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RADIATION MEASUREMENTS FROM NCAR AIRCRAFT

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1. INTRODUCTION

The NCAR Research Aviation Facility (RAF) provides instruments for the airborne measurement of radiation in several wavelength bands. Basically these measure hemispheric (i.e., over 2π steradians) radiation, surface temperature, and radiance useful for determining the presence of surface vegetation or phytoplankton. Hemispheric measurements in the infrared, visible, and ultraviolet are obtained through the use of three types of devices based on designs by Eppley Laboratories, Inc. Measurements of surface temperature are obtained through the use of a very sensitive radiometer operating in the 9.5 to 11.5μm infrared band. The device currently in use for this purpose is the model PRT-5 Infrared Thermometer formerly manufactured by Barnes Engineering Company. The RAF has recently developed a radiometer for the determination of surface vegetation by means of comparative measurements in the viable band at two wavelengths.

This bulletin provides a overview of each of these instruments along with a discussion of their performance characteristics. Radiometers are not considered as part of a basic or standard RAF instrumentation configuration and therefore, requests for RAF aircraft support on projects which require them must specify them as part of the scientific payload.

Data from these radiometers are recorded during flight and are also available for real time display. The data from each of the radiometers is produced in the form of a dc voltage which is amplified and filtered in the RAF Aircraft Data System (ADS) on the airplane. Real time displays are provided in engineering units that include calibrations, and in the case of hemispheric infrared radiation, compensation for internal offsets. Generally, a sample rate for data recording is selected which is consistent with the time response of the instrument and the requirements of the scientific experiment. More detail on the acquisition of airborne data is given in *RAF Bulletin 9*.

2. MEASUREMENT OF HEMISPHERIC RADIATION

Three types of instruments for the measurement of hemispheric radiation are in use at the RAF. All three are based on designs by Eppley Laboratories. In the descriptions that follow the visible wavelength radiometer, based on the Eppley model PSP, is presented first. Next the infrared radiometer, based on the Eppley model PIR is described. It is essentially the PSP with a different passband and a means for measuring internal temperatures. The last part of this section describes the ultraviolet radiometer, based on the Eppley model TUVR.

All three of these radiometers have been modified by the RAF to make them more suitable to the airborne measurement environment and to make them compatible with the RAF airborne data acquisition system. One modification common to all three is the addition of an high quality electronic amplifier circuit to the output of the radiometer sensor. These unamplified outputs are small, on the order of millivolts, and are therefore susceptible to degradation by local noises. The gain of these amplifiers is set to 100 and provides a radiometer output in the range of 0 to 1 volt.

The hemispheric radiometers are usually mounted on the exterior of the aircraft hull (or in a "boat" which facilitates mounting) and are therefore exposed to the environmental extremes at the altitude of the aircraft.

2.1 Pyranometer

The RAF repackaged the Eppley PSP pyranometer sensor and filters to get a configuration more suitable to aircraft mounting requirements and to provide space for the internal signal amplifier. Some weight was saved by using light weight materials in the modified housing. Eppley's version of the pyranometer uses a white collar that covers all of the radiometer (when seen in plan view with the filter dome on top) except the dome. This collar is intended to protect the body of the radiometer from solar heating. In the RAF version of the pyranometer the collar has been eliminated because the housing temperature is largely determined by ventilation at the aircraft true airspeed and ambient temperature. Photograph 1 is a depiction of the RAF pyranometer and Table 1 lists the specifications for the RAF version of the Eppley model PSP.

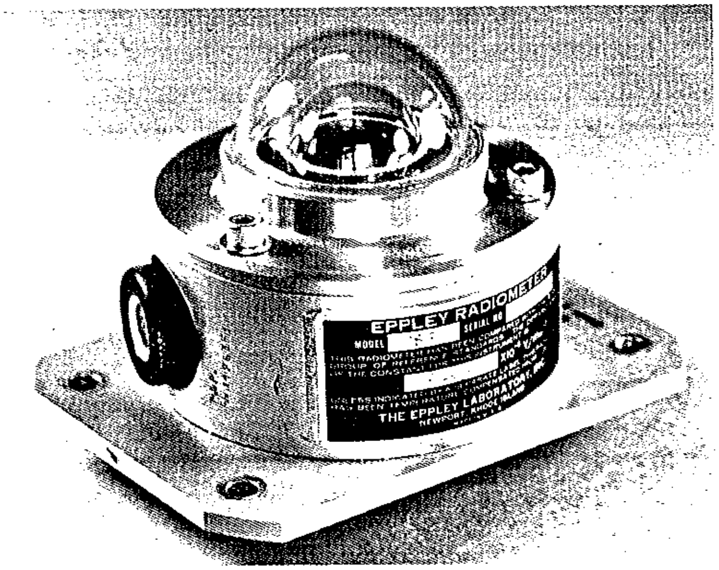

Photo by Bob Bumpas

Photograph 1: RAF Version of Eppley Model PSP Pyranometer

Table 1

Instrument Characteristics
NCAR/RAF Version of Eppley Model Pyranometer

Receiver:	Circular 1 cm^2, coated with Parsons' black optical lacquer
Temperature Dependence:	± 1%, -20 to +40°C (nominal)
Linearity:	± 0.5%, 0 to 2800 Wm^{-2}
Response Time:	1 s (63% response to step function)
Directional Sensitivity:	± 1% deviation from 0 to 70° Zenith angle; ± 3% deviation from 70 to 80 ° Zenith angle
Orientation:	No effect on instrument performance
Mechanical Vibration:	Capable of withstanding up to 20 g's

Incoming radiation is sensed with a thermopile of copper-constantan junctions that are coated with Parsons' black lacquer. Absorption by this finish is essentially independent of wavelength for the passband of the pyranometer (and pyrgeometer). Over the temperature range of -20 to 40°C the thermopile is temperature compensated for non-linearities in sensitivity. Below -20°C the sensitivity typically decreases by about 0.15%/°C (Smith Jr., *et al*, 1987).

Since the sensitivity of the coated thermopile is independent of wavelength, the passband of the radiometer is determined by the filter characteristics of the domes. Usually the pyranometer is fitted with two domes of WG295 Schott filter glass and consequently has a passband of 0.285 to 2.80μm. Other passbands can be obtained by combinations of filters described in Table A1 at the back of this Bulletin (supplied by Eppley Laboratories, Inc.). The RAF does not stock all of these filters. The pyranometer is calibrated with domes of WG295. When measurements are made with filters other than WG295 the calibration factor is adjusted by the filter factors given in Table A1. For example, if a GG395 filter (filter factor = 1.11) is substituted for one of the WG295 filters (filter factor = 1.09), the appropriate pyranometer sensitivity would be (1.09/1.11) times the calibration factor.

RAF pyranometers are periodically returned to the Eppley Laboratories for calibration. The comparison reference is a working, standard pyranometer calibrated against the Eppley group of primary pyrheliometers which maintain and reproduce the World Radiation Reference for the United States. The calibration method, described in Eppley Reprint No. 30, essentially exposes the radiometer and the reference to a hemisphere of tungsten-filament lamps. A long history of RAF experience with calibrations by Eppley (and other calibrators) indicates that the thermopile sensitivity is very stable. Although these calibrations do not normally include verification of the cosign response of the pyranometers, spot checks confirm the stability of this response characteristic.

The PSP pyranometers have very good performance specifications for the applications for which they were designed, namely ground based. When used on aircraft however, the measurements require interpretation not usually applied to ground-based measurements. The most serious of these is the attitude of the radiometer in airborne situations. Normal aircraft maneuvers result in a constantly changing radiometer attitude. These maneuvers produce errors in the measured irradiance that can be significant. Another difficulty presented by airborne use of this radiometer is the compounding of the mixture of direct and diffuse components of the irradiance. Changes in aircraft heading, pitch and roll vary the contribution of each of these components in a manner that is not typical of ground based measurements. Methods for treating these and other difficulties are addressed by Bannehr and Glover (1991). Even small misalignments between the plane of the thermopile and the aircraft inertial navigation system can cause significant errors when correcting irradiances for aircraft attitude. Bannehr and Schwiesow (1992) present a method for using flight data to determine the misalignment. The RAF does not provide corrections to the irradiance since the standard data set contains enough information to allow investigators to apply their own processing algorithms.

2.2 Pyrgeometer

The RAF repackaged version of Eppley's model PIR pyrgeometer is like that for the pyranometer except for the inclusion of temperature sensors. These provide indications of the sink and dome temperatures necessary for the compensation of indicated irradiance. Also, like the RAF version of the Eppley pyranometer, the reflective collar on the pyrgeometer has been eliminated. Photograph 2 is a depiction of the RAF version of the PIR. A silicon dome provides the 3.5 to 50μm passband filtering for this radiometer. Figure 1 (provided by Eppley Laboratories, Inc.) is the passband response of the dome. The upper curve in this figure represents the radiant intensity of the calibrating source. Table 2 lists the characteristics of the RAF version of the Eppley model PIR pyrgeometer.

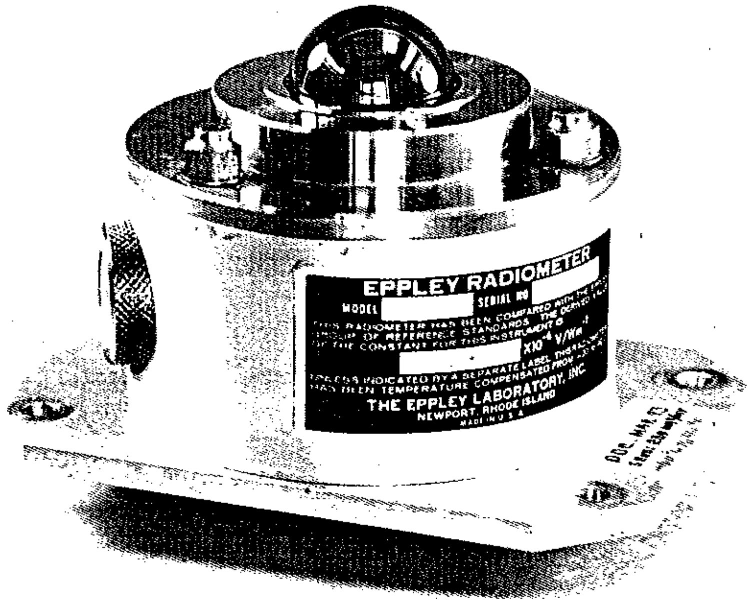

Photo by Bob Bumpas

Photograph 2: RAF Version of Eppley Model PIR Pyrgeometer

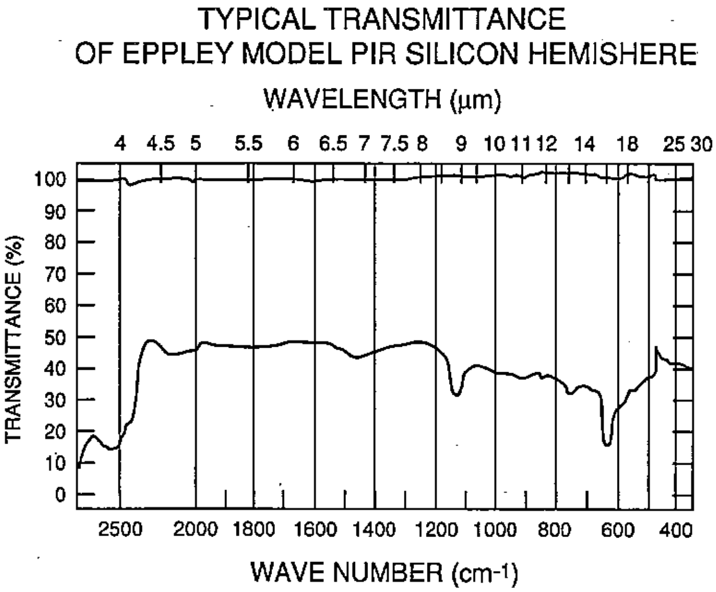

Figure 1: Passband of Eppley Silicon Dome

Table 2

Instrument Characteristics
NCAR/RAF Version of Eppley Model PIR Pyrgeometer

Receiver:	Circular 1 cm^2, coated with Parsons' black optical lacquer
Temperature Dependence:	± 1%, -20 to +40°C (nominal)
Linearity:	± 1% from - to 700 Wm^{-2}
Response Time:	2 s (63% response to step function)
Directional Sensitivity:	Better than 5% from normalization, insignificant for a diffuse source
Orientation:	No effect on instrument performance
Mechanical Vibration:	Capable of withstanding up to 20 g's
Calibration Method:	Black body reference

In the Eppley version of this radiometer the outputs of the sensors that monitor the sink and dome temperatures are used in an electronic circuit that modifies the thermopile output. This is necessary because the sink and dome each emit energy that influences the energy impinging on the thermopile. Although this compensation circuit works well in ground based installations, it does not in airborne applications. A review of the equation describing pyrgeometer response will help in understanding the application of the sink and dome temperatures to the derivation of irradiance.

Albrecht, *et al,* (1974) derived the relationship between the actual irradiance and the indicated irradiance, the sink temperature, and the dome temperature. That relationship is given here using RAF variable names:

$$\mathrm{IRC} = \mathrm{IR} + \varepsilon_0\sigma(\mathrm{TS})^4 - k\sigma((\mathrm{TD})^4 - (\mathrm{TS})^4). \qquad (1)$$

In this expression the quantity IRC is the corrected infrared irradiance (W/m^2). The quantity IR is the calibrated, amplified thermopile output (W/m^2), TD is the dome temperature (K), TS is the sink temperature (K), ε_0 is the emissivity of the blackened thermopile surface, k is the ratio of the dome material emissivity to transmissivity, and σ is the Stefan-Blotzmann constant.

Various investigators (e.g., Albrecht, *et al,* 1974 and Foot, 1986) have found the need to adjust the value of k in the expression for IRC. For this reason the RAF has provided direct measurement of sink and dome temperatures to allow investigators the possibility of further refinement of the corrections. In the RAF processing k is given a value of 4.3 (an average for in-house calibrations).

In flight situations the indicated temperatures of the sink and dome may lag the actual temperatures so that the term $k\sigma((\mathrm{TD})^4 - (\mathrm{TS})^4)$ in equation 1 represents a correction different from that which is actually appropriate. Griffith and Glover (1987) developed lag correction techniques that improved pyrgeometer performance, but these lack generality and are not included in RAF data processing.

Because of atmospheric attenuation and scattering, a large portion of the solar radiation in the pyrgeometer passband does not reach the surface. For this reason, there is no direct solar infrared radiation reaching ground level. However, at some flight levels it can be significant. Glover and McFarland (1991) reported on the need to be aware of the PIR sensitivity to direct solar IR and that the pyrgeometer is sensitive to the attitude of the aircraft with respect to the sun.

2.3 Ultraviolet Radiometer

This RAF radiometer, shown in Photograph 3, is a repackaged version of the Eppley Laboratories, Inc. model TUVR. The passband of this radiometer is .295 - .385 μm, which covers both the UV-A and UV-B bands. The Eppley components that have been incorporated are the diffusing disc, the detector, and the filter. Like the repackaging for the PIR and PSP radiometers the repackaging of this one was done for reasons of system compatibility. The height of the Eppley configuration is large in comparison to the PIR and PSP, and special precautions have to be observed in order to prevent the TUVR from shadowing the other two when used together. The RAF version of the TUVR is about the same height as the PIR and PSP. Consequently, these devices can now be mounted side-by-side without concern for shadowing.

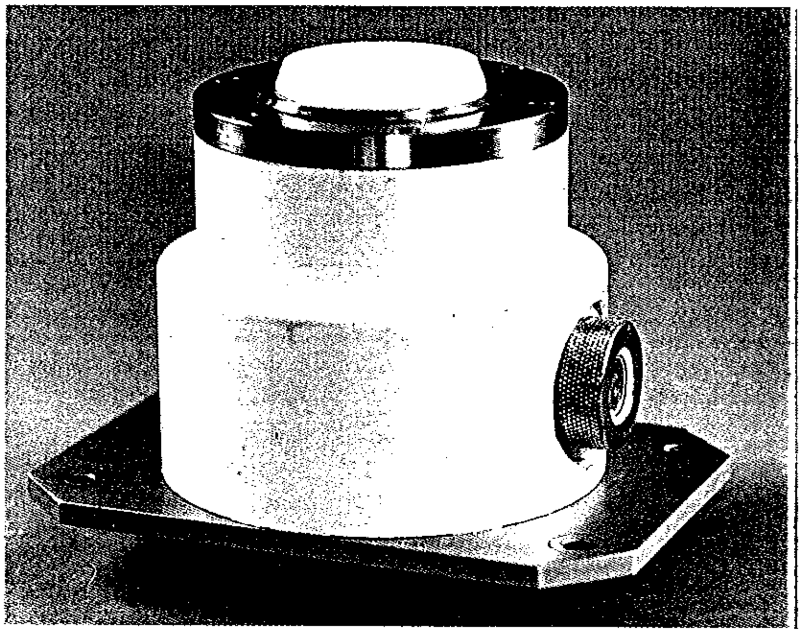

Photo by Bob Bumpas

Photograph 3: RAF Version of Eppley Model TUVR Radiometer

2.3.1 Design of the TUVR

Incoming radiation impinges on an opaque quartz disc where it is diffused and passed through to the filter and detector. The design of diffuser disc gives the instrument a cosign response to hemispheric radiation. Several centimeters behind the diffuser is the passband filter. It is an interference filter with a passband of .295 to .385 μm as shown in Figure 2 (on Page 8). Immediately behind the filter is the detector, a selenium barrier-layer photocell. The frequency response of the detector is shown in Figure 3. (The information in Figures 2 and 3 was provided by Eppley Laboratories.) Table 3 (on Page 8) lists the characteristics of the RAF version of the Eppley model TUVR. Experience with the TUVR at the RAF has indicated virtually no temperature sensitivity (actually, much less than the Eppley specification of 0.1%/C).

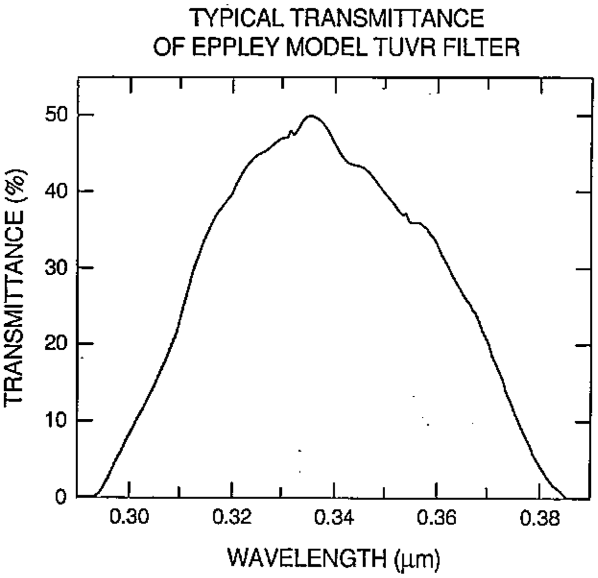

Figure 2: Passband of Eppley TUVR Filter

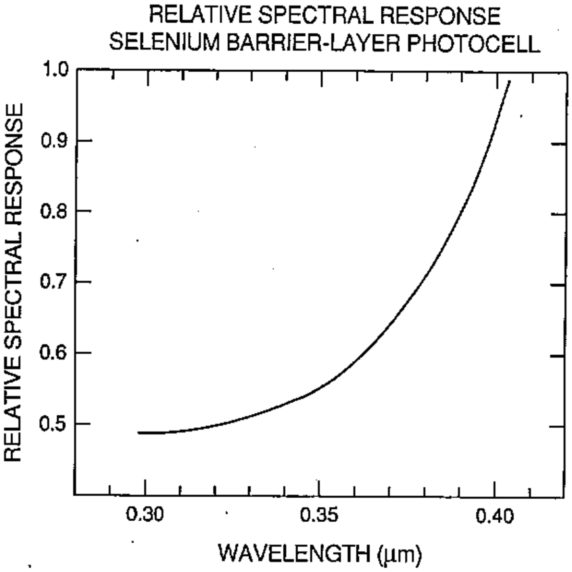

Figure 3: Response of Eppley TUVR Selenium Barrier Layer Photocell

Table 3

Instrument Characteristics
NCAR/RAF Version of Eppley Model TUVR Ultraviolet Radiometer

Temperature Dependence:	0.1%/°C from -40 to +40°C
Linearity:	± 2% from -0 to 700 Wm^{-2}
Response Time:	Milliseconds
Directional Sensitivity:	±2.5% from normalization, 0-70° Zenith angle
Orientation:	No effect on instrument performance
Mechanical Vibration:	Capable of withstanding up to 20 g's
Size:	146 mm diameter, 171 mm high
Weight:	1.8 kg

Just as the infrared and viable radiometers are periodically returned to Eppley Laboratories for calibration, the ultraviolet instruments are also. Also like the other two the TUVR has excellent stability. The calibration technique is based on work by Ångstrom and Drummond (1962). This technique exposes the radiometer to a NIST calibrated tungsten-iodine lamp. A combination of the spectral characteristics of the calibration lamp, the radiometer filter, and the radiometer detector is used to determine the sensitivity of the radiometer in the spectral band of .295 to .385 μm.

3. INFRARED THERMOMETER

3.1 Instrument Design

Airborne surface temperature measurements at the RAF are made with the Barnes Engineering Co. model PRT-5 Precision Radiation Thermometer. This device focuses the surface of interest (whether sea or land surface, or clouds) on a detector contained within a temperature controlled chamber. Before reaching the detector, radiation from the surface passes through a filter and focusing lens. The filter limits the passband to 9.5 to 11.5 μm or 8 to 14 μm and the choice of passband depends on the requirements of the project. The focusing lens limits the field of view of the instrument to 2°. A chopper blade outside the temperature controlled chamber modulates the radiation coming from the surface of interest before it reaches the detector. The blade, which is highly reflective in the infrared, presents the detector with a reflection of itself during the time when the target surface is obscured. Thus, the detector is alternately exposed to the target surface and a precision reference. All surface temperature measurements are made with respect to this reference. Electronic circuits process the difference between the detector output on alternate positions of the chopper to produce an indication of the surface temperature.

In some flight situations it is not possible to maintain temperature control of the reference. This is because aircraft mounting considerations allow for heat losses that cannot be compensated for. When this happens the reference temperature falls off and the instrument no longer makes accurate measurements. In order to provide investigators with information about when such accuracy loss occurs, the RAF has modified the PRT-5 to include a measurement of the chamber temperature. This temperature is not used to correct the instrument reading but is provided only to flag times when temperature control has been lost. The RAF did a calibration of the sensitivity of indicated surface temperature to changes in cavity temperature, this sensitivity, however, is not constant for all surface temperatures. For surface temperatures between 0 and 50°C and cavity temperatures between 39 and 48°C, the sensitivity (Δ surface temperature/Δ cavity temperature) is .9 ± .1.

The PRT-5 radiometers at the RAF receive periodic calibration at the RAF calibration laboratory. The reference for this calibration is the Eppley Laboratories, Inc. Infrared Blackbody Source model BB16T. This Black body has a temperature accuracy and uniformity of 0.1°C over the temperature range of -10 to +60°C. The emissivity is 0.995.

Although it is possible to do accurate calibrations on these radiometers, environmental effects of airborne usage degrade the useable accuracy of PRT-5 surface temperature measurements. In the final data processing, the RAF does not make any corrections to the raw PRT-5 output. The calibrated temperature output might be termed the apparent surface temperature. There are adjustments that can be made for water vapor between the surface and the aircraft, the radiative "blackness" of the surface, and the overhead sky conditions. These somewhat complex corrections are left to the judgement and skill of the investigator, since they must be handled on a case by case basis. A general discussion of these effects and their consequences is given by Church and Twitchell (1972). Table 5 summarizes the performance of the PRT-5.

Table 4

Instrument Characteristics

Barnes Engineering Co. Model PRT-5 Precision Radiation Thermometer

Equivalent Black Body Temperature Measurement Range:	-20 to +75°C
Accuracy:	± 1.0°C
Response Time:	0.5 s
Reference Cavity Temperature:	45°C ± 0.5°C
Operating Temperature Range (Ambient):	-20 to +40°C
Detector:	Hyperimmersed Thermistor Bolometer
Lens:	F.L. 10 mm, IRTRAN 2, F/2.8
Filter Spectra Bandwidth:	8 to 14 or 9.5 to 11.5 μm
Field of view:	2°

4. Spectral Vegetation Radiometer

The RAF has developed a vegetation radiometer based on the work of Bannehr (1990). This device measures surface radiances in three bands. A detailed description of this instrument, depicted in Photograph 4, is given in Bannehr and Glover (1992).

Vegetation has chlorophyll absorption bands in the 400 to 680 nm part of the visible spectrum. In this band incident radiation is absorbed and scattered by the photosynthetic pigment in the leaves. Beyond 680 nm and out to 750 nm the absorption is three or four times less than it is in the 400 - 680 nm band. Ground that is not covered with vegetation does not show a large change in spectral reflectance with wavelength. These different spectral characteristics of photosynthetically active plants and other surface types make it possible to classify the ground cover.

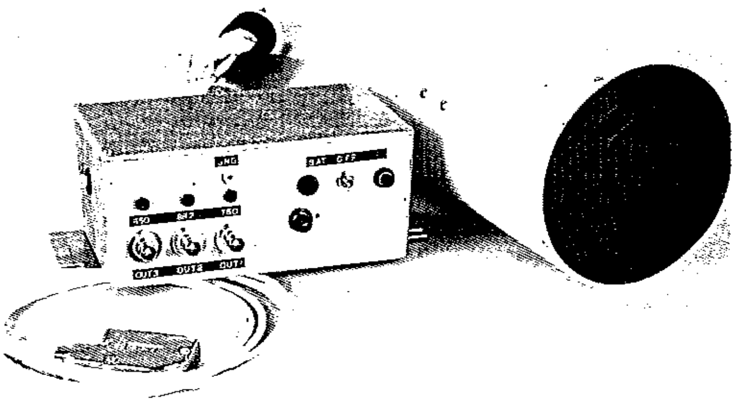

Photo by Bob Bumpas

Photograph 4: RAF Spectral Vegetation Radiometer

4.1 Design of the Spectral Vegetation Radiometer

The spectral vegetation radiometer is a three wavelength device. It uses three light barrels each with a optical filter and a detector. Ultraviolet enhanced silicon photo diodes are used as detectors. The field of view of the instrument is 2.3°. Each of the filters has a half bandwidth of 10 nm. Also, each has a quasi-monochromatic bandwidth as required by the ratio-Langley calibration technique described by Forgan (1986). The nominal wavelengths chosen for the radiometer are 650, 760, and 862 nm. At 650 nm extinction occurs by molecules, aerosols, and ozone. This wavelength is close to the chlorophyll absorption band. At 760 and 862 nm the radiance signals are affected by molecular scattering and aerosol extinction. The wavelengths 760 and 862 nm are outside the chlorophyll absorption bands of plant leaves and needles. Also these two wavelengths are outside of the spectral areas that have absorption by water vapor, which quantity varies drastically.

The output of each detector is amplified within the instrument housing. These high-quality amplifiers improve the noise immunity of the signals as is the case for the hemispheric radiometers. Three separate data system channels are required for recording these signals. Table 5 lists the characteristics of the Spectral Vegetation Radiometer.

Although there is not an generally accepted definition for the vegetation index, the RAF has chosen the Normalized Difference Vegetation Index (NDVI) to represent this quantity. It is defined as:

$$\mathrm{NDVI} = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$$

where ρ_1 and ρ_2 are the respective radiances of the wavelengths 650 and 862 nm. The 760 nm wavelength is included for research purposes and may be changed at the investigator's option.

Investigators should be aware that the NDVI is calculated from the radiance signals and not from reflectances as is usually the case with satellite data.

Table 5

Instrument Characteristics

NCAR/RAF Spectral Vegetation Radiometer

Size:	Diameter: 140 mm, Height: 270 mm, Weight: 5 kg
Opening Angle:	2.3°, variable by changing apertures
Sensor:	UV-BG 215 BQ silicon UV-enhanced photodiode
Inference Filters:	Nominal wavelengths: 650, 760, and 862 nm Bandwidth: 10 nm
Instrument Time Response:	Response from 0% to 99%: 24 ms
Output:	0V to 5V for each channel
Power:	±9V, 30 mA, operation either batteries of 110V

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Appendix Table A1

Representative Values for the Transmittance of Schott Filter Glass
(2.0 mm thickness, +25°C)

Wave-Length μm	WG295	GG395	GG400	GG495	OG530	RG610	RG630	RG695	RG715	RG805
.270	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	.41									
90	.60									
.300	.74									
20	.83									
40	.90	.00								
60	.91	.01	.00							
80	.91	.31	.01							
.400	.91	.68	.52							
20	.91	.82	.78							
40	.91	.87	.83	.00						
60	.92	.88	.87	.01						
80	.92	.88	.89	.27						
.500	.92	.89	.90	.80	.00					
20	.92	.90	.90	.88	.05					
40	.92	.90	.90	.90	.76					
60	.92	.90	.90	.90	.88					
80	.92	.90	.90	.91	.90	.00				
.600	.92	.90	.90	.91	.91	.33	.00			
20	.92	.90	.90	.91	.91	.83	.26			
40	.92	.90	.90	.91	.91	.89	.85			
60	.92	.90	.91	.91	.91	.90	.91	.00	.00	
80	.92	.90	.91	.91	.91	.91	.91	.27	.01	
.700	.92	.90	.91	.91	.91	.91	.91	.84	.25	.00
20	.92	.90	.91	.91	.91	.91	.91	.91	.74	.00
40	.92	.90	.91	.91	.91	.91	.92	.92	.89	.00
60	.92	.90	.91	.91	.92	.91	.92	.92	.91	.02
80	.92	.90	.91	.91	.92	.91	.92	.92	.92	.09
.800	.92	.90	.91	.91	.92	.91	.92	.92	.92	.34
20	.92	.90	.91	.91	.92	.91	.92	.92	.92	.68
40	.92	.90	.91	.91	.92	.91	.92	.92	.92	.84
60	.92	.90	.91	.91	.92	.91	.92	.92	.92	.88
80	.92	.90	.91	.91	.92	.91	.92	.92	.92	.89
.900	.92	.90	.91	.91	.92	.91	.92	.92	.92	.89
1.000	.92	.90	.91	.91	.92	.91	.92	.92	.92	.90
1.200	.92	.90	.91	.91	.92	.91	.92	.92	.92	.90
1.500	.92	.90	.91	.91	.92	.91	.92	.92	.92	.90
2.000	.91	.89	.90	.90	.90	.91	.91	.91	.91	.88
2.500	0.85	0.86	0.85	0.85	0.87	0.87	0.87	0.87	0.87	0.82
Center of cutoff (μm)	2.81	.385	.397	.485	.529	.603	.623	.686	.707	.807
Filter Factor	1.09	1.11	1.10	1.10	1.09	1.10	1.09	1.09	1.09	1.11

Variation of up to ±0.01 from these values of transmittance and of up to ±.002 μm in center of cutoff can occur.