PARAMETERIZATION AND OPTIMIZATION OF THE ERROR PROPAGATION IN STAR TRACKERS FOR BUDGET-CONSTRAINED CUBESATS

A Thesis presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Aerospace Engineering

by

Gagandeep Thapar

June 2023

COMMITTEE MEMBERSHIP

TITLE:	Parameterization and Optimization of the Error Propagation in Star Trackers for Budget-Constrained CubeSats
AUTHOR:	Gagandeep Thapar
DATE SUBMITTED:	June 2023
COMMITTEE CHAIR:	Leo Torres, Ph.D. Professor of Aerospace Engineering
COMMITTEE MEMBER:	John Bellardo, Ph.D. Professor of Computer Science
COMMITTEE MEMBER:	Kira Abercromby, Ph.D. Professor of Aerospace Engineering
COMMITTEE MEMBER:	Eric Mehiel, Ph.D. Professor of Aerospace Engineering

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 1

THE FUNDAMENTAL QUESTION

Observing and measuring nature are the basic tools we can use to characterize the world around us. We can use increasingly accurate sensors to measure different properties of the universe, however, we must come to terms with a fundamental reality. True values of these measurements are non-observable, that is, we can never verify our measurements in nature and are doomed to contain some error in our work. We can attribute these errors to our measurement techniques and the idea that we only have discrete tools trying to measure a continuous reality.

In space, a key property to measure is the attitude, or orientation, of our spacecraft. The direction we point in is imperative for a variety of reasons such as pointing for power generation, pointing to observe interesting phenomena, and pointing to survive the environment. One such sensor to measure our attitude is the star tracker; a clever technology that utilizes the positions of the stars in the universe to ascertain its attitude. The star tracker, similar to any other sensor, is ladened with pitfalls in its measurement process and, due to a variety of factors, is prone to error. Before we move forward, we must determine why analyzing the error propagation in a star tracker is worth doing; what will benefit from studying how star trackers err.

CubeSats

CubeSats, developed by the Cal Poly CubeSat Lab in 1999 by Prof. Jordi Puig-Suari and Prof. Bob Twiggs, have long been used as a bus for university programs and commercial businesses to fly experiments in Low Earth Orbit, or, LEO. CubeSats typically use COTS, or commercial-off-the-shelf, components as they're characterized by their ease and low-cost of development. While CubeSats have typically been used for simpler observation missions, the technology has been maturing and, as a consequence, as have their mission requirements. Attitude determination and control have been an increasingly popular requirement imposed on CubeSats as a means to accomplish more complex missions i.e., optical-communication demonstrations (SOTA, OSIRISv2)[2]. With the attitude determination requirements becoming increasingly stringent, the sensor selection space converges to only a few select types considering the constraints CubeSat developers are forced to deal with such as lack of payload volume, limited power options, and especially total cost. Star trackers are a prime example of a sensor that fits the mission criteria but are overlooked due to their cost. Star trackers for CubeSats can start at $30,000 and only go up from there; an cost that can sometimes equal if not be greater than the total budget for a mission. However, with attitude determination requirements becoming stricter, a need for a low-cost solution emerges.

The fundamental question to ask is whether or not a star tracker, traded on performance for cost, is a viable solution for CubeSat attitude determination in the future. This thesis aims to answer the question by analyzing where errors exist, how they propagate, and how different hardware can influence the expected attitude accuracy.

Chapter 2

THE LITERATURE

2.1 Background Knowledge and Context

CubeSats and Pointing

Since their inception in 1999, CubeSats have been employed for a variety of mission types. From measuring elements in the Earth's exosphere, to testing vibration and dampening experiments in microgravity, to experimenting accelerated deorbit times via dragsail [3], it's clear to see that CubeSats are not pigeonholed into a single mission archetype. However, as the technology has matured and missions become more complex, their requirements, especially for pointing, have become stricter.

CubeSats, being developed at a university, continue to be designed at universities such as California Polytechnic State University - San Luis Obispo (Cal Poly SLO) or University of California - Davis (UC Davis). The initial design made it possible for organizations with limited resources and funding to still be able to develop functional spacecraft with unique mission objectives. While CubeSats have emerged into the greater market and can be developed with upwards of $1 Million, typical budget-constrained or university CubeSat programs can be expected to spend on the order of $50,000 - $200,000 [4]. While a large sum of funds, it should be noticed that a CubeSat is a complicated amalgamation of instruments, supporting avionics, structure, and software, all of which is still expected to undergo and survive testing such as vibration and thermal vacuum tests to comply with launch vehicle standards. Each of these subsystems and requirements requires some amount of the total funding. As a consequence, funds allocated towards supporting sensors, such as attitude determination sensors, are typically a small portion of the total funding. Despite the limited funding available for such CubeSat programs, technology demands and mission requirements have increased in complexity, creating a need for more affordable component alternatives. Pointing requirements, in specific, have become increasingly strict. As CubeSats continue to demonstrate their capabilities for missions, earth-sensing missions and inter-satellite communication systems have slowly been outsourced from traditional, larger spacecraft to the modern CubeSat. As a result, pointing has become increasingly important to consider and control.

QuakeSat and CLICK

QuakeSat was a mission which would measure and record earthquakes on the surface [5]. The team from Space Systems Development Laboratory (SSDL) reported, for mission success, they used a wide-angle light sensor and magnetometer; they "were not ideal for attitude determination"[5]. Stories like QuakeSat characterize the the early missions of CubeSats - where attitude was not a major concern and, as a consequence, became afterthoughts in the design cycle. With more modern missions, however, attitude has become the forcing function for mission success. The CubeSat Laser Infrared CrosslinK (CLICK) was a technology demonstration for an inter-satellite laser-based communication system from MIT[6]. The demonstration, through analysis of the inter-satellite distance and relative motion, required the pair of CubeSats to point in a single axis to within $\pm$ 5.18 arcsec of each other. Another optical mission, ASTERIA, looks to optimize beam pointing control and requires 3.3 arcsec [7] of pointing accuracy to complete its objective. The trend of CubeSats taking on complex technology demonstration and requiring strict pointing requirements has only and will only increase as the confidence in CubeSat technology improves. A worrying observation, however, is that the list of sensors able to meet requirements is starting to narrow down. Without a suitable sensor, CubeSat capabilities can stagnate indefinitely.

With other sensors, sun sensors, for example, accuracy begins to fall. Sun sensors can be as accurate as 0.1 deg [8], or 360 arcsec, and cost as much as $9,000 [9]. While sun sensors were once the standard for attitude determination on budget-constrained CubeSats, it's clear that they can no longer fulfill the requirements being imposed on modern day CubeSat mission. On the opposite end of the spectrum, however, star trackers can be as accurate as 5 arcsec but as expensive as $120,000 [10] or more. CubeSats - particularly developed in university settings or those that are budget constrained - are typically underfunded to afford such star trackers. Other attitude determination alternatives include magnetometers (whose accuracy can vary depending on the orbit type and can be as accurate as 0.01 degrees [11]), horizon sensors (which can be accurate to approximately 0.1 degrees [12]), or passive systems such as gravity-gradient which are only accurate to approximately 15 degrees [13] depending on the construction and mass properties of the spacecraft. While alternatives may be cheaper, it's clear to see that the performance gap compared to star trackers is great and needs to be closed. This gap can be filled by trading on star tracker performance for cost, allowing for more affordable alternative options while still outperforming less expensive sensors. Parameterizing the error in star trackers based on selected hardware and expected environmental conditions are one such method to determine how to perform the performance trade.

Figure plotting star tracker and other attitude sensor cost vs performance

Parameterization of Error

While other approaches in determining how to develop more affordable star trackers are viable, analyzing the error propagation allows us to determine additional information about the system and develop a tool for CubeSat developers. By looking at each physical step of the star tracker from end-to-end, a complete mathematical model of the star tracker can be deduced, including, but not limited to, where errors occur for one reason or another. For example, by identifying flaws in the camera construction such as the normality of the boresight vector or the tilt of the focal array, immediate errors can be characterized and modeled as the ideal model for centroiding would be based on a skewed representation of the celestial sphere. By incorporating different effects, specifically the camera hardware and noise, the algorithmic errors, and the leading environmental errors in low earth orbit (LEO), a model can be devised where a given set of inputs (i.e., from a list of mission requirements) can be used to devise how accurate a theoretical star tracker would be. This black box would enable CubeSat developers to determine if investing in a low-cost star tracker will be sufficient for the mission without needing to experimentally test for it using their expected mission parameters.

Investigating the error propagation also enables us to determine where the most errors are prone to occur and where it is worth the time and resources to optimize a process. By fully understanding and parameterizing the star tracker process, a greater understanding of how to model the star tracker accuracy in on-orbit conditions can be determined and used to drive decision making for attitude determination sensor selection without *a priori* experimental information.

Alternative methods in reducing the cost of the star tracker include optimizing hardware or writing custom firmware for the optical module. While worthwhile efforts, the same pitfalls of high development costs still persist. Optimizing the hardware will still require some knowledge of how the optical system works and how different decisions and hardware permutations will affect the estimated accuracy. This black box devised through analyzing error propagation allows developers to take the guess work out of the hardware selection and reduces the development cost and time in broad iteration. Software optimization is another alternative, however, without a great understanding of the physics, image analysis process, and flight software knowledge, developing personalized algorithms will prove to be burdensome and can still lead to expensive development cycles. Analyzing the error propagation through a theoretical lens allows us to specifically determine where errors, or losses, are generated and how hardware selection can help mitigate errors. It also enables us to selectively allow errors to persist by choosing affordable hardware, thereby reducing the total cost of the star tracker.

It should be clear that, due to the rapid maturation of CubeSat technology and capability, a demand for equally capable attitude determination sensors needs to be met, especially one that fits within the confines of a typical CubeSat budget.

What Is a Star Tracker and How Do They Work?

A star tracker is an optical-based sensor that uses the position of stars to determine its attitude; it relies on the notion that relative star movement is low and can be effectively mapped to each other. This mapping exists within catalogs formulated over several years from different organizations such as the Yale Bright Star Catalog 5 (BSC5). The catalog contains key information such as Star ID, right ascension and declination in the celestial sphere, brightness magnitude, right ascension and declination motion, and other features.

Catalog Number	B1950 Right Ascension	B1950 Declination	Spectral Type	V Magn. x100	R.A. Proper Motion	Dec.Proper Motion	Radial Velocity	Object Name
				...				
123	0.138637	0.951592	B8	4.73	2.181662e-07	-4.848137e-08	-	-
124	0.138259	0.922222	K2	5.60	-2.569512e-07	-9.211460e-08	-	-
125	0.137081	-0.851784	A0	4.77	6.932835e-07	8.241832e-08	-	-
				...				

Figure 2.1: Sample star catalog entry from Yale Bright Star Catalog

A copy of the catalog can then be modified to include information, called features, such as inter-star angles, ratio of triangle legs created by 3 stars, or even pyramidal information; the specific feature generated is determined by the specific identification method employed. The modified catalog contains the permutations of the stars that comprise the given feature set. The identification algorithm can then be used to identify each star in a given image; once each star is identified, a final calculation to determine the star location and the center of the image is processed and mapped to the original catalog. Given the position of the star in the image, the star tracker can determine its own position (in right ascension and declination) based on the image center (as this is where the boresight of the star tracker lies). The QUEST algorithm can then be used to determine a quaternion representation of the star tracker's attitude from the right ascension and declination.

Star A ID	Star B ID	cos(Inter-star Angle)
	...	
123	124	-
123	125	-
124	125	-
	...	

Figure 2.2: Sample modified star catalog using inter-star angle identification

Onboard the star tracker, images are captured of the stars and processed by the star tracker. During the centroiding process, the star tracker will read the image and determine where the stars are located within the image plane. It will then create the aforementioned features and store it in memory. During the identification process, the features in memory are recalled and compared to against the modified catalog where potential matches are found. Once a suitable match, typically characterized by high likelihood of similarity in combination with a filter, the attitude is recalled from the entry in the modified catalog. It is not uncommon for the star tracker to fail in finding a sufficiently confident match due to the nigh-infinite number of variations a single feature set can have due to image positioning and centroiding errors. To combat this, star trackers typically take multiple images per second to try to find better matches. This process repeats indefinitely and will generate high-accuracy determinations of attitude.

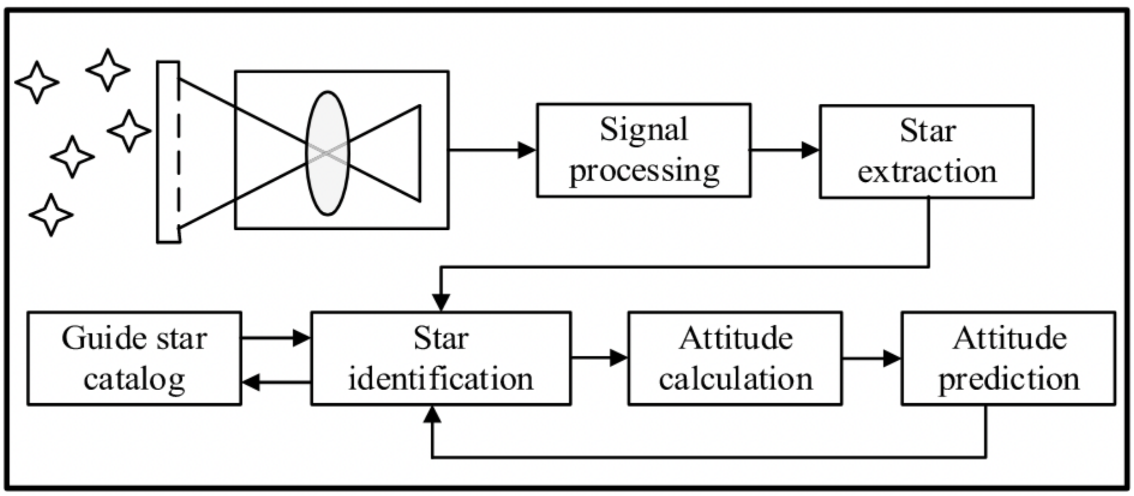

Figure 2.3: Working principle of the star tracker system [1]

The star tracker, in addition to its 2 main process phases, has 2 operating phases. If the star tracker has some *a priori* knowledge of its attitude in recent time, i.e., based on previous star tracker readings, then the star tracker only has to search a small portion of the modified catalog in order to find a match as the catalog can be ordered by attitude. If, however, the star tracker has no *a priori* knowledge of its attitude, i.e., post-detumble, then the star tracker must search the entire modified catalog. Because the modified catalog is so large and can contain a great number of combinations for an even greater number of stars, the process to determine the attitude can take significantly longer. This operating phase is typically called the *Lost in Space* problem and is a unique metric in comparing star tracker performance.

Flowchart of entire star tracker process including Lost in Space problem

2.2 Errors in Star Trackers

Now that we understand what a star tracker is and how they work, it's imperative to describe what error propagation is and how it affects the star tracker. Error propagation is "a basic problem analyzing the uncertainty of reliable systems" [14]; we want to determine why a star tracker is not totally accurate, where errors originate, and how they persist through the star tracker process to affect its final estimated accuracy. According to Jia et al. (2010), "[t]he most important factors that affect star tracker accuracy include thermal drift, optical aberration, detector noise, and systematic error of star image centroid estimation algorithm" [15]. We can characterize these errors by analyzing the physics behind their presence and how different factors affect their intensity. Following the advice of Jia et al. (2010), this thesis aims to analyze errors due to the optical system hardware defects, optical sensor noise, algorithmic assumptions and errors, and the thermal environment of LEO, and how each error tracks through the attitude determination process and its affect on the expected accuracy.

Error Propagation Techniques

test

Hardware Limitations

The physical hardware of the star tracker will always be the first source of error and will be compounded upon throughout the process. Inaccuracies in the optical axis, focal plane flatness, and lens distortion all contribute to errors in the centroiding process, leading to errors in attitude determination. Camera calibration is a common technique to reduce hardware inconsistencies propagating error through the attitude determination model. Sun et al (2013) proposes a model to handle the uncertainty of where the incident light rays from the navigation stars fall on the focal plane. [16]

$$\xi_A = \left(\frac{\left(\frac{f+\Delta f+\Delta s * tan(\theta)}{cos(\theta+\beta_{ri})} * sin\left(\beta_{ri}\right) + \frac{\Delta s}{cos(\theta)} + \Delta x + \Delta d \right)}{f} \right) - arctan\left(\frac{\Delta s}{f cos(\theta)} \right) - \beta_{ri} \tag{2.1}$$

where

ξ_A defines the star tracker measurement accuracy

f represents the focal length of the star tracker

Δs represents the deviation of the optical axis with respect to the boresight

Δx represents the star point-extraction error

Δd represents radial distortion in the lens

β_{ri} represents the angle between the optical axis and incident light ray

θ represents in the inclination of the focal plane

Error due to the optical system hardware can be presented via Monte Carlo Analysis. Sun et al. (2013)

While Sun et al. (2013) devised this model to generate estimated attitude determination accuracy, it should be noted that only hardware limitations were considered. In addition to the inaccuracies of the focal system on the star tracker, additional considerations from Liu et al. (2010) address radial distortion, decentering, and thin prism distortions [17]

$$\begin{bmatrix} \delta_u(u',v') \\ \delta_v(u',v') \end{bmatrix} = \begin{bmatrix} u' \\ v' \end{bmatrix} - \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} (g_1+g_3)u'^2 + g_4u'v' + g_1v'^2 + \kappa u'(u'^2+v'^2) \\ g_2u'^2 + g_3u'v' + (g_2+g_4)v'^2 + \kappa v'(u'^2+v'^2) \end{bmatrix} \tag{2.2}$$

where

$[g_1, g_2, g_3, g_4]$ each represent a different distortion property.

CCD Noise

Sensor noise, specifically from the CCD, is another factor we must analyze when determining how our system and the environment affect attitude determination. CCD Noise often appears as partially illuminated pixels in the absence of a real incident light and is caused by the noise in the Analog to Digital Converter during the image capture process. G.E. Healey et al. (1994) proposes a model that relates the irradiance, dark current, and quantization to the expected noise level in a given pixel[18].

$$D(a,b) = \mu(a,b) + N(a,b) \tag{2.3}$$

$$N(a,b) = N_I(a,b) + N_C(a,b) \tag{2.4}$$

where

D represents the digital value of a pixel at location (a, b) on the focal plane

$\mu(a, b)$ represents the expected digital value based on standard camera principles

$N(a, b)$ represents the noise of a given pixel

$N_I(a, b)$ represents the noise part that varies with the image

$N_C(a, b)$ represents the noise part that is invariant of the electrons captured

CCD Noise is composed of several different sources, as hinted at in equation 2.4 such as unintentional light scattering from other bodies, analog-digital converter noise, and Dark Current. Dark Current is a form of CCD Noise that is a result of residual electric current in the pixel buckets while there is no incident light being projected on the focal plane. Dark Current can worsen with age of the sensor, among other factors.

G.E. Healey et al. (1994) proposes a model to account to account for different noises in CCD sensors.

$$D_C(a, b) = \left(I(a, b) + \frac{N_S(a, b)}{\hat{K}(a, b)} + \frac{N_R(a, b)}{\hat{K}(a, b)} \right) A + \frac{N_Q(a, b)}{\hat{K}(a, b)} \tag{2.5}$$

where

D_C represents the corrected digital value of a pixel at location (a, b)

I represents the irradiance on a given pixel

N_S represents shot noise, a type of noise that deals with the uncertainty of the number of electrons captured

N_R represents zero-mean amplifier noise

N_Q represents noise from the quantization process

$\hat{K}$ represents the estimate of number of captured photoelectrons

CCD Noise varies between cameras and can come in the form of several kinds of noises. To reduce noise (and improve centroiding), it's important that the noise be calculated to set a *Noise Floor*, or a filter that attempts to remove as much noise from the image without removing stars. A typical Noise Floor can be calculated using the average and standard deviation of the brightness of the pixels in the image [19]:

$$NF = \bar{B} + 5 * \sigma_B \tag{2.6}$$

where

$\bar{B}$ represents the average brightness value

σ_B represents the standard deviation in brightness

The Noise Floor is a parameter that is typically calculated during operation and will change between image captures. This ensures the Noise Floor is not over-filtering clean photos or under-filtering noisy photos.

Thermal Effects

One of the larger effects from the environment is the rapidly changing thermal environment. In Low-Earth Orbit, or, LEO, spacecraft can experience a temperature swing between -65C and +125C[20] which can cause thermal stresses on all hardware. For star trackers in particular, the lens is of interest when analyzing thermal cycles. For one, the lens can change shape, lengthening or shortening the focal length in times of extreme heat or cold respectively. Jamieson et al. (1981) thoroughly describes the relation between optical systems and thermal effects, especially noting how the focal length changes with temperature [21]

$$x_f = \frac{1}{f}\frac{df}{dt} = x_g - \frac{1}{n - n_{air}}\left(\frac{dn}{dt} - n\frac{dn_{air}}{dt}\right) \tag{2.7}$$

$$n_t - 1 = (n_{15} - 1)\left(\frac{1.0549}{1 + 0.00366t}\right) \tag{2.8}$$

$$(n_{15} - 1) * 10^8 = 8342.1 + \frac{2406030}{130 - \nu^2} + \frac{15996}{38.9 - \nu^2} \tag{2.9}$$

$$n_{abs} = n_{rel} n_{air} \tag{2.10}$$

$$x_g = \frac{1}{R_1}\frac{dR_1}{dt} = \frac{1}{R_2}\frac{dR_2}{dt} \tag{2.11}$$

where

f is the focal length

x_g is the change of surface radii of the lens with respect to temperature

n is the refractive index at a given temperature

n_{air} is the refractive index of air $\equiv 1.0$

Thermal expansion will directly affect the hardware and, in turn, will influence centroiding processes. Understanding how best to approach minimal thermal deformation in the lens can help lead to greater consistency if not accuracy with star tracker measurements.

Chapter 3

THE PROPOSAL

While not expected to be included in the final thesis (at least in this form), the proposal is left here for completeness.

3.1 Motivation

- CPCL already developing a star tracker to deploy in orbit and open sourcing the software
- Would be useful for other universities and low-budget developers to be able to determine if star tracker is worth putting money into
- Allows cubesats to stay competitive in the maturing spacecraft market

3.2 Contribution to the Field

- No other tool to determine star tracker accuracy
- Focused on CubeSats i.e., low-cost, low-size
- Allows cubesat developers to estimate their accuracy to determine if a low cost star tracker is inline with the pointing direction

3.3 Scope and Statement of Work

- Determine major effects to consider

  - Hardware
    * Normality of boresight
    * Focal plane distortions
    * Size of focal array
    * CCD Noise (ADC Noise, Dark Current)
  - Environment
    * Thermal Environment (Distortions, Cycling)
    * Body Rates
  - Algorithmic
    * Centroiding Errors
    * Identification Errors
    * QUEST Errors
- Discover or determine mathematical models or relations between effects and star tracker accuracy on each step in star tracker process (image capture, centroiding, etc)
- Create function/black box for inputs to feed through and spit out star tracker accuracy
- Use CPCL star tracker hardware + software as case study
- Determining variables to randomize for Monte Carlo Analysis
  - Absortivity/Emissivity for thermals
  - CCD Noise
  - Focal Plane distortions
  - Boresight Normality

  - Radiation
  - Centroiding Accuracy (likely discrete set)
  - Identification Accuracy (likely discrete set)

- Determining variables to keep consistent
  - QUEST performance
  - LEO altitude   90min orbit period
  - CubeSat sizes (1-3U)

3.4 Schedule

- Through Fall Quarter:
  - Finish Centroiding Algorithm
  - Analyze Centroiding Performance
  - Finalize list of effects to consider
  - Find environmental models to use for black box
  - Propose

- Through Winter Quarter:
  - Find additional models to complete larger order error sources
  - Combine models to create "black box" of inputs that outputs estimated accuracy
  - Requires validation
  - Analyze identification performance
  - Devise and validate cost functions

- Determine optimal solutions for the cost functions

- Through Spring Quarter
  - Finish analysis of all models
  - Write up thesis
  - Defend

3.5 Methodology

- Find models relating effects to star tracker accuracy
- Combine models where appropriate (i.e., thermal effect on focal length where f becomes a function instead of a constant)
- Determine how effects affect the star tracker (i.e., during the centroiding process will propagate from there on)
- Determine how accurate each physical process can be at its max as a function of the different effects
- Create black box based on Monte Carlo analysis looking at discrete sets of camera characteristics and continuous sets of physical properties to estimate star tracker accuracy
- Devise cost function based on community needs and use black box to suggest optimal camera and environment opportunities

3.6 Success Criteria

- Black box where various inputs (camera properties, environment, etc.) are fed to estimate star tracker accuracy with some confidence level
- Black box is opened up to show models and how it affects each step in attitude determination

3.7 Expected Challenges

- Finding models
- Combining models
- Devising the cost function

The literature offers several suggestions in analyzing the error propagation within the sensor such as hardware considerations, "thermal drift, optical aberration, detector noise"[15], and systematic algorithmic errors. However, before we can analyze where error is prone to occur, we must first understand what a star tracker is and how they work.

BIBLIOGRAPHY

[1] Yongyong Li, Xinguo Wei, Jian Li, and Gangyi Wang. Error correction of rolling shutter effect for star sensor based on angular distance invariance using single frame star image. *IEEE Transactions on Instrumentation and Measurement*, 71:1–13, 2022.

[2] Alberto Carrasco-Casado, Abhijit Biswas, Renny Fields, Brian Grefenstette, Fiona Harrison, Suzana Sburlan, and Morio Toyoshima. Optical communication on cubesats — enabling the next era in space science. In *2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, pages 46–52, 2017.

[3] PolySat. Missions launched, 2015.

[4] Anders Nervold, Joshua Berk, Jeremy Straub, and David Whalen. A pathway to small satellite market growth. *Advances in Aerospace Science and Technology*, 01:14–20, 01 2016.

[5] Matthew Long, Allen Lorenz, Greg Rodgers, Eric Tapio, Glenn Tran, Keoki Jackson, Robert Twiggs, T.E. Bleier, and Stellar Solutions. Ssc02-ix-6 a cubesat derived design for a unique academic research mission in earthquake signature detection. 10 2022.

[6] Peter Grenfell, Alexa Aguilar, Kerri Cahoy, and Michael Long. Pointing, acquisition, and tracking for small satellite laser communications. 2018.

[7] Ondrej Čierny and Kerri L Cahoy. On-orbit beam pointing calibration for nanosatellite laser communications. *Optical Engineering*, 58(4):041605, 2018.

[8] Josh O'Neill, Nadja Bressan, Grant Mcsorley, and Nicholas Krouglicof. Development of a high-accuracy low-cost sun sensor for cubesat application. *Aeronautics and Aerospace Open Access Journal*, 4:142–146, 09 2020.

[9] CubeSatShop. Bison64-et.

[10] Rocket Lab. St-16rt2 star tracker.

[11] Nils Olsen. Magnetometer data from the grace satellite duo. *Earth, Planets and Space*, 73(1):62, Mar 2021.

[12] Mohamad Dol Bahar, Mohd Effandi, Mohd Khair Bin Hassan, Norhizam Hamzah, Ahmad Sabirin Arshad, Xandri C. Farr, Lourens Visagie, and Willem H. Steyn. Modular cmos horizon sensor for small satellite attitude determination and control subsystem. 2006.

[13] Dmitry Roldugin and Michael Ovchinnikov. Dual-spin satellite motion in magnetic and gravitational fields. *Keldysh Institute Preprints*, page 20, 01 2015.

[14] Jianfang Zhang. The calculating formulae, and experimental methods in error propagation analysis. *IEEE Transactions on Reliability*, 55(2):169–181, 2006.

[15] Hui Jia, Jiankun Yang, Xiujian Li, Juncai Yang, MengFei Yang, YiWu Liu, and YunCai Hao. Systematic error analysis and compensation for high accuracy star centroid estimation of star tracker. *Science China Technological Sciences*, 53:3145–3152, 11 2010.

[16] Ting Sun, Fei Xing, and Zheng You. Optical system error analysis and calibration method of high-accuracy star trackers. *Sensors (Basel, Switzerland)*, 13:4598–623, 04 2013.

[17] HaiBo Liu, Xiujian Li, Ji-Chun Tan, Jian-Kun Yang, Jun Yang, De-Zhi Su, and Hui Jia. Novel approach for laboratory calibration of star tracker. *Optical Engineering*, 49:3601–, 07 2010.

[18] G.E. Healey and R. Kondepudy. Radiometric ccd camera calibration and noise estimation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 16(3):267–276, 1994.

[19] C.C. Liebe. Accuracy performance of star trackers - a tutorial. *IEEE Transactions on Aerospace and Electronic Systems*, 38(2):587–599, 2002.

[20] Dynamic Range Corporation Jeannette Plante, Brandon Lee. Environmental conditions for space flight hardware - a survey, 2004.

[21] Thomas H Jamieson. Thermal effects in optical systems. *Optical Engineering*, 20(2):156–160, 1981.

[22] Juan Shen, Guangjun Zhang, and Xinguo Wei. Simulation analysis of dynamic working performance for star trackers. *Journal of the Optical Society of America. A, Optics, image science, and vision*, 27:2638–47, 12 2010.