Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Arcminute Attitude Estimation for CubeSats with a Novel Nano Star Tracker ⋆

Alexander O. Erlank * **Willem H. Steyn.** **

* *Electronic Systems Laboratory, Stellenbosch University, Stellenbosch, South Africa (e-mail: alexerlank@gmail.com).*
** *Electrical and Electronic Engineering Department, Stellenbosch University, Stellenbosch, South Africa (e-mail: whsteyn@sun.ac.za)*

Abstract: The next generation of CubeSats will require accurate attitude knowledge throughout orbit for advanced science payloads and high gain antennas. A star tracker can provide the required performance, but star trackers have traditionally been too large, expensive and power hungry to be included on a CubeSat. This paper briefly surveys the state of current CubeSat ADCS systems and goes on to describe the development of a CubeSat-compatible star tracker. Algorithms for star detection, matching and attitude determination were investigated and implemented on a CubeSat-compatible embedded system. The resultant star tracker, named CubeStar, is one of the smallest star trackers in existence. It can operate fully autonomously, outputting attitude estimates at a rate of 1 Hz. An engineering model was completed and demonstrated an accuracy of better than 0.01 degrees during night sky tests.

1. INTRODUCTION

A new class of nano-satellites, called CubeSats, is rapidly maturing. Traditionally, these small satellites have been primarily a teaching aid for universities training engineers. Their attitude determination and control systems (ADCSs) have often been crude, only partially stabilizing the satellite. However, CubeSats are reaching the point of maturity where they could potentially take over the work of much larger satellites. If this is to be the future of CubeSats, their attitude determination and control systems will have to receive a major upgrade.

Sun and horizon sensors, magnetometers, magnetorquers and reaction wheels have all been miniaturized to the point where they can be used on board CubeSats. The majority of CubeSats currently in development aim to make use of these components to achieve full three-axis stabilization. Using the sun and horizon sensors, CubeSats can hope to achieve an attitude knowledge accuracy in the order of 0.1 degrees. However, this will only be possible in the sunlit part of the orbit, as the sun and horizon vectors are unavailable during eclipse. Once this performance has been proven in orbit, the next generation of CubeSats will require even higher performance, which will only be possible with a star tracker.

A star tracker makes use of the stars to determine the satellite's attitude. A star tracker typically consists of a sensitive camera, an embedded processor and a list of known stars. The camera takes images of parts of the sky and the processor attempts to match each imaged star to a star from the onboard list. By comparing the locations of the imaged stars on the image plane to the known locations of those stars on the celestial sphere, the star tracker can estimate the satellite's attitude. Star trackers can achieve accuracies two orders of magnitude better than other absolute attitude sensors and work throughout the orbit. Star trackers have traditionally been large, power hungry and expensive, prohibiting their use on board CubeSats. However, several key technologies have advanced to the point where a CubeSat compatible star tracker is possible.

This paper describes the development of a CubeSat compatible star tracker named *CubeStar*. The paper begins with a brief survey of CubeSat ADCS achievements to date. Thereafter, several key design decisions are discussed and a brief overview of the hardware implementation is given. The paper concludes with a description of the testing performed on CubeStar and the results achieved.

2. CUBESAT ADCS ACHIEVEMENTS

Many successful CubeSats have been launched to date, but most have contained only a basic attitude determination and control system.

The most elementary form of attitude control, called passive control, cannot achieve accuracies better than approximately 5 degrees. Most CubeSats to date have been university projects with the aim of training new engineers. These CubeSats have no major scientific goal or experiment to conduct in orbit and as such, can use passive control. The most popular form of passive control is to include a permanent magnet and some hysteresis material on the CubeSat. The permanent magnet will cause the CubeSat to align itself with the earth's magnetic field. The hysteresis material is required to dampen attitude oscillations. CubeSats with passive attitude control require no attitude sensors or actuators and will remain stable throughout the orbit. However, they have no ability to reorient themselves in space. The Colorado Student Space Weather Experiment CubeSat successfully used a passive magnetic stabilisation system to align itself within approx-

⋆ This work was supported in part by the South African National Research Foundation.

imately 10 degrees of the Earth's magnetic field (Gerhardt and Palo [2010]).

Better performance can be achieved using active magnetic control, which makes use of three orthogonal electromagnets, called magnetorquers. The magnetorquers interact with the earth's magnetic field to create control torques. Magnetic control allows a CubeSat to be stabilized into any attitude and is often used by more complex satellites as an initial detumbling controller. Active magnetic control requires at least a magnetometer for detumbling and an additional attitude sensor for three-axis attitude estimation. Coarse sun sensors, which can be as simple as reading the currents from each of the solar panels, are popular in this category of ADCSs. The disadvantage of magnetic control is that only two axes of the satellite can be controlled at any one time, depending on the satellite's position in orbit. Many CubeSats, including as CanX-1, DTU-Sat and COMPASS have been designed to achieve 10 degree pointing accuracy using active magnetic control.

Active magnetic control can be supplemented with a momentum wheel to achieve better disturbance rejection and attitude accuracies of better than 5 degrees. The 3U, CanX-2 CubeSat has demonstrated attitude control with an accuracy of 2 degrees using this method (Grant et al. [2008]).

An ADCS that can achieve an attitude accuracy in the 1-0.1 degree range has not been successfully demonstrated on a CubeSat in orbit. However, fine sun and horizon sensors have accuracies approaching 0.1 degrees and small reaction wheels have been demonstrated in orbit. Therefore, a fully three-axis stabilized satellite with at least 1 degree pointing accuracy should be demonstrated in the near future. This system will only work in the sunlit part of the orbit as both the sun and visible light horizon sensors do not work in eclipse.

Attitude accuracies better than 0.1 degrees can only be achieved using a star tracker and 3-axis reaction wheels. These kinds of accuracies are required by high gain antennas and optical instruments with long focal lengths. Even if the mission does not require such accurate pointing capabilities, accurate attitude knowledge is still important to many science instruments. No CubeSat to date has included a star tracker. The majority of commercially and scientifically useful satellites require accurate attitude control throughout the orbit, so a star tracker is an essential component of future CubeSat ADCSs.

3. IMPORTANT DESIGN DECISIONS

A star tracker is a complex electro-optical instrument. While star trackers have been around since the 1970's, developing one that can operate with the limited resources available on a CubeSat is challenging. All design decisions had to ensure that the following specifications could be met:

- Accuracy: 0.01 degrees RMS
- Average Power Consumption: <500mW
- Size: <0.5U
- Weight: <500g
- Cost: as low as possible

Specification	Value	Units
Optical Specifications		
Resolution	1024 x 512	pixels
Pixel Size	5.6 x 5.6	μm^2
Optical Format	1/3	inches
Sensitivity (SNR10)	25	nW/cm^2 @ 535nm
Dark Current Leakage	1008	DN12/s @ 65°C
Electrical Specifications		
Supply Voltages	1.8 and 3.3	V
Power Consumption	250	mW @ 35fps
Interface Specifications		
Control	I2C slave	
Data	8-12 bit parallel	

Table 1. Specifications of the Melexis MLX75412 image sensor.

3.1 Choosing an Image Sensor

Choosing an image sensor is arguably the most important step during the development of a star tracker. The image sensor needs to be sensitive enough to detect at least three stars at any point on the celestial sphere. Typical star trackers make use of purpose-built, radiation-hardened image sensors such as the STAR series from ON Semiconductor. These sensors are very sensitive due to large pixels and low electrical noise. Unfortunately, they are also physically large and prohibitively expensive for use on a CubeSat.

The CubeSat community advocates using commercial, off-the-shelf components wherever possible to minimize costs. A large number of commercial, general purpose image sensors exist on the market. These range from $5 sensors used in smartphones to high-end medical and scientific sensors costing thousands of dollars. The challenge is determining whether any given sensor will be sensitive enough to image stars.

CubeStar makes use of an image sensor originally developed for the automotive industry. The Melexis MLX75412 CMOS Active Pixel Sensor has several features which make it attractive for use in a star tracker. These include: fixed-pattern noise and dead pixel correction, the option to output average frame brightness and an operational temperature range of -40 to +85 degrees Celsius. Its specifications are given in Table 1.

The quoted sensitivity is a single figure of merit, incorporating a large number of variables such as fill-factor and noise sources. It states that 25 nW/cm^2 of radiant energy is required to obtain a signal-to-noise ratio (SNR) of 10. Using the simplifying assumption that all starlight is confined to a single wavelength, 25 nW of electromagnetic radiation at 535 nm is equivalent to $6.733 \cdot 10^{10}$ photons per second. Therefore, $6.733 \cdot 10^{10}$ photons per second per cm^2 are required to get a signal to noise ratio of 10. That equates to $21.115 \cdot 10^3$ photons per second per pixel, since each pixel has a size of 5.6 x 5.6 μm^2.

This sensitivity is compared with the number of incoming starlight photons. The number of starlight photons captured by the optics is given by (1), where N_{php} is the number of photons per second hitting the image plane, A_l is the lens aperture in cm^2, T_l is the permeance rate of the optics (usually between 0.6 and 0.8), ΔB is the bandwidth of the lens (usually between 3000 and 6000 Angstrom),

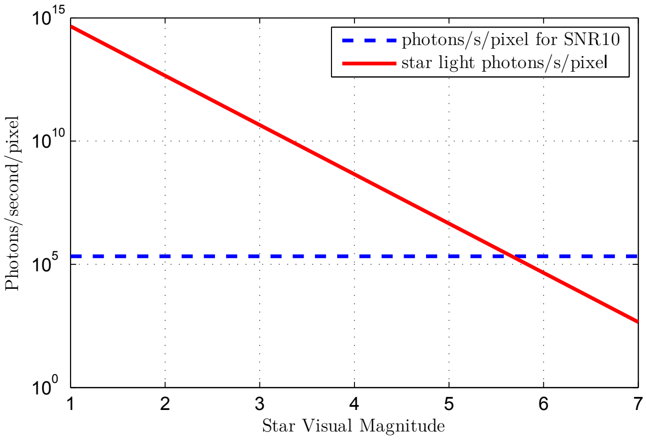

Fig. 1. Starlight photons per pixel per second vs required photons per pixel per second to achieve SNR10

ϕ_m is the luminous flux of M visual magnitude and T is the exposure time. Equation 1 is reproduced from Li et al. [2007]. By setting T equal to 1 second, (1) gives the number of photons per second which hit the image plane.

$$N_{php} = A_l \cdot T_l \cdot \Delta B \cdot \phi_m \cdot T \tag{1}$$

For the order of magnitude equation the lens radius was chosen as 1 cm, the permeance was chosen as 0.6 and the bandwidth was chosen as 3000 Angstrom. If the optics were perfectly focused, the resultant photons per second calculated in (1) would all fall on a single pixel. However, to enable subpixel centroiding techniques, the optics are purposely defocused and the starlight spans several pixels, often over a 3 x 3 or 5 x 5 grid. Therefore, the resultant photons per second per pixel can be approximated by dividing the total photons per second by the number of pixels that are covered.

Figure 1 plots the required number of photons per second per pixel to achieve SNR10, against the number of starlight photons per second per pixel for stars of varying magnitudes. The plot shows that stars down to magnitude 5.5 should be detectable against background sensor noise.

To calculate the maximum possible exposure time, it is necessary to look at the second optical characteristic given in the datasheet: dark current leakage. The datasheet states a dark current leakage of 1008 ADC units per second at 65°C. This means that the image sensor will output a value of 1008 (out of 2^{12} for 12-bit mode) for each pixel if a 1 second exposure is taken in a perfectly dark environment. An ideal image sensor would output zero, but dark current leakage causes a non zero value to be output. Therefore, exposures longer than $2^{12}/1008 = 4.06$ seconds will saturate the sensor.

3.2 Field of View

To determine the minimum FOV required to ensure three stars will always be in the FOV, a simulation was run in MATLAB. Figure 2 was generated using Monte Carlo simulations. For each data point, 20 000 simulated star images from various, random parts of the sky were generated. Each set of 20 000 images was generated using a specific circular FOV and limiting magnitude. Then the images were investigated to determine what fraction contained at least three stars, giving the sky coverage. A sky coverage of 1, or 100%, is desirable, as this means that the star tracker will work over the whole celestial sphere. The majority of commercial star trackers have sky coverages of around 99.9%.

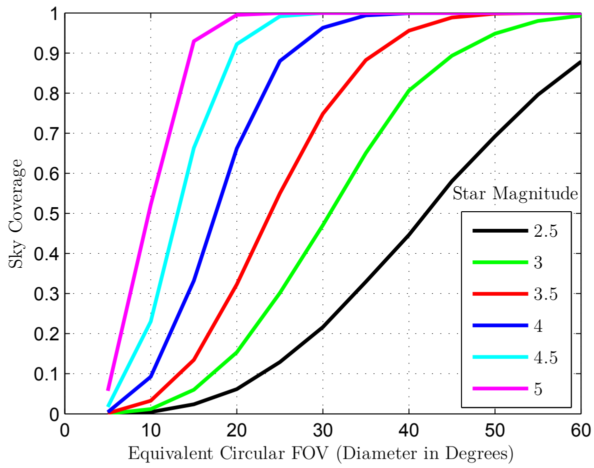

Fig. 2. Sky coverage for various combinations of FOV and limiting magnitude

Early in CubeStar's development process it was decided that CubeStar would use a wider FOV than the majority of star trackers. A wide FOV has several advantages for a CubeSat star tracker:

- A less sensitive image sensor is required
- A smaller onboard star list is required
- Less computional effort is required to match stars

The disadvantage of a larger FOV is the increased chance of unwanted objects, such as the sun or moon, entering the FOV. This risk can be minimised by careful placement of the star tracker on the satellite and the inclusion of a stray light baffle. The majority of star trackers are designed to have an equivalent circular FOV of approximately 20 degrees and must therefore detect stars down to 5th magnitude. Tests with CubeStar's image sensor suggested that stars down to magnitude 3.8 would be visible with exposure times in the order of 100 ms. Figure 2 shows that a limiting magnitude of 3.8 necessitates a minimum FOV of approximately 40°.

A commercial lens with an equivalent circular FOV of 42° was found. The lens was specifically designed for low light conditions and has an f-number of 1.2. Together, the image sensor and lens ensure that at least three stars are in the FOV over more than 99.9% of the celestial sphere and at least five stars are in the FOV over more than 98.9% of the celestial sphere.

4. ALGORITHMS

The process of going from a raw star image to an attitude estimate can be split into four steps: star detection, centroiding, star matching, and attitude determination. Multiple algorithms exist to perform each of these steps. However, the CubeStar processor has limited resources and therefore only the most efficient algorithms can be implemented.

4.1 Star Detection

In its simplest form, detecting a star in the raw star image would require checking more than half a million pixels against a brightness threshold. Fortunately, this search can be sped up. Like most star trackers, CubeStar's optics are purposefully defocused to spread each pixel's light over an area of several pixels. This allows sub-pixel centroiding techniques to be used, but also speeds up the star detection process. Starting from the first pixel in the top left corner of the raw image, only every third pixel in the row is checked against a brightness threshold. Since every detectable star will have a diameter of at least 3 pixels, no stars will be missed. When the end of the row is reached, the algorithm skips two rows and starts again on the fourth row of the image. In this way only 1/9th of all the pixels need to be checked.

Whenever a pixel above the threshold is detected, a recursive region growing algorithm is called to find all pixels belonging to the detected star. When the region growing algorithm completes, the search over the image plane continues.

The region growing algorithm returns a list of pixels belonging to the same star as the seed. Two checks are performed on this list to determine whether it represents a star and not a dead pixel or other image artifact. The list must contain a minimum number of pixels. Too few pixels indicate a dead pixel or star which is too faint to detect reliably. The list may also not contain too many pixels, as this indicates that the moon, earth, or reflections from the sun are entering the FOV. Lists with too few or too many pixels are discarded.

4.2 Centroiding

Once all the pixels belonging to each star have been found, the centroid of each star must be calculated. Two algorithms are commonly used for this purpose: Guassian curve fitting and center of gravity.

The pattern of light caused by a single star on the image plane is often approximated as a 2D Gaussian function. Gaussian curve fitting attempts to fit a Gaussian function to the pattern of light caused by each star. Once this is achieved, the centroid of the star can be found by calculating the location of the fitted Gaussian function's peak. This is the more accurate of the two methods (Kolomenkin et al. [2008]). However, Gaussian fit is a very processor intensive operation.

To apply a center of gravity equation to star centroiding, each pixel is weighted according to its brightness. Compared to Gaussian curve fitting, a center of gravity equation is less accurate, but it is also simpler and less processor intensive. Tests with noisy, simulated star images indicate that a center of gravity can achieve an accuracy of better than 0.2 pixels. This gives CubeStar a theoretical accuracy of better than 0.01 degrees, which fulfills the specification. Therefore, there is no need to implement the more complicated Gaussian fit algorithm.

4.3 Star Matching

Many star matching algorithms have been developed since the 1970's. The majority of matching algorithms can be classified as implementations of either subgraph matching or pattern matching. Three of the most fundamental and important algorithms are:

- Triangle Algorithm
- Match Group Algorithm
- Grid Algorithm

A 1996 Jet Propulsion Laboratory study compared these algorithms with respect to their required catalogue size, RAM usage, execution speed and robustness to inaccurate measurements and false stars (Padgett et al. [1996]). The study concluded that the Grid Algorithm was the most efficient in all categories, and that the Triangle Algorithm was the worst.

A newer comparison paper by Spratling and Mortari was published in 2009 (Spratling and Mortari [2009]). It examines the evolution of the matching algorithms. The paper notes the advantages of the Grid Algorithm. However, it goes on to explain that advances in database search techniques have resulted in even faster and more efficient algorithms. These include the Search-Less- Algorithm (SLA), the Pyramid Algorithm and the Geometric Voting Algorithm, all of which make use of Mortari's k-vector database search technique. The paper concludes that the two fastest and most robust algorithm families to date are versions of the Grid Algorithm, and versions of the Search-Less Algorithm.

Flash storage limitations of CubeStar rule out the Triangle Algorithm, as it requires the largest star catalogue. The Triangle Algorithm is also the slowest algorithm of those compared, making it the least desirable. The Grid algorithm requires dense stellar images as it uses each star's close neighbours to generate a unique fingerprint. Sparse or spread out stellar images, like those produced by CubeStar, will not produce good fingerprints. Unfortunately, while versions of the Grid Algorithm are very fast and memory efficient, they are not suitable for the CubeStar project. This leaves versions of the Search-Less-Algorithm as top contender.

Kolomenkin et al. [2008] published the Geometric Voting Algorithm, which is a modification of the Search-Less Algorithm. It was chosen as CubeStar's matching algorithm. It claims to be as fast as the fastest published methods to date, while being more robust.

The Geometric Voting Algorithm consists of a voting scheme based on pairs of stars. For every imaged pair of stars the inter-star distance is measured. Then the catalogue is searched for star pairs with similar inter-star distances. Each of the imaged stars in the pair then gets a vote from each of the stars of the matching catalogue pair. These votes are possible identities for the imaged stars. Once all the star pairs in the image have been considered, each imaged star will have many votes from different catalogue stars. Usually, the correct identity for the imaged star is the one which got the most votes. This voting stage is followed by another verification voting stage before the matching process is considered complete.

The matching algorithm can perform either a lost-in-space (LIS) match, or an assisted match. During a LIS match, the algorithm is forced to search through the whole star catalogue. During an assisted match, a rough attitude estimate is supplied to the algorithm, either from the previous match or from other attitude sensors. Using the rough attitude estimate, the matching algorithm only needs to search through a subset of the star catalogue. Assisted matching is faster and more robust.

	Lost-In-Space	**Assisted ±5°**
Cutoff Mag 3.6		
% Stars Matched	75.45	84.7
% >2 Matched	80	89
Cutoff Mag 3.7		
% Stars Matched	85.2	86.62
% >2 Matched	92	94
Cutoff Mag 3.8		
% Stars Matched	84.01	89.62
% >2 Matched	93	98.5

Table 2. The effect of magnitude cutoff on the performance of the matching algorithm

The matching algorithm was tested by giving it hundreds of simulated star images containing known stars. The algorithm was tested in both LIS and assisted match modes and with different limiting magnitudes. Table 2 gives a summary of these results. The tests proved that, using a limiting magnitude of 3.8, CubeStar has a theoretical sky coverage of 93% in LIS mode and 98.5% in assisted match mode. Since a rough attitude estimate is almost always available, CubeStar will spend the majority of its time in assisted match mode.

4.4 Attitude Determination

The aim of the attitude determination algorithm is to use a pair of vector lists, one in inertial coordinates and the other in sensor body coordinates, to determine the rotation matrix between the inertial frame and the sensor body frame. These vector lists, known as the reference and measured vectors, are the result of the star matching process.

Early solutions to the attitude determination problem include the TRIAD algorithm and Davenport's q-method. However, both of these algorithms are unsuitable for a CubeSat star tracker. TRIAD is not accurate enough as it discards too much information and the q-method is too computationally intensive. The QUEST algorithm was developed in the late 1970's to speed up the q-method by using an approximation. Due to its computational efficiency, QUEST has become one of the most frequently implemented attitude estimation algorithms.

Since QUEST, many other solutions to the attitude determination problem have appeared, including Markley's Singular Value Decomposition algorithm and FOAM algorithm, Mortari's ESOQ2 algorithm and several other adaptations (Markley and Mortari [2000]). Despite all of these new algorithms, no significant improvement in robustness or speed over the QUEST algorithm has been achieved. In fact, as the available computing power on spacecraft increases, the choice of attitude determination algorithm is becoming less significant.

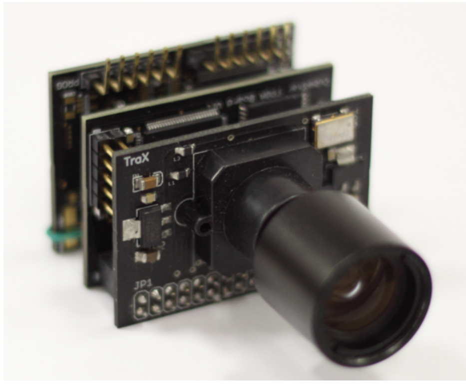

Fig. 3. The CubeStar nano star tracker engineering model.

The QUEST algorithm was chosen for the CubeStar project because of its long flight heritage, good efficiency and robustness. The QUEST algorithm takes less than 5 ms to execute on the CubeStar processor.

5. HARDWARE

Most CubeSat components are implemented in a PC104 format. However, CubeStar was implemented as three separate printed circuit boards (PCBs) which stack on top of one another. Each PCB is approximately 3 x 4.5 cm and was designed to be as small as possible to minimize CubeStar's volume.

The top PCB contains the Melexis image sensor and acts as a mount for the lens. The middle PCB contains an FPGA and an SRAM module, which together act as a frame buffer. The bottom PCB contains an ARM Cortex M3 processor and various supporting electronics.

All image processing, star matching and attitude determination algorithms run on the processor. The processor, clocked at 48MHz, is fast enough to output attitude updates at 1Hz in either LIS or assisted match mode. The processor also monitors the current consumption of the SRAM module and performs a power cycle if abnormal currents are measured.

CubeStar is designed to be flexible in operation. Theoretically, it could be reprogrammed in orbit to track the earth's horizon or the moon, instead of the stars.

CubeStar runs off a single 3.3V supply and has I^2C and TTL Serial interfaces.

6. CALIBRATION

The calibration procedure is essential for obtaining good performance from a star tracker. The calibration procedure consists of focusing the optics to obtain the desired point spread function and then determining the resultant focal length, principal point and lens distortion coefficients. Typically, such calibration requires expensive equipment and complex procedures. However, due to CubeStar's lower accuracy requirements, the calibration was successfully performed using simple equipment and procedures.

Focusing the optics was performed manually while taking images of real stars. The focal length was determined by taking images of known constellations and measuring

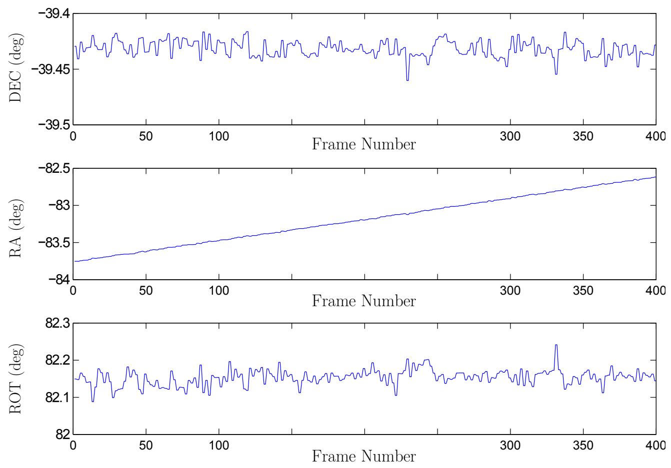

Fig. 4. The attitude output of CubeStar during the Earth-fixed test.

inter-star distances. Finally, the principal point and distortion coefficients were determined by imaging a specially designed checkerboard pattern from several angles.

There is room for improvement in the calibration procedures. Any improvements in the quality of the calibration will lead directly to improvements in CubeStar's accuracy.

7. TESTING AND RESULTS

A full engineering model of CubeStar was tested under the night sky. CubeStar was pointed towards zenith and fixed relative to the Earth. CubeStar's attitude estimate output was logged over several minutes while the stars moved through its FOV due to the rotation of the earth.

Figure 4 shows CubeStar's attitude output during the earth-fixed test. CubeStar outputs its attitude estimates as quaternions, which were converted to celestial coordinates for ease of interpretation. The right ascension was expected to increase linearly over time due to the rotation of the earth, while the declination and rotation remained constant. This behaviour can be seen in CubeStar's output, with superimposed noise. The random fluctuations around the expected outputs can be used as a measure of its RMS accuracy.

Figure 5 shows an error distribution for the right ascension output during the earth-fixed test. To generate this error distribution, a straight line was fitted to the output plot. The straight line, which represents the rotation of the earth at the sidereal rate, was used as the true attitude with which to compare the raw CubeStar output. The error distribution has a roughly Gaussian shape, which proves that any errors in the attitude output are due to noise sources and not errors in the algorithms. CubeStar demonstrated a cross-boresight accuracy of 0.0051 degrees RMS and an about boresight accuracy of 0.0203 degrees RMS during the night sky test.

A summary of CubeStar's specifications is given in Table 3. CubeStar's processor, memory and FPGA are expected to be space rated in the first half of 2014 as part of other CubeSat subsystems. Environmental testing of CubeStar should be completed before the end of 2014. CubeStar is currently scheduled to fly as an experimental payload on ZA-AeroSat as part of the QB50 constellation.

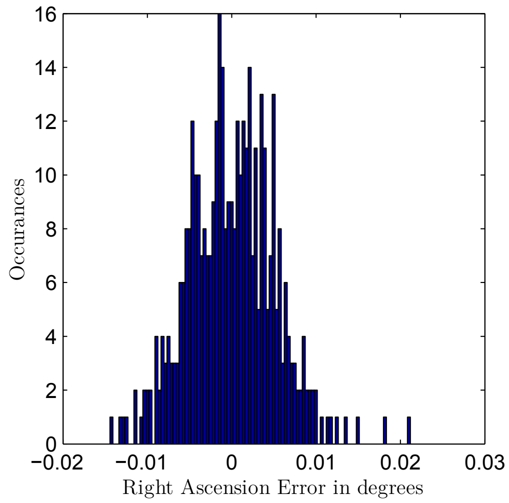

Fig. 5. Error distribution of the attitude output from the Earth-fixed test

Specification	Value	Units
Weight	<90	g
Dimensions	46 x 33 x 70	mm
Accuracy (cross bore)	better than 0.01	deg RMS
Accuracy (roll)	better than 0.03	deg RMS
Update Rate	1	Hz
Power (avg/peak)	350/550	mW
Data Interface	I2C/UART	-

Table 3. CubeStar V1 Specifications (without enclosure or baffle)

REFERENCES

David T Gerhardt and Scott E Palo. Passive Magnetic Attitude Control for CubeSat Spacecraft Conference on Small Satellites. In *24th Annual AIAA/USU Conference on Small Satellites*, 2010.

Cordell Grant, Daniel D Kekez, and Robert E Zee. Canadian advanced nanospace experiment 2: on-orbit experiences with a three-kilogram satellite. In *22st Annual AIAA/USU Conference on Small Satellites*, 2008. ISBN 1416667792.

Michael Kolomenkin, Sharon Polak, Ilan Shimshoni, and Michael Lindenbaum. A Geometric Voting Algorithm for Star Trackers. *IEEE Transactions on Aerospace and Electronic Systems*, 44(2):441–456, 2008.

Jie Li, Jinguo Liu, and Guangze Li. Study on the Detection Sensitivity of APS Star Tracker. In *3rd International Symposium on Advanced Optical Manufacturing and Testing Technologies*, volume 6723, December 2007. doi: 10.1117/12.783754.

FL Markley and Daniele Mortari. Quaternion Attitude Estimation Using Vector Observations. *The Journal of the Astronautical Sciences*, 48(2-3):359–380, 2000.

C Padgett, K Kreutz-Delgado, and S Udomkesmalec. Evaluation of Star Identification Techniques. Technical report, Jet Propulsion Laboratory, 1996.

Benjamin B. Spratling and Daniele Mortari. A Survey on Star Identification Algorithms. *Algorithms*, 2(1):93–107, January 2009. ISSN 1999-4893. doi: 10.3390/a2010093.