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The ST5000: An Attitude Determination System with Low-Bandwidth Digital Imaging

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Abstract. The Space Astronomy Laboratory is building an attitude determination and digital imaging system with embedded compression. The attitude determination system uses a 30-square-degree field of view and an embedded star catalog to determine the Right Ascension and Declination of its line of sight to better than 5 arcseconds. The digital imaging subsystem uses a scheme of "progressive image transmission" in which the image is sent out over a very-low-bandwidth channel, such as a spacecraft telemetry downlink, in such a way that it can be reconstructed "on the fly" and updated as more data arrive. Large (768×474) useful images can be obtained over a 4-kbit downlink in as little as 10 seconds.

In addition to its use in sounding rockets and spacecraft, we are planning to use it for two ground-based applications at the Southern Africa Large Telescope (SALT). We will explore its use in generating real-time measurements of the telescope pointing, independent of the telescope control system, and we will use the low bandwidth imaging capability for public outreach.

1. Flight Test

We tested the ST5000 on a sounding rocket flight (36.172, PI K. Nordsieck) in April 1999. The ST5000 was mounted beside a Ball STRAP tracker, which was in control of the rocket, and was optically aligned with it. During the two guide star acquisitions, the ST5000 measured pitch and yaw errors, which were telemetered by the rocket ACS. During the science phase of the mission, the ST5000 generated pitch, yaw, and roll errors while progressively transmitting the acquisition field over a 19,200 baud RS-232 downlink.

Figure 1 shows the Ball STRAP pitch and yaw errors (solid line) during the first guide star acquisition. The dotted line shows the ST5000 error signals. Note that they match those of the STRAP tracker, but with much lower noise.

2. Ground Tests

We ground-tested the ST5000 while attached to the side of a small telescope (used as a convenient, pointable mount) at night from a rooftop observatory of the University of Wisconsin's Department of Astronomy. This testing had two purposes: to measure the sensor performance (noise and sensitivity) as a

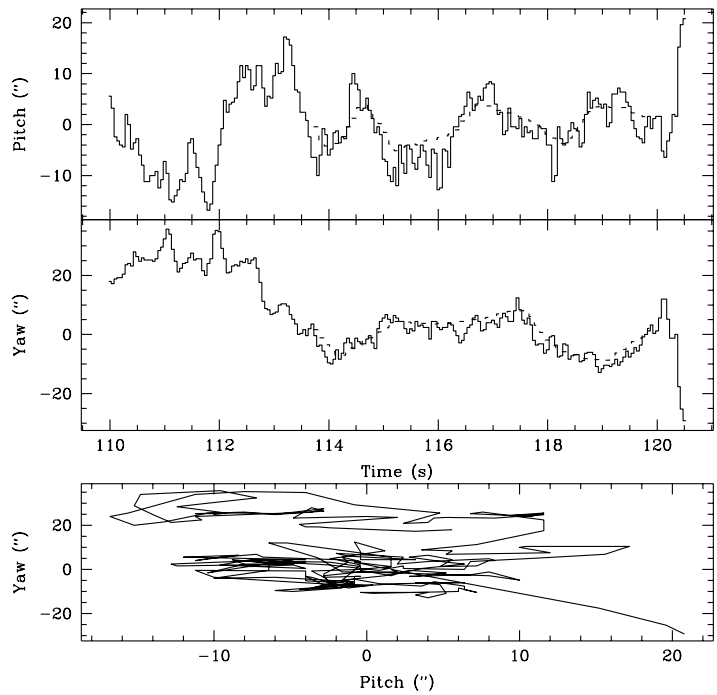

Figure 1. Pitch and Yaw errors during the test flight. Solid lines are the Ball STRAP signals; dotted lines are the ST5000 signals.

function of camera gain and exposure time, and to verify the performance and robustness of the acquisition and tracking operations on real star fields.

Figure 2 shows the Noise Equivalent Angle (NEA) single-star tracking measurements obtained with the ST5000. Also shown are two points representing (for comparison) the Ball STRAP tracker specification, and the predictions from our numerical model for both the prototype ST5000 and the ST5000 upgrade. The solid line and filled triangles represent the performance at low camera gain, set electronically by the ST5000 software. The long-dashed line and open triangles show the numerical model and data at medium gain. We tested the camera at high gain, but found that the increased pixel noise did not justify the higher sensitivity. The short-dashed line represents the model predictions for the ST5000 upgrade, with its improved lens and more sensitive CCD. We also show the measured and expected performance with an update rate of 5 Hz, allowing longer exposure time. We point out the excellent correlation between the numerical model and the measurements. The ST5000 acquired and tracked stars as faint as magnitude 6.5 with an NEA better than 7 arcseconds in the middle of the city of Madison, through more than 1 air mass, in the presence of atmospheric turbulence (seeing) larger than 1 arcsecond. The numerical model does not consider the effect of seeing, which has the effect of moving the points upward, off the model prediction. This is noticeable for the faintest acquisitions (the x's), which we would expect to be the most susceptible to turbulence in the atmosphere. The departure of the measurements from the model predictions at the bright end (filled triangles) is due to saturation of the CCD pixels during the

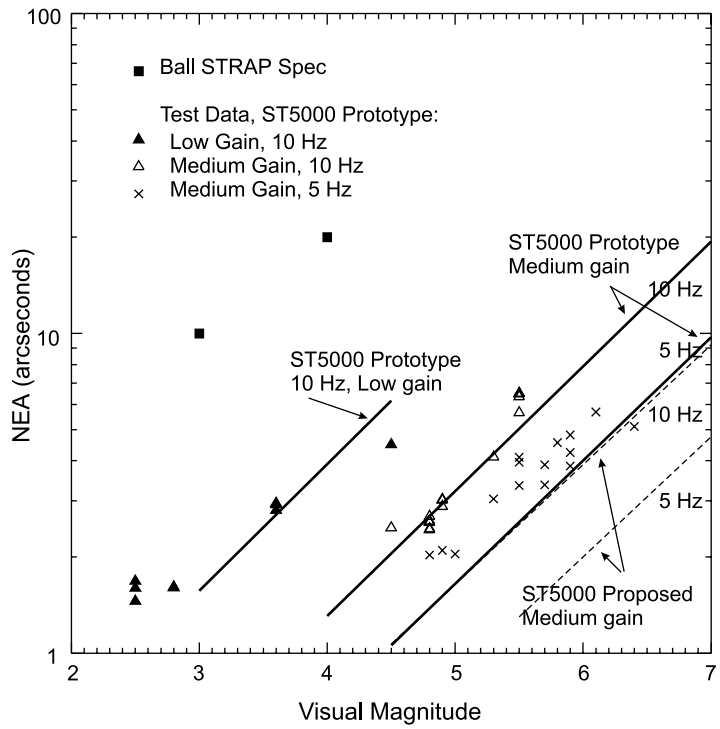

Figure 2. ST5000 Single-star Noise Equivalent Angle.

exposures. The ST5000 upgrade will use electronic shuttering to allow shorter exposures. In any case, the ST5000 can track on any of the detected objects, easily ignoring any saturated stars.

3. Attitude Determination

The ST5000 can determine its attitude with respect to an absolute coordinate system (say, FK5 Equatorial) by analyzing the star patterns in a single frame. It can do so without any a-priori knowledge of attitude, plate scale, or image orientation. The determination is insensitive to stray objects in the field such as glints, hot pixels, airplanes, satellites, or asteroids. It does not depend on star brightnesses, colors, or any knowledge of the sensor's spectral sensitivity.

The algorithm comprises two major steps. First, the stars in the field must be identified. We use the "star triangles" technique of Valdes et al. (1995). We form all possible triangles in a given frame, and plot each one as a single point in a triangle-shape space. We compare this frame's shape space to an all-sky shape space catalog embedded inside the unit. This allows us to associate stars in the frame with specific entries in an all-sky catalog.

Second, given the association between frame and catalog stars, the attitude must be derived. We use the "q-method" of Lerner (1997) to determine the attitude in the form of a quaternion. This method is suitable for a CCD image, which produces many simultaneous vector measurements.

The principal challenges in doing this attitude determination in an embedded system are making it fast and implementing it with modest computing resources. Space-qualified processors typically lag the consumer marker in both speed and available memory, both of which are important in this application. The all-sky triangle catalog, for example, contains 43.7 million triangles with sides no longer than 6 degrees and member stars no fainter than 8th magnitude. We prune this catalog by keeping a much smaller number of "good" triangles, and we emphasize a fast catalog search during the star identification phase.

4. Progressive Image Transmission

The NASA-funded Progressive Image Transmission (PIT) System (Percival & White 1993; White & Percival 1994, NAG5-2694) offers a number of features that make it especially appropriate for supporting low-bandwidth digital imaging from telescopes or spacecraft. First, it uses a state-of-the-art wavelet transform to achieve very high compression. Second, it implements this as a fast, exactly-reversible in-place integer transform that can be easily ported to older, slower, memory-challenged flight processors. Finally, it formats and transmits the compressed data bytes in a way that allows progressive visualization: the image appears very quickly, immediately showing full-frame detail at all spatial scales and intensities, and as more bytes are received, the image keeps improving, asymptotically converging to losslessness (if time allows).

In progressive transmission, the image can be truncated at any point (say, due to fixed-length downlink windows or the unexpected arrival of a new imaging event), and the currently received bytes always allow the wavelet transform to be reversed and the image reconstructed.

In the example of a SALT-mounted aspect camera, PIT would allow intercontinental distribution of large CCD images at very low bandwidth. For a typical CCD size of 768×474 pixels sampled to 8 bits transmitted over a 19,200 baud Internet connection (many homes do not have high-speed Internet connections), the uncompressed digital image would take an unacceptable 152 seconds. With PIT, a usable version of the image could be transmitted in 3–4 seconds, and would be suitable for many outreach activities. The image would continue to improve with time, without any pre-chosen compression cutoff, allowing the scientific user to achieve the fidelity desired for more technical applications such as target identification or attitude determination.

References

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