Accuracy Assessment of SGP4 Orbit Information Conversion into Osculating Elements

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ABSTRACT

The SGP4 model is one of the analytical orbit models applied for the orbit prediction using TLE orbit information. For the orbit accuracy improvement, a model conversion was performed to apply a more precise model. Assuming that a TLE data set is the best possible fit to the observation data, the orbital arc in a specified time span was reconstructed from several TLE sets. Using osculating elements of the SGP4 output as measurements data, the orbit determination as well as the orbit propagation were performed with the numerical orbit model. The performance of this process was assessed by a comparison with precise orbit information. After the inherent model accuracy analysis using the best-fitted TLE based on GPS data, the process was applied to the publically available TLE, where an accuracy improvement was achieved for some objects. The same process was also successfully applied to re-entry prediction calculations. The more advanced process needs to be studied for a general application.

1 INTRODUCTION

The catalogue of Twoline-Elements (TLEs) maintained by the US Strategic Command (USSTRATCOM) is currently the publicly available and reasonably comprehensive source of orbit information for known space objects in Earth orbits. However, TLEs are not suitable for a precise orbit estimation due to the inaccuracy of the modeling, timeliness and inconsistency of the available orbital information, and other error sources. Additionally, the orbit accuracy is not available.

The assessment of the TLE orbit accuracy has been performed in several methods. In [1], initial covariance information was estimated from orbit determination results using pseudo-observations, which were derived from TLE data. In [3], the TLE accuracy was analyzed by a comparison with the precise orbits of operational satellites. For the accuracy improvement, the method of using multiple TLEs to create pseudo-observations in order to perform an orbit determination and prediction was introduced and applied to several satellites [2], which is similar to the process used in [1].

In this paper, the orbit conversion process was first applied to the best-fitted TLE based on GPS data, to analyze the inherent model accuracy. The process was then applied to the public TLE provided by USSTRACOM for operational satellites and also for other space objects. Furthermore, a re-entry prediction of the PHOBOS-GRUNT mission was performed using the same process together with the long-term orbit propagator.

2 TLE ORBIT CONVERSION FROM SGP4 MODEL TO NUMERICAL MODEL

2.1 SGP4 Model Precision Analysis

The TLE sets contain mean orbital elements obtained by removing periodic variations in a particular way. In order to obtain good predictions, these periodic variations must be reconstructed by the prediction model in exactly the same way as they were removed. The SGP4 model is one of such orbit models used for orbit prediction of satellites in the near-Earth space (period < 225 minutes).

The inherent modeling accuracy of the SGP4 analytical orbit model was first analyzed using 'ideal' TLE data sets, which were generated based on precise orbit data available for the operational satellites. In this process, a TLE set was generated by using GPS receiver navigation solutions as measurements data. The step size between two used measurements was set to one minute. An orbit determination was then performed by a least squares fit, and the SGP4 mean elements as well as the ballistic coefficient were estimated. Several lengths of the fitting arc from one to five days backwards from the same reference epoch were applied for comparison, which therefore result in the same TLE epoch.

This analysis was performed based on the precise orbits of the locally operated satellite GRACE-1 (at an altitude of 450 km) during the period in December 2011. The 'real orbit' as reference was generated by the software modules POSFIT or RDOD, which are part of the GHOST (GPS High Precision Orbit Determination Software Tool) package developed by GSOC/DLR. POSFIT performs a reduced dynamic orbit determination from a given a priori orbit. It estimates

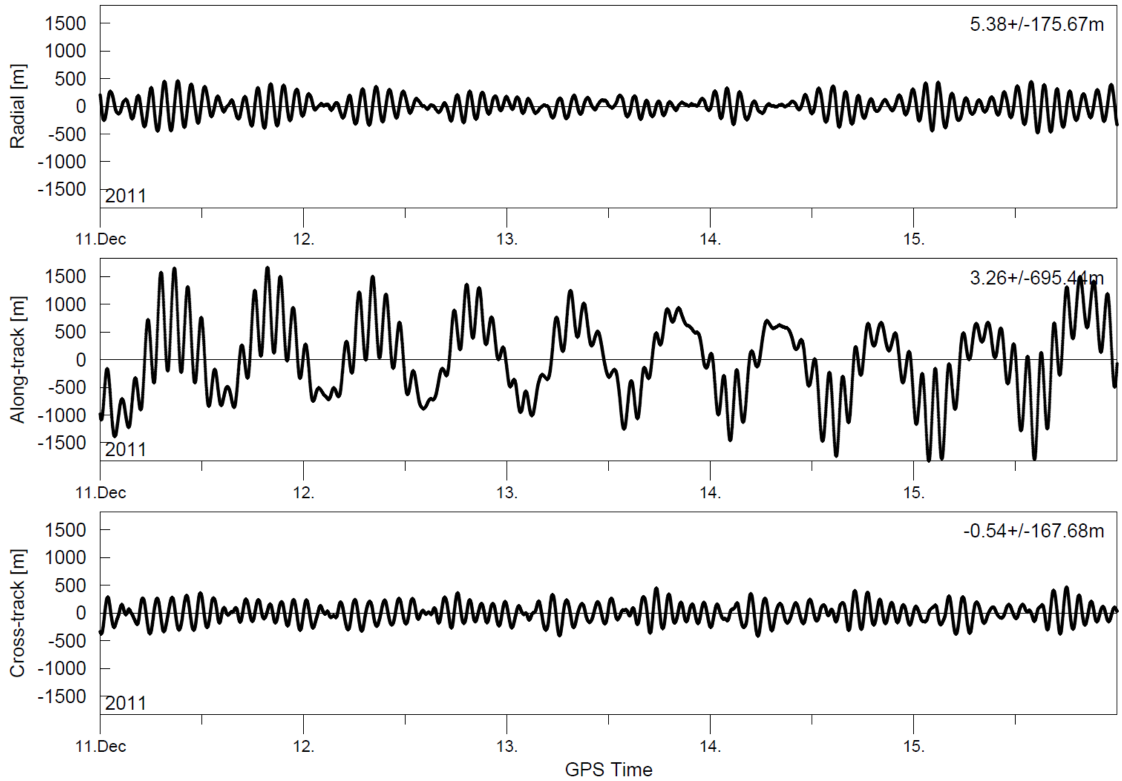

Figure 1 Orbit Error of the Fitted TLE during OD Period (5d Fit)

initial conditions, dynamical model parameters and empirical accelerations in a least squares fit. In addition, RDOD uses raw GPS measurements as observations for a precise orbit determination (POD). The position accuracy of the orbits based on POSFIT and POD is better than 2 m and 10 cm, respectively.

The resulting TLE sets were propagated forward and backward from the TLE epoch, and compared with the precise orbit data during the corresponding orbit determination (OD) period (backward) and also the orbit propagation (OP) period (forward). The comparison was performed with a step size of 30 seconds.

Table 1 shows mean and standard deviation of the orbit error in the R (radial) / T (along-track) / N (normal or out-of-plane) components, regarding three sets of TLE with the different fit length. In the radial component, the mean error during the propagation period remains smaller compared to the sigma value, whereas the mean error becomes dominant after the longer propagation in case of the along-track direction. For the out-of-plane direction, the fluctuating error with the same size of sigma remains even after the propagation. During the OD period, all RTN error components show a continuous increase with the fit length. However, the OP period of the one day fit show larger errors in the tangential direction. It can be explained by a bad estimation of the ballistic coefficient and semi-major axis.

The error pattern during the OD period looks very similar for each fit length, where a 'long-term-periodic' variation (twice a day) is superimposed by a 'short-term-periodic' (each orbit) one. As an example, the RTN errors for a five day fit are plotted in Figure 1, which show the differences between the SGP4 model and the real orbit.

Table 1 Orbit Error of the Fitted TLE

Orbit Determination Period						
Fit days	R [m]		T [m]		N [m]	
	mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	14	95	1	547	4	153
3d	7	124	3	641	-1	164
5d	5	176	3	695	-1	168
Orbit Propagation Period (2-3 days)						
Fit days	R [m]		T [m]		N [m]	
	mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	-32	338	4984	1701	3	152
3d	-29	425	5231	1567	3	155
5d	-44	534	7849	1979	2	164
Orbit Propagation Period (6-7 days)						
Fit days	R [m]		T [m]		N [m]	
	mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	-122	805	33127	3283	-5	176
3d	-59	873	24464	2542	-4	169
5d	-119	991	34871	3245	-4	165

2.2 Numerical Model Precision Analysis

Using the TLE generation process in 2.1 in reverse direction, the osculating orbital arc can be obtained from a set of TLE by adding the periodic variations with the SGP4 model. Using the obtained osculating orbital ephemeris as measurements data, the OD as well as the OP can be performed with the numerical orbit model. The orbit accuracy after this orbital model conversion was analyzed by comparing the results with the precise orbit data.

The analysis was performed using the well-established OD and OP software ODEM (Orbit Determination for Extended Maneuvers). The OD inside ODEM is formulated as a sequential non-linear least-squares problem based on Givens rotations and the OP is based on a standard numerical integration method for initial value problems. In particular an Adams-Bashforth-Moulton method for numerical integration of ordinary differential equations is adopted. This method employs variable order and step-size and is particularly suited for tasks like the prediction of satellite orbits. The numerical orbit propagator is using a comprehensive model for the acceleration of an Earth orbiting spacecraft under the influence of gravitational and non-gravitational forces, which comprises

- the aspherical gravitational field of the Earth, the Luni-Solar third body gravitational perturbations, the Solid Earth tides among the mass forces,
- atmospheric drag and solar radiation pressure (SRP) among the surface forces
- and thrust forces.

The pseudo-measurements data were prepared with a step size of 10 minutes, using the TLE sets with a different fit length generated in 2.1. After the ODEM process, the orbit was compared with the precise data with a step size of 30 seconds. Table 2 shows the resulting errors for each fit length. By propagating the orbits using the well-modeled propagator, errors are small especially for the radial and out-of-plane components and also for the along-track component during the short-term propagation. However, the longer propagation results in a bad orbit prediction especially in along-track. Additionally, the one day fit results show larger errors in the along-track direction during the OP period, as seen also in Table 1.

The results are comparable to the statistical analysis of the numerical orbit propagation accuracy [4], despite of the distinct model error of the measurements data generated from TLE, which is already shown in Figure 1. The analysis in [4] also shows that a longer propagation leads to a larger error in the along-track direction due to the prediction error of the solar flux, which becomes larger at higher solar flux periods. To verify this effect, the same process was repeated for a lower solar flux period (June 2009, $F_{10.7} = 70$) as comparison with the Table 2 for December 2011 ($F_{10.7} = 150$). Table 3 shows the results for the five day fit length. It clearly shows a better orbit prediction especially in the along-track direction even after a longer propagation period.

Table 2 Orbit Error after ODEM Process

Orbit Determination Period						
Fit days	R [m]		T [m]		N [m]	
	Mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	-0.2	3	2	11	-0.0	5
3d	0.1	2	4	11	0.0	4
5d	-0.2	3	-1	38	-0.0	7
Orbit Propagation Period (2-3 days)						
Fit days	R [m]		T [m]		N [m]	
	mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	-14	5	2369	564	-0.2	11
3d	-9	4	1277	367	-0.2	11
5d	-9	5	1337	374	-0.1	7
Orbit Propagation Period (6-7 days)						
Fit days	R [m]		T [m]		N [m]	
	mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
1d	-63	41	17982	1628	0.3	21
3d	-38	31	12200	1141	0.3	20
5d	-39	32	12367	1150	0.2	16

Table 3 Orbit Error after ODEM Process (Low Solar Flux)

Period	*Fit days*	R [m]		T [m]		N [m]	
		mean	*1σ*	*mean*	*1σ*	*mean*	*1σ*
OD	*5d*	-0.0	4	7	19	0.0	4
OP 2-3d	*5d*	-1	5	249	33	0.3	11
OP 6-7d	*5d*	-3	10	1382	129	-0.3	16

3 ORBITAL MODEL CONVERSION USING SUCCESSIVE TLES

The results in the previous section show the inherent model error of SGP4 propagator and the orbit accuracy improvement by reconstructing the osculating orbit from TLE based on an OD with the numerical model. For a general use of the orbital model conversion process, a software tool was developed which generates an osculating elements ephemeris from several sets of TLE.

3.1 Orbital Model Conversion Tool

In the application to the public TLE, the osculating orbital arc can be obtained from a single TLE set except any errors caused in the TLE generation process, when an appropriate arc period is applied. In [3], the length of the orbital arc for the generation of TLE provided by USSTRATCOM was estimated as approximately five days for the operational satellites TerraSAR-X and GRACE-1. However, when this does not apply for other objects, the process of the orbit reconstruction could introduce other errors. If e.g. the OD period for a TLE is only 3 days and we use a 5 day span for the orbit reconstruction, a TLE propagation of 2 days with larger errors compared to the OD span is used. Or if a shorter part of the TLE OD span is used measured from the epoch of the TLE, the part with the larger radial errors is used. In both cases the resulting orbit will show larger errors compared to the optimum one (please refer to Figure 1). Furthermore, the inconsistency of each TLE is not negligible. For these reasons, a software tool TLEOD (TLE-based Orbit Determination with numerical model) was developed and tested which generates pseudo-measurements data from several sets of TLE by a backward propagation, and performs an OD using the ODEM software.

3.2 TLEOD Test Using Fitted TLE

The TLEOD tool was first tested using the 'ideal' TLE as in 2.1, which was generated using GPS receiver navigation solutions as a measurements data. For the TLE generation, the step size between two used measurements was again set to one minute, and the fitting arc of five days was applied. The TLE sets were generated with the different interval of 0.5-2 days, in every case backwards from the same reference epoch as used in 2.1. In the TLEOD process, the pseudo-measurements data were generated by propagating each element set backwards to the next TLE epoch with a step size of 10 minutes. After the OD process, the quality of the resulting osculating orbit was evaluated by a comparison with precise orbit data .

The upper part in Table 4 shows the RMS error for each component, depending on how many TLE sets are available per day. The results are apparently contradictory in some aspects. First, the precision is much worse than the results in Table 2. For the radial component, the results are not better compared to the errors in Table 1 even after the orbital model conversion to the numerical model. Secondly, the use of more TLE sets leads to a worse orbit quality. These contradictions can be explained from the error pattern as shown in Figure 1. The fluctuation of the error in the radial direction is not constant during the whole OD period, it is smaller in the middle of the arc and larger at the edges. In the TLEOD process, only the part with the latest error of the orbital arc from each TLE was collected for the measurements data, which could lead to the bad quality of the determined orbit. To verify this assumption, another analysis was performed, which is described in the next section.

Figure 2 shows the error pattern during the OD period after the orbital model conversion . The variation in the along-track direction is of double size compared to the radial one, which can be explained by an error in the determination of the eccentricity. The overlaid variation in along-track direction can be explained by uncertainties in the knowledge of the atmosphere.

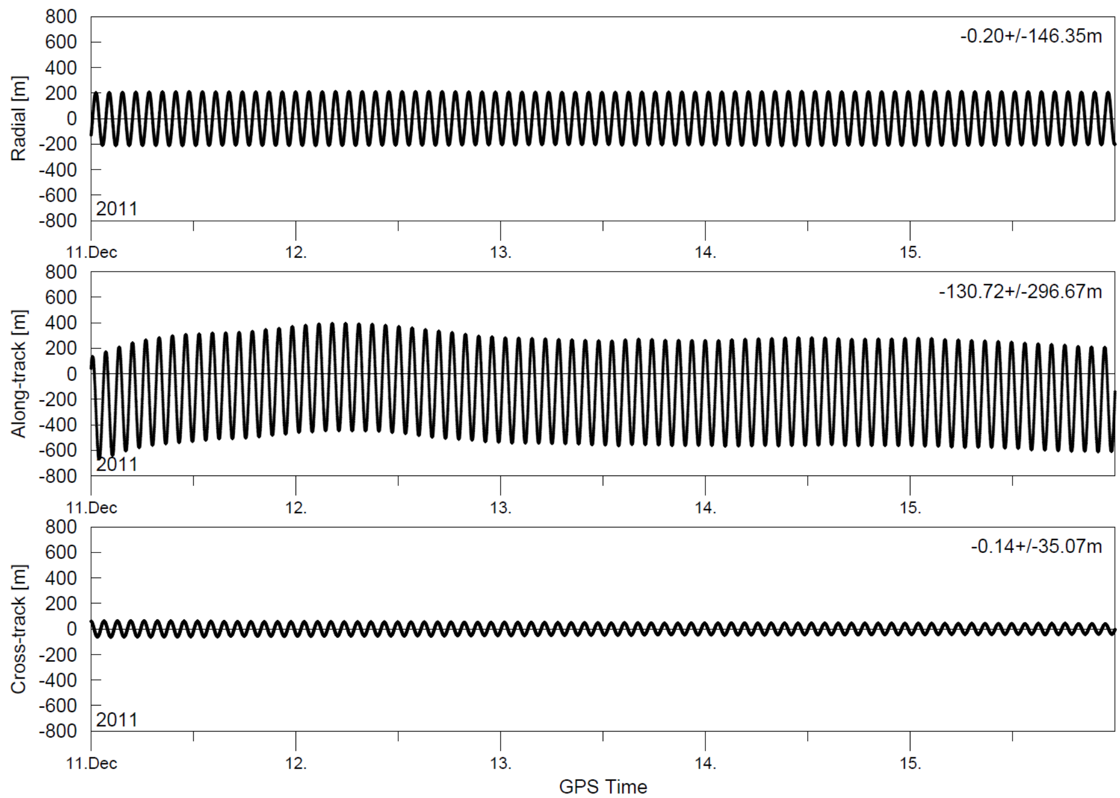

Figure 2 Orbit Error of the Fitted TLE Sets after TLEOD Process (5d Fit, OD Period)

3.3 TLEOD Test with Epoch Offset

In this analysis, the same process as in 3.2 was performed, but the middle part of the orbital arc was selected by introducing the epoch offset parameter, where the start of the backwards propagation was shifted a few days backwards from the corresponding TLE epoch. The offset parameter was adjusted so that the exactly middle part of the orbital arc is used for each TLE set.

The resulting RMS error is shown in the lower part in Table 4. Compared to the results without offset, the accuracy was much improved using the same TLE sets only by shifting the part of the orbital arc. The results are also comparable to Table 2, where the whole measurements data were generated from a single TLE set.

Table 4 RMS Error of TLE Sets after TLEOD Process (5d Fit, OD Period)

Without Offset				
N.TLE/d	Offset [d]	R [m]	T [m]	N [m]
0.5	0	146	324	35
1	0	209	434	49
2	0	236	518	51
With Offset				
N.TLE/d	Offset	R [m]	T [m]	N [m]
0.5	1.5	15	52	3
1	2	12	51	4
2	2.25	12	50	5

4 APPLICATION TO PUBLIC TLE

For the general application, the publicly available TLE provided by USSTRATCOM needs to be used as the TLEOD input. The orbit accuracy after the orbital model conversion was analyzed using the public TLE sets for operational satellites and some selected objects.

4.1 Test with GRACE-1 Orbit

The TLEOD tool was first tested using only a single TLE set with the epoch of 16 December 2011. Therefore, the results are comparable to the previous analysis using the 'ideal' TLE data under the same solar flux condition. Several fit lengths were applied for the pseudo-measurements data generation, and the OD results were compared with the precise orbit of GRACE-1.

The RMS error for each fit length in Table 5 shows that the osculating orbit was better reconstructed in case of the five day fit. It agrees with the estimated orbital arc length for the generation of TLE provided by USSTRATCOM, which is described in [3]. Compared with Table 2 which is based on an 'ideal' TLE (based on GPS data), it is assumed that the remaining errors were produced mostly due to the different process of TLE generation (based on radar tracking data).

Table 5 RMS Error of Single TLE after TLEOD Process

Fit days	R [m]	T [m]	N [m]
1d	251	841	41
3d	164	533	50
5d	74	348	85
7d	94	1475	119

The TLEOD process was further applied to the available sets of TLE. The reference epoch was again set to 16 December 2011, and the pseudo-measurements data up to seven days were generated backwards from the reference epoch. In this analysis period, the TLE for GRACE-1 was updated 1-2 times per day, e.g. 11 sets in seven days. Each element set was propagated backwards to the next TLE epoch with a step size of 10 minutes, and this process was repeated until the corresponding data arc is covered. Likewise in 3.3, several cases of the epoch offset from zero to two days and additionally a variable offset were examined. The variable offset case was considered, since the interval of the TLE update is not constant. Assuming that the length of the orbital arc for the TLE generation is five days, the measurements data at each epoch was generated using a set of TLE, which generates a smaller fluctuating error, i.e. near the middle of the orbital arc.

Table 6 shows the RMS error for each component. The results are comparable to Table 4 which is based on the 'ideal' TLE sets. However additional errors can be observed, which indicates errors introduced by the TLE generation process performed by USSTRATCOM. After applying the epoch offset, a final orbit accuracy of ~40 m in radial, ~150 m in along-track, and ~70 m in out-of-plane direction was achieved for GRACE-1. Compared with the results using a single TLE set as shown in Table 5, a better orbit accuracy can be obtained by selecting the specific part of the measurements data from several sets of TLE.

Table 6 RMS Error of TLE Sets after TLEOD Process

GRACE-1 (~1.5 TLEs per day)				
Fit days	Offset [d]	R [m]	T [m]	N [m]
5d	0	923	715	59
5d	2	50	116	69
5d	variable	43	162	77
7d	0	235	692	70
7d	2	42	193	71
7d	variable	36	159	75
TerraSAR-X (~3.5 TLEs per day)				
Fit days	Offset [d]	R [m]	T [m]	N [m]
5d	0	64	514	136
5d	2	55	293	109
5d	variable	60	305	106
TET (~1 TLE per day)				
Fit days	Offset [d]	R [m]	T [m]	N [m]
5d	0	96	236	173
5d	1	124	303	159
5d	2	161	427	145

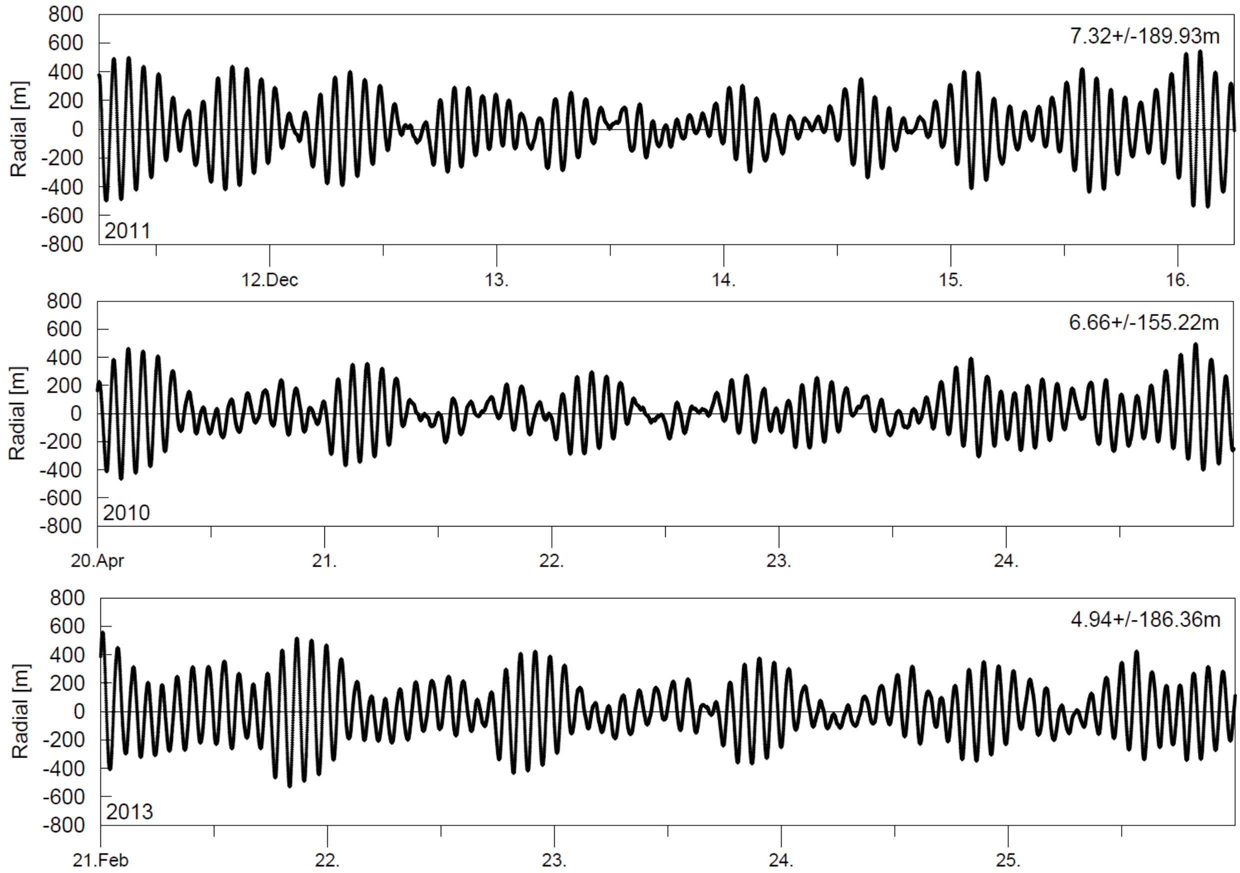

Figure 3 Radial Error of Single TLE during Five Days Backwards Propagation (Top: GRACE-1, Middle: TerraSAR-X, Bottom: TET)

4.2 Test with Other Operational Satellites

The TLEOD process was used also for other operational satellites at GSOC, TerraSAR-X and TET (at an altitude between 500 and 510 km). For both satellites, the precise orbit data based on the GPS measurements is available, which can be used as a reference orbit.

During the analysis period, ~3.5 TLE sets were daily available for TerraSAR-X (April 2010) and ~1 set for TET (February 2013). Due to the frequent orbit control maneuver performed for TerraSAR-X, a period for the analysis was selected, where the maneuver interval is large enough that the maneuver information contained in the orbital elements could be negligible.

The results for the five day fit are shown in Table 6. The TerraSAR-X orbit accuracy was slightly improved by setting offsets as in the case of GRACE-1. Contrary to that, the TET results showed that the pseudo-measurements data generation without offset leads to a better orbit accuracy. For a better understanding of this behavior, the error pattern of a single TLE was analyzed by the backwards propagation from its epoch. Figure 3 shows the radial error for GRACE-1, TerraSAR-X, and TET. The GRACE-1 results fit very well with the orbit error of the 'ideal' TLE data in Figure 1. The TerraSAR-X error pattern is similar to GRACE-1, however the variation of each long-periodic (each-day) fluctuation is slightly smaller. For TET, such a symmetric behavior cannot be seen. The first two days show larger fluctuations than the following three days. Therefore it can be assumed that the used OD arc seems to be shorter than for the other two satellites. In this case, the use of the latest part of the orbital arc would be enough for the pseudo-measurements data generation.

4.3 Application to CSM Secondary Objects

The next step is to apply the TLEOD process to the TLE sets for other space objects. The precise orbit as a reference is in principle not available, however the CSM (Conjunction Summary Message) provided by JSpOC (Joint Space Operations Center) gives the state vector as well as its accuracy at the TCA (time of the closest approach) for both objects, the primary and the secondary. Using the past CSM information, it is possible to extract the orbit information for some objects with a better orbit accuracy. Another consideration is the propagation error due to the numerical model, which is different from the model used by JSpOC for the generation of CSMs. For the operational satellites, the osculating orbit generated from CSM information fits well with the precise orbit. Assuming that the error for another numerical model is comparable with the numerical model error of ODEM in Table 2, the radial and out-of-plane error after a few days propagation is ~10 m, which is acceptable as a reference orbit accuracy. For these reasons, the state vector at the TCA was propagated backwards up to several days and only the radial and out-of-plane components were referenced as the 'real' orbit.

From the past CSMs available for GSOC's LEO satellites from January to July in 2012, 11 out of the 12 secondary objects were selected, which satisfy the following requirements.

- provided orbit uncertainty: better than ~10 m in radial and out-of-plane directions
- available TLE sets in a year: more than ~500

The first requirement is to have a reliable reference orbit, and the second is to use a moderate number of TLE sets, at least three sets to generate the osculating orbital arc of five days. Another reason for the second requirement is to have a better consistency of the neighboring TLE sets.

Table 7 shows a TLE consistency statistics of the selected objects which are available during a year prior to the TCA. The same statistics for GRACE-1 and TET are also listed. Each element set was propagated to the epoch of the following (newer) TLE, and the two positional state vectors were compared in the RTN frame. The resulting RMS error shows that each element set is relatively consistent in case of a frequent orbit update, which could lead to better OD results.

Table 7 One-Year TLE Statistics of Secondary Objects

ID	NAME	RCS	N.TLE	R	T	N
		[m^2]	/year	[m]	[m]	[m]
04394	SL−3 R/B	7.6	563	60	677	38
06350	COSMOS 546	1.8	591	81	1211	150
08688	COSMOS 803	1.4	603	80	577	95
11933	SL−3 R/B	5.6	582	68	1551	42
20547	USA 55	0.2	594	86	750	41
24094	PEGASUS DEB	0.1	561	95	1050	70
24114	PEGASUS DEB	0.1	570	131	1164	108
25505	OKEAN 3 DEB	0.1	556	219	2307	133
26959	BIRD	0.5	1240	39	390	31
32477	PSLV R/B	8.0	585	110	931	126
27391	GRACE	0.6	547	109	565	25
38710	TET	0.5	171/0.5	111	2365	71

The TLE sets of each object used as input to the TLEOD process were extracted for the corresponding period near the TCA to generate the pseudo-measurements data for five days backwards from the TCA and to be used for the OD. In addition to the TLEOD results, a single TLE set near the TCA was selected to generate an osculating orbit with the SGP4 orbital model, covering the same period as the orbital arc used in the TLEOD process. This orbit was used for comparison, representing the osculating orbits before orbital model conversion. Both types of the osculating orbit (before and after TLEOD, using the numerical or SGP4 model) were compared with the reference orbit which was generated from the CSM information.

The results of this analysis are summarized in Table 8 and show that the TLEOD process can improve the errors only in a few cases. Independent of the object size estimated from RCS or the TLE consistency, the radial error component amounts to ~200m for most cases. The reason could be a bad quality of the measurements data or other errors in the TLE generation process performed by USSTRATCOM.

Table 8 RMS Error before/after TLEOD process

ID	TCA	Before TLEOD		After TLEOD		
	[UTC]	R [m]	N [m]	Offset	R [m]	N [m]
04394	2012/06/14	223	238	0	218	225
06350	2012/03/04	262	424	0	300	723
				4	278	149
08688	2012/07/12	387	436	0	489	454
				5	281	224
11933	2012/07/01	248	201	0	179	121
20547	2012/07/05	205	204	0	298	90
				2	149	95
24094	2012/05/27	225	305	0	280	174
				2	206	223
24114	2012/02/10	263	196	0	126	142
25505	2012/04/21	251	295	0	262	309
26959	2012/05/30	195	227	0	9	264
26959	2012/07/05	190	271	0	50	181
32477	2012/04/13	174	529	0	176	546
				1	117	508

5 APPLICATION TO RE-ENTRY PREDICTION

Like for the critical conjunction monitoring, the TLE can also not be used for long-term predictions, as for orbit decay predictions due to the limited SGP4 model precision especially in the decay modeling. On the other hand, after end-of-life of a satellite when normally the on-board systems are switched off, orbit information for not classified objects is available only as SGP4 mean elements generated and released by USSTRATCOM.

The same TLEOD process presented before can be applied for LEO satellite lifetime or re-entry prediction calculations. The ballistic coefficient together with a set of orbital elements can be estimated, which will be used by a numerical orbit propagator using a precise model of the atmosphere like the Jacchia or MSIS models. For a reliable ballistic coefficient estimation, the fit period used in the TLEOD has to be adjusted according to the altitude and solar activity.

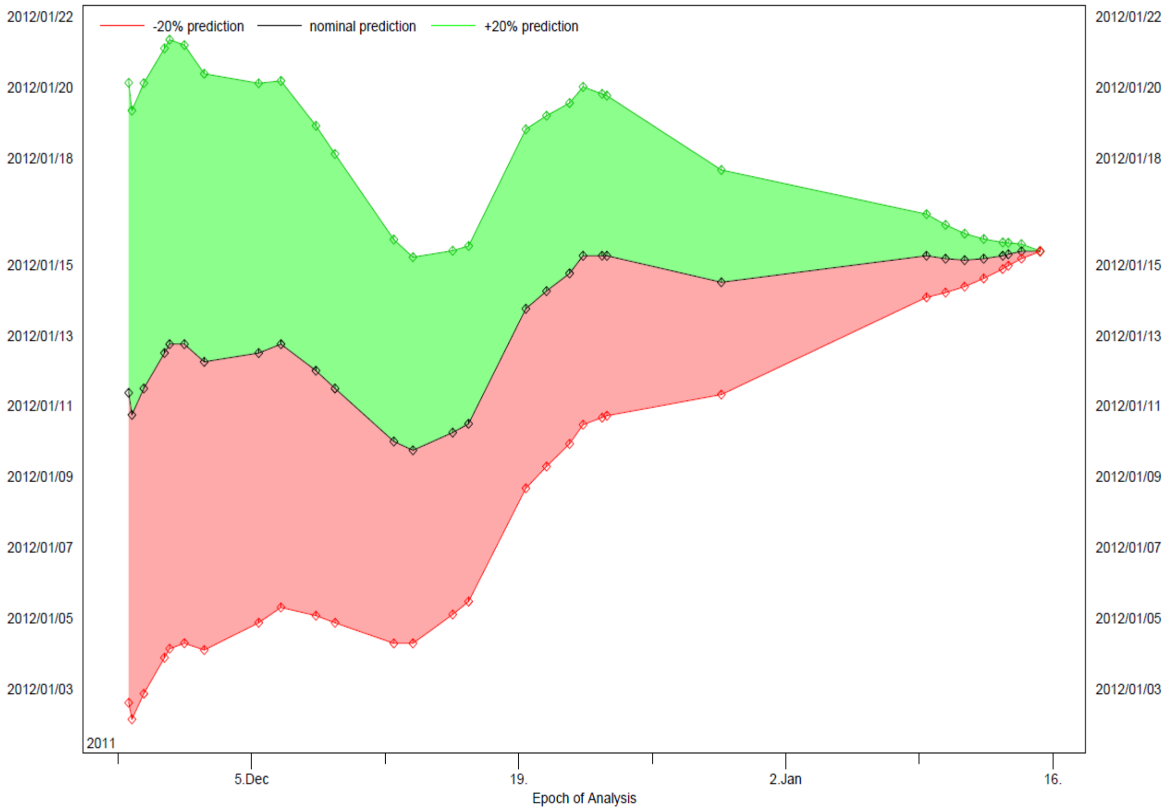

Figure 4 Re-entry Window Calculation Statistics for the PHOBOS-GRUNT Mission

For the long-term propagation, the same propagator was used, which is part of ODEM. To verify that the TLEOD algorithm can be applied for re-entry predictions together with the long-term orbit propagator, the malfunctioned PHOBOS-GRUNT mission was selected, which ended begin of 2012.

The lifetime and re-entry prediction analysis started end of November 2011, where the probe had a mean altitude of about 260 km. The fit period was initially set to seven days, but had to be changed step by step to three days in the last week of the lifetime. For the orbit propagation, predicted flux values were used, which were provided daily by ESOC, and for the re-entry window a 20% uncertainty of the remaining lifetime was applied.

Figure 4 shows the development of the re-entry window depending on the date, when the calculation was performed. One can see that the prediction became relatively stable about four weeks before end-of-mission.

The predictions were always compared with the official predictions released by Space-Track and other parties on the web. The comparison showed a good match and the calculated impact point was less than 20% off the official final one.

6 CONCLUSION

The performance of the TLEOD tool was assessed. Using public TLEs, an accuracy improvement was achieved for operational satellites and some secondary objects. The process was successfully applied to re-entry prediction calculations. The more advanced process needs to be studied for a general application.

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