INFRARED CLOUD IMAGING DURING THE
2017 TOTAL SOLAR ECLIPSE

by

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Bachelor of Science

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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

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ABSTRACT

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The polarization of light in nature is affected by many different factors including clouds. In preparation for measuring the polarization of the skylight during the 2017 total solar eclipse, we manufactured and tested an infrared cloud imager. By taking IR images during the eclipse and observing the differences between a clear sky model we can say exactly where clouds were in the sky during the eclipse. This was invaluable to building a polarization model.
ACKNOWLEDGMENTS

I am humbled to be graduating from BYU-I. I was changed for the better here and it will forever be special to me. I was inspired to come by my father David Weiss and I must give thanks to my parents for believing in me and pushing me to do my best in school even if I wanted to play or read instead.

I had a wonderful opportunity to go to Montana State University to research cloud imaging technology. Dr. Joe Shaw encouraged me to be the best scientist I could by always asking new questions and his excitement about what we researched. Thanks to Paul Nugent, Martin Tauc, Laura Eshelman, and Preston Hooser for helping me to learn about optics and IR technology.

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Chapter 1

Introduction

Every electromagnetic wave has an oscillating electric field that is perpendicular to the oscillating magnetic field and both fields are perpendicular to the direction of the wave’s propagation. The orientation of that electric field is called the polarization.

The polarization state of light can vary between random and complete depending on the circumstances of emission. Randomly polarized light has an electric field orientation that changes randomly in time. Completely polarized has an electric field orientation that remains constant at all times. Most light has partial polarization, with both random and predictable components. The degree of polarization (DoP) is a number between 0 and 1 that quantifies the percentage of light that is polarized.

Sunlight is emitted with a random polarization. Light with a random polarization can be made more uniformly polarized by collisions. An example of this happens in the atmosphere. Sunlight passing through the atmosphere become partially polarized when it is scattered by gas molecules in the atmosphere. This process leads to maximum polarization in a band located approximately 90 degrees from the sun. In this band the DoP is often only 50% or so, although in extremely clean air it can reach 90%. This value depends primarily on multiple scattering from aerosols, clouds, and
even the surface of the earth in that vicinity of the scattering event. In Figure 1.1 there is an all sky image that shows the band of maximum polarization in terms of the DoP of that pixel. The band is always located 90 degrees away from the sun which, in this image, is covered by the occulting band.

During a solar eclipse, the totality sky is weakly illuminated by light that leaks into the umbra (shadow region) through multiple scattering from the sun-illuminated region surrounding the umbra. This leads to a very different spatial pattern of skylight polarization that is expected to be nominally symmetric about the zenith. Therefore, a solar eclipse is an opportunity to test our understanding of the principles of polarization in nature. While in normal daylight conditions we expect a band of maximum polarization to be located 90 degrees away from the sun’s location, but the question our team researched was how does that pattern change when the sun is completely covered.
To answer this question, we gathered all the information that we would need to make a good polarization model. We measured all the environmental parameters that we could, including: pressure, humidity, temperature, aerosols, surface reflectance and the clouds. The focus of my research was this measuring of the clouds. I helped build, test, calibrate, and deploy an infrared cloud imager. With this sensor, we could say with confidence what clouds were in the sky during the day of the eclipse and where they were located. This paper is focused on the development and testing of that cloud imager.

1.1 Why study clouds?

Clouds are important in more situations than just the study of polarization during an eclipse. They play an important role in the current issues of climatology. The greenhouse effect is intimately related to clouds in the atmosphere. Especially interesting is the study of clouds in the arctic regions of our planet because those regions average temperature has been increasing over the last two decades. The clouds act as a blanket and keep the warmth in the earths atmosphere instead of letting it radiate out to space to keep the planet cool. [2]

Beyond the global issues of the climate, the US military branches fund research into polarization to help them with their surveillance technology and clouds can be critical elements of these studies. The military also need to understand polarization and need to be able to differentiate between what might be a metal object buried in the sand or hiding in the tree line and a bit of light reflecting off of a leaf or pond hidden in forest undergrowth. For all these reasons this is an interesting study, but we often seek new knowledge for the sake of knowledge alone. If we are right in our understanding of the principles of polarized light then we are happy and if we are
incorrect, then we will have discovered new knowledge while enjoying one of the rarest of natural events.

1.2 The scope of our experiment

Obviously, one experiment cannot look at all the possibilities in a given situation. In this experiment, we limit our scope to imaging clouds at thermal infrared wavelengths because the radiation emitted by clouds remains essentially constant in daytime and nighttime conditions. During a solar eclipse the amount of light drops by approximately 3-5 orders of magnitude and our cloud sensor needs to still be able to gather data in the dark.

Satellites are obviously very powerful tools for imaging clouds because their point of view allows them to see so much contrast between the white clouds and the dark earth, but we focused on ground based observation so we could more readily relate the cloud images to the upward-viewing all-sky polarization images. Satellites could produce that imagery, but relating the pixels from the satellites pictures taken above the eclipse to the pixels of the polarization pictures below the eclipse shadow would be very difficult.

Because the focus of the overall experiment was the all sky polarization pattern, our sensor also needed to be able to look at the whole sky at once. For that same reason, we decided against using tools like LIDAR and Radar. While both are very effective in most conditions, they require lengthy scans to cover the entire sky. The eclipse only lasted 2 minutes and approximately 15 seconds, making scanning instruments problematic. So, we decided to use passive methods of all-sky cloud imaging. Our instrument is an all sky ground based infrared sensor. We call it the infrared cloud imager (ICI) and it is the fourth generation of infrared cloud imagers built and
1.2 The scope of our experiment

Figure 1.2 A basic illustration of the structure of a microbolometer [1]

tested by MSU (ICI4).

Compact IR imagers became available with the invention of microbolometer. This revolution in IR imaging began in the 1990s and continued as the technology improved and the prices of the sensors continued to go down. The microbolometer uses the incoming IR radiation to heat a piece of metal and as the metals temperature changes, so does its electrical resistance. Reading a voltage across the metal piece allows one to calculate how much IR radiation is hitting the array of pixels. Groups in the USA [3], Turkey [12], France [14], and many others have worked on improving uncooled microbolometer technology.

The unique capabilities of our instrument allow us to fill in gaps that exist in past experiments. In 1973 Shaw et. al. used a scanning instrument to measure the polarization of the skylight during a total solar eclipse in Africa. [9] That instrument only looked at a slice of the sky and because of the dynamic nature of the eclipse and the instruments scanning functionality, the results may have been skewed. To remedy this, our polarization instrument uses a lens that sees the whole sky at once. Our cloud imager does the same so that we can relate the images to each other.
While there is geometric compression of the data near the horizons, we do not miss any clouds and can say exactly where they were located in the sky instead of vague statements such as “Thick fluffy clouds in the western part of the sky.”

1.3 A preview of the paper

In the following discussion the science of the imaging method is discussed and the initial test and calibrations are described. Chapter 2 touches on the science behind our ICI starting from the principles of the blackbody. Chapter 3 talks about what things were done at Montana State University to build and prepare the ICI4 for the eclipse. Chapter 4 shows some of the actual images taken by the sensor during the eclipse and discusses the performance of the ICI4 during that experiment. It also describes the setup of the experiment for the eclipse. Chapter 5 concludes the thesis by briefly describing the clouds we did observe and how the ICI4 contributed to the overall success of the experiment. We then evaluate this iteration of the ICI family and what improvements we hope to make in the future.
Chapter 2

Infrared Imaging background

In this chapter we discuss a little about blackbodies and some of the technology that goes into the ICI instruments. Then we show why we use certain wavelengths in the IR.

2.1 Blackbodies

Blackbodies have been very important to science ever since they first pushed us towards solving the problem of the UV catastrophe. A blackbody acts as a perfect absorber and perfect emitter of light of any wavelength. A kiln is a good example of a blackbody. Our sun is also well approximated by the idea of a blackbody.

\[ E_\lambda = \frac{8\pi hc}{\lambda^5 \left( \exp \frac{hc}{\lambda kT} - 1 \right)} \quad (2.1) \]

Observing the light that is emitted, we find a spectrum that looks like Figure 2.1 and that is mathematically described by Equation 2.1. In this equation \( h \) is Planck’s constant and \( c \) is the speed of light. \( k \) is Boltzmann’s constant and \( T \) is the temperature.
Figure 2.1 This is a general plot of the Blackbody equation. The vertical axis represents energy and the horizontal axis represents the wavelength. See Equation 2.1

There is a relation between the temperature emitted and the dominant wavelength that is emitted. That relationship is described by Wien’s Law as shown in Equation 2.2.

\[
\lambda_{\text{max}} T = 2.898 \times 10^{-3} \text{mK} \tag{2.2}
\]

With Wien’s Law and the blackbody spectrum we have rough estimate of the temperature of objects that are observed in images.

2.2 Background of ICI development

The following information came from personal communication with Joseph Shaw (2018). The development of ICI started with Dr. Joseph Shaw at the National Oceanic and Atmospheric Administration (NOAA) research labs in Boulder, Colorado. He built the first prototype ICI system in the late 1990s with an early mi-
2.2 Background of ICI development

Figure 2.2 This shows the basic concept of identifying clouds. The total radience from the sky minus the radience of a clear sky model leaves the clouds in sharp contrast. [10] The units of these images are in terms of radiances, \( \frac{W}{m^2 \cdot sr} \).

crobolometer camera and brought it with him to Montana State University in 2001. The first ICI was tested in short-term deployments at the NOAA Research Labs in Boulder, Colorado and then first deployed in the field at Poker Flat Research Range near Fairbanks, Alaska from September 2000 until early 2001. This first ICI system was installed in the roof of the optics observatory at Poker Flat and was next mounted in a stand-alone box that could be deployed outdoors at more remote locations. Its next field deployment was at the Department of Energy’s climate observatory in Oklahoma during February-May 2003 and then at the DoE climate observatory in Barrow, Alaska during February-April 2004. [13]

Paul Nugent came to Bozeman to study and started working on the ICI program in about 2004-2005. [11] He helped develop new, improved radiometric calibration methods and extended the ICI technique to increasingly larger fields of view (the original ICI only had about a 20-degree full-angle field of view). With Paul and other students, the group deployed various versions of the ICI2 (with about 60-degree full-angle field of view) at the Table Mountain Facility operated by NASA’s Jet Propulsion Laboratory in Pasadena, California and at several other locations, including most notably Bozeman, Montana. [5] [6] [10] The ICI3 was developed with 100-degree full-angle field of view and was deployed to Barrow Alaska from August 2012 to Aug.
2.3 The IR transmittance window

Almost all of the light that the earth is hit by comes from the sun. Because of our atmosphere some of that light, and especially some of the more dangerous light, is reflected back into space. If we limit our focus to the infrared spectrum we see that there are certain frequencies that work very well for imaging clouds and for transmitting through our atmosphere. [10]

If you observe the band of wavelengths between approximately 8-12 micrometers the light in that part of the spectrum has a transmittance of nearly 80% for almost that whole band. In other words, there is a lot of light that makes it through the atmosphere at those wavelengths. We call this the infrared transmittance window. See
2.3 The IR transmittance window

Figure 2.3. The valley in this otherwise clear window comes from ozone absorption. Knowing that there are relatively few ozone molecules in the atmosphere we neglect this. The water molecules in clouds emit IR, and because they emit it day or night we can also keep the sensor deployed day or night.

A blackbody emits light in many different wavelengths simultaneously, but depending on the temperature of the blackbody there will be a dominant wavelength. You can use a blackbody to calibrate the sensor of an infrared camera. A simplified description of this procedure follows. You take one image of a cold blackbody and another of a hot blackbody and interpolate the slope of the line connecting them. The intercept of that line on the vertical axis of a spectral radiance versus the voltage read by the sensor will give you a calibration constant that you can apply to images you take with that sensor. [8]
Chapter 3

Methods

Remember that the overall focus of our research group was to study the skylight polarization pattern during an eclipse. Normal sky polarization has a band of maximum polarization centered 90 degrees away from the sun, as shown in Figure 1.1. As our group prepared for the experiment, it was decided that we needed to track the clouds during the eclipse. The ICI4 was already in development at that time and I was tasked with finishing the basic design and manufacture.

PhD student Paul Nugent was my mentor for this task. I finished a CAD design of the ICI4 and fit all of the components into a new plastic waterproof container. Once we knew they would fit, I manufactured metal shelves and then some cables for power and communication between the sensor and recording device. At the end of the summer we assembled the bare minimum of the ICI (sensor, power source for sensor, translator between sensor and computer) and we used that to collect raw data through the sensor.

Summer 2017 Preston Hooser and I worked together to calibrate the sensor and finish the manufacturing. First, we had to calibrate the Field of View (FOV) by creating an angle map of the sensor. We did this by painting a checker-board pattern
of black and white on a 3 foot by 3 foot piece wood, letting it heat in the sunlight, and then recording thermal images of it once it was warm. We moved the board around to get all the angles and distances that we could. After taking the images we used software initially developed by JPL and modified by Paul to assign each pixel an identity to an angle from the zenith. As expected there was a lot of image compression around the edges of the images.

Next, I helped Preston calibrate the sensor with a blackbody. First, we calibrated the sensor in space by moving the sensor around the blackbody and keeping the blackbody stationary. The ICI4 is calibrated in terms of radiance (Watts per meters squared per steradian), but by integrating the product of the Planck function and the spectral response function of the ICI4, we can determine an effective temperature for
each radiance value. See Figure 4.3 for an example image of that.

After that calibration was done we performed a thermal calibration by sticking the sensor and blackbody in an thermal chamber and taking images at different temperatures. We did this so that the ICI4 can eventually be deployed in varying weather conditions. Microbolometer detectors produce an output that depends strongly on the detector temperature, so this part of the calibration was to characterize this temperature-dependent response. We then ordered and installed a thermoelectric heater/cooler. Even though the calibration covers a variety of temperatures keeping the temperature constant helps the calibration stay true for longer.

We also took data with the previously deployed ICI3 and simultaneously took data with the ICI4. We used this data to double check the functionality of the ICI4 before the eclipse. We visually compared the images from the ICI3 side by side with the images from the ICI4 and saw no major discrepancies. A more in depth analysis analysis is in progress by current Montana State University PhD student Preston Hooser. This check was our final reassurance that the ICI4 was working correctly before the eclipse.

The eclipse experiment was an opportunity to develop a smaller and more portable version of the ICI than the previous generations. With the thermoelectric heater/cooler and a cover for the lens, this instrument will eventually be able to be deployed for long periods of time. To get ready for that, this excursion was a good test of the equipment including the software and cables.
Chapter 4

Results of manufacturing and calibration

To get ready for the eclipse, we practiced running the ICI4 as much as we could leading up to the date of the eclipse. We used the twilight light levels, when the sun down to approximately 10 degrees below the horizon, to simulate the decrease in light as the eclipse progressed.

During the eclipse, we set up the ICI4 on the roof of the BYU-Idaho Observatory. We had to be mindful of our position and get as much of the sky light as we could. Therefore, we positioned the ICI4 on the NE corner of the roof to have the best view of the eclipse and the least amount of the BYU-Idaho observatory dome in our images as possible. See figure 4.1. The dome of the observatory was visible in the images only barely because of the compression of the data around the edges of the image.

We set up the ICI4 and leveled the instrument using the tripod that we had mounted the instrument upon. We moved the rocks covering the roof so that the tripod was stable and on the actual roof of the building and then used the tripods own adjustments to achieve a level setting.
Chapter 4  Results of manufacturing and calibration

Figure 4.1 This gives the reader an idea of the surrounding landscape. The top of this image is oriented towards the north.

Figure 4.2 This an image of the actual setup on the roof of the observatory. This image is looking approximately north. Photo credit to Joe Shaw
We ran the ICI4 at the BYU-Idaho observatory for one whole day prior to the eclipse and for the entire day of the eclipse (i.e., 20-21 Aug. 2017). We had to be careful because we were not staying on site and we did not want it to suddenly rain and get the sensor wet or the lens dirty. To be sure this didn’t happen one of us was on site all day and spent the night there. We wanted this data to compare against any clouds that might be there during totality. After the eclipse, we continued to run the instrument for another 4-5 hours to make sure we had a good baseline of what the clouds were like during that day. The ICI4 did detect some clouds near the horizon at sunrise, but those clouds burnt away as the sun continued to rise. During the eclipse there were no clouds in the sky. See Figure 4.3
Figure 4.3 These are images the ICI4 captured the day of the eclipse. The left column is at sunrise and the right column is from totality. The colors indicate the temperature of a blackbody that would emit the same amount of radiation in the same bandwidth. Figures courtesy of Preston Hooser and Laura Eshelman.
Chapter 5

Conclusion

In conclusion, we were very pleased with the performance of the ICI4 and we were especially pleased to have such clear weather the day of the eclipse. Having such a small and portable cloud imager will make all future measurements for various types of models that much more accurate. The ICI4 did detect some clouds near the horizon at sunrise, but there were no clouds in the sky during totality. The polarization model was recently presented and defended by Laura Eshelman as her PhD thesis. The ICI4 images were instrumental in eliminating the possibility of clouds impacting the polarization of the light that day.

The development of the ICI4 is not complete. The eclipse experiment was an opportunity to develop a smaller and more portable version of the ICI than the previous generations. With the thermoelectric heater/cooler and a cover for the lens, this instrument will be able to be remotely deployed for long periods of time. To get ready for that, this excursion was a good test of the equipment including the software and cables. Before that happens the calibrations need to be fine-tuned so that we can use the data in the polarization model developed by Laura Dahl and Joseph Shaw. [4] After that is completed we want to continue to improve the design so that it can be
deployed.

To be ready for future deployment we need to test and establish just how long the calibration of the sensor stays constant and confirm the software we write works independently for long periods of time without any bugs or major issues. Along with finishing the software there would need to be a dedicated computer and a data storage device and make sure that those things all works together. To keep the sensor and optics safe from exposure to moisture a precipitation sensor needs to be integrated and a mechanical lens cover that was partially developed by Paul Nugent needs to be finished and installed. There also needs to be further testing of the heating capacity of the thermoelectric heater in winter conditions. Finally, hopefully in the summer of 2019 the ICI4 can be deployed on the roof of the Cobleigh building and the results it collects will continue to be compared against the data collected by the ICI3.
Bibliography


