ANALYSIS OF NANO STALLITE ATTITUDE ESTIMATION WITH OPTICAL SENSORS AND A NUMERICAL MODEL BASED ON TRISAT MISSION DATA

Nejc Kosanič(1), dr. Iztok Kramberger(2)

(1) *University Of Maribor, Faculty of Electrical Engineering and Computer Science, +386 (2) 22 07 240, nejc.kosanic@um.si*

(2) *University Of Maribor, Faculty of Electrical Engineering and Computer Science, +386 (2) 22 07 178, iztok.kramberger@um.si*

ABSTRACT

In order to improve satellite attitude prediction an albedo model was made and tested. The model in combination with magnetic sensors and gyro meters an ACDS onboard the TRISAT mission was used to try and match recorded Sun vector from photodiodes also onboard the satellite. The model tracks Sun beams and considers the angles between the normal to the surface and both the Sun and the satellite, as well as the incoming angle to the photodiode on TRISAT. It then computes a small surface area of Earth for which a reflection coefficient is given. Integrating over satellite visible and Sun-lit smaller areas gives us an energy flux on the satellite's diode normalised in respect to the Sun flux energy. While the model is working as predicted, the mission recorded data has shown some bias and is thus making the effort to recreate recorded Sun vector parameters harder. Further improvements are also discussed.

1. INTRODUCTION

Satellite attitude determination and control systems are placed on satellites to better track satellites and describe their movements. The main and usually most accurate pointing vector prediction and its stability is achieved using a star-tracker. With the recent advancements and ever-growing usage of micro and nano satellites, a need for star tracker alternatives with good pointing vector accuracy and stability is needed [1]. In this article we will discuss using simple photo diodes as solar sensors to predict a pointing vector.

Using photo diodes with dimensions of about 5 mm * 5 mm * 5 mm instead of a star-tracker dramatically increases free volume in small satellites, which can be used for other scientific equipment. Due to its simplicity, such diodes provide a direct linear response to incoming light. Using at least three non-zero values on three orthogonal sides of the satellites gives us the Sun vector estimation. But a problem arises when using photo diodes in visible or ultra-violet spectra, because the Earth reflected light affects the photo current reading and a correction is needed for improving the attitude estimation.

The second part of the presentation will focus on an Earth albedo algorithm [2][3][4], which is being tested for TRISAT missions. The albedo model considers the position of Earth, Sun and the satellite and uses raytracing in combination with precise geometric description of the satellite to account for light each sensor receives. It is vital to properly understand Earth reflected light to accurately assess the photo current values [5].

2. PHOTODIODES AND SUN ESTIMATION

To properly determine the satellite orientation attitude determination and control systems (ACDS) are put on satellites (Figure 1). With the help of GNSS positional estimation is done. While satellite orientation may seem arbitrary at first glance, it is of vital importance to understand and correct satellite behaviour to accumulate as much sunlight on solar panels as possible. As such satellites usually rely on star trackers to produce a precise satellite attitude which is very accurate, but during stabilisation periods both the GNSS and star-tracker may be inactive, and an alternative is required. The solution is found in solar sensors in the form of photodiodes, which when placed orthogonally on the Sun-lit site produce a Sun position estimation.

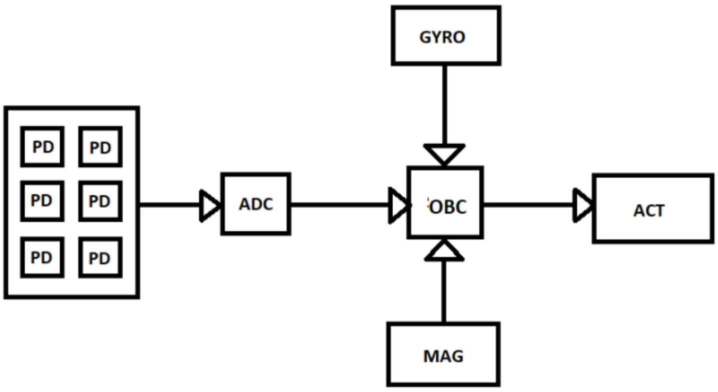

Figure 1: TRISAT ADCS blocks scheme during periods of stabilisation (ADC – analogous to digital converter, PD – photodiodes, OBC – on-board computer, GYRO – gyroscope, ACT – actuators, MAG – magnetometer).

The diodes on board TRISAT have been calibrated and shown to have directly linear power-to-current response, with the best responsivity around 360 nm and a full viewing angle of about 160°. While the Sun-lit site may produce a correct Sun position estimation, because TRISAT is in low Earth orbit flight path, at around 550 km, the viewing angle of Earth is quite large at 134°, meaning the sensor viewing angle is more than enough to encompass the whole Earth and have Sun in its sights as well. This becomes a two-fold problem: the Earth albedo must be properly accounted for in the ADCS instead of always using a constant and secondly, the maxima of photodiode produced current can become higher than it would be were the diode only Sun-lit.

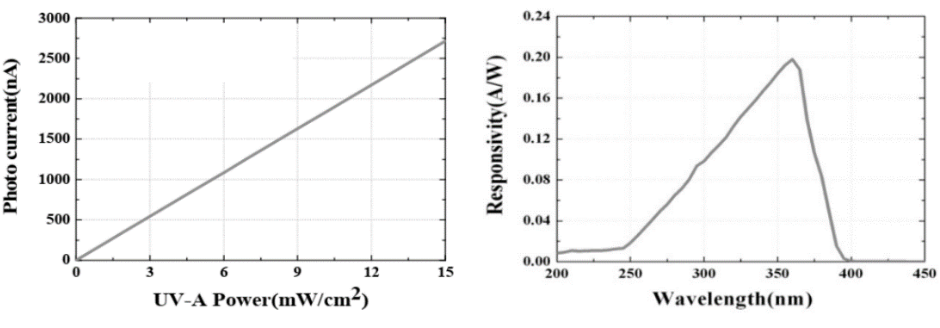

Figure 2: LEFT: linear photodiode responsivity in power spectrum, RIGHT: current response in wavelength spectrum

The difference between recorded Sun vector from photodiodes and the Sun's actual position might not be great but should still be accounted for. As far as the solar panels charging is concerned, keeping in mind that if the Sun were 15° from the normal to photodiode, the recorded current would still be 95% of the maximal Sun current, so small inaccuracies do not pose a challenge to satellite lifetime but rather to precise sensors, such as cameras, which need high pointing vector accuracy to produce significant results.

3. MAGNETIC FIELD DATA

While the three orthogonal Sun sensors are needed for Sun vector prediction, a failure of a photodiode results in a failure to determine the Sun vector over a half-sphere around the satellite. We can circumvent this problem by analysing the Kalman filter and thus focusing on the magnetometer onboard the satellite. Using a Python library for magnetic models (SGP4) the satellite orientation can be calculated by comparing the satellite magnetic vector to the model.

Due to some unknown bias on the satellite magnetometer, the recorded data has some inaccuracies. Validity check of the accuracy of magnetic data is done by interpolating the magnetic data and calculating the rotation of the satellite followed by a comparison between the calculated magnetic rotation and gyroscope data. It can still be seen that some of the bias is present even with interpolation, but general trends of the rotation are still comparable – at most times at least 2 out of 3 axes are within a comfortable comparable range between gyroscopic recorded and magnetometer derived rotation. This in term suggests that magnetic data can be used for basic satellite orientation estimation.

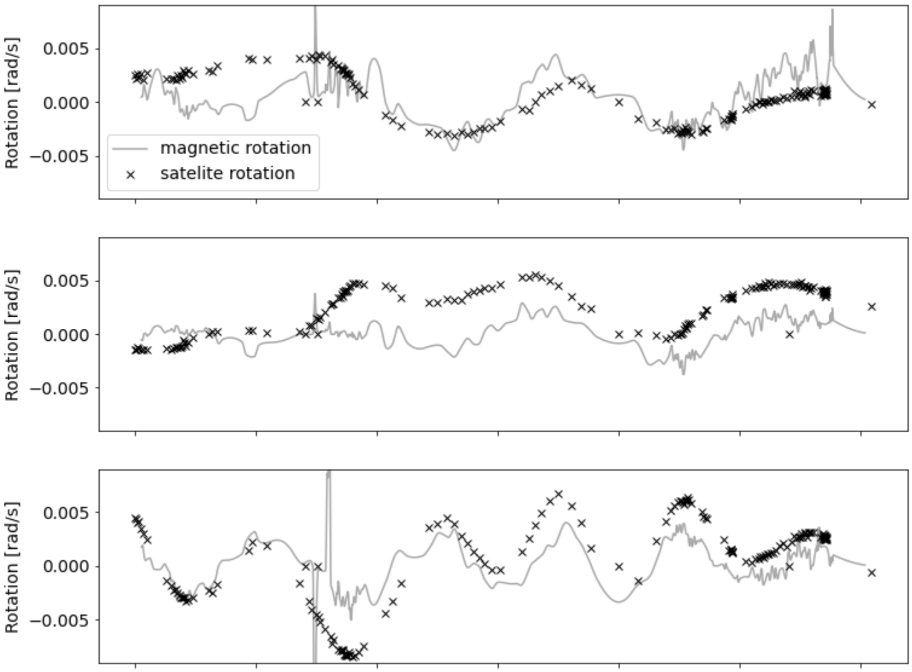

Figure 3: Comparing gyro recorded rotation (x, 'satelite rotation') with magnetic field derived rotation (full line, 'magnetic rotation'). TOP: x-axis, MIDDLE: y-axis, BOTTOM: z-axis.

4. EARTH ALBEDO MODEL

A model is needed to analyse and properly describe how the Earth reflected light from Sun scatters and arrives to the satellite as well as to establish more accurate maximal values diodes will produce. When this is achieved, the accuracy of Sun vector during stabilisation periods will be greatly improved.

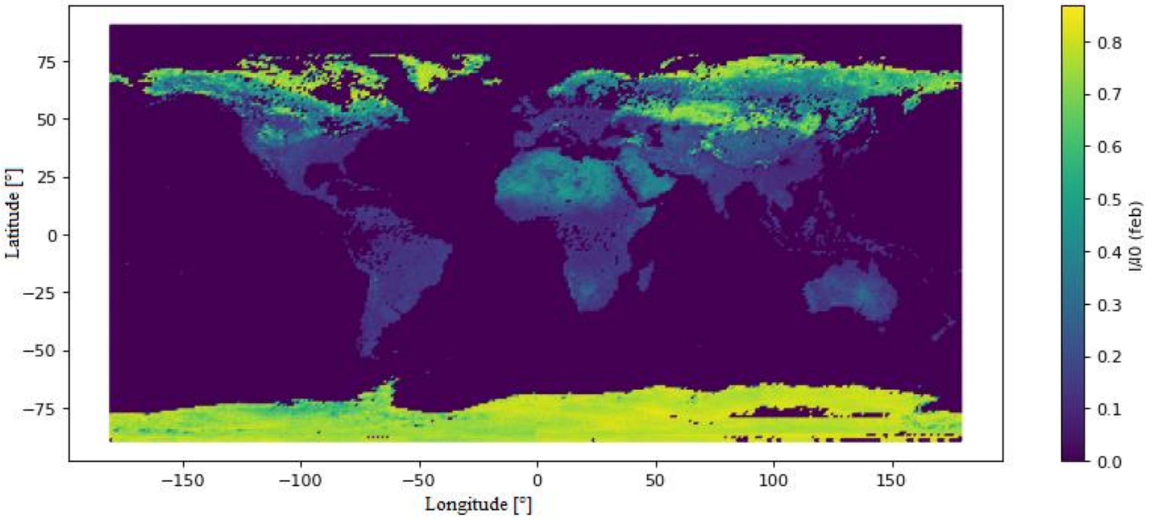

Figure 4: Earth albedo [6]

The first numerical model we made was done envisioning the Earth's surface as a flattened spherical albedo map. Putting the satellite above a certain point on the surface with the help of satellite telemetry data and acquiring Suns position, the algorithm first check whether the satellite is Sun-lit or if it is over a Sun-lit Earth surface. Next step is to calculate the amount of direct sunlight the satellite receives and to account for the shadowing objects around the diodes, which can be seen on Fig 5. With x-positive photodiode pointing at (0°, 0°), one can clearly distinguish some of the more obvious shadowing features such as solar panels (middle panel, both top and bottom).

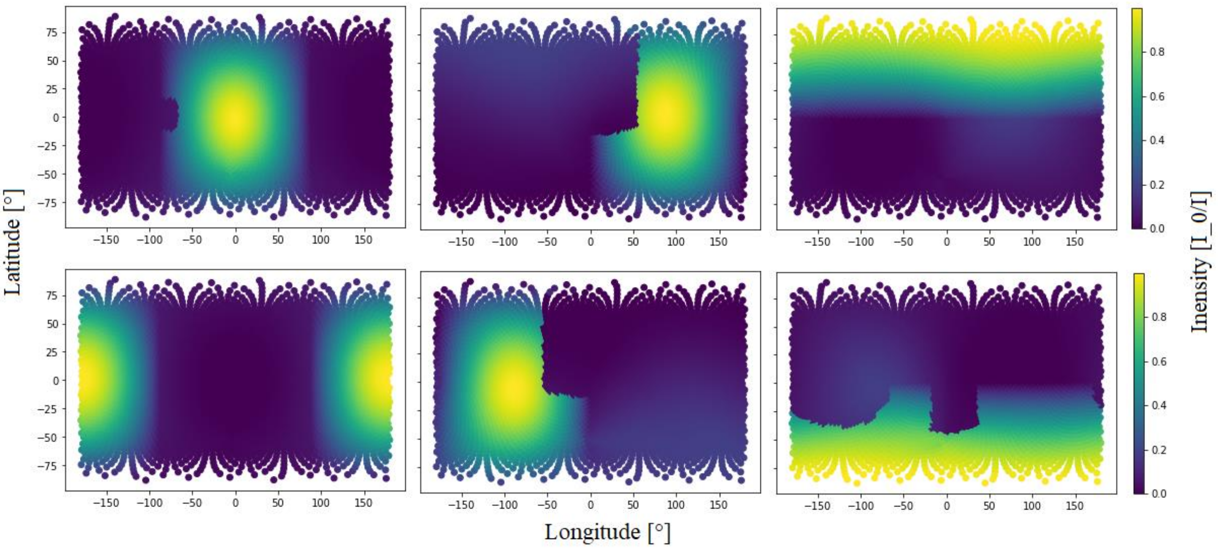

Figure 5: LEFT TOP: X-positive diode (centre at 0°, 0°), LEFT BOTTOM: X-negative diode (centre at 180°, 0°), MIDDLE TOP: Y-positive diode (centre at 90°, 0°), MIDDLE BOTTOM: Y-negative diode (centre at 270°, 0°), RIGHT TOP: Z-positive diode (centre at 0°, 90°), RIGHT BOTTOM: Z-negative diode (centre at 0°, -90°).

The algorithm to describe the amount of Earth reflected light considers a latitude dependant surface area on a sphere (the surface of a square of dimensions 1°*1° of Earths radius becomes smaller further from equator we go), the angle between the surface normal and the Sun vector (α) and similarly the angle between surface normal and the satellite vector (β), while it also considers the angle between the sun sensor normal and the incoming light (γ) - Eq 1. It does the computation for every Sun-lit spot on the 360° by 180° albedo grid field that is visible to the satellite. Once computed, the brightest spot on the grid is considered the point of origin of all reflected light to simplify computational power needed for calculations.

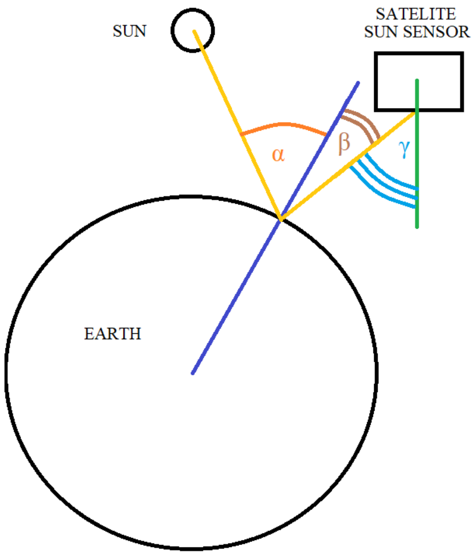

Figure 6: Schematic of Sun, Earth and a satellite placed sun sensor and angles α, β and γ.

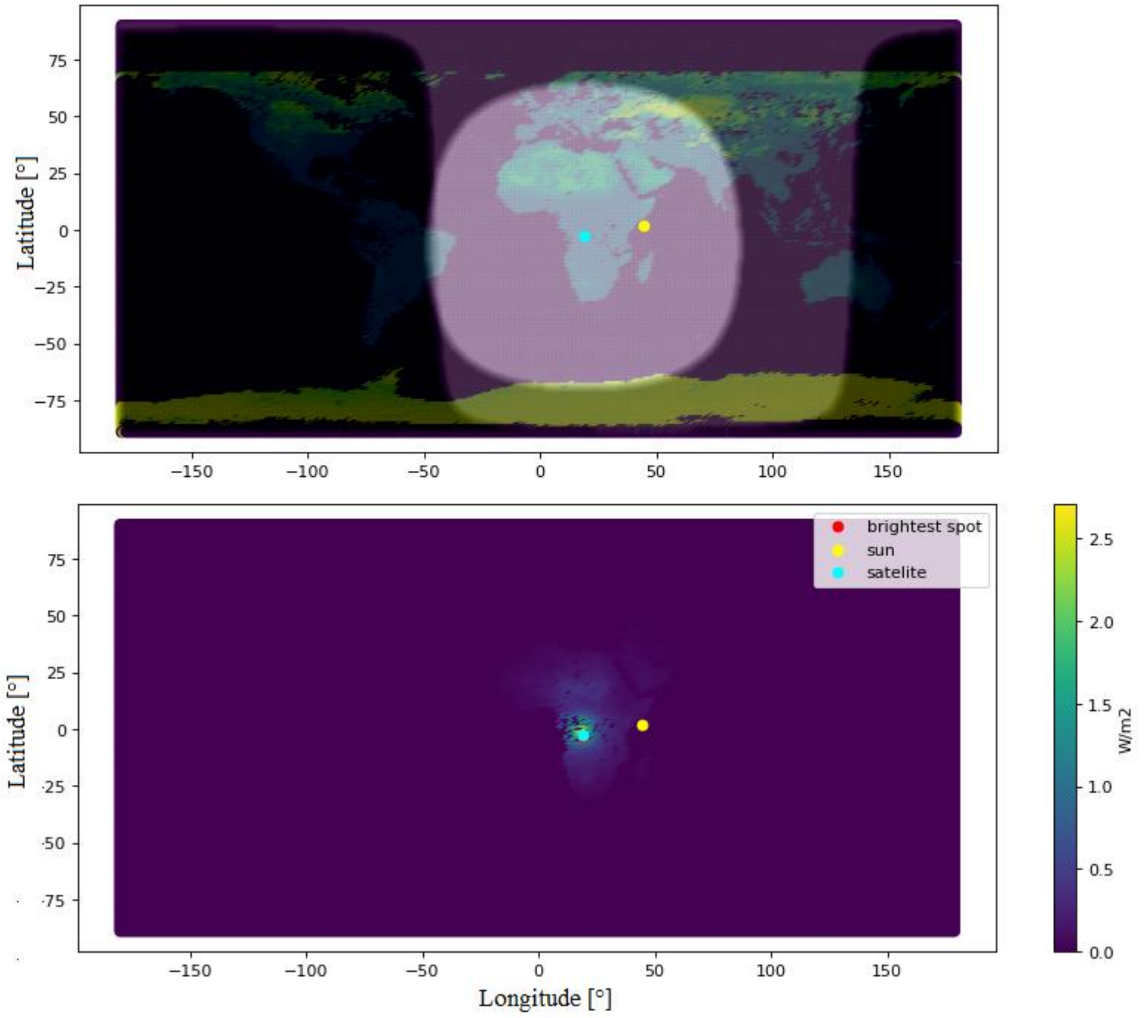

Figure 7: ABOVE: Earth albedo map with larger Sun-lit highlighted area, Sun being yellow, and satellite viewing area extra highlighted, satellite being cyan; BELLOW: map with computed reflected light energy (brightest spot is directly under satellite in this example).

The exact relation between Sun, Earth and satellite position is given by:

$$\boldsymbol{E_C(\phi_g, \theta_g) = S_{\phi_g,\theta_g} * R * E_{AM0} * cos(\alpha) * cos(\beta) * cos(\gamma)} \,, \tag{1}$$

where S_{ϕ_g,θ_g} is the observed surface area with its respected reflectivity R, and E_{AM0} energy of modelled Sun light (considering atmospheric scattering) at Earths surface.

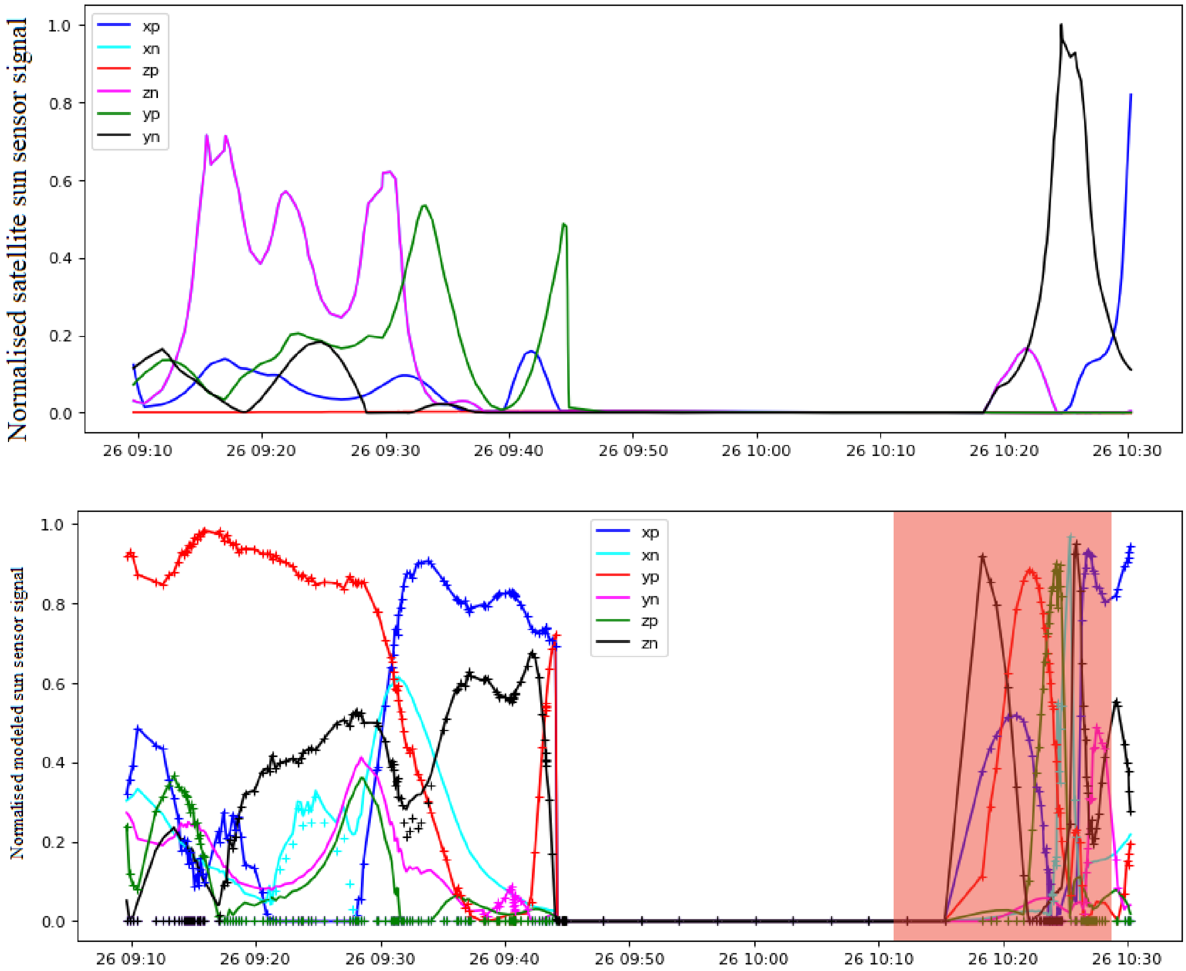

Figure 8: TOP: normalised satellite data for a certain timeframe; BOTTOM: normalised modelled Sun sensor signal (full line represents Sun light + reflected light, crosses represent Sun light only). In red: model magnetic pole interference.

While the model is still being tested and further optimized for processing power, primary results show some promise and some shortcomings of the model. The modelled reflected light is mostly within expectations and is in line with the literature.

Focusing on the shortcomings, Figure 8 shows comparison between one of the least successful matches to better illustrate further improvements: while the zero light levels clearly illustrate that the model GPS position is in perfect alignment with the recorded position, the light levels in the model are not properly representative of the measured values. This is due to the inaccuracies in both solar sensor bias and recorded magnetic field bias.

Furthermore, while the magnetometer onboard the TRISAT operates within the satellite, we have concluded that the surrounding casing is in some way affecting it, meaning the satellite has some internal magnetic field which corrupts the measurements in a marginal way. What can be seed painted in orange is the effect of modelled predicted magnetic field over the Earth’s magnetic pole changing rapidly in both direction and size while the recorded magnetic field changes slower. We have already shown at the beginning that the magnetic field can be interpolated, and its rotational change is comparable to gyroscope measurements.

What has also been discussed is the false maximal readout value from satellites photodiodes, for which correct Sun-only value has not yet been established but is in the process of measuring. Further improvement of the model is to correct the albedo map in way to represent only the UV-spectra that our diode is responsive to.

5. CONCLUSION

As of lately, most of the satellites are being produced purposely to fly in a low-Earth orbit, and it is obvious that there is a need for a simple solution during the satellite stabilisation period or to remove the need for a star-tracker completely. This short paper has shown that the method to use photodiodes and the help of an Earth albedo model in further combination with real-time gyro meter and magnetic sensor is a viable low-cost significant-accuracy option. While all satellites are affected by Earth reflected light, it has been shown that LEO are the ones with the highest amount of reflected light and are as such our primary goal of study. While the cases shown in this short paper have been primarily focusing on things to be careful about and to improve, we are in full development of an accurate albedo model to be incorporated into ADCS’ and used on future TRISAT missions and are awaiting further data from satellites in both LEO and MEO.

6. LITERATURE

[1] P. M. Akhmet’ev, A. Y. Smirnov: *Determination of the Orientation of an Artificial Satellite from Magnetic Field Data in Orbit*, Geomagnetism and Aeronomy, Vol. 60, No. 3, pp. 289-291, 202

[2] T. W. Flatley, W. A. Moore: *NASA Technical Memorandum 104596*, Greenbelt, Maryland, USA, january 1994

[3] D. Bhanderi, T. Bak, *Modeling Earth Albedo for Satellites in Earth Orbit*, Proceedings of AIAA Conference on Guidance, Navigation and Control, Aalborg University, Denmark, 2005

[4] D. D. V. Bhanderi: *Modeling Earth Albedo Currents on Sun Sensors for Improved Vector Observation*, AIAA Guidance, Navigation, and Control Conference and Exhibit, 21.- 24., Keystone, Colorado, August 2006

[5] S. A. O’Keefe: *Autonomous Sun-Direction Estimation Using Partially Underdetermined Coarse Sun Sensor Configurations*, Department of Aerospace Engineering Sciences, Faculty of the Graduate School of the University of Colorado, 2015

[6] Albedo map: https://neo.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA