Development of the Arcsecond Pico Star Tracker (APST)*

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The second-generation star tracker estimates pointing knowledge of a satellite without a-priori knowledge. But star trackers are larger in size, heavier, power hungry and expensive for nanosatellite missions. The Arcsecond Pico Star Tracker (APST) is designed based on the limitations of nanosatellites and estimated to provide pointing knowledge in an arcsecond. The APST will be used on the SNUSAT-2, Earth-observing nanosatellite. This paper describes the requirements of APST, trade-off for the selection of image sensor, optics, and baffle design. In addition, a survey of algorithms for star trackers and a comparison of the specifications of APST with other Pico star trackers are detailed. The field of view (FOV) estimation shows that 17° and 22° are suitable for APST and this reduces stray light problems. To achieve the 100% sky coverage, the FOV of 17° and 22° should able to detect the 5.85 and 5.35 visual magnitude of stars, respectively. It is validated by estimating the signal to noise ratio of APST and night sky test results. The maximum earth stray light angle is estimated to be 68° and a miniaturized baffle is designed with the exclusion angle of 27°.

Key Words: Nanosatellite, Attitude Determination, Pico Star Tracker, APS Camera, Baffle

1. Introduction

The SNUSAT-2 is a technology demonstration mission for the nanosatellite platform. One of the technical objectives of this mission is to develop a pico star tracker that can estimate the attitude of a satellite with arcsecond accuracy. The star trackers in the commercial market are heavy, larger in size, power consuming, and costly for nanosatellites. Hence, an optimized Arcsecond Pico Star Tracker (APST) for SNUSAT-2 is under development at Seoul National University. The APST is designed based on the mission requirements and limitations of nanosatellites. The main components of the APST are image sensor, imaging lens, and a processor that are selected from commercially-off-the-shelf (COTS) products. The baffle for the star tracker has been designed and fabricated in-house. The selection of image sensor, imaging lens, processor and baffle design are interconnected and, this determines the capability and performance of the star tracker. This paper describes the important parameters to consider for selecting the image sensor, imaging lens, processor, and baffle design. In addition, the design of various pico star trackers and their algorithms are analyzed in detail.

2. Current Pico Star Trackers

The star trackers for pico and nanosatellites are developed by various institutions around the world. The most prominent five pico star trackers that have produced results during the ground based testing is discussed in this section. Table 1 shows the important parameters of the pico star trackers and their corresponding imaging sensor and lens.

In general, pico star trackers weigh up to 90 g but this does not include the weight of the baffle. The STC-2 has the lowest weight of 65 g, developed by Sternberg Astronomical Institute, Lomonosov Moscow State University. The size of the pico star tracker is designed to fit within a volume of 30 mm × 30 mm × 38.1 mm3 which is half the size of a cubesat platform. The ST-200 is the smallest pico star tracker at 30 mm × 30 mm × 38.1 mm3 without including the baffle developed by Berlin Space Technologies, Germany. The ST-200 has the lowest nominal power consumption of 220 mW. The ST-16 has the highest accuracy of 7 arcseconds (pitch/yaw) and a 70 arcsecond (roll) developed by Ryerson University, Canada. When lost in space (LIS) a-priori information about satellite is unknown; hence, the update rate is lower. However, when in tracking mode (TM) a-priori information about satellite is known using other sensors; hence, there is a higher update rate. The nominal required slew rate in LEO is 0.1° to 0.3°/s. When conducting a satellite maneuver higher than the nominal slew rate, the image of star will blur. But ST-16 is operational up to 3°/s by post-processing the image. Most pico star trackers use a low resolution image sensor having 1 mega pixel (MP) resolution or less. However, the ST-16 and ST-200 have high resolution image sensor of 4 MP and 5 MP, respectively. The selection of image sensor includes various aspects, which will be detailed in the next sections.

Due to the limitation in size the pico star tracker uses an
imaging lenses with a low focal number, which comparably produces brighter images. The focal ratio of 1.2 to 1.8 is optimum for pico star tracker. Most pico star trackers are designed with a FOV of less than 20 but the CubeStar developed by the University of Stellenbosch, South Africa uses wide FOV (WFOV) of 42° that requires fewer stars to be cataloged but has relatively low accuracy and is vulnerable to stray light.\(^4\) Based on the FOV requirement, the focal length of the imaging lens varies from 6 to 16 mm. The focal length of 16 mm would be the upper limit due to the constraints like weight, size and accuracy. The limiting magnitude of the star tracker is the magnitude of the faintest star detectable by the star tracker. The pico star tracker developed by the University of Wuerzburg, Germany has a high sensitivity image sensor; hence, it can detect stars up to a magnitude of 6.46.\(^5\) Based on a literature review and mission requirements, the possible design requirements for APST are listed in Table 2.

The ST-16 pico star tracker was launched into space as part of SkySat-1 in 2013\(^3\); however, it performed lower than the expectations due to chromatic aberration of the lens. The ST-16 RT, a modified version equipped with a customized lens, was launched as part of skySat-2 and skySat-2C in 2014 and 2016, respectively.\(^6\) It produced better results after implementing the customized lens. The ST-200 and Cube Star will be launched into orbit for the QB50 mission.

### 3. FOV Estimation

The High Precision Parallax Collecting Satellite (HIP-PARCOS-2) catalog is used for APST. The catalog contains 118,218 stars in total, and the accuracy of star magnitude is up to a factor of 4.\(^7\) In APST, the stars of magnitude brighter than 6 are used. Hence, for initial analysis, only 4,558 stars are used. Figure 1 shows the number of stars brighter than the magnitude of 6. The number of stars increases exponentially as the apparent magnitude of the star increases. The stars are non-uniformly distributed over the sky because the star density is higher in the galactic plane and lower at the galactic poles. Figure 2 shows the distribution of stars of magnitude brighter than 6 in June 2016, clearly implying that the stars nearer the poles have a relatively lower magnitude compared to those nearer the equator. The average density of stars brighter than a magnitude of 6 over entire sky, galactic plane, and galactic poles is 0.15, 0.32, and 0.13 per square degree, respectively.\(^8\)

The FOV of a star tracker is a crucial factor that determines the requirements for the image sensor, optics, and baffle. A star tracker with a WFOV ranging from 15° to 40° is the optimum range for the nanosatellites. The WFOV has advantages like lower memory, less processing time, and moderate accuracy. In general, star tracker need two stars to determine the attitude of the satellite. We use a sub-graph method that applies the angular distance between stars to

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### Table 2. Requirements of Arcsecond Pico Star Tracker (APST).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>&lt; 150</td>
</tr>
<tr>
<td>Size including baffle (mm(^3))</td>
<td>48 × 48 × 90</td>
</tr>
<tr>
<td>Nominal power (mW)</td>
<td>&lt; 500</td>
</tr>
<tr>
<td>Accuracy 3(\sigma) (arcsecond)</td>
<td>&lt; 50 (PY), &lt; 200 (R)</td>
</tr>
<tr>
<td>Update rate LIS (Hz)</td>
<td>1</td>
</tr>
<tr>
<td>Slew rate (°/s)</td>
<td>0.1 to 0.3</td>
</tr>
</tbody>
</table>

### Table 1. Parametric study of current Pico star trackers.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ST-16</th>
<th>ST-200</th>
<th>Cube star</th>
<th>STC-2</th>
<th>Pico star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>90</td>
<td>74</td>
<td>90</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>Size (mm)</td>
<td>60 × 46 × 58</td>
<td>30 × 30 × 38.1</td>
<td>46 × 33 × 70</td>
<td>57 × 23 × 73.5</td>
<td>30 × 38 × 80</td>
</tr>
<tr>
<td>Power (mW)</td>
<td>250</td>
<td>220</td>
<td>350</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Accuracy (arcsec)</td>
<td>PY-7, R-70</td>
<td>PY-30, R-200</td>
<td>PY-36</td>
<td>PY-10, R-50</td>
<td>PY-36, R-144</td>
</tr>
<tr>
<td>Update rate (Hz)</td>
<td>LSM-1</td>
<td>LSM-1, TM-4</td>
<td>LSM-1</td>
<td>TM-10</td>
<td>LSM-4</td>
</tr>
<tr>
<td>Max Slew rate (deg/s)</td>
<td>3</td>
<td>0.3</td>
<td>0.3</td>
<td>2</td>
<td>0.3</td>
</tr>
</tbody>
</table>

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Fig. 1. Number of stars corresponding to their magnitude.
identify stars. When there are only two or three stars in a FOV, there is a high probability of mistakenly identifying or not identifying the stars. If the angular measurement error of the star tracker is 0.005° and there are a minimum of four stars in the FOV, then all the four of the stars can be successfully identified. There is always a possibility of false stars being in a FOV and to compensate for this, we used five stars for the FOV estimation. The larger the number of stars in the FOV, the higher the accuracy and success rate; however, this consumes more operation time. Therefore, we should make a trade-off based on the accuracy and update rate requirement. Accordingly, a minimum of five stars is required in the FOV to identify the real stars. The APST is required to have a minimum of 99% sky coverage containing a minimum of five star in a FOV to determine the attitude of the satellite.

The simulations are performed in MATLAB to determine the required FOV containing minimum five stars in any part of the sky. The stars of brighter than a magnitude of 6 are used for this simulation. The Circular FOVs (CFOVs) of 17°, 20°, 22°, 25°, 30°, 35° and 40° are used for analysis. In order to estimate the FOV, a unit celestial sphere is created using real star coordinates and the star tracker is assumed to be in the center of the unit sphere. The simulation also generates a random location on a unit sphere which represents the pointing direction of the star tracker. Then the number of stars present in the FOV is estimated for 10,000 iterations, which are randomly selected sky locations. This program performs many iterations to collect statistics about how many stars lie within the FOV of the star tracker. The error in the approach is \(1/\sqrt{N}\), where \(N\) is the number of iterations. Hence, result contains an error of 1 in every 100 random locations. This means the higher the number of iterations, the higher the accuracy of identifying the number of stars in the location. The simulation method and codes for FOV estimation were made by "Scott Mulligan" and readers can go through for the details of this simulation and code.9)

Figure 3 shows the required star magnitudes for different FOV and their corresponding sky coverage. Based on the required sky coverage, the limiting magnitude can be determined. The minimum sky coverage required for APST is 99% and maximum is 100%. Table 3 shows the required limiting magnitude for sky coverage of 99% and 100% for various CFOVs. To acquire 100% sky coverage, the CFOV of 17° requires a limiting magnitude of 5.85, whereas the limiting magnitude is 4.4 at 40°. This implies that a wider FOV requires the minimum of number of stars and processing time can be significantly reduced. However, wide FOVs of 40° and 30° are more vulnerable to stray light from the sun, earth, and moon. Therefore, the CFOV of 17° and 22° are selected for initial analysis because they are less vulnerable to stray light and relatively accurate. Either one of these FOVs can be selected for APST. The selection of imaging sensor and optics for a star tracker should be based on the FOV and limiting magnitude requirement. The image sensor and optics of the APST are selected based on the CFOV 17° and 22° and limiting magnitude of 5.85.

4. Selection of Image Sensor and Imaging Optics

The image sensor contains various parameters that determine its function and performance. The active pixel sensor (APS)-based CMOS sensor is preferred instead of a CCD due to the advantages of windowing, lower power consumption, and lower price. The fabrication of the radiation-tolerant CMOS APS image sensor using standard CMOS processes provides a considerable cost advantage over other image sensors fabricated using specialized radiation tolerant processes. Moreover, other radiation tolerant electronics can be integrated with CMOS APS image sensors using the same design and standard CMOS fabrication process. This enables miniaturization of the radiation tolerant imaging system. These advantages make CMOS APS a viable alternative to CCD for space applications.
The image sensor can either be monochrome or color. Monochrome is preferred because its quantum efficiency is higher than a color sensor, and a star tracker does not need color information of the star. The usage of a color sensor for star tracker will be one of the research topics in the future. Table 4 shows three CMOS-based monochrome image sensors and the important parameters to be considered.10) The sensor size of 1/3" to 1/2" is suitable for APST. The pixel size is the important factor for determining the accuracy of the sensor; the smaller the pixel size, higher the accuracy. The star tracker usually has an image sensor with a resolution less than 1 MP.

The problem with a high-resolution sensor is it takes a longer processing time, which will reduce the update rate of the star tracker. The higher the quantum efficiency, the lower the read noise and dark noise is better because it enables the imaging of faint stars. The full well capacity determines the brightest star it can image. The dynamic range is the ability to image the brightest and faintest star in the sky. The star tracker needs an image sensor with higher dynamic range. The CMOS sensor usually has a rolling shutter but the CMOS sensors have a global shutter. The global shutter can image without smearing even if a satellite maneuvers at a relatively high rate, whereas the rolling shutter will smear the image. Therefore, the global shutter is preferred over the rolling shutter. The final important thing is the availability of the image sensor in the market.

The first preference is the AR1034 because among the three it has highest sensitivity, quantum efficiency, and dynamic range. However, only the MT9P031 is the only one available, and it satisfies most of the requirements. The ON-Semi MT9P031 has already been used in the ST-16 star tracker developed by University of Ryerson, Canada and have been successfully operated in many missions since 2013. Accordingly, the MT9P031 monochrome image sensor was selected for APST. Based on the MT9P031 image sensor, an imaging lens was selected. The S-mount lenses were chosen because they weigh less. The lens with a low focal ratio (1.2 to 1.8) maximizes the light collection, but aberration increases rapidly as the focal ratio decreases. Spherical and chromatic aberration in the lens may cause failure during the execution of star identification. The equations (1 to 3) shows the relationship between the aberration and focal ratio. The focal length of 16 mm and 12 mm provides the FOVs of 15° and 20°, respectively. Additionally, the focal length determines the accuracy of the star tracker; higher the focal length the better the accuracy of the star tracker. Using 16 and 12 mm focal lengths, the theoretical pixel accuracies of 28.4 arcsec and 37.8 arcsec are obtained, respectively.

The resolution of the image sensor lens should be in high-resolution MP, otherwise the image that is output will be blurred. This means the magnitude of the signal is reduced in the image sensor. A lens with a resolution of 1 to 3 MP is chosen. Theoretically, the 1 MP and 3 MP lenses can resolve at 8.9 μm/line and 5.9 μm/line, respectively. These characteristics will be studied in detail during laboratory and night sky testing. Based on the testing results, B3M16018 lens in Table 5 is chosen. Distortion is one of the important factors in determining the quality of the lens. There are three types of distortion: barrel, pincushion and mustache. We use a distortion correction algorithm in the post-processing to overcome the error due to distortion in the lens. This enables distortion to be compensated. The B3M16018 lens has a pincushion distortion of 0.65%. Based on the suggestions from experts, we opted for lenses with less than 1% distortion. An antireflection coating for the lens increases transmission of the light. An imaging lens with filters and customized lenses would enhance the quality and performance of the star tracker, but these are expensive and will be considered for development in the future.

### 5. Sensitivity of APST

The previous sections have established the required FOV, available image sensor, and optics. The signal to noise ratio (SNR) of the APST is one of the factors for verifying if the image sensor and imaging lens meets the FOV requirements. If the APST has a minimum SNR of 8, it can easily detect stars. The signal of the APST is estimated using Eq. (6), where $R$ is the radius of the lens, $t$ is exposure time (0.1 s),

$$
\text{SNR} = \frac{S}{\sqrt{N_r + N_d}}
$$

where $S$ is signal, $N_r$ is read noise, and $N_d$ is dark noise.
The noise estimation of the MT9P031 image sensor can be estimated using Eq. (7)

\[
\text{Total signal} = (3.14 R^2 t F_0)/ (2.5^m) 
\]

\[
\text{Total noise} = \sqrt{S + D + DCNU + R^2 + Q^2} 
\]

The number of pixels included in the star image is based on the Point spread function (PSF), by increasing the PSF, the number of pixels that contribute to the noise increases, whereas the magnitude of the signal decreases. The symmetric PSF is considered for analysis, and due to the slowness of the satellite, the noise in the pixels increases, which is a function of focal length. The total number of pixels in the PSF is estimated using Eq. (8)

\[
N_p = \sqrt{3.14 P^2 + 2 P (F \tan(\alpha_t)/\gamma)} 
\]

Where \( P \) is the PSF radius in pixels, \( F \) is the focal length (mm), \( \alpha_t \) is the slowness \( 0.1^\circ/s \), \( t \) is the exposure time (0.1 s) and \( \gamma \) is pixel size (2.2 \( \mu \)m). The SNR for various PSF radii and for the corresponding focal ratio of the lens are estimated in Eq. (9). The graph in Fig. 4 implies that the PSF radius of 0.5 has higher SNR when compared to a PSF radius of 3. Focal ratio is another important factor increasing the SNR, the lower the focal ratio the better signal, so it has higher SNR.

\[
\text{SNR} = S_c/(N_c N_p) 
\]

The stars can be easily detected with a SNR of 8. The analysis shows that the lenses with a focal ratio of 1.2 to 1.8 have a SNR higher than 8 for the PSF radius of 0.5 to 3. The focal ratio of 1.2 with a PSF radius of 0.5 has the highest SNR, 84.6, and whereas focal ratio of 1.8 and PSF radius of 3 has the lowest SNR, 13.4. The higher the PSF radius, the better the centroiding ability; however, the higher PSF reduces the SNR, which leads to the inability to detect faint stars. Therefore, SNR and PSF should be chosen based on the requirements of the star tracker.

Table 7 shows the estimated SNR for star magnitudes of 5.85 and 5.35 using 16 mm and 12 mm lens respectively. The PSF of 0.5 is when a star is focused in single pixel and a PSF of 3 is when a star is defocused at around six pixels. In APST we prefer focal ratio of 1.8 and PSF of 1 to 2 (PSF 0.5 is practically not achievable). For example, when imaging 5.85 magnitude, the SNR is 72.8 (using 16 mm lens, PSF 1, and focal ratio 1.2) and the SNR decreases to 34 (using a focal ratio of 1.8), whereas the same lens with PSF 3 reduces the SNR to 13.4.

Based on the analysis from previous sections, two possible designs for the star tracker are chosen. The MT9P031 image sensor with a focal length of 16 and 12 mm have CFOVs of 17° and 22°. Based on the sensitivity analysis of APSTs with CFOV of 17° and 22° can detect stars with magnitudes of 5.85 and 5.35, respectively, which assure sky coverage of 100%. Table 8 lists the two possible designs for the APST. The both design \( \alpha \) and \( \beta \) have their own advantages and disadvantages. Design \( \alpha \) has better accuracy, but the total number of stars is higher. Therefore, the algorithm execution time would be relatively longer. The total number of stars in design \( \beta \) is less. Therefore, the execution time is relatively less, but accuracy is lower as well. Both of this design are suitable for an APST, based on night sky results, the design \( \alpha \) is chosen.

6. Operational Algorithms

The star tracker image processing consists of four important steps,
i) Star detection

ii) Centroiding

iii) Identification

iv) Attitude determination

Star detection is based on the sensitivity of the APST and background threshold. The previous section of this paper detailed the theoretical estimation of star detection. The pixel size and focal length limit the star tracker accuracy. To obtain sub-pixel accuracy, the star tracker is purposely defocused to spread over many pixels (i.e., the PSF of the star image is enhanced). A centroid algorithm is then used to identify the centroid of the star image. Basically, centroiding has two types of algorithms: Centre of mass or weight, which uses the number of pixels, and light intensity to estimate the center point of a star.

The accuracy is up to 1/10 of a pixel. The Gaussian distribution method produces an accuracy of 1/100 of a pixel, but it’s complex to implement. Therefore, the centre of mass or weight is easier to implement and achieve reasonable accuracy.\(^{15}\) Centroiding without defocusing would be advantageous for achieving higher SNR and to overcome aberration issues.

Using the centroid coordinates of star images, the identification algorithm is implemented. The identification algorithm identifies stars in the image by matching them with the onboard star catalog. The identification algorithm contains two main classifications: pattern recognition and subgraph. The pattern recognition is based on the patterns produced by connecting the stars (e.g., star constellations) using grid algorithm or ring algorithm, but the pattern recognition must have higher star density, which means more faint stars. The sub-graph method uses the distance and angle information between the stars for identification. Table 9 contains a list of important identification algorithms and their characteristics. The main characteristics of an efficient identification algorithm are being highly robust, less complex, having a small database, and requiring less time for execution.

Comparing the four algorithms in Table 9,\(^{16}\) geometric voting is more suitable for APST because it is highly robust, has a high success rate and require only small database, but one disadvantage is it requires more time for execution when comparing to other algorithms. The second option would be a pyramid algorithm (K-Vector search) due to its well-known success rate, robustness and shorter execution time. Grid algorithm or any other based on pattern recognition would be the option for future development because pattern recognition requires a lower percentage of trigonometrical information of stars. This could be a serious problem due to aberration in lens, noises, and stray light and this can be overcome using pattern recognition but it requires higher star density. Further work on developing optimized pattern based algorithm would be efficient. The triangle algorithm is well known for its lower complexity and smaller database but it does not have a high success rate. The pyramid algorithm will be used for star identification.\(^{17,18}\)

The final operation is determining the 3-axis attitude solution from star vector observation. The triad algorithm will be used by APST to determine the attitude of the satellite. It’s simple to execute, requires less memory and reduces computation time. The star tracker is basically a camera that images the part of the celestial sphere and post-process the image to determine the attitude of the satellite.

Figure 5 shows the inverted projection of a celestial sphere on a sensor frame. In the sensor frame, the stars are located based on sensor origin and focal distance \((x, y, f)\). Therefore, the rotation between the sensor frame and inertial frame (celestial sphere) has to be determined to estimate the attitude of the satellite.

Using identification algorithm inertial coordinates of two vectors, \((a_i, b_i)\) is obtained from the mission catalog. Then the two corresponding star vectors in the sensor frame \((a_s, b_s)\) are estimated. Using these four star vectors, the rotation matrix \(R_{as}\) is determined using a triad equation shown Eq. (10). The rotation matrix is converted to represent Euler angles.

\[
a_s = R_{as}a_i \quad \text{and} \quad b_s = R_{as}b_i \quad (10)
\]

### 7. Night Sky Testing

Based on the theoretical estimation of sensitivity of the image sensor and imaging lens, a MT9P031 demonstration kit and Lensation lenses are used for the testing, which is shown in Fig. 6 and Fig. 7. The MT9P031 demonstration kit contains a wide angle lens, which has been replaced with a lensation lens, using an adapter as shown in Fig. 6. The parameters of the MT9P031 image sensor and lensation lenses are shown in Table 4 and Table 5 respectively. In this night sky testing, the hardware is tested to see if it can image stars of 5.85 magnitude with an exposure time of less than 200 ms to ensure APST has 100% sky coverage. But the algorithms for star detection, centroiding, and identification have not been implemented yet. First night sky testing is performed.
at the Seoul National University and around Seoul but, the
test results were poor due to the city lights. Therefore, we
traveled 160 km southeast of Seoul to Yongjin-ri which is lo-
cated in the state of Danyang-gun. This location is a remote
area and there are no artifi-
cial lights in the surrounding area.

Based on the Accu Weather forecast there were no clouds
(i.e., 100% clear sky) on August 12, 2016 at 1:00 a.m. The
humidity was above 90%, but dry weather is a better condi-
tion for star imaging.
tudes of 2.25, 2.65 and 3.35 show aberration and distortion in the lens. The B3M16018 has a focal number of 1.8 and resolution of 3MP. Figure 9 and Fig. 11 contain images using the image of B3M16018, are not as bright as BHR16012, it can still image a star with a magnitude of 6 using an exposure time of 200 ms.

But the B3M16018 produced symmetric images without aberration and distortion in Fig. 9 and Fig. 11 which is better than BHR16012. The stars imaged using the B3M16018 are more symmetrical than those imaged using the BHR16012 and this will help to accurately define the centroid of the star and high success rate of identifying the stars. Therefore, B3M16018 lens is chosen for APST. These tests confirmed that existing hardware can detect stars of 5.85 magnitude with an exposure time of less than 200 ms. This shows that the APST will have 100% sky coverage during static imaging, but the sky coverage will be decreased under dynamic condition (high slew rate). This night sky testing is done without the operation of algorithms and baffle. A night sky test with various slew rate will be performed.

8. Baffle Design

The stray light from the Sun, Earth and Earth’s moon is one of the major factors in lowering the performance of the star tracker. It could even lead to failure in certain conditions. As APST will be operating in a Low-Earth orbit, the dominant stray light source is the Earth. The SNUSAT-2 orbital altitude will be around 400 to 700 km, which is far less than the radius of the Earth. Therefore, the Earth is viewed as an extended stray light source. However, the bright stray light sources like the Sun and Earth’s moon are viewed as point sources due to their long distance from the LEO satellites. To successfully image the faint stars of 5.85 magnitude, the background stray light must be lower than the magnitude of 5.85. The optical axis of the star tracker should be oriented normal to the Sun to reduce the stray light intensity. Since the Earth is an extended surface, the effective stray light region of the Earth is calculated. Figure 12 shows the orientation of APST, which is almost normal to the Sun and Earth. It also shows the effective stray light region of the Earth. The maximum stray light angle is due to the Earth, incident on the APST is known as \( \Phi_{\text{max}} \).

The maximum stray light angle is due to the Earth, incident on the APST is known as \( \Phi_{\text{max}} \). The average radius of the Earth \( R_{\text{earth}} \) is 6.370 km, \( H \) is the altitude of the orbit (500 km) and the \( \Phi_{\text{max}} \) is 68°. The maximum radius of the effective stray light region \( R_{\text{max}} \),

\[
\Phi_{\text{max}} = \arcsin \left( \frac{R_{\text{earth}}}{(R_{\text{earth}} + H)} \right) \quad (11)
\]

\[
R_{\text{max}} = R_{\text{earth}} \cos \Phi_{\text{max}} \quad (12)
\]

The \( \Phi_{\text{max}} \) is useful when designing the baffle and star tracker orientation. The maximum irradiance from the sun is 918.1 W/m² and the Earth reflects 35% of the Sun’s light, which is known as albedo.

The maximum irradiance from the Earth is 321.3 W/m². The irradiance of the Earth’s moon when it’s full is 1.4 mW/m². The function of the baffle is to prevent stray light from bright objects (i.e., Sun, Earth and Earth’s moon) outside the FOV from directly reaching the lens surface and to reduce the intensity of stray light so that the star tracker can identify the stars effectively. A single-stage, diffused cylindrical baffle with straight vanes has been designed for the APST. A two-stage baffle is efficient for reducing stray, light but due to volume constraints, a single stage baffle is used for APST. Baffles can be designed in either cylindrical or conical shape. A baffle with specular reflection is highly dependent on low reflective paint and precise machining, and because of this reason diffused baffle is easier to fabricate. The baffle with a straight vane has a lower Point Source Transmittance (PST) of \( 10^{-6} \), whereas baffle that are grooved vanes and have no vanes have PST of \( 10^{-5} \) and \( 10^{-3} \), respectively. It has a half FOV of 7.5° and exclusion angle of 27°. The detailed method for baffle design is explained by Jacobs.

The baffle design should consider the following guidelines, which were suggested by Heinisch. The star tracker FOV should not interfere with the baffle wall or edges. At least two reflections from a blackened surface are required between stray light source and the optical elements. The stray light within the baffle is required to have a maximum number of reflections before it enters the sensor. Minimum number of edges should be exposed to the Sun. The vanes of the baffle should have sharp edges. The baffle is to be designed based on the required star tracker FOV and exclusion angle. The exclusion angle is the minimum angle at which light from a bright object outside the FOV can reach the lens surface. The lower the exclusion angle the better the attenuation to stray light. A baffle with higher length to diameter \( (L/D) \) ratio has a lower exclusion angle, but a baffle with a higher \( (L/D) \) ratio becomes heavier and larger. The baffle being...
been reported by Fest. Another important factor is the re-
1 mm. The details regarding vane design and placement have
rectly to the optics. The thickness of the ba-
thes the risk of re-
t between the vanes. The number of vanes should be optimized
vanes. In order to reduce the re-
etects the stray light di-
angle in the baffle is shown.

If the orientation of the APST optical axis is normal to the
Sun, it’s estimated that only the Sun directly illuminates the
first vane. If the orientation of the APST optical axis is nor-
mal to the Earth, it illuminates up to the third vane directly.
The illumination of stray light attenuates as it undergoes mul-
tiple reflections within the baffle before it reaches the lens
surface. The maximum stray light angle from the earth is
68°, which is shown in Fig. 12 and Fig. 14. The APST
should maintain a minimum offset angle of 42° and 68° from
the Sun and Earth respectively, to efficiently identify the stars
with a visual magnitude of 5.85. Based on this design, a baffle
for the APST will be manufactured and tested using a so-
lar simulator.

9. Radiation Tolerance

The APST will be installed in the SNUSAT-2 Earth obser-
vation nanosatellite. It’s planned to be operated in a Sun
synchronous polar orbit. The altitude of the orbit has not
been fixed but it will be around 400 to 600 km. The elec-
tronics in a satellite are always vulnerable to charged par-
ticles from radiative sources. The energy, flux, and fluency
of these charged particles varies based on the altitude and in-
clination of the orbit. Due to the radiation, electronics in sat-
ellite malfunctions and can even lead to functional failure.
This is overcome by using radiation-hardened devices. How-
ever, due to high cost and limited availability, it’s not acces-
sible for nanosatellites.

The COTS components are accessible for nanosatellite,
but they are not qualified for space environment. Therefore,
the components are qualified by radiation ground testing to
determine the lifetime in the target orbit. The main radiation
sources are trapped charged particles in Van Allen’s Belt
which extends from 300 to 36,000 km. The South Atlantic
Anomaly is one of the main problems faced by satellites in
LEO. Next, solar particle events like solar flares and coronal
mass ejection occurrence are based on an 11 year solar cycle.
Finally, galactic cosmic rays which are dominant over the
poles due to the weak magnetic field. In SPace ENVIronmen-
tal Software (SPENVIS), all of these radiative sources are
given as inputs and the radiation exposure in the target orbit
is estimated. The ionizing particles lose their energy when
traveling through matter and the energy is deposited in the
matter. Over time, the charge accumulates, and this is known
as total ionizing dose (TID). The TID for silicon for a period
of one year at the orbital altitude of 400 to 600 km and incli-
nation of 90° is estimated using SPENVIS.

Table 10 shows the TID accumulation for different shield-
ing thicknesses over one year. By increasing shielding thick-
ness, the accumulated dose is reduced; however due to
weight constraints, a thickness of 2 to 3 mm is feasible.
Based on the literature review, at high inclination orbit
(705 km, 98°) with shielding of 2.54 mm, the component ac-
cumulates a TID of 4 krad and this data is close to our es-
timation using SPENVIS. In general, COTS components
have a radiation tolerance of 1–10 krad/year and silicon
has a dose limit of 5 krad/year. These numbers convey that, if the APST has (Al) shielding of 3 mm, it can survive in orbit for a period of one year.

### Table 10. Total mission dose for one year.

<table>
<thead>
<tr>
<th>Aluminum shielding thickness (mm)</th>
<th>Total ionizing dose (krad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>3.040</td>
</tr>
<tr>
<td>1.4</td>
<td>5.9</td>
</tr>
<tr>
<td>2</td>
<td>3.04</td>
</tr>
<tr>
<td>3</td>
<td>1.39</td>
</tr>
</tbody>
</table>

10. Conclusion

This paper details the hardware requirements of Pico star trackers. The focus of this paper is selection of an image sensor and imaging optics based on the estimation of FOV, SNR, PSF, focal ratio because most current research papers on Pico star trackers have not revealed information on the details of selecting images sensor, and optics, which are the most important factors for a star tracker. The next important factor is baffle design, since the current research paper illustrates baffle design for a larger scale, a proper design is needed to reduce the size of the baffle. Therefore, important aspects in baffle design and estimation of maximum Earth stray light angle are estimated. In addition, the feasible algorithms for star trackers and their characteristics are briefed. Finally, two possible design for the Arcsecond Pico star tracker are established.

Based on this analysis, it’s estimated that the ON-Semi MT9P031 image sensor combined with Lensation low focal ratio lenses of 1.2 to 1.8 can achieve the required limiting magnitude of 5.85 and 5.35 for the CFOVs of 17° and 22°, respectively. The night sky test results show that the BHR16012 lens with a focal ratio of 1.2 (1 MP) and B3M16018 with a focal ratio of 1.8 (3 MP) detect stars of 6 magnitudes with exposure time of less than 200 ms. The focal number of 1.2 shows unsymmetrical images of stars (aberration and distortion), whereas 1.8 focal lens shows more symmetric images, which will help in accurate centroiding and successful identification of the stars. Therefore, the MT9P031 image sensor and B3M16018 imaging lens were selected for the APST. The test results show that the APST will be able to detect stars with a magnitude of 5.85 with an exposure time of less than 200 ms. Accordingly, this ensures 100% sky coverage during static imaging. However, the sky coverage will decrease during dynamic imaging (i.e., due to high slew rate). The night sky test to estimate the sky coverage at slew rate of 0.1 to 0.5°/s will be tested in the future. The author detailed two possible designs, α and β for APST in Table 8. Design α has been selected for the APST based on the availability of a quality lens (i.e., focal ratio of 1.8) that can produce symmetric images without aberration and doing so with high accuracy. However, the authors also suggest readers to select either design α or β based on mission and system requirements, which is explained in the fifth section of this paper.

The maximum stray light angle from Earth is estimated to be 68°. A baffle with a length of 50 mm and exclusion angle of 27° has been designed with beveled vanes. The advantages of an APST include a small size that fits in pico-, nano- and micro-satellites, light weight, and low power consumption, while providing high accuracy. The software development and testing of an engineering model will be conducted by the end of 2017 and the flight model will be ready by the first quarter of 2018.

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