Improvements to the SGP4 propagator (SGP4-XP)

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ABSTRACT

To help improve the Deep Space sensor association process performance additional and improved perturbations modeling have been implemented in the Simplified General Perturbations 4 (SGP4) model. This new model is called SGP4-XP (eXtended Perturbations) and includes more precise modeling of effects of gravity from the moon and sun, more generalized approach for modeling of earth gravity resonance effects, addition of modeling solar radiation pressure effects to help address High Area to Mass Ratio (HAMR) satellites and a new branch of code for dealing with earth bound orbits that reach into cis-lunar altitudes. SGP4-XP also includes extended perturbations geared toward near earth satellite orbits including more complete gravity modeling and improved atmospheric modeling. Both SGP4 and SGP4-XP models will be operationally supported. The new SGP4-XP model has been developed with ease of transition in mind. This paper discusses the discovery of the limitations of the current SGP4 and resulting modeling enhancements, prediction improvements, compatibility issues and implementation considerations of SGP4-XP.

1. INTRODUCTION

In 2017 the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) System Program Office (SPO) commissioned a sensor observation association process performance improvement effort (objects are considered to be Deep Space satellites if their orbital periods are greater than 225 minutes). As part of this effort, it was discovered that the number of observations not meeting the desired correct satellite identity association, also referred to as UnCorrelated Target (UCT) rates, fluctuated by more than 10% depending on the day. Given the magnitude of this variation it could not be explained by old or missing element sets or poor sensor tracking data accuracy. Upon further investigation it was determined that the UCT rate varied (went up and down) systematically as a function of the day of the year. (See Fig. 1)

This same pattern occurred in phase with all three of the GEODSS sites and space based optical systems. Although not plotted here the same pattern also exists with Ground-Based Radar systems when tracking similar objects. This pattern repeated every 28 days suggesting perhaps something to do with the period of the moon. When the lunar phases of the moon are overlaid on the chart, a pattern emerges. UCT rates are much higher in the 1st and 3rd quarters and are lower in full and new moon phases.

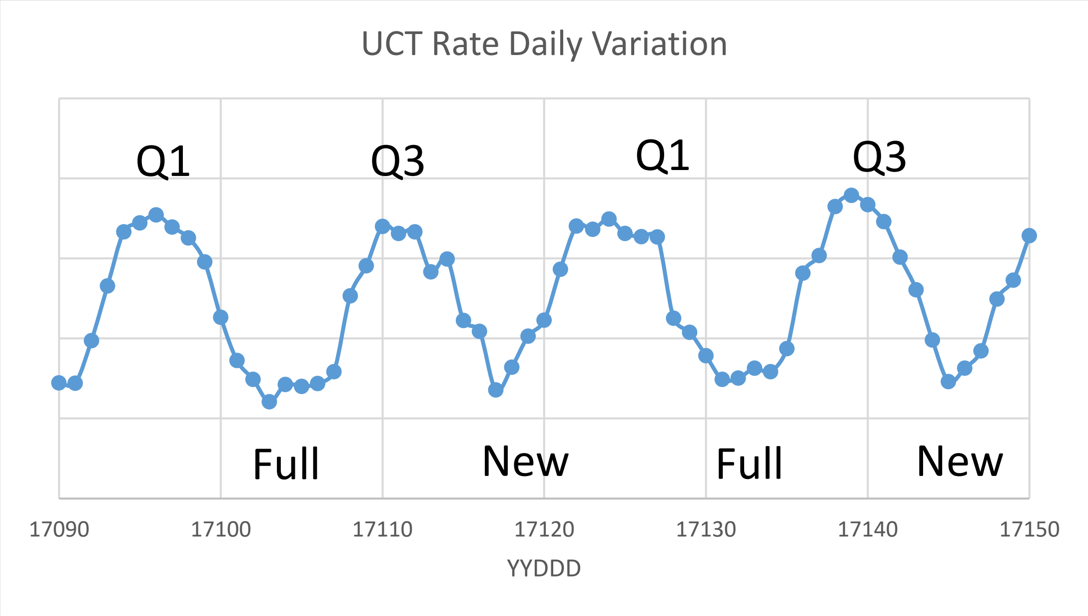


Fig. 1: Deep Space Optical Sensor (Ground and Space Based) UCT Rate vs. Day of the Year

Intrigued by this finding, additional analysis was conducted by the SPOC DCG-T/S9I analysis team. First the delta time residuals (delta time is the in-track component of the difference between the observed and predicted position of the satellite) were calculated utilizing a NASA derived TDRS reference orbit. The GEODSS sensor observations residuals were very small demonstrating that the GEODSS observation data is very accurate. (See Fig. 2)

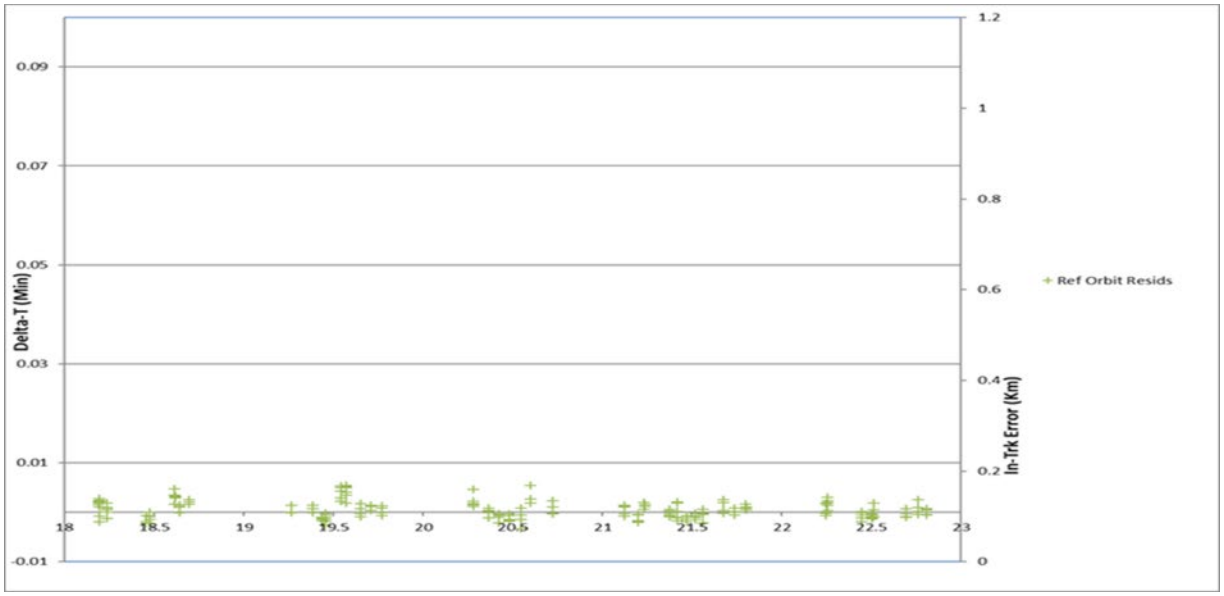


Fig. 2: GEODSS Sensor Data Delta-T Residuals Compared to TDRS Reference Orbit

The next step was to compare the same GEODSS observation data to the residuals calculated using the SGP4 Two-Line Element sets (TLE) the tracking site would have employed for its association calculation. Using the exact same observation data, the SGP4 TLE predicted position caused an order of magnitude higher delta time residual when compared to the reference orbit. (See Fig. 3)

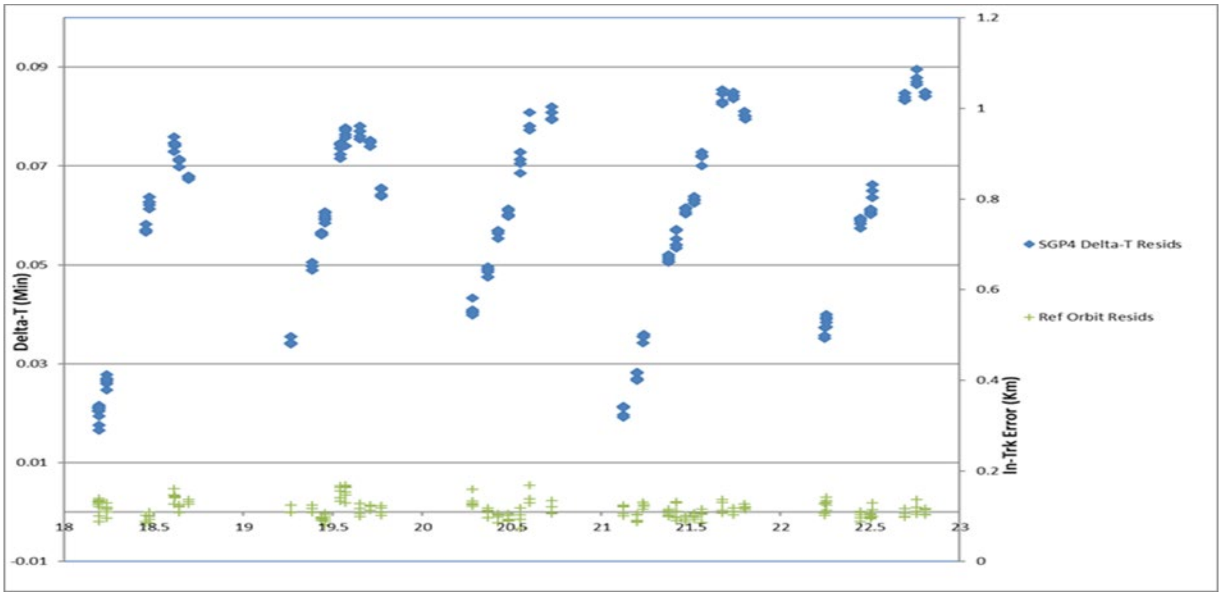


Fig. 3: GEODSS Sensor Data Delta-T Residuals Compared to an SGP4 TLE

Next the in-track error distance component of the SGP4 TLE was calculated when compared to the reference orbit. Using the alternate y-axis on the right in kilometers, the large delta time residuals are an artifact of the cyclical in-track differences caused by SGP4 propagation. (See Fig. 4) The results of these analysis efforts coupled with the fact that Deep Space optical sensor accuracies have improved by over an order of magnitude since SGP4 was fielded many years ago seem to indicate that the fidelity of the Deep Space perturbations, especially the lunar perturbations, in SGP4 needed to be improved.

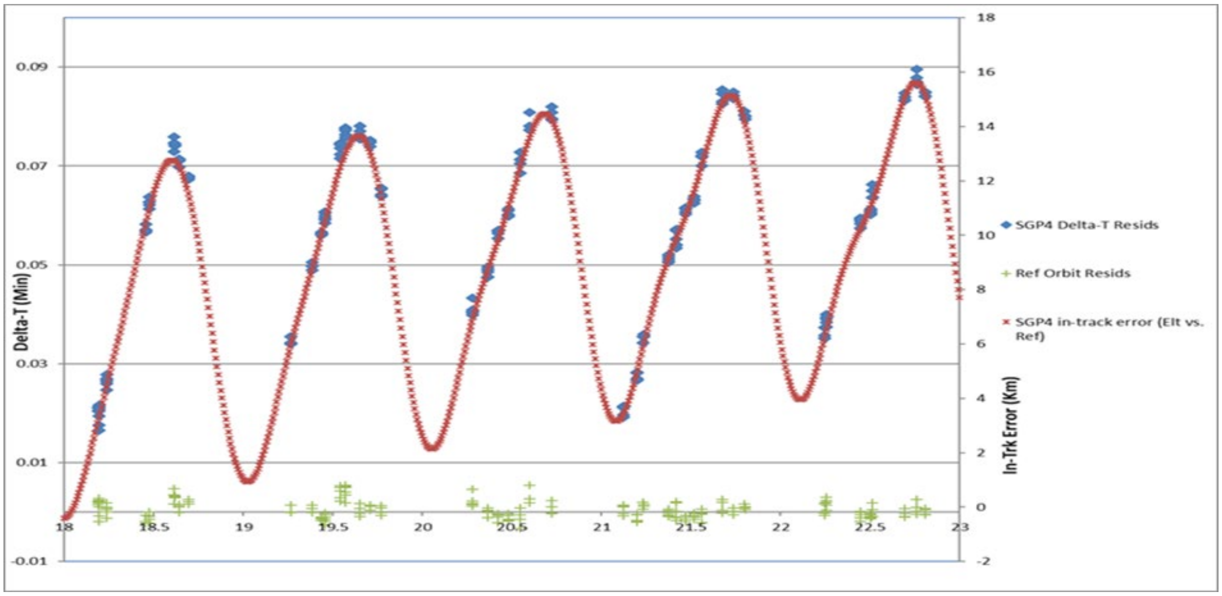


Fig. 4: SGP4 TLE in-track error vs. TDRS Reference Orbit

2. PERTURBATION FIDELITY IMPROVEMENTS IN SGP4

To help improve the Deep Space sensor association process performance additional and improved perturbations modeling have been implemented in the SGP4 model. This new model is called SGP4-XP (eXtended Perturbations) and includes:

- More precise modeling of effects of gravity from the moon and sun
- More precise modeling of earth gravity resonance effects with extension to other resonance classes
- Addition of modeling solar radiation pressure effects
- A separate branch in the code for dealing with earth bound orbits that reach into cis-lunar altitudes

Additionally, Near Earth perturbation improvements have also been added to the model. These include:

- A more complete modeling of primary earth gravity terms
- A complete rework of atmospheric drag modeling. (The model now accounts for solar activity effects and produces a true ballistic coefficient)

The following paragraphs highlight details of these improvements.

The original SGP4 development of lunar and solar gravity perturbations relied on a series expansion in powers of distance to the satellite divided by distance to the perturbing body. In this expansion, only the first order term was retained and did not address the periodics of the satellite motion within one revolution. These equations were replaced with an expansion to higher order that also includes the one revolution periodics.

The earth geopotential resonance affects were expanded. The original SGP4 development was very specially tailored for geosynchronous and Molniya orbits. Thus, they are not applicable for the wide variety of deep space orbits used today. For example, in the current SGP4, the resonance effects on GPS type orbits are ignored. Resonance perturbations now include a totally generalized approach valid for any eccentricity or inclination and is applicable to 24 hr, 16 hr, 12 hr, and 8 hr period orbits.

Since the development of SGP4, a whole new subcategory of satellites has been discovered that are significantly perturbed by solar radiation pressure. These are referred to as High Area to Mass Ratio (HAMR) satellites. The current SGP4 formulation lacks this important perturbative effect. The new SGP4-XP model now includes both the average solar radiation pressure effect as well as the periodics over one rev of the satellite.

To address new cis-lunar missions a closed form representation of third body perturbations is employed. This provides excellent modeling for all cis-lunar orbits present in the satellite catalog. Investigation is just beginning to evaluate the performance of SGP4-XP in extreme regions near halo orbits.

Having the most effect on Near Earth satellites, the earth gravity portion of the original SGP4 model was truncated by dropping all terms of any order in eccentricity and did not include J5 term. In other words, the gravity periodics assumed circular orbits. This has been replaced by the complete set of equations developed by Brouwer to include J5.

Another primarily Near Earth satellite improvement is the changes to atmospheric drag modeling. The power law static atmospheric density model of SGP4 has been replaced with the Jacchia 70 atmospheric density model. This is the same model that forms the basis for the Special Perturbations density modeling. To avoid the requirement for a TLE recipient to obtain solar flux values, a generic solar flux model [1] has been implemented. The generic model is based on the behavior of solar flux averaged over multiple solar cycles. The model simply uses the epoch of the TLE to determine where the elset falls in the generic cycle. It then uses that average value of solar flux as input to the Jacchia model. Usage of this model allows production of a meaningful ballistic coefficient rather than the B* drag term used in SGP4.

Table 1 summarizes the improvements in SGP4-XP perturbation modeling compared to the existing SGP4 perturbation modeling. The + indicates addition in SGP4-XP of a perturbation model that was not included in SGP4. The comment "*improved*" denotes corrections or additions to the SGP4 modeling.

Table 1: Summary of Perturbation Improvements in SGP4-XP

Subgroup	**Resonance**	**Full Brouwer gravity**	**2^{nd} order L/S + periodics**	**Dynamic atmosphere model**	**Solar pressure + periodics**	**Extended deep space modeling**
8hr Resonance	✚		✚			
16hr Resonance	✚		✚			
600km Perigee ht.		✚	✚	✚		
718 min circular	✚		✚			
GEO Operational	***Improved***		✚			
HEO ecc > 0.75	***Improved***	✚	✚	✚		
HAMR > 0.1 m2/kg					✚	
Very Deep Space (cislunar)						✚

3. SGP4-XP TESTING RESULTS

Fig. 5. shows the previous TDRS 11 SGP4 time residuals along with the improved SGP4-XP time residuals.

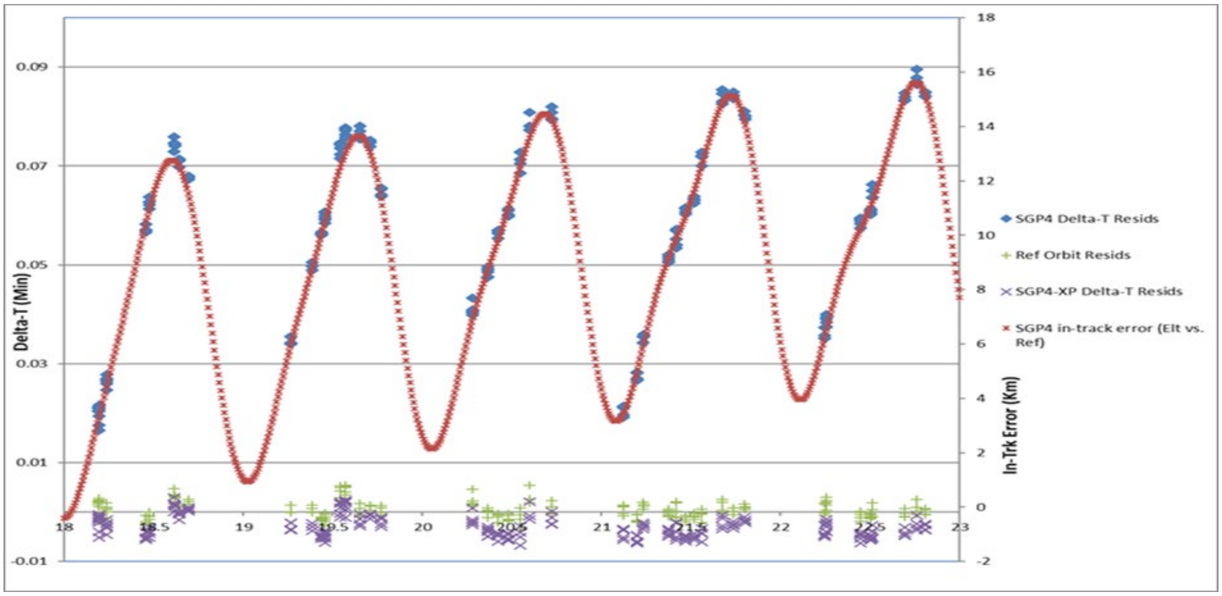


Fig. 5: GEODSS Sensor Data Delta-T Residuals Compared to a SGP4-XP TLE

Fig. 6. includes the SGP4-XP element set in-track error compared to the reference orbit (right hand y-axis). From these two plots you can see that the SGP4-XP has improved these residuals by an order of magnitude over the SGP4 TLE.

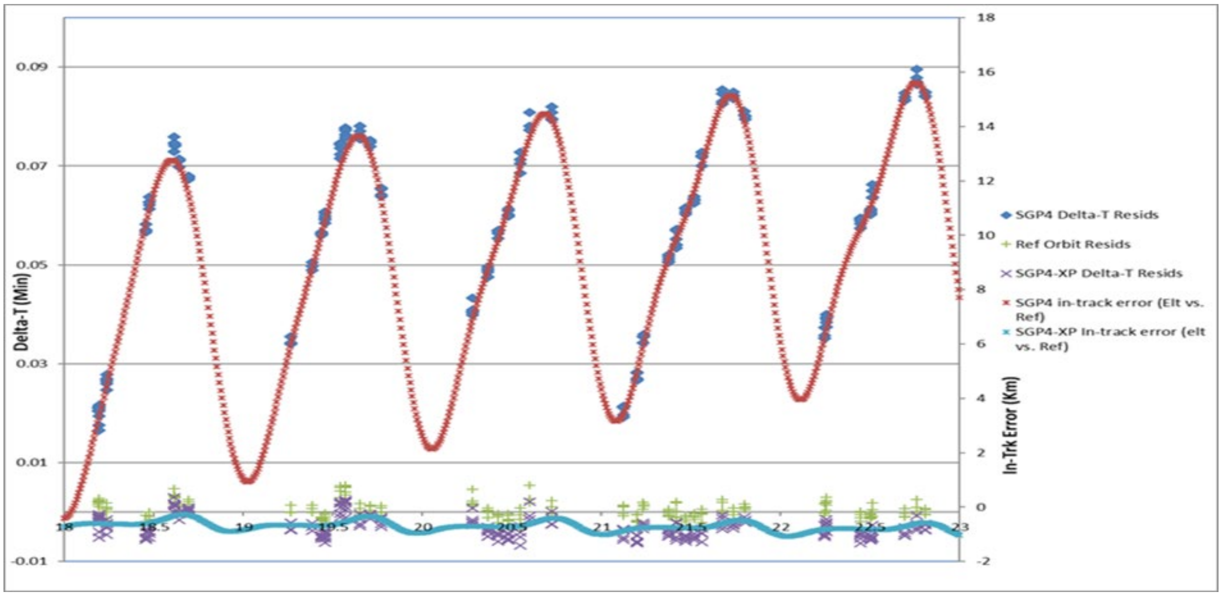


Fig. 6: SGP4-XP TLE in-track error vs. TDRS Reference Orbit

The results so far have only demonstrated the SGP4-XP improvements on one satellite. Next, SGP4 is compared to SGP4-XP for a subset of the geosynchronous satellite catalog (> 5º Inc.). In Fig. 7, we use 40 days of Space Surveillance Network (SSN) optical satellite observations as our truth source of the satellite position. The observations are then compared to predictions generated by both an SGP4 TLE and a SGP4-XP TLE. The epoch of each TLE is less than or equal to 1 day prior to the time of the observation. The zero-center line is where the satellite is located, the red dots are the SGP4 predicted satellite positions and the blue dots are the SGP4-XP predicted satellite positions. The red SGP4 sinusoidal shape is caused by the lower fidelity lunar perturbation modeling, the daily width of the red sinusoidal shape is caused by its lower fidelity solar perturbation modeling.

Focusing in on the right ascension residual you can see the overall improvement that the extended perturbations in SGP4-XP provide over SGP4. The mean after a 100 arc second outlier rejection for this data sample for SGP4-XP is -1.111 arc seconds compare to -13.629 arc seconds for SGP4. Likewise, the standard deviation for SGP4-XP is 5.120 arc seconds compared to 34.757 arc seconds for SGP4. Also, from the graph it is apparent that the lunar phase dependency on prediction quality of SGP4 has been eliminated in SGP4-XP.

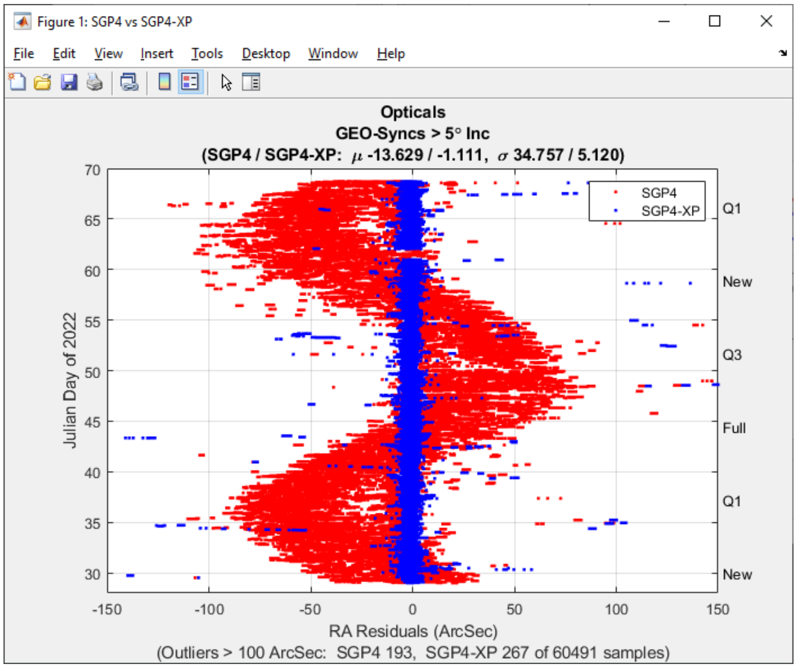


Fig. 7: Optical sensor right ascension residuals

SGP4 is then compared to SGP4-XP prediction results of other subsets of the satellite catalog. Looking at the Multi-Day orbits (defined as having a period of 2 days or greater) subset, it is observed that the new branch of code for dealing with earth bound orbits that reach into cis-lunar altitudes greatly improves the prediction quality over SGP4 (See Fig. 8). Likewise, the addition of solar radiation pressure modeling to SGP4-XP help address High Area to Mass Ratio (HAMR) satellites and greatly improves the prediction quality over SGP4 (See Fig. 9)

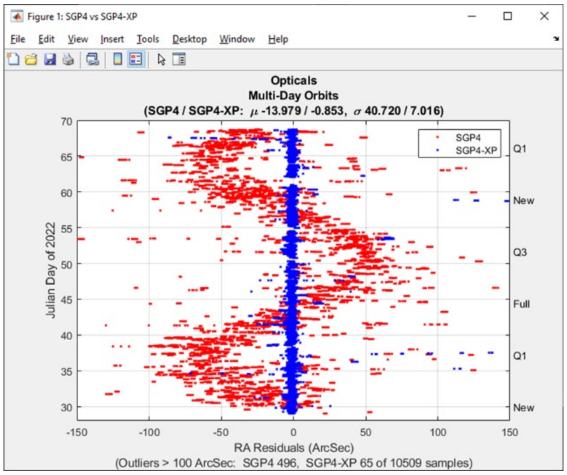


Fig. 8: Multi-day orbit optical sensor right ascension residuals

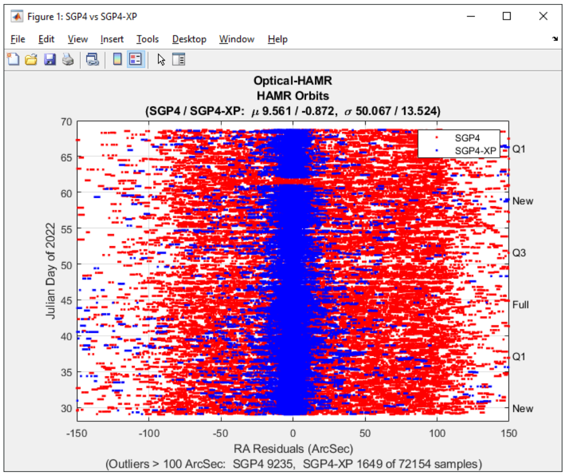


Fig. 9: HAMR optical sensor right ascension residuals

Another SGP4-XP perturbation enhancement is improved atmospheric modeling. With the inclusion of the Jacchia 70 dynamic atmosphere model and the implementation of a generic solar flux model, SGP4-XP users now have a true ballistic coefficient drag term. This results in improved high drag regime predictions, especially reentry predictions. Fig. 10 shows a comparison of reentry predictions. The dotted line boundaries in the graphs are the +/- 20% historical rule of thumb for decay prediction accuracy. Weekly decay predictions for 60 days in the future have been operationally accomplished using an analytic technique based on SGP4 TLEs. SGP4-XP generates decay predictions which are much improved over SGP4.

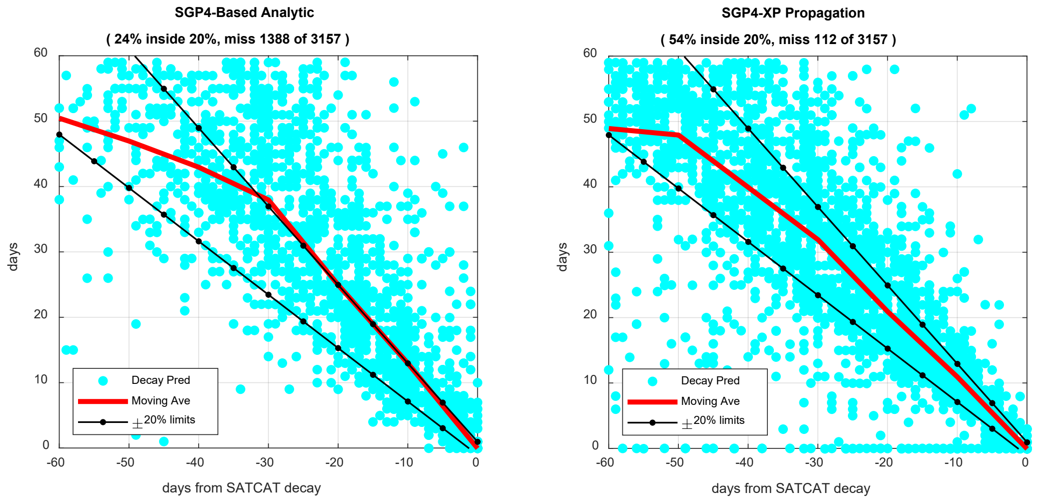


Fig. 10: Reentry Predictions

Table 2 summarizes the prediction accuracy improvement of various satellite catalog subsets highlighting the SGP4-XP performance improvements over SGP4. In addition, SGP4-XP reduced the number or outliers that did not meet the desired accuracy for successful correlation by on average a factor of 5. This reduction was most prominent in the Very Deep Space subset where it reduced outliers by nearly a factor of 150.

Table 2: Summary of SGP4-XP performance improvements over SGP4 compared to SSN observations.

Subgroup	HAMR	Very Deep Space	Eccentric Deep Space	GEO < 5º Inclination	GEO ≥ 5º Inclination	Circular ~ 718m periods	Near Earth
Prediction Improvement	2.7x	3.4x	3.6x	1.9x	6.9x	2.4x	1.2x

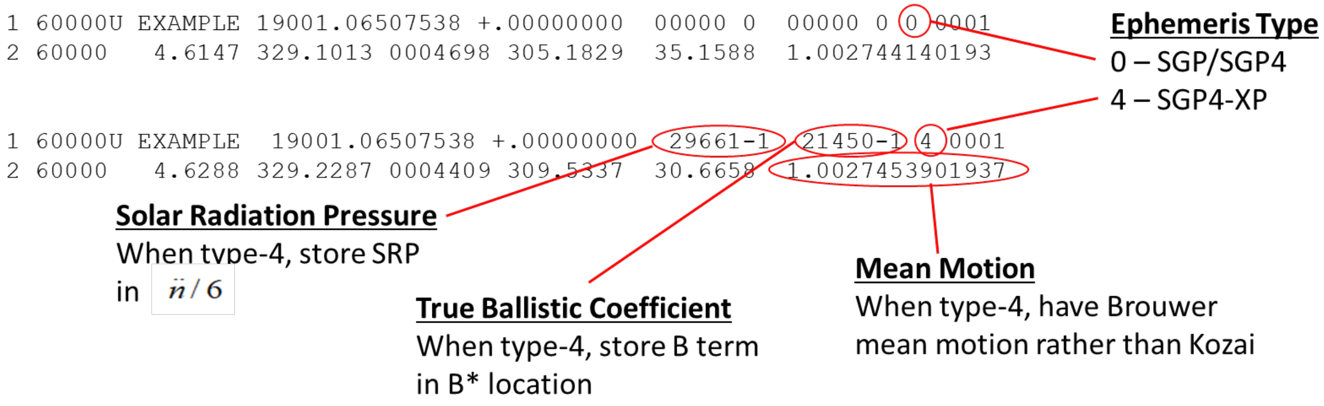
4. IMPLEMENTATION CONSIDERATIONS

Because of the extensive perturbation fidelity improvements to SGP4-XP it is NOT BACKWARD COMPATIBLE with existing SGP4 element sets. In fact, if you use a new SGP4-XP derived element set with an existing SGP4 propagator you will experience extremely poor propagation results. Likewise, if use an existing SGP4 element set with the SGP4-XP propagator you again will experience extremely poor propagation results. Table 3 highlights the proper propagator/element set use.

Table 3: Propagator Compatibility

	Existing SGP4 Propagator	NEW SGP4-XP Propagator
Existing SGP4 TLEs Input	Continue current baseline propagation performance	Significantly reduced propagation performance over baseline
NEW SGP4-XP TLEs Input	Significantly reduced propagation performance over baseline	Significantly improved propagation performance over baseline

To differentiate element sets that have been derived for the legacy SGP4 and the new SGP4-XP propagation theory the TLEs format has been modified. None of the existing fields or formats have changed - just the interpretation of some of the fields. The most important is column 63 of the first line. An existing legacy SGP4 element set is designated by a 0 (zero) in this field, while an SGP4-XP element set is designated by a 4 in this field. With an existing SGP4 TLE all of the field interpretations remain the same. With an SGP4-XP element set, the N double dot over six field is now the Solar Radiation Pressure coefficient (SRP) (Cr*M2/Kg) and the B* drag term field is now a true Ballistic coefficient (B-term) (Cd*M2/Kg). All of the remaining field interpretations remain the same except the mean motion which is now a Brouwer mean motion as opposed to the legacy SGP/SGP4 Kozai mean motion. Fig. 11 below provides examples of both an SGP4 element set and an SGP4-XP element set.



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1 60000U EXAMPLE 19001.06507538 +.00000000  00000 0  00000 0 0 0001
2 60000   4.6147 329.1013 0004698 305.1829  35.1588  1.002744140193

1 60000U EXAMPLE  19001.06507538 +.00000000  29661-1  21450-1 4 0001
2 60000   4.6288 329.2287 0004409 309.5337  30.6658  1.0027453901937
```

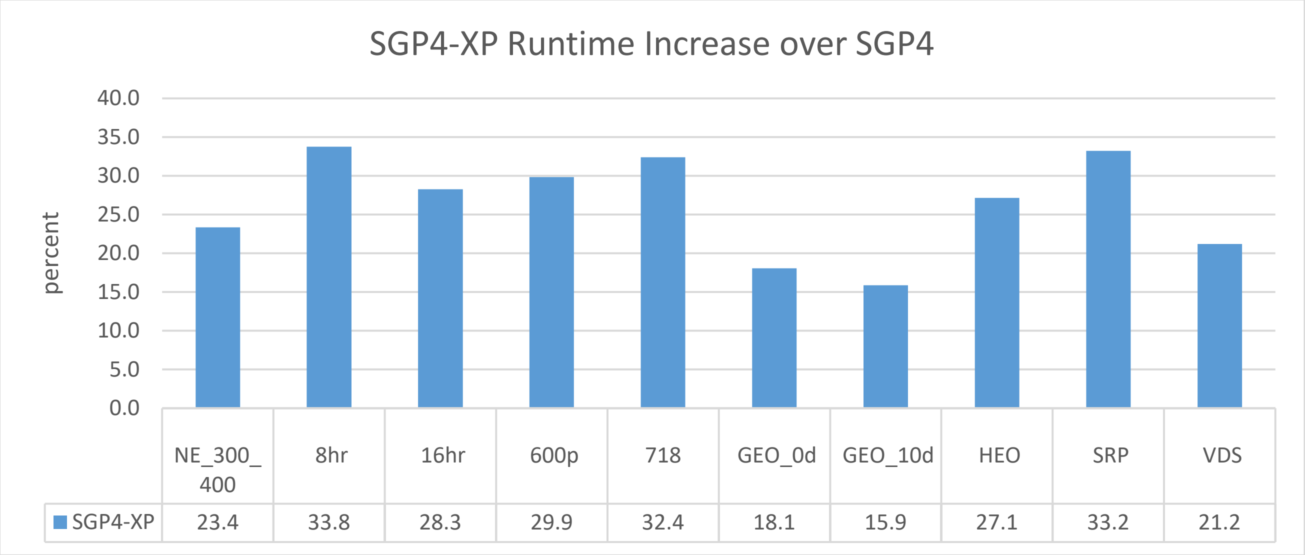
Fig. 11: Two-Line Element sets (TLE) field interpretation

The Space Operations Command (SPOC) Astrodynamic Standard SGP4 v8.0 or later contains both the SGP4 and SGP4-XP propagators. To help ensure that the SGP4 propagator is only used with an SGP4 TLE and that SGP4-XP propagator is only used with SGP4-XP TLE, SGP4 v8.0 or later reads column 63 of the first line of the TLE. It then seamlessly auto configures to automatically use the compatible propagator with the input TLE.

The current implementation strategy is for both SGP4 and SGP4-XP TLEs to be operationally available to all users. This will allow users to implement SGP4-XP on their own schedule. Depending on the users' needs and implementation difficulties some may decide to delay or to not implement SGP4-XP and can continue to use SGP4.

With the improved perturbations modeling that has been implemented in the SGP4-XP the runtime performance is only slightly slower. Figure 12 depicts the percent increase SGP4-XP has over SGP4 for 10-subgroups. SGP4-XP is only 15-35% slower than SGP4 depending on orbit type of satellite.

The SGP4/SGP4-XP code exist in a binary shared object/dynamic link library (so/dll) format on space-track.org. This format will allow users to easily drop in the latest version whenever there is an update. These libraries have the added benefit of being callable from almost any language.



	NE_300_400	8hr	16hr	600p	718	GEO_0d	GEO_10d	HEO	SRP	VDS
■ SGP4-XP	23.4	33.8	28.3	29.9	32.4	18.1	15.9	27.1	33.2	21.2

Fig. 12: SGP4-XP Runtime Performance

5. SUMMARY

Significant additional and improved perturbations modeling has been implemented in the SGP4 orbit propagation model. The new model is called SGP4-XP (eXtended Perturbations). It offers significant performance improvements over SGP4 for all orbit types. Usage of SGP4-XP is expected to reduce sensor mistags and Uncorelated tracks. This in turn will improve catalog completeness and integrity. Public users of TLEs will enjoy greatly improved prediction accuracy. The current implementation strategy is for both SGP4 and SGP4-XP TLEs to be operationally available to all users. The new SGP4-XP model has been developed with ease of transition in mind. It uses the same TLE format as SGP4 and is only marginally slower than SGP4. Current estimates are that SGP4-XP TLEs will be available Spring of 2023 for distribution to users.

6. REFERENCES

[1] Potter, Robert T., “A Generic Solar Flux and Geomagnetic Activity Model Development and Evaluation,” The Aerospace Corporation, Aug. 17, 2020. TOR-2020-01981