# Bulletin No. 25

## PASSIVE BROADBAND AND SPECTRAL RADIOMETRIC MEASUREMENTS AVAILABLE ON NSF/NCAR RESEARCH AIRCRAFT

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### 1. INTRODUCTION

The NCAR Research Aviation Facility (RAF) provides instruments for obtaining broadband and spectral radiometric measurements from NSF/NCAR research aircraft. Broadband measurements available within the RAF instrumentation suite include measurements of ultraviolet (UV), shortwave, and infrared (IR) hemispheric (i.e., measured over 2 Pi steradians) radiation and IR measurements of surface temperature. Hemispheric radiation measurements are obtained using RAF-modified Eppley radiometers. Surface temperature measurements are made available through the use of Heimann radiation pyrometers. These latter instruments were recently adopted by the RAF to replace the Barnes Precision Radiation Thermometers (PRT-5s) previously flown on NSF/NCAR aircraft to obtain surface temperature measurements.

Spectral radiometric instrumentation presently available at the RAF includes two instruments. The first, the Spectral Vegetation Radiometer (SVR), was designed and built by the RAF for the purpose of examining the spectral characteristics of plants and other types of surface cover. These spectral data can then be used to classify the type of ground cover studied with the instrument. The second spectral instrument that has recently been acquired by the RAF is the Multichannel Cloud Radiometer (MCR). Designed and built by the NASA/Goddard Space Flight Center (GSFC), the MCR is a seven-channel scanning radiometer that was originally built and deployed on NASA aircraft for the purpose of obtaining narrow bandwidth near-infrared (NIR) and IR spectral data to be used in the remote retrieval of various cloud properties. The MCR was transferred to the RAF in 1993 and subsequently underwent modifications to allow for the deployment of the instrument on the NSF/NCAR C-130Q (hereafter referred to as the C-130) in a wing pod and to make two of the channels more suitable for the remote retrieval of aerosol properties. As of this writing, extensive modifications are being made to the MCR to repair and/or replace outdated optical and electrical components of the instrument and to return it to fully operational status. It is expected that the MCR will once again be available for deployment on the NSF/NCAR C-130 by early spring 1998. At present, the C-130 is the only NSF/NCAR aircraft on which the MCR can be supported.

Yet another instrument of possible interest to users of the NSF/NCAR aircraft is the Airborne Imaging Microwave Radiometer (AIMR). Manufactured by MPB Technologies, the AIMR was acquired by the RAF from the Atmospheric Environment Service (AES) of Canada in 1993. In 1996, possession of the AIMR and the associated instrument support responsibilities were transferred to the Remote Sensing Facility (RSF) in the Earth Observing Laboratory (EOL) at NCAR. Users can obtain specific information on the AIMR by contacting the RSF. Briefly, however, the AIMR is a scanning passive remote sensing device that measures microwave emissions at 37 and 90 GHz and produces images of terrain and clouds below the aircraft. At present, the AIMR can only be deployed on the NSF/NCAR C-130.

It should be noted that the hemispheric radiometers and Heimann radiation pyrometers are now considered part of the basic, or standard, RAF instrumentation package and are therefore deployed on NSF/NCAR aircraft for each project supported by the RAF. Because of their more specialized operations and support requirements, the SVR and MCR are not considered part of the standard RAF instrumentation package. A separate request for the deployment of either of these instruments on an NSF/NCAR aircraft must be submitted to the RAF for consideration. Similarly, a separate request for use of the AIMR must be submitted to the RSF. The RAF, RSF (for cases in which the AIMR has been requested), and EOL management review these requests and jointly determine if it is feasible to deploy and support the instrument(s) on the requested aircraft.

Users should also be aware that, as of this writing, no NSF deployment pool funds are made available for the support of either the MCR or the AIMR. Users requesting either one or both of these instruments are expected to provide the funds needed to pay for special instrument modifications and/or calibration services and for the support of the instrument(s) in the field. (The latter funds include the RAF and/or RSF staff travel costs and field support materials and expendables charges.) Budgets for deployment of the MCR and the AIMR are prepared by the RAF and the RSF, respectively, upon receipt of a formal instrumentation request and are provided to the requestor(s) so that they may arrange for acquisition of the funds needed to support either one or both of these specialized instruments.

In the remaining sections of this bulletin, overviews of each of the RAF-supported broadband and spectral instruments discussed above are presented and the instrument performance characteristics of each are outlined. Whenever appropriate, supplemental references are given to provide the user with additional (and in some cases, more detailed) sources of information on a particular instrument and/or measurement/data-reduction technique. Each section describing a particular radiometric instrument also contains a brief discussion of how data obtained from that instrument are recorded and made available (both in-flight and in post-project processed format) to users of the RAF aircraft.

## 2. BROADBAND RADIOMETRIC MEASUREMENTS

### 2.1 Hemispheric Radiometers

As was stated above, the hemispheric radiometers supported by the RAF are modified versions of commercially-available Eppley radiometers. Each class of radiometer (shortwave, IR, and UV) has undergone unique modifications in order to make that type of radiometer more suitable for obtaining measurements in the airborne environment. The specific modifications made to the shortwave, IR, and UV radiometers deployed by the RAF are discussed in the subsections that follow. In addition to the radiometer-specific modifications, a general modification has been made to all of the hemispheric radiometers supported by the RAF. A high quality electronic amplifier circuit has been added to the signal output stream of each radiometric sensor. The standard, unamplified Eppley radiometer outputs are small (typically on the order of millivolts) and are therefore susceptible to degradation by local noise. The electronic amplifier circuits installed by the RAF are designed to yield a gain of 100, boosting the radiometer signal outputs to a range of 0 to 1 volt and thereby minimizing the problem of local noise degradation.

For deployment on NSF/NCAR aircraft, hemispheric radiometers are mounted on both the top and bottom of the aircraft fuselage in order to provide users with both down-welling and up-welling (respectively) radiometric data. Each of the top and bottom mounts consists of a radiometer "boat" containing one each of the shortwave, IR, and UV hemispheric radiometers. Thus, a total of six radiometers are deployed on each aircraft. In this mounting configuration, the radiometers are all exposed to the environmental extremes at the altitude of the aircraft. Signal outputs from each of the six radiometers are recorded on the RAF-designed Aircraft Data System-2 (ADS-2).

#### 2.1.1 Pyranometers--Shortwave Radiometers

The pyranometers supported by the RAF are modified versions of the Eppley Model PSP pyranometers. Alterations made by the RAF involved a re-packaging of the PSP sensor and filters into a configuration better suited to aircraft mounting requirements and to provide space for the internal signal amplifier discussed above. Lighter weight materials were used by the RAF in the construction of the modified housing in order to lower the weight of the pyranometer. Also, the white collar that is found on Eppley PSP pyranometers was removed by the RAF. This collar, which covers all portions of the radiometer (except the filter dome on top), is intended to protect the body of the radiometer from solar heating. The collar was removed from all RAF pyranometers after it was determined that the dual effects of ventilation due to air motion at the aircraft's true airspeed and changes in ambient temperature to which the pyranometers are exposed both played a greater role in determining the housing temperature of the pyranometer. The specifications for this radiometer are given in Table 2.1.

| Table 2.1. NCAR/RAF Pyranometer Specifications | |
|---|---|
| Receiver: | Circular area of 1 $cM^2$<br>coated with Parsons' black optical lacquer |
| Passband*: | 0.285 to 2.80 $\mu$M |
| Temperature Dependence: | ± 1%, -20 to 40 C (nominal) |
| Linearity: | ± 0.5%, 0 to 2800 $W/M^2$ |
| Response Time: | 1 sec (63% response to step function) |
| Directional Sensitivity: | ± 1% deviation from 0 to 70° zenith angle<br>± 3% deviation from 70 to 80° zenith angle |
| Orientation: | No effect on instrument performance |
| Mechanical Vibration: | Capable of withstanding up to 20G |
| RAF Variable Names: | SWT, SWB, and SWTC ($W/M^2$) |
| Variable Name Definitions: | Shortwave radiation, top (SWT) and bottom (SWB)<br>shortwave radiation, top, attitude-corrected (SWTC) |
| * Passband when WG295 Schott filter glass domes are used on the pyranometer (the standard RAF pyranometer configuration). See text for additional discussion regarding setting the pyranometer passband. | |

Radiation incident on the pyranometer is detected by a thermopile composed of copper-constantan junctions coated with Parsons' black lacquer. Absorption by this lacquer finish is essentially independent of wavelength over the passband of the pyranometer. Over the temperature range of -20 to 40 C, the thermopile is temperature-compensated for non-linearities in sensitivity. Below -20 C, the sensitivity of the thermopile typically decreases by about 0.15% per °C (Smith, Jr. *et al*., 1987). Because the sensitivity of the coated thermopile is independent of wavelength, the passband of the radiometer is determined by the filter characteristics of the pyranometer domes. As operated at the RAF, the pyranometers are usually fitted with two domes of WG295 Schott filter glass. This dome configuration yields a passband of 0.285 to 2.80 $\mu$M. Other passbands can be obtained by outfitting the pyranometers with other combinations of filter glass. Detailed information on other filter glass domes and the in-house availability of such domes for use with the RAF pyranometers can be obtained by contacting the RAF.

The RAF pyranometers are periodically returned to Eppley Laboratories for calibration. The comparison reference employed by Eppley during the calibration of pyranometers is a working, standard pyranometer that has been calibrated against the Eppley group of primary pyrheliometers. This latter group of pyrheliometers is used to maintain and reproduce the World Radiation Reference for the United States. Calibration of the pyranometers basically involves the exposure of both the radiometer to be calibrated and the reference pyranometer to the output of a hemisphere internally lit by tungsten-filament lamps. This procedure yields data relating the pyranometer's output in volts to the hemisphere's output in $W/M^2$. The RAF's experience with calibrations performed by Eppley Laboratories (as well as other calibration facilities) indicates that the pyranometer thermopile (i.e., signal) response is very stable. It should be noted that calibration of the RAF pyranometers does not normally include verification of the cosine response of the pyranometers. However, spot checks of the cosine response are performed occasionally and have confirmed the stability of this response characteristic.

The Eppley PSP pyranometers typically perform very reliably when employed in ground-based measurement applications. However, when these pyranometers are deployed on aircraft, additional problems are encountered that must be addressed in order to allow for the collection of shortwave irradiance (flux, in units of $W/M^2$) data of acceptable quality. The most serious problem that must be dealt with is the effect of aircraft attitude on the measured down-welling shortwave irradiance values. Normal aircraft maneuvers (i.e., changes in the heading, pitch, and roll of the aircraft) result in constant changes to the attitude of the upward-looking pyranometer relative to the position of the sun. These attitude changes introduce significant errors into the measured down-welling shortwave irradiance data. Aircraft maneuvers, as well as the altitude of the aircraft, further complicate the collection of data from the upward-looking pyranometers due to the impact on the fractions of direct and diffuse radiation that reach the radiometer. The direct and diffuse shortwave radiation fractions will typically vary continuously as the aircraft attitude and altitude change. Because it has been determined that only the direct fraction of shortwave radiation must be corrected for the effects of aircraft attitude [see Rockwood and Cox (1976) or Glover and McFarland (1991)], it is, therefore, necessary to either directly measure the direct and diffuse shortwave radiation fractions on the aircraft or be able to estimate these fractions in order to insure that any attitude correction algorithm is applied to the collected data reliably. Bannehr and Glover (1991) present a method for the removal of the effects of aircraft attitude from collected pyranometer data, and their work has recently been incorporated into an algorithm developed at the RAF to process pyranometer data collected on NSF/NCAR aircraft and remove the effects of aircraft motion. This algorithm has recently been incorporated in the library of standard RAF NIMBUS data processing routines. (See RAF Bulletin No. 9 for further discussion of the NIMBUS processing software.) Thus, attitude-corrected down-welling shortwave flux data are now available in all standard RAF aircraft data sets.

Users should be aware, however, that despite the application of an attitude correction algorithm during processing of down-welling shortwave flux data, yet another significant limitation sometimes exists in shortwave flux data sets generated by the RAF. This limitation is imposed by the combined effect of aircraft heading/orientation and low solar elevation (high solar zenith) angles. For those instances in which the aircraft is heading either toward or away from the sun and the sun is at a low elevation angle, the fuselage of the aircraft obstructs the field of view of the up-looking shortwave radiometer and artificially lowered shortwave flux values are recorded. Sharp turns (i.e., significant rolls) of the aircraft away from the sun when the sun is at low elevations can also cause the same flux depression effect. Given that this lowered flux values effect is caused in part by the orientation and shape of the aircraft, it is not possible to correct for the full magnitude of flux depression via the attitude correction algorithm. Users are, therefore, advised to examine shortwave flux data closely and to exercise vigilance in looking for cases of artificially-induced shortwave flux depressions (e.g., by examining aircraft heading and/or roll values and solar elevation angle values for the same time periods in question).

Finally, it is worth noting that, while the RAF has attempted to locate the up-looking shortwave radiometers in the most optimal location on the NSF/NCAR aircraft, the field of view of these radiometers (and, indeed, of the co-located UV and IR hemispheric radiometers) is unavoidably partially obstructed by features on the upper fuselage of the aircraft (tail, radio antennas, etc.). At present, it is not possible to exactly quantify the magnitude of this obstruction effect on the down-welling shortwave flux data. The RAF will, however, soon begin studies of this problem in an effort to better understand and quantify the magnitude of this effect.

### 2.1.2 Pyrgeometers--IR Radiometers

The RAF-modified version of Eppley's model PIR pyrgeometer is similar in configuration to the modified pyranometer discussed in section 2.1.1 above. Like the pyranometers, the reflective collar on the RAF pyrgeometers has been removed. The primary difference between the two types of radiometers is the inclusion of temperature sensors in the RAF pyrgeometers. These latter sensors provide measurements of the sink and dome temperatures, the effects of which must be corrected for during processing of the pyrgeometer data (see further discussion below). Table 2.2 lists the specifications of this instrument.

| **Table 2.2. NCAR/RAF Pyrgeometer Specifications** | |
|---|---|
| Receiver: | Circular area of 1 $cM^2$<br>coated with Parsons' black optical lacquer |
| Passband: | 0.3 to 50 $\mu$M |
| Temperature Dependence: | ± 1%, -20 to 40 C (nominal) |
| Linearity: | ± 1%, from 0 to 700 $W/M^2$ |
| Response Time: | 2 secs (63% response to step function) |
| Directional Sensitivity: | Better than 5% from normalization<br>insignificant for a diffuse source |
| Orientation: | No effect on instrument performance |
| Mechanical Vibration: | Capable of withstanding up to 20 G |
| RAF Variable Names: | IRTC and IRBC ($W/M^2$) |
| Variable Name Definitions: | Infrared radiation, top and bottom (respectively), corrected |

The radiation detection mechanism in the pyrgeometers is similar to that used in the pyranometers; i.e., a circular receiver coated with black optical lacquer. A silicon dome, rather than the two filter glass domes used in the pyranometers, provides the 0.3 to 50 $\mu$M passband characteristic of this radiometer.

As is done with the pyranometers, the RAF pyrgeometers are periodically returned to Eppley Laboratories for calibration. Two methods are employed by Eppley during the calibration of pyrgeometers. The first method involves the exposure of the instrument being calibrated to a reference blackbody. This blackbody is a low-temperature (0 to 50 C) source with a circular opening of ~10 cM in diameter. The temperature of the blackbody source is stabilized by circulating oil. The second method used by Eppley involves the comparison of the output from the pyrgeometer being calibrated with the output from a calibrated working standard pyrgeometer.

As was mentioned above, pyrgeometer data must be corrected to remove the effects caused by the sink and dome temperatures. The specific problem caused by the sink and dome components is that both emit energy that artificially influences the actual ambient energy detected by the thermopile. Albrecht *et al*. (1974) derived the equation that relates the actual (corrected) irradiance to the indicated (uncorrected, or recorded) irradiance and the sink and dome temperatures. This relationship is used by the RAF to process pyrgeometer data collected on NSF/NCAR aircraft and is given by:

$$\mathrm{IRxC} = \mathrm{IRx} + e_0 \,\mathrm{sigma}\, (\mathrm{STx})^4 - k \,\mathrm{sigma}\, \{(\mathrm{DTx})^4 - (\mathrm{STx})^4\} \quad (2.1)$$

where:

IRxC = corrected IR irradiance ($W/M^2$)
IRx = calibrated but uncorrected IR irradiance ($W/M^2$)
STx = sink temperature (K)
DTx = dome temperature (K)
$e_0$ = emissivity of the blackened thermopile surface
k = ratio of the dome material emissivity to the transmissivity
sigma = Stefan-Boltzmann constant.

In the variable names IRxC, STx, and DTx, which are the variables names used in RAF data sets, x represents B for the down-looking pyrgeometer data and T for the up-looking data.

Various investigators (e.g., Albrecht *et al*., 1974; Foot, 1986) have found it necessary to adjust the value of k used in equation (2.1). The sink and dome temperatures for each of the two pyrgeometers flown on the NSF/NCAR aircraft are, along with the uncorrected (IRx) IR data, recorded and distributed in RAF data sets. This procedure provides users with all of the variables needed to calculate corrected IR (IRxC) values, should they wish to experiment with different k values. Corrected up-welling and down-welling pyrgeometer data are also output in all RAF aircraft data sets. As of this writing, a k value of 5.5 is used by the RAF for this processing.

It should be noted that, in actual flight situations, the measured sink and dome temperatures (STx and DTx, respectively) may lag the actual temperatures. In this situation, the term

$$k \text{ sigma } \{(DTx)^4 - (STx)^4\}$$

in equation (2.1) will yield a correction factor that is slightly incorrect. Griffith and Glover (1987) developed lag correction techniques that yielded improved pyrgeometer data. However, these lack generality and presently are not employed by the RAF during the processing of pyrgeometer data.

Due to atmospheric attenuation and scattering, a large portion of the direct solar radiation within the 0.3 to 50 $\mu$M passband of the pyrgeometers does not reach the surface of the earth. The consequence of this phenomenon is that, when operated at ground level, pyrgeometers will measure primarily diffuse (scattered) radiation. However, when operated on research aircraft flying at higher levels in the atmosphere, larger amounts of direct solar radiation can reach the pyrgeometers, and it becomes critical to be able to distinguish between the direct and diffuse IR radiation fractions. Such differentiation is required in order to be able to reliably correct the pyrgeometer data for the effects of aircraft attitude, as is required for the pyranometer data. As of this writing, methods for accurately estimating the direct and diffuse IR radiation fractions are being investigated at the RAF but have not yet been implemented. Thus, aircraft attitude corrections are not presently applied to pyrgeometer data collected on NSF/NCAR aircraft.

### 2.1.3 TUVRs--UV Radiometers

The UV radiometers supported by the RAF are re-packaged versions of the Eppley model TUVR. As with the modifications made to the pyranometers and pyrgeometers flown on the NSF/NCAR aircraft, the modifications made by the RAF to the TUVRs were carried out in order to make the latter UV radiometers more suitable for flying on research aircraft. In the original Eppley configuration, the TUVRs are significantly taller than both the pyranometers and the pyrgeometers. If left unmodified, the TUVRs will, consequently, shadow the pyranometers and pyrgeometers when mounted side by side with the latter two instruments in a radiometer "boat." The RAF versions of the TUVRs have been re-packaged to yield shorter radiometer housings that are now similar in profile to the pyranometer and pyrgeometer housings. Thus, all three types of radiometers can be flown together in the "boats" on the NSF/NCAR aircraft. The RAF UV radiometer specifications are given in Table 2.3.

| **Table 2.3. NCAR/RAF TUVR Specifications** | |
|---|---|
| Receiver: | Opaque quartz diffusing disc combined with interference filter and selenium barrier layer photocell |
| Passband: | 0.295 to 0.385 $\mu$M |
| Temperature Dependence: | 0.1% per °C from -40 to +40 C |
| Linearity: | ± 2% from 0 to 700 W/M$^2$ |
| Response Time: | Milliseconds |
| Directional Sensitivity: | ± 2.5% from normalization<br>0-70° zenith angle |
| Orientation: | No effect on instrument performance |
| Mechanical Vibration: | Capable of withstanding up to 20 G |
| RAF Variable Names: | UVT and UVB (W/M$^2$) |
| Variable Name Definitions: | Ultraviolet radiation, top and bottom (respectively) |

The UV radiation detection system employed in the TUVRs consists of a diffusing disc, an interference (bandpass) filter, and a detector. Incoming radiation first impinges on an opaque quartz disc, where it is diffused and then passed through to the filter and the detector. The design of this quartz disc results in a cosine response for the instrument. The interference filter is located several centimeters behind the diffusing disc and has a passband of 0.295 to 0.385 $\mu$M. This bandwidth covers both the UV-A and UV-B bands of the electromagnetic spectrum. The detector, a selenium barrier layer photocell, is located immediately behind the filter. Experience working with the TUVR at the RAF has indicated that the instrument's performance is virtually insensitive to temperature. In fact, the RAF has determined that the TUVR's actual temperature sensitivity is significantly less than the value of 0.1% per °C that is quoted by Eppley Laboratories.

As is done with the shortwave and IR hemispheric radiometers, the UV radiometers are periodically returned to Eppley Laboratories for calibration. The technique used for this calibration is based on the work of Ångstrom and Drummond (1962) and involves exposing the radiometer to the output from a NIST-calibrated tungsten-iodine lamp. A method which combines analyses of the spectral characteristics of the calibration lamp, the radiometer's passband filter, and the radiometer's detector is used to determine the response of the UV radiometer over the spectral band of 0.295 to 0.385 $\mu$M. As with the pyranometer calibrations, the RAF's experience to date is that the outputs from the UV radiometers show very little drift between calibrations of the instruments performed by Eppley Laboratories.

## 2.2 Infrared Radiation Thermometers

As was stated in the Introduction, airborne surface temperature measurements onboard NSF/NCAR aircraft are now made using EG&G Heimann Optoelectronics radiation pyrometers, instruments which were recently adopted by the RAF to replace the previously-used Barnes PRT-5s. Several different models of pyrometers are manufactured by EG&G Heimann for the purpose of measuring the temperatures of various materials (metals, plastics, glass, etc.). The RAF deploys Heimann Model KT 19.85 pyrometers on each of the NSF/NCAR aircraft. These latter instruments operate within the spectral range of 9.6 to 11.5 $\mu$M, a portion of the electromagnetic spectrum in which atmospheric transmission is high. Thus, the KT 19.85 pyrometers are, with a notable exception (see discussion below), specifically suited for making surface temperature measurements on board research aircraft. Specifications of this instrument are given in Table 2.4.

**Table 2.4.**
**Heimann KT 19.85 Pyrometer Specifications**

| | |
|---|---|
| Passband: | 9.6 to 11.5 $\mu$M |
| Measurement Range: | -50 to 400 C |
| Resolution: | ~1°C, depending on radiative temperature of surface |
| Response Time: | Adjustable (RAF recommends 0.3 sec to reduce noise in data) |
| Field of View: | 2° |
| RAF Variable Names: | RSTB and RSTB1 |
| Variable Name Definitions: | Radiometric surface temperature, first and second units (respectively) |

The KT 19.85 pyrometer is a measuring transducer. Infrared radiation emitted by the object being studied (e.g., ground or sea surface, cloud top) passes through a filter mounted in the instrument and is sensed by a pyroelectric detector. This incoming radiation is transformed into a standardized output signal. A reference target inside the KT 19.85 housing is used to convert the signal generated by the incoming IR radiation into a temperature measurement. Electronic circuits within the pyrometer process the difference between the transducer output from the reference target and the transducer output from the surface being studied to determine the temperature of the surface. Signal outputs from the Heimann pyrometers are recorded on the ADS-2 on the NSF/NCAR aircraft.

Calibration of the Heimann pyrometers flown on the NSF/NCAR aircraft is carried out periodically in the RAF calibration laboratory using an Eppley Laboratories, Inc. Infrared Blackbody Source Model BB16T. This blackbody target has a temperature accuracy and uniformity of 0.1°C over a temperature range of -10 to +60 C and an emissivity of 0.995.

RAF experience working with the Heimann pyrometers on several recent aircraft deployments has brought to light two instrument limitations that are of potential importance to users of NSF/NCAR aircraft. The first such limitation is related to the choice of response times for the Heimann radiometers. As is indicated in Table 4, the response times for these instruments are variable and include settings of 0.03, 0.10, 0.30, 1.00, 3.00, and 10.00 seconds. The RAF has determined during field deployments and laboratory testing that the noise level present in the pyrometer signals increases significantly for response times faster than 0.3 second. Consequently, it is the recommendation of the RAF that the Heimann pyrometers be programmed for a response time of no faster than 0.3 second when used on NSF/NCAR aircraft.

The second potential problem encountered by the RAF during use of the Heimann pyrometers relates to the performance of these instruments in colder environments. Initial usage and testing of the pyrometers by the RAF revealed that, at temperatures less than approximately 10 C, the calibrations of the pyrometers began to drift and regular noise spikes began to appear in the instruments' data signals. To circumvent this problem, the RAF installed heating devices in the vicinity of the pyrometer housings to keep the temperature of the sensor heads from falling below 10 C. While this in-house modification has significantly improved the quality of data obtained from the Heimann pyrometers, more recent aircraft deployments have given some indication that the threshold temperature value of 10 C may be slightly too low to eliminate all of the effects introduced by exposure to cold temperatures. As of this writing, the RAF is considering increasing the pyrometer heating threshold value to approximately 20 C.

It should also be noted that certain environmental effects can degrade the accuracy of surface temperature measurements obtained from Heimann pyrometers flown on aircraft. Of particular importance are the potential errors introduced into surface temperature measurements by the following: 1) non-unity emittance and non-zero reflectance of the ground or sea surface being studied; and 2) the emission of IR radiation by water vapor in the atmospheric layer between the pyrometer and the surface. The first problem, which is discussed by Lind and Shaw (1989), basically pertains to the adverse effects introduced into surface temperature measurements by both spatial variability in the surface emittance and by the fact that, in many cases, a portion of the IR radiation detected by a down-looking pyrometer is reflected radiation from the skyward hemisphere (what Lind and Shaw term "sky effects"), rather than being radiation emitted by the surface. The second problem, that of IR radiation emission by intervening atmospheric water vapor layers, is discussed by Weiss (1970). This author also discusses some possible methods for minimizing the adverse effects caused by such water vapor emissions. As of this writing, the RAF does not apply corrections to Heimann pyrometer data collected on NSF/NCAR aircraft to remove the effects of either of the two problems outlined above. However, techniques for further improving the quality of surface temperature measurements obtained from NSF/NCAR aircraft are presently being explored, and in future, ideas such as those outlined by Lind and Shaw (1989) and Weiss (1970) may be incorporated into better pyrometer data processing routines employed by the RAF.

## 3. SPECTRAL RADIOMETRIC MEASUREMENTS

### 3.1 Spectral Vegetation Radiometer (SVR)

The spectral vegetation radiometer (SVR) developed and supported by the RAF is based on the work of Bannehr (1990). A brief outline of the theoretical background for, and operational characteristics of, this instrument is presented below. For more detailed information on the SVR, the user is referred to Bannehr and Glover (1992).

The scientific basis for measurements made with the SVR is the variance in surface spectral reflectance between the chlorophyll and non-chlorophyll absorption bands of the electromagnetic spectrum. Within the chlorophyll absorption band, which spans 400-680 nM, incoming solar radiation incident on the photosynthetic pigment in vegetation is strongly absorbed and scattered. Beyond 680 nM and out to approximately 750 nM, the absorption of incoming radiation by vegetation is roughly three to four times less than within the 400-680 nm band. Thus, simultaneous measurements at wavelengths both within and outside the chlorophyll absorption band can be used to classify and differentiate between different types of vegetative cover and also to distinguish between vegetated and non-vegetated areas.

The RAF SVR is a three-wavelength instrument that is designed to make surface radiance measurements at wavelengths of 650, 760, and 862 nm. The 650 nM channel, which is inside the chlorophyll absorption band, is susceptible to extinction by molecules, aerosols, and ozone. The 760 and 862 nM channels are outside of the chlorophyll absorption band. While these two wavelength choices allow for radiance measurements in spectral regions unaffected by water vapor absorption, these two SVR channels are, nevertheless, affected by molecular scattering and aerosol extinction.

Surface radiance measurements at each of the three SVR wavelengths are made using a separate light barrel for each channel. Each of the three barrels contains an optical filter and a UV-enhanced silicon photodiode detector. Each of the three optical filters has a bandwidth of 10 nM. The output of each channel's detector is amplified within the SVR housing in order to eliminate local noise degradation of the output signals. As of this writing, only two of the SVR output signals--those for the 650 and 862 nM channels--are recorded on board the NSF/NCAR aircraft data systems when the SVR is in use. This is due to the fact that only these two channels are required to make chlorophyll absorption/non-absorption measurements. The 760 nM channel is maintained in the instrument for research purposes only. Calibration of the SVR is carried out using the ratio-Langley technique, which is described by Forgan (1986). The RAF SVR characteristics are summarized in Table 3.1.

**Table 3.1.**
**NCAR/RAF Spectral Vegetation Radiometer (SVR) Specifications**

| | |
|---|---|
| Channel Wavelengths: | 650, 760, and 862 nM |
| Channel Bandwidths: | 10 nM each channel |
| Measurement Range: | 0 to 5 Volts each channel |
| Response Time: | 24 msec (from 0 to 99%) |
| Field of View: | 2.3°<br>variable by changing apertures |
| RAF Variable Names: | WV650 and WV862* |
| Variable Name Definitions: | 650 and 862 nM channel output voltages, respectively |

* At present, only the 650 and 862 nM channel outputs are recorded on board the NSF/NCAR aircraft data systems.

Data collected from the SVR can be used to determine vegetation index values. While there is generally no standard definition for such an index, scientists at the RAF have previously calculated and made use of a quantity referred to as the normalized difference vegetation index (NDVI). The value of the NDVI is given by:

$$NDVI = (rho_2 - rho_1)/(rho_2 + rho_1) \qquad (3.1)$$

where:
$rho_1$ = radiance measured with the 650 nM channel
$rho_2$ = radiance measured with the 862 nM channel

It is important to note that the above index value is calculated using radiance values rather than reflectance values, which are typically used in vegetation index calculations carried out using satellite data.

### 3.2 Multichannel Cloud Radiometer (MCR)

As stated in the Introduction, the MCR is a seven-channel scanning radiometer originally built by NASA/GSFC and transferred to the RAF in 1993. Major modifications and upgrades have been made to the MCR under the direction of RAF staff in order to return the instrument to fully operational status. Discussion below provides a brief outline of the operating principles of the MCR, the intended instrument channel configurations and expected general specifications. MCR calibration procedures and proposed research applications for instrument data are also discussed. Users who wish to obtain more detailed information on the MCR should contact Julie Haggerty, Scientist [via email; phone: (303) 497-1090; fax: (303) 497-1092].

Briefly, the MCR measures spectral radiance (in units of mW/cM$^2$ sr $\mu$M) at seven narrow bandwidths in the visible, near-IR, and IR portions of the EM spectrum. These measurements are made using a series of dichroic (beamsplitting) filters, focussing lenses, interference filters, and optical detectors. Successive dichroic filters are used to separate radiation at the desired wavelengths from an incoming beam of solar radiation, which is directed into the optical bench of the MCR using a rotating scan mirror and a 12.38 cm Dall-Kirkham telescope. After passing through the dichroic filters, radiation partitioned into a particular channel passes through an interference filter designed to pass radiation at a specific central wavelength and over a specified bandwidth. Optical detectors for each of the seven channels convert the measured radiation into analog signals, and these signals are amplified and recorded. It should be noted that silicon photodiode detectors are used for channels 1-5 (visible and near-IR channels). The detectors for channels 6-7 are mounted inside cryogenic (liquid nitrogen) dewars and, in the original NASA/GSFC MCR configuration, were of photovoltaic and photoconductive types. The layout of the original NASA/GSFC MCR is described in greater detail by Curran *et al*. (1981). The RAF-modified MCR consists of the same optical layout as was originally implemented by NASA/GSFC. Consequently, users interested in obtaining more specific information on the exact optical layout and design theory for the MCR should consult the paper by Curran *et al*.

The MCR modification effort at NCAR returned the instrument to a fully functional (and also improved) status as a seven-channel, high-resolution scanning radiometer (Tschudi and Laursen, 2001). The majority of the optical components (interference filters, cryogenic dewars, detectors, etc.) have been replaced in order to provide users of the MCR with spectral radiance data at requested wavelengths of interest and of higher quality than was previously possible given the age of most of the MCR's optical filtration and detection parts. The MCR electronics (i.e., signal and heater wiring, analog cards, etc.) have been modified and, in many cases, re-packaged and condensed in order to improve the overall performance of the instrument and to lower the amount of payload space required to deploy the instrument in a C-130 wing pod. Signal outputs from the seven MCR channels, as well as several additional variables containing MCR "housekeeping" data, are recorded on the RAF ADS-2 on the C-130. The new MCR channel wavelengths, bandwidths, and proposed research applications are listed in Table 3.2. Table 3.3 outlines the general instrument specifications.

**Table 3.2.**
**NCAR/RAF MCR Channel Specifications**

| Channel Number | Central Wavelength ($\mu$M) | Bandwidth (FWHM*; $\mu$M) | Proposed Research Application(s) |
|---|---|---|---|
| 1 | 0.640 | 0.063 | Cloud, aerosol, surface mapping |

| | | | |
|---|---|---|---|
| 2 | 0.470 | 0.040 | Sea ice, ocean color, soil type |
| 3 | 0.870 | 0.040 | $O_2$ A-band studies |
| 4 | 1.06 | 0.07 | Water vapor amount studies |
| 5 | 1.64 | 0.05 | Snow and ice difference and cloud phase studies |
| 6 | 2.16 | 0.08 | Cloud phase and particle size studies land surface properties imaging |
| 7 | 10.9 | 0.9 | Thermal (temperature) mapping |
| * FWHM = Full Width at Half Maximum | | | |

| **Table 3.3. NCAR/RAF MCR General Specifications** | |
|---|---|
| Field of View: | 0.007 radians |
| Mirror Scan Rate: | 3.47 revolutions/sec |
| Data Sampling Rate: | ~4600 sps (each channel simultaneously) |
| Pixel Size: | Variable, depending on aircraft altitude |
| RAF Variable Names: | MCR1, MCR2, MCR3, MCR4, MCR5, MCR6, and MCR7 |
| Variable Name Definitions: | MCR channels 1 to 7 raw voltage outputs |

Calibration of the first six (visible and near-IR) channels of the MCR was originally carried out at NASA/GSFC using a large integrating sphere (uniform source). The response of the six channels to the radiance exiting the sphere was measured, and plots of radiance versus signal response yielded the calibration slope and intercept for each channel. Channel 7 (the thermal channel) was calibrated at NASA/GSFC by measuring the signal response of this channel during exposure to a thermal calibration source inside an evacuated chamber. As with channels 1-6, plots of radiance (derived from the calibration source temperature data using Planck's relationship) versus signal response yielded the calibration slope and intercept for channel 7.

Similar calibration methods to those applied by NASA/GSFC were conducted at the Los Alamos National Laboratories during 1998 and 1999. These calibrations confirmed the linear response of channels 1-6 and near-linear response of the thermal channel (7). In-house calibrations (i.e. at RAF) for all MCR channels are performed before and after each field experiment. Since the major upgrade of the instrument, the MCR has been successfully deployed in the right wing pod of the C-130 during the 1999 INDOEX (Liu *et al*., 2003) and 2001 DYCOMS-II (Tschudi, 2002) field experiments, as well as the IDEAS 1, 2, and 3 (2002-2003) campaigns. The MCR was also recently deployed on a Twin Otter for the CSTRIPE experiment (2003).

Processing software developed at RAF applies calibrations for each channel, geolocation, and correction for aircraft attitude. Raw and processed MCR data for each field experiment are available on NCAR's Mass Store system. Free software that produces mapped images of the processed MCR data is available for free download from RAF. This viewing tool can be used by any researcher using the IDL Portable Workstation, available for free download from RSI.

Some of the potential research applications for the MCR are outlined in Table 3.2. To date, studies involving MCR data analyses has included the retrieval of cloud optical depth and effective radii values from MCR data (Liu *et al*., 2003; Tschudi, 2002). Nakajima and King (1990) and Nakajima *et al*.(1991) also provide discussions of such MCR-derived cloud parameter data. Sea ice properties have also been derived from MCR analyses (Tschudi and Laursen, 2001b). As the information in Table 3.2 implies, the potential exists for various other types of cloud, aerosol, and surface properties studies to be carried out using MCR data. While these studies have, for the most part, not yet been pursued using existing MCR data, the theoretical precedent for such studies is present in the literature.

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