The ST5000
An Ultra-Low-Cost Star Tracker and Low-Bandwidth Digital Imager

ST5000 The Next Generation Star Tracker

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Overview

The Space Astronomy Laboratory has built and flown a very-low-cost (~$50K) star tracker and digital imaging system with embedded compression. The star tracker is suitable for all rocket and spacecraft applications, and provides pitch, yaw, and roll updates at rates up to 10 Hz. The digital imaging subsystem uses a novel NASA-funded scheme of "progressive image transmission" in which the image is sent out over a very-low-bandwidth channel, such as a telemetry downlink, in such a way that it can be reconstructed "on the fly" and updated as more data arrive. Large (768x474) useful images can be obtained over a 4-kbit downlink in as little as 10 seconds. This device can act as an aspect camera, a deployment monitor, or a science imager in situations where low bandwidth is desired or high bandwidth is not available.

We are now upgrading the prototype device in two ways. We are adding a full "lost in space" gyroless attitude determination capability. We are also upgrading the prototype optics, electronics, and associated hardware for lighter weight, smaller size, lower power, and faster image processing.

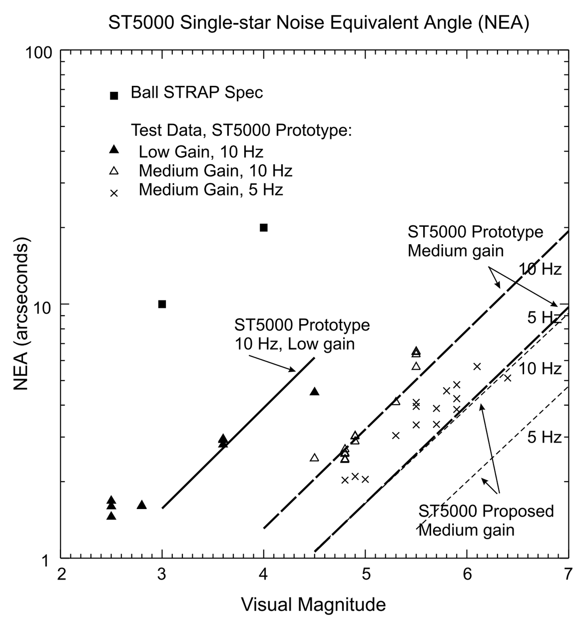
We expect the device to cost between 1% and 10% that of other modern, solid-state star trackers (which don't provide a low-bandwidth imaging capability). This will satisfy a critical need for low-cost attitude determination, fine pointing, and imaging in small satellites, sounding rockets, balloons, and other "cheaper faster better" applications, and will be suitable for space science missions of any programmatic scope.

	Ball CT-602	Ball CT-633	Lockheed AST-201	UW-SAL ST5000
Update Rate (Hz)	10	5		10 Hz / 5 Hz
Weight (lb)	12	6	10	5
Power (W)	8	8	16	8
FOV (deg)	8x8	20x20	9	9.2x6.7
Limiting Mag.	6	4.5		8.0 / 8.7
NEA (")	5		< 1	0.8 / 0.5
# Stars Tracked	1-5	1-5		1-8
Low B/W Imaging	No	No	No	Yes
Lost In Space	No	Yes	Yes	Yes

This table summarizes the high end of trackers currently available. There appears to be no single product that optimizes all of the desirable qualities of a modern, solid state star tracker. For example, the Ball CT-631 features low weight while sacrificing high-end performance. The Ball CT-602 offers the highest accuracy, but weighs 12 pounds. The CT-633 offers a fully autonomous attitude determination capability, but has a limiting magnitude of only 4.5 and does not track at 10 Hz. Our use of modern, small format, low power, off-the-shelf components, with high sensitivity, low measured Noise Equivalent Angle (NEA) and open, non-proprietary software has allowed us to optimize all of the important parameters in one package.

This shows the camera head of the prototype unit flown on the sounding rocket. This camera head contains an F/0.95 lens and the board-level CCD camera. It is connected to the star tracker electronics box using cables, allowing the electronics box to be conveniently placed somewhere else in the rocket.

Ground Tests



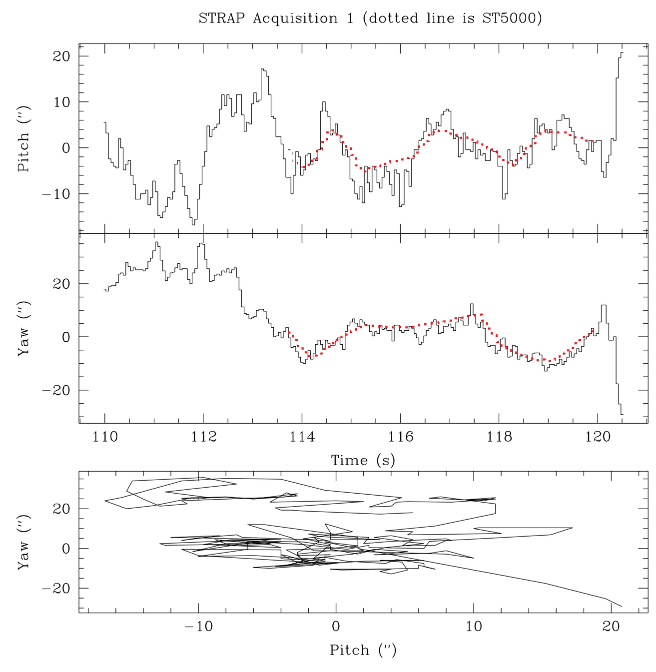
We ground-tested the ST5000 while attached to the side of a small telescope (used as a convenient, pointable mount) at night from a rooftop observatory of the University of Wisconsin's Department of Astronomy. This testing had two purposes: to measure the sensor performance (noise, sensitivity) as a function of camera gain and exposure time, and to verify the performance and robustness of the acquisition and tracking operations on real star fields.

This figure 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.

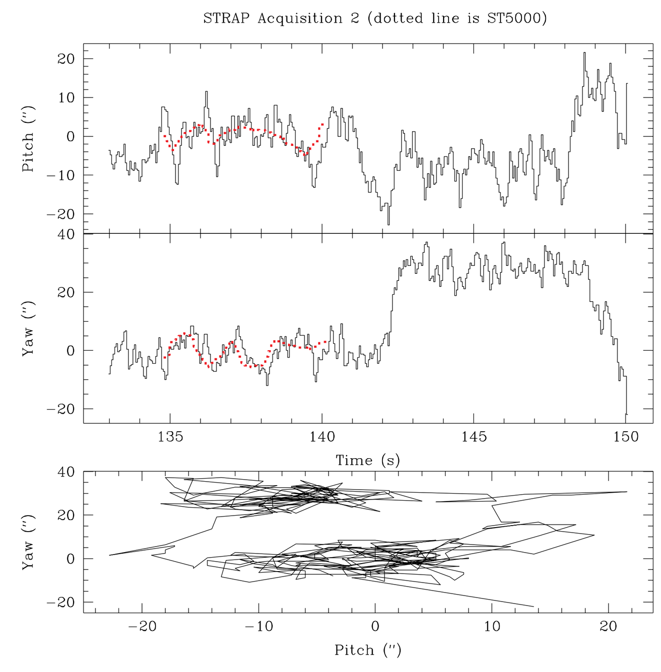
We point out the excellent correlation between the numerical model and the measurements. The ST5000 acquired and tracked stars as faint as 6.5 with an NEA better than 7 arc seconds in the middle of the city of Madison, through more than 1 air mass, in the presence of atmospheric turbulence (seeing) larger than 1 arc second. 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 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.

Flight Test

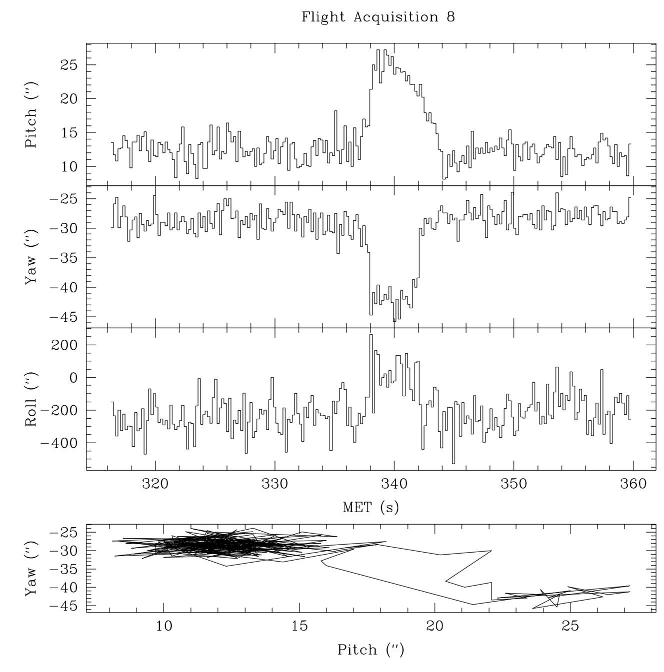
We tested the ST5000 on a sounding rocket flight (36.172, PI K. Nordsieck) in April 1999. The ST5000 was mounted beside the Ball STRAP tracker, which was in control of the rocket, and was optically aligned with it. During the two guide star acquisitions, the ST5000 measured pitch and yaw errors, which 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.



This chart 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 the ST5000 signals match those of the STRAP tracker, but with much lower noise.



This chart shows the Ball STRAP pitch and yaw errors during the second guide star acquisition. As with the first acquisition, the ST5000 signals match the STRAP tracker but with much lower noise.

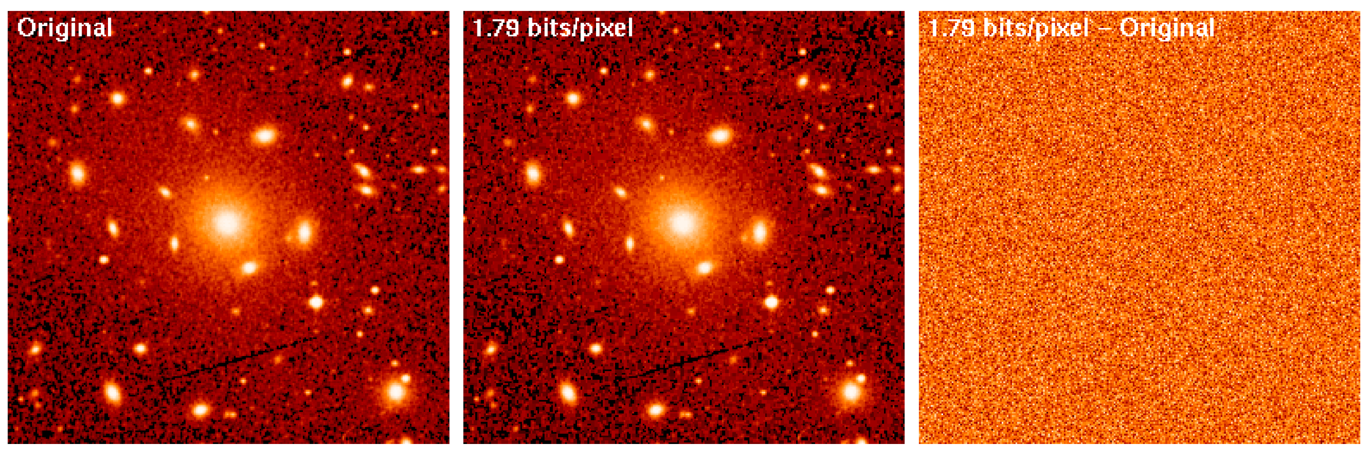


This chart shows an excursion in pitch, yaw, and roll during part of the science phase of the flight. This excursion was caused by the movement of a mechanism in the payload, which was quickly corrected by the control system.

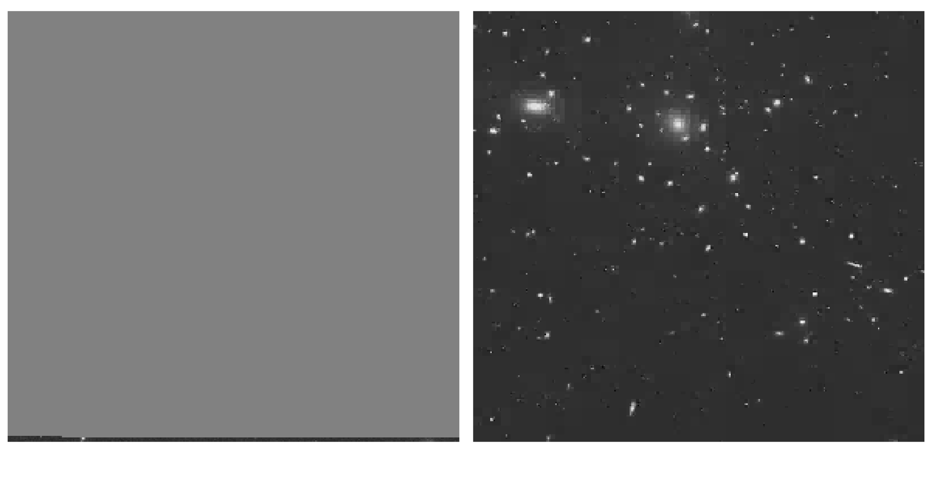
This represents a relatively rare situation in which a roll error was available in the analysis of a rocket mission's data.

Progressive Image Transmission

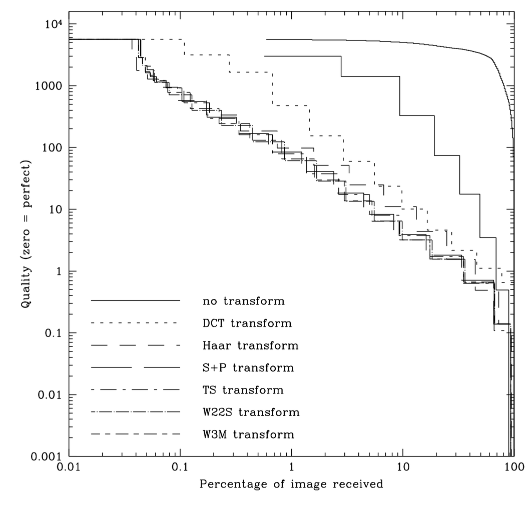
The NASA-funded Progressive Image Transmission (PIT) System (Percival & White, 1993, NAG5-2694) offers a number of features that make it especially appropriate for supporting low-bandwidth digital imaging from spacecraft. First, it uses a state-of-the-art wavelet transform (White & Percival, 1994) to 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).



This figure demonstrates the fidelity of a PIT progressive visualization (in this case, using a digitized photograph of the Coma cluster of galaxies). The left image is the original, and the center image shows the received image after only 10% of the image bytes have been transmitted. Note that the 10% version (in the middle) shows all the major features in the original, including both bright and faint luminosity, and both diffuse and point-like structures. At right is the difference between these two images. The lack of any discernible structure shows the degree to which PIT preserves the essence of the original in the presence of lossy compression.



These two images compare normal sequential transmission with Progressive Image Transmission. The left image shows a line-by-line transmission over a 2400 baud link after 60 seconds. Note the tiny bit of received image at the bottom. The right image shows the same amount of data, over the same 2400 baud link, also after 60 seconds. Progressive Image Transmission has delivered information at all spatial and intensity scales, allowing a rapid assessment of the image content.



This chart shows the image quality (measured as the mean squared error) as a function of the percentage of the image that has been received. The dotted line shows the performance of the DCT, while the cluster of lines to the left represent a family of related wavelet transforms.

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 an interactive target acquisition during a sounding rocket flight, PIT could completely replace the RS-170 video downlink, eliminating the extra flight hardware, additional power requirements, and associated ground system. For a typical CCD size of 768x474 pixels sampled to 8 bits telemetered over a 19,200 baud downlink, 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 an interactive acquisition. The image would continue to improve with time, without any pre-chosen compression cutoff, allowing the user to select the target as soon as the required fidelity has been achieved.