Flight results of ESTCube-1 attitude determination system

Andris Slavinskis¹, Hendrik Ehrpais², Henri Kuuste³, Indrek Sünter⁴, Jaan Viru⁵, Johan Kütt⁶, Erik Kulu⁷, and Mart Noorma⁸

ABSTRACT

This paper presents the characterization and in-orbit validation of the ESTCube-1 attitude determination system (ADS). ESTCube-1 is a one-unit CubeSat built by students and launched on May 7, 2013 to a Sun-synchronous, 700 km, polar low Earth orbit. Its primary mission is to centrifugally deploy a tether as a part of the first in-orbit demonstration of electric solar wind sail (E-sail) technology. The ADS uses magnetometers, gyroscopic sensors, Sun sensors and an Unscented Kalman Filter for attitude determination. Here we share the performance of commercial off-the-shelf (COTS) sensors and results from tuning the system — re-calibration, software and Kalman Filter adjustments. We validate the system by comparing the attitude determined by the on-board ADS with the attitude determined from on-board camera images. Uncertainty budgets for both attitude determination methods are estimated. The expanded uncertainty of comparison (95% confidence level, \( k=2 \)) is 1.75° and the maximum difference between attitudes determined by both methods is 1.43°.

Keywords: ESTCube-1, CubeSat, nanosatellite, attitude determination, characterization, uncertainty budget.

INTRODUCTION

The main mission of the ESTCube-1 satellite is to perform the first in-orbit electric solar wind sail (E-sail) experiment (Janhunen and Sandroos 2007), (Janhunen et al. 2010). The experiment requires the spinning up of the satellite, monitoring of the attitude and taking decisions based on the attitude (Lätt et al. 2014). Therefore an on-board Attitude Determination System (ADS) has been developed, characterized in a laboratory and simulated for ESTCube-1 (Slavinskis et al. 2014a), (Slavinskis et al. 2014b).

Several teams have published flight results of nanosatellite (1–10 kg) on-board ADSs — ASUSat1 (Friedman et al. 2000), UWE-1 (Barza et al. 2006), TNS-0 (Ovchinnikov et al. 2007), TestBed 1 (Taraba et al. 2009), CanX-2 (Sarda et al. 2009), COMPASS-1 (Scholz et al. 2010), ZDPS-1A (Xiang et al. 2012), PRISM (Inamori et al. 2013), BRITE-Constellation (Johnston-Lemke et al. 2013), UWE-3 (Busch et al. 2014), as well as RAX-1 and RAX-2 (Springmann and Cutler 2014).

¹Junior Research Fellow, MSc in Tartu Observatory, Department of Space Technology, Töravere, 61602, Estonia. PhD student in the University of Tartu, Institute of Physics, Ravila 14C-D601, Tartu, 50411, Estonia. Guest researcher in the Finnish Meteorological Institute, Erik Palménin aukio 1, P.O. Box 503, FI-00101, Helsinki, Finland. E-mail: andris.slavinskis@estcube.eu.
²BSc student in the University of Tartu.
³Engineer, BSc in Tartu Observatory. MSc student in the University of Tartu.
⁴Engineer, MSc in Tartu Observatory.
⁵MSc student in the University of Tartu.
⁶Engineer, BEng in Tartu Observatory.
⁷Engineer, MSc in Tartu Observatory.
⁸Senior research fellow, PhD in Tartu Observatory. Associate professor in the University of Tartu.
While some of the teams discuss flight results of ADSs briefly or describe the performance of specific sensors, most teams provide detailed analyses and validation of their ADSs. For example, the COMPASS-1 team used models to validate sensor data; the ZDPS-1A team presents in-orbit data and discusses their experience; PRISM, BRITE-Constellation and UWE-3 teams present on-board calibration of sensors; the RAX team, in addition to on-board calibration, provides an accuracy estimate of attitude determination using the state error covariance matrix of the Kalman Filter; and the TestBed 1 team validated attitude determination by comparing an on-board camera image with an image from the USGS (United States Geological Survey) Global Visualization Viewer captured using the attitude measured at the same time that the on-board camera image was taken. However, to the best knowledge of the authors, an uncertainty budget and validation of on-board attitude determination using another on-board source of the attitude has not been presented previously for a nanosatellite.

In this paper, we present validation of the ESTCube-1 ADS by comparing 15 samples of the attitude from the on-board ADS with the attitude determined from on-board camera images. The ADS is characterized by performance of its commercial off-the-shelf (COTS) sensors, by tuning of measurement processing, and by an uncertainty budget of attitude determination. The camera is characterized by an uncertainty budget of image-based attitude determination.

SYSTEM OVERVIEW

The main design driver for the ESTCube-1 ADS has been the E-sail experiment which requires the attitude to be determined on-board with an accuracy better than 2°. The requirements, the system design and the simulation results are presented in detail in (Lätt et al. 2014), (Slavinskis et al. 2014a), (Slavinskis et al. 2014b). Here just a brief overview of the ADS design is given.

ESTCube-1 has been built according to the one-unit CubeSat standard (SLO 2009) with a size of approximately 10 × 10 × 10 cm and a mass of 1.050 kg. Figure 1 shows the data acquisition, processing and validation scheme of the ADS. Measurements are acquired from two magnetometers, four gyroscopic sensors, six Sun sensors (one per side), and two temperature sensors. Raw measurements are processed, corrected and extrapolated. To correct magnetometer and gyroscopic sensor measurements, the temperature is taken into account. Over an orbit, the temperature changes between 0 and 30 °C. The magnetic field vector and the Sun vector are extrapolated, before being used by the Kalman Filter, up to the time when the attitude will be controlled. Models are also calculated for that time instance. An Unscented Kalman Filter (UKF) (Larsen and Vinther 2011) is used to determine the attitude. In addition to sensor measurements, the UKF requires the following inputs: a modeled geomagnetic field vector, a modeled Sun vector, and a measurement noise covariance matrix. For geomagnetic field modeling, the International Geomagnetic Reference Field 11 (IGRF) (Finlay et al. 2010) is used; and for Sun direction modeling, the method described in (Montenbruck and Pfleger 1994, p. 39) is used. Two supporting models are required to provide inputs to the IGRF and Sun direction models. The orbit is propagated using the Simplified General Perturbation model 4 (SGP4) (Hoots and Roehrich 1980). The Earth rotation model is described in (Jensen and Vinther 2010, p. 65).

The UKF is based on a sigma point sampling method called unscented transform. Sigma points are a structured set of sample points selected in such a way, that the sigma points give an adequate coverage of the input and output probability distribution. In short, the UKF consist of the following steps. 1) Calculate the sigma points using the error state covariance matrix. 2) Propagate all sigma points with the nonlinear system model and the input vector. 3) Calculate the a priori state estimate...
FIG. 1. Data acquisition, processing and validation scheme of attitude determination system.

and the a priori error covariance matrix. 4) Predict measurements by propagating the sigma points through the sensor model to obtain the transformed sigma points. 5) Calculate the a posteriori state estimate using the measurement vector. 6) Calculate the a posteriori error covariance. (Vinther et al. 2011)

Measurement noise covariances for the UKF are estimated using in-orbit measurements by minimizing the error between the attitude from on-board ADS measurements and the attitude determined from on-board camera images. The initial Sun sensor measurement noise covariance is $1.75 \cdot 10^{-6}$ rad. Note that the Sun sensor covariance varies depending on the incidence angle and is explained in detail in Section 3. The magnetometer measurement of the magnetic field vector direction noise covariance is $2.4 \cdot 10^{-7}$ rad. The gyroscopic sensor measurement noise covariance is $6 \cdot 10^{-6}$ rad·s$^{-1}$.

Figure 2 shows the timeline of attitude determination and control. It can be run with a configurable frequency of up to 10 Hz; the figure shows the timeline for 7 Hz (one iteration takes 143 ms). The top part of the figure shows attitude determination operations and the bottom part—attitude control operations. Each iteration starts with taking measurements, pre-processing and correcting them; simultaneously coil activation settings are sent to the electrical power system. The coil activation settings are an output of the attitude controller from the previous iteration. After sending the settings, a wait function is introduced to ensure that the electrical power system has re-
Measurements, pre-processing and correction

Attitude determination

Attitude control

Models

Attitude controller

Coil activation

settings

Coil activation toggle

Wait

20 ms

4–7 ms

90 ms

Wait

Up to 123 ms

143 ms

FIG. 2. Timeline of attitude determination and control (not to scale).

Received the settings. Next, coil activation for attitude control is toggled, and new measurements are processed — models are run first, then the attitude is determined by the UKF, and an attitude controller is used to calculate the required magnetic moment, from which the coil activation settings are calculated. Then attitude determination waits for attitude control to be completed.

After 21 months in orbit COTS sensors are still functioning correctly. One Sun sensor and one gyroscopic sensor have failed (see Section 3 for more details) but that has not compromised the mission due to redundant sensors on-board.

ADS CHARACTERIZATION

Sun sensors

In order to obtain the Sun vector, a geometrical model of Sun sensors is combined with voltage outputs from position sensitive devices (PSDs). If the Sun is not in the field of view (FoV), the Sun vector is set to zero.

On one side a Sun sensor is broken. The fault was detected before the launch but after the final integration, therefore it was not possible to fix it. Most likely it was caused by a loose wire. Nevertheless, overcoming problems caused by the fault required only minor changes in software because if the Sun vector is not available the satellite is assumed to be in an eclipse and the UKF accounts for it.

Sun sensors were designed with a FoV of $\pm 45^\circ$, but in-orbit measurements showed a growing error in Sun direction measurements when the Sun is viewed at the limit of the FoV, therefore it is limited by software to $\pm 36.7^\circ$. Possible causes are 1) calibration by rotating a sensor only around a single axis, 2) temperature influence that is not taken into account, and/or 3) drifting of the reference voltage that is not measured. Due to the growing error, the measurement noise covariance matrix for the UKF is varied depending on the Sun direction. If the direction is in a range of $\pm 20^\circ$, the covariance matrix elements are set to default $1.75 \times 10^{-6}$, but, when the Sun direction changes to a far range on either of the PSDs, the covariance matrix elements are quadratically increased up to 0.01. If the Sun is not in the FoV, the covariance matrix elements are set to one.

Typical Sun sensor measurements are presented in Figure 3. Zero values of the Sun vector indicate periods when the Sun is not in the FoV.

Magnetometers

Pre-processing of magnetometer measurements is performed in two stages.

Firstly, raw measurements of both sensors are processed individually. Faulty measurements are discarded meaning that the vector is set to zero. A measurement is considered faulty if an $I^2C$ error has occurred when reading the sensor, if all vector components are zero, or if any of the components are out of the range. Next, analog-to-digital units (ADUs) are related to physical
quantities, as well as zero-offsets and temperature corrections are applied. Zero-offsets were found iteratively during the in-orbit calibration phase by minimizing the error between the measured magnetic field and the modeled geomagnetic field. The temperature is measured from temperature sensors in analog-to-digital converters (ADCs) that are placed on the same board as the magnetometers. Calibration curves and temperature correction parameters were tuned by using statistical analysis of in-orbit measurements and by minimizing the error between corrected measurements and the modeled geomagnetic field. If the difference between the corrected value and the previous value exceeds a configurable limit, the measurement is discarded. Once the number of discarded measurements exceeds a configurable limit, the filter is restarted. Weights are used to smoothen the signal. Samples with a large derivative have a small weight.

Secondly, the magnetic field vector is calculated — corrected values as well as extrapolated values from both sensors are averaged together using sensor weights.

Typical magnetometer measurements are presented in Figure 4.

**Gyrosopic sensors**

The ADS of ESTCube-1 has four gyrosopic sensors, but a few weeks after the launch one of the sensors started to malfunction. Most of its measurements give an incorrect value if compared with data from other sensors; correct values appear only as jumps from the incorrect value. This behavior might be caused by 1) a radiation damaged charge pump, 2) a cold solder joint, 3) a malfunctioning I²C interface, and/or 4) infant mortality (an early failure caused by not wearing the sensor before the launch). The malfunctioning sensor is not used to take measurements.

Pre-processing of gyroscopic sensor measurements is performed in three stages.

Firstly, raw measurements of each sensor are processed separately. They are compared with the value extrapolated from historical measurements. If the measured value is unrealistic it is discarded and the extrapolated value is used. Then ADUs are related to physical quantities, as well as zero-
offsets and temperature corrections are applied. Calibration of gyroscopic sensors were performed in the laboratory and fine-tuned iteratively after the launch by fitting in-orbit measurements with the angular velocity output of the UKF. Gyroscopic sensors have built-in temperature sensors, but the ones in ADCs are used due to a lower noise level.

Secondly, measurements are weighted. The weight of a measurement is smaller when more extrapolated results are used in a row. The malfunctioning sensor has a weight zero. Weighted measurements are averaged together to make pairs.

Thirdly, weights are determined for each pair and the mean average of the pairs is taken to provide the final result.

Typical gyroscopic sensor measurements are presented in Figure 5. A typical attitude determination result acquired using all sensor measurements is presented in Figure 6.

Uncertainty budget

Table 1 presents the uncertainty budget of attitude determination by the ADS. Methods used for uncertainty estimation are described by (Metrology 2008). In cases of rectangular distribution, all measured or modeled values are assumed to have a maximum limit of error. In order to estimate an equivalent of normal distribution, the maximum limit is divided by \( \sqrt{3} \).

The simulation-based uncertainty estimated by standard deviation in parts of the orbit where images are taken, \( \delta u_{STD}^{ADS} \), is based on a study presented in (Slavinskis et al. 2014a), where uncertainties of ESTCube-1 attitude determination sensors have been estimated based on laboratory measurements. In the same study, standard deviation of the attitude has been estimated by simulating attitude determination. In the simulations, the following factors have been taken into account: the uncertainty of sensor measurements, the uncertainty of the moment of inertia, disturbances (radiation, atmospheric, gravity, magnetic residual), and the time uncertainty (for on-board calculations and for IGRF-11 coefficients). In this study, we use a similar simulation set-up that has
FIG. 5. A typical gyroscopic sensor measurement sample.

FIG. 6. A typical attitude sample.
TABLE 1. Uncertainty budget for ADS

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Standard uncertainty</th>
<th>Probability distribution</th>
<th>Uncertainty contribution, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta u_{\text{STD}}$</td>
<td>0.6°</td>
<td>Normal</td>
<td>0.6°</td>
</tr>
<tr>
<td>$\delta u_{\text{Mag}}$</td>
<td>105 nT</td>
<td>Normal</td>
<td>0.42°</td>
</tr>
<tr>
<td>$\delta u_{\text{Prec}}$</td>
<td>0.15°</td>
<td>Rectangular</td>
<td>0.15°</td>
</tr>
<tr>
<td>$\delta u_{\text{Pos}}$</td>
<td>3.5 km</td>
<td>Rectangular</td>
<td>0.1°</td>
</tr>
<tr>
<td>$\delta u_{\text{Sun}}$</td>
<td>0.01°</td>
<td>Rectangular</td>
<td>0.01°</td>
</tr>
<tr>
<td>$\delta u_{\text{Nut}}$</td>
<td>0.0015°</td>
<td>Rectangular</td>
<td>0.0015°</td>
</tr>
</tbody>
</table>

Combined standard uncertainty 0.76°

$\delta U_{\text{ADS}}$, expanded uncertainty (95% confidence level, $k=2$) 1.52°

been improved by including the broken Sun sensor, the limited FoV of Sun sensors (see Section 3), as well as a new inertia matrix from an improved computer-aided design (CAD) model.

The geomagnetic field model uncertainty, $\delta u_{\text{Mag}}$, contributes directly to the uncertainty budget as a maximum angular error introduced by an error in the magnetic field strength. The standard uncertainty of the IGRF-11 model is 26 nT per year (Maus et al. 2010) which cumulates to the uncertainty of 105 nT in 2014, the year of logging data for this article. The contribution is direct because geomagnetic field model provides a reference for attitude determination.

The Earth precession uncertainty, $\delta u_{\text{Prec}}$, and the Earth nutation uncertainty, $\delta u_{\text{Nut}}$, contribute to the uncertainty budget because the Earth rotation model does not compensate for those components of the rotation. The rotation from the Earth centered inertial frame to the Earth centered Earth fixed frame is based on a fixed point when both reference frames were equal at the very beginning of 1997 (Jensen and Vinther 2010, p. 65). The Earth rotation axis precesses 50 seconds of arc per year and nutates with an amplitude of 9.2 seconds of arc per 19 years (Wertz 1978, p. 27). The Earth rotation model is only used by the geomagnetic field model (see Figure 1) hence an error introduced in the Earth rotation model contributes directly to the attitude determination uncertainty budget.

The orbit propagator uncertainty, $\delta u_{\text{Pos}}$, contributes to the uncertainty budget as a maximum angular error introduced by a position error. An extensive literature search of SGP4 model uncertainty analysis did not yield a coherent estimation for satellites in low Earth orbits. Therefore we are using a maximum error of 6 km (Dong and Chang-yin 2010) as the worst case scenario in the case two-line elements are up-to-date and the time uncertainty is included in $\delta u_{\text{STD}}$. Similarly to the Earth rotation model, the orbit propagator is only used by the geomagnetic field model.

The Sun direction model uncertainty, $\delta u_{\text{Sun}}$, is based on an estimation presented in (Montenbruck and Pfleger 1994, p. 39). The accuracy of the Sun direction model is 1 minute of arc and it contributes directly to the attitude determination uncertainty because the Sun direction model is used as a reference.

IMAGE-BASED ATTITUDE DETERMINATION
Camera

Images of the Earth are taken by an on-board camera and are used as a source of the attitude for validation of the ADS. The camera employs a 4.4 mm telecentric lens and a 640 × 480 pixel sensor (Kuuste et al. 2014). Image-based attitude determination is not performed on-board but in the post-processing phase. In order to determine the attitude from images, three inputs are required: a set of coordinates of points in an image coordinate system; a set of coordinates of corresponding points in a geographic coordinate system (longitude, latitude and altitude); and time when an image was taken to calculate an orbital position of the satellite. The set of points is given such that the system is overdetermined and a statistical method is used to determine the attitude — the method minimizes the angular error between two sets of camera space vectors. The first set consisting of vectors pointing from the camera to the points in the geographic coordinate system; the second consisting of vectors pointing to the corresponding pixels on the image.

A typical image with landmarks used for image-based attitude determination is shown in Figure 7.

Uncertainty budget

Table 2 presents the uncertainty budget of image-based attitude determination.

The point selection uncertainty, \( \delta u_{Sel}^{Cam} \), is introduced by manual selection of points on images and in the geographic coordinate system. The uncertainty is estimated by taking the maximum within all samples of the mean average of angles between vectors pointing to pixels on images and to geographical coordinates.

The time uncertainty, \( \delta u_{Time}^{Cam} \), contributes to the uncertainty budget as a rotation over a given time and with a maximum rotation rate within all samples. To match the absolute time of images with the time of the ADS, 50 ms steps are used when the attitude from images is determined (more
TABLE 2. Uncertainty budget of image-based attitude determination.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Standard uncertainty</th>
<th>Probability distribution</th>
<th>Uncertainty contribution, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta u_{Cam}$</td>
<td>0.37°</td>
<td>Rectangular</td>
<td>0.37°</td>
</tr>
<tr>
<td>$\delta u_{Time}$</td>
<td>29 ms</td>
<td>Rectangular</td>
<td>0.21°</td>
</tr>
<tr>
<td>$\delta u_{Res}$</td>
<td>0.04°</td>
<td>Rectangular</td>
<td>0.04°</td>
</tr>
<tr>
<td>$\delta u_{Lens}$</td>
<td>0.02°</td>
<td>Rectangular</td>
<td>0.02°</td>
</tr>
<tr>
<td>Combined standard uncertainty</td>
<td>0.43°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\delta U_{Cam}$, expanded uncertainty (95% confidence level, $k=2$) 0.86°

Details about time synchronization is in Section 5). The maximum rotation rate is 7.1 deg·s$^{-1}$.

The camera resolution uncertainty, $\delta u_{Res}$, contributes to the budget because objects within one pixel cannot be distinguished (Kuuste et al. 2014).

The lens distortion uncertainty, $\delta u_{Lens}$, is introduced by a simplified barrel distortion model used to correct distortion.

COMPARISON RESULTS

To validate the on-board ADS we calculate differences between the attitude from the ADS and the attitude determined from images. We use logs of attitude determination sessions; during each session sets of two or three images are captured. Due to an absence of clouds, easily distinguishable landmarks and a specific natural rotation of the satellite, attitude determination sessions were performed in low latitudes (mostly over Africa).

More than one image is needed to allow time synchronization with the ADS. While the relative time, when images within one set are captured, is well known, the absolute time is not as precise. The best absolute time match is assumed when the total error between the attitude from the ADS and the attitude from images within a set is minimal without varying the relative time.

Due to ferromagnetic bolts and battery casings, the satellite body aligns with the geomagnetic field. The unwanted magnetic field produces a magnetic moment in the direction roughly diagonal from one edge to another. Under stable unactuated conditions the spin axis of the satellite is roughly aligned with its internal magnetic moment vector which in turn follows the geomagnetic field. The angular rate is from about 5 to 8 deg·s$^{-1}$. For this article, logs were taken in an actuated conditions (without using the attitude control system).

Since images might be captured between on-board attitude samples, the spherical linear interpolation (Slerp) method is used to match time instances of on-board attitude samples with images. The results are presented in Table 3. The expanded uncertainty of comparison (95% confidence level, $k=2$) is

$$\delta U = \sqrt{(\delta U_{ADS})^2 + (\delta U_{Cam})^2} = 1.75°.$$ 

DISCUSSION AND CONCLUSIONS

We have validated the on-board ADS of the ESTCube-1 CubeSat by comparing the attitude
TABLE 3. Difference between on-board and image-based attitude.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Difference, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>1.26</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>5</td>
<td>1.16</td>
</tr>
<tr>
<td>6</td>
<td>1.32</td>
</tr>
<tr>
<td>7</td>
<td>1.43</td>
</tr>
<tr>
<td>8</td>
<td>0.17</td>
</tr>
<tr>
<td>9</td>
<td>1.14</td>
</tr>
<tr>
<td>10</td>
<td>0.45</td>
</tr>
<tr>
<td>11</td>
<td>0.78</td>
</tr>
<tr>
<td>12</td>
<td>0.32</td>
</tr>
<tr>
<td>13</td>
<td>0.18</td>
</tr>
<tr>
<td>14</td>
<td>0.31</td>
</tr>
<tr>
<td>15</td>
<td>0.42</td>
</tr>
</tbody>
</table>

determined by the ADS with the attitude determined from on-board camera images. All 15 samples have differences less than 1.44° which is well within the expanded uncertainty of comparison (95% confidence level, \( k=2 \)) of 1.75°. These results indicate that the ADS fulfills the mission requirement to determine the attitude with an accuracy better than 2°. The methodology for evaluating and characterizing the ADS can be used for other missions.

The uncertainty budget is valid for parts of the orbit where images are taken. The budget is relevant for the E-sail mission requirement because in parts of the orbit, where the experiment is to be performed, the standard deviation is smaller than in the parts of the orbit where images are taken. Nevertheless, in (Slavinskis et al. 2014a) it is shown that the attitude determination error increases during an eclipse and in parts of the orbit where the Sun direction vector is close to parallel with the magnetic field vector.

The uncertainty budget is valid for spin rates of up to 7.1 deg·s\(^{-1}\) because such angular speed was used for estimating the time uncertainty. For higher spin rates, the time uncertainty has to be recalculated accordingly. The team has also seen that spin rates of tens of degrees per second introduces larger attitude determination uncertainty. However, results have not been presented in this article because cannot be validated using the same method — images of sufficient quality cannot be taken at spin rates of tens of degrees per second. The ESTCube-1 ADS has been used to provide inputs to the attitude control system which is able to reach the angular rate higher than two revolutions per second. These results will be presented in a dedicated article.

Lessons learned from the ESTCube-1 mission indicate several ways that the attitude determina-
tion accuracy for future missions can be improved. Laboratory tests cannot fully imitate conditions in orbit, therefore preparing and implementing in-orbit calibration methods can significantly improve the attitude determination performance. Having redundant sensors is beneficial, not only for risk mitigation, but can also improve the measurement accuracy and measurements can be cross-validated. In the case of COTS components, similar to those on-board ESTCube-1, additional sensors do not increase the mass budget much, but a microcontroller should have enough interfaces and the power budget might be increased significantly. At the same time, cost-effective COTS components tend to have a high temperature dependence, therefore having a temperature sensor in close proximity to every attitude sensor can provide additional means to correct measurements. Stress-testing sensors before the launch can avoid unexpected sensor failures due to infant mortality. Analog Sun sensors can be improved by taking reference voltage measurements. While having a higher FoV for Sun sensors introduces higher Albedo impact, FoV with margins (higher than ±45°) can improve the accuracy.

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