COMPARISONS OF NORAD TWO-LINE ELEMENTS WITH INTELSAT ORBITAL ELEMENTS

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ABSTRACT

We have compared the publicly accessible NORAD Two-Line Elements (TLE) provided by the US Air Force with the INTELSAT proprietary orbital elements derived from our dual station ranging system. The comparisons were performed for the INTELSAT fleet of geosynchronous satellites, which are distributed over three ocean regions, for a one-year time span. INTELSAT undertook these comparisons to assess the reliabilities of using NORAD TLE for conjunction detection analysis. The objectives of these comparisons are: (1) To study the time history of the differences of the TLE and INTELSAT orbital elements in order to analyze the temporal variations in the TLE; (2) To study the differences of the TLE and INTELSAT orbital elements by ocean regions in order to analyze the spatial variations in the TLE; (3) To study degradation in the TLE accuracy within the update intervals due to the scheduled maneuvers and the accuracy of the TLE at update epoch.

1. BACKGROUND

In the summer of 1999 INTELSAT initiated the task of monitoring the space environment near the geostationary ring to mitigate the risk of collisions of its satellites with space objects. We were interested in determining the proximity of spacecraft operated by other operators and other space debris orbiting near our satellites. Aerospace Corporation was tasked to assist us in this project. We have employed a two-tier approach in this monitoring task. The first tier consists of computing the probability of conjunctions using the publicly accessible NORAD Two-Line Elements (TLE). This probability of conjunction is a function of close approaches between two spacecraft and the uncertainties of the orbital elements used in the computation. This probability is an assessment of the tier is dedicated to give special attention to cases in which the probabilities of conjunctions are higher than certain threshold, the so-called red alert conjunctions. For these special cases, we would request the high accuracy special perturbation (SP) data from the US Airforce through Aerospace Corporation. This data would serve to verify our initial analysis with the TLE. We have received a few red conjunction alerts since we deployed the system. We have documented the red conjunction alert cases for the past six months in Table 1. In all the cases the red conjunction alerts were downgraded upon the analyses using the SP data. One of the difficulties in accurately computing the probabilities of conjunction is the lack of knowledge of the errors and uncertainties of the TLE. The equations used for the probability computations in the monitoring system is described in Ref. [1]. One of the key parameters in the equations is the uncertainty of the orbital elements. Intuitively the dependency of the probability of conjunction with the accuracy of the orbital elements is clear: the better we know the orbit the more precisely we can assess the probability of collision.

This study was carried out to gain better understanding of the errors and uncertainties of TLE. We analyzed the time history of TLE over three ocean regions to study for any temporal and spatial variations in the TLE accuracy. In addition, we also studied the effects of maneuvers on the accuracy of TLE. To this end, we analyzed the update frequencies of the TLE and the degradation in TLE accuracy as a result of maneuvers.

2. METHODOLOGIES

All the comparisons were performed against the INTELSAT orbits obtained using dual station ranging. The propagation of the INTELSAT orbits was based on our operation flight software. The force model employed in our flight software includes the

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

Table 1. Six months of red alert conjunction report

Conjunction Time (UTC)	TLE Probability	Min. Range (km)	SP Probability	Remarks
1999/12/25 20:56:16.0	3.42E-06	6.75	1.14E-10	
1999/12/30 02:36:41.7	1.27E-06	6.207	Not Calculated	
1999/12/26 14:03:44.0	1.02E-06	3.825	'Negligible'	
1999/12/25 20:56:14.7	3.06E-06	11.203	1.82E-07	
1999/12/30 02:36:40.2	1.63E-06	1.995	1.38E-09	
2000/02/02 00:32:34.7	5.72E-06	1.58	Not Calculated	Threat object maneuvered
2000/03/02 11:03:48.5	1.58E-06	25.205	Not Calculated	New miss distance: 157.259 km
2000/03/04 11:54:20.9	1.83E-06	10.276	Not Calculated	New miss distance: 194.127 km
2000/03/09 05:40:13.7	3.68E-06	5.517	2.44E-14	

Goddard Earth Model (GEM-L2) [2] up to degree and order 4, and complete solar and lunar perturbations. The predicted uncertainties in our orbit based on a 10 m range noise are shown in Fig. 1. Over 14 days, the maximum position uncertainty is below 250 meters.

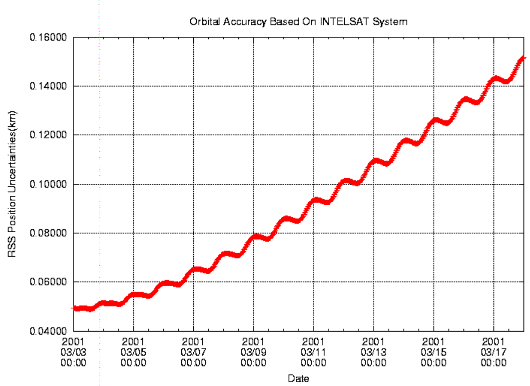

Fig. 1. Predicted position uncertainties of INTELSAT propagator over 14 days based on 10 meter range noise.

The TLE elements used for the comparisons were obtained from the publicly assessed Web server [3]. The TLE propagator employed, SDP8, was obtained from the SPACETRACK Web server [4]. Certain modifications were made on the download version including the Y2K compliance changes made on the date conversion subroutine used for the lunar perturbation. We have tested our version of SDP8 TLE propagator against the TLE propagator, MSGP4, available on STK [5]. The tests were performed on three different satellites located in three different ocean regions over a 2-week time span. The results for the comparisons on IS-701 are shown in Fig. 2a. and 2b. The comparisons showed very close agreement between our version of SDP8 and the MSGP4 TLE propagator.

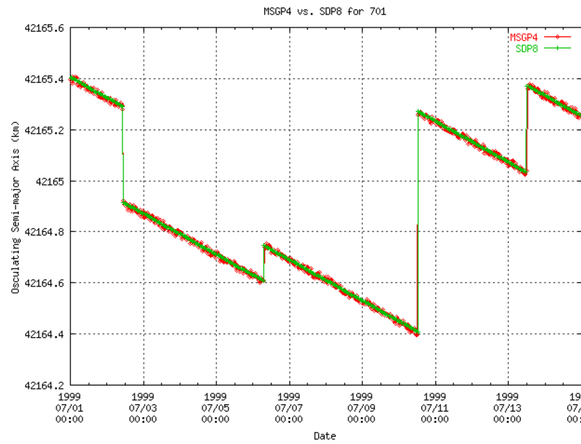

Fig. 2a. Comparisons of semi-major axis between SDP8 and MSGP4

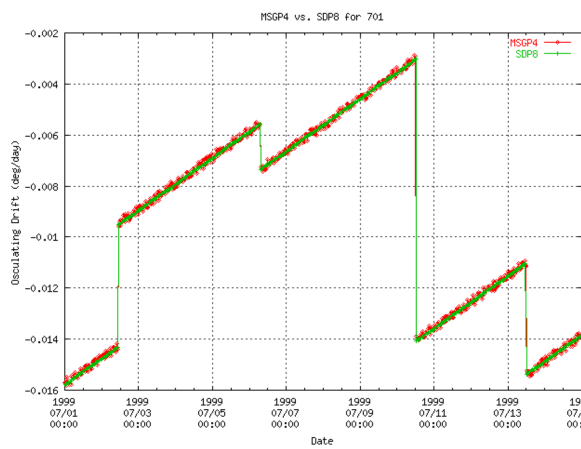

Fig. 2b. Comparisons of drift rate between SDP8 and MSGP4

3. RESULTS

Sample results of the time history differences over one-year from different ocean regions are shown in Fig. 3-5. These differences are shown in the orbital frame and also in selected equinoctial elements. Besides a few anomalies there is no temporal variations observed in the orbital differences. The behavior of the differences seems to be consistent over the one-year time span being studied. Note that, the “X” on the figures indicates update points of the TLE.

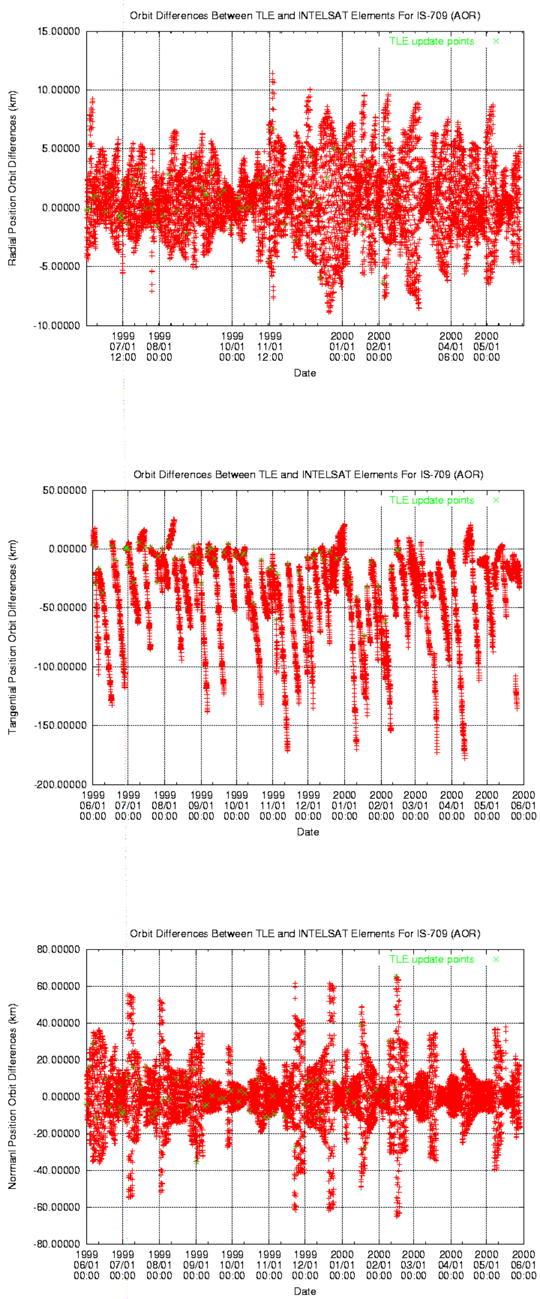

Fig. 3a. Orbit differences between TLE and INTELSAT elements in orbital frame for IS-709 (AOR).

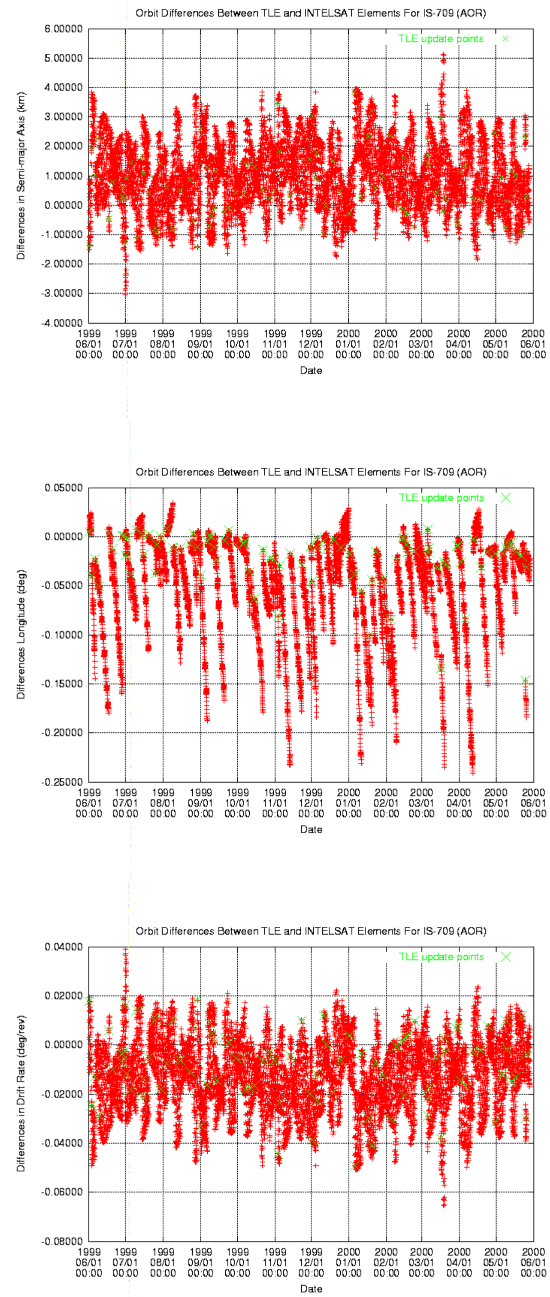

Fig. 3b. Orbit differences between TLE and INTELSAT elements in selected equinoctial elements for IS-709 (AOR).

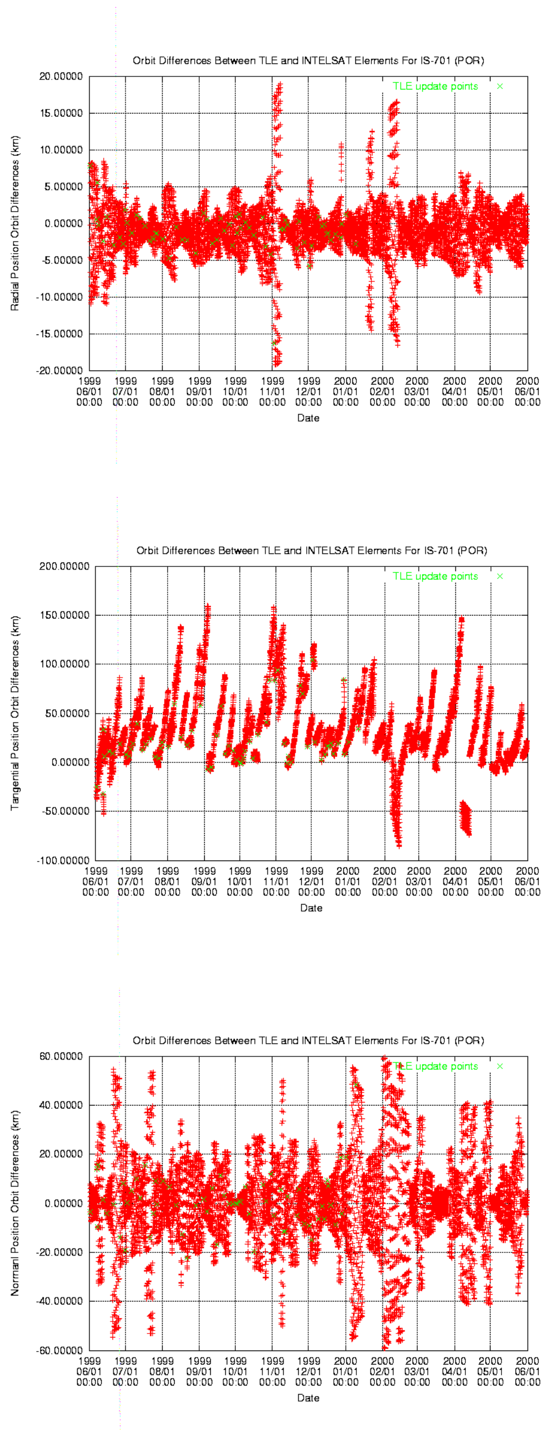

Fig. 4a. Orbit differences between TLE and INTELSAT elements in orbital frame for IS-701 (POR).

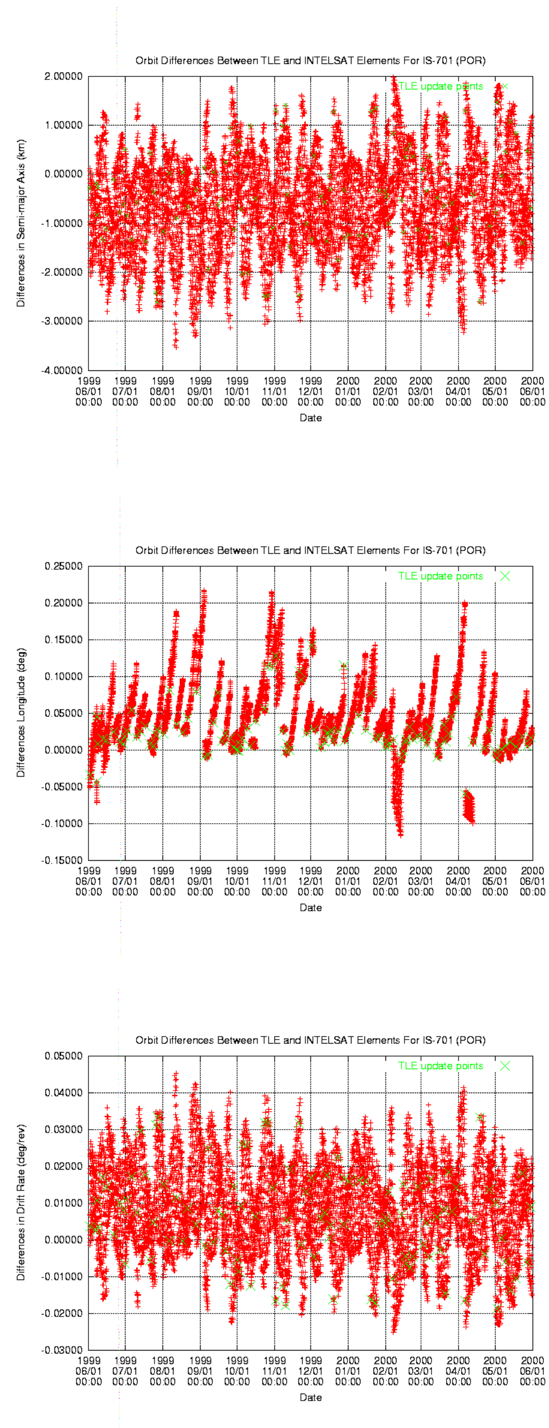

Fig. 4b. Orbit differences between TLE and INTELSAT elements in selected equinoctial elements for IS-701 (POR).

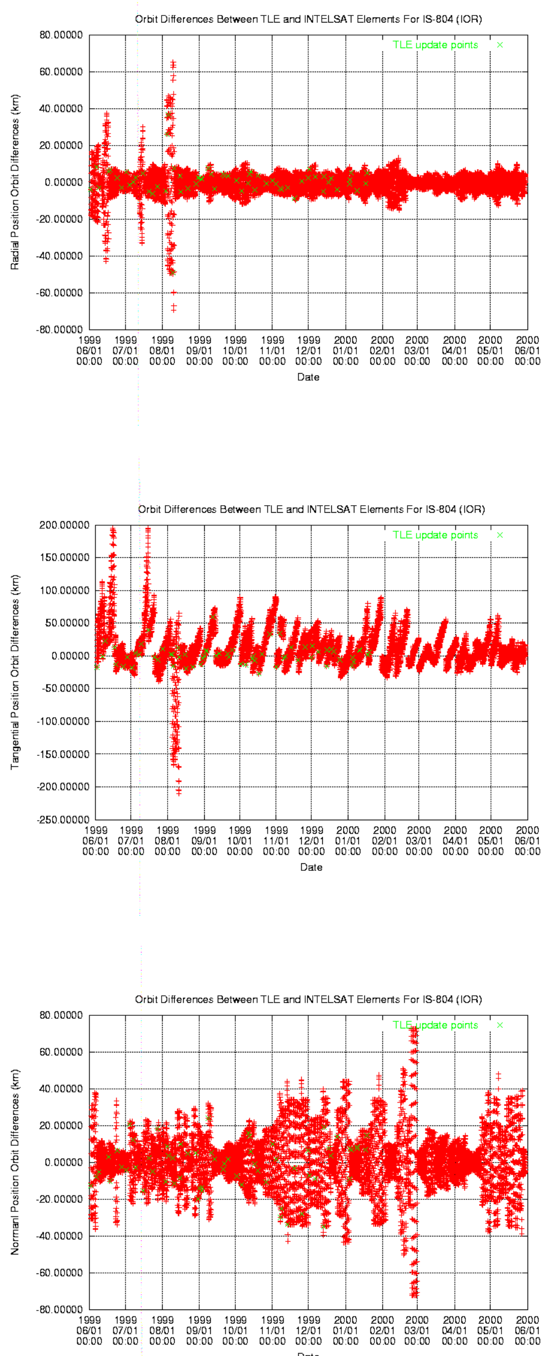

Fig. 5a. Orbit differences between TLE and INTELSAT elements in orbital frame for IS-804 (IOR).

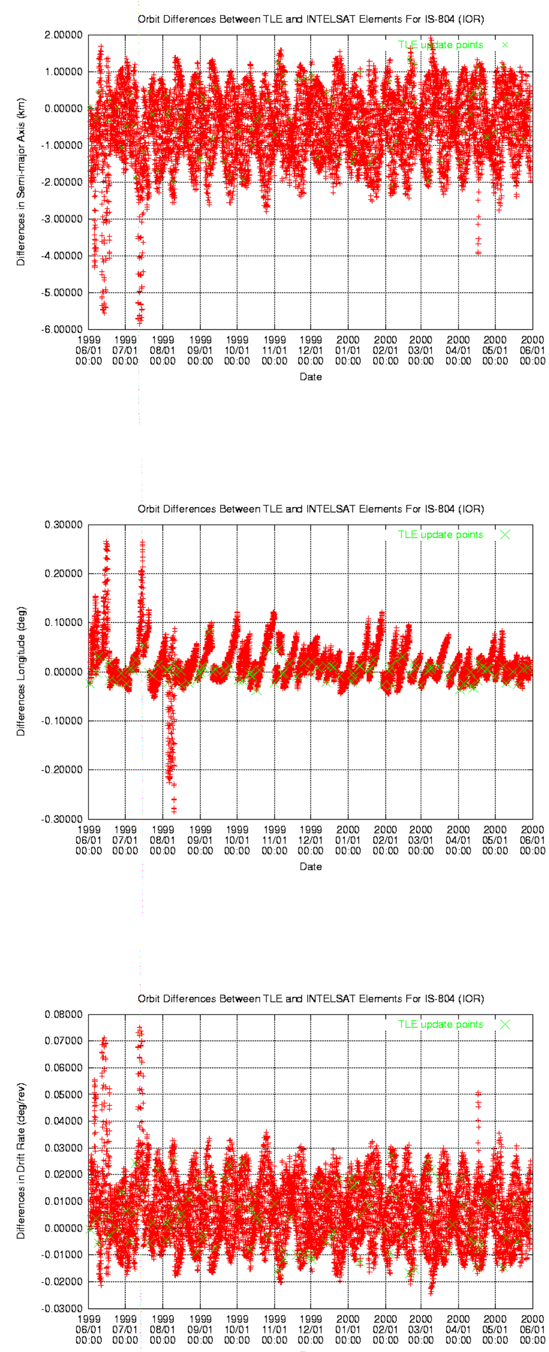

Fig. 5b. Orbit differences between TLE and INTELSAT elements in selected equinoctial elements for IS-804 (IOR).

Systematic biases in the orbit differences over different ocean regions were observed from these time history plots. For the satellite in the Atlantic Ocean Region (AOR) we observed in Fig. 2a. negative biases in the tangential position comparisons and in Fig. 2b. positive biases in semi-major axis comparisons and negative biases in drift rate comparisons. Similarly, we observed an opposite behavior for the satellites in the Pacific Ocean Region (POR) and the Indian Ocean Region (IOR) as shown in Fig. 3a, 3b, 4a and 4b. Tables 2a and 2b. show the result summaries for the INTELSAT fleet over the different ocean regions. It is consistent that positive biases for the tangential position components and negative biases for semi-major are observed for all the AOR satellites. In contrast, negative biases for the tangential position components and positive biases for semi-major axis are observed for all the POR and IOR satellites.

A more careful examination shows the correlation of the sign and magnitude of the biases with the gravitational well based on the terrestrial geopotential harmonics. In Fig. 6. we plot the biases as a function of the geopotential longitude acceleration. It shows a direct relationship between the longitude acceleration and the biases. For positive longitude acceleration we observed positive biases and similarly, for negative longitude acceleration we observed negative biases. In addition, the magnitude of the biases seems to be proportional to the magnitude of the longitude acceleration. One of reasons for the observed biases could be attributed to the differences in the modeling of the terrestrial geopotential harmonics between TLE model and INTELSAT model.

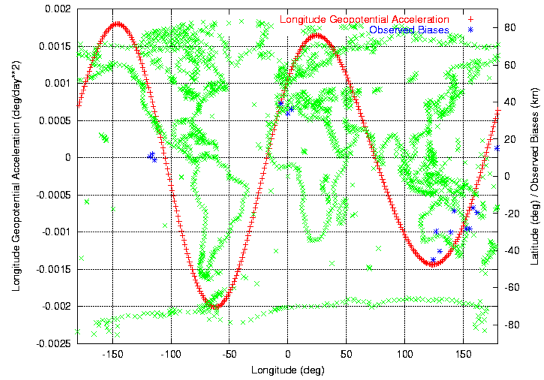

Fig. 6. Observed tangential biases as a function of geopotential acceleration.

Shown also in Tables 2a and 2b. are the Root-Mean-Square (RMS) values for the position and velocity differences for the INTELSAT fleet over one year. The RMS position differences range from about 30 km to 60 km and the RMS velocity differences range from 2 m/sec to 4 m/sec. There is no obvious correlation of the RMS orbital differences with the satellite locations.

We have also studied the effects of station-keeping maneuver on the TLE. The maneuvers degrades the TLE in two areas: (1) the maneuver occurs between two TLE updates and (2) the maneuver occurs within the data time span used for updating the TLE elements. In the case of (1), the

Table 2a. Orbit difference summary in orbital frame

	s/c ID	R (km)			T (km)			N (km)			RSS
		Mean	Sigma	RMS	Mean	Sigma	RMS	Mean	Sigma	RMS	(km)
AOR	805	0.97	9.11	9.16	-44.98	49.22	66.67	0.16	14.45	14.45	68.83
	706	0.50	2.54	2.59	-29.77	40.54	50.29	0.07	15.24	15.24	52.61
	709	0.66	2.99	3.07	-40.36	37.84	55.32	0.00	15.19	15.19	57.45
	806	0.37	10.06	10.06	-30.07	44.59	53.78	0.16	14.03	14.03	56.48
	515	0.30	3.25	3.26	-18.57	42.61	46.48	0.01	2.58	2.58	46.67
	605	0.30	9.45	9.46	-28.29	43.60	51.97	-0.21	15.57	15.57	55.07
	603	0.18	8.75	8.75	-28.23	35.14	45.07	-0.23	13.46	13.46	47.85
	803	0.07	3.03	3.03	-17.16	21.94	27.85	0.17	15.09	15.09	31.82
	705	-0.07	2.97	2.97	-19.47	14.36	24.19	0.00	21.58	21.58	32.55
	707	-0.69	2.70	2.79	15.07	16.96	22.69	-0.02	15.67	15.67	27.71
POR	802	-1.02	6.60	6.68	39.19	40.01	56.01	-0.21	16.13	16.13	58.67
	701	-1.03	3.45	3.60	33.64	35.53	48.93	0.02	17.26	17.26	52.01
	513	-0.92	3.89	4.00	16.12	36.16	39.59	0.01	6.62	6.62	40.34
IOR	602	-0.92	5.53	5.61	10.57	24.81	26.96	-0.30	14.89	14.89	31.31
	804	-0.94	5.92	5.99	11.92	26.62	29.17	0.19	16.03	16.03	33.82
	704	-0.75	4.59	4.65	8.73	22.62	24.24	0.08	14.75	14.75	28.75

Table 2b. Orbit differences summary in selected equinoctial elements

	s/c ID	Semi-major axis (km)			Inclination (deg)			Longitude (deg)		
		Mean	Sigma	RMS	Mean	Sigma	RMS	Mean	Sigma	RMS
AOR	805	1.210	1.792	2.162	-0.001	0.020	0.020	-0.061	0.067	0.091
	706	0.903	1.105	1.427	-0.009	0.014	0.017	-0.040	0.055	0.068
	709	1.014	1.117	1.509	-0.006	0.015	0.016	-0.055	0.051	0.075
	806	0.761	2.023	2.161	0.001	0.020	0.020	-0.041	0.061	0.073
	515	0.696	1.314	1.487	0.001	0.003	0.003	-0.025	0.058	0.063
	605	0.654	1.010	1.203	0.013	0.018	0.022	-0.038	0.059	0.070
	603	0.508	0.974	1.099	0.006	0.018	0.019	-0.038	0.048	0.061
	803	0.430	0.922	1.017	0.002	0.021	0.021	-0.023	0.030	0.038
	705	0.471	1.051	0.940	-0.008	0.017	0.018	-0.027	0.027	0.038
	707	-0.279	0.880	0.923	-0.007	0.015	0.017	0.020	0.023	0.030
POR	802	-0.645	1.111	1.285	0.007	0.021	0.022	0.053	0.054	0.076
	701	-0.644	0.940	1.051	-0.003	0.019	0.019	0.046	0.048	0.066
	513	-0.516	1.305	1.404	-0.001	0.007	0.007	0.022	0.049	0.054
IOR	602	-0.451	0.878	0.987	0.008	0.017	0.019	0.014	0.034	0.037
	804	-0.504	0.939	1.066	0.012	0.018	0.022	0.016	0.036	0.039
	704	-0.286	0.881	0.927	-0.008	0.016	0.018	0.008	0.029	0.030

effect of the maneuver is expected to degrade the TLE orbit within a TLE update cycle before the next TLE update. In the case of (2), the TLE update using data containing maneuvers that is not accounted for in the orbit determination process will produce error of TLE at the update epoch. Shown in Fig. 7. are the orbital differences for an AOR satellites over a 30-day interval. The vertical bar indicates the occurrence of maneuvers and * indicates the TLE update epoch.

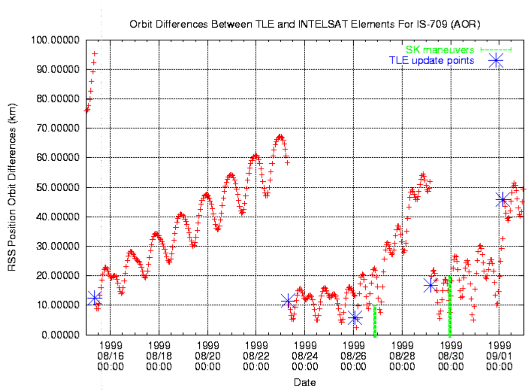

Fig. 7. Effects of station-keeping maneuvers on the accuracy of TLE within TLE update cycles.

The results indicated that there is no significant degradation in the TLE accuracy due to station-keeping maneuvers within a TLE update cycle. The observed growth in orbital differences between TLE and INTELSAT orbital elements within a TLE update cycle seems to be mainly due to the differences in the modeling between the two propagators. Table 3. shows the average TLE update cycle and station-keeping maneuver cycle for the INTELSAT fleet over one-year period. Generally, the TLE update cycles is less than the maneuver cycle by at least a factor of 2. The implication is that any effects of the maneuvers will not be propagated for more than half of the maneuver cycle.

Table 3. Average days between maneuvers and TLE updates for 1999.

S/C ID	Avg. maneuver cycle (days)	Avg. TLE update cycle (days)
805	8.9	4.5
706	11.9	4.1
709	11.4	4.1
806	9.1	4.3
515	30.0	3.1
605	14.1	4.2
603	14.5	3.8
803	8.5	3.8
705	17.2	3.6
707	14.1	3.7
802	9.4	4.6
701	15.7	3.5
513	40.1	2.3
602	14.0	3.8
804	9.1	3.6
704	14.0	3.9

In Fig 8. we show the TLE comparisons with INTELSAT at TLE updates and the proximity of maneuvers prior to the update. The results demonstrate that there is no apparent correlation between the errors at TLE updates and the proximity of maneuvers prior to the update.

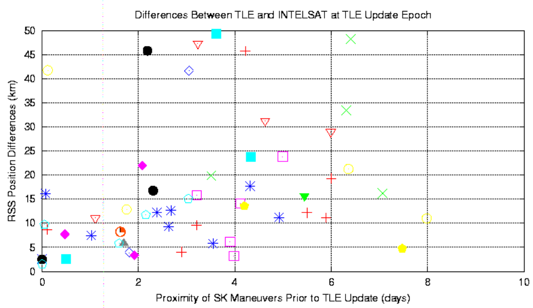

Fig. 8. Effects of station-keeping maneuvers on the accuracy of TLE at TLE update epoch.

We have also noticed the lack of short period perturbations in the TLE orbits. Shown in Fig. 9. is a typical TLE projection in semi-major axis over one week. Without loss of generality we have used IS-803 in this example. Compare that with INTELSAT elements over the same period shown also in Fig. 9. This behavior is consistent with the limited documentation [3] on the propagator that the short period perturbations from the sun and moon are not applied to the propagator. The amplitude of the short period terms on the semi-major axis is 0.75 km and this accounts for most of the differences observed between the TLE and INTELSAT elements that are shown in Tables 2a and 2b. This indicated that most of the errors observed between the TLE and INTELSAT elements may be due to the un-modeled short period terms in the sun and moon perturbations.

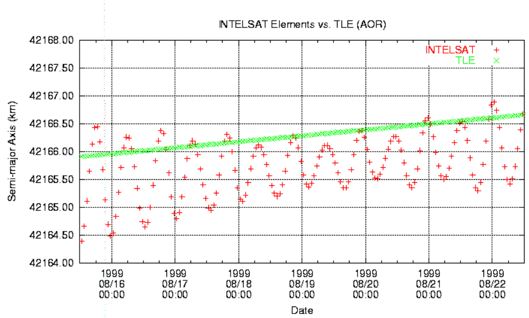

Fig. 9. Comparisons of semi-major axis between TLE and INTELSAT orbits.

A simple experiment was performed where the differences between the INTELSAT osculating and mean semi-major axis were added to TLE and then formed the modified TLE, i.e.,

$$TLE\_\text{mod} = TLE + (INTELSAT\_osc - INTELSAT\_mean)$$

The modified TLE are then compared with INTELSAT elements. The results are shown in Figure 10. Very close agreement was obtained. The result suggested that it is possible to reduce the TLE errors by adding back the short period perturbations. The experiment performed was simply rough approximation of the missing short period perturbations in TLE. Future work will be performed to provide a better methodology to systematically “correct” the TLE. This will be the topic for our future effort.

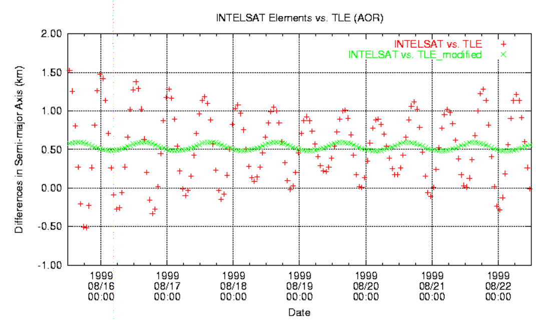

Fig. 10. Modified TLE comparisons with INTELSAT orbit.

4. CONCLUSION

One year of orbital differences between TLE and INTELSAT elements for the entire INTELSAT fleet was computed. No systematic temporal variations were detected over the 1-year span. The orbital differences showed the RMS values of 30 to 60 km in position and 2 – 4 m/sec in velocity. Opposite signs in the systematic biases on the differences of certain equinoctial elements (semi-major axis and drift rate) were detected for satellites in the AOR and satellites in the POR and the IOR. This behavior shows high correlation with the geopotential acceleration and the results suggest the behavior is due to the differences in the modeling of the terrestrial geopotential harmonics. In addition, based on the 1-year analysis we have shown that the effects of maneuvers are within the TLE uncertainties. We have also shown that the un-modeled short period perturbations are the major source of errors in TLE. We have demonstrated with a simple experiment that by including the un-modeled accuracy of the TLE. Future work is being pursued at INTESAT to validate this conjecture and to provide a systematic methodology to "correct" TLE for our applications.

5. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Haisam Ido at INTELSAT for his assistance in writing an automated script to download the TLE from the Web site. In addition, the authors would like to thank Mr. Daniel Oltrogge at Aerospace Corporation for his helpful discussions. Finally, we would also like to thank Ms. Beverley Shaw for reviewing the manuscript.

6. REFERENCES

[1] Patera, Russell, " A General Method For Calculating Satellite Collision Probability", AAS 00-182, pages 1275-1290.

[2] F.J. Lerch, S.M. Klosko, G.G. Patel, "A Refined Gravity Model from Lageos (GEM-l2)", Geophysical Research Letters, 9, 1263-1266 (1982)

[3] ftp://celestrak.com/pub/elements/geo.txt

[4] http://clestrak.com/NORAD/documentation/spacetrk.pdf

[5] Satellite Tool Kit, STK v4.1, Analytical Graphics, Inc.