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ALSAT-2A MISSION: EXPERIENCE OF THREE YEARS OF STATION KEEPING ORBIT MAINTENANCE

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On 12th July 2010 at 03h52’ UT, ALSAT-2A has been launched by PSLV-C15 from Sriharikota, Chennaï (India). Nine days after, the satellite has been placed on its mission orbit. This paper describes the in-orbit results of the orbit maintenance maneuvers performed by using a new version of flight dynamics software. The obtained results on the ground track corrections demonstrate that with the new version, the realization of small maneuvers become as accurate as for strong ones.

INTRODUCTION

ALSAT-2A is the second Earth Observation spacecraft for Algeria and it is the first satellite of a constellation composed of two identical satellites. ALSAT-2B is the second satellite of the constellation planned to be launched on early of 2015 and will be phased with ALSAT-2A. The reference mission orbit of ALSAT-2A is a phased Sun-synchronous orbit with 14+19/29 revolutions per day repetitivity of ground track and an altitude over equator around 670 km.

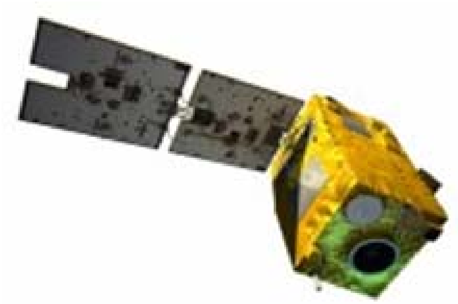

Figure 1. View of ALSAT-2A spacecraft.

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The satellite ALSAT-2A is composed of an optic payload capable to acquire images with a resolution of 2.5 m in panchromatic mode, 10 m in multispectral mode and a swath of 17.5 m for both modes. The satellite is 3-axis stabilized. Attitude sensing is provided by three sun sensors, a star sensor, a magnetometer, and an inertial measurement unit. The actuation is provided by four reaction wheels and three magnetorquers. A GPS receiver is used for onboard location and time services. The spacecraft has a body-pointing capability of ±30º in along and cross-track.[1]

The electric power subsystem is based on GaAs solar array providing a power of 180 Watt at the end of life, a Li-ion battery of 15 Ah capacity and a module for management and distribution. The communications with the ground segment are provided in X-band with a useful downlink rate of 56 Mb/s for image telemetry and in S-band with a downlink rate of 384 kb/s for house-keeping telemetry and an uplink rate of 20 kb/s for telecommand.[1]

The propulsion subsystem is identical to the generic definition of Myriade. It is a mono propellant system based on hydrazine and operating in decreased pressure mode also called blow down. It is composed of four thrusters which each one is equipped with two valves in series and are controlled to realize the maneuvers. These thrusters can operate in continuous mode or pulsed mode. The spacecraft has a total mass of 120 kg and a nominal lifetime of 5years.[1]

On 12th July 2010 at 03h52' UT, ALSAT-2A has been launched by PSLV-C15 from Sriharikota, Chennaï (India). On 21st July, the satellite has been placed on its mission orbit. This was the starting point of the station keeping and routine operations to be performed daily by flight dynamics team in order to remain the evolution of the ground track and the local solar time within predefined control windows by performing several maneuvers. The maneuvers can be performed in in-plane to correct the semi-major axis or in out-of-plane to correct inclination. In practice, the frequency of the out-of-plane corrections is less than the frequency of in-plane corrections but more expensive in velocity increment ΔV. In order to save propellant, the station keeping strategy considered to control the phasing of the ground track is based on the in-plane corrections. To fulfil this strategy, the target orbit reached at the beginning of life has been optimised to avoid corrections of the local solar time at least during the nominal mission lifetime. This orbit is defined by a semi-major axis of 7048 km and an inclination of 98.23 deg. At the end of the LEOP phase, the station keeping initial conditions were a ground track error of +39 km and a local solar time of 21:30 PM.[1]

During the first three years of operations, many Orbit Control Maneuvers OCM were performed as regular station keeping OCM for ground track corrections and two OCM were performed as collision avoidance maneuvers due to the space objects close approach to ALSAT-2A on April and July 2012. The magnitudes of these maneuvers were small and have been performed with an over efficiency up to ±22%. To overcome this problem, a new version of the flight dynamics software has been developed and implemented from mid of 2012. With the new version, the small maneuvers are now realized as expected by the mission team. The in-orbit results and the accuracy of many performed maneuvers are described in the following sections.

STATION KEEPING ORBIT MAINTENANCE

The orbit maintenance strategy to be considered shall not disturb the payload operation. Therefore, the station keeping shall be optimized to plan only necessary maneuvers. The two parameters to be considered are ground track error and local solar time error. Ground track of the orbit is defined as the locus of points projected on the Earth's surface directly "beneath" the spacecraft orbit. It is recalled that the decrease of the semi-major axis depends on the satellite mass and the projected surface. The projected surface taken into account for the air drag perturbation calculation depends on the mean argument of latitude of the satellite.[3] The attitude mode for air drag effect estimation considered is that ALSAT-2A is pointing towards the Earth in the eclipse zone. Out of the eclipse zone it is inertial sun pointed.[4]

For sun-synchronous orbits, the sun attraction creates an inclination secular drift in which magnitude depends on the local solar time. The evolution of the mean solar local time depends highly on the evolution of the mean inclination. In theory, only the second term of the earth potential J2 is always considered because the fluctuations of this term affect strongly the evolution of the parameters of orbit compared to the next terms of the earth potential.

The acceleration on the solar local time affected by the inclination secular drift is estimated as[5]

$$\frac{d^2}{dt^2}(\Delta H) \approx -\frac{T_{TE}}{T_{SO}}.\left[\tan i\frac{di}{dt} + \frac{7}{2a}.\frac{da}{dt}\right] \tag{1}$$

where, *da/dt* is the semi-major axis secular drift and *di/dt* is the inclination secular drift due to sun attraction, calculated by[5]

$$\frac{di}{dt} \approx \frac{3\pi}{2}.\frac{T_0}{T_{SO}^2}.\sin i.\cos^4\left(\frac{i_{SO}}{2}\right).\sin\left[4\pi\left(\frac{H}{T_{TE}} - \frac{1}{2}\right)\right] \tag{2}$$

i_{SO} is the inclination of the ecliptic equal to 23.439 deg, T_{SO} is the sun period equal to 31557600 second, and T_{TE} is the period of a mean solar day equal to 86400 second.

The evolution on the ground track affected by the inclination secular drift and the semi-major axis secular drift is estimated as[5]

$$\frac{d^2}{dt^2}(\Delta\ell_0) \approx -\frac{3\pi}{T_{TE}}.\left(\frac{a_e}{a}\right).(1+\varepsilon)\left[\left(\frac{da}{dt}\right) - \left(\frac{da}{di}\right)_P.\left(\frac{di}{dt}\right)\right] \tag{3}$$

where,

$$\left(\frac{da}{di}\right)_P = -\frac{2}{3}.a\tan i.\frac{T_{TE}}{T_{SO}}.\frac{(1+\eta)}{(1+\varepsilon)} \tag{4}$$

$$\varepsilon \approx \frac{7}{3}\frac{T_{TE}}{T_{SO}} + \frac{7}{2}J_2\left(\frac{a_e}{a}\right)^2\left(4\cos^2 i - 1\right) \tag{5}$$

$$\eta = 12J_2\left(\frac{T_{SO}}{T_{TE}}\right)\left(\frac{a_e}{a}\right)^2\cos^2 i \tag{6}$$

The station keeping strategy consists to remain the evolution of the ground track and the local solar time within predefined control windows by performing several maneuvers. The maneuvers can be performed in in-plane to correct the semi-major axis or in out-of-plane to correct inclination. Due to the time varying nature of the perturbations on the orbit, deviations from the reference orbit lead to ground track drift. To understand this, consider the orbit as it crosses the equator (called ground track error), as the earth rotates from one node crossing to the next the ground track moves westward. If the orbital period is exactly right, successive node crossings match successive reference nodes. If the period is too short, the earth does not rotate quite far enough, and the true node falls eastwards of the reference node. If the period is too long, the earth rotates too far, and the true node falls westwards. After several orbits, the ground track moves further and further to one direction or another and a ground track drift develops. Ground track maintenance maneuvers must be performed to maintain the ground track within a predefined control window around the reference ground track. For ALSAT-2A, this window is ±40 km as shown in Figure 2.

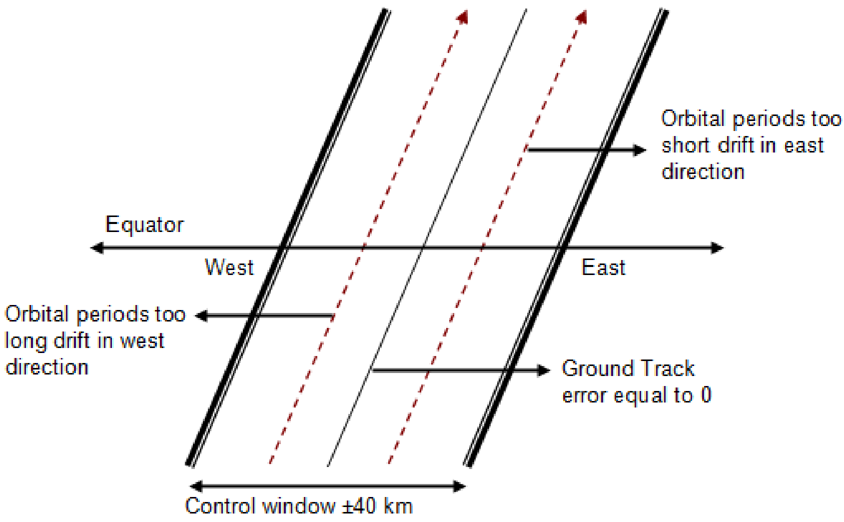


Figure 2. Ground track drift measured at the equator.

Regarding the evolution of the solar local time, for the reference value of 21h50, the inclination secular drift and the acceleration on the solar local time are estimated respectively to -0.036417 deg/year and -6.13 minute/year2.[4] Figure 3 presents the evolution of the mean solar local time when the initial parameters are voluntarily and optimally biased to reduce the number of maneuvers. In the case of ALSAT-2A, the mean solar local time can be limited between 21h30 and 22h10 around the mission value over 5 years without any inclination corrections. The initial Δi can be performed directly by the launcher or by the satellite when it is in piggyback configuration.

In practice, the frequency of the out-of-plane corrections is less than the frequency of in-plane corrections but more expensive in ΔV. In order to save propellant, the station keeping strategy considered to control the phasing of the ground track is based on the in-plane corrections. No corrections of inclination will be performed as explained in (Reference 2).

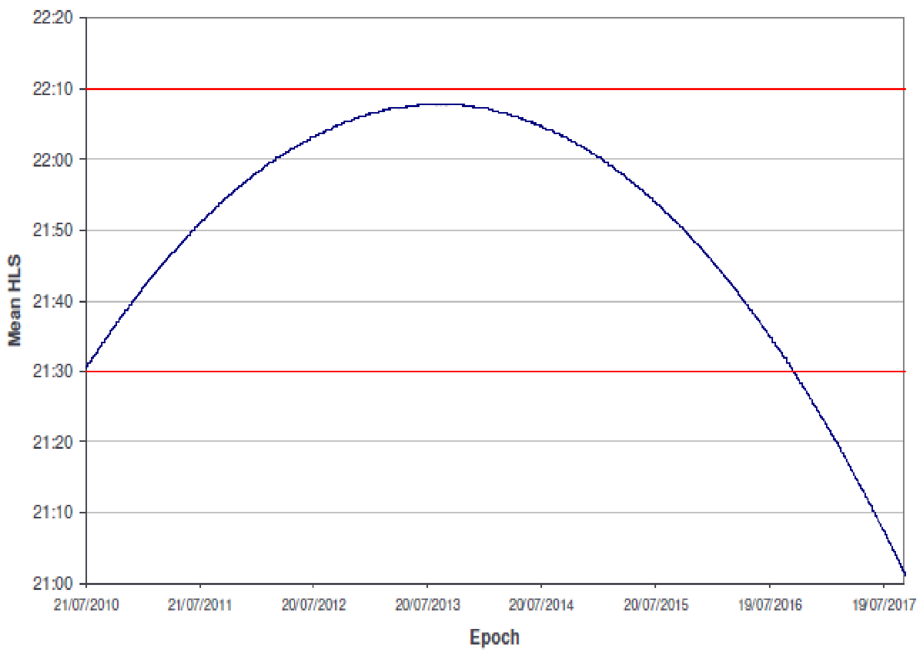


Figure 3. Mean solar local time evolution predicted at the end of transfer.

IN-ORBIT RESULTS

In practice, the operators performed station keeping long-term prediction based on weekly basis to check evolution of ground track and local solar time. The ground track and local solar time real evolutions since the LEOP have demonstrated that with the real solar activity and the others perturbations, the maneuver size and epoch are not exactly the predicted values. In fact the semi-major axis decreases not as expected. Then the maneuver is refined, implemented, simulated and checked before being sent to the spacecraft. Then the corresponding satellite Tele-command plan has been generated and uploaded. After the maneuver, OCM performance is assessed in order to compute calibration coefficient that will be used for next maneuver.

As explained higher, the small maneuvers calculated using the first version of the flight dynamics software are generally less accurate. This problem has been already observed during the transfer phase where a strong over-efficiency has been observed for small OCM as the propulsion model used was known to be less accurate for small maneuvers.[2] Table 1 summarizes the efficiency observed on each couple of maneuvers performed during LEOP phase. A slight over-efficiency was observed for long OCM. However an over efficiency up to 25 % was observed when the amplitude of maneuvers were small. This phenomenon still observed during the first years of station keeping maneuvers.

Table 1. Computed and realized transfer plan.

OCM Summary			Computed		Observed		
	Date	PSO (deg)	ΔV_T (m/s)	ΔV_N (m/s)	ΔV_T (m/s)	ΔV_N (m/s)	Efficiency
OCM1	14/07/2010 12:46:26	167	0.374	0.000	0.390	-0.098	+5.4
OCM2	14/07/2010 15:40:22	90	0.374	0.000	0.394	0.026	+5.4
OCM3	16/07/2010 01:24:02	10	2.670	1.074	2.499	1.053	-5.3
OCM4	16/07/2010 03:44:52	170	2.370	-1.074	2.279	0.921	-5.3
OCM5	17/07/2010 00:10:18	11	2.783	1.196	2.780	1.210	+0.25
OCM6	17/07/2010 02:30:53	169	2.483	-1.067	2.516	1.026	+0.25
OCM7	18/07/2010 00:36:09	8	2.420	1.775	2.439	1.709	+0.75
OCM8	18/07/2010 02/58/38	172	2.420	-1.775	2.451	1.774	+0.75
OCM9	19/07/2010 01:05:40	8	2.420	1.758	2.435	1.813	+0.95
OCM10	19/07/2010 03:28:25	172	2.420	1.758	2.478	1.760	+0.95
OCM11	20/07/2010 00:22:15	90	0.770	0.000	0.882	0.000	+14.9
OCM12	20/07/2010 03:38:39	90	0.770	0.000	0.882	0.000	+14.9
OCM13	21/07/2010 00:30:00	-4.35	0.320	0.000	0.353	0.033	+25.4
OCM14	21/07/2010 03:13:08	-126.58	0.346	0.000	0.378	-0.007	+25.4

Since the end of transfer phase, many station keeping maneuvers have been performed for ground track corrections and two avoidance maneuvers have been performed due to the space objects close approach to ALSAT-2A on April and July 2012.[6] Before the implementation of the new version of the flight dynamics software, many maneuvers of them have been performed with an over efficiency varying from -22 to 22 %. The investigations have demonstrated that the method followed in calculation of maneuvers does not fit accurately the propulsion model. This problem is also observed on other satellites based on the same platform or other spacecrafts when small maneuvers.[7] To overcome this problem, a new version of the flight dynamics software has been developed by Astrium and implemented on ALSAT-2 ground control centre from mid of 2012. The new algorithm is based on an iterative method which allows to take into consideration the spreading effect of a maneuver during its implementation. Indeed, spreading factor depends on the duration of the maneuver and further the force of the thrusters. On the other hand, the force of thrusters depends on the off-modulation rate per cycle and this one depends on the spreading factor. So, spread maneuvers are more efficient regarding maneuvers without spreading effect at a given off-modulation rate. Thus, to consider this cross-dependence, the new model is based on iterative method. At each iteration, the spreading is updated in the force models in order to converge at the end to a spread maneuver at the given off-modulation rate, and thus at forces accurately estimated.

With the new version, many station keeping maneuvers have been performed for ground track correction to prevent ALSAT-2A from exiting the ground track window. The performances of the last maneuvers performed respectively, on June, September, November 2013 and January 2014 are presented. The programmed maneuvers are summarized in Table 2.

On 23rd of June 2013, a correction of 805 m on the semi-major axis has been performed to prevent ALSAT-2A from exiting the ground track window on the east side. To correct the eccentricity as well, the maneuver was divided into two OCM of +310m and +495m. These maneuvers were designed to be robust to a 5% maneuver realization uncertainty. Figure 4 shows the satellite depointing on the three axes during maneuvers. The experience has demonstrated that when the commanded OCM maneuvers were assumed to thrust only in the tangential direction, some transverse components were observed after execution. Their magnitude are not negligible when the maneuvers are small.[2] After calibration, a small over performance with a global satellite depointing of -1.7 deg have been estimated. An over performance of +17 m on semi-major axis and a small involuntary correction on inclination of 0.00053 deg have been observed.

On 10th of September 2013, a correction of -250 m on the semi-major axis has been performed. To correct the eccentricity, the maneuver was divided into two OCM of -318 m and +68 m and was designed to be robust to a 5% maneuver realization uncertainty. The programmed maneuvers are summarized in Table 2. After calibration, An under performance of 8 m on semi-major axis, a small involuntary correction on inclination of -0.0004 deg and a global satellite depointing of 3.21 deg have been observed. Figure 5 illustrates the satellite depointing on the three axes during maneuvers.

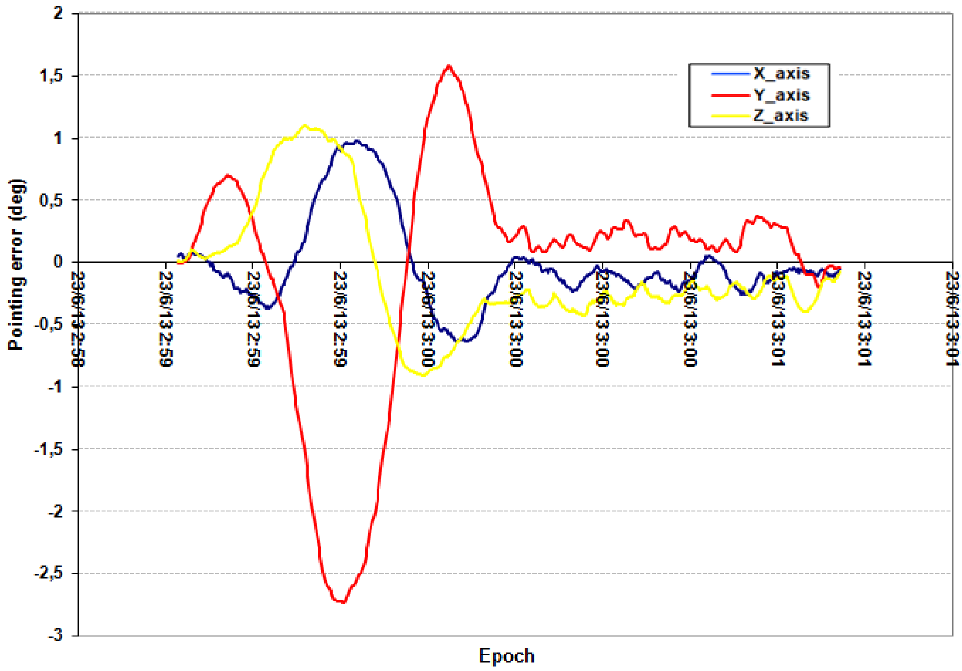
On 26th of November 2013 a correction of +505 m on the semi-major axis has been performed. To correct the eccentricity as well, the maneuver was divided into 2 OCM. After calibration, a small over performance of +3 m on semi-major axis, a small involuntary correction on inclination of -0.00038 deg and a global satellite depointing of 2.8 deg on the OCM1 and 0.4 deg on the OCM2 have been observed. The satellite depointing on the three axes during maneuvers is depicted in Figure 6.

And finally, on 26th of January 2014 a correction of +280 m on the semi-major axis has been performed. After calibration, a small over performance of +12 m on semi-major axis, a small involuntary correction of -0.0002 deg on inclination and a global satellite depointing of 1.35deg on the OCM1 and 5.56 deg on the OCM2 have been observed. Figure 7 illustrates the satellite depointing on the three axes during maneuvers.

All these maneuvers have been realized with a small over efficiency less than 5% and confirm that with the new version of flight dynamics software, the realization of small maneuvers become as accurate as for large ones. Table 2 summarizes a comparison between the calculated and the realized corrections using the new version of flight dynamics software.

Table 2. Computed and realized corrections using new version of flight dynamics software.

OCM Summary	Computed corrections		Computed maneuvers			Observed corrections	
Date	Δa (m)	Δi (deg)	OCM	ΔV_T (m/s)	ΔV_W (m/s)	Δa (m)	Δi (deg)
23/06/2013	805	0.000	OCM1 OCM2	0.1766 0.2526	0.00 0.00	822	0.00053
10/09/2013	-250	0.000	OCM1 OCM2	-0.1648 0.0423	0.00 0.00	-242	-0.00040
26/11/2013	505	0.000	OCM1 OCM2	0.1204 0.1477	0.00 0.00	508	-0.00038
26/01/2014	280	0.000	OCM1 OCM2	-0.0249 0.1745	0.00 0.00	292	-0.00020



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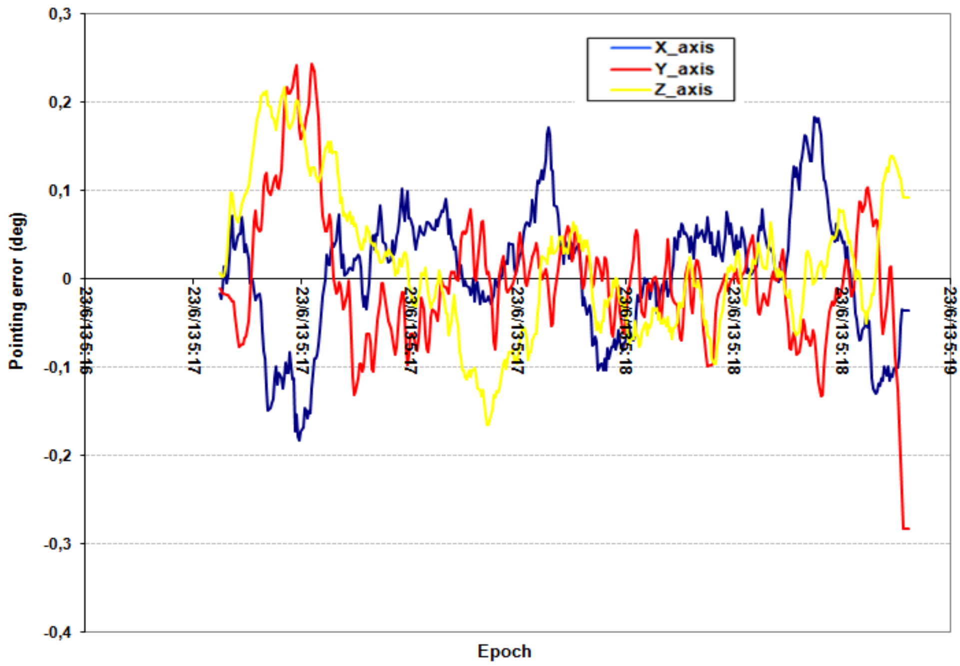
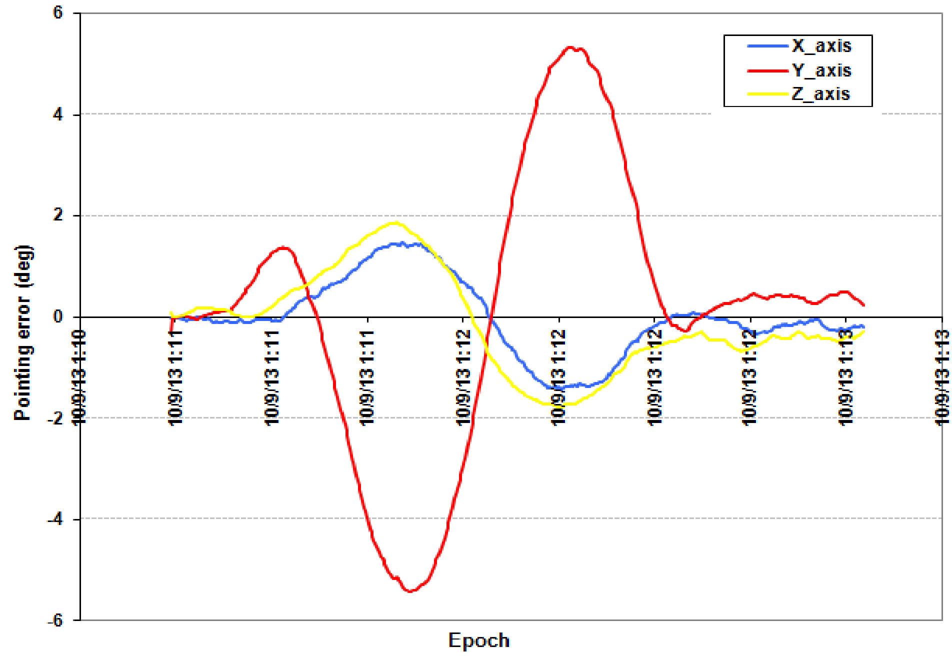


b)

Figure 4. Satellite depointing on the three axes during maneuvers performed on June 2013.
***a)* OCM1, *b)* OCM2.**



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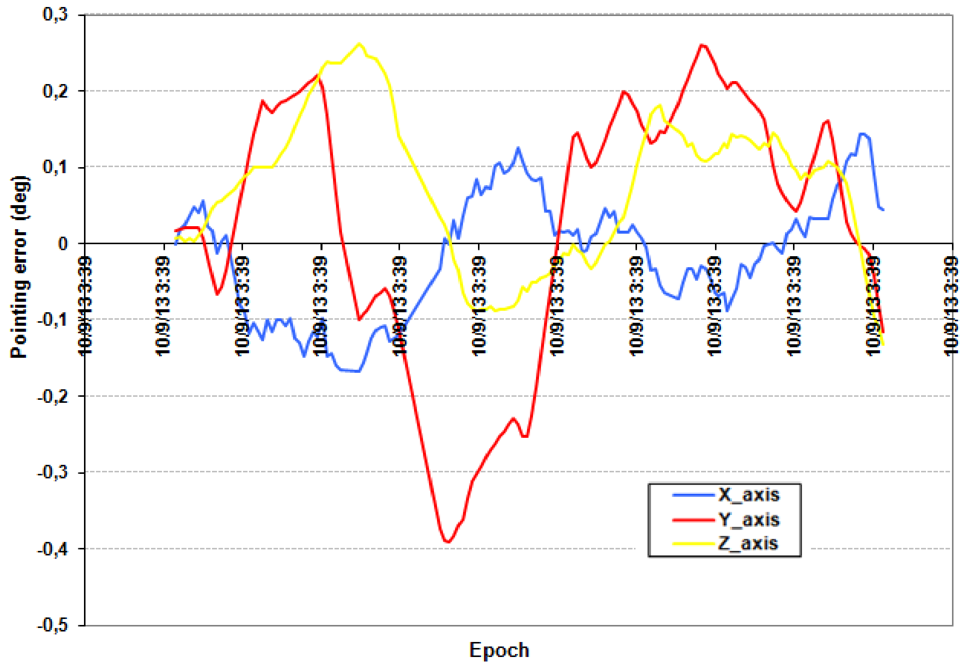
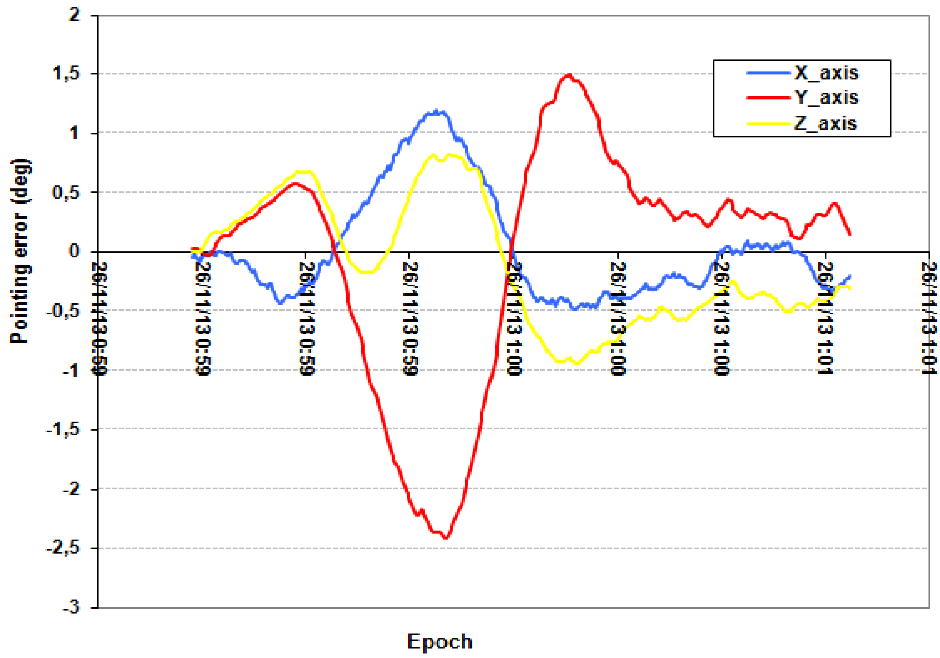


b)

Figure 5. Satellite depointing on the three axes during maneuvers performed on September 2013.
***a)* OCM1, *b)* OCM2.**



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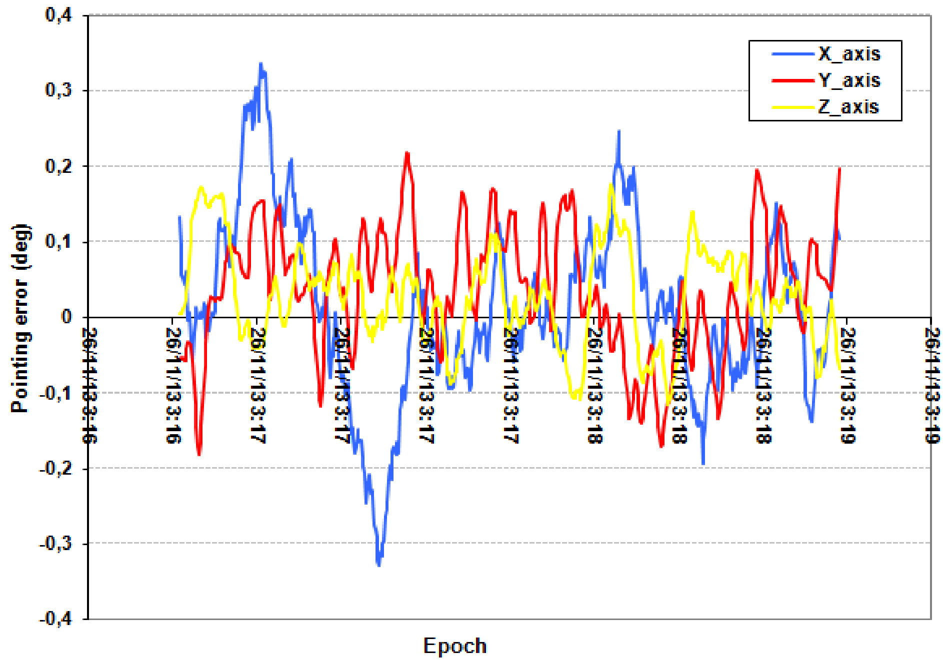
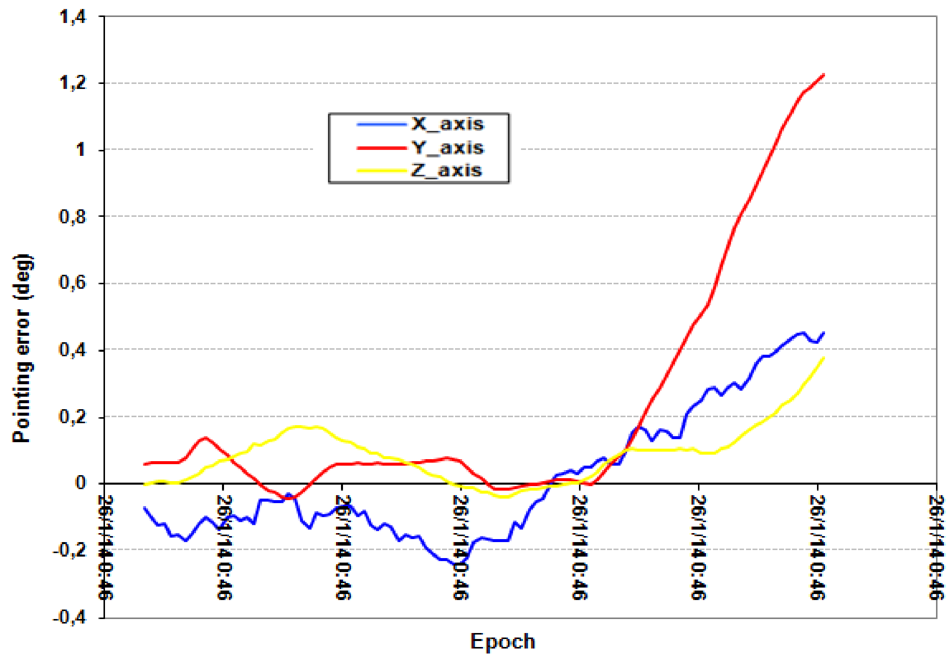
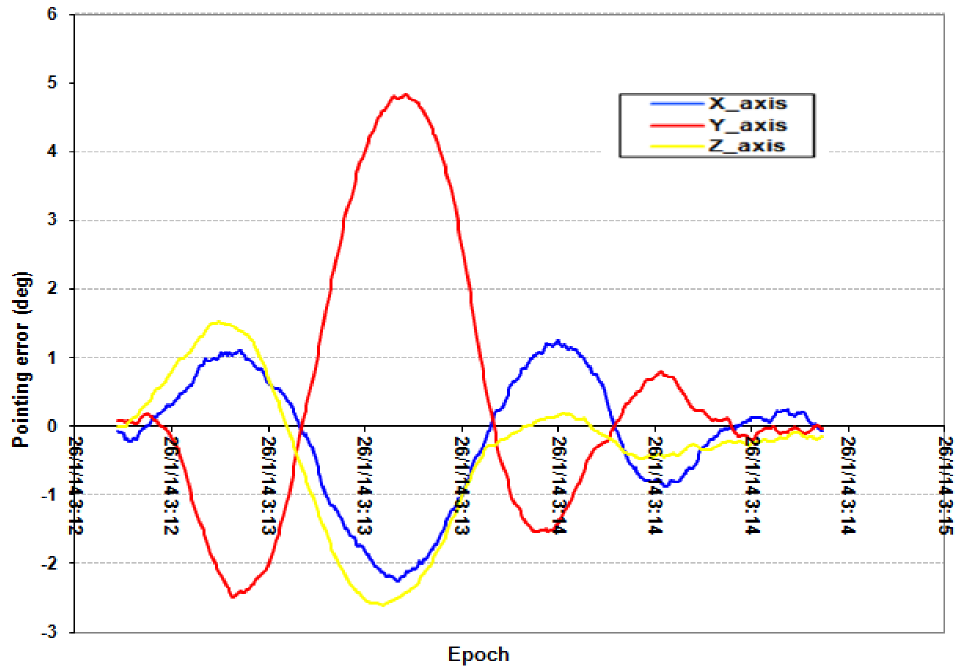


b)

Figure 6. Satellite depointing on the three axes during maneuvers performed on November 2013.
***a)* OCM1, *b)* OCM2.**



a)



b)

Figure 7. Satellite depointing on the three axes during maneuvers performed on January 2014. *a)* OCM1, *b)* OCM2.

As post maneuvers activities, the efficiency of the maneuvers using GPS and Doppler measurements and the consumed propellant mass after thrust are estimated. After the last couple of station keeping maneuvers realized on January 2014, the remaining propellant as shown in Table 3 is currently around 2.9 kg which is sufficient for orbit maintenance over additional 10 years.

Figure 8 illustrates the evolution of the mean local solar time for the observed period as well as the prediction for the future up to the beginning of 2016. The obtained evolution demonstrates that no correction on inclination will be performed before mid 2017, so, 2 years after the nominal life time of mission. At the end of February 2014, the ground track error at equator and local solar time are respectively -11.5 km and 22h07. The next foreseen OCM should occur in mid of April 2014 and will be planned as in-plane maneuver.

Table 3. Satellite and remaining propellant mass update.

SK OCM	Date	Before OCM		After OCM		Consumption (kg)
		Satellite mass (kg)	Fuel mass (kg)	Satellite mass (kg)	Fuel mass (kg)	
1	26/10/2010	115,73050000	3,10050000	115,72821312	3,09821312	0,00228688
2	04/11/2010	115,72821312	3,09821312	115,71899985	3,08899985	0,00921327
3	30/01/2011	115,71899985	3,08899985	115,70882972	3,07882972	0,01017013
4	16/05/2011	115,70882972	3,07882972	115,69931895	3,06931895	0,00951077
5	17/10/2011	115,69931895	3,06931895	115,68661195	3,05661195	0,01270700
6	26/12/2011	115,68661195	3,05661195	115,65609214	3,02609214	0,03051981
7	26/03/2012	115,65609214	3,02609214	115,64733591	3,01733591	0,00875623
8	12/04/2012	115,64733591	3,01733591	115,64347827	3,01347827	0,00385764
9	29/04/2012	115,64347827	3,01347827	115,64172372	3,01172372	0,00175455
10	30/06/2012	115,64172372	3,01172372	115,63718110	3,0071811	0,00454262
11	13/07/2012	115,63718110	3,00718110	115,63471048	3,00471048	0,00247062
12	18/09/2012	115,63471048	3,00471048	115,61810234	2,98810234	0,01660814
13	22/04/2013	115,61810234	2,98810234	115,60792250	2,9779225	0,01017984
14	23/06/2013	115,60792250	2,97792250	115,59340324	2,96340324	0,01451926
15	10/09/2013	115,59340324	2,96340324	115,58152110	2,95152110	0,01188214
16	26/11/2013	115,58152110	2,95152110	115,56610129	2,93610129	0,01541981
17	26/01/2014	115,56610129	2,93610129	115,55470968	2,92470968	0,01139161
Total consumed fuel mss (kg)						0,17579032
Remaining fuel mass (kg)						2,92470968

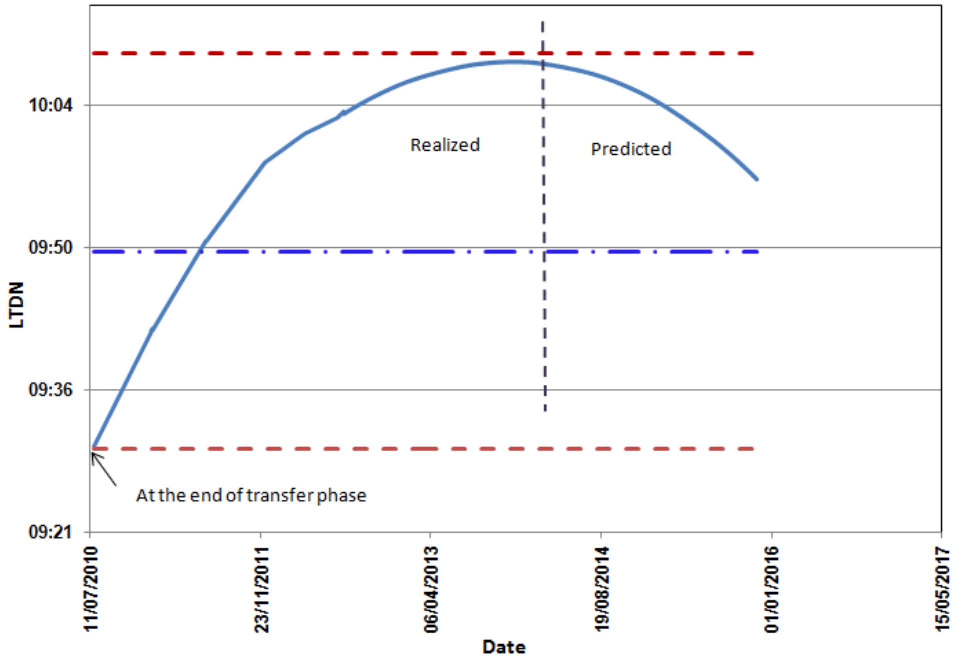


Figure 8. Evolution of Local Solar Time.

CONCLUSION

The in-orbit results of station keeping orbit maintenance performed for ground track correction, using a new version of flight dynamics software have been presented. The obtained results demonstrate that with the new version, the realization of small maneuvers become as accurate as for strong ones. After the last couple of station keeping maneuvers realized on January 2014, the remaining propellant is currently around 2.9 kg which is sufficient for orbit maintenance over additional 10 years. Also, the local solar evolution demonstrates that no correction on inclination will be performed before mid of 2017. At the end of February 2014, the ground track error at equator and local solar time are respectively -11.5 km and 22h07. The next foreseen OCM should occur in mid of April 2014 and will be planned as in-plane maneuver.

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