DayStar: Modeling and Test Results of a Balloon-Borne Daytime Star Tracker

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***Abstract*—High altitude balloons are capable of supporting astronomical observations with virtually no image degradation due to atmospheric turbulence. To take advantage of this space-like seeing, a telescope must be pointed and stabilized with sub-arcsecond precision. This problem consists of two parts: providing an error signal, and using it to correct the pointing. This paper addresses error signal acquisition, specifically focusing on modeling and flight testing of the DayStar star tracker.**

DayStar is a star tracker designed under the University of Colorado Aerospace Capstone Program with support from Southwest Research Institute. It is intended to improve upon the pointing accuracy and daytime performance of the ST5000, a star tracker commonly used in NASAs sounding rocket program. The ST5000 was shown to work on a balloon at night, but failed to acquire stars during daytime. DayStar remedies this issue by filtering light below 620 nm and by using a CMOS sensor with high red-performance and resolution. This attenuates most of the sky background, which, combined with custom star identification algorithms, allows stars be seen during the day.

To validate modeling and demonstrate daytime star acquisition, a DayStar prototype flew on a high altitude balloon in September, 2012. The filtered camera typically saw four or more stars during daytime, proving the ability to operate diurnally. This paper will further discuss DayStars ability to obtain a Lost-in-Space solution during daytime as a function of sky background and galactic latitude of the field of view. It will also focus on the precision of star centroiding algorithms and the pointing acuity for both day and night conditions. These findings will be used to validate the performance model and examine DayStar as a potential star tracker for high altitude balloon observatories.

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1. INTRODUCTION

This section will introduce the daytime startracker problem, and give the background and motivation necessary to setup our prototype and the importance of its performance.

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Figure 1. The optimal size for a star in pixels is determined by centroid accuracy to be between 4 and 6 pixels

2. MODELING

The modeling for DayStar is split into two parts: image quality and algorithm performance. The two are functionally independent, and must be linked by one or more parameters. The primary link is signal-to-noise ratio (SNR), though the shape of stars in the image is also important. The following sections describe how a threshold SNR and star shape are set by the algorithms analysis, and how image quality analysis is then used to support DayStar's design parameters and predict daytime performance.

Algorithms Analysis

KEVIN, you write here. Please place a figure that shows why we want between 4 and 6 pixels.

Image Quality Analysis

Given a minimum SNR and a star blur of 4 to 6 pixels square, the goal of the image modeling is to determine the number of stars visible during night and day. This requires identification of signal and noise sources; we assume that the sky background and stars generate Poisson shot noise, and also consider dark current (DC) and read noise (RN) from the image sensor. On a star-by-star basis, SNR is given by Equation 1, in which F is the flux from the star or background in photons per second per pixel, t is exposure time in seconds and n is the number of square pixels that totally encompass the star as specified in Figure 2.

$$SNR = \frac{F_{\text{star}} t}{\sqrt{F_{\text{star}} t + F_{\text{sky}} nt + DCnt + RN^2 n}} \tag{1}$$

The dark current and read noise are properties of the sensor. The flux from the star and the background, however, must be modeled based on DayStar's environment and pointing. The background flux can be estimated from the MODTRAN model for sky brightness, as seen in Figure 2. The unit of kilo-Rayleighs is equvialent to $\frac{10^9}{4\pi}$ photons/s/cm^2/steradian. Also note that the flux in Figure 2 is parameterized by wavelength; this will be important in analyzing the effect of quantum efficiency and optical filtering.

Estimating the flux from a star is a more involved process, which owes its complexity to the standard use of visual magnitude (m_v) as a measure of star brightness. In order to generalize magnitude to all wavelengths, the temperature of a star (which is also a common value in star catalogues) is used to calculate an empirically-determined correction. This yields the bolometric magnitude via:

$$m_b = m_v + BC(T) \tag{2}$$

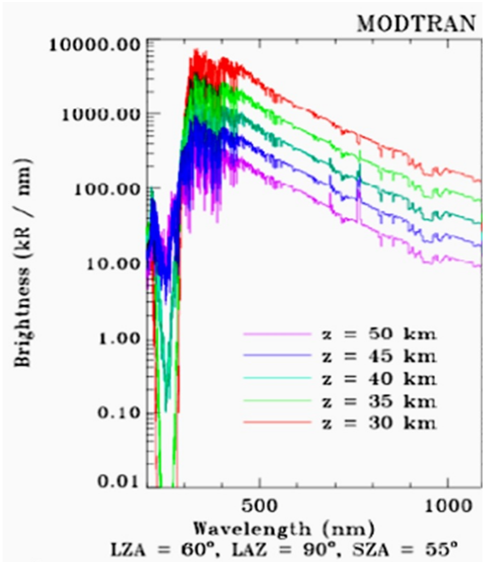

Figure 2. The sky background is found by interpolation for a 38km flight with 90 degree solar azimuth

The bolometric magnitude is a logarithmic scale just like visual magnitude, so it can be used to compare a given star to a known source with magnitude $m_{b,0}$ and total flux F_0 (the Sun is a likely candidate). This yields the integrated flux from the star across all wavelengths:

$$F_{\text{star, total}} = F_0 10^{0.4(m_{b,0} - m_{b,\text{star}})} \tag{3}$$

Now, since the total flux is known, it can be used to scale the Planck blackbody curve for the star, which is a function again of the star's temperature:

$$I(\lambda, T) = \frac{2c}{\lambda^4 \left[\exp \frac{hc}{\lambda k T} - 1\right]} \tag{4}$$

Once the blackbody curve is known, its area is normalized, at which point flux as a function of wavelength is simply:

$$F_{\text{star}}(\lambda) = F_{\text{star,total}} \frac{I(\lambda, T)}{\int_0^\infty I(\lambda, T)\, d\lambda} \tag{5}$$

Now, the flux from the background and star are parameterized by wavelength. This allows us to incorporate the quantum efficiency of the optics and any optical filtering, whose attenuation of light is described by $Q(\lambda)$. At last, the flux seen by the camera from both sources is found by integrating over all wavelengths, though in practice this range is bounded by a longpass filter on one end and the camera QE on the other.

$$F = \int_{\lambda_1}^{\lambda_2} Q(\lambda) F(\lambda)\, d\lambda \tag{6}$$

At the end of this process, the flux terms in Equation 1 have been defined in terms of system and operational parameters. The background relies chiefly on altitude, while star flux is a function of visual magnitude and temperature. In addition

Performance Analysis

Define total performance by looking at stars in FOV by GL.

3. Test Flight Results

This is the money section. We will summarize our test flight (very briefly) and then launch into our results. Again, the focus will be on daytime, and we will hammer home how well we see stars and track during the day.

Tracking Performance

Without a true attitude solution, it is still possible to obtain a performance metric for how well the DayStar tracks stars. This is done with a purely numerical analysis.

Given a set of images, the first task is to obtain a list of star centroid locations. By comparing the stars in each image to a reference (epoch) set of star vectors, in this case, just the first image in a set, the motion in said star locations can be described as a set of rotations. The "q-method" is a widely used method to determine rotations based on minimizing the rms of the residuals between coordinate frames. It was employed here to find the quaternion rotation between the reference frame and each subsequent.

Quaternion rotations were then converted into the Euler angles: roll,pitch, and yaw. Each set of angles contain information about the change in star locations in time. The predominant modes of change are low-frequency rotations, and high frequency rotations. The low frequency observations are due to the motion of the gondola, while high frequency observations are due to the inaccuracies of the DayStar system.

A measure of the system's precision is desired, so the low-frequency rotations need to be removed. This was done by examining the rotations in the frequency domain, using fast fourrier transforms, and applying a high-pass filter to the transformed rotations. Transforming back into the time domain, the rms of each the resulting rotation sets describes DayStar's ability to identify and track stars over an image set.

4. Conclusions

Here we will inspiringly conclude by tying our results and modeling together, and saying why this is so important to the future of balloon science.

5. References

6. Biography

Appendices

Acknowledgments

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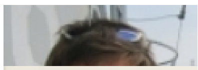
BIOGRAPHY

Nick Truesdale is a graduate student in Aerospace Engineering at the University of Colorado. He has been the Electrical Systems Lead for four balloon payloads, and has a wealth of experience designing power sytems and embedded electronics. His other projects have included CubeSats with the University of Colorado and radar scattering simulation with MIT Lincoln Laboratory. Nick enjoys playing guitar and marimba as well as downhill skiing.



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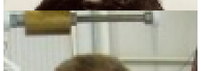

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Eliot F. Young Eliot F. Young received an A.B .in Physics from Amherst College in 1984, an S.M. in Aeronautical Engineering from M.I.T. in 1987, an S.M. in Earth, Atmospheric and Planetary Science (EAPS) from M.I.T. in 1990, and an Sc.D. from M.I.T. (EAPS) in 1992. He is currently a Principal Scientist at Southwest Research Institute in Boulder, CO, in the Department of Space Studies. His current areas of study include the surfaces and atmospheres of Pluto, Tri- ton, Eris and other large Trans-Neptunian Objects, as well as the distributions of aerosols and trace gases in Titan's atmosphere and the wind fields on Venus. He has led ob- serving campaigns on four continents.