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ABSOLUTE RADIOMETRIC CALIBRATION OF A SPECTROPOLARIMETER

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ABSOLUTE RADIOMETRIC CALIBRATION
OF A SPECTROPOLARIMETER

by

Kenneth Robert Castle

A Dissertation Submitted to the Faculty of the
COMMITTEE ON OPTICAL SCIENCES (GRADUATE)
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

1985
The University of Arizona
Graduate College

As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Kenneth R. Castle entitled Absolute Radiometric Calibration of a Spectropolarimeter and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

John A. Reagan  
Date  
May 20, 1985

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Date  
5/20/85

James M. Palmer  
Date  
5/20/85

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director  
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SIGNED: Kenneth Robert Castle
DEDICATION

I would like to dedicate this dissertation to a special group of people, whose help and encouragement has enabled me to pursue and complete the requirements set forth by the Committee on Optical Sciences (Graduate) for the degree of Doctor of Philosophy.

To My Family
ACKNOWLEDGMENTS

There are many people whose ideas and assistance enabled me to clearly define and direct my research, whom I would like to acknowledge at this time. First, Dr. Philip N. Slater, my principal advisor, who helped me determine the scope of my research; second, Dr. James M. Palmer, my secondary advisor, whose assistance in the lab, and pointed discussions, allowed me to conduct my research in a clear and definitive manner; and third, to my fellow members of the White Sands research trips, whose camaraderie and enthusiasm made all the hard work enjoyable.
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ABSTRACT

Two identical instruments have been developed for use in the field to make radiometric measurements. They have been described as spectropolarimeters because of their ability to make polarization measurements in narrow spectral passbands. They have been used as part of a NASA sponsored project to monitor the spectral and temporal response of the thematic mapper satellites. These satellites allow many natural and man-tended resources to be monitored over years of time, thus allowing their use to be planned for in the future.

The dissertation discusses the design, fabrication, testing and absolute radiometric calibration of these spectropolarimeter instruments. The outstanding feature of these instruments are that they have been calibrated absolutely, for radiance measurements, to an accuracy of \( \pm 2\% - 3\% \), in the range of 400 nm to 1040 nm over selected spectral passbands. Previously, field measurements were considered good if they had an absolute accuracy of \( \pm 10\% \), implying that the present accuracies are advancing the state-of-the-art for field instrument calibrations. These improved accuracies are the result of using two recently developed calibration standards, both of which use detector based methods. These standards are the Electrically Calibrated Pyroelectric Radiometer (ECPR), and the QED-100 quad detector.

The end of the dissertation discusses the attempts made to verify that the accuracies claimed are indeed valid, and it is the author's belief that these accuracies have been verified completely.
CHAPTER 1

INTRODUCTION

This dissertation covers the aspects of radiometric calibration as applied to a specific instrument, a spectropolarimeter. However, the context in which this was done must also be noted in order to appreciate the decisions that were made in the course of this work. This chapter gives a brief overview of the satellite sensor calibration project for which the spectropolarimeter was developed.

The objective of the project is the absolute radiometric calibration of the in-orbit Thematic Mapper systems on Landsats 4 and 5, and the French SPOT system, using a ground site of known reflectance as a reference target. The Landsat 4 and 5 satellites are part of the remote sensing program initiated by NASA in 1972 with the launch of Landsat 1. The goal of the program is to provide low resolution (30m - 80m) imagery of the Earth's surface for use in a variety of disciplines, from agricultural studies in forestry and farming, to geological studies such as the identification of mineraly enriched outcrops and linear feature analysis (fault lines), to hydrological studies such as natural and man-made water pollution. Current studies have mainly used band ratioing to analyze the sensor data, where one spectral band's digital counts are divided by another's covering the identical ground feature. More recent research and modelling by scientists have shown a need for knowing the absolute radiance detected by the sensor in addition to the
relative digital count output gathered to date. The ratio of the radiance at the entrance pupil of the satellite sensor to the digital counts output is referred to as the absolute calibration factor of the sensor. It requires that the response of the total system be determined over the lifetime of the sensor system, thus allowing temporal continuity to be maintained for a single sensor. In addition to providing a calibration factor for single scene data, absolute calibration also allows for the intercomparison of the responses of different sensor systems, thus allowing the user community to utilize the data more effectively from many sensor systems.

It has been decided to perform the absolute calibration of Landsats 4 and 5, and the French SPOT system, from the ground at White Sands, NM. This site was chosen for its large, bright, flat geometry, its nearness to the University of Arizona, and the support available from the personnel at the White Sands Missile Range. To perform the required calibration calculations has meant the use of a sophisticated radiative transfer computer program developed in the Atmospheric Sciences Department at the University of Arizona (Herman and Browning 1975). This program allows us to calculate the effects that the atmosphere and ground have on the radiance that reaches the entrance pupil of the satellite sensor. Obviously the computer program requires data for input and this is where the spectropolarimeter instrumentation discussed below is needed.
To date, a solar multiband radiometer (Shaw 1973) and a reflectance multiband radiometer (Robinson, et al 1979), have been borrowed to collect the data, but these instruments suffer from four limitations:

1. The accuracy with which the instruments have been absolutely calibrated
2. The temporal accuracy with which the data can be collected
3. The difficulty of manually operating these instruments
4. Lack of an ability to make polarization measurements

It has been suggested (Herman 1983) that it may be necessary to take polarization into account if the desired accuracy of 3 - 5 percent is to be achieved.

It was with all these factors in mind that the author was encouraged to effect the design, fabrication, testing and absolute radiometric calibration of a spectropolarimeter system with which to make measurements of the sun, sky, and earth's surface as needed. In the chapters that follow, the author describes the factors that affected the instrument design criteria, presents a general overview of the instrumentation, and describes in detail the calibration procedures implemented. Finally, the results of the calibration will be presented followed by actual field measurements recorded by the spectropolarimeters.
CHAPTER 2

ATMOSPHERIC PARAMETER AND POLARIZATION THEORY

This chapter presents some theoretical considerations concerning parameters used to describe the atmosphere, and also explains how polarization within the atmosphere arises. These are not rigorous treatments, but instead are intended to provide an overview of the subjects. For further reading, the reader will be directed elsewhere.

Radiometric Considerations

To perform the satellite sensor calibration, one must be able to relate the power received at the entrance pupil of the sensor to the digital counts transmitted by the sensor. NASA supplies the latter in their raw, uncorrected form, so the experiment has as its goal determination of the former. To start, one must ask the question "How does the input power arise?" If the earth had no atmosphere the answer would be simple, namely direct reflection off the earth's surface. The equation describing the spectral power at the satellite would then be (assuming a flat, horizontal surface):

\[ \phi_{\lambda} = E_{\lambda} \cos \theta_Z \cos \phi_Z \cos \phi_S \cos \theta_s A_s S_s \]  

(2.1)

where: \( E_{\lambda} \) = exoatmospheric solar spectral irradiance; \( \theta_Z \) = solar zenith angle; \( \phi_Z \) = solar azimuthal angle; \( \theta_s \) = sensor
zenith viewing angle; \( \phi_s \) = sensor azimuthal viewing angle; \( A_s \) = satellite entrance aperture area; \( \Omega_s \) = solid angle subtended by the instantaneous field of view (IFOV) at the sensor system; and \( \rho(\lambda; \theta_z, \phi_z, \theta_s, \phi_s) \) = spectral bi-directional reflectance distribution function of the surface.

This equation assumes \( \Omega_s \) is small such that \( \theta_s \) and \( \rho(\lambda) \) are constant across the IFOV. If we assume the surface to approximate a Lambertian surface (radiance is constant with viewing angle) and that the sensor observes from near nadir, then

\[
\phi_{s\lambda} = \frac{E_s \lambda \cos \theta_z \rho(\lambda) A_s \Omega_s}{\pi}
\]  

(2.2)

A similar quantity of interest is the radiance at the sensor and this is expressed as

\[
L_{s\lambda} = \frac{\phi_{s\lambda}}{A_s \Omega_s} = \frac{E_s \lambda \cos \theta_z \rho(\lambda)}{\pi}
\]  

(2.3)

As \( L_{s\lambda} \) is the desired value, the only quantities which would need to be measured are on the right side of Eq. 2.3.

However, it is not this simple out in the field. The earth is surrounded by an atmosphere that both scatters and absorbs incident radiation. The net effect is that the radiance in Eq. 2.3 must be
reduced due to this attenuation by the atmosphere, and another term must be added to account for the scattered light entering the IFOV. This additional term is referred to as the path radiance and accounts for all the non-direct radiance terms. Examples of paths that the incident radiation might follow are shown in Fig. 2.1. These include: 1) light that directly strikes the surface and then reflects directly into the sensor; 2) light which never strikes the surface and so is independent of the surface reflectance; 3) light that is scattered and then reflects directly into the IFOV, and 4) light which directly strikes a different portion of the surface and is then scattered into the IFOV. Unless the observed surface is very large, the \( \rho(\lambda) \) value may be very different. Other higher order terms also contribute, but those outlined above are the major ones. Two points to be noted are:

a) When \( \rho(\lambda) = 0 \), over the entire irradiated surface, the sole radiance term measured by the satellite sensor is due to solar flux scattered only by the atmosphere. All the other terms are zero. In this case, it is usually sufficient to know only the backscatter characteristics, as most of the forward scattered light is absorbed by the surface.

b) When \( \rho(\lambda) \) is nearly unity, a large fraction of the incident light will be returned to the atmosphere. This indicates that the atmospheric parameters governing scattering and absorption should be well characterized, particularly the angular parameters of scattering as a function of angle.
Figure 2.1 Major Radiance Beam Paths

PATH | TYPE
--- | ---
1 | DIRECT–DIRECT RADIATION
2 | DIFFUSE RADIATION
3 | DIFFUSE–DIRECT RADIATION
4 | DIRECT–DIFFUSE RADIATION
Some computer programs have been developed to model the effects that the atmosphere and surface have on incident radiation (e.g. Dave and Gazdag (1970), Herman and Browning (1975), Plass and Kattawar (1968)). In this study, the program developed by Herman and Browning was used; the major parameters required for input will be discussed below.

Optical Depth

\( \tau(\lambda) \) is the spectral optical depth and is a measure of the attenuation of the atmosphere. It can be separated into two terms, \( \tau_s(\lambda) \) and \( \tau_A(\lambda) \) which represent the scattering and absorptive optical depths respectively. The equation relating these three quantities is simply

\[
\tau(\lambda) = \tau_s(\lambda) + \tau_A(\lambda)
\]  \hspace{1cm} (2.4)

Note the dependence on wavelength \( \lambda \). In general, all of these values vary as a function of \( \lambda \). To see how \( \tau(\lambda) \) arises, consider the following. Imagine that a beam of light (\( E_0 \)) is incident normal to the surface of a slab of an attenuating medium (Fig. 2.2). Assume the slab has an attenuation value of \( \beta \) units of light per unit thickness of the medium. After traversing the slab of thickness \( z \) the resultant beam has a value \( E \). We may express this arithmetically as

\[
(E - E_0) = \Delta E = -E_0 \beta z
\]  \hspace{1cm} (2.5)
The minus sign arises from the fact that $E < E_0$. For small $z = dz$, this approaches the differential form

$$dE = -E \beta dz \quad (2.6)$$

$$\frac{dE}{E} = -\beta dz \quad (2.7)$$

Integrating Eq. 2.7 from $E$ to $E_0$ on the left and 0 to $z$ on the right, we get
\[
\ln(E) - \ln(E_o) = \ln\left(\frac{E}{E_o}\right) = -\int_0^Z (\beta dz)
\] (2.8)

Taking the exponential of both sides yields

\[
E = E_o \exp\left(-\int_0^Z (\beta dz)\right)
\] (2.9)

Defining

\[
\tau = \int_0^Z (\beta dz)
\] (2.10)

we finally get

\[
E = E_o \exp(-\tau)
\] (2.11)

For radiation entering the slab at an angle \(\theta\) from the normal, Eq. 2.11 can be shown to have the following form

\[
E = E_o \exp(-\tau/cos\theta) = E_o \exp(-\tau sec\theta)
\] (2.12)
This is the well-known Lambert-Beers law and holds true for small values of $\tau$ and $E_0$. As $\tau$ is increased, effects such as multiple scattering into the emergent beam occur, and at this point Eq. 2.12 requires higher order terms.

Surface Reflectance

$\phi(\lambda)$ is the surface spectral reflectance and the radiative transfer program assumes the surface to be infinite in extent, flat, uniform in $\phi(\lambda)$, and Lambertian. This last constraint implies that $\phi(\lambda)$ falls off as $\cos \theta$. In the field these conditions generally are not valid. However, if an observation site is carefully selected, the above conditions can be seen to be good approximations. Portions of White Sands Missile Range in New Mexico contain such sites, and it is here that most of the experimental efforts have been focussed.

Particulate Parameters

The atmosphere is contaminated by particulates and for the radiative transfer program to account for their interaction with light, a number of parameters must be known. These are:

$$n_\lambda = m_\lambda + ik_\lambda$$
the complex index of refraction of particles

$f(r)$
the number distribution of particles as a function of radius

$q(z)$
the distribution of particles as a function of height $(z)$ above the surface
Other important parameters are:

\[ P(z) \] the barometric pressure at the observation site (influences molecular optical depth)
\[ \lambda \] the wavelength of interest
\[ \theta_z \] the solar zenith angle

Of these parameters, only \( \tau(\lambda) \), \( \rho(\lambda) \), \( P(z) \), and \( \theta_z \) are measured; for the others, certain average values are assumed. Usually it is assumed that \( q(z) \) follows the distribution outlined by Elterman (1968), and that \( f(r) \) follows a Junge distribution (Junge 1960) with a value \( \nu = 2.5 \), and the complex index = \( 1.48 - .005i \) (Reagan, et al 1984a). Ongoing attempts are being made to extract \( f(r) \) from observational data (see King 1978). The field measurements are made in the following way:

\( P(z) \) is measured with an accurately calibrated barometer
\( \theta_z \) is calculated using a computer program developed by J. A. Reagan (Reagan 1981), which requires as input the site latitude, longitude, elevation, and time of the measurement.

\( \rho(\lambda) \) is measured by comparing the radiance values of a known target to those of the actual site. Assuming the target reflectance to be known absolutely, then the ratio will give the site reflectance absolutely. The most accurate method to make these measurements is to measure the target values immediately before and after each site measurement in order to reduce errors introduced by changes in
atmosphere or solar zenith angle. The largest error is due to not knowing accurately the target's reflectance.

\( \tau(\lambda) \) is the result of a linear least-squares fit to the measured irradiance data. These data consist of irradiance measurements of the sun as a function of time. The output voltage measured is proportional to the irradiance observed and so the usual practice is to use the voltage measured, especially when uncalibrated instrumentation is used.

Solving Eq. 2.12 for \( \tau \) yields

\[
\frac{\ln(E) - \ln(E_0)}{\sec^6 z} = \tau
\]  

(2.13)

From this equation it can be seen that if \( \ln(E) \) is plotted versus \( \sec^6 z \), the slope of the resultant line is equal to minus \( \tau \). This graph is known as a Langley plot, a representative example of which is shown in Fig. 2.3 (a more detailed discussion can be found in Kobayashi (1981)). In general, the values of reliable data occur for \( 1 \leq \sec^6 z \leq 6 \). The value of \( \sec^6 z \) is more generally defined as the airmass looked through; thus, the vertical distance from sea level, at standard temperature and pressure, to an exoatmospheric point, is equal to an airmass of one. When airmass > 6, inaccuracies occur, due to inhomogeneities in the long atmospheric path lengths and refraction. For airmasses < 1, the data must be collected at higher elevations, such as the top of a mountain or a balloon supported platform. Note that for these values, \( \sec(\theta) \) is never less than one; thus, the airmass must be measured as a proportion
Figure 2.3 Typical Langley Plot

SLOPE = $-\tau_\lambda$

Y-INTERCEPT = $\log_e(V_0)$

$V_0 \propto E_0$

$E_0 = $ EXOATMOSPHERIC IRRADIANCE
of the actual amount of vertical atmosphere to the amount associated with an airmass of one.

In order to achieve the highest accuracy, a narrow spectral filter must be used to isolate the wavelength of interest. Use of a narrow filter minimizes errors arising from solar spectral variations and spectral variations in the atmospheric attenuation function. Additional errors may arise if the instrumentation used has a tracking error such that it is not pointing directly at the sun for each measurement.

One more quantity of interest which is needed for the calibration procedure, but not for the radiative transfer calculations, is the exo-atmospheric spectral irradiance. Data currently exist accurate to nearly 1 percent (Neckel and Labs 1981) which could be used after being properly scaled to account for sun-earth distance variations. A separate method could also be employed by simply determining the y-intercept of the Langley plot - this value equals \( \ln(E_{o\lambda}) \). This requires that the instrumentation be absolutely calibrated radiometrically. This process could give the value of \( E_{o\lambda} \) more accurately if successful, provided the absolute calibration is performed to < 1.0% uncertainty. Scattering also contributes to the polarization of light, and this will be considered below.
**Scene Polarization**

Electromagnetic radiation can be represented by oscillating electromagnetic fields. Detectors only measure the E field, and in the discussions which follow, it will be the only field considered.

The instrumentation developed for the in-flight calibration of the Thematic Mapper has been designed to measure the amount of radiation from three sources: the sun, the surface, and the sky. For the solar case, radiation is emitted by randomly oriented sources at the sun and hence there is no preferred direction of oscillation. Sometimes the oscillations will be in the x-direction, other times in the y-direction, and most of the time somewhere between. Thus, there is a random distribution to the oscillation direction. Since we can always decompose a particular oscillation direction into x and y components, it can be said that there is no fixed phase relationship between the x and y oscillations. The category that this radiation falls into is that of unpolarized radiation. When a measurement of the sun is made, it is a "long-term" one, which will tend to average out the temporal changes in oscillation direction. If a polarizer is placed in the beam, one would expect the same output regardless of the orientation of the transmission axis. Thus the x-direction measurement equals the y-direction measurement.

The reflected radiation from most surfaces is unpolarized (for near-normal incidence and viewing), exceptions being large, flat, single surfaces (such as the surface of a lake). Generally, the smoother the surface, the more polarization is evident. Depolarizing surfaces are generally composed of very small, randomly oriented particles which
scatter and reflect the incident radiation many times. The gypsum at White Sands, N.M. is a fine example of this surface type. To further ensure that the measured radiation is unpolarized and of a uniform radiance, a moderate field-of-view should be employed when making a measurement (5 to 15 degrees) in order to spatially average the scene. Additionally, the ground dimension must be much larger than the size of the average scatterer, and if a choice of 10 cm diameter is made (approximately 100 times the diameter of a grain of gypsum), the surface should then be viewed from a height of at least 1.5 meters using these FOV's.

This leaves the sky radiance to be considered, and indeed it appears to be polarized to some degree. The atmosphere is composed of two types of particles; molecules whose dimensions are much, much smaller than the wavelength of the incident radiation, and particulates whose size is comparable to that of the radiation wavelength. These two sizes contribute to what are known as Rayleigh and Mie (or aerosol) scattering respectively. Consider the Rayleigh condition first.

Rayleigh Scattering

These molecules are essentially freely oscillating with no intermolecular binding force to hold them together; they move and oscillate in all directions. A molecule can be thought of as a central positive charge surrounded by a cloud of negative charge. When the electric field of a passing beam of light interacts with the molecule, it causes a displacement of these two charge groups transverse to the beam direction (the plane of the electric and magnetic fields) forming a
dipole charge distribution. We can consider these "induced" dipoles as absorbing and re-emitting photons and that the interaction of radiation with these dipoles gives rise to the scattering process. One significant feature of dipole radiation is that dipoles do not radiate along their axes. The importance of this will be shown below.

Consider the following geometry (Figure 2.4): the sun at a zenith angle \( \theta_z \) and the observer on the ground looking up at zenith angle \( \theta \) and azimuthal direction \( \phi \) (the sun is at an azimuth of \( \phi_s = 0 \)). Assume the \((\theta, \phi)\) coordinates to be restricted to a plane which is perpendicular to the observer's line-of-sight to the sun. The angle contained by the sun, \((\theta, \phi)\), and the observer is 90 degrees and it would be expected that dipoles within the plane containing this angle would be viewed as well as those dipoles perpendicular to it. From the discussion above it is clear that only those dipoles oriented perpendicular to this plane would radiate in the direction of the observer. Therefore, the light would be 100\% linearly polarized perpendicular to this plane.

This conclusion assumes that only single scattering is occurring. If multiple scattering occurs, it is clear that there can be many different input directions for the dipoles along the line-of-sight in the \((\theta, \phi)\) direction. Thus, the radiation received will have a reduced linear component (multiple scattering implies larger extinction factor) plus a roughly unpolarized component. It may be concluded that a pure Rayleigh atmosphere would show a highly polarized scattering profile in a band 90 degrees from the sun falling off to unpolarized light in the direction of the sun. The amount of polarization will vary as a function of optical
depth, implying that radiation in the blue portion of the spectrum will be polarized less than that in the near-IR due to multiple scattering effects. Also, radiation from near the horizon will be polarized less for the same reason.

Aerosol or Mie Scattering

Unfortunately, the atmosphere is not composed only of molecules; rather it has a distribution of larger particles as well which are normally found in the lower atmosphere. These aerosol scatterers are primarily due to sulphuric acid, wind-blown crustal dust, man-made
pollution, and ash from volcanic eruptions. Aerosol scattering is a much more complicated process than simple Rayleigh and an in-depth discussion is beyond the scope of this dissertation. Some references to be used for more information are van de Hulst (1957) and McCartney (1976). A monodispersion (all particles having the same radius) of aerosols would be observed to have a very large forward scattered component, perhaps with side-lobes at specific off-axis angles. These angles depend on the wavelength/particle size ratio. If these aerosols form a polydispersion, then the wavelength dependent side-lobes will smear together producing the typical aerosol scattering curve shown in figure 2.5. This figure also shows the Rayleigh scattering profile (these curves are also known as scattering phase functions).

In addition to this, aerosols are usually composed of materials with an index of refraction that is sometimes complex and always much different from that of the surrounding gas. Values generally range from 1.33-1.65. The complex index indicates some absorption is occurring and represents a new attenuation process to consider. These complex indices may also introduce right- or left-handedness to the beam by creating elliptically polarized light. Most investigators assume the amount of ellipticity to be negligible. Figure 2.6 illustrates the concept of linearly and elliptically polarized light.

In general, aerosols tend to depolarize incident radiation, so it would be expected that the amount of polarization present in the skylight would be less than that due to a pure Rayleigh atmosphere. Additionally, there exist points in the sky where polarization minima occur. Obviously the polarization is zero at the solar and anti-solar
Figure 2.5 Rayleigh and Mie Scatter Profiles (Phase Functions)

Figure 2.6 Visualization of Linearly and Elliptically Polarized Light
positions, but there exist other points in the sun-observer plane where it is a minimum. These points are the Arago, Babinet and Brewster points (see McCartney) and their location is a function of the aerosol properties. As these properties vary, so too do the position of the minima points. It may be possible to extract information concerning the aerosol scatterers by measuring the positions at which the minima occur.
CHAPTER THREE

DESIGN OF THE SPECTROPOLARIMETER

The design of the instrumentation was divided into three phases. The first phase identified the performance required of the instrument based on the field measurements which were to be made. In the second phase, components were selected to meet the established performance requirements. Finally, the components were arranged in a system layout in a manner which best achieved the desired results. This chapter describes these three phases as applied to the design of the spectropolarimeter.

Phase One: Performance Requirements

1) Spectral coverage – the instrument should make measurements in selected areas of the visible and near-IR spectral regions in order to adequately cover the spectral regions utilized by the spectral bands of the satellite sensor. For the case of the Landsat satellites, the spectral regions of interest lie between 0.4 and 1.0 μm, plus bands at 1.6 μm and 2.2 μm.

2) Polarization capability – due to the lack of detailed knowledge of the effects which polarization might have on the data analysis, a decision was made that the instrument should make measurements relating to the polarization parameters of any incident radiation, particularly the linear and elliptical components. This feature should prove to be most useful when surveying the sky.
3) Large signal-to-noise ratio - noise represents an error in the measurement and is observed as random fluctuations in the output signal. If the signal is large compared to these random fluctuations, then it is relatively easy to extract the true signal. It was decided that a signal-to-noise ratio of 100:1 (i.e. the signal is 100 times larger than the noise) would be an acceptable standard for the instrumentation to meet. This would imply a measurement error of 1%. 

4) Large target dynamic range - It had been suggested that the proposed targets (the sun, the sky, and the earth's surface) comprise a dynamic range variation of $10^5$ (see Henderson 1970). The 12-bit A/D chosen to digitize the data has a dynamic range of 4000 (40 if a signal-to-noise ratio of 100:1 is desired where noise represents an error of 1 count). Therefore, additional attenuation is required.

5) Multiple fields of view - different fields of view (FOV) should be provided in order to best collect the three different types of data. For example, a 1 degree FOV should be used when making solar measurements to limit the incident radiation to that of the sun whereas a 5 - 15 degree FOV should be used to do large scale averaging when making surface radiance measurements. 

6) Automated instrument operation - lack of an accurate knowledge of the precise time of measurement was one of the main problems faced in the preliminary field measurements using manual instrumentation. In order to improve the measurement accuracy, the instrument should be driven by a computer with an on-board clock and the time should be recorded at the same moment that a datum was measured. In addition, it would be more efficient if the computer operated the
instrumentation and recorded the position settings of all filter wheels, etc. thus enabling the operator to do other tasks.

7) Portability - the instrument should have its own power supply, thus implying battery operation. Therefore low-power electrical components should be used. Provisions should be made for the use of standard line voltage contingent upon its availability.

8) Durability - the instrument would be used extensively in the field and would need to be built to withstand the vibrations encountered when hard-mounted to a helicopter.

9) Backup operation - to serve as a backup as well as to collect data on its own, a second instrument should be built in tandem with the first.

**Phase Two: Component Selections**

1) A silicon photodiode was chosen as the detector because it has a large dynamic range, a relatively simple operational circuit, and is extremely rugged, thus suiting it to field work. Its disadvantage is that it has a limited spectral range (0.35 - 1.10 μm).

2) Due to the detector choice above, the spectral range was chosen to be from 0.4 μm to 1.04 μm in discrete intervals using bandpass filters. A nominal bandwidth of 10 nm was chosen as a starting point for radiometric calculations with the appreciation that these could be changed as needed in order to insure that the voltage into the A/D remained within a selected range.

3) A Glan-Thompson polarizer was chosen for the polarization measurements because of its large acceptance cone angle of 15 degrees
and high extinction ratio of $10^5$. It also could be rigidly mounted and so seemed well suited for field work.

4) A mica retarder was chosen as the waveplate which would be used in conjunction with the polarizer mentioned above. It is well known (eg. Shurcliff 1962) that these two components are needed when determining the polarization properties of the incident radiation. A discussion of their use is found later in this chapter.

5) Four field of views were originally chosen, again with the appreciation that these could be changed at a later time based on further analysis. Their nominal values were 1, 2, 5, and 15 degrees with the 1 or 2 degree FOV to be used for solar radiometric measurements, the 1 and 2 degree FOVs for the sky measurements near the sun, the 5 degree field for sky scans far from the sun, and the 5 and 15 degree FOV for measurements of the earth's surface and comparison targets.

6) A Radio Shack TRS-80 Model 100 computer was chosen to operate the instrument due to its portability, a maximum of 32K of memory, battery operation, availability of external ports, and its user-friendly BASIC language.

7) Based on calculations, it was found that the detector would be operating at the lower end of its dynamic range. This is an area where the detector output starts to become non-linear. It was decided to limit the detector input, thus limiting the dynamic range to a small region. Over this small region the detector output remains linear. To increase the dynamic range of the system, a series of neutral density filters were chosen to attenuate the incident radiation to the proper level. The final choices were deferred until after some calculations
and experiments were performed; the original choices were ND = 0, 1, 2, 3, and 4.

8) Lightweight stepper motors from the Hurst Motor Company were chosen to drive the system, partly because of their light weight, but also because Hurst manufactures an IC chip which performs all the logic routines required in the operation of these motors. Two stepper motor models were needed, one for which the steps were in increments of 7.5 degrees to rotate the filter and field stop wheels, and the other with 1.5 degree steps to rotate the polarizer.

9) High speed CMOS integrated circuits were chosen as the logic components. They were low in power consumption and so were compatible with battery operation of the instrument.

These were the components selected for use in the instruments. The next step was to perform radiometric calculations in order to define the components which were not yet specifically selected.

Spectral Filter Selection

The choice of the spectral filters to be incorporated into the instruments was based on the examples set forth by Shaw (1982). The data base incorporated in the LOWTRAN V program (Kneizys 1980) was first examined because it listed the many absorptive gases present in the atmosphere including O₂, H₂O vapor, and O₃ (ozone). These three constituents are the primary absorbers in the region of the spectrum which is used by the instruments. A graph of the LOWTRAN V output is shown in Figure 3.1 for a typical atmosphere. A design goal was set to use a sequence of 10 spectral bands with the following usage in mind.
1) 5 or 6 bands which are free of gaseous absorption. These bands will allow the extraction of the aerosol spectral optical depth curve after the Rayleigh and ozone components are subtracted (see King 1978).

2) 2 or 3 bands in the Chappuis ozone band to aid in the determination of the ozone optical depth.

3) 1 or 2 bands in the water vapor bands to determine the water vapor optical depth.

4) 1 band in an oxygen band to account for the oxygen optical depth.

After careful analysis of the LOWTRAN V data, it was determined that an oxygen filter would not be needed as the oxygen spectral bands are very narrow and not very strong, thus having a negligible effect upon the measurements. Also, it seemed necessary to only have one water vapor filter in the deep water vapor band near 0.94 μm in order to characterize the effects of water vapor. Most of the satellite sensor spectral bands attempt to avoid water vapor bands and so water vapor absorption should not affect the calculations to a large degree.

From a graph in Kondratyev (1969), shown in Figure 3.2, information was found concerning the ozone absorption profile. Notice that although the ozone band does not have a large optical depth contribution, it is a very broad feature and may affect many of the satellite sensor bands to some degree. Therefore, it was decided to pick three filters, one at the ozone band center, and two near the 1/e
Figure 3.1 Atmospheric Transmittance vs Wavelength from LOWTRAN V
points. Specifying the filter locations in this manner should help to readily determine the ozone optical depth.

This allows six filters to be placed in regions of little or no absorption with the latter condition being preferable. A typical optical depth curve is shown in Figure 3.3 and shows $\tau_\lambda$ versus $\lambda$. Note the steepness of the curve in the blue spectral region. It would seem advantageous to be able to accurately define the curve at this point so three of the filters were chosen to lie in this region. The other three are located in the near-IR regions beyond 0.7 µm. A summary of the positions of the filters is given below.
1) Non-absorptive range - 0.400, 0.420, 0.440, 0.780, 0.860, and 1.040 μm
2) Chappuis ozone absorption band - 0.525, 0.604, 0.660 μm
3) The ρ, σ, τ water vapor band - 0.948 μm

The next design factors to be determined were the bandwidths to be used by each filter. In order to get the most accurate data it is necessary to use very narrow filters, but the obvious tradeoff is the amount of light passed by the system. A narrow filter is not effective if the output signal-to-noise ratio is too low. As a starting point, 10 nm was chosen as a typical bandwidth in the calculations. Figure 3.4

![Figure 3.3 Typical Optical Depth Variation vs Wavelength](image_url)
shows the spectral distribution of sunlight at the top of the atmosphere from 0.375 μm to 1.100 μm multiplied by a typical responsivity curve for a silicon photodiode. This implies that the detector output is roughly constant from 0.550 to 0.800 μm but drops by a factor of three by the 1.0 μm and 0.4 μm points. It would seem judicious then to increase the bandwidths of the near-IR bands in order to make the detector signal roughly a constant for all wavelengths. This would not work as well for the blue bands as the solar spectral variation is not nearly as flat. Therefore the three bands 0.860, 0.948, and 1.040 μm have bandwidths of 15, 20 and 20 nm respectively. These bandwidths are actually larger than necessary for solar observations, but are more suitable for observations of the sky. When the filters were ordered, an additional tolerance was added of 10^5 rejection in the out-of-band wings.

ND Filter Selection

In order to confirm that these bandwidths are appropriate, some calculations were made to predict the maximum and minimum signal currents out of the detector. The following tables show the results of the calculations. Table 3.1 shows the case of maximum expected signals and assumes the exo-atmospheric sun as the source of the incident radiation. In practice, the solar values measured should be less than these, due to atmospheric attenuation. Table 3.2 shows the case of radiation reflected from a surface with a Lambertian reflectance of 0.05 and Table 3.3 covers the case of skylight for low sun elevation angles. This last case assumes that only 10% of the light scatters at large angles. These last two conditions represent the typical minimum signals
Figure 3.4  Solar Spectral Irradiance Modified by Detector Responsivity

that the instruments should deliver with a SNR of 100. In this case noise is assumed to be a 1 count error, so a minimal signal of 100 counts should be observed out of the A/D.

As indicated by these calculations, the difference between the maximum and minimum expected values approaches $10^5$ (a factor of nearly 10 in $I_{\text{Sig}}$ as well as $10^5$ from the ND = 4.0 filter ($T_{\text{ND}} = 0.0001$)) which was expected from the literature. Therefore, the choices of the neutral density filters has been substantiated.
### Table 3.1 Maximum Expected Values Due to Solar Irradiance

<table>
<thead>
<tr>
<th>$\lambda$ ((\mu\text{m}))</th>
<th>$\Delta\lambda$ ((\mu\text{m}))</th>
<th>$E_A$ (mW/cm(^2))</th>
<th>$E$ (mW/cm(^2))</th>
<th>$\phi_{\text{det}}$ (nW)</th>
<th>$R$ (A/W)</th>
<th>$I_{\text{sig}}$ (na)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.400</td>
<td>0.010</td>
<td>147.0</td>
<td>1.470</td>
<td>104.2</td>
<td>0.20</td>
<td>20.8</td>
</tr>
<tr>
<td>0.420</td>
<td>0.010</td>
<td>172.4</td>
<td>1.724</td>
<td>122.2</td>
<td>0.20</td>
<td>24.4</td>
</tr>
<tr>
<td>0.440</td>
<td>0.010</td>
<td>183.6</td>
<td>1.836</td>
<td>130.1</td>
<td>0.21</td>
<td>27.3</td>
</tr>
<tr>
<td>0.525</td>
<td>0.010</td>
<td>187.2</td>
<td>1.872</td>
<td>132.7</td>
<td>0.31</td>
<td>41.1</td>
</tr>
<tr>
<td>0.604</td>
<td>0.010</td>
<td>175.0</td>
<td>1.750</td>
<td>124.0</td>
<td>0.40</td>
<td>49.6</td>
</tr>
<tr>
<td>0.660</td>
<td>0.010</td>
<td>154.0</td>
<td>1.540</td>
<td>109.2</td>
<td>0.47</td>
<td>51.3</td>
</tr>
<tr>
<td>0.780</td>
<td>0.010</td>
<td>121.0</td>
<td>1.210</td>
<td>85.8</td>
<td>0.56</td>
<td>48.0</td>
</tr>
<tr>
<td>0.860</td>
<td>0.015</td>
<td>97.4</td>
<td>1.461</td>
<td>103.6</td>
<td>0.60</td>
<td>62.2</td>
</tr>
<tr>
<td>0.948</td>
<td>0.020</td>
<td>82.0</td>
<td>1.640</td>
<td>116.2</td>
<td>0.60</td>
<td>69.7</td>
</tr>
<tr>
<td>1.040</td>
<td>0.020</td>
<td>66.2</td>
<td>1.324</td>
<td>93.8</td>
<td>0.36</td>
<td>33.8</td>
</tr>
</tbody>
</table>

\[ \phi_{\text{det}} = E \cdot T_{\text{pol}} \cdot T_{\text{ND}} \cdot T_{\text{sp}} \cdot A_I \]

where:  
- $T_{\text{pol}} = 0.5$ (transmission through polarizer);  
- $T_{\text{ND}} = 0.0001$ (transmission through ND filter);  
- $T_{\text{sp}} = 0.5$ (transmission through spectral filter);  
- $A_I = 2.835$ cm\(^2\) (clear aperture area)
Table 3.2 Minimum Expected Values Due to Ground Radiance ($\rho = 0.05$)

<table>
<thead>
<tr>
<th>$\lambda$ $\mu$m</th>
<th>$\tau$</th>
<th>$E_{\exp(-\tau)}$ mW/cm$^2$ sr</th>
<th>$\Phi_{\text{det}}$ nW</th>
<th>$R$ A/W</th>
<th>$I_{\text{sig}}$ na</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.400</td>
<td>0.550</td>
<td>0.848</td>
<td>57.0</td>
<td>0.20</td>
<td>11.5</td>
</tr>
<tr>
<td>0.420</td>
<td>0.475</td>
<td>1.072</td>
<td>72.5</td>
<td>0.20</td>
<td>14.5</td>
</tr>
<tr>
<td>0.440</td>
<td>0.425</td>
<td>1.200</td>
<td>81.0</td>
<td>0.21</td>
<td>17.0</td>
</tr>
<tr>
<td>0.525</td>
<td>0.275</td>
<td>1.422</td>
<td>96.0</td>
<td>0.31</td>
<td>29.8</td>
</tr>
<tr>
<td>0.604</td>
<td>0.215</td>
<td>1.411</td>
<td>95.0</td>
<td>0.40</td>
<td>38.0</td>
</tr>
<tr>
<td>0.660</td>
<td>0.170</td>
<td>1.299</td>
<td>87.5</td>
<td>0.47</td>
<td>41.1</td>
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<tr>
<td>0.780</td>
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<td>1.084</td>
<td>73.0</td>
<td>0.56</td>
<td>40.9</td>
</tr>
<tr>
<td>0.860</td>
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<td>1.322</td>
<td>89.0</td>
<td>0.60</td>
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<tr>
<td>0.950</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>0.60</td>
<td>------ *</td>
</tr>
<tr>
<td>1.040</td>
<td>0.090</td>
<td>1.210</td>
<td>81.5</td>
<td>0.36</td>
<td>29.3</td>
</tr>
</tbody>
</table>

$\Phi_{\text{det}} = \frac{T_{\rho 0}^*T_{\text{ND}}^*T_{\text{bp}}^*\Omega_{I}^*I_{E}(e^{-T})^*\rho}{\pi}$

where: $T_{\text{ND}} = 1.0$; $\Omega_{I} = .000598$ sr; $\rho = 0.05$; all other quantities as defined above.

* not computed due to variability of water vapor
<table>
<thead>
<tr>
<th>$\lambda$ (µm)</th>
<th>$\tau$</th>
<th>$E(1-\exp(-\tau))$</th>
<th>$\phi_{det}$</th>
<th>$R$ (A/W)</th>
<th>$I_{sig}$ (na)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.400</td>
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<td>0.622</td>
<td>83.9</td>
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<td>16.8</td>
</tr>
<tr>
<td>0.420</td>
<td>0.475</td>
<td>0.652</td>
<td>87.9</td>
<td>0.20</td>
<td>17.6</td>
</tr>
<tr>
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<td>0.21</td>
<td>18.0</td>
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<td>0.450</td>
<td>60.7</td>
<td>0.31</td>
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<td>0.241</td>
<td>32.5</td>
<td>0.47</td>
<td>15.3</td>
</tr>
<tr>
<td>0.780</td>
<td>0.110</td>
<td>0.126</td>
<td>17.0</td>
<td>0.56</td>
<td>9.5</td>
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<tr>
<td>0.860</td>
<td>0.100</td>
<td>0.139</td>
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<td>11.3</td>
</tr>
<tr>
<td>0.950</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>0.60</td>
<td>----- *</td>
</tr>
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<td>0.114</td>
<td>15.3</td>
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<td>5.5</td>
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</table>

$$\phi_{det} = \frac{T_{pol} * T_{ND} * T_{sp} * A_I * \Omega_I * E(1-e^{-\tau}) * P_\theta}{\pi}$$

where: $T_{ND} = 1.0; P_\theta = 0.1$ (defined as 90% light scattered in a forward direction, 10% elsewhere); all other quantities defined as above.

* not computed due to variability of water vapor
Polarization Analysis

The next aspect of the instrument operation to be examined was the determination of the polarization state of the incident radiation. Shurcliff (1962) gives a good explanation of polarization and the discussion which follows basically summarizes those points which are applicable to the configuration of the spectropolarimeters.

As originally expressed by Stokes in the 1850's, the polarization state of light can be represented by four parameters labelled I, Q, U, and V. They are known as the Stokes' parameters and are defined below.

\[ I = \text{the total amount of radiation incident upon a detector} \]
\[ Q = \text{a value which indicates whether the radiation is oscillating more in a horizontal plane or more in a vertical plane} \]
\[ U = \text{a value which indicates whether the radiation is oscillating more in the } +45 \text{ degrees plane or more in the } -45 \text{ degree plane (the horizontal plane is at 0 degrees)} \]
\[ V = \text{a value which indicates whether the electric field vector of the incident radiation is rotating more in a clockwise direction or more in a counter-clockwise direction.} \]

These four parameters uniquely describe the polarization state of the incident radiation; therefore, it was desirable for the instrument to be able to make measurements which would lead to their calculation. The simplest method for achieving this is to use a linear polarizer in
conjunction with a quarter-wave retardation plate. Four measurements would be necessary and are as follows:

1) no waveplate, with analyzer at 0 degrees (A₁)
2) no waveplate, with analyzer at 45 degrees (A₂)
3) no waveplate, with analyzer at 90 degrees (A₃)
4) waveplate, with analyzer at 45 degrees (A₄)

Implicit in the last measurement is that the fast axis of the waveplate is oriented at 0 degrees. This sequence of measurements would work well if only a single wavelength were to be considered. However, it has already been determined that 10 wavelengths are to be used in the spectropolarimeter. Since retarders are not quarter-wave at all wavelengths, the measurements above would require a separate retarder for each filter, and this was not feasible for reasons of cost. The most promising solution is to use a single retarder and to account for its varying phase.

As detailed by Shurcliff, the action of the polarizer and the retarder can be thought of as matrix operators and the Stokes' parameters as a column vector. Multiplying the Stokes' vector by each matrix operator in the proper order will result in a new column vector corresponding to the Stokes' parameters of the resultant radiation. In an appendix, Shurcliff describes the matrices corresponding to many polarization-modifying objects including two of special interest to this work. They are a linear polarizer oriented at any angle θ and a linear retarder of any phase δ, fast axis at 0 degrees. Both of these are presented below.
Linear polarizer at angle $\theta$

\[
M_1 = \frac{1}{2} \begin{bmatrix}
1 & \cos 2\theta & \sin 2\theta & 0 \\
\cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\
\sin 2\theta & \sin 2\theta \cos 2\theta & \sin^2 2\theta & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

Linear retarder any $\delta$, fast axis at 0 degrees

\[
M_2 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \cos \delta & \sin \delta \\
0 & 0 & -\sin \delta & \cos \delta
\end{bmatrix}
\]

For a given matrix $M$

\[
\begin{bmatrix}
I' \\
Q' \\
U' \\
V'
\end{bmatrix} = [M] \ast \begin{bmatrix}
I \\
Q \\
U \\
V
\end{bmatrix}
\]

where $[M] = [M_1] \ast [M_2]$

$I' = m_{11}I + m_{12}Q + m_{13}U + m_{14}V$ (m_{1j}'s are the matrix elements of $M$)

Every measurement made by the instrument is an $I'$ shown above, but the coefficients $m_{1j}$ differ due to the different polarizer orientations and the presence or not of the waveplate. The four measurements detailed above contribute to four linearly independent equations in four unknowns. Therefore the problem can be solved and the Stoke's parameters are thus determined. After performing the required
matrix mathematics for each measurement configuration, it can be shown that the four solved equations are:

\[ I = A_1 + A_2 \]

\[ Q = A_1 - A_2 \]

\[ U = 2A_2 - I \]

\[ V = \frac{2A_1 - I - U \cos \delta}{\sin \delta} \]

(In the measurement of \( A_1 \), it was assumed that the waveplate preceded the polarizer in the optics train.)

Obviously it is imperative that \( \delta \) be well known if \( V \) is to be determined with any precision, and this then becomes one of the quantities which must be measured in the calibration process.

Phase Three: Optical and System Layouts

Optical Layout

The layout chosen for the instrument is straightforward and simple. It is a standard non-imaging, refractive design employing two lenses and is depicted in Figure 3.5 (a). The first lens images an infinitely distant source onto a defining aperture, the field stop. The second lens is located near the field stop and images the first lens onto the detector. The entrance pupil is defined to be at the first lens in this application and thus the detector is uniformly illuminated. This has
the advantage of averaging out any non-uniformities in response across the
detector's surface, thus causing the signal out of the detector to be
independent of these non-uniformities. The focal lengths of the lenses
were chosen to keep the overall system length short, but long enough to
fit the other components into the system, in particular the polarizer.

It was desired to keep the polarizer small to cut procurement
costs and this dictated that its position would be between the detector
and the field stop where the beam has its smallest cross-section. Some
of the incident angles onto the polarizer at this point could be 5 or more
degrees, reinforcing the choice of the Glan-Thompson configuration which
is unaffected by incident angles of this magnitude.

It was also desired that as many angle-dependent components as
possible be placed in the non-converging portion of the beam as in this
region the ray angles are less than 2.5 degrees. Thus, the spectral and
neutral density filters were located in front of the imaging lens.

The waveplate is not as dependent on angle as these filters so it
could be placed anywhere in the beam, in front of the polarizer. In order
to conserve space, it was decided to place it between the two lenses.
Finally, a window was added as the first optical element in order to
provide protection from dust and other contaminants.

The optical design program ACCOS V was next used to optimize the
location of all the elements, to verify that the full field response was
not vignetted, and to aid in the determination of the baffle dimensions of
the system. The initial design was modified to allow room for the lens
and filter mounts, but it was not necessary to significantly alter the
basic optical design.
Figure 3.5 Optical Layout of the Spectropolarimeter - a) Basic System; b) 15° FOV with Diverging Lens; c) 15° FOV with Afocal System

1 WINDOW 2 ND FILTER 3 SPECTRAL FILTER 4 IMAGING LENS
5 WAVEPLATE 6 RELAY LENS 7 FIELD STOPS
8 POLARIZER 9 DETECTOR 10 DIVERGING LENS 11 AFOCAL SYSTEM
The design described above did not provide for a 15 degree FOV. Figure 3.5 (b) shows the optical layout for this FOV. A negative lens is positioned in front of the system to enable the acceptance angle to be increased. The stop remains at the first lens provided that a different aperture is used. Also note that the light is no longer focused at the original field stop position. A new field stop is located on the detector side of the polarizer. The major problem associated with this design is the inconvenience incurred by requiring a new clear aperture to be defined. This is implemented by placing each spectral filter in a modified mount with the correct aperture located on the back of the mount.

Another system that could be implemented would be afocal comprising two positive lenses, again in front of the system. This would have the advantage of using the original aperture stop and field stop diameters and locations (see Figure 3.5 (c)).

System Layout

The next step was to determine the best system design to facilitate taking measurements. Figure 3.6 represents the final design in block format and demonstrates how the system functions as a whole.

Light enters the system through the window and is immediately attenuated, if necessary, by a neutral density filter. Next, a spectral filter selects the wavelength region of interest and the entrance pupil at the imaging lens defines the clear aperture. Each filter module actually consists of a filter wheel turned by a stepper motor; thus, if a new filter is to be placed into the beam, the computer issues the
Figure 3.6 Opto-Electronic-Mechanical System Layout
appropriate command and the desired filter is rotated into position. An absolute encoder system enables the computer to differentiate between the filters on each wheel.

The light is next focussed by the imaging lens and then it passes through the waveplate module, consisting of a "dummy" and the "real" waveplate mounted on a lateral slide. The dummy waveplate provides the same optical path length as the real waveplate. The light next passes through the relay lens which images the imaging lens on the detector (thus providing a more uniform illumination of the detector). Next, the field stop limits the angular extent observed and the light then passes through the polarizer, striking the detector.

Recall that three measurements are required with the real waveplate out of place. These can be made by rotating the polarizer through 90 degrees. The real waveplate is only needed when the polarizer is next positioned at 45 degrees. This occurs 180 degrees after the second measurement due to the symmetry of linear polarization (up-down = down-up, etc.). This implies that the dummy waveplate can be in place for 180 degrees of rotation and then the real waveplate can be in position for the remaining 180 degrees of rotation. Actually, this sequence can be simplified so that the polarizer is first rotated 90 degrees with the dummy waveplate being present, followed by moving the real waveplate into position during the next 90 degrees of rotation. The polarizer is then rotated 90 degrees with the real waveplate in place, followed by moving the dummy waveplate back into position during the final 90 degrees of rotation. This motion is accomplished by utilizing a cam arrangement to tie the polarizer and waveplate motions together, thus
allowing the use of a single stepper motor. To enable measurements to be made at points other than those described above, a stepper motor with more steps was used (1.5 degrees per step resolution).

The aperture module consists of a rotating disk with precisely sized holes (field stops) driven by a fourth stepper motor, thus allowing the computer to select the field of view which best compliments the observing conditions. Again, absolute encoding systems are present to enable the computer to differentiate between the possible configurations. Note: the polarizer encoder only references the major measurement points; other points would need to be identified by counting steps.

It was determined that a need existed for a second detector to be incorporated into the system to allow measurements to be made at wavelengths between 1.0 and 3.0 μm. Provisions were made for the inclusion of this detector at a later date. A fifth stepper motor was added to facilitate the multiple detector configuration and this was also computer controlled (detector module). Figures 3.7 and 3.8 show top and side views respectively, of the actual opto-mechanical layout of the system. The actual unit measures 19 x 26 x 28 cm in size, weighs 20 lbs, and requires 6 watts of power.

Two additional points of interest should be noted concerning the instrument operation. The first is that the detector is heated to a temperature of approximately 42° C to prevent response fluctuations due to changes in the outside air temperature. The spectral responsivity R(λ) varies with temperature, particularly for wavelengths over 0.9 μm (approaching the silicon absorption edge). Cooling the detector is difficult; heating it above ambient is much easier using a resistance
Figure 3.7 Top View of the Instrument Assembly
Figure 3.8 Cross-Sectional View of the Instrument Assembly
heater. The detector specifications indicated that the detector noise doubles for every 10° C. increase in temperature. This implies that the detector should not be operated at too high a temperature in order to maintain a large signal-to-noise ratio.

The second point concerns the nature of the absolute encoding system. This system consists of reflective opto-electronic switches placed above a black disk with reflective strips aligned radially. Each switch is tied to a data line and so acts as a bit. Each bit is determined by its radial distance on the disk and whether it is on (reflective) or off (black). Figure 3.9 shows the layout of a typical 4-bit encoder disk.

![4-bit Encoder Disk Configuration](image-url)
The radiation incident onto the detector is converted into electrons corresponding to the signal current $I_{\text{sig}}$ found in the preliminary calculations above. It is amplified by a pre-amplifying circuit that also converts the current into a voltage. This voltage is converted by the 12-bit A/D into a digital number which can be accepted by the computer as a valid input value. The computer acts as the system controller. Proper software implementation (see Appendix A) enables the computer to poll the encoders and analyze the current configuration. It then issues commands to change the configuration as necessary and determines when this new configuration has been achieved. It then asks that a datum point be measured and stores this value, the current encoder values, and the measurement time into its data file. After the measurement run has been completed, this data file can be transferred to a second computer and stored on a magnetic disk for later analysis.
CHAPTER 4

ABSOLUTE SPECTRAL CALIBRATION OF THE SPECTROPOLARIMETERS

The spectropolarimeter system calibration involves the characterization of many system parameters. Only one of these is an absolute relationship and that is output voltage (digital counts) to input power (watts). A measurement of this relationship requires a device that has already been absolutely calibrated to act as a comparison standard. The calibration of the spectropolarimeters used two different standards for two separate spectral regions. A device manufactured by United Detector Technology, the QED-100, was used to calibrate the instruments in the 400 nm to 700 nm spectral region. A second device, the Electrically Calibrated Pyroelectric Radiometer (ECPR), manufactured by Laser Precision Corporation, was used in the 700 nm to 1100 nm spectral region. A discussion on their theories of operation follows the description of the absolute spectral responsivity measurements.

Absolute Spectral Responsivity Calibration

The spectropolarimeters utilize 10 spectral bands when making radiance measurements. A detailed knowledge of the system spectral response is required in order to determine precisely the energy distribution of the incident radiation. The spectral responsivity relates the output digital counts to the incident power and represents the only
absolute measurements made in the calibration procedure. Figure 4.1
depicts the laboratory set-up

A 100 Watt, current-stablized, tungsten lamp was used as the
source and its radiation was focussed onto the entrance aperture of the
monochromator. The monochromator dispersed this radiation into a
spectrum which fell across the exit aperture of the monochromator.
Rotation of the grating allowed different spectral regions to be
selected. When measurements were made at wavelengths greater than 700
nm, a cut-off filter was placed between the focussing lenses and passed
only those wavelengths longer than 680 nm. This prevented the overlap
of higher orders of the grating. For example, 400 nm in order 2 occurs
at the same location as 800 nm in order 1. The use of a small exit
aperture limited not only the bandwidth of the exiting beam, but it also
affected the total output power. Obviously, a compromise needed to be
reached to balance spectral purity against adequate signal output. The
exit aperture finally chosen yielded the response shown in Figure 4.2.
This response represents the line response of the monochromator system
when a single, low-pressure, mercury source was used as input to the
monochromator, and it represents measurements of the response as the
monochromator setting was varied. Note that this is not a δ-function
response; it is instead a sum of weighted responses, implying that any
response measured using the monochromator was actually a sum of
responses. In order to recover the "true" response, the measured
response was deconvolved with the line response curve in Figure 4.2.

The exit beam was then collimated and passed through a polarizer
and an aperture. The spectropolarimeter passes only one orientation of
Figure 4.1 Top View of the Absolute Spectral Responsivity Laboratory Set-up
Figure 4.2 Normalized Slit Response of the Monochromator

light at a given moment, and if partially polarized light were to fall on the absolute detectors and not on the spectropolarimeter detector, then an obvious measurement error would occur. The calibration polarizer enables all of the devices to view the same input. The aperture performs a similar function. It was used to reduce the 19 mm clear aperture of the spectropolarimeter to match the 7 mm and 5 mm entrance apertures of the QED-100 and ECPR calibration standards, respectively.

An alignment of the spectropolarimeters was initially performed to correctly orient the internal polarizer and waveplate axes. First, the calibration polarizer was vertically oriented using a square on the optical table (the polarizer transmission axis was known). Next, the
transmission axis of the spectropolarimeter polarizer was oriented horizontally by rotating it until a zero signal output was obtained from the spectropolarimeter. The "real" waveplate was next oriented with its fast axis horizontal by rotating it until a zero output was again achieved. The fast axis had previously been determined by applying Tutton's test (Driscoll 1978). Both instruments were aligned in this fashion and thus were identical in orientation.

The spectral response measurements were performed as follows:

1) The spectropolarimeter was optically aligned by positioning it in such a manner as to generate a maximum signal. A neutral density filter, ND = 0.04, the "dummy" waveplate, and the 2° field stop were used for all measurements.

2) The wavelength corresponding to maximum signal output for a given spectral band was determined and then the positions at which the output went to zero were noted.

3) Starting at the shorter wavelength zero signal setting, the monochromator was stepped in one nanometer increments until the longer wavelength zero signal setting was reached. A datum point was taken at each of the wavelength positions.

4) A calibration standard (QED-100 if \( \lambda < 700 \) nm, ECPR if \( \lambda > 700 \) nm) was interposed immediately in front of the spectropolarimeter and the measurements were repeated again starting with the shorter and ending with the longer
wavelengths. This short-long directionality reduced errors due to backlash in the grating angle screw adjustment.

5) Repetition of step 3. Averaging the values acquired in this step and step 3 minimized errors due to variations in the source output.

6) Steps 2 - 5 were repeated for all 10 wavelengths. Note that step 1 need not be repeated if the calibration devices are placed into the beam in front of the spectropolarimeter, since only one optical axis exists for all of the spectral bands.

7) Steps 1 - 6 were repeated for the second spectropolarimeter.

Figure 4.3 shows the deconvolved results from the QED-100. It was found that the curve remained sufficiently accurate if the measured response was divided by the area under the response curve instead of applying a deconvolution which enhanced noise (measurement error) in the data. This procedure was also followed for data measured by the ECPR and in both cases is supported by the fact that tungsten lamps have smoothly varying spectral outputs. Figure 4.4 (a) shows a typical data run and Figure 4.4 (b) shows the deconvolved curve. The deconvolution routine used a smoothing function to remove negative side lobes while maintaining the usual bell-shaped curve.

Figure 4.5 shows two curves. Curve (a) represents the result of dividing the curve in Figure 4.4 (b) by the curve in Figure 4.3 on a point by point basis. Curve (b) depicts the equivalent ideal response as
Figure 4.3 QED-100 Deconvolved Power Response from 0.590 - 0.620 μm

Figure 4.4 Instrument #97 Band 5 Response - a) Raw Data; b) Deconvolved Response
Figure 4.5 Instrument #97 Band 5 Absolute Responsivity - a) Actual Responsivity; b) Equivalent Responsivity Showing $\lambda_0$, $\Delta \lambda$, and $R_{\lambda}$.
determined by the Palmer-Tomasko method (Palmer and Tomasko, 1980). The areas under these two curves are equal. The three important quantities derived using this method are: $\lambda_o$, the central wavelength; $\Delta \lambda$, the bandwidth, symmetrical about $\lambda_o$; and $R_{\lambda}$, the spectral responsivity in digital counts per nW. Table 4.1 lists these three factors for both instruments and all 10 spectral bands.

Estimation of Errors

Table 4.2 shows the error estimates of this calibration procedure and is applicable to both instruments since they had similar responses. Instrumental digitization errors are a result of digitization of the low source irradiance by the spectropolarimeter. For example, a 20 count value has a 5% error ($1/20$), while a 3000 count value has a 0.03% error ($1/3000$). QED-100 and ECPR errors are a result of low source irradiance and are actually due to low signal-to-noise ratios. Deconvolution errors represent the error in $R_{\lambda}$ due to the deconvolution process. RSS is the root-sum-square of all the measurement errors. All errors are expressed as a percentage. Improvements in the blue spectral region could be achieved by using a brighter source. However, an uncertainty of less than 0.7% RSS is not anticipated.

Spectral Calibration Standards

QED-100 Photodiode Standard

In general, a photodiode operates by converting a fraction of the incident photons into electrons (due to a less than unity quantum efficiency and a non-zero surface reflection). Low energy photons are
Table 4.1 Central Wavelength, Bandwidth, and Absolute Spectral Responsivities of the Two Spectropolarimeters

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_0$ (μm)</th>
<th>$\Delta \lambda$ (μm)</th>
<th>#97 $R_\lambda$ (cnts/nW)</th>
<th>$\lambda_0$ (μm)</th>
<th>$\Delta \lambda$ (μm)</th>
<th>#98 $R_\lambda$ (cnts/nW)</th>
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<td>0.02426</td>
<td>3.75062</td>
<td>0.9496</td>
<td>0.02560</td>
<td>3.68136</td>
</tr>
<tr>
<td>10</td>
<td>1.0423</td>
<td>0.02263</td>
<td>2.25904</td>
<td>1.0427</td>
<td>0.02221</td>
<td>1.85919</td>
</tr>
</tbody>
</table>

where: $\lambda_0$ = the central wavelength; $\Delta \lambda$ = the bandwidth; and $R_\lambda$ = the absolute spectral responsivity.
Table 4.2 Error Estimates Applicable to the Responsivities Displayed in Table 4.1

<table>
<thead>
<tr>
<th>Band</th>
<th>$I_e$</th>
<th>$C_e$</th>
<th>$D_e$</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0</td>
<td>1.0</td>
<td>0.5</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>7</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>8</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>9</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>1.0</td>
<td>0.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

where: $I_e$ = the Instrument digitization error (relative to the peak inband response); $C_e$ = the Calibration standard error (0.5 for the QED-100 (except for Band 1), 1.0 for the ECPR); $D_e$ = the Deconvolution error; and RSS = the Root-Sum-Square error. All errors are expressed as percentages.
not collected due to the band-gap energy of the photodiode being greater than the photon energy. A portion of the generated electrons recombine with holes and are not detected if the lifetime of the electron-hole pair is short compared to the transit time of the electron across the photodiode junction. The remaining electrons are then detected as the signal current. In an ideal photodiode detector, one electron/hole pair per incident photon is generated (unity quantum efficiency), and all of these generated electrons are detected as a signal current.

A relatively new device, known as an inversion layer photodiode, very nearly achieves unity quantum efficiency over the 400 nm to 700 nm spectral region. All photodiodes are junction devices, meaning that photons are absorbed at the junction between two different types of material. A natural electric field is created at this junction and separates those electron/hole pairs that are generated in the junction region. By applying an additional bias voltage, this junction region can be increased to such a point that all the electron hole pairs are separated. This means that all of the created electrons are detected as a signal current. Thus, if an inversion layer photodiode is used, the only error in the measured signal is due to reflection losses at the surface.

The QED-100 overcomes reflection losses in a clever manner - it uses four silicon inversion layer photodiodes in the configuration depicted in Figure 4.6. The outputs of all detectors are added together to yield the total signal current. As can be seen, the incident beam undergoes seven reflections, so that for even a high reflectance of 0.35 per surface, the amount of light lost is less than 0.1%. Thus, the
implied measurement error is less than 0.1%, assuming that the quantum efficiency equals one, an adequate bias voltage is applied, and that monochromatic light is used. If the monochromatic light were used, then the 0.1% error would apply to the absolute measurement. As shown below, the QED-100 can be characterized by such a relationship between output current and input power. However, if the observed beam is polychromatic, the measurement error increases, and it has been assumed in the course of this work that the QED-100 had a measurement error no smaller than 0.5%. This error was determined by assuming that the monochromator was a smoothly varying source and that the 0.1% error was associated with a bandwidth of 0.2 nanometers. The monochromator slit function has a 5 nm bandwidth, corresponding to 25 of the 0.1% error.
bandwidths. The square root of 25 times 0.1 squared equals 0.5 (this is simply an RSS calculation).

Consider the conditions outlined above. A photon has an energy

\[ \phi = h\nu = \frac{hc}{\lambda} \quad (4.1) \]

where: \( h \) = Planck's constant = \( 6.63 \times 10^{-34} \) J*s; \( c \) = speed of light in vacuo = \( 2.998 \times 10^8 \) m/s; \( \nu \) and \( \lambda \) are the frequency and wavelength of light, respectively.

and is able to produce \( \eta e \) electrons (\( \eta \) = the quantum efficiency and \( e \) is the electron charge = \( 1.6 \times 10^{-19} \) coul). The number of amps per watt generated is

\[ R = \frac{\eta e}{hc/\lambda} = \frac{\lambda}{hc/\eta e} \quad AW^{-1} \quad \text{for } \eta > 0.999 \approx 1.000 \quad (4.2) \]

\[ R = \frac{\lambda}{hc/e} = \frac{\lambda}{1239.5} \quad \text{AW}^{-1} \quad (\lambda \text{ in nanometers}) \quad (4.3) \]

As seen in Figure 4.6, two additional constraints are placed on the operation of the QED-100. Due to the geometry of the device, the cone angle of the beam must be restricted to less than 4° convergence. In addition, as with all calibration devices, the entire beam must be seen by both the calibration standard and the system being calibrated.
In the case of the QED-100, this implies a circular beam of no more than 7 mm diameter.

In summary, the QED-100 can enable the determination of the power of an incident beam to an uncertainty of 0.1% in the 400 nm to 700 nm spectral region. In the present study, the actual uncertainty is estimated to be 0.5% due to a polychromatic input beam. Outside this range, a decrease in the quantum efficiency in the IR, and an increase in surface reflectance in the blue tend to increase the error associated with the measurement process. More information on this self-calibrated photodiode configuration can be found in Zalewski and Duda (1983).

**ECPR Pyroelectric Standard**

The ECPR is a device which equates optical power with electrical power. As shown in Figure 4.7, the detector head consists of three layers:

1) A gold black absorbing layer/heater/front contact
2) A lithium tantalate (LiTaO₃) detector layer
3) A gold rear contact

The schematic operation of the ECPR is depicted in Figure 4.8. Radiation emitted by the source to be measured is immediately chopped to produce a square wave signal, as well as to reduce background radiation which could introduce error into the measurement. The radiation then strikes the gold black absorber which converts the photons into heat energy, thus heating the detector. A temperature change is induced,
Figure 4.7 Detailed Construction Layout of the ECPR Detector

Figure 4.8 Electronic Block Diagram of ECPR Operation
causing a change in current out of the detector and eventually creating a change in voltage out of the pre-amp. The chopper has a 50% duty cycle and is open twice per revolution. A sensing element within the chopper mount determines when the chopper has rotated 90° from the open position. The heater is then turned on and it also induces a temperature change in the LiTaO₃ detector. The total resultant signal out of the detector is nearly flat, consisting of a square wave due to optical energy, while the gaps are filled by the signal due to electrical energy. The electronics which analyze the signal current adjust the heater current until the signal caused by the heater is equal to that caused by the incident radiation. At this point the electrical power equals the optical power and this power value is displayed via a digital metering system.

Many factors must be characterized to achieve a high level of precision and accuracy in the measurement process. The most significant of these are discussed below.

1) Surface reflectance - The incident radiation is not transmitted; thus all light not absorbed must be reflected. In general, gold black has a reflectance of 0.004 in the visible, increasing at the longer IR wavelengths to 0.03 at 3 μm. Measurements which characterize the reflectance can be made using a detector, which is rotated over a hemisphere in front of the ECPR, and an incident beam, which is incident at an angle near, but not at, normal incidence (for example 5°, to enable the specular component to be determined). A measurement of the incident power will enable the fraction of light reflected into the hemisphere
away from the ECPR to be determined. This fraction is the hemispherical reflectance.

2) Response non-uniformity - Variations in surface response occur over all of the absorber surface; however, incident radiation is constrained to fall on those portions behind the entrance aperture. Thus, there will be differences in the signals due to the incident radiation and the heater. These differences can be taken into account by mapping out the variations in the average surface response in a grid-like fashion, and then dividing the average clear aperture response by the average total response.

3) Lead heating - The gold lead contacts have a non-zero resistance and so will also heat to some extent. The implication here is that more power than necessary is required to enable the electrical power to equal the optical power. However, this effect can be well characterized.

4) Absorber thermal resistance - Optical radiation only heats the surface of the gold black absorber while electrical heating occurs throughout the absorber. The surface heating is very localized, and for a non-zero thermal resistance, a gradient is formed from the front surface to the detector. More heat is lost to air than with the bulk heating, and it is this difference in heat source location that leads to measurement errors. Additionally, a phase delay in the signal occurs between the time the radiation strikes the absorber and the time that the LiTaO₃ detector begins to change temperature. This is due to the non-zero thermal resistance of the absorbing layer. If this phase delay is small compared to the measurement time period, the error introduced is negligible. If
the thermal resistance were zero, the surface and bulk heating would generate identical results with no phase delay.

These errors are the most significant but they can be well characterized. It has been estimated that the ECPR has an inherent error of 2% if the errors mentioned above are completely ignored, but if the described effects can be characterized, then the ECPR can be calibrated to an uncertainty of <1% over the entire wavelength range from 0.25 μm to 2.0 μm. A more detailed description of this device can be found in Doyle, et al (1976).
RELATIVE RADIOMETRIC CALIBRATION OF THE SPECTROPOLARIMETERS

There are many other quantities that need to be calibrated than were described in the previous chapter. These include the transmission through the waveplate as well as its phase retardation; the scaling of the neutral density filters for measuring dynamic range; the area of the entrance pupil; and the fall-off in response as a function of look angle (field-of-view calibration). These quantities are measured in a relative sense; that is, they are referenced to the value 1.0 (except for the phase retardation which in a sense is referenced to the quarter-wave value of 90 degrees). The procedures used in the determination of these quantities, the values of the quantities themselves, and an estimation of the measurement errors are presented in this chapter.

Waveplate Retardation Calibration

As mentioned previously in the polarization section of Chapter 3, it is necessary to know the retardation phase value \( \delta \) in order to adequately determine the polarization characteristics of the incident radiation. It has no influence on the radiance or irradiance values calculated. Its importance lies in the calculation of the handedness of the polarization. The laboratory set-up used was the same as in the spectral responsivity calibration (figure 4.1). The monochromator was tuned to the \( \lambda_o \) determined previously for each spectral filter. The spectropolarimeter polarizer was next rotated to the 45\(^\circ\) position and
the calibration polarizer rotated until a zero count output was achieved. This indicated that the incident light was linearly polarized at 135°. A full set of data points, as described in Chapter 3, was taken, and the results are analyzed below.

\[ I = M_1 + M_2 \]
\[ U = 2M_1 - I = -I \] (provides a check since linear at 135°)
\[ V = 0 \] (since light is linearly, not circularly, polarized)

\[ \cos\delta = \frac{2M_1 - I}{U} \]
\[ \delta = \cos^{-1}\left(\frac{2M_1 - I}{U}\right) \]

Table 5.1 lists the values of \( \delta \) for each wavelength for each spectropolarimeter.

Estimation of Errors

The error in each calculation depends on the data errors and also on the nearness of \( \delta \) to 90° (where \( \cos\delta = 0 \)). The instrumental digitization errors are the same as determined for the absolute spectral response. Table 5.2 lists the estimated errors associated with the values of \( \delta \) found in Table 5.1, expressed in degrees.
Table 5.1 Values of $\delta$, the Phase Retardation Angle, Measured for Each Spectropolarimeter Waveplate

<table>
<thead>
<tr>
<th>Inst.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>#97</td>
<td>109.9</td>
<td>104.3</td>
<td>100.0</td>
<td>86.8</td>
<td>75.8</td>
<td>69.9</td>
<td>60.6</td>
<td>53.7</td>
<td>48.4</td>
<td>46.6</td>
</tr>
<tr>
<td>#98</td>
<td>111.2</td>
<td>103.4</td>
<td>99.5</td>
<td>86.0</td>
<td>74.8</td>
<td>68.2</td>
<td>59.1</td>
<td>53.6</td>
<td>48.5</td>
<td>46.1</td>
</tr>
</tbody>
</table>

All values are expressed in degrees

Table 5.2 Estimated Errors of $\delta$, from Table 5.1

<table>
<thead>
<tr>
<th>Rel. ±Error</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.7</td>
<td>0.5</td>
<td>0.2</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

All values are expressed in degrees

--- indicates negligible relative error
Dynamic Range Calibration

The dynamic range of the spectropolarimeters is controlled through the use of neutral density filters ranging from ND = 0.04 to ND = 4.0. The different radiation sources observed require these instruments to use a range of ND filters which implies a need to relate measurements made with different ND filters. A detailed knowledge of these relationships had to be obtained, especially the relationship between the ND = 0.04 filter (which was used in the absolute spectral calibration) and the other ND filters. The determination of the factors relating the ND filters represented the calibration of the dynamic range of the system for each instrument.

Figure 5.1 depicts the laboratory configuration used in this calibration procedure. A large current-stabilized lamp (an aircraft landing light) was used to provide a slightly divergent beam. The spectropolarimeter was located approximately one meter distant and was aimed at the light source. An attempt was made to place it in a uniform portion of the beam. The spectropolarimeter was optically aligned as in previous procedures, by rotating and tilting until a maximum signal was achieved. The lamp was initially set at low intensity and the instrument placed in the ND = 0.04 configuration. As the lamp intensity was increased, the digital count output was observed. Whenever a given spectral band showed a digital count greater than 3000, the digital count was recorded, the ND filter wheel rotated, until the next higher ND filter was in position. The new digital count value was also recorded. Dividing the larger number by the smaller yields the relating factor. For example, if ND = 0.04 showed a digital count of 3000 and
\( \text{ND} = 1.0 \) showed a count of 300, the resultant factor would be 10. Thus, if a measurement was made using the \( \text{ND} = 1.0 \) filter, its value in \( \text{ND} = 0.04 \) units would be 10 times as much (700 in \( \text{ND} = 1.0 \) units is 7000 in \( \text{ND} = 0.04 \) units). Multiplying factors together can yield factors which relate any \( \text{ND} \) filter to the \( \text{ND} = 0.04 \) filter. Table 5.3 lists these calibration factors for both spectropolarimeters and all 10 spectral bands.

Estimation of Errors

The light source which was used enabled all measurements using filters \( \text{ND} = 0.04, \text{ND} = 1.0 \) and \( \text{ND} = 2.0 \) to reach counts greater than 3000. The corresponding measurements with the next denser filters had counts between 300 and 400. The error is one digital count as the lamp

![Diagram](image)

**Figure 5.1** Side View of the Dynamic Range Calibration Laboratory Set-up
Table 5.3 Calibration Factors for Dynamic Range for Spectropolarimeters #97 and #98 Relative to ND = 0.04

<table>
<thead>
<tr>
<th>Band</th>
<th>0.04</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>#97 ND Filter</th>
<th>0.04</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>#98 ND Filter</th>
</tr>
</thead>
<tbody>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0 6.690 66.64 634.3 619.0 712.9</td>
<td>1.0 6.950 68.25 619.0 712.9</td>
<td></td>
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<tr>
<td>2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0 6.904 67.25 645.8 619.0 712.9</td>
<td>1.0 7.200 69.04 629.7 712.9</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>1.0 7.400 69.04 633.8 712.9</td>
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<td></td>
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<td>4</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0 8.259 69.18 510.7 4666 712.9</td>
<td>1.0 8.490 69.19 519.0 4831</td>
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<td>8</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>9</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0 8.261 60.70 386.1 2891 712.9</td>
<td>1.0 8.670 63.03 405.3 3137</td>
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<td>10</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0 8.150 56.96 333.1 2349 712.9</td>
<td>1.0 8.490 58.24 352.9 2474</td>
<td></td>
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</tbody>
</table>
was current stabilized to better than a one count change. Therefore, the error is 0.3%. For the ND = 3.0 filter, bands 1-3 did not reach the 3000 count level and the corresponding ND = 4.0 measurements were diminished even further, to the extent that no ratio was determined. It is anticipated that no natural sources will require ND = 4.0 for these bands. Table 5.4 shows the errors as related to the ND = 0.04 configuration. The Table can be applied to both spectropolarimeters since the results were very similar. The amount of error in a measurement is dependent upon which ND filter is used. In a relative sense, the average error is 0.3% from one filter to the next, but in an absolute sense, it can be up to 1.2% since absolute measurements are referenced to the ND = 0.04 configuration.

Waveplate Transmission Calibration

The absolute measurement configuration utilized the "dummy" waveplate. In order to relate measurements made with the "real" waveplate to those made with the "dummy" waveplate, a determination of the spectral transmission characteristics of the "real" waveplate was required. The laboratory set-up used was the same as that used in the ND filter calibration (figure 5.1). Four measurements were made for each spectral filter and consisted of the polarizer horizontal, then vertical, for the real waveplate being present, and not present. The average waveplate spectral transmittance was equal to the sum of the two dummy waveplate values divided by the sum of the real waveplate values. If the transmission characteristics for each axis were needed, a polarizer could have been placed in front of the instruments and
Table 5.4 Estimated Errors for the Dynamic Range Factors, Expressed as a Percentage

<table>
<thead>
<tr>
<th>Band</th>
<th>ND FILTER</th>
<th>0.04</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>***</td>
<td></td>
</tr>
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<td>2</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
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</tr>
<tr>
<td>5</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
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</tr>
<tr>
<td>7</td>
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<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

where: *** indicates that the light levels were insufficient to generate a useful signal; therefore no attempt was made to determine ratios, and hence, no errors were incurred. It should also be noted that even under the best conditions, direct sunlight (the brightest target) is unable to force the instruments to use this neutral density filter at these wavelengths, so no ratios need to be determined.
radiation along each axis could have been measured and ratioed. This extra polarizer would remove any effects introduced by the real waveplate on radiation not parallel to either of its axes. However, it was decided that a detailed analysis of this sort was unnecessary. Table 5.5 lists these relative transmittance values.

Estimation of Errors

All of the individual measurement values were greater than 3000 digital counts implying errors on the order of 0.03% which are negligible.

Field-of-View Calibration

Radiance measurements are dependent upon the field of view of the spectropolarimeters. In general, radiometers do not have flat angular responses. Figure 5.2 shows an ideal response curve, (a), superimposed upon a typical response curve, (b). Its appearance is similar to that of the system's absolute spectral response. However, in this case, the volume under the curves is desired, not the area. The peak-normalized equivalent response is a cylinder of unit height with a radius determined by taking the square-root of the volume divided by \( \pi \). The typical curve is a superposition of two bell-shaped curves, usually with an approximately flat top, and always with wings extending to large angles. Characterization of the effect of these wings is the goal of the field of view calibration.

Early measurements showed that the spectropolarimeters had a symmetrical profile for orthogonal cross-sections. Thus, it was necessary to only measure the fall-off in response (normalized to the
Table 5.5 Relative Transmission Values for the Spectropolarimeter Waveplates

<table>
<thead>
<tr>
<th>Band</th>
<th>#97 Dummy</th>
<th>#97 Real</th>
<th>#98 Dummy</th>
<th>#98 Real</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>1.105</td>
<td>1.0</td>
<td>1.095</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>1.095</td>
<td>1.0</td>
<td>1.081</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.076</td>
<td>1.0</td>
<td>1.067</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>1.052</td>
<td>1.0</td>
<td>1.041</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>1.035</td>
<td>1.0</td>
<td>1.024</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>1.024</td>
<td>1.0</td>
<td>1.014</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
<td>1.014</td>
<td>1.0</td>
<td>1.008</td>
</tr>
<tr>
<td>8</td>
<td>1.0</td>
<td>1.014</td>
<td>1.0</td>
<td>1.009</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>1.013</td>
<td>1.0</td>
<td>1.006</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>1.011</td>
<td>1.0</td>
<td>1.004</td>
</tr>
</tbody>
</table>
Figure 5.2 Field-of-view Response Curves - a) Ideal Peak Normalized Response; b) Typical Response. Both Curves Contain the Same Volume peak) for one cross-section. A full cross-section is needed to determine room-induced effects due to scattering of light off of the walls of the room. Figure 5.3 depicts the laboratory test configuration, both top and side views. A very small (1 mm diameter) source emitted light which passed through a defining aperture, and then reflected off a parabolic
Figure 5.3  Side and Top Views of the Field-of-view Laboratory Set-up
mirror into a collimated, cross-sectionally uniform beam. The lamp intensity was adjusted so that the digital counts were less than 4000 when the instrument was on axis and the ND = 0.04 filter was in place. The other ND filters and all of the spectral filters transmitted light differently as a function of angle. Thus, it was desirable to keep these filters out of the beam where their angle dependent properties would not influence the field-of-view calibration measurements. As shown in Figure 5.3, the spectropolarimeter was rotated about the front end of the sunshade. This allowed the same portion of the beam to enter the instrument and reduced the effects of whatever beam non-uniformities were present. The measurements were made as follows:

1) The instrument was aligned as before to give a maximum on-axis response. The front of the sunshade was located directly over the rotation point.

2) The ND filter wheel was rotated to select the ND = 0.04 filter and one spectral filter was removed and that empty space was rotated into place. Note that the lamp output and detector response are at a maximum in the near-IR. Thus, the results might be potentially biased towards the near infrared.

3) The field stop of interest was rotated into position. The instrument was then rotated in both directions off the maximum until the fall-off to the wings began. Two points were located, defined to be where the detector outputs were equal and approximately half of the maximum response. The
actual on-axis position was defined as the midpoint between these two points. This allowed the midpoint to be determined when the angular response had a flat top.

4) The spectropolarimeter was set at the midpoint position, and the detector response was measured. The lamp intensity was adjusted to give a digital output between 3500 and 4000 counts. This is the on-axis response and represents the normalizing factor for this field stop.

5) The spectropolarimeter was rotated in 5 minutes of arc (1.454 milliradians) steps in one direction and a measurement was taken at each point. When the counts decreased to values between 300 and 800 counts, the lamp intensity was increased to give counts above 3500 again. Both the low and high values at this step location were recorded and the ratio of the low to the high is a scaling factor used to relate the wings to the on-axis value. The lamp intensity was increased through an increase in the current until the maximum current was reached. The 5 minute step size continued through 4 degrees, after which 30 minute (8.727 milliradians) steps were taken. Measurements ceased at 24 degrees or at the point where the digital count signal reached zero.

6) Steps 4 and 5 were repeated for rotation in the other direction.

7) Steps 3–6 were repeated for the remaining field stops.
8) Steps 1-7 were repeated for the second spectropolarimeter.

The data were analyzed in the following manner. For a particular field stop, each rotation direction was assumed to be rotationally symmetric. The volume under the corresponding curve was calculated using the following equation:

\[ \Omega = \sum_{n=0}^{N} (\pi h_n (r_{n+1}^2 - r_n^2)) \]

where: \( h_n \) is the height of a cylindrical shell; \( \Delta r \) = the shell thickness; \( r_n = r_i - \Delta r/2 \) = the inner radius of the shell; \( r_i \) = the angular point at which a measurement was made (eg. 0', 5', 10', ... , etc.).

\[ \Delta r = 5.0' \text{ (1.454 milliradians)} \quad 0 \leq r_i \leq 4^\circ \]
\[ = 30.0' \text{ (8.727 milliradians)} \quad r_i > 4^\circ \]

The summation process calculates the volume under the curve by summing cylindrical shells. In the wings of the curve, the shell thickness was allowed to increase since the changes in the curve were more gradual. All angular values were expressed in radians during the computation.
The values of $\Omega_{\text{ave}}$ are an average of the two curves measured for each FOV; one to the right, and one to the left, measured from the center. It represents the solid angle field of view for that field stop configuration. Dividing $\Omega_{\text{ave}}$ by $\pi$ and taking the square-root yielded the half angle of the field-of-view. Table 5.6 lists the values of $\Omega_{\text{ave}}$ and $r_{\text{ave}}$ of each spectropolarimeter for the 1°, 2°, and 5° field stop configurations. The small source was used to eliminate the need for deconvolution of the data. At the field stop of the spectropolarimeter, the 1 mm source subtended 7.5 minutes of arc, or about 1/8 of the 1° field diameter. The predominant effect on the data was to widen the true curve by 7.5 minutes of arc and round off the peak response. The net change in the calculated volume was negligible, and so the values in Table 5.6 were not corrected for this effect.

Estimation of Errors

Two sources of errors are present - measurement errors and positioning errors. The positional error is most critical at the steep slopes occurring near the $r_{\text{ave}}$ points. A slight shift in position causes a large response change. Position error is estimated to be $\pm 0.2$ minutes of arc. Averaging the two $\Omega$ values reduced the effect of this error since one $\Omega$ could have a positive error and the other could have a negative error which would average to zero error. The overall estimated RSS error due to this effect is 0.1%. The measurement error is the digitization noise level and corresponds to 0.03% near the peak and 100% at the edge of the wings. However, at this point the wings are down to a value near 0.000002 and the solid angle contribution is negligible.
Table 5.6 $r_{ave}$ and $\Omega_{ave}$ for the 1°, 2°, and 5° Fields of View (FOV) for the Spectropolarimeters

<table>
<thead>
<tr>
<th>FOV</th>
<th>$r_{ave}$</th>
<th>$\Omega_{ave}$</th>
<th>$r_{ave}$</th>
<th>$\Omega_{ave}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>0.4848</td>
<td>0.0002249</td>
<td>0.4485</td>
<td>0.001925</td>
</tr>
<tr>
<td>2°</td>
<td>0.9625</td>
<td>0.0008866</td>
<td>0.9198</td>
<td>0.0008096</td>
</tr>
<tr>
<td>5°</td>
<td>2.4208</td>
<td>0.0056081</td>
<td>2.4122</td>
<td>0.0055686</td>
</tr>
</tbody>
</table>

where: $r_{ave}$ is expressed in degrees, and $\Omega_{ave}$ is expressed in steradians
The largest error occurs where the scale changes, and this yields an RSS error of 1.0% over all of the measurements. Therefore, the overall RSS error for the field of view calibration is 1.0%.

**Entrance Pupil Area Calibration**

The aperture of each instrument was clearly defined in the design procedure and corresponds to the imaging lens mount. These pieces were carefully machined to a diameter of 19.05 mm ± .05 mm.

**Estimation of Errors**

The clear aperture area is equal to 2.85 cm² with an error of 0.5%.
CHAPTER SIX

FIELD MEASUREMENTS

The two spectropolarimeters were calibrated as described in the previous chapter, but it remained to be shown that the calibrations were indeed valid. To validate the calibrations, a number of independent measurements were made using calibrated sources, and comparisons were made between the spectropolarimeters themselves, and also with other instruments. The generalized formulae using the previously determined calibration values are

\[ F_m = \frac{(M_1 + M_2) \cdot T_{WP} \cdot RANGE_{ND}}{R_{\lambda} \cdot A_p} \]  

(6.1)

\[ L_m = \frac{E_m}{\Omega_{ave}} \]  

(6.2)

where: \( M_1 + M_2 \) = sum of two orthogonal polarization measurements (total light received); \( T_{WP} \) = transmittance of the waveplate; \( RANGE_{ND} \) = Neutral Density filter range value; \( R_{\lambda} \) = absolute spectral responsivity; \( A_p \) = area of pupil; and \( \Omega_{ave} \) = average steradian field-of-view. To convert the radiance and irradiance values into band-averaged spectral quantities, \( E_m \) should be divided by the spectral bandpass \( \Delta \lambda \).
A calibrated tungsten lamp, manufactured by Optronic Laboratories, Inc. (model HTS-75), was used as a source of irradiance. The absolute accuracy of the spectral irradiance is quoted as being 5% in the visible portion of the spectrum, through the infra-red, at a standard distance of 41.2 cm. The lamp irradiated a barium sulphate target panel located 308.5 cm from, and normal to, the filament, reducing the irradiance at the panel by a factor of $(41.2/308.5)^2 = 0.0178$. The reflectance of the panel had been measured for four wavelength bands (Nianzeng 1984), and this curve is shown in Figure 6.1. Radiance values were calculated from equation 6.3

\[ L_0 = \frac{E_0 \times (0.0178) \times \rho_F}{\pi} \quad (6.3) \]

except for bands 1, 2, 9, and 10, where \( \rho_F \) was not measured. Curve (a) in Figure 6.2 depicts the calculated radiance ± 5% error envelope for this source. Table 6.1 lists these radiance values and also shows the measured digital counts from the two spectropolarimeters and the corresponding measured radiance values. The non-uniformity in reflectance of the barium sulphate surface was estimated to be <1.0%. As can be seen, the agreement between the two instruments is very good, averaging 1.5%. However, a comparison between the calculated radiance and the instrument measured radiance shows an average difference of 7.7% over the spectral region 0.50 - 0.86 \( \mu \)m, increasing to 30.0% at
0.44 μm (see Figure 6.1, curve (b)). These differences can be attributed to errors associated with the instrument calibration and data collection, interpolation of the panel reflectance, and the manufacturer's lamp calibration. Additionally, the operational source current may have been less than that suggested by the manufacturer. This last consideration would explain why the measured curve falls below the calculated curve. Table 6.2 also shows the differences between the instruments, the differences between each instrument and the calculated radiance, and the calculated differences based on the calibration measurements and the digitization of the data. Note that the differences between the two instruments is less than these latter values.
Figure 6.2 Radiance Measurements - a) ± 5% Error Envelope for Calculated Radiance; b) Measurements from Instruments #97 and #98 with Error Bars
Table 6.1 Calculated and Measured Radiances, \( L \), From a BaSO\(_4\) Panel Illuminated by a Standard Lamp.

<table>
<thead>
<tr>
<th>Band</th>
<th>( \phi_F )</th>
<th>( L_0 )</th>
<th>D.C.</th>
<th>( L_m^{97} )</th>
<th>D.C.</th>
<th>( L_m^{98} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>------</td>
<td>------</td>
<td>2</td>
<td>0.2295</td>
<td>2</td>
<td>0.3890</td>
</tr>
<tr>
<td>2</td>
<td>------</td>
<td>------</td>
<td>6</td>
<td>0.4782</td>
<td>4</td>
<td>0.4161</td>
</tr>
<tr>
<td>3</td>
<td>0.9572</td>
<td>1.0819</td>
<td>14</td>
<td>0.8159</td>
<td>12</td>
<td>0.8353</td>
</tr>
<tr>
<td>4</td>
<td>0.9526</td>
<td>2.3592</td>
<td>54</td>
<td>2.1485</td>
<td>52</td>
<td>2.1538</td>
</tr>
<tr>
<td>5</td>
<td>0.9444</td>
<td>3.8662</td>
<td>126</td>
<td>3.4634</td>
<td>123</td>
<td>3.5847</td>
</tr>
<tr>
<td>6</td>
<td>0.9371</td>
<td>4.6181</td>
<td>172</td>
<td>4.2242</td>
<td>170</td>
<td>4.2844</td>
</tr>
<tr>
<td>7</td>
<td>0.9201</td>
<td>6.4531</td>
<td>331</td>
<td>5.9559</td>
<td>313</td>
<td>6.0314</td>
</tr>
<tr>
<td>8</td>
<td>0.9084</td>
<td>8.1334</td>
<td>362</td>
<td>7.8933</td>
<td>355</td>
<td>7.9208</td>
</tr>
<tr>
<td>9</td>
<td>------</td>
<td>------</td>
<td>793</td>
<td>13.2285</td>
<td>762</td>
<td>13.0423</td>
</tr>
<tr>
<td>10</td>
<td>------</td>
<td>------</td>
<td>399</td>
<td>11.1722</td>
<td>314</td>
<td>10.6844</td>
</tr>
</tbody>
</table>

where: \( L \) is expressed in units of \( \mu W \, cm^{-2} \, sr^{-1} \)
SBRC Measurements Using Halon Target

One instrument, #97, was taken to Santa Barbara Research Center (SBRC) in Galeta, CA, and tested using a calibration standard traceable to NBS. The lamp irradiated a Halon target at normal incidence. The instrument observed the Halon target under three different measurement geometries (variations in angle off normal and the separation distance), and since the results agreed so well, they have been averaged and are shown in Table 6.3. As before, only bands 3-8 are presented and they show a trend similar to that displayed in figure 6.2; that is, the measured values lie an average of 4% within the calculated calibration values, except for band 3 which is 17% low.

Tucson Verification Measurements

Additional data was collected during April 1985 in Tucson, AZ to independently verify the author's calibration data as well as the SBRC calibration data. A BaSO₄ panel was used as the calibrated target, and a tungsten lamp, traceable to NBS was used as the calibrated source, in a geometry similar to that employed in the SBRC measurements. Table 6.4 presents these results. As can be seen, these results agree very well with the author's results based on the expected measurement errors. The agreement is also good with the SBRC data, again with the exception of band 3. These results support the author's contention that the overall calibration was performed to within an accuracy of 2%-3%.
Table 6.2 Percent Differences Between the Two Instruments, Instruments and Source, and Calculated Differences Based on Calibration Data.

<table>
<thead>
<tr>
<th>Band</th>
<th>$\Delta L_{97-98}$ Meas.</th>
<th>$\Delta L_{97-98}$ Calc.</th>
<th>$\Delta L_{97-0}$</th>
<th>$\Delta L_{98-0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-69.5</td>
<td>100.0</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>2</td>
<td>+13.0</td>
<td>40.0</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>3</td>
<td>-2.4</td>
<td>15.5</td>
<td>-32.6</td>
<td>-29.5</td>
</tr>
<tr>
<td>4</td>
<td>-0.2</td>
<td>4.1</td>
<td>-9.8</td>
<td>-9.5</td>
</tr>
<tr>
<td>5</td>
<td>-3.5</td>
<td>2.2</td>
<td>-11.6</td>
<td>-7.9</td>
</tr>
<tr>
<td>6</td>
<td>-1.4</td>
<td>1.9</td>
<td>-9.3</td>
<td>-7.8</td>
</tr>
<tr>
<td>7</td>
<td>-1.3</td>
<td>1.6</td>
<td>-8.3</td>
<td>-7.0</td>
</tr>
<tr>
<td>8</td>
<td>-0.3</td>
<td>1.6</td>
<td>-3.0</td>
<td>-2.7</td>
</tr>
<tr>
<td>9</td>
<td>+1.4</td>
<td>1.6</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>10</td>
<td>+4.4</td>
<td>1.6</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

where: $\Delta L_{x-y} = 100 \% \frac{(L_x - L_y)}{L_x}$

$x = 97$ or $98$; $y = 98$ or $0$
Table 6.3 Calculated and Measured Radiance From a Halon Panel Illuminated by a Standard Lamp

<table>
<thead>
<tr>
<th>Band</th>
<th>( L_o )</th>
<th>Ave</th>
<th>( L_m )</th>
<th>( \Delta L_{m-o} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>.01370</td>
<td>199.67</td>
<td>.01164</td>
<td>-17.7</td>
</tr>
<tr>
<td>4</td>
<td>.02772</td>
<td>660.33</td>
<td>.02627</td>
<td>-5.5</td>
</tr>
<tr>
<td>5</td>
<td>.04596</td>
<td>1623.3</td>
<td>.04462</td>
<td>-3.0</td>
</tr>
<tr>
<td>6</td>
<td>.05470</td>
<td>2183.0</td>
<td>.05361</td>
<td>-2.0</td>
</tr>
<tr>
<td>7</td>
<td>.07957</td>
<td>4380.0</td>
<td>.07881</td>
<td>-1.0</td>
</tr>
<tr>
<td>8</td>
<td>.10460</td>
<td>5018.3</td>
<td>.10942</td>
<td>+4.4</td>
</tr>
</tbody>
</table>

where: \( L \) is expressed in mW cm\(^{-2}\) sr\(^{-1}\) and

\[
\Delta L_{m-o} = 100 \times \frac{(L_m - L_o)}{L_m}
\]
Table 6.4 Calculated and Measured Radiance of a BaSO$_4$ Panel in Tucson, April 1985

<table>
<thead>
<tr>
<th>Band</th>
<th>Dig. Cnts</th>
<th>$L_\text{o}$</th>
<th>$L_\text{m}$</th>
<th>$\Delta L_{\text{m-o}}$</th>
<th>$\Delta L_{\text{m-o}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>2.159</td>
<td>2.480</td>
<td>+10.4</td>
<td>10.4</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>2.878</td>
<td>2.949</td>
<td>+ 2.4</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>67</td>
<td>3.944</td>
<td>3.904</td>
<td>- 1.0</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>208</td>
<td>8.475</td>
<td>8.276</td>
<td>- 2.4</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>485</td>
<td>13.762</td>
<td>13.332</td>
<td>- 3.2</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>635</td>
<td>16.006</td>
<td>15.595</td>
<td>- 2.6</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>1206</td>
<td>22.193</td>
<td>21.700</td>
<td>- 2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>1292</td>
<td>29.126</td>
<td>28.172</td>
<td>- 3.4</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>2863</td>
<td>45.177</td>
<td>47.759</td>
<td>+ 5.4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

where: $L_\text{o}$ is calculated radiance, $L_\text{m}$ is measured radiance (units of radiance are $\mu$W cm$^{-2}$ sr$^{-1}$), and

$$\Delta L_{\text{m-o}} = 100\times(L_\text{m} - L_\text{o})/L_\text{m}.$$ Average difference for bands 3 - 8 is 2.5%.

* Heater was not activated, so this band's data may be in error.
Solar Illuminated BaSO₄ Target

The next test performed was similar to the first one above because a barium sulphate (BaSO₄) panel was used as the target, but under solar illumination. Both instruments were mounted in tandem so that they observed neighboring portions of the panel (see Figure 6.3). A number of measurements were made with each instrument, and then the panel was rotated 90° to enable each instrument to view a different portion of the panel. The panel was rotated four times, as shown. Averaging these results minimized the errors due to reflectance non-uniformities. This was not done in the previous tests because of the difficulty in maintaining a constant source-panel separation. This outdoor test does not suffer from this problem; since the sun is so far away, centimeter changes in the distance are negligible. However, there is the disadvantage of source variability, but as both instruments made measurements at the same moment, the errors due to this potential problem were also minimized.

Table 6.5 lists the measured radiances for each instrument for the 5° FOV. The average absolute differences between the instruments is 1.9% while the calculated differences are 1.6%, for all 10 bands. Since the two instruments had the same geometry and saw the same radiance, any differences in the measurements made using other FOV's, must be due to variable field-of-view solid angles. Although not displayed, this is confirmed by good agreement in the IR, diverging as one moves toward the blue, for both the 1° and 2° FOV's of both instruments. Table 6.6 lists the new fields-of-view for each instrument as a function of wavelength.
As the agreement is best between the instruments for the 5° FOV's, these values are assumed to be correct and insensitive to variations with \( \lambda \). This was also shown in the first test described in this chapter. Note also that the agreement is best in the IR, as predicted at the end of Chapter 5.
Table 6.5 Measured, Passband Averaged, Spectral Radiance From Each Instrument Using a Solar Illuminated BaSO₄ Panel

<table>
<thead>
<tr>
<th>Band</th>
<th>Ave Dig Cnt</th>
<th>$L_{mA}$</th>
<th>Ave Dig Cnt</th>
<th>$L_{mA}$</th>
<th>$\Delta L_{97-98}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2995.8</td>
<td>30.67</td>
<td>1808.3</td>
<td>30.32</td>
<td>+1.1</td>
</tr>
<tr>
<td>2</td>
<td>4557.5</td>
<td>32.60</td>
<td>3454.0</td>
<td>32.14</td>
<td>+1.4</td>
</tr>
<tr>
<td>3</td>
<td>7772.5</td>
<td>37.41</td>
<td>6806.3</td>
<td>38.03</td>
<td>-1.7</td>
</tr>
<tr>
<td>4</td>
<td>13376.4</td>
<td>48.08</td>
<td>12997.5</td>
<td>47.94</td>
<td>+0.3</td>
</tr>
<tr>
<td>5</td>
<td>19338.1</td>
<td>46.39</td>
<td>19036.0</td>
<td>48.62</td>
<td>-4.8</td>
</tr>
<tr>
<td>6</td>
<td>19747.9</td>
<td>44.45</td>
<td>19276.8</td>
<td>44.12</td>
<td>+0.7</td>
</tr>
<tr>
<td>7</td>
<td>24954.6</td>
<td>36.71</td>
<td>24173.2</td>
<td>37.87</td>
<td>-3.2</td>
</tr>
<tr>
<td>8</td>
<td>20964.2</td>
<td>30.21</td>
<td>20538.3</td>
<td>30.16</td>
<td>+0.2</td>
</tr>
<tr>
<td>9</td>
<td>22777.6</td>
<td>15.66</td>
<td>22607.0</td>
<td>15.11</td>
<td>+3.5</td>
</tr>
<tr>
<td>10</td>
<td>17324.9</td>
<td>21.44</td>
<td>13673.1</td>
<td>20.95</td>
<td>+2.3</td>
</tr>
</tbody>
</table>

where: $L_{mA}$ is expressed as mW cm$^{-2}$ sr$^{-1}$ um$^{-1}$ and

$$\Delta L_{97-98} = 100\% \frac{(L_{98} - L_{97})}{L_{97}}$$
Table 6.6 Updated Values for the Fields-of-view Calibration Using a Solar Illuminated BaSO₄ Panel

<table>
<thead>
<tr>
<th>Band</th>
<th>#97</th>
<th>#98</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ω(1°)</td>
<td>Ω(2°)</td>
</tr>
<tr>
<td>1</td>
<td>.0002190</td>
<td>.0008354</td>
</tr>
<tr>
<td>2</td>
<td>.0002147</td>
<td>.0008312</td>
</tr>
<tr>
<td>3</td>
<td>.0002127</td>
<td>.0008317</td>
</tr>
<tr>
<td>4</td>
<td>.0002029</td>
<td>.0008059</td>
</tr>
<tr>
<td>5</td>
<td>.0002016</td>
<td>.0008048</td>
</tr>
<tr>
<td>6</td>
<td>.0002013</td>
<td>.0008062</td>
</tr>
<tr>
<td>7</td>
<td>.0002032</td>
<td>.0008161</td>
</tr>
<tr>
<td>8</td>
<td>.0002028</td>
<td>.0008150</td>
</tr>
<tr>
<td>9</td>
<td>.0002111</td>
<td>.0008278</td>
</tr>
<tr>
<td>10</td>
<td>.0002030</td>
<td>.0008070</td>
</tr>
</tbody>
</table>

where: Ω(FOV) is expressed in units of steradians
The instruments now agree to within 3\% for all FOV's and all wavelengths, with the exceptions of Bands 1 and 9, due to possible filter leakage in the IR, and to H\textsubscript{2}O variability, respectively.

**Band-Limited Exo-atmospheric Solar Irradiance**

The spectropolarimeters were designed to operate in one mode as solar radiometers to enable the calculation of the atmospheric optical depth (previously outlined in Chapter 2) by means of the Langley plot method. In addition, the band-limited exo-atmospheric solar irradiance can be determined by extrapolating the straight line of the Langley plot to the zero airmass point. The instruments only measure radiance, but since the direct solar radiation is effectively collimated, the irradiance can be determined. Band limited data determined by Neckel and Labs (1981) can be compared to the values determined through the use of the Langley plot. An additional comparison can be made to a manually operated solar radiometer (Shaw 1973) presently used in the experiment at White Sands, NM. This allows an independent determination of the optical depth. One of these tests was performed on October 31, 1984 on the University of Arizona campus utilizing that manually operated radiometer and the spectropolarimeter designated as #98. Another test was performed in Tucson on December 31, 1984 using instrument #97 and the manual radiometer. Figure 6.4 depicts the variation of $\tau$ with $\lambda$ as measured by the two instruments on Oct. 31 while figure 6.5 does the same for the Dec. 31 data. Table 6.7 lists the values of $\tau$ for each instrument, on both dates. Comparing the $\tau$ values shows a relative accuracy of about 5\%, and since $\tau$ is fairly insensitive to measurement
Figure 6.4 Optical Depth Data for October 31, 1984

Figure 6.5 Optical Depth Data for December 31, 1984
Table 6.7 Comparison Between the Spectropolarimeters and a Manually Operated Radiometer for Optical Depth

<table>
<thead>
<tr>
<th>( \lambda ) (( \mu \text{m} ))</th>
<th>10/31/84</th>
<th>( \tau )</th>
<th>12/31/84</th>
</tr>
</thead>
<tbody>
<tr>
<td>.400</td>
<td>.4358</td>
<td>.3841</td>
<td>.3864</td>
</tr>
<tr>
<td>.420</td>
<td>-----</td>
<td>.3296</td>
<td>-----</td>
</tr>
<tr>
<td>.440</td>
<td>.3061</td>
<td>.2779</td>
<td>.3090</td>
</tr>
<tr>
<td>.525</td>
<td>.1753</td>
<td>.1771</td>
<td>.1889</td>
</tr>
<tr>
<td>.605</td>
<td>-----</td>
<td>.1380</td>
<td>-----</td>
</tr>
<tr>
<td>.612</td>
<td>.1299</td>
<td>-----</td>
<td>.1540</td>
</tr>
<tr>
<td>.662</td>
<td>-----</td>
<td>.1019</td>
<td>-----</td>
</tr>
<tr>
<td>.671</td>
<td>.0865</td>
<td>-----</td>
<td>.1030</td>
</tr>
<tr>
<td>.712</td>
<td>.0777</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>.780</td>
<td>.0580</td>
<td>.0528</td>
<td>.0728</td>
</tr>
<tr>
<td>.860</td>
<td>.0419</td>
<td>.0394</td>
<td>.0508</td>
</tr>
<tr>
<td>.948</td>
<td>-----</td>
<td>.2815</td>
<td>.2370</td>
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<tr>
<td>1.040</td>
<td>.0176</td>
<td>.0389</td>
<td>.0373</td>
</tr>
</tbody>
</table>
noise over the course of the data run, the implication is that
atmospheric conditions were not stable. Looking carefully at the data
shows this to be true, that the atmospheric attenuation was not constant
over the measurement period and hence generated noise in the data.
Therefore, the 5\% discrepancy is most likely due to a large spread in
the varying input signal.

Another test used the spectropolarimeter labeled #97 over a two
day period on Dec. 30 and 31, 1985. This instrument made three separate
sets of measurements as follows: morning of the 30th, morning of the
31st, and afternoon of the 31st. The optical depths and exo-atmospheric
intercept values were computed and compared to the Neckel and Labs
values. As seen in Table 6.8, The intercept values from the morning run
on the 31st shows excellent agreement with the Neckel and Labs data,
five bands being within 2 percent. The other bands (with the exception
of bands 1 and 9) are within 4 percent. Band 1 may suffer from IR
leakage and, as a result, its importance will be de-emphasized. Band 9
is centered on a water vapor band which is subject to strong variations
in optical depth with time of day. A better test of band 9 would be to
make measurements at a location above most of the water vapor, such as
a mountain top. The other runs do not show the same level of accuracy,
averaging 5\% - 10\% too low. Explanations for this follow below.

Figure 6.6 depicts the variation in optical depth if the Neckel
and Labs data is used as the true intercept values for band 3. Identical
plots for the other bands show a similar trend. These plots depict the
instantaneous optical depths as a function of airmass, and show that on
the morning of the 30th, the optical depth increased by approximately
Table 6.8 Comparison of Three Sets of Data Collected by Instrument #97 with Data Collected by Neckel and Labs (1981)

<table>
<thead>
<tr>
<th>Band</th>
<th>N&amp;L</th>
<th>12/30</th>
<th>12/31 AM</th>
<th>12/31 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_0$</td>
<td>$\tau$</td>
<td>$E_0$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>1</td>
<td>1.6924</td>
<td>-----</td>
<td>0.4224</td>
<td>2.1217</td>
</tr>
<tr>
<td>2</td>
<td>1.9289</td>
<td>0.3263</td>
<td>1.7002</td>
<td>1.9298</td>
</tr>
<tr>
<td>3</td>
<td>2.2021</td>
<td>0.2809</td>
<td>1.9673</td>
<td>2.1963</td>
</tr>
<tr>
<td>4</td>
<td>2.0725</td>
<td>-----</td>
<td>1.694</td>
<td>1.9894</td>
</tr>
<tr>
<td>5</td>
<td>1.9876</td>
<td>-----</td>
<td>1.572</td>
<td>1.9925</td>
</tr>
<tr>
<td>6</td>
<td>1.6705</td>
<td>-----</td>
<td>1.124</td>
<td>1.6083</td>
</tr>
<tr>
<td>7</td>
<td>1.4161</td>
<td>0.0687</td>
<td>1.3577</td>
<td>1.3900</td>
</tr>
<tr>
<td>8</td>
<td>1.4962</td>
<td>0.0580</td>
<td>1.3951</td>
<td>1.3931</td>
</tr>
<tr>
<td>9</td>
<td>1.9095</td>
<td>-----</td>
<td>1.2419</td>
<td>1.3797</td>
</tr>
<tr>
<td>10</td>
<td>1.5486</td>
<td>0.0564</td>
<td>1.4203</td>
<td>1.5058</td>
</tr>
</tbody>
</table>

where: $E_0$ is expressed in units of mW cm$^{-2}$
Figure 6.6 Variation in $\tau$ with Airmass for Band 3 of Instrument #97 on December 30 and 31, 1984
5 percent, was nearly constant during the morning of the 31st, and
decreased by approximately 10 percent during the afternoon of the 31st.
These results indicate that the data collected for all three runs were
not of high quality, with the morning of the 31st being the best. This
is consistent with the weather patterns which occurred during this same
time period. Prior to the 30th, the weather was rainy, thus clearing the
air of aerosols and producing a lower optical depth. The two
observation days were clear but slightly windy. It is hypothesized that
dust and automotive pollutants were introduced into the lower
atmosphere at this time, increasing the optical depth until a steady­
state value was reached. Late in the afternoon of the 31st, the wind
velocity increased as a new storm system entered the region. Wind can
either disperse or concentrate the aerosols, so a change in optical depth
should be observed. The 10 percent decrease noted above is larger than
would be expected, but not unreasonable (Reagan 1985, Reagan, et al.
1984).

Summation of Spectropolarimeter Accuracies

It can be seen that the spectropolarimeters show an average
intercomparative radiometric difference of less than 2% when measuring
the spectrally smooth sources described above. For sources whose
spectral characteristics vary sharply over the 10 nm passbands, the
measurements made by these spectropolarimeters would have a larger
associated error. The average absolute radiometric inaccuracy appears
to be near 3% - 5% over a majority of the bands, for both instruments.
However, due to the inherent measurement errors encountered above when
using the standard sources and targets, it can only be said that the overall differences were overlapping. This implies that the instruments have accuracies no worse than these sources and targets, and could have even smaller errors.

Field Measurement Flexibility

The next three sections describe other field measurements which the spectropolarimeters currently are able to make, thus demonstrating the flexibility with which these instruments can be used. More complicated observation modes could be used, but they are left for future experimentalists to explore.

Azimuthal Scan

An examination of the skylight at the same elevation as the sun but at varying azimuthal angles from the sun (an almucantar scan) can be performed. All 10 wavelengths can be used and a full set of polarization measurements can be taken for each wavelength, for each angle. Measurements of this type may be useful in determining characteristics of the aerosol phase function and refractive index. A variation of this scan is an elevation scan, a vertical version which can also be performed by the instrumentation through proper software implementation. From the field-of-view measurements, it was determined that measurements of the sky could be made no closer than 10 degrees from the sun using the 1 degree field of view without additional shielding. Therefore, the azimuthal/elevation scans could be made from 10° to 180° from the sun, selecting the most logical FOV's and degree step increments. Table 6.9 lists the details of an azimuthal scan going
Table 6.9 Stoke's Parameters for an Azimuthal Scan from 20° to 140°
in Bands 1, 5, and 7 of Instrument #97

<table>
<thead>
<tr>
<th>Angle °</th>
<th>Band 1</th>
<th>Q/I</th>
<th>U/I</th>
<th>V/I</th>
<th>%Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>-0.073</td>
<td>+0.012</td>
<td>-0.005</td>
<td>7.41</td>
<td></td>
</tr>
<tr>
<td>40.0</td>
<td>-0.159</td>
<td>+0.062</td>
<td>-0.001</td>
<td>17.07</td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>-0.286</td>
<td>+0.179</td>
<td>+0.001</td>
<td>33.74</td>
<td></td>
</tr>
<tr>
<td>80.0</td>
<td>-0.367</td>
<td>+0.372</td>
<td>+0.007</td>
<td>52.26</td>
<td></td>
</tr>
<tr>
<td>100.0</td>
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<td>+0.562</td>
<td>+0.015</td>
<td>65.14</td>
<td></td>
</tr>
<tr>
<td>120.0</td>
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<td>+0.588</td>
<td>+0.001</td>
<td>59.93</td>
<td></td>
</tr>
<tr>
<td>140.0</td>
<td>+0.114</td>
<td>+0.465</td>
<td>-0.005</td>
<td>47.88</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle °</th>
<th>Band 5</th>
<th>Q/I</th>
<th>U/I</th>
<th>V/I</th>
<th>%Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>-0.041</td>
<td>+0.005</td>
<td>-0.001</td>
<td>4.13</td>
<td></td>
</tr>
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</tr>
<tr>
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<td>+0.146</td>
<td>+0.002</td>
<td>26.66</td>
<td></td>
</tr>
<tr>
<td>80.0</td>
<td>-0.324</td>
<td>+0.337</td>
<td>+0.005</td>
<td>46.75</td>
<td></td>
</tr>
<tr>
<td>100.0</td>
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<td>+0.523</td>
<td>+0.009</td>
<td>59.71</td>
<td></td>
</tr>
<tr>
<td>120.0</td>
<td>-0.093</td>
<td>+0.588</td>
<td>+0.010</td>
<td>59.54</td>
<td></td>
</tr>
<tr>
<td>140.0</td>
<td>+0.150</td>
<td>+0.469</td>
<td>+0.004</td>
<td>49.24</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle °</th>
<th>Band 7</th>
<th>Q/I</th>
<th>U/I</th>
<th>V/I</th>
<th>%Pol</th>
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</thead>
<tbody>
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<td>20.0</td>
<td>-0.046</td>
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<td></td>
</tr>
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<td>40.0</td>
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<td></td>
</tr>
<tr>
<td>60.0</td>
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<td>20.77</td>
<td></td>
</tr>
<tr>
<td>80.0</td>
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<td>+0.008</td>
<td>39.75</td>
<td></td>
</tr>
<tr>
<td>100.0</td>
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<td>+0.449</td>
<td>+0.017</td>
<td>50.89</td>
<td></td>
</tr>
<tr>
<td>120.0</td>
<td>-0.083</td>
<td>+0.530</td>
<td>-0.001</td>
<td>53.65</td>
<td></td>
</tr>
<tr>
<td>140.0</td>
<td>+0.141</td>
<td>+0.414</td>
<td>-0.006</td>
<td>43.74</td>
<td></td>
</tr>
</tbody>
</table>

where: I is defined to be 1.000 (the Stoke's parameters are unitless)
from 0° to 180° in 20° step intervals. Bands 1, 5, and 7 were used in a configuration utilizing a 2° FOV. The data were collected on November 28, 1984 on the University of Arizona campus. Figure 6.7 depicts the variation in the amount and degree of polarization as a function of wavelength. A combination of stepping in both azimuth and elevation could enable one to make an all-sky scan, thus mapping out the sky radiance and polarization as a function of wavelength and time.

Aureole Scan

The aureole scan is similar to the almucantar scan, but for angles less than 20° from the sun. To get within 11°, an observing aid was used, consisting of an opaque circular shield placed at the end of a boom in such a manner as to shield the end of the nose baffle from direct solar radiation. This direct component causes the most error at off axis angles because it is 10° larger than the radiation to be measured. Preventing this direct radiation from entering the instrument allowed the internal baffles to operate properly on the remaining radiation. Measurements of the solar aureole can enable an observer to determine the scattering characteristics of the aerosols as pointed out by Deepak, et al. (1982). Measurements were made on December 31st, 1984, in Tucson in three separate wavelength bands using instrument #97. These three bands were 3, 5, and 7, and the results are displayed in Table 6.10. Figure 6.8 also graphically illustrates the fall-off in radiance with increasing angle from the solar disk.
Figure 6.7 Variation of the Amount and Tilt Angle of Polarization for Band 7, #97
Table 6.10 Aureole Radiance Measurements from 2° to 20° for Bands 3, 5, and 7 of Instrument #97

<table>
<thead>
<tr>
<th>Degrees from sun</th>
<th>Instrument #97 Band Radiances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2.0</td>
<td>.7113</td>
</tr>
<tr>
<td>4.0</td>
<td>.4649</td>
</tr>
<tr>
<td>6.0</td>
<td>.3529</td>
</tr>
<tr>
<td>8.0</td>
<td>.2998</td>
</tr>
<tr>
<td>10.0</td>
<td>.2668</td>
</tr>
<tr>
<td>12.0</td>
<td>.2429</td>
</tr>
<tr>
<td>14.0</td>
<td>.2260</td>
</tr>
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<td>16.0</td>
<td>.2114</td>
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<tr>
<td>18.0</td>
<td>.1996</td>
</tr>
<tr>
<td>20.0</td>
<td>.1929</td>
</tr>
</tbody>
</table>

where: Radiances are in units of mW cm⁻² sr⁻¹
Figure 6.8 Aureole Radiance Values as a Function of Angle for Bands 3, 5, and 7 of Instrument #97
Helicopter Scan Mode

The instrument can also be bolted to the step of a helicopter and flown over a site at varying altitudes. The data collected is useful for two reasons:

1) At low altitudes the reflecting ground radiance can be measured and, assuming that the atmospheric path radiance between the helicopter and the ground is negligible, the ground reflectance can also be determined, provided that simultaneous determinations of the incident solar irradiance are made.

2) At higher altitudes, the increase in path radiance due to the intervening atmosphere can be monitored and compared against the theoretical calculations generated by a modified program based on the one by Herman and Browning (1975). It is interesting to note that for elevations greater than 3000 m above sea level, the measureable irradiance is within 1% of the exoatmospheric irradiance for wavelengths greater than 600 nm.

Table 6.11 lists a number of measurements made from a helicopter flown at White Sands Missile Range over a test site during a satellite overflight on October 28th, 1984. These measurements were collected over one site at elevations of 150 m, 600 m, and 1800 m above ground (the elevation at WSMR is 1200 m). Also listed is the solar
Table 6.11 Radiances $L_m$ Measured at Altitudes of 150, 600, and 1800 meters Above Ground Level from a Helicopter Platform

<table>
<thead>
<tr>
<th>Band</th>
<th>$\theta_z$ (°)</th>
<th>$L_m$ (mW cm$^{-2}$ sr$^{-1}$)</th>
<th>$\theta_z$ (°)</th>
<th>$L_m$ (mW cm$^{-2}$ sr$^{-1}$)</th>
<th>$\theta_z$ (°)</th>
<th>$L_m$ (mW cm$^{-2}$ sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53.646</td>
<td>1.049</td>
<td>49.018</td>
<td>1.218</td>
<td>51.326</td>
<td>1.176</td>
</tr>
<tr>
<td>2</td>
<td>53.633</td>
<td>1.091</td>
<td>49.010</td>
<td>1.258</td>
<td>51.315</td>
<td>1.207</td>
</tr>
<tr>
<td>3</td>
<td>53.621</td>
<td>1.374</td>
<td>49.003</td>
<td>1.560</td>
<td>51.306</td>
<td>1.491</td>
</tr>
<tr>
<td>4</td>
<td>53.610</td>
<td>1.654</td>
<td>48.994</td>
<td>1.851</td>
<td>51.295</td>
<td>1.736</td>
</tr>
<tr>
<td>5</td>
<td>53.590</td>
<td>1.778</td>
<td>48.986</td>
<td>1.959</td>
<td>51.284</td>
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<td>48.970</td>
<td>1.707</td>
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<td>1.645</td>
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<td>1.822</td>
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<tr>
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<td>48.954</td>
<td>1.080</td>
<td>51.243</td>
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<tr>
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<td>1.783</td>
<td>48.946</td>
<td>1.892</td>
<td>51.232</td>
<td>1.875</td>
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</table>

where: Radiances are in units of mW cm$^{-2}$ sr$^{-1}$ and $\theta_z$ is expressed in degrees.

As is evident from the solar zenith angle $\theta_z$, the measurements were first taken at the 600 m elevation, followed by the 1800 m elevation, finally ending with the 150 m elevation.
zenith angle at the time of the measurement. Note that one must be
careful not to assume that an increase in radiance is due solely to path radiance; changes in the solar zenith angle can also cause such a variation.
CONCLUSIONS

This dissertation has covered many aspects of instrument development, from concepts and design, fabrication, and calibration. Chapter 1 discussed the initial reasons for which the spectropolarimeters were developed. Chapter 2 discussed the quantities which were needed to be measured as part of the ongoing satellite calibration program. These included the ground radiance and the atmospheric optical depth, among others. Chapter 3 presented the design of the instruments, from the selection of components, to the actual optical and system layouts.

An additional goal was set of calibrating, both in a relative, and in an absolute sense, both instruments. Chapter 4 discussed the techniques used in the absolute radiometric calibration, followed in chapter 5 by the discussion of the relative radiometric calibrations. In both chapters, the errors accrued in the calibration process were tabulated, along with the appropriate calibration values. A typical inaccuracy of 10% has been associated with field instrument calibration in the past. To quote from Grum and Becherer (1979),

"In comparison with the measurement of other physical quantities, the level of uncertainty involved in the measurement of radiant energy or power is very high. Uncertainties of 1% are considered to be very good and are achieved only in those situations where great care has been
taken and where the available components, techniques, and measurement standards are consistent with this level of uncertainty. More typically, uncertainties of 10% or greater are considered adequate and are the result of good measurement technique."

This 10% value has been improved upon through the use of detector based technology, and for the spectropolarimeters discussed above, it has been calculated that the average level of uncertainty is less than 2%.

Finally in chapter 6, tests of the instrument calibrations were performed which demonstrated a 5-7% uncertainty. This uncertainty represents more of the limits to which the comparison standards were known (to 5%), rather than of the actual inaccuracies inherent in the instrumentation. A discussion of the flexibility in measurement programs available to these spectropolarimeters ended chapter 6.

To conclude, the author is of the opinion that detector based calibrations are as accurate as, if not better than, source based calibrations under most situations, and therefore, will become more prevalent in the future as the need for more accurately calibrated instrumentation increases. Improvements on the accuracies attained above can be brought about by a combination of factors. First, any instrument to be calibrated must be properly designed from an optical calibration standpoint. Next, more careful attempts must be made to reduce environmental effects and to stabilize sources and calibration standards. Finally, improvements should be made in the deconvolution
procedure, including a better knowledge of the slit function of the monochromator.

The instruments developed in this work are tools to be used in gaining a better understanding of the earth/atmosphere environment. The author hopes that they will be put to effective and frequent use in studies of this subject.
APPENDIX A

This appendix presents a documented computer program listing of the program currently being used to operate the spectropolarimeters as solar radiometers. Some of the code operates an automated tracking stand, some calculates solar ephemeris values, and the remainder operates the spectropolarimeters. It should be noted that this code is specifically configured for this specific instrument circuitry, but the flow of the program as a driver of the instruments is applicable to any data gathering machine.

10 REM THIS TRACKING PROGRAM FOR 3 IR FILTERS INCORPORATES A DELAY IN THE PbS DETECTOR ROUTINE FOR TEMPERATURE STABILIZATION
20 OUT(107),0:OUT(80),0:OUT(48),0: GOTO 930
30 MP=80:KS=150:ON MF GOTO 40,50,60,70,80'MOTOR STEP SUBROUTINE:
   MOTOR=MF, STEPS=NS, DIRECTION=DI; 30 - 70 SET INDIVIDUAL MOTOR PARAMETERS
40 MV=1:PL=1:DT=19: GOTO 90'ND FILTER MOTOR (DI=0 IS CCW, DI=2 IS CW)
50 MV=2:PL=4:DT=49: GOTO 90'SPECTRAL FILTER MOTOR (DI=0 IS CCW, DI=8 IS CW)
60 MV=4:PL=16:DT=4:KS=100: GOTO 90'APERTURE MOTOR (DI=0 IS CW, DI=32 IS CCW)
70 MV=8:PL=64:DT=2:KS=5:GOTO 90'POLARIZER MOTOR (DI=0 IS CW)
80 MP=48:MV=128:PL=128:DT=4:KS=50'DETECTOR MOTOR (DI=0 IS CCW, DI=8 IS CW)
90 OUT(MP),MV:FORII=1T0N:OUT(64),DI:NEXTJJ: OUT(64),DI+PL: OUT(64),DI: NEXTII: FORKK=1TOKS: NEXTKK: OUT(MF),0:RETURN'TURN ON MOTOR; STEP MOTOR; DELAY TO ALLOW MOTOR TO SETTLE IN DETENT; TURN OFF MOTOR'
100 OUT(80),48:A1=INP(16)AND15:A2=(INP(16)AND240)/16'DECODE ENCODERS TO A1 AND A2
110 OUT(80),192:A3=INP(0)AND7:A4=(INP(0)AND56)/8:A5=(INP(0)AND192)/64:
   OUT(80),0:RETURN'DECODE ENCODERS TO A3, A4, AND A5
120 HR=VAL(LEFT$(T$,2)): MN=VAL(MIDS$(T$,4,2)): UC=VAL(RIGHT$(T$,2)):RETURN
   'DECODE TIME STRING'
130 OUT(48),1: FOR I=1TO5:OUT(120),0'SELECTS THE PbS DETECTOR AMPLIFIER;
   STROBES ON THE A/D 5 TIMES'
140 IF (INP(122)AND128)=0 THEN 140 ELSE NEXTI'WAIT FOR A/D TO FINISH CONVERSION'
121

150 HB=INP(122): VA=INP(121)+256*(HBAND15): BT=(HBAND16):
IF (HBAND32)=0 THEN VA=VA': ASSIGN A/D VALUE TO VA'; CHECK OVERANGE; ASSIGN CORRECT SIGN'

160 AV(N9)=VA: RETURN'PUT VALUE IN ARRAY FOR AVERAGE ROUTINE; RETURN'

170 MF=5: NS=18: DI=8: GOSUB 30: GOSUB 100'MOVE TO DETECTOR #2 AND READ ENCODER'

180 IF A5=2 THEN DN=2: GOTO 210 ELSE IF A5=0 THEN 190 ELSE 200'CHECK DETECTOR POSITION THEN CORRECT IF LOST OR WRONG'

190 NS=1: DI=8: GOSUB 30: GOSUB 100: IF A5=0 THEN 190 ELSE 180' STEP UNTIL ENCODER VALUE OTHER THAN 0 FOUND'

200 IF A5=3 THEN DI=8: NS=1: MF=5: GOSUB 30: GOSUB 100 ELSE IF A5=1 THEN 170 ELSE 180' IF ON DET 1, GO TO MOVE STEP ELSE RECHECK'

210 GOSUB 100: IF A2=M+1 THEN 250' READ ENCODERS; IF ON CORRECT SPECTRAL FILTER (M+1), LOOP AROUND MOVE SECTION'

220 MF=2: IF A2=0 THEN NS=1: DI=0: GOSUB 30: GOTO 210'SELECT SPECTRAL FILTER MOTOR; IF LOST, MOVE ONE STEP UNTIL FOUND'

230 IF A2>M+1 THEN NS=4*(A2-M-1): DI=8 ELSE NS=4*(M+1-A2): DI=0'SELECT NUMBER OF STEPS AND DIRECTION'

240 GOSUB 30: GOTO 210' STEP MOTOR; RECHECK'

250 IF A1=1 THEN 280' IF ON OPEN ND POSITION (1) THEN SKIP AROUND MOVE


270 MF=1: GOSUB 30: GOTO 210'SELECT ND MOTOR; STEP MOTOR; RECHECK'

280 T$=TIME$: GOSUB 120: UZ=UC+3: IF UZ>60 THEN UZ=UZ-60: MZ=MN+1: IF MZ>60 THEN MZ=MZ-60: HZ=HR+1 ELSE HZ=HR ELSE MZ=MN: HZ=HR'READ TIME AND DECODE TIME; ADD 10 SECONDS

290 TZ=UZ+100*MZ+10000*HZ'BUILD TZ FOR COMPARISON'

300 TIME$:ON: T$=TIME$: GOSUB 120: TY=UC+100*MN+10000*HR'READ TIME; BUILD TY FOR COMPARISON'

310 IF TY<TZ THEN 300'LOOP UNTIL DELAY DONE'

320 TIME$:STOP'TURN OFF INTERRUPT DURING DATA CYCLE'

330 M=M+1'INCREMENT M (SETS UP MOVE OF SPECTRAL FILTER)'

340 TIME$:ON'TURN ON TIME INTERRUPT FOR TRACKING'

350 TIME$:STOP'TURN OFF TIME INTERRUPT

360 GOSUB 100'READ ENCODER

370 IF A2=M THEN 420' IF ON CORRECT SPECTRAL FILTER THEN JUMP AROUND MOVE ROUTINE'

380 MF=2'SELECT SPECTRAL FILTER MOTOR'

390 IF A2=0 THEN NS=1: DI=0: GOSUB 30: GOTO 360' IF LOST STEP 1; RECHECK

400 IF A2=M THEN NS=4*(A2-M): DI=8 ELSE NS=4*(M-A2): DI=0'SELECT DIRECTION AND NUMBER OF STEPS'

410 GOSUB 30: GOTO 360'Step Motor; Recheck'

420 FOR N=1 TO 2'FOR EACH POLARIZATION'

430 N9=1'INITIALIZE COUNTER FOR AVERAGING DARK VALUE

440 N9=N9+1'INCREMENT COUNTER'

450 GOSUB 100: IF A1=2 THEN GOSUB 130: GOTO 470 ELSE IF A1=0 THEN NS=1: DI=0 ELSE IF A1=1 THEN NS=4: DI=0 ELSE IF A1<8 THEN NS=4*(A1-2): DI=2 ELSE NS=(14-A1)*4: DI=0'CHECK IF ND FILTER ON OPAQUE POSITION; THEN CALL A/D ROUTINE ELSE SET UP MOVE'
122

460 MF=1: GOSUB 30: GOTO 450 'STEP MOTOR; RECHECK'
470 N9=N9+1: IF N9>3 THEN 540 'INCREMENT COUNTER, IF 2ND DARK DONE GOTO AVERAGE ROUTINE'
480 NS=ABS(DF(M-1)-A1): IF A1<DF(M-1) THEN DI=0 ELSE DI=2 'SELECT NUMBER OF STEPS AND DIRECTION TO MOVE TO DEFAULT'
490 IF A1<DF(M-1) THEN GOSUB 130 ELSE IF A1=0 THEN NS=1: DI=0: GOSUB 30: GOSUB 100 'STEP MOTOR, READ ENCODERS'
500 IF (ABS(VA)<=200 AND A1<>1) THEN DI=2: MF=1: NS=8: GOSUB 30 ELSE IF A1=0 THEN NS=1: DI=0: MF=1: GOSUB 30: GOTO 510 'IF LOST, STEP 1 UNTIL FOUND'
510 A9=A1: A8=A5: GOTO 440 'ENTERS ENCODERS A1 AND A5 IN DUMMY VARIABLES'
520 IF A1=1 OR A1=3 OR A1=5 OR A1=7 OR A1=9 OR A1=11 THEN GOSUB 130: GOTO 500 ELSE IF A5=0 THEN NS=1: MF=5: DI=8: GOSUB 30: GOTO 510 'READ ENCODERS; IF A5 LOST, STEP ONE AT A TIME TIL DETECTOR POSITION FOUND'
530 T$=TIME$: GOSUB 100: A1=A9: A5=A8: GOTO 850 'READ TIME; GO TO FORMATING CODE'
540 PRINT"F#","M","N1","N2" DV DIFFERENCE=";AV(0)-AV(2) '"PRINT FILTER #, DARK VALUE DIFFERENCE'
550 VA=ABS(AV(1)-(AV(0)+AV(2))/2)'CALCULATE PbS SIGNAL'
560 IF (M=12 AND DN=2) AND N=2 THEN MF=5: NS=18: DI=0: GOSUB 30 ELSE IF 580' TEST (DETECTOR POSITION AND SPECTRAL FILTER 12 AND SECOND POLARIZATION) THEN SET UP AND MOVE TO DET 1 ELSE NEXT TEST'
570 GOSUB 100: IF A5=0 THEN NS=1: MF=5: DI=8: GOSUB 30: GOTO 510 'CHECK IF ON ND FILTER THEN TO A/D OR STEP TO ND FILTER '
580 IF A5=1 THEN DN=1: GOTO 590 ELSE IF (((M=10 OR M=11) AND DN=2) OR (M=12 AND N=1)) THEN 590 ELSE 560' CHECK IF ON DETECTOR #1 OR (M=10 OR 11 AND ON DET #2) OR (M=12 AND 1ST POLARIZATION) THEN CONTINUE OR LOOP BACK TO REPOSITION'
590 T$=TIME$: GOSUB 100: A1=A9: A5=A8: GOTO 850 'READ TIME; READ ENCODERS; GO TO FORMATING CODE'
600 OUT(107),0: GOSUB 100: ZZ=A3: IF ZZ=AA THEN 620 'READ ENCODERS; IF ON REQUESTED FOV CONTINUE ELSE NEXT LINE'
610 DI=0: MF=3: NS=1: GOSUB 30: GOTO 600 'MOVE APERTURE WHEEL 1 STEP; RECHECK'
620 BEEP: CALL 16964: PRINTFRE(0); P1+1: CALL 16959: IF FRE(0)<1000 THEN 1390 'START OF DATA TAKE; TURN ON SCREEN SCROLLING; CHECK AND PRINT FREE MEMORY; TURN OFF SCREEN SCROLLING; IF FREE MEMORY LESS THAN 1000 GO TO END'
630 M=0 'INITIALIZE M (SPECTRAL FILTER) COUNTER'
640 M=M+1: TIMESTOP' LOOP FOR SPECTRAL FILTER, TURN OFF TIME INTERRUPT'
650 GOSUB 100: ZZ=A2: IF ZZ=M THEN 690 'READ ENCODER FOR SPECTRAL FILTER'
660 IF ZZ=0 THEN MF=2: DI=0: NS=1: GOSUB 30: GOTO 650 'STEP 1 UNTIL SPECTRAL FILTER ENCODER READS OTHER THAN 0'
670 MF=2: IF ZZ=12 THEN NS=4: DI=0 ELSE IF ZZ>M THEN NS=ABS(DF(M-1)-A1): IF A1<DF(M-1) THEN DI=0 ELSE DI=2 'SELECT NUMBER OF STEPS AND DIRECTION TO MOVE TO DEFAULT'
680 GOSUB 30: GOTO 650 'MOVE TO CORRECT SPECTRAL FILTER; RECHECK
690 GOSUB 100: IF A1=0 THEN NS: DI=0: GOTO 710 'CHECK IF ND FILTER ENCODER LOST; SET UP TO FIND
700 IF A1=DF(M-1) THEN 720 ELSE IF A1>DF(M-1) THEN NS=4*(A1-DF(M-1)) : DI=2 ELSE NS=4*(DF(M-1)-A1) : DI=0 'CHECK ND FILTER ENCODER, IF NOT ON DEFAULT, SET UP TO MOVE TO DEFAULT'
710 MF=1: GOSUB 30: GOTO 690 'STEP MOTOR; READ ENCODERS; RECHECK'
720 FOR N=1 TO 2 'OPERATES THE A/D FOR EACH POLARIZATION'
730 OUT(18),0: FOR I=1 TO 5: OUT(120),0 'SELECTS Si DETECTOR AMPLIFIER; STROBES A/D 5 TIMES'
740 IF (INP(122) AND 128)=0 THEN 740 ELSE NC=0: GOTO 830 'IF OVERANGE AND NOT AT ND=1 THEN SKIPS NEXT LINE'
750 IF (BT=16) AND ZZ<9 THEN 780 ELSE NC=0: GOTO 830 'IF ON GOOD ND FILTER COMPLETE, ELSE STEP TO GOOD FILTER; RECHECK'
760 IF NC=1 THEN 730 'LOOP BACK TO A/D FOR READING WITH NEW ND FILTER (AUTORANGING COMPLETE)'
770 QA=A1+100*A2+10000*A3+1000000*A4+QB=A5:B3$(N)=RIGHT$(STR$(100+VA),4) 'FORMAT OUTPUT STRING'
780 DF(M-1)=A1 'UPDATE DEFAULT ND FILTER
790 MF=1: NS=8: GOSUB 30 'MOVE ND FILTER
800 GOSUB 100: ZZ=A1: IF ZZ<0 THEN DI=2: MF=1: NS=1: GOSUB 30: GOTO 810 'READ ENCODER; IF LOST THEN STEP 1 UNTIL FOUND
810 IF ZZ<1 OR ZZ<3 OR ZZ=5 OR ZZ=7 OR ZZ=9 OR ZZ=11 THEN 830 ELSE DI=0: MF=1: NS=4: GOSUB 30: GOTO 810 'IF ON GOOD ND FILTER COMPLETE, ELSE STEP TO GOOD FILTER; RECHECK'
820 IF NC=1 THEN 730 'LOOP BACK TO A/D FOR READING WITH NEW ND FILTER (AUTORANGING COMPLETE)'
830 IF M=9 THEN 170 ELSE IF (M=10 OR M=11) THEN 330 'GO TO PbS DETECTOR ROUTINE IF APPROPRIATE'
840 TIME$: GOSUB 100 'READ TIME AND ENCODERS'
850 QA=A1+100*A2+10000*A3+1000000*A4+QB=A5:B3$(N)=RIGHT$(STR$(10000+VA),4) 'FORMAT OUTPUT STRING'
860 DF(M-1)=A1 'UPDATE DEFAULT ND FILTER
870 B5S=RIGHT$(STR$(QB),1)+RIGHT$(STR$(QA),6)+T$: DI=0: MF=4: NS=60: GOSUB 30 'FORMAT STRING; MOVE POLARIZER 90 DEGREES
880 GOSUB 100: ZZ=A4: IF ZZ<0 THEN NEXTN ELSE NS=1: GOSUB 30: GOTO 880 'CHECK POLARIZER POSITION; IF ON GOOD POSITION GO TO NEXT N ELSE STEP UNTIL NOT LOST; RECHECK
890 PRINT#1,'"P-"'; B3$(1); B5S; "S-"; B3$(2); CHR$(13); CHR$(10)'WRITE TO OUTPUT FILE
895 PRINT "P-"'; B3$(1); B5S; "S-"; B3$(2)'WRITE TO SCREEN'
900 IF M=9 THEN 170 ELSE IF (M=10 OR M=11) THEN 330 'GO TO PbS DETECTOR ROUTINE IF APPROPRIATE'
910 TIME$: IF M<10 THEN 640 ELSE P1=P1+1:RETURN 'TURN ON TIME INTERRUPT, LOOP BACK FOR NEXT SPECTRAL FILTER; INCREMENT P1; END DATA RUN IF M=12'
920 REM START INITIALIZATION OF INSTRUMENT
124

940 INPUT"APERTURE SETTING(1=1,2=2,3=5,4=15 DEGREES)";AA'INITIAL USER QUESTIONS
950 INPUT"FILE NAME FOR DATA STORAGE";F$'GET DATA STORAGE FILE NAME'
960 INPUT"TYPE 0 FOR FILE OUTPUT, 1 FOR FILE APPEND";CH'OPEN NEW FILE OR APPEND TO EXISTING FILE'
970 P1=0: IF CH=0 THEN OPEN F$ FOR OUTPUT AS 1: GOTO 990 'INITIALIZE PI; OPEN NEW FILE'
980 IF CH=1 THEN OPEN F$ FOR APPEND AS 1 ELSE GOTO 950 'OPEN EXISTING FILE'
990 OUT(107),0: OUT(80),0: OUT(48),0 'TURN ON PATH TO INSTRUMENT; TURN OFF MOTORS'
1000 FOR M=0 TO 1: DF(M)=5: NEXT M: FOR M=2 TO 8: DF(M)=7: NEXT M: DF(9)=1: DF(10)=1: DF(11)=1: DF(12)=1 'SET DEFAULT VALUES FOR EACH SPECTRAL FILTER'
1010 GOSUB 100 'READ ENCODERS'
1020 IF A1=DF(0) THEN 1060 ELSE IF A1<>0 THEN 1040 'CHECK IF ND FILTER IS ON DEFAULT VALUE FOR SPECTRAL FILTER 1 ELSE IF A1 OTHER THAN 0'
1030 NS=1: MF=1: DI=0: GOSUB 30: GOTO 1010 'SINGLE STEP UNTIL A1<>0'
1040 IF A1>DF(0) THEN NS=4*(A1-DF(0)): DI=2 ELSE NS=4*(DF(0)-A1): DI=0 'SELECT DIRECTION AND NUMBER OF STEPS'
1050 MF=1: GOSUB 30: GOTO 1010 'SET UP AND STEP MOTOR; RECHECK'
1060 IF A2=1 THEN 1100 ELSE IF A2<>0 THEN 1080 'CHECK IF SPECTRAL FILTER IS #1 ELSE IF A2 OTHER THAN 0'
1070 NS=1: MF=2: DI=0: GOSUB 30: GOSUB 100: GOTO 1060 'SINGLE STEP UNTIL A2<>0'
1080 IF A2<=6 THEN DI=8: D1=A2-1: GOTO 1090 ELSE IF A2>6 THEN 1080 'SET UP DIRECTION AND NUMBER OF STEPS'
1090 NS=4*D1: MF=2: GOSUB 30: GOTO 1010 'SET UP AND STEP MOTOR; RECHECK'
1100 IF A3=1 THEN 1140 ELSE IF A3<0 THEN 1120 'CHECK IF APERTURE SET TO 1 DEGREE FOV ELSE IF A3 OTHER THAN 0'
1110 NS=1: MF=3: DI=0: GOSUB 30: GOSUB 100: GOTO 1100 'SINGLE STEP UNTIL A3<>0'
1120 IF A3<=2 THEN DI=32: D1=A3-1: ELSE IF A3>2 THEN DI=0: D1=5-A3 'SELECT DIRECTION AND NUMBER OF STEPS'
1130 NS=12*D1: MF=3: GOSUB 30: GOTO 1010 'SET UP AND STEP MOTOR'
1140 IF A5=1 THEN DN=1: GOTO 1170 ELSE IF A5=2 THEN NS=18: MF=5: DI=0: GOTO 1160 'CHECK IF ON SI DETECTOR; IF PB# THEN SET UP MOVE ELSE GO TO LOST CHECK'
1150 NS=1: MF=5: DI=8 'SET UP MOTOR FOR SINGLE STEP'
1160 GOSUB 30: GOTO 1010 'STEP MOTOR; RECHECK'
1170 IF A4<>7 THEN NS=1: MF=4: DI=0: GOSUB 30: GOSUB 100: GOTO 1170 'SET POLARIZER TO POSITION 7'
1180 NS=60: MF=4: GOSUB 30: GOSUB 100 'ROTATE POLARIZER 90 DEGREES; READ ENCODERS'
1190 CLS: PRINT "NEUTRAL FILTER #"; A1: PRINT "SPECTRAL FILTER #"; A2: PRINT "APERTURE #"; A3
1200 PRINT "POLARIZER POSITION #"; A4: PRINT "DETECTOR #"; A5
1210 PRINT "HIT ANY KEY WHEN THE TRACKER IS ALIGNED WITH THE SUN"
1220 P2$=INKEY$: IF P2$="" THEN 1220 'WAIT FOR ANY KEY STROKE'
1230 P3=0 'INITIALIZE P3 COUNTER'
D$=DATE$:YR=VAL("19"+RIGHT$(D$,2)):MO=VAL(LEFT$(D$,2)):DY=VAL(MID$(D$,4,2))'
"READ AND DECODE DATE'
D=INT(275*MO/9)-30+DY:D=D-INT((MO+9)/12)*(1+INT((YR+2-4*INT(YR/4))/3))
"COMPUTE DAY # (1-366) FROM YEAR, MONTH AND DAY'
LO=106.351;LA=32.919;Z=7:PRINT"LAT:";LA;" ""LONG:";LO'WSNM POSITION
(U/A POSITION 110.944;32.228)'
ONTIME$="00:00:00"GOSUB 1400:IV=25:GOSUB 1400
T$=TIME$:GOSUB 120'READ TIME; DECODE TIME STRING'
WH=2: WJ=7: IF MO<4 OR MO)9 THEN WH=I:WJ=6
HI=ABS(FIX(VAL(LEFT$(TIME$,2)-11.5»: IF HI<WH THEN IM=10 ELSE IM=WJ-HI
IA=IM:IB=HR'SELECT DATE TAKE INTERVAL'
IF MN)=IA THEN IA=IA+IM: IF IA)=60 THEN IA=0:IB=IB+1: GOTO 1340 ELSE GOTO 1330
TB=STR$(IB)+"+RIGHT$(STR$(IA+100),2)+":00"'BUILD TB'
CALL 16964:PRINT"PRESS SHIFT&>CODE-C TO CLOSE DATA RUN";TB=TIME$;PRINTT$;TB: CALL 16959
GM=6.5905966#+.0657098242#*D+1.00273791#*T:
IF GM)=24 THEN GM=GM-24:
PRINT"GMST=";GM;
GA=-2.472*R+.9856*R*(T-.5)
L7=280.46*R+.985647*R*(T-.5)
LS=1.916*R*SIGN(AC)+.02*R*SIN(2*G)
L9=L7+L8:EF=23.441*R
IF L9=TP THEN L9=L9-TP: GOTO 1490
IF L9<0 THEN L9=L9+TP: GOTO 1500
F1=COS(E):F2=SIN(L):F3=COS(L):FA=ATN(F1*F2/F3)
IF L9<3*QI/2 THEN RA=FA: GOTO 1550
IF L9<QI/2 THEN RA=ATN(F6): GOTO 1640
RA=TP+FA
LH=15*R*(GM-RA)-LO*R: IF LH<0 THEN LH=LH+TP ELSE IF LH)=TP THEN LH=LH-TP
FB=SIGN(L)*R:FC=COS(L)*R:GB=SIGN(LD):GC=COS(LD):FD=COS(LH):GD=SIGN(LH)
F5=FB*GB+FC*GC*FD=E=ATN(F5/SQR(1-F5*F5))
F6=CD/(FD*FB*GB*FC/GC)
IF LH<QL THEN IF F6)=0 THEN F9=QL+ATN(F6): GOTO 1640: ELSE 1610 ELSE 1620
F9=TP+ATN(F6): GOTO 1640
IF LH>QL THEN IF F6)=0 THEN F9=ATN(F6): GOTO 1640
1630 \text{F9}=Q1+\text{ATN}(F6)
1640 \text{PRINT}'ELEVATION (DEG)= ";}E/R
1650 \text{PRINT}'AZIMUTH (DEG)= ";}F9/R
1660 \text{REM HERE GOETH THE ENCODER READ AND MOTOR STEP ROUTINE FOR TRACKER}
1670 EE=E/R*11.378;AEI=F9/R*11.378
1680 \text{OUT}(107),16;AZ=4096-(\text{INP}(104)+\text{INP}(105)\text{AND}240)*16):
1690 \text{EL Z}=\text{INP}(106)+\text{INP}(105)*15*256; \text{OUT}(107),0'\text{READ AZ AND EL ENCODERS}
1690 \text{IF} P3=1 \text{THEN} 1710
1700 AO=AEI-AZ;EO Z=EE-EL %;P3=1
1710 DEI=EE-EL %;DAI=AEI-AZ-AO
1720 \text{PRINT }"DE";DEI;"DA";DAI;
1730 \text{IF} \text{ABS}(DEI)<.5 \text{THEN} 1750 \text{ELSE} AD=((\text{SGN}(DEI)+1)/2+1)*64:
1740 \text{NS}=\text{INT}(\text{ABS}(DEI)*2.19727); \text{PRINT}"NSE";NS;
1750 \text{GOSUB} 1770'\text{STEP AZ AMD EL MOTORS'}
1760 \text{IF} \text{ABS}(DAI)<.5 \text{THEN} 1780 \text{ELSE} \text{NS}=\text{INT}(\text{ABS}(DAI)*2.19727):
1770 \text{AD}=((\text{SGN}(DAI)+1)/2+1); \text{PRINT }"NSA";NS
1780 \text{GOSUB} 1770; \text{GOTO} 1780
1790 \text{DT}=2;\text{OUT}(107),0';\text{FORL}=1;\text{TONS}';\text{FORK}=1;\text{TODT}';\text{OUT}(107),0';\text{NEXTK}';\text{OUT}(107),0';\text{NEXT L}';\text{RETURN}
1790 \text{CALL} 16959; T$=\text{TIME} $; \text{GOSUB} 120; \text{UD}=\text{UC}+\text{IV}; \text{HP}=\text{HR}; \text{MP}=\text{MN}; \text{IF} \text{UD}>59 \text{THEN} \text{UD}=\text{UD}-60; \text{MP}=\text{MP}+1 '\text{TIMINT'}
1800 \text{IF} \text{MP}>59 \text{THEN} \text{MP}=\text{MP}-60; \text{HP}=\text{HR}+1
1810 \text{IF} \text{HP}>23 \text{THEN} \text{HP}=\text{HP}-24
1820 G1=\text{HP}/10; D1=\text{INT}(G1); D2=10*(G1-D1)
1830 G2=\text{MP}/10; D3=\text{INT}(G2); D4=10*(G2-D3)
1840 G3=\text{UD}/10; D5=\text{INT}(G3); D6=10*(G3-D5)
1850 \text{POKE63810},D1: \text{POKE63809},D2: \text{POKE63808},D3
1860 \text{TIME} $0; \text{RETURN}
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Nianzeng, C. (1984) Personal communication concerning the reflectance factor of BaSO₄ panel #5. Che Nianzeng is affiliated with the Beijing Institute of Technology, People's Republic of China, and was a visiting scholar with the Optical Sciences Department from 1982 through 1984. He was responsible for the manufacture and reflectance factor measurement of a number of BaSO₄ panels during his stay.


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