
FASTRAC DATA PROCESSING

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Final Report

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1.0 SUMMARY

The Formation Autonomy Spacecraft with Thrust, Relnav, Attitude, and Crosslink (FASTRAC) satellites were launched on November 19, 2010 from Kodiak, AK as part of the Space Test Program STP-S26 launch aboard a Minotaur IV rocket. Throughout the first six months of operations the satellites underwent an extensive check out period ensuring all subsystems were working nominally. During the first year of operations, enough data has been gathered to show that all of the mission objectives have satisfied the minimum success criteria. The data collected during the first six months of operation are presented and analyzed showing the status of the spacecraft health and the primary GPS experiment. The data received thus far demonstrates that the GPS receivers of both satellites have been capable of fixes regularly and have performed to the level of accuracy expected from ground simulations. From the GPS messages received, several types of measurements such as position fixes and pseudoranges have been post-processed using a batch estimation algorithm to determine daily nominal satellite trajectories. When the GPS receivers have been position fixing, they have also been able to obtain on-orbit single GPS antenna attitude solutions matching the predicted accuracies from ground simulations.

2.0 INTRODUCTION

The Formation Autonomy Spacecraft with Thrust, Relnav, Attitude, and Crosslink (FASTRAC) student satellite program started in 2003 as part of the third installment of the University Nanosatellite Competition (NS-3) which is sponsored by the Air Force Office of Scientific Research (AFOSR) and managed by the Air Force Research Labs (AFRL). In early 2005, the project was chosen as the winner of the competition, at which point the team started working closely with personnel at AFRL to transform the FASTRAC Engineering Design Unit (EDU) into two flight-ready satellites to ensure they would survive the launch and space environments. This required some of the components to be redesigned or modified, such as the enclosure boxes for Electromagnetic Interference (EMI) protection. (Greenbaum 2006) The satellites were first delivered to AFRL to undergo a series of qualification and environmental tests in summer 2006 which led to additional hardware modifications, a process which lasted until February 2010. This final development time took longer than planned. The satellites were first ranked on the Department of Defense (DoD) Space Experiments Review Board (SERB) in November 2006 and were manifested in late 2007 for launch in late 2009. Due to delays unrelated to FASTRAC, the actual launch occurred in late 2010. Once manifested, additional hardware modifications were made to ensure compliance with the newly defined launch envelope which resulted in several of the qualification and environmental tests having to be redone. After these tests were complete, the satellites were shipped to Kodiak, AK for integration with the Launch Vehicle (LV) adapter plate in July 2010 as shown in Figure 1.

On November 19, 2010 at 7:22 PM CST, FASTRAC was launched into a 650 km altitude circular orbit at 72 degrees inclination along with 6 other satellites. The other satellites, listed in order of separation from the LV are: STPSat-2 (AFRL/STP), RAX (University of Michigan), O/OREOS (NASA Ames Research Center), FASTSAT and NanoSail-D (NASA Marshall Space Flight Center), and FalconSat-5 (US Air Force Academy). The last satellites separated from the launch vehicle were the FASTRAC satellites as shown in Table 1.



Figure 1. FASTRAC (Center) Mated onto the adapter plate of STP-S26. (Hernandez 2011)

Table 1. STP-S26 Mission Satellites with Separation Times, (STP-S26 Mission Profile 2010).

	Satellite	Separation Time After Launch
1	STPSat-2	16 m 39 s
2	RAX	17 m 39 s
3	O/OREOS	18 m 39 s
4	FASTSAT + NanoSail-D	21 m 39 s
5	FalconSat-5	26 m 39 s
6	FASTRAC	31 m 39 s

After separation, the FASTRAC satellites underwent several phases of operations which are discussed in the following sections. With the help of the amateur radio operator (HAM) community, the FASTRAC team has collected more than 16500 beacon messages from the satellites as of April 24, 2012. Throughout this time, the operations team has also been able to collect other types of telemetry such as health, GPS, thruster, and inertial measurement unit (IMU) messages that have shown that all subsystems are functioning nominally. Most of these messages have been analyzed and in some cases post-processed to assess the performance of the mission.

For details about the design of FASTRAC satellites please refer to several historical articles: (Holt, Stewart, et al. 2003), (Holt, Campbell and Lightsey 2004), (Stewart and Holt 2005), (Diaz-Aguado 2005), (Campbell 2006), (Diaz-Aguado, Greenbaum, et al. 2006), (Greenbaum 2006), (Greenbaum, Stewart, et al. 2008), (Zwerneman 2008), (Smith, et al. 2008), (Muñoz, Greenbaum and Campbell, et al. 2010), and (Muñoz, Greenbaum and Lightsey, et al. 2011). These pre-launch articles describe the FASTRAC mission and the satellite design in detail.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

FASTRAC's mission is to demonstrate enabling technologies that will allow small satellites to work collaboratively in space and enable formation flying missions. (Holt, Stewart, et al. 2003) and (Holt, Campbell and Lightsey 2004) From this mission statement, the primary objectives were defined to be: 1) demonstrate two-way intersatellite crosslink with verified data exchange; 2) demonstrate on-orbit real-time GPS relative navigation to accuracies matching ground simulations; and 3) demonstrate autonomous thruster firing using single-antenna on-orbit real-time GPS attitude determination. A secondary objective of the FASTRAC mission was also to: 4) demonstrate a distributed ground station network.

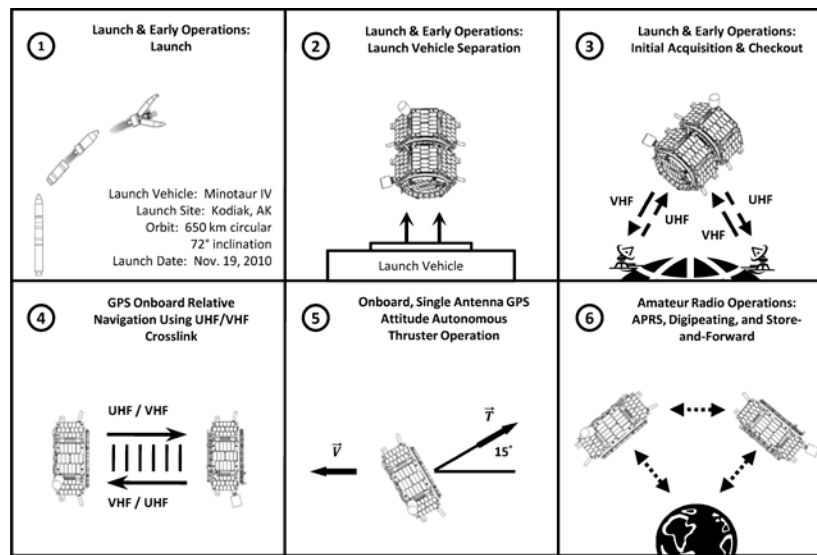


Figure 2. FASTRAC Concept of Operations.

To achieve the mission objectives, the FASTRAC mission was divided into six operational phases as shown in the Concept of Operations (Figure 2), including: 1) launch; 2) launch vehicle separation; 3) initial acquisition and checkout; 4) GPS onboard relative navigation with two freely drifting satellites; 5) onboard single antenna GPS attitude autonomous thruster operation; and 6) amateur radio operations. After more than a year of operations, most of these phases have been completed and most of the mission objectives have been met. For a detailed description of the operational milestones and activities completed during the first six months of operations, refer to (Muñoz, Greenbaum and Lightsey, et al. 2011). A summary and status of the mission objectives along with their minimum and full success criteria is shown in Table 2.

As can be seen from Table 2, all the mission objectives have been completed or are in the process of being completed to at least satisfy the minimum success criteria for each objective. For the one minimum success criterion that is in progress to be satisfied, the team has gathered enough GPS data from the satellites and is post-processing these to obtain relative navigation solutions. This work is

currently in progress and will be completed in the near future. As of January 2012, the full success criterion of performing on-orbit real-time relative navigation between two freely drifting spacecraft is not expected to be completed because one of the on-board microcontrollers that operates the GPS receivers has stopped responding to ground commands and hence is no longer allowing the satellites to exchange two-way GPS messages when the satellites are in crosslink range. It is also seen from the table that full success criteria for the autonomous thruster firing mission objective has not been met and is not expected to be completed. The reason for this is that during pre-launch integration, a leak was discovered in the thruster subsystem which caused the propellant tank to become empty. Fixing the leak would have increased the risk of being able to deliver the satellites in time for integration with the launch vehicle and hence a decision was made by the team to fly the thruster subsystem without propellant. Based on this development, the full success criterion for this mission objective was modified to include the performance of the autonomous thruster logic which has been successfully demonstrated.

Table 2. FASTRAC Mission Objectives, Success Criteria and Status.

	Primary Mission Objective	Success Criteria	Status
1	Demonstrate two-way intersatellite crosslink with verified data exchange	Minimum: Receive evidence of crosslink telemetry at least in one ground station from one of the satellites	Met
		Full: Receive evidence of crosslink telemetry at least in one ground station from both of the satellites more than once	Met
2	Demonstrate on-orbit real-time GPS relative navigation to an accuracy matching ground simulations	Minimum: Perform GPS relative navigation in post-processed solution from data downloaded from both satellites	In Progress
		Full: Receive on-orbit relnav data in telemetry stream and demonstrate real-time, on-orbit relnav solution to an accuracy of ± 1 km versus post-processed solution	Not Expected
3	Demonstrate autonomous thruster firing using single-antenna on-orbit real-time GPS attitude determination	Minimum: Perform real-time on-orbit single antenna GPS attitude determination	Met
		Full: Receive evidence in telemetry stream of valves opening based on attitude determination solution	Not Expected
		Modified Full: Receive evidence of autonomous thruster operation logic using single-antenna on-orbit real-time GPS attitude determination	Met
	Secondary Mission Objective	Success Criteria	Status
4	Demonstrate distributed ground station network	Minimum: Receipt of satellite data from either satellite by at least 2 ground stations	Met
		Full: Receipt of satellite data from both satellites by at least 2 ground stations, at least one of which is remotely commanded	Met

4.0 RESULTS AND DISCUSSION

4.1 Mission Data

The FASTRAC team has been able to collect different types of data during the first year of operations that have verified that all the subsystems have been working properly. From the data obtained, there are several types of messages that are of particular importance which include the beacon, health, and GPS messages. A summary of the information contained within these messages is provided in Table 3. The data collected from these messages are presented in the following sections to discuss the health of the satellite and the on-orbit performance of the GPS receiver from post-processed solutions.

Table 3. FASTRAC Telemetry Data Used for Post-Processing. (Muñoz 2010)

Type of Message	Summary of Type of Information Contained in Message	Length (Bytes)
Beacon	Time, GPS Position and Velocity, Health (5 V, 12 V, Battery Bus Voltages, One Temperature Sensor from each subsystem)	122
Health	Time, Health (Voltage from all subsystems, all temperature sensors)	357
GPS Data	Time, GPS Position and Velocity, Pseudoranges, Attitude Quaternion Solution, Crosslink Status	989

4.2 Satellite Health Status

The FASTRAC satellites are composed of two identical hexagonal structures and four common subsystems: communications (COM), command & data handling (CDH), electrical power system (EPS), and Global Positioning System (GPS). Apart from these, FASTRAC-1, known as “Sara Lily”, also has a micro discharge plasma thruster (THR), and FASTRAC-2, known as “Emma”, has an inertial measurement unit (IMU) and control circuitry for the intersatellite Lightband separation system (SEP).

The EPS subsystem has three DC-DC converters that are contained within the Voltage Regulator (VREG) Box and convert the unregulated battery (BAT) bus voltage to a 5 V bus, a 12 V bus, another 12 V Bus in the case of Sara Lily for thruster operations, and a 24 V bus in the case of Emma for the intersatellite Lightband separation system (Campbell 2006). The first two buses power all the electronics in the satellite apart from subsystems mentioned above. For the health of the satellite it is important that these are maintained at appropriate levels for the satellites to remain operational.

Figure 3 shows the battery bus voltage, 5 V bus, and 12 V bus data gathered from beacon and health messages. A summary of these bus voltage levels is shown in Table 5 and shows that all three voltage buses have been maintained within acceptable levels.

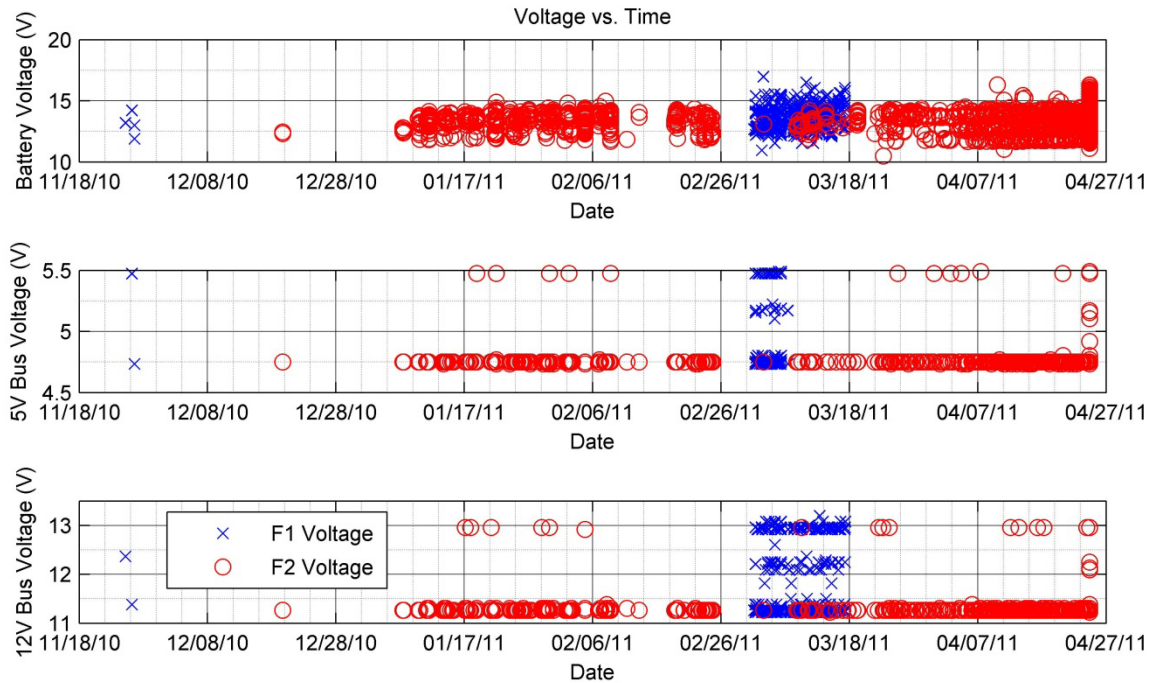


Figure 3. Voltage Bus Levels on FASTRAC Satellites.

Equally important for the health of the satellites is that the temperature levels throughout the satellite do not reach extreme values that could cause any of the components to become stressed. An exploded view of Sara Lily showing the locations of the temperature sensors is shown in Figure 4. Table 4 shows a summary of the temperature extremes each subsystem has measured while operational, the mean temperatures when in the Sun or in eclipse, the nominal temperature range of each, and temperature extreme data gathered from previous thermal vacuum tests.

Table 4. Summary of FASTRAC Satellite's Subsystem Temperatures (°C).

Subsystem Enclosure	FASTRAC-1 Sara Lily			FASTRAC-2 Emma			Nominal Temperature Range	Temperature Extremes from Thermal Vacuum Tests (Diaz-Aguado 2005)
	Temp. Extremes in Orbit	Mean Temp (Sun)	Mean Temp (Eclipse)	Temp. Extremes in Orbit	Mean Temp (Sun)	Mean Temp (Eclipse)		
Battery Box	+18 to +76	58.8	23.1	+1 to +44	19.3	13.2	-20 to +60	+7 to +44
Battery AVR Box	+17 to +50	37.3	17.7	+4 to +51	19.5	14.5	0 to +70	+8 to +60
COM Box	+13 to +52	34.9	16.1	+7 to +45	20.5	15.9	0 to +60	+8 to +60
COM AVR Box	+10 to +43	33.3	13.4	+6 to +53	16.3	12.0	0 to +70	+5 to +55
VREG Box	+23 to +66	51.7	29.8	+11 to +59	29.2	25.7	0 to +100	+25 to +65

Table 5. Voltage Bus Maximum, Minimum, and Acceptable Levels.

V. Bus	FASTRAC-1	FASTRAC-2	Acc. Levels
Battery	10.9 – 16.9	10.5 – 16.3	10 – 17
5 V	4.7 – 5.5	4.7 – 5.5	4.5 – 5.5
12 V	11.2 – 13.2	11.2 – 13.0	11 - 13

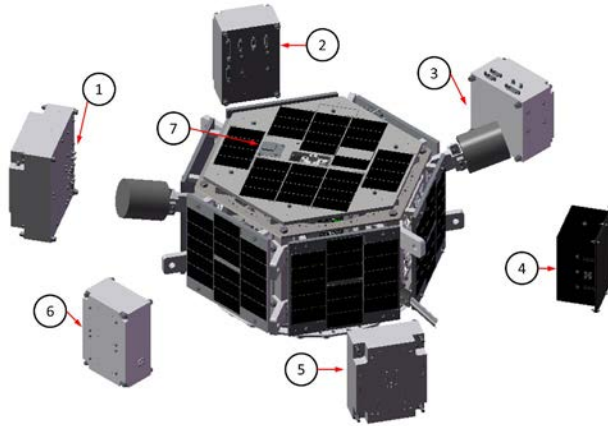


Figure 4. Exploded View of Sara Lily's subsystem enclosures: 1) VREG Box; 2) COM AVR Box; 3) GPS Box; 4) BATT Box; 5) COM Box; 6) BAT AVR Box; and 7) GPS +Z Antenna.

From the data shown in the table it is seen that the satellites tend to run warmer while they are exposed to sunlight than during eclipse as expected. However, all reported temperatures are within acceptable values. From these data it can also be seen that the temperature extremes from thermal vacuum tests are similar to those seen on-orbit validating the analysis and tests done before launch. It should be noted that there are fewer data collected from Sara Lily due to a minor software bug in the Dallas 1-wire sensor network where not all of the sensors are recognized to be present on the network at all times.

For a more detailed time history of the temperatures during the first six months of operations please refer to (Muñoz, Greenbaum and Lightsey, et al. 2011).

4.3 GPS Performance

4.3.1 GPS Receiver Position Fixing Capabilities

Throughout the first year of operations, data gathered from the beacon and downloaded GPS messages have shown that the GPS receivers on both satellites have routinely obtained many position fixes, as shown in representative sample in Figure 5. This figure shows the time when beacon messages have reported a distinct position fix based on the number of tracked GPS satellites being at least 4. The reason that there are more beacon messages than GPS messages is that the downloaded

full GPS messages can only be obtained by ground command from UT-Austin and partner ground stations while beacons are collected by amateur radio operators all over the world. Also, since these GPS data messages are longer as shown in Table 3, the amount of messages that can be downloaded during a single pass is limited.

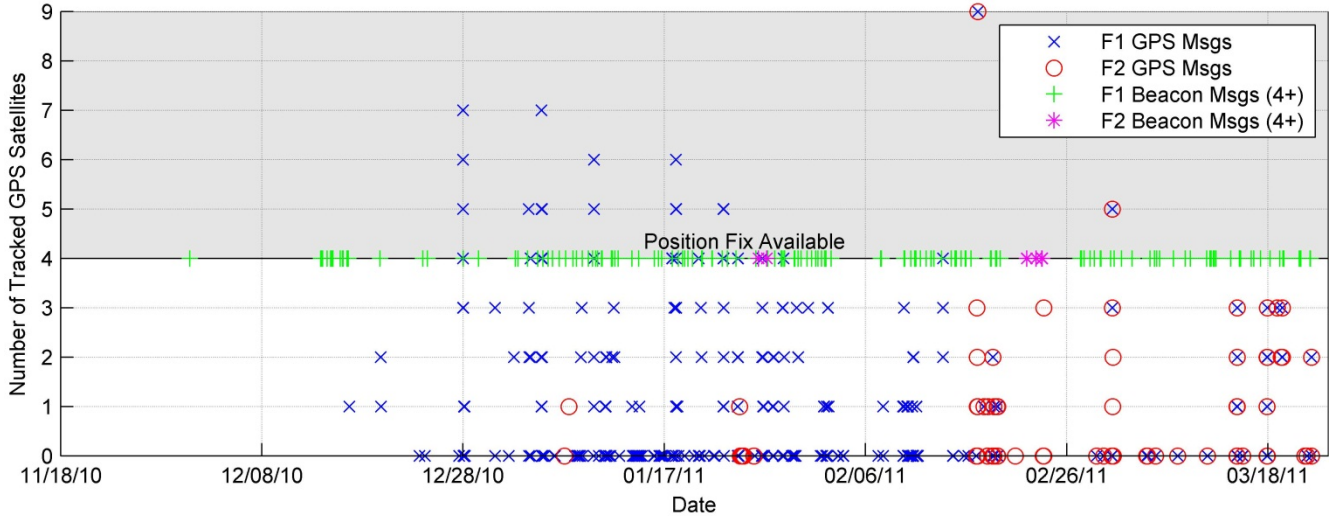


Figure 5. Reported GPS Receiver Position Fixes from Sara Lily (F1) and Emma (F2).

The periods of time when the GPS receivers have not been reporting or have not been capable of obtaining a position fix are explained by the fact that the satellites do not have active attitude control. It should be noted that when the two satellites separated from each other on March 22, 2011 the tumble rate of each satellite increased to approximately 0.5 revolutions per minute for Sara Lily and 2.3 revolutions per minute for Emma as confirmed by independent observations. Over time, these tumble rates have slowed down resulting in longer periods of favorable GPS antenna pointing.

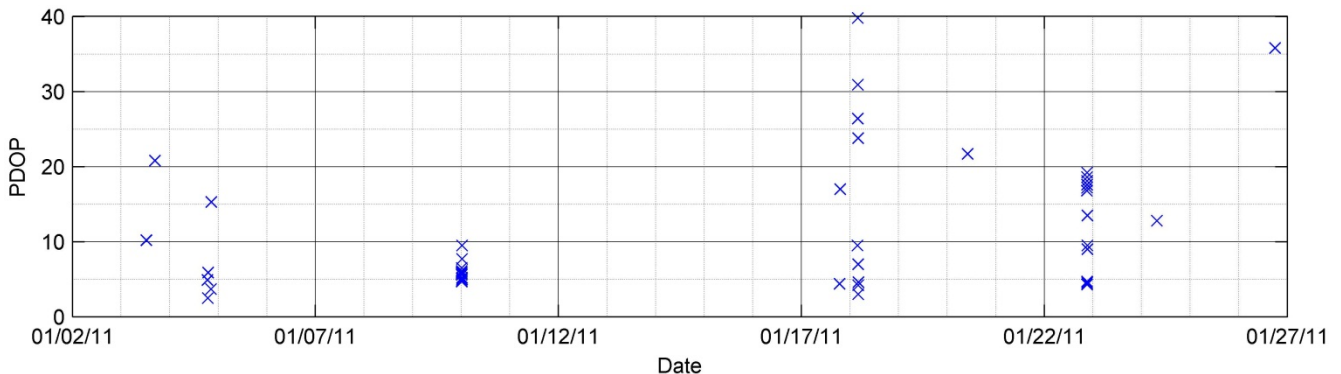


Figure 6. Reported PDOP from downloaded GPS messages showing on-orbit position fixes.

From the GPS messages that were downloaded and shown in Table 3, another useful parameter that is used to assess the performance of the position fix is the reported positional dilution of precision

(PDOP) shown in Figure 6. PDOP is a geometric figure of merit that indicates the quality of the GPS solution. (Misra and Enge 2004) From this figure, it is seen that most of the position fixes have a PDOP below 15 - 20 which means that the quality of the position is good, especially for a GPS receiver which is pointed away from the vertical direction.

4.3.2 GPS Post-Processed Performance

The GPS messages that have been downloaded from the satellites have also been post-processed using a batch estimation algorithm for days when there are enough measurements to produce an estimated nominal trajectory. This has been done in two ways: the first method uses the reported on-orbit position fixes from the GPS receiver as measurements, and the second method uses the raw pseudorange measurements in the GPS messages. In the first scenario using on-orbit position fixes, it was required that at the time the message was processed the GPS receiver was actively position fixing. This means that the GPS receiver was tracking at least 4 or more GPS satellites at the time. Also, in the first scenario, two nominal trajectories were estimated; the first weighed all the measurements equally while the second used the reported PDOP to weigh the measurements. In the second scenario, the pseudorange measurements were processed as long as the GPS receiver was locked on to the signal from at least one GPS satellite. In both cases, the messages were inspected to discard any measurements that might have been corrupted in the space to ground transmission from the satellites.

4.3.2.1 Nominal Trajectory Batch Algorithm

The post processing algorithm used to process the measurements consists of a batch estimation algorithm in which a nominal initial trajectory is estimated until the deviation away from the current best estimate converges below a certain threshold. Each set of measurements is represented as:

$$Y_i = G(X_i, t_i) + \epsilon_i \quad (1)$$

such that the measurements are a nonlinear function of the state (X_i) at time (t_i) with some added error (ϵ_i) with weight (W_i). In both simulation scenarios an initial estimate of the state (X_o) for the start of each day (t_o) when measurements were processed was obtained from either two line elements (TLEs) for that day or from propagating previous position fixes from the satellites to the start of that day. For the batch algorithm, all of the measurements are accumulated and mapped back to the initial time through the state transition matrix ($\Phi(t_{i-1}, t_o)$). Once all the measurements have been accumulated, a deviation away from the initial estimate is obtained (\hat{x}_o). If the magnitude of the deviation is below a certain threshold then the batch process has converged to a solution, otherwise the nominal trajectory is updated and the steps are repeated until the process converges. Figure 7 shows a summary of the batch post-processing algorithm. (Tapley, Schutz and Born 2004)

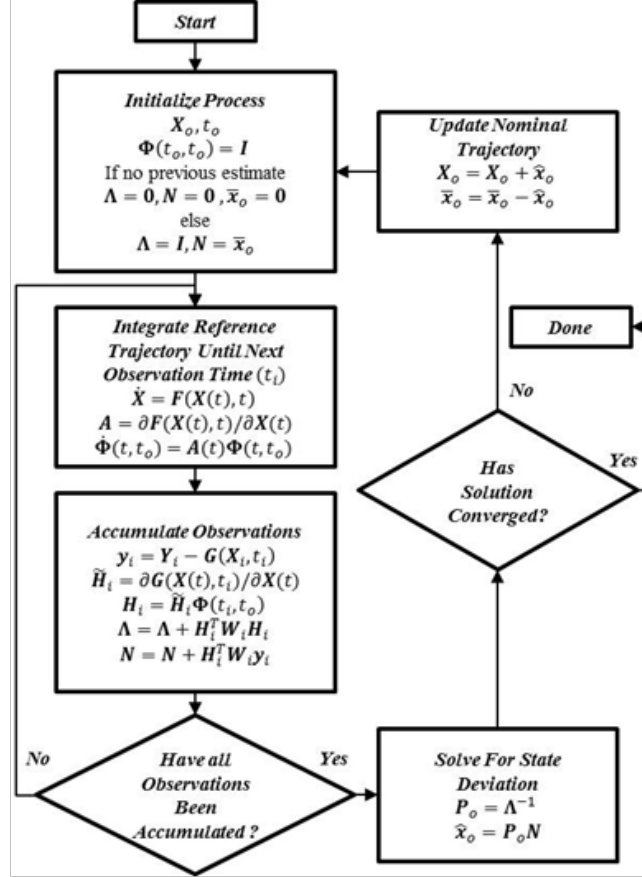


Figure 7. Batch Post-Processing Algorithm.

In both cases, the dynamic model of the nominal estimated trajectory included two-body motion, non-spherical central body perturbations up to 10th order, and third-body perturbations from the Sun and the Moon. (Vallado 2004) Atmospheric drag forces were not included because the altitude of the orbit is high enough (650 km) that this term does not have a significant effect.

4.3.2.2 Estimated Nominal Trajectory from On-orbit GPS Position Fix Measurements

In the scenario where the on-orbit GPS position fix measurements were used to obtain a post-processed nominal solution of the state ($X_o = [R_o^T \ V_o^T]^T$) the measurements had the form

$$Y_i = \begin{bmatrix} R(t_i) \\ V(t_i) \end{bmatrix} + \epsilon_i \quad (2)$$

where $R(t_i)$ and $V(t_i)$ are the on-orbit GPS position and velocity fixes and ϵ_i is the associated error with these measurements. In this scenario, two cases were analyzed, the first weighing all the measurements equally and the second using the PDOP to weigh the corresponding measurement. The results of both of these scenarios are shown for four data collections in January 2011 in Figure 8 and Figure 9 where the measurement residuals for the on-orbit position and velocity measurements are shown.

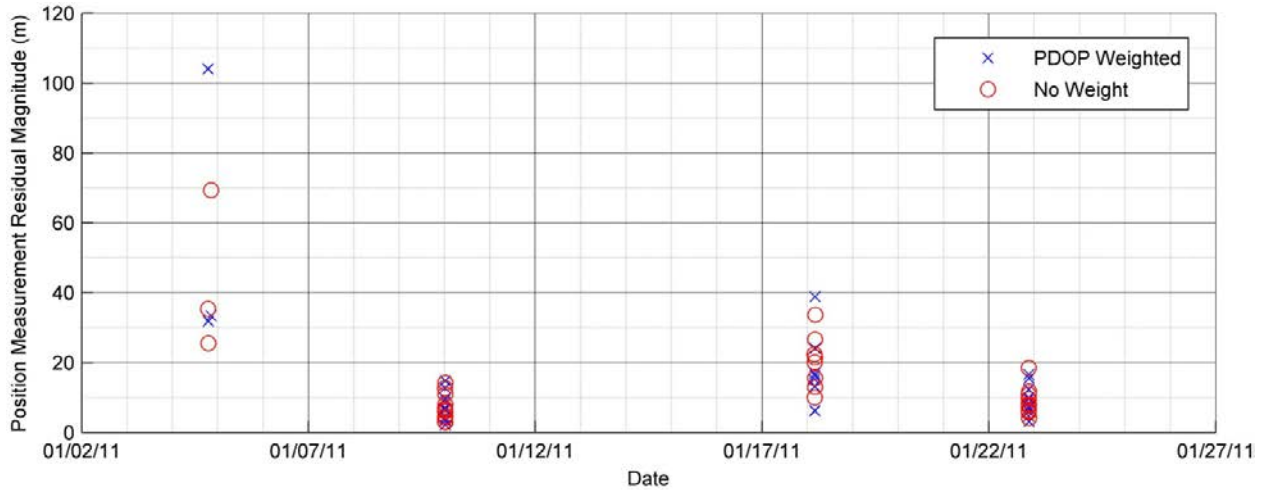


Figure 8. Position Measurement Residuals from Batch Post-Processing Algorithm Using Position Fixes As Measurements.

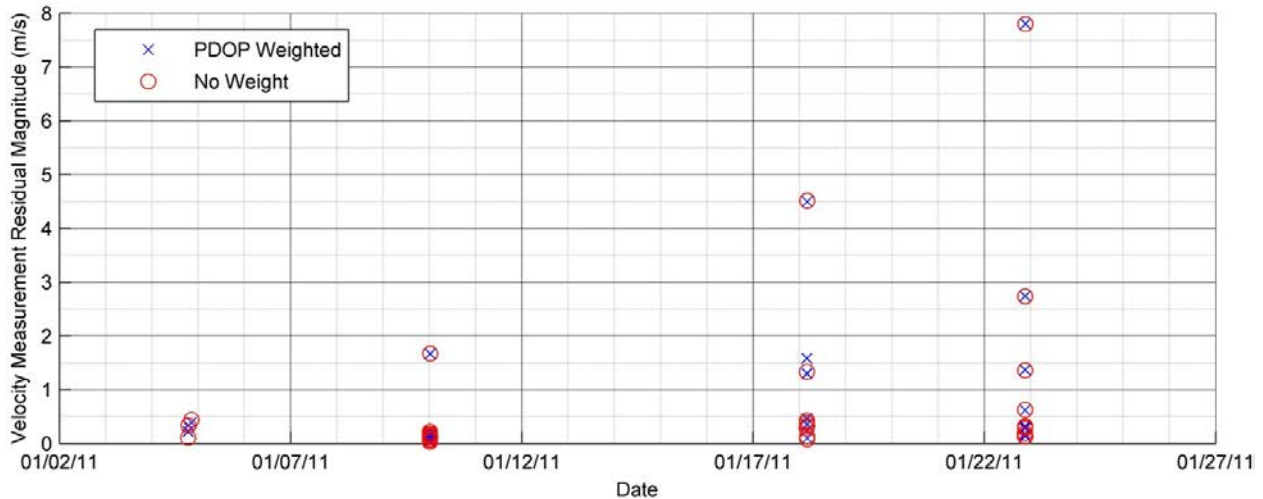


Figure 9. Velocity Measurement Residuals from Batch Post-Processing Algorithm Using Position Fixes as Measurements.

In both plots, there are 4 days in January 2011 where the nominal trajectory was estimated. Comparing the solution residuals on these 4 days shows that when more measurements are available the residuals are smaller. In most cases the position measurement residuals are below 20 meters, and in two of the days all of the residuals are below this level, which agrees with the expected post-processed performance from the GPS receivers based on simulation. (Zwerneman 2008) An example to illustrate the GPS receiver performance more clearly is shown in Figure 10 where the position residuals on January 10, 2011 are the lowest. Finally, when the measurements are weighted with the PDOP, the norm of state deviation is smaller and hence the convergence conditions for the batch post-processing algorithm are met with a much tighter tolerance.

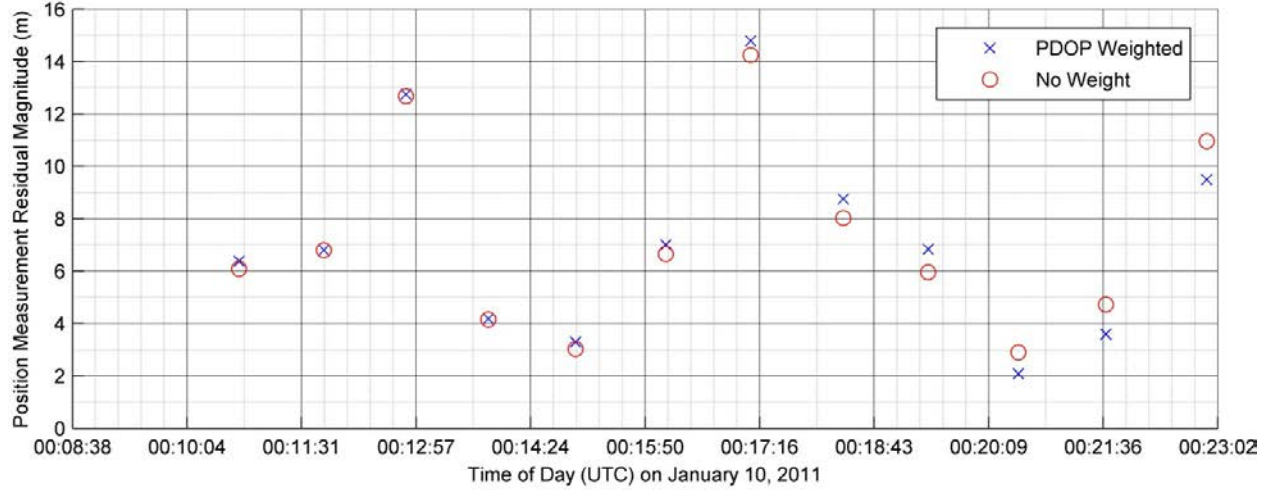


Figure 10. Position Measurement Residuals on January 10, 2011 from Batch Post-Processing Algorithm Using Position Fixes As Measurements.

4.3.2.3 Nominal Trajectory Batch Algorithm

In the scenario where the raw GPS pseudorange measurements were used to obtain a nominal post-processed solution of the state ($\mathbf{X}_o = [\mathbf{R}_o^T \quad \mathbf{V}_o^T \quad \delta t_u]^T$), the measurement had the form

$$Y_i = \rho^k(t_i) + c\delta t_u + \varepsilon^k \quad (3)$$

$$\rho^k(t_i) = \sqrt{(R_x^k - R_x)^2 + (R_y^k - R_y)^2 + (R_z^k - R_z)^2} \quad (4)$$

where the k^{th} superscript refers to the k^{th} GPS satellite, $\rho^k(t_i)$ is the range of the k^{th} GPS satellite to the GPS receiver, c is the speed of light, δt_u is the receiver clock offset, and ε^k represents the combined effect of all other errors such as ionospheric, modeling, and other residual errors. (Misra and Enge 2004) To obtain the GPS satellite positions, RINEX files for the days that were analyzed were downloaded and propagated to obtain the correct GPS satellite ephemeris data at the desired time.

In this case measurements were processed even if the GPS message from the satellite did not show the satellites were position fixing at that time which allowed more measurements to be processed. Figure 11 shows a representative sample of data showing the magnitude of the pseudorange measurement residuals for the same days as with the previous post-processing case for comparison. Only days where downloaded messages with enough pseudorange measurements to generate a post-processed solution were analyzed. It is shown that in this sample, for most processed days the majority of the measurement residuals are below 100 meters. Although these accuracies are larger than standard GPS position fixes, the batch solutions obtained validate the on-orbit position fixes that were recorded.

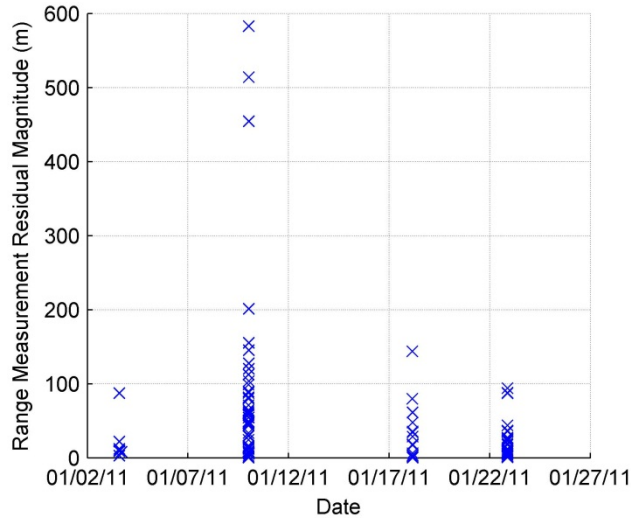


Figure 11. Range Measurement Residuals from Batch Post-Processing Algorithm Using Pseudorange Measurements.

In this scenario the measurement residuals were larger than the previous case because at any particular time there were not enough reported GPS measurements for the satellite to obtain a good clock bias estimate which must be removed to obtain accurate range measurements. This performance is due to the lack of an attitude control system, which causes the GPS antenna to point in less than ideal directions some of the time. However, a nominal trajectory estimate was still achieved in post-processing.

4.3.3 GPS Receiver Attitude Estimation Capabilities

The GPS receivers on board FASTRAC are capable of estimating the real-time attitude of the spacecraft in a sensor fusion algorithm that combines the signal-to-noise (SNR) measurements from a single GPS antenna for each of the GPS signals that it is tracking with measurements from an on-board magnetometer as discussed in (Stewart and Holt 2005) and (Greenbaum, Stewart, et al. 2008). A sample of the reported attitude solutions from January 10, 2011 from one of the satellites' GPS receivers is presented in Figure 12.

Figure 13 shows the 3-axis standard deviation of the reported attitude solutions shown on the previous plot. This plot shows that the reported accuracy of the attitude solution is below 10 degrees for all solutions except for the first data point. This data point corresponds to the time when the GPS receiver was just starting to acquire a position fix which explains the higher level of uncertainty. The other data points all have a reported standard deviation below 10 degrees which agrees with the expected accuracy of the GPS attitude determination algorithm as discussed in (Greenbaum, Stewart, et al. 2008) and (Stewart and Holt 2005).

It should be noted that since magnetometer measurements are used to generate these attitude

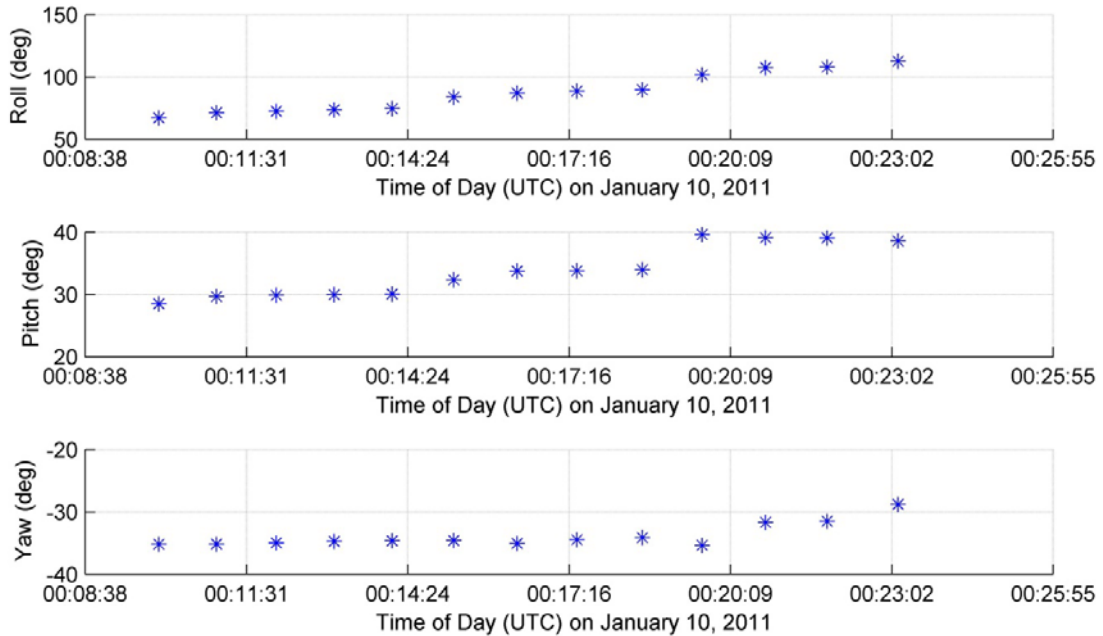


Figure 12. Reported GPS Receiver Attitude Solutions from January 10, 2011.

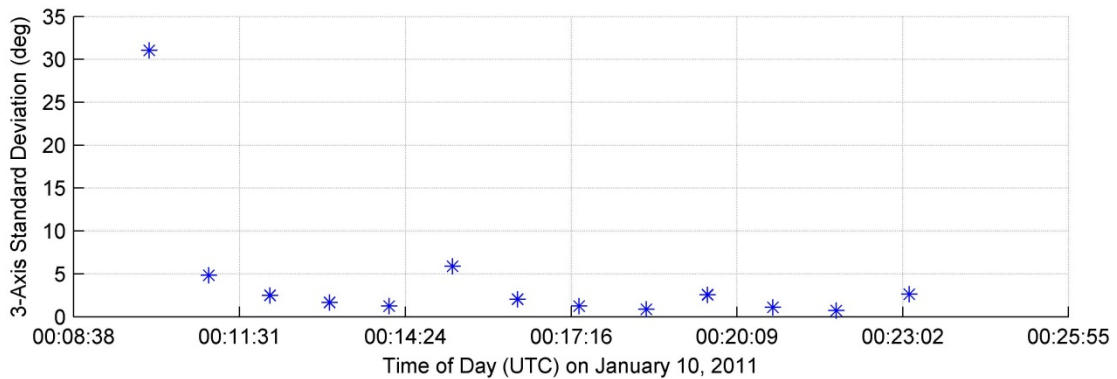


Figure 13. Reported Attitude Solution 3-Axis Standard Deviation from January 10, 2011.

solutions, the solutions are most accurate when a current position fix is available as this knowledge is used to compare the magnetometer measurements against an on-board geomagnetic model. These sample attitude solutions show that in stacked configuration the satellites were rotating roughly at 0.6 deg / min in the roll axis, 0.1 deg / min in the pitch axis, and 0.1 deg / min in the yaw axis when these samples were taken. These measurements were taken on January 10, 2011 prior to spacecraft separation and confirm that the combined satellite stack was rotating slower prior to separation on March 22, 2011.

5.0 CONCLUSION

During the first year of operations, the FASTRAC satellites have been continuously operational and have performed within expected bounds. All of subsystems have been verified and both satellites are still producing valuable data that will continue to be analyzed as long as the satellites remain healthy. At this point the minimum success criteria for all of the mission objectives have been met or work is in progress to complete them. The only full success mission objective that is not expected to be met is that of the satellites computing real-time relative navigation solutions. This is because one of the on-board microcontrollers that operates the GPS receiver on Sara Lily has stopped responding to ground commands. The data that have been gathered and analyzed thus far from the first year of operation have shown that the GPS receivers on board both satellites have operated as expected.

The post-processed nominal trajectory solutions have also shown that the GPS receiver has been performing within the expected bounds by comparison with results obtained from pre-flight GPS simulations. The GPS receiver performance is normal for the observed satellite rotation rates, which are due to the lack of an attitude stabilization system on these satellites. This analysis has validated the GPS receiver's performance and its capabilities as a space GPS receiver. A sample of attitude solutions obtained from the GPS receiver was also demonstrated reasonable attitude determination performance within expected accuracies according to ground simulations.

As part of the University Nanosatellite Program, the FASTRAC project was designed, built, tested, and operated by a team of university students with professional advice and assistance. More than a year of successful space operation for FASTRAC validates the student built satellite model. While many costs of this process are not fully known, there is unquestioned educational benefit. FASTRAC simultaneously performed a relevant space technology demonstration mission and provided a unique training experience for dozens of students, many of whom have entered the workforce since graduation and are now contributing engineers and scientists at aerospace companies, government research labs, and academia.

REFERENCES

- Campbell, Thomas. "Design and Use of the FASTRAC Nanosatellite Bus." Master's Thesis, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2006.
- Diaz-Aguado, Millan F. "Formation Autonomy Spacecraft with Thrust, Relative navigation, Attitude and Crosslink program (FASTRAC) Thermal Vacuum Test and Thermal Model." Master's Thesis, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2005.
- Diaz-Aguado, Millan F., Jamin Greenbaum, Wallace T. Fowler, and E. Glenn Lightsey. "Small satellite thermal design, test, and analysis." *Proceedings of SPIE: Modeling, Simulation, and Verification of Space-based Systems III*. Orlando, FL, 2006.
- Greenbaum, Jamin. "Flight Unit Fabrication of a University Nanosatellite: The FASTRAC Experience." Master's Thesis, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2006.
- Greenbaum, Jamin, et al. "A Combined Relative Navigation and Single Antenna Attitude Determination Sensor on the FASTRAC Student-Built Nanosatellite Mission." *Proceedings of the ION National Technical Meeting*. San Diego, CA, 2008.
- Hernandez, Lou. "Four satellites sit atop a Minotaur IV launch vehicle at Kodiak Launch Complex, Alaska, Oct. 18, 2010." U.S. Air Force. October 18, 2011.
<http://defenseimagery.mil/imagery.html#a=search&s=STP-S26&chk=6cfe0&n=90&guid=4503f830bb3ea1a0ba8d184cf0e4eb969e97f215> (accessed Dec 7, 2011).
- Holt, Greg, et al. "Relative Navigation, Microdischarge Plasma Thruster, and Distributed Communications Experiments on the FASTRAC Mission." *Proceedings of the 17th Annual AIAA/USU Conference on Small Satellites*. Logan, UT, 2003.
- Holt, Greg, Thomas Campbell, and E. Glenn Lightsey. "GPS, Distributed Communications, and Thruster Experiments on the University of Texas FASTRAC Mission." *Proceedings of the AMSAT 22nd Space Symposium and Annual Meeting*. Washington, DC, 2004.
- Misra, Pratap, and Per Enge. *Global Positioning System: Signals, Measurements, and Performance*. Ganga-Jamuna Press, 2004.
- Muñoz, Sebastián. "SYS103-3.7 FASTRAC Telemetry Budget." November 2010.
http://fastrac.ae.utexas.edu/for_radio_operators/users/phpBB3/SYS103-3.7_Telemetry%20Budget.pdf.
- Muñoz, Sebastián, Jamin Greenbaum, E. Glenn Lightsey, Thomas Campbell, Shaun Stewart, and Greg Holt. "The FASTRAC Mission: Operations Summary and Preliminary Experiment Results." *Proceedings of the 25th Annual AIAA/USU Conference on Small Satellites*. Logan, UT, 2011.
- Muñoz, Sebastián, Jamin Greenbaum, Thomas Campbell, Greg Holt, and E. Glenn Lightsey. "The FASTRAC Experience: A Student Run Nanosatellite Program." *Proceedings of the 24th Annual AIAA/USU Conference on Small Satellites*. Logan, UT, 2010.
- Smith, Aaron, Sebastián Muñoz, Eric Hagen, Greg P. Johnson, and E. Glenn Lightsey. "The FASTRAC Satellites: Software Implementation and Testing." *Proceedings of the 22nd Annual AIAA/USU Conference on Small Satellites*. Logan, UT, 2008.

Stewart, Shaun, and Greg Holt. "Real-Time Attitude Determination of a Nanosatellite Using GPS Signal-to-Noise Ratio Observations." *Proceedings of the 19th AIAA/USU Conference on Small Satellites*. Logan, UT, 2005.

STP-S26 Mission Profile. November 2010.

<http://spaceflightnow.com/minotaur/stps26/images/timeline.jpg> (accessed September 1, 2011).

Tapley, Byron D., Bob E. Schutz, and George H. Born. *Statistical Orbit Determination*. Elsevier Academic Press, 2004.

Vallado, David A. *Fundamentals of Astrodynamics and Applications*. Microcosm Press, 2004.

Zwerneman, Ryan. "GPS Performance Assessment for FASTRAC Student Nanosatellite Mission." Master's Thesis, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 2008.

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