Mounted Polarimeter Radiometer
for Dark Sky Atmospheric
Polarization Study

By
Kendra Gillis

A senior thesis submitted to the faculty of
Brigham Young University-Idaho
In partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics
Brigham Young University-Idaho
December 2017
Of a senior thesis submitted by

Kendra Gillis

This thesis has been reviewed by the research committee, senior thesis coordinator and department chair and has been found to be satisfactory.

__________________________________________________________________________
Date ________________________________ Todd Lines, Advisor

__________________________________________________________________________
Date ________________________________ Stephen McNeil, Committee Member & Chair

__________________________________________________________________________
Date ________________________________ Richard Hatt, Committee Member

__________________________________________________________________________
Date ________________________________ Evan Hansen, Senior Thesis Coordinator
ABSTRACT

Mounted Polarimeter Radiometer for Dark Sky Atmospheric Polarization Study

Kendra Gillis
Department of Physics
Bachelor of Science

Light polarization varies across the sky due to Rayleigh scattering. The polarization pattern is determined by the position of the light source relative to the observer. Disturbances in the polarization can help detect airborne objects. Because of symmetry, polarization of light of the entire sky can be determined with some accuracy by measuring one narrow strip of sky stretching from one horizon, through the zenith across the sun and down to the opposite horizon.

An instrument was built with the ability to measure light polarization in two different wavelengths (450 nm and 650 nm) in a low light setting. The effect of the beam splitters on polarization were tested to see that they functioned as desired. All other parts were tested to make sure none of them were polarization sensitive. The sensitivity of the PMTs light intensity was tested. All the additional elements were tested to determine how they effected the light intensity.

Data taken at sunrise and sunset was graphed and analyzed. The data matches expected polarization patterns at these times of day and adds an interesting look into polarization at different wavelengths.
Acknowledgements

I would like to thank my mentor, Dr. Joseph Shaw for all that he did to assist me in my research. I would like to thank Montana State University for allowing me to do research at their facilities. I would like to acknowledge Laura Dahl, Martin Tauc and William Weiss for their participation and help with this research.
Table of Content

1 Introduction 1
   1.1 All Sky Light Scattering ......................................................... 1
   1.2 The Effects of Light Scattering in the Atmosphere .......................... 2
   1.3 Light Polarization .................................................................. 2
   1.4 Usual Polarization of Daytime Scattering ..................................... 4
   1.5 Nature of the Instrument ............................................................ 5

2 Materials and Methods 6
   2.1 Instrument Schematics ............................................................... 6
   2.2 Calibration ................................................................................. 7
   2.3 Set-Up for Measurement ............................................................. 9
   2.4 Data Analyses .......................................................................... 9

3 Results 10

4 Conclusion and Future Work 14
List of Figures

1 Electromagnetic Wave................................................................. 3
2 Polarization of Reflected Light......................................................... 4
3 Polarization of Scattered Light.......................................................... 4
4 Polarization of Light in the Atmosphere............................................. 5
5 Diagram of Instrument...................................................................... 6
6 Photograph of Radiometer................................................................. 7
7 Polarization Calibration...................................................................... 8
8 Telescope Calibration.......................................................................... 8
9 Light Intensity Graph, Without Beam Splitters................................. 10
10 Light Intensity Graph, With Beam Splitters.................................... 11
11 Wavelength Graph........................................................................... 12
12 Rooftop Measurements................................................................. 13
1. Introduction

Because of society’s increased ability to send objects into the sky, studying the sky is becoming of greater interest. Detecting airborne objects and particulates cannot always be done efficiently by just using frequency changes in visible or radio light. In order to detect more accurately, there must be a thorough study of all types of light scattering in the atmosphere\(^1\). One type of light scattering which occurs regularly in the atmosphere is Rayleigh scattering, which produces a specific pattern of light polarization. This sky pattern can be studied by measuring the light polarization of a strip of sky from one horizon, through the zenith down to the other horizon\(^2\).

1.1. All sky light scattering

Societies are taking to the sky more now than ever before. They have built airplanes, rockets and missiles by the thousands. This influx of sky bound inventions means that, as time goes on, it is becoming more important to be able to detect and recognize objects in the sky. There is greater opportunity to detect things from the air and more need to detect things in the air. Being able to detect and monitor airborne objects from great distances is a matter of highest interest.

In the past, we have used mostly the detection of variations in the wavelength and intensity of light, mostly in the visible and radio frequencies\(^3\). However, as airborne objects become more common, their detection has grown more difficult. Objects are often camouflaged, intentionally or naturally, so they do not look different than the sky in visible and radio frequencies.
Another way to detect airborne objects is with disturbances in the way the light usually
scatters naturally off the particles in the atmosphere. Studying of scattering can be more efficient
and effective\(^4\). Even if the light coming off an object has the same frequencies as its
surroundings, the scattering pattern of the light will often change.

**1.2. The effects of light scattering in the atmosphere**

There are many types of light scattering caused by the light’s interaction with different
properties of the substance from which it reflects\(^5\). The two most common methods of scattering
in atmospheric studies are Rayleigh scattering and Mie scattering. Rayleigh scattering is light
scattering off of smaller gas molecules, such as N\(_2\) or O\(_2\). Mie scattering is light scattering from
larger particles, such as dust, smoke or water droplets. Because the concentration of N\(_2\) and O\(_2\)
molecules in the atmosphere is more constant than the concentration of particulates, the patterns
caused by Rayleigh scattering are more consistent and easier to predict.

When light experiences Rayleigh scattering, it becomes polarized in a distinct manner.
When a light photon is scattered off of a small particle in the atmosphere, its direction is random.
However, its direction does determine its polarization. The light is most highly polarized when
there is a specific angle between the line from the light source to molecule and the line between
the molecule and the observer. For the molecules which cause Rayleigh scatter, the angle is very
close to ninety degrees.

**1.3. Light polarization**

Light is a coupled electric and magnetic wave. The electric and magnetic field
compounds oscillate perpendicular to each other and to the direction of motion. The orientation
of the electric wave is known as the light’s polarization. If a single photon of light is moving in
the y direction, its electric wave is oscillating in the x direction and its magnetic wave is
oscillating in the z direction. In this case, it is polarized in the x direction. A figure of such a wave is shown in Figure 1.

Figure 1. Electromagnetic wave. The wave is traveling in the y direction. The magnetic wave’s oscillation is in the z direction, perpendicular to the direction of motion. The electric wave is in the x direction, perpendicular to both the direction of motion and to the magnetic wave. This wave is polarized in the x direction.

Polarization can be in any direction in the plane perpendicular to the direction of motion. All photons have a polarization, but polarization generally refers to the overall polarization of a beam of light. If the light has equal parts of all different polarization types in it, it is known as randomly polarized or unpolarized. If many of the photons have the same or very similar polarization states, it is partially polarized. The more photons which have that polarization, the higher the degree of polarization.

Light generally changes from randomly polarized to having a dominant polarization when it reflects off of something. When light bounces off of something shiny but nonmetallic, the electric waves which are perpendicular to the surface are absorbed and the electric waves which are parallel to the surface are reflected. So, the polarization of light off of a perfectly reflective, nonmetallic object will be perpendicular to the motion of the light and parallel to the surface, as shown in Figure 2.
1.4. Usual polarization of daytime sky

Reflecting off of or being readmitted by particles can cause polarization the same way being reflected off a shiny surface can. Figure 3 shows some possible outcomes of a photon scattering of a molecule.
Rayleigh scattering causes a predictable pattern of light polarization in the sky. Light polarization is dependent on the angle between the particle and the sun and the angle between the sun and the observer, as shown in Figure 4.

![Diagram of light polarization](image)

Figure 4. Polarization of light when scattering through the atmosphere.

The light polarization pattern of a clear sky is symmetric about the sun. Since the angle of maximum polarization is about ninety degrees, there is a circular ring of maximum polarization ninety degrees from the sun in all directions.

Because of this symmetry, the light polarization pattern can reasonably be measured by measuring just a small strip of sky from horizon, through the zenith, through the sun and back to the opposite horizon. Even though this type of scan does not show the light polarization of the whole sky, when coupled with other instruments it can give vital data.

1.5. Nature of the Instrument

An instrument was built which detected polarization at two different light frequencies, one in the mid red and one in the mid blue. This instrument was mounted on a rotational mount which panned it from one horizon through the zenith to the next horizon in about 19 seconds. Before it is run, it is positioned to be in line with the sun. The instrument was designed to be run in low light conditions similar to just after sunset or just before sunrise. If the sun is bright, the
direct sunlight is blocked out of the run so the photomultiplier tubes (PMTs) are not over exposed.

2. Materials and Methods

2.1. Instrument schematics

The instrument is split into two parts which are mirror images of each other. Both parts begin with a telescope, which collects and collimates the light. After each telescope is a passband filter which then leads to a polarization beam splitter. After the beam splitter is a focusing lens, which focuses the collimated light down into the sensor of the PMT. A diagram of one half of the instrument is shown in Figure 5. The other half is exactly the same except mirror imaged and with a different passband filter after the telescope.

Figure 5. Diagram of one half of instrument.
The instrument was calibrated to take in collimated light in a two-inch-diameter apparatus and then produce collimated light of one-half-inch diameter through a one-inch-diameter lens. The telescope inverts the light, but our readings are intensity based so it does not matter. The light is then passed through a filter which blocks all light except a narrow frequency passband. The passband filters were different for the two halves of the instrument, one red(450nm), one blue(650nm). Next, the light is passed through a polarization dependent beam splitter. On either side of the beam splitter is a PMT. There are four separate PMTs in all. Each one is separately attached to a computer through an ADC. A photograph of the instrument is shown in Figure 6.

Figure 6. Photograph of radiometer. (Photograph provided by Dr. Joseph Shaw)

2.2. Calibration

Polarization calibration was done by putting the PMTs in front of a randomly polarized light source. A polarization filter was placed in between the sensor and the light source. Figure 7 is a diagram of the calibration setup.
The polarization filter was then rotated 360° in 10° increments. The intensity was read for every increment. This calibration was done with each of the four PMTs. Then, the beam splitters were placed in front of the PMTs. Both beam splitters were checked going both ways. The beam splitters were taken off and the frequency filters were tested the same way. Lastly, the frequency filters were taken off and the telescopes were tested for polarization dependence.

The telescopes were calibrated using a large source of collimated light. Each telescope was placed in front of the source of collimated light and the distance between the two lenses were shifted until collimated light was coming out the smaller end. Figure 8 is a diagram of the calibration.

Figure 7. Polarization calibration.

Figure 8. Telescope calibration.
The front aperture was two inches in diameter with a focal length of 160 mm. The smaller lens was one inch in diameter with a focal length of 40 mm. The light coming out of the second aperture was one half an inch in diameter.

The frequency filter was placed in between a light sensor and a light source which varied in wavelength over time. A graph was created of the amount of light let through the filter based on the wavelength of the light.

The receptiveness of the PMTs were tested by placing them in front of a known light source. The light source was varied to several known intensities and a reading taken at each one. The PMTs alone were tested, then the polarization beam splitter was added, then the passband filter was added to that, and then the telescopes were placed in front of that. The system was re-tested with every addition.

2.3. Set-up for measurements

The instrument was set up so that the telescopes were pointing at the zenith. It was placed on a rotating mount which would rotate it from one horizon to the other, passing through the zenith and the sun. During lighter parts of the day, the sun would be blocked so that it would not burn out the PMTs. The system was designed to be used in lighting conditions similar to when the sun was 5° below the horizon. So as to not damage it, the instrument was generally used about an hour before sunrise or after sunset.

2.4. Data Analyses

A central computer was used to control the PMTs gain settings and control the movement of the mount. The intensity being recorded by the PMTs was also sent to this computer. A laptop could be hooked up to the computer and used to both communicate to it and to graph the
information from the PMTs. Because the rotation of the mount was constant, the intensity versus time graphs could be used to interpret the intensity versus degree.

3. Results

Shown in Figure 9 is the data and graphs from the polarization calibration of just the PMTs. The y-axis is intensity; the x-axis is angle of the polarized filter.

![Polarization Calibration](image)

Figure 9. Light intensity vs. polarization angle graph of PMT polarization calibration.

Shown in Figure 10 is the data and graph from the polarization calibration of one of the beam splitters in front of a PMT. The points have been drawn together so the sine wave can more easily be seen. The y-axis is intensity; the x-axis is angle of the polarized filter.
Figure 10. Light intensity vs. polarization angle graph of beam splitter polarization calibration.

If there is a horizontal line it means that the component being tested has no polarization dependence. If it is a sinusoidal function, it means the component being tested has a polarization dependence. The amplitude is proportional to how strong a dependence the component has. The PMTs have small enough fluctuation that they have essentially no polarization dependence. The beam splitters have the sinusoidal function wanted. This graph is what was wanted because the beam splitter was meant to split the light depending on polarization.

Next is a graph from the light frequency calibration shown in Figure 11. The y-axis is intensity; the x-axis is the wavelength of light being shown into the system.
As can be seen, the passband filters block all light except for small ranges of wavelengths. One of the passband filters peaks close to 450nm, the other one peaks close to 650nm.

Shown are several graphs depicting results from morning and evening runs. The y-axis is intensity; the x-axis is time which, with knowledge of the speed of the mount, can be converted into angle. The mount moved from horizon to horizon in about 19 seconds. Figure 12 is of the horizontal polarization and the vertical polarization.
Figure 12. Light intensity vs. time for rooftop measurement. The two lines represent light transmitted through the beam splitter, and light reflected by the beam splitter.

These results are what we expect to find because the largest change in polarization is ninety degrees away from the sun.
4. Conclusion and Future Work

With this instrument, we were able to get readings in low light situations. We took readings with the sun above the horizon at the horizon and below the horizon down to about 12°. For the day time readings, a large portion of the sky around the sun had to be blocked out to keep the PMTs from over saturating. After the sun had set, the instrument was able to take data for the entire stretch of sky without being saturated. The data seemed to be reliable until the sun was about 10° below the horizon. The instrument is capable of taking reliable polarization readings in relatively low light conditions. This instrument could be used to measure light polarization in other low light situations such as full moon, bright auroras, sunset, sunrise or heavily clouded days. It was built with the intention of measuring light polarization during a solar eclipse. The instrument was brought to the 2017 solar eclipse, but the instrument failed for unknown reasons during the actual eclipse. It was speculated to be a computer coding problem. The instrument began working again after totality and may still be used to measure light polarization during a different eclipse.

Future work would include going over the software used to run the instrument more thoroughly. Also, the timing of the movement of the mount needs to be finalized. The instrument itself works as desired.
References


