USING BLACK-SUN EFFECT TO IMPROVE UNSCENTED KALMAN FILTERING OF TRISAT-R SATELLITE ATTITUDE PREDICITON

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ABSTRACT

Due to the nature of monetary and spatial constrictions, larger systems on small satellites are getting replaced by smaller but more inaccurate sensors. To improve the satellite orientation estimate, multiple different optical sensors may be used. In the case of TRISAT-R, the satellite is equipped with photodiodes and small cameras (CMOS sensors) in parallel, to establish the position of the Sun and calculate the satellite attitude. Due to the intensity of solar radiation, the “black-Sun” effect can be clearly distinguished: a black circle in a photo of a CMOS sensor. The black circle is smaller than the whole Sun on the photo, which provides a more accurate estimate of Suns position.

In this paper we will discuss the use of an Unscented Kalman Filtering, which uses magnetometer, gyro meter and optical sensor data, and then calculates the satellites attitude and error estimation. The accuracy of attitude estimation between photodiodes and CMOS sensor images will be compared and conclusion that CMOS sensors can be used to calibrate photodiodes in orbit will be presented.

1 INTRODUCTION

While the nano-satellite technology is advancing at a rapid pace, the drawbacks of small dimensions and low weight is impacting some of the low-level satellite operations. Main necessity is to have a stable satellite vector, where proper estimation of satellite orientation to align the Sun and the satellite is needed [1][2]. While the output from solar panels needs to be maximized, proper satellite orientation is needed for ground station communication as well [3]. Star-trackers have been widely used as a primary satellite orientation system, as they provide much needed accuracy, but can be large and heavy and thus pose a problem to be fitted on smaller satellites. In this regard, small optical sensors – photodiodes - are increasingly common among nano satellites to be used as main orientation devices [4][5][6][7][8], but also come with their intrinsic shortcomings: the temperature of the photodiode greatly impacts the photodiodes reading and may compromise the accuracy of such prediction, where the calibration of such a diode is also non-trivial, as a proper Sun specter lighting is not easy to come by and any deviation from this calibration procedure results in discrepancies while in orbit. Alternatively, CMOS sensors can be used for accurate Sun vector prediction, but as they are prone to radiation, they are typically not suitable for missions of longer duration.

Even with proper Sun vector calibration, the satellites attitude is prone to error with insufficient time sampling, as the satellite rotation is not a problem to be solved linearly. Different effects of aerodynamic torques, Earth’s gravity, magnetic torques and even solar radiation create an analytically non-predictable behavior, which imposes the need for high sampling rate or the use of some adaptive filtering method, which can self-correct.

Kalman filtering has been proven to be helpful regarding this matter, especially Extended Kalman Filtering (EKF), as it can provide an efficient solution with linearization of non-linear problems. The main advantage of EKF is the ability of filtering out the noise from measurement data and thus improving the accuracy of predicted data but has a critical fallacy when dealing with complex non-linearity, where divergence in error estimation can cause a runaway effect and make accurate predictions an impossibility. For such cases the Unscented Kalman Filter (UKF) provides an even better solution, as it computes a true mean and a covariance of systems state distribution with the help of set sigma points, thus bypassing the linearization problems which arise with the use of EKF [9][10][11]. With the addition of Modified Rodriquez Parameters (MRP), which lower the quaternion 4-dimensional approach to 3 dimensions, the filter provides a much-needed method to increase the accuracy of low-level optical sensors to satellite attitude prediction.

In this paper we focus on the description of small satellite systems which provide optical data for satellite orientation prediction, where TRISAT missions are used to model the system and provide a solution for future missions. Following that is the mathematical description of a stable and specific UKF filter, namely the "USQUE" filter, where the main advantages of UKF filtering are presented. Lastly the modeling of a future mission with the help of the USQUE filter is provided, which shows that the short-lasting CMOS sensors can be effectively used for in-orbit photodiode calibration.

2 TRISAT MISSIONS

TRISAT heritage begins with the first satellite, namely "TRISAT", which has been launched in 2020 and had on-board photodiodes to be used as a primary method for satellite orientation. In combination with magnetic sensors and a gyroscope, the results of the mission were what was described in the introduction: the calibration of the photodiodes was slightly off and resulted in quite a small error. While the satellite is able to maintain a good enough alignment with the Sun to power the solar panels, and effectively communicate with the ground station, a higher degree of accuracy for the satellite is still desired.

Improving the calibration for the next mission, the satellite TRISAT-R was launched in 2022 on an inaugural launch of VEGA-C and sent to almost 6000 km in the middle-Earth orbit. With a different mission requirement, the satellite was changed greatly, with an additional emphasis on correct diode calibration. Even with this step to increase the accuracy of photodiode readout, some inaccuracies were discovered post-launch. The satellite was designed to study the increased radiation in the lower van Allen belt and carries alongside basic instrumentation, such as gyro meter, magnetometer and GNSS receiver, several different radiation monitors.

Due to its relatively high orbit, the precise attitude determination is crucial to align the antennas on board with the ground station to achieve proper communication. The satellite thus makes use of the B-dot algorithm for orientation analysis, which uses the magnetometer and gyro readouts to make the orientation estimation. This poses a different kind of a problem, as the magnetic field strength at this altitude is much weaker than at the Earth's surface and noisy magnetometer measurements may provide large errors in attitude estimation. Secondly, since the gravitational pull of Earth is slightly smaller than at the surface, gyro-meter drift was discovered, which also effects the attitude estimation. With careful analysis both problems have been solved, but they have outlined a clear drawback of the B-dot algorithm.

Figure 1: TRISAT-R with a photodiode inside the black circle.

To solve this problem an orthogonally placed array of Sun sensors (Figure 1) has been placed on the satellite, to provide for a relatively easy way to establish the Sun vector while not greatly effecting the mass of the satellite or the electrical consumption. Each of the sensors outputs a voltage, which corresponds to the angle of the Sun above the sensor. The only downside of the sensor is the thermal instability of the photodiode, as they are greatly affected by their temperature and while thermistors are placed alongside the photodiodes to measure the temperature, there can still be some difference between the thermistor and true photodiode temperature.

Assuming precise knowledge of the diode's temperature, the solution to the beforementioned problem of diode calibration has been to place additional CMOS sensors (Figure 2) alongside the diodes to provide for an extra set of information about the Suns position. The 2 mm^2 cameras have a resolution of 350x350 pixels with a 120° diagonal FOW, which captures the Suns position with less than a degree of error. We have found that photographs of the Sun may sometimes be overexposed or slightly blurry due to reflection of the satellite.

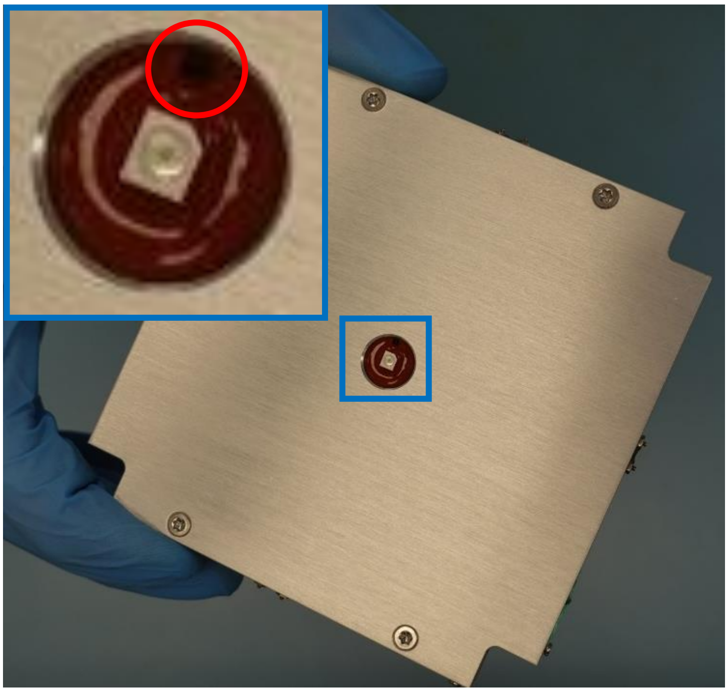

Figure 2: The CMOS camera on TRISAT-R in red circle at the top, above the photodiode in white.

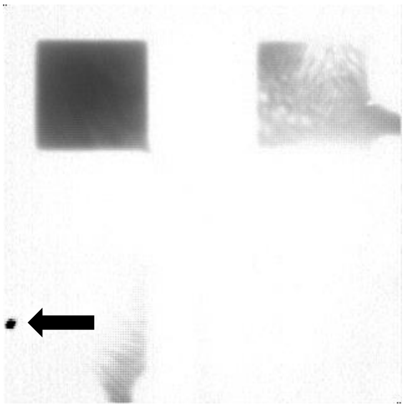

Figure 3: Overexposed TRISAT-R photo with the “black Sun” effect clearly visible on the left side.

Combating pure image quality, the “black Sun” effect can be used: if a camera sensor is greatly exposed, the overexposed pixel will overspill, which results in a black pixel(s) on the image (Figure 3). Knowing the properties of the Sun light, we know that the solar flux current is strongest at the center of the Sun – the black spots on the image are position in the middle of the Sun, thus the Suns center can be positioned with less than 0.5° of error, which is a great improvement over initial Sun position estimation and can be derived from overexposed or blurry images as well. This can then be used as an additional reference point in the USQUE filter.

Table 1: USQUE filter model

Model	$x_{k+1} = f(x_k, w_k, u_k, k)$ $\tilde{y}_k = h(x_k, u_k, v_k, k)$
Initialize	$\hat{q}(k_0) = \hat{q}_0$ $\beta(k_0) = \beta_0$ $P(k_0) = P_0$
Gain	$K_k = P_k^{xy}(P_k^{vv})^{-1}$
Update	$\hat{x}_k^+ = \hat{x}_k^- + K_k\upsilon_k$ $P_k^+ = P_k^- - K_k P_k^{vv} K_k^T$ $\upsilon_k = \tilde{y}_k - \hat{y}_k^- = \tilde{y}_k - h(\hat{x}_k^-, u_k k)$
Propagation	$\hat{x}_{k+1}^- = \sum_0^{2L} W_i^{mean}\, \chi_{k+1}^x(i)$ $P_{k+1}^- = \sum_0^{2L} W_i^{conv}\, [\chi_{k+1}^x(i) - \hat{x}_{k+1}^-][\chi_{k+1}^x(i) - \hat{x}_{k+1}^-]^T$ $\hat{y}_{k+1}^- = \sum_0^{2L} W_i^{mean}\, \gamma_{k+1}^x(i)$ $P_{k+1}^{yy} == \sum_0^{2L} W_i^{conv}\, [\gamma_{k+1}(i) - \hat{y}_{k+1}^-][\gamma_{k+1}(i) - \hat{y}_{k+1}^-]^T$ $P_{k+1}^{\upsilon\upsilon} = P_{k+1}^{yy}$ $P_{k+1}^{xy} = \sum_0^{2L} W_i^{conv}\, [\chi_{k+1}^x(i) - \hat{x}_{k+1}^-][\gamma_{k+1}(i) - \hat{y}_{k+1}^-]^T$

3 USQUE FILTER and the MODEL SETUP

With many different components on boards the satellites, their center of mass is commonly different from their geometric center, which must be considered to properly calculate the effects of different torques on the satellite. An inertia matrix is used to describe the off-center mass and is crucial for accurate satellite motion simulation. Then different on-board sensors are combined, and their data put in the simulator, which together with the inertia matrix forms the basis for the USQUE Unscented Kalman filter. Table 1 shows the basic setup of the filter, where quaternions are used for the model initialization. The main advantage of quaternions is that they avoid the Gimbal lock problem which arises from the use of Euler angels, but to improve the filter even further, devolving quaternions to Modified Rodriquez Parameters (MRP) can be achieved, where that quaternion is defined as $q = [q_{1-3}^T \; q_4^T]^T$, with $q_{1-3} = [q_1 \; q_2 \; q_3]^T$ and q_4 being the scalar component:

$$\delta p = f \; \frac{\delta q_{1-3}}{a + \delta q_4}. \tag{1}$$

We describe the error quaternion as $\delta q = [\delta q_{1-3}^T \delta q_4]^T$, where parameter a is a scalar between the values 0 and 1 and f is a scale factor. To convert the MRPs back to quaternions, equation 2 and 3 may be used:

$$\delta q_4 = \frac{-a\left|\left|\delta p\right|\right|^2 + f\sqrt{f^2 + (1 - a^2)\left|\left|\delta p\right|\right|^2}}{f^2 + \left|\left|\delta\right|\right|^2}, \tag{2}$$

$$\delta q_{1-3} = f^{-1}(a + \delta q_4)\delta p. \tag{3}$$

The USQUE model is then initialized with the state estimation $\hat{x}_0^+$ set as:

$$\hat{x}_0^+ \equiv \begin{bmatrix} \delta\hat{p}_k^+ \\ \hat{\beta}_k^+ \end{bmatrix}, \tag{4}$$

Te attitude error angles, and gyro bias σ_u and σ_v give as the initial covariance:

$$P_0^+ = \begin{bmatrix} diag(P_{att}) & 0_{3x3} \\ 0_{3x3} & diag(P_{bias}) \end{bmatrix}. \tag{5}$$

We then move on to calculating the process noise covariance $\bar{Q}_k$ as:

$$\bar{Q}_k = \frac{\Delta t}{2}\begin{bmatrix} \left(\sigma_v^2 - \frac{1}{6}\sigma_u^2 \Delta t^2\right) I_{3x3} & 0_{3x3} \\ 0_{3x3} & \sigma_u^2 \mathrm{I}_{3x3} \end{bmatrix}, \tag{6}$$

and sigma points σ_k as:

$$\sigma_k = \pm\sqrt{(\mathrm{n} + \lambda)[\mathrm{P}_\mathrm{k}^+ + \bar{Q}_k]}. \tag{7}$$

The model then computes corresponding error quaternions and sigma-point quaternions, which are then propagated forward in time. This leads to propagated error quaternions and calculation of propagated sigma points. It is then possible to obtain the predicted mean and covariance, alongside with mean observations. The final step is to compute the output covariance, innovation covariance and the cross-correlation matrix, followed by updating the state vector and quaternion, as well as the covariance. The $\delta\,\hat{p}_{k+1}^{+}$ is then reset to zero.

In our simulation the propagation of TRISAT-R, we have computed the state vector of the satellite in two full orbits at the altitude of 6000 km. The specific orbit was chosen to focus on UKF performance of attitude prediction, so the Sun-synchronous orbit of inclination 90° was chosen, to be performed in 13700 seconds.

While completing a full orbit, the satellite has performed on full rotation around the y-axis, which would correspond to a nadir-pointing simulation. The data for magnetic vector simulation was obtained from the World Magnetic Model 2020 Python library and fitted with zero-mean Gaussian noise. Additionally, the data for the gyroscope was simulated using the $\sigma_u = 3.1623 * 10^{-4}\ \mu rad/sec^{\frac{3}{2}}$ and $\sigma_v = 0.3126 * 10^{-4}$ [11] and fitted with white noise.

Quaternion $q_0^+ = [0,0,0,1]^T$ was used for the initial state estimate and the initial covariance P_0^+ was set to $P_{att} = (1°)^2$ in the left part and $P_{bias} = (0.5°/hour)$ in the right part for photodiodes, with $P_{att} = (0.1°)^2$ and $P_{bias} = (0.1°/hour)$ for CMOS sensors. Parameters $a = 1$ and $f = 4$ were used.

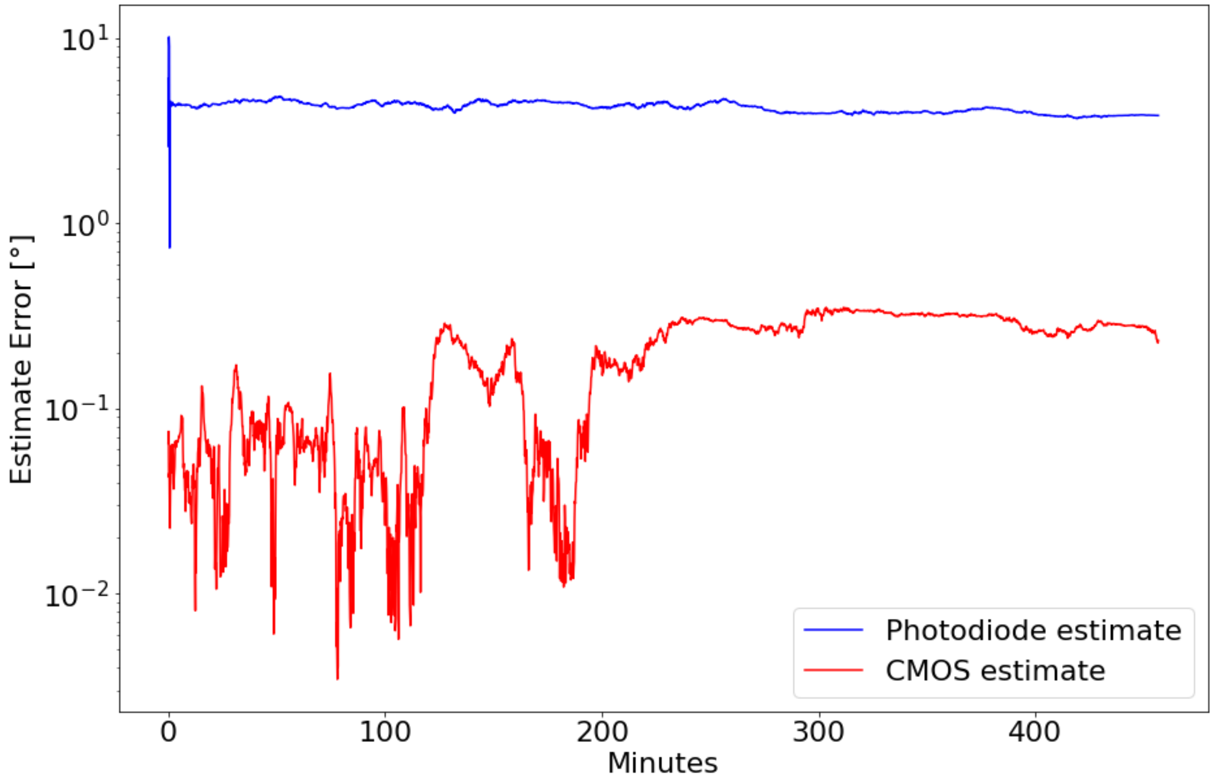

Figure 4: UKF simulation showing comparison between photodiode estimation and CMOS sensor estimation.

4 RESULTS AND DISCUSSION

While simulating the TRISAT-R orbit, the behavior of USQUE filter predictions vary greatly between the photodiodes and CMOS sensors (Figure 4): the obvious dramatic increase in error of photodiode estimate is a product of the filter, and the values quickly settle, while the CMOS sensor prediction values vary greatly at the beginning and then settle, after some balance is achieved. While observing the prediction estimates, it can be clearly seen that the error in the attitude estimate with the help of CMOS sensors is almost two full orders of magnitudes lower, which confirms our belief that CMOS sensors can be effectively used to help calibrate the photodiodes in orbit.

TRISAT-R has now been operational for 21 months and has shown signs of slow degradation of solar cell efficiency due to irradiation. With the focus on studying temporary and permanent irradiation damage from charged particles trapped in the lower Van Allen belt, the downloaded data focused primarily on the scientific part of the mission. Thus, the data from magnetometers, gyro meters and sun sensors was sent to Earth rather scarcely, with images from TRISAT-R being very rare, as the memory heavy downlink streams were mainly avoided to favor data from the scientific part of the mission. To get enough sample points for our filtering tests, the downloaded data served as the basis for error analysis, upon which then 2 full satellite orbits were sampled.

With our main scientific mission well underway, more and more images were downloaded to show the efficiency of "black Sun" spot tracking, even in overexposed scenarios. To showcase the capabilities of our miniature camera, also a photo of the Earth was captured (Figure *5*: TRISAT-R photo of the Earth from 6000 km), which shows that even small sensors can be used for extensive research, if properly used.

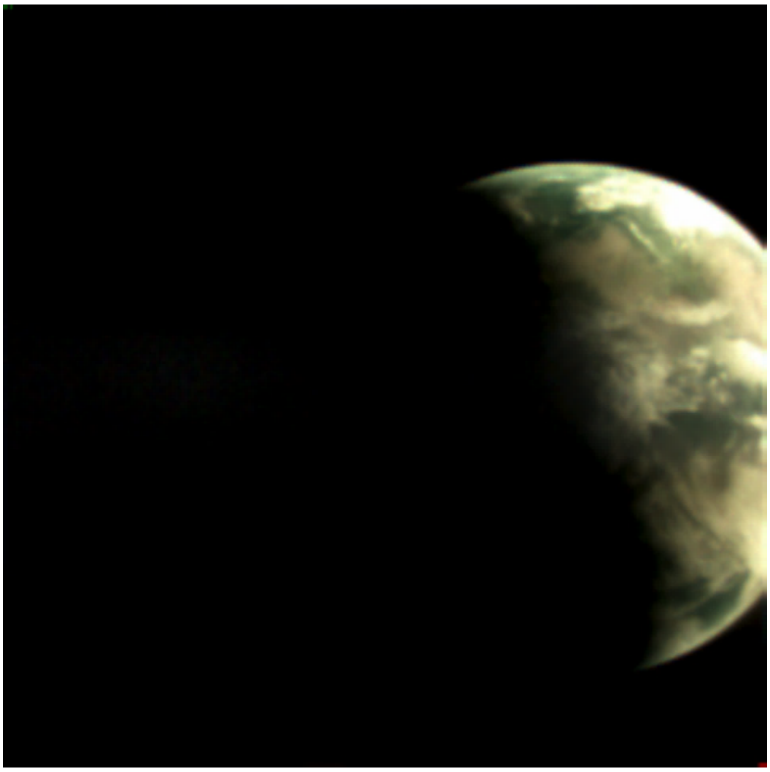

Figure 5: TRISAT-R photo of the Earth from 6000 km

5 CONCLUSION

The goal of achieving good miniature satellite attitude estimation has been pestering scientists for the last couple of decades. With the recent advancements in photodiodes and the use of Unscented Kalman Filtering, a new way of attitude determination was possible with smaller sensors and an acceptable error in estimation. What we have shown in this short article is that we can use the black Sun effect in our favor, to determine the Sun vector with less than 0.5° error from CMOS sensors, which with the help of UKF may be used as an in-orbit mechanism for proper diode calibration. While the CMOS sensors may be used to directly estimate the Sun vector, the cameras are prone to radiation and may falter relatively fast, but still provide us with enough time to re-calibrate photodiodes to be used as fallback attitude determination system. Future work will focus on collecting more data from the ongoing TRISAT-R mission and further improve attitude determination with the help of more precise black-Sun readout and better photodiode calibration.

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