Abstract

The purpose of this project is to observe the visible Solar spectrum during a high altitude balloon flight by measuring changes in absorption spectra at varying altitudes and atmospheric densities. A pan-and-tilt mechanism will be used to autonomously track and point a spectroscope toward the sun during flight. Photos of the solar spectrum will be taken at regular intervals during the ascent of the balloon. The number of absorption lines in each photo will be analyzed and the absorption patterns will be compared to known spectra.
Introduction

Of all the things that exist in our universe, none have more to tell us than light. For as long as humans have gazed out at the stars, we have relied on electromagnetism as a source of information about the things beyond our reach. Indeed, the very purpose of Spectroscopy is to investigate and measure the spectrum of electromagnetic radiation as it interacts with matter. (Wiggins, n.d.)

Modern understanding of electromagnetic radiation, or light, tells us that it behaves as both a wave and a particle. (Kulesa, 1997) As a wave-like object, light is made up of a broad spectrum of wavelengths, ranging from the very short wavelengths of high-energy gamma radiation to those of much lower energy radio waves. The visible light that we see falls roughly in the middle, making up only a very small piece of the total spectrum. Visible light can also be separated into a range of wavelengths which make up the colors of the rainbow, starting from red, the longest, to violet, the shortest. (Goody & Walker, 1972) For the remainder of this paper, we will focus on the visible light spectrum.

Analyzing light spectra can tell us a lot about the source from which it was emitted, as well as the medium through which it moves. When light is emitted from a hot, dense source such as our Sun, it produces a full, continuous spectrum. However, when that light is observed through a medium with lower density and temperature than the source, some pieces of the spectrum will be missing, appearing as a pattern of discrete black lines. (Bennett, Donahue, Schneider & Volt, 2014) This incomplete spectrum is called an absorption spectrum, and it can be explained by the particle nature of light. When light interacts with matter, it behaves like a particle, which we call a photon. An atom of a given element will absorb a photon with sufficient energy to raise one of its electrons to a higher energy level. (Hollas, 2004) Because energy is related to wavelength, the absorption of these photons causes some wavelengths of light to be

Figure 1: Diagram of the Electromagnetic Spectrum showing that Frequency (hertz) and Energy (electron-volts) are inversely proportional to Wavelength (meters). (Laboratory for Atmospheric and Space Physics, University of Colorado)
missing from the resulting spectrum. These patterns of dark lines correspond to bright emission lines that occur when an element is heated. Just as particles in a relatively cool substance will absorb a photon from a hot, dense light source, particles in a heated substance will emit photons as they cool and the excited electrons move to lower energy levels. The resulting pattern of bright, colorful lines is an emission spectrum. (Bernath, 1995) We can compare the patterns of absorption lines to the known emission spectra of various elements to determine the composition of a medium through which light is observed, whether that medium is the atmosphere of the Earth or Sun, or that of a distant stellar body.

**Figure 2:** Comparison of absorption and emission spectra of Hydrogen, Carbon, and Oxygen

**Mission Overview**

Our goal for this mission is to effectively use the principles of spectroscopy to observe both the Sun and Earth’s atmosphere. To do this, we have designed and built a compact spectroscope to be flown on a high altitude balloon to a maximum altitude between 80 and 120 thousand feet above sea level. The spectroscope is mounted to a pan-and-tilt mechanism designed to autonomously search for the sun as the payload sways and rotates on its flight string. The mechanism will then adjust the position of the spectroscope such that it points toward the sun for as much of the duration of flight as is possible.

During the balloon’s ascent, photos will be taken through the spectroscope at regular intervals and stored for later analysis. Each photo will include a timestamp, and will be correlated with a log of the balloon’s altitude with respect to time.

Our expectation is that these photos will reveal absorption spectra and that the pattern of discrete black lines in these spectra will be consistent with known concentrations of particles in the Earth’s atmosphere. Furthermore, we expect that the number of visible black lines will decrease as altitude increases and the atmosphere thins. Eventually, the only absorption patterns that should remain in our photos should be those resulting from the absorption of photons by particles in the Sun’s atmosphere. To test these hypotheses, the patterns of lines in the absorption spectra we observe will be compared to those of known elements, and the number of lines in each photo will be counted and correlated with our altitude data.

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Design

The optical components of the spectroscope are contained within a 3-D printed box, approximately 4.75” x 4.75” x 2” in size. When light enters the box through a thin slit on one of its sides, it passes through a collimating lens which focuses the light onto a reflective diffraction grating positioned at an angle. The diffraction grating is the key component of the spectroscope. It resembles a mirror with a cube of grooved glass mounted on it. These grooves cause the light that passes through the glass to diffract, with different wavelengths of light bouncing off of the mirror at different angles. Finally, a GoPro camera is aligned with the grating to capture images of the spectra that reflect off of it. The thin slit through which light enters the box is covered by a polarizing light filter to reduce glare on the diffraction grating and allow for a clearer picture of the spectrum.

Figure 3: Prototype spectroscope with collimating lens, diffraction grating and camera in place.

Four photoreceptors are positioned on the outside of the spectroscope in a cross configuration near the slit opening. These photocells are sectioned off from each other with relatively tall walls designed to cast shadows on the cells if the spectroscope is not looking directly at a light source. Using the relative differences in intensity of light reaching each photocell and a memory of the brightness at each tested location, the flight computer manipulates the two servos in the pan-and-tilt apparatus to dynamically point the spectroscope in the direction of the greatest concentration and most even distribution of light.

Preliminary Testing
Because the spectroscope was of our own design, a significant amount of time was spent testing optical components to determine which configuration of lenses, mirrors and other elements would give us the clearest and most consistent spectral data. We began with a very basic diagram of a linear diffraction

**Figure 4: Diagram of Linear Diffraction Spectroscope**

spectroscope, which we used to construct a large-scale prototype on an optics bench. Since this prototype was too cumbersome to carry outside, we used an incandescent light bulb as a substitute for the Sun.

**Figure 5: Large-scale optics bench prototype of spectroscope**

With this prototype, we were able to experimentally determine the optimum distance between the entrance slit, collimating lens, diffraction grating and camera. Ultimately, the distance from slit to lens is dependent on the focal length of the lens, and the distance from the lens to the grating should be approximately the same. The clearest spectra can be seen when the camera is as close to the diffraction grating as possible, and tilted 4 degrees off center from the grating. We also found that all of these distances scale linearly, and were thus able to shrink the model down to dimensions that would be suitable for a balloon payload.

Additionally, the dimensions remain the same when a reflective diffraction grating is used instead of a clear, transmissive grating, allowing for a “folded” design that is smaller and easier rotate and balance during flight.

To calibrate our camera settings, photos of both the incandescent spectrum and the emission spectrum of a helium lamp were taken in the lab. Additionally, the finished spectroscope was used to photograph both the sun and a patch of partly cloudy sky from the ground. These photos will be used to train our analysis software to detect absorption lines.
Figure 6: Helium emission spectrum observed with a 0 degree (right) and 4 degree (left) camera angle with respect to the center of the diffraction grating.

Figure 7: Incandescent spectrum recorded with a linear prototype prior to scaling down the dimensions.

Figure 8: Solar spectrum photographed from the ground with the completed spectroscope.

Analysis and Expected Results

The Earth’s atmosphere is composed of approximately 78% Nitrogen, 21% Oxygen, 0.9% Argon and 0.04% Carbon Dioxide. The remaining 0.06% of the atmosphere is made up of trace elements, particularly Neon, Helium, Methane, Krypton and Hydrogen. (Williams, 2016) This distribution suggests that there is a high probability of detecting Nitrogen and Oxygen absorption spectra during flight.

The Sun has an atmosphere as well, composed of approximately 91% Hydrogen and 8% Helium. (Williams, 2016) Because the concentration of Hydrogen and Helium is much higher in the Sun’s atmosphere than in Earth’s, we can expect that the Sun is the likely source of any Hydrogen and Helium absorption spectra we detect. Furthermore, these spectra should be present...
in our data even as the spectroscope reaches its highest altitude and the density of Earth’s atmosphere is low enough to be negligible. To test this, we will visually compare the absorption spectra to the spectral fingerprints of various elements and record how often and at what altitude each element appears in our data.

Additionally, because the density of Earth’s atmosphere is inversely proportional to altitude, we expect that the number of visible absorption lines in our spectra will decrease during flight as altitude increases. To measure this, we are writing a program in Python that will detect and count the number of absorption lines in each spectral image.

Conclusion

There is nothing in the universe that carries as much information as light. Our understanding of light enables us study objects and phenomena that are too small, too volatile or too far away to otherwise comprehend. It is our expectation that the design and implementation of a compact, balloon-borne spectroscope capable of autonomously tracking objects in the sky will open the door to a deeper understanding of the electromagnetic spectrum and the many things it can tell us about the matter in our universe for students and scientists alike.

References


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