J. Astron. Space Sci. 17(2), 285–294 (2000)

POST LAUNCH MISSION ANALYSIS FOR THE KOMPSAT-1

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(Received October 12, 2000; Accepted November 15, 2000)

ABSTRACT

The post-launch mission analysis of the KOMPSAT-1 spacecraft was carried out. The injection accuracy of the Taurus launch vehicle was analyzed by comparison of the target and the realized orbit parameters. The tracking station contact analysis was also performed based on the state vectors applied at the day of launch. The offset angles between the predicted orbit and realized orbit were calculated for various tracking stations. The injection orbit parameters of the KOMPSAT-1 were analyzed for the possible options in Launch and Early Orbit Phase(LEOP) operations. Variations of the Local Time of Ascending Node(LTAN) were also obtained.

Key words: satellite, mission analysis, orbit, LEOP, KOMPSAT

1. INTRODUCTION

The Korea Multi-Purpose Satellite-1 (KOMPSAT-1) was successfully launched by the Taurus launch vehicle at 07:13:00 UT, December 21, 1999, from Vandenberg Airforce Base, California, U.S.A. The KOMPSAT-1 was injected into the mission orbit after 802.06 seconds from lift-off. The Launch and Early Orbit Phase (LEOP) operation was performed from the launch day. Although the injection orbital elements of the KOMPSAT-1 satisfied the allowable tolerances of the Taurus launch vehicle, the size of the injection orbit was somewhat larger than that of the nominal size and the inclination of the orbit was greater than that of the nominal inclination. At that time three kinds of options could be applied for the KOMPSAT-1 operation. The first option was performing the orbit lowering maneuvers for achieving the nominal KOMPSAT-1 orbit. The second option was maintaining the KOMPSAT-1 orbit in injection state. The third option was letting the KOMPSAT-1 for decaying to the nominal orbit by natural air drag. These kinds of analysis were performed within a few days after the launch. Actually the first option was selected and then the KOMPSAT-1 spacecraft was inserted into the nominal mission orbit after two in-plane and two out-of-plane orbit maneuvers (Lee et al. 2000).

In this paper, the post-launch mission analysis of the KOMPSAT-1 spacecraft is performed. The injection accuracy of the Taurus launch vehicle is analyzed based on the KOMPSAT-1 definitive

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Table 1. KOMPSAT-1 reference state vector from TLE-5.

Elements	Value	Elements	Value
a (km)	7090.222	Ω (deg)	251.0743
e (-)	0.00307565	ω (deg)	186.6595
i (deg)	98.2670	M (deg)	354.0667

Epoch: 1999/12/21 07:26:22.06 UTC.

Table 2. Comparison of the target orbit and realized orbit.

Parameters	Target by OSC	Realized	Difference
Osculating Injection Apse (km)	7069.2±10	7068.414	-0.786
Osculating Opposite Apse (km)	7075.7±50	7112.029	+36.329
Osculating Inclination (deg)	98.125±0.15	98.2670	+0.142
Mean Injection Apse (km)	7063.275±10	7062.396	-0.879
Mean Opposite Apse (km)	7063.275±50	7099.902	+36.627
Mean Inclination (deg)	98.13±0.15	98.2733	+0.1433
Mean LTAN (mm:ss)	10:50 AM±5 min	10:46:34	-03:26

orbit. The tracking station contact analysis is performed based on the state vectors applied at the day of launch. In addition, the injection orbit parameters of the KOMPSAT-1 are analyzed in the sense of the Sun-synchronism of the orbit. The decay of the semi-major axis of the orbit and the variation of the mean Local Time of Ascending Node (LTAN) are predicted. Also, the variation of the mean LTAN is derived when the semi-major axis is maintained at the injection orbit.

2. INJECTION ACCURACY ANALYSIS OF THE TAURUS T-4 MISSION

Orbit injection requirement of the KOMPSAT-1 mission is described in the Taurus T-4 Interim Mission Analysis (Duquette 1999). In this document, the target mean orbit and the osculating orbit of the T4 mission are defined with the allowable tolerances. Table 1 shows the reference state vector for the KOMPSAT-1 injection. The fifth release of the NORAD TLE (TLE-5) for the KOMPSAT-1 is chosen as the realized reference orbit for the analysis and it is well matched to the ground-based orbit determination. The TLE-5 was propagated by the SGP4 (Hoots & Roehrich 1980) orbit propagator for converting to the osculating orbital elements. Then the osculating orbital elements were converted using the algorithm by Guinn et al. (1992) for comparison.

Table 2 shows the comparison of the target orbit and the realized injected orbit of the KOMPSAT-1. All of the parameters are within the allowable tolerances as specified in the Taurus T4 Interim Mission Analysis document. The semi-major axis and the inclination are somewhat greater than those of the nominal target by Orbital Science Corporation (OSC). Three minutes and twenty six seconds faster than nominal target of the mean local time of the ascending node were achieved by the launch vehicle.

Stress testing of the trajectory design was performed by OSC via Monte Carlo analyses in which hundreds of trajectory simulations were performed (typically in sets of 800 runs), each with a random set of more than 200 perturbed vehicle parameters and each flown through a different measured wind profile (Duquette 1999). Table 3 shows the 3-sigma injection accuracy via Monte Carlo analyses and the realized injection. All of the parameters except inclination are within the 3-sigma accuracy limit. The realized inclination is somewhat above the 3-sigma values. The realized inclination is within the allowable tolerances whereas above the 3-sigma values. According to the comparison between

Table 3. Three-sigma injection accuracy and the realized injection difference.

	Pre-launch analysis by OSC	Realization
Injection Apse	±6.5 km	-0.786 km
Opposite Apse	±43.4 km	+36.329 km
Inclination	±0.10 deg	**+0.142** deg
Time of Injection	±68.6 sec	-16.75 sec
Semi-Major Axis	±22.0 km	+17.772 km

Table 4. Tracking stations for KOMPSAT LEOP.

Tracking Station	Abbreviation	Longitude (deg)	Latitude (deg)	Altitude (m)
McMurdo	MGS	166.6671	-77.8391	153.053
Wallops	WPS	284.5250	37.9273	-19.732
PokerFlat	PKF	212.5409	65.1172	431.420
Svalbard	SGS	15.3928	78.2303	455.010
Weilheim	GSOC	11.0850	47.8800	662.143
TaeJon	KGS	127.3547	36.3748	93.507

the target injection parameters and realized parameters, the Taurus T-4 mission for the KOMPSAT-1 was successfully completed within the allowable tolerances.

3. TRACKING STATION CONTACT ANALYSIS

Six S-band tracking stations were participated in the KOMPSAT-1 LEOP operation. Table 4 shows the station names and coordinates. The GSOC Weilheim station was directly linked to the Taejon station for the telemetry and commanding. The predicted antenna pointing data for GSOC Weilheim station were generated based on the state vector provided by Taejon station. Four NASA tracking stations such as McMurdo, PokerFlat, Svalbard, and Wallops station were linked to the GSOC Weilheim station. The telemetry monitoring and command transmission from Taejon station were established via GSOC Weilheim station. The antenna pointing data for the KOMPSAT-1 at NASA stations were generated by themselves using NORAD TLE data.

Figure 1 shows the ground trace of the KOMPSAT-1 after injection and the ground coverage of the tracking stations. The following tracking stations were scheduled for the contact after the KOMPSAT-1 injection until the second contact at Taejon station.

$McMurdo \rightarrow Weilheim \rightarrow PokerFlat \rightarrow Weilheim \rightarrow PokerFlat \rightarrow Taejon \rightarrow Wallops \rightarrow Taejon$

In the real situation, only the tracking of the KOMPSAT-1 at the first three stations were accomplished. The tracking at the latter five stations were not performed due to the injection errors. The followings are dedicated to the contact analysis for the tracking station according to the various state vectors at the injection time.

The actual launch campaign was broadcasted to the Taejon station. The Taurus was launched at 07:13:00.00 UTC. The predicted injection time and orbital elements were calculated based on the pre-defined nominal injection time of 818.81 seconds after launch. The Earth-Centered-Earth-Fixed (ECEF) coordinate was transformed to the Earth-Centered-Inertial (ECI) coordinate system. The epoch and ECI orbital elements were transferred to GSOC Weilheim station for antenna pointing. Table 5 shows the first predicted orbit state parameters for the KOMPSAT-1 after launch.

The state vector in Table 5 was used for the antenna pointing at the McMurdo, Weilheim and

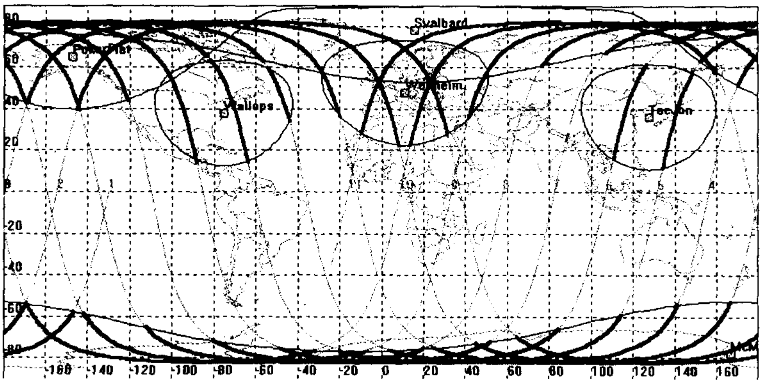

Figure 1. KOMPSAT-1 ground trace and station coverage.

Table 5. Predicted KOMPSAT-1 separation state vector based on the launch time.

Cartesian	ECEF	ECI	Keplerian	ECI
X (km)	-451.982	2301.859	a (km)	7073.4048
Y (km)	-5405.272	6681.239	e (-)	0.0005782
Z (km)	-196.789	-196.779	i (deg)	98.1301
V_x (km/s)	-1.073128	0.937001	Ω (deg)	251.2178
V_y (km/s)	1.175379	-0.542587	ω (deg)	192.3702
V_z (km/s)	-7.432607	-7.432609	M (deg)	349.2534

Launch Time: 1999/12/21 07:13:00.0 UTC, Injection Time: T0 +818.81 sec.
Epoch of the injection : 1999/12/21 07:26:39.0 UTC.

PokerFlat station. For deriving the difference between the predicted antenna angle and the real KOMPSAT-1 position angle, the fifth release of the NORAD TLE (TLE-5) in table 1 was used for the reference.

Figure 2 shows the angular difference between the predicted antenna angle and the realized satellite angle for the 1^{st} MGS, 1^{st} GSOC, and 2^{nd} GSOC contact. The date and time in the figure indicate the start time of the contact. The angular differences are described as the offset angles. The offset angle (θ_0) is derived from the cosine law of spherical triangle as in Equation (1).

$$\theta_0 = \cos^{-1}[\cos(El_{pred})\cos(El_{real})\cos(Az_{pred} - Az_{real}) + \sin(El_{pred})\sin(El_{real})] \quad (1)$$

where, El is elevation angle, and Az is azimuth angle from ground antenna.

Smaller than 1 degree offset angles are shown at the satellite rising time in MGS contact. The KOMPSAT-1 was rising 5 seconds earlier than that of the expected time. Then the MGS antenna tracked the satellite when the antenna was scanned at the predicted position in the early acquisition time. Actually the KOMPSAT-1 telemetry was monitored at Taejon station during the 1^{st} MGS pass. The maximum elevation angle is about 70 degrees.

The next contacts at GSOC and PokerFlat station were also established. The errors of the predicted antenna pointing data based on the nominal injection parameter were increased as time passed because the real injection state vector of the KOMPSAT-1 was biased from the nominal one. The KOMPSAT-1 was rising about 2 seconds earlier than that of expected time for the 1^{st} GSOC contact. The offset angles for the first three minutes of the satellite rising were from 0.8 degrees to 2 degrees. The GSOC Weilheim station covered these amounts of the offset angles at the satellite rising time using another tracking antenna for the satellite acquisition. The maximum offset angle at the maxi-

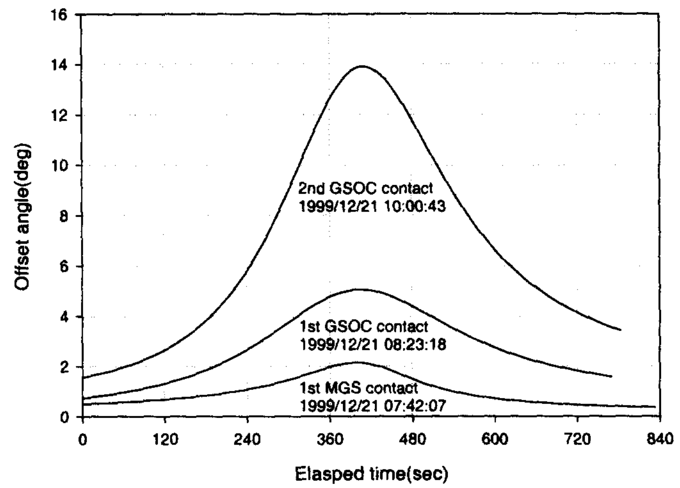

Figure 2. Offset angle for the 1^{st} McMurdo, 1^{st} GSOC, and 2^{nd} GSOC contact.

Table 6. KOMPSAT separation state vector from OSC.

Cartesian	ECEF	ECI	Keplerian	ECI
X (km)	-4538.113	2291.7719	a (km)	7090.1669
Y (km)	-5420.306	6687.4487	e (-)	0.0028854
Z (km)	-84.752	-84.7423	i (deg)	98.10752
V_x (km/s)	-1.150274	0.973913	Ω (deg)	251.1814
V_y (km/s)	1.081242	-0.429537	ω (deg)	184.3338
V_z (km/s)	-7.443819	-7.443821	M (deg)	356.3808

Epoch: 1999/12/21 07:26:22.06 UTC.

Table 7. 1^{st} NORAD TLE for the KOMPSAT-1.

Sat. No.	ID	Epoch	1_{st} Deriv.	2_{nd} Deriv.	BSTAR	
26032U	99070A	99355.34418619	-.00000046	00000-0	00000+0	
Sat. No.	Inclination	RAAN	Eccentricity	Arg. of Peri.	MA	Mean Motion
26032	98.2798	251.1140	0025217	201.6572	158.3506	14.54320950

mum elevation time was about 5 degrees and the maximum elevation angle was about 30 degrees. The results are very comparable to the prelaunch analysis for the first GSOC contact by Lee & Lee (1998). The contact from the PokerFlat station was occurred just after the GSOC pass. So, the very similar situation was happened.

The 2^{nd} GSOC Weilheim station and the 2^{nd} PokerFlat station contact were not realized due to the increased antenna pointing errors. The KOMPSAT-1 was rising 22 seconds earlier than that of expected time for the 2^{nd} GSOC contact and the offset angle at the first three minutes ranged from 1.8 degrees to 4 degrees. These numbers show that the tracking was impossible during that time. The maximum offset angle was reached to 14 degrees and the maximum elevation angle was 37 degrees for the 2^{nd} GSOC contact.

The injection state vector estimated by OSC was released after one hour from injection. The epoch of the injection was 1999/12/21 07:26:22.06 UTC. The time duration from lift-off to separation was 802.06 seconds instead of 818.81 seconds which was originally planned. The coordinate system for the separation state vector was ECEF and the coordinate transformation to ECI was re-

Table 8. Injection state vector from NORAD TLE-1.

Cartesian	ECI	Keplerian	ECI
X (km)	2311.7753	a (km)	7095.9589
Y (km)	6686.6320	e (-)	0.00280211
Z (km)	-125.7713	i (deg)	98.2744
V_x (km/s)	0.979570	Ω (deg)	251.0763
V_y (km/s)	-0.477463	ω (deg)	178.2455
V_z (km/s)	-7.436442	M (deg)	2.7681

Epoch: 1999/12/21 07:26:22.06 UTC.

Table 9. Differences between the separation state vectors from OSC and NORAD TLE-1.

ECI Cartesian	difference	ECI Keplerian	difference
X (km)	-20.0034	a (km)	-5.792
Y (km)	0.8167	e (-)	8.33E-05
Z (km)	41.029	i (deg)	-0.16688
V_x (km/s)	-0.00566	Ω (deg)	0.1051
V_y (km/s)	0.047926	ω (deg)	6.0883
V_z (km/s)	-0.00738	M (deg)	353.6127

Epoch: 1999/12/21 07:26:22.06 UTC.

quired. Table 6 shows the KOMPSAT ECEF separation state vector from OSC and the transformed ECI state vector.

Also, the 1^{st} NORAD Two-Line Elements (TLE-1) was released about one hour later after KOMPSAT-1 launch. The epoch of the TLE-1 is 1999/12/21 08:15:37.687 UTC. Table 7 shows the contents of the NORAD TLE-1.

The NORAD TLE-1 for the KOMPSAT-1 was transformed to the normal state vector at injection time using NORAD SGP4 (Hoots & Roehrich 1980). Table 8 shows the transformed state vector from NORAD TLE-1.

Both separation state vectors from OSC and the NORAD TLE-1 were quick orbit determination solutions using less than one hour tracking data of the KOMPSAT-1. Table 9 shows the differences of the two state vectors. There are very big differences between the two state vectors.

The NORAD TLEs were updated five times for the 1^{st} day of the KOMPSAT-1 launch. Table 10 shows the state vectors from NORAD at the injection time of 1999/12/21 07:26:22.06 UTC. Actually the epoch of the NORAD TLEs were different for the releases. However, the orbital elements at the different epoch were propagated to the injection time for comparison. The NORAD TLEs seem to be converged to the latest one as time passed. So, NORAD TLE-5 was chosen as a realized KOMPSAT-1 orbit for post launch mission analysis.

Table 11 shows the difference among the state vector from TLE-5, OSC, and TLE-1. There are big differences in the position-Z component and the velocity-Y component of the TLE-1. It also resulted in the semi-major axis of the TLE-1. There are large inclination differences between the TLE-5 and OSC.

Two KGS contacts were not realized due to the increasing antenna pointing errors. TLE-1 was used for the antenna predictions at that time. Figure 3 shows the offset angles for the 1^{st} and 2^{nd} KGS contact using TLE-1. For generating the offset angles, TLE-5 was used as the reference orbit of the KOMPSAT-1. The KOMPSAT-1 rose 20 seconds earlier than expected for the 1^{st} pass and 28 seconds earlier for the 2^{nd} pass. The offset angles were about 2 degrees at the rising time and bigger than 7 degrees at the maximum elevation angle for two cases.

Figure 4 shows the offset angles for the 1^{st} and 2^{nd} KGS contact when using the state vector

Table 10. NORAD TLEs update for the launch day.

	TLE-1	TLE-2	TLE-3	TLE-4	TLE-5
Original epoch (UTC)	1999/12/21 08:15:37.687	1999/12/21 14:51:16.377	1999/12/21 19:48:18.031	1999/12/21 21:27:15.454	1999/12/22 05:42:01.876
ECI X (km)	2311.7753	2303.4457	2304.0810	2303.0034	2304.0309
ECI Y (km)	6686.6320	6680.8979	6681.0141	6681.3408	6681.9537
ECI Z (km)	-125.7713	-82.5256	-87.9585	-81.1736	-84.1957
ECI V_x (km/s)	0.979570	0.993496	0.991497	0.9928	0.992719
ECI V_y (km/s)	-0.477463	-0.437594	-0.442963	-0.435811	-0.438615
ECI V_z (km/s)	-7.436442	-7.443355	-7.442952	-7.443274	-7.442141
a (km)	7095.9589	7090.1508	7090.2597	7090.1548	7090.2221
e (-)	0.00280211	0.00324315	0.00320367	0.00320826	0.00307565
i (deg)	98.2744	98.2687	98.2680	98.2596	98.2670
Ω (deg)	251.0763	251.0740	251.0758	251.0769	251.0743
ω (deg)	178.2455	187.6242	187.5818	187.8043	186.6595
M (deg)	2.7681	353.0967	353.1825	352.9062	354.0667
$\omega + M$ (deg)	181.0136	180.721	180.764	180.7105	180.7262

Epoch: 1999/12/21 07:26:22.06 UTC.

Table 11. Difference among TLE-5, OSC, and TLE-1.

ECI Cartesian	TLE-5/OSC difference	TLE-5/TLE-1 difference	Keplerian	TLE-5/OSC difference	TLE-5/TLE-1 difference
X (km)	12.259	-7.7444	a (km)	0.0552	-5.7368
Y (km)	-5.495	-4.6783	e (-)	0.00019	0.000274
Z (km)	0.5466	41.5756	i (deg)	0.15948	-0.0074
Vx (km/s)	0.018806	0.013149	Ω (deg)	-0.1071	-0.002
Vy (km/s)	-0.00908	0.038848	ω (deg)	2.3257	8.414
Vz (km/s)	0.00168	-0.0057	M (deg)	-2.3141	351.2986

Epoch: 1999/12/21 07:26:22.06 UTC.

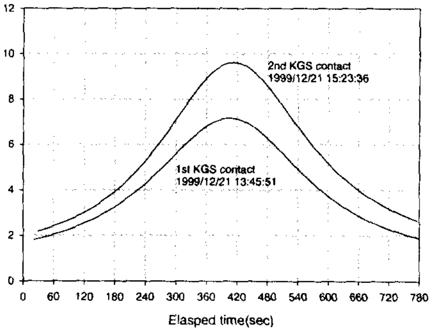

Figure 3. Offset angles for the 1^{st} and 2^{nd} KGS contact using TLE-1.

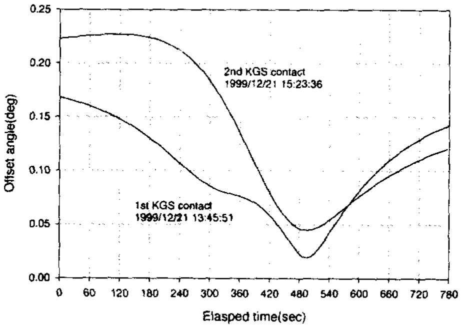

Figure 4. Offset angles for the 1^{st} and 2^{nd} KGS contact using state vector from OSC.

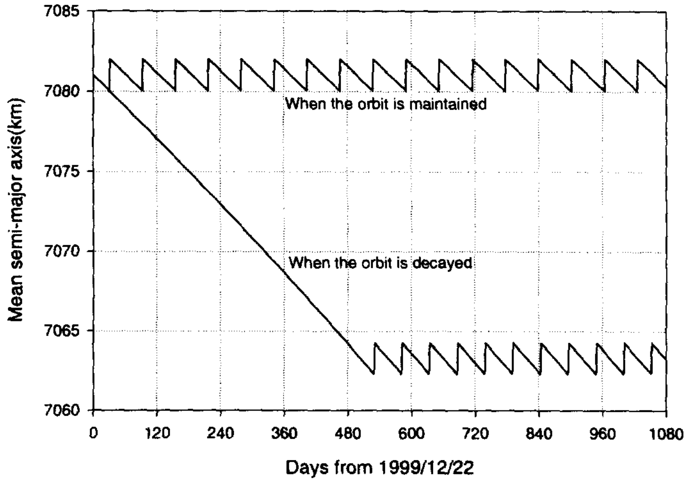

Figure 5. Mean semi-major axis variations for two options.

from OSC. The offset angles are very small compare to Figure 3. If the state vector from OSC was used, the KOMPSAT-1 tracking for the 1^{st} and the 2^{nd} pass might be realized. But at that time the state vector from OSC could not be used for the KGS passes because the previous passes in GSOC and PKF was not realized when using the state vector from OSC. The reason is not clarified yet.

4. ANALYSIS OF THE LOCAL TIME OF ASCENDING NODE

The optimal initial inclination of the KOMPSAT-1 for minimizing the variations of the LTAN was investigated by Lee (1999) for the nominal orbit insertion. However, the KOMPSAT-1 was placed into the higher than nominal orbit. So, further analysis should be performed for possible options. Three kinds of options could be applied for the KOMPSAT-1 at that time. The first option was performing the sequence of orbit maneuvers for achieving the nominal KOMPSAT-1 orbit. The second option was maintaining the KOMPSAT-1 orbit in current injection state, i.e., higher than the nominal orbit. The third option was letting the KOMPSAT-1 for decaying to the nominal orbit by natural air drag and after that maintaining the nominal orbit. The first option was simple and the maneuver planning could be performed using KOMPSAT-1 Mission Analysis and Planning System (Won et al. 1999, Lee et al. 1999). However, further analysis was required for the last two options.

At first, the mean orbital elements of the KOMPSAT-1 at injection state was propagated using the Long-Term Orbit Propagator developed by Kwok (1986). The integration step size was one day. The orbit was decayed by the air drag effect that was modeled by simple exponential formula. The atmospheric density used in this simulation was the maximum density in Cappelari et al. (1976). Figure 5 shows the mean semi-major axis variations for two options. The injection orbit is decayed to the nominal KOMPSAT-1 altitude within one and half year interval. The orbit maintenance maneuver was applied after that.

Figure 6 shows the mean LTAN variations for the two options. The mean LTAN is gradually

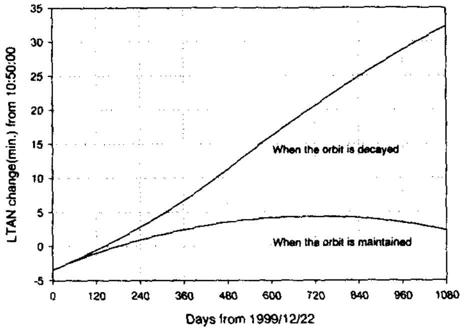

Figure 6. Mean LTAN variations for two options.

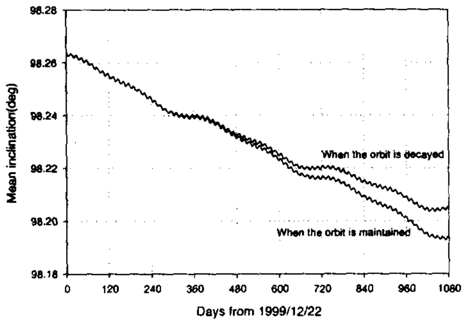

Figure 7. Variation of the mean inclination for two options.

increased upto the 10:54:32 AM and then decreased when the orbit is maintained at the injection orbit. The mean LTAN is maintained at 10:50AM±5 minutes during the 3-year of mission lifetime for the second option. The injected semi-major axis and inclination is well matched for the sun-synchronized property. On the other hand, the mean LTAN is continuously increased upto 11:23 AM when the orbit is decayed to the 685 km altitude of the KOMPSAT-1. The Sun-synchronism is destroyed from the beginning and the required nominal mean LTAN of 10:50AM+10 /-15 minutes is not satisfied for the third option.

Figure 7 shows the decreasing of the mean inclinations during the 3 years from launch. The inclination was reflected on the mean LTAN variations in Figure 6. The magnitude of the inclination decrease for the third option is smaller than that of the second option.

5. CONCLUSIONS

The injection accuracy of the Taurus launch vehicle was analyzed based on the KOMPSAT-1 definitive orbit as a post-launch mission analysis. The KOMPSAT-1 was injected into the mission orbit with allowable tolerances that were defined in the Taurus documents. However, the inclination of the KOMPSAT was exceeded the 3-sigma bound which was analyzed by OSC.

The tracking station contact analysis was also performed based on the state vectors applied at the day of launch. The contacts of the first three passes were realized, however no ranging operations were scheduled at that time. Therefore no initial orbit determination was performed and then the antenna pointing angle prediction was heavily relied upon the NORAD TLEs and the injection state vector from OSC.

The injection orbit parameters of the KOMPSAT-1 were analyzed in the sense of the Sun-synchronism of the orbit. The decay of the semi-major axis of the orbit and the variation of the mean LTAN were analyzed. Also, the variation of the mean LTAN was derived when the semi-major axis was maintained in the injection orbit. The mean LTAN was maintained at 10:50AM±5 minutes during the 3-year of mission lifetime when the orbit was maintained at the injection orbit. In such a case, the orbit raising maneuver should be performed according to the decay rate. The injected semi-major axis and inclination was well matched for the sun-synchronized property. Whereas, the mean LTAN was continuously increased upto 11:23 AM when the orbit was decayed to the 685 km altitude. The Sun-synchronism was destroyed from the beginning and the required nominal mean

LTAN of 10:50AM+10 /-15 minutes was not satisfied.

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