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A CATALOGUE-WIDE IMPLEMENTATION OF GENERAL PERTURBATIONS ORBIT DETERMINATION EXTRAPOLATED FROM HIGHER ORDER ORBITAL THEORY SOLUTIONS

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The proliferation of the use of higher-order orbital theories (HOTs) has greatly expanded satellite state estimate accuracy expectations, yet much of the existing space surveillance software and infrastructure has been built around the Simplified General Perturbations Theory #4 (SGP4) analytic orbital theory and its associated two-line element set (TLE). One approach to realizing greater orbital accuracy without modifying recipients' communications and processing software is the use of the "extrapolation differential correction," in which the analyst uses a HOT ephemeris (of which some portion is propagated into the future) to create synthesized sensor observations and employs these to perform a correction with the analytic theory to produce the desired TLE. By fitting a high-fidelity future prediction, the analytic theory can inherit a substantial measure of the HOT's accuracy. This methodology, previously used on only a small number of satellites, has been prepared for catalogue-wide deployment at the Joint Space Operations Center; and satellites will be transferred to this approach in groups until most of the space catalogue is maintained this way. Full-catalogue test results show a substantial improvement in state estimate accuracy, as well as an extension of the element set's useful life for many orbital regions.

INTRODUCTION

In the earlier days of space surveillance, satellite orbit determination and propagation were heavily dominated by analytical theories. Computing power was at a premium, and the accuracies rendered by analytical general perturbations (GP) theories were adequate for nearly all of that era's space surveillance applications. Higher-order orbital theories (HOT), which contained more explicit geopotential and non-conservative force models, did exist; but not only did they lack some of the important features of modern versions, computing limitations also restricted their operational application to only a handful of satellites. These conditions resulted in the establishment of the SGP4 (Simplified General Perturbations Theory #4) analytic theory, and the two-line element set used to capture and distribute SGP4 results, as the typical representation for satellite space surveillance orbital information. Because historically this theory's accuracy

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remained adequate for most space surveillance activities, especially the usual task of reliable sensor reacquisition of relatively large space objects, system upgrades at both space sensors and correlation centers were performed in a manner that left the GP approach largely in place.

Within the last decade, there has been an explosion in the use of HOTs, driven largely by the number of commercial astrodynamics packages now available that include this capability. The substantial increase in desktop computing power has made the use of even the most demanding HOT approaches possible from a typical machine, and the expansion of filter-based techniques has further expanded HOT availability. During this period, what is now called the Joint Space Operations Center (JSpOC) pursued its own increased HOT capabilities, overseeing the deployment of the Astrodynamics Support Workstation (ASW), which is an off-line capability, underwritten originally by NASA Johnson Space Center, to perform special perturbations (SP) batch orbit determinations on all objects with perigee heights less than 600 km to support manned-flight orbital safety calculations. Since its deployment, the ASW's scope has increased gradually to include maintenance of the whole of the space catalogue and to sustain a number of important model upgrades, such as the High-Accuracy Satellite Drag Model (HASDM),[1] segmented drag solutions and a dynamic batch fit-span[2] to maximize short-duration (up to 72-hour) propagation accuracy. The state estimates of this SP-maintained catalogue are a substantial improvement over those of its GP counterpart, both in fit (at epoch) and in prediction; and there has been a persistent desire throughout many parts of the space surveillance community to make more and broader use of this catalogue in space surveillance operations.

Distribution and compatibility issues, however, have conspired to stymie any substantial increase in the use of this high-accuracy catalogue. There is at present no automated communications path by which the ASW catalogue can be circulated to a broader set of users. Additionally, many military users of catalogue data do not have an integrated version of the SP propagator to allow their systems to process these data, and some such users are unlikely ever to have such a capability. While there are initiatives to expand communications approaches to include SP catalogue data and strategically to upgrade certain military users to employ this catalogue, it is unlikely that a broad increase in catalogue access and utility will take place anytime soon. So the question naturally arises whether it is possible substantially to improve catalogue accuracy while remaining within the confines of the TLE orbital data format and the SGP4 propagator. Addressing this question leads to the concept of the extrapolation differential correction.

SPACE DEFENSE OPERATIONS CENTER (SPADOC) EXTRAPOLATION DIFFERENTIAL CORRECTION (DC)

The general problem of how to migrate the improved accuracy of a HOT to a GP theory was addressed to some degree in the SPADOC software suite. This system includes two higher-order theory orbit determination (OD) methods, SP and Semi-Analytic Liu Theory (SALT), and three general perturbations theories, Simplified General Perturbations (SGP), SGP4, and Hoots Analytical Dynamic Ephemeris (HANDE). The original concept of operations was to maintain the orbit determination of a small number of objects (100 or fewer) with one of the two HOTs and to transfer the increased accuracy from this HOT maintenance to the GP theory with which each object was paired. Direct conversion of the output of a HOT to that of a GP theory, while possible, yields only a starting point with the new theory, not a representation that preserves the HOT's accuracy. The method thus developed for transitioning at least some of the HOT accuracy to the GP theory, called an "extrapolation differential corrector," involves manufacturing synthetic observational data from a HOT ephemeris (these data are called "pseudo-obs") and executing an orbit determination with the GP theory using the synthetic observations. The basics of the approach are explained thoroughly by Cappellucci[3,4] and are thus given only a summary treatment below.

The process, which is laid out in diagram form in Figure 1, begins with the HOT ephemeris that will serve as the source for the pseudo-obs, and the length and start-end points with respect to the current time must be decided. The overall length of ephemeris will determine the length of the GP orbit determination (OD's) fit-span, and of course there are many rules of thumb regarding the desirable length of a fit span for a batch correction in order to produce a certain OD longevity and accuracy, such as mandating a fit-span of equal length to the desired prediction interval. But the situation is somewhat altered here because of the fresh issue of how this fit-span should be positioned *vis-à-vis* the current time, which will also probably serve as the OD epoch time. With the usual sensor-observation-based OD, one begins at the current time and proceeds backwards in time for the length of the fit-span, using for the DC all of the sensor observations that fall within that time interval. In the case of the extrapolation DC, one is not bound to past observations or ephemeris: one can use HOT ephemeris both from the HOT fit interval in the

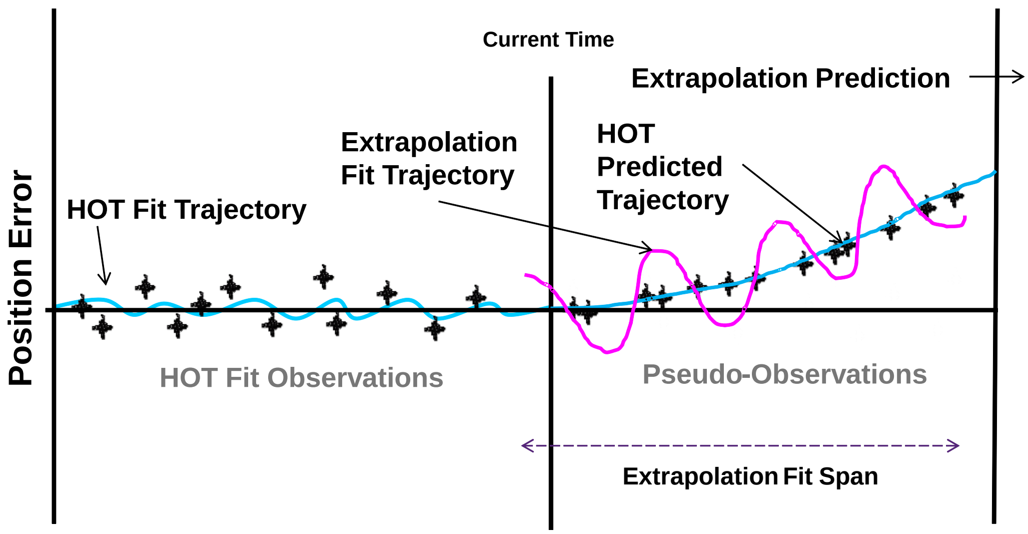

Figure 1: Extrapolation DC fitting approach diagram.

past and propagated HOT ephemeris that runs into the future. In fact, one of the chief virtues of the extrapolation DC technique is the ability to fit HOT future predictions and thus greatly improve the GP theory's performance in prediction; since the GP DC's fit-span actually can be composed largely of future predictions, it is little surprise that its ability to model satellite behavior in the future can be greatly improved. In practice, usually a fit-span definition that is composed of notably more future ephemeris (HOT prediction) than past (HOT fit interval) is selected, with its precise past-to-future ratio and overall length based on orbital region and satellite-specific considerations. Once the length and temporal orientation of ephemeris are selected, the pseudo-obs to be used for the GP fit can be created. The pseudo-ob convention used in SPADOC is the "type 10" observation, which is an Earth-Centered Inertial (ECI) XYZ position and time. In the simplest lay-down, the pseudo-obs can be evenly spaced in time, although for eccentric orbits this presents a difficulty because it tends to create oversampling near apogee and undersampling near perigee, where the orbit is changing most rapidly. To address this problem, the spacing between pseudo-obs is determined by the time-regularized Cowell step-size approach used for SP numerical integration (commonly called *s*-integration)[5]; the integration step size will naturally shrink when the object is close to the attracting body and moving more quickly, and expand when far away and moving more slowly. Once the pseudo-obs data are produced, it remains merely to execute the GP OD in the usual way; in nearly all cases of actual operational use SGP4 was the GP theory of choice for compatibility reasons, but the SPADOC functionality allows any of the three GP theories to be the selected as the destination theory (that is, the particular GP theory used to fit the pseudo-obs). Once completed, the results of this fit can then be sent to users.

The advantages of this approach are many. First, certain orbit types cannot be modeled well with SGP4 (*e.g.*, orbits with large solar radiation pressure or eccentric orbits, both of which are subjected to over-simplification and truncation in SGP4); the extrapolation DC allows a HOT that includes these perturbations to be used for the actual orbit determination, with some portion of the benefits of this HOT to be passed on to the GP theory, which can be used by recipients who lack the HOT propagator. Second, a substantially improved GP prediction accuracy can be achieved by the fitting of an ephemeris produced by HOT propagation, especially given that much of the ephemeris to be fit represents a high-accuracy statement of satellite future position. Third, this accuracy improvement does not require any change to the communications protocols or propagators used by legacy military systems. It is not as large of an accuracy gain that would be realized by a native use of the HOT results, but it is a substantial improvement that requires absolutely no modification to presently-fielded systems.[*] For these reasons, the creation of a catalogue-wide extrapolation DC capability, which would use ASW-produced SP vectors to maintain the SPADOC-hosted SGP4 element sets (and thus the orbital information distributed worldwide to users via www.space-track.org), would be beneficial to a large number of users. An initial test version of this capability was incorporated into the operational system in the fall of 2011, the associated multi-stage numerical validation program was largely complete by summer 2012, and the transition of groups of satellites (as described below) from regular GP maintenance to this new technique began in fall 2012. With this transition, a fourth advantage arises: relieving the overtasked SPADOC system of the processing requirement to perform all of the GP differential corrections from observations; instead, it can receive these updates from the ASW and use them for its other mission applications and catalogue distribution, with more of its computer power now available for these activities.

ASW EXTRAPOLATION DC ALGORITHM IMPROVEMENTS

While the implementation of the ASW extrapolation DC (called "eGP") has largely mirrored the SPADOC implementation, there are a few algorithmic improvements that deserve mention. First, the SPADOC approach applied DC controls (such as fit-span length) determined by fixed formulae; for the maintenance of an entire catalogue using the eGP technique, it was recognized that customizable controls, based on satellite groupings more appropriate to the SP correction, would be necessary. The primary method by which satellites are "binned" is first by the traditional large-scale orbital regimes (based on period and eccentricity, giving the common divisions of LEO, HEO, MEO, and GEO; the precise definitions used for these common orbital

[*] Some would argue that this statement is not precisely true in that certain systems may include functionality that has been tuned to the historical accuracy of SGP4 element sets; thus, a change in the expected element set accuracy, even if is an improvement, will necessitate modifications to system settings. Typically, such empirical settings apply themselves to functions that will still operate properly with more accurate element sets, but additional tuning would allow the receiving system to operate more efficiently. It seems acceptable to introduce changes into the using community under such conditions: some improvements will be available with no modifications at all, and any accommodating adjustments are to improve the efficiency of system operations rather than to accommodate the new element set constitution *per se.*

divisions are included as part of Table 2) and within each of these regimes by a more recent categorization called "energy dissipation rate," or EDR, which is the dot product (averaged over the fit-span) of the inertial drag acceleration vector and the velocity vector, characterizing the amount of energy being lost by the orbit (or, in the more unusual case, gained by the orbit) and thus representing more fully the actual effect of the non-conservative forces acting upon the satellite. The contribution of satellite area-to-mass properties can thus be considered together with the actual atmospheric or solar-radiation-pressure properties and their combined effect used as the discriminator, as it is this combined effect that dictates the ease or difficulty of the resultant orbit maintenance. The initial roll-out of this approach in 2001 defined eleven EDR "bins" as a proposed orbital taxonomy (bins 0-10, as shown in Table 1); subsequent experience with this technique has determined that these divisions are often unnecessarily fine, leading to the grouping of some of these bins to form an overall set of five divisions (0, 1, 2-4, 5-7, 8-10, with these condensed bins shown in the lower part of the table).[6] It is also possible to have positive energy dissipation rates (the last line of Table 1), although these cases were not considered in the present analysis. eGP control parameters, such as the length of the ephemeris fit-span and its orientation with regard to the current epoch, are governed for the general case by a rule-set that considers satellite EDR bin, period, eccentricity, and perigee height; additionally, any satellite can have its eGP controls specified directly, in which case any automatic assignments are overridden. Another feature of the ASW eGP implementation is additional options for epoch placement in the resultant GP element set, including support for both conventions used historically with TLEs (placement of epoch at the right ascension of the ascending node just prior to the time of the most recent observation used in the correction or, alternatively, simply the time of most recent observation used in the correction). A third feature is the ability for the extrapolation technique to execute weighted as well as unweighted GP DCs, enabling fit-weighting to produce a greater evenness of fit residuals with regard to GP theory error.

Table 1: Energy Dissipation Rate (EDR) Bins.

EDR Bin	Lower W/kg Value	Higher W/kg Value	% of Catalogue (May 2012)
0	0.0000	0.0000	13.5
1	0+	0.0006	53.2
2	0.0006	0.0010	8.2
3	0.0010	0.0015	5.1
4	0.0015	0.0020	3.3
5	0.0020	0.0030	3.7
6	0.0030	0.0060	4.4
7	0.0060	0.0090	1.7
8	0.0090	0.0150	1.5
9	0.0150	0.0500	1.9
10	0.0500	0.0500+	1.1
2-4	0.0006	0.0020	16.6
5-7	0.0020	0.0090	9.8
8-10	0.0090	0.0500+	4.5
< 0	< 0	< 0	2.3

EGP RESULTS EVALUATION METHODOLOGY

While it would seem that the chief motivation for an eGP paradigm would be an increase in state estimate accuracy, in fact at present the principal operational benefit is to free up processing power on the SPADOC system. In recognition of this, in evaluating eGP performance a Hippocratic Oath dynamic is in play: the overriding performance criterion for eGP is to "do no harm"—eGP-produced element set error should not exceed that for the traditional, obs-based SPADOC SGP4 DC. To be sure, one hopes that there may be a substantial accuracy benefit to the technique, and past experiments with the extrapolation DC have certainly suggested such a result; but the overriding operational objective can be met simply by demonstrating accuracy parity between catalogues generated with eGP and the SPADOC SGP4 DC.

To perform such an accuracy comparison, one must establish both the period of time and propagation states to use for the comparison, as well as the actual accuracy calculation technique. Regarding the time and propagation periods, there are no *a priori* answers, as there is no general consensus regarding the appropriate "shelf life" (period of time during which an element set can be considered viable) of TLEs (and thus no accompanying confidence level that might dictate an appropriate sample size for performance evaluation). For this analysis, a one-month dataset of eGP and GP element sets for the entire satellite catalogue (April 2012) and a fifteen-day propagation period for each element set was chosen. Operationally, satellites are placed on the "attention" list when their epoch age reaches five days, the point at which JSpOC analysts need to take proactive action in order to keep the element set from aging to a degree that reacquisition becomes difficult; a period three times that duration (fifteen days) was selected as a reasonable shelf-life limit to impose.

There are a number of methodologies for calculating element set accuracy. The most reliable and least controversial is to compare predicted positions to those given by an externally-determined precision reference orbit; as there is no sharing of observational data, there are no issues regarding data independence. However, the number of satellites with such reference ephemerides is small, and the reference satellites that are available do not represent all of the orbit regimes for which evaluation is desired. A second possibility is to compare TLE predicted positions to those given by Space Surveillance Network (SSN) metric observations. While this approach does give a more ecumenical orbit regime representation, it suffers from several problems: observation errors that in some cases are quite large; a reduced dimensionality for the great majority of deep-space observations, which typically report only angles and not range measurements; and the fact that all too often there are no SSN observations near the propagation point at which an evaluation is desired. What is needed is a HOT-quality reference ephemeris for each object; this would allow comparison at all desired points and serve as a reasonable yardstick for evaluating the accuracy of eGP and regular SGP4 TLEs.

Fortunately, a feature of the current ASW system is the creation of a reference ephemeris, using a method similar to that for satellite laser-ranging (SLR) reference orbit construction, for every catalogued object for the purposes of SP vector accuracy assessment; these reference ephemerides can be used as a basis to evaluate the accuracy of eGP and regular SGP4 TLEs. The approach is described more completely in a separate conference paper,[7] but an abbreviated summary (taken from Reference 3) can be given here:

> "A common method of reference orbit construction involves the linking together of pieces of ephemeris taken from the fit-spans of moving-window DCs. If the construction process is set up properly, these fit-spans do not share observational data and are therefore (essentially) statistically independent; and it can be shown that in this case the variance of the reference ephemeris abutment errors (which can be measured) is twice the variance of the actual ephemeris error. When building a small number of reference orbits, the situation can be massaged to get the DC fit-spans to align properly so that the ephemeris-pieces can be stitched together easily. However, when reference orbits are attempted on an entire catalogue of satellites, in which operational requirements require updates when new observations are available (in eight-hour batch intervals presently), arranging for the ideal fit-span definitions is simply not possible; but if some overlap of fit-spans is allowed, a reasonable reference orbit can still be constructed despite the introduction of a certain amount of correlation between ephemeris pieces. In fact, if one

can achieve a 50% overlap between fit-spans, the factor of two difference between the variance of the abutment errors and the variance of the actual ephemeris error disappears, allowing a direct relationship. The "adjudicated settlement" for the operational implementation was to take ephemeris pieces from as close to the middle of the fit-span as possible, try for situations that give approximately 50% overlap, and use pieces from intervening updates if necessary. This will allow for the efficient creation of a reference orbit for every object. While clearly not as reliable as satellite laser-ranging (SLR) reference orbits, by some measures they compare favorably: for a test set of eight calibration satellites, for example, epoch accuracies of produced vectors differed, on average, by only 8.3 m when assessed against the constructed reference orbit versus the SLR reference orbit; at the 18-hour prediction point, the mean difference was 5.5 m."

Given that these reference orbits exist for every object, it is a straightforward undertaking to compare GP element sets, at propagation points of interest, to this reference orbit to determine component-level and overall vector-magnitude errors. While there is some inherent error in these reference orbits, this error is so much smaller than that of the GP theory, especially in propagation (where the secular error growth in the GP model will be substantially greater), that it is acceptable to neglect any reference orbit error.

Table 2: Orbital regions examined in present analysis.

EDR Bin	**LEO** Period < 225 min	**HEO** Period > 225 min Eccentricity > 0.25	**MEO** Period > 225 min and < 1300 min Eccentricity < 0.25	**GEO** Period > 1300 and < 1800 min Inclination < 15º Eccentricity < 0.25
0	✓	✓	✓	✓
1	✓	✓		
2 – 4	✓	✓		
5 – 7	✓	✓		
8 - 10	✓	✓		

The one month's worth of element sets for the whole main catalogue, maintained both using eGP and through traditional SPADOC SGP4 DCs, was compared to these reference orbits. A vector magnitude (Vmag) error was calculated for each element set at propagation points of interest from epoch to fifteen days. Satellites were then grouped into categories for analysis, as indicated in Table 2, and analyzed collectively within these groups. To remove the perturbations that maneuvering satellites bring to an accuracy evaluation, active payloads were excluded from the analysis.

4. EGP AND REGULAR SGP4 EVALUATION RESULTS

The following nine graphs (Figures 2-7) chronicle the results of this catalogue-wide investigation at the 50th percentile (50ile) Vmag level. Behavior similar to that at the 50th percentile is observed at other percentile levels of interest, such as the 68th and 95th percentiles. Interpretive comments will be provided subsequent to the graphs' presentation. In each graph the designation "GP" indicates OD performed from observations using regular SGP4 and "eGP" indicates using the eGP technique with SGP4 used to fit the pseudo-obs generated from the SP predicted ephemeris.

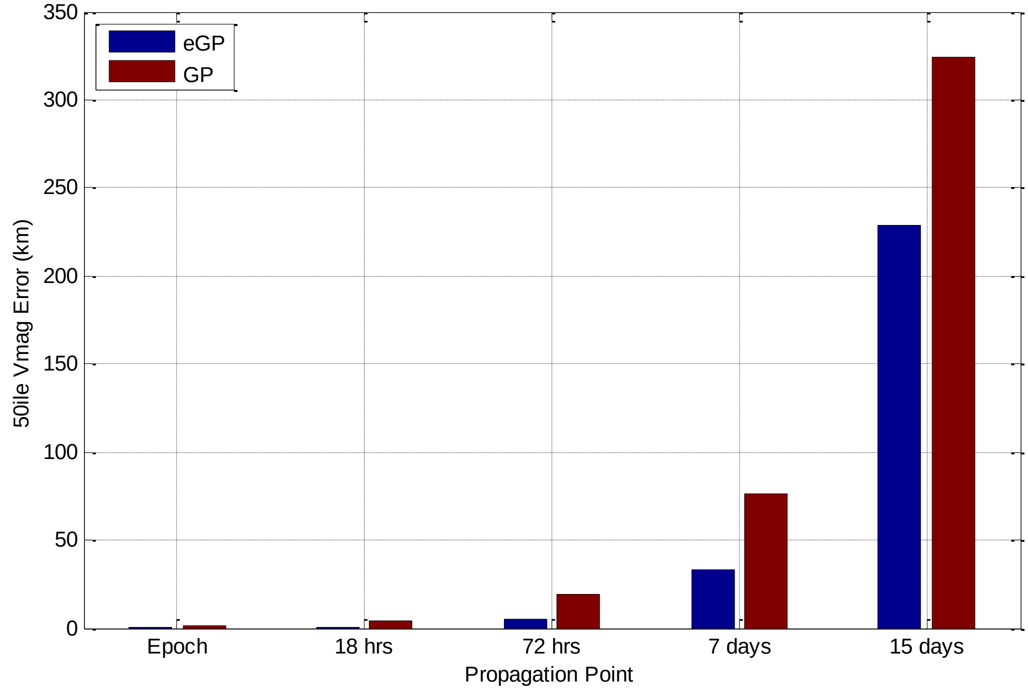

Figure 2a: eGP and regular SGP4 errors: LEO < 500 km.

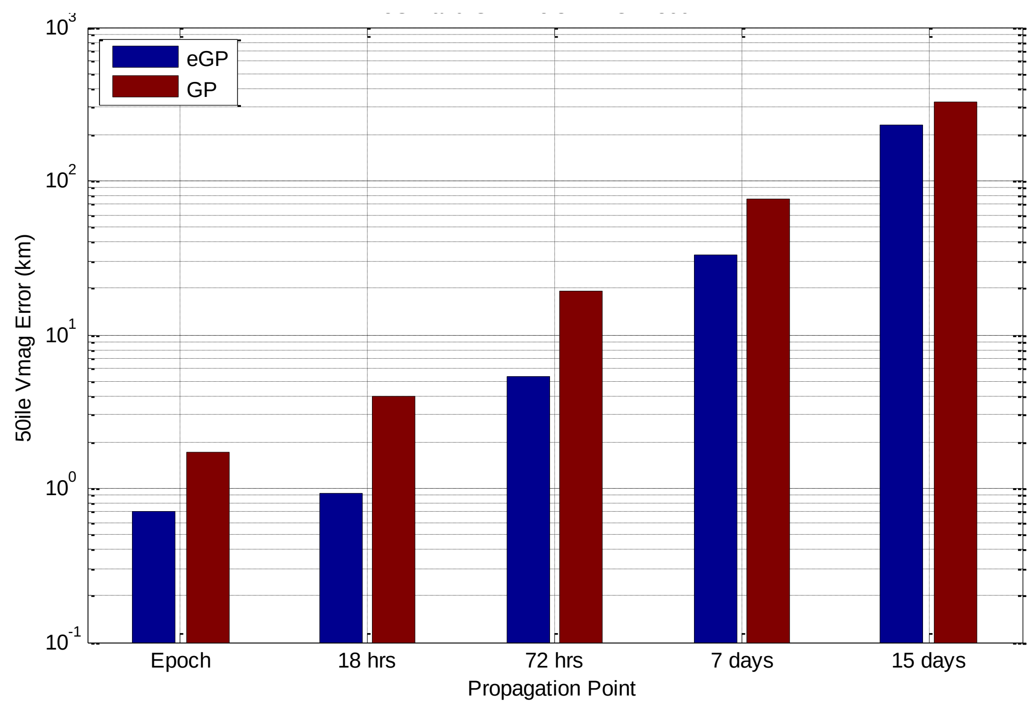

Figure 2b: eGP and regular SGP4 errors: LEO < 500 km (log scale).

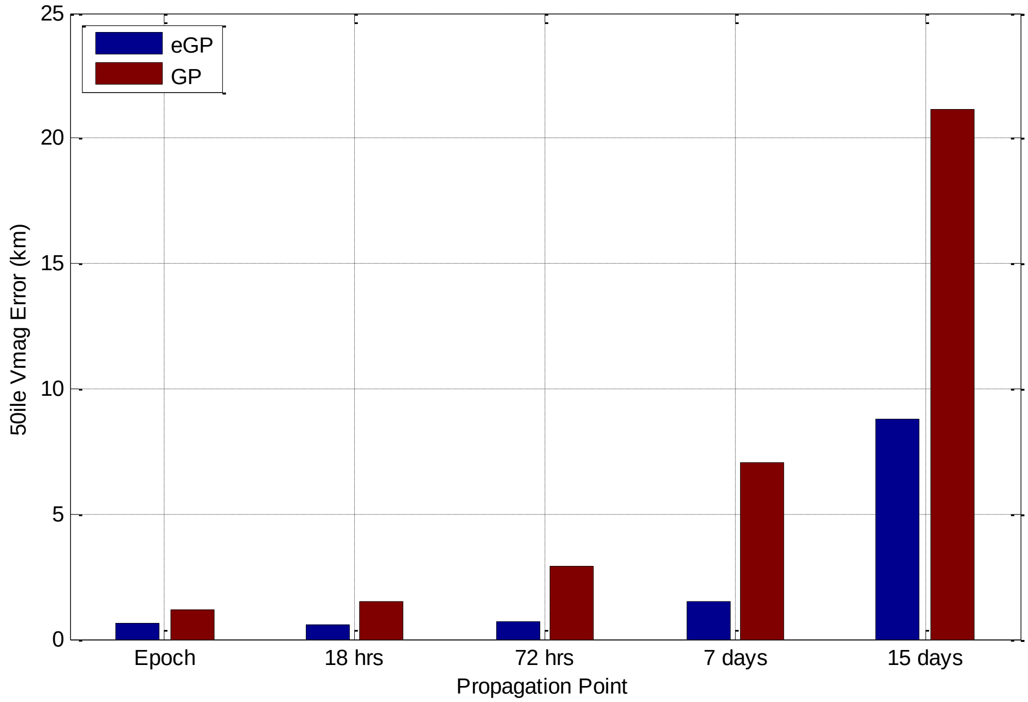

Figure 3a: eGP and regular SGP4 errors: LEO > 500 km.

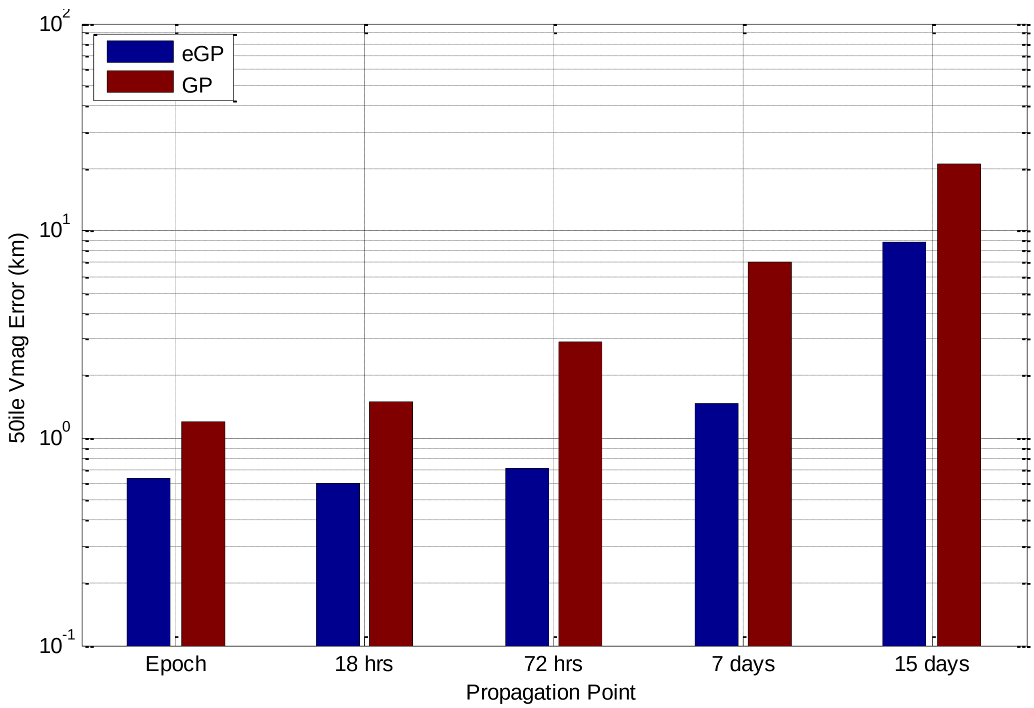

Figure 3b: eGP and regular SGP4 errors: LEO > 500 km (log scale).

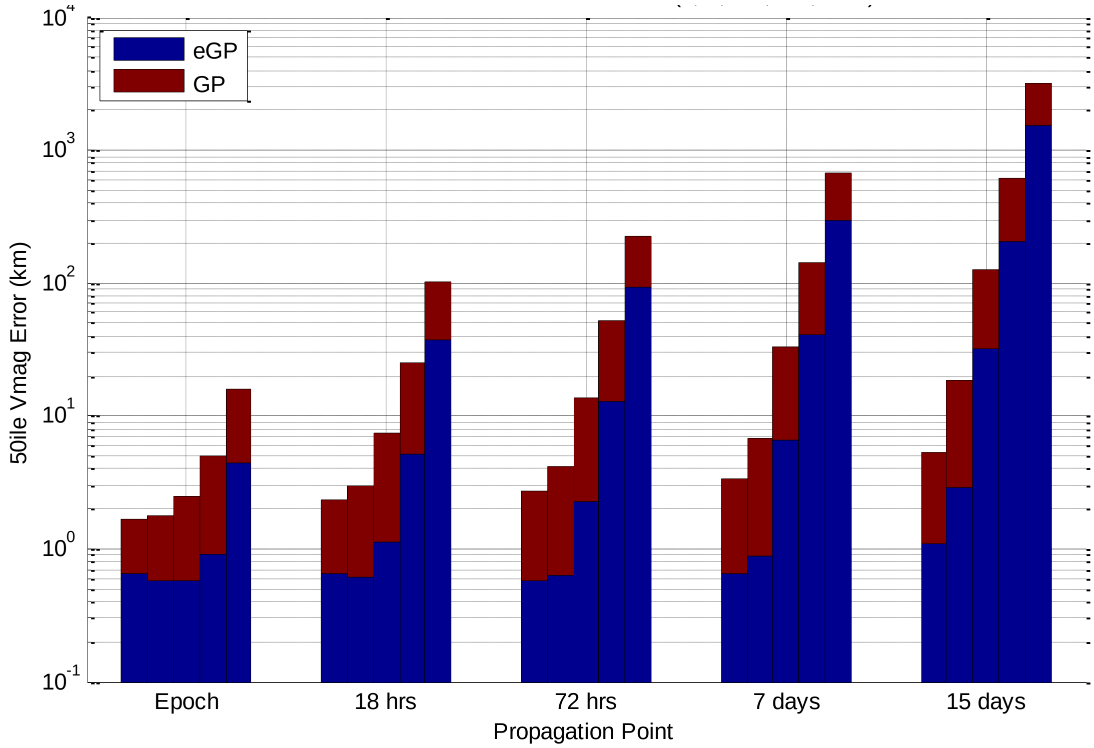

Figure 4: LEO eGP and regular SGP4 errors by EDR bin. For each cluster of bars in the bar graph, the EDR bins represented are 0, 1, 2-4, 5-7, and 8-10, respectively.

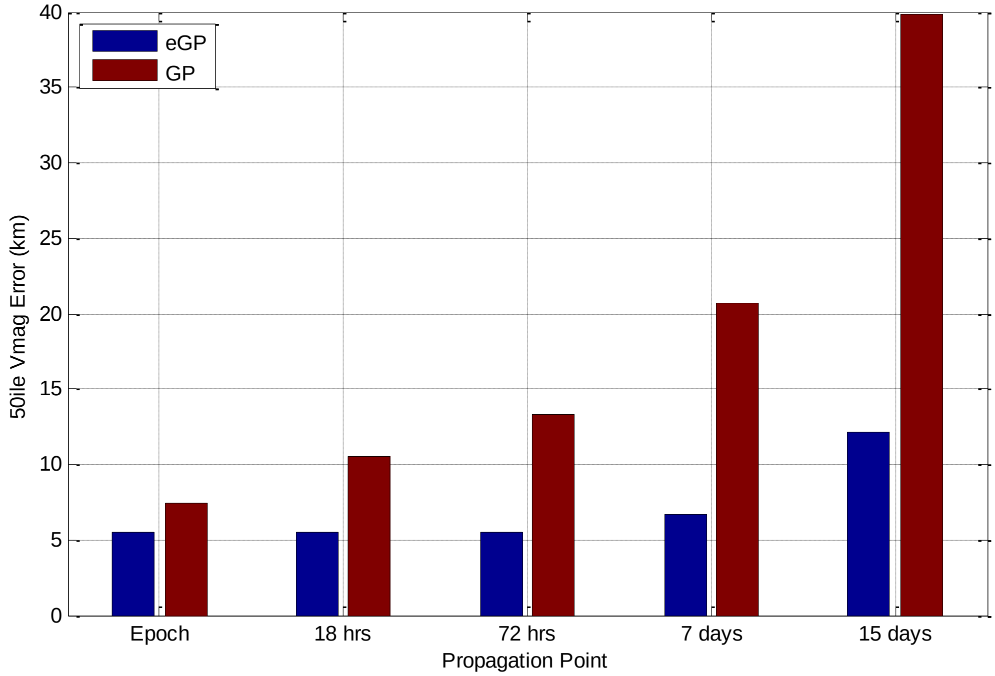

Figure 5a: eGP and regular SGP4 errors: HEO

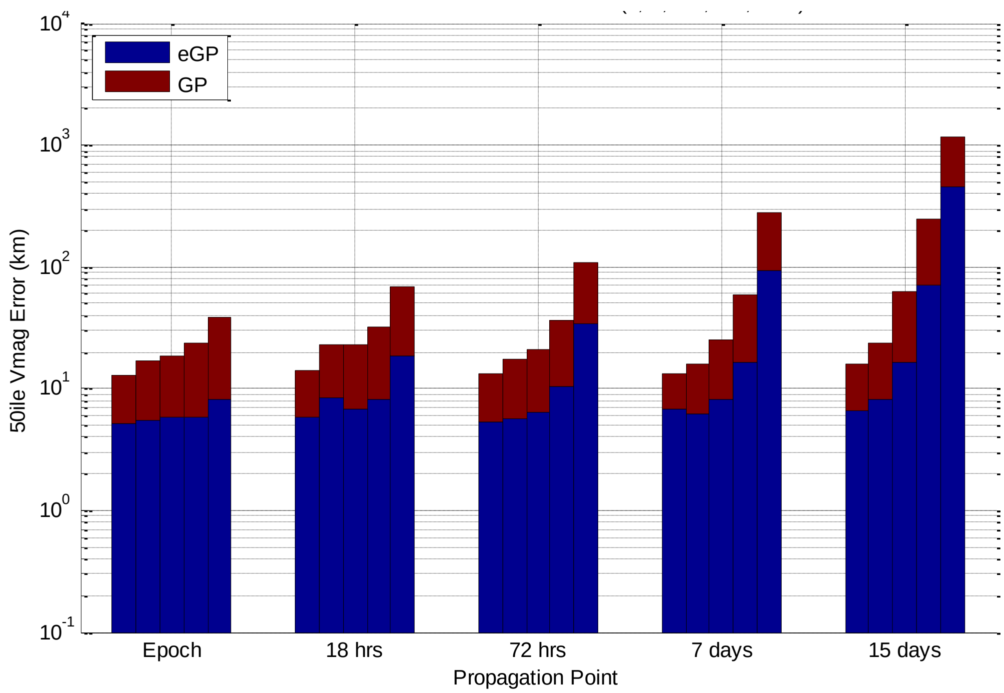

Figure 5b: HEO eGP and regular SGP4 errors by EDR bin. For each cluster of bars in the bar graph, the EDR bins represented are 0, 1, 2-4, 5-7, and 8-10, respectively.

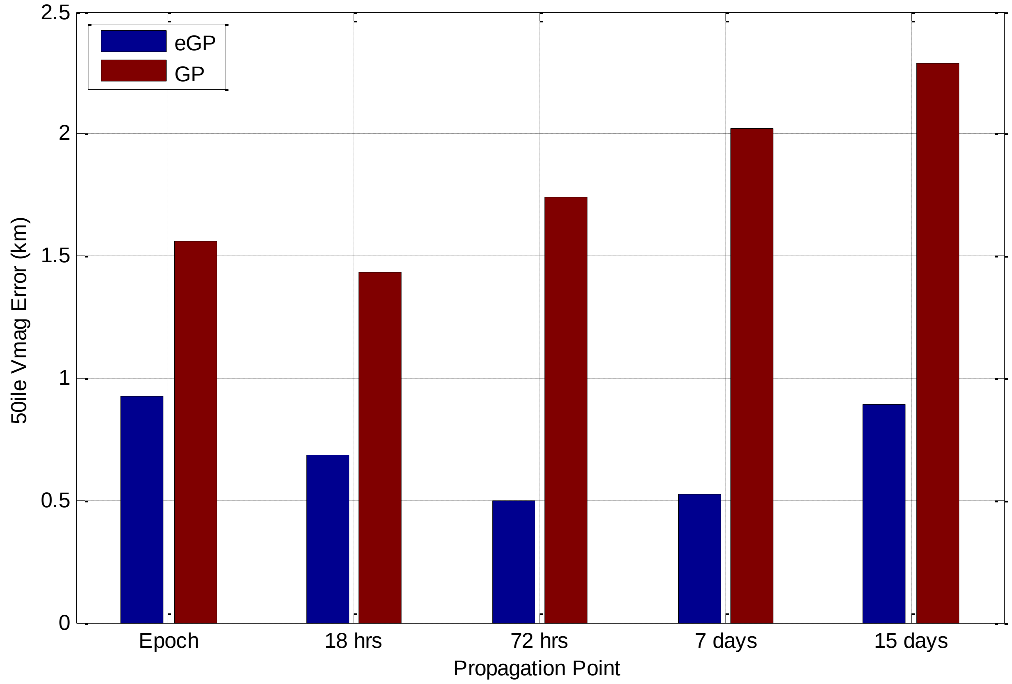

Figure 6: eGP and regular SGP4 errors: MEO.

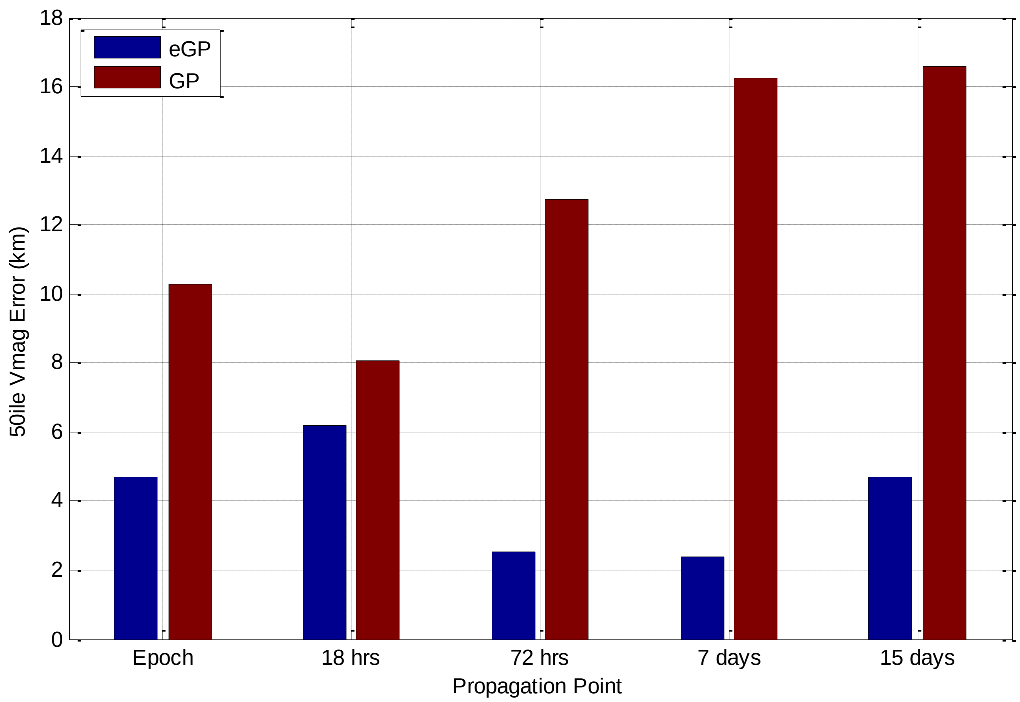

Figure 7: eGP and regular SGP4 errors: GEO.

The first observation one makes in examining these results is the degree to which they are favorable to the eGP paradigm at the 50th (and other) percentile levels: for every orbit regime at every propagation interval examined, the eGP results are superior to the SPADOC regular SGP4 results; and this superiority can in some cases be as much as a factor of seven or more. Some specific items of note by orbit regime are as follows:

- While eGP does provide ubiquitous improvement for the LEO < 500 km case (Figures 2a and 2b), the improvements are the most modest of any orbit regime examined. This is because the primary difficulty in this regime is predicting the future atmospheric neutral density in support of the drag model in propagation, a problem that affects HOTs and GP theories alike. As one would expect, therefore, improvement is greatest near epoch and becomes much less substantial as the propagation periods are expanded, showing improvement to only 70% of the SPADOC GP value at fifteen days' propagation time.
- In the LEO > 500 km regime (Figures 3a and 3b), the differences are more marked, with improvement at factors of three to four at some of the propagation states. Here one can observe a "flare up" of error at epoch: a phenomenon in which the epoch error is somewhat greater than at a more distant propagation state, such as that of 18 hours. This effect is due to the proportion of past (fit-span) to future (propagation) portions of the HOT ephemeris used in the correction, as well as the overall length of the ephemeris. Preference here was given to reducing the error at more distant propagation points, such as fifteen days, even if that produces a small increase in error at epoch. There is also the issue of propagator periodic terms; these play a smaller role in LEO orbit determination but will be discussed more extensively with regard to the MEO and GEO results.
- In examining the LEO behavior by EDR bin (Figure 4), in general error ratios between eGP and regular SGP4 are smaller at the smaller EDR bins and increase with EDR bin number. These results are reasonable, as the problem of predicted atmospheric density will stymie both HOTs and GP theories equally, thus eroding much of the advantage of the HOTs at the higher EDR bins.
- The HEO results (Figure 5) show a very interesting stability of response for the eGP element sets: the error is stable at 6-7 km through 7 days of propagation and then doubles to 12 km at 15 days; the SPADOC regular SGP4 errors show more of an exponential growth that, at 15 days, are four times greater than the eGP values. Such behavior is understandable in that the SGP4 theory truncates higher-order eccentricity terms, producing a more error-infused result relative to HOT-based performance than is observed for some of the other orbital regimes.
- The results for the MEO and GEO regimes (Figures 6 and 7) are favorable but do manifest some counter-intuitive elements. It is important to recall that the accuracy values at each propagation state are simply state comparisons between a reference orbit and the state estimate at those specific propagation times; they are not the result of a secular error growth modeling effort. To produce the latter, this comparison would need to be made at very frequent intervals (perhaps on the order of minutes) to produce the on-average increasing yet sinusoidal error growth curve and fit a function (a second-order polynomial is frequently used) to the data to produce an average error growth curve. For the purposes of the present study, in which the comparative behavior of the eGP to the regular SGP4 element sets is the item of interest, the more elaborate approach of secular error growth determination was not necessary; however, this approach produces the non-intuitive accuracy behavior caused by the "overlaid" periodics on top of the monotonic secular error growth. In the GEO accuracy plot, for example, the eGP 72-hour error appears much smaller than the 18-hour error; this is an artifact of the amplitude of the periodic terms at those particular points (peak at 18 hours, trough at 72 hours). In any

case, at all such points (peaks or troughs) the eGP element sets significantly outperform the regular SGP4 analogues.

- In all but the highest drag situations (and those with severe solar radiation pressure modeling issues, which were not called out separately), the "shelf life," or period of time during which an element set can be considered viable, is extended, often considerably, by the eGP paradigm. There is no set standard describing when an element set becomes too inaccurate to be useful, and clearly such a standard would need to vary by orbit regime anyway; but even if one did not wish an improvement in the accuracy of element sets, it is clear that the eGP approach will keep an element set within certain accuracy tolerances far longer than that for the current, observation-based approach. This improvement alone should be of great assistance of a number of space surveillance applications.

CONCLUSIONS

This analysis demonstrates that using the eGP method for catalogue maintenance provides greater element set accuracy for every orbit regime at propagation points up to fifteen days, and in many of these cases the improvement is substantial (factors of four to five improvement over the current SPADOC GP approach). Air Force Space Command Space Analysis Division (AFSPC/A9) has thus recommended that maintenance of most of the GP catalogue be migrated, in a measured way, to the eGP paradigm. Tuning of eGP fit and control parameters in order to optimize eGP performance is expected to be a continuous exercise for the near future; GP maintenance parameter settings have evolved over some forty years of use of that theory, so it is only expected that some extended period of time will be necessary to find and implement the appropriate eGP parameter settings for all satellites. But the accuracy improvements and lengthening of the "shelf life" of element sets, available to general users without having to change propagators or data transmission formats—thus at no cost to users—are significant even with the initial set of tuning parameters, allowing for an immediate recommendation of operational migration.

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