means of determining gross problems with the incoming data are visually. It is highly recommended that the DAS be capable of providing near-real-time (minutes) graphical displays of the data, whether converted to engineering units or simply transducer signals. A preliminary conversion provides the technician a better appreciation for the data, but large changes such as infinite resistance or zero signal can be determined easily even from transducer signals. While the data being stored at one minute intervals provide significant information for later quality assurance testing, the initial display need only be the mean values. The more frequent the processed signal is output, the better chance the observer has of observing unusual phenomena.

On clear days, rapid sampling of the data can provide a graphical means of ascertaining whether individual instruments are level, or if there are any biases in the solar-tracking instruments being used. Such changes will be obvious through the asymmetry of the data.

Grouping of incoming values is also beneficial. For example, placing the temperature signals of all of the pyranometers on one graphical display can provide a rapid means of determining if one instrument (or its ventilator) is malfunctioning by showing large temperature departures from the other instruments.

9.3.1.3 Limits checking

Automatic limits checks can be programmed into many DAS. These limits can be such that flags are automatically inserted into the data stream to warn the operator of potential problems. A key example of such testing is the use of limits to test the resistance of instruments on a frequent basis (hourly, daily) and provide a warning if the resistance is above or below a normal set of limits. Resistance limits of this type can also be effectively set out with respect to thermistor measurements.

Similar checks can be set up with respect to voltage signals. If instruments have known ranges, limits can be set to warn the operator if the instruments exceed the range. Two types of ranges must be considered in these cases. The first is the normal range of the instrument, for example a pyranometer range may be -0.1 to 12 mV, while the second is the absolute range such as 0 - 5 V for a pressure transducer. In setting bounds checks on the former, one can simply be observing an unusual phenomenon, while on the latter, if the limit is exceeded, an instrument problem has occurred.

9.3.1.4 Conversion to solar time

While visually inspecting the data while it is being archived in local standard or UTC is useful, converting the data, either in real time or post-processing, provides a excellent means of determining accuracy of the system time. For systems recording data with a frequency of one-minute or greater, the symmetry around solar noon (clear or partly clear days) can provide a means of independently checking the system time. Corrections to the

time can made by adjusting the time stamp on the data to restore the curve's symmetry. Care must taken in correcting data in this manner and a timing flag should be set to allow future users to know a time shift has occurred. Once noted, correction of the problem should be undertaken as rapidly as possible.

9.3.1.5 Scanning Minimum, Maximum, Standard Deviations

While difficult to accomplish in real time, post-processing scans or plots of the min, max, and standard deviations of the signals should be done both on an individual channel basis and on multiple common channels to test for any short term uncertainties that may not be noticed with the mean values. Minimum values dipping below zero or maximums exceeding reasonable values, particularly in comparison with other instruments measuring similar signals, provides a rapid means of focussing on potential problems. A simple example would be the cleaning of the dome of an instrument during cloudy bright conditions. Although the mean value of one minute may not be significantly altered, the minimum value and the standard deviation could be altered profoundly. In this manner, single data points could be flagged for times of increased uncertainty.

During any period, if a number of peculiar events occur, the frequency and periodicity of the events should be tested. Such periodic problems could indicate potential electronic failures, buffering problems in the transfer of data or difficulties associated with the DAS.

9.3.2 Procedures for specific fluxes

9.3.2.1 Direct, diffuse and global

Testing the direct and diffuse against the global radiation is a simple and straightforward test, with the exception of time near sunrise and sunset, and to a lesser extent during times of rapidly changing irradiance levels (because of different instrument response times). This test should be done on all irradiance data before submitting the data to the archive. Simply,

$$Global = Diffuse + Direct(\cos\theta)$$

where the zenith angle (θ) must be calculated according to the station location, date and time (Annex I provides an algorithm)

During clear sky or stable conditions, the difference between the global and the summation should be within the uncertainty levels given to the instruments. In the case of a cavity radiometer and two well-calibrated pyranometers the differences should be less than 2% or 15 W m^{-2}, whichever is less, at solar elevations greater than 10°. At lower solar elevations and during changing conditions, the differences should be less then 3.5% or 20 W m^{-2}, whichever is less. At differences greater than these further tests should be done to determine the cause of such large differences.

NOTE: If the direct and shaded radiometers are on the same platform care must be taken when using this procedure. During times when the tracking is slightly off target, the errors in the direct beam and the diffuse can be offsetting within the range of the uncertainty values given above.

9.3.2.2 Downwelling infrared radiation

The downwelling infrared signal should be compared against the effective longwave irradiance derived from the air temperature at the same location,

$$L_{eff} = \sigma T_a^4$$

where L_{eff} is the effective radiation signal in Wm^{-2}, σ is the Stefan-Boltzmann constant and T_a the air temperature in Kelvin.

With the exceptions of isothermal fog and strong inversions over cold surfaces, the effective irradiance should be greater than that measured by the pyrgeometer. In the case of fog, the two values should be nearly equal.

Including a surface emissivity term of 0.75, provides a reasonable lower bound against which the instrument radiation should be consistently greater.

In both cases these values should be used conservatively as a means of flagging suspect data and determining whether problems exist with the instrument components. Data should only be flagged if, upon examination, an instrument defect is discovered.

9.4 Data Submission to the BSRN Archive

Data, once quality assured by the site scientist, are to be submitted to the BSRN archive at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. Full documentation on the BSRN database is found in: *Technical Plan for BSRN Data Management, World Radiation Monitoring Centre (WRMC) Technical Report 1. Version 2.1*[9]. A brief summary of this and other information concerning access to the database can be found on the internet at bsrn.ethz.ch/wrmc/database_internal.html. Annex Q provides information on the linkages between the data acquisition at the BSRN station and the WRMC, ETH.

Data submission requires that the format set out in the above manual be adhered to strictly. To support this effort, WRMC has developed a program, F_CHECK.C which performs checks on line length, illegal characters and line format. This program can be obtained directly from the archive and should be requested at the same time as the necessary access permissions are established (data manager email: bsrnadm@geo.umnw.ethz.ch).

The procedure for submitting data to the archive begins with obtaining an account on a secure ftp server for which only the station scientist (or named designates) have access. This is accomplished by informing the database administrator of the intent to submit data and providing the ftp addresses of one or two machines from which the data will be submitted. In response the archive will set up a secure directory on their server and provide the requestor account information and a password. These will only function from the machines with the submitted ftp addresses. Following logon, the system will place the user directly into the directory in which to submit the data files for the station.

Upon receipt of the data files (monthly blocks in sequential order are preferred) the data are automatically moved from the input directory into a second directory from where they are automatically checked for formatting problems etc. If errors in the data are found an error log is produced and returned to an error directory associated with the station name. This error log can then be downloaded and the erroneous data files deleted from the BSRN server. Once corrected the data are re-submitted. It is suggested that the first block of data submitted to the archive be only one month because of the usual problems associated with correctly formatting the data files.

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[9]Gilgen, H. *et al*: Technical Plan for BSRN Data Management, World Radiation Monitoring Centre (WRMC) Technical Report 1, Version 2.1. *World Climate Research Programme WMO/TD-No. 443*. 1995

Annex A Site Description Documentation

Templates for use with the site description documentation found in Section 3.2.

BSRN STATION DESCRIPTION

STATION MANAGER	STATION LOCATION

TOPOGRAPHIC MAP OF SURROUNDING 15 KM RADIUS

1

BSRN SITE DESCRIPTION

SITE DESCRIPTION	CLIMATE

DESCRIPTIVE MAP OF SURROUNDING 2 KM RADIUS

2

BSRN SITE DESCRIPTION

INSTRUMENT DESCRIPTION

INSTRUMENT LOCATION MAP

HORIZON MAP OF CENTRAL INSTRUMENT

DESCRIPTION OF METEOROLOGICAL INSTRUMENTS

3

BSRN STATION VIEWS

VIEW 1	DESCRIPTION

VIEW 2	DESCRIPTION

4

BSRN STATION VIEWS

VIEW 3	DESCRIPTION

VIEW 4	DESCRIPTION

5

Annex B Selected Instrumentation

B1 Instrument Specifications

B1.1 Introduction

The information found in this annex is based upon the use of particular instruments within the BSRN network. When used following the instructions given within the manual it is believed that these instruments can meet the accuracy requirements specified by the BSRN. Other instrumentation may meet these accuracies but have not been used within the program at the time of publication of this manual.

The instrument specifications provided are those of the manufacturers. Independent tests of the instruments have been made by a variety of laboratories and have been published in the open literature and through technical agencies such as the International Energy Agency. For further information on any of these instruments the reader is advised to contact either a WMO Regional Radiation Centre or the manufacturer directly.

The purpose in providing these specifications is to enable both data users and site scientists to gain information about particular instrument configurations. For the former, this should aid in gaining a better understanding of the data measured by particular instruments; both strengths and weaknesses. For the latter, the choice of an instrument for a particular site can be better determined by knowing what others are using in similar situations. Furthermore, by understanding the differences between instruments, questions concerning differences in data quality can be addressed.

The instruments are given in alphabetical order with the specifications provided by the manufacturers. Where possible, common specifications are matched. However, like most manufactured goods, there are no standard methods of specifying all of the various attributes of an instrument. The International Standards Organization (ISO) (ISO 9060, Solar Energy - Specification and classification of instruments for measuring hemispherical solar and direct solar radiation) and the WMO (WMO No. 8, Commission on Instruments and Methods of Observation (CIMO) Guide to Instruments and Methods of Observation) have recommended some guidelines, but these have yet to be universally accepted. Tables B1 and B2 on pyranometer specifications and pyrheliometer specifications found in the ISO document are provided below as a general guide on instrument quality.

Table B1 Pyranometer specification list from ISO 9060

Pyranometer Specification List			
Specification	Class of Pyranometer[10]		
	Secondary Standard	First Class	Second Class
Response time: time for 95% response	< 15 s	< 30 s	< 60 s
Zero off-set: (a) Response to 200 Wm^{-2} net thermal radiation (ventilated) (b) response to 5 K h^{-1} change in ambient temperature	+ 7 Wm^{-2} ± 2 Wm^{-2}	+ 15 Wm^{-2} ± 4 Wm^{-2}	+30 Wm^{-2} ± 8 Wm^{-2}
Resolution (smallest detectable change)	± 1 Wm^{-2}	± 5 Wm^{-2}	± 10 Wm^{-2}
Stability: percentage change in responsivity per year	± 0.8 %	± 1.8 %	± 3 %
Non-linearity: percentage deviation from the responsivity at 500 Wm^{-2} due to change in irradiance within 100 Wm^{-2} to 1000 Wm^{-2}	± 0.5 %	± 1 %	± 3 %
Directional response for beam radiation (the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring, from any direction, a beam radiation whose normal incidence irradiance is 1000 Wm^{-2}	± 10 Wm^{-2}	± 20 Wm^{-2}	± 30 Wm^{-2}
Spectral selectivity: percentage deviation of the product of the spectral absorptance and the spectral transmittance from the corresponding mean within 0.3 µm and 3.0 µm	± 2 %	± 5 %	± 10 %
Temperature response: total percentage deviation due to change in ambient temperature within in interval of 50 K	2 %	4 %	8 %
Tilt response: percentage deviation form the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1000 Wm^{-2} irradiance	± 0.5 %	± 2 %	± 5 %

[10] Pyranometers, pyrheliometers and pyrradiometers have been categorized into three groupings depending upon the quality of the instrument. The instrument must meet all the specifications of a given category before being classified within the category. The highest category for pyranometers is the secondary standard because the most accurate determination of global irradiance is believed to be the sum of the direct beam irradiance as measured by an absolute cavity radiometer and the diffuse solar irradiance as measured by a secondary standard pyranometer shaded from the sun by a disc.

Table B2 Pyrheliometer specification table from ISO 9060

Pyrheliometer Specification List			
Specification	Class of Pyrheliometer		
	Secondary Standard	First Class	Second Class
Response time: time for 95% response	< 15 s	< 20 s	< 30 s
Zero off-set: response to 5 K h^{-1} change in ambient temperature	± 2 Wm^{-2}	± 4 Wm^{-2}	± 8 Wm^{-2}
Resolution (smallest detectable change in Wm^{-2})	± 0.5 Wm^{-2}	± 1 Wm^{-2}	± 5 Wm^{-2}
Stability (percentage of full scale, change/year)	± 0.5 %	± 1 %	± 2 %
Non-linearity: percentage deviation from the responsivity at 500 Wm^{-2} due to change in irradiance within 100 Wm^{-2} to 1000 Wm^{-2}	± 0.2 %	± 0.5 %	± 2 %
Spectral selectivity: percentage deviation of the product of the spectral absorptance and the spectral transmittance from the corresponding mean within 0.3 µm and 3.0 µm	± 0.5 %	± 1 %	± 5 %
Temperature response: total percentage deviation due to change in ambient temperature within in interval of 50 K	± 1 %	± 2 %	± 10 %
Tilt response: percentage deviation form the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1000 Wm^{-2} irradiance	± 0.2 %	± 0.5 %	± 2 %
Traceability: maintained by periodic comparison	with a primary standard pyrheliometer	with a secondary standard pyrheliometer	with a first class pyrheliometer or better

B2 Pyranometers

B2.1 Eppley Laboratory Model PSP Pyranometer

The Precision Spectral Pyranometer is designed for the measurement of sun and sky radiation totally or in defined broad wavelength bands. It comprises a circular multi-junction wire-wound Eppley thermopile. The thermopile has the ability to withstand severe mechanical vibration and shock. Its receiver is coated with Parson's black lacquer (non-wavelength selective absorption). This instrument is supplied with a pair of removable precision ground and polished hemispheres of Schott optical glass. Both hemispheres are made of clear WG295 glass which is uniformly transparent to energy between 0.285 to 2.8 μm. Other Schott coloured glass outer hemispheres include clear (GG395), yellow (GG495), orange (OG530), red (RG630), and dark red (RG695). For special applications, other Schott glasses and Infrasil II quartz hemispheres are available.

Included is a spirit level, adjustable levelling screws and a desiccator which can be readily inspected. The instrument has a cast bronze body with a white enamelled guard disk and comes with a transit/storage case.

A calibration certificate traceable to the World Radiation Reference and a temperature compensation curve is included.

Specifications

Sensitivity:	approx. 9 µV $W^{-1}m^2$
Impedance:	approx. 650 Ω
Temperature Dependence:	±l % over ambient temperature range -20 to +40 C temperature compensation of sensitivity (can be supplied over other ranges at additional charge)
Linearity:	±0.5% from 0 to 2800 Wm^{-2}
Response time:	1 second (1/e signal)
Cosine:	±1% from normalization 0-70° zenith angle; ±3% 70-80° zenith angle
Mechanical Vibration:	tested up to 20 g's without damage
Calibration:	integrating hemisphere
Size:	5.75 inch diameter, 3.75 inches high
Weight:	7 pounds
Orientation:	Performance is not affected by orientation or tilt

B2.2 Kipp & Zonen Delft BV CM11 Pyranometers

The CM11 incorporates a 100-thermocouple sensor, imprinted on a thick-film substrate, housed under K5 glass domes. The sensor is rotationally symmetrical. A white screen prevents the body from heating up. The pyranometer is supplied with a spirit level and screws for accurate levelling. A drying cartridge keeps the interior free from humidity.

All pyranometers are supplied with a calibration certificate which also shows the level of directional error.

Specifications

Response time time for 95 % response	< 15 s
Zero off-set a)response to 200 Wm^{-2} net thermal radiation (ventilated)	+ 7 Wm^{-2}
b)response to 5 K h^{-1} change in ambient temperature	± 2 Wm^{-2}
Non-stability percentage change responsivity per year	± 0.5 %
Non-linearity percentage deviation from the responsivity at 500 Wm^{-2} due to the change in irradiance within 100 Wm^{-2} to 1000 Wm^{-2}	± 0.6 %
Directional response for beam radiation The range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring from any direction a beam radiation whose normal incidence irradiation is 1000 Wm^{-2}	± 10 Wm^{-2}
Spectral selectivity percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within 0.35 µm and 1.5 µm	± 2 %
Temperature response percentage deviation due to change in ambient temperature from -10 to +40 C relative to 20 C	±1%

Tilt response percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1000 Wm^{-2} irradiance	±0.25%
Viewing angle	2 π sr
Irradiance	0 - 1400 Wm^{-2} (max.4000 Wm^{-2})
Spectral range	305-2800 nm (50% points) 335-2200 nm (95% points)
Sensitivity	between 4 and 6 µV/(Wm^{-2})
Impedance	700-1500 Ohm

Instrument Construction

Receiver paint	Carbon black
Glass domes	Schott K5 optical glass 2 mm thick, 30 mm and 50 mm outer diameter
Desiccant	Silicagel
Spirit level	Sensitivity 0.1 degree (bubble half out of the ring) Coincident with base of the instrument. Detector surface and base are coplanar within 0.1°
Materials	Anodized aluminium case. Stainless steel screws in stainless steel bushes. White plastic screen of ASA Drying cartridge PMMA
Weight	830 g
Cable length	10 m (standard)
Dimensions	91.5 mm total height, 150 mm diameter, 25 mm dome height, 50 mm dome diameter

B2.3 Kipp & Zonen Delft BV CM21/31 Pyranometers

Suitable for the measurement of solar irradiance on a plane surface.

- improved specifications in comparison with the CM11.

- also available with quartz domes (CM31) yielding a broader range and reduced offsets.

Essentially the pyranometer CM21 has the same characteristics as the CM11. Some of these specifications have however been improved:

Sensitivity
Impedance
Temperature response
Non-linearity
Response time

Specifications

Response time time for 95 % response	< 5 s
Zero off-set a) response to 200 Wm^{-2} net thermal radiation (ventilated)	+ 7 Wm^{-2}
b) response to 5 K h^{-1} change in ambient temperature	± 2 Wm^{-2}
Non-stability percentage change in responsivity per year	± 0.5 %
Non-linearity percentage deviation from the responsivity at 500 Wm^{-2} due to the change in irradiance within 100 Wm^{-2} to 1000 Wm^{-2}	± 0.25 %
Directional response for beam radiation The range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring from any direction a beam radiation whose normal incidence irradiation is 1000 Wm^{-2}	± 10 Wm^{-2}
Spectral selectivity percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within 0,35 µm and 1,5 µm	± 2%
Temperature response percentage deviation due to change in ambient temperature within an interval of -20 to +50 C, relative to 20 C.	± 1%

Tilt response percentage deviation from the responsivity at 00 tilt (horizontal) due to change in tilt from 00 to 90° at 1000 Wm^{-2} irradiance	0.25%
Viewing angle	2 π sr
Irradiance	0 - 1400 Wm^{-2} (max.4000 Wm^{-2})
Spectral range	305-2800 nm (50% points) 335-2200 nm (95% points)
Sensitivity	between 7 and 25 µV $W^{-1}m^{2}$
Impedance	40-100 Ohm

Instrument Construction

Receiver paint	Carbon black
Glass domes	Schott K5 optical glass 2 mm thick, 30 mm and 50 mm outer diameter
Desiccant	Silicagel
Spirit level	Sensitivity 0.1° (bubble half out of the ring) Coincide with base of the instrument. Detector surface and base are coplanar within 0.1°
Materials	Anodized aluminium case Stainless steel screws in stainless steel bushes. White plastic screen of ASA Drying cartridge PMMA
Weight	830 g
Cable length	10 m
Dimensions	91.5 mm total height, 150 mm diameter, 25 mm dome height, 50 mm dome diameter

B2.4 Kipp and Zonen Delft BV PYRANOMETER CM 31 (additions/changes to CM 21)

Spectral Range	200-4000 nm (50% points) 290-3500 nm (95% points)
Spectral selectivity	max. 2% in the spectral range 300 to 3000 nm
Zero off-set response to 200 Wm^{-2}	+ 4 Wm^{-2}

Directional response for beam radiation	5 Wm^{-2}
Quartz domes	Infrasil II

B3 Cavity Radiometers and Pyrheliometers

B3.1 Eppley Laboratory HF/AHF Cavity Radiometer

The self calibrating Absolute Cavity Pyrheliometer has been a reference standard device for many years. The sensor consists of a balanced cavity receiver pair attached to a circular wirewound and plated thermopile. The blackened cavity receivers are fitted with heater windings which allow for absolute operation using the electrical substitution method, which relates radiant power to electrical power in SI units. The forward cavity views the direct solar beam through a precision aperture. The precision aperture area is nominally 50 mm^2 and is measured for each unit. The rear receiver views an ambient temperature blackbody. The HF radiometer element with baffle tube and blackbody are fitted into an outer tube which acts as the enclosure of the instrument. The instrument is weather proof when the window is mounted. The model AHF has an automatic shutter attached to the outer tube. A separate, mounted window is supplied with each unit for continuous operation of the radiometer, but at reduced accuracy. An adaptor is supplied for mounting to Eppley solar trackers. The HF cavity radiometer has been used for measurement of the extraterrestrial solar radiation from the Nimbus 7 (14 years) and the LDEF (6 years) satellites and is space proven.

The operation of the cavity radiometer, and the measurement of the required parameters, is performed using the appropriate control box. The control functions include setting of the calibration heater power level, activation of the calibration heater, selection of the signals to be measured and control of the meter measurement functions and ranges. The measured parameters include the thermopile signal, the heater voltage and the heater current which is measured as the voltage drop across a 10 LI precision resistor. The instrument temperature may also be measured using an internally mounted thermistor. The meter resolution of 100 nV allows for a thermopile signal equivalent in radiation of approximately 0.1 Wm^{-2}.

Control boxes for manual only, manual and automatic and automatic only operation are available. The control box can operate either one radiometer in the measurement mode or two radiometers in the comparison mode by changing from single to dual operations cable. Two cables are supplied with each unit. The automatic operation allows for computer control of all shuttering, calibration heating and measurement functions. Calculation operations and data storage are also possible under computer control. Programs for independent, automatic measurement and cavity radiometer comparison are supplied with automatic units.

Although these are absolute devices, the radiometers are compared with the EPLAB reference cavity radiometers which have participated in the EPC's and other inter-comparisons and are directly traceable to the WRR. The References are HF's SN 14915 and SN 27798. The HF which is part of the WSG is SN 18748.

Specifications

Radiometer:

Sensor:	60 junction circular wirewound and plated thermopile with balanced cavity receivers (≈ 350 Ω)
Cavity:	Inverted cone within a cylinder coated with specular black paint. emissivity ≥ 0.999
Aperture area:	nominal 50 mm^2: each measured using precision pins
Field of view:	5° central; 1.6° unencumbered (0.8° slope); 8.5° max.
Heater resistance:	150 Ω (Approx.)

Irradiance sensitivity:	I µV $W^{-1}m^2$ (approx)
Size:	5.5 in. diameter at base; 13.32 in long without connector and adaptor, 7 in x 5 in at shutter housing; 3.5 in. dia. outer tube
Weight	9.25 lb; 11.5 lb with tracker adaptor
Window material:	Corning 7940
CONTROL BOX:	
Size:	7 in. high x 17 in. wide x 16 in. deep
Weight:	23 lb (approx)
Power requirement:	115 VAC 60 @ or 230 VAC 50 Hz selectable

B3.2 PMOD/PMO6

PMO-6 Absolute radiometer (excerpted from Applied Optics, Vol. 25, Page 4173, November 15, 1986)

The PMO6 radiometer is based on the measurement of a heat flux using an electrically calibrated heat flux transducer. The radiation is absorbed in a cavity which ensures a high absorptivity over the spectral - range of interest for solar radiometry. The heat flux transducer consists of a thermal impedance with resistance thermometers to sense the temperature difference across it. Heat developed in the cavity is conducted to the heat sink of the instrument and the resulting temperature difference across the thermal impedance is sensed. The sensitivity of the heat flux transducer is calibrated by shading the cavity and measuring the temperature difference while dissipating a known amount of electrical power in a heater element which is mounted inside the cavity It is advantageous to determine the electrical power which is needed to produce the same temperature difference as was observed with the cavity irradiated, because in this case the heat losses are the same during radiative and electrical heating—even if nonlinear effects are involved. During practical operation of the instrument, an electronic circuit maintains the temperature signal constant by controlling the power fed to the cavity heater—independent of the mode, that is, whether the cavity is shaded or irradiated. The substituted radiative power is then equal to the difference in electrical power as measured during the shaded and irradiated periods, respectively.

Changes of the temperature of the heat sink may also produce a temperature signal. Therefore, two heat flux transducers with matched time constants are combined to form a differential heat flux transducer. The temperature difference measured between the two tops of the thermal impedances is then—depending on the quality of the matching—largely insensitive to changes of the temperature of the heat sink.

The instrument measures irradiance, hence its receiver area has to be accurately known. A precision aperture of nominally 5-mm diameter is placed in front of the primary cavity. A second aperture of 8.35-mm diameter acting as a view-limiting aperture and defining a field of view of 5° is placed 95.4 mm in front of the precision aperture. This geometry puts only a moderate ~ 0.75° requirement on the solar pointing. All the apertures of the so-called muffler are in the shadow of the view-limiting aperture. The purpose of the muffler is to reduce the sensitivity to wind effects and to increase the thermal mass of the heat sink of the instrument.

The cavities are made of electro-deposited silver and are gold-plated on their outside. They are soldered onto the thermal impedances made from stainless steel. The thermal impedances are in turn soldered to the copper heat sink of the instrument. The heater element in the cavities is a flexible printed circuit. It is etched in a 5 µm constantan foil supported by a 20 µm Kapton foil. It is glued to the cone-shaped part of the cavity at the same spot as the radiation entering the cavity first impinges on the cavity walls. Its resistance is ~90 Ω and a four-wire terminal configuration is provided to allow for accurate measurements of the electrical power dissipated in the heater. All the inner surfaces of the cavity are coated with a thin layer of specularly reflecting black paint. The resistance thermometers are made from copper wire of 0.03-mm diameter by winding it around the joint of the thermal impedance with the cavity and the heat sink, respectively. The four thermometers of the two heat flux transducers, each with a resistance of ~100 Ω, are wired in a bridge circuit to sense the difference of temperature between the two cavities. The bridge is trimmed with a piece of the same copper wire to yield zero response with the two cavities held at the same temperature. The precision aperture is fabricated from tempered stainless steel. Its roundness is better than 0.2 µm and the cylindrical part of the aperture edges has a length of only 20 µm.

Characteristics

Working Principle	Electrically calibrated cavity radiometer. Automatic operation with alternating observation and reference phases.		
Receiver	Cavity with inverted cone shaped bottom, coated with specular black paint cavity (absorptance : >.9998).		
Detector	Electrically calibrated differential heat flux transducer with resistance thermometers as sensors		
Accuracy	Measurement uncertainty (referred to SI-Units)		< ± 0.25%
	Precision		± 0.01%
Mechanical Dimensions			
	Diameter		75 mm
	Length		200 mm
	Weight, approx.		2.2 kg
	Field of view (full angle)		5°
	Slope angle		1°
	Receiver aperture diameter (nominal)		5 mm
Control Electronics			
	Plug-in circuits (electronic prints) inserted in a cabinet with power supply and control panel		
	Cabinet	width	290 mm
		height	70 mm
		depth	330 mm
Power Supply	110 V/220 V 50 Hz/60 Hz 10 W		

B3.3 Eppley Normal Incidence Pyrheliometer

The Eppley Normal Incidence Pyrheliometer (NIP), as the name implies, was designed for the measurement of solar radiation at normal incidence.

The NIP incorporates a wire-wound thermopile at the base of a tube, the aperture of which bears a ratio to its length of 1 to 10, subtending an angle of 5°43'30". The inside of the brass tube is blackened and suitably diaphragmed. The tube is filled with dry air at atmospheric pressure and sealed at the viewing end by an insert carrying a 1 mm thick, Infrasil II window. Two flanges, one at each end of the tube, are provided with a sighting arrangement for aiming the pyrheliometer directly at the sun. A manually rotatable wheel which can accommodate three filters, while leaving one aperture free, is provided.

The pyrheliometer is mounted on a power-driven equatorial mount for continuous readings.

A calibration certificate traceable to the World Radiation Reference and a temperature compensation curve are included.

Specifications

Sensitivity	approx. 8 μV $W^{-1}m^{2}$
Impedance	approx 200 Ω
Temperature Dependence	±1% over the ambient temperature range -20° +40° C (temperature compensation of sensitivity can be supplied over other ranges at additional charge)
Linearity	±5% from 0 to 1400 Wm^{-2}
Response time	1 second (1/e signal)
Mechanical vibration	tested up to 20 g's without damage
Calibration	reference Eppley primary standard group of pyrheliometers
Size	11 inches long
Weight	5 pounds

B3.4 Kipp and Zonen Delft BV CH1

The pyrheliometer CH1 is designed to measure direct solar irradiance at normal incidence. Its main characteristics are:

Built in accordance with ISO 9060 specifications for first class pyrheliometer

Slope and opening angle according to WMO recommendations

Equipped with an easily serviceable drying cartridge

Suitable fro continuous outdoor use

Light weight

According to clients' specifications: (optional) internal filter, sensor temperature measurement, extended cable and connector

Specifications

Response time	95%	7 s
	99%	10 s
Zero offset: Caused by 5 K/H change in ambient temperature		± 3 Wm^{-2}
Non-stability		< ± 1 % per year
Non-linearity		± 0.2 % (< 1000 W/m)
Spectral selectivity within 0.35 to 1.5 µm.		± 0.5 %
Temperature response percentage deviation due to ambient temperature (relative to 20 °C)		± 1 %, -20 to +50 ± 1.5 %, -40 to +70
Tilt response		None
Traceability		To WRR
Sensitivity		7-15 µV $W^{-1}m^{2}$
Spectral range		0.2 to 4 µm, 50 % points
Impedance		50-70 Ω.
Irradiance		0-4000 Wm^{-2}
Operating temperature		-30 to +60 °C
Full opening angle		5° ± 0.2° (To WMO Recommendations)
Slope Angle		1° ± 0.2° (To WMO Recommendations)

Sight accuracy	+0.2° from optical axis
Materials	Anodised aluminum case, stainless steel screws
Window material	Infrasil 1-301
Weight	700 grams
Desiccant	Silica gel
Cable length	10 m (Standard)
Absorber coating	Kipp & Zonen carbon black

B4 Pyrgeometers

B4.1 Eppley Precision Infrared Radiometer (PIR)

This pyrgeometer is a development of the Eppley Precision Spectral Pyranometer. It is intended for unidirectional operation in the measurement, separately, of incoming or outgoing terrestrial radiation as distinct from net long-wave flux. This instrument comprises the same type of wirewound-plated thermopile detector and cast bronze desiccated case as the PSP. Temperature compensation of detector response is likewise incorporated. Radiation emitted by the detector in its corresponding orientation is automatically compensated, eliminating that portion of the signal. A battery voltage, precisely controlled by a thermistor which senses detector temperature continuously, is introduced into the principle electrical circuit.

Another innovation is aimed at isolating longwave radiation from solar short-wave radiation in daytime. This is accomplished by replacing the glass hemispherical system of the pyranometer with a silicon hemisphere. On the inner surface, there is a vacuum-deposited interference filter. The transmission range of the pyrgeometer window is approximately 3.5-50 µm.

A calibration certificate and a wiring diagram are included.

The Eppley Ventilator is designed for use with either the Precision Spectral Pyranometer or the Precision Infrared Radiometer. A "muffin" fan in the base blows air over both the instrument case and onto the dome to remove possible frost and moisture. The fan provides approximately 30 CFM of ventilation and draws approximately 0.15 amps, or 11 watts. The clear plastic upper housing allows the instrument, connector, and desiccator window to be viewed. A white enamelled guard disk, levelling screws and hold down holes are provided.

Specifications

Sensitivity**:**	approx. 4 $\mu VW^{-1}m^2$
Impedance**:**	approx. 700 Ω.
Temperature Dependence:	±1 % over ambient temperature range -20 to +40 °C.
Linearity**:**	±1 % from 0 to 700 Wm^{-2}
Response time:	2 seconds (1/e signal).
Cosine:	better than 5% from normalization, insignificant for a diffuse source.
Mechanical Vibration:	tested up to 20 g's without damage.
Calibration:	blackbody reference.
Size:	5.75 inch diameter, 3.5 inches high.
Weight:	7 pounds.
Orientation:	Performance is not affected by orientation or tilt.

Specification for ventilator

Input Power:	110 - 120 V, 60 Hz (or other specified supply).
Output:	approx. 30 CFM.
Size:	8 inch diameter, 5.75 inches high.
Weight:	5.5 pounds.

Annex C Pyrheliometers and Pointing (G. Major)

C1 The Role of Geometry amongst the standard pyrheliometers

Published in *Időjárás, Quarterly Journal of the Hungarian Meteorological Service*, 99 (2), 77 - 84 as The role of geometry in the comparison of standard pyrheliometers.

THE ROLE OF GEOMETRY AMONGST THE STANDARD PYRHELIOMETERS

G. Major
Hungarian Meteorological Service, H-1675 Budapest, P.O.Box 39,
Hungary

Summary

The recently valid pyrheliometric scale (World Radiometric Reference) is based on cavity pyrheliometers. The geometrical characteristics of these cavity instruments are closer to each other than those of pyrheliometers manufactured earlier. Some of the Regional and National Standard Pyrheliometers are different types of Angstrom pyrheliometers, their geometry differ significantly from that of the cavity ones and from each other. Using different distribution of scattering aerosol, calculations have been made for determining the difference of the circumsolar radiation measured by the standard pyrheliometers altogether with the actual direct one. The geometrical factor, necessary to calculate the longwave radiation exchange between the pyrheliometric sensor and the outer environment, has also been derived. The results show that in the case of high precision comparison of standard pyrheliometers the circumsolar effect is in the same order as the reliability of the comparison.

Keywords: pyrheliometer, circumsolar radiation, pyrheliometric IR loss

Introduction

In 1977 the World Meteorological Organization changed its Technical Regulations (WMO 1977): after 1 January 1981 all pyrheliometric measurements should be expressed in the scale of the World Radiometric Reference (WRR). Since in the meteorological radiometry the pyrheliometers are the only absolute instruments, therefore this change affects all solar radiation measurements. The WRR is maintained by a group of selected cavity pyrheliometers.

The most of the existing cavity pyrheliometers were designed after 1970. Previously the different types of pyrheliometers were significantly different in respect of geometry. The different view limiting geometry results different circumsolar radiation measured altogether with the actual direct radiation, that is the outputs of the instruments could not been precisely compared. The geometry of different cavity pyrheliometers is more uniform than that of the older pyrheliometers. The International Pyrheliometer Comparisons have proved that the ratio of the measurements of cavity pyrheliometers has the precision of 10^{-4}. Regarding this high precision of comparability, all factors have to be taken into account that might affect the ratio of the measurements of pyrheliometers.

In this paper the effect of view limiting geometry is analyzed regarding the circumsolar irradiation and the longwave radiation exchange of the pyrheliometric sensors. Not only the cavity type instruments are taken into account but the other standard pyrheliometers too that took part in the last International Pyrheliometer Comparison in 1990.

Method

In this work the geometry of pyrheliometers is described by their penumbra function (the derivation is shown in Pastiels 1959 or Major 1994). The effective penumbra function, F(z,φ), gives the sensitivity weighted part (fraction) of the receiver surface that can be seen from the (z,φ) direction. Here z is the angle between the optical axis of the pyrheliometer and the viewing direction, φ is the azimuth angle of the direction in a plane perpendicular to the optical axis. The geometrical penumbra function, G(z,φ), gives the fraction of the receiver surface that can be seen from the (z,φ) direction. If the receiver has uniform sensitivity along its surface, the two functions are identical.

In the case of cavity pyrheliometers the entrance of the cavity is regarded as receiver surface. According to the physical nature of the cavity, this "receiver surface" has uniform sensitivity distribution. Moreover these pyrheliometers have rotational symmetry around their optical axis, that is the penumbra values do not depend on the azimuth, so the geometry of the cavity pyrheliometers is fully described by the G(z) geometrical penumbra function. In the case of circular pyrheliometers, having the radius of the entrance aperture (R), the radius of the receiver (r) and the tube length (L, the distance between them), the geometrical penumbra values can be calculated by an analytical form (Pastiels 1959).

In the case of Angstrom pyrheliometers and NIP (the Eppley factory made Normal Incidence Pyrheliometer) the sensitivity is not uniform along their sensing surface. The ouput of these instruments is connected to their effective penumbra function. For the NIP this function has been derived by numerical simulation (Major 1994), for different types of Angstrom pyrheliometers the "analog" procedure suggested by Pastiels (1959) has been used taking into account calculated sensitivity distribution (Major 1968).

To calculate the difference of the circumsolar radiation involved in the outputs of different pyrheliometers, the radiance distribution has to be known along the circumsolar sky. These so called sky functions have been calculated by Putsay (1995) using different model aerosol distributions.

To calculate the longwave radiation exchange between the receiver and the environment outside the pyrheliometer let us define the following ratio:

$$\psi = \frac{\text{irradiation received through the aperture}}{\text{irradiation received from the hemisphere}}$$

This ratio can be calculated if the radiance distribution is isotropic. It can be shown easily, that for a pyrheliometer

$$\psi = \int_0^{z_l} F(z)\sin(2z)\,dz$$

Here z_l is the limit angle of the pyrheliometer. This is the largest angle from the optical axis from which the receiver can be seen at all. For the circular case z_l = atn((R+r)/L).

The assumed isotropy does not limit the applicability of this ratio, since within the field of view of a pyrheliometer the atmospheric infrared radiation is almost isotropic at any elevation angle.

If the pyrheliometer has a uniform sensitivity receiver and circular structure, the ψ value can easily be calculated using Pastiels' (1959) theoreme:

$$\psi = (a^2+b^2+1) - \sqrt{((a^2+b^2+1)^2 - 4a^2)}$$

here a = R/r and b = L/r.

Basic geometric data

Table 1 is taken from the report of the IPC VII (1991). It contains the basic geometric data of the different types of standard pyrheliometers took part in the comparison.

The given sizes do not characterize directly the viewing angles, therefore in Table 2 the characteristic angles are shown for the circular pyrheliometers. (It should be noted that NIP is not a cavity pyrheliometer.) Here the slope angle is the largest angle measured from the optical axis from that the full receiver can be seen. In the circular case z_s = atn((R-r)/L).

The PCC3 differs much from the other cavity instruments. A bolometric pyrheliometer constructed by Sklyrov had similar geometry (Voytyuk and Sklyrov 1973). It is an experimental version, commercially not available. The limit angles of the other standard pyrheliometers are relatively similar to each other. The CROM 3L has the smallest, the PMO6-10 has the largest slope angle. The remaining devices are quite similar, so their group will be represented by a symbolic ABS instrument (R=8.2 mm, r=5.7 mm, L=191 mm) in this paper. Similarly, the Angstrom pyrheliometers have been grouped into 4 symbolic instruments: Eppley Angstrom (EPA), Smithsonian Angstrom (SMA), Short Tube Angstrom (SHA) and Modern Angstrom (MOA). In Table 3 the effective penumbra functions are shown for the above mentioned pyrheliometers.

The angstrom pyrheliometers have negative penumbra values at certain angles. This mean that larger part of their shaded strip seen from that angle than the seen part of the open strip.

The sky functions

The model atmnospheres are plan-parallel and cloudfree. Molecular scattering, water wapor and ozone absorption, as well as aerosol scattering and absorption are taken into account. The calculations were made for two groups of aerosol distribution. The first group contains three models from the Standard Radiation Atmosphere (WCRP, 1986): continental (CONT), maritime (MAR), and URBAN. The second group contains four models, described by Major (1980): continental background (B), urban (U), oceanic (O) and mountain (M) aerosol. The two urban models are similar to each other in having high turbidity values, but they differ in the size distribution.

The details of the calculation are described by Putsay (1995). In this work only those results are used that refer to the optical depth typical for the given aerosol and to the 20, 45 and 60 degrees of solar elevation angle.

Calculated circum differences

Using the sky functions derived for the mentioned aerosol models, differences of circumsolar radiation between the reprezentative pyrheliometers and the ABS have been calculated (see Table 4). Applying the penumbra functions, the following formula served this purpose (shown the CROM as example):

$$C_{CROM-ABS} = \pi \int_0^{z_l} (F(z)_{CROM} - F(z)_{ABS}) \sin(2z)\, dz$$

As it is expected (knowing the characteristic angles and the penumbra functions), the CROM 3L mesures less, the PMO6-10 measures more circumsolar radiation than the ABS. The difference is less than 0.5 W/m^2, but it is in the order of 10^{-4}. The WRR definig World Standard Group of cavity pyrheliometers ought to avoid such possibility of disturbance.

The PCC instrument has to be reconstructed from the point of geometry. The deviation of the different Angstrom type instruments is in the order of 10^{-3}.

TABLE 1
The basic geometrical data of cavity, NIP and Angstrom pyrheliometers taken part in the 1990 International Pyrheliopmeter Comparisons. (Here v is the length, w is the width of the entrance aperture of Angstrom pyrheliometers.)

Instrument	R (mm)	r (mm)	L (mm)
Cavity			
PMO2	3.6	2.5	85.0
PMO5	3.7	2.5	95.4
CROM 2L	6.29	4.999	144.05
CROM 3L	6.25	5.0	144.0
PAC 3	8.18	5.64	190.5
HF 18748	5.81	3.99	134.7
MKVI 67814	8.2	5.65	187.6
PMO6generic	4.1	2.5	94.0
PMO6-5	3.6	2.5	84.2
PMO6-10	4.25	2.5	95.4
EPACgeneric	8.32	5.64	190.5
HFgeneric	5.81	3.99	134.7
MKVIgeneric	8.2	5.65	187.6
MKVI 67401	8.2	5.64	190.5
PCC3-005	10.0	5.0	114.5
Thermopile			
NIP 18653	10.3	4.0	203.0
Angstrom	v (mm)	w (mm)	
A-7	9.5	7.5	150.0
A-171	10.25	2.4	72.2
A-212	11.8	2.5	50.0
A-559	10.0	8.0	70.0
A-564	10.3	2.5	75.1
A-568	10.6	4.0	55.5
A-576	10.0	2.5	82.0
A-578	10.3	2.5	70.5
A-Eppley	10.3	4.1	111.0

TABLE 2
Characteristic angles of the circular pyrheliometers taken part in the 1990 International Pyrheliometer Comparisons.

Instrument	Slope angle (deg)	Limit angle (deg)
PMO2	0.74	4.10
PMO5	0.72	3.72
CROM 2L	0.51	4.48
CROM 3L	0.50	4.47
PAC 3	0.76	4.15
HF 18748	0.78	4.16
MKVI 67814	0.78	4.22
PMO6generic	0.98	4.02
PMO-5	0.75	4.14
PMO6-10	1.05	4.05
EPACgeneric	0.81	4.19
HFgeneric	0.77	4.16
MKVIgeneric	0.78	4.22
MKVI 67401	0.77	4.16
PCC3-005	2.50	7.46
NIP 18653	1.78	4.03

TABLE 3

Effective penumbra functions of the reprezentative standard pyrheliometers.

z(°)	ABS	CRO3	PMO6	PCC	EPA	SMA	SHA	MOA
0	1.00	1.00	1.00	1.00	0.95	1.00	1.00	1.00
1	0.95	0.88	1.00	.	0.92	0.96	1.00	0.99
1.5	.78	.72	0.87	.	0.60	0.62	1.00	.92
2	.59	.56	.67	.	0.29	.22	1.00	.85
2.5	.41	.41	.46	1.00	0.03	-.04	0.99	.69
3	.25	.27	.26	.93	-.04	-.12	.96	.53
3.5	.11	.15	.10	.82	-.09	-.19	.91	.42
4	.01	.05	.03	.73	-.13	-.23	.85	.30
6	0	0	0	.21	-.12	-.01	.33	-.06
8	0	0	0	0	-.03	0	-.01	-.15
10	0	0	0	0	-.01	0	-.09	-.07
15	0	0	0	0	0	0	-.06	-.02

TABLE 4

The difference between the circumsolar radiation measured by the pyrheliometers named in the left column and the ABS. The values are in W/m^2, for 20, 45 and 60 degrees of solar elevation angle.

	O	M	MAR	B	CONT	U	Urban
CROM	-0.21 -0.15 -0.13	-0.04 -0.03 -0.03	-0.11 -0.08 -0.07	-0.01 -0.01 -0.01	-0.11 -0.09 -0.08	-0.01 0 -0.01	0 0 -0.01
PMO	0.54 0.37 0.32	0.34 0.24 0.21	0.46 0.33 0.29	0.50 0.41 0.37	0.32 0.27 0.23	0.33 0.49 0.50	0.07 0.12 0.12
PCC	5.53 3.82 3.35	4.86 3.28 2.84	5.68 4.06 3.56	7.88 6.40 5.74	3.73 3.12 2.82	5.47 7.97 7.94	1.12 2.02 2.14
EPA	-2.44 -1.68 -1.47	-1.96 -1.32 -1.14	-2.36 -1.69 -1.49	-3.09 -2.51 -1.26	-1.56 -1.30 -1.18	-2.12 -3.11 -3.10	-0.42 -0.76 -0.81
SMA	-2.70 -1.87 -1.63	-2.29 -1.55 -1.35	-2.71 -1.94 -1.70	-3.68 -2.99 -2.68	-1.76 -1.47 -1.33	-2.55 -3.71 -3.70	-0.51 -0.92 -0.97
SHA	4.42 3.05 2.67	3.91 2.63 2.29	4.55 3.36 2.86	6.36 5.17 4.64	3.31 2.51 2.28	4.43 6.44 6.43	0.90 1.64 1.74
MOA	1.98 1.36 1.19	1.66 1.12 0.98	1.97 1.41 1.24	2.66 2.16 1.95	1.31 1.10 1.39	1.84 2.69 2.69	0.37 0.67 0.71

The infrared radiation exchange

The thermal environment of a pyrheliometer receiver is homogenuous except the open aperture hole. The infrared or longwave radiation energy exchange through the aperture can be calculated using the forementioned ψ factor:

$$IR = \psi\sigma((T_r)^4 - (T_e)^4)$$

where Tr is the temperature of the receiver,
Te is the effective environmental temperature outside of the pyrheliometer.

Table 5 contains values of ψ factor for some cavity pyrheliometers altogether with some examples of the infrared energy loss.

Except the PCC instrument, the atmospheric infrared energy loss is almost the same for the other standard pyrheliometers. The difference remains negligible even in the hypotetical case of looking into the deep space (Te=0) through an open aperture.

TABLE 5
The IR exchange factor and energy loss values (W/m$^{2)}$ for some pyrheliometers. The receiver temperature is 300 K.

Inst.	ψ	Te=290	Te=280	Te=270	Te=0
ABS	0.00184	0.11	0.20	0.29	0.85
PMO6-10	0.00198	0.12	0.22	0.31	0.91
CROM 3L	0.00188	0.11	0.21	0.30	0.87
PCC	0.00756	0.44	0.84	1.20	3.49

Conclusions

The latest development in pyrheliometry, the appearance of cavity instruments has led to the definition a much more precise pyrheliometric scale than the previous one, but the problem of different geometry has not been eliminated fully, since the effect of circumsolar radiation is in the same order as the comparability (10^{-4}) of this instruments.

The WRR scale would be transferred more reliably if all the Regional and National Standard Pyrheliometers would be cavity instruments, since the deviation of other type pyrheliometers is in the order of 10^{-3}.

The infrared energy loss of most of the cavity pyrheliometers is quite similar. In the case of extreme geometry it should be taken into account.

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C2 On the Pointing Error of Pyrheliometers

Material prepared by G. Major for the BSRN discussion held in Davos, Switzerland, in October of 1995

Introduction

The direct radiation is the shortwave (solar) radiation coming from the solid angle determined by the solar disk. The pyrheliometers are designed to measure the direct radiation. Their view limiting angles (slope, opening and limit angle) are larger than the visible radius of the solar disk. This is partly due for the easier tracking of the Sun: if the limiting angles are larger than the solar disk, it is not necessary to follow the Sun quite precisely.

How large pointing errors or inaccuracies occur in the everyday practice ? Let us take a hand-operated pyrheliometer. If its adjustments are made once in a minute, its largest mispointing in azimuth angle would be one quarter of a degree. The deviation from the right position in elevation angle is in the same order. Regarding the pointing devices of the pyrheliometers, 1 mm deviation of the illuminated spot from its proper position could be regarded as large mispointing. Depending on the length of the pointing path, this deviation means about half a degree of pointing error.

The purpose of this document is to present calculated values of the errors in the output of pyrheliometers caused by pointing uncertainty up to 2 degrees. Two atmospheric conditions are taken into account:

-- mountain aerosol, optical depth: 0.07, solar elevation: 60 degrees, direct radiation: 1000 W/m^2;

-- continental background aerosol, optical depth: 0.23, solar elevation: 20 degrees, direct radiation: 461 W/m^2.

The calculations have been made for 3 pyrheliometers: the PacRad size cavity instrument (ABS), the KIPP and NIP pyrheliometers. Their slope angles are: 0.75, 1.0 and 1.78 degrees respectively.

The method of calculation

The calculation is based on the Pastiels' theory (see for example in Major 1994). The irradiance given by a circular pyrheliometer can be written as:

$$I = \frac{V}{KS} = \pi \int_0^{z_l} F(z) L(z) \sin(2z)\, dz$$

where V: is the output of the pyrheliometer,
K: is the average sensitivity of the receiver,
S: is the area of the receiver,
z_l: is the limit angle of the pyrheliometer,
F(z): is the penumbra function of the pyrheliometer,
L(z): is the radiance (=sky function)
z: is the angle between the direction of radiance and the optical axis of the pyrheliometer.

Circular pyrheliometer means that all the view limiting diaphragms and the receiver are circular in shape, that is the whole pyrheliometer has a rotational symmetry around its optical axis. In the equation the same rotational symmetry is supposed for the solar disk and the circumsolar sky.

If the optical axis of the pyrheliometer is not directed to the solar centre, than the angle measured from the solar centre (z1) differs from the angle measured from the optical axis (z). The transformation:

$$\cos(z1) = \cos(d)\cos(z) + \sin(d)\sin(z)\cos(\varphi),$$

here d: is the deviation between the solar centre and the optical axis, that is the pointing error,

φ: is an azimuth angle measured in the plane of the receiver, it is zero if the radiance comes from the solar centre.

Radiance along the solar disk

Photospheric models of the Sun produce one-dimensional radiance distribution across the solar disk, that is the so called limb darkening function. According to theoretical calculations (Allen 1985, Zirin 1988) the radiance depends near linearly on the cosine of the zenith angle at the solar "surface". Taking into account some observations too (Zirin 1988) and using z1 as variable instead of the aforementioned zenith angle, the following radiance distribution along the solar disk has been used:

$$L(z1) = Lo\,(0.3 + 0.7\,SQR(1-(z1/0.26)^2))$$

Here Lo is the radiance at the solar centre,
0.26 is the radius of the solar disk in degrees.

This way the atmosphere affects the absolute value of the radiance coming from the solar disk, but not the relative distribution along it. If the direct radiation is 1000 W/m^2, then Lo = $2.01565*10^7$ $W/(m^2*sr)$, while at 461 W/m^2 it is $9.29216*10^6$. Since the gradient at the solar edge is very large, the step of integration in Eq. 1 has to be 0.0001 degree to obtain 0.1 W/m^2 accuracy.

Radiance along the circumsolar sky

For several atmospheric aerosol content and solar elevation angle the radiances coming from the circumsolar sky have been calculated by Putsay (1995). To make our calculation more practical, second order polynoms have been fitted to the logarithm of the two selected circumsolar sky function. The fit is not quite perfect, but it is not significant since we want to obtain the effect of the shift caused by the uncertain pointing.

On Fig. 1 the whole (solar and circumsolar) sky functions are shown for the two selected atmospheric models.

The penumbra functions

To make the computations faster, the penumbra functions have been approximated by third order polynoms in the interval between the slope and limit angles. Again, the fit is not perfect, but this has small effect on the deviations of the values calculated for different pointing uncertainty.

Results

In the calculations the effect of the solar disk and that of the circumsolar sky could be separated. On Fig. 2 and 3 the actually direct irradiance of the pyrheliometric sensor can be seen. If the pointing error is smaller than the slope angle, the irradiance is not affected. If the solar disk is in the penumbra region of the pyrheliometer, the irrdiance decreases rapidly with the increasing pointing error.

On Fig.4 the irradiance coming from the circumsolar sky is seen for all pyrheliometers and for both atmospheric conditions. The decrease is continuous but the effect is not significant compared to that

of the solar disk.

Conclusions

-- If the pointing error of a pyrheliometer is smaller than its slope angle, the effect is negligible.

-- If the pointing error of a pyrheliometer is larger than its slope angle, the irradiance of the pyrheliometric sensor decreases rapidly with increasing mispointing. The value can be estimated using Fig. 2 and 3.

References

Allen, C.W. 1985: Astrophysical Quantities. The Athlone Press, London.

Major, G. 1995: Circumsolar Correction for Pyrheliometers and Diffusometers. WCRP, WMO/TD-No.635

Putsay, M. 1995: Circumsolar Radiation Calculated for Various Aerosol Models. IDŐJÁRÁS, vol 99, pp 67-76.

Zirin, H. 1988: Astropysics of the Sun. Cambridge University Press, Cambridge-New York-London-New Rochelle-Melbourne-Sydney.

Fig.1. The sky functions used in this calculation.

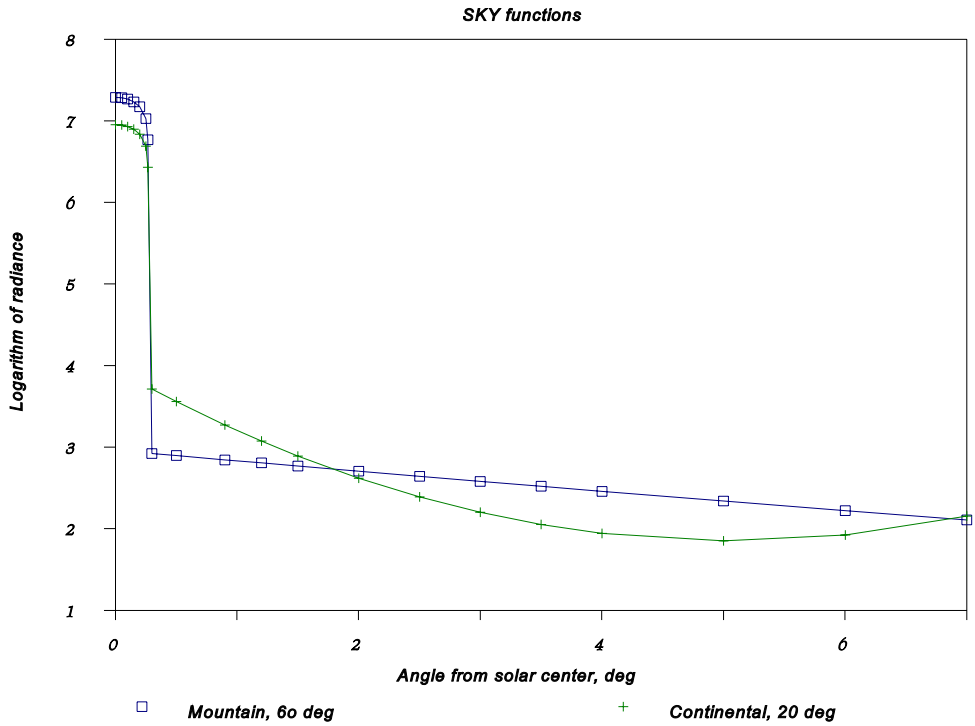


Fig. 2. The contribution of the solar disk to the irradiance of pyrheliometric sensors depending on the pointing error. Case of mountain aerosol and 60 degrees solar elevation.

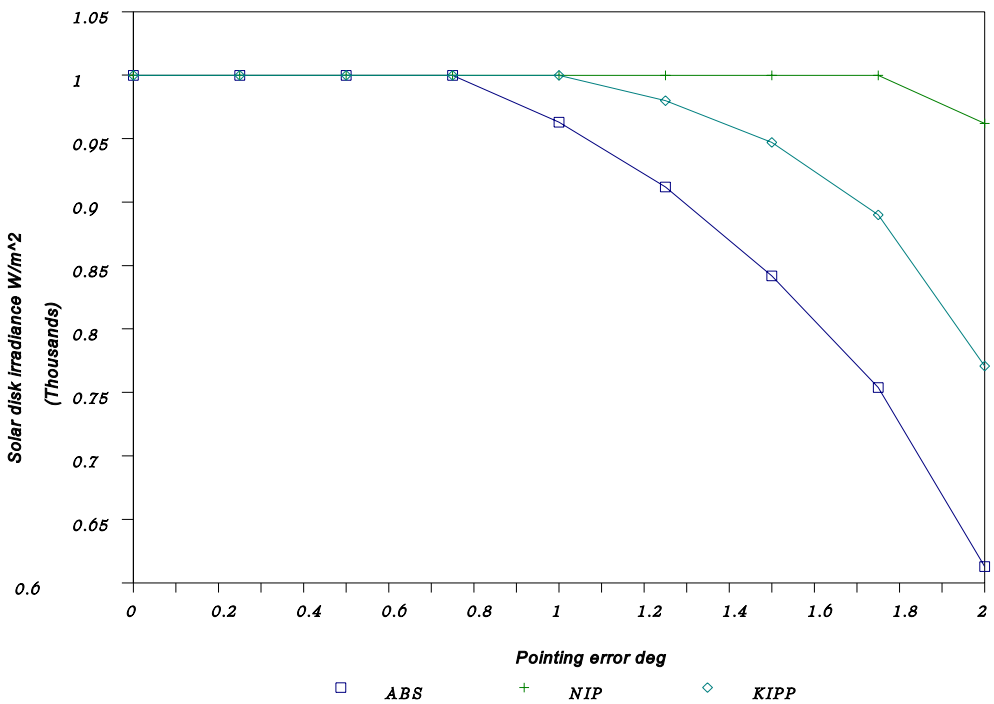


Fig.3. Same as Fig.2 except the case is continental background aerosol and 20 degrees solar elevation.

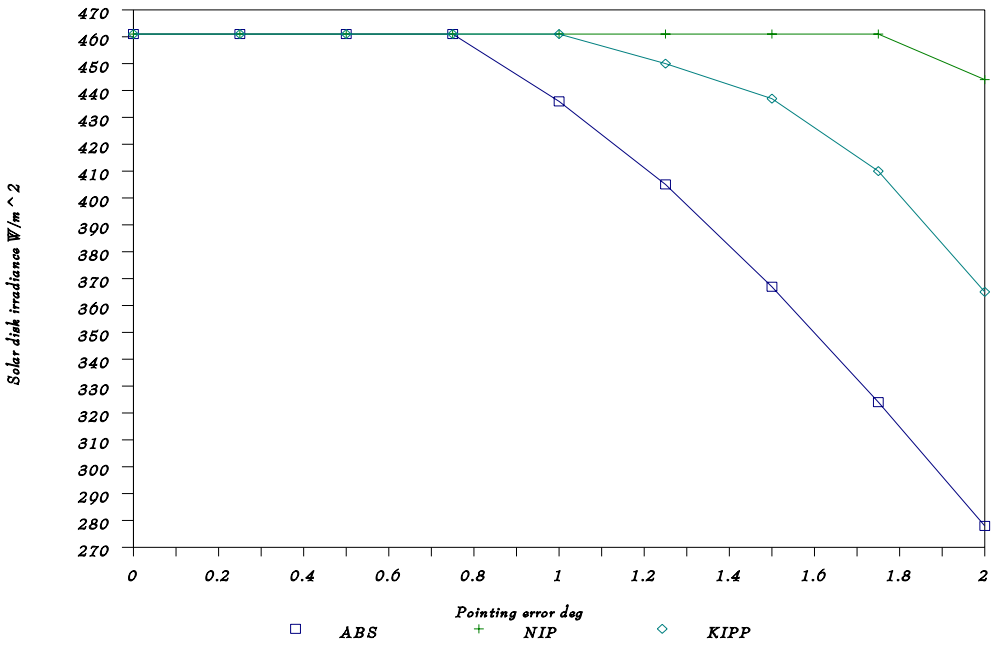
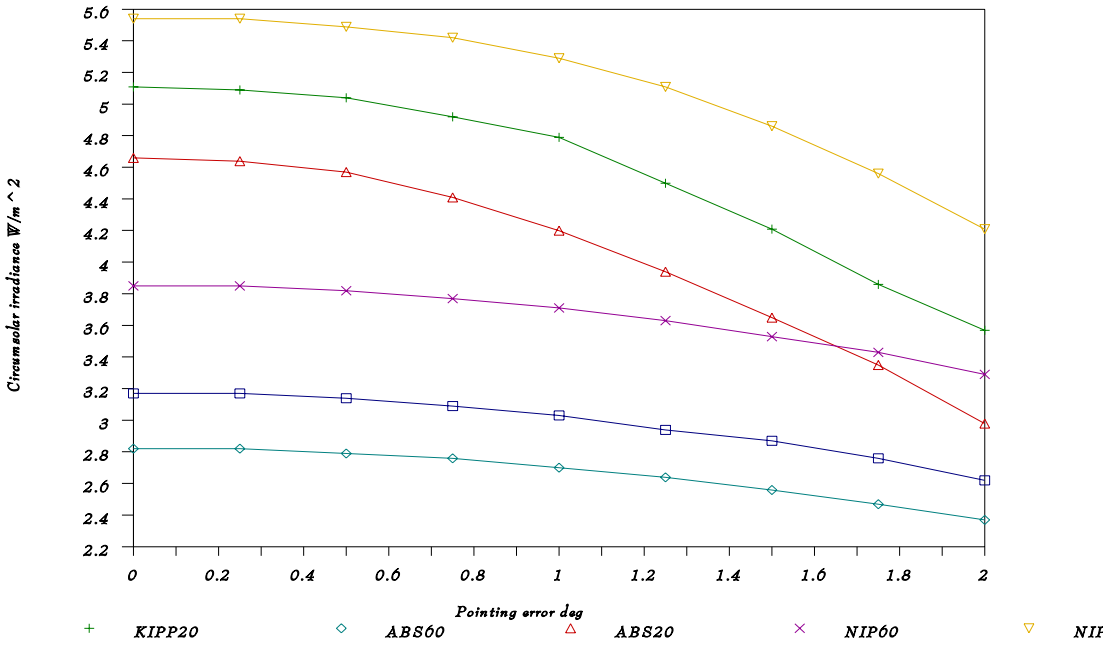


Fig.4. The contribution of the circumsolar sky to the irradiance of pyrheliometric sensors. The upper 3 curves belong to the case of continental background aerosol and 20 degrees solar elevation, the lower 3 curves belong to the case of mountain aerosol and 60 degrees solar elevation. In both group of curves the instruments are from the top to down: NIP, KIPP and ABS.



C3 Effect of Clouds on the Pyrheliometric Measurements

Science report prepared by G. Major (gmajor@met.hu) for the BSRN Workshop to be held in Boulder, Co,
12-16 Aug. 1996

Introduction

In the last year BSRN Meeting (Davos, October 1995) the question aroused: how large could be the effect of variable clouds around the Sun on the pyrheliometric measurements ?
In this report some results are presented.

The basic difficulty of making model calculations is the lack of proper radiance distributions around the Sun for cloudy situations. (For cloudless sky there are radiance distributions for several aerosol types and optical thickness values from several authors.) In this report "cloudy situation" mean that there is cloud near to the Sun (in the ring limited by the circles of 1 and 4 degrees from the solar centre) but not in between the Sun and the measuring pyrheliometer, that is the effect of transmission of cloud layers is not regarded here. High geometrical resolution radiance measurements were made from the solar centre up to 3 degrees by the Lawrence Berkeley Laboratory. The data are available from the National Renewable Energy Laboratory (NREL). They cover all weather situation at one dozen stations in the U.S.A (Noring et al., 1991). A sample of these data has been involved into this work.

Oversimplified assumptions have been used to derive the radiance distributions applied in calculating of the effect of clouds.

The geometry

The base height of our rectangular model cloud is 2 km, its geometrical thickness is 0.5 km, optical thickness is 25, it is 1 km wide and its length is perpendicular to the solar vertical plane, the solar elevation angle is 45 degrees. The scene is irradiated by the direct and circumsolar beam, the surface irradiance is seen in Fig. 1 (personal communication from T. Varnai, McGill University). The edges of the cloud shadow are not sharp, since the left lower and right upper edges of the cloud scatter the solar beam. In this geometrical situation (cloud below or above the Sun) side reflectance into the pyrheliometer is not possible, the cloud affects the pyrheliometric measurement by scattered radiation only (edge scattering).

In the other special geometrical situation the cloud length is parallel with the solar vertical plane, that is the cloud is in the right or left side of the Sun. Now the cloud affects the pyrheliometric measurement by side reflection only.

Cloud edge scattering

For the example calculation, in Fig. 2, the model cloud is above the Sun. In the cloud the geometrical path length of the radiation beam falling into the pyrheliometer:

$$x = H\left[\frac{ctg(h+\beta)}{\cos(h+z)} - \frac{1}{\sin(h+z)}\right]$$

The meaning of the symbols is seen in Fig. 2.

Taking into account that the optical depth of the cloud is 25, the optical path length of the beam in the cloud:

$$\tau(h,\beta,z) = 100\left[\frac{ctg(h+\beta)}{\cos(h+z)} - \frac{1}{\sin(h+z)}\right], \qquad z \geq \beta$$

It can be supposed that the radiance along the cloud as seen from the pyrheliometer

Using the data of Fig. 1

$$L(z) = A(\beta)\ \tau\ \exp(-\tau)$$

$$A(\beta) = A_o \exp(-0.7\beta)$$

where the constant Ao has to be determined to calculate absolute radiance values.

Cloud side reflectance

Fig. 3 shows a cloud in the right side of the Sun. It is supposed that

-- the radiance coming from the cloud side is proportional to the direct radiation,

-- the radiance is constant in the viewing angle of the cloud side,

-- the viewing angle does not depend on the solar elevation,

-- the viewing angle is proportional to the distance from the solar centre.

Again, the absolute value has to be determined.

Measurements

The National Renewable Energy Laboratory kindly forwarded the circumsolar measurements made at Boardman, OR (latitude 45,7°N) in April and May of 1977. During the daytime the instrument scanned the solar disk and the circumsolar sky (up to 3.2 degree) in every 10 minutes. The resolution is 1.5‘ in the solar disk and 4.5‘ in the outer parts. When the solar elevation is low, the scan is parallel with the surface. At solar noon the scan occurs in the solar vertical.

This way, cases for side reflectance could be found in the morning or evening measurements. An example is seen in Fig. 4 altogether with the least turbid cloudless cases found in the sample for both the low and high Sun. While the circumsolar radiances are quite near in the clear cases, the cloudy radiances differ significantly from them even in the clodless part of the sky.

Fig. 5 shows circumsolar functions for the edge scattering altogether with the case of the cloudless high Sun. Again: the clear parts of the cloudy cases show much higher radiance than the absolutely clear atmospheric column.

Looking at Figs. 4 and 5 one has to remember that real clouds differ much from the above described model one.

The applied radiance distributions

Considering only the above described measurements and model, the following radiance distribution functions have been selected for further calculation:

-- 60 degrees solar elevation, mountain aerosol for the solar disk and clear sky radiances (high

clear case)

-- 20 degrees solar elevation, continental background aerosol for the solar disk and clear sky radiances (low clear case)

-- the above clear cases combined with clouds at 1, 2 and 3 degrees from the solar centre for both the edge scattering and side reflectance situations.

The radiance functions are shown in Figs. 6, 7 and 8. For example to calculate the effect of side reflected radiation if the cloud begins at 2 deg, the clear function has been used for the solar disk and circumsolar sky up to 2 degrees, from 2 deg to 2.4 deg the radiance seen in Fig 6, for angles larger 2.4 deg (bottom of the cloud) zero radiance has been taken in to account.

The cloud radiances have been tuned to the measured ones, while the cloudless parts are the same as calculated for the atmospheric column containing the named model aerosol. This latter does not agree with the measurements.

The pyrheliometers

Geometrical differences can be found even amongst the newly developed pyrheliometers. The calculations were made for 4 pyrheliometer geometry (see Fig. 9). ABS represents PMO2, PMO5, Pacrad and HF instruments. CRO3 is the Crommelynck 3L pyrheliometer that has the smallest slope angle and the largest limit angle. The KIPP and NIP thermoelectric pyrheliometers are used for continuous recording of the direct radiation.

The effect of clouds

Calculations have been made for the cloudless atmosphere and for both types of cloudy situation. The distance of clouds from the solar centre was 1, 2 and 3 degrees respectively.

The deviations of calculated outputs of pyrheliometers between the clear and cloudy situations are presented in Figs 10-13. In all cases the cloud increases the radiation entering into the instrument, but the increase never reaches 1 percent.

Conclusions

1. The presence of clouds in the circumsolar part of the sky increases the output of pyrheliometers but this increase does not exceed 1 percent.

2. It seems that the observed changes in the output of a pyrheliometer in cloudy conditions are related mainly to changes in the transmission and scattering of the atmospheric column, the scattering and reflection of clouds have smaller effect.

Reference

Noring, J.E., Grether, D.F. and Hunt A.J. 1991: Circumsolar Radiation Data: The Lawerence Berkeley Laboratory Reduced Data Base NREL/TP-262-4429

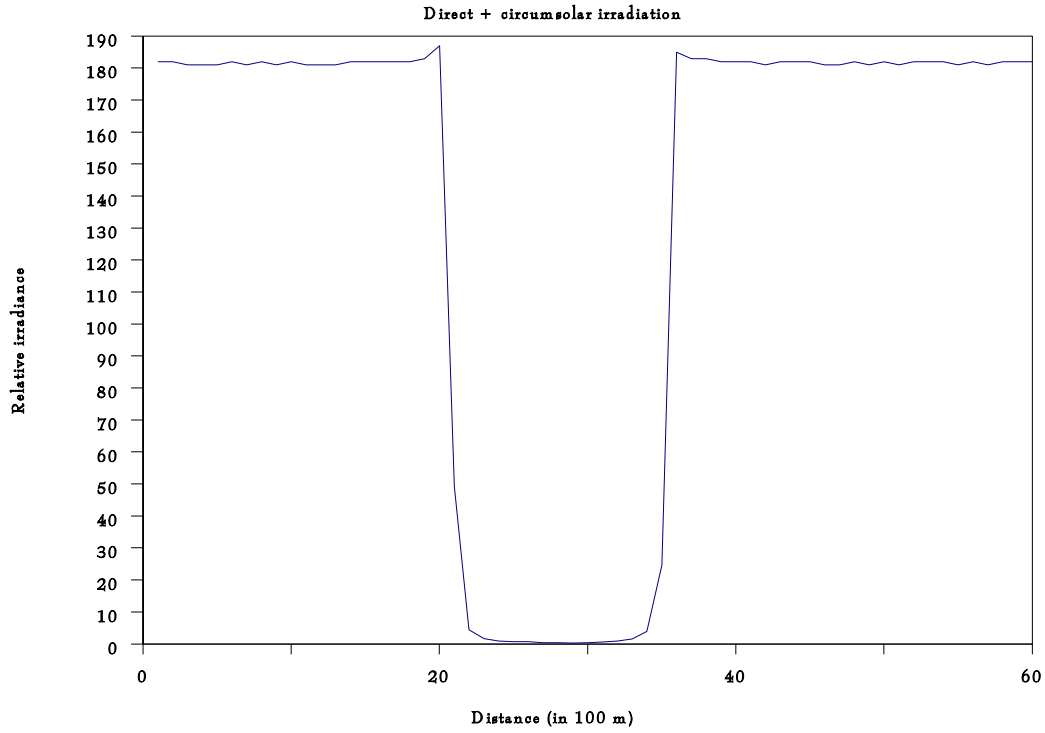


Figure 1. Surface Irradiance: the shadow of the model cloud.

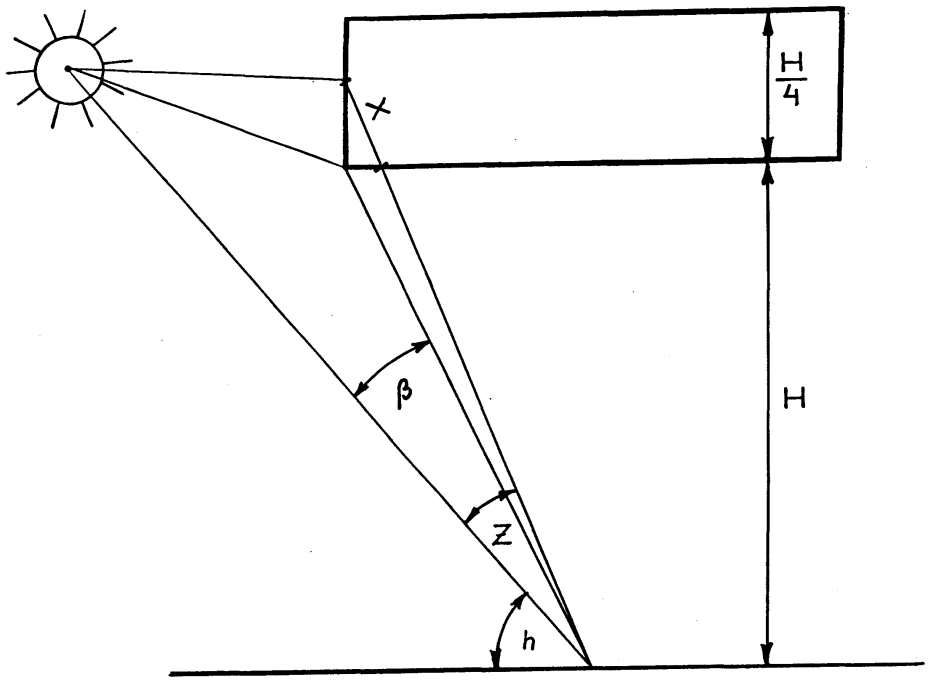


Figure 2. The geometry of cloud edge scattering.

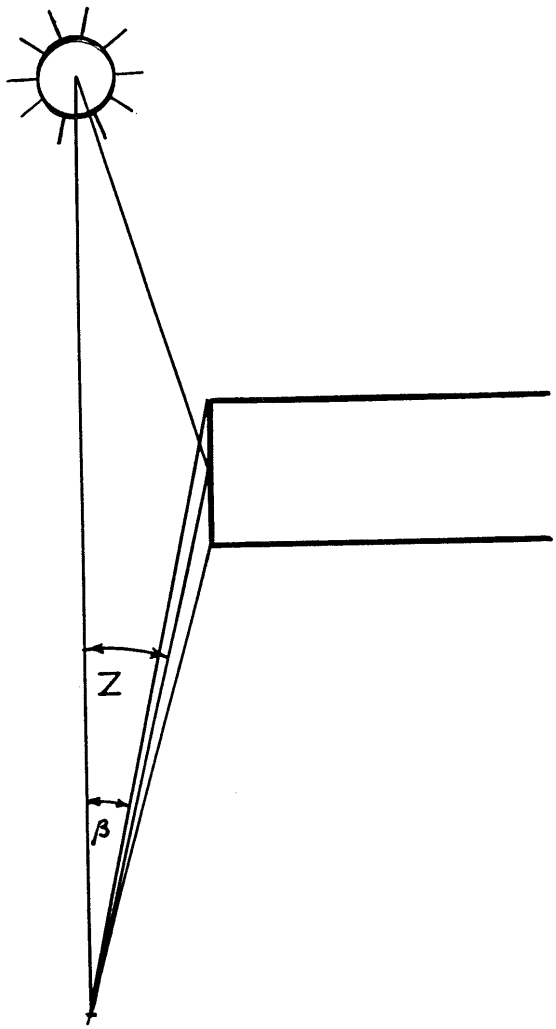


Figure 3. The geometry of cloud side reflectance.

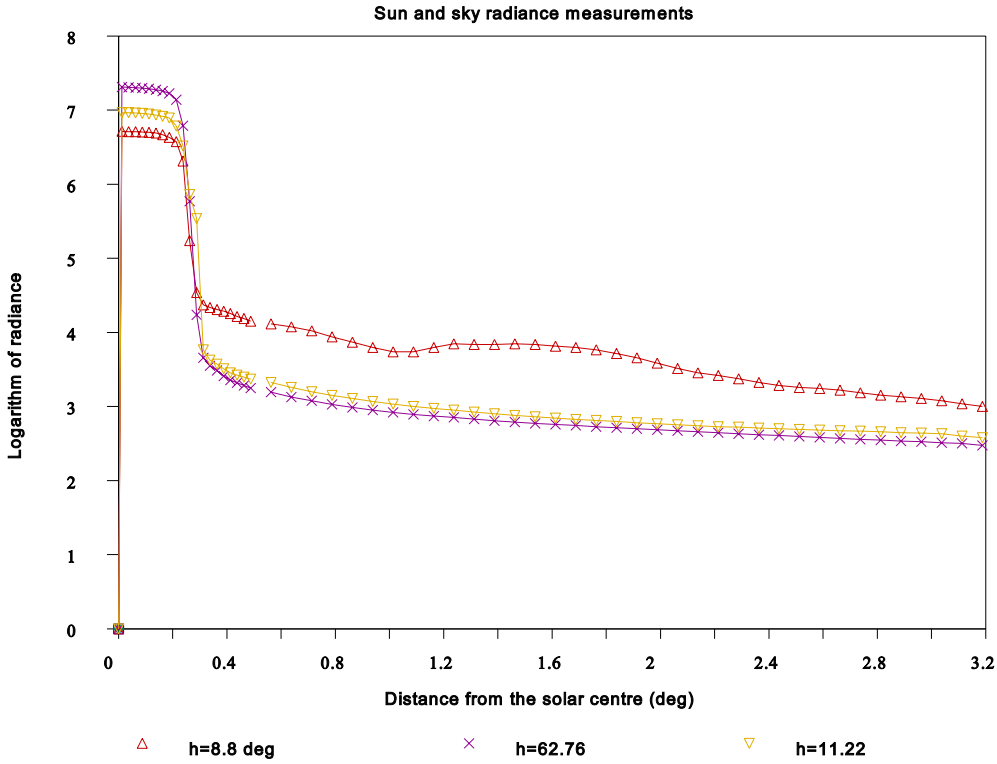


Figure 4. Measured radiance functions: example for the cloud side reflectance (upper curve) as well the clearest cases for high and low solar elevation.

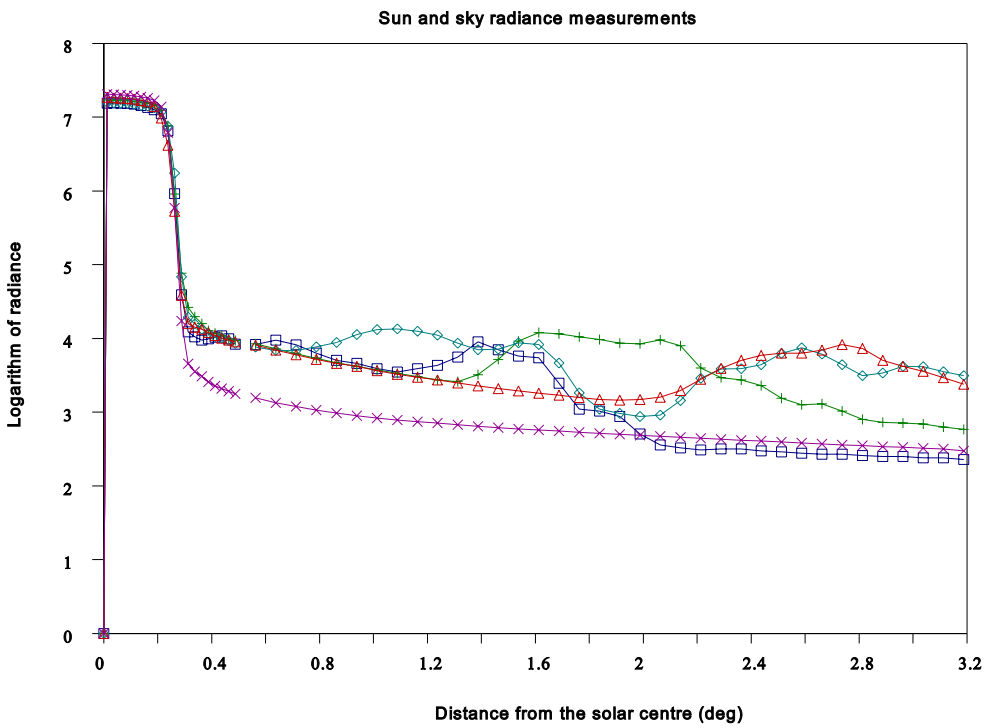


Figure 5. Measured radiance functions: examples for cloud edge scattering and the clearest case. In all cases the solar elevation is around 60 degrees.

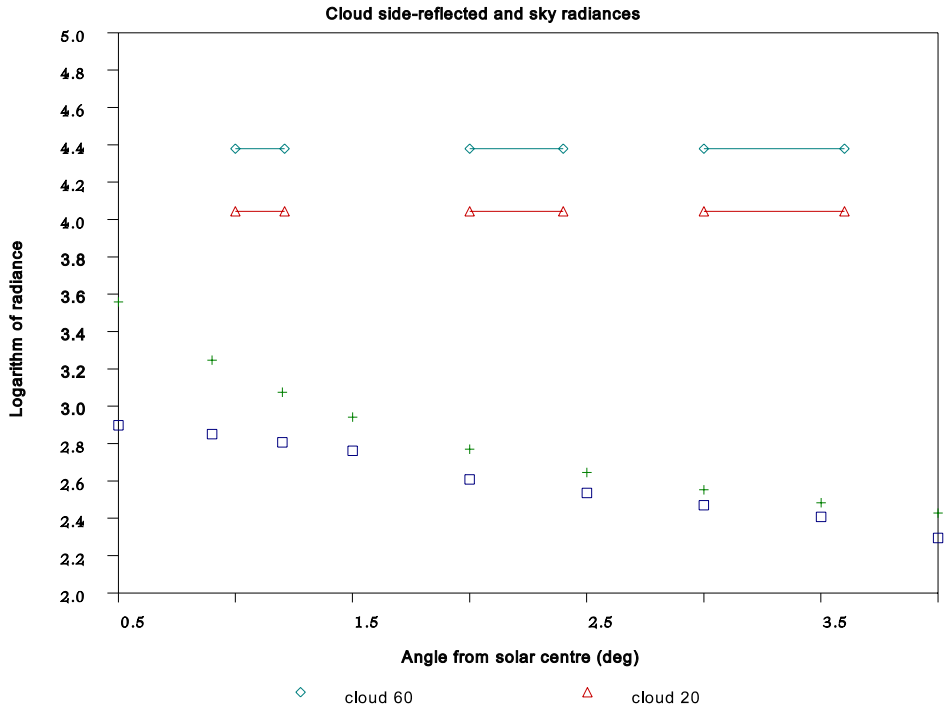


Figure 6. Model radiances for cloud side reflection and for mountain and continental background aerosol.

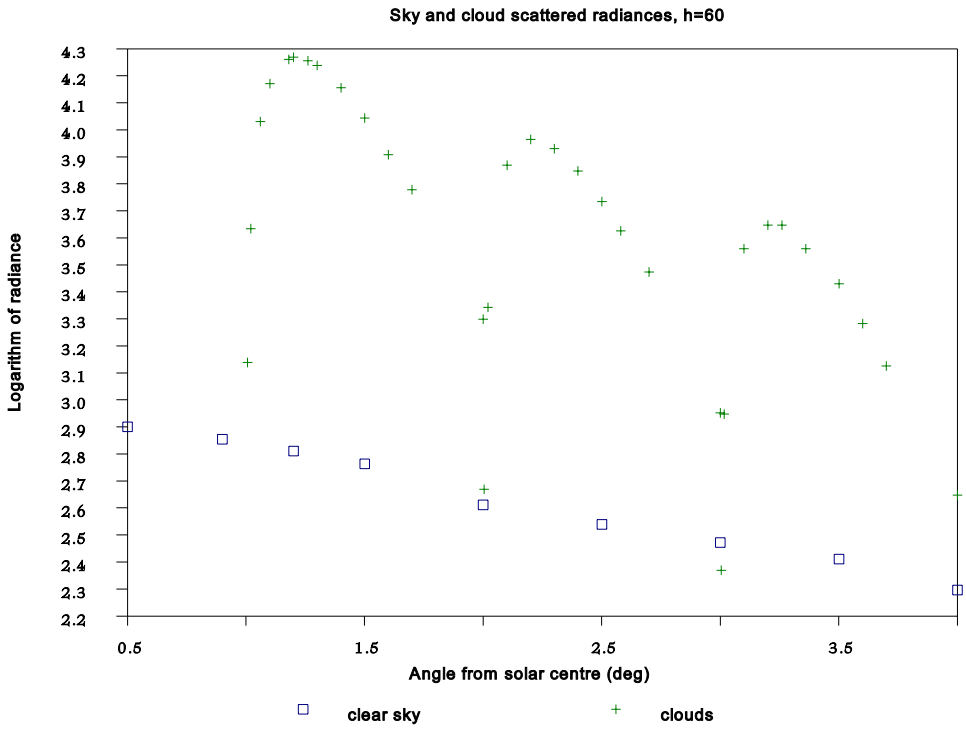


Figure 7. Model radiances for the cloud edge scattering and for the clear sky, mountain aerosol, h=60 degrees.

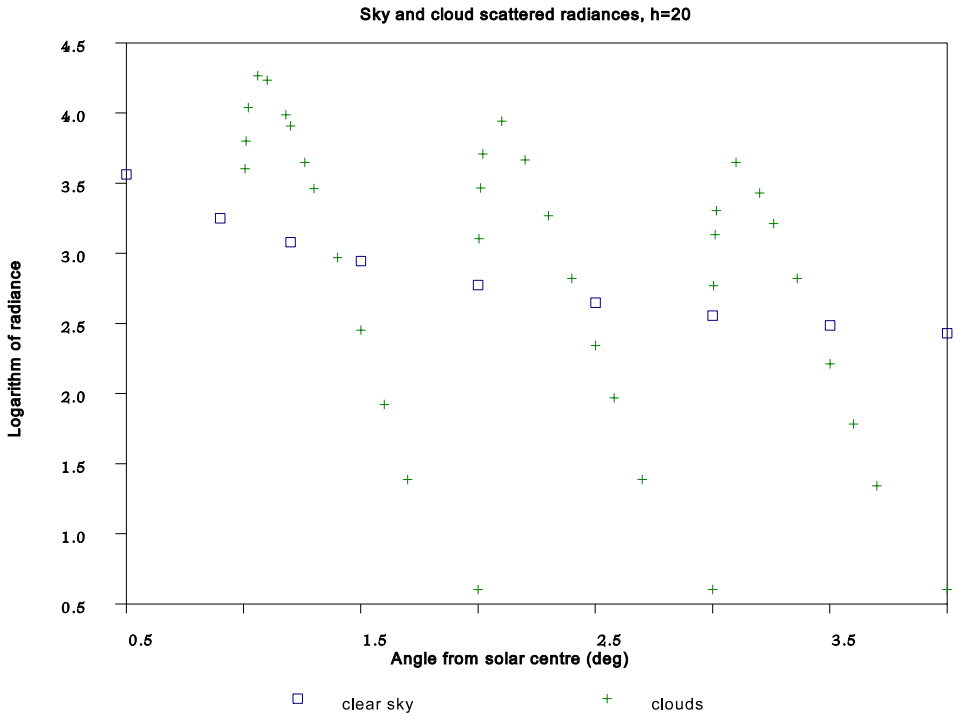


Figure 8. Model radiances for the cloud edge scattering and for the clear sky, background aerosol, h=20 degrees.

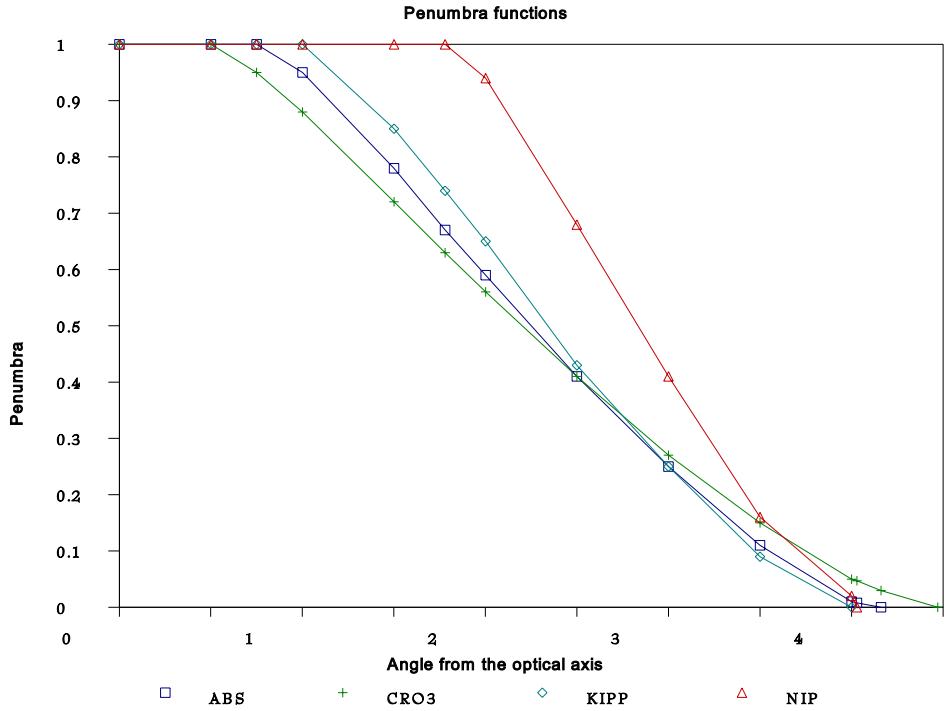


Figure 9. The basic geometrical characteristics of the pyrheliometers involved into the calculation.

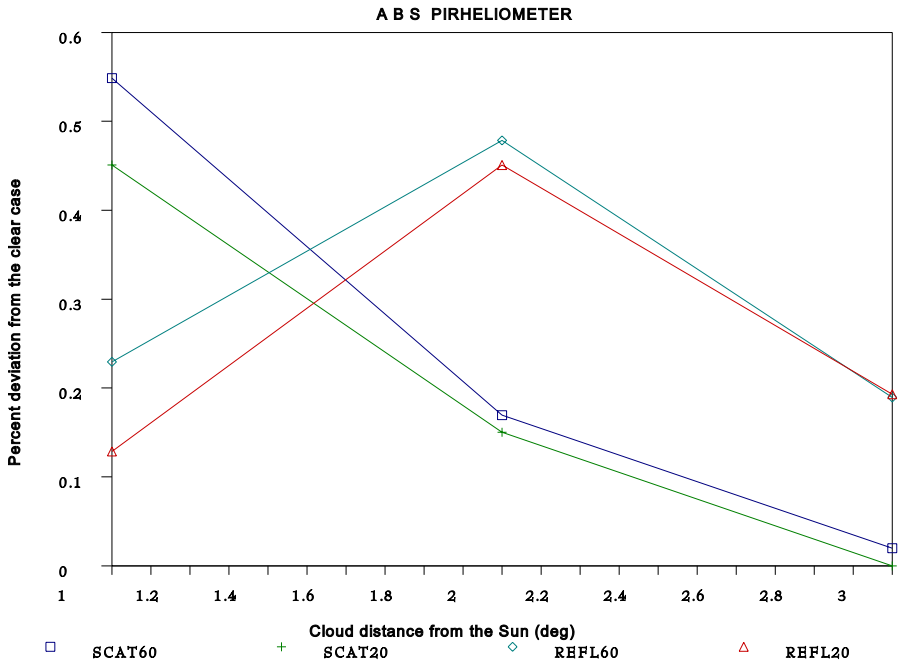


Figure 10. Cloud effect for the ABS pyrheliometer group.

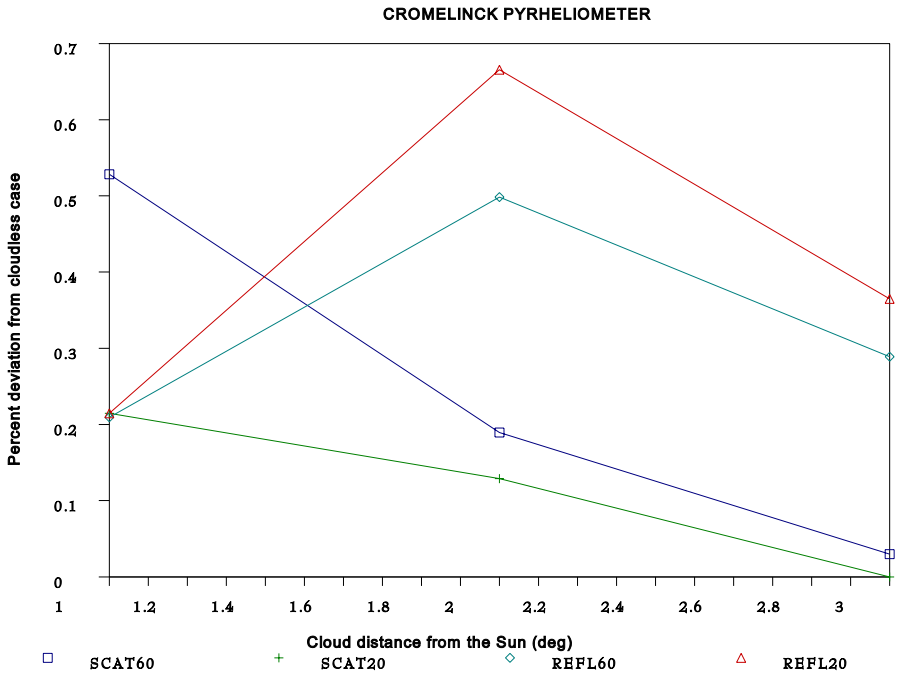


Figure 11. Cloud effect for the Crommelynck 3L pyrheliometer.

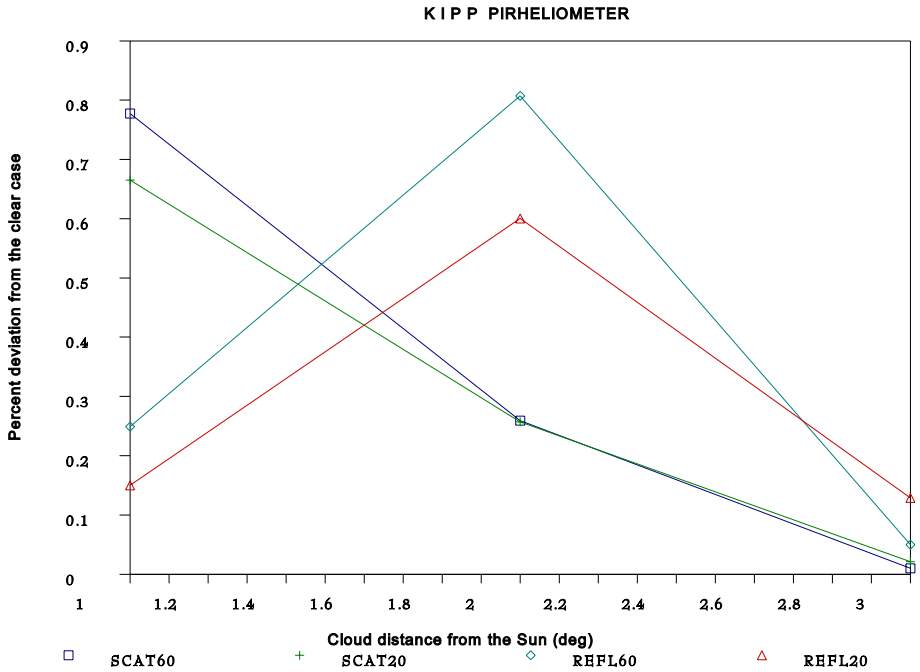


Figure 12. Cloud effect for the KIPP pyrheliometer.

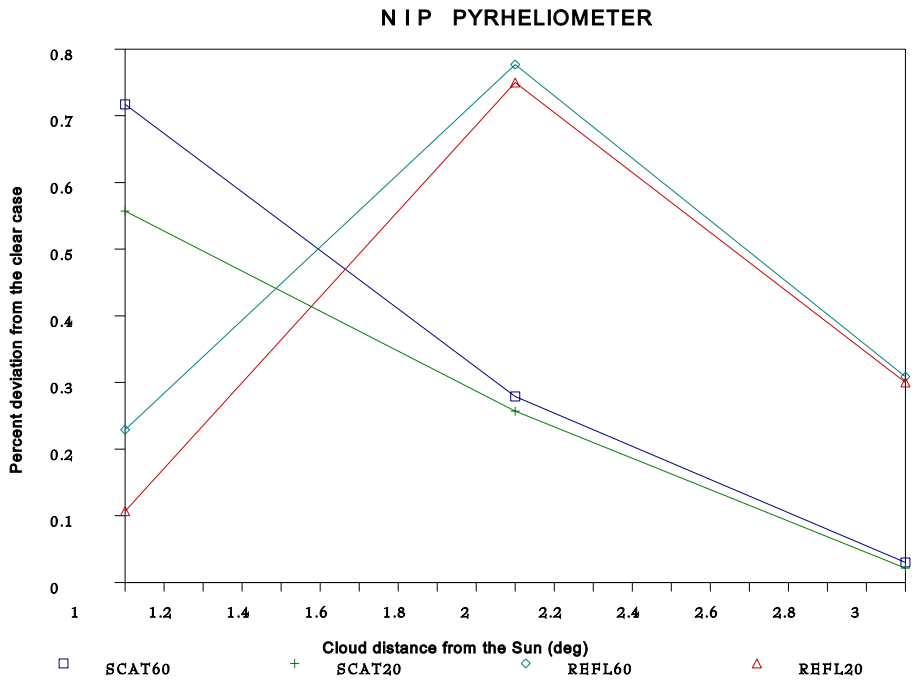


Figure 13. Cloud effect for the NIP pyrheliometer.

Annex D Installation of an Equatorial Mount (Eppley Laboratories)

The instructions below are given as an aid for the installation of equatorial trackers, not only for the measurement of direct beam irradiance, but also for the measurement of diffuse irradiance using a single axis tracker.

The pyrheliometer can be mounted on a power driven equatorial mount such as the Eppley Solar Tracker, Models ST-1 and ST-3, for continuous readings.

The site for the tracker should be chosen to ensure that the tracker will be free to rotate 360 ^{o}and that no objects will cast a shadow over the location at any time during the entire year.

There are four settings that have to be aligned to ensure proper tracking of the sun: North to South, latitude, declination, and time of day.

(1) North to South:

The axis of the tracker has to be set in a North to South direction put it in the same plane as the axis of rotation of the earth. The drive end of the tracker should be pointing South in the Northern Hemisphere and North in the Southern Hemisphere. (It should be noted that the tracker must rotate in the opposite direction in the Southern Hemisphere. Unless otherwise specified, the trackers are wired for use in the North Hemisphere. To reverse direction, simply reverse the lead wires that run from the capacitor to the drive motor.) Determine the geographical N-S meridian, orient and level the tracker in the N-S meridian. Two holes, one slotted, are provided for bolting the tracker in position on the mounting platform (not provided).

(2) Latitude:

The drive shaft housing of the tracker must be rotate until the correct site latitude value is indicated on the latitude scale, located on top of the stand upright. Generally, the mark engraved will be a satisfactory reference, but for best solar tracking, it may be necessary to correct this slightly by the trial and error method (see below).

Before proceeding with declination and time of day, the pyrheliometer must be mounted on the solar tracker.

(3) Declination:

The declination adjustment is accomplished through movement of the pyrheliometer in the "U" block support, after loosening the clamping hand screw which should be tightened when desired adjustment is affected. When first setting up the tracker, the declination setting should be achieved from the appropriate tables. Once the mount is tracking properly, this can be set by using the sights on the pyrheliometer. The sight consists of a pin hole on the front flange which cast an image of the sun on the black and white circular target on the rear flange. The image of the sun should be in the centre of the target. Checking the sights should be done daily, although the declination may not change rapidly from day to day (especially around June 21 and December 21). The most rapid change is around March 21 and September 21.

(4) Time of Day

This setting is accomplished by rotating the pyrheliometer by hand after loosening the three thumb screws located under the pyrheliometer support plate. Line the sun's image up with the spot provided on the sight.

If, after the operations described above have been undertaken, the solar tracking is not as precise as desired (as evidenced by the light spot position on the sighting target), then further trial and error attempts should be made. At Solar Noon, adjust time of day (if needed) and take up half of the error with latitude adjustment and the other half with declination adjustment, until spot is aligned on the target. Then , at sunrise, align the spot on the target by adjusting the north to south line. Repeat solar noon and sunrise

adjustments as needed. It has been Eppley's experience that one adjustment procedure like this takes up all errors in the manufacturing of the solar tracker. Remember, the objective is to prevent the light spot from drifting away from target by a distance not greater than the spot diameter, however, for practical purposes, this drift may reach two diameters without the introduction of significant error.

Annex E Suppliers of Data Acquisition Systems (Partial Listing)

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 upon 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.

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)

Annex F Sample log sheets

The primary reasons for keeping a log of the activities about the station is to help in determining the quality of the data. Until recently such logs were kept either by filling out forms on a daily basis or writing information into a station log book. The former has a tendency to encourage the observer/technician to record only those activities that are required by the sheet, while the latter is often used only for extraordinary occurrences or events (e.g. the station was hit by a tornado), but not the routine activities associated with the day-to-day operation of the observatory (e.g. cleaning the instruments). Whatever form is used must be determined in concert with the observer so that the information required by the scientist analysing the data can be easily discovered. Log sheets are essential in the rapid and accurate quality assurance of solar radiation data.

Recently, with the development of sophisticated computer data acquisition programs, the normal log sheet can be completed electronically. The advantage of such a form is that flags set by the data acquisition system can be written to the log automatically. Electronic logs provide a means of directly and permanently linking the data with a record of activities at the observatory. Care must be taken in the design of such a log so that text can be easily added beyond the normal “check-off” information. Furthermore, no matter how automated the site, it is essential to provide a forum for the technician responsible for the maintenance of the instruments, etc. to note any abnormalities.

Most log sheets provide basic checks for the instruments, the trackers, the data acquisition system and the clock. Many provide areas where the technician can insert the local temperature, cloud amount, surface conditions, etc. The overall design should also encourage comments beyond the daily routine information for which the sheet is designed.

The next three pages contain samples of log sheets which have been used successfully. Example 1 is from the University of Calgary, where the log was designed for the International Daylight Measurement Program (only the radiation portion is reproduced). Example 2 is a log sheet developed by the National Renewable Energy Laboratory for the Historically Black Colleges and Universities (HBCU) network of solar radiation stations. Example 3 is a former log sheet developed for the Canadian BSRN site.

U. of C. G. C. Daily Inspection Log Sheets U. of C. Station		Date: Julian:	T1: T3:	T2: MST DST
Parameter	Instrument	Cleaned	Remarks	Tracking
Beam Irradiance	NIP 28053E6			
Global Illuminance	ELV-641/89			
Global Irradiance	CM11/923949			
Diffuse Illuminance	ELV-641/92			T1
Diffuse Irradiance	CM11/924208			
North Illuminance	ELV-641/87			
East Illuminance	ELV-641/91			
South Illuminance	ELV-641/90			
West Illuminance	ELV-641/88			T2
North Irradiance	CM11/923952			
East Irradiance	CM11/926954			
South Irradiance	CM11/924210			
West Irradiance	CM11/923951			
Thermistor	107F/C1191			T3
Additional Information:				
WWV Time Signal :				

Figure F1. Sample log sheet from the University of Calgary.

Station Name: SERI/SRRL For the Period: 5/26/85 to 5/31/85

KEY: ✓ = found in GOOD condition X = found in BAD condition O = corrected
A = adjusted

Clouds: ◯ = Clear (Amount < 1/10)
◐ = Scattered (1/10 ≤ Amount < 5/10)
◑ = Broken (5/10 ≤ Amount < 9/10)
⊕ = Overcast (Amount ≥ 9/10)

DATE & TIME							
Day of Year	146	147	148	148	149	150	151
Day of Week	SUN	MON	TUE	TUE	WED	THR	FRI
Month/Day/Year	5-26-85	5-27-85	5-28-85	5-28-85	5-29-85	5-30-85	5-31-85
Standard Time	13:30	07:45	08:10	11:15	09:25	15:10	09:35
Observer (Initials)	TLS	TLS	TLS	VS	VS	MDR	MDR
GLOBAL HORIZONTAL							
Dome Condition	⊗	✓	✓	✓	⊗	X	⊗
Sensor Level	✓	✓	✓	✓	✓	✓	✓
Desiccant	✓	✓	✓	✓	✓	X	O
DIFFUSE HORIZONTAL							
Dome Condition	⊗	✓	✓	✓	⊗	X	⊗
Sensor Level	✓	✓	✓	✓	✓	✓	✓
Desiccant	✓	✓	✓	✓	✓	✓	✓
Shading Band	✓	A	✓	✓	✓	A	✓
DIRECT NORMAL							
NIP Window Condition	⊗	✓	✓	✓	⊗	X	⊗
Tracker Alignment	✓	✓	X	O	✓	✓	✓
Signal Cable	✓	✓	⊗	✓	✓	✓	✓
DATA ACQUISITION							
Time Display	✓	✓	✓	✓	✓	✓	A
Battery Voltage	12.2	12.2	12.1	12.1	12.2	12.1	12.2
Recorder Counter	125	130	135	137	140	150	155
Tape Change? (Y=yes)							Y
Printer Status	✓	✓	A	✓	✓	✓	✓
WEATHER OBSERVATION							
Cloud Amount	◐	◐	◯	◯	◑	⊕	◑
Temperature	79	65	68	85	72	67	65
COMMENTS	MODERATE DUST SPOTS ON DOMES	ADJUSTED SHADOW BAND TO +21° NIP ALIGNMENT IN "SAFE" ZONE	TRACKER OUT OF ALIGNMENT, SIGNAL CABLE SNAGGED ON MOUNTING FIXTURE	TRACKER REPROGRAMMED/ALIGNED AT 11:31 (MST)	LIGHT DUST SPOTS ON DOMES	ADJUSTED SHADOW BAND TO +22° RAIN SHOWERS BEGAN ~ 9:00 am (MST) DESICCANT TURNING WHITE	CR-21 TIME RESET AT 9:40 am (4 MINUTES SLOW) DESICCANT REPLACED IN HORIZONTAL PSP. TAPE OFF: 09:41 ON: 09:46
NIP Target:	X	⊙	X ⊙	X	NO SUN ⊙	NO SUN ⊙	X

SERI, 1617 Cole Blvd., Golden, CO 80401
ATTN: Val Szwarc 215 16/3

Send Completed Form(s) EACH FRIDAY To:

16

Figure F2. Sample log sheet from the NREL HBCU solar radiation network.

BSRN DAILY LOG AND MAINTENANCE RECORD

A) Inspection performed by (print): _____

B) Date (MM/DD/YY): ___/___/___ Time: IN ___:___ OUT ___:___

C) Present Conditions:

1. Temperature Interior ____ Degrees C Exterior ____ Degrees C
2. Relative Humidity Interior ____ % Exterior ____ %
3. Cloud Amount ___/10 Cloud Type _____
4. Wind Speed _____ km/hr Wind Direction _____ Degrees
5. Surface Condition _____

D) Radiation Instrument Maintenance:

	Domes Cleaned	Spirit Level Bubble In Circle	Corrected	Desiccant Active	Replaced
East Tracker NIP	____	____	____	____	____
East Tracker PIR	____	____	____	____	____
East Tracker CM21	____	____	____	____	____
West Tracker NIP	____	____	____	____	____
West Tracker PIR	____	____	____	____	____
West Tracker CM21	____	____	____	____	____
Table East PSP	____	____	____	____	____
Table East CM21	____	____	____	____	____
Table West PSP	____	____	____	____	____
Table West CM21	____	____	____	____	____

E) Tracker Operation:

	East Tracker Correct	Corrected	West Tracker Correct	Corrected	Explanation
NIP on Target	____	____	____	____	_____
Shade Balls on Target	____	____	____	____	_____
Computer Time	____	____	____	____	_____
Computer Date	____	____	____	____	_____

F) Data Acquisition System:

Date (MM/DD/YY): ___/___/___
Time: ___:___
Free Disk Space: _____ days
DAS resistances checked? ____ Are they in range? ____

G) Comments:

_____
_____
_____

Figure F3. Sample log sheet from the Canadian BSRN site.

Annex G*

Annex H*

* (Not included in this reprint of the Operations Manual)

Annex I Solar Position Algorithm

An algorithm is provided for the calculation of astronomical parameters in QuickBasic. The subroutine is based upon the publication of Michalsky (1988) and uses the approximation formulae found in the Astronomical Almanac. Figure I1 compares the results of the approximation with values published in the Nautical Almanac.

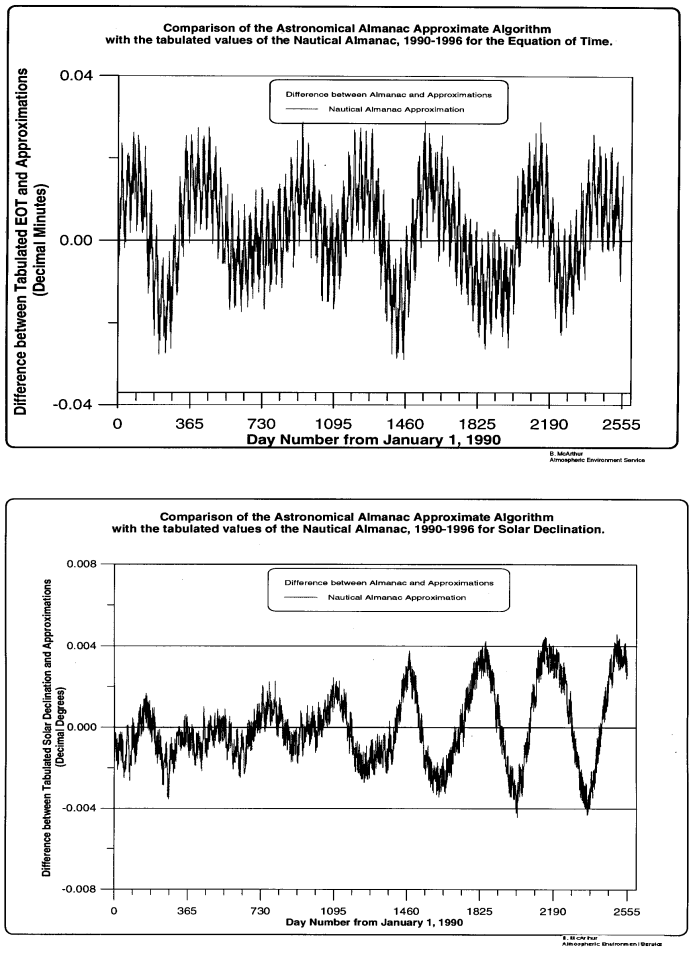


Figure I1. Comparison of approximations derived from the Astronomical Almanac against published values from the Nautical Almanac. (Upper) Equation of Time, (Lower) Solar Declination.

Subroutine Solar: 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
```

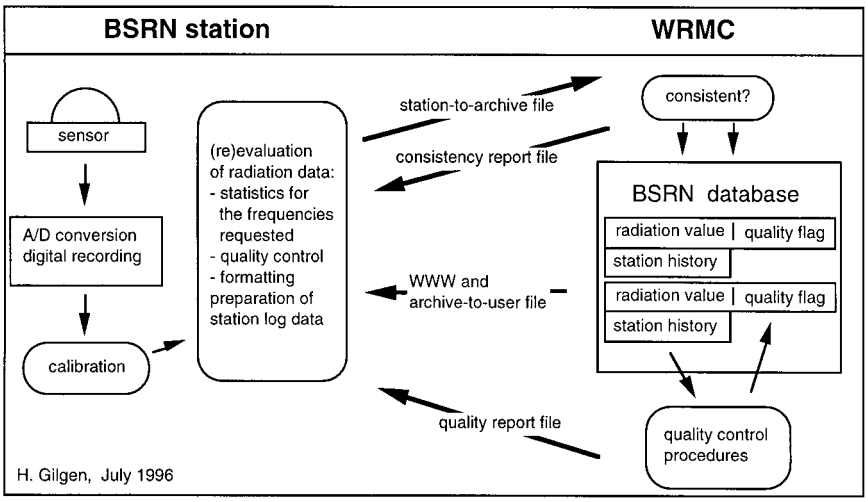
```
   Lat = Lat / Rad
' MnLon in degrees, GMST in hours, JD in days if 2.4e6 added;
' MnAnom, EcLon, OblqEc, Ra, Dec, LMST, and Ha in radians.

' 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
```

Annex J BSRN Data Management (H. Gilgen)

This annex contains an outline of the BSRN data management. A comprehensive description is given in (Gilgen et al. 1995).

The relationships between the BSRN stations and the WRMC are shown in Fig. J1 which is a simplified version of Fig. 2.1 in (Gilgen et al. 1995). The observations are made at the BSRN stations. The data are accumulated during a month and their quality is checked by the station scientist. The monthly data sets are then forwarded to the WRMC using the BSRN station-to-archive file format in ASCII code. Data transfer is made preferably by electronic means. The BSRN stations keep the log and the original readings for the duration of the BSRN project to allow anytime for a re-evaluation.

Fig. J1: A BSRN station and the WRMC



A monthly data set consists of station log data and of atmospheric data (including the radiation data) formatted as prescribed in (Gilgen et al. 1995) and (Hegner et al. 1996). The station log data describe the station, the radiation instruments and the measurements. They are semantically much richer than the atmospheric data and thus are often afflicted with omissions and/or contradictions. Consequently, rules asserting the consistency of the station log data have been incorporated in the definition of the station-to-archive file format, e.g., "an instrument is assigned to every radiative flux". The station log data are written in the first part of the station-to-archive file. The radiation and the other atmospheric data are written in the second part of the station-to-archive file.

The WRMC data manager supports the BSRN station scientists when they start to prepare the monthly data sets: sample station-to-archive files and a format check program are available. It is recommended to apply the format check program before a station-to-archive file is forwarded to the WRMC. The format check program however does not perform consistency checks for the following reason. The consistency checks not only validate the data across the different parts in a site-to-archive file using the rules which are part of the format definition, but they also compare the station log data with the data already stored in the database. Thus, the consistency of a station-to-archive file is checked at the WRMC. If a station-to-archive file is found to be consistent, the data are inserted in the BSRN database. If a file is found to be

inconsistent, a detailed consistency report is forwarded to the station concerned. The BSRN station scientist then prepares a consistent monthly batch of data.

On the one hand, the formalization of the descriptions of a station and of the measurements needs some effort when the monthly data sets are prepared for shipping. On the other hand, it is a prerequisite for the systematic treatment of station log data in a database. Only accurate and consistent station log data can be integrated with the radiation data and the other atmospheric data in the BSRN database. The consistency checks assert that the data in the BSRN database do not violate the integrity constraints which are part of the database definition. The BSRN database is managed by the WRMC.

All data in the BSRN database are consistent. The radiation data however may be afflicted with error, though their quality was controlled by the station scientists. Therefore at the WRMC, automated quality control procedures are applied to the radiative flux data to detect erroneous values which subsequently are flagged. The radiation data flagged at the WRMC as being afflicted with error and the reason for the flagging are reported to the station concerned. If the station scientist judges the flagged and/or other data to be questionable, he/she re-evaluates the monthly data set and forwards the new version to the WRMC. The WRMC processes updated versions of the monthly data sets in the same way as the original data sets, except that the older data are deleted from the database. Thus the BSRN database always contains the radiation data judged to be most reliable.

The data in the BSRN database are available to the BSRN station scientists (and to external scientific institutions after a certain delay) in archive-to-user files which are requested by means of a WWW-interface.

The integration of consistent station log data, high-quality radiative flux data and auxiliary atmospheric data in the BSRN database run by the WRMC enables an efficient production of datasets meeting the objectives of the BSRN project.

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