Balloon Observatory for Wavelength and Spectral Emission Readings
BOWSER
Feasibility of a Balloon-Stationed Optical System

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Kevin Dinkel
COSGC/ASEN Student
kevin.dinkel@colorado.edu

Andrew Zizzi
COSGC/ASEN Student
andrew.zizzi@colorado.edu

Taylor Boe
COSGC/ASEN Student
taylor.boe@colordo.edu

I. Abstract

The celestial images produced by the orbiting Hubble Space Telescope have not only shown the indescribable beauty of the heavens, but have also provided key answers to the scientific origin of the universe. However, it may now be possible to entertain the same capabilities of Hubble for a fraction of its multi-billion dollar cost with the use of lighter-than-air vehicles. Floating above 99% of Earth's distorting atmosphere, the near space environment may be a perfect viewpoint for capturing clear images of the cosmos. The BOWSER payload, equipped with a customized Newtonian telescope designed to baffle out scattered light, an LED light sensing array, and six photodetectors analyzing the orange through infrared range of the electromagnetic spectrum, shall ascend to 36 kilometers on a NASA high altitude balloon and float for 25 hours. BOWSER will conduct experiments pertaining to the scattering effects of the atmosphere, the stability of a hovering platform, and the viability of a balloon stationed star tracker at various altitudes. Data obtained from the flight, scheduled for September 2009, will provide evidence suggesting the possibility of an optical system stationed in near space.

II. Background

The cosmos has always been a focus of fascination for man. Until the 20th century, outer space investigations into the contents of the universe could not be conducted. However, with experiments aimed to obtain deep space images, invaluable information about outer space has been discovered and our efforts continue to bring fourth astonishing visuals portraying the vastness of the universe.

Ground based telescopic observatories are the oldest and most used facilities for astronomical observing and imaging to date. However, even as the primary mirrors of these instruments have grown larger over time, grounded telescopes have never been able to avoid the atmosphere's unruly distortion which plagues all images captured from the Earth's surface, Figure 1. An alternative to ground based arrays is the orbiting telescope. Hubble Space Telescope (HST), currently orbiting 559 km above the Earth's surface, has been one of the most rewarding scientific investments ever built. Far above the atmosphere, HST has captured crystal clear images that have furthered the field of astrophysics and even given insight into the origin of the universe. However, HST was a large investment – the total cost now approaching 6 billion dollars. The third and newest alternative to these two methods may not only share the outstanding optical conditions of an orbiting telescope but also comes at a much lower price. It may now be possible to station a telescopic observatory on a high altitude balloon, floating above 99% of the Earth's atmosphere, unharmed by the weather. By comparison it costs around $600 per kilogram to launch a payload into the upper-stratosphere propelled a lighter-than-air vehicle, while prices soar upwards of $20,000 to launch a single kilogram into Low Earth Orbit (LEO) on a rocket. For a fraction of the price of the HST, multiple balloon observatories could be stationed all over the globe.

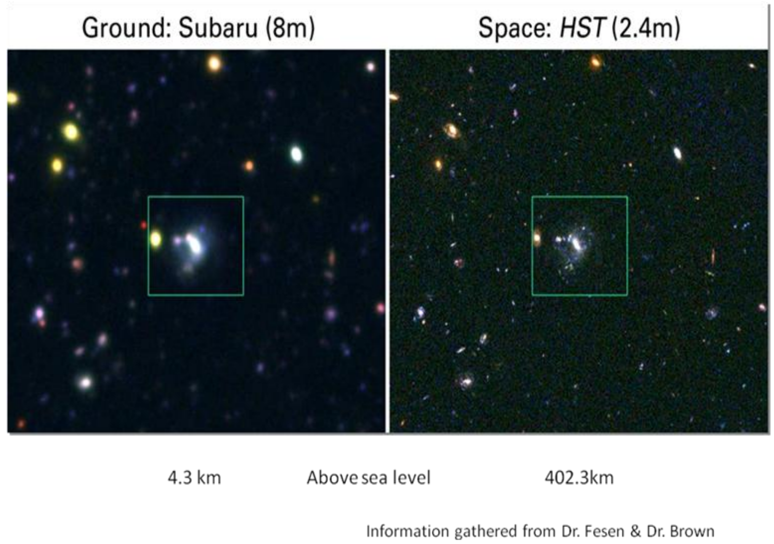

Figure 1: Even the 8 meter aperture of the ground based Subaru telescope cannot compare with the 2.4 meter aperture of the orbiting Hubble Telescope.

The main advantage to a telescope deployed in the stratosphere compared to a ground based observatory is the significantly reduced sky background and decrease in atmosphere above 35 kilometers. This means that a telescope at this altitude should be able to achieve diffraction-limited performance without any adaptive optics, such that ground observatories utilize. Also, because these platforms would be stationed above the weather, no observation time is lost to cloudy nights. A telescope in the stratosphere will outperform any analogous ground based observatory any night of the year. A balloon-borne telescope will also have the ability for daytime observing. The daytime sky background decreases by roughly a factor of two for every 5 kilometers in altitude. This means that bright objects, such as Uranus and Neptune are easily acquired with a good signal-to-noise ratio during the day.

Nevertheless, how will a lighter-than-air observatory perform compared to orbiting telescopes like HST? The conditions that each of the platforms experience are surprisingly similar. Both are above almost all of Earth's atmosphere, experience zero pressure, and are relatively stable for optical instruments. Most importantly, every night in the upper-stratosphere is photometric, with a sky background nearly as low as what HST experiences. A hovering telescope also presents many advantages over an orbiting telescope. First, because a balloon platform will remain relatively stationary in comparison to a satellite traveling approximately 30,000 kilometers per hour in LEO, it has the ability to visit many celestial objects in the same time that it requires HST to visit one. Also, because balloon-stationed platforms are so much cheaper, they are more expendable. Many can be operated at one time and still stay within a reasonable budget. Telescopes in the stratosphere will also be easier and less expensive to access for any necessary maintenance or adjustments. Balloon-borne telescopes may provide the perfect alternative to expensive orbiting observatories.

The first balloon-stationed observatories appeared in the 1950's. Efforts to investigate the makeup of planetary atmospheres involved balloon-borne telescopes like Stratoscope I and II. Stratoscope II was a 36 inch telescope, radio-controlled from the ground, directed to observe planets through television monitoring. In particular, Stratoscope II captured images of Uranus that provided new insight into the relative size and density of the planet. Investigative missions following Stratoscope into the 1980's and 1990's would prove even more beneficial but vastly more expensive. HST is one of many high cost orbiting observatories engineered during this time.

Figure 2: The ST5000 is making strides in improving the attitude determination, mapping and imaging of stars from sounding rockets, satellites, and balloons.

Newly proposed ideas involving the sensing and imaging capabilities of HST may be attainable at a fraction of the cost. One particular project, Stabilized High Altitude Research Platform (SHARP), seeks high resolution images of planetary targets including asteroid binaries and Trans-Neptunian Objects from a balloon-stationed platform. The SHARP payload will also include the high precision Star Tracker 5000 (ST5000), designed to autonomously record triple axes stability (roll, pitch and yaw), Figure 2.

Aside from the ST5000, other technology is being developed to counteract the foreseeable jitters on a balloon stationed observatory. A precise pointing and stabilizing telescope, developed by Left Hand Design, is a plausible answer for correcting and stabilizing a telescope imaging system. Future missions like SHARP will be able to utilize such technology to obtain high resolution images of the cosmos.

Through generating concepts for SHARP, professional scientists developed a MODTRAN model for the behavior of sky brightness as a function of wavelength, altitude and azimuth angle from the sun, Figure 3. If this model is an accurate description of the sky brightness at altitudes within our stratosphere, missions like SHARP will be able to obtain diffraction-limited, high resolution images of planetary bodies. MODTRAN indicates the ideal imaging configuration and targeting for daytime observations from the stratosphere. However, MODTRAN is only a formulated graphical model and must be verified through experimental missions using light sensing devices that can quantify brightness through an analysis of the different wavelengths and azimuth angle from the sun throughout ascent. The BOWSER payload is designed to obtain this data and provide a profile for the behavior of a platform stationed in the stratosphere.

Although SHARP is a concept waiting for its opportunity and available funds, with the help of projects like BOWSER, it will potentially pave

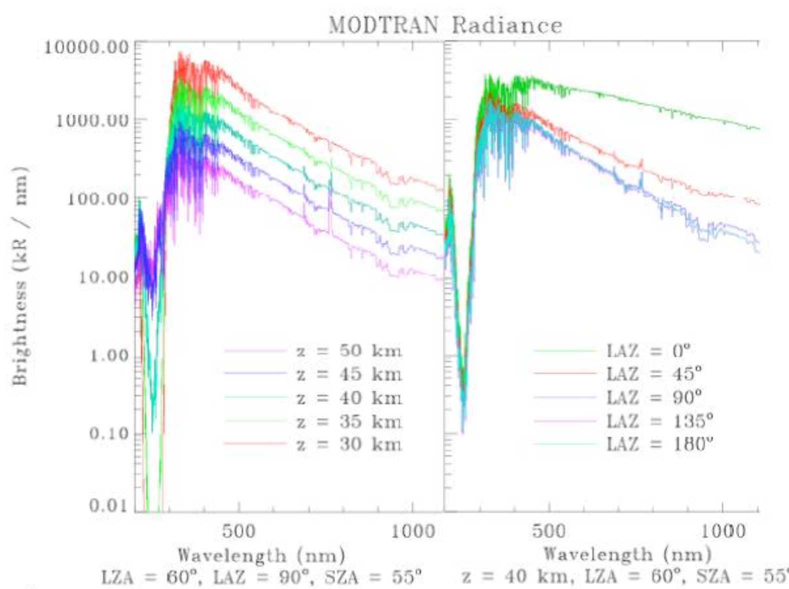

Figure 3: The MODTRAN model displays sky background as a function of wavelength, altitude, and angle from the sun.

a route for credible high altitude observation missions in the future.

III. High Altitude Student Platform

In January 2009, team BOWSER submitted and won a proposal to fly a payload on the High Altitude Student Platform (HASP). The HASP flight program is supported by the NASA Balloon Program Office and the Louisiana Space Consortium. Currently, HASP flies once a year in September from the Columbia Scientific Balloon Facility in Fort Sumner, New Mexico.

HASP provides students with an opportunity to conduct experiments in a near-space environment during nighttime and daytime conditions. Payloads are launched at 7:00 AM and float for 25 hours. The platform, which provides power and downlink for all payloads, is stable when suspended from NASA's high altitude balloon. The HASP platform is a wonderful opportunity for student teams to design balloon payloads and explore space.

IV. Mission Requirements

Team BOWSER's ultimate goal is to provide support for the diffraction-limited performance of balloon-borne telescopes. However, the BOWSER payload itself focuses more exclusively on the feasibility of using balloon-stationed star trackers. To do this, BOWSER must tackle the more explicit problem of compensating for mechanical disturbances on a balloon platform. The payload will measure the amplitude and frequency of disturbances in the balloon environment and characterize the stratospheric sky brightness in order to determine the performance requirements for a balloon stationed star tracker.

The payload achieves this mission in two ways. The first is to measure the amplitude and frequency of pointing errors in the typical balloon environment. Disturbances on a balloon platform range from the sluggish swinging of the platform under the balloon to the high frequency disturbances of onboard motors. Thus, BOWSER must be able to sense disturbances ranging from 0.5 Hz to 1000 Hz in the X, Y, and Z axes. To accurately depict the balloon environment and provide useful empirical data, BOWSER shall determine the pitch rate, roll rate, and yaw rate to a tenth of a degree per second. BOWSER shall also measure pitch, roll, and yaw to one hundredth of a G-Force at a minimum of 2000 readings per second. With a system capable of this performance, BOWSER will supply an exact portrayal of disturbances in the balloon environment. Once these disturbances are well quantified, an orientation system for a balloon observatory can be properly engineered.

The second method for achieving the BOWSER mission is to characterize the stratospheric sky brightness. A balloon star tracker must be able to recognize constellations of stars very rapidly, during day and night, in order to provide correct optical alignment for the platform. To prove that this is possible, team BOWSER will measure sky brightness diurnally as a function of altitude, wavelength, and angle from the sun. The primary purpose of this is to verify the MODTRAN model for sky brightness behavior. If this model can be validated, telescopes in the stratosphere should be able to obtain diffraction-limited, high quality images of celestial bodies. To achieve this authentication, BOWSER must be able to sample wavelengths spanning from 400-1000 nm at different altitudes and positions relative to the sun. Altitude must be known to an accuracy of at least 1000 meters, and BOWSER's instantaneous angle of elevation and azimuth must be known within 2 degrees of accuracy. With these known positions, the payload will conduct light intensity readings for at least 4 discrete wavelengths within the 400-1000 nm range to one hundredth of a W/m^2 accuracy. This will be achieved by a series of light detecting arrays, aimed to characterize sky brightness at different wavelengths, altitudes, and angles from the sun.

BOWSER must also discover the faint limit of detectable stars to verify that a star tracker can obtain enough starlight to calculate its orientation. To meet this requirement, BOWSER shall capture images of the sky during the flight with the ability to identify constellations that consist of stars characterizing a minimum of 8^{th} magnitude brightness. The payload must sense stars of this faintness to prove that instruments like the ST5000 will be useful in the upper stratosphere. This will be achieved by an imaging pair. One imager will be stationed behind a telescope designed to eliminate stray light; the other will provide a wide angle observation of the sky. Data collected from these instruments will simultaneously characterize the relative sky background brightness and faint limit of detectable stars with accuracy pertinent to supporting the BOWSER mission.

The final measurement that BOWSER will record in order to sense sky brightness pertains to the number density of the atmosphere around the platform. This measurement involves a calculation combining relative temperature and pressure. Number density data will provide an accurate portrayal of the surrounding atmosphere and its possible scattering effects. This data will be obtained with a series of temperature sensors accurate to one tenth of a degree Celsius and a pressure sensor accurate within one tenth of a PSI. This measurement, along with imaging and light sensing data, will help to verify the MODTRAN model, characterize relative sky brightness, and ultimately help support the use of star trackers on balloon-borne observatories.

V. Mission Design

The BOWSER payload, under guidelines set by HASP, is slightly larger than one cubic foot. The payload contains all data storage and imaging devices. Protruding from one side of the BOWSER payload will be an array of photodetector baffles and a telescope. An array of LED light sensing devices will protrude from the top in a concentric arrangement, Figure 4.

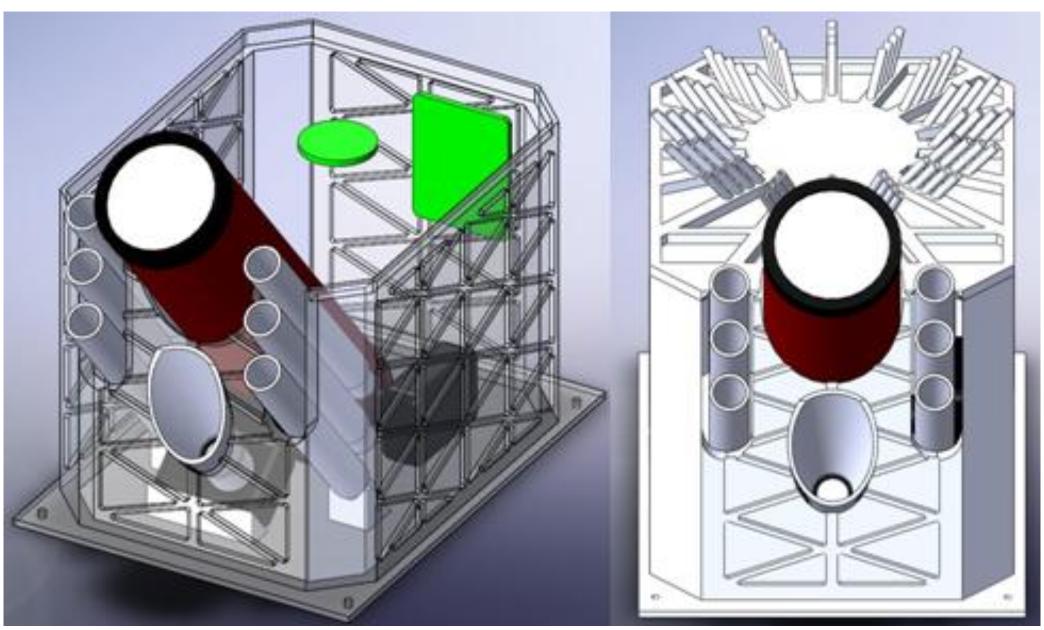

Figure 4: The two drawings show the preliminary design for the BOSWER payload. Notice the camera mounted for a wide angle view directly below the narrow telescope field of view

Relatively little is known about the use of LEDs as light sensors. It is a process that has many advantages, but has not been fully explored. BOWSER's science mission will utilize the properties of these one-directional diodes. When a voltage is applied to a diode – as found in LEDs – electrons travel from an anode into the diode's n-type material and jump (via the conduction band) to a p-type material which is attached to a cathode, Figure 5. The p-type material contains a valence band that is deprived of electrons. As electrons fill the valence shell, energy in the form of light is emitted. LEDs are controlled to only emit energy in specific wavelengths by restricting the size of the jump between the conduction band and the valence band in the p-type material.

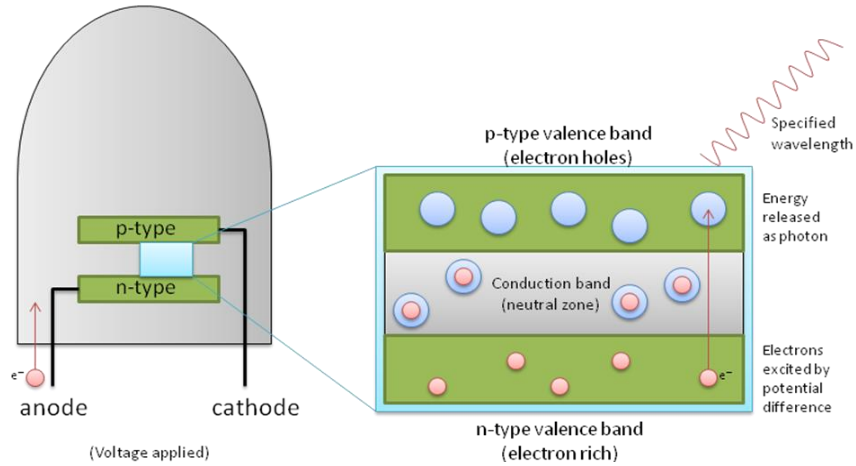

Figure 5: This diagram represents the functionality of an LED in the forward direction.

LEDs are a good choice for light sensors because the entire process can be run in reverse. When a photon from the LED's corresponding output wavelength range strikes the p-type material of the diode, it excites an electron. The excited electron compensates for its excited state by moving into the conduction band. The building charge in the conduction band can be relieved if a connection exists between the anode and the cathode. Completing this circuit with a device such as a voltmeter allows the user to measure the voltage created by photons striking the diode. BOWSER shall use multiple LEDs to observe wavelength light intensities between 400 nm and 1000 nm in order to verify the MODTRAN model.

The BOWSER payload not only presents an opportunity to verify the viability of MODTRAN and high altitude observatories like SHARP, it also has the opportunity to test new means of data collection. In order to accomplish BOWSER's science missions, the payload will use two unique scientific instruments: an LED light sensing array and a customized telescope.

The LED array is designed to take photons of light and convert the energy into a voltage by wiring the LEDs in reverse. Photodetectors accomplish the same goal more efficiently, but LEDs can discriminate against the wavelength of the photons without a filter. Team BOWSER has taken what little was known about this subject and pioneered a way to utilize it to accomplish its mission. BOWSER will fly an LED array on the roof containing at least 70 LEDs. Each of these diodes will take data during the flight at 1 Hz. The result will be over six million altitude, angle, and wavelength-specific data points. This data will cover the entire flight and will allow team BOWSER to verify the MODTRAN model of sky brightness behavior as a function of wavelength, altitude, and azimuth angle from the sun.

BOWSER will also be flying several photodetectors that will be oriented at fifty degrees above the horizon. These detectors each have a different optical filter in front of them that limit the wavelengths of light in the visible spectrum that each detector receives. The bandwidth for each filter is roughly 50 nm. Taking simultaneous data from each detector will produce a graph of background light in the atmosphere as a function of altitude and wavelength. This will allow team BOWSER to draw conclusions on the effectiveness of the MODTRAN model.

Directed at the same field of view as the photodetectors will be a wide-angle CCD camera. The purpose of this camera will be to provide a wide-angle field of view of the sky. It will allow the data obtained from the photodetectors to be compared to tangible images of the sky. If stars clusters can be identified in this field of view, this camera can help simultaneously characterize the relative sky background brightness and faint limit of detectable stars.

The camera chosen to fulfill this requirement will be an off-the-shelf Canon 12.1 mega pixel PowerShot G9. This point-and-shoot, SLR hybrid, camera offers many features vital to the BOWSER mission. The G9 supports the Canon Hack Development Kit (CHDK), which allows the user to run automated scripts that can control not only various optical settings, but can automatically capture pictures on a timed program. The G9's high resolution CCD will produce high definition images of celestial bodies. The G9 also offers a manual ISO sensitivity toggle which allows for various gain settings on the CCD. This feature, along with adjustable exposure times, makes this camera perfect for the low-light settings of the dark sky. The G9 also offers the option to take uncompressed RAW images. This allows for finer images because no data is lost due to JPEG compression. With these abilities, the Canon PowerShot G9 will be programmed to take RAW images throughout the flight. The camera will be installed with a cone baffle at the lens to prevent light approaching at extreme angles.

A second imager will also be included on the BOWSER payload. The purpose of this secondary imager is to test the feasibility of balloon-stationed star trackers. Star trackers are used in observatories to orient a telescope's position in the sky. It is impossible for BOWSER to fly a star tracker because they greatly exceed the project's budget. However, a star tracker is essentially a telescope with a programmed imaging device that can determine where the telescope is pointed. BOWSER will include a telescope with an attached CCD camera to simulate what a star tracker could see from the stratosphere – both at night and during the day. It is critical to know if a star tracker can see stars during the day in the stratosphere because if they cannot, a balloon observatory would only be able to operate at night.

The telescope flown on BOWSER will be a modified, off-the-shelf Orion Newtonian. Team BOWSER is working closely with Russ Mellon, an optics professional, to machine parts that will complete the modifications. A typical Newtonian has only one focal point with the eyepiece located near the aperture. The problem with a Newtonian is that stray light can enter the aperture at extreme angles and still get reflected through the eyepiece. The new layout, Figure 6, for BOWSER's telescope

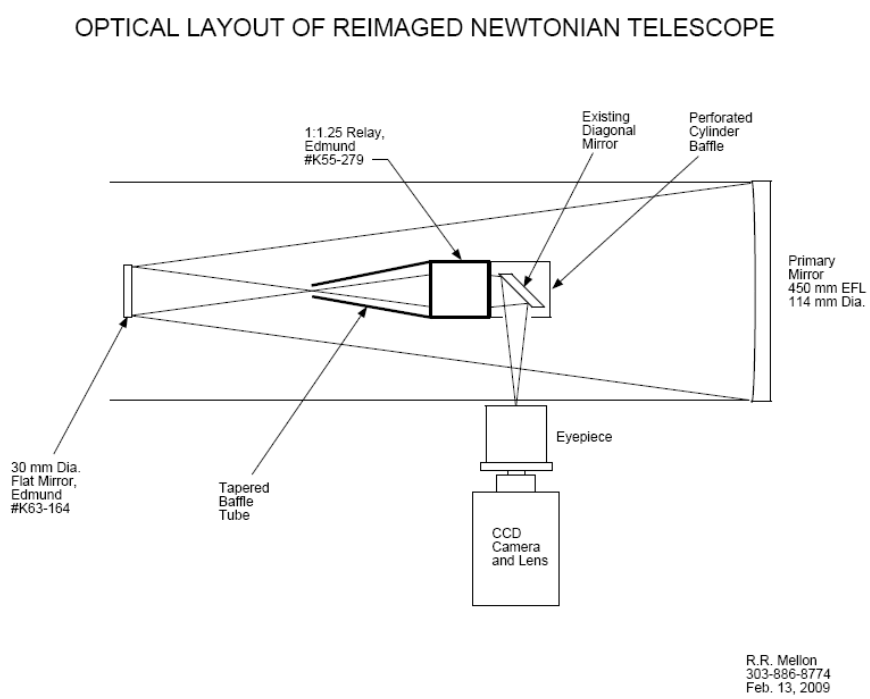

Figure 6: This drawing shows the optical layout for BOWSER's modified Newtonian Telescope, designed to baffle stray light to achieve images of starts from Earth's stratosphere during the day.

collects light through the same aperture and redirects it off the primary mirror to a flat mirror positioned near the aperture. The flat mirror sends the light back down the tube to its focal point and through a conical baffle. The baffle prevents stray light entering the aperture from joining the light beam that goes to the eyepiece. This baffle is critical if team BOWSER hopes to see stars during the day. After the light passes through the baffle it is sent to a lens relay which takes the expanding beam of light and refocuses it at a shorter focal length. The altered light beam hits the original Newtonian diagonal mirror and is redirected to a columnator in front of the camera lens. This design will hopefully allow BOWSER to image stars from the stratosphere during the day.

The viability of a star tracker also relies heavily on the stability of the platform it is installed on. A balloon hovering in the stratosphere can experience various disturbances that must be counteracted by an optical pointing system. However, the requirements for a balloon pointing system have not yet been defined. To make this possible, BOWSER will characterize the disturbances experienced by the balloon platform by measuring the amplitude and frequency of pointing errors in the typical balloon environment. The disturbances that a balloon platform experiences range from the slow pendulum movement of the platform tethered to the balloon to the high frequency disturbances of onboard motors. BOWSER must be able to detect both of these motions as well as the platforms orientation at all times during the flight.

To measure high frequency disturbances, rotations, and rotational rates of the platform, an Inertial Measurement Unit equipped with a three axis accelerometer and a three axis gyroscope will be implemented on the BOWSER platform. This device will be sampled at a rate of 2000 Hz in order to ensure that vibrations as high as 1000 Hz can be detected. The pitch and roll of the platform will be accurately detected by the three axis gyroscopes. BOWSER will also contain an accurate, pitch-compensated digital compass that will provide information regarding the pointing direction, rotational velocity, and rotational period of the HASP balloon platform. These instruments together will make it possible to characterize the disturbances that a balloon-stationed pointing system would have to compensate for in order to successfully image the cosmos.

VI. Conclusion

The most critical element of verifying the possibility of a high altitude observatory is determining which magnitudes of stars can be seen from the upper stratosphere and whether a star tracker can be used to orient a telescope from a balloon platform. The data obtained by BOWSER will provide the evidence necessary to support the use of diffraction-limited balloon-borne telescopes in the stratosphere.

VII. References

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