GPS and SGP4 based Orbit Propagation Onboard the Galassia-2 Nanosatellite

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GPS AND SGP4 BASED ORBIT PROPAGATION ONBOARD
THE GALASSIA-2 NANOSATELLITE

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ABSTRACT

With an increasing demand for nanosatellites to perform accurate pointing such as Earth observation missions, the availability and accuracy of the orbital position and velocity information on board the satellite's computer becomes indispensable. The conventional way of providing this information is to run an orbit propagator such as the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) onboard the satellite, supplied with the Two-Line Elements (TLE) obtained from NORAD and uploaded from the ground station on a regular basis, e.g. every one or two days. For a satellite mission with a more stringent requirement such as Galassia-2, however, an onboard Global Positioning System (GPS) receiver is desirable to get a much higher accuracy. Additionally, the GPS receiver can be used for time synchronization in-orbit and for accurately timing the image captures. In this paper, we describe the design, implementation and preliminary pre-flight testing of the GPS receiver and SGP4 orbit propagator. We also explain the technique to generate the satellite's TLE in-orbit from GPS data as a more up-to-date and accurate backup compared to NORAD TLE. Lastly, we describe our plans on how to test and operate the GPS receiver in-orbit.

1   INTRODUCTION

Galassia-2 is a 3U CubeSat under development at the Satellite Technology and Research Centre (STAR) at the National University of Singapore (NUS). The 4 kg nanosatellite is equipped with a multispectral camera payload designed for precision agriculture. This project is funded by the Engineering Design and Innovation Centre (EDIC) and the Department of Electrical and Computer Engineering (ECE), and the team consists of research engineers and undergraduate students primarily within the education curriculum of the Innovation & Design-Centric Program (iDCP).

1.1 Mission Requirements
The mission objective is twofold: to successfully demonstrate agricultural remote sensing with a nanosatellite and to build up our university's capability through qualifying in-house developed

subsystems in space. At a reference orbit altitude of 550 km, Galassia-2 will capture images with a ground resolution of 40 m and swath width of 80 km, with the image capture accuracy defined to be within 10 km radius from the intended imaging centre. These images will be captured at four spectral bands: Green (580 nm), Red (650 nm), Red-Edge (720 nm), and NIR (800 nm). With these four bands, a number of analysis can be performed including Normalised Difference Vegetation Index (NDVI) and Soil-adjusted Vegetation Index (SAVI).

After capturing the images, the payload computer shall follow with demosaicing process and lossless compression. These compressed images shall then be transferred to the ground station in NUS over S-band up to speeds of 2 Mbps using the Software-Defined Radio (SDR) controlled by the same payload computer. Onboard processing and compression are mandatory due to the short ground contact window and the physical speed limit of the wireless transmission.

1.2 Orbit Determination and Time Requirements

Deriving from the mission requirements, there are two main tasks that the onboard GPS receiver and orbit propagator have to accomplish. First, images shall be tagged with position information of < 1 km and time information of < 1 ms. Second, both state vector and time are required for the Attitude Determination and Control System (ADCS) for attitude estimation and manoeuvres such as sun and nadir pointing. Attitude information will also be tagged to the captured images for further post-processing on the ground such as orthorectification.

Both tasks are easily achieved when GPS lock is maintained. However, there are several constraints that may prevent the GPS receiver from maintaining a lock, such as antenna pointing constraints and link margin constraints. When real-time GPS data is unavailable, the conventional backup strategy is to use NORAD TLE, uplinked from the ground station, and propagate it with an orbit propagator such as SGP4. This approach, however, has its own constraints, i.e. it is not as accurate as GPS data and the TLE is only updated every one or two days, which can result in an error of up to 10 km for a two-day old TLE [1]. We are exploring a better backup strategy for our mission.

2   DESIGN and METHODOLOGY

To fulfil the orbit determination and time requirements, we have to select a suitable set of hardware and implement a set of strategies in the software running on the ADCS computer, which controls the GPS receiver and runs the calculations for orbit propagation.

2.1 GPS Receiver, Antenna and LNA

The GPS receiver selected for Galassia-2 is the NovAtel OEM615, a geodetic grade dual-frequency GPS receiver capable of tracking all GNSS constellations including GPS, GLONASS, Galileo, BeiDou and QZSS. It has a high Technology Readiness Level (TRL), flown on board a few missions including GOMX-3 (2015) and VELOX-II (2015). Earlier versions of receiver from NovAtel have also been successfully demonstrated, such as OEMV-1-L1 on board RAX nanosatellites (2010, 2011) and OEM4-G2 on board CanX-2 (2008).

The OEM615 is mounted on the ADCS motherboard next to the ADCS computer as can be seen in Figure 1 and Figure 2. It has a size of 46 x 71 x 11 mm and a mass of 24 g. The receiver typically draws < 1 W at 3.3 V and based on our satellite's power budget, it is not a problem to operate it full-time including in eclipse. Based on the datasheet, OEM615 can provide a position accuracy of < 1.5 m and time accuracy of < 20 ns. The ADCS computer communicates with the receiver over UART in order to request state vector and time information as well as to set important parameters.

There are several important considerations in order to use a geodetic grade receiver in space. To allow high speed and high altitude operation, the limits from the Coordinating Committee for Multilateral Export Controls (CoCom) have to be disabled. Additionally, corrections from tropospheric effects have to be removed and because the relative velocities between our satellite in the Low Earth Orbit (LEO) and GPS satellites are quite significant, the Doppler windows have to be expanded. Based on our calculation, we are expecting a Doppler shift of up to 40 kHz at L1 frequency.
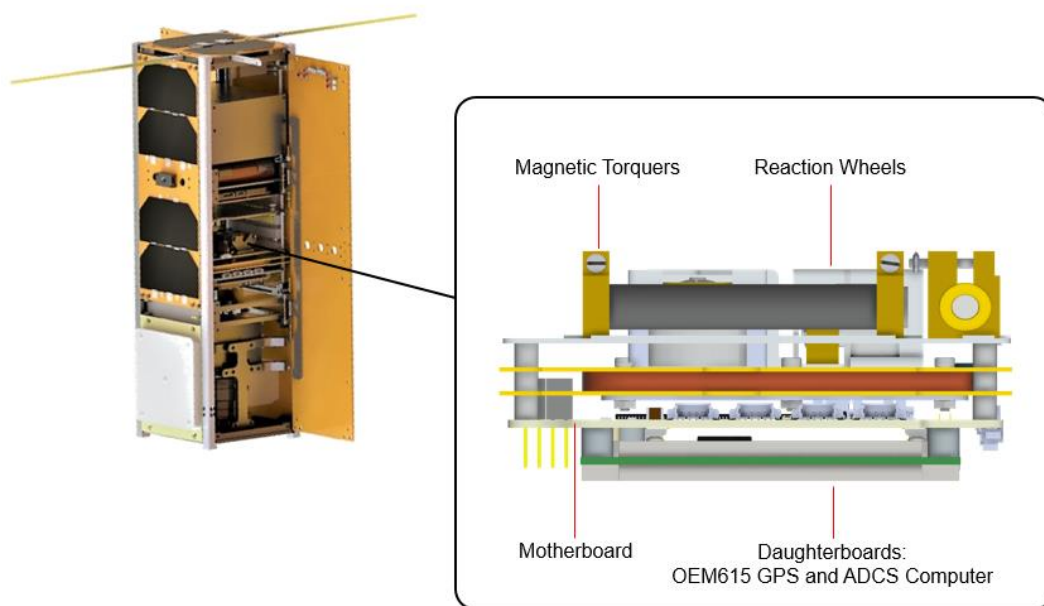

Figure 1. Mounting Location of the OEM615 GPS Receiver on Galassia-2

Figure 2. OEM615 Mounted at the Bottom of the Motherboard

The ACTPAT154 patch antenna from Inventek Systems was selected for our mission. It has a very small size of 15 x 15 x 7 mm and hence we do not need to sacrifice much space that otherwise can be used for solar cells. The antenna comes with a built-in LNA providing 26 to 35 dB gain and has a 3 dB beamwidth of about 120°. Because we expect Galassia-2 to perform sun pointing most of the time, we decided to place the antenna on the -X surface of the satellite as shown in Figure 3, which is also the face of the solar panels once deployed, such that the antenna's boresight is pointed as close to zenith as possible. The effects of the choice and location of the antenna were studied through link budget and simulations as shown in Section 3.
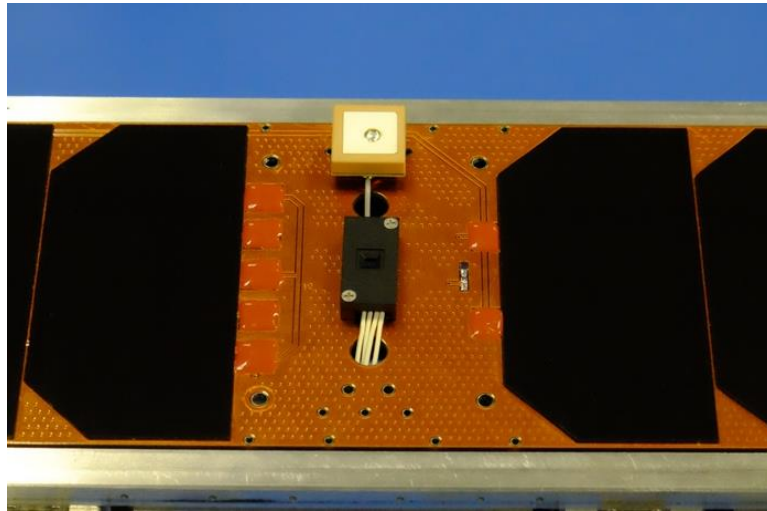

Figure 3. ACTPAT154 Patch Antenna Mounted on the -X Body Mounted Solar Panel

2.2 Orbit Determination Strategy

Once Galassia-2 is fully commissioned, the preferred way of providing orbital position and velocity information will be to enquire the GPS receiver in real-time, i.e. at a defined sampling time within the ADCS software. In the event that GPS lock is lost, a TLE is immediately generated on board the ADCS computer using the position and velocity obtained from the GPS at the most recent epoch, and the SGP4 propagator takes over. This strategy, which we will demonstrate in orbit, would be beneficial in a way that it can provide a more accurate and up-to-date TLE as compared to the conventional way of using NORAD TLE that is only updated every one or two days. However, a fallback plan to utilise NORAD TLE uploaded from the ground station is also made available.

A similar motivation to increase the accuracy of orbit determination came from the CanX-2 team by downloading the GPS data and subsequently converting it to a TLE using an MS-DOS program called VEC2TLE before propagating it with the SGP4 propagator [2]. We would like to test and validate our strategy if it would yield a better result in improving the accuracy of an onboard orbit determination system both for Galassia-2's remote sensing mission and for research purposes.

2.3 Time Synchronization Strategy

In addition to providing orbital position and velocity information, the GPS receiver can be used for a more accurate time synchronization and time propagation. The conventional way of synchronizing the clock on board a satellite is to uplink the time from the ground station, which is also how we perform time synchronization on Galassia-1, our university's first nanosatellite [3]. The flight

computer would then be responsible for propagating (ticking) the time. In the case of our new mission, we would like to achieve a better accuracy by using the GPS receiver to obtain the time information and propagate it with interrupt triggers from the receiver's Pulse-Per-Second (PPS) output. A PPS is an electrical signal that precisely triggers at the beginning of a second. The PPS output works even when the GPS lock is lost, however it will drift. It is important to characterise how long it takes for the drift to grow and fail the mission requirement. If the satellite is unable to maintain a GPS lock, the ADCS computer will use its own clock as a fallback.

3 GPS LOCK and LINK ANALYSIS

Before implementing our strategy, it is important to evaluate the constraints in orbit in order to verify our design decisions. In the case of the GPS receiver, we run a simulation to calculate the number of visible GPS satellites it can lock onto under different attitude scenarios and a given antenna field of view (FOV). This is important because the state vector can only be solved when the receiver locks to 4 GPS satellites or more. We also create both worst-case and best-case link budgets to calculate the expected received signal power at Galassia-2's GPS receiver and determine if the link satisfies our requirement.

3.1 Orbit Simulations
There are three attitude scenarios that we consider when running simulations in STK to evaluate the visibility of the GPS satellite constellation from Galassia-2 when in orbit: sun pointing, nadir pointing, and tumbling at rates of 0.1°/s, 1°/s, and 10°/s on all 3 axes. In these simulations, the GPS antenna cone angle is set to 180°. To take the effect of this cone angle into account, the worst-case link budget uses the side lobe gain of the antenna, i.e. 90° away from the boresight.

Galassia-2 will be spending most of its time performing sun pointing to generate as much energy as possible through its 3 x 7.2 W solar panels. Since the antenna is mounted on the same surface as the solar panels, we expect the GPS receiver to perform best during this pointing mode. When Galassia-2 takes pictures, it will point its camera to the Earth using nadir pointing mode. During this mode, the GPS antenna will be pointing 90° away from zenith and hence it might be more difficult for the receiver to maintain a lock as it does not have a full view of the constellation. Other than the two pointing modes, we also perform a simulation when Galassia-2 is tumbling, which is the case when it is initially deployed by the launch vehicle or whenever an ADCS fault or reset happens. Figure 5 shows a visualization of the different attitude scenarios studied.
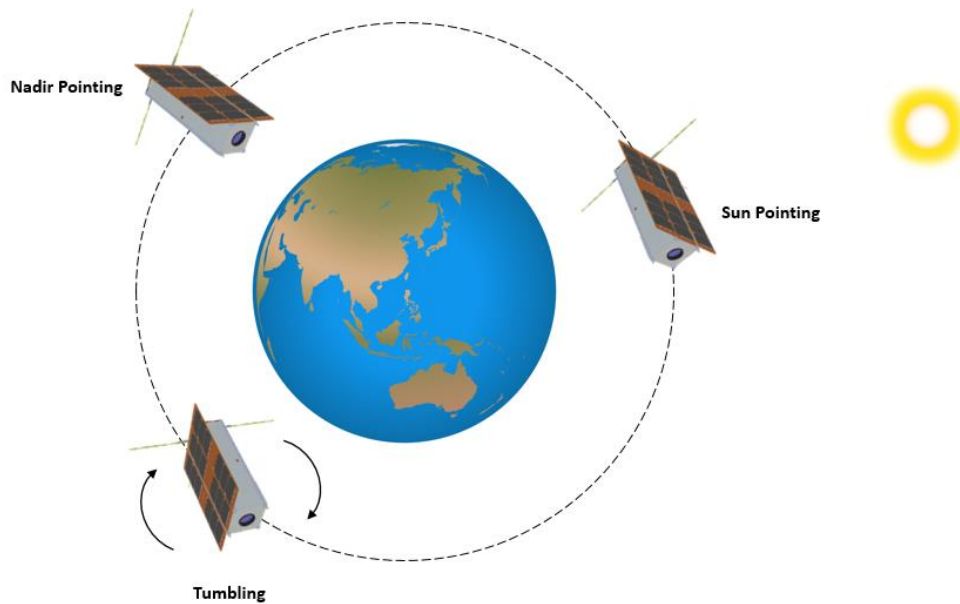
Figure 5. Various Attitude Scenarios Studied to Determine GPS Visibility

Figure 6 shows the simulation result of the number of GPS satellites in view during a sun pointing scenario over 1 day. In most cases, there are sufficient number of GPS satellites that Galassia-2 can possibly lock to, however there are some instances in eclipse when the number of GPS satellites fall below the minimum requirement. In eclipse, Galassia-2 is planned to perform a standby pointing mode, which means it will hold its last attitude before entering eclipse and hence the GPS antenna may be blocked by the Earth at times.
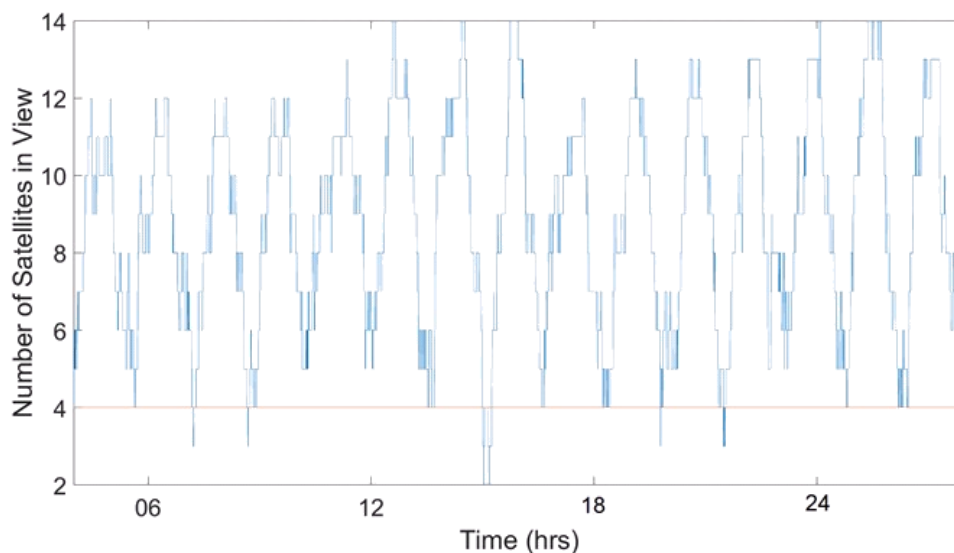

Figure 6. Number of Satellites in View for Sun Pointing Scenario

It is also of interest to know how the GPS receiver performs when Galassia-2's attitude is out of control, i.e. tumbling. Figure 7 shows the simulation result when Galassia-2 is tumbling on all its 3 axes. Even though the number of satellites in view is similar to the sun pointing scenario, the viewing time is much less. Since the OEM615's Time to First Fix (TTFF) is 35 seconds for a hot start and 50

seconds for a cold start, it is expected that Galassia-2 will have to be detumbled at least at 1°/s before a solution can be computed by the receiver. A summary of all the attitude scenarios is presented in Table 1.

(a)

(b)
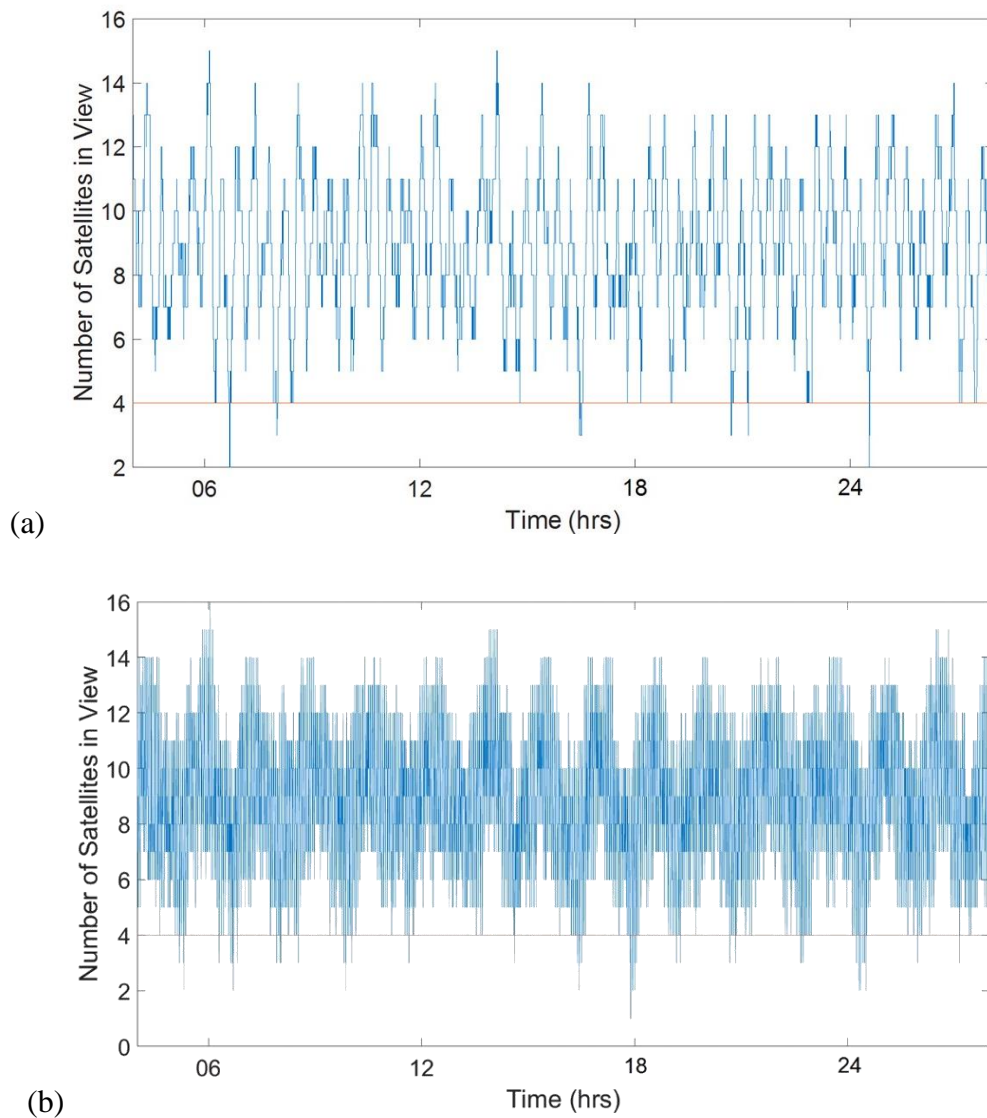
Figure 7. Number of Satellites in View for Tumbling Scenario at (a) 0.1°/s and (b) 1°/s

Table 1. Expected GPS Constellation Visibility from Galassia-2

Scenario	Average Number of GPS Satellites in View	Average Viewing Time per GPS Satellite
Sun Pointing	8.839	39 min 54 sec
Nadir Pointing	8.872	36 min 57 sec
Tumbling at 0.1°/s	8.982	16 min 41 sec
Tumbling at 1°/s	8.905	2 min 11 sec
Tumbling at 10°/s	8.854	13 sec

3.2 Link Budget

A link budget is developed to ensure the received signal power at the GPS receiver is sufficiently higher than the noise level, given the antenna and LNA chosen. Best-case scenario is achieved when Galassia-2 is closest to the GPS satellite (19,011 km), whereas worst-case happens when Galassia-2 is farthest from the GPS satellite (29,168 km) and its antenna facing 90° away. Based on the link budget calculated and shown in Table 2, the best-case and worst-case links are both healthy, with margins of 16.6 dB and 5.4 dB, respectively.

Table 2. GPS Link Budget for Best-Case and Worst-Case Scenarios

Parameter	Value (Best-Case / Worst-Case)	Unit
GPS Satellite		
Frequency (L1)	1,575.42	MHz
Distance to Galassia-2	19,011 / 29,168	km
Transmitting Power	14.25	dBW
RF Losses in Transmitter Path	-1.25	dB
Antenna Gain	13.5	dBi
EIRP	23.5	dBW
Free space propagation loss	181.97 / 185.69	dB
Galassia-2		
GPS Antenna Gain	0 / -7.5	dBic
GPS Antenna to LNA Connector Loss	0.05	dB
LNA Noise Figure	1.4	dB
LNA Gain	26	dB
LNA to Receiver Connector Loss	1.5	dB
Power Received at GPS Receiver	-105.42 / -116.64	dBm
Link Margin	**16.58 / 5.36**	**dB**

4   ONBOARD TLE GENERATION FROM GPS DATA

As mentioned in Section 2.2, when real-time GPS information in unavailable, we intend to use the last available GPS orbital state for orbit propagation with SGP4. To do so, we wrote a software code that runs on the ADCS computer to convert the position, velocity and time information from the GPS into a TLE.

In order to assemble a TLE, we need to identify the important parameters for orbit determination. There are 8 parameters in total to be calculated. These are the classical orbital elements, the epoch time, and the drag term called B-Star. The first and second time derivatives of mean motion are not

used by the SGP4 model and thus can be omitted [4]. Other details such as the satellite number, classification, designator, and other non-orbit state related information will be appended after these 8 parameters are calculated to form a TLE, represented in two arrays of characters.

4.1 Deriving Classical Orbital Elements and Epoch Time

The classical orbital elements are six parameters required to uniquely determine a specific orbit and are all specified in a TLE. It comprises of

1. a: Semi-Major Axis - defines the size of the orbit
2. e: Eccentricity - defines the shape of the orbit
3. i: Inclination - defines the orientation of the orbit with respect to the equator
4. ω: Argument of Perigee - defines where the perigee is with respect to the Earth's surface
5. Ω: Right Ascension of the Ascending Node - defines the location of the ascending and descending nodes with respect to the equatorial plane
6. v_o: Mean Anomaly - defines where the satellite is within the orbit with respect to perigee

It should be noted that the Semi-Major Axis is expressed as Mean Motion in the TLE. The mean motion is defined as the mean number of orbits per day a satellite travels around the Earth, and the relationship between the two can be expressed by Eq. 1, where $n_o^{''}$ is the mean motion, a is the semi-major axis, and μ is the standard gravitational parameter.

$$n_o^{''} = \sqrt{\frac{\mu}{a^3}} \tag{1}$$

These classical orbital elements located on the second line of the TLE can be derived from an orbital state vector (position and velocity) such as from the GPS using a set of equations written in [5], which are also well summarised in [6]. The epoch time, located on the first line field 7 and 8 of the TLE, can be derived immediately from the GPS time, i.e. the time at which the orbital state vector is obtained. The process of deriving these parameters is summarised in Figure 9.
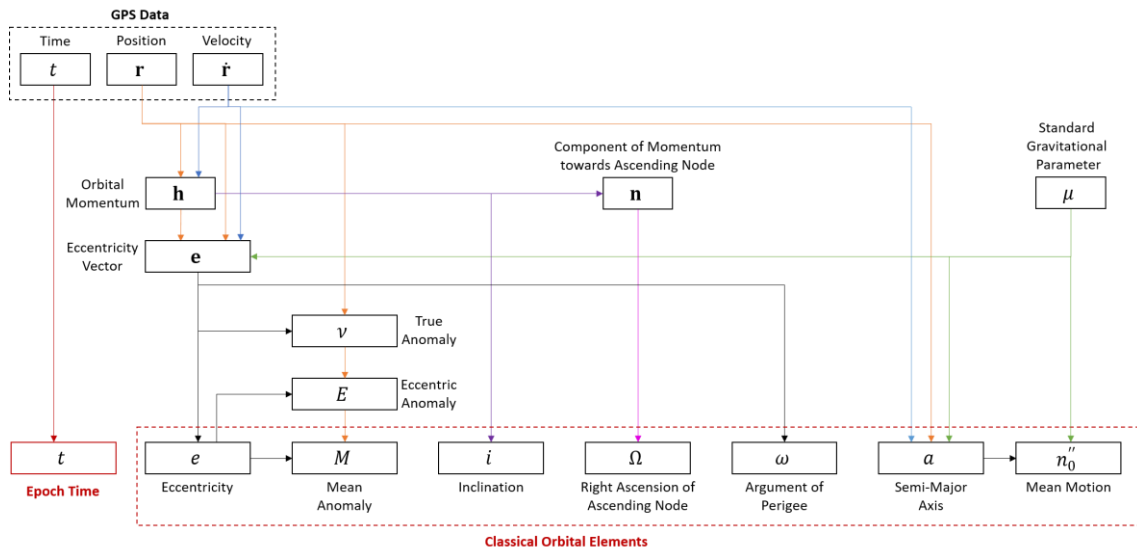

Figure 9. Overview of Derivation of Classical Orbital Elements and Epoch Time from GPS Data

4.2 B-Star (B^*)

The B-Star parameter is used to model the aerodynamic drag and is a measure of how susceptible the satellite is to drag. A higher B-Star means more susceptibility to drag. It affects how much the satellite is expected to slow down in the propagation of its orbit. B-Star is defined by Eq. 2 [5].

$$B^* = \frac{C_d A}{2m} \rho_0 R_+ \tag{2}$$

Where C_d is the drag coefficient, A is the frontal area of the satellite (surface area perpendicular to the velocity vector of the satellite), m is the mass of the satellite, ρ_0 is the atmospheric density at perigee and R_+ is the Earth radius.

Based on our simulations in STK with a TLE of an existing 3U CubeSat in the Low Earth Orbit with a similar mass and surface area to Galassia-2, we found that the effect of the B-Star drag term is insignificant. For example, changing the B-Star parameter to zero from the original 6.7×10^{-4} give insignificant maximum deviations of less than 0.1 km in range over 4 days. Changing it to two orders of magnitude larger, however, results in a maximum range deviation of a little less than 10 km. The range deviations are plotted in Figure 10.
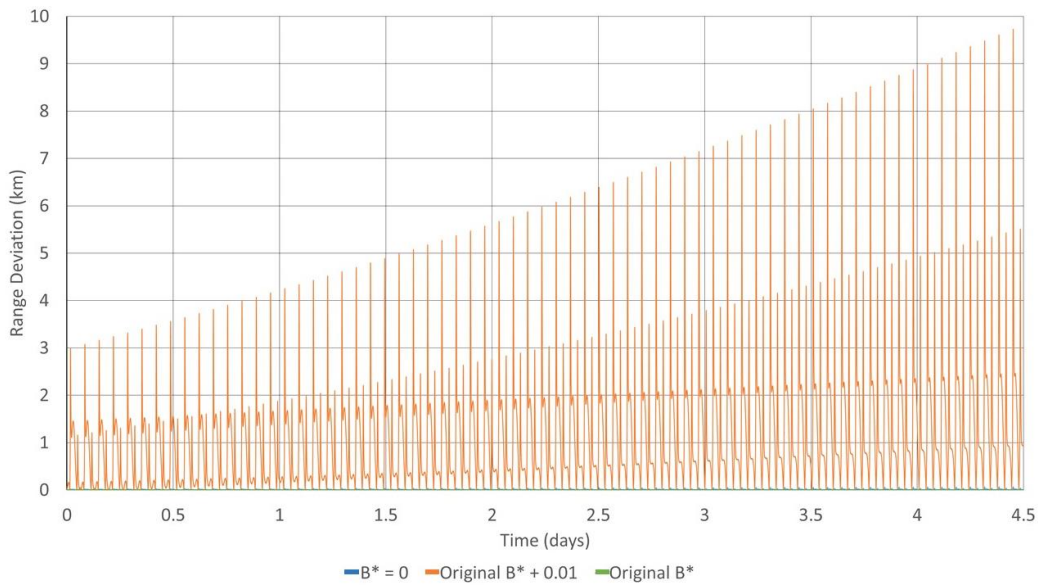

Figure 10. Maximum Range Deviations between the Original and Various B-Star Values

It is therefore reasonable to set the B-Star parameter to zero for our purpose. An alternative would be to use the B-Star parameter as specified in the latest TLE from NORAD.

5   PRE-FLIGHT TESTING and IN-ORBIT TEST PLAN

To test the functionality of both the receiver and the antenna, the ACTPAT154 antenna was mounted on the roof of our lab building in the Faculty of Engineering of NUS to get a good view of the GPS constellation in the sky. The OEM615 receiver was located in the lab and was connected to the

antenna over a 40 metre LMR-600 coaxial cable. With such a long cable, a bias-tee was required to transfer the DC power reliably to the ACTPAT154's built-in LNA.

Basic functions such as obtaining position and time information were tested using the commands *log bestxyza* and *log timea*. The GPS receiver replies with other useful information that can be logged for research and testing purposes, such as the number of GPS satellites the receiver manages to track and the number of GPS satellites used in the solution. Standard deviation values of the position and velocity are also important to determine the precision of each computation by the receiver. In addition to testing through the serial commands, the PPS output from the receiver can also be tested while the receiver is locked to the GPS constellation. The PPS output is available even when the receiver loses lock, however it will drift. Every time the receiver locks back to the GPS constellation, the PPS will synchronise again.

It is understandable that operating a GPS receiver on the ground and in Low Earth Orbit are very different. Due to the large relative speed between the GPS satellites and the receiver onboard Galassia-2, we are expecting a large Doppler shift of up to 40 kHz at L1, which the OEM615 receiver might not be able to handle without any software mitigation. It is therefore of our interest to test the receiver with a GPS Satellite Simulator in the near-future to generate multiple GPS signals and characterise the Doppler windows required to be assigned on the OEM615 onboard Galassia-2.

The next item to be tested is the quality of the conversion of TLE from the orbital state information obtained from the GPS receiver. For this purpose, the VEC2TLE software [7] is used as a benchmark and a set of position and velocity vectors from a given satellite found in STK's database is used as an input to both VEC2TLE and our software running on the ADCS computer. The test satellite in our case is Galassia, satellite number 41170. The TLE generated by both VEC2TLE and our implementation are then propagated using STK's SGP4 propagator over 6 days. Figure 11 shows a comparison of the propagated orbital positions between three TLEs: NORAD TLE and TLEs generated by VEC2TLE as well as our implementation, termed PV2TLE.
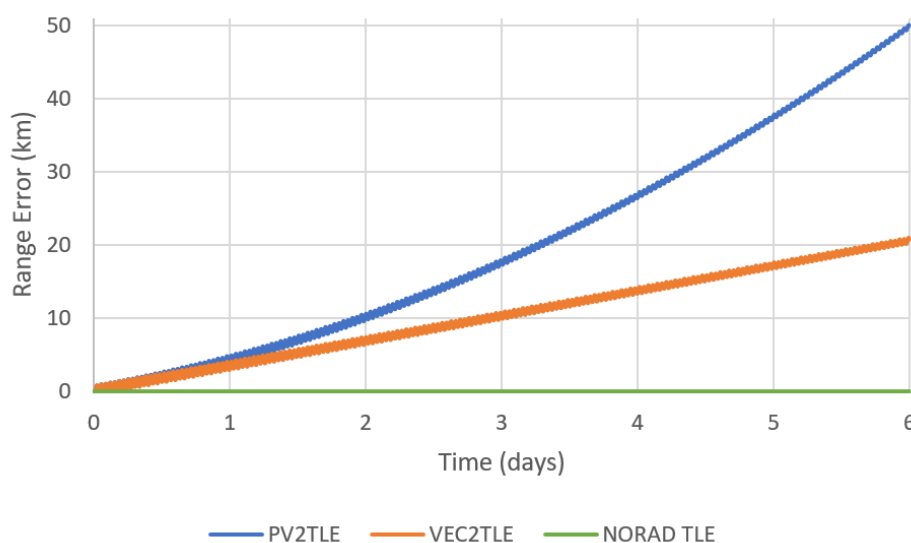

Figure 11. Comparison of Propagated Positions from VEC2TLE, PV2TLE and NORAD TLE

From this test, we observe that even though PV2TLE shows a larger error in the long term, it is comparable to VEC2TLE within the first day (within 0.8 km). This test however is not able to validate the accuracy of our implementation because a NORAD TLE propagated with SGP4 is far from good as a truth data. In order to fully test the accuracy, we plan to test it in orbit and benchmark it against real-time position information from the GPS, which is able to provide truth data of up to three orders of magnitude better accuracy (in the range of a few metres).

Other in-orbit tests will include collecting all GPS data at the various attitude scenarios, i.e. sun pointing, nadir pointing and tumbling, to validate the number of GPS satellites that can be locked and corresponding Time to First Fixes. These test outcomes will be useful for other and following satellite programs from our university. In addition, to be able to access and fully test the OEM615 while in orbit, we also implemented a debug mode on the ADCS computer where any NovAtel OEM6 Family ASCII command can be sent or scheduled from the ground station to the OEM615 GPS receiver.

The main goal of the in-orbit tests will be to validate our strategy as described in the previous sections. We hope that by being able to generate a TLE on board the satellite, it can give a better performance compared to using the NORAD TLE in terms of accuracy and update frequency and that it can better serve Galassia-2's remote sensing mission.

6   CONCLUSIONS and FUTURE WORK

Design, methodology, preliminary pre-flight testing and in-orbit test plan of the GPS and SGP4 based orbit propagation onboard Galassia-2 have been presented. As a nanosatellite with remote sensing mission, the capability of accurately determining both position and time in orbit is critical. We presented our strategy of generating a TLE onboard the satellite utilising the last available GPS data as a more up-to-date and possibly more accurate backup as compared to NORAD TLE. A comparison between an existing software called VEC2TLE and our implementation have also been presented. Future work includes testing the GPS receiver with a GPS Satellite Simulator and validating our strategy in orbit once launched. In-orbit analyses of our orbit and time determination strategy associated with Galassia-2's mission will be reported in future publications.

7   ACKNOWLEDGMENTS

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