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Satellite Planning Models

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SATELLITE PLANNING MODELS

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EXECUTIVE SUMMARY

Project Summary

Naval forces need prior knowledge of overflight by satellites for effective planning. This includes positions of friendly satellites that are expected to provide intelligence, surveillance, and reconnaissance (ISR) and communications support to our forces as well as positions of adversary and commercial satellites that could potentially detect and report planned Navy activities via various onboard sensors.

We identified differences between the Simplified General Perturbations model 4 (SGP4) United States Air Force (USAF) and Position and Partials as a function of Time v3 (PPT3) United States Navy (USN) orbit propagation models, and determined their impact on positional error in orbit determination. PPT3 and SGP4 both perform well within the expected accuracy limits inherent in analytical models, with neither propagator demonstrating an accuracy rate decay that was significantly better or worse than the other.

The two-line element (TLE) format is under change now, the new TLE and three-line element (3LE) formats are still under review, data in the new format is not being distributed, and the current version of SGP4 does not support the new formats. The new formats are to add additional types of information about the satellites, many not related to their orbits. Information in the new third line related to primary payload mission, primary mission status, and payload owner/operator provides context for satellite vulnerability planning, and is relevant for deciding which satellites should be monitored closely and choosing update rates for TLEs and 3LEs.

Keywords: *Naval Ship Vulnerability, Satellite Overflight Prediction, Accuracy Assessment, SGP4, PPT3*

Background

The purpose of the research is to assess the difference between the two models of orbit propagation that are currently in use (SGP4 and PPT3). Specific research objectives were:

1. Assess which model characteristics are most significant for satellite planning systems.
2. Compare the relevant aspects of legacy models and the newer models.

The classical textbook solutions that yield elliptical orbits assume that gravity comes from a single point mass and that there are no other forces acting on the satellite. The real situation is different: motion of near-earth satellites is affected by (1) drag from the thin vestiges of the atmosphere at their altitude, (2) deviations from the point mass approximation because the earth is not perfectly spherical and the distribution of mass in the earth is not perfectly uniform, (3) other sources of gravity, (4) light pressure, (5) the solar wind, and so on. While all of these effects are much smaller than that of the earth's gravity approximated as a point mass, over time they build up to produce deviations from the stable elliptical trajectory described by the textbook solution to the simplified orbital problem.

Astrodynamics was a quiet scientific endeavor of little national import until October 4, 1957 when the Union of Soviet Socialist Republics (USSR) launched *Sputnik-1*, the first artificial Earth earth satellite. On November 29 of the same year, the Air Force established Project Space Track to track and compute orbits for all artificial Earth satellites, including U.S. and Soviet payloads, booster rockets, and debris. On March 17, 1958, the U.S. launched *Vanguard 1*. Then Dirk Brouwer and Yoshihide Kozai wrote their articles on artificial satellites in November 1959 (Brouwer, 1959 and Kozai, 1959). They utilized spherical harmonics for Earth's non-uniform gravity field, and their work laid the foundation for today's orbital prediction theory.

To translate the theory into a working computer model, other research had to be incorporated. The usage of R. H. Lyddane's solution to small *e* and *I* divisors (Lyddane, 1963) and the King-Hele atmospheric model allowed Brouwer to develop the PPT model. It ran on the IBM 7090 computer at Dahlgren, VA, was the largest available in 1964. Brouwer and Kozai would later collaborate on the SGP4 model, which included fewer zonal harmonic terms and used a simple atmospheric model, though this was changed to a more complex model in 1969. It remains the Air Force's primary tracking system.

PPT3 and SGP4 use different simplified models of atmospheric drag. PPT3 is a simplified version of PPT that drops some of the less significant parts to speed up the computation. This was necessary to make the computations practical on computers available when the models were developed. Initially the computations took 15 minutes per satellite (Hoots, Schumacher, & Glover, 2004). They are much faster now due to better hardware. The benchmark for Naval Postgraduate School Satellite 1 (NPSAT1), a small spacecraft built at NPS that uses an ARM LH79520 (a 32-bit ARM7TDMI core) that runs at 51 MHz (no floating point hardware), does one iteration of SGP4 in just under 5 msec. Processor cores in most current laptop computers are about 50 times faster than that. This implies that processor speed is not a limiting factor for the models any more, and that it should now be feasible to use the full PPT model if needed.

Findings and Conclusions

Material was gathered and analyzed on the larger context for this inquiry, such as publications and the Navy context regarding motivations for accurate satellite tracking and prediction. Results were reported to more than three dozen interested people from the DCNO for Information Warfare (N2/N6), the DCNO for Operations, Plans and Strategy (N3/N5), Director, Fiscal Management Division (N82), Director, Innovation, Test and Evaluation, and Technology Requirements (N84), DCNO for Warfare Systems, Director for Undersea Warfare (N97), Naval Information Forces (NAVIFOR), Space and Naval Warfare Systems Command (SPAWAR), and NPS in a summary teleconference on June 22, 2017. A master's student was extensively involved in this study, resulting in a master's thesis (Wildt, 2017) and a conference publication (Lan, 2018). The two analytic models studied, SGP4 and PPT3, are not the most accurate ones currently available, but they require significantly less computation than the more accurate numerical models, resulting in faster response times. Both of the models need to be frequently recalibrated using least squares fits to measured satellite position data, and the accuracy of both SGP4 and PPT3 is good enough for satellite vulnerability (SATVUL) planning if that is done. The extra accuracy of the numerical models is needed in other contexts such as satellite maneuvering, rendezvous operations, etc.

Differences between the models were validated and assessed by comparing model predictions to real-world satellite measurements, with the following findings:

- Both propagators calculate drag within analytical expectations (1-3 km per day margin)
- Neither has a significantly better error rate than the other
- Accurate input data is needed to get good predictions
- Imperfections in the TLE data were observed, along with effects on model predictions
    - In particular, the B*(best-first graph search algorithm) component was incorrectly set to zero in multiple TLEs
    - This affected SGP4 but not PPT3, whose drag model does not use B*
- Accuracy increases outside of the atmosphere for both models
- For satellite vulnerability planning:
    - Timeliness of orbit element [TLE] input is important!
    - Altitude of the satellite should be considered before extending predictions 3+ days past epoch – the errors accumulate faster for satellites in lower orbits.
    - Build time buffers into SATVUL plans, for immunity to accuracy errors

The errors for both SGP4 and PPT3 were found to be within the expected range of 1km ± 3km/day. We believe the accuracy of both models is good enough for Navy satellite vulnerability planning if the orbital elements driving the models are updated frequently enough, for the following reasons:

- Procedures for stowing sensitive equipment, turning off radiating signals, or concealing local presence will take time on the order of minutes, not less than a second, and that satellite vulnerability planning scenarios will include enough extra lead time to ensure that detection by satellites is avoided despite expected variations in predicted overflight times.
- Typical speeds of satellites in low earth orbit are about 7.5 km/sec. An expected 4 km error in predicted position therefore corresponds to an overflight time error of 4/7.5 sec = 0.53 seconds, which would not be significant under the above assumptions.
    - The expected error in this scenario corresponds to TLE updates once per day.
    - Solar storms can change the atmospheric density, increasing expected prediction errors for both models. TLEs should be updated more frequently during periods of increased solar activity to compensate for this effect.

Since there are web tools for updating satellite orbital elements, they can be updated frequently, and training for every Strike Group Communication Officer and N6 emphasizes this prior to deployment.

Factors other than accuracy of orbit predictions also affect SATVUL planning. Satellite vulnerability windows depend on the position of the ship, as well as the position of the satellite and the field of view of its instruments. The actual positions of Navy ships can deviate substantially from their planned position of intended movement (PIM) due to emergent operational needs and other unpredictable disturbances. For this reason, it is recommended to calculate satellite vulnerability windows in real time on board ships in a battle group, using orbit model parameters disseminated from satellite tracking centers. This concept of operation (CONOP) should be more effective than centralized calculation and dissemination of the SATVUL predictions. Local SATVUL processing would enable accurate real-time ship positions to be used in the calculations, as measured on board the ship, instead of relying on the ship's planned PIM. This should lead to more accurate satellite vulnerability window predictions.

Since error of predicted satellite prediction increases with time since the last measured position of the satellite, it is also recommended to disseminate real-time updates of model parameters to ships for automatic update whenever there is bandwidth in the communications system that is not needed for higher priority information. This would remove risk due to possible delayed human action, because the people currently responsible for updates are likely to have more pressing concerns during crises.

Since the accuracy of both models improves for higher orbits, it is recommended that the priority for orbit parameter updates consider orbit altitude in addition to risk factors associated with the satellite, with more frequent updates for lower orbits. Frequent TLE updates would also reduce exposure to prediction errors caused by changes to satellite configuration, such as navigational maneuvers and modifications to a satellite's shape and orientation that affect its drag coefficient.

Recommendations for Further Research

Additional research and development are recommended with the following objectives:

- Engagement with Air Force Space Command (AFSPC) to acquire full PPT3 and model calibration codes, make comparison of more satellites possible, and enable thorough validation and assessment.
- Gain full understanding of PPT3 initialization, to enable development of a more usable and portable application programming interface.
- Additional analysis of the variation/errors seen in TLE data, to enable assessment of data feed quality. Predictions are no better than the data they are based on, and our initial study found data with unexpected values (Wildt, 2017).
- Additional analysis of variation/errors seen in 3LE and 4LE data and prediction improvements enabled by that data.
- Development of full data models for orbit data that completely specify the meaning of the data, in addition to its format. The additional information needed includes measurement units, coordinate system origin and orientation, and conventions for defining all the orbit parameters, with emphasis on details of the ones that are interpreted differently in the two main propagation models, such as mean motion and semimajor axis.
- Alternatively, develop a full data model for the de facto TLE standard matching SGP4, and transform the front end of the PPT3 implementation to read an SGP4-dialect TLE and internally convert it to the form needed by the PPT3 algorithm, to prevent confusion between different variants of TLE data.
- Since computers are much faster now than in the 1960's, consider implementing the full PPT model. PPT3 dropped some of the terms in PPT to speed up the computation as needed then to keep up with the TLE update rate, introducing some loss of accuracy. PPT should provide better accuracy than PPT3 while keeping the computation time less than that of more accurate numerical orbit prediction

models, which estimate satellite positions and velocities at many intermediate points in time and hence require more computation for orbit prediction than analytical models such as SGP4, PPT3 and PPT.

- Revise I/O routines to accommodate the new TLE/3LE formats, revise the SGP4 and PPT3 models to fully the new information in them, and start distributing data in the new formats.

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Acronyms

3LE - three-line element
AFSPC - Air Force Space Command
B* - best-first graph search algorithm
CONOP - concept of operations
ISR - intelligence, surveillance, and reconnaissance
N2/N6 - DCNO for Information Warfare
N3/N5 - DCNO for Operations, Plans and Strategy
N7 - DCNO for Warfare Requirements and Programs
N82 - Director, Fiscal Management Division
N84 - Director, Innovation, Test and Evaluation, and Technology Requirements
N97 - DCNO for Warfare Systems, Director for Undersea Warfare
NAVIFOR - Naval Information Forces
NPS - Naval Postgraduate School
NPSAT1 - Naval Postgraduate School Satellite 1
PIM - position of intended movement
PPT - Position and Partials as a function of Time
PPT3 - Position and Partials as a function of Time v3
SATVUL - satellite vulnerability
SGP4 - Simplified General Perturbations (model 4)

SPAWAR - Space and Naval Warfare Systems Command
TLE - two-line element
USAF-United States Air Force
USN - United States Navy
U.S. – United States
USSR – Union of Soviet Socialist Republics