Analysis on the Long-term Orbital Evolution and Maintenance of KOMPSAT-2

Ok-Chul Jung[1]
Korea Aerospace Research Institute (KARI), 45 Eoeun-dong, Daejeon, South Korea, 305-333

Jung-Hoon Shin[2]
Korea Advanced Space Technology Agency (KASTA), 45 Eoeun-dong, Daejeon, South Korea, 305-333

and

Su-Jin Choi[3], Dae-Won Chung[4], Eun-Kyu Kim[5], and Hak-Jung Kim[6]
Korea Aerospace Research Institute (KARI), 45 Eoeun-dong, Daejeon, South Korea, 305-333

This paper introduces the flight dynamics operations of KOMPSAT-2, and summarizes the long-term orbital evolution and maintenance throughout the 5 years. In case of KOMPSAT-2, orbit determination, orbit prediction, and fuel estimation is carried out on a daily basis. And, most routine tasks are fully automated in order to reduce the human error, and to maximize the operational efficiency. With the operational results from daily activities, the orbital characteristics is examined and compared with theoretical orbit variation. In this paper, the orbital overlapping solution has been examined in order to check the accuracy level of the precise orbit determination. Using the 20 IGS station data and broadcasting GPS ephemeris as well as GPS pseudo-range and carrier phase data from KOMPSAT-2 flight data, the POD accuracy satisfies approximately 2-3 meter RSS in one sigma. This paper also describes the recent orbit maneuver activities, which includes maneuver planning, execution, and its evaluation. The objective of orbit maneuver was to change the LTAN (local time of ascending node) indirectly with inclination offset from ideal sun-synchronous orbit. The total 17 times thruster firings were successfully executed, and the results of orbit maneuver were almost same as initially planned and expected.

I. Introduction

KOrea Multi-Purpose SATellite-2(KOMPSAT-2) is an earth observation satellite, developed and operated by KARI (Korea Aerospace Research Institute), which was launched on July 28th, 2006. Mission orbit of KOMPSAT-2 is a sun-synchronous circular orbit with the altitude of 685.13 km +/-1 km. Orbit inclination is 98.13° ± 0.05 degrees and eccentricity is 0 to 0.001. Also, the satellite is to be operated in a nominal local time of ascending node of 10:50 A.M. +10/-15 min. The KOMPSAT-2 satellite was designed for an operational service life of 3 years on mission orbit. KOMPSAT-2 has successfully completed its original mission lifetime, and now its mission has been extended for further services to the users. KOMPSAT-2, equipped with an MSC (Multi-Spectral Camera) and capable to acquire 1 m resolution panchromatic images and 4 m resolution color images, can resolve a building and even a car. The high resolution images will be used for various applications such as surveillance of massive natural disasters such as earthquake, tsunami, utilization of mineral resources, construction of Geographic Information System (GIS), and cartography.

[1] Flight Dynamics Engineer, LEO Satellite Mission Operation Team, Satellite Information Research Center
[2] Flight Dynamics Engineer, Korea Advanced Space Technology Agency
[3] Flight Dynamics Engineer, LEO Satellite Mission Operation Team, Satellite Information Research Center
[4] Head of LEO Satellite Mission Operation Team, Satellite Information Research Center
[5] Director of Satellite Operation Division, Satellite Information Research Institute
[6] Principle Research Engineer, Satellite Information Research Institute

Flight dynamics operations is one of the core activities in the satellite mission operations for comprehensive orbital analysis and mission planning support as well as orbit data provision for image processing enhancement. Main activities of flight dynamics operations include orbit determination, orbit prediction, orbit data provision, mission analysis and orbit maneuver planning, and fuel accounting. In order to support of mission operations, orbit determination, prediction, and precise ephemeris data provision are fully automated. This enables flight dynamics engineers to reduce their workload and focus on the other activities, for example, future mission preparations.

This paper introduces the operational result of KOMPSAT-2 for 5-years (from launch to current), and represents the orbital characteristics of KOPMSAT-2. In chapter II, the variations of mean orbit of KOMPSAT-2 including semi-major axis, inclination, eccentricity, right ascension of ascending node, and local time of ascending node are represented. In chapter III, the accuracy of precise orbit determination is examined using overlapping method. The maneuver planning, executions, and fuel estimation are also summarized in chapter IV.

II. Orbital Evolution of KOMPSAT-2

Mission orbit of KOMPSAT-2 was successfully achieved by launch vehicle with the tolerant range[1]. During LEOP (Launch and Early Operations Phase), the test calibration burn and in-plane maneuver were executed without any anomalous event. After commissioning phase, the orbit of KOMPSAT-2 keeps changing due to natural perturbation. Satellite orbit is affected by gravitational force of the Earth, atmospheric drag, luni-solar attraction, and solar radiation pressure and so on. These perturbation forces make the satellite deviate from its original mission orbit[2]. However, the amount of orbit variation was very small, thank to the low solar activities[3]. During the period of 2006-2011, solar cycle (F10.7cm radio flux) has the lowest value, which makes the small change of satellite altitude.

Figure 1 represents the mean altitude and eccentricity. The first in-plane maneuver was executed during LEOP, and the second in-plane maneuver was executed in 2011. Maneuver activities are described in more detail in later chapter. As mentioned earlier, daily decay rate of KOMPSAT-2 is very small, approximately 1 to 3 meters per day. And, the maximum difference between perigee and apogee altitude is 45.45km. This value is also changing with times due to eccentricity variation. Time histories of mean inclination and right ascension of ascending node is depicted in figure 2. In 2011, out-of-plane maneuver was executed in order to adjust the inclination and local time of ascending node. Yearly rate of inclination change of KOMPSAT-2 is about -0.03 degree/year, which is very similar to the analytical computation. And, the daily rate of right ascension of ascending node of KOMPSAT-2 is approximately 0.97-0.98 degree/day. In general, ideal value of secular rate of the right ascension of the ascending node for sun-synchronous orbit is 0.9856 degree/day. In case of KOMPSAT-2, this value is slightly different from ideal one, but it has no impact on mission operations. Figure 3 depicts the time history of local time of ascending node. It kept decreasing initially, but it started to increase after out-of-plane maneuver in 2011.

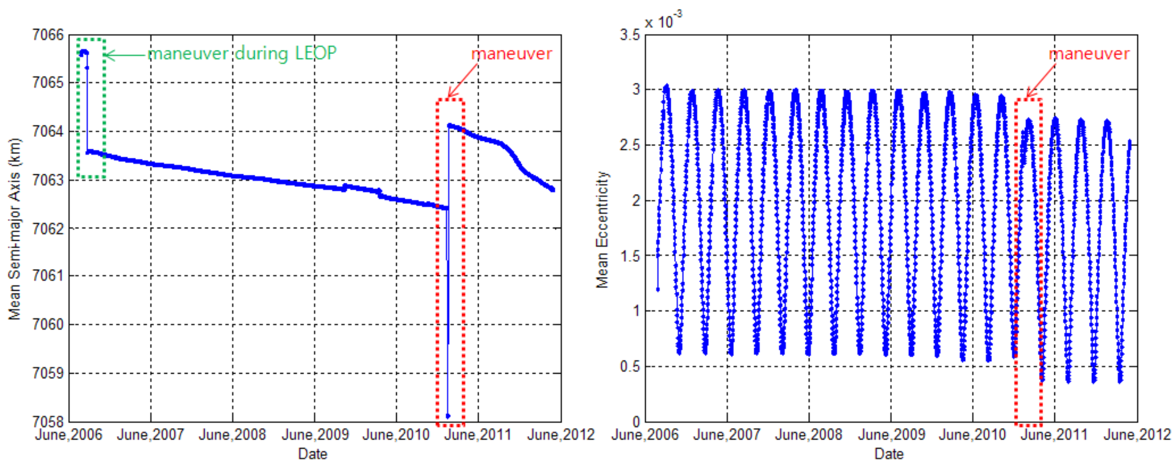

Figure 1. Time History of Mean Altitude and Eccentricity (From Launch to Current)

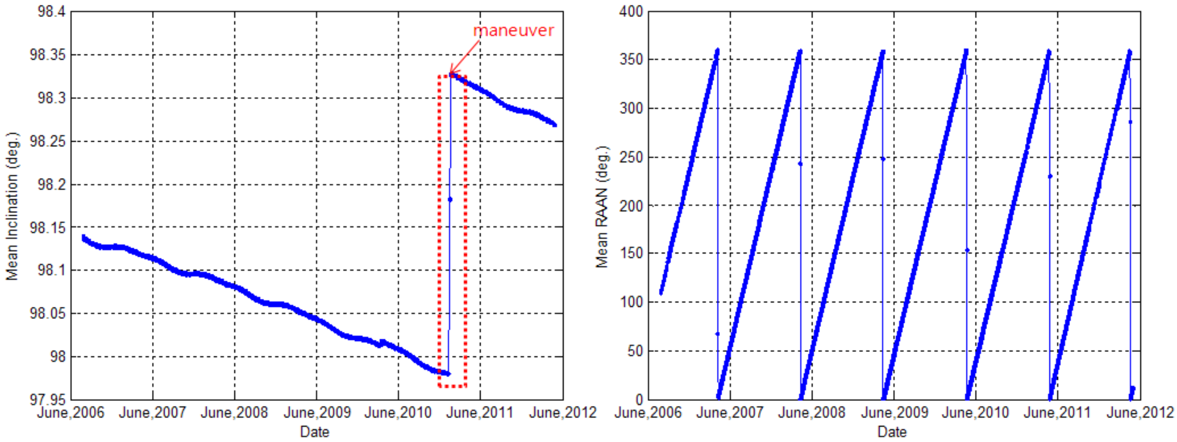

Figure 2. Time History of Mean Inclination and RAAN (From Launch to Current)

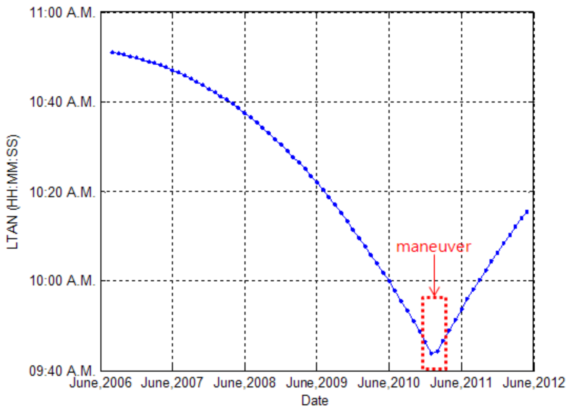

Figure 3. Time History of Local Time of Ascending Node (From Launch to Current)

III. Orbit Determination

KOMPSAT-2 carries TOPSTAR-3000 as a single frequency GPS receiver, which provides a reference time signal, GPS navigation solution, and raw GPS data including pseudo range, and carrier phase. Using these data, orbit determination is executed on a daily basis. There are two kinds of orbit determination process, which is called operational orbit determination and precise orbit determination. The operational orbit determination uses the GPS navigation solution only as observations. On the other hand, the precise orbit determination makes use of the raw GPS data of KOMPSAT-2 and world-wide distributed IGS station data. In addition, double differenced GPS measurements are internally generated using two GPS satellites and two IGS stations. This eliminates the common biases of clock, and hardware. Therefore, the accuracy of the precise orbit determination is better than the operational orbit determination.

In order to check the accuracy level of the precise orbit determination for KOMPSAT-2, the orbital overlapping solution has been examined. The overlapping method is a common approach for evaluating the POD accuracy, which compares ephemerides that are adjacent in time[4,5]. In this paper, data arc length of 27 hours (1 day and 3 hours) is processed with 4-hour overlap in order to eliminate the end effect. Basic scheme of overlapping method is shown in figure 4. The total 20 IGS stations are processed, and their selection is taken into account global distribution as shown is figure 5. The contour in figure 4 represents the elevation angle of 20 degree between ground stations and GPS satellites considering elevation cut-off angle. The precise orbit determination is executed by MicroCosm software by Van Martin Systems, Inc.[6] The initial condition of the estimation came from the result of operational orbit determination. Microcosm has three steps to determine the orbit of LEO (Low Earth Orbit) satellite. Step-1 uses GPS carrier phase double differential measurements from 20 ground based receivers to determine the orbits of the entire GPS constellation. Step-2 uses GPS navigation solution of KOMPSAT-2 to determine the position of it. Finally, step-3 uses the GPS orbit solutions from step-1 and orbit ephemeris from step-2 to determine the orbit of KOMPSAT-2 precisely.

Table 1 summarized the RMS of position difference in Earth-centered and Earth-fixed (ECEF) coordinate. Two sample periods were arbitrarily chosen every year, that is June 10th, December 10th, in order to check the long-term evaluations. The POD accuracy satisfies approximately 2-3 meter RMS in one sigma.

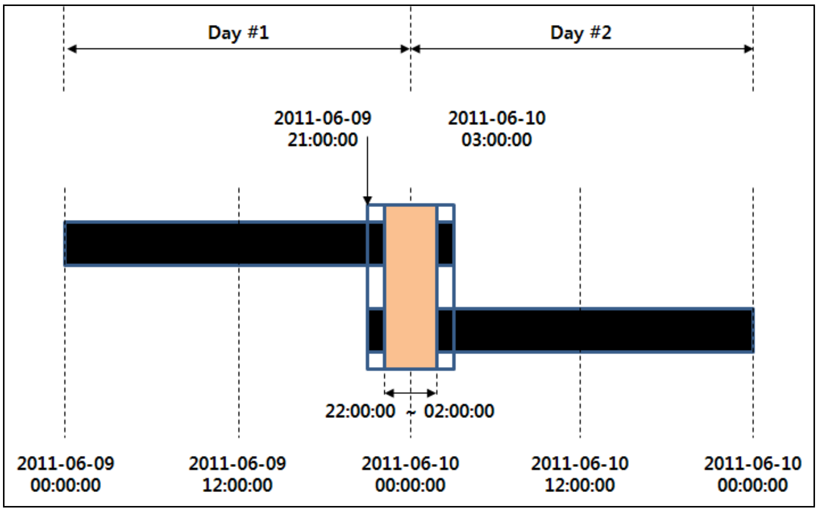

Figure 4. Schematics of POD Overlapping Method

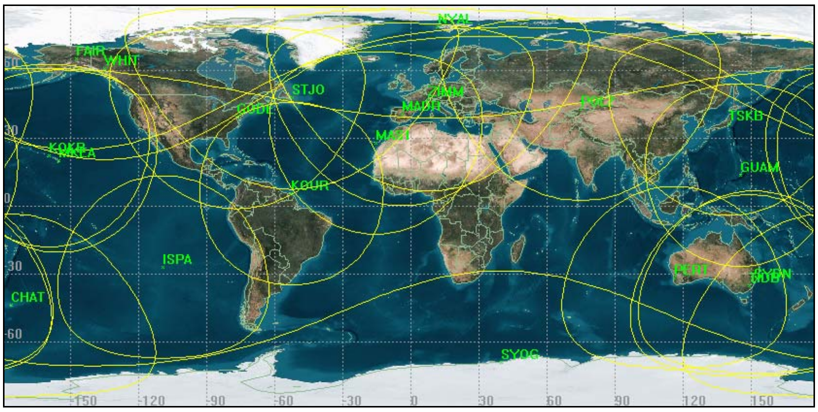

Figure 5. IGS Stations Selected for POD Evaluation

Table 1. POD Overlapping Solution: ECEF Position Difference

	X in ECEF (m)	Y in ECEF (m)	Z in ECEF (m)	3D (m)
Jun, 2007	0.7295	0.6029	0.4858	1.0638
Dec, 2007	0.4748	0.5258	0.5268	0.8828
Jun, 2008	0.5395	0.2922	0.6514	0.8949
Dec, 2008	1.0808	0.4528	0.9181	1.4886
Jun, 2009	0.5821	0.2369	0.5446	0.8316
Dec, 2009	0.9711	0.7098	1.2792	1.7558
Jun, 2010	1.1044	0.8635	1.3664	1.9577
Dec, 2010	0.9188	0.8489	1.0315	1.6214
Jun, 2011	0.5046	0.3216	0.7241	0.9394
Dec, 2011	1.5105	1.1033	2.2158	2.8998
Average	0.8416	0.5958	0.9744	1.4336

Figure 6 represents the time histories of position x, y, and z-difference in ECEF coordinate (Left: June 10th, Right: December 10th). The worst results are shown in December 2011, which has maximum difference of 3 meter in 3D range. At the end of 2011, the F10.7cm radio flux indicated the higher value than other periods, i.e. 2007-2009, and started to rise. This might cause the degradation of orbit determination accuracy. In order to enhance the POD accuracy, best combination IGS station data should be selected and final product of GPS ephemeris should be considered. In addition, the general empirical acceleration should be included in estimation process to compensate for the unknown dynamics model.

The left side of figure 7 depicts the position difference between precise orbit determination and operational orbit determination. Assuming the precise orbit determination as a reference orbit, we can check the operational orbit determination has an accuracy of less than 10 meter in one sigma. And, the right side of figure 7 is position difference between operational orbit determination and GPS navigation solution, which is determined by onboard GPS receiver. Without 53 bad data not shown in figure, GPS navigation solution of KOMPSAT-2 has an accuracy of less than 30 meter in one sigma.

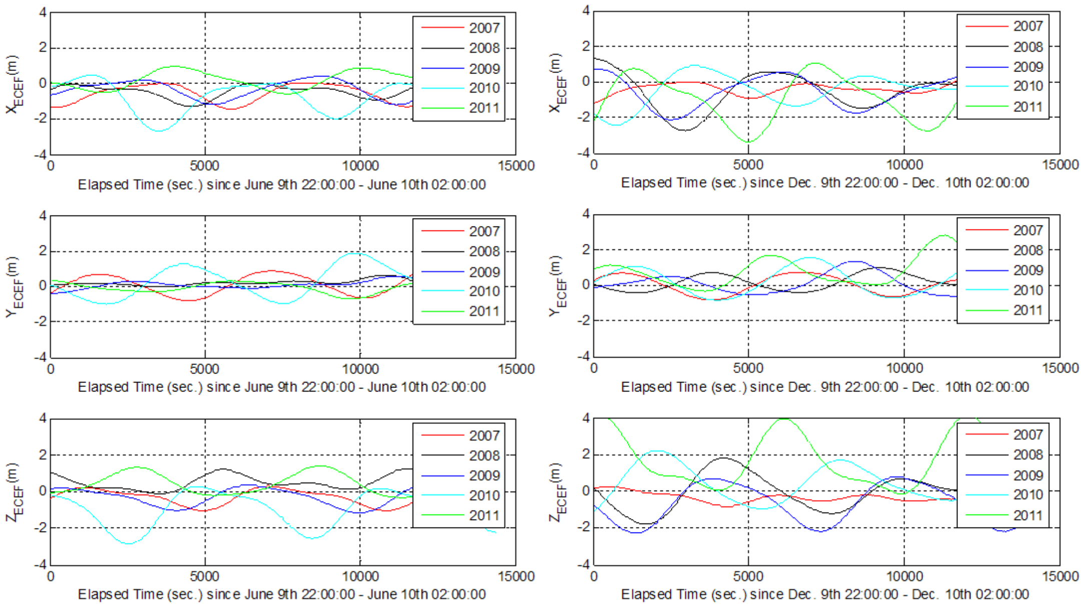

Figure 6. Time Histories of POD Overlapping Solution

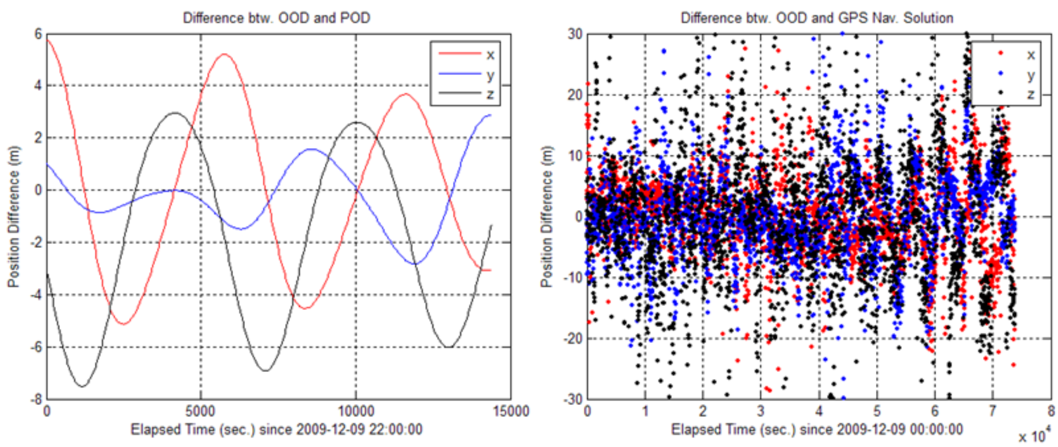

Figure 7. Position Difference between POD vs. OOD [Left] and OOD vs. GPS Nav. Solution [Right]

IV. Orbit Maneuver

The mission orbit of KOMPSAT-2 was achieved during LEOP, but the orbit continues to drift gradually due to the various perturbation forces. And, the inclination and local time of ascending node had started to deviate from mission orbit since the end of 2009. At this time, the altitude was 684.65km, still in operational range. However, the inclination was 98.023 degree, and local time of ascending node was 10:12 A.M., which is slightly out of range. In order to change the local time of ascending node directly, the required delta velocity should be 1.266 km/second, which is not feasible solution. To resolve this, the flight dynamics team carried out the various trade-off studies to establish an optimal planning strategy for orbit maneuver. The proposed solution was to increase the inclination more than that of sun-synchronous orbit, and then local time of ascending node could be indirectly adjusted with time. In other word, the inclination was increased with additional bias (+0.2 degree), keeping the altitude of sun-synchronous orbit.

The phase-1 of orbit maneuver was to increase the inclination into 98.13 degree (the same value of sun-synchronous orbit with 685.13km), which requires 7-8 times of 300 seconds delta-V burn. The inclination change with 1 burn of 300 seconds was expected to be 0.025 degree. After the phase-1 execution and evaluation, the phase-2 was also prepared. The objective second phase was to increase the inclination with additional 0.2 degree in order to have an inclination bias (offset) with respect to sun-synchronous mission orbit. And, the compensation of unexpected change of altitude due to misalignment of del-V direction was also considered in phase-2.

Out-of-plane maneuver was executed at the descending node with roll attitude maneuver -90 degree. The total 15 times thruster firings were successfully executed for inclination change. In similar way, the 2 times thruster firing with pitch attitude maneuver +90 degree was done to make up the altitude change. Total fuel consumption was 20.66kg. Table 2 summarizes the detailed result of each orbit maneuver execution. The altitude change in No. 1-15 was induced from unwanted velocity component in along-track direction.

Table 2. Summary of Orbit Maneuver Result

	No.	Altitude Change (km)	Inclination Change (deg.)	Fuel Consumption (kg)
Phase-1: 2011-01-11 ~2011-01-12	1	-0.66	+0.028	1.67
	2	-0.62	+0.027	1.41
	3	-0.48	+0.026	1.36
	4	-0.54	+0.025	1.32
	5	-0.54	+0.025	1.30
	6	-0.49	+0.024	1.29
	7	-0.57	+0.023	1.22
	8	-0.41	+0.023	1.21
Phase-2: 2011-01-18 ~2011-01-20	9	-0.49	+0.023	1.22
	10	-0.37	+0.022	1.21
	11	-0.52	+0.021	1.15
	12	-0.31	+0.021	1.12
	13	-0.44	+0.020	1.15
	14	-0.42	+0.020	1.12
	15	-0.42	+0.019	1.10
	16	+4.49	+0.001	1.00
	17	+4.50	+0.001	0.88
Total	17 times	1.7 km	0.35 deg.	20.66 kg

Table 3 shows the priori and posterior orbital elements by executing orbit maneuver. After maneuvering, orbit altitude and inclination was successfully achieved as planned. Local time of ascending node is slowly increasing at a rate of 2 minutes per month. At the end of 2012, it is expect to reach 10:30 A.M., which is original mission orbit. Therefore, flight dynamics team is preparing the upcoming activities for orbit maneuver for the inclination recovery.

Table 3. Priori and posterior orbital elements

Orbital Elements	Before Maneuver	After Maneuver	Change
Altitude	684.27 km	685.976 km	1.706 km
Inclination	97.979 deg.	98.328 deg.	0.349 deg.

Figure 8 depicts the remaining fuel by calculating PVT method with spacecraft telemetry. The remaining fuel onboard was estimated as 46.3kg (64% remained). With this amount of fuel available, there is no problem with extended mission operations.

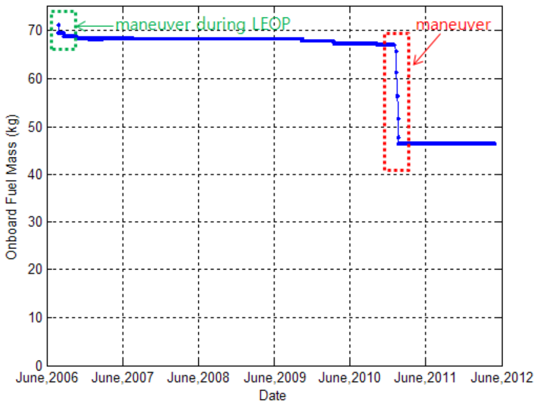

Figure 8. Time History of Fuel Mass (From Launch to Current)

V. Conclusion

This paper introduces the flight dynamics operations of KOMPSAT-2, and summarizes the long-term orbital evolution and maintenance throughout the 5 years. Flight dynamics operations is one of the core activities in the satellite mission operations for comprehensive orbital analysis and mission planning support as well as orbit data provision for image processing enhancement. Main activities of flight dynamics operations include orbit determination, orbit prediction, orbit data provision, mission analysis and orbit maneuver planning, and fuel accounting. Most routine tasks are fully automated in order to reduce the human error, and to maximize the operational efficiency. In order to check the accuracy level of the precise orbit determination for KOMPSAT-2, the orbital overlapping solution has been examined. With 10 cases investigated, the POD accuracy satisfies approximately 2-3 meter RMS in one sigma. This paper also describes the recent orbit maneuver activities, which includes maneuver planning, execution, and its evaluation. The objective of orbit maneuver was to change the LTAN (local time of ascending node) indirectly with inclination offset. After the execution of 15 out-of-plane maneuvers and 2 in-plane maneuvers, orbit altitude and inclination was successfully achieved as initially planned. Local time of ascending node is slowly increasing at a rate of 2 minutes per month. Lessons learned from these operational flight dynamics activities are expected to be valuable assets for the upcoming satellite mission operations.

References

[1]Hae-Dong Kim, Ok-Chul Jung, Eun-Kyu Kim, Hyo-Choong Bang, "Orbit Determination and Orbit Maneuver Performance for the KOMPSAT-2," *Proceeding of the 2006 Korean Society for Aeronautical and Space Science Fall Conference*, 2006.

[2]Vladimir A. Chobotov, *Orbital Mechanics, Second Edition*, AIAA, 1996.

[3] http://www.swpc.noaa.gov

[4]Yoola Hwang, Byoung-Sun Lee, Young-Rok Kim, Kyoung-Min Roh, Ok-Chul Jung, and Haedong Kim, "GPS Based Orbit Determination for KOMPSAT-5 Satellite," *ETRI Journal*, Vol. 33, No. 4, 2011, pp. 487-496.

[5]Schutz, B, Rim, H, Webb, C, Yoon, S, Shelus, P, "Precision Orbit Determination, Validation and Orbit Prediction for ICESat," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, 2008.

[6] http://www.vmsi-microcosm.com