Quick Evaluations of the KOMPSAT-1 Orbit Maneuvers Using Small Sets of Real-time GPS Navigation Solutions

Byoung-Sun Lee, Jeong-Sook Lee, and Jae-Hoon Kim

Abstract: Quick evaluations of two in-plane orbit maneuvers using small sets of real-time GPS navigation solutions were performed for the KOMPSAT-1 spacecraft operation. Real-time GPS navigation solutions of the KOMPSAT-1 were collected during the Korean Ground Station(KGS) pass. Only a few sets of position and velocity data after completion of the thruster firing were used for the quick maneuver evaluations. The results were used for antenna pointing data predictions for the next station contact. Normal orbit maneuver evaluations using large sets of playback GPS navigation solutions were also performed and the result were compared with the quick evaluation results.

Keywords: orbit determination, orbit maneuver, GPS navigation solutions, KOMPSAT-1

I. Introduction

The Korea Multi-Purpose Satellite-1(KOMPSAT-1) was successfully launched by the Taurus at 07:13:00 UT, December 21, 1999, from Vandenberg Airforce Base, California, U.S.A. Although the injection orbit of the KOMPSAT-1 was within the allowable tolerances of the Taurus launch vehicle, the size of the orbit was somewhat larger than that of the nominal size and the inclination of the orbit is greater than that of the nominal inclination[1]. So, both in-plane and out-of-plane maneuvers were required to achieve the nominal orbit of the KOMPSAT-1. Totals of four orbit maneuvers were performed for the KOMPSAT-1 spacecraft in Launch and Early Orbit Phase(LEOP) operation. Two In-Plane Maneuvers(IPM) and two Out-of-Plane Maneuvers(OPM) were performed for reducing the orbit size and decreasing the orbital inclination, respectively.

The first KOMPSAT-1 IPM for decreasing the semi-major axis was performed on Jan. 1, 2000. The first OPM for decreasing the inclination was performed on Feb. 2, 2000 and the second OPM for achieving the final target inclination was performed on Feb. 9, 2000. The second IPM for decreasing the semi-major axis to the operational KOMPSAT-1 orbit was performed on Feb. 16, 2000.

Thruster firing should be executed for orbit maneuver and performance of the thruster firing affects the maneuver results. So, orbit maneuver should be evaluated for precision maneuver planning and execution. Normally, evaluation of the orbit maneuver starts from the Orbit Determination(OD) using post-burn tracking data. The OD result shows the realized orbit maneuver. Then, thruster calibration factor is derived from the comparison between the planned orbit and the realized orbit. Maneuver evaluation is very important because satellite ground station could not contact with the spacecraft after the maneuver execution with the wrong thruster calibration factor.

In this paper, the evaluation of the first and second IPM for the KOMPSAT-1 is described. Only a few sets of real-time GPS navigation solution data after the completion of the thruster firing are used for the quick maneuver evaluations. The results are used for antenna pointing data predictions for the next station contact. Normal orbit maneuver evaluations using large sets of playback GPS navigation solutions are also performed and the result are compared with the quick evaluation results.

II. First in-plane orbit maneuver

1. Orbit Maneuver and Evaluation

The first IPM was performed at near perigee point by thrusting backward to the orbit direction. The maneuver planning was performed using KOMPSAT-1 MAPS[2,3,4]. Table 1 shows the maneuver parameters. The first IPM was performed as a calibration burn. So, no calibration was applied to the thruster and specific impulse from database values in maneuver planning. The used fuel was expected to 1.229 kg for the 180 seconds burn. The applied pitch attitude is – 90 degrees for reducing the orbital velocity. The planned delta velocity was worth of decreasing the semi-major axis of 10.708 km.

Table 1. The 1st IPM planning parameters.

Burn Start Time	2000/01/01 23:37:22.000
Burn Duration(sec)	180.0
Maneuver Target(km)	-10.708 km of semi-major axis
Thruster Calibration Factor	1.0
Effective Thrust(Newton)	14.669
Effective Isp(sec)	214.414
Expected Fuel Used(kg)	1.229
Delta Velocity Magnitude(m/sec)	- 5.615

The maneuver was executed during the German Space Operations Center(GSOC) contact time. The thruster firing and the attitude were monitored in Korean Ground Station(KGS) via communication link. Also, Earth-Centered-Earth-Fixed(ECEF) position and velocity of the KOMPSAT-1 from on-board GPS receiver were gathered every 32-seconds interval. Totals of 20 GPS navigation solutions were collected from GSOC.

Figure 1 shows the KOMPSAT-1 ground track and station coverage in LEOP operations. The ground station contacts in GSOC and KGS are shown in bold trace. One-day ground track is shown in the figure. The pass numbers are presented based on the ascending node.

Fig. 2 shows the variation of the osculating semi-major axis with and without maneuver. The osculating semi-major axis vaues from GPS navigation solutions are used as thrust values. Orbit propagation without maneuver is used as no thrust

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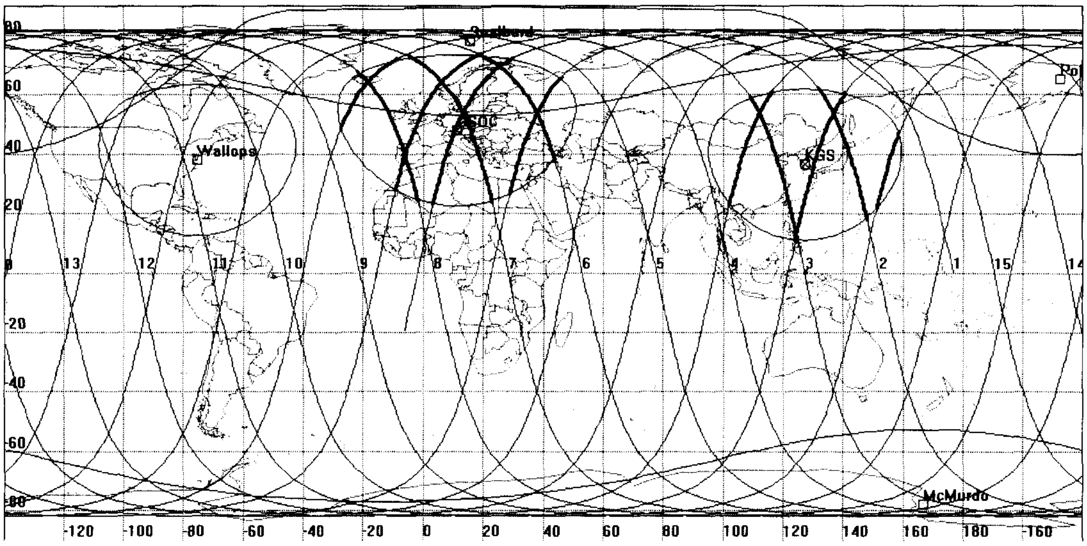

Fig.1. KOMPSAT-1 ground trace and station coverage(2000/01/01 23:00:00 ~ 2000/01/02 23:00:00).

values. The thruster firing was executed in between the two vertical lines of 416 seconds and 576 seconds in Fig. 2. There is discrepancy between the propagation and GPS navigation solutions during pre-burn time. It is because GPS navigation solutions include many error factors. The semi-major axis of the orbit for thrust is decreased from the maneuver start point.

Fig. 3 shows the variation of the osculating eccentricity. The eccentricity of the orbit for thrust is also decreased from the maneuver start point. Two data points before the maneuver are noisy GPS data.

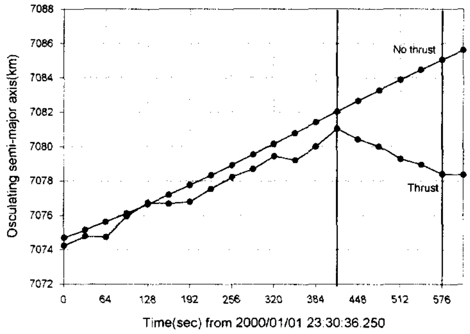

Fig. 2. Semi-major axis variation during the 1st IPM.

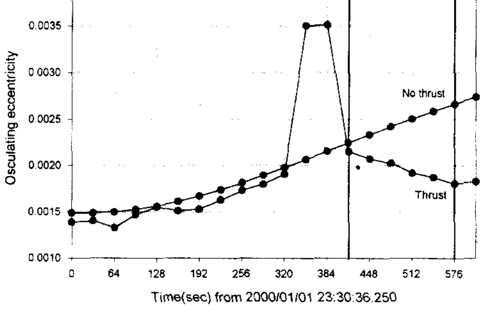

Fig. 3. Eccentricity variation during the 1st IPM.

There was KGS contact after the orbit maneuver execution in GSOC contact. Twelve sets of the real-time GPS navigation solution data during the KGS pass time were collected. And 275 sets of post-burn playback telemetry data were gathered in the next KGS pass.

Table 2 shows the Maneuver Planning orbit(MP), Quick Orbit Determination(QOD) using 12 sets of the real-time GPS data, and the Normal Orbit Determination(NOD) using 275 sets.of the playback GPS data. The NOD using post-burn playback data was used as a realized reference orbit. The differences among MP, QOD, and NOD are also shown in Table 2.

The difference between the MP and QOD is about –3.8 km and it means that the maneuver is undershot. The difference between the MP and NOD is about –3.518 km and it also shows undershot. The difference between the QOD and NOD data is about 282 meters. So, quick maneuver evaluation using QOD is useful for initial thruster calibration.

Table 2. Post-burn OD results for the 1st IPM (Epoch : 2000/01/02 00:00:00 UTC).

Osculating Keplerian	Maneuver plan(MP)	12 real-time QOD	275 playback NOD
Iterations	N/A	5 for 5%	5 for 5%
a (km)	7072.499	7076.299	7076.017
e (-)	0.0008257	0.0012674	0.0013180
i (deg)	98.2726	98.27238	98.27202
Ω (deg)	262.6743	262.64803	262.64765
ω (deg)	121.2820	131.45405	133.27082
M (deg)	97.7451	87.53035	85.70839
Difference	MP-QOD	QOD-NOD	MP-NOD
Δa (km)	-3.8	0.282	-3.518
Δe (-)	-0.00044	-5.1E-05	-0.00049
Δi (deg)	0.00022	0.00036	0.00058
$\Delta\Omega$ (deg)	0.02627	0.00038	0.02665
$\Delta\omega$ (deg)	-10.1721	-1.81677	-11.9888
ΔM (deg)	10.21475	1.82196	12.03671

Table 3 shows the comparison between the post-burn orbit. and the pre-burn orbit. The pre-burn orbit was derived by propagation from the original epoch orbit. Although the semi-major axis decrease of −10.708 km was planned as in Table 1, the semi-major axis decrease of −7.190 km was achieved by the first in-plane orbit maneuver. The thruster was undershot during the maneuver. So, thruster calibration is required for the next maneuvers. The thruster calibration factor of 67.3 % was derived when matching the orbit determination results to the maneuver planning.

Table 3. Comparison between the orbit after thrust and no thrust(Epoch : 2000/01/02 00:00:00 UTC).

Osculating Keplerian	After Thrust	No Thrust	Delta (After-No)
a (km)	7076.017	7083.207	-7.190
e (-)	0.0013180	0.0022975	-0.00098
i (deg)	98.27202	98.27265	-0.00063
Ω (deg)	262.64765	262.64729	0.00036
ω (deg)	133.27082	134.64028	-1.36946
M (deg)	85.70839	84.20459	1.5038
Mean Keplerian	After Thrust	No Thrust	Delta (After-No)
a (km)	7074.119	7081.304	-7.185
e (-)	0.0017959	0.0027669	-0.00097
i (deg)	98.27501	98.27564	-0.00063
Ω (deg)	262.64134	262.64100	0.00034
ω (deg)	145.54398	142.30358	3.2404
M (deg)	73.38573	218.79555	-145.41

Fig. 4 shows the azimuth and elevation plot for the 2nd KGS pass after maneuver. It is predicted using NOD results. The maximum elevation angle is about 38 degrees. The spacecraft rises from Southwest direction and set to Northwest direction.

Fig. 5 shows offset angle of the antenna pointing when MP and QOD results are used for antenna pointing prediction. The offset angle is the difference of the two pointing angles at the same time. It is derived from azimuth and elevation. The NOD results are used for the reference antenna pointing direction. The offset angles of the maneuver plan orbit start from 0.4 degrees and reaches up to 3.2 degrees. Whereas, the offset angles of the QOD are under 0.2 degrees. The Half-Power-Beam-Width(HPBW) of the 9 m S-band tracking antenna in KGS is about 1.2 degrees[5]. The automatic tracking of the KOMPSAT-1 could be performed within the HPBW. Scanning of the tracking antenna should be performed when the predicted antenna pointing angle is greater than the HPBW.

The antenna pointing angle using QOD was used for the 2nd KGS pass. If the antenna pointing angle using MP was used, the tracking was hardly accomplished.

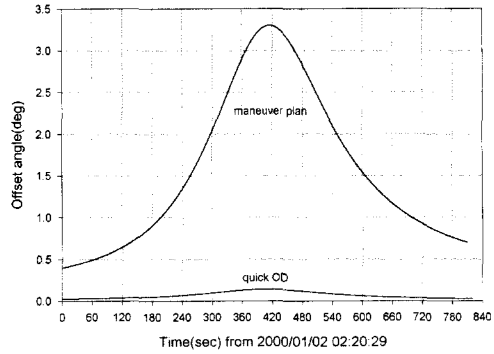

Fig. 5. Offset angle for the 2nd KGS contact.

2. Variation of the mean orbital elements after 1st IPM

The mean orbital elements of the KOMPSAT-1 was propagated using the Long-Term Orbit Propagator developed by the NASA/JPL[6]. The integration step size was one day. The orbit was decayed by the air drag effect that was modeled by exponential formula. Based on the mean orbital elements in Table 3, the orbit is propagated for 3-years mission lifetime and the variation of the mean LTAN is derived. Fig. 6 shows the mean semi-major axis variation for the 3 years when the semi-major axis was allowed to be decreased by the atmospheric drag and then maintained within the nominal semi-major axis of the KOMPSAT-1. The maximum atmospheric density was applied to orbit propagation[7]. The semi-major axis is decreased to the nominal KOMPSAT-1 value within one year.

Fig. 7 shows the mean LTAN variations from the nominal KOMPSAT-1 LTAN value of 10:50 AM. The mean LTAN is ever increased upto 11:35 AM after 3 years. The mean LTAN will be reached to the nominal KOMPSAT-1 LTAN within 2

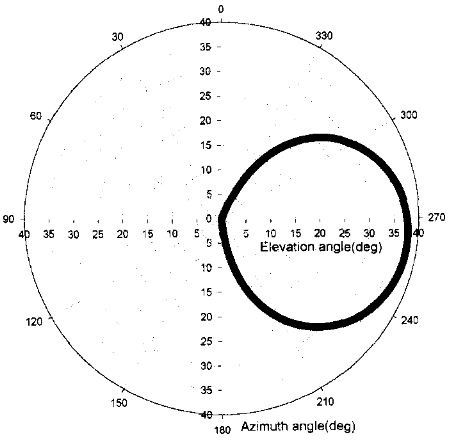

Fig. 4. Azimuth and elevation plot for the 2nd KGS contact.

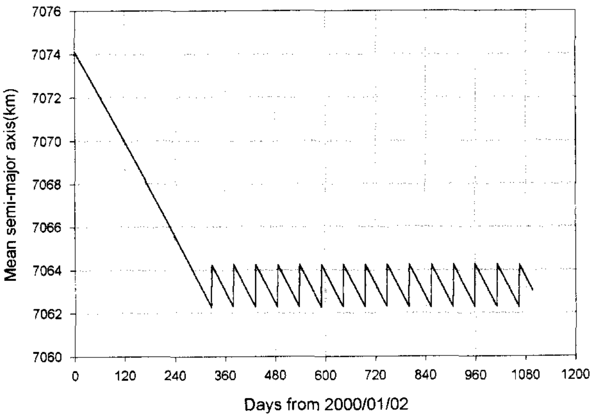

Fig. 6. Mean semi-major axis variation.

months and then exceeded to the upper limit of the KOMPSAT-1 LTAN of 11:00 AM within 10 months. The execution of the out-of-plane maneuver for controlling the LTAN is required as soon as possible.

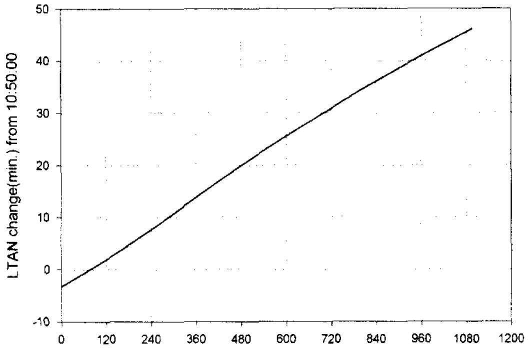

Fig. 7. Mean LTAN variation.

Fig. 8 shows the mean inclination variations for 3 years. The inclination is reflected to the mean LTAN variations in Fig. 7.

Fig. 9 shows the mean argument of perigee vs. mean eccentricity plot for 3 years. The mean eccentricity is decreased when the semi-major axis is decreased by the atmospheric drag.

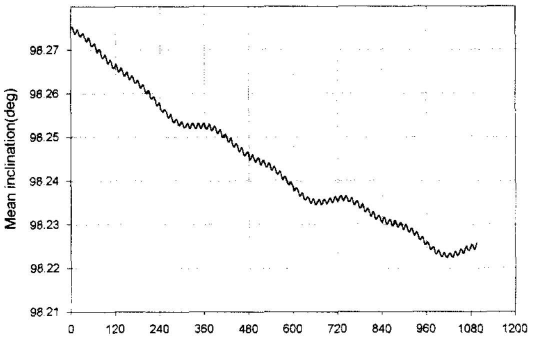

Fig. 8. Mean inclination variation.

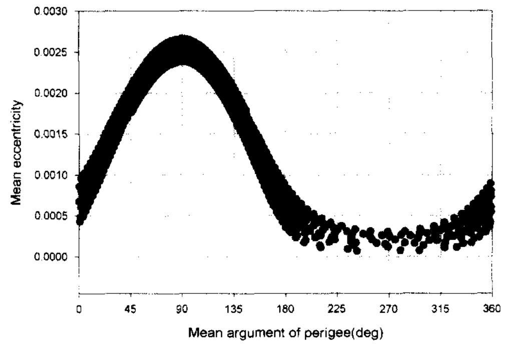

Fig. 9. Mean argument of perigee vs. eccentricity plot.

III. Second in-plane orbit maneuver

1. Orbit Maneuver and Evaluation

The second IPM was performed at near perigee point on 16th of Feb. followed by two OPM. By the orbit maneuver, the apogee and eccentricity were decreased to the operational KOMPSAT-1 orbit[8].

Table 4 shows the maneuver parameters. Thruster calibration factor after the second OPM was applied to the thruster and specific impulse. The used fuel was expected to 1.797 kg for the 263 seconds burn. The applied pitch attitude was -90 degrees for reducing orbital velocity. The delta velocity magnitude was worth of decreasing the semi-major axis of 9.810 km.

Table 4. The 2nd IPM planning parameters.

Burn Start Time	2000/02/16 00:53:00.000
Burn Duration(sec)	263.0
Maneuver Target(km)	-9.810 km of semi-major axis
Thruster Calibration Factor	0.518
Effective Thrust(Newton)	7.602
Effective Isp(sec)	111.113
Used Fuel(kg)	1.7973
Delta Velocity Magnitude(m/sec)	- 4.327

The maneuver was executed during the KGS contact time. The thruster firing and the attitude were monitored via real-time telemetry link.

Fig. 10 shows the osculating semi-major axis difference between the thrusting and no thrusting. Thrust values are derived from real-time GPS navigation solutions and no thrust values are propagated from initial orbital elements. The thruster firing is represented in between the two vertical lines of 192 seconds and 416 seconds in Fig. 10. The difference of the osculating semi-major is decreased from the point at 192 seconds. It agrees with the maneuver start time. Fig. 11 shows the differences of the osculating eccentricity between the thrusting and no thrusting.

Six real-time GPS data from the maneuver stop point were collected during the KGS contact. The real-time GPS data were processed and the QOD solution was obtained as in Table 5. Playback telemetry data were gathered in the next KGS pass and the 182 GPS data sets after the maneuver were processed for NOD solution.

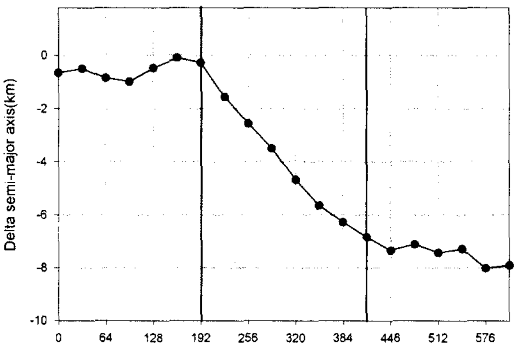

Fig. 10. Semi-major axis difference during the 2nd IPM.

The difference between MP and QOD is about –578 m and it means that the maneuver is slightly undershot. Whereas, the difference between MP and NOD is about 56 m and it shows very small overshot. The difference between the QOD and NOD is 634 m and it shows that the accuracy of the MP is better than that of the QOD. It is because the thruster calibration factor is much improved after evaluations of the previous three orbit maneuvers and the QOD was performed using only 6 sets of the real-time GPS data available after the maneuver. In this case the quick maneuver evaluation using QOD is not useful for maneuver evaluation.

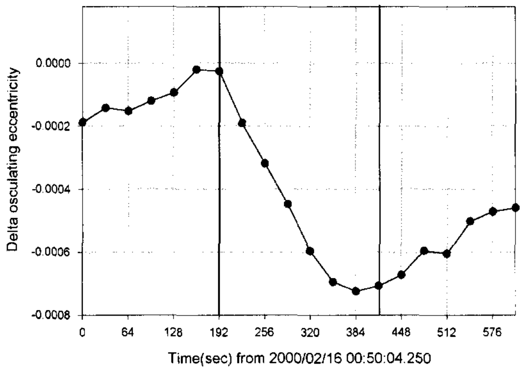

Fig. 11. Eccentricity difference during the 2nd IPM.

Table 5. Post-burn OD results for the 2nd IPM (Epoch:2000/02/16 00:57:23.000).

Osculating Keplerian	Maneuver plan(MP)	6 real-time QOD	182 playback NOD
a (km)	7065.525	7066.103	7065.469
e (-)	0.0010964	0.0011138	0.0011523
i (deg)	98.18277	98.18345	98.18343
Ω (deg)	307.34284	307.34275	307.34329
ω (deg)	111.90563	106.89988	112.93124
M (deg)	289.38989	294.39389	288.37207
Difference	MP-QOD	QOD-NOD	MP-NOD
Δa (km)	-0.578	0.634	0.056
Δe (-)	-1.7E-05	-3.8E-05	-5.6E-05
Δi (deg)	-0.00068	2E-05	-0.00066
$\Delta\Omega$ (deg)	9E-05	-0.00054	-0.00045
$\Delta\omega$ (deg)	5.00575	-6.03136	-1.02561
ΔM (deg)	-5.004	6.02182	1.01782

Table 6 shows the comparison between the orbit after maneuver and the orbit without maneuver. The orbit without maneuver was derived by propagation from the original epoch orbit. The osculating semi-major axis decrease of –9.810 km was planned as in Table 4, and the semi-major axis decrease of –9.866 km was achieved by the second in-plane orbit maneuver. The thruster was slightly overshot during the maneuver but no thruster calibration is required in this order. The thruster calibration factor of 51.8% could be used for the next orbit maneuver.

Table 6. Comparison between the orbit after thrust and no thrust(Epoch : 2000/02/16 00:57:23.000).

Osculating Keplerian	After Thrust	No Thrust	Delta (After-No)
a (km)	7065.469	7075.335	-9.866
e (-)	0.0011523	0.0021645	-0.00101
i (deg)	98.18343	98.18137	0.00206
Ω (deg)	307.34329	302.43219	4.9111
ω (deg)	112.93124	75.31601	37.61523
M (deg)	288.37207	321.44028	-33.0682
$\omega + M$ (deg)	41.30331	36.75629	4.54702
Mean Keplerian	After Thrust	No Thrust	Delta (After-No)
a (km)	7064.301	7072.694	-8.393
e (-)	0.0010818	0.0022067	-0.00112
i (deg)	98.18311	98.18291	0.0002
Ω (deg)	307.33861	302.42701	4.9116
ω (deg)	78.17876	61.75628	16.42248
M (deg)	323.07107	334.95313	-11.8821

Fig. 12 shows the azimuth and elevation plot for the next KGS pass after the second IPM. The maximum elevation angle is about 32 degrees. The spacecraft rises from Southwest direction and set to Northwest direction and the profile is very similar to Fig. 4.

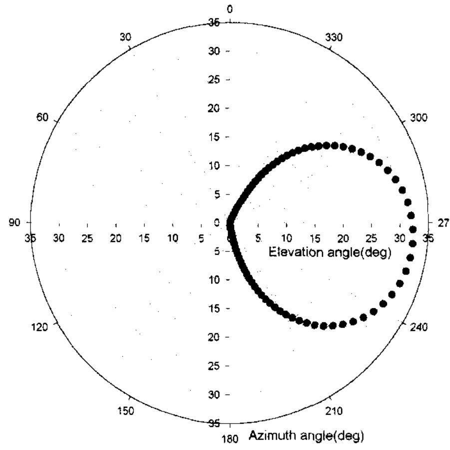

Fig. 12. Azimuth and elevation plot for the next KGS contact.

Fig. 13 shows offset angle of the antenna pointing when MP and QOD results are used for antenna prediction. The NOD results are used for the reference antenna pointing direction same as the previous case. The offset angle of the QOD orbit starts from 0.07 degrees and reaches up to 0.3 degrees. Whereas the offset angle of the MP is under 0.04 degrees. Different from the previous case, the offset angle of the MP is smaller than that of the QOD. As mentioned earlier, the thruster calibration factor in the 2nd orbit maneuver planning is very accurate and the QOD using only 6 sets of the GPS navigation solution is not that much accurate.

The antenna pointing data were generated using the QOD results at that time of the satellite operation. And the offset angle of the QOD was small enough to acquire the signal, so the automatic tracking was accomplished and the playback GPS data were collected.

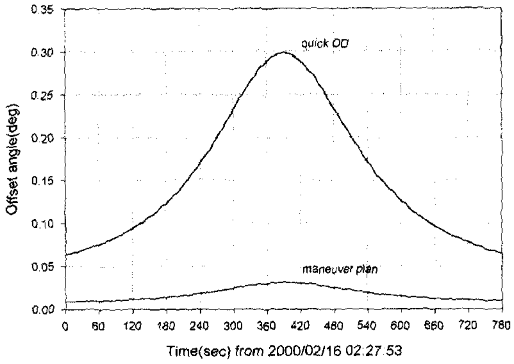

Fig. 13. Offset angle for antenna prediction.

2. Variation of the mean orbital elements after 2^{nd} IPM

The mean orbital elements of the KOMPSAT-1 after the 2^{nd} in-plane orbit maneuver is propagated using the Long-Term Orbit Propagator developed by the NASA/JPL[6]. The orbit is decayed by the air drag effect that was modeled by exponential formula. Based on the mean orbital elements in Table 6, the orbit is propagated for 4 years and the variation of the mean LTAN is derived. Fig. 14 shows the variation of the mean semi-major axis for the 4 years when the semi-major axis was maintained within the nominal orbit of the KOMPSAT-1. The maximum atmospheric density was applied to orbit propagation.

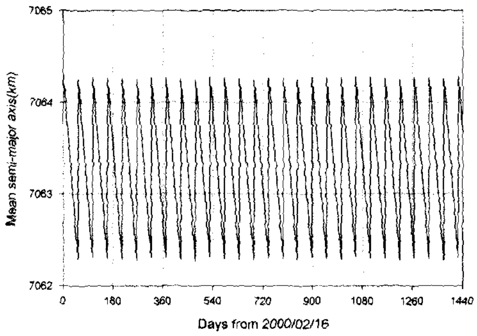

Fig. 14. Mean semi-major axis variation.

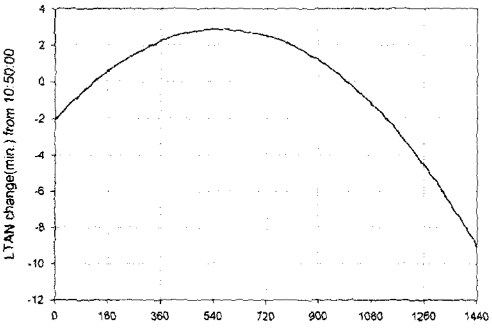

Fig. 15. Mean LTAN variation.

Fig. 15 shows the mean LTAN variations from the nominal KOMPSAT-1 LTAN value of 10:50 AM. The mean LTAN is increased upto 10:53 AM after one and half years and then decreased to 10:47 after three years and then decreased further to 10:40 after 4 years. No additional out-of-plane maneuver for controlling LTAN is required for 4 years.

Fig. 16 shows the mean inclination variations. The inclination is reflected to the mean LTAN variations in Fig. 15.

Fig. 17 shows the mean argument of perigee vs. mean eccentricity plot for 4 years. Near frozen orbit is achieved after the 2^{nd} in-plane orbit maneuver. The mean argument of perigee is maintained in 90 ± 13 degrees.

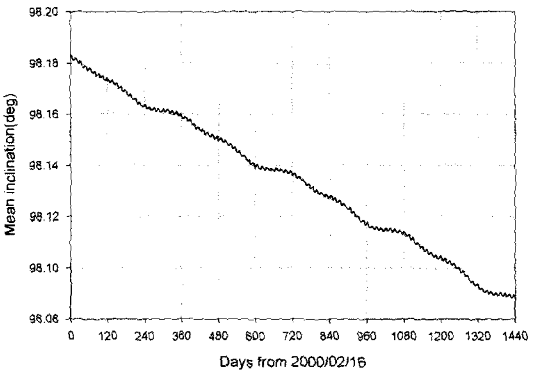

Fig. 16. Mean inclination variation.

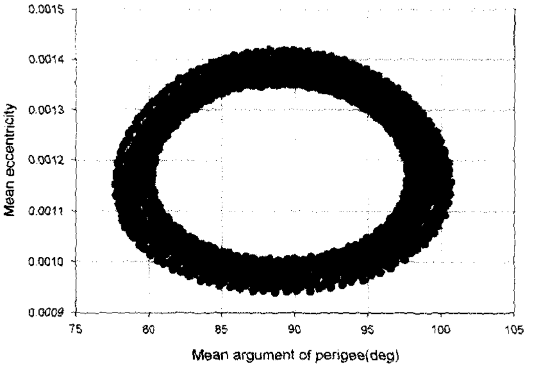

Fig. 17. Mean argument of perigee vs. eccentricity plot.

IV. Conclusions

Quick evaluations of two in-plane orbit maneuvers using small sets of real-time GPS navigation solutions were performed for the KOMPSAT-1 spacecraft operation. The results were used for antenna pointing data predictions for the next station contact. Normal orbit maneuver evaluations using large sets of playback GPS navigation solutions were also performed and the result were compared with the quick evaluation results.

Quick evaluation of the first in-plane orbit maneuver turned out to be very useful because the evaluation shows that the maneuver was undershot. Also, the errors in antenna pointing predictions using quick orbit determination were small enough for automatic tracking of the KOMPSAT-1.

Quick evaluation of the second in-plane orbit maneuver turned out to be less accurate than that of maneuver planning. It was because the thruster calibration factor for maneuver planning was much improved after evaluations of the previous three orbit maneuvers, and the quick orbit determination was performed using only 6 sets of the post-burn data. However, the antenna prediction using quick evaluation was good enough for acquisition of the spacecraft.

Quick evaluation of the orbit maneuver should be used for the fast realization of the maneuver. It is also used for the antenna pointing predictions for re-acquisition of the signal after maneuver when the thruster is not fully calibrated in launch and early orbit phase operation.

References

[1] B.-S. Lee, J.-S. Lee, and J.-A. Kim, "Post launch mission analysis for the KOMPSAT-1", J. Astron. and Space Sci., vol. 17, no. 2, pp. 285 – 294, 2000.

[2] C.-H. Won, J.-S. Lee, B.-S. Lee, and J.-W. Eun, "Mission analysis and planning system for korea multipurpose satellite-1", ETRI Journal, vol. 21, no. 3, pp.29 – 40, Sep. 1999.

[3] B.-S. Lee, J.-S. Lee, C.-H. Won, J.-W. Eun, H.-J. Lee, K.-M. Lee, Y.-M. Choi, C.-M. Lew, H.-D. Kim, and S.-J. Park "Test of the KOMPSAT mission analysis and planning software", *Proceedings of the KSAS Fall Annual Meeting '98*, Nov. 14, pp. 559 – 563, 1998.

[4] B.-S. Lee, J.-S. Lee, C.-H. Won, J.-W. Eun, and H.-J. Lee, "Orbit determination and maneuver planning for the KOMPSAT spacecraft in launch and early orbit phase operation", *Proceedings of the 14th KACC,* pp.E-29 – E-32, *Oct. 1999.*

[5] B.-S. Lee and J.-S. Lee, "Sun interference predictions for the KOMPSAT TT&C station", *J. Astron. Space Sci.*, vol. 14, no. 1, pp.158 – 165, 1997.

[6] J. H. Kwok, *The Long-Term Orbit Predictor(LOP)*, JPL, Pasadena , 1986

[7] J. O. Cappelari, C. E. Velez, and A. J. Fuchs(eds.), *Mathematical Theory of the Goddard Trajectory Determination System*(GSFC : Maryland), pp. 4-53 – 4-57, 1976.

[8] B.-S. Lee, S. Lee, H.-J. Lee, J.-A. Kim, E.-K. Kim, and H.-J. Choi, "Near frozen orbit achievement of the KOMPSAT-1 spacecraft", Proceedings of the KSAS Spring Annual Meeting 2000, pp. 127 – 130, Apr. 29, 2000.

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