GPS Results for the Radio Aurora Explorer II CubeSat Mission

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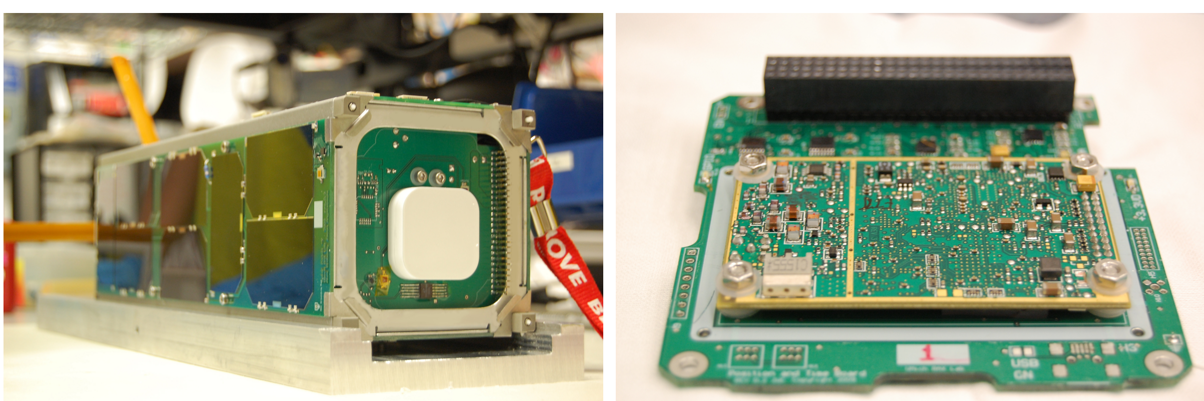
This paper presents the performance of the Global Positioning System (GPS) subsystem for the Radio Aurora eXplorer II (RAX-2) CubeSat mission. The GPS subsystem is required to satisfy the science mission objectives to study space weather. In particular, the GPS subsystem must provide accurate spatial and temporal data. To verify the mission requirements and assess GPS subsystem performace in on-orbit conditions, we assess the carrier-to-noise ratio and position accuracy. Additionally, we study the accuracy of the current method of orbit tracking by comparing the orbital elements from Two Line Element sets to the RAX-2 GPS data. The results presented confirm functionality of the GPS subsystem and provide useful information for future small satellite teams considering flying a GPS.

I. Introduction

The Radio Aurora eXplorer (RAX) is the first CubeSat mission sponsored by the United States National Science Foundation (NSF) to study the formation of the magnetic field-aligned plasma irregularities (FAI) in polar regions of the ionosphere [1]. A Global Positioning System (GPS) subsystem is required for the RAX mission to provide accurate spatial and temporal data to satisfy the science mission objectives. Two identical 3U RAX CubeSats, RAX-1 and RAX-2, were launched on November 19, 2010 and on October 28, 2011, respectively, with the same science mission and GPS subsystem.

The primary objective of the RAX GPS subsystem is to provide time with 1 microsecond accuracy and position to within 1 km while the satellite is within the experimental zone over the science target located at Poker Flat, Alaska [2]. These subsystem objectives are satisfied when the receiver has acheived GPS fix, when there are at least four GPS satellites in the constellation in view with sufficiently high signal strengths. Due to power constraints on a CubeSat, a low-power GPS receiver was chosen to fly on the RAX missions, namely the NovAtel OEMV-1-L1 model. The GPS antenna patch and the Position and Time Board of the subsystem are pictured in Figure 1.



a) Antcom antenna installed into the RAX engineering design unit **b) The Position and Time Board before encapsulation**

Figure 1. RAX GPS Subsystem Hardware [3].

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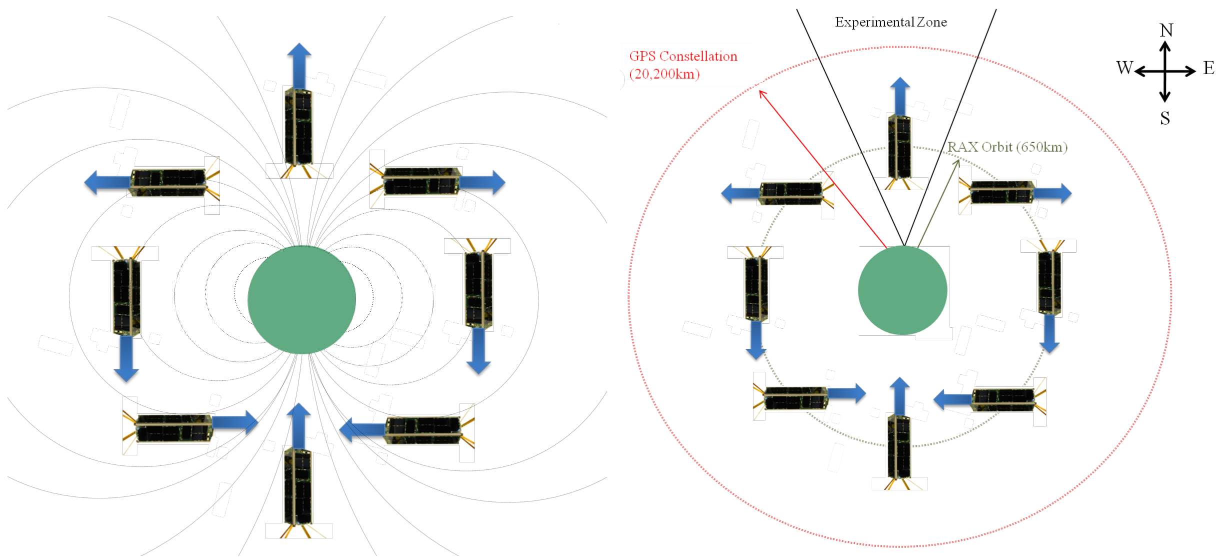
RAX is passively magnetically stabilized, therefore its long axis is aligned with the Earth's magnetic field using a permanent magnet. The orientation of the spacecraft throughout an orbit can be seen in Figure 2. This control scheme ensures that RAX has the proper orientation while passing over the experimental zone to collect the required temporal and spatial information for the science mission. The passive system is designed such that the science antennas are located on the spacecraft such that it is pointed towards the Earth over the experimental zone. The GPS antenna was a secondary decision and was located on the other side of the spacecraft such that it was visible to the GPS constellation during the experiment. RAX rotates about magnetic field lines which would reduce the visability of the GPS constellation and may negatively impact the performance of the receiver.



a) RAX-2 orientation and orbit relative to the Earth magnetic field lines.

b) RAX-2 orientation and orbit relative to experimental zone.

Figure 2. The orientation of RAX-2 due to the passive control scheme where the blue arrow indicates the orientation of the GPS antenna. The schematic is not to scale [3].

The focus of this paper is the GPS subsystem results of the most recent spacecraft, RAX-2, which was launched into an eccentric low Earth orbit (LEO) with 820 km apogee and 480 km perigee with an inclination of 101.5° and is operating as expected. Table 1 provides the information for the two tests performed on the RAX-2 GPS receiver that will be analyzed in this paper. Both flight tests used NovAtel-specific logs (GPGSV and BESTXYZ) that could be logged from the receiver by the user. It should be noted that roughly 9% of the data from Flight Test 2 was lost.

Table 1. RAX-2 GPS flight test information. Data was recorded about five minutes after the receiver had been turned on for each GPS experiment.

Test	Date	Time Data First Recorded (UTCG)	Test Frequency (Hz)	Test Duration (min)
1	Nov 11, 2011	07:14:05	0.2	100
2	Nov 12, 2011	18:34:05	0.2	100

Each section of this paper investigates different results of the RAX-2 GPS subsystem. We will examine the carrier-to-noise ratios in relation to the number of GPS satellites in view, which are valuable metrics by which to evaluate GPS performance. Additionally, we will evaluate the position and velocity accuracy of the GPS receiver by analysing the errors reported from Flight Test 2. Next, we will discuss the evolution of the orbital elements exhibited by the TLEs and compare to the GPS data. We will conclude with a summary of our GPS test results for the RAX-2 mission and dicuss future project work.

II. Results from GPS Testing

Within this section, we will evaluate the results and performance of the RAX-2 GPS subsystem by investigating the carrier-to-noise ratio, which provides information on the quality of the received signal. Further, we will examine the accuracy of the position and velocity measurements of the receiver to verify whether or not the GPS subsystem satisfies the 1 km accuracy requirement of the mission. All of these results enable verification of the mission requirements as well as direct comparison with other satellite missions, such as the RAX-1 mission, which will be addressed in future work. Additionally, we will examine Two Line Element sets (TLEs) for orbit determination and compare the accuracy to GPS data results.

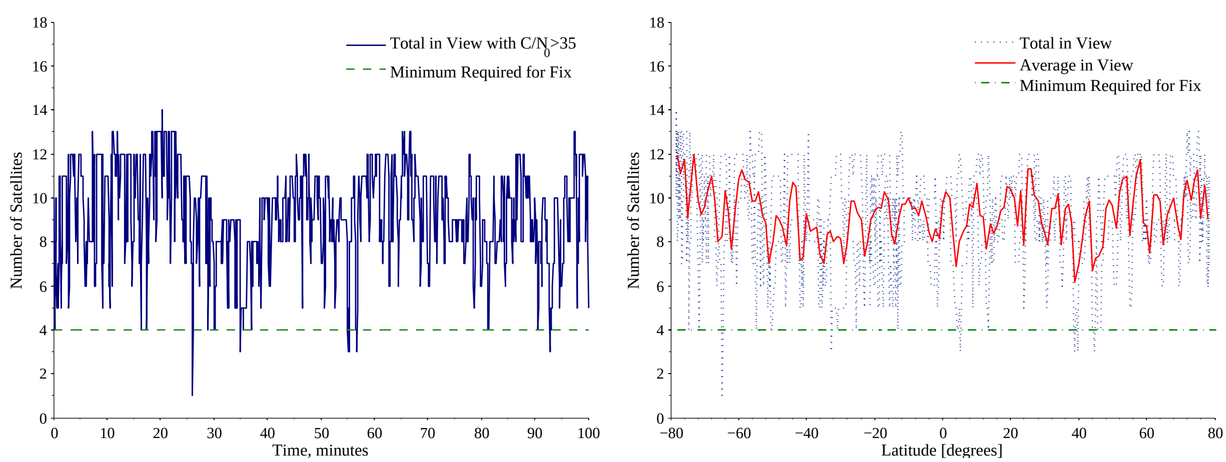
A. Carrier-to-Noise Ratios

The GPS Flight Test 1 used the GPGSV log which provided information on the number of spacecraft in view from the GPS constellation, their location (azimuth, elevation, and range which are standard from the receiver), and their carrier-to-noise ratio (CNR) information which provides information on the quality of the received signal. Provided below is an example GPGSV log from Test 1 (see Table 3 in the Appendix for an explanation of the log information):

$GPGSV,3,1,12,16,71,347,42,03,54,158,48,06,51,130,45,32,42,333,41*7D

The number of satellites in view determines whether or not the receiver was able to maintain fix on the GPS constellation. At least four satellites must be in view for a receiver to achieve fix. The receiver calculates the position by measuring the time delay between the transmission and reception of each GPS radio signal from at least three GPS satellites. An additional fourth satellite is then used to account for clock error [4]. In general, errors in the GPS data are reduced if the number of satellites in view exceeds the four satellite minimum, where the relative effect depends on spacecraft geometry.

We were able to determine from the data logs from GPS Test 1 the number of satellites in view with a carrier-to-noise ratio greater than the required threshold of 35 dB, which indicated a quality signal was received. The minimum threshold for the CNR was mission defined according to specifications supplied by NovAtel which stated that carrier-to-noise ratios less than 35 dB are ”Poor”, and the RAX team determined that values above this would be acceptable [5]. The number of spacecraft visible above the minimum threshold is plotted as a function of time into the test in Figure 3a).



a) Number of Satellites in View as a Function of Time **b) Number of Satellites in View as a Function of Latitude**

Figure 3. Number of Satellites in View and with Carrier-to-Noise (CNR) $\geq$ 35 for RAX-2 GPS Flight Test 1.

From relevant TLEs, it was possible to determine the latitude of RAX-2 throughout Test 1 using a Simplified General Perturbations Satellite Orbit Model 4 (SGP4) propagator in Systems Tool Kit (STK). TLEs provide basic orbit information from a specified orbit epoch (more detailed information on TLEs can be found in II.C) which can be propagated to give an orbit estimate. A TLE with orbit epoch 10 Nov 2011 20:35:36.258 UTCG (0.4 days before Test 1 start time) was propagated over the 100 minute test to determine the latitude of RAX-2 every 5 seconds. Figure 3b) shows the number of spacecraft as a function of latitude. RAX-2 has an orbital inclination of about 101.6° and therefore the orbit latitude range is between approximately -78° to 78°. In Figure 3a) and 3b) we show the minimum number of four satellites required in view to maintain fix on the GPS constellation. The average number of satellites in view above the CNR threshold was 9.23 satellites, which exceeds the number required for fix. Expected reasons a satellite might lose fix with the GPS constellation are that the GPS satellites are clustered in the field of view, are along the same line of sight, or that some satellites may be offline for maintenance.

Finesteering is a time status that indicates that receiver clock adjust is enabled so that the receiver time will be updated continuously to minimize the receiver range bias and that the time is accurate to 1 microsecond [5]. A finesteering status is obtained soon after GPS fix. The RAX-2 receiver maintained GPS fix throughout the full orbit test, indicated by the finesteering status on the timestamp logs associated with the GPGSV log, except for several abrupt drops below the minimum of four. Each drop occured for only one data point at a time where data is sampled every five seconds, which translates into a maximum of a 10 second drop out of fix. However, finesteering was maintained, so the data can be trusted. The minimum number of satellites in view was one, which occured at 64.8° S and was just over twenty-five minutes into the orbit. This drop as well as the one that occurs at 32.7° S are most likely due to the geometry of the RAX satellite relative to the GPS constellation. The receiver does not have an ideal orientation to the GPS constellation to maintain fix as RAX-2 passes over the southern hemisphere due to the passive magnetic stabilization system, seen in Figure 2. Therefore the drops below the minimum number of satellites are likely due to poor geometry and can be explained by RAX-2's receiver spinning out of visibility or from interference with other subsystems.

B. Position Accuracy

Error estimates of the position and velocity data are available from the receiver and allow us to investigate receiver performance as a function of spacecraft position and geometry relative to the GPS constellation. This information is recorded in a BESTXYZ log, an example condensed log from GPS flight Test 2 is provided (see Table 4 in the Appendix for an explanation of the condensed log information; the full log contains more information):

SOL_ COMPUTED SINGLE -1709628.9493 1021713.3953 6875739.5613 1.1180 1.1570 2.8812
SOL_COMPUTED DOPPLER_VELOCITY -1304.3352 7217.6625 -1498.1223 0.1336 0.1383 0.3444

The accuracy of the position estimate is expected to be dependent on the satellite's position and geometry relative to the GPS constellation. Figure 4 shows the position and velocity errors of the GPS receiver. The errors in the position and velocity have a similar profile throughout the orbit because the calculation of velocity is a function of position. The errors in position are explained by external effects, such as satellite geometry, ionospheric effects, ephemeris errors, satellite clock errors, multipath distortion, tropospheric effects, and numerical errors on the receiver itself.

The errors from the GPS Flight Test 2 BESTXYZ log are summarized in Table 2. The low errors reported from the RAX-2 GPS are significantly below the 1 km subsystem requirement. The errors in GPS position and velocity shown both in Table 2 and in Figure 4 were considerably better for RAX-2 than for other CubeSat missions. For example, CanX-2 used a OEM4-G2L receiver which had position errors greater than 10 meters and the average errors were around 30 m when GPS fix was maintained [6].

Table 2. GPS flight Test 2 average position and velocity standard deviation errors for the full orbit, where $\|R\|_2$ and $\|v\|_2$ are the Euclidean norms of the error in the position and velocity components (x, y, z), respectively.

Magnitude	$\|R\|_2$	$\|v\|_2$
Average Error	2.89 m	0.34 m/s
Minimum Error	2.33 m	0.27 m/s
Maximum Error	4.02 m	0.48 m/s

C. Two Line Element Set Analysis

The United States Strategic Command (STRATCOM) provides orbit estimates for satellites in the form of TLEs that are generated about once a day for LEO satellites [7]. The TLEs are available online from the North American Aerospace Defense Command (NORAD). The TLEs are based on measurements from orbit tracking which provide specific orbital elements for an epoch.The epoch is the time the orbit measurement was taken and is a reference time from which subsequent times are measured. TLEs are currently the conventional approach to CubeSat orbital tracking.

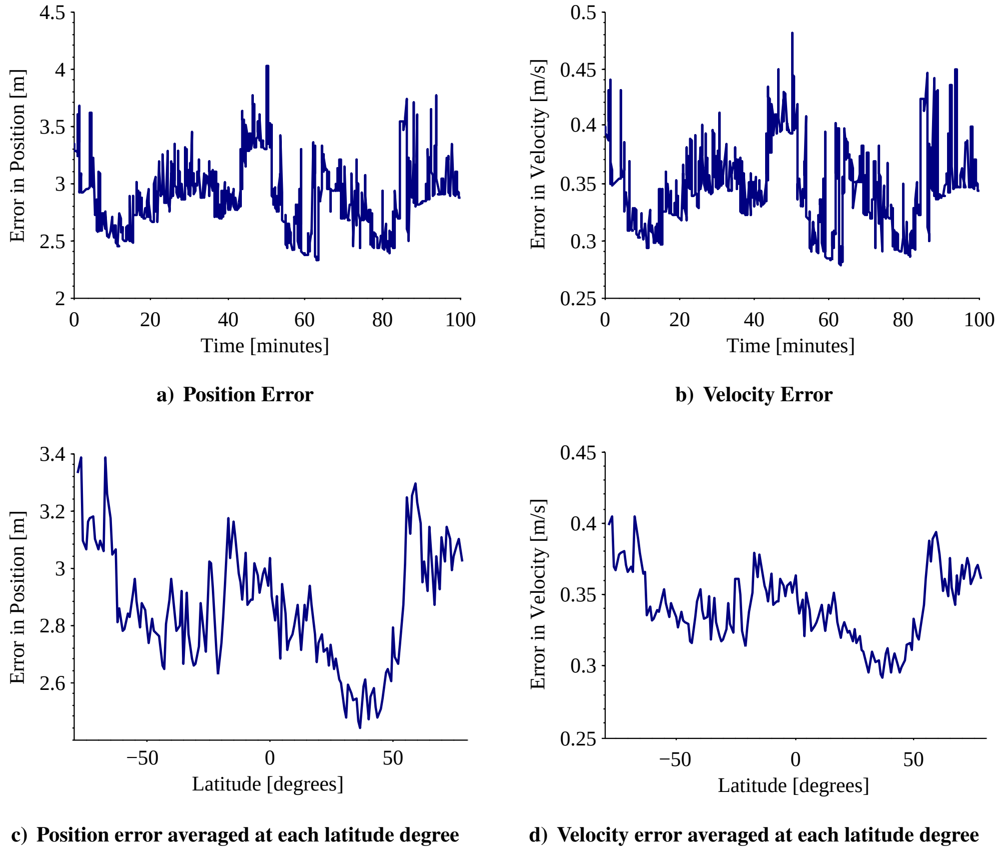
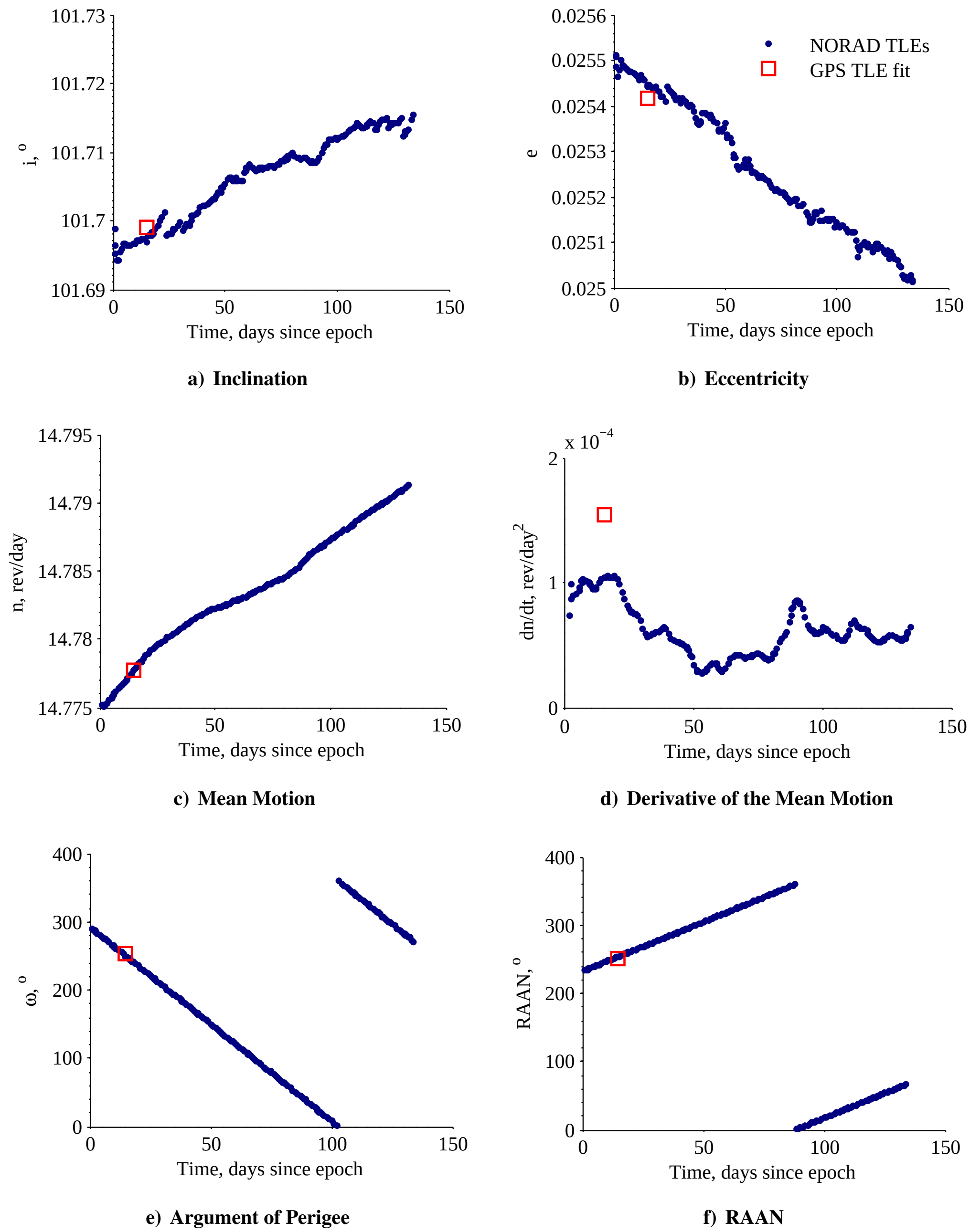


Figure 4. Euclidean norms of the position and velocity errors components for GPS Flight Test 2.

They are able to provide sufficient orbit determination about once a day for most CubeSats and are an inexpensive and passive approach to orbit determination for satellite operations since STRATCOM tracks these objects for the protection of the North American continent and US and Canadian interests worldwide against threats from space [8].

The orbital elements of the RAX-2 TLEs were obtained about once a day starting on the date that the first TLE was obtained (October 28, 2011) until March 11, 2012 and are plotted in Figure 5. Plotting the elements throughout the mission timeframe provides insight into how the orbit is evolving. The decreasing eccentricity shows that the original eccentric (approximately 820 km apogee and 480 km) orbit is circularizing, as expected, primarly due to drag. The effects of drag are greatest at the perigee of the orbit because the satellite is at its greatest velocity and the atmosphere is the most dense, which causes a decrease in velocity, an ”aero braking” effect. RAX-2 is a low Earth Orbit (LEO) satellite in an elliptical orbit and is therefore more susceptible to aero braking at the perigee. This effect at the perigee reduces the altitude of the apogee, thus circularizing the orbit.

The expected precession of the orbital plane is observed by the change in the argument of perigee and the right ascension of the ascending node (RAAN), in Figures 5e) and 5f) respectively. The Earth is an oblate spheriod which causes a zonal variation in the gravity force with latitude due to the mass concentration at the equator [9]. This variation results in perturbation accelerations and a non-radial gravity force vector; therefore the angular momentum and eccentricity vector directions are not conserved in this orbit. Since these vectors are not conserved, the orbital plane essentially precesses and nutates rather than remaining on a fixed plane which would be the case if Earth was spherical and the mass was evenly distributed. RAX-2 is in LEO and is therefore more susceptible to effects from the equatorial bulge of the Earth relative to a spacecraft in medium Earth orbit (MEO) or geostationary orbit (GEO) because it is closer to the equatorial bulge. The effects of the oblateness of the Earth on RAX-2 can be quantified using zonal harmonics. J_2 is the second zonal harmonic and is the primary constant used to quantify the alterations of the orbit of the satellite due to the Earth's oblateness. Higher order zonal harmonics do not have as strong of an effect on the orbit; the effect of J_2 at any orbital altitude is about 1000 times greater than either J_3 or J_4, therefore their influence on the orbit is minimal [10]. Analytical expressions were used to verify the observed rates of change in the argument of perigee and the RAAN, and will be investigated in future work, see Section III. The combined effects of the orbital element evolution will be included in the further studies.



a) Inclination

b) Eccentricity

c) Mean Motion

d) Derivative of the Mean Motion

e) Argument of Perigee

f) RAAN

Figure 5. RAX-2 orbital elements from TLEs.

Additionally, we compared the TLE data to an orbit fit generated from the GPS Flight Test 2 (which was over a full orbit worth of position and velocity data) in Figure 5. This comparision was done by generating an ephemeris file from the flight Test 2 raw data, which was then converted into a TLE using a SGP4 propagator in STK. The mean motion, argument of perigee, and RAAN from the TLEs match the GPS fitted TLE closely. The inclination, eccentricity, and the derivative of the mean motion have a slight variance between data sets, which will be investigated in future work, but the TLEs still provide a relatively accurate estimate for the orbital elements.

III. Conclusions and Future Work

This paper investigates the GPS results of two full-orbit flight tests on the RAX-2 mission. We investigate the carrier-to-noise ratio, position accuracy, and the current method of orbit tracking. The GPS receiver maintains fix throughout the orbit with the carrier-to-noise ratios of the satellites in the GPS constellation in view above the minimum threshold. Additionally, the accuracy of the position and velocity was examined and the position accuracy was determined to be approximately less than 4 m, which is within the required 1 km of the GPS subsystem. Two Line Element set orbital elements for RAX-2 were examined to track the progression of the orbit, from launch to present, and enabled us to compare the accuracy of the tracking method to the GPS data from one of the flight tests.

We will continue to analyze the carrier-to-noise ratios and position accuracy of the on-orbit RAX-2 GPS subsystem data. We will analyze the relative error in position and velocity as a function of time, latitude, in-track, out-of-track, and radial directions. Additionally, we will investigate how the RAX-2 GPS subsystem results compare to RAX-1 data, other CubeSat missions, and terrestrial and simulated tests on similar receivers. We will also continue the analysis on the Two Line Element sets and how the data compares to GPS data as well as to other CubeSats from the RAX-2 launch.

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Appendix

The information contained in the GPGSV log and the BESTXYZ log are described in Tables 3 and 4 respectively.

Table 3. Information contained in the GPGSV log [11].

Field	Field Description	From Example Log
1	Log header	$GPGSV
2	Total number of messages	3
3	Message number	1
4	Total number of satellites in view	12
5	Satellite pseudorandom number (PRN)	16
6	Elevation in degrees	71
7	Azimuth in degrees	347
8	Carrier-to-noise ratio (CNR)	42
...	Next satellite PRN, elevation, azimuth, CNR	
...	Last satellite PRN, elevation, azimuth, CNR	
variable	Checksum	*7D

Table 4. Information contained in the BESTXYZ log [11].

Field	Field Description	From Example Log
1	Position solution status	SOL_COMPUTED
2	Position type	SINGLE
3	Position x-coordinate (P-X) [m]	-1709628.9493
4	Position y-coordinate (P-Y) [m]	1021713.3953
5	Position z-coordinate (P-Z) [m]	6875739.5613
6	Standard deviation of P-X [m]	1.1180
7	Standard deviation of P-Y [m]	1.1570
8	Standard deviation of P-Z [m]	2.8812
9	Velocity solution status	SOL_COMPUTED
10	Velocity type	DOPPLER_VELOCITY
11	Velocity x-coordinate (V-X) [m/s]	-1304.3352
12	Velocity y-coordinate (V-Y) [m/s]	7217.6625
13	Velocity z-coordinate (V-Z) [m/s]	-1498.1223
14	Standard deviation of V-X [m/s]	0.1336
15	Standard deviation of V-Y [m/s]	0.1383
16	Standard deviation of V-Z [m/s]	0.3444