DEIMOS-1 MID-LIFE LOCAL TIME CONTROL STRATEGY: ANALYSIS AND OPERATIONAL IMPLEMENTATION

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Abstract: DEIMOS-1 is a LEO mission dedicated to Earth Observation, fully owned and operated by Deimos Imaging (Spain), a subsidiary of UrtheCast Corp. (Canada). DEIMOS-1 reached five years of operations, its original design lifetime, in July 2014. The excellent status and performance of the satellite allowed a mission extension of another five years. At that time, the Local Time at Ascending Node (LTAN) was naturally lowering towards dawn with a parabolic behaviour. Within a year or two, the illumination conditions would not have been suitable anymore for commercial imagery. Deimos Imaging performed a dedicated study both at flight dynamics and operational level, to design the optimal mid-life manoeuvring campaign which assured the best orbital evolution. The campaign was designed in order to keep payload performances like the TDI Line Rate range and the GSD, maintaining key mission parameters such as repeat-cycle, revisit time and frozen conditions. Finally, 395 out-of-plane manoeuvres were carried out over two and a half months, starting on November 2014, bringing to the expected change of 0.096º in mean orbit inclination. DEIMOS-1 is now on an orbit which guarantees, through a sound LTAN evolution, stable illumination conditions for its imagery at least until the end of 2019.

Keywords: *DEIMOS-1, LTAN control, LEO, Earth Observation*

1. Introduction

DEIMOS-1 was developed in collaboration with Surrey Satellite Technology Limited (SSTL) and it is based on a SSTL-100 platform. Successfully launched on 29th July, 2009 from Baikonur Launch Complex (Kazakhstan) on board a Dnepr launcher, it was manoeuvred to reach its operational orbit at the reference altitude (H_{ref}) of 663 km, starting to provide multispectral imagery worldwide for commercial applications, for government use, and for rapid-response following disasters.

Composed by two identically imager banks of Red (R) , Green (G) and Near-Infrared (NIR) bands, the payload camera covers a combined swath of 650 km with a 22-m Ground Sample

Distance (GSD) and 10 bits radiometric depth. Its unique combination of wide swath and spatial resolution has converted DEIMOS-1 in one of the most used satellites for agriculture monitoring worldwide and a successful Copernicus Contributing Mission.
Such a kind of payload is not much affected by orbital variations proper of DEIMOS-1 H_{ref}, so at the early stages of mission definition, it was decided to design the orbit to avoid any orbital maintenance. The designed optimal orbit resulted in a Sun-Synchronous frozen orbit (SSFO), having 14 + 11/16 orbits/day.

This decision relaxed the delta-v requirement, fact that was favourable for propulsion subsystem and simplified Flight Dynamics operations throughout the nominal mission lifetime.
As part of FOP (Flight Operations Plan), orbit assessment was being performed on a monthly basis. After 5-year of nominal lifetime, it showed that the mean local time at ascending node (MLTAN) evolution was following quite accurately the behaviour predicted by the mission analysis phase, however resulting in a MLTAN near the initial value and with a negative slope. Due to the great commercial success of the DEIMOS-1 mission and the good health of its components, it was decided to extend the mission lifetime up to ten years, so in terms of Flight Dynamics a new orbit evolution reassess was needed.

2. DEIMOS-1 platform

2.1 AOCS

The DEIMOS-1 AOCS allows three-axis stabilization with a maximum deviation of 2.4º on each axis at 3σ.
Sensors like magnetometers and coarse sun sensors are used to estimate the satellite position and velocity in an inertial frame. Magnetorquers and reaction wheels are used as actuators to compensate the external torques that try to deviate the platform from the target position.

The high dependence on the Sun to acquire attitude information has a direct impact on the satellite orientation in eclipse, while having a negligible impact on operations as the payload is only used in sunlight. At the beginning of the mission, the impact on the AOCS behaviour in eclipse during manoeuvres was still to be discovered.

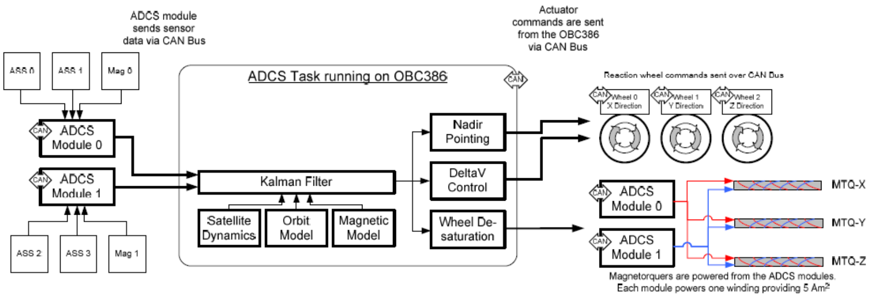

Figure 1: DEIMOS-1 AOCS functional diagram.

2.2 Propulsion Subsystem

DEIMOS-1 propulsion subsystem has a low cost resistojet which makes use of butane as propellant. It was designed by SSTL for EO missions that do not require systematic orbital control. Indeed, due to a careful selection of the initial orbit and the adaptability of the payload to the expected range of altitudes over the Earth ellipsoid (650 km - 690 km), no orbit maintenance was scheduled for the nominal lifetime, apart from initial manoeuvre campaign.
In the table below, the main characteristics of the propulsion subsystem at beginning of life (BOL) and nominal performances are listed, which are expected to change over the mission lifetime according to the propulsion system architectural design.

Table 1: Summary of DEIMOS-1 Propulsion Subsystem parameters.

Isp [s]	~100
Nominal Thrust [mN]	~50
δv [m/s]	26.7
m_p [kg] (BOL)	2.31
P_0 [bar] (BOL)	3

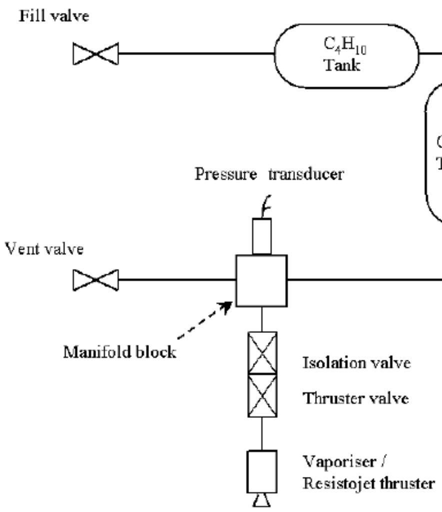

Figure 2: DEIMOS-1 Propulsion System functional scheme.

Butane propellant is stored in two tanks, part in liquid phase and part in gas at butane's vapour pressure according to the tanks temperature: as there is no active thermal control, tanks' temperature oscillates between 4.4ºC and 10ºC, and consequently tanks' pressure between 1.25 - 1.45 bar. Whenever valves are open, the butane in gas phase flows down-stream, towards the nozzle. Just before exiting, the gas is heated by the electrical coil located in that area, in order to increase the efficiency and to minimize the possibility of liquid exhaustion.

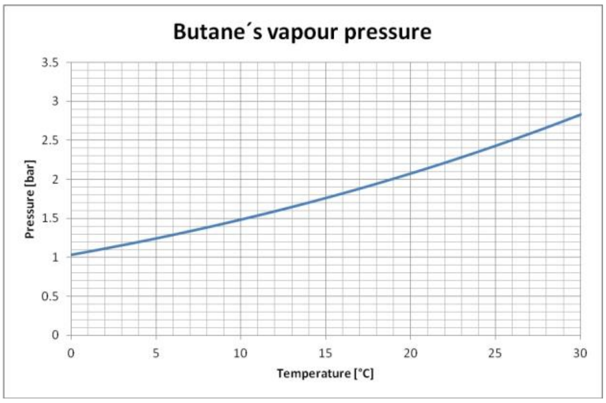

Figure 3: Butane Vapor Pressure versus temperature.

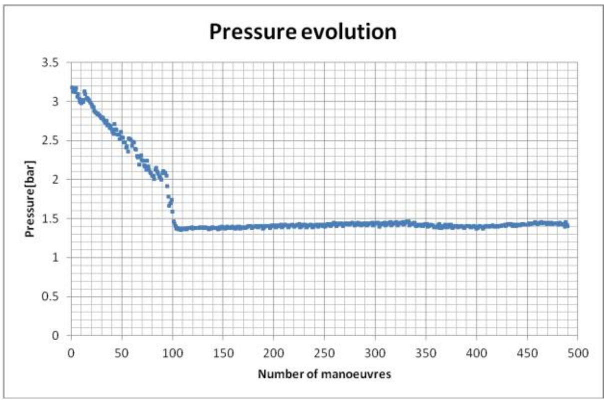

Figure 4: Tanks Pressure evolution with manoeuvres' number.

After each manoeuvre, a small decay in the tanks' pressure is observed, quickly recovered when the liquid evaporates reaching equilibrium in negligible time (for manoeuvre planning considerations). When almost all the propellant is consumed (near 99%), there will be no more butane in liquid phase and the propulsion subsystem will work in "blow-down" mode for the last manoeuvres.

As the mid-life manoeuvre campaign was performed while the propulsion subsystem was working with propellant in equilibrium between phases, at the constant pressure of 1.4 bar (see Figure 4), thus thrust was also constant (~39 mN), leading to a simplified manoeuvre planning.

2.3. Delta-v and fuel budget at 5 years lifetime

Table 2 shows the satellite status in terms of delta-v and fuel expended during the first 5 years of lifetime. These data correspond to the summary results after the propulsion system calibration, launcher injection correction phase, orbit acquisition manoeuvres and collision avoidance events.

The remaining propellant on-board ensured the execution of the mid-life orbital change presented in this paper, and it is still providing service for collision avoidance activities.

Table 2: Delta-v and fuel at 5 years of lifetime.

m_0 [kg] (BOL)	m_1 [kg] (5 years)	delta m_p [kg]	delta-v [m/s]	remaining fuel [kg]	available delta-v [m/s]
84.95	83.92	1.03	11.87	1.28	15.7

3. DEIMOS-1 orbit evolution

3.1. 5-year orbit assessment

The satellite Sun-Synchronous, frozen orbit was designed to have a Local Time of Ascending Node (LTAN) centred at 10:30, and varying within a band of ± 30 minutes over the nominal lifetime (5 years). Thanks to a careful design of its initial operational orbit and its evolution, the MLTAN behaviour in Figure 5 was achieved without any orbital maintenance, due to the balancing effects of the natural evolution of orbit inclination and of the orbit altitude decay. Only small gaps in semi-major axis (see Figure 4) can be noticed, caused by of the five collision avoidance manoeuvres performed during the first five years in orbit.

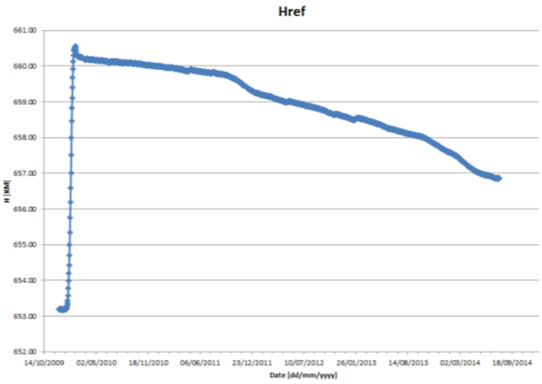

Figure 5: H_{ref} evolution of DEIMOS-1 orbit over the first 5 years.

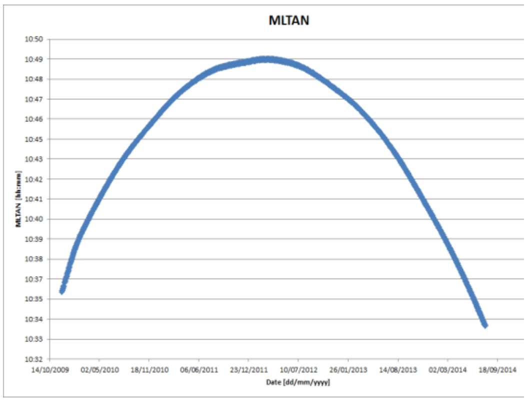

Figure 6: MLTAN evolution of DEIMOS-1 orbit over the first 5 years.

3.2. Long term analysis

Propagating the orbit up to July 2019 (see Figure 7), such that to reach 10 years lifetime, it was clear that the long-term evolution of the MLTAN for the next five years would continue its parabola-like behaviour, heading quickly towards dawn. As this would worsen the quality of the acquired imagery (e.g. because of different illumination conditions), an in-depth study to assess the situation and implement corrective measures was started.

A manoeuvre campaign was needed to change MLTAN evolution as soon as possible, having the objective in mind to keep MLTAN higher than 9:30. The first step was to evaluate the impact of corrective in-plane versus out-of-plane manoeuvres on mission performances.

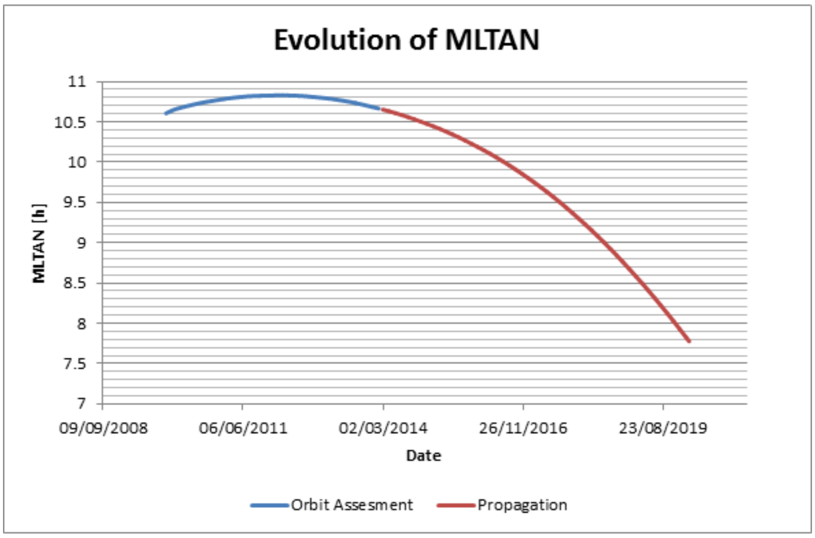

Figure 7: MLTAN prediction with 50% CL of solar activity, as function of date.

4. Study of DEIMOS-1 lifetime extension

Basically, two options allow increasing the MLTAN slope: increase inclination or decrease semi-major axis. The final strategy was decided after a trade-off between benefits and drawbacks, taking into account all the constraints exposed in the following paragraphs. The table below illustrates all the points considered for the analysis.

Table 3: Comparison between semi-major axis and inclination change strategies.

	Advantages	**Disadvantages**
SMA strategy	• +/-DV manoeuvring experience • FDS finely calibrated for these manoeuvres. • Good attitude precision and stability.	• Critical heights for Repeat Cycle. • Changes the period → complicate payload operations • Effect on GSD • Lower orbit implies higher decay rate → even more problems with GSD • Manoeuvring only in eclipse would lead to an increase in eccentricity.
Inclination strategy	• Minimum impact on operations. • Minimum impact on any other associated orbit parameter. • It is possible to perform them at descending node for full performance.	• No previous experience • Attitude precision and stability uncertainties.

4.1 Repeat Cycle/Revisit Time

If the mid-life manoeuvring campaign executed in-plane delta-v manoeuvres to decrease semi-major axis, there would be the risk to worsen repeat cycle characteristics, ending within the lower resonance region (see Figure 8).

One of the mission drivers for the choice of the strategy type is to maintain a sustainable revisit time, in order to guarantee a full coverage of the Earth within reasonable time. The main parameters that contribute to this are semi-major axis, eccentricity and inclination (i).

Assuming a circular orbit, an analysis of all the orbits between H_{ref} = 600 km and H_{ref} = 700 km and for i = 97º, 98º and 99º was performed to sort-out resonant combinations and to pre-assess the feasibility of a given orbit (see ref.[3]).
As it can be seen in Figure 8, there are two main resonant regions close to the nominal DEIMOS-1 orbit, namely between 653 and 645 km and 660 and 675 km. Effects of inclination change manoeuvres are almost negligible, affecting only the final revisit time by a small amount.

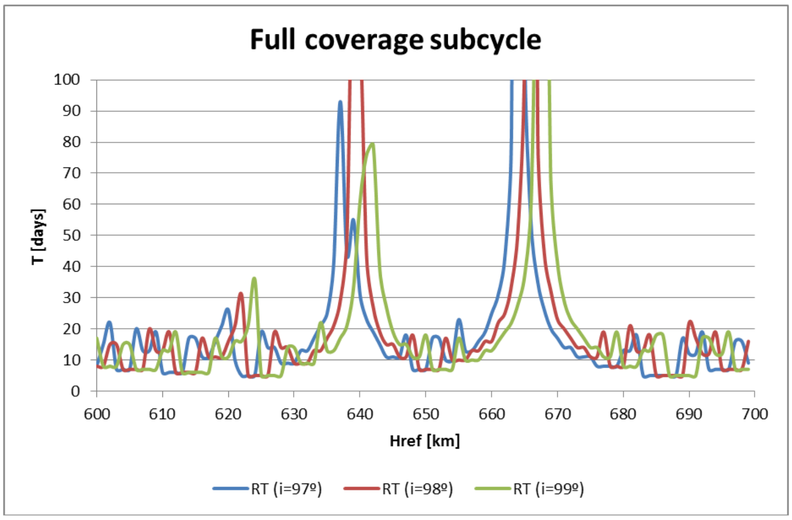

Figure 8: Cycle Length as a function of H_{ref}, for different values of inclination.

4.2. TDI Line Rate and Integration Time

The Multi-Spectral Imager (MSI) uses a push-broom as sensor, which integrates photons received in the along-track direction in order to have enough information when moving at high speeds relative to the target. The cross-track GSD is fixed for a given height, depending only on the size of each pixel and the focal length of the camera.
The rate at which each "row" is integrated directly impacts on the along-GSD: the higher the integration time (or the lower the time delay and integration (TDI) line rate), the higher the GSD. Then, this integration time shall be set in such a way that, for a given height, the cross-track and along-track GSD match.

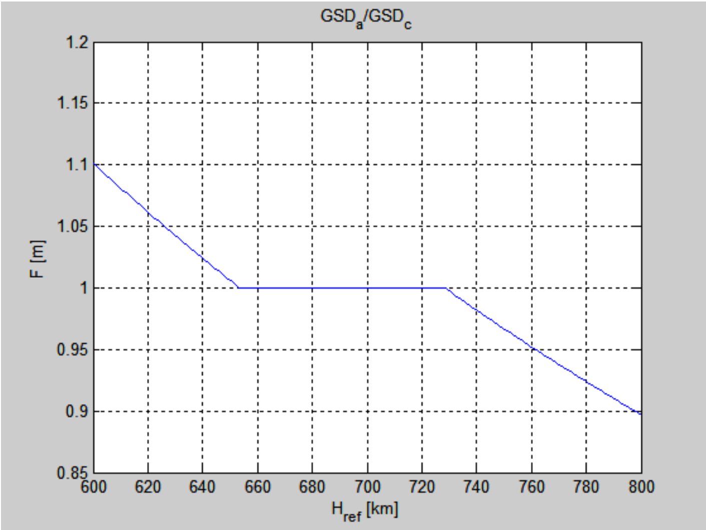

Figure 9: Deformation factor for Deimos-1.

Referring to Figure 9, the payload has a fixed range of line-rates where both GSDs match, which correspond to heights between 653.3 and 727.6 km. This means that, if the satellite is placed in an orbit with a height outside of the aforementioned range, then the GSDs both cross-track and along-track will not match, deforming the image.

The previous identified lower limit of 653 km was identified as the lower threshold not to be violated when considering the possibility of in-plane manoeuvres.

4.3. Payload operations

In order to comply with contractual obligations with its customers and long-term archive plan, routine acquisitions needed to be maintained.

In the case out-of-plane manoeuvres should be the baseline strategy, they would be executed at the line of nodes to change inclination (see paragraph 4.5.). The time DEIMOS-1 takes to rotate, achieve the target attitude, perform the thrusting, and then restore the Nadir-pointing attitude, is close to 40 minutes. This meant that images could not be acquired for latitudes between 75º N and 75º S, which covers the totality of areas of interest for the mission.

For this reason, the main constraint for the out-of-plane strategy was:

- ❑ Manoeuvres should be performed in eclipse

In addition, it is worth to say that manoeuvres can not drive the satellite to point towards sun.

4.4. Propellant available

The estimated remaining delta-v after the nominal lifetime was around 15 m/s (Table 2). With this amount, the platform should be able to perform the mid-life orbital change in only one campaign, such that to optimize the man effort. At second, it should keep the ability to face with collision alerts.

Indeed, the expected number of collision avoidance manoeuvres is one per year according to [4] which, in fact, coincides with the operational experience. That means an estimation of 5 manoeuvres for the rest of the extended lifetime, so enough delta-v for 6 manoeuvres (5 plus margin) is needed at the end of the campaign.

4.5. Manoeuvre Strategy

It was decided to implement out-of-plane manoeuvres, since payload operations had the maximum priority and they could not be affected.

Evaluating the long term behaviour of MLST up to 2019 considering 50% confidence level of solar activity, the expected manoeuvre campaign would introduce:

- delta-inclination: ~0.1 degrees
- delta-v: ~13 m/s
- fuel mass consumption: ~1 kg

Thus, the expected MLST at 10 years lifetime would be higher than 9:30 (Figure 10).

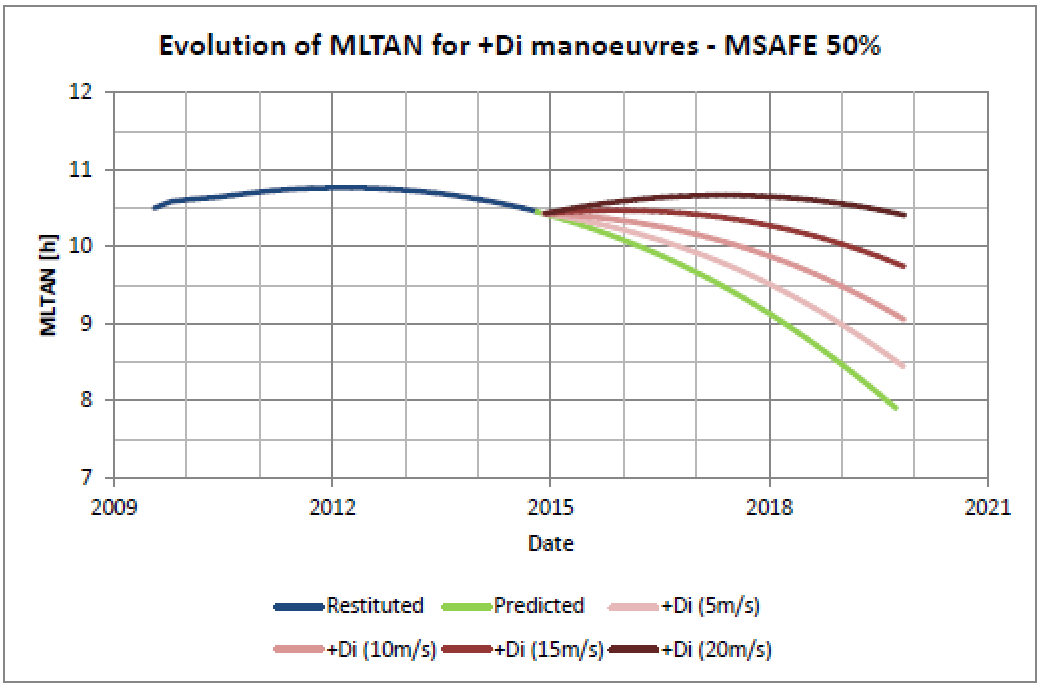

Figure 10: MLTAN evolution as function of date for different out-of-plane manoeuvres.

4.6. Power

One of the key components that drives a mission survival is the battery. As DEIMOS-1 mission has already reached its nominal lifetime, significant battery degradation would be expected, but it is not the case. Only very small variations of battery parameters have been detected since launch. In addition, it is important to note that the power subsystem was not dimensioned to perform both full payload operations and manoeuvring campaign at a time, thus, a power trade off was needed.

Simplifying the analysis, two basics parameters were considered to design the manoeuvre implementation plan:

- ❏ Minimum battery voltage above a given threshold (32 V)
- ❏ Positive DoD balance per day (14 - 15 orbits)

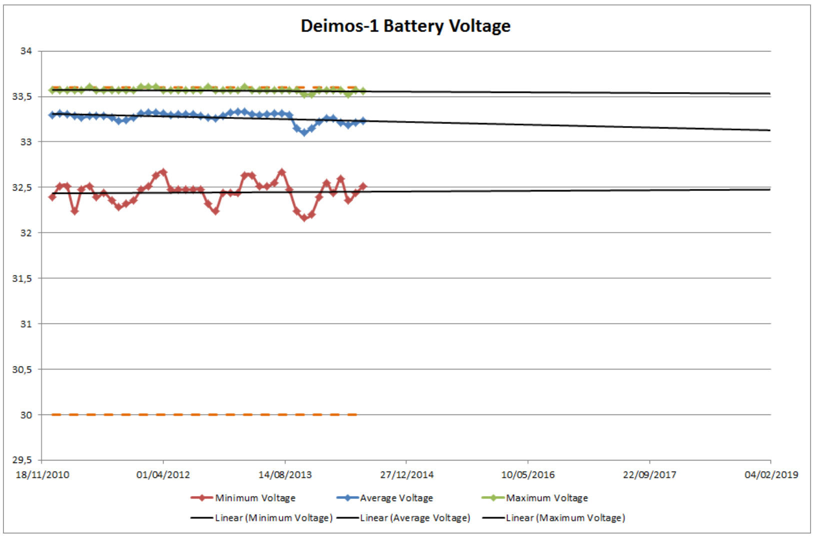

Figure 11: Battery voltage data and trend over DEIMOS-1 lifetime.

Since the most power demanding operation is the X-band download performed about 4 times per day in autumn-winter period, the first action taken was not to plan any manoeuvre in any orbit with X-band activity. As both stations (Boecillo and Svalbard) are located in the north hemisphere, generally the battery experiences the eclipse phase without being fully charged, which means that DoD is lower at the beginning of the next sunlit phase. Due to this effect, a spare orbit was left between X-band and manoeuvre orbits.

5. Manoeuvre campaign implementation

From the AOCS point of view, to main points were open during the preparation phase of the campaign:

- ❑ Time needed for the platform to achieve the target orientation, remain stable and then return to nominal nadir-pointing (about 40 minutes)
- ❑ Ability of the satellite to withstand sustained firing for several minutes.

As not enough technical information was available to correctly model the expected behaviour of the platform during a manoeuvre, a calibration campaign was designed to generate flight data that could be used as input to properly address this topic.

5.1. Calibration

As no inclination manoeuvre was ever done before with DEIMOS-1, a calibration campaign took place between the 30 of October and the 4 of November 2014. The objective of the campaign was to:

- Assess the capability of the platform to perform out-of-plane manoeuvres while in eclipse
- Analyse the impact of the duration of the manoeuvre in the AOCS, that is, for how long the AOCS was able to maintain the target pointing without significant deviations

- Observe the manoeuvre performance from the propulsion point of view.

The campaign was divided in three phases:

1. First phase, without firing, were only the rotation of the platform towards the target orientation was performed. The objective was to characterize the time that takes to the platform to slew from nadir-pointing towards the out-of-plane attitude, and back to nadir pointing.
2. Second phase, with small firing, to verify the target orientation is effectively the one that makes the thrust force to be perpendicular to the orbit.
3. Third phase, with firings of increasing durations, to verify the stability of the pointing over time.

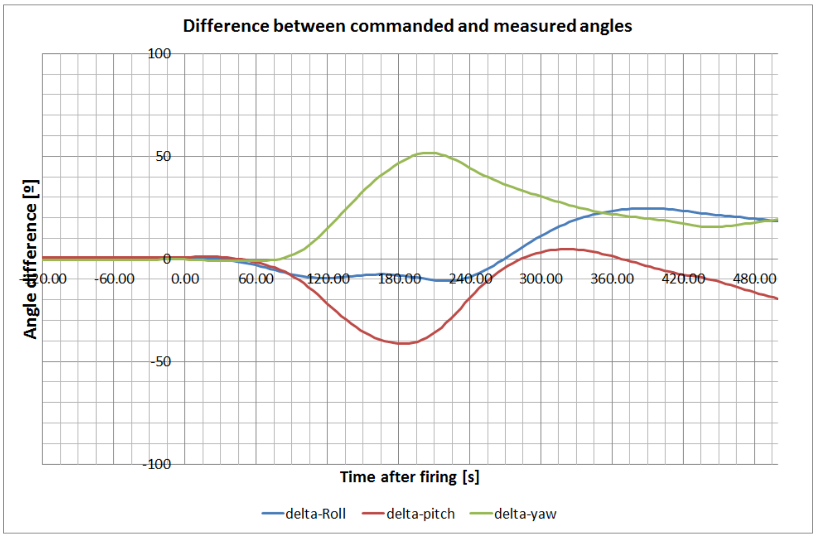

Figure 12: Euler Angles errors for a 70 s out-of-plane manoeuvre.

Based on the attitude data obtained from the campaign, a duration of 70 s was selected as the compromise between small-enough angular deviations (see figure above) and high-enough thrusting force per manoeuvre, which in turn meant less overall duration for the campaign. Also, the eclipsed region of the orbit was deemed enough to perform the rotation towards the target and back to the nadir-pointing: this allowed guaranteeing maximum availability of the payload and no risk in term of sun blinding.

On the other hand, the calibration campaign showed that a spurious in-plane delta-v component would be generated: a mean change of δa = -3+/-1 m and δi = +0.00025º (per manoeuvre) were expected. Thus, the total change on semi-major axis for the whole campaign was expected to be 1.5 km: the impact of this was analysed before performing any further action in order to guarantee that none of the previously exposed constraints was going to be violated, while an analysis in order to compensate the effect by modifying the pointing target for the manoeuvres was started in parallel.

6. Overview of the implementation strategy

Considering together the requirements in terms of change in inclination from the theoretical analysis and the outcome of the calibration campaign, about 400 manoeuvres were forecasted to be performed between November, 2014 and January, 2015.

6.1. Manoeuvres planning

A baseline of 6 manoeuvres per day was considered as the best compromise to minimize the duration of the campaign without violating any of the constraints, especially related to payload and battery.
The following plan was adopted as baseline:

1. Payload activities between 5 UTC and 15 UTC
2. One orbit un-planned for the battery to recover
3. Two manoeuvres in consecutive orbits
4. Spare orbit
5. One manoeuvre
6. S-band download
7. Two manoeuvres
8. Spare orbit
9. One manoeuvre

6.2. Manoeuvres implementation

Due to the location of the antennas used for telemetry and tele-commanding, real-time monitoring of each manoeuvre was not possible. To guarantee fast response in case any deviation from the expected behaviour arose, manoeuvre calibration was performed more than once per day (24/7 basis), as soon as new data was available. Manoeuvre data was downloaded after any manoeuvre. Immediately after processing the data, an analysis of the propulsion performances (thrust, mass, pressure, I_{sp}) and of the orbital changes (variation in inclination, semi-major axis, eccentricity and argument of perigee) was performed.
In case of anomaly, a set of commands to delete the pending manoeuvres was always ready, to avoid further degradation. These set of commands were never needed.
Figure 13 shows the resulting increment in inclination performed by each out-of-plane manoeuvre, over the campaign.

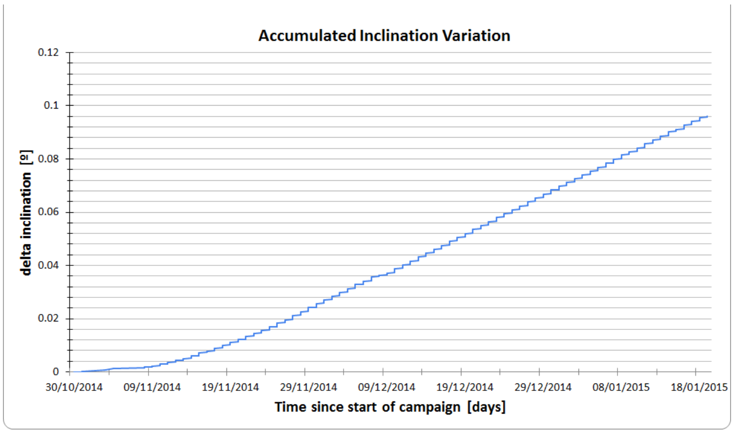

Figure 13: Accumulated inclination variation over mid-life campaign.

7. Final orbit

The final results are summarized in Table 4. With the achieved inclination change of 0.096°, the predicted evolution of DEIMOS-1 LTAN clearly satisfies the initial objective as it is expected to remain higher than 9:30 for the extended lifetime.

Table 4: state of delta-v and fuel at 5 years of lifetime.

m_1 [kg] (5 years)	delta m_p [kg]	delta-v [m/s]	delta-i [deg]	delta-sma [km]	delta-ecc	delta-argp [deg]
83.92	1.01	12.65	0.096	-1.67	1.7e-5	-10.8

In terms of remaining propellant, the estimation is to have enough for collision avoidance. Regarding the changes in semi-major axis (delta-sma) and consequently eccentricity (delta-ecc) and argument of perigee (delta-argp), a final analysis of the deviation with respect to frozen conditions was done: as visible from Figure 17, the altitude profile over the Earth ellipsoid at the end of mid-life campaign follows the footprint at the beginning of campaign and has acceptable variation for each latitude value.

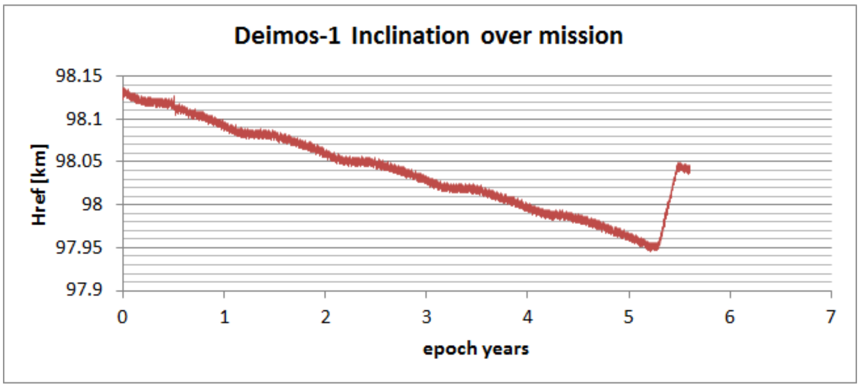

Figure 14: Inclination evolution in True of Date frame over time.

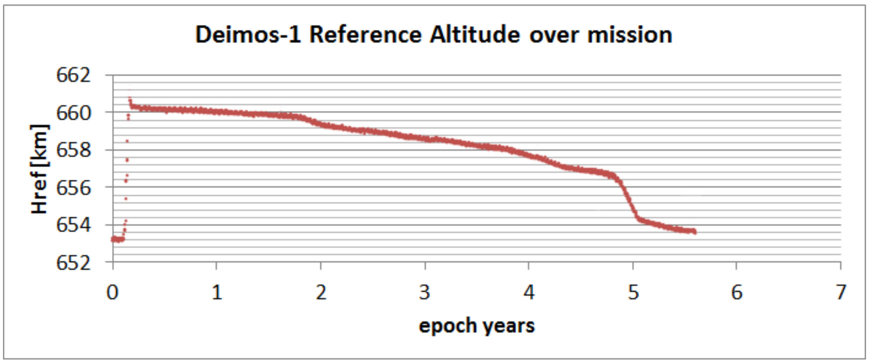

Figure 15: H_{ref} evolution in True of Date frame over time.

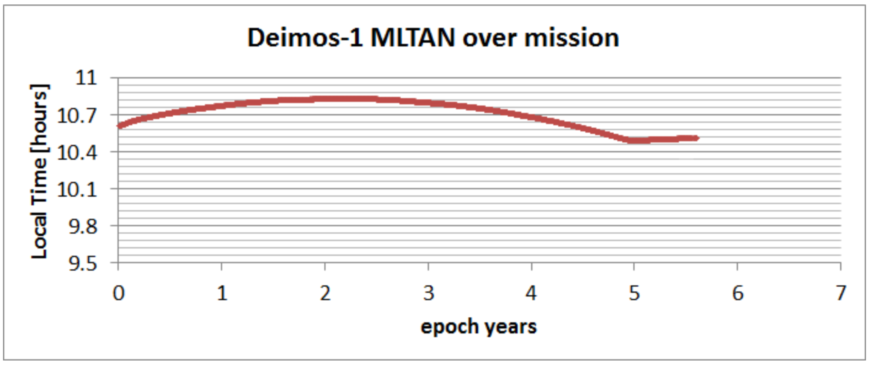

Figure 16: MLTAN evolution in True of Date frame over time.

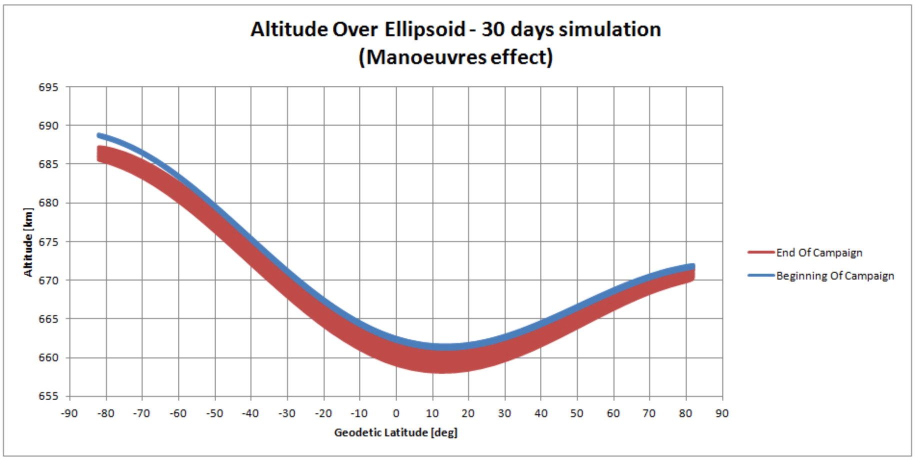

Figure 17: Osculating DEIMOS-1 altitude over Earth ellipsoid at the beginning of campaign and at the end of campaign.

8. Conclusions

On July 2009, DEIMOS-1 was left in an orbit that did not require orbit maintenance for the nominal lifetime. Due to the good health of the satellite, an extension for another five years was approved as long as MLTAN behaviour was modified in order not to cross the lower limit of 9:30.

The theoretical analysis showed that a change of +0.1º in inclination would allow to correct the MLTAN long-term evolution, complying with the constraints imposed by the payload and the mission.

After a calibration campaign, to assess the capabilities of the platform in terms of pointing performance, the manoeuvring campaign started, extending between November 2014 and January 2015. A total of 395 manoeuvres were performed.

Now the spacecraft is in a stable orbit that fulfils DEIMOS-1 payload requirements for the rest of the extended lifetime in terms of MLTAN, GSD and repeat cycle.

The remaining propellant allows performing at least 6 collision avoidance manoeuvres.

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