SSC09-X-7

Increasing the Accuracy of Orbital Position Information from NORAD SGP4 Using Intermittent GPS Readings

Michael. R. Greene, Robert E. Zee

UTIAS Space Flight Laboratory
4925 Dufferin St., Toronto, ON. Canada M3H 5T6; +1-416-667-7993
michael.greene@utoronto.ca; rzee@utias-sfl.net

ABSTRACT

Paramount to any satellite mission is the acquisition of accurate vehicle position and velocity information at any particular point in time. With several satellite tracking and propagation methods available, the use of the Two-Line Elements (TLEs) supplied by the North American Aerospace Defense Command (NORAD) in conjunction with the Simplified General Perturbations Satellite Orbit Model 4 (SGP4) is considered the most popular choice for many low-Earth missions. This is primarily due to the fact that the SGP4 algorithm is open-source and that the TLEs are readily available to the public. Furthermore, they are updated on a fairly consistent – albeit infrequent – basis. If a particular mission requires more stringent accuracy than the SGP4 model can provide, an on-board GPS receiver is often a natural choice. GPS receivers can provide much greater orbital position knowledge at the cost of consuming relatively large amounts of power. This paper describes a technique for increasing orbital determination accuracy through the SGP4 model using a GPS receiver for intermittent orbital information, complemented with a TLE from the most recent epoch. The goal is to increase the precision of the estimates obtained from SGP4 with an effort to minimize the duty cycle required by an onboard GPS receiver. This propagation technique is primarily geared towards nanosatellite-scaled missions with regards to stringent power and antenna pointing requirements.

INTRODUCTION

The ability of present day satellites to perform high resolution remote sensing of the Earth's surface, deep-space astronomy, obtain high accuracy state information, and facilitate communications all over the globe has become indispensable to many people. However, irrespective of the advances in space technology, these satellites would quickly become useless if we lost ability to accurately locate them in space, as this would render communication with these satellites virtually impossible. Spacecraft navigation is therefore vital for all space missions. It involves satellite tracking and orbital determination, prediction, propagation, and trajectory correction. The investigation into more accurate, efficient, and cost-effective means of orbital determination and propagation is of great interest, particularly for the microsatellite and nanosatellite communities where resources are limited.

Background

The North American Aerospace Defense Command (NORAD) is currently responsible for space surveillance using traditional and phased-array radar systems, as well as some electro-optical methods. Upon detection of any space object, NORAD produces ephemeris in the form of a Two-Line Element (TLE), which contains, among other things, a drag term (also known as the B* term), and the mean Keplerian orbital elements of the spacecraft.

A NORAD-generated TLE is the input to the well-known SGP4 (for low-Earth orbiting spacecraft) or SDP4 (for deep-space missions) propagators. The SGP4 propagator continually predicts the position and velocity of the spacecraft in discrete time intervals. This propagator accepts only mean orbital elements as computed by NORAD as input. These mean values are the result of removing short- and long-periodic variations of these elements. The SGP4 model considers secular effects of J_2, J_4, and J_2^2, long-periodic effects of J_3, and short-periodic effects of J_2, along with atmospheric drag [1].

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) developed the Canadian Advanced Nanospace eXperiment 2 (CanX-2) nanosatellite. It was launched in April of 2008 on board the PSLV-9 launch vehicle from Sriharikota, India. This 3.5 kg satellite is currently performing a GPS occultation experiment of the Earth's atmosphere using an on-board GPS receiver. Professor Susan Skone, principal investigator the GPS occultation team, leads a research group at the University of Calgary devoted to this experiment. GPS data from this satellite has been used to obtain results described in this paper. Results are also plotted against a high-fidelity numerical method, namely, Satellite Tool Kit's (STK's) High-Precision Orbital Propagator (HPOP).

Motivation

There are two motives for investigating alternatives to relying solely on NORAD for state determination. First, there are several sources of error associated with TLE propagation. There is no error covariance estimate associated with TLEs; however, efforts have been made towards quantifying the intrinsic error. In [2] SGP4 is compared with GPS precision ephemerides. The results show error accumulation of up to 50 km range error after a period of 15 days. This value is unacceptable for certain missions. This error accumulation is both a function of initial TLE error, as well as internal error propagation intrinsic to the SGP4 model. A secondary motive is to resolve issues associated with the irregular distribution of the TLEs.

The CanX-2 GPS receiver provides low Earth orbiting (LEO) satellites with position information accurate to the meter-level. The use of a GPS receiver to obtain a position, velocity, and time (PVT) solution should therefore likely satisfy the orbital knowledge requirements for virtually any LEO satellite. However, as previously mentioned, there is a disadvantage to using a GPS receiver — its high power consumption. Also, on certain spacecraft, like the CanX-2, the GPS receiver is not always available for real-time state determination. In order to minimize the use of the GPS receiver while still benefiting from the increased positional information it can provide, a complementary method of determining spacecraft position and velocity is investigated.

Objective

As previously stated, the errors associated with using NORAD TLEs may, at times, be considered too great, and the constant use of a GPS receiver may not be feasible. A third option for determining the spacecraft state at some future time involves propagating the PVT solution obtained from GPS-based methods. Although this virtually eliminates the concern of initial state error, a sufficiently accurate on-board orbital propagator (including high-order Earth gravity, third body effects, atmospheric drag, solar radiation pressure, etc.) would be too computationally intensive to run on a typical nanosatellite on-board computer. The computational overhead is greatly alleviated with the SGP4 method using general perturbation theory. Consequently, the SGP4 model is used whenever possible.

The objective is to demonstrate a method for improving the orbital propagation for nanosatellite missions using both NORAD TLEs and GPS, and ultimately to determine the reduced GPS receiver duty cycle which will result in practical and accurate state determination. Through the use of GPS PVT for preliminary orbital determination, any initial error associated with NORAD TLEs will vanish. What remains is quantifying the subsequent error accumulation of the SGP4 propagator.

Previous Work

Motivated by the irregular periodicity of NORAD TLE generation, [3] developed a least-squares approach to estimate the NORAD TLE parameters from osculating orbital elements. This method also includes a process of determining the B* term, however it requires three days of prior observations. Therefore this technique does not depend on NORAD for tracking, merely the SGP4 propagator and osculating orbital elements. Results show this method to be valid within certain periods of time before the errors accumulate beyond reasonable limits (i.e. 1 km over 1 day). By contrast, the technique described here uses a simpler, more succinct method of orbital propagation which does not require extensive additional computation. Although both methods could be used in unison, the primary concern here is regarding those missions which are not capable of obtaining GPS measurements for long periods of time. This technique is geared towards any LEO spacecraft mission equipped with a GPS receiver, regardless of the receiver's original purpose.

METHODOLOGY

The NORAD TLEs required for the SGP4 model include parameters which must be supplied in the same format as they are issued from NORAD. In order to obtain mean orbital elements from osculating position and velocity from the GPS receiver, *Ernandes (1994)* developed a transformation program, VEC2TLE, which runs in the MS-DOS environment. This program was used to convert GPS PVT solutions obtained from the CanX-2 nanosatellite into the mean orbital elements in the appropriate TLE format. CanX-2 GPS data obtained from the 12-minute GPS lock on April 19, 2009 and the 20-minute lock on the following day will be used in the remaining sections of the work presented here.

RESULTS

During the weeks leading up to April 20, NORAD generated at least one TLE per day for the CanX-2 nanosatellite. CanX-2 mission control uploads a new TLE to the spacecraft on a bi-weekly basis as part of nominal ground operations. Therefore, CanX-2 is rarely propagating the TLE from the most recent epoch. Figure 1 shows the propagated position error of the

TLE relative to the satellite position estimated by the GPS receiver during the GPS lock that day. The TLE running on CanX-2 at that time (April 8) is shown in pink.

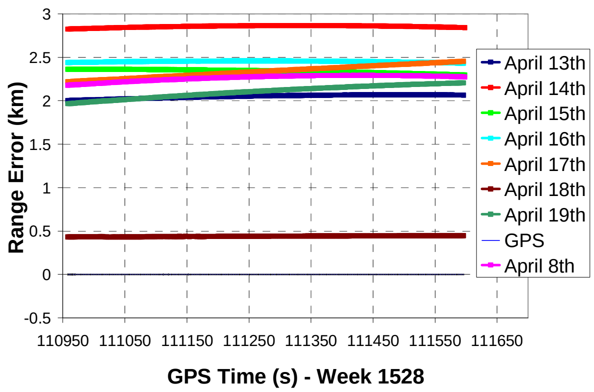

Figure 1: SGP4 model of TLE vs GPS reading

Here we can see that the majority of TLEs issued by NORAD result in SGP4 state predictions which differ from GPS by 2–3 km in most cases. On CanX-2, which was propagating the TLE from April 8th, we see a 2.2 km offset from the GPS solutions. Range error illustrated in Figure 1 is defined as the magnitude of the distance between the GPS and TLE estimates. It is the norm of the radial, in-track, and cross-track (RIC) errors.

Determination of the true accuracy of the GPS receiver is beyond the scope of this work, however the error of the GPS solution is not assumed to be zero. Ongoing work at the University of Calgary focuses on quantifying this error. The assumption made here is that the error estimates provided by the GPS receiver are accurate. The GPS receiver used on CanX-2 operates on dual frequencies (L1 and L2) whose error estimates are likely derived from the main diagonal terms of the covariance matrix of the sequential least-squares filter. These estimates represent the 1σ error associated with each element of the GPS state vector. The greater number of GPS satellites that are in view, the smaller these estimates, and hence more precise the GPS accuracy, due to redundant pseudorange observations included in the calculation.

Although the GPS receiver error estimates are included as error bars in Figure 1, they are so small as to be indiscernible from the data. The error covariance for this GPS reading is shown more clearly in Figure 2.

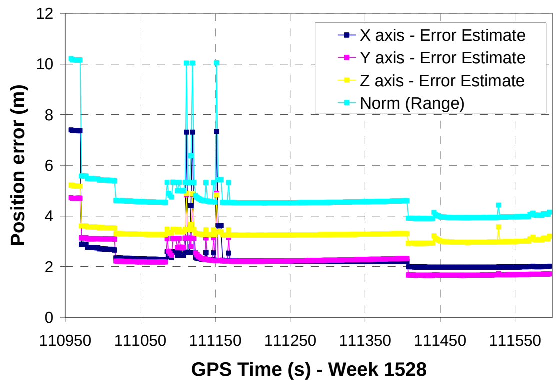

Figure 2: GPS error estimates 1σ per axis.

We see the GPS error estimate to be on the order of several meters. This error decreases with time as the number of satellites in view increases, thus causing the GPS solution to converge. Figure 2 represents the error estimate of the GPS receiver to an approximation of 1 standard deviation (a plus-or-minus value). The range bias induced due to receiver clock error is negligible in this case, as *FineSteering* status was maintained on the receiver during the GPS lock shown here. This means that upon receiving initial position information, the GPS receiver internally models the position range biases and the receiver clock offset. This continues until the model is a good estimation of the actual receiver clock behavior, accurate to ±1 microsecond [4].

It is interesting to note that if CanX-2 was propagating the TLE from April 18 it would have a better position estimate (relative to GPS) than it would using the TLE from April 19, the more recent epoch. Therefore, there exist anomalous TLEs which lead to much better estimates. However, there is no way of determining TLE accuracy a priori.

The most accurate position and velocity of CanX-2 obtained on April 20, 2009 from the GPS receiver is shown in Table 1. Included are the corresponding GPS error estimates.

Table 1: GPS PVT

CanX-2 GPS Measurement		
20 Apr 2009 06:57:53.000 UTCG		
Position (m) - ECEF		
Component	Value	1σ Error
x	2808187.5186	1.9796
y	1330229.2195	1.6605
z	-6273855.7531	2.9577
Velocity (m/sec) - ECEF		
Component	Value	1σ Error
x-dot	-4697.6095	0.2366
y-dot	-5076.8138	0.1985
z-dot	-3185.8990	0.3535

This state vector was then converted into the corresponding mean orbital elements suitable for a TLE using VEC2TLE. These elements are found in Table 2. The resulting TLE was then complemented with the B* from the TLE of the most recent epoch (April 19).

Table 2: Mean Orbital Elements

Mean Orbital Elements	
Time: 20 Apr 2009 06:57:53.000 UTCG	
Epoch [yyddd]	9110.290197
Inclination (i)	97.9477°
Right Ascension of the Ascending Node (Ω)	174.699°
Eccentricity (e)	0.0014503
Argument of the Perigee (ω)	215.99°
Mean Anomaly (M)	28.6721°
Mean Motion (n)	14.8145rev/day
B* [1/Earth Radii]	4.4279 x 10-5

The complete constructed TLE was then propagated using the SGP4 model for the duration of the GPS lock obtained on April 20th. This provides a comparison to the estimation provided by NORAD, illustrated in Figure 3. Here we see an orbital position estimate which agrees much more closely to the estimates provided by GPS from what will now be referred to as the *Joint* method.

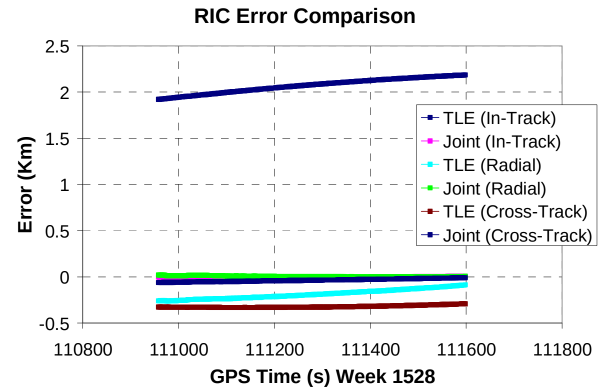

Figure 3: RIC errors of the Joint method vs. TLE.

Similarly, STK's HPOP was used to propagate the same state vector obtained from the GPS receiver, which is used here as a numerical spacecraft orbital dynamics model for comparison during longer periods of propagation. STK's HPOP is an extremely precise orbital propagator that uses numerical integration to propagate the satellite using a seventh-order Runge-Kutta-Fehlberg method. The gravitational model employed here was a 70 by 70 EGM96 for Geoid approximation, with WGS84 as the reference ellipsoid model. Atmospheric drag (Jacchia-Roberts) and solar radiation pressure (dual-cone) are modeled. The HPOP model was also configured to considered Solar, Lunar, Jupiter and Venus induced perturbations, as well as relativistic effects, and ocean and solid tidal forces.

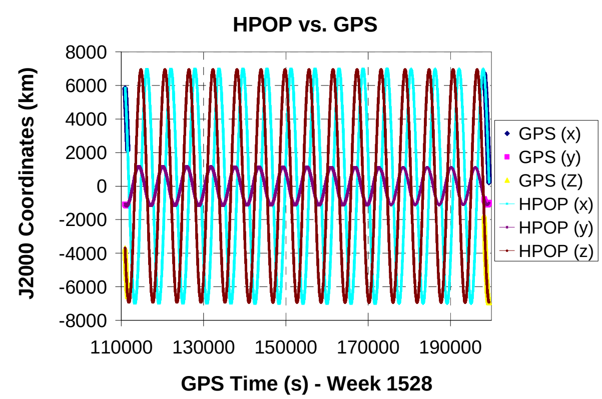

Figure 4: HPOP vs CanX-2 GPS readings

Figure 4 shows that the HPOP model aligns with CanX-2 GPS measurements on both April 20 and 21, 2009. This provides us with some level of confidence in the HPOP model. Note, however, that neither GPS nor HPOP should be considered a perfect truth model, as there are no means to determine the exact position of CanX-2 on April 20th. Notwithstanding, HPOP will be used as the truth model in order to quantify the accuracy associated with the Joint method over longer periods of time. Figures 5-7 illustrates the RIC errors of the Joint method relative to HPOP, plotted with the TLE from April 19th, the most recent TLE issued from NORAD. Range error is also included in each plot in order to illustrate the contribution that each type of error has to the overall position error. This propagation was preformed for a period of one day.

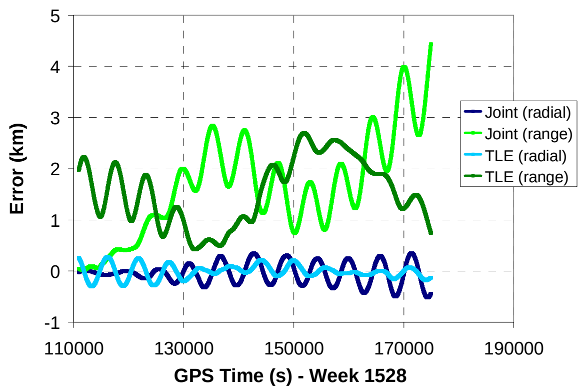

Figure 5: Joint and TLE radial error

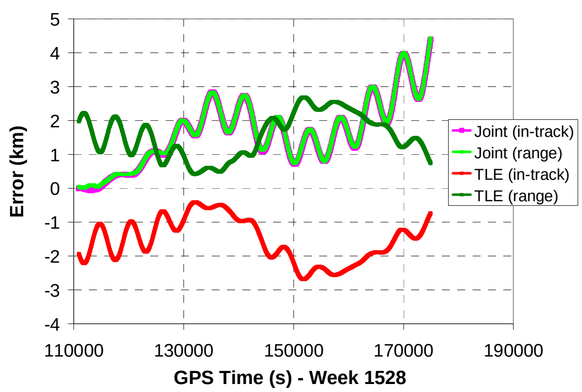

Figure 6: Joint and TLE in-track error

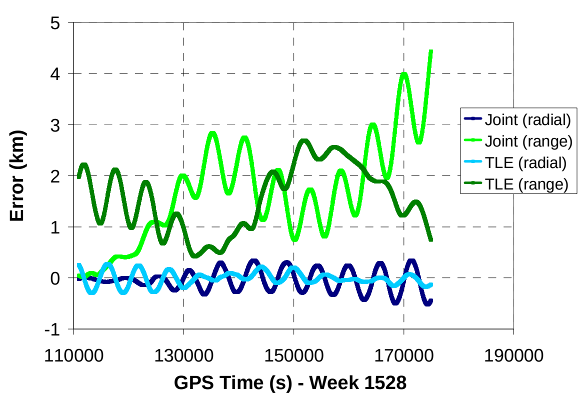

Figure 7: Joint and TLE cross-track error

It is apparent from Figures 5-7 that the in-track errors contribute the greatest amount to the overall error estimate for both NORAD TLE and the Joint method. Inaccuracies in this parameter point to improper drag modeling. The commonality here is in the B* term used in both methods (as well as the SGP4 model itself). Future implementation of a B* estimate may therefore be a reasonable suggestion for future work as an attempt to refine the drag modeling.

From Figures 5-7 we see that the two methods obtain similar values after a relatively short period of time — however, as expected, the Joint method is initially far more accurate.

Figure 8 shows a zoomed in view of the propagated RIC errors associated only with the Joint method. Here we see the region of early propagation more clearly, from which we can obtain more useful results.

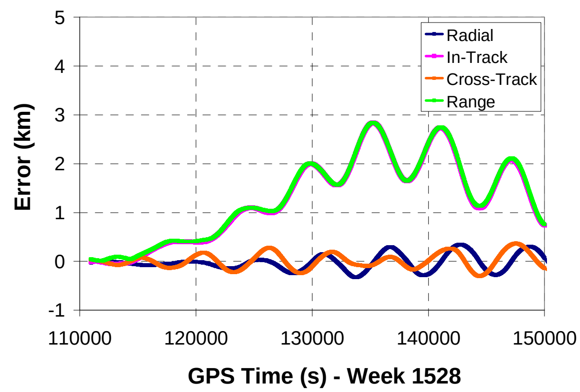

Figure 8: Joint method propagation error

From Figure 8 we see a range error of 1 km is reached in approximately 3 hours, 18 minutes. An error accumulation of up to 2 km occurred in approximately 5–6 hours. Therefore, in order to remain under 1 km, the GPS receiver would need to be updated roughly once every 2 orbits. Likewise, to remain within 2 km, a GPS update is required once every 3 to 4 orbits, for a spacecraft orbiting at an altitude of 650 km. This error accumulation is a function of the initial GPS error, the precision loss during the VEC2TLE conversion process, and the intrinsic error propagation of the SGP4 propagator.

It is interesting to note that the oscillation of the RIC errors appear to have a period of about 90 minutes. This is approximately equal to the orbital period of CanX-2. From this we should consider possible differences between the SGP4 model and STK's HPOP, which would cause such oscillations. This periodic variation is likely caused by a cyclical disturbance force in the space environment that is accounted for in one model but not in the other. Higher order gravity terms, neighboring celestial bodies, tidal forces and relativistic effects are not accounted for in SGP4, which may attribute to the divergence seen here.

Several assumptions have been made here, namely that the error associated with STK's HPOP is essentially ignored, and the initial GPS error is noted, however not used to provide a resulting error covariance.

Suggestions to use a post-processing method of smoothing the set of GPS solutions are proposed for future work. This would, in theory, narrow the error covariance of each GPS PVT solution obtained, provided a reasonable dynamics model is used. This would ultimately result in refined mean orbital elements through VEC2TLE, or a similar process, and would therefore improve the overall accuracy of the combined method described in this paper. An effort to use both GPS measurements and TLEs in a weighted combination, as opposed to completely replacing the TLEs, may also prove advantageous for future work.

CONCLUSION

The accuracy of orbital propagation using the SGP4 model with intermittent GPS measurements has been quantified. In order to obtain accuracies greater than 1 km, updating of the GPS PVT solution is required about once every 3 hours (or 2 orbits – for a 650 km altitude spacecraft). To remain within 2 km, the GPS orbital position must be updated once ever 5-6 hours (or 3-4 orbits).

Although it is conceivable that the estimate provided by NORAD will prove more accurate in some cases, there is no guarantee, as it is not possible to know TLE accuracy a priori. The main advantage of the method described here is the added reliability of the acquisition of the orbital position information, as well as prior knowledge of the behaviors and expected achievable accuracy of the state vector estimation. Suggestions on how to improve this method have been stated.

ACKNOWLEDGEMENTS

The authors would like to thank the following contributors:

- Ontario Graduate Scholarships (OGS)
- Dr. Susan Skone, University of Calgary
- Defence Research and Development Ottawa
- Canadian Space Agency (CSA)
- Natural Sciences and Engineering Research Council of Canada (NSERC)
- MDA Space Missions
- Ontario Centres of Excellence (OCE)
- Sinclair Interplanetary

REFERENCES

1. Bandyopadhyay, P. Sharma, R.K., and Adimurthy, V. Space debris proximity analysis in powered and orbital phases during satellite launch. Advances in Space Research 24, 1125-1129, 2004.
2. Kelso, T.S., "Validation of SGP4 and IS-GPS-200D Against GPS Precision Ephemerides," presented at the 17th AAS/AIAA Space Flight Mechanics Conference, Sedona, AZ, 2007 January 29.
3. Cho, C.H., Lee, B.S., Lee, J.S., Kim, J.H., Choi, K.H., "NORAD TLE Type Orbit Determination of LEO Satellites using GPS Navigation Solutions". J. Astron. Space Sci. 19(3), 197-206. August 27, 2002.
4. NovAtel, "OEM4 Family of Receivers – User Manual – Volume 2, Command and Log Reference", 31 July, 2003.
5. Vallado, David A., Paul Crawford, Richard Hujsak, and T.S. Kelso, "Revisiting Spacetrack Report #3," presented at the AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, 2006 August 21–24.
6. Hoots, F. R., Roehrich, R. L., "Spacetrack Report No. 3: Models for Propagation of NORAD Element Sets". December 1980 – Compiled by: Kelso, T.S. 31 December 1988.
7. Lee, B. S, "NORAD TLE Conversion from Osculating Orbital Element". J. Astron. Space Sci. 19(4), 395-4026. November 18, 2002.
8. Moraes, R.V., Kuga, H.K., Dampos, D.Y., "Orbital Propagation for Brazilian Satellites using NORAD Models". 2002.