CHAPTER 2

SCIENTIFIC PLAN

In any scientific endeavour, the existence and application of a sound scientific plan is an important link. Within the BSRN, it takes the form of a data measurement and data management plan. Many of the aspects of this plan were already directly or indirectly addressed in the previous Chapter, hence this Chapter does not endeavour to be a repetition, but a contextualization and in some ways, expansion. Having sketched the plan, this Chapter then moves forward to focus on processes leading to radiation fluxes in the Earth's atmosphere, as well as associated measurement techniques to best capture those radiation fluxes. This comprises relevant instrumentation, completing the larger picture of a radiation measurement plan.

2.1 SCIENTIFIC GOALS AND OBJECTIVES OF THE BSRN

Unlike networks that have evolved from a hypothesis through a design phase and then proceed to instrumentation implementation, the BSRN has developed in a "segmented" manner (Mc Arthur as quoted by Dutton, 1996). For BSRN to become a reality, much resources were drawn from existing infrastructure. In some cases, upgrades to meet BSRN standards were made as described by Heimo *et al.* (1993). Notwithstanding these facts, the mission and vision for the BSRN remained clearly defined as outlined in section 2.1:

2.1.1 Goals

The original goals for measurements in the BSRN, as defined at the 1990 Washington workshop and associated correspondence, are as follows (Gilgen *et al.*, 1991; Mc Arthur, 1998):

Goal 1: To monitor surface radiation fluxes to the best possible accuracy using the best possible methods.

Goal 2: To provide data for calibrating satellite-based estimates of surface radiative fluxes.

Goal 3: To provide data suitable for boundary values in atmospheric modelling and application in atmospheric model verification.

2.1.2 Objectives

These goals are now further expressed in terms of specified objectives, as sketched by authors such as Mc Arthur (1998):

Within goal 1:

Objective 1.1: To measure both the surface SW and LW radiation components at specific locations with sufficient accuracy in order to reveal long-term trends.

Objective 1.2: To standardize and maintain the best possible site operation procedures throughout the global network.

Objective 1.3: To obtain simultaneous (parallel) measurements of meteorological parameters such as clouds, ozone and upper air profiles, that may contribute to research related to the measurement of solar radiation fluxes.

Objective 1.4: To establish a cost-effective central data processing, archiving and data management centre.

Within goal 2:

Objective 2.1: To determine specific parameters to characterize a site for satellite applications (albedo, clouds, aerosols) in a quantitative manner.

Objective 2.2: To validate a site for remote sensing measurements by performing in-situ measurements of surface reflectance over a large area comparable to one pixel of satellite imagery.

Objective 2.3: To develop cost-effective equipment and methods for spectral ultraviolet (UV) and infrared (IR) solar radiation budget measurements that will contribute to the improvement of satellite algorithm design and validation of satellite SRB determinations.

Objective 2.4: To perform 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-observation abilities of the global BSRN.

Within goal 3:

Objective 3.1: To meet SRB measurement standards by improving the quality of measurement, especially downwelling irradiance, being quantities included in the basic BSRN measurement programme.

Objective 3.2: To study the radiative properties of broken and inhomogeneous clouds, in order to improve the current understanding thereof.

2.1.3 Practical significance

These objectives find practical significance in the following way:

Objective 1.1

The measurement of surface fluxes is the very basic and most feasible form of radiation measurement, since ground-based equipment can best utilize manageability and uniform global deployment in a terrestrial network. It can also best exploit existing radiometric infrastructure. Although the emphasis in basic measurements is placed on downwelling parameters, upwelling parameters from various tall structures of varying height should not be neglected, when measurable. Upwelling quantities add significant value when combined with the basic (downwelling) quantities, as described in Section 6.3.2.8. It also provides a firmer ground for quality control techniques as discussed in various sections of Chapter 4, and summarized in Section 6.3.2.8.

It is desirable to measure both SW and LW radiation fluxes to foster a sound understanding of solar-earth-radiation fluxes and processes. The specificness of locations is aimed at reaching a fair amount of representativity of sites with comparable radiation accuracy transcending global climate zones, as elucidated in Section 2.2.7.2. The objective of revealing long-term trends reflects on the need for superior accuracy, since a trend is only visible once a "signal" is significantly discernible from "noise".

Objective 1.2

Any form of measurement is only as good as the procedures followed to attain it, like "a chain is only as strong as its weakest link". The establishment of standard operating procedures and their deployment, as far as practically possible in terms of procedures, cleaning, maintenance and calibration at all sites in the network, is a necessary condition towards producing data of comparable quality on a global scale.

One proven way to effectively ensure data and procedural uniformity in a truly global project, is the implementation of site audits. Site audits are successfully in operation in other WMO measurement endeavours such as GAW, where the Swiss Federal Laboratory for Materials Research and Testing (EMPA) is conducting regular site audits. This takes the form of data audits, as well as system performance audits, as described by Hofer *et al.* (1998) and WMO (2003).

In the BSRN context, however, the added value versus cost factor remains to be justified. Large amounts of travel and subsistence fees will have to be spent over a long period to drive this process, and a suitably qualified candidate is most likely involved in a number of research projects at his/her institution. The author suggests, that partnerships with other GAW institutions, sharing resources and expertise, can be formed to partially address this issue.

Objective 1.3

Simultaneous measurement of meteorological parameters at sites within a reasonable distance of the radiation measuring site, preferable on the same site, greatly improves the understanding of behaviour in radiation parameters.

The surface measurement of temperature and humidity aids in understanding the clear-sky LWD flux, whilst knowledge on aerosol loading improves the understanding of diffuse radiation. Knowledge on surface vegetation aids in quantifying surface albedo and associated radiation processes. Knowledge on surface and upper-air winds aids in trajectory modelling that can explain the transport to and existence of aerosol loading in a particular area. Ozone measurements complements measurement of UV readings, whilst knowledge on Precipitable Water Vapour (PWV) also enhances understanding of pressure, temperature and humidity of the upper-air profile as measured directly using balloon-tethered rawinsondes. The upper-air profile creates a three-dimensional picture of the atmosphere, which leads to the foundation of a Radiative Transfer Model (RTM) input. The said measurements are also input parameters to aid the modelling of global climate change.

Objective 1.4

The effective management of any dataset is vital towards the success of the associated measurement endeavour. Therefore, central responsibility with respect to data management must be assumed by a well-established institution and the data must be uniformly quality controlled, using the same procedures for all captured data. In the case of BSRN, this role is well assumed by the WRMC in ETHZ. This centre serves as the focal point from which queries with respect to the data can be answered, and effectively addresses the question of where data-ownership and the associated intellectual property resides.

Objective 2.1

One of the original aims of the BSRN programme at its inception was to serve as a measure for satellite ground truthing (WCRP-64, 1991). Remote sensing is the most effective and area-efficient way of surface-data collection in the SH since it has less land available for the deployment of terrestrial stations compared to the NH. However, remote sensors such as satellites, need a reliable ground measuring site which can serve as a reference. Another factor that must be taken into consideration, is that the characteristics of remote sensors change with time (WCRP-64, 1991), therefore, the satellite involvement with ground sites also has a dynamic and sustained character. The BSRN can determine, in a quantitative manner, specific parameters to characterize a site for satellite applications (albedo, clouds, aerosols), and in this way establish a sound partnership with the satellite community.

Objective 2.2

Representativeness of the measurements, in terms of usefulness to the satellite community, is also an important link in any measurement plan. In the case of De Aar, it was ascertained before assuming the site, that the surrounding geography ("Karoo-koppies") exhibits the most practically uniform land in the vicinity of a suitable site in South Africa (as discussed in Section 1.2.3) It can also be mentioned that, in order to validate the site for remote sensing measurements, in-situ measurements of surface reflectance over a large area should be comparable to one pixel of satellite imagery. Therefore the usefulness of De Aar as a satellite site is probably the best South Africa can offer.

Objective 2.3

The specific measurement of radiation in bands of the electromagnetic spectrum outside visible wavelengths is justified, since it is known that a small variability in solar output translates to significant changes in, for example, UV irradiance (Fröhlich, 1989). The involvement of special measurements is therefore another branch of BSRN having potential to serve additional needs. In the Southern African context, BSRN measurements of UV radiation can also link to the public UV irradiance awareness campaign of the SAWS since South Africa is one of the countries in the world that has exceptionally high UV irradiance exposure during the Austral summer.

Furthermore, cost-effective equipment and methods for the measurement of the spectral UV and IR radiation budget will contribute to the improvement of satellite algorithm design and validation of satellite SRB determinations.

Objective 2.4

Special emphasis is placed upon the deployment of sunphotometry and cloud-imaging by means of automatic video capturing and analysis. The influence of the erring human hand are increasingly excluded in routine observations in order to obtain the quality of observation required for measurements of high accuracy. Despite the automation of almost all weather measurements, the quantification and identification of cloud types in SYNOP and other observations were one of the parameters that was still measured manually. Recent developments now facilitate the recording of clouds automatically and in greater detail, using software analysis of video-captured images.

Objective 3.1

The specific referral to SRB standards is aimed towards being representative of rendering data for verification of remotely sensed quantities. Other institutions and projects involved in this effort are the Global Energy and Water Cycle Experiment (GEWEX), the European Centre for Medium Term Weather Forecast (ECMWF), the National Oceanic and Atmospheric Administration (NOAA), as well as a variety of local and regional radiation climatologies with the potential of many applications (Dutton, 2002). Modern remote sensing is capable of accurately sensing downwelling quantities.

Objective 3.2

As mentioned in Objective 2.4, cloud studies can now be automated. Therefore digital ways of comparing cloud properties and radiation numbers can lead to the better understanding of how especially broken and inhomogeneous clouds influence the micro-climate.

2.2 ASPECTS OF THE SCIENTIFIC PLAN

2.2.1 Data sampling rate

The uniform standard format of BSRN measurements, is one-second samples of each quantity, summarized and archived every minute as the average, standard deviation, minimum and maximum of all the samples for that particular minute (WCRP-54, 1991;

WCRP-64, 1991). The decision for 1 Hz sampling was based upon the $1/e$ response time for first-class instruments. The ratio $1/e$ constant for a given radiometer is the time necessary for the radiometer output to become equal to $1/e$ = 1/2.718 = 0.368 of the initial input value. In first-class radiometers it is close to one second, therefore, 1 Hz- samples are an attempt not to misrepresent any feature in radiation fluxes (Ohmura *et al.*, 1998).

The logical unit of data submission to the central data centre in Zürich is one month. In that monthly report, the radiation data are reported in the said quantities per minute. The time-frame (being an international network) is Universal Time (UT) for all measurements (no daylight savings are incorporated).

2.2.2 Accuracy

Since the Würzburg meeting, certain radiometric accuracy targets were set. It was hoped that with improved observational techniques and deeper research, those targets would be met. Table 2.1 reflects the evolution of these BSRN targets through the years.

Table 2.1 *Evolution of target radiometric accuracy in BSRN. Values in W.m^{-2}*

Quantity	1	2	3	4
Direct radiation	2	-	2	2
Diffuse radiation	5	10	5	5
Global radiation	5	15	5	5
Reflected SW radiation	-	15	-	-
Downwelling LW radiation	20	30	10	10
Upwelling LW radiation	-	30	-	-

Key to columns of Table 2.1:

1. Initial excpected accuracy as deemed necessary by satellite and model communities (Morel,1990).

2. First refinement (WCRP-54) in March 1991.

3. Second refinement (WCRP-64) in November 1991.

4. Achieved in 1995 (Ohmura *et al.*, 1998, Mc Arthur, 1998) and based upon uncertainty estimates for best-known practices in calibration and quality control at existing BSRN sites. The numbers are expected acceptable maximum deviations from the "true" measured values in Watts per square metre (W.m^{-2}). The deviations are expressed as the uncertainty from the true value for a 1-minute average over an ensemble of 1Hz measurements (Ohmura *et al.*, 1998).

Discussion of Table 2.1 in terms of each measurement quantity:

2.2.2.1 Direct radiation

The target accuracy for direct radiation is 2 W.m^{-2} – therefore the most accurate radiometer, a cavity, (Figure 2.4), needs to feature in the measurements. However, this poses a challenge to BSRN for two reasons:

- A cavity radiometer samples once roughly every 1 to 3 minutes when in full operation (WRC, 2001), while the BSRN requires one-second samples on a continuous basis.

- For operation in all weather conditions, protection is needed. The delicate inner parts need to be protected from rain. Wind protection is also needed to preserve the thermal properties of the radiometer. However, this protection (typically a window) is known to absorb significant portions of the solar spectrum (discussed in Section 3.1.1.2). The presence of a window therefore limits the radiometer in terms of desired accuracy.

To resolve these issues, simultaneous operation of a thermopile pyrheliometer (Figure 2.5), together with the cavity radiometer was recommended by Mc Arthur (1998). This is expected to take the form of parallel measurements. While the thermopile samples at 1 Hz, the cavity takes measurements as often as practically possible (1 to 3 minutes).

A further recommendation is, that the pyrheliometer has a body temperature sensor in order to compensate for thermal offsets that may be experienced by the thermopile. The pyrheliometer and cavity radiometer ideally forms part of a tracker system, which makes use of a quadrant sensor to actively point the radiometers towards the sun.

2.2.2.2 Global radiation

Global radiation is measured with an unshaded pyranometer (Figure 2.6), preferably on a fixed stand, to allow for minimum distortion of azimuthal errors induced if mounted on a horizontally rotating tracker platform. Target accuracy is also 2 $W.m^{-2}$ - though a number of factors lead to uncertainties in the measurement. These factors include non-linear output of the sensor, uneven response of the thermopile, the cosine error, as described in Section 3.1.2.2, and thermopile thermal offsets, as discussed in Section 3.1.2.3. The standard BSRN one-minute statistics reported are derived from 1 Hz samples taken on a continuous basis. The pyranometer is recommended to be perpetually ventilated and to have a body temperature sensor to compensate for thermal offsets not covered by the ventilation.

2.2.2.3 Diffuse radiation

The target accuracy of diffuse radiation is 4 $W.m^{-2}$. This is less strict than the direct and global components since additional factors impact on the measurement accuracy. These factors are: unevenness of the solar occultation (shading), uneven balance of the radiometer resulting from unsteadiness of the solar tracker table and uneven azimuthal responses of the radiometer due to a horizontally revolving tracker table. Diffuse radiation is measured by means of a shaded pyranometer, preferably identical to the global irradiance pyranometer. The pyranometer should also be ventilated to minimize thermal offsets, and a body temperature sensor should be present in order to attempt to correct recorded data for thermal offsets.

2.2.2.4 Reflected SW radiation

A pyranometer, mounted on a tall structure and facing downwards, is recommended. This pyranometer should be treated in any other respect like a global pyranometer, except for a shielding plate to block direct radiation at very low solar elevation angles. A minimum height of 30 metres is recommended to yield a representative view of the surroundings.

2.2.2.5 Downwelling LW radiation

Target accuracy for downwelling LW radiation is the lowest for basic quantities: 10 $W.m^{-2}$.

This accuracy is believed to be improved (Philipona *et al.*, 2001) by Swiss modification of the pyrgeometer instrument, where the dome temperature is measured on more than one spot. (Philipona, 1995). The quantities associated with long-wave radiation, are (a) output from the thermopile, (b) body temperature, and (c) dome temperature. The one-minute statistics of LW irradiance are compiled from 1 Hz samples. However, a few practical challenges lead to the calculation of the LW irradiance using the logger's internal programming. Such a programme requires extensive coding and can only be executed in the course of two to three seconds, rendering the frequency of sampling less than 1 Hz. The pyrgeometer must also be ventilated (Van Lammeren and Hulshof, 1994) and shaded continuously (Section 3.1.3). The reported parameters towards WRMC are one-minute statistics of LW irradiance only.

2.2.2.6 Upwelling LW radiation

The instrument and operational procedure to measure upwelling LW radiation is identical to the one for downwelling LW radiation, except that it is facing downward and supported by a similar structure to the description in Section 2.2.2.4.

2.2.2.7 Ancillary measurements

Surface meteorological parameters are needed to add value to the understanding of surface fluxes of especially the LW portion of the electromagnetic spectrum. They are (a) Stevenson screen temperature, (b) relative humidity and (c) pressure. These quantities are measured, at the same height from ground level as the LW instrument. The standard WMO meteorological instrument height is 1.2 metres (Meteorological Office, 1982).

2.2.3 Data acquisition

Time accuracy should be of highest quality. Mc Arthur (1998) recommended that it to be less than 1% of the averaging period (in the BSRN case less than 1 second). Data needs to be acquired in the most economical format possible, as far as space restrictions on the logging devices and the required number of significant figures for accuracy are concerned (discussed in Section 3.1.6).

2.2.4 Calibration

Accurate calibration is a critical component of any radiometric system (Asmus and Grant, 1999). In wide terms, calibration of an instrument is performed when a reliable reference instrument is operated side by side with the site's operational instrument. The reference instrument has traceability to a world standard, and the resultant deviations from the site operational instrument output, with respect to the standard, are used to rectify the field instrument sensitivity (Reda, 1996) and possibly retrospectively recalculate recorded data from the field instrument (discussed in Section 3.2.2).

2.2.5 Data management

Effective data management is a vital link between data acquisition and submission to the international database. This process is ideally performed by the site scientist, since this person is involved in the entire station operation and is therefore in the best position to judge the validity of any given set or subset of data. The De Aar data management is described in more detail in Section 3.3.

2.2.6 International database

Communication to the international database is established using fixed formats and established protocols, detailed in Appendix B. For data submission, FTP channels to WRMC at ETHZ in Zürich were established. Upon completion of a dataset and subsequent submission to WRMC, the datafile is handled in a way prescribed by the database, details of which are referred to in Section 3.4.2.

2.2.7 Site selection criteria

Selection of suitable sites, addressing the necessary criteria, is also critical for the functioning of a global network, such as the BSRN. Criteria for site selection, as formulated after the Würzburg meeting (De Luisi, 1989) are outlined in the following two sections, viz. Section 2.2.7.1 and Section 2.2.7.2.

2.2.7.1 Satellite measurements

Geographical locations most suitable for satellite validation algorithms were proposed by Schiffer (1990) and Mc Arthur (1998), and are listed in Table 2.2.

Table 2.2 *Site evaluation criteria based upon a selection of desirable surface/atmospheric characteristics and satellite algorithm comparisons*

Characteristic	Locations representing	Example location
Radiation field values	Large variability in synoptic and seasonal time 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 dependance on orbit, viewing angle, overlap regions	Spitzbergen, Norway
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 climatic 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 at Boulder, Colorado, USA
Calibration	Locations possessing relatively uniform and high surface reflectance properties for satellite calibrations	Prairie, Amazon basin

Surface radiation flux information, disseminated at a spatial resolution suitable for climate research, especially over oceans, is presently obtained from satellites. However, there is evidence in the literature, that satellite measurements are in “acute” need for ground-truthing (Whitlock *et al.*, 1995; Pinker *et al.*, 1995; also quoted by Ohmura *et al.*, 1998). The analysis under discussion by these authors was specifically performed over the African continent where little snow is expected. Yet there were systematic differences in albedo measurements, despite the fact that it was expected that the improved algorithm should at least make a distinction between snow and clouds. These inconclusive results indicated that more reliable remotely sensed information is needed, in which BSRN data may be of significant value.

2.2.7.2 Climate zones

Application of the Köppen climate zone criteria (described in Appendix D) shows how the evolution of the network continued to cover climate zones in a fair and representative way.

Table 2.3 *Evolution of the BSRN climate zone representation*

Group of stations	**Climate zone (A to E)**					**Total**
	A	**B**	**C**	**D**	**E**	
Pioneer group of 1992	Bermuda (Af) Kwajalein (Aw)	Boulder (BS)	Payerne (Cfb)		Ny Alesund (ET) Barrow (ET) Neumayer (EF) South Pole (EF)	**8**
Group up to 1996			Carpentras (Cs) Billings (Cfa) Tateno (Cfa)	Regina (Dfb)		**4**
Group up to 1998	Ilorin (Aw)	Sede Boqer (BW) Alice Springs (BW) De Aar (BS)	Florianopolis (Cwa) Lindenberg (Cfb)	Toravere (Dfc)	Syowa (EF)	**8**
Additions up to 2003	SGP1 (Am) Manus (Aw) Nauru (Am)	Tamanrasset (BW) Boulder SURFRAD (BS) Desert Rock (BW)	Lauder (Cfa) Penn State (Cfa) Goodwin Creek (Cfb)	Fort Peck (Dfb) Bondville (Dfb)		**11**
Total	**6**	**7**	**9**	**4**	**5**	**31**

In Table 2.3, the active BSRN sites up to 2003 are classified into the five main climate zones, and it is also shown how this classification came about by considering the network evolution since 1992. It shows that the total number of stations per climate zone represents a fair distribution. Keep in mind that *not* all provisional sites as described in Chapter 1 eventually became active.

This Section concludes elucidation of aspects of the scientific plan. The measurement plan can best be described, if specific information regarding radiation processes in the atmosphere are first exposed. Hence, in the next Section, a basic introduction to radiation in the atmosphere leads to a discussion of measurement techniques and associated instrumentation.

2.3 RADIATION

Planck's Equation expresses electromagnetic radiation emitted by a black body (irradiance) as a function of temperature and wavelength (Iqbal, 1983):

$$E = \frac{2hc^2}{\lambda^5} * \frac{1}{e^{hc/\lambda\kappa T} - 1} \tag{2.1}$$

where

E = Radiant energy flux density from a radiation source (W.m^{-2})

T = Absolute temperature of the source (K)

h = Planck's constant (6.62 x 10^{-34} J.s^{-1})

c = Speed of light in vacuum (3 x 10^{8} m.s^{-1})

κ = Stefan-Bolzmann's constant in specific corresponding units (1.38 x 10^{-23} J.m^{-2}.K^{-1})

λ = Wavelength (m)

In a meteorological context, Equation 2.1 may be applied to two sources of significance. They are the Sun as the primary source of radiation (solar radiation) and the Earth as a secondary source (terrestrial radiation). Figure 2.1 features graphs of E versus λ using the assumed mean temperatures of the two sources, (Sun: 5800K and Earth: 288K, respectively).

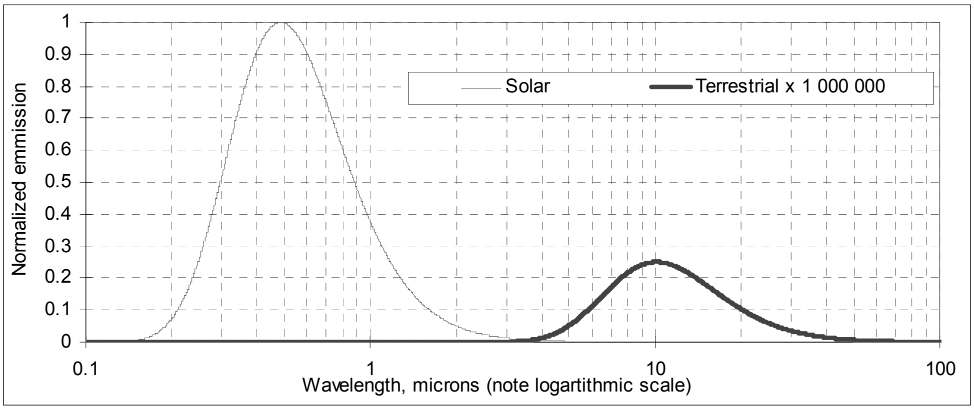

Figure 2.1 *Normalized emission (E) versus wavelength (λ) plots of Planck's Equation (2.1) for both solar and terrestrial radiation. Thin black line: Solar radiation, thick black line: Terrestrial radiation*

Discussion of Figure 2.1:

- For all practical terms, solar (SW) and terrestrial (LW) radiation occupy discrete portions of the electromagnetic spectrum. The overlap between the two spectra is small - about 1 part in 4 x 10^4 of the area under the SW portion of Figure 2.1. Therefore, no ambiguity should exist between reference to SW or LW radiation. According to Kondratyev (1972), wavelengths larger than 3.5 µm occupy about 0.9 % of the radiant energy in the extraterrestrial solar spectrum.

- SW radiation peaks at 0.5 µm while LW peaks at 10 µm. These numbers (λ_{max}) are confirmed by Wien's displacement law, denoting radiation peaks as a function of absolute temperature only ($\lambda_{max} = 2897 / T$), with λ in µm and T in Kelvin.

- The relative magnitude of LW radiation is several orders of magnitude less than that of SW radiation. In real terms, the two radiation peaks in Figure 2.1 have a ratio of 1 to 4 million (4 x 10^6).

2.3.1 Radiation in the atmosphere

A beam of incident solar radiation entering the atmosphere, is scattered in all directions (vertically and horizontally) by clouds and other particles, as it traverses the atmosphere. A part of the beam is reflected by clouds and absorbed by atmospheric constituents, such as water vapour (H_2O), oxygen (O_2) and ozone (O_3). The respite (remainder) of this beam reaches the surface of the Earth, where it is either reflected or absorbed (Figure 2.2).

The reflected beam traverses the atmosphere a second time and hence experience the same absorption and scattering for a second time. Since atmospheric pressure (and therefore absorbing gases) has a maximum closest to the Earth's surface, the lower part of the atmosphere absorbs the largest portion of incident, as well as reflected SW radiation. This absorbed energy is re-radiated as LW radiation in all directions, partially contributing to the Earth's greenhouse effect.

The solar radiation not taken up by sensible heating of the Earth's surface, adjacent atmosphere and latent heat of evaporation, is absorbed by the surface of the Earth and re-radiated as LW radiation, where the Earth serves as a secondary source. The emitted LW radiation is absorbed (more efficiently than SW radiation) by the atmosphere as it leaves the surface of the Earth. However, not all outgoing LW radiation is absorbed, only the portion within the “atmospheric window” (8 µm to 11 µm) – (Bunskoek *et al.*, 1998).

The re-absorbed LW radiation is subsequently re-radiated again in all directions, including back towards the surface of the Earth, causing a counter-effect. This counter-radiation is also responsible for the Earth’s greenhouse effect, maintaining the surface and lower atmosphere of the Earth at a much higher temperature than would be the case for an Earth without an atmosphere.

2.3.2 The greenhouse effect

Consider the sun as an isotropic (omni-directional) source of radiation that has an energy flux of S_0 = 3.877 x 10^{26} W. Next, consider the Earth as an object at an annual mean distance of one astronomical unit AU = 1.5 x 10^{11} m intercepting a fraction of the solar radiation equal to the projected fraction area of the Earth in its orbit around the sun, when seen as a sphere of radius A. The radiation reaching the Earth at the Top Of Atmosphere (TOA), as an annual mean value, is now equal to

$$\begin{aligned} E \quad &= S_0 / 4\pi.(AU)^2 \\ &= 3.877 \times 10^{26}\ \mathrm{W} / (4\pi * (1.5 \times 10^{11}\ \mathrm{m})^2) \\ &= 1371\ \mathrm{W.m^{-2}} \end{aligned}$$

The calculated value (1371 $\mathrm{W.m^{-2}}$) for E equals the widely used annual average value of extra-terrestrial solar radiation, known as the *solar constant*, exhibiting a ± 3 % variation through the course of one year under the influence of varying Sun-Earth distance.

Note that S_0, the radiant energy flux of the sun, has internal variations due to solar sunspot cycles. Although there is a discernible cycle of 11 years in sunspot activity on the solar surface, its influence on the actual value of the solar constant is negligible - about 0.07 % between the minimum and maximum irradiance measured as a result of sunspot activity (Fröhlich, 1989).

Consider now that the Earth absorbs a portion of this radiation (incoming flux) and re-radiates it (outgoing flux), and that the Earth is in radiative equilibrium. This is not an exact assumption, but to disregard imbalances over time periods shorter than one year due to seasonality, assume this happens over the time-span of several years.

The incoming flux depends upon the absorbed fraction intercepted on the projected area of a sphere with the size of the Earth. The projected area is a disk of radius R_E, while the absorbed portion equals the remainder not reflected as a result of the planetary albedo. Hence

$$\textit{Incoming flux} = S\,.\,(1-\alpha).\ \pi R_E^2 \qquad (2.2\text{ a})$$

where

α = Planetary albedo, estimated at 0.3

S = Solar constant, 1379 $W.m^{-2}$

The outgoing flux consists of all the absorbed radiation re-radiated from the entire surface of a sphere (Earth) of radius R_E. Hence

$$\textit{Outgoing flux} = E_{OLR}\,.\ 4\pi R_E^2 \qquad (2.2.\text{b})$$

where

E_{OLR} = Outgoing Longwave Radiation (OLR) flux per unit area.

If

$$\begin{aligned} \textit{Incoming flux} &= \textit{Outgoing flux} \\ S.(1-\alpha).\pi R_E^2 &= E.4\pi R_E^2 \end{aligned}$$

which re-arranges to

$$\begin{aligned} E_{OLR} &= (1-\alpha) * (S/4) \\ &= (1-0.3) * (1379/4) \\ &= \underline{241\ W.m^{-2}} \end{aligned}$$

Applying Stefan-Bolzmann's law to equate this energy per unit area flux to a temperature T, assuming the Earth is a blackbody, leads to

$$E_{OLR} = \sigma T^4$$

and therefore

$$\begin{aligned} T &= (241/\sigma)^{1/4} \\ &= 255\text{ K} = \underline{-18\ ^\circ C} \end{aligned}$$

This means, that the Earth, when viewed in pure theoretical terms, should have an *average* annual temperature of -18°C. This is the *average* Earth blackbody temperature as seen from space.

However, the mean surface temperature, as measured on the Earth, is 288 K, or +15°C. The 33°C difference is directly attributed to the greenhouse effect, whereby atmospheric constituents render the atmosphere opaque to long-wave radiation leaving the Earth's surface. The opaqueness of the atmosphere is mostly due to the presence of gases, such as water vapour (H_2O), oxygen (O_2) and carbon dioxide (CO_2).

2.3.3 Radiation fluxes on Earth

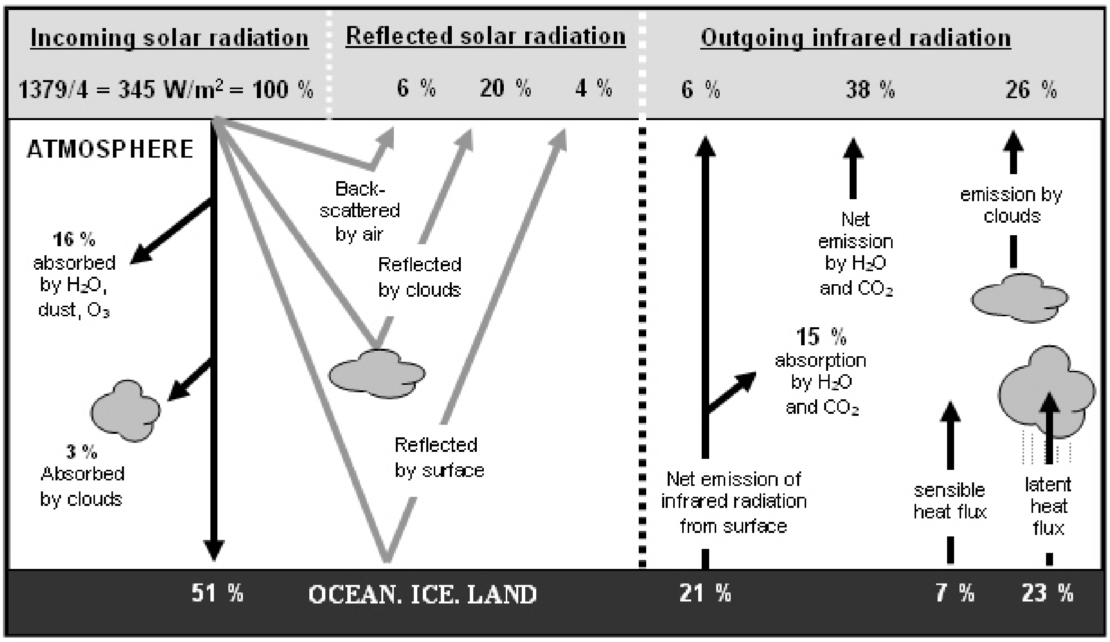

Figure 2.2 *Schematic representation of radiative fluxes in the atmosphere (after Wallace and Hobbs, 1977). The primary short-wave radiation component is direct solar radiation (left panel), while diffuse radiation is composed of scattered radiation by clouds and aerosol particles in the air (right panel). For an observer on the ground, global radiation is the sum of the diffuse and direct components. The reflected short-wave radiation is the portion not absorbed by Earth-atmosphere system (30% or albedo = 0.3). Long-wave radiation emitted by the Earth is partially absorbed by the atmosphere and re-radiated to the Earth-atmosphere system.*

Any observer on the surface of the Earth facing the sky, will experience a variety of energy fluxes, summarized and quantified in Figure 2.2 (Wallace and Hobbs, 1977), and described in the following short paragraphs.

- Downwelling SW radiation is a combination of direct (beam) and diffuse (scattered in all directions, therefore indirect), collectively known as global radiation.

- Upwelling SW radiation represents reflected radiation, dependent upon the reflectivity (surface albedo) of the Earth's surface. Surface albedo is a function of surface characteristics (soil and vegetation type, water, ice, etc.) and is defined as the ratio of reflected radiation to incoming radiation.

- Downwelling LW radiation is counter-radiation in the atmosphere, as LW radiation leaving the Earth's surface is absorbed and re-radiated in all directions, including downwards. It also includes a small portion of extraterrestrial solar radiation within the LW spectrum.

- Upwelling LW radiation is terrestrial radiation not absorbed by the atmosphere, plus the portion radiated upwards by the lower atmosphere.

Clear skies (free from scattering clouds and with few aerosols) is known to transmit a large percentage of the solar beam and therefore exhibits a relatively small amount of diffuse radiation at the surface, while a partly cloudy sky and / or more turbid sky has progressively more diffuse radiation as the cloudiness and / or turbidity increases (Long and Ackerman, 2000). An overcast sky transmits little or no direct radiation and almost all radiation reaching the surface is then diffuse.

2.4 MEASURING RADIATIVE FLUXES

Radiant energy dE arriving from the solar surface at the Earth, may be expressed (Seckmeyer *et al.*, 2001) as follows:

$$E_{SW} = \frac{dQ}{dt dA d\lambda} \qquad (2.3)$$

where

E_{SW} = SW radiative flux density for an observer on Earth

Q = Radiative flux from the surface of the sun, arriving at the TOA

t = Time interval

A = Unit area

λ = Wavelength

The individual components such as global, direct or diffuse components are redefined from the definition of Q in Equation 2.3 using appropriate restrictions such as

- Direct radiation: limit the field of view as to include only the solar disk
- Diffuse radiation: including all except the solar disk
- Global radiation: the entire field of view

As far as LW radiation is concerned, it may be regarded as emanating from a grey body (i.e., not an entirely "black" body) at temperature T with emmissivity ε:

$$E_{LW} = \varepsilon\sigma T^4 \qquad (2.4)$$

where

E_{LW} = LW radiative flux density for an observer on Earth

ε = Atmospheric emmissivity (the "greyness" of the radiating object)

σ = Stefan-Bolzmann constant

T = Absolute effective temperature of radiating atmosphere

In order to measure radiation flux densities as described in Section 2.3.3, instrumentation needs to respond positively, exclusively, predictably and unambiguously to radiation input signals. The measurement of radiative flux density requires that flux density be measured from a certain solid angle, within a certain spectral range and with a certain spectral response (Kipp and Zonen, 1997a). The entire celestial dome (sky) irradiates towards the Earth from a solid angle of 2π sterradians. A physical instrument having a field of view facing the celestial dome, therefore receives radiation represented by the integral of radiation elements across its entire field of view. Therefore it has to be perfectly aligned with the horizon (i.e., radiometrically levelled) so that the instrument's field of view co-incides with the radiation source.

Quantifying the energy incident on a plane surface is a difficult field exercise, since it involves a series of conversion processes. Incident solar energy is converted into thermal energy, which is converted to electrical energy (NREL, 1993) that can be measured by a millivoltmeter. One such device is the thermopile - the heart of the most types of modern radiation instruments (described in Section 2.5.1).

From Section 2.3.3, the following surface radiative fluxes are measurable quantities:

- Downwelling SW: Direct solar beam radiation
- Downwelling SW: Global solar radiation
- Downwelling SW: Diffuse solar (sky) radiation
- Upwelling SW: Reflected solar radiation
- Downwelling LW: Terrestrial sky radiation
- Upwelling LW: Terrestrial earth radiation

In order to qualify as a BSRN site, it was decided that the measurement of all downwelling quantities must be undertaken, in a specific frequency as listed in Table 2.4(a).

Table 2.4 (a) *Basic radiation measurement parameters at BSRN stations*

Quantity	Unit	Reporting resolution	Sampling interval	Reporting interval
Global radiation	$W.m^{-2}$	1	1 sec	1 min
Direct radiation	$W.m^{-2}$	1	1 sec	1 min
Diffuse radiation	$W.m^{-2}$	1	1 sec	1 min
Downward LW radiation	$W.m^{-2}$	1	1 sec	1 min

Another set, listed in Table 2.4(b), of non-radiation quantities to increase understanding of the measured radiation quantities is also a pre-requisite for a site to qualify as a BSRN station (Hegner *et al.*, 1998).

Table 2.4 (b) *Basic non-radiation measurement parameters at BSRN stations*

Quantity	Unit	Reporting resolution	Sampling interval	Reporting interval
Air temp at long-wave instrument height	°C	0.1	-	1 min
Relative humidity at long-wave instrument height	%	0.1	-	1 min
Pressure at long-wave instrument height	hPa	1	-	1 min
Meteorological SYNOP observations	various	-	-	hourly
Upper-air rawinsonde meteorological balloon observations	various	-	-	daily

These basic measurements are not the only measurement efforts that sites should embark upon. The *expanded* programme of BSRN allows sites to measure one or more of the parameters listed in Table 2.5, to both serve as checks and balances for related basic BSRN quantities, but also to aid as en enrichment of existing data in future research.

Table 2.5 *Extended measurement parameters at BSRN stations*

Quantity
Direct SW radiation at WMO wavelengths (368nm, 500nm, 778 nm) and specified bandwidths
Cloud amount and type – if possible by video camera imaging
Vertical distribution of temperature and water vapour (lidar), cloud-base height and aerosol
Precepitable water measured with microwave radiometer, or newly developed GPS techniques
Ozone (total column amount using Dobson spectrophotometer and/or vertical distribution using ozone-sounding or Dobson Umkehr technique)
Reflected (upwelling) SW radiation from a tall tower
Upwelling LW radiation from a tall tower
Thermal spectral infrared radiation
Hemispherical total solar spectral irradiance
Spectral albedo measurements

2.5 INSTRUMENTATION

2.5.1 A vital component: Thermopile

The basic radiation-sensing element of a modern non-photovoltaic radiometer, as used at BSRN stations, is a thermopile. All four sensors that measure basic quantities at BSRN stations have thermopile sensing elements.

A thermopile (Figure 2.3) is an array of several thermocouples and makes use of the Seebeck effect, discovered in 1821 by Thomas Seebeck. When thin strips of two dissimilar metals, such as bismuth and copper, are connected on one end, but not the other, a small electric potential is detected when the temperature is raised at one open end (“hot” end) with respect to ambient temperature.

While one open end ("cold" end) is maintained at ambient temperature by embedding it in a metallic body with large thermal inertia, the other, "hot" end, is exposed to solar radiation and allowed to rise in temperature[1]. In a thermopile, a larger effective area is created by joining the "hot" junctions thermally. The effect is further enhanced by covering it with black, allowing for the absorption of as much incident radiation as possible.

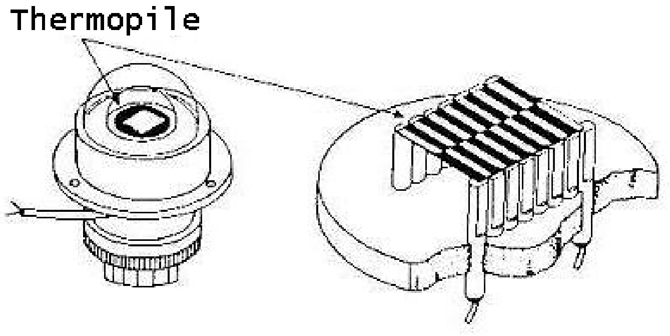

Figure 2.3 *A typical thermopile's position in a radiometer (left) and from closer up (right). The "hot" junctions are situated in the middle line between the two rows of spindles, housing the "cold" junctions firmly anchored in the radiometer body.*

Credit for the idea of combining several thermocouples into one thermopile goes to the Italian physicist Macedonio Melloni (1798-1854), who first constructed a thermopile for use in thermal radiation research. Later, his idea was developed by the Dutch professor Dr W.J.H. Moll (1876-1947) who introduced a more sensitive thermopile, which he used in his studies on infrared radiation based on W.C. Röntgen's research (the discoverer of X-rays). In 1924, the Polish meteorologist L. Gorczynski adapted the method even further to make the first pyranometer (Van Cittert-Eymers, 1979). In 1927, the first Moll-Gorczynsky pyranometers were in full production at the Kipp & Zonen factory in Delft, Netherlands.

Incident solar or terrestrial radiation raises the temperature of the "hot" end of the thermopile to produce an electric potential with respect to the "cold" junctions. This potential is directly proportional to the incident irradiance, and the proportionality, known as the calibration constant, a direct indication of the radiometer's sensitivity. These numbers range typically from about 5 $mV.K^{-1}.W.m^{-2}$ to 15 $mV.K^{-1}.W.m^{-2}$ in SW radiometers and about 4 $mV.K^{-1}.W.m^{-2}$ in LW radiometers.

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[1] http://physics.kenyon.edu/EarlyApparatus/Thermodynamics/Differential_Thermopile/Differential_Thermopile.html

A thermopile has the following positive characteristics:

- Low impedance, thereby making the associated circuitry (such as data acquisition systems, e.g., data loggers) less susceptible to extraneous radiation and electrical noise[2].

- Spectral response in general is "flat", i.e., its response is very close to uniform throughout the spectral range in which it is sensitive and outside – 0.1 µm to 50 µm. (Kipp & Zonen, 1997b). This means that the relative intensity of an amount of measured SW radiation with respect to an amount of LW radiation would be the same for practical purposes between two different instruments. The latter is particularly important when calibrations are done.

- Sensitive to a wide range of electromagnetic radiation in general (typically including both SW and LW), making it versatile. If only sensitivity for a specific wavelength band is required, selectively transmitting domes are usually utilized.

2.5.2 Measuring direct radiation

Direct radiation forms the basis for SW radiation measurements since it has the least uncertainty of the basic BSRN irradiance quantities (Ohmura *et al.*, 1998). The instrument used for direct radiation measurements is known as a pyrheliometer. In this discussion two types are highlighted:

- Absolute cavity radiometer

- Thermopile pyrheliometer

Both instruments need to be pointed continually towards the sun in order to operate correctly, in other words, a method of continuous solar tracking needs to be applied.

The word *pyheliometer* comes from the Greek words *πυρ* (fire), *ηελιοσ* (sun) and *μετρον* (measure) – signifying "that which measures fire coming from the sun" (Dominguez, 2001). Therefore, the pyrheliometer measures radiation emanating from the sun.

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[2] http://www.fuji-piezo.com/Thermopile.htm

The International Pyrheliometric Comparison (IPC) events, which are regularly held (normally every 5 years) at the World Radiation Centre (WRC) in Davos, Switzerland, attract various standard pyrheliometers from participating countries. Instruments like the Eppley self-calibrating AHF, that is deployed at the BSRN site at De Aar (Figure 2.4), participated directly in three of the recent IPC events, i.e., 1980, 1985 and 1990 (Eplab, 1997). Furthermore, one such unit is a member of the World Standard Group (WSG).

The WSG is a group of seven carefully characterized reference cavity pyrheliometers held at WRC and used to define the WRR. These instruments are calibrated once a year to ensure stability (WMO, 1983) and must have a long-term stability of less than 0.2 %, as well as a precision better than the WRR, which is 0.3%. During IPC events, invited radiometers are compared to the WRR, using the sun as source and those radiometers then have direct traceability to the WSG (WRC, 2001).

Since the invention of pyrheliometers, the WRR underwent slight changes, as the scientific understanding and analysis techniques have improved. The current reference is just known as WRR, valid since 1 July 1980. The names, dates and relative magnitude (SAWB, 1959 and WMO, 1983) of the previous radiometric references are:-

- Angström scale (1905) = WRR / 1.026
- Smithsonian scale (1913) = WRR / 0.977
- International Pyrheliometric Scale (1956) = WRR / 1.022

2.5.2.1 The cavity radiometer

The cavity radiometer is considered to be a standard pyrheliometer – i.e. an instrument used by national solar radiation networks to standardize instruments deployed in routine measurements.

It works on the principle that electrical substitution in a specific cavity equals incident solar energy. Incident solar energy heats up a specially prepared cavity in a black tube known to have almost perfect emmissivity, through an aperture. When temperature equilibrium (which is accurately noted) is reached, the aperture is closed and heaters in the cavity are switched on, until the original noted temperature is reached. Power (P) of the heater can be accurately measured and noted by using the relationship $P = V.I$, where V and I are the potential difference and current through the heating element, respectively. The aperture is then opened again and the process repeated. All of these functions can be done by manual controls on the control box, or automatically, and logged to a PC. (Hickey and Nelson, 1993).

Figure 2.4 *An Eppley AHF absolute cavity radiometer with control box*

Absolute cavity instruments are developed from first principles (Foukal, 1985), and are therefore the basis of radiometric measurements at a specific station or group of stations in a region. The drive in earlier BSRN years was therefore, to use cavity radiometers as primary routine sampling instruments, but it has shifted over the years more towards the cavity radiometers fulfilling the role of supportive instruments for operational pyrheliometers, operating in parallel at the most (Mc Arthur, 1998).

Arguments for and against using this instrument routinely, were discussed in Section 2.2.2.1.

2.5.2.2 The thermopile pyrheliometer

This aluminium tubular instrument (Figure 2.5) only has a very accurately levelled thermopile sensor at the back of the tube. It is characterized in such a way that its mV output is proportional to solar input (Kipp & Zonen, 1997a)

It has two sights in the form of small holes perfectly aligned with the field of view enabling accurate alignment with the solar beam. An Infrasil-1 quartz window in front protects the delicate interior from rain and dust and compensation is made for the “lost” radiation due to the presence of the window during calibration. The window is transmissible for wavelengths within the solar spectrum excluding IR. Desiccant at the back keeps the interior free from moisture condensation and subsequent corrosion (Kipp & Zonen, 1997a).

Figure 2.5 *A Kipp & Zonen CH1 pyrheliometer. 1,2= beam sights, 3= quartz window, 4= (behind) desiccant gel*

The instrument's field of view is set at 5°. The apparent solar disk size is 0.5°, varying slightly inter-annually as the Sun-Earth distance changes. The remaining 4.5° allows for small solar tracker errors plus a certain amount of circumsolar radiation. In effect, a small area of the atmosphere around the Sun (solar aureole) is also in the field of view, sometimes causing errors in situations of low solar angle.

The field of view of such a pyrheliometer is also expected to be equal or at least closely comparable to the viewing area of the diffuse pyranometer occulted out by the disk, so that direct comparisons between direct, global and diffuse components can be made, for example, in the quality control tests described in Section 4.3.3.3 and 4.3.3.4.

2.5.3 Measuring diffuse radiation

A diffusometer is a conventional pyranometer with a shading device, usually connected to a tracker that continually blocks the direct solar beam from the pyranometer's field of view. A diffusometer is thus continually exposed to all of the diffuse radiation of the celestial dome.

The word *pyranometer* comes from the Greek words *πυρ* (fire), *ανα* (up) and *μετρον* (measure) – signifying "that which measures fire coming from above" (Dominguez, 2001). Therefore, the pyranometer measures radiation emanating from the sky.

A pyranometer (Figure 2.6), has a thermopile, covered by a double dome made of the same infrasil-1quartz, as the window of the CH1, and includes transmissibility for meteorological wavelengths, i.e., 0.3 µm to 28 µm (Van Lammeren and Hulshof, 1994). The reason for a double dome is for protection of the delicate thermopile, for insulation against environmental temperature shocks, and it serves as a shield that prevents radiation losses to the environment in cloudless conditions - a 'cold' sky (Campbell, 2001). The housing (body) is covered by a white cap, in order to shield the instrument metal body from excessive direct SW solar heating and subsequent false signals such as thermal offsets, described in more detail in Section 3.1.2.3. A desiccant plug keeps the instrument interior free from moisture and prevents rusting.

Figure 2.6 *A Kipp & Zonen CM21 pyranometer. 1= inner quartz dome, 2= outer quartz dome, 3= bevelled protective shield, 4= dessicant, 5= leveling bubble, 6= levelling screws*

The diffuse quantity is second in line with respect to the relative uncertainty for BSRN measurements (Ohmura *et al.*, 1998). There are specific reasons for this:

- The diffuse radiation quantity is small compared to direct, especially under clear-sky conditions. A low relative error results in a small absolute error.
- The diffusometer signal is the result of a 2π-steradian response - therefore the possible effect of "weak" or "strong" spots on the thermopile element are masked.
- The masking effect also reduces the impact of less-than-perfect levelling of the diffuse pyranometer.

The diffusometer shading is established either by means of a shading sphere, or a shading ring. Ideally a shading sphere, having the same field of view than the associated pyrheliometer on site, is used. If a shading sphere is chosen, some form of solar tracking is needed to cover the diffuse pyranometer dome continuously as the sun is "moving".

A shading ring is employed at sites where a tracking device is not available. The ring is set up with its centre line tangent to the earth, parallel to the celestial equator and facing away from the nearest pole, inclined at an angle equal to the site's latitude. The ring casts a shadow on the diffuse pyranometer dome for an entire day without the need for solar tracking. The only adjustment needed from time to time is compensations for the solar declination, which cycles between extremes at the solar solstices. However, this ring also blocks a significant portion of the diffuse radiation, and a correction factor involving solar declination and estimated cloud cover needs to be applied (Batlles, 1995).

2.5.4 Measuring global radiation

Global radiation is measured by the same pyranometer used for measuring diffuse radiation, the only difference being that it is unshaded. The poor uncertainty of measurements taken by a single pyranometer is due to its poor directional response. The pyranometer is also more sensitive towards tilting errors, as opposed to the diffusometer. In the BSRN, the more accurate quantity of global irradiance (Dominquez, 2001) is derived from combining the diffuse and normal direct radiation components using Equation 2.5:

$$global(t) = diffuse(t) + direct(t).\ cosZ \qquad (2.5)$$

To clearly distinguish between calculated and directly measured global radiation, the BSRN literature refers to calculated global radiation using Equation 2.5 as DSGL1 (also referred to as "global1"), while the directly measured quantity using an unshaded pyranometer is DSGL2 (also known as "global2") (Gilgen *et al.*, 1995).

Despite the poor relative performance of global pyranometry, DSGL2 is still included in the basic BSRN measurement programme for the following reasons:

- It provides closure of the solar measurement program (NREL, 1993).
- It provides a means of continuously validating direct and diffuse measurements by direct comparison of DSGL1 and DSGL2.

- It provides a good quality control procedure (described in Sections 4.2.3.2 and 4.3.3.4) to identify questionable data, which have escaped other quality control procedures.

- It provides a means of calibrating the pyranometers, when the global/diffuse swopping method as proposed by Forgan (1996), is used in connection with the global/diffuse/direct relationship.

Global pyranometers are ventilated in the BSRN context, apart from uniformity, in an attempt to reduce thermal offsets to a minimum.

2.5.5 Measuring LW radiation

The pyrgeometer (Figure 2.7) as developed since 1970 by Eppley Laboratories at Newport, Rhode Island, is available in its present form since 1982.

The word *pyrgeometer* comes from the Greek words *πυρ* (fire), *γαια* (Earth) and *μετρον* (measure) – signifying "that which measures fire coming from the Earth" (Dominguez, 2001). Therefore, the pyrgeometer measures radiation emanating, or similar to those emanating, from the Earth.

Figure 2.7 *An Eppley Precision Infrared Radiometer*

A pyrgeometer contains the same thermopile as a pyranometer and pyrheliometer. The only significant difference is, that the dome is coated on the inside by silicon, which is selectively transmissible to only longer wavelengths (4 µm to 50 µm). In this way, SW radiation is prevented from reaching the thermopile. In operation, the pyrgeometer is also shaded in the same way as the diffusometer, and ventilated. This is discussed in Section 3.1.3.

At the first BSRN meeting in Washington (WCRP-54,1991), the target uncertainty for LWD measurements was set at 30 W.m^{-2}, as opposed to 5 W.m^{-2} to 10 W.m^{-2} for SW measurements at the time. That figure was anticipated to drop to 10 W.m^{-2} with the implementation of improved measurement techniques, which was realized in 1995 (Ohmura *et al.*, 1998), thanks to an improved way of measuring the dome temperature by means of two thermistors instead of one. This is known as the Swiss modification and is expected to improve instrument performance considerably (Philipona *et al.*, 1998). With correct calibration (using Equation 3.3, (the PMOD Equation) and absolute calibration coefficients), an uncertainty of 5 W.m^{-2} to 20 W.m^{-2} is attainable and as little as 2 W.m^{-2} with the Swiss modification.

2.6 CONCLUSION

To summarize, the BSRN is a small global network of quasi-homogeneous radiation stations striving to deliver the best quality radiation data aimed at specific applications, viz., climate research and satellite ground-truthing. Unique radiation processes in the atmosphere require specialized instrumentation, in order to detect and quantify them correctly and meet the high ideals set forth in BSRN.