Towards Star Tracker Only Attitude Estimation

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ABSTRACT
Star trackers can provide full information about satellite attitude information from a single sensor. In this paper, we examine the feasibility of designing attitude determination systems using only star trackers. Star trackers can provide direct inertial attitude estimates without the need for sensor fusion, but current sensors are not robust enough to provide effective attitude estimates in all mission scenarios. Specific technical capabilities must be developed before star tracker only schemes could be practical. To this end, we discuss the performance, robustness, and survivability requirements that would be demanded of a star tracker only system and illustrate important developmental milestones delivered by the recently developed S3S star tracker. To illustrate the star tracker only approach, we present a case study showing variant designs for the CanX-4/5 satellites.

INTRODUCTION.
Three-axis stabilized spacecraft in low-Earth orbit (LEO) typically carry a suite of sensors to determine their attitude. Almost every one will have a magnetometer, and one or more sun sensors. Earth horizon sensors may be added for higher performance, and inertial rate sensors to propagate the state when other sensors are unavailable. Star trackers are the highest performance sensors available, and are added to those missions whose demanding payloads require precise pointing.

Sun sensors, magnetometers, and (most) Earth horizon sensors produce only two angles of attitude data. To determine a full three-axis attitude solution at least two types of sensor must be used. By contrast, star trackers produce all three angles (roll, pitch and yaw) in one device. The aim of this study is to determine whether a star tracker can be used alone. Can the attendant sun sensors, magnetometers, etc., of a typical LEO satellite be stripped off leaving only a star tracker?

The authors have developed a star tracker aimed primarily at the nanosatellite market. This is the Sinclair-SAIL-SFL Star tracker, abbreviated as S3S. Throughout this paper we will look at the particular requirements for implementing Star Tracker Only Attitude Estimation (STOAE). We will then look at the relevant details of the S3S device to determine whether it is suitable for the purpose. Finally, we will explore the potential to use S3S on a particular upcoming satellite mission.

Motivation
Attitude sensors directly add mass and cost to a satellite. They also consume surface area that could otherwise be used for payload apertures, solar panels or thermal coatings. Removing extraneous sensors frees
satellite resources for other purposes. Since the size of a sensor is independent of the size of the satellite, small satellites have proportionally more to gain by implementing STOAE.

Star trackers are typically easier to integrate than other sensors. They provide direct inertial attitude readout without secondary sensor fusion, ephemeris or propagation. Their output data is either present, or not. This greatly reduces the satellite software complexity, compared with a traditional architecture where there are many sensors each of which may be accurate, or degraded (i.e. a sun sensor interfered with by Earth albedo) or non-functional (i.e. an Earth horizon sensor pointed at zenith). Reduced complexity makes the satellite easier to test and makes the attitude performance easier to predict under all conditions.

Outline

In the first part of this paper we lay the groundwork for our study by motivating the work, presenting the S3S star tracker, and introducing key STOAE concepts. The second part of the paper takes a closer look at performance, robustness, and survivability demanded of star trackers as they perform expanded roles in the ADCS. The third part presents a detailed case study of the CanX-4/5 mission and compares STOAE capabilities to real mission requirements. We conclude with a summary of our findings and some suggestions for further technical development.

THE S3S NANOSATELLITE STAR TRACKER

The S3S has been developed over the past 24 months by a collaboration of Sinclair Interplanetary, UTIAS SFL and Ryerson SAIL. It is intended primarily for nanosatellite missions, but may also be applicable to larger spacecraft. It is distinguished from other devices by its extremely powerful internal computer, small size and weight, low power, and low cost. This section provides a brief summary of the design.

Two S3S units are shown in Figure 1, with a penny for scale. The devices are compact and fully integrated, with no additional processor box required. The optional baffle is not shown.

[Figure 1 - S3S Star Tracker]

Table 1. S3S Interface Requirements

<table>
<thead>
<tr>
<th>Size:</th>
<th>59 x 56 x 31.5 mm (excluding baffle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass:</td>
<td>~90g (excluding baffle)</td>
</tr>
<tr>
<td>Alignment:</td>
<td>2 precision pins on satellite</td>
</tr>
<tr>
<td>Power:</td>
<td>&lt;1W peak, &lt;0.5W average (excluding TE cooler)</td>
</tr>
<tr>
<td>Data:</td>
<td>RS485 command and telemetry</td>
</tr>
</tbody>
</table>

The interface requirements of the S3S are very modest. It is intended to be compatible with spacecraft as small as 3U Cubesats.

Table 2. S3S Internal Components

<table>
<thead>
<tr>
<th>Optics:</th>
<th>16 mm Focal length F/1.2 multi-element glass lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector:</td>
<td>Aptina MT9P031. Monochrome 5 megapixel CMOS detector</td>
</tr>
<tr>
<td>Field of View:</td>
<td>15° x 20.2°</td>
</tr>
<tr>
<td>Thermal Control:</td>
<td>Peltier-junction solid-state thermo-electric cooler</td>
</tr>
<tr>
<td>Processor:</td>
<td>600 MHz 32-bit processor (primary)</td>
</tr>
<tr>
<td>Memory:</td>
<td>256 MB RAM</td>
</tr>
<tr>
<td></td>
<td>256 MB Flash</td>
</tr>
</tbody>
</table>

[Figure 2. Cutaway of S3S star tracker showing interior components.]
The optics are upscreened industrial lenses with heritage to previous orbital and interplanetary missions. The detector is also an industrial device. A Thermo-Electric (TE) cooler is used to keep dark noise to a minimum.

The processing electronics use low-power mobile computer parts originally intended for digital cameras and cellular phones. The high-speed primary processor handles the image processing while the supervisory microcontroller communicates with the host satellite and mitigates radiation upsets.

### Table 3. S3S Internal Star Catalog

<table>
<thead>
<tr>
<th>Limiting stellar magnitude</th>
<th>5.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stars in catalog</td>
<td>3746</td>
</tr>
<tr>
<td>Number of triangles in catalog</td>
<td>2.1 million</td>
</tr>
</tbody>
</table>

The internal computer contains a large star catalog, preprocessed to show all of the possible stellar triangles. The limiting magnitude is chosen so that there is at least one triangle in the field-of-view over >99.99% of the sky.

### STOAE Concepts

In this section we develop several background concepts that explain the challenges and promise of STOAE systems. We first highlight past findings that examine advanced star tracker concepts. We then consider some scenarios that help define how an STOAE system might be realized. We conclude this section with a discussion of how the imaging capabilities of star trackers can be used to derive attitude information from other targets.

### Prior Work

Star trackers have traditionally occupied the 'top-tier' in the attitude estimation system, providing high precision attitude estimates once other sensors and actuators have brought the satellite's dynamics under tight control. No sensor system can match the precision of star tracking, but this elevated performance often comes at the cost of a relatively small operational envelope. Many investigators have recognized the flexibility of star tracking and have devised schemes to help cope with some of its limitations.

Several researchers have looked at broadening the use of star tracker readings to include rate estimation as well as orientation. One set of techniques, proposed separately by Podgorski [1] and Gai, et al [2], estimates the satellite angular velocity using multiple observations of a single bright star. While not providing a complete attitude solution, an effective measurement of the satellite's rate of rotation in two axes can be acquired. The estimation process is limited by the rate of rotation and cannot handle high-speed rates, such as those prior to spacecraft de-tumbling.

Another approach to rate determination is considered by Liebe and Meller [3]. They propose a novel technique that divides the operation of a star tracker either into attitude or rate estimation modes. In the rate mode, when the spacecraft is spinning at a certain angular rate, the observed stars become smeared across the field of view. Analyzing the curvature and length of the smear provides an estimate of the magnitude and axis of rotation. The direction of the rotation cannot be determined from a single observation. In attitude mode, estimation solutions are found using conventional techniques. In contrast to the first technique, rate estimates can be found for much greater rotation speeds, eliminating the need for rate gyros.

Operational failures have sometimes forced star trackers to provide rate information on mission that had intended to use inertial rate sensors. The Satellite for X-ray Astronomy (BeppoSAX) [4] is an example of this.

BeppoSAX was built by the Italian Space Agency (ASI) and put into orbit on April 30, 1996. It originally had three active and three reserve rate gyros for continuous rate measurement. As these mechanical devices failed one by one, operators forced to rely more heavily on star trackers for rate information. As of September 2001, all the gyros had failed leaving the star trackers as the only functioning rate sensors. The satellite continued to operate within the specified requirements until the mission ended on April 30, 2002.

### Implementation Concepts

Implementation of an STOAE design can take many forms. Switching abruptly from a conventional attitude determination and control system (ADCS) design to one employing only a star tracker is admittedly risky and unlikely to appeal to mission planners. Instead, evolutionary steps can be used to move towards STOAE as new technologies become available. The following three concepts capture some of these possibilities:

- **Partial STOAE** using a star tracker plus a greatly reduced set of conventional sensors (e.g., just a magnetometer). This might include instruments such as the Inertial Stellar Compass [5] in which additional sensors are packaged with an optical star imager.
- **Redundant STOAE** using multiple star trackers on a single spacecraft, but no other sensors. These sensors may or may not be identical units.
• Full STOAE using a single star tracking instrument.

Although this does not represent an exhaustive list, it does help to provide some context for discussion further star tracker development.

**Tracking Non-Stellar Targets**

Stars are dim, and star trackers tend to be blinded by stray light when pointed near to bright objects such as the moon, sun or sunlit Earth. A STOAE system has only two choices when confronted with this problem. It can use more than one star tracker, arranged so that at least one has a clear view of a dark sky. Alternatively, a single star tracker can be used if it is sufficiently flexible to switch to tracking other bright objects as needed.

**Sun Tracking** — It is conceptually simple for a star tracker to fall back to sun sensor operation when the sun enters the field-of-view. This would produce two axes of attitude information. More problematic is the scenario when the sun is close enough to the field-of-view to obscure the stars with stray light, but not close enough to be directly seen.

The S3S cannot be used as a sun sensor. The detector has a minimum exposure time, and even at this minimum every single pixel saturates when the sun is in the field of view.

**Moon Tracking** — The moon is much less bright than the sun. In addition, it has recognizable features, be they mare at a full moon or a phase at crescent moon. We have investigated the problem of determining a three-axis attitude solution from lunar observations, and it appears to be quite possible [6]. While the baseline S3S software does not contain this feature, adding moon tracking is feasible.

**Earth Tracking** — The Earth is a visually complex target. It blocks a large fraction of the celestial sphere when seen from LEO, so there is a strong motivation to be able to derive useful attitude information from it. The sunlit Earth limb is an obvious feature, and so a star tracker can operate as an Earth horizon sensor in certain situations. The eclipsed Earth limb is a more difficult target. It is difficult to see in visual images which is why typical Earth horizon sensors operate in the thermal infra-red.

A sensor looking towards the Earth might be able to match day-time surface features such as coastlines to an internal map and thus determine its attitude in three axes. Night-time features will be more sparse, though an instrument capable of seeing stars should have no trouble locating the glow of major cities. Cloud cover is a problem, though it may not be insurmountable if fresh weather maps are uploaded to the satellite on a daily basis.

Even without matching features to a map, optical-flow algorithms from an Earth-facing camera could be used to determine the satellite’s velocity vector and thus its yaw angle.

The S3S instrument has sufficient computational resources to tackle some of these problems. However the effort to design and test these algorithms would be significant, and on-orbit images would certainly be required. The baseline S3S software does not derive any attitude information from Earth tracking.

**Planetary Tracking** — Planets have well known positions and some are brighter than the brightest stars. Stray light from bright planets may swamp adjacent faint stars, making tracking the planet itself even more attractive.

Since planets move with respect to the fixed stars the “star” catalog must be continually updated. It may make sense to structure it in two parts. The pre-computed list of millions of stellar triangles can be fixed. The star tracker can then generate a second list of a few dozen triangles incorporating a planet as one of their vertices. This list would be short enough to search linearly, whereas the large triangle table requires a more sophisticated search algorithm.

S3S has a nominal catalog magnitude of 5.75. The following planetary bodies may be viable targets: Mercury, Venus, Mars, Jupiter and Saturn. The planet Uranus and the asteroid Vesta are both marginal targets. While the baseline S3S software does not track planets, this functionality will be added soon. S3S does not have a particularly accurate onboard realtime clock, so it is reliant on the satellite main computer to give it periodic time and date information.

**Utility of S3S** — The S3S device cannot operate when pointed near to the sun or Earth. These limitations are fundamental, and are unlikely to be overcome with minor revisions. Any STOAE mission using only a single S3S will be severely constrained in its attitude knowledge. More than one S3S must be used to achieve robustness.

**MAINTAINING PERFORMANCE**

The two primary performance metrics for a star tracker are accuracy and update rate. In this section we examine how performance requirements may change for STOAE missions, and how the S3S compares.
Performance Requirements

Accuracy requirements are very much driven by the particular mission payload. In general, STOAE is contemplated for missions that are constrained in resources. These are usually not the missions with the very highest pointing requirements. Thus, a STOAE device may be acceptable even if it does not have the accuracy of the very best standalone star trackers. We assume the target accuracy is likely in the range of 0.01 to 1°.

Traditional architectures often use star trackers with a slow update cadence (~1 Hz) and add inertial rate sensors to fill in at higher bandwidths. A STOAE mission will have no inertial rate sensors, and so the star tracker update cadence may have to be faster. Expected cadences may be in the range of 2-10 Hz. It may also be useful for the star tracker to output angular velocity (i.e. from motion blur) in addition to orientation.

S3S Performance Capabilities

Design simulations for the S3S predict attitude accuracies on the order of 0.01° (3-σ). Our initial field trials are encouraging and suggest that achieving this performance is not unreasonable. Figure 3 shows results from a recent night-sky test with the sensor. The inertial attitude has been converted into the right ascension and declination of the sensor boresight, combined with a roll angle.

In this type of imaging configuration, with the unit fixed with respect to Earth, we expect to see the declination and roll remain constant, while the right ascension will change linearly as the earth rotates. That is exactly what the results show. The standard deviation of these measurements is 0.002-deg in declination, and .018-deg in roll. This is quite typical of star trackers; the roll error is almost always the largest component. The roll error is a little higher than our target performance, but we expect that tuning the processing may provide additional improvements.

The target update rate of the S3S sensor is 2Hz. All essential algorithmic steps have been tested on the sensor processor, and benchmarks show that this rate is easily achievable. Table 4 shows the time required for the various steps in the processing chain. By far, the greatest proportion of time is spent handling the raw detector image. Subsequent optimization may enable operation at 4-5Hz, but higher rates will be difficult to achieve with the current design.

![Figure 3. Attitude test of S3S sensor (observing Ursa Major).](image)

Table 4. Processing Benchmarks

<table>
<thead>
<tr>
<th>Processing Step</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image Exposure</td>
<td>100</td>
</tr>
<tr>
<td>Thresholding and Star Detection</td>
<td>200</td>
</tr>
<tr>
<td>Star Matching</td>
<td>35</td>
</tr>
<tr>
<td>Quaternion Solution</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>337</strong></td>
</tr>
</tbody>
</table>

One design feature that places an upper limit on the sensor update rate is the decision to make the sensor essentially memory-less. To provide robustness to SEUs and other radiation effects, the processor is completely reset between exposures. The only persistent state is the detector exposure time, and a ‘lost-in-space’ estimate is calculated separately for each image. This makes the sensor operation more robust and uniform, but prevents very rapid updates.

The S3S is able to meet the performance requirements of many STOAE missions. However it is not suited to those that require exceptional accuracy or bandwidth.

MAINTAINING ROBUSTNESS

The robustness of a satellite’s attitude estimation system refers to its ability to give useful attitude estimates, regardless of mission phase or spacecraft state. A lack of robustness would signify that there are some circumstances under which the star tracker will not be effective. Maximizing robustness is then a matter of minimizing the situations that cannot be handled. Modest star tracker robustness can be tolerated in a traditional architecture, where other sensors or careful planning of maneuvers or observations can be used to compensate for limitations in the star tracker’s operational envelope. For a STOAE system, this is not the case; the system’s robustness is the star tracker’s robustness.
We consider two general categories of robustness: static availability and motion tolerance. The former refers to the factors that govern the availability of an adequate attitude solution from a non-rotating spacecraft, while the latter examines complications that can arise once angular motion is considered. These distinctions are somewhat arbitrary, but help to frame our examination of the problem.

Several factors will affect the static availability of star trackers. The electro-optical design of the instrument will establish a field of view, bounds on exposure time, and a threshold visual magnitude for star detection. These parameters establish the likelihood that a particular satellite orientation can yield an attitude solution. The presence of the sun, moon, and earth in or near the field of view will frequently interfere with normal star tracking operations, limiting instrument robustness.

Motion tolerance refers to the ability of a star tracker to maintain its performance in the presence of satellite motion. Several distinct phenomena contribute to this problem; some are common to all star trackers, others depend on particular implementations. Motion during a finite length image exposure turns star ‘spots’ into star ‘streaks’. This motion blur spreads incident starlight over a larger number of pixels than normal, and can impair the sensor’s ability to detect dim stars. A secondary effect of this motion blur is to elongate the star images, making centroid locations more difficult to determine. In addition to these common motion blur effects, some designs suffer from additional motion-related problems. Imagers that use rolling shutters can suffer from geometric distortions because each row of the image is exposed at a slightly different time. Algorithms that rely on image-to-image point tracking can have difficulty when successive images have only a few stars, and are quite different from one another.

**Robustness Requirements**

In the absence of interference from sun, moon or Earth a robust STOAE device should always be able to report attitude data when pointed at any area of the sky. To do this it must be able to see dim stars, and/or have a wide Field Of View (FOV), so that it is always able to detect at least three stars. Figure 4 shows the trade space, based on numerical simulation of all pointing angles and the known location of all stars above the target magnitude. A STOAE star tracker should have availability of almost 100%.

**Figure 4. Detail star tracker availability tradespace.**

In contrast to the raw availability, star tracker operation is often limited by bright bodies in or near the FOV. This can be mitigated by minimizing the FOV (which requires a device sensitive to dimmer stars), and by adding an optical baffle. Even with baffles, exclusion angles of 40° around the sun are not uncommon. For a star tracker in LEO (FOV of 10°, and 60° earth angular radius), the Earth and the sun can together obscure 37% of the sky, even with zero exclusion angle around the Earth. As noted earlier the spacecraft must either carry two star trackers or be able to directly track these bright objects in order to be fully robust.

Motion tolerance requirements can be divided into two subcategories. Motion during normal operations, and motions during anomalies. Each scenario is quite different. In the former case, the star tracker must provide full precision attitude estimates, but rates are often quite modest. In anomalous scenarios, the rates can be very high, but attitude estimates need only be accurate enough to restore safe operations.

With the exception of missions that require exceptional agility (e.g., inspection or docking), body rates of 1°/s or more are ‘fast’. As a representative scenario illustrating fast motion, consider the slew-rate requirements to maintain pointing at a ground target using satellite motion alone. Using simple orbital kinematic relations, we can estimate peak rates. Targets along the satellite track will see the fastest motion, and these will peak at nadir. A plot of the resulting body rates is shown in Figure 5. Even for relatively low altitudes, the body rates are less than about 0.8°/s. Many other Earth- or inertial-pointing applications have less stringent requirements for normal mission operations. Thus, maintaining full-precision performance up to about 1°/s represents a reasonable STOAE benchmark.
Anomalous rates may be much higher. Table 5 shows our assumptions regarding these requirements.

Table 5: Anomalous Rate Requirements

<table>
<thead>
<tr>
<th>Launcher separation tip-off</th>
<th>10 °/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACS malfunction</td>
<td>180 °/sec</td>
</tr>
</tbody>
</table>

**S3S Robustness**

Static availability of the S3S star tracker is very good. The sensor is designed with rectangular FOV of 15° x 20.2°, and a target detection threshold of magnitude 5.75. The matching algorithms require at least three stars for an attitude fix. We can eliminate the effect of sensor roll and calculate a conservative estimate of static availability by considering the number of stars within 7.5° (i.e., the semi-minor axis of the FOV) of boresight. In only 0.011% of cases (about 1.4×10⁻³ steradians), do we have less than three stars in view.

Table 6 illustrates some sample validation results from the S3S protolight unit, showing that the optical design works as intended. Other tests have even shown reasonable signal to noise for magnitude 6.2 stars. The signal is calculated from the integrated response over a 9x9 pixel window around the target star, and the noise is estimated from the RMS dark response of the sensor.

Motion tolerance qualification of the S3S has not yet been completed but we expect performance to be robust to moderate slew-rates. Although some of these motion compensation approaches are merely conceptual or prototyped algorithms, we would like to highlight some key features of the development roadmap.

As discussed previously, one of the most direct effects of motion blur is to reduce the signal to noise during star detection. The number of photons collected from a given star remains roughly constant, but because the light is spread over a larger number of pixels, more noise is collected, lowering the SNR. If we compare the window sizes needed to collect the same number of incident photons, we can estimate the effect on SNR. Figure 6 shows the result of such a calculation, with the relative SNRs expressed as a difference in visual magnitude. The S3S sensor uses a nominal window size of 9x9 pixels, but the performance is quite close to the \( w=10 \) curve. From these curves we expect that magnitude 5.75 stars imaged while moving at 1°/s to have roughly the same SNR as a magnitude 6.2 star. Because we know that we can detect magnitude 6.2 stars, we are confident that we can maintain adequate star detection while moving.

![Figure 5. Slew rate to maintain pointing at ground target located along satellite ground track.](image1)

![Figure 6. Effect of motion blur on detection threshold.](image2)

![Table 6. Night-time Observations with S3S Prototype](table1)
enough for proper matching. The ability to accurately centroid a streak must still be verified through laboratory and field testing. One other important correction currently under development is a compensation scheme for the ‘rolling shutter’ found in the S3S detector. Row exposures are displaced slightly in time, creating a geometric distortion that depends on the angular rates. This distortion is easy to correct if the rates are known, but it is difficult to predict directly. Two solutions are currently under study. The first would rework the star matching processing as an optimization to simultaneously find the best star matches and angular velocity components. The second concept would take two images in quick succession, and then estimate the angular velocity using common features between the two images.

High rate tracking under off-nominal conditions remains an obstacle to STOAE. Many of the phenomena that have minimal impact at a few degrees per second become much more important at greatly elevated angular rates. The current S3S design is not well suited for arbitrarily high rotation rates, and from a review of other sensors on the market, this limitation is common to most small star trackers. One technique that may have some promise is proposed by Wang and Chun [7]. They use a combination of conventional matching with a secondary match against star density over different regions of the sky. This may help in situations where centroid accuracy limits successful matching. Ultimately, partial STOAE schemes (e.g., star tracker, plus magnetometer) may provide the best guarantees of robustness.

MAINTAINING SURVIVABILITY

All spacecraft equipment must deal with the hostile launch and space environment, including vibration, shock, temperature extremes and radiation (nuclear and solar). A star tracker must deal with these whether it is supported by other sensors or not, and so there are not many new requirements placed on a STOAE device. There are, however, some subtle differences.

Survivability Requirements

Pointing a telescope of any significant size at the sun is always a concern. The concentrated sunlight can bring the focal plane to very high temperatures, potentially damaging detectors and adjacent circuits. Some star tracker designs mitigate this danger with opaque shutters. These may be one-time deployable lens covers that are discarded once the satellite has achieved its nominal attitude. Alternatively, they may be fast-acting doors that blink closed when the sun approaches the field-of-view [8].

It would be difficult for a STOAE device to use any sort of a shutter, since it must be available to generate attitude data through all phases of the mission. The STOAE star tracker will have to be intrinsically capable of surviving a prolonged stare at the sun. This places requirements on aperture, focal length, and detector choice.

The details of radiation environment survivability may differ for a STOAE device. If the star tracker is supplemented by other sensors then it might be acceptable for a radiation-induced upset or latchup to cause an interruption in data output. The spacecraft would revert to a coarse pointing mode until the fault was cleared, possibly by the operator. For a STOAE device the spacecraft is left with no attitude knowledge when the star tracker stops, and so rapid autonomous recovery from faults becomes even more important.

S3S Survivability

The S3S was designed from the start to be intrinsically safe when pointed at the sun. The 13 mm clear aperture of the lens can focus less than 0.2 W of sunlight onto the detector. Prototype S3S devices have been pointed at the sun for tens of minutes with no observed change in dark noise or gain.

Testing the S3S for radiation tolerance yielded some unexpected results. It is known that displacement damage leads to increased dark noise [9]. It is also known that raising the detector temperature leads to increased dark noise. What was not expected was that raising the temperature of a device that has already been irradiated would dramatically increase the dark noise.

![Figure 7. Dark Noise vs Temperature, after irradiation with $10^{11}$ p/cm² 105 MeV protons.](image)
This temperature dependency is illustrated by Figure 7. At 40°C the irradiated detector has dark noise equivalent to the control detector at 85°C. With the irradiated detector at 70°C the dark noise is ten times greater. At these levels it may become impossible to discern faint stars.

The dose here represents 9 krad of TID, which is a suitable design dose for a five year LEO mission. The irradiated part has already been fully annealed. Surviving this dose and remaining functional is a real challenge.

Informed by the results of this testing, the S3S sensor mitigates the increased dark noise by adding a thermoelectric cooler to the focal plane. This keeps the detector at a reduced temperature, moderating the dark noise. The PCB layout thermally isolates the detector, surrounding it with a moat of sparsely hatched ground and power planes. It is expected that temperature reductions of 20°C (and thus dark noise reductions of 3x) can be achieved with less than 0.5 W of additional power input.

The S3S electronics have also been shown to be radiation tolerant. Proton testing has verified TID survival to at least 9 krad, and no destructive single-events (though we must acknowledge that there might be a cross-section at higher linear energy transfer than protons can achieve).

The electronics architecture is intended to mitigate the effect of any single-event upsets. In addition to the main high-performance processor there is a supervisory microcontroller with a characterized (and very low) SEU cross-section. The microcontroller can reset the processor, and can also remove power from the processor and detector. Resets and power cycles are issued at regular intervals. The microcontroller will also respond rapidly if there is an unexpected input current step or if the processor becomes silent. All host communication passes through the microcontroller, so no packets or commands are lost when this occurs.

**CANX-4/-5 CASE STUDY**

To explore the practical implementation of STOAE we look at the impact it would have on a real mission being developed by SFL. The CanX-4/-5 formation flying mission [10] is a dual-satellite mission scheduled to be launched in late 2011 with a requirement to demonstrate accurate (<1m) autonomous formation flying algorithms using highly fuel-efficient algorithms. To accomplish position determination the satellites use differential GPS techniques and to control their positions they use cold-gas thrusters.

Attitude control during thrusts must be accurate to a level of a few degrees. Because the thrusters are rigidly mounted on only one face of the cubical spacecraft, before each thrust, the satellite must slew to align the thrusters with the desired thrust vector. Thrusts occur with a frequency of approximately once per minute, and so peak slew rates can be as high as 5°/s, but fine attitude knowledge is not required during this period.

At the same time that thrusters are being aligned, the GPS antenna must be oriented so that GPS lock is maintained as much as possible. To minimize coupling, the satellite has been laid out with the thrusters and GPS antenna pointed perpendicular to each other. Finally, for the differential GPS algorithms to work, both CanX-4&-5 must see the same GPS satellites. Hence, one satellite must always follow the other’s attitude. This mirroring implies that conclusions drawn about the applicability of STOAE to one satellite can be extended to other.

To achieve their mission, the CanX-4&-5 satellites (which are identical to each other) are using a suite of attitude sensors including six sun sensors (one on each face), a three-axis magnetometer and a three-axis rate sensor as well as a dedicated computer to run the attitude determination and control algorithms. The sun sensors and magnetometer are used during sunlight. During eclipse, when the sun sensors are of no use, the rate sensors supplement the magnetometer to improve the accuracy of the attitude solution. A figure of the CanX-4 satellite, with the items of relevance identified, is shown in Figure 8.
that the attitude computer would not be replaced. It should be noted that the S3S star tracker is a more powerful computer than the CanX-4/-5 attitude computer. With the proper interface, it is entirely possible that the S3S star tracker could take over the role of the attitude computer as well. Even retaining the attitude computer, STOAE represents a mass saving and would reduce the number of wires in the harness by approximately 30.

In assessing the applicability of STOAE to the CanX-4/-5 mission, it must be decided where the star tracker should be positioned on the spacecraft. Much like a GPS antenna, a star tracker works best when it is pointed away from the Earth. The Earth obscures the unit’s best source of attitude information (the stars) and does not provide any reliable or easy to use information of its own. Hence, it makes the most sense for the star tracker to be co-aligned with the GPS antenna. This positioning also serves to decouple the star tracker’s orientation from the thruster orientation, as was the case for the GPS antenna.

With this positional constraint in mind, the question of whether STOAE can satisfy mission requirements is most easily answered by examining the mission in reverse chronological order, from end to beginning.

Formation Flying Phase
The culmination of the CanX-4/-5 mission is the formation flying segment itself. During this period the spacecraft are re-orienting themselves with a frequency of about once per minute throughout the entire orbit (eclipse and sunlight). The thrusters can be commanded to any orientation and the GPS antenna must be kept as close to zenith as possible at all times. With the spacecraft layout as it is, it is theoretically possible to ensure that, regardless of thruster orientation, the GPS antenna and star tracker are never forced to be pointed outside of the zenith hemisphere (see Figure 9). It therefore makes sense to divide the analysis between the zenith hemisphere and the nadir hemisphere.

Zenith Hemisphere
Star tracker availability will be good in the zenith hemisphere, but there will be blind spots around the sun (and possibly the moon). The spacecraft layout allows rotation of the star tracker and GPS antenna without changing the thrust vector, and so an appropriately intelligent ADCS algorithm could predict and avoid blind spots with the possible tradeoff being a less than optimal GPS antenna pointing vector. The blind spot size is a function of the baffle design, and an appropriate baffle could be used to help shrink the dead zones to tolerable fractions of the sky.

Figure 9. Simplified view of CanX4/5 orbit.

For the CanX-4/-5 mission, it is believed that sun sensor availability would be good in most orbits, and would be tolerable in the worst case orbits. For example, in a noon-midnight sun synchronous orbit a strictly zenith-pointed star tracker with a wide FOV will be pointed near the sun for some portion of each orbit. However, accounting for the fact that the star tracker/GPS can (within limits) be rotated about the thrust vector for sun avoidance, the actual amount of time that the spacecraft would be blinded would actually be quite small.

Nadir Hemisphere
With the zenith hemisphere analyzed and (for CanX-4/-5) shown to be largely compatible with STOAE, a complete STOAE implementation for the formation flying portion of the mission now requires that a strategy be developed for the nadir hemisphere.

For simplicity, it can be assumed that in the nadir hemisphere the star tracker cannot see any stars since the boresight will at best be very close to the Earth’s limb (In reality this will not be true since the portion of the limb closest to the boresight will not always be illuminated). Hence, the only attitude information likely to be available to the star tracker in the nadir hemisphere is that provided by using the star tracker as a horizon sensor.

It should be noted that, because the instrument functions in the visible region of the EM spectrum and not the infrared, the horizon would only be visible when lit by sunlight. It should also be noted that horizon sensing would, of course, require the appropriate algorithms be running on the star tracker. However, the algorithms are believed to be within the capabilities of the S3S computer.
The conclusion therefore is that, if the star tracker is pointed in the nadir hemisphere, attitude solutions are likely to be unavailable most of the time. This suggests that the best strategy for dealing with a star tracker that is pointing somewhere in the nadir hemisphere is to initiate an action that will ensure that the star tracker ends up back in the zenith hemisphere. Once nadir hemisphere pointing is detected (by loss of solution for an extended period of time or by propagation from the last known attitude state), a return to the zenith hemisphere can be quite easily accomplished by initiating an open loop spin about an axis perpendicular to the star tracker boresight. By spinning up or down the reaction wheel controlling that axis, the star tracker will be very likely to pass into the zenith hemisphere where it will quickly obtain an attitude lock.

More intelligent ADCS routines on the spacecraft could also be used to backtrack along the path that brought the star tracker into the nadir hemisphere to achieve a shorter path back to the zenith hemisphere. Such routines would be identical to those used to avoid sun or blind spot pointing, as discussed in the section on the zenith hemisphere.

Hence, for the formation flying portion of the CanX-4/-5 mission, STOAE seems workable. A STOAE solution may even provide better performance than the current solution which relies heavily on propagation during lengthy eclipses (supplemented by inertial rate sensors and magnetometer). The main drawback of STOAE is the potential for elevated periods of propagation on the sunlit side of the orbit. However, as discussed, since these periods are largely avoidable and likely to be brief when not avoidable, they are probably acceptable for the CanX-4/-5 mission.

Commissioning Phase
Prior to formation flying the satellites spend their commissioning phase connected to each other using a devise called the intersatellite separation system (ISS) [10]. This device keeps the satellites rigidly joined until they are commissioned and the ground commands them to separate. During this phase of the mission the satellites are required to maintain a nadir aligned orientation with an accuracy, again, on the order of a few degrees.

Since it was desirable to be able to test the GPS before separation, the satellite layout was designed so that, in the joined configuration, the GPS antennas face outward and are not obscured by the other satellite. Since the star tracker is co-aligned with the GPS antenna, it would also not be obscured during this time. Figure 10 shows CanX-4/-5 in their joined configuration.

Figure 10. CanX-4/-5 in stowed configuration.

Also of note is that, during the commissioning period, since the satellites are rigidly connected, only one satellite needs to maintain attitude control for the pair. Hence, only one of the two satellites needs a reliable attitude solution at any given time. This is a critical point since, in the joined configuration, pointing one star tracker into the zenith hemisphere guarantees that the star tracker on the other spacecraft is pointed in the nadir hemisphere where attitude solutions are unlikely.

Therefore, in terms of analyzing the applicability of STOAE, the commissioning phase of the mission is a simplified case of the formation flying phase. Since there are no requirements for pointing the thrusters, one star tracker can always be oriented in the zenith hemisphere in a direction that minimizes the probability of blind spots occurring.

Separation Phase and Detumbling
The final phase of the mission needing analysis is the separation and early operations phase in which the spacecraft are ejected from the launch vehicle with non-zero tip off rates and must be detumbled before stabilizing in the nadir-aligned commissioning attitude. It is expected that tip off rates caused by ejection may be as high as 10 °/s. On CanX-4/-5 there are no strict requirements for how long detumbling from these rates should take, but significantly less than a day would certainly be desirable.

Detumbling is most commonly accomplished on small spacecraft using B-dot magnetic control algorithms. B-dot algorithms use successive measurements of the Earth’s magnetic field to calculate a magnetic dipole that will counteract the spin of the satellite, thereby damping out some of its rotational kinetic energy. No direct calculation of attitude is required for B-dot control, which is what makes it so simple and so attractive to spacecraft designers.
In STOAE, the magnetometer no longer exists and so rate determination must be performed using techniques like those developed in [1],[3]. However, because rotation spreads each star’s light over many pixels, the signal to noise ratio for each star is lower under rotation than in a stabilized condition. The net effect of this lower signal to noise ratio is that the star tracker will have a lower (i.e. brighter) magnitude threshold for identifying stars and the sky coverage of the unit will be reduced. Fortunately, rate determination and detumbling do not necessarily require attitude solutions anywhere near the 99.99% coverage that the S3S unit can provide when stable.

Every spacecraft attitude control filter has an aliasing limit. This aliasing limit is mainly a function of the frequency at which attitude solutions are calculated. For example, if solutions are returned at 1Hz, most filters will start aliasing as they approach 180 °/s (the 1Hz filter on CanX-2 aliases at around 145 °/s [11]). Hence, the S3S star tracker, operating at 2Hz, would be expected to have an aliasing limit somewhere closer to 360 °/s (assuming the associated filter can keep up). If the star tracker produces an attitude solution only a quarter of the time while spinning at 10 °/s, this would, from the filter’s perspective, be equivalent to reducing the sample frequency by a factor of four to 0.5Hz, and reducing the aliasing limit proportionally (i.e. from 360 °/s to 90 °/s). Since this is still about an order of magnitude larger than 10 °/s, the filter should still be able to reliably calculate rates.

With rates calculated, the spacecraft then has the option to try to absorb that energy using onboard storage (i.e. reaction wheels) or by dumping it via magnetic torquers. In the case of CanX-4/-5 the reaction wheels are sized to absorb spacecraft rates of at least 30 °/s, well in excess of the 10 °/s assumed as the worst case tip off rates. In a STOAE configuration, which lacks the ability to perform direct B-dot control, dumping momentum from a stabilized attitude is certainly easier than doing so when tumbling. Hence, detumbling would likely become a two step process of first, transferring momentum to the wheels, and then, dumping that momentum from the wheels using the magnetic torquers. Since both of these functions are required spacecraft functionality anyway, no additional algorithms are required to perform detumbling in this two step process.

It is worth noting that, without a magnetometer, an estimate of the Earth’s magnetic field vector in the spacecraft frame is still required to dump momentum magnetically. Such an estimate can be obtained using any number of models, with the model of choice for CanX missions being IGRF [12]. Using IGRF, and knowing the spacecraft’s position in orbit (which the spacecraft would need to know anyway if performing attitude determination with a magnetometer) the spacecraft can estimate the Earth’s magnetic field at any given time and therefore calculate the magnetic torque required to help desaturate the reaction wheels. Although IGRF will not provide as reliable a magnetic field reading as a magnetometer would, it will have the right sign significantly more often than it will have the wrong sign. Hence, although the applied torques may not be optimal, they will be largely in the right direction and the wheels will eventually spin down.

**Overall Applicability of STOAE to CanX-4/-5**

The discussion in the previous sections has demonstrated that STOAE is potentially feasible for the CanX-4/-5 mission. However, there clearly are tradeoffs associated with implementing STOAE. In general, while the hardware complement of the spacecraft would be greatly reduced, leading to reductions in mass, complexity and cost, the software complement would need to be significantly enhanced as several new algorithms would be required to deal intelligently with blind spots and new sources of attitude information (e.g. lunar and horizon sensing).

The purpose of this case study is to assess feasibility of STOAE for CanX-4/-5. Hence, it is beyond the scope of this discussion to speculate on whether or not STOAE would be a net gain for the mission. This question will however be put to the test in the near future as it is quite likely that CanX-4&5 will each fly a S3S star tracker as an engineering payload. When the formation flying mission is complete, it will be possible to simulate STOAE missions and experiment with algorithms running on the star tracker and the spacecraft that might one day enable operational STOAE.

**CONCLUSIONS**

Star tracker only attitude estimation has potential to greatly simplify ADCS integration and recent sensors designs such as the S3S have improved the practicality of the STOAE concept. From the analysis in the previous sections, the following conclusions are clear.

- **Performance requirements are largely driven by mission needs, not by star tracker capabilities. Star tracker accuracy and update rates are suitable for many missions and may be much more precise than the mission requires.**
- **Robustness, particularly to bright body incursions and high rate motion during non-routine mission phases (e.g., detumble) remain the largest technical hurdle.** Additional
developments are needed before single-sensor STOAE is truly practical

- Survivability remains an area to watch. The lifetime dose during many LEO missions may increase dark noise to the point where dim stars cannot be reliably detected. Active cooling may help mitigate this effect and a gradual degradation in performance may be acceptable depending on the mission.

- The CanX-4/5 case study shows that STOAE can be contemplated even for a complex mission requiring frequent retargeting.

In reflecting on these findings, we conclude that the redundant (i.e., multi-aperture) or partial (i.e., a reduced suite of external sensors) implementation may be significantly more practical than a design relying solely on optical star tracking. Each of these two concepts addresses one of the primary obstacles; redundant sensors avoid problems with starfield visibility, and secondary sensors can provide added robustness to high-rate motion. Focusing on these two concepts we can see how innovations in the S3S sensor move star tracker technology in the right direction:

- Low power, low mass, and low volume, are even more important when considering the use of multiple star trackers.

- Excess processing capability on the star tracker could be used to perform the sensor fusion with any external sensors directly.

We hope to have S3S units on-orbit in the near future. Test images from these will help immensely, allowing us to quantify the solar exclusion zone, stellar motion blur, and the effects of space radiation. With this information in hand we can begin to contemplate true STOAE missions.

REFERENCES


