Flight Dynamics Experience on Target Orbit Acquisition and Maintenance Operations for Germany's Hyperspectral Satellite Mission EnMAP

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The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission that aims at monitoring and characterizing Earth's environment on a global scale. The satellite was successfully launched with SpaceX's Falcon 9 Transporter-4 mission on April 1st, 2022. This paper elaborates on the in-flight results obtained during the EnMAP Launch and Early-Operations Phase (LEOP) and the first months of the commissioning phase. Besides the flight dynamics operations, this paper addresses the repeat ground-track orbit control concept and discusses novel flight dynamics functionalities implemented to optimize the scientific return of the EnMAP mission, such as microservices for fast data exchange between the flight dynamics and mission planning systems.

Keywords: *EnMAP, Flight Dynamics Operations, Orbit Control, Repeat Ground-Track.*

1 EnMAP Mission Characteristics

Germany's hyperspectral satellite mission, the Environmental Mapping and Analysis Program (EnMAP), has the objective to globally monitor and characterize Earth's environment [1]. EnMAP measures and models key dynamic processes of Earth's ecosystems by extracting geochemical, biochemical and biophysical parameters that provide information on the status and evolution of various terrestrial and aquatic ecosystems. The core of the EnMAP satellite is the hyperspectral instrument that records the reflected sunlight from the Earth at wavelengths between 420 nm and 2450 nm in more than 240 adjacent spectral bands with a spatial resolution of 30 m [1].

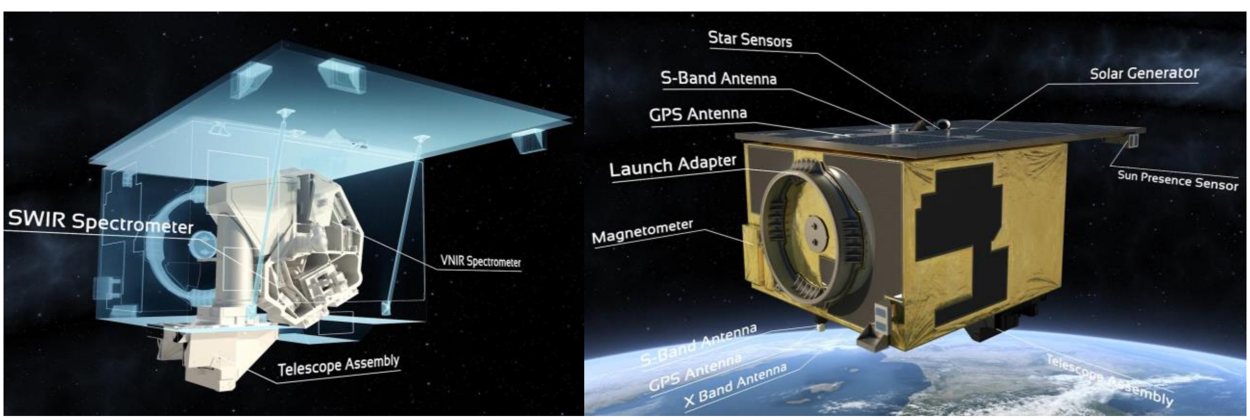

Figure 1. EnMAP hyperspectral instrument (left) and exterior AOCS sensors (right).

The EnMAP spacecraft is depicted in Figure 1. The characteristics which are relevant for flight dynamics are the launch mass of 916 kg, and the 5 m² cross-section for drag and radiation pressure computation. The Attitude and Orbit Control System (AOCS) comprises of a single-frequency GPS receiver, three star-sensors, Sun presence sensors, magnetometers, four reaction wheels, and two 1-Newton thrusters. At launch, EnMAP carried 59 kg of hydrazine propellant.

The EnMAP repeat ground-track orbit is Sun-synchronous at 642 km mean altitude and 97.978 deg inclination, and has a mean Local Time at Descending Node (LTDN) of 11:00 h. The EnMAP reference orbit is the fundamental basis for image acquisition planning as well as orbit acquisition and orbit maintenance maneuver planning. Besides the traditional design considerations for Sun-synchronous, frozen eccentricity repeat orbits, the reference orbit must be a closed orbit with matching states at the beginning and end of each 27-day repeat cycle comprising 398 orbits. Therefore, the reference orbit design has been formulated as an optimization problem [2]. The implemented reference orbit is expressed in an Earth-fixed frame and can be repeated in 27-day intervals throughout the entire mission. In combination with ±30 deg tilt angles, the repeat cycle allows to revisit targets within less than 4 days.

2 Repeat Ground-Track Orbit Control

EnMAP's osculating orbit is controlled within a "rim" defined about the Earth-fixed reference orbit. In contrast to DLR's TerraSAR-X radar mission, where the satellite is controlled within a "tube" of 250 m radius surrounding its reference orbit, the EnMAP control box is much wider, i.e. ±6 km in radial direction and ±22 km in normal direction. These dimensions correspond to the maximum allowed deviation of the EnMAP orbit position from the reference orbit in the plane perpendicular to the flight direction. The implementation of the EnMAP orbit ground-control is very similar to the TerraSAR-X control concept [3], which in more than 15 years of operation has proved to work remarkably well, e.g. more than 99% of the time TerraSAR-X was inside the 250 m control tube [5].

At DLR, the generic RGT (repeat ground-track) software suite has been developed, based on the in-house developed TerraSAR-X software programs, and successfully applied to the EnMAP mission. The RGT suite comprises of all guidance and control functionalities needed, i.e. reference orbit optimization, orbit monitoring, and maneuver planning for orbit acquisition and maintenance.

For the 11:00 LTDN mission orbit, the orbit inclination naturally drifts by −0.025 deg per year. For inclination correction, a total velocity change in out-of-plane direction of 3.29 m/s per year is necessary. Because of the maximum ΔV capability of 0.4 m/s per maneuver, the yearly inclination correction has to be performed by up to nine single maneuvers. Each of these maneuvers increases the inclination by 0.003 deg. Because of the negative inclination drift rate, only a lower control limit needs to be defined for the inclination, i.e. nominal inclination of 97.978 deg and a lower limit of -0.0015 deg (relative inclination). The concept has been proofed by means of numerical orbit simulations featuring a full force model. Figure 2 depicts the simulation results for a 1-year simulation, presenting the evolution of the inclination and relative semi-major axis.

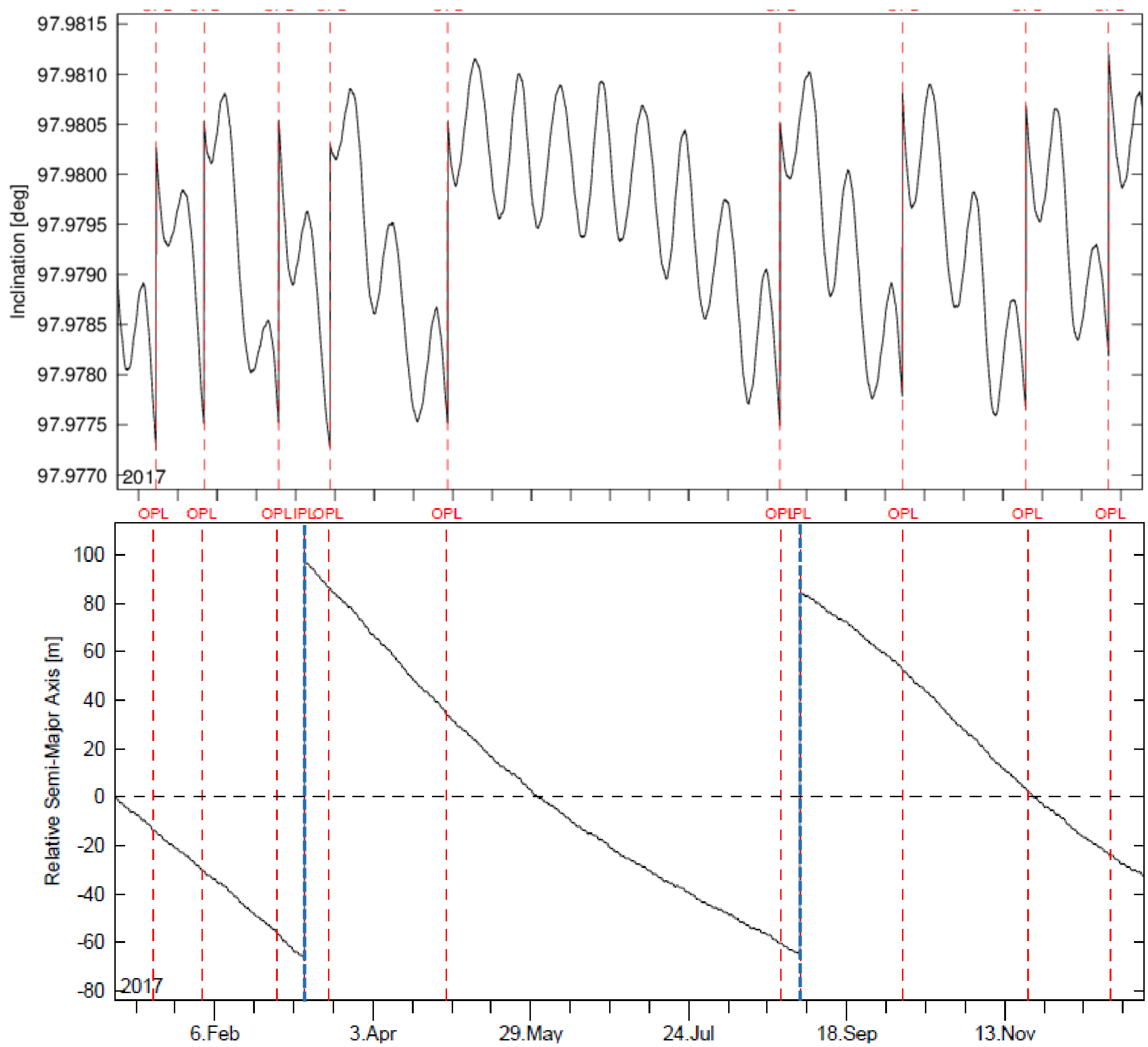

Figure 2. Numerical simulation of inclination evolution (top) and relative semi-major axis (bottom) over a one-year period. The red vertical lines indicate the inclination correction maneuvers, blue vertical lines indicate the drag make-up maneuvers.

The main driver for in-plane control is the required ground track stability (i.e. lateral deviation of the actual satellite ground track with respect to the reference ground track) of ±22 km at the equator. The most important disturbance force acting on the satellite is atmospheric drag. The decay of the semi-major axis changes the orbital period, which in combination with the Earth rotation causes a change in the ground-track. For a detailed description please refer to [3].

Figure 3 illustrates the in-plane control concept based on the numerically simulated results of the EnMAP (EN1) ground-track evolution with respect to that of the reference (REF) orbit (EN1-REF). The starting point to discuss the space error evolution is indicated by a red dot at April 11, 2017. Here, the EN1 semi-major axis (SMA) is about 57 m higher than the REF SMA (refer also to bottom of Figure 2). Consequently, the nodal period of EN1 is larger than for REF, and EN1 arrives at the equator later than REF.

Because of the Earth's eastward rotation, the EN1 ground-track shifts towards the west of the REF ground-track; the larger the SMA offset, the stronger the ground-track drift. The drift of the normal space error is naturally reversed when the EN1-REF semi-major axis difference becomes negative. In Figure 3, this happens in the middle of the maneuver cycle at May 31, indicated by a green dot. The eastward shift continues to grow as the SMA difference increases. At September 1 the lower limit of the normal space error (i.e. -22 km) is reached (refer to Figure 3), and a SMA raising maneuver is necessary in order to revert the space error drift. In this example, the tangential maneuver takes place at September 1, 2017 at 10:10 UTC (indicated by the right green vertical) and raises the SMA by 144 m. Thereafter, the evolution repeats.

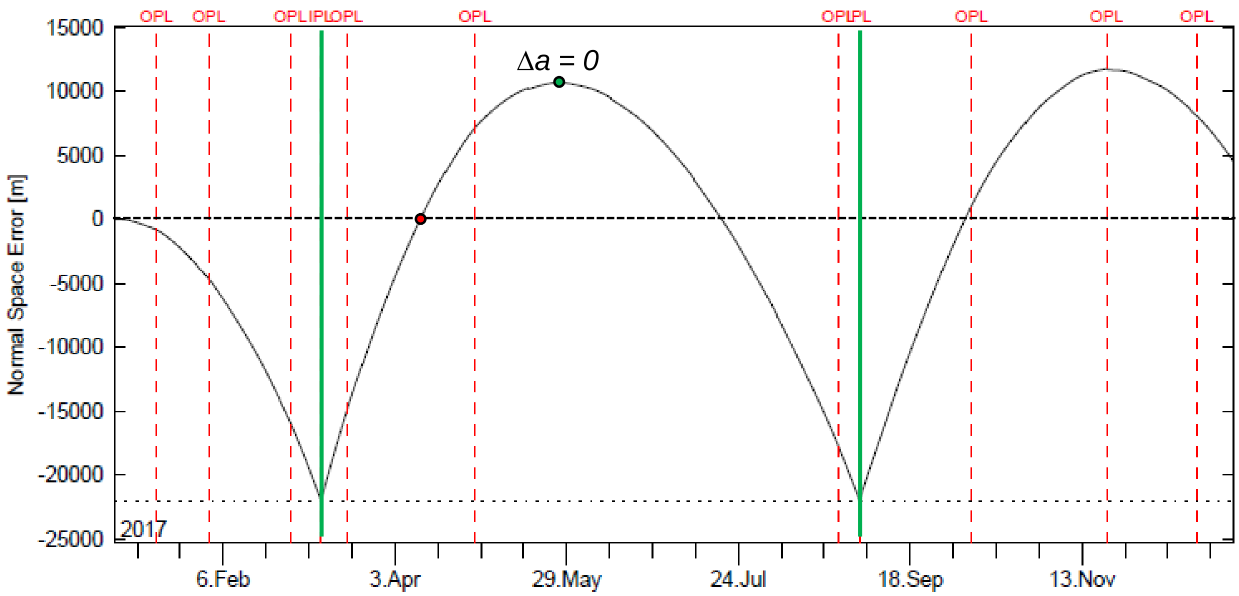

Figure 3. Numerical simulation of EN1-REF ground-track evolution over one-year period with low solar activity. The normal space error is shown at ascending node passages only. The vertical lines indicate the drag make-up maneuvers (green, label: IPL for in-plane) and the inclination correction maneuvers (red, label: OPL for out-of-plane).

The total ΔV budget for orbit control is summarized in Table 1. Considering the actual launch mass of 916 kg including 59 kg of hydrazine (unusable ~1.7 kg), a maneuver capability of 135 m/s results. This is clearly higher than the required ΔV budget, resulting in a significant margin for lifetime extension (nominal: 5 years) and more sophisticated de-orbiting scenarios and end-of-life operations.

Table 1. Total ΔV budget for orbit control maneuvers.

ΔV budget [m/s] for orbit control maneuvers	In-plane	Out-of-plane
Target orbit acquisition (worst case injection)	7.6	6.7
Drag compensation during low / normal / high solar activity, 5 yrs	1.0 / 3.1 / 8.6	-
Debris collision avoidance, 5 yrs (estimate: 6 critical events p. a.)	0.8	-
Inclination maintenance, 5 yrs	-	16.4
De-orbiting (perigee lowering to 500 km, re-entry < 25 yrs)	38.6	
Sum	48.0 / 50.1 / 55.6	23.1

3 Special FD Functionalities

Before diving into the operational experience gained during EnMAP's LEOP and early commissioning phase, novel flight dynamics functionalities implemented for this mission are presented. Ultimately, with these special FD functionalities, the scientific return of the EnMAP mission is optimized. Below, two FD functionalities are elaborated on: the maneuver options manager for a more flexible approach to orbit maintenance and microservices for fast data exchange between the flight dynamics and mission planning systems [4].

Maneuver Options Manager

To facilitate orbit maintenance, a responding software for file-based exchange of maneuver options and selections between the Mission Planning System (MPS) and the Flight Dynamics System (FDS) was implemented. The main functionalities can be summarized as follows:
For maneuver options generation, FDS proposes one or more options with constant maneuver size for an upcoming orbit maneuver to MPS, which subsequently selects the option with minimum impact on the image acquisition and mission timeline. Four distinct maneuver types are supported as described:

- **Collision Avoidance Maneuver (COLA)**: Exactly one maneuver option is provided to MPS, which cannot be withdrawn.
- **Target Orbit Acquisition Maneuver (ACQ)**: Exactly one maneuver option is announced to MPS with the possibility to withdraw the maneuver option either by FDS or MPS.
- **In-Plane Maneuver (IPL)**: Several maneuver options are delivered for a given orbital position at each full orbit for a given number of orbits.
- **Out-of-Plane Maneuver (OPL):** For a given orbital position at ascending or descending node, several maneuver options are submitted at each half orbit for a given number of orbits.

Lists of previously announced maneuver options in IPL and OPL cases are continuously updated, particularly including a possible withdrawal of all previously announced maneuver options. MPS informs FDS which of the announced maneuver options is actually being planned.
This selection can subsequently be changed through updates by MPS as long as there is more than one option available. The selection is also sent as an immediate response to a new list of maneuver

options that contains only a single option (e.g. for COLA maneuver) or none at all (withdrawal of all previous maneuver options). Next, FDS acknowledges the receipt of the selection.

When FDS releases a maneuver, MPS shall be informed that this maneuver is mandatory. For this purpose, FDS updates the maneuver options to which the released maneuver belongs to, such that only the released maneuver is included. This update is sent to MPS in order to assure that MPS no longer adapts the maneuver selection for these maneuver options.

It should be noted that each of the 8-9 yearly inclination control maneuvers (OPL) offers high flexibility in terms of planning. The center of the extended maneuver can either be at ascending or at descending node passage. Furthermore, because of the slow inclination evolution, it hardly impacts the orbit control performance when the execution time of such a maneuver is shifted by a few orbits forward or backward in time. This results in very high planning flexibility and hence very low probability of interference with planned Hyperspectral Imager (HSI) acquisitions.

Microservice: Attitude Profile Service

Nominally, the satellite is orbiting Earth in a Sun-pointing attitude (also referred to as normal mode), which means the HSI – aligned with the spacecraft's z-axis $Z_{S/C}$ – is pointing in anti-Sun direction, while $Y_{S/C}$ is parallel to the Earth's equator and $X_{S/C}$ completes the right-handed reference frame (see Figure 4 showing EnMAP's body frame). This nominal attitude is established autonomously onboard.

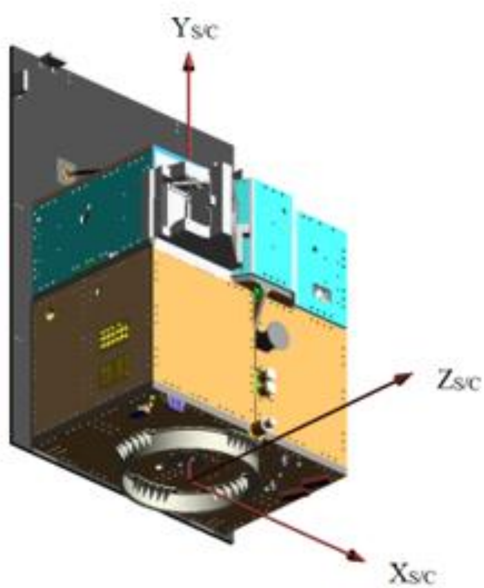

Figure 4. EnMAP's body frame, with the center of origin being the center of the satellite separation system, $Y_{S/C}$ in the direction of the normal of the ideal launcher interface plane, $Z_{S/C}$ in the opposite direction of the normal of the ideal solar panel plane and $X_{S/C}$ completing the right-handed reference frame (Credit: OHB).

Any other orientation is defined as precise AOCS sub-modes. For these sub-modes the required attitude guidance profiles are computed by FDS on ground and commanded to the spacecraft. The following eight sub-modes are supported as described:

- **Image Acquisition**: HSI (aligned with $Z_{S/C}$) points nadir. $Y_{S/C}$ points to the negative orbit momentum and $X_{S/C}$ completes the right-handed reference frame. An additional roll angle around the x-axis can be applied.
- **Data Download**: X-band antenna ($Z_{S/C}$) points to the given ground station coordinates. Other axes are free and internally defined such that $Y_{S/C}$ points to the negative orbit momentum and $X_{S/C}$ completes the right-handed reference frame.
- **Sun Calibration**: $X_{S/C}$ in anti-Sun direction, $Y_{S/C}$ parallel to the Earth's equator, $Z_{S/C}$ completes the right-handed reference frame.
- **Deep-Space Calibration**: $Z_{S/C}$ in anti-Sun direction, $Y_{S/C}$ parallel to the Earth's equator, $X_{S/C}$ completes the right-handed reference frame.
- **Lunar Calibration**: $Z_{S/C}$ points to the Moon's center, $Y_{S/C}$ parallel to the Earth's equator, $X_{S/C}$ completes the right-handed reference frame. Additionally, a constant slew around y-axis is applied to screen over the complete Moon.
- **ACS Sun Calibration**: $Z_{S/C}$ in anti-Sun direction, $Y_{S/C}$ parallel to the Earth's equator, $X_{S/C}$ completes the right-handed reference frame. Additionally, a constant offset and/or a slew rate around any of the axes can be applied.
- **ACS Inertial Calibration**: $X_{S/C}$ in direction of Vernal Equinox at J2000, $Z_{S/C}$ to northern direction (i.e. normal to the Earth's equatorial plane), $Y_{S/C}$ completes the right-handed reference frame. Additionally, a constant offset around any of the axes can be applied.
- **Orbit Change Maneuver**: depending on the nature of the maneuver, different attitude laws are applied:
    - **In-Plane maneuvers**: $Y_{S/C}$ points to either positive or negative tangential direction of the orbital RTN reference frame, depending on the desired in-plane effect to either increase or decrease the SMA (thrusters are mounted pointing towards minus $Y_{S/C}$). $Z_{S/C}$ points opposite to the radial direction (anti-Nadir) and $X_{S/C}$ completes the right-handed reference frame.
    - **Out-of-Plane maneuvers**: $Y_{S/C}$ points to either positive or negative normal direction of the orbital RTN reference frame (depending on the desired out-of-plane effect). $X_{S/C}$ points to the cross product between $Y_{S/C}$ and the Sun direction. $Z_{S/C}$ completes the right-handed reference frame.

To support the computation of attitude guidance profiles for all of the above-mentioned sub-modes, except for the Orbit Change Maneuver sub-mode, a microservice was developed. This means that MPS sends a request to FDS for a dedicated time period and sub-mode, and it receives a real-time response in return, containing the corresponding attitude guidance profile, which is further converted into a command and uploaded to the spacecraft. This way, no file transfers are needed between MPS and FDS and independent, real-time processing of mission planning requests is guaranteed.

To exchange Chebyshev orbit information, the service-based approach is also applied. On average, 200 Chebyshev requests and 1,700 attitude profile requests, including image acquisition requests, are handled in real-time every day. Microservices allow for such frequent exchange of information in a smooth and reliable manner, which is essential in spacecraft operations. By using microservices, the customer receives tailored products in a fast and reliable way, with no compromise at performance, while reducing the amount of transferred data [4].

Orbit Change Maneuvers on the other hand, are usually planned directly by FDS depending on the orbit maintenance computation and is therefore not applicable to the new FDS-MPS request-response-approach. Furthermore, next to the maneuver-specific attitude guidance profile, FDS also provides the maneuver command parameters itself. Since these must be commanded together, it was decided to keep the traditional file-based transfer for this scenario.

4 Operational Experience from LEOP and Early Commissioning Phase

The EnMAP satellite was successfully launched on April 1, 2022 by a Falcon 9 from Space Launch Complex 40 at Cape Canaveral, Florida. On board this Transporter-4 flight, SpaceX's fourth dedicated SmallSat Rideshare mission, 40 spacecraft were launched into space. EnMAP was the first passenger to be separated into a Sun-synchronous orbit at 640 km mean altitude (see Figure 5).

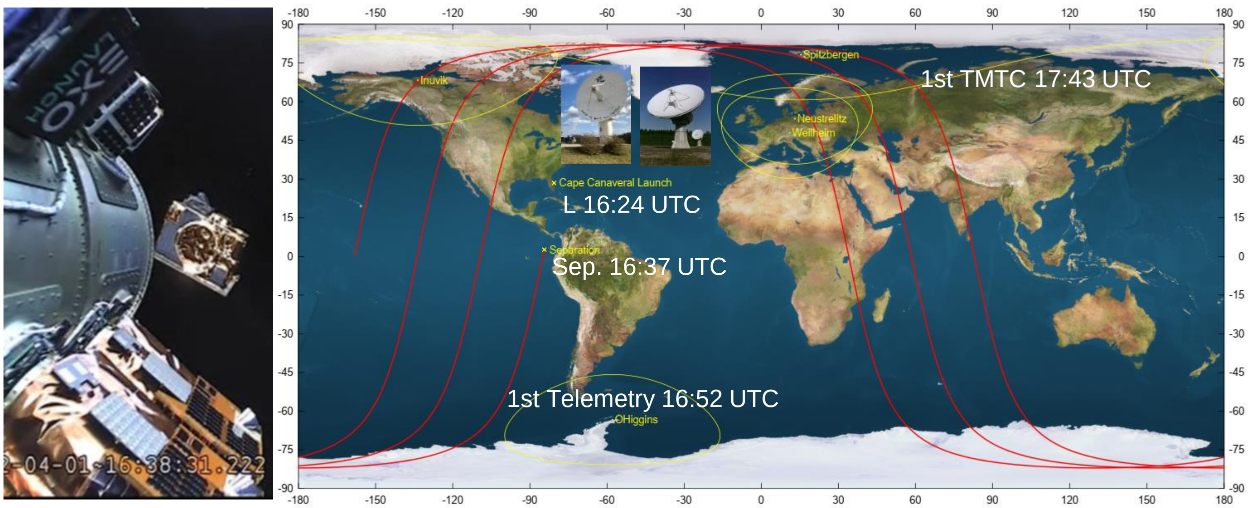

Figure 5. EnMAP separation (left, Credit: SpaceX) and ground-track of the first three orbits with the LEOP ground-station network (yellow curves depict the 5 deg elevation mask).

After successful checkout and calibration of the attitude and orbit control systems, 14 orbit control maneuvers were conducted between April 5 and 9, 2022, to acquire the final target orbit. Since then, EnMAP has been operated in the mission reference orbit at 642 km mean altitude and 97.978 deg inclination. The target orbit acquisition process is depicted in Figures 6 and 7 for the relative (i.e. EnMAP with respect to the reference orbit) semi-major axis (Figure 6 top), relative inclination (Figure 6 bottom) and relative eccentricity vector magnitude (Figure 7). EnMAP's first orbit maneuver was a 100 sec burn-duration test maneuver at 3:11 UTC on April 5, 2022 (ΔV of 0.27 m/s), followed by another test maneuver with maximum impulse of 400 Ns at 17:53 UTC the same day (ΔV of 0.41 m/s). Both maneuvers were raising the orbit, and together with the final three in-plane maneuvers on April 6 and 7, they were dedicated to eccentricity vector correction. Here, the objective was to align the osculating EnMAP orbit with its mission reference orbit to within a control box of ±6 km in radial direction and ±22 km in normal direction. For that reason, the five in-plane maneuvers decreased the initial radial separation of 8.8 km to 5.7 km and installed the targeted mean semi-major axis.

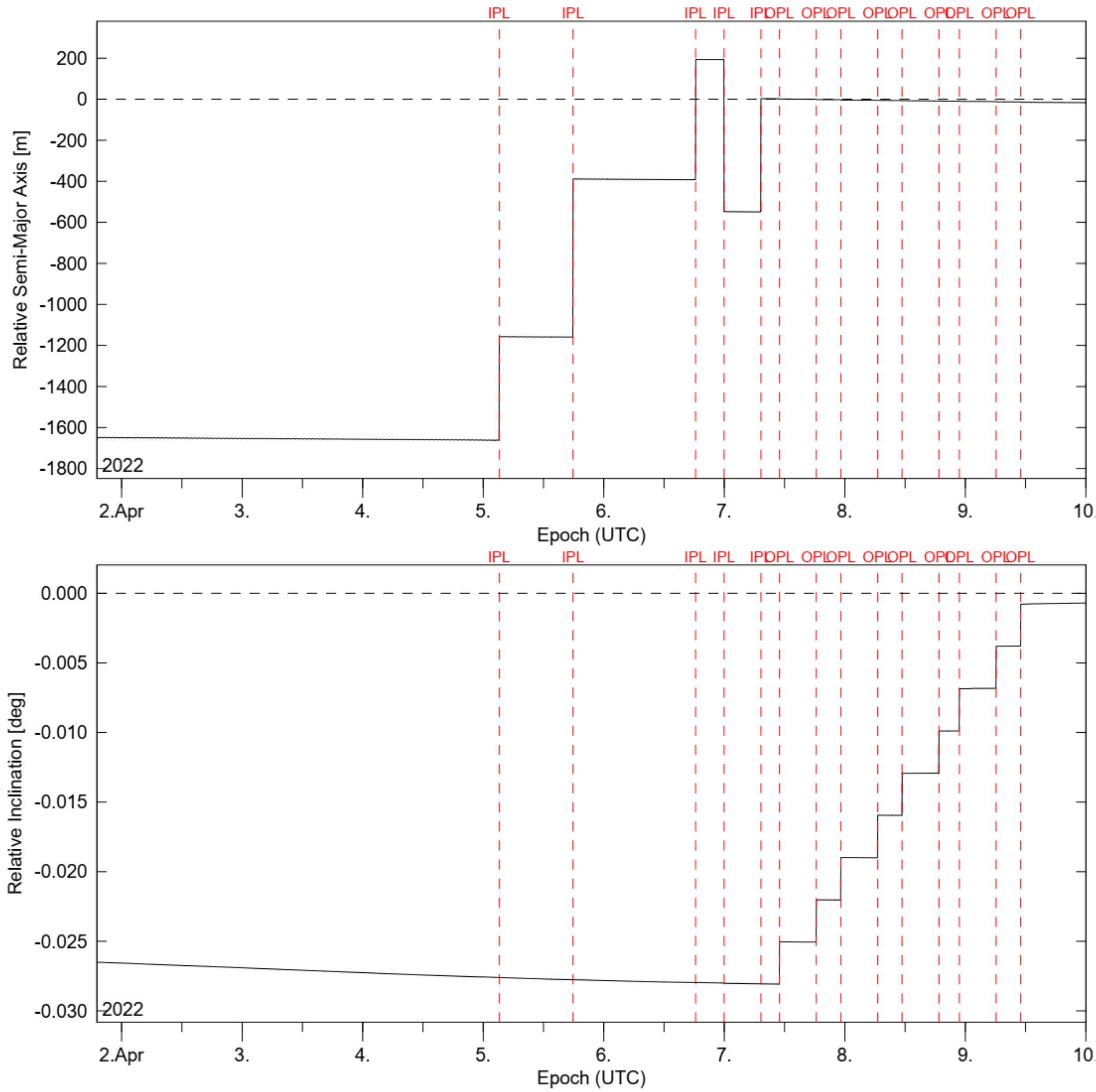

Figure 6. EnMAP target orbit acquisition in April 2022. The plots depict the relative semi-major axis (top) and relative inclination (bottom). The in-plane (IPL) and out-of-plane (OPL) maneuvers are indicated by dashed red verticals.

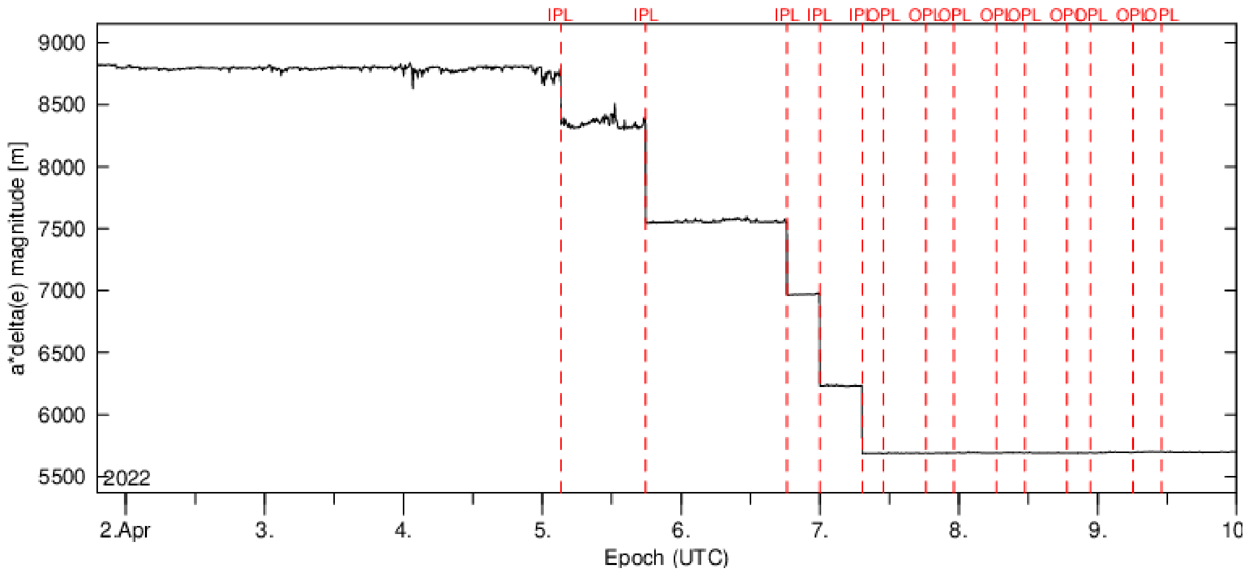

Figure 7. EnMAP target orbit acquisition in April 2022: relative eccentricity vector magnitude. The in-plane (IPL) and out-of-plane (OPL) maneuvers are indicated by dashed red verticals.

The remaining nine acquisition maneuvers were all executed with ΔV of 0.4 m/s, step-wise correcting the inclination towards the targeted 97.978 deg. After parameter tuning with calibration results obtained from the first maneuvers, the maneuver performance was better than 1% off the commanded maneuver. The total ΔV over all 14 maneuvers was 5.33 m/s and hence clearly within the (worst-case) budget of 14.3 m/s allocated for target orbit acquisition.

As described in Section 2, the satellite orbit is controlled with respect to an Earth-fixed reference orbit over the entire orbit, analogous to a rim, with a control box of ±6 km in radial direction and ±22 km in normal direction. After successful acquisition of the reference orbit on April 9, 2022, only one inclination control maneuver (April 20, 0.40 m/s) and one drag make-up maneuver (May 16, 0.14 m/s) were performed in the period until June 30, 2022. The orbit maintenance performs nominally and the control performance is as depicted in Figure 8. A small violation of the normal space error (left side of control box in Fig. 8) resulted from planning of the orbit raising maneuver for the moment of space error violation but selecting a later maneuver slot. In order to prevent a future control box violation, the threshold for maneuver planning was decreased from 22 to 21.5 km, allowing for sufficient margin in case the maneuver execution is scheduled few integer orbits later by MPS.

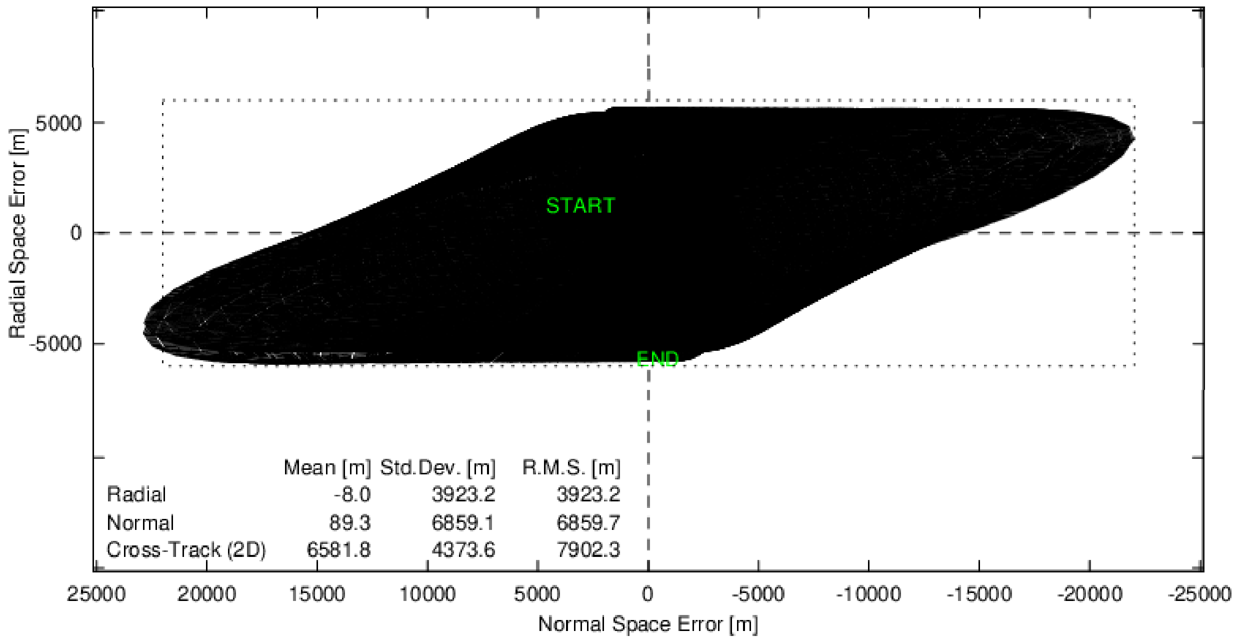

Figure 8. EnMAP space error evolution during the first 2.5 months of the commissioning phase (April 10 to June 30, 2022). The dotted box illustrates the radial and normal control limits.

At 642 km altitude, EnMAP is operated inside the denser populated low-Earth orbit region. Following orbit determination and maneuver planning processes, CCSDS Orbit Ephemeris Messages (OEM) are regularly generated and uploaded to 18 SDS. On average, warnings for 126 conjunction events involving EnMAP are received and processed per month. Only few are critical (i.e. probability of collision > 1E-5), and so far, only one critical event required a collision avoidance maneuver. On July 24, 2022 at 20:23 UTC the first COLA maneuver took place with 1 cm/s in anti-flight direction, 2.5 orbits before time of closest approach, and increased the radial separation from a SL-14 rocket-body debris from initially 8 m to 45 m, thereby significantly reducing the probability of collision from the initial 4E-4 to below the critical threshold of 1E-5.

5 Conclusion

EnMAP is Germany's high-resolution imaging spectroscopy Earth observing mission. The 916 kg satellite was successfully launched by a Falcon 9 on April 1st, 2022. This paper reports on the experience gained from a Flight Dynamics perspective, with the main objective to share in-flight results and experiences, especially on the target orbit acquisition and maintenance operations for DLR's latest launched satellite. After describing the main characteristics of EnMAP, the paper focuses on the repeat ground-track orbit and elaborates on how the control of this orbit is performed. To handle orbit maintenance, the maneuver options manager is presented as a Flight Dynamics functionality developed for EnMAP, which also applies for the microservice to compute and deliver attitude guidance profiles. Finally, this paper covers the Flight Dynamics experience during EnMAP's LEOP and first few months of the commissioning phase.

After successfully checking out and calibrating the attitude and orbit control systems, 14 orbit control maneuvers were performed between April 5 and 9, 2022, with a total ΔV of 5.33 m/s.

Following these maneuvers, EnMAP's mission reference orbit was acquired. From that point on, EnMAP has been operated in its 27-day repeat ground-track orbit at 642 km mean altitude and 97.978 deg inclination. The orbit control concept is based on the flight-proven TerraSAR-X concepts, and EnMAP is the first DLR mission that makes use of the in-house developed generic RGT suite for orbit guidance, monitoring and control.

EnMAP is currently completing its instrument commissioning phase and will soon start to routinely measure and model key dynamic processes of Earth's ecosystems.

6 Acknowledgements

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7 References

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