THE PRISMA STORY: ACHIEVEMENTS AND FINAL ESCAPADES

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Abstract: *The Prisma mission is divided into four phases; the nominal mission, the extended mission, the external parties' mission and the final mission. The milestones switching from one phase to the next are unique occasions that have brought the mission forward, whereof some were planned before the launch of the satellites and some were adaptations along with the development of the mission timeline. In particular, the current execution of the final phase contains Mango alone operation, which means Mango has abandoned Tango and has started a journey on its own for transfer to and rendezvous with a still to be decided space debris object. The rendezvous will be performed based upon TLE and angular measurements from the on-board camera and after the rendezvous a visual inspection and characterization of the object will be performed, utilizing the on board high resolution PR camera. This paper explains these milestones and the turn of events leading up to the events that were not planned. It also describes the past mission phases in a broader sense and the current final phase in more detail.*

Keywords: *Visual Inspection and Characterization, Non cooperative Rendezvous, Final Approach and Recede Maneuvers of Space Debris, Autonomous Formation Flying, Autonomous Rendezvous*

1 Introduction

OHB Sweden (OHB-SE) is the prime contractor for the Prisma mission which is funded by the Swedish National Space Board (SNSB). The mission is further supported by the German Aerospace Center (DLR/GSOC), the French Space Agency (CNES), and the Technical university of Denmark (DTU). Prisma consists of two spacecraft: Mango and Tango. The orbit altitude is 750 km, sun synchronous with 06:00 ascending node. The satellites were launched clamped together on June 15, 2010. Tango was separated from Mango on August 11 the same year.

Chapter 1 gives the background of the Prisma satellite and the basic operations control center that has been used throughout the mission. Chapter 2 contains the Prisma story, i.e. the time in orbit since launch and up till today, divided in four subchapters; the Nominal mission phase, the Extended mission phase, the External parties mission phase and the Final phase.

1.1 Background

Formation flying and rendezvous has been identified as key enabling technologies in several advanced disciplines involving scientific applications, on-orbit servicing and assembly[1,2,3,4]. Applications include distributed satellite systems for enhanced remote sensing performance, for planetary science, astronomy, the assembly of large structures on-orbit as well as re-supply or repair of orbital platforms and space debris removal. For all these applications, there is a need to implement on-board guidance, navigation, and control (GNC) with a high degree of autonomy. This aspect motivated SNSB and OHB-SE to initiate the development of the PRISMA mission in 2004[5,6]. Potential participants were invited by the prime to contribute to the mission with different key technologies and to also implement self-defined experiments sharing mission time and resources. The resulting mission consisted of several hardware and software experiments involving new technologies for propulsion, vision based sensors, GPS and RF-based navigation, as well as GNC-algorithms. OHB-SE as well as DLR/GSOC and CNES have developed their own GNC software for the execution of a series of closed loop orbit control experiments.

1.2 Basic Operational Structure

The operational concept of Prisma constitutes linked entities to execute the mission, and this structure[7] has been intact throughout the entire mission lifetime. The entities are seen in Figure 1-1, where the hierarchical structure from the experimenters to the spacecraft is depicted. As can be seen in the figure, the experimenters only interface the mission control team, which validates each experiment and supports the operations control team during each experiment execution. However, the geographical location of the teams and the layout of the control centers have varied several times during the mission which is explained in each subchapter of chapter 2.

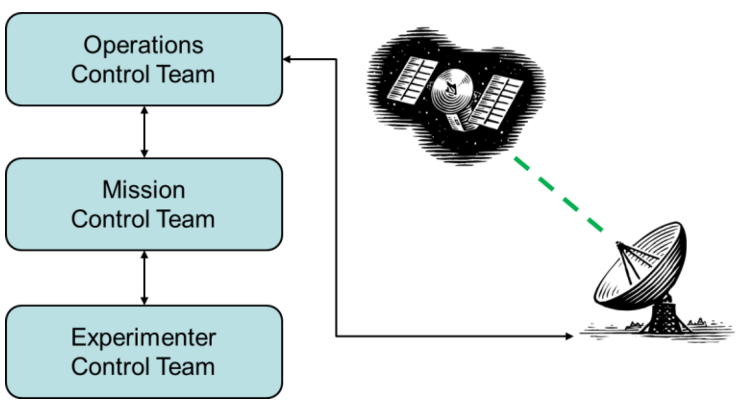

Figure 1-1: Satellite access hierarchy

While the location of the operations team and control centers have varied, the structure of the control center has not changed. It has always contained room for the operations team (usually a single person), the mission control team (the flight director and at least the guidance and navigation expert) and one or more experimenters. Figure 1-2 shows the layout of the initial control center in Solna, where the mission control team was sitting in the MCC and GNC positions which both had a clear view of the operator in the OCC position. The experimenters could be located either next to the flight director and/or in separate rooms depending on experiment criticality. During the DLR/GSOC operations, the control room was inverted and all positions had their back towards each other.

To increase the publicity of the Prisma mission, the mission control team also maintained a blog*, in real time, while executing the experiments. At the separation of the Space Systems Division from SSC to OHB-Sweden in July 2011, the blog was discontinued but has recently been brought to life again during the on-going final phase.

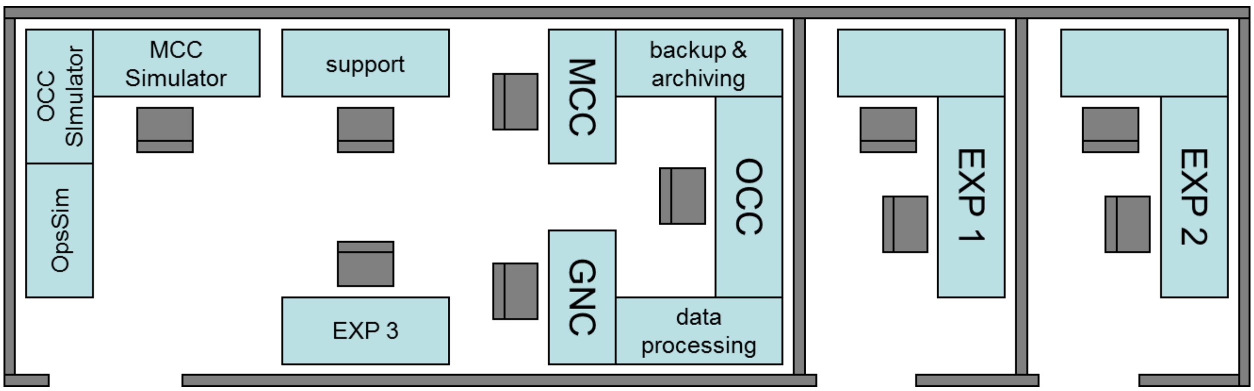

Figure 1-2: Overview of the Mission Operations Control Center

The control center utilizes the ground control system RAMSES (Rocket And Multi Satellite EMCS System) developed by OHB Sweden in parallel to the satellite, and it is a modular and flexible ground system for small satellites. It was also used throughout the entire development phase of the satellite, so there is a strong heritage in the flight procedures from the manufacturing and test phases.

2 The Prisma story

Prisma has been orbiting the Earth for more than 1000 days, and the mission has been divided in four phases according to Table 2-1. Only the first two phases were planned by the time of launch and both of them were supposed to be operated by OHB-SE (former Space Systems Division of SSC) in the purpose-built control-room in Stockholm, Sweden, using the company's own GNC and platform experts to conduct the mission.

Mission phase	Start Date	Duration	Operator
Nominal mission	2010-06-15	273 days	OHB-SE (SSC)
Extended mission	2011-03-15	160 days	DLR/GSOC
External parties mission	2011-08-22	588 days	OHB-SE
Final mission	2013-04-01	Ongoing…	OHB-SE

Table 2-1: The PRISMA mission phases

* www.prismasatellites.se

But as an experimental technology demonstrator, the large number of in-orbit experiments initially planned exceeded the constraints of available funding. In an effort to extend the use of the satellites and enable more experiments, DLR/GSOC offered to temporarily operate the satellites from their control center in Munich, Germany, for a period of five months during 2011, leading to the first phase shift of the mission into the extended phase.

Since the extended mission phase contained a finite set of pre-defined experiments, the phase ended when all activities were concluded and the satellite was returned back to OHB-SE. This event led to the second phase shift of the mission, the external parties phase, which was designed such that any interested organization was invited to participate in the mission and conduct its own experiments according to its own needs and requirements, at the time when the satellite was already in orbit.

However, the external parties phase also contained extended periods of idle time where the satellite was idling, waiting for new partners to come perform newly defined experiments. This idling time enabled the mission management to start planning for the grand finale, the final phase, where the Mango-Tango formation were supposed to be broken and Mango to start a journey on its own towards a space debris object to demonstrate rendezvous and inspection technologies with a non-cooperative space debris target.

This last phase shift was recently conducted when the final phase was initiated by terminating the Tango spacecraft and large dV-maneuvers are applied to the Mango spacecraft to start approaching another object. The final phase is divided in several parts; transfer start, transfer orbit, transfer stop and debris orbit alignment, and finally the debris inspection part which is called IRIDES[†].

The four mission phases are explained in more detail in the subchapter below.

2.1 Nominal Phase

The nominal phase started with the launch in June 2010 and ends with the handover event in March 2011 when the operations control was transferred to DLR/GSOC. During this phase the ground antenna was located at Esrange and the control center in Stockholm, since the satellite was operated by SSC alone at that time, see Figure 2-1. But when the decision was taken to switch operations over to DLR/GSOC, a parallel operations center was built up and new staff was prepared in Germany, in preparations of the handover.

[†] Iterative Reduction of Inspection Distance with Embedded Safety

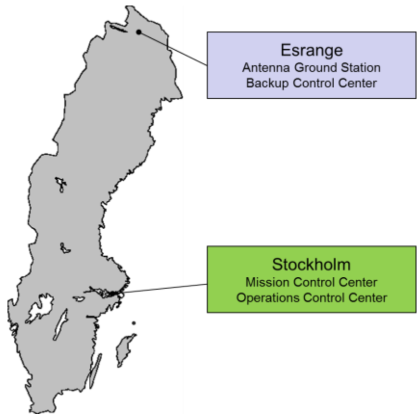

Figure 2-1: Operational concept during the nominal phase

2.1.1 Nominal phase Experiments

In the nominal phase, apart from the LEOP and Tango separation events, most experiments had their first dry-run in orbit to determine the methodology for each experiment set. Some experiments were successful already on the first run, but some encountered initial problems that required tuning or even re-design and new timeslots were scheduled for those experiments in the extended phase.

The mission timeline in the nominal phase was occupied by a mix of autonomous formation flying (AFF) experiments[8,9] by OHB Sweden, DLR[10] and CNES, and propulsion experiments by ECAPS with the new propellant HPGP[11]. In addition to this, OHB Sweden successfully performed several autonomous rendezvous (ARV) experiments[12] from 30km down to 50m, and final approach and recede maneuver (FARM) experiments[13] as close as two meters between the two spacecraft center of mass.

The experiment timeline is shown in the left half of Figure 2-2.

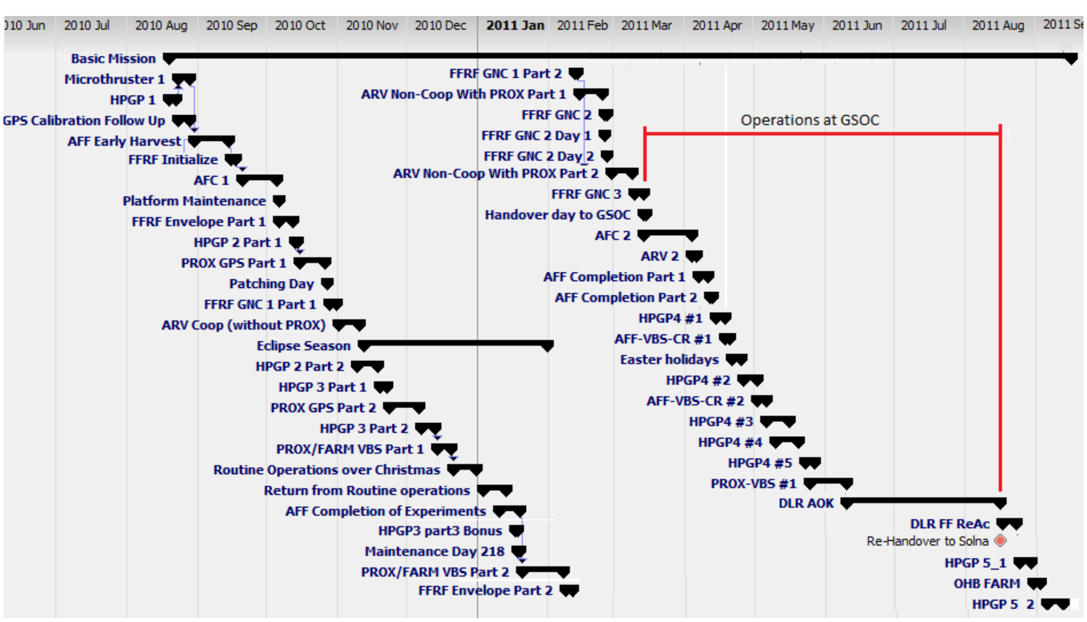

Figure 2-2: Overview of the nominal and extended mission phases (basic mission)

2.2 Extended Phase

The extended phase was five month long from the handover event in March 2011 to August 2011 and was operated by DLR/GSOC. A parallel mission control center and a completely new staff were established at DLR's premises outside Munich, ready to take over the operations at the time of the handover[14]. The Stockholm control center became an experiment control center for this period, since several OHB Sweden experiments were scheduled in this phase and were executed remotely.

DLR/GSOC extended the antenna ground station network to include not only the Esrange station, but also the local Weilheim station and the antenna ground station in Inuvik, Canada, see Figure 2-3. The extended network of antennas provided the possibility of daytime passages which was not achievable from Esrange, and it also provided the opportunity to take a three-station passage, Inuvik-Esrange-Weilheim, which created a 33 minute passage for a LEO orbit.

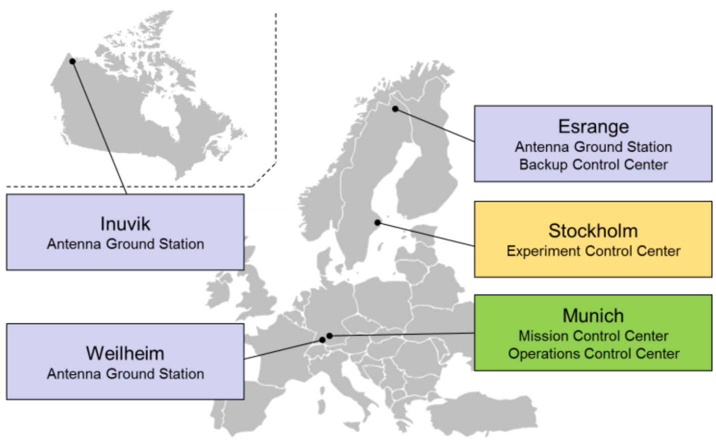

Figure 2-3: Operational Concept during the Extended phase

2.2.1 Extended phase Experiments

The experiments of the extended phase were mainly improved re-runs of experiments already performed in the nominal mission and a few experiments that had been unsuccessful on the first tries. A completely new experiment in this phase was the autonomous orbit keeping (AOK) experiment[15] by DLR.

The AOK experiment was the first experiment to not utilize the formation partner Tango, and the formation was released for the first time. Mango was autonomously controlled in the same orbit while Tango's orbit changed slightly due to the natural orbital dynamics. The relative distance between the two spacecraft reached approximately 65 km at the end of the experiment, which was a record at that time. When the AOK experiment was finished after 71 days, the formation was brought back in closed loop after seven days of reacquisition.

The right half of Figure 2-2 shows the mission timeline for the extended mission phase.

2.3 External Parties Phase

The external parties phase started shortly after the re-handover from DLR/GSOC in August 2011 and lasted until April 2013. As DLR/GSOC did no longer operate the satellite, the Weilheim and Inuvik antenna ground stations were no longer available and the operational concept was back to the initial one, with Esrange as antenna ground station and Stockholm as mission control center. However, investigations started to utilize the Norwegian antenna ground station network through Kongsberg Satellite Services (KSAT), and in August 2012 satellite communications were seamlessly transferred from Esrange to Tromsø. The current planning involves the expansion within the KSAT network to use other antennas for daytime passages.

Figure 2-4 shows the operational concept during the external parties phase.

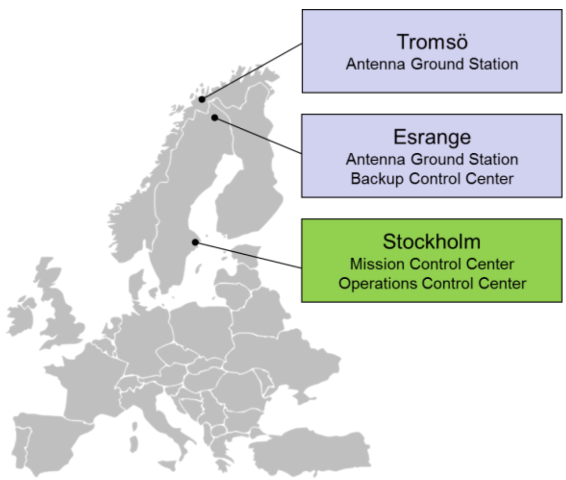

Figure 2-4: Operational concept during the external parties phase

2.3.1 External Parties phase Experiments

The external parties phase was very hectic in the beginning, since several new partners had waited for the opportunity to implement their own experiments, and the participating organizations are shown in Table 2-2.

Organization	Experiment	Start Date	Duration
Space-SI	Interferometry, Space debris, Distributed instrument, Formation flying	2011-09-19	7 days
GMV	HARVD	2011-10-03	5 days
CNES	FFRF cont.	2011-10-10	23 days
DLR	ARGON	2012-04-16	5 days
CNES	µNEAT	2012-09-19	3 days
ECAPS	HPGP6	2013-02-15	1 day

Table 2-2: External parties participants

The mission control group was increased significantly and divided into three teams, to be able to interface new requests from the new experimenters in time. The teams were composed with different expertise to become versatile enough for all the new experiment ideas, e.g. Space-SI designed an experiment formation with Mango, Tango and Cape Town align for several minutes[16]. This experiment was successfully conducted, but it did consume both on-board and on-ground resources.

GMV designed an experiment to collect in-flight data for ground validation of a formation flying simulator and DLR performed an interesting experiment named ARGON[17]. The ARGON experiment was designed to simulate rendezvous with a non-cooperative target, but since Tango is a cooperative target data access to the experimenting DLR team was limited to make it non-cooperative, and dV maneuvers were performed in open loop. The setup was such that an OHB Sweden team, with full access to satellite telemetry to maintain the formation safety, monitored the DLR team that only had GPS measurements of Mango and visual information of Tango while they performed the dV maneuvers. The visual information was taken from the vision based system (VBS) and the simulated rendezvous was successfully performed from 30km to 5km.

The first CNES experiment in the external parties phase was a continuation of experiments performed during the extended phase but also a brand new experiment[18] where the CNES GNC algorithms, normally used together with the CNES delivered RF-relative sensor, were used to control the formation with measurements from the VBS instead. This experiment required an update to the on-board software, which was also performed as part of the experiment.

The second CNES experiment was a mimic of the scientific NEAT mission, called µNEAT, and was designed such that Mango and Tango mimicked a detector-telescope formation. In µNEAT, Mango and Tango was aligned with scientific objects from the actual NEAT catalogue, which were located well out of the orbital plane.

2.4 Final phase

The current and presumably last phase is the final phase, or the IRIDES phase, which started in April 2013 and is expected to last until December 2014. This phase is divided into five parts according to Figure 2-5, which shows the current timeline planning.

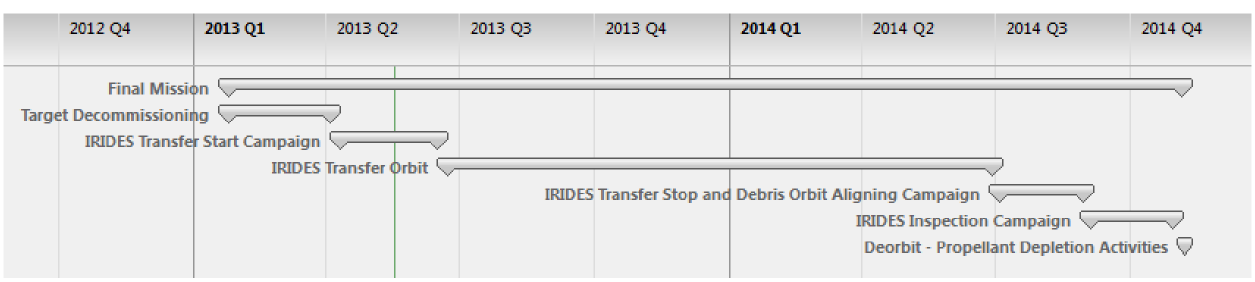

Figure 2-5: Overview of the final mission phase

It is a phase with extremely limited budget and all included activities must spend as little resources as possible. In order to meet this requirement, daytime passages would be in favor, which is about to be established through the KSAT network, as shown in Figure

2-6. Furthermore, the number of passages has been limited to two passages per day during the high activity campaigns (transfer starting and stopping activities) and only four passages per week during the non-campaign periods (while in transfer orbit). Exact number of passages for the IRIDES inspection campaign is not yet determined but will most likely be higher than two per day. The staffing is also brought down to a bare minimum reaching 0.4 of a person at the minimum.

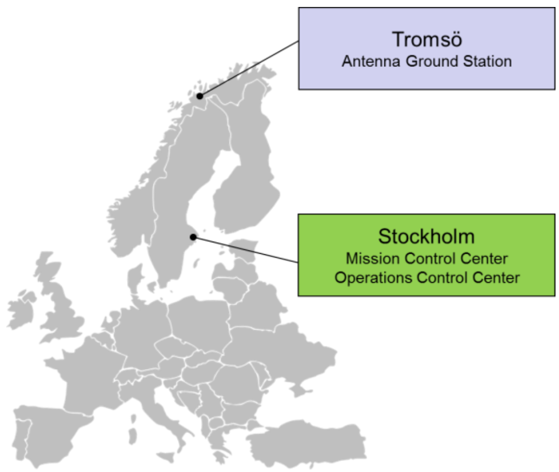

Figure 2-6: Operational concept during the final phase

The goal of this phase is to abandon the Tango spacecraft and to reorient the Mango orbit in several steps to finally align with a space debris object. This is foreseen to take approximately two years since the available amount of propellant is limited, and relative orbit drift rate with the debris object must be kept small, not to exceed the dV budget. When the Mango orbit is neatly aligned with the debris, the IRIDES inspection phase will begin. The orbit transfer part and the IRIDES inspection part are explained in subchapters hereafter.

2.4.1 Final Phase - Transfer Part

In order to maneuver Mango from the Tango chasing orbit to a debris orbit in a fuel efficient way, a strategy has been established that manipulates both the semi-major axis and the inclination in the same dV-maneuver to maximize the use of the propellant. This dV-maneuver is repeated over and over again for a selection of equator crossings, selected depending on the effect they have on the eccentricity.

Figure 2-7 shows a sketch of the Mango altitude, which starts from the Tango altitude and after a starting dV campaign reaches a transfer orbit altitude (below the targeted debris altitude). Mango then stays in the transfer orbit as long as required before a stopping dV campaign is initiated, to raise the Mango altitude to match the debris orbit. During the starting dV campaign, only the equator crossings on the apogee arc of the orbit are selected, since they will increase the eccentricity and lower the perigee. Nature’s forces will then cause drag at the perigee which will lower the apogee without spending any propellant. Since this eccentricity effect depends on solar activity, which makes it difficult to estimate, it is only seen as a bonus effect and the benefit from it is not considered in the dV budget of the experiment. The stopping campaign follows the same strategy, but with the goal to match all orbit parameters with the orbit of the debris.

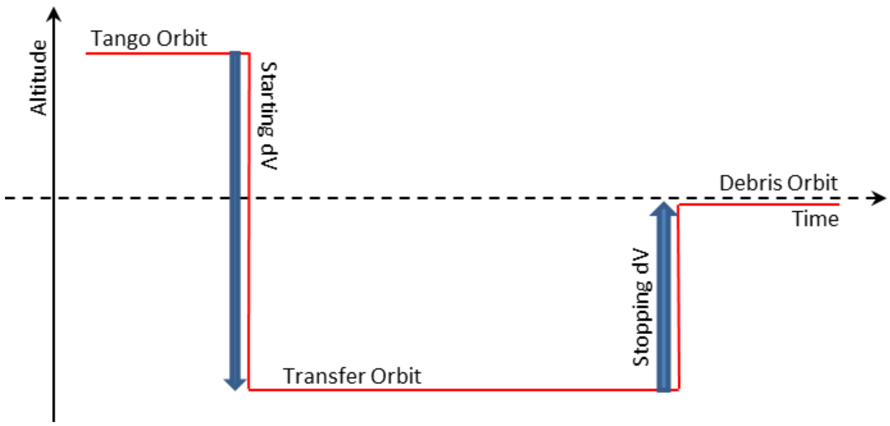

Figure 2-7: Start, transfer and target orbit for the IRIDES transfer.

The execute one day of the dV campaigns, a static procedure is followed. Figure 2-8 shows on overview of the daily work, where first approximately five hours of dV free GPS data is downloaded from the satellite automatically early in the morning. This data is then used by an operator to determine the orbit parameters after the most recent dV slot. When the orbit is determined it is used to calculate new equator crossing for the following night, and at which of them to apply a particular dV. Normally four consecutive equator crossings are used, following directly after the afternoon passage where they are uploaded. In parallel, a post-burn TLE is estimated in the calculation process and this TLE is sent to the antenna ground station to update the antenna pointing for the next day's ground contacts. This procedure is repeated each day of dV burns. It would be possible to interlace this procedure with itself, i.e. a second operator working night shift could be 12 hours out of sync of the scheme in Figure 2-8, allowing for a second dV slot each day. Unfortunately, the budget doesn't allow for it during the on-going starting dV campaign.

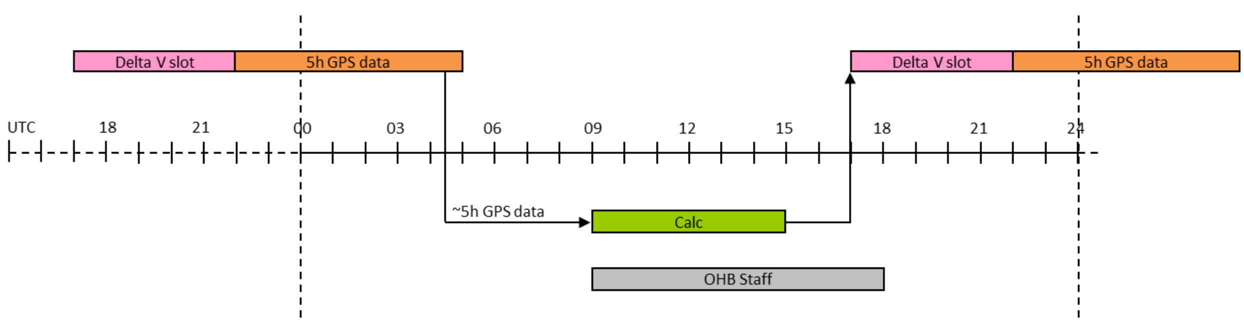

Figure 2-8: One operational day during IRIDES dV campaigns

Each uploaded dV slot contains four equator crossings, and at each crossing two dV pulses are applied as close as possible to the equator crossing, while still respecting the thermal constraints of the thruster. Figure 2-9 shows an enlarged dV slot with a dV-pair centered at each of the four equator crossing.

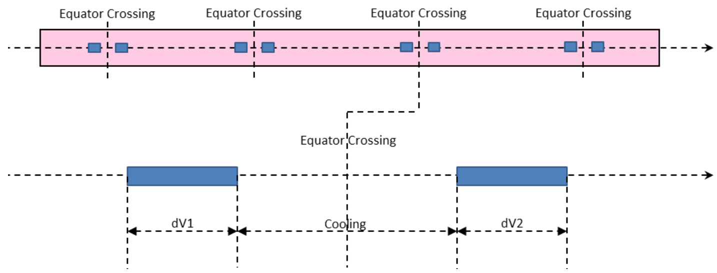

Figure 2-9: Detailed figure of each dV slot containing four equator crossings.

2.4.2 Final Phase - IRIDES Part

When the transfer to the debris object is complete, and the orbit of Mango is adjusted to a point with a relative long-track distance of 100-200km, and relative cross-track and radial components of a couple of kilometers, the IRIDES inspection phase begins. This point will be acquired based on absolute GPS measurements on Mango, absolute TLE information of the debris, and for relative navigation the optical line of sight measurements from the VBS.

The navigation will be performed on-board with the navigation software validated during the PRISMA rendezvous experiments. Navigation performance at a distance of 50m is expected to be better than [10 1 1] m (along-track, cross-track, radial). The proposed strategy is based on establishing a constant separation between Mango and the debris in the cross-track and radial plane at a very early phase of the approach.

The inspection of the debris object will then use the following IRIDES strategy:

- Mango drifts from behind the debris to the other side, still with a constant distance in the cross-track and radial plane.
- The drift is stopped at a safe distance away on the other side.
- The distance in the cross-track and radial plane is then reduced by execution of a dV maneuver.
- Validate that the correct cross-track and radial separation has been established.
- The drift is again initialized to pass the debris, but this time in the other direction.

These back and forth motions are repeated until it is judged that the distance between Mango and the debris object can no longer be reduced while at the same time guarantee the safety of Mango. Mango will be pointing towards the debris based on VBS navigation during the inspection flyby. This will allow for VBS and Digital Video System (DVS) image capturing of the debris from every side.

The approach is very dV lean and as very loose control of the along-track drift is expected; only dV for initiating and stopping the drift is needed in the for long-track direction. Cross-track and radial components will only require dV at the times when the distance in the cross-track and radial plane should be reduced, i.e. when at a very safe long-track distance away from the debris.

3 Conclusion

The Prisma story has been very demanding but successful, with almost no routine operations, which has proven the flexibility of the mission operations and also pushed the limits of the satellite design. During the four phases of the mission many challenging experiments has been performed, such as GPS and VBS based autonomous rendezvous, GPS and VBS based final approach and recede maneuvers, autonomous formation flying based on GPS, VBS and RF sensors, telescope alignment formations, mission control center handovers and multiple antenna ground stations. All in all, a lot of experience has been gained from the mission, and the decision to transfer to and inspect a space debris object in orbit further demonstrates the capabilities of Prisma.

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