A Model of Sky Brightness in the Stratosphere

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In the interest of supporting the feasibility of diffraction-limited, balloon-borne telescopes, students from the Colorado Space Grant Consortium at the University of Colorado developed the Balloon Observatory for Wavelength and Spectral Emission Readings (BOWSER) and launched it as part of the High Altitude Student Platform (HASP), a program run by Louisiana State University. Relying on the natural rotation of a zero pressure balloon, BOWSER analyzed sky background brightness in the stratosphere utilizing an array of diodes to sample a ninety degree field of view over the course of an eighteen hour flight. Based on the MODTRAN model of sky irradiance, it was predicted that sky brightness would vary primarily as a function of three parameters: altitude, wavelength and angle from the sun. The diode array provided empirical evidence that characterizes the influence of each of the three variables on sky background brightness. This model will enable future high altitude observatories to anticipate the optimal pointing and filtering conditions necessary for observing the cosmos.

Nomenclature

P	=	power
V	=	voltage
I	=	current
R	=	resistance

I. Mission Premise

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 at obtaining deep space images, invaluable information about outer space has been discovered, and our efforts continue to bring forth astonishing visuals portraying the vastness of the universe.
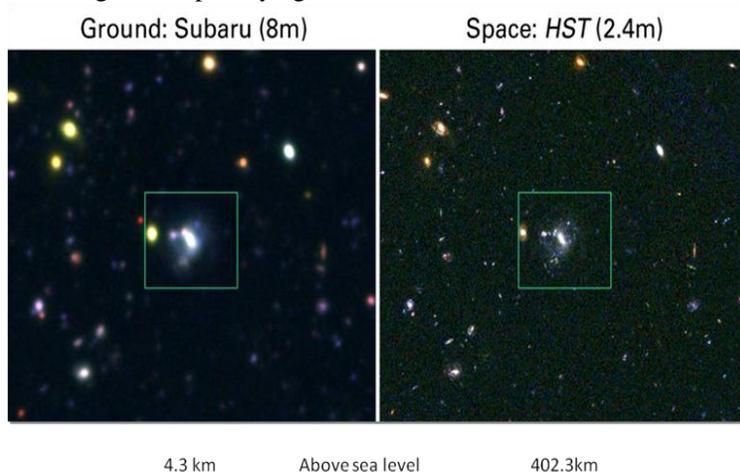
Figure 1: Even the 8 meter aperture of the ground based Subaru telescope cannot compare with the 2.4 meter aperture of the orbiting Hubble Telescope.

Ground based telescopic observatories are the oldest and most used facilities for astronomical observing and imaging. However, even as the primary mirrors of these instruments have grown larger over time, grounded telescopes have never been able to avoid atmospheric distortion which plagues all images captured from the Earth's surface, Figure 1. An alternative to ground based arrays is orbiting telescopes. 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 is now possible to station a telescopic observatory on a high altitude balloon, floating above 99% of the Earth's atmosphere, unaffected by the weather. By comparison, it costs around $600 per kilogram to launch a payload into the upper-stratosphere propelled by 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.

The main advantage to a telescope deployed in the stratosphere compared to a ground based observatory is the significantly reduced sky background brightness 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, like used by ground observatories. 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. It is believed that the daytime sky background decreases by roughly a factor of two for every 5 kilometers in altitude. If this is true, bright objects, such as Uranus and Neptune, can easily be acquired with a good signal-to-noise ratio during the day.

In spite of their benefits over ground-based telescopes, 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 a viable alternative to expensive orbiting observatories.

To truly discover the benefits of observing the cosmos from the stratosphere, the actual sky brightness must be characterized at variable altitudes, angles from the sun, and also for discreet wavelengths. The brightness of the background in the stratosphere determines what kind of science can be conducted at this location. It should be noted that many balloon stationed telescopic observatories are being designed with advanced star tracking systems for pointing and attitude due to strict precision requirements. It is important to consider the performance of these instruments when dealing with the stratospheric sky brightness.
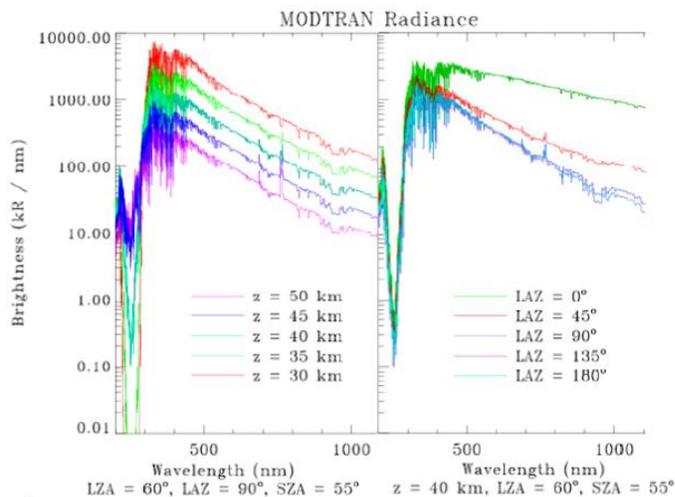

Figure 2: The MODTRAN model displays sky background as a function of wavelength, altitude, and angle from the sun.

To serve this purpose, a model of sky brightness has been developed by Spectral Sciences Inc. and the US Air Force called the Moderate Resolution Atmospheric Transmission model (MODTRAN). The MODTRAN model characterizes the atmospheric propagation of electromagnetic radiation for the entire spectral range. In particular it predicts sky brightness as a function of wavelength, altitude, and azimuth angle from the sun, Figure 2. MODRAN predicts this brightness by solving the radiative transfer equation, including the effects caused by molecular and particulate emissions, absorptions, scattering, and spherical refraction, as well as the effects caused by surface reflections and emissions. If this model truly is an accurate description of the sky brightness at altitudes within our atmosphere, balloon missions in the stratosphere will be able to obtain diffraction-limited, high resolution images of planetary bodies. However, MODTRAN is only a

formulated graphical model derived from the radiative transfer equation and does not include data collected from experimental missions. To be fully confident in the performance of a telescope and its tracking system from the stratosphere, this sky brightness must be characterized first hand.

II. High Altitude Student Platform

Figure 3: HASP balloon being filled prior to launch

The High Altitude Student Platform (HASP) program, based out of Louisiana State University, provides students with the opportunity to launch payloads to the edge of space on a NASA high-altitude, zero-pressure balloon. The HASP team from the Colorado Space Grant Consortium, comprised mostly of sophomore and freshman engineers and astrophysics students, is currently working alongside Eliot Young of the South West Research Institute in an effort to investigate the possibility of balloon stationed optical observatories. The prospect of affordable cosmic imaging above earth's distorting atmosphere would be an invaluable asset to fields such as astronomy and astrophysics. The HASP 2009 payload, coined BOWSER (Balloon Observatory for Wavelength and Spectral Emission Readings) flew to 120,000 feet on the 11th of September, 2009. BOWSER's mission was to characterize the sky brightness in the stratosphere as a function of altitude, wavelength, and angle from the sun. The method by which this was achieved will be discussed in the following sections.

III. The Array

In order to create a comprehensive model of sky brightness in the stratosphere, three variables had to be characterized: altitude, angle from the sun and wavelength. The first of these was satisfied by the motion of a balloon satellite, namely its ascent. Gathering data for the last two, however, hinged upon the design of the LED light sensing array.

In designing the LED array, it was assumed that the motion of a stable balloon platform is restricted to rotation about the flight string. This allowed for a design in which the elevation of the LEDs remained constant. This constant elevation was chosen to be 50° in the interest of minimizing the amount of atmosphere being observed, as seen in Figure 4. Optimally, the LEDs would have been pointed straight up, but the balloon obstructed vision down to 50° above the horizon. With the elevation held constant, data pertaining to angle from the sun could be obtained by varying the azimuth of the LEDs only and by relying on the platform's rotation.

Ground testing showed that when varying the angle of the LEDs relative to the sun, it took roughly 10° to drop from the peak intensity to the minimum. Using this data, the spacing between LEDs on the array was chosen as 2.5°. This allowed for sufficient sample density, with at least four data points on either side of the peak.

Sky brightness data for differing wavelengths was obtained by using three different colored LEDs – red, orange and yellow. These three colors each had a specific wavelength spectrum as sensors. Red spanned 500 nm to 660 nm, orange was 440 nm to 620 nm, and yellow absorbed 500 nm to 620 nm. When combined, nearly the entire visible spectrum was covered. To maintain equal exposure between colors, the LEDs were arranged in stacks of three, one of each color. This resulted in an array containing 120 LEDs – 40 of each color. In all, these 40 stacks had a total field of
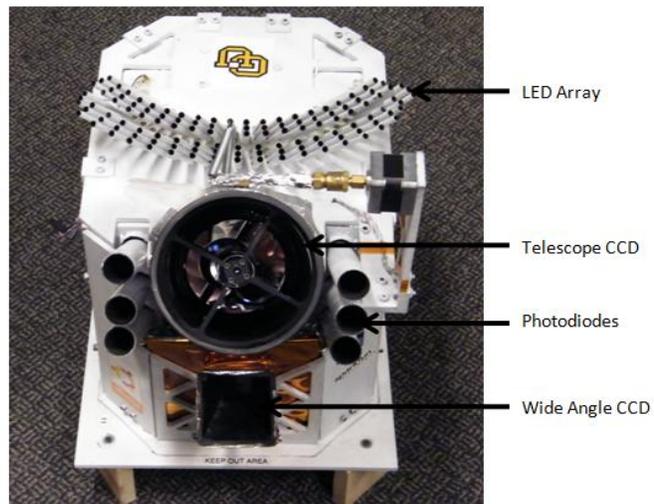

Figure 4: The BOWSER payload with critical components labeled

view of 97.5°.

In order to measure the intensity of the light hitting the LEDs, the current produced had to be measured. This was accomplished by placing a resistor in parallel, then measuring the voltage across it using ADCs. To save board space, only four ADCs were used, each with a 32-channel multiplexer. These multiplexers cycled through the entire array with a frequency of approximately 1 Hz, obtaining data as close to simultaneously as possible.

IV.   LEDs as Light Sensors

The BOWSER payload was constrained by a relatively conservative budget. To accommodate this, the team turned to Light Emitting Diodes (LEDs) as an affordable means of collecting a large amount of light intensity data. Little is known about the use of LEDs as light sensors. BOWSER's science mission utilized the properties of these diodes to measure the light intensity of several wavelength ranges in the visible spectrum. When a voltage is applied to a diode, electrons travel from the anode into the diode's n-type material and jump (via the conduction band) to the p-type material which is attached to the cathode, Figure 5. The p-type material contains a valence band that is deprived of electrons. As electrons fill the material's 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.
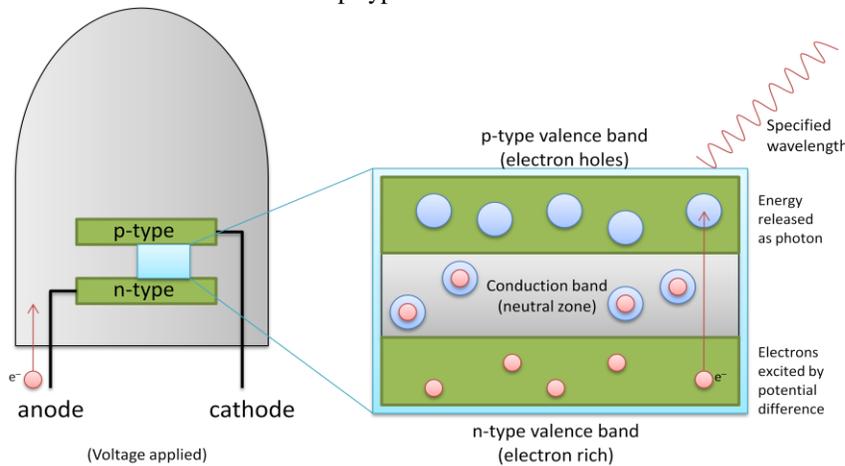

Figure 5: This diagram represents the functionality of an LED in the forward direction.

LEDs can be used as light sensors because this 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 resistor allows the user to measure the voltage created by photons striking the diode. The current can be calculated from the value of the resistance and the recorded voltage. BOWSER used multiple LEDs to observe wavelength light intensities between 420 nm and 700 nm in order to compare with the MODTRAN model.

The BOWSER payload not only presented an opportunity to prove the viability of MODTRAN, it also provided the opportunity to test a new means of data collection. The LED array was designed to absorb 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 discriminate the absorbed wavelengths without a filter. BOWSER flew an LED array on the roof of the payload containing 120 LEDs. Each of these diodes took data during the flight at approximately 1 Hz. The result was over six million wavelength-specific data points. This data spanned the entire flight and will allow team BOWSER to characterize sky brightness behavior as a function of wavelength, altitude, and angle from the sun.

V.   Electronics

An LED can be used as a light sensing element, so long as it is treated as a photodiode in a circuit. Photodiodes, or in this case, the LED, will generate current proportional to the intensity of the electromagnetic radiation striking the PN junction of the diode. Intensity is a measure of power, therefore to measure the incident light intensity, it is necessary to know the power of the electron charge emitted by the diode.

There are several methods for calculating the power in an electrical circuit. For direct current, the following equation may be used:

$$P = IV \tag{1}$$

For all practical purposes, the current in a circuit is a difficult property to measure quantitatively. Therefore it is useful to rearrange equation 1 using Ohm's law.

$$P = \frac{V^2}{R} \tag{2}$$

Both voltage potential and resistance are simple electrical properties to measure. The problem simply becomes how to generate a voltage.
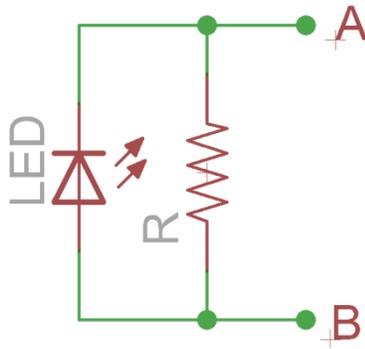

Figure 6: BOWSER LED circuit

A PN junction will create electrical charges when it is hit by electromagnetic radiation, however for a voltage potential to exist, these charges must flow through a complete circuit. One method is to simply measure the potential across the anode and cathode of the LED. This method was not used because it is very difficult to measure the equivalent resistance of this circuit because it is dominated by the internal characteristics of the voltage measuring device, and the diode itself. The solution used by the BOWSER team was to place a resistor in parallel with the LED and measure the potential across the resistor (Figure 6).

This circuit allows for charge generated by the LED to flow through a resistor and therefore creating a voltage drop across the resistor. The voltage was then measured using a high input impedance analog to digital converter (ADC). Using the known resistance of the resistor, and the voltage measured by the ADC, it is simple to calculate the total power generated by this circuit using equation 2. This can then be directly related to the power or intensity of the incoming light.

The choice of resistor in this circuit is not a trivial matter. Too low a resistance causes current to flow easily across the resistor. This also requires the diode to produce much more current. Using too high of a resistance will stop all current flow.

The resistance used in the circuit was chosen experimentally. A constant light source was used to illuminate each LED and varying resistors values were used to determine the optimum resistance for each detector. The resistance that created the highest output voltage for each LED was then used in the circuit. This was found to be 11.2 $k\Omega$ for the orange LED, 42.7 $k\Omega$ for the red LED and 61.3 $k\Omega$ for the yellow LED.

VI. LED Calibration

In order to model the sky brightness as a function of altitude, wavelength and angle from the sun, the LEDs must be characterized as scientific sensors. Two goals must be met to achieve this. The first objective is to convert the raw voltages read during flight to the true intensity of the sky background. The second is to discover how the measured intensity varies over the detectable spectrum of the sensor so that the true intensity can be modeled as a function of wavelength. These objectives can be accomplished with a single calibration test.

To find the scale factor between the voltage readings produced by the LEDs and the true intensity observed by the LEDs, the response of the diode to a white light source must be determined. It is necessary to know the response of the diode because the voltage produced by the LEDs does not necessarily vary directly with intensity. The expected linearity is shown in Figure 7:

The linearity will be found using an adjustable aperture heliostat. The optical bench setup for the heliostat is shown in Figure 8. To determine the range of intensities the LEDs detects, the maximum and minimum intensities will be found by opening and closing the aperture until the voltage output from the LEDs does not change with the changing aperture. A power meter will then be used to record the intensity of

Figure 7: Linearity of LED Response

the sun at the two apertures. The range of the LED's detection will be arbitrarily divided into five equally spaced intensity points that will be used to accomplish the second objective.
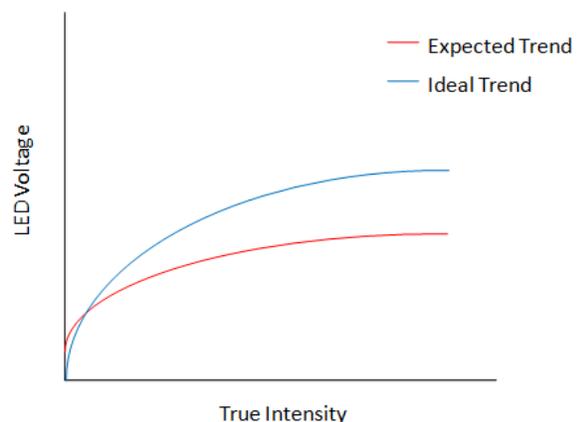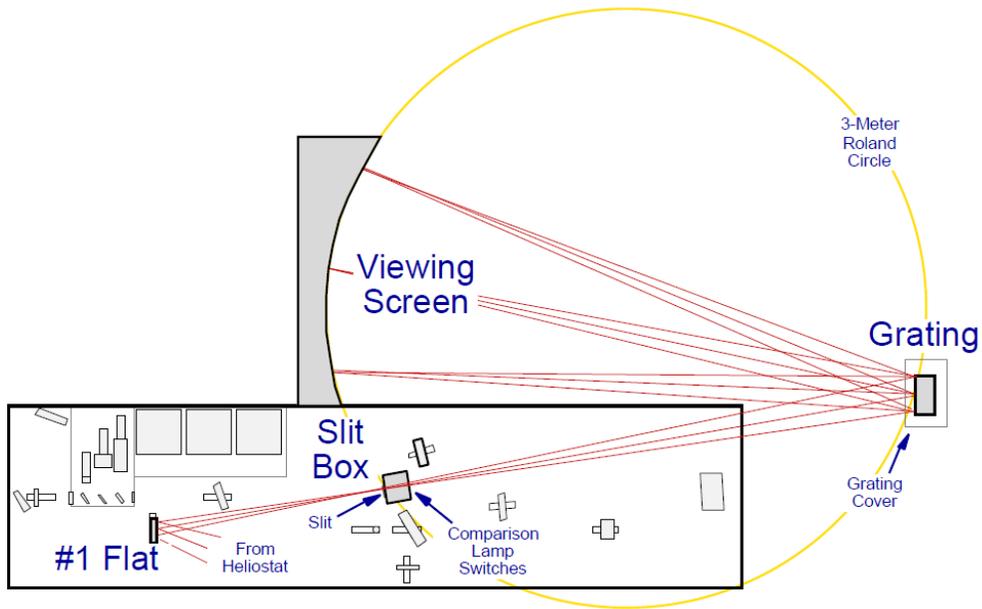
Figure 8: Heliostat Setup

The second phase of the testing is to determine how this response, characterized in phase one, varies as a function not only of intensity, but also of wavelength. The discrete intensities of white light from phase one will then be spread by the diffraction grating into its spectral components. The LED's response as a function of wavelength can then be discovered by comparing the true intensity at discreet wavelengths to that measured by the LED sensor.
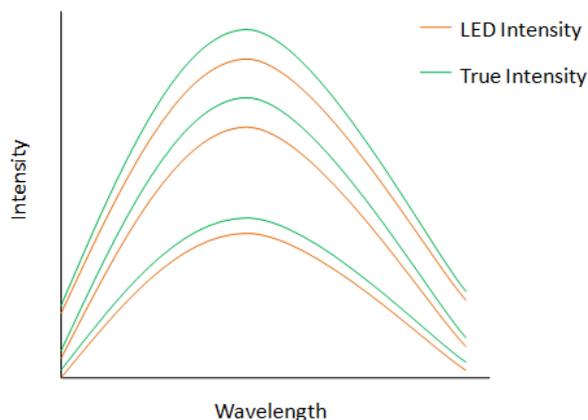

Figure 9: Spectral Response as a Function of Wavelength at Known Source Intensities

The expected results are shown in Figure 9. Three white light intensity distributions are plotted with their resulting LED intensity distributions.

The first step is to use the power meter placed right before the diffraction grating to adjust the aperture of the heliostat so the intensity of the sun is at one of the five data points determined in phase one. After the aperture is set, the power meter will be used to record the intensity at the 400 nm mark of the spectrum. The LED apparatus will then be swept down through the 400 nm mark until all the LEDs have been exposed to the spectrum.

Once all the LEDs have been swept through, the aperture will be changed so the total intensity of the sunlight is at the next intensity point from phase one. The intensity at 400 nm will be recorded and the LEDs swept through again. This process will be repeated for all five intensity data points at wavelengths starting at 400 nm and increasing to 700 nm in increments of 10 nm.

Once the response at varying wavelengths is known for a specific diode, any voltage recorded during flight can be converted to the true intensity. This true intensity is the actual wattage per unit area of the sky background measured during flight. These tests are currently being conducted by the BOWSER team at the University of Colorado at Boulder. Once completed, the LED sensor data will be converted into true sky intensity. From these results, the flight data can be analyzed in order to characterize sky brightness as a function of wavelength, altitude, and angle from the sun. The trends found will then be quantified into an experimental sky brightness model, which can then be compared to existing models like MODTRAN.

VII. Conclusion

While great strides have been made in the field of celestial imaging, there is still much that can be done to further improve the means by which telescopes obtain their images. A promising area of research for this is balloon-based telescopic observatories, due to their superior performance capabilities and low cost. However, before a new "Hubble" can be put in the sky on a balloon, the flight environment must be characterized. Models such as MODTRAN currently exist, but these are mathematical and not based on hard data. This is what the data gathered by BOWSER aims to remedy.

BOWSER's data will soon produce a sky background brightness model, but this hinges upon a comprehensive understanding of the operation of LEDs as sensors. The benefits of using LEDs are numerous: they are affordable, can be obtained in large quantities, and filter by wavelength naturally. In order to use them as calibrated sensors, however, numerous tests must be done to fully characterize their response. These tests analyze the linearity and spectral detection range, which can then be used to correlate flight data to actual stratospheric conditions. With this accomplished, the intensity data gathered by BOWSER will be used to create a comprehensive sky background brightness model, paving the way for telescopic observatories in the stratosphere.