

Development of the Arcsecond Pico Star Tracker (APST)

Vishnu Anand Muruganandan¹⁾ Ji Hyun Park¹⁾ Abhas Maskey¹⁾ In-Seuck Jeung^{*1)} Sangkyun Kim²⁾ Gwanghyeok Ju³⁾

¹⁾ Institute of Advanced Aerospace Technology, Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea

²⁾ Laboratory of Space Environment Interaction Engineering, Kyushu Institute of Technology, Japan

³⁾ Lunar Exploration Program Office, Korea Aerospace Research Institute, Daejeon, Korea

The second generation star tracker estimates pointing knowledge of the 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 nanosatellite and estimated to provide pointing knowledge in an arcsecond. The APST is planned to be operated in 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, survey of algorithms for star trackers, and comparison of the specifications of APST with other Pico star trackers are detailed. The Field of View estimation shows that 17° and 22° is suitable for APST and it reduces stray light problems. In order to achieve the sky coverage of 100%, 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 Signal to Noise Ratio of APST and night sky test results. The maximum earth stray light angle is estimated to be 68° and miniaturized baffle is designed with the exclusion angle of 27°.

Key Words: Nanosatellite, Attitude determination, Pico Star Tracker, APS camera, and Baffle.

1. Introduction

The SNUSAT-2 is a technology demonstration mission in nanosatellite platform. One of the technical objectives of this mission is to develop Pico Star Tracker which can estimate the attitude of the satellite in arcsecond accuracy. The star trackers in commercial market are heavy, larger in size, power consuming, and costly for nanosatellites. Hence optimized Arcsecond Pico Star Tracker (APST) for SNUSAT-2 is under development in Seoul National University. The APST is designed based on the mission requirement and limitations of nanosatellite. The main components of APST are image sensor, imaging lens, and processor which are selected from COTS (Commercially off-the-shelf). The baffle for the star tracker is designed and will be 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 the selection of image sensor, imaging lens, processor and baffle design. In addition the design of various Pico star trackers and their algorithm are analyzed in detail.

2. Current pico-star trackers

The star trackers for pico and nanosatellites have been developed by various institutions around the world. The most prominent five pico-star trackers which have produced results in the ground testing are discussed in this section. Table 1 shows the important parameters of the pico-star trackers and its corresponding imaging sensor and lens. In general pico-star trackers have the weight up to 90 g but they do not include the weight of the baffle. The STC-2 has

lowest weight of 65 g, developed by Sternberg Astronomical Institute Lomonosov Moscow State University¹⁾. The size of the pico star trackers are designed to fit within 0.5 U (50mm x 100mm x 10mm) which is half the size of the cubesat.

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

Parameters	ST-16	ST-200	Cube star	STC-2	Pico star
Weight (g)	90	74	90	65	70
Size (mm)	60x46 x58	30x30 x38.1	46x33 x70	57x23 x73.5	30x38 x80
Power (mW)	250	220	350	250	250
Accuracy (arcsec)	PY-7 R-70	PY-30 R-200	PY-36	PY-10 R-50	PY-36 R-144
Update rate (Hz)	LSM-1	LSM-1 TM-4	LSM-1	TM 10	LSM-4
Max Slew rate (deg/s)	3	0.3	0.3	2	0.3
Image sensor specifications					
Resolution (MP)	5	4	0.5	0.6	0.3
Pixel size (µm)	2.2	2.2	5.6	10	5.6
Sensitivity (V/lux.s)	1.4	1.4	--	--	16.5
Imaging lens specifications					
Focal ratio	1.2	--	1.2	1.17	1.8
Focal length (mm)	16	--	6	10.5	16
CFOV (deg)	20.03°	--	42.33°	19.64°	12.51°
Limiting Magnitude	5.75	6	3.8	5.5	6.46

The ST-200 is the smallest pico star tracker of 30x30 x38.1 mm³ without including baffle developed by Berlin Space Technologies, Germany. The ST-200 has the lowest nominal power consumption of 220 mW²⁾. The ST-16 has the highest accuracy of 7 arcsecond (Pitch/Yaw) and 70 arcsecond (Roll) developed by Ryerson University, Canada³⁾. In LIS (Lost in Space) a-prior information about satellite is not known hence update rate is lower. But in TM (Tracking Mode) a-prior information about satellite is known using other sensors hence it has higher update rate. The nominal required slew rate in LEO is 0.1° to 0.3°/s. When satellite maneuver higher than nominal slew rate, the image of star will smear. But ST-16 is operational up to 3°/s by post processing the image. The most of the pico-star trackers uses low resolution image sensor of less than 1 Mega Pixel (MP) except ST 16 and ST-200 uses high resolution image sensor of 4 MP and 5MP respectively. The selection of image sensor include various aspects which will be detailed in the next sections.

Due to the limitations in size the pico-star tracker are using imaging lenses with low-focal number which comparably produce bright images. The focal ratio of 1.2 to 1.8 is optimum for pico-star tracker. Most of the pico star tracker are designed with FOV of less than 20 but Cube Star developed by University of Stellenbosch, South Africa uses WFOV of 42 which requires less number of stars in catalogue but relatively low accuracy and vulnerable to stray lights⁴⁾. Based on the FOV requirement the focal length of imaging lens varies from 6mm to 16mm. The focal length of 16mm 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 which is detectable by star tracker. The Pico-star developed by University of Wuerzburg, Germany has the high sensitivity image sensor hence it can detect stars up to 6.46 magnitude⁵⁾.

As per the current status ST-16 is the only Pico star tracker which has been launched in space on 2013 in SkySat-1³⁾. But the performance of ST-16 was lower than the expectation due to chromatic aberration of the lens. The modified ST-16 RT contains the customized lens and launched in 2014 and 2016 in SkySat-2 and SkySat-2C respectively⁶⁾. It produced better results after implementing customized lens. The ST-200 and Cube Star will be launched into orbit in QB50 mission. Based on the literature review and mission requirement, the possible design requirement for APST are listed in the Table 2.

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

Parameters	Requirements
Weight including baffle (g)	< 150
Size including baffle (mm ³)	48x48x90
Nominal Power (mW)	< 500
Accuracy 3σ (arcsecond)	< 50 (PY), < 200 (R)
Update rate LIS (Hz)	1
Slew rate (°/s)	0.1 to 0.3

3. Field of View (FOV) estimation.

The HIPPARCOS-2 (High Precision Parallax Collecting Satellite) catalog is used for APST. The HIP-2 contains 118,218 stars in total and accuracy of star magnitude is up to a factor of 4⁷⁾. In APST, the stars of magnitude brighter than 6 are used. Hence for initial analysis, only 4,558 stars are used. The Fig.1 shows number of star 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 in the galactic poles. The Fig.2 shows the distribution of stars of magnitude brighter than 6 at 2016 June and its clearly implies the stars around the poles are relatively less when compared to the equator. The average density of stars brighter than 6 magnitude over entire sky, galactic plane, and galactic pole are 0.15, 0.32, and 0.13 per square degree respectively⁸⁾.

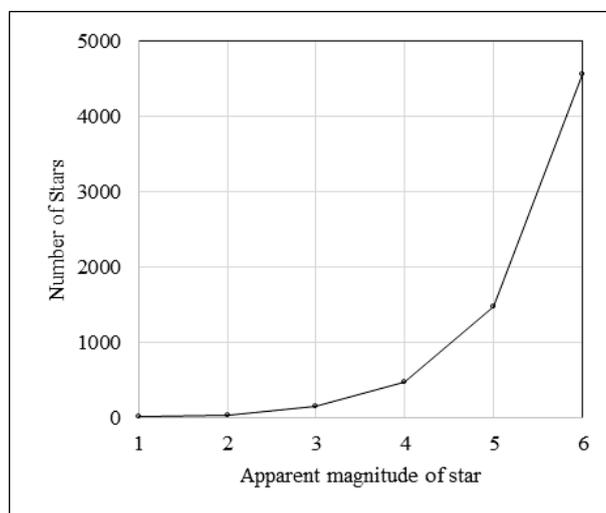


Fig.1. Number of stars corresponding to its magnitude

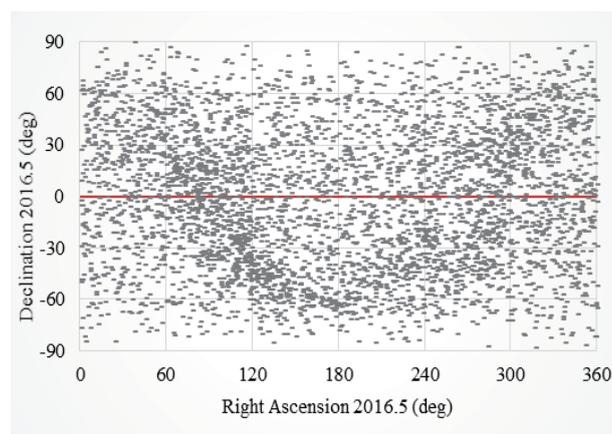


Fig.2. Distribution of stars over the sky.

The FOV of star tracker is a crucial factor which determines the requirement of image sensor, optics and baffle. The star tracker with Wide Field of View (WFOV) of 15° to 40° is the optimum range for the nanosatellites. The WFOV has advantages like lower memory, less processing time and moderate accuracy. The star tracker needs minimum three star in the field of view to determine the attitude of the satellite. But there are possibilities of occurring false star in the image due to stray light from the sun, earth, moon and thermal noise of the image sensor. Hence minimum five stars is required in the FOV to identify the real stars. The APST is required to have minimum 99% sky coverage containing minimum 5 star in a FOV to determine attitude of the satellite.

The simulations are performed in MATLAB to determine the required FOV containing minimum five stars at any part of the sky. The stars of brighter than 6 magnitude are used for this simulation. The Circular Field of View 17°, 20°, 22°, 25°, 30°, 35° and 40° are used for analysis. The right ascension and declination of stars are projected into the unit sphere and the simulation creates the pointing direction of the star tracker in random location. The stars within half of the FOV are assumed to be in the FOV of star tracker. The simulation is performed by generating 10,000 randomly generated locations. The error in this simulation is $1/\sqrt{N}$ where N is the randomly generated locations. The results contain error of 1 in every 100 random locations. The simulation method and codes for FOV estimation are made by “Scott Mulligan” and the readers can go through for the details of this simulation and code⁹⁾. The Fig.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 required sky coverage for APST is 99% and the maximum of 100%. The Table 3 shows required limiting magnitude for sky coverage of 99% and 100% for various CFOV.

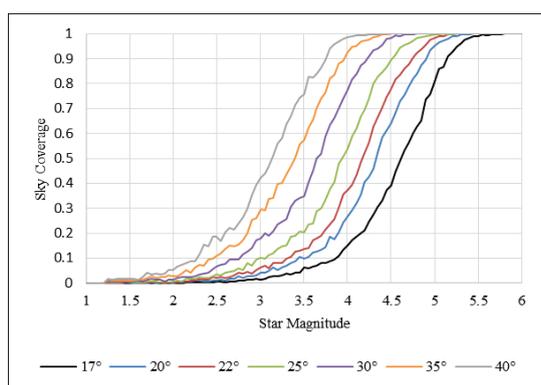


Fig.3. Sky coverage for various FOV and required star magnitude

In order to acquire 100% sky coverage, the CFOV of 17° requires limiting magnitude of 5.85 whereas at 40° limiting magnitude is 4.4. It implies wider the FOV requires minimum of number of stars and processing time can be significantly reduced. But however the wide FOV of 40° and 30° is more vulnerable to stray lights from sun, earth and moon. Hence 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 FOV will be selected for APST. The selection of imaging sensor and optics for star tracker should be based on the FOV and limiting magnitude requirement. The image sensor and optics of APST are selected based on the CFOV 17° and 22° and limiting magnitude of 5.85.

Table 3. Required limiting magnitude for sky coverage of 99% and 100% for various Circular Field of View

CFOV (deg)	Limiting magnitude for sky coverage of 99%	Limiting magnitude for sky coverage of 100%
17	5.5	5.85
20	5.25	5.5
22	5.1	5.35
25	4.9	5.3
30	4.55	5
35	4.35	4.55
40	4.05	4.4

4. Selection of image sensor and imaging optics

The image sensor contains various parameters which determines its function and performance. The APS (Active Pixel Sensor) based CMOS sensor is preferred instead of CCD due to advantages of windowing, lower power consumption, resistance to radiation, and lower price. The image sensor can either be monochrome or color. The monochrome is preferred because its quantum efficiency is higher than color sensor and star tracker does not need color information of the star. The usage of color sensor for star tracker will be one of the research topic in future. The Table 4 shows the three CMOS based monochrome image sensor and the important parameters to be considered¹⁰⁾. The sensor size of 1/3" to 1/2" inch is suitable for APST.

Table 4. Important parameters of image sensors

Parameters	MT9P031	AR0134	Python 1300
Sensor size (inch)	1/2.5	1/3	1/2
Pixel size (μm)	2.2	3.75	4.8
Resolution (MP)	5	1.2	1.3
QE at 525 nm (%)	63	77	59
Sensitivity (V/lux.s)	1.4	7.7	6.1
Read noise (e ⁻)	7.64	6.58	9.28
Full Well Capacity (e ⁻)	6693	5542	6057
Dynamic range (dB)	58.3	64	55.84
Shutter	Rolling	Global	Global

The pixel size is the important factor in determining accuracy of the sensor, smaller the pixel size higher the accuracy. The star tracker usually have image sensor with resolution less than 1 MP (Mega Pixel). But the problem with high resolution sensor is it takes longer processing time which will reduce the update rate of star tracker. Higher the quantum efficiency, lower the read noise and dark noise are better

because it will able to image 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 images sensor with higher dynamic range. The CMOS sensor usually have rolling shutter but the latest CMOS sensor have global shutter. The global shutter has the ability to image without smearing even if satellite maneuvers relatively high rate whereas the rolling shutter will smear the image. Hence global shutter is preferred over rolling shutter. Final important thing is availability of the image sensor in the market.

The first preference is AR1034 because among three it has higher sensitivity, Quantum Efficiency and dynamic range. But only MT9P031 is available and it satisfies most of the requirements. The ON-Semi MT9P031 has already been used in star tracker ST-16 developed by University of Ryerson, Canada. which have been successfully operated in many missions since 2013. Hence MT9P031 monochrome image sensor is selected for APST. Based on the MT9P031 image sensor, the imaging lens is selected. The S-mount lenses are chosen due to less weight. The lens with low focal ratio (1.2 to 1.8) maximize the light collection but aberration increases rapidly with decreasing focal ratio. Spherical and chromatic aberration in lens may cause failure during the execution of star identification. The following equation shows the relationship between the aberration and focal ratio.

$$\text{Spherical aberration} \propto 1/(\text{focal ratio})^3 \quad (1)$$

$$\text{Coma} \propto 1/(\text{focal ratio})^2 \quad (2)$$

$$\text{Astigmatism} \propto 1/(\text{focal ratio}) \quad (3)$$

The focal length of 16mm and 12mm provides the FOV of 15° and 20° respectively. Also the focal length determines the accuracy of the star tracker, higher the focal length better the accuracy of the star tracker. Using 16mm and 12mm focal length the theoretical pixel accuracy of 28.4 arcsec and 37.8 arcsec are obtained respectively.

$$\text{Field of View} \propto \arctan(\text{sensor size}/\text{focal length}) \quad (4)$$

$$\text{Pixel accuracy} \propto \arctan(\text{pixel size}/\text{focal length}) \quad (5)$$

The resolution of the lens should be in MP for high resolution image sensor otherwise the output will be blurred image. Which means the magnitude of signal is reduced in the image sensor. The lens are chosen with 1 MP to 3MP resolution. Theoretically the 1MP and 3MP lens can resolve 8.9µm/line and 5.9µm/line respectively. This characteristics will be studied during laboratory and night sky testing in detail. Based on the testing results, one of these lens from Lensation in Table 5 will be chosen. The distortion is one of the important factor in determining the quality of the lens. There are three types of distortion, barrel, pincushion, and mustache distortion. The distortion of lens should be less than 1 %. Antireflection coating for the lens increases the transmission of the light. The imaging lens with filters and customized lenses will enhance the quality and performance of the star tracker, but these are expensive for and will be

considered for the development in future.

Table 5. Important parameters of imaging lenses

Parameters	BHR 16012	BL 16014	B3M 16018	BSM 12016
Optical format (inch)	1/2"	1/3"	1/2"	1/2"
Focal length (mm)	16	16	16	12
Focal ratio	1.2	1.4	1.8	1.6
FOV (deg)	15	15	15	19.6
Resolution (MP)	1	1	3	<1
Resolution (µm/line)	8.98	5.96	5.18	9.21
Weight (g)	12	16	--	5
Picture of the imaging lenses				

5. Sensitivity of APST

The previous sections have established the required FOV, available image sensor, optics. The Signal Noise Ratio (SNR) of APST is one of the factor to verify if the image sensor and imaging lens meets the requirement of FOV. If the APST has minimum of SNR 8, it can easily detect star. The signal of the APST is estimated by using Eq. 6, where R is the radius of the lens, t is exposure time (0.1s), $F_0 = 21,161 \text{ ph/s/mm}^2$ is the theoretical flux of zero magnitude star detected by MT9P031 image sensor (based on the Quantum efficiency of image sensor)¹¹, m is the limiting magnitude of the star tracker ($m = 5.35, 5.85$).

$$S_e = (3.14 R^2 t F_0) / (2.5^m) \quad (6)$$

The noise estimation of MT9P031 image sensor is shown in Table 6. the detail method of estimation of noise for APS based image sensor is given^{12) 13) 14)} and estimated by the Eq.7

Table 6. Noise estimation for MT9P031 image sensor.

Parameters	Noise (e)
Dark current (D)	0.39
Dark current non	0.04
Read noise (R)	3.5
Quantization noise (Q)	0.46
Photon shot noise (S)	$\sqrt{S_e}$

$$\text{Total Noise} (N_e) = \sqrt{S+D+DCNU+R^2+Q^2} \quad (7)$$

The number of pixels included in the star image is based on PSF (Point Spread Function), by increasing the PSF the number of pixels that contribute noise increase whereas the magnitude of signal decrease. The symmetric PSF is considered for analysis and due to the slew rate of the satellite, the noise in the pixels will increases, it is function of focal length. The total number of pixels in PSF is estimated by the Eq. 8¹⁴⁾

$$N_p = \sqrt{3.14 P^2 + 2P (F \tan(\omega t) / \gamma)} \quad (8)$$

Where P is the PSF radius in pixels, F is the focal length (mm), ω is the slew rate ($0.1^\circ/s$), t is the exposure time (0.1 s) and γ is pixel size ($2.2 \mu m$). The SNR for various PSF radius and for corresponding focal ratio of lens are estimated in Eq. 9. The graph in Fig.4 implies that, the PSF radius of 0.5 has higher SNR when compare to PSF radius of 3. Focal ratio is another important factor increasing the SNR, lower the focal ratio has more signal hence it has higher SNR.

$$SNR = S_e / (N_e N_p) \quad (9)$$

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

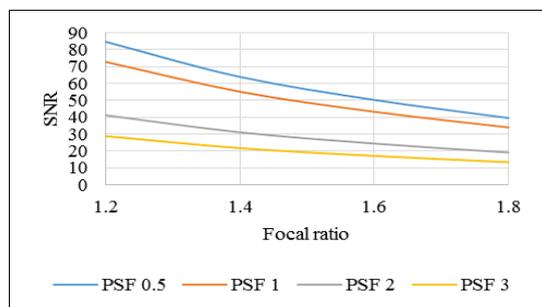


Fig.4. SNR Vs Focal ratio of various PSF

Table 7. Estimation of SNR for various focal ratio and PSF.

Focal Length (mm)	Focal ratio	SNR PSF0.5	SNR PSF 1	SNR PSF 2	SNR PSF 3
16	1.2	84.6	72.8	41.2	28.8
	1.4	63.9	55.1	31.1	21.8
	1.6	50.3	43.3	24.5	17.1
	1.8	39.6	34	19.2	13.4
12	1.6	50.2	38.8	21.5	14.9

Based on the analysis from previous sections, two possible design of the star tracker is chosen. The MT9P031 image sensor with focal length of 16mm and 12mm have CFOV of 17° and 22° . Based on the sensitivity analysis APST with CFOV of 17° and 22° can detect stars of 5.85 and 5.35 respectively which assures sky coverage of 100%. The Table 8 lists the two possible design of APST. The both of the design α and β have its own advantage and disadvantage. The design α has better accuracy but total number of stars are higher hence execution time for algorithm would be relatively high. The total number of stars in design β are less hence it consumes relatively less execution time but the accuracy is relatively lower. Yet both of this design are suitable for APST, based on night sky results any one of the design will be selected.

Table 8. Two possible design for APST

Parameters	Design α	Design β
Min. No. of stars in a FOV	5	5
CFOV (deg)	17	22
Limiting Magnitude	5.85	5.35
Total No. of Stars	3897	2237
Focal length (mm)	16	12
Focal ratio	1.2, 1.4, 1.6, 1.8	1.6
Accuracy (arcsecond)	28	38
Executing time	Higher	Lower

6. Operational Algorithms

The star tracker operation consist of four important steps,

- i) Star detection
- ii) Centroiding
- iii) Identification
- iv) Attitude determination

The star detection is based on the sensitivity of APST and background threshold. The previous section of this paper detailed on the theoretical estimation of star detection. The star tracker accuracy is limited by the pixel size and focal length. In order to obtain subpixel accuracy, the star tracker is purposefully defocused to spread over many pixels (which means the PSF of the star image increases). Then centroiding algorithm is used to identify the centroid of the star image. Basically centroiding has two types of algorithm, Centre of mass which increase the accuracy up to 1/10 of a pixel. Gaussian distribution method produces accuracy of 1/100 of a pixel but it's complex to implement, hence of Centre of Mass would be easier to implement and achieve reasonable accuracy.¹⁵⁾ But still centroiding without defocusing would be advantage in achieving higher SNR and to overcome the aberration issues.

Using the centroid coordinates of star images, the identification algorithm is implemented. The identification algorithm identifies stars in the image by matching it with onboard star catalog. The identification algorithm contains two main classification, pattern recognition and sub-graph. The pattern recognition is based on the patterns produced by connecting the stars (like Constellation of the stars) ex: grid algorithm, ring algorithm but the pattern recognition need higher star density which means more faint stars. The sub-graph method use the distance and angle information between the stars for identification. The Table 9 contains the list of important identification algorithm and their characteristics. The main characteristics of efficient identification algorithm are highly robust, less complex, small database, less time for execution.

Comparing the four algorithms in Table 9¹⁶⁾ geometric voting is more suitable for APST because it is highly robust, high success rate and small database require, but one disadvantage is it requires more time for execution when comparing to other algorithms. The second option would be Pyramid algorithm due to well know success rate, robustness and less execution time. Grid algorithm or any other based on

pattern recognition would be the option for future development because the pattern recognition need less percentage of trigonometrical information of stars, this could be serious problem due to aberrations, noises and stray light and this can be overcome by pattern recognition but it need higher star density, further work on developing optimized pattern based algorithm would be efficient. Triangle algorithm is well known for its less complexity and lower database but it does not provide high success rate. The final operation is determining the attitude from the identified stars in the image. The attitude determination algorithm is used to estimate the rotation angle between the star tracker frame to inertial frame. The commonly used algorithms are TRIAD, QUEST, ESOQ.^{16) 17) 18)}

Table 9. Comparison of various identification algorithms

Parameters	Triangle	Pyramid	Geometric voting	Grid
Robust	Low	High	High	High
Complexity	Normal	High	Normal	Normal
Database	Small	Small	Small	large
Accuracy	Sub pixel	Sub pixel	Sub pixel	Pixel
Time	Less	Less	normal	Less

7. Night Sky Testing

Based on the theoretical estimation of sensitivity of image sensor and imaging lens, the MT9P031 demo-kit and Lensation lenses is used for the testing which is shown in Fig.5 and Fig.6. The MT9P031 demo-kit contains the wide angle lens which has been replaced by lensation lens using an adapter is shown in Fig.5.

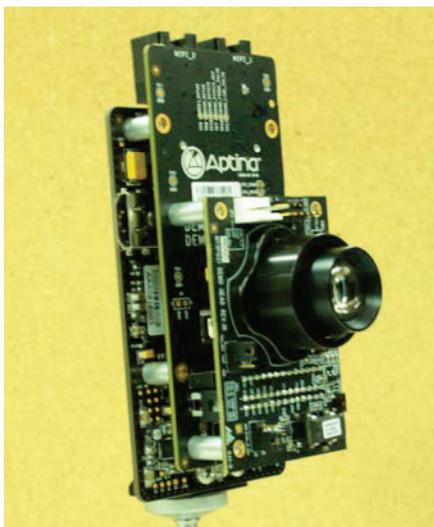


Fig.5 ON Semiconductor MT9P031 demo kit

night sky testing, the hardware is tested if it can able to 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 in Seoul National University and around Seoul but due to city lights, the test results was poor. Hence we traveled 160 km south east of seoul to yongjin-ri which is located in the state of danyang gun. This location is remote area and there are no artificial lights in the surrounding. Based on the Accu weather forecast there was no clouds (100% clear sky) on August 12, 2016 at 1 am. The humidity was above 90%, but dry weather is better condition for star imaging.

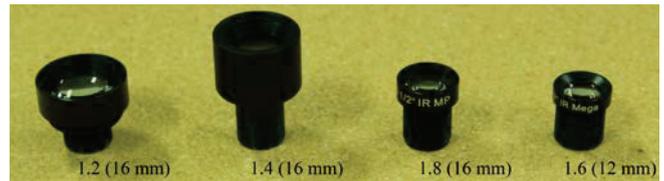


Fig.6 Lensation imaging lenses for APST

The stars near the zenith have the brightness loss of 0.2 visual magnitude and stars near the earth surface have the brightness loss of 1 visual magnitude due to the high atmospheric air mass. Hence stars within the zenith angle of 45° is imaged during the night sky testing which have the brightness loss of 0.3 visual magnitude¹⁹⁾. Which mean if APST can detect 5.7 visual magnitude stars then in orbit, it could detect 6 visual magnitude stars. All the four lens in Table 5 are tested with MT9P031 demo kit for the exposure time of 200ms and with maximum gain value.

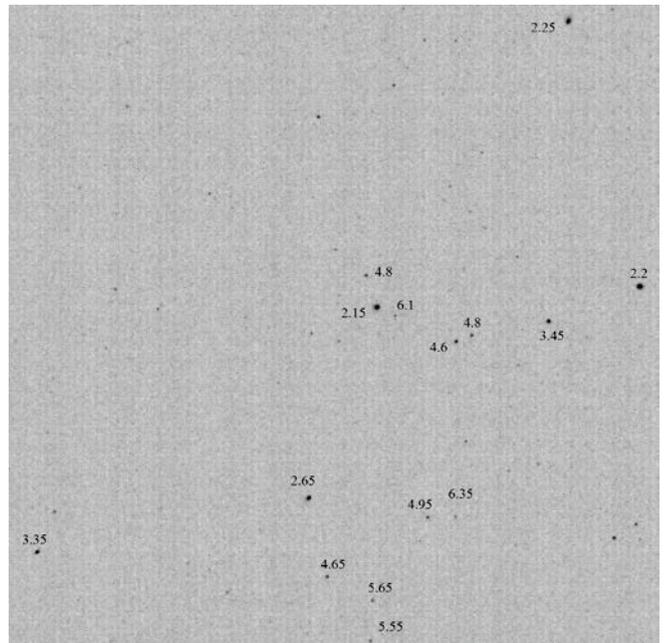


Fig.7 Cassiopeia constellation imaged by BHR16012 lens with exposure time of 200 ms and maximum gain.

The paramters of MT9P031 image sensor and Lensation lenses is shown in Table.4 and Table.5 respectivley. In this

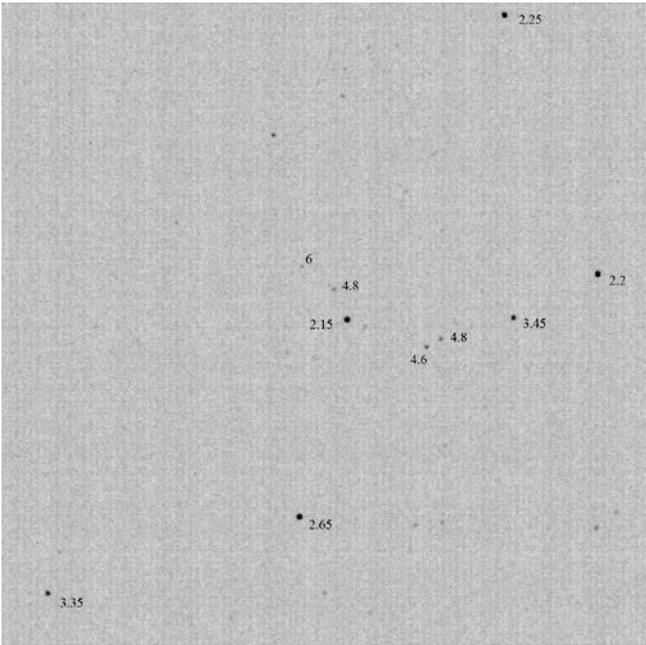


Fig.8 Cassiopeia constellation imaged by B3M16018 lens with exposure time of 200 ms and maximum gain.

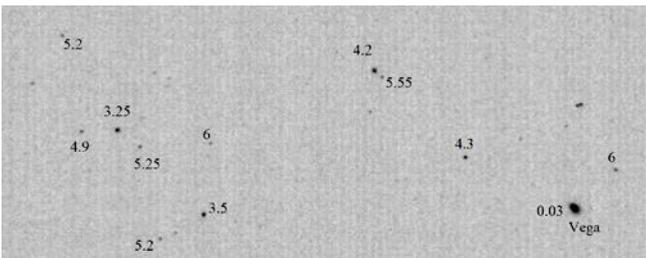


Fig.9 Lyra constellation imaged by BHR16012 lens with exposure time of 200 ms and maximum gain.

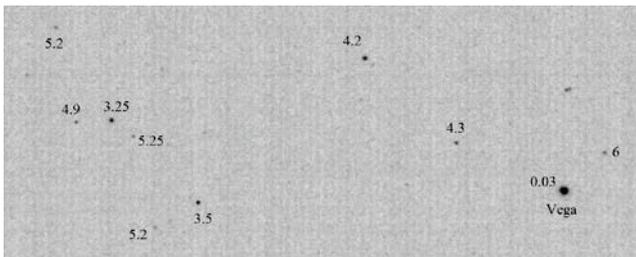


Fig.10 Lyra constellation imaged by B3M16018 lens with exposure time of 200 ms and maximum gain

The two lenses are selected based on night sky testing. The BHR16012 is the brightest lens of focal number 1.2 and resolution of 1 MP. The Fig.7, and Fig.9 are images of Cassiopeia and lyra constellation imaged by BHR16012 at 200 ms exposure. The numbers in the Fig.7 to Fig.10 shows the visual magnitude of the stars. The BHR16012 lens imaged star of visual magnitude of 6.1 which means in orbit it can detect stars of 6.4 magnitude. The APST requires only visual magnitude of 5.85 hence it can operate with exposure time less than 200 ms. The disadvantage of BHR16012 are low resolution and aberration. In Fig. 9 the star vega shows aberration (unsymmetrical) and in Fig.7 stars with magnitude

of 2.25, 2.65, 3.35 shows aberration and distortion in the lens. The B3M16018 has focal number of 1.8 and resolution of 3MP. The Fig.8 and Fig.10 which contains the image of B3M16018 are not as bright as BHR16012 but still it can image star of 6 magnitude at 200 ms exposure time. But the B3M16018 have produced symmetric image in Fig.8 and Fig.10 without aberration and distortion which is better than BHR16012. The stars imaged by B3M16018 are more symmetrical than BHR16012, it will help to accurately define the centroid of the star and high success rate of identifying the stars. Hence B3M16018 lens is chosen for APST. These testing confirms that existing hardware can detect stars of 5.85 magnitude with the exposure time of less than 200 ms. This shows that APST will have 100% sky coverage during static imaging but the sky coverage will decreased during dynamic condition (high slew rate). This night sky testing is done without the operation of algorithms and baffle. The night sky test with various slew rate will performed.

8. Baffle design

The stray light from sun, earth and moon are one of the major factor in lowering the performance of the star tracker, even it could lead to failure in certain conditions. As APST will be operational in Low Earth Orbit, the dominant stray light source is earth. The SNUSAT-2 orbital altitude will be around 400 to 700 km which is far less than the radius of the earth, hence the earth is viewed as extended stray light source. Whereas the bright stray light sources like sun and moon are viewed as point source due to their long distance from LEO satellites. In order 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 in order to reduce the stray light intensity. Since earth is extended surface, the effective stray light region of the earth is calculated. The Fig.11 shows the orientation of APST which is almost normal to sun and earth, also it shows the effective stray light region of earth.

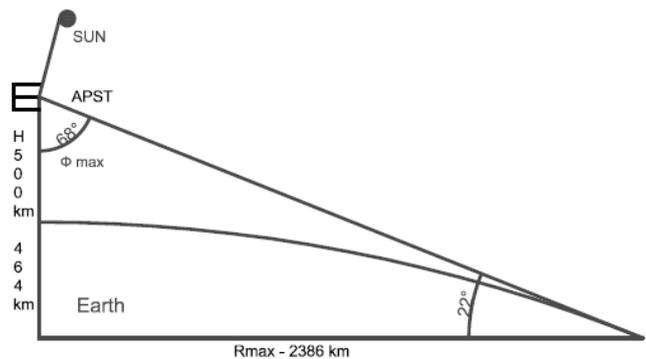


Fig.11 Extended stray light source from earth

The maximum stray light angle due to earth, which incident on the APST is known as Φ_{\max}^{20} .

$$\Phi_{\max} = \arcsin (R_{\text{earth}} / (R_{\text{earth}} + H)) \quad (10)$$

The average radius of earth R_{earth} is 6370 km, H is the altitude of the orbit (500 km) and the Φ_{max} is 68° . The maximum radius of the effective stray light region R_{max} ,

$$R_{\text{max}} = R_{\text{earth}} \cos\Phi_{\text{max}} \quad (11)$$

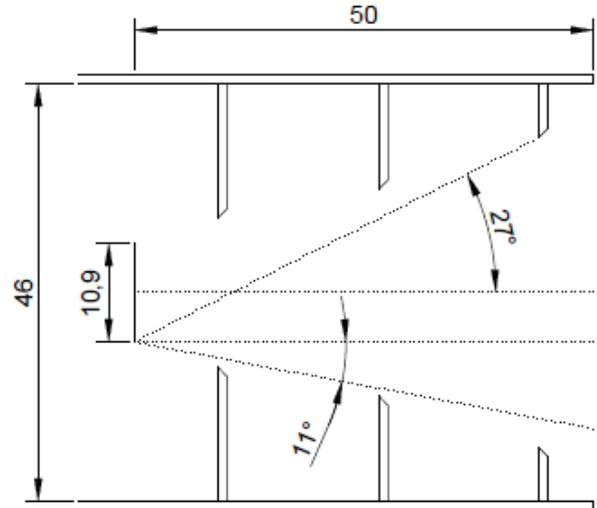
The Φ_{max} is useful in designing the baffle and star tracker orientation. The maximum irradiance from sun is 918.1 W/m^2 and earth reflects 35% of the sun light which is known as albedo. The maximum irradiance from earth is 321.3 W/m^2 . The irradiance of full moon is 1.4 mW/m^2 ²¹⁾. The function of baffle is to prevent stray lights from bright objects (sun, earth, and moon) outside the FOV from directly reaching the lens surface and to reduce the intensity of stray light, so that the star tracker able to identify the stars effectively. The single stage diffused cylindrical baffle with straight vanes is designed for APST. The double stage baffle is efficient in reducing stray light but due to volume constraints, single stage baffle is designed for APST. Baffle can be designed in either cylindrical or conical shape. The baffle with specular reflection is highly dependent on low reflective paint and precise machining due to this reason diffused baffle easier to fabricate. The baffle with straight vane has lower PST (Point Source Transmittance) of 10^{-6} whereas baffle with grooved and no vanes have PST of 10^{-5} and 10^{-3} respectively ²²⁾.

The baffle design should consider the following guidelines suggested by "Heinsich" ²³⁾. The star tracker FOV should not interfere with baffle wall or edges. At least two reflection from blackened surface are required between stray light source and the optical elements. The stray light within the baffle is required to have maximum number of reflection before it enter the sensor. Minimum number of edges should be exposed to sun. The vanes of the baffle should have sharp edges. The baffle is 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. Lower the exclusion angle has better attenuation to stray light. The baffle with higher L/D ratio (Length and Diameter of the baffle) has lower exclusion angle, but the baffle with higher L/D ratio become heavier and larger. Based on the MT9P031 image sensor and B3M16018 the baffle is designed. The baffle design for APST show in Fig. 12 has diagonal FOV of 22° , baffle length of 50 mm, diameter of the lens and baffle are 10.9 mm and 46 mm respectively. The half field of view of 7.5° and exclusion angle of 27° . The detailed method for baffle design is given by "Jacobs" ²⁴⁾.

Next step is the vanes placement in the baffle. The APST baffle design in Fig.12 contains three straight beveled vanes. In order to reduce the reflecting surface of the vane edge, the edge of the vanes are sharpened, it's known as beveled vanes. The vanes designed with constant beveled angle of 45° because it easier to manufacture. The vane edge thickness of 0.1 mm is achievable. Number of vanes and depth of the vanes in the baffle determines the spacing between the vanes. The number of vanes should be optimized because it enhance the risk of reflecting the stray light directly to the optics. The vanes edges are placed with 1° offset from the FOV to avoid direct illumination. The thickness of the

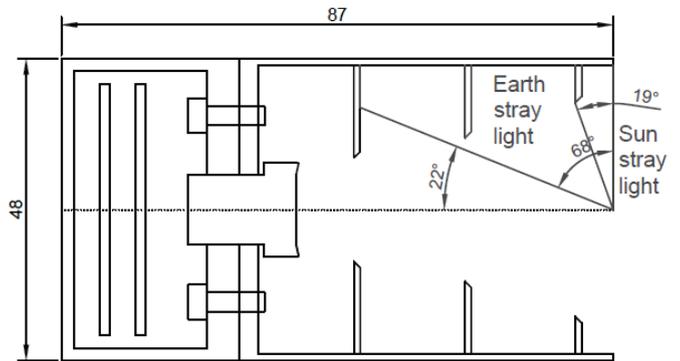
baffle and vanes is 1mm. The detail method of vane design and placement is given by "Eric" ²²⁾

Fig.12 Baffle design for APST



Another important factor is the reflectivity of the black paint, the inner surface of the baffle is painted in order to reduce the scattering of the stray light. The 3M black velvet, Aerogalze Z306, Martin black, Parson black, 3M 401-C10 paint have very low reflectivity. But due to lack to availability black anodized is easier to obtain.

Fig.13. APST design with stray light illumination



The Fig.12 shows the design of APST. The total length of APST is 87 mm and breadth of 48 mm, without baffle the dimension is 37.5mm x 48mm. The left side of the figure includes the optics and two PCB which contain image sensor, processor and flash. The electronics are shielded by Aluminum of 2mm thickness to protect it from space radiation. In the Fig.13 the maximum stray light angle in the baffle is shown. If the orientation of star APST optical axis is normal to the sun it's estimated that only first vane is illuminated directly by the sun. If the orientation of APST optical axis is normal to earth it illuminate up to third vane directly. The illumination of stray light attenuates as it undergoes multiple reflection within the baffle before it enters the lens surface. The maximum stray light angle from earth is 68° which is shown in Fig. 11 and Fig. 13. The APST should maintain minimum offset angle of 42° and 68° from sun and earth respectively in order to efficiently identify the stars of visual magnitude of

5.85. Based on this design baffle for APST will be manufactured and tested using solar simulator and Zemax.

9. Conclusion

This paper details about the hardware requirement of Pico star trackers. The main focus of this paper is selection of image sensor and imaging optics based on the estimation of FOV, SNR, PSF, Focal ratio because most of current research papers on Pico star tracker have not exposed lights on the details of selection images sensor and optics, which are the most important factors in star tracker. The next important factor is baffle design since current research paper illustrates baffle design for larger scale, it's needed to have proper design method for miniaturized baffle. Hence the important aspects in baffle design and estimation of maximum earth stray light angle are estimated. In addition the feasible algorithm for star trackers and their characteristics are briefed. Finally two possible design for Arcsecond Pico star tracker are established.

Based on this analysis it's estimated that 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 CFOV of 17° and 22° respectively. The night sky test results shows that lens BHR16012 with focal ratio of 1.2 (1 MP) and B3M16018 with focal ratio of 1.8 (3 MP) detects stars of 6 magnitude with exposure time of less than 200 ms. The focal number of 1.2 shows unsymmetrical images of star (aberration and distortion) whereas 1.8 focal number lens shows more symmetric images which will help in accurate centroiding and successful identification of the stars. Hence MT9P031 image sensor and B3M16018 imaging lens is selected for APST. The testing results shows APST can detect stars of 5.85 magnitude with exposure time of less than 200ms and hence it assures 100% sky coverage during static imaging but the sky coverage will decrease during dynamic imaging (high slew rate). The night sky test to estimate the sky coverage at slew rate of 0.1 to 0.5 deg/s will be tested in future. The author have detailed two possible design α and β for APST in Table 8. The design α has been selected for APST based on the availability of quality lens (focal ratio of 1.8) which can produce symmetric images without aberration and high accuracy. But the author suggest readers to select either design α or β based on their mission and system requirement which is explained in the fifth chapter of this paper.

The maximum stray light angle from earth is estimated to be 68° . The baffle with length of 50 mm and exclusion angle of 27° are designed with beveled vanes. The advantage of APST are smaller in size which fits in pico, nano, micro satellites, low weight and low power consumption with high accuracy. The software development and testing for engineering model will be conducted by the end of this year, the flight model will be ready by the first quarter of 2017.

Acknowledgments

This research is financially supported by the Space Technology Development Program (NRF-2015M1A3A4A01065787) through the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) and J.H. Park, M. Vishnu Anand, M. Abhas are supported by the Brain Korea 21 program in 2016 (F14SN02D1310).

Reference

- 1) Mikhail Prokhorov, Marat Abuberkerov, Anton Biryulkov, Oleg Stekol shchikov, Maksim Tuchin, and Andrey Zakharov: Star Tracker on Chip, 27th Annual AIAA/USU, 2013.
- 2) Tom Segert, Steven Engelen, Matthias Buhl, Bert Monna: Development of the Pico Star Tracker ST-200 – Design Challenges and Road Ahead, 25th Annual AIAA/USU, 2011.
- 3) Tom Dzamba, John Enright, Doug Sinclair, Kofi Amankwah, Rony Votel, Ilija Jovanovic, Geoffrey McVittie: Success by 1000 Improvements: Flight Qualification of the ST-16 Star Tracker, 28 Annual AIAA/USU, 2014.
- 4) Alexander O. Erlank, Willem H. Steyn: Arcminute Attitude Estimation for Cubesats with a Novel Nano Star Tracker, IFAC, 2014.
- 5) Tobias Schwarz: Prototyping of a Star Tracker for Pico-Satellites, Master thesis, Julius-Maximilians-University Wuerzburg, Germany, 2015.
- 6) Sinclair Interplanetary, <http://www.sinclairinterplanetary.com/> (cited July 2016)
- 7) HIP-2, <http://www.cosmos.esa.int/web/hipparcos/hipparcos-2> (cited July 2016)
- 8) Zakharov, Prokhorov, Tuchin, and Zhukov: Minimum Star Tracker Specification Required to Achieve a Given Attitude Accuracy, Astrophysical Bulletin, 2013.
- 9) Matthew N. Cannata, Michael R. Greene, Scott J. Mulligan, Valdpopovici: Autonomous Star-Imaging Attitude Sensor, York University, Canada, 2007.
- 10) Mono Camera Sensor Review, Point Grey, <https://www.ptgrey.com/camera-sensor-review>, 2015.
- 11) Martin Marciniak, John Enright: Validating Microsatellite Tracker Baffle Tests, AIAA/AAS, 2014
- 12) Kara M. Huffman, Raymond J. Sedwick, James Stafford, James Peverill, William Seng, "Designing Star Tracker to Meet Micro Satellite Requirement, AIAA, 2006.
- 13) Carl Christian Liebe, Leon Alkalai, George Domingo, Bruce Hancock, Don Hunter, Jeff Mellstrom, Ian Ruiz, Cesar Sepulveda, Bedabrata Pain: Micro APS Based Star Tracker, IEEE, 2002.
- 14) John Enright, Doug Sinclair, Tom Dzamba: The Things you can't Ignore: Evolving a Sub-Arcsecond Star Tracker, AIAA/USU, 2012
- 15) Gwanghyeok Ju: Autonomous star sensing, Pattern Identification and Attitude Determination for Spacecraft: An Analytical and Experimental Study, Ph.D thesis, Texas A&M, University, 2001.
- 16) Benjamin B. Spratling, IV and Daniele Mortari: A Survey on Star Identification Algorithms, Algorithms, 2009.

- 17) Ju, G. and Junins, J. L., "Overview of Star Tracker Technology and Its Trends in Research and Development," AAS Paper No. 03-285, AAS John L. Junkins Astrodynamics Symposium, College Station, TX, USA, May 23-24, 2003.
- 18) Ju, G, Kim, H., Pollock, T. C., Junkins, J. L., Juang, J., and Mortari, D., "Lost-In-Space: StarPattern Recognition and Attitude Estimation for the Case of No Prior Attitude Information," 23rd Annual AAS Guidance and Control Conference, Breckenridge, CO, Feb. 2-6, 2000.
- 19) Stewart McKechnie, General Theory of Light Propagation and Imaging Through the Atmosphere, Scotland, Springer, 2016.
- 20) Yujun Du, Yinghong He, Haibin Chen, Weijuan Xin, Bing Xue: Calculation Method of Earth-Atmosphere Stray Light Illuminance on Low-orbit Space Cameras, Journal of Multimedia, Vol. 8, No.6,
- 21) Zhao Shu-fang, Wang Hong-tao, Wang Yu, Ji Cai-yan: Space Luminous Environment Adaptability of Missile-borne Star Sensor, Central South University Press and Springer-Verlag Berlin, Heidelberg, 2012.
- 22) Eric C. Fest: Stray Light Analysis and Control, SPIE Press, USA, 2013.
- 23) Heinisch, Jolliffe: Light Baffle Attenuation Measurement in the Visible, Applied Optics, Vol.10, No.9, 1971.
- 24) Jacobs: A Low Cost High Precision Star Sensor, Master thesis, University of Stellenbosch, South Africa, 1995.

