Selective Pointing Apparatus for Research of Turbulence and Atmospheric Noise Variation

SPARTAN-V

Feasibility of Balloon Stationed Pointing System

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I. Abstract

Looking towards the beauty of the night sky, humanity has always questioned the possibility of discovering terrestrial planets to harbor the final frontier of human exploration. On March 7th, 2009, the Kepler Spacecraft was launched into a 3.5 year orbit in the hopes of discovering habitable Earth-sized planets through observing the photometric output of a collection of stars, and viewing if there is a periodic dip in a star’s brightness. Presently, Kepler has discovered 1,235 planet candidates with 15 of these already confirmed as planets in just over two years of flight. However, it may now be possible to entertain the same capabilities of Kepler for a fraction of its 600 million dollar cost with the use of lighter than air vehicles. Floating above 99.5% of Earth’s distorting atmosphere, the near space environment may be a perfect viewpoint for capturing clear imaging of the cosmos. The SPARTAN-V mission will be characterizing the distorting effects of the remaining 0.5% of the Earth’s atmosphere. This will be accomplished through analyzing the photometric stability of a star at this altitude. The SPARTAN-V payload will require the construction and use of an autonomous pointing system to be tested upon a NASA high altitude balloon, ascending to a height of 120,000 feet (36 km), float for 24 hours, and descend. This pointing system will be an innovative technology to be flown on a High Altitude Balloon; the intricacies of designing such a system provide complex and interesting topics of discussion. SPARTAN-V 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 August 2011, will provide evidence suggesting the possibility of an optical system stationed in near space.
II. Background

Humankind has always questioned the possibility of discovering planets that resemble the characteristics of Earth. Of the stars surrounding our system, we still hold very little knowledge of the planets which orbit these stars.

51 Pegasi b was the first exoplanet to be discovered in 1995 by Michel Mayor and Didier Queloz using radial-velocity, otherwise known as the Doppler effect method. As a planet orbits a star, that planet's gravitational field will cause the star to be periodically pulled towards and away from Earth and our observation point. This causes the light waves from the star to shift into shorter wavelengths as the star is moving towards us, and longer wavelengths when moving away from us, otherwise known as Doppler Shifts. The size of the planet, as well as the distance from its star are able to be deduced from how fast that star is being pulled towards, and away from us. Other methods that have been used to detect exoplanets consist of direct imaging of planets, observing a star's movement across the sky, in which a planet will cause a star to move in small circular or elliptical orbits, and the transit method. The transit method is similar to the radial-velocity method, using an observer on Earth and viewing a periodic dip in the star's brightness from a planetary transit. Of the total 430 exoplanets discovered, over 90% of those have been discovered in the past 10 years, with a majority of those found through the radial velocity and transit methods.

NASA’s Kepler Spacecraft was launched on March 7th of 2009, for a 3.5 year mission to survey and discover hundreds of Earth-size and smaller planets within our region of the Milky Way. Kepler focuses on Earth sized planets, as a majority of extrasolar planets discovered thus far have been giant planets, mostly the size of Jupiter or larger. Kepler will view the same region in the Milky Way for the entire duration of its flight, measuring the brightness of select stars to detect if there are planets transiting there stars. Kepler’s mission monitors the brightness of the stars within its Field of View (FoV) of 10 degrees squared. Within this 10 degrees squared, it consists approximately of 500,000 star, of which, 100,000 star are being simultaneously observed and measured for differences in brightness every 30 minutes. In order to ensure that a planet has been discovered, Kepler must see at least three transits to be sure the dip in the star’s brightness was caused by a planet. Thus, a 3.5 year mission is required to detect planets with similar orbits and characteristics to Earth’s. Assuming that planets are orbiting stars that are common to our Sun, it is estimated that 50 Earth-planets with a single year orbit will be discovered in the 3.5 year flight. The information collect from Kepler will also support future NASA projects of Space Interferometer Mission (SIM) and Terrestrial Planet Finder (TPF).
As of February of 2011, Kepler has announced 15 confirmed planetary discoveries. Being that these planets have short orbital periods, a max of 4.9 days, Kepler is able to verify that the periodic dip in brightness is due to a transiting planet. Even with 1,235 planetary candidates found in just two years, the majority of discoveries are not expected to be found until Kepler’s 3rd year in flight.

For a 3.5 year flight, Kepler is estimated to cost $600 million. It has also been speculated that Kepler could be extended to a 4 year or even a 6 year flight, causing the $600 million cost to increase. The alternative use of a Balloon-Based Observatory (BBO) to view and measure the photometric output of stars could achieve Kepler’s mission for a fraction of the cost. By comparison it costs around $600 per kilogram to launch a payload into the upper-stratosphere upon 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. BBOs ascend to an altitude of 120,000 feet, above 99.5% of Earth's atmosphere. At such an altitude, there is little to no influence from the weather, making the flight environment highly stable for optical devices. Also, since balloon vehicles are significantly cheaper, it is possible to station more than one in Earth's upper atmosphere. BBOs are also more easily accessible for maintenance or adjustments. Balloon Based Observatories may be the perfect alternative for discovering more of the universe we still know so little about.

The SPARTAN-V Mission will not be attempting to discovery any new planets, but to determine how great the interference from the remaining 1% of Earth's atmosphere affects observations of exoplanets, and if changes in brightness of a star are distinguishable between atmospheric disturbances and a planetary transit. SPARTAN-V's mission is to point at a star of magnitude zero to four, and take in photometric data of that star for as long as possible creating a stack of images that can be analyzed post-flight. The data from the flight will consist of at least 2,000 images of multiple stacks of stars. Due to our tracking method, it is unlikely that the star will be located in the exact same position in every image. It is also unlikely that the temperature conditions will be the same in each image. Therefore the best method to analyze the images will be on an individual basis and combine the final results. The most useful tool for accomplishing this will be IDL, as it performs matrix operations on the arrays of pixel values (counts) of the images taken.

To analyze the photos after flight, the following steps will be carried out in an IDL environment. First the read noise from each image will be subtracted, during this process the CCD temperature associated with each image will be extracted. This temperature will be converted to a dark current value which will then be subtracted from each image. Next, the average local background per pixel around each target star will be determined and this will be subtracted from each pixel in the image. The remaining number of counts from the target star will then be recorded and using the area of the star in

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**Figure 3: The Transit Light Curves of the 5 Kepler Exoplanets discovered.**
the image its total counts can be found. This process will be repeated for each image and the results will be summed to produce the mission’s scientific findings.

The first step will be to remove the read noise from the image; the manufacturer given value is 15 electrons per pixel. However, the values on the image are in counts or ADU, therefore SPARTAN-V will need to convert the 15 electrons to counts using the CCD’s gain which is 2.5 electrons per count. These values will be used to convert the read noise to counts and subtract this value per pixel from every pixel in the image.

The second, third, and fourth steps will be to remove the dark current/noise. First we will need to associate a CCD temperature with each image; this will be included in an information stamp embedded within each image. The temperature of the CCD will have an associated dark current based on previous calibration and testing results, we will convert this temperature to a dark current per pixel value. If an exact match for this value does not exist then we will round up to the nearest higher temperature. It is important to record this value per pixel for SNR calculations and then subtract it from each pixel in the image.

It is unlikely that a flat field will be able to be taken during flight and after landing any flat fields will prove to be useless due to contaminate introduced post imaging therefore the normal flat field normalization will be skipped.

The fifth and sixth steps will be removing the background. First we will determine the average background counts per pixel around the star and then subtract this value per pixel from every pixel in the image. We can subtract the localized background from the entire image because we are only interested in the target star. This average background value per pixel will be recorded for SNR calculations.

The seventh step will be to measure the amount of counts from the target star. In IRAF a method using a circular aperture with specified radius can be used to sum its contents. Record the area used to sum the star counts for SNR calculations.

The eighth step will be to calculate the total background and dark current present in the area used to sum the star counts. Although they have been subtracted these values play a role in the SNR calculations. We will record the total background and dark noise counts for the star area separately.

These columns can be plotted to see variability in the values and summed to attain the total star counts and each column sum (except area) can then be used in the following equation to calculate the signal to noise ratio.

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\text{SNR} = \frac{\text{Star Counts}}{\sqrt{\text{Star Counts} + \text{(Dark noise) + (Background counts)}}}
\]
III. High Altitude Student Platform

In January 2010, team SPARTAN-V 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 Grant 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

The SPARTAN-V mission is aiming towards the eventual goal of supporting balloon-based observatories. SPARTAN-V is focusing on the more specific issue of identifying the atmospheric distortion of optical reading above 99.5% of the earth’s atmosphere. As well SPARTAN-V shall attempt to characterize the stability of a balloon platform in the X, Y and Z directions both for vibrations and rotations. Finally, in order to achieve the first stated mission objective, SPARTAN-V is engineering an optical pointing system, which in turn implements the data retrieved in order to achieve objective two. In this way the mission objectives for SPARTAN-V are very inter-dependent, linking the success of one objective to the remaining two.

The payload will achieve the primary objective of characterizing the atmospheric disturbance of the remaining 0.5% of the atmosphere on optical readings by analyzing the photometric stability of a star. The issue in question is the fact that atmospheric gases will deflect (scintillation) or absorb (extinction) incoming light, and thus interfere with observation of that light. By characterizing the atmospheric effects on imaging at the given altitude, SPARTAN-V will be able to establish the precision with which imaging research may be performed from a balloon-borne platform. In order to create a realistic analog to scientific optical research, SPARTAN-V wishes to support the feasibility of locating super-earth sized exoplanets orbiting distant stars. Given the relative sizes of the earth to the sun, this will require the payload to sense a decrease in photometric stability with a minimum precision of $10^5$ which would be indicative of an earth-sized planet crossing between a star and the optical bay of the payload. As the HASP flight duration has been stated as an average of 15 hours, it is highly unlikely that SPARTAN-V will encounter such a crossing, rather SPARTAN-V will characterize the stability of the photons emitted by that star over a given duration, and determine whether they are varying with a degree greater than $10^5$.

The secondary objective of characterizing the stability of the balloon platform will be achieved by measuring accelerations in the X, Y and Z direction, and rotations in pitch, roll and yaw. The payload will need to measure a wide range of accelerations, from the slow swaying of the platform beneath the
balloon to the minute but rapid vibrations of internal motors and other systems located on the platform. As a result, it will be necessary to take recordings from 0.5 Hz to 1000 Hz to capture this wide variance of accelerations which could potentially affect optical readings. The rotational rates of the balloon are known to be relatively low, yet are a major factor for the pointing requirements for any observing instrument. SPARTAN-V will record these rotational rates to a precision of one-tenth of a degree per second. With this information, the pointing system mounted on the SPARTAN-V payload will be capable of tracking a given target with the necessary precision to accomplish our primary mission objective.

The pointing system on the SPARTAN-V payload will require the precision and torque capabilities to maintain a point source (star) within the field of view of the telescope. To current specifications, this field of view will be approximately 1300 arc-seconds, or 0.33°. This indicates that the yaw and elevation aspects of the pointing design must be capable of manipulating the telescope to within 0.33° precision. As well, drawing from previous HASP flight data, the average rotational rates recorded have been around 17 °/min with a maximum of 90 °/min, because of this, the SPARTAN-V team is requiring that the pointing system be able to accelerate from stand-still to 0.28 °/s in 1.18 seconds. This serves to specify the necessary torque applied to the pointing systems in both yaw and elevation aspects. Achieving these pointing requirements will be vital to the success of the primary mission, as keeping a star within the field of view of the telescope for the necessary duration of exposures is required in order to meet our primary mission objective.

Finally, SPARTAN-V shall be recording multiple other data, including temperature (both of system and external), magnetic direction, and relative rotation of rotary through accelerometers and gyroscopes. All of these data will provide necessary feedback in order to insure and improve the functionality of the SPARTAN-V payload

V. Mission Design

The dimensions of the HASP large payload are given as: 15” x 12” x 12” (LxWxH), however the SPARTAN-V team has acquired special exemptions on height in order to allow full capability of the active pointing system, thus pushing the dimensions to: 15” x 12” x 17”. This was necessary to accommodate the size of the telescope with respect to the yaw rotation. The entire payload is broken down as follows: The base electrical housing, which serves as mounting for the majority of electronics including motherboard and memory storage devices, the rotary table is then positioned at the top of the electrical housing, followed by the pitch arms which mount the telescope and allow for elevations manipulations. See figure 7 below.
The electrical casing will be constructed with a primary skeleton of honey-combed 6061-T6 Aluminum Alloy for maximum strength, as well as insulated with foam core in order to maintain as stable a thermal environment as possible, and protect from solar radiation. The wiring harness for the electronics is kept relatively simple through this implementation of a regular polygon for electrical mounting. As well the thermal conditions of the electronics is easily maintained with the freedom of choice for positions, allowing for the placement of high thermal output items next to those requiring heat for optimum performance. A visual of the current electrical positions can be seen in figure 8 to the left.

The yaw motor assembly is one of the most difficult engineering challengers SPARTAN-V must overcome. The primary issues arise from the ability to create a non-stepping gear system which has extremely low slippage and performs in the extreme conditions of upper atmosphere. As well a motor must be implemented that operates in such conditions, without needing much lubricant.
(as most water-based lubricants will boil off at altitude). The solution SPARTAN-V has come up with involves mounting a rotary table on a thin-plate bearing at the top of the electrical housing. This rotary table will then maintain a pressure connection with a smaller wheel which is driven by a stepper motor. The pressure connection between the rotary table and wheel is maintained by a spring system on the stepper motor itself, which allows for dynamic pressures to be applied as needed by the wheel, this will prevent both slipping and jamming assuming proper functionality. The rotary table itself will be constructed out of aluminum alloy, the edges to increase friction coefficient with the drive wheel. The drive wheel will have a soft outer edge, allowing the motor disk to effectively dig into the wheel and once again increase frictional coefficient to prevent slippage. The spring loading system will be constructed by providing a spring between the electrical housing and a plate mounted on the motor, which itself is mounted on a two bars allowing for linear translation. See figure 9 to the right for a detailed drawing.

The choice of a stepper motor for the drive system was not made lightly. A stepper motor provides high repeatability and precision with each given step of the motor. They function by having two coiled wire phases which run different currents at different voltages to produce varying magnetic fields, which then rotate a central shaft. By “stepping” these magnetic fields, the motors are capable of producing extremely precise positional steps of the drive shaft. Furthermore, SPARTAN-V will be implementing an Allegro Motor Driver which allows for eight micro-steps per step, effectively reducing the 1.8° standard step to 0.225° steps. This coupled with the 10:1 ratio between the wheels produces an effective 0.0225° per step on the rotary table itself, equivalent to 81 arc-seconds per micro-step which is well within the 1300 arc-second field of view.

The pitch arms are mounted directly to the rotary table, and will be responsible for mounting the elevation motor and telescope. The motor used for the elevation adjustments is the same model as that for yaw manipulation, however there is no gearing system that will act as a multiplier for the elevation connection. Thus, as part of the SPARTAN-V mission design, the payload will look at stars near the celestial plane which will not have much elevation changes during the course of the flight (they will remain relatively parallel to the horizon) which will help to reduce the amount of elevation adjustment necessary in order to track a star. The telescope itself will be mounted onto a bearing attachment to the
pitch arms, which will be directly manipulated by the stepper motor. The mounting will take into account the moment of inertia of the telescope, working to center the mount on the telescopes center of gravity in order to reduce the necessary torque from the motor to make elevation adjustments.

The telescope that the SPARTAN-V payload will carry was custom-manufactured by the SPARTAN-V team with the assistance of Russ Melon and Equinox Interscience. This telescope employs a double-refracted design which uses only flat mirrors in order to manipulate the incoming light. In this way the SPARTAN-V team will minimize the effects of thermal expansion on the focal length of the telescope, thereby drastically increasing the allowable operating temperature range of the optics system. Refer to Figure 7 below, the light enters the telescope through the primary lens shown in the upper left hand corner; it then proceeds to the first mirror (75x75mm) then the second mirror (40x40mm), effectively doubling the focal length of the telescope as it enters into the QSI 504ME CCD.

To achieve the characterization of the balloon platform stability, the SPARTAN-V payload will implement gyroscopes and accelerometers in order to measure both spin rates and accelerations in the X, Y and Z directions. The primary goal of the gyros is to characterize and provide feedback to the pointing system of the rotational rates in pitch, roll and yaw, which will be vital to the success of the pointing system. The gyros will need to achieve a precision of one tenth of a degree measurements in order to provide for the relatively slow rotations of the balloon platform. The current gyros to be flown measure at a precision of 33.3 mV per °/s with a four times amplification, establishing a precision well beyond those required. As well these gyros are very robust towards temperature variance and zero-point drifts, which will drastically reduce pointing errors in the system. Failure of this system will result in a possible failure of the primary mission objective. The accelerometers however will be mostly focused around characterizing high frequency vibrations within the platform itself. While our payload will not need to adjust for these vibrations, as our exposure times will be minimal and the star placement within the CCD is irrelevant to our science mission, future optical missions, especially those focusing on scene of a star,
will need to be able to account for such vibrations when taking long duration exposures. As such, the payload will sample the accelerometers at a rate of 2000 Hz, allowing for a characterization of frequency to 1000 Hz. This data will provide the information needed to design future, more advanced and precise, pointing systems on balloon-borne observatories.

VI. Conclusion

The data obtained by SPARTAN-V will provide sufficient evidence to determine if exoplanet detection is feasible on a balloon-based observatory. It is critical that the SPARTAN-V payload be able to locate and maintain a star within its field of view, and take in photometric data of that star.

VII. References