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# PRISMA IRIDES: PERFORMANCE AT THE END OF THE DRIFT PHASE & PLANNED RENDEZVOUS EXPERIMENTS

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**ABSTRACT**

*PRISMA was launched on June 15, 2010 to demonstrate strategies and technologies for formation flying and rendezvous. OHB Sweden is the prime contractor for the project which is funded by the Swedish National Space Board with additional support from DLR, CNES, and DTU.*

*PRISMA consists of two spacecraft: Mango and Tango. The Mango spacecraft is 3-axis stabilized and has a propulsion system providing full 3D orbit control. Tango is 3-axis stabilized with a solar magnetic control system and does not have orbit control capability. The two spacecraft were launched clamped together into a 700 km SSO and Tango was successfully separated from Mango on August 11, 2010.*

*In April 2013, when both the nominal and extended mission phases were successfully completed, new objectives were assigned to the Mango spacecraft and the Tango spacecraft was shut down permanently. An eighteen month journey was started towards a new, non-cooperative space object to demonstrate rendezvous and inspection within an experiment called IRIDES (Iterative Reduction of Inspection Distance with Embedded Safety). The baseline rendezvous target is Picard.*

*Since the start of IRIDES, the Mango spacecraft has completed a large series of optimized orbit manoeuvres that has put the spacecraft on a drift towards the new object. The rendezvous is expected in the second half of 2014 and will demonstrate optical relative navigation technologies and the characterization of the rendezvous object and its motion with the use of the on-board video system. The rendezvous strategy within IRIDES includes a series of collision free drift manoeuvres past the rendezvous object successively reducing the closest relative distance. The demonstrated technologies for this rendezvous are believed to play an important role in the future developments associated with space debris mitigation.*

*The paper gives a brief introduction to PRISMA including a retrospective of the different achievements made in the mission. The paper then describes the optimized orbit manoeuvres made to acquire the drift orbit. The status of the drift finalization is then given where the initial manoeuvres performed to finalize the drift are described. The final part of the paper describes the planned activities within the rendezvous phase with focus on the IRIDES experiment.*

## 1. INTRODUCTION

The PRISMA mission demonstrates technologies related to Formation Flying and Rendezvous in space. OHB Sweden (OHB-SE) is the prime contractor for the mission which is funded by the Swedish National Space Board (SNSB). The mission was further supported by the German Aerospace Centre (DLR/GSOC), the French Space Agency (CNES), and the Technical university of Denmark (DTU). PRISMA consists of two spacecraft: Mango and Tango. The orbit is sun synchronous with the ascending node at 06:00 and has an altitude of 700 km. The satellites were launched clamped together on June 15, 2010, and Tango was separated from Mango on August 11 the same year.

The Tango separation event defined the start of the nominal mission, which included a series of experiments defined to demonstrate formation flying techniques and technologies. Following the nominal mission, an extended mission phase was initiated in August 2011, where time and on-board resources were offered to external parties to exploit the platform as an in orbit flying test bench. This part of the mission was concluded by the entrance of the eclipse season starting in November of 2011, where a 16 month idle-period started where the satellite formation was placed into a hibernation state. During this time, the future of PRISMA was contemplated and in March 2013 a new mission objective was decided upon, which had the goal to rendezvous with and inspect a non-cooperative space debris object, based on the experience gathered during the nominal mission during which the Tango spacecraft was the origin of the formation.

This paper outlines the final ongoing experiment IRIDES (Iterative Reduction of Inspection Distance with Embedded Safety) with the overall goal to capture high resolution images of the non-cooperative French satellite Picard, which can only be achieved after several phases of orbit manoeuvres. The paper starts with a background description followed by an overview of the PRISMA system including a summary of the mission phases already completed before the IRIDES experiment. The subsequent chapter introduces the experiment and gives the background for the IRIDES experiment in view of previous PRISMA flight results. This is followed by a detailed description of the phases of the experiment and finally, some conclusions are made.

## 2. BACKGROUND

Formation flying and rendezvous has been identified as key enabling technologies in several advanced disciplines involving scientific applications or 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 in orbit as well as re-supply or repair of orbital platforms and in-orbit debris removal. For all these applications, there is a need to implement on-board guidance, navigation, and control (GNC) functionality 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] under the primeship of OHB-SE. Potential participants were invited by the prime to contribute to the mission with different key technologies and to also implement their own 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 additional RF-based navigation systems, as well as newly developed 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.

## 3. PRISMA SYSTEM OVERVIEW

The PRISMA space segment consists of a small satellite Mango (150 kg), and a microsatellite Tango (40 kg). Mango has full 3-dimensional attitude independent orbit control capability and is 3-axis attitude stabilized using star trackers and reaction wheels. Tango does not have any orbit control capability and is equipped with a solar magnetic attitude control system still providing 3-axis stabilization. The primary propulsion system on Mango is based on six 1-N hydrazine thrusters directed through the spacecraft centre of mass and the delta-V capability was approximately 120 m/s at the time of the launch. All ground communication is made with Mango. Communication with Tango is made via an inter-satellite link (ISL). The GPS is distributed between the two satellites and GPS messages are transferred from Tango to Mango via the ISL. The GPS navigation software resides within the on-board software of Mango. In this way, relative GPS navigation between Mango and Tango is achieved. Apart from supporting the experiments, the GPS navigation system acts as the primary navigation system in Safe Mode when a safe orbit constellation is entered.

The mission includes hardware and software experiments from several contributors [7]. Apart from the mission and system primeship, OHB-SE implements three groups of GPS and vision-based GNC experiments involving passive as well as forced motions [8], [9], [10]. DLR/GSOC provides the GPS absolute and relative navigation system including both the GPS hardware and the on-board navigation software [11]. DLR implements also two different types of closed loop orbit control experiments as well as the on-ground verification precise orbit determination layer [12], [13], [14]. CNES provides the Formation Flying RF (FFRF) sensor and performs also dedicated closed-loop GNC experiments under the Formation Flying In-Orbit Ranging Demonstration (FFIORD) [15], [16], [17]. DTU contributes the vision-based sensor (VBS) which is implemented within the autonomous star tracker with an addition of two dedicated rendezvous cameras [18]. SSC/ECAPS provides the High Performance Green Propellant (HPGP) propulsion system. Two thrusters are included which can be used to replace the nominal hydrazine system in dedicated parts of the mission [19]. SSC/Nanospace includes a MEMS-based cold-gas micro-propulsion system for flight qualification [20]. A Digital Video System (DVS) from Techno System Developments in Naples, Italy is also included [21] as well as a newly developed mass spectrometer from the Institute of Space Physics in Kiruna, Sweden [22].

A summary of the different experiments types within PRISMA is given in Table 1. In addition to these experiments, PRISMA provides a test flight for a newly developed Data Handling System and Power Conditioning and Distribution Unit with battery management electronics. PRISMA also acts as a model project for new on-board software developed with model-based design techniques, demonstrates the newly developed ground support and operations software RAMSES and provides a test flight for the DVS and the particle mass spectrometer.

| GNC Experiments | | | |
|---|---|---|---|
| ***Experiment Set*** | ***Description*** | ***Organization*** | ***Key Sensor*** |
| Autonomous Formation Flying (AFF) | Passive GPS-based formations and reconfiguration. | OHB-SE | GPS |
| Proximity Operations and Final Approach/Recede (PROX/FARM) | Three-dimensional forced motion under the constraints of virtual structures. Docking simulation. | OHB-SE | GPS or VBS |
| Autonomous Rendezvous (ARV) | Autonomous vision based rendezvous. | OHB-SE | VBS |
| Spaceborne Autonomous Formation Flying Experiment (SAFE) | Passive GPS-based formation flying. Formation keeping and reconfiguration. | DLR | GPS |
| Autonomous Orbit Keeping experiment (AOK) | Autonomous orbit keeping of single spacecraft. DLR's secondary mission objective. | DLR | GPS |
| Precise Orbit Determination (POD) | On-ground verification layer. | DLR | GPS |
| GNC part of Formation Flying In-Orbit Ranging Demonstration (FFIORD) | Closed loop GNC experiments involving passive and forced motion within rendezvous, relative orbit keeping, and collision avoidance. | CNES | FFRF |
| **Hardware Experiments** | | | |
| ***Unit*** | ***Description*** | ***Organization*** | |
| High Performance Green Propellant | Flight qualification of new propulsion technology. | SSC/ECAPS | |
| Micro Propulsion | Flight qualification of MEMS based cold-gas propulsion. | SSC/Nanospace | |
| FFRF | In-orbit sensor validation. | CNES | |
| VBS | Flight qualification of vision-based sensor technology. | DTU | |

***Table 1:*** *Summary of PRISMA experiments.*

## A. MISSION SUMMARY

After launch, operations included the initial acquisition, LEOP, Tango separation and the nominal and extended mission phases [23]. The Mission Control Centre (MCC) in Stockholm, Sweden is based on the in-house developed RAMSES ground control software and because of the experimental characteristics of the mission; PRISMA was operated by GNC and platform experts from OHB Sweden. An exception was the extended mission phase, where operations were temporarily transferred to DLR/GSOC between March and July 2011. The mission was then operated from Oberpfaffenhofen, Germany, in order to further support the mission and in this way prolonging its operational lifetime [24], [25]. A cloned MCC was set up at DLR/GSOC and personnel were trained at OHB-SE. During this period and in addition to the Kiruna antenna, DLR/GSOC also made use of ground stations in Weilheim, Germany, and Inuvik, Canada. This allowed for an increased amount of passages and day-time operations. The PRISMA mission phases are outlined in Table 2.

| **Mission Phase** | **Start Date** | **Duration** |
|---|---|---|
| Nominal Mission | 2010-06-15 | 273 days |
| Extended Mission[*] | 2011-03-15 | 160 days |
| External Parties Mission | 2011-08-22 | 82 days |
| Hibernation | 2011-11-12 | 506 days |
| Final Mission | 2013-04-01 | Ongoing |

***Table 2:*** *Summary of mission phases.*

[*] The extended mission phase was operated by DLR/GSOC from Oberpfaffenhofen, Germany.

After the Extended mission phase, the PRISMA satellites were again operated from OHB-SE premises but this time using one of Kongsberg Sat's (KSAT) ground antennas in Tromsø, Norway. The switch from the initial SSC ground station Esrange in Kiruna to the KSAT ground station took place in August 2012. The orbit and the antenna position result in late afternoon and night-time passages with up to 10 passages per day, but as a result of the transition to KSAT, the inclusion of the antenna station at Svalbard is being planned which will provide a passage on every orbit, i.e. up to 15 passages per day.

At this point in the mission, all pre-launch decided experiments were successfully concluded [26] and external parties were invited to participate in the mission to utilize the PRISMA formation flying test bed. These new partners formed the External Parties Mission phase where flight time, on-board resources and software updates were performed to optimize the results of the additional experiments. After the External Parties Mission phase, no more experiments were in the timeline and the satellite was commanded into hibernation mode, awaiting a decision for the future operations.

Reference [27] gives a summary of the different experiments, including some flight results. More details can be found in [28], [29], [30], [31], [32], [33], [34] concerning descriptions of the experiments and in [35], [36], [37], [38], [39], [40], [41] for flight results from the mission.

### B. INTRODUCTION TO IRIDES

Already in the end of the extended mission phase, it was observed that there would be a considerable amount of remaining delta-V also after the completion of the External Parties Phase. Because of the emerging interest in space situation awareness as well as in space debris mitigation, it was investigated if the remaining delta-V could be used to navigate to some inoperable space object and to observe and characterize this object optically. A candidate list of objects was obtained and the navigation and rendezvous strategies were outlined in an experiment called IRIDES – Iterative Reduction of Inspection Distance with Embedded Safety. For over a year, the IRIDES experiment grew more and more mature and in the beginning of 2013 it was decided to break the Mango-Tango formation and initiate the implementation of IRIDES [42], [43].

The decided debris object on the list of candidates is the French owned satellite Picard. At the start of the drifting phase, the difference between the two orbits was 28 km in semi major axis, 0.022 degrees difference in inclination and about 14 degrees difference in right ascension of the ascending node.

The IRIDES experiment is designed to further exercise, utilize and expand the PRISMA capabilities within the area of Multi Vehicle Operations, most notably the rendezvous and optical inspection of a non-cooperative target. Although it would have been natural (as a phase within the IRIDES experiment) with a physical encounter and interaction with the target, this is currently excluded from the current IRIDES objectives since PRISMA is not equipped with any grappling device.

What motivated the decision to initiate the IRIDES experiment were the results from the nominal mission where several rendezvous experiments had been performed together with Tango. These experiments made use of the relative GPS navigation as well as the relative VBS navigation systems. In these experiments, both sensors were operated in parallel although only one of them was in closed loop control. The other navigation system then served as an independent real-time reference, used for safety, and both sensor performances were later evaluated against the precise orbit determination obtained from post processing on ground.

The navigation performance for IRIDES at a distance of 50 m is expected to be better than 10 m in along-track direction and 1 m in cross-track and radial direction. ***Fig. 1*** shows the achieved navigation performance during the final phases of a rendezvous experiment performed in formation with Tango during the nominal mission. The Mango spacecraft autonomously approached the Tango spacecraft based on the VBS sensor measurements and finally stopped at the hold point at 50 meters for a full orbit. The figure show the relative navigation results from the Vision Based navigation in blue while the relative GPS navigation used for evaluation is shown in red. The errors to the right come from the fact that at this distance, Tango starts to be sufficiently large in the field-of-view in order for the sensor to start to track different parts of the Tango spacecraft.

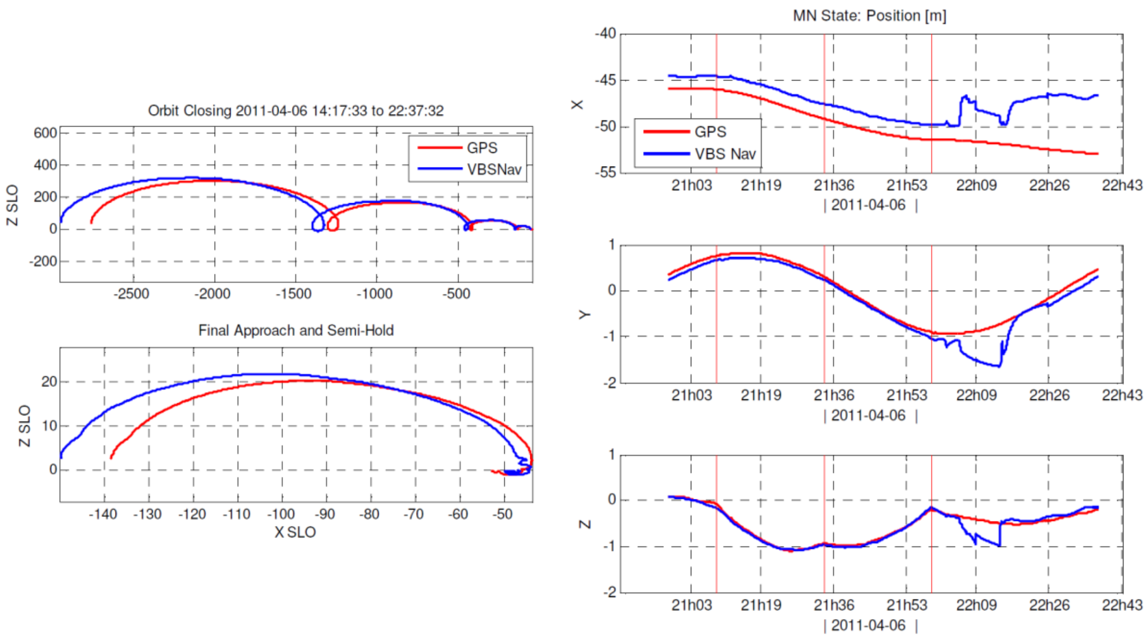


***Fig. 1****: Expected Navigation Performance. Left: Autonomous final approach and semi hold point at 50m relative to Tango during a rendezvous experiment in the nominal mission. Right: Along-track, cross-track and radial distance to Tango for the autonomous semi-hold point of one of the rendezvous experiment in the nominal mission.*

## 4. DETAILED OUTLINE OF THE IRIDES EXPERIMENT

The IRIDES experiment is divided into several consecutive phases of which the first three are completed and the fourth is on-going. The phases are outlined in Table 3. The table summarizes the status, success criteria and main sensors used in each phase. Details of each phase are described in the subchapters of this section.

| Phase | Status | Success criteria | Sensor(s) |
|---|---|---|---|
| Tango Termination | Completed | RF instruments disabled. | N/A |
| Starting delta-V campaign | Completed | Transfer drift orbit reached | GPS |
| Transfer drift orbit | Completed | | GPS |
| Stopping delta-V campaign/ Far range rendezvous | On-going | Relative handover point reached. | GPS, TLE (and VBS) |
| Inspection (IRIDES) | In preparation | Captured high resolution images of the target satellite. | GPS, VBS and DVS |
| De-orbit | In preparation | Minimizing decay time in orbit | GPS |
| Characterization | Additional activity in preparation | Estimated pose and tumble rate of target satellite. | N/A |

***Table 3:*** *IRIDES Experiment phases.*

### A. TANGO TERMINATION

The first thing to do in the IRIDES experiment was to terminate the old formation origin spacecraft Tango and ensure all its radio transmitters were disabled. This was done by setting two end-of-mission flags in the software and then re-boot the on-board computer. The last bytes of data from Tango were received at 17:12:48 UTC on April 05, 2013, which defined the start of the IRIDES experiment.

### B. ORBIT PLANE DRIFT START CAMPAIGN

Shortly after the Tango termination campaign, the drift starting delta-V campaign was initiated. Due to the low and decreasing nominal thrust, the campaign had to be implemented as a segmented, multi-revolution transfer.

In principle, the operations were facing a multi-revolution optimal control problem with many degrees of freedom in the control variables. However, a J2-modified Kepler orbit dynamics model captures very well the fundamental and decisive phenomena of the dynamics. By using this simplified dynamics model together with a calculus of variations approach, the structure of the problem becomes clearly visible and the structure and the nature of useful solutions could easily be captured and formalized. This was done and after taking all the operational constraints into account, finally a total of 57 individual burns spread out over 37 days were executed to modify the three orbit parameters: semi major axis, inclination and eccentricity. These three were used as control variables for the optimization process. The following paragraphs describe some of the resulting consequences.

The campaign was initiated at a time when the argument of perigee of the Mango orbit was in a favourable position. This position appeared naturally only once every 60 days, and following a few calibration burns, the drift start campaign begun on May 13, 2013, and lasted for 37 days. To establish relative navigation between Mango and Picard, the navigation solution from the GPS receiver on Mango was used in combination with Space Track on-line TLE information of Picard. An SGP4 propagator was used for the orbit determination and manoeuvre planning.

The favourable argument of perigee at the start of the campaign was 50 degrees before it passed the equator on its way from the south to the north hemisphere, i.e. when the perigee was at 230 degrees and decreasing. At this point the effect on the argument of perigee for each delta-V burn, which was always actuated at the ascending equator crossing on the apogee side of the orbit, would coincide with the effect of the natural drift of the argument of perigee towards the equator, resulting in a perigee step towards the equator for each burn. In fact, the applied delta-V can analytically be proven to always push the perigee towards the equator crossing, regardless of whether the perigee is on the north hemisphere or on the south hemisphere at the time of firing. This means that the delta-V's applied at the equator always pushed the apogee and perigee towards the equator. This is illustrated in the left of ***Fig. 2***, where three orbits are depicted, one with the apogee/perigee perfectly aligned with the equator (bold) and two with the apogee/perigee at twenty degrees before and after the equator crossing (dashed). The left part of the picture also shows a delta-V applied at the equator, in the anti-velocity direction, in order to lower the perigee for each individual burn.

The reason the perigee was desired to stay at the equator was because the delta-V manoeuvres were supposed to simultaneously increase the inclination in order to save propellant, which is optimally done at the equator. Hence, the optimal way to increase the inclination and lower the perigee simultaneously could only be achieved when the apogee and perigee were perfectly aligned with the equator.

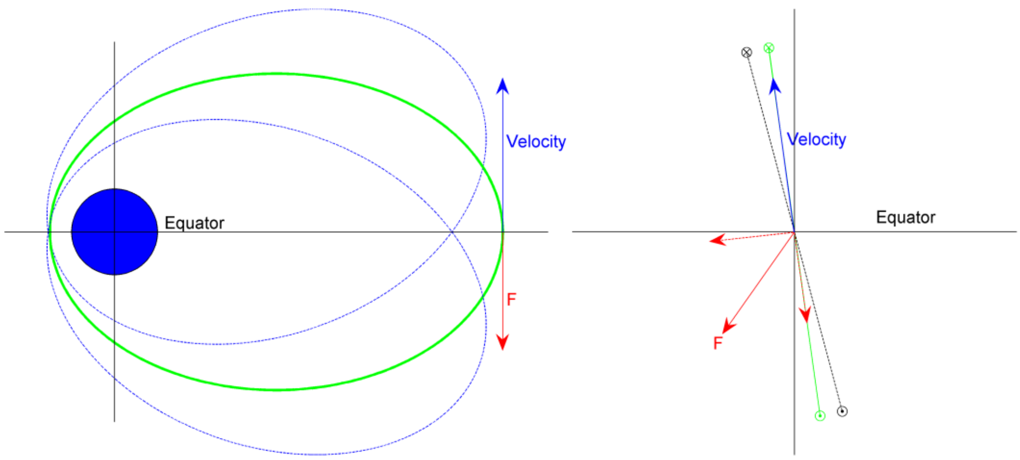


***Fig. 2****: Left: Applied delta-V at apogee pushes apogee and perigee towards the equator, increasing or counteracting the natural perigee drift. Right: The applied delta-V has an in-track and cross-track component to modify the inclination and perigee height simultaneously. In the figure, green (solid) line is the orbit plane before the applied delta-V and black (dashed) is after.*

As this implies, each delta-V consisted of a cross-track component and an along-track component to modify the inclination and the perigee altitude respectively. Analysis gave the optimum combination of the two components to be almost equal. The right part of ***Fig. 2*** shows the orbit manoeuvre *(F)* and its cross-track and anti-velocity components, and the effect is illustrated with the black (dashed) orbit plane with higher inclination (and also lower perigee). It shall be noted that the Mango orbit is a retrograde orbit which explains why an increased inclination takes the orbit further away from the Earth's rotational axis.

After 37 days and 32 m/s of delta-V, the drift start campaign was completed and the evolution of the argument of perigee, the inclination and the eccentricity is shown in the top half of ***Fig. 3***. As can be seen from the plots, the campaign was paused after the seventh day due to performance evaluation of the propulsion systems as well as the assessment of feasibility to increase the duration of each pulse. The lower left plot of ***Fig. 3*** shows the evolution of the perigee height (red), apogee height (green) and the semi-major axis with the Earth radius subtracted (blue) and the lower right shows the relative RAAN drift (right ascension of the ascending node) relative to Picard.

As shown in the figure, the RAAN drift has been reversed and accelerated in the opposite direction to create a relative drift of the orbital plane of Mango towards the orbital plane of Picard, instead of a relative RAAN drift that separates the two orbital planes even more. The goal of the starting campaign was to achieve as much relative RAAN drift as possible towards Picard, while spending the least amount of propellant possible to allow for the stopping campaign, the close range inspection and the de-orbit at the end of the experiment. The figure shows horizontal lines indicating the required drift time for a specific relative RAAN drift. The goal of creating a drift resulting in a rendezvous with Picard in September 2014 wash reached, and the drift start delta-V campaign was successfully concluded.

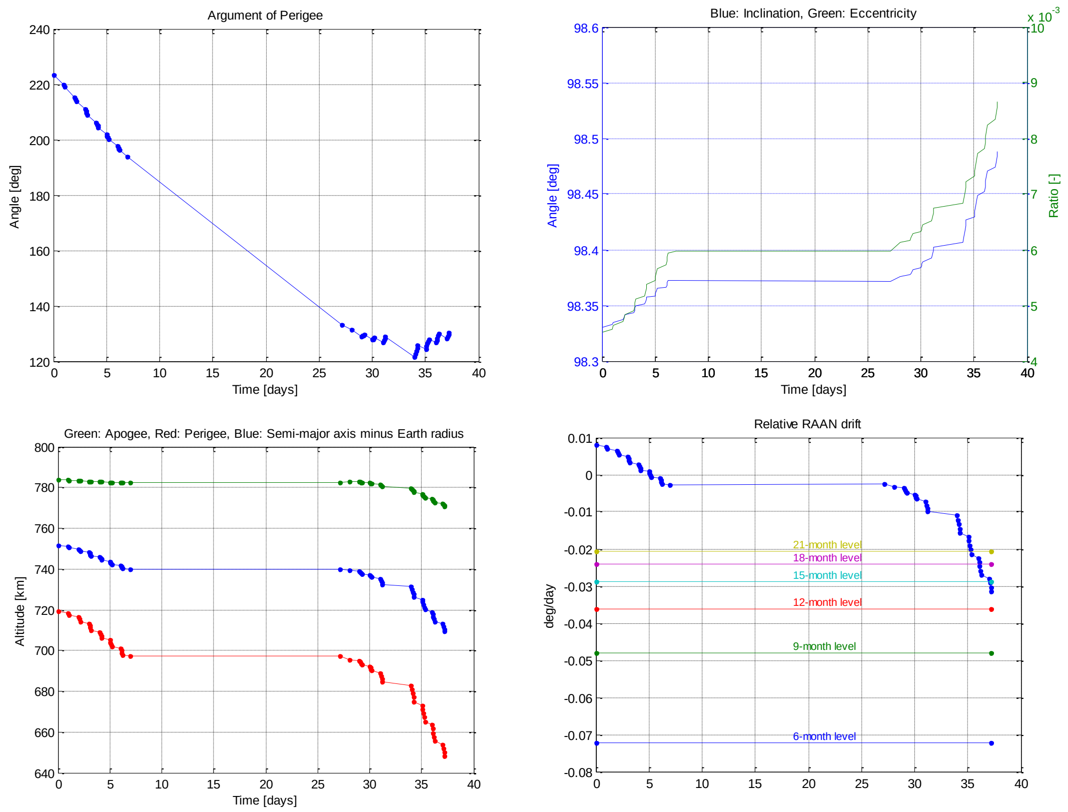


***Fig. 3****: Evolution of the modified orbit parameters after the drift start campaign. Top left: argument of perigee. Top right: inclination (blue) and eccentricity (green). Lower left: Apogee, perigee and semi-major axis. Lower right: Relative RAAN drift vs. Picard.*

## C. TRANSFER DRIFT ORBIT

Since the start of the orbit plane transfer phase, the Mango operations have been minimized to only three passages per week, where the system health is checked and upcoming events are scheduled in the on-board schedule. The low intense drift phase spanned over a full eclipse season and all propulsion systems and unused units were disabled to preserve power.

***Fig. 4*** shows an illustration of the orbits of Tango (purple), Mango (yellow) and Picard (red) as of January 2014, and shows clearly the separation between the Tango orbit and the Picard orbit. In between these two orbits is the Mango orbit which at the time of the drift start campaign was aligned with the Tango orbit and is now being transferred to the Picard orbit where it will be aligned and synchronized with Picard satellite. The rendezvous with Picard is estimated to occur in mid-September.

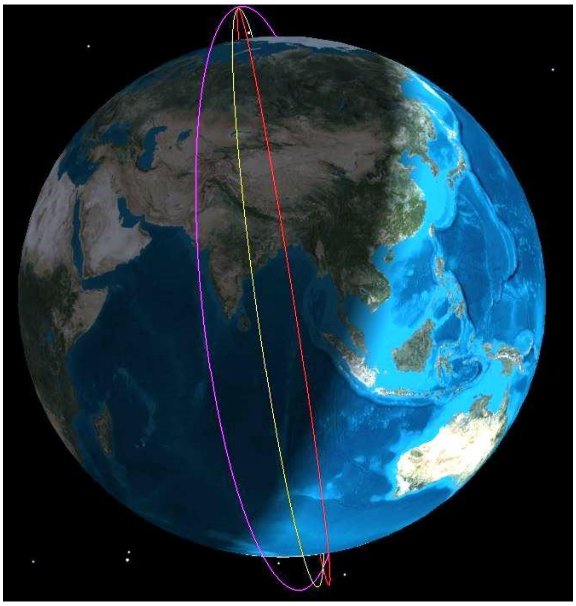

***Fig. 4****: The orbits of Tango (purple), Mango (yellow) and Picard (red) as of January 2014.*

### D. ORBIT PLANE DRIFT STOP CAMPAIGN AND FAR RANGE RENDEZVOUS

This phase was initiated in the middle of May 2014, where approximately 7 m/s were applied which corresponds to about 25% of the required amount of delta-V to align Mango with Picard. At this occasion, the line of apsides passed through the equator plane, and at this occasion the applied delta-V could be used to manipulate all orbit parameters required to start matching the Picard orbit. This only happens every 60 days, and the next two occasions are planned to be used as well in mid-July and mid-September for orbit manoeuvring.

In this campaign, the delta-Vs were applied at both the apogee and the perigee to reduce the eccentricity and also to raise the semi-major axis to start level with Picard. This makes the Mango orbit more circular and it also means the relative drift is decreased. This campaign and the one in July will focus on circularisation and orbit plane drift reduction. The third and final campaign, planned in September, has the goal of bringing Mango to a stable relative orbit from where a handover to the inspection phase can take place.

For all manoeuvres in this phase, also the inclination is reduced to finally match the Picard inclination, by applying the delta-V such that there is always a cross-track component in the same manner as in ***Fig. 2***.

The transfer stop and far range rendezvous phase has the success criteria to position Mango in a non-drifting, passively collision free orbit relative to Picard at a long-track distance of several tens of kilometres and with a small difference in the cross-track/radial plane. There are two goals; one to stop the relative drift of the orbital planes and one to phase Mango within the orbit plane to reach the safe along-track position relative to Picard. To achieve these goals, essentially the same strategy will be applied as in the starting campaign where the GPS on Mango and on-line TLE information of Picard were used. In addition, there is a possibility to use the far range VBS camera at the end for a seamless transition to the close range inspection.

### E. CLOSE RANGE INSPECTION

The critical phase of the IRIDES experiment is the close range inspection of the non-cooperative satellite Picard and this phase is planned to start in the end of September 2014. The goal is to capture high resolution images of Picard from a close but safe distance while performing collision free fly-by trajectories and keeping the cameras correctly pointing. The nature of these relative trajectories is such that all possible illumination conditions may occur, including pointing the cameras towards the sun as well as pointing them towards the Earth or into deep space. The camera for image capturing will not be the relative VBS sensor, but instead the high resolution colour capturing DVS camera.

The relative navigation will be based on the far range VBS camera and can be performed autonomously by the on-board computer, but, for the IRIDES experiment, this functionality will be duplicated on ground in order to increase the accuracy and safety since Picard will be a non-cooperative target. The outcome of the current analysis shows that the on-ground navigation with this man-in-the-loop approach will be utilized for the close range inspection. A first glimpse of Picard is shown in ***Fig. 5*** which was captured on 18$^{th}$ of March 2014. The image is one of a series of images taken that day and it exemplifies what will be captured and used in the on-ground relative navigation.

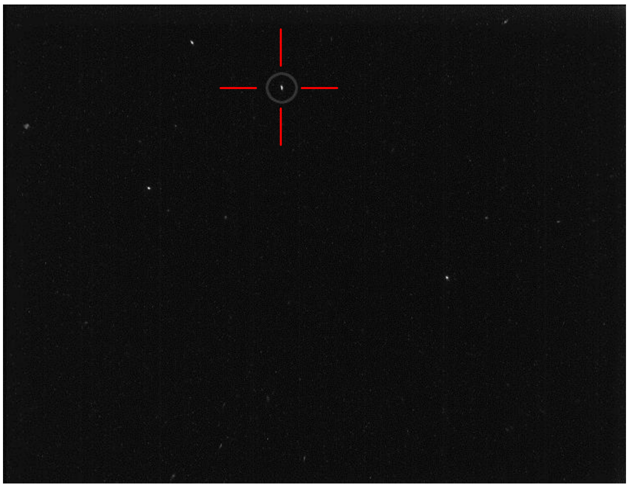

***Fig. 5****: First image of Picard, captured on March 2014.*

To achieve the goal of this phase, the close range inspection is divided into the following steps:

1. Estimate the Picard absolute orbit parameters with the VBS system from the current safe relative position. To do this, a known delta-V manoeuvre needs to be applied in the cross-track/radial plane to create observability of the relative distance to Picard. This delta-V manoeuvre is planned such as it will reduce the relative cross-track and radial components.
2. With the Picard orbit and hence the relative distance determined to a certain accuracy, a small long-track drift will be initiated to create a slow collision free helix shaped trajectory, circling the Picard satellite.
3. During this trajectory the cameras on Mango will be pointing towards Picard based on either an attitude profile or using the autonomous target pointing mode on-board Mango. Due to the forced attitude, the solar panels will no longer be sun pointing and as much payload as possible needs to be powered off to be able to capture a long series of images with the DVS camera.
4. When safely at the other side of Picard, the relative drift will be stopped and the procedure will be repeated in the opposite direction until the accuracy of the estimated Picard orbit parameters is comparable with the stepwise constant cross-track/radial minimum distance.

The entire close range inspection procedure is illustrated in ***Fig. 6***, showing the helix trajectory closing in on Picard.

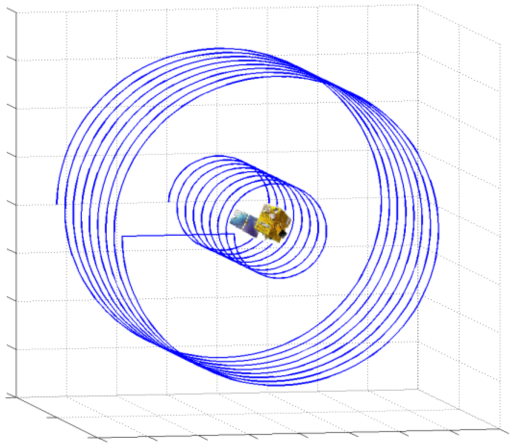

***Fig. 6***: *Principle for helix shaped close range inspection of Picard.*

As an alternative to the above mentioned helix inspection orbit, a less delta-V consuming option has been identified. This option is based on not cancelling entirely the eccentricity, resulting in higher relative velocities but less consumed propellant. This is attractive for a mission where several inspections are envisioned, before determining the state of a target and a decision is taken if a de-orbit operation shall be initiated or not.

The alternative means that only the inclination is cancelled with respect to the target spacecraft, and some eccentricity separation is left. This will produce a warped helix with a large extension in the along-track direction as can be seen in ***Fig. 7***, which is called an elliptic inspection orbit. In the figure, the inspection will take place when Mango is at the extreme cross-track position with respect to Picard (top of figure), and the distance to Picard can be controlled with the same precision as in the helix case. However, only this section of the orbit can be used for inspection, but instead of having along-track drift back and forth and only one close encounter each day, this elliptic orbit offers an inspection opportunity at every revolution, and the along-track drift will be maintained at zero while inspecting.

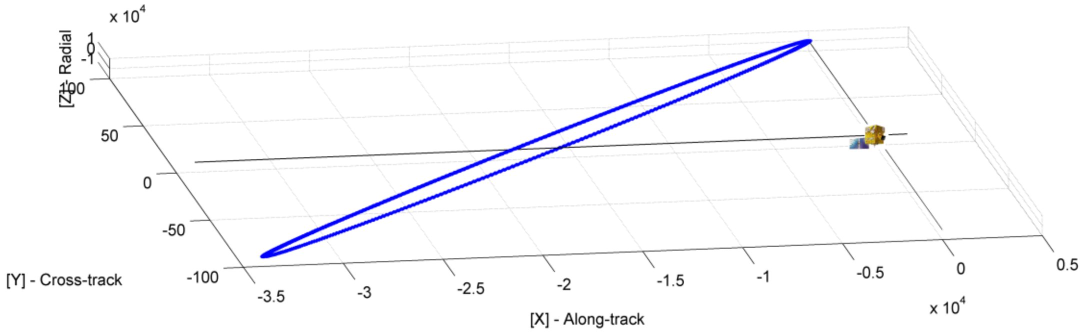


***Fig. 7***: *Elliptic (warped helix) inspection orbit with remaining eccentricity. The orbit is still collision free but has higher relative velocity at the closest point to the target.*

The close range inspection is expected to be finalized before the end of October, and the type of inspection orbit is not yet determined.

### F. DEORBIT

With the successful close range inspection finished it only remains to empty the propellant tanks in a way to minimize the remaining time Mango has left in orbit. The goal within IRIDES is to lower the perigee as much as possible.

The methodology for the deorbit will be similar to the drift start campaign, using the GPS receiver on Mango for orbit estimation and then apply manual delta-V manoeuvres at apogee to lower the perigee as much as possible. This manoeuvring includes analysing the effect of each burn in advance by comparing the estimated post-burn TLEs with the current set of online TLEs provided by JSpOC in order to avoid unnecessary conjunctions. Decisions can then be taken to delay the manoeuvre sequence if necessary. This method will be gradually applied for the far range rendezvous and also for the close range inspection.

### G. OBJECT CHARACTERISATION

As a result of the close range experiment, several image sequences of Picard will be available, captured with the DVS. These images will be processed on-ground to estimate the relative pose and range of Picard, including its tumbling rate and spin axis. The goal is to develop object characterization algorithms that can produce estimates of the parameters needed for a capturing manoeuvre. This will have a challenging aspect due to the extreme variation of the illumination conditions formed by the relative helix trajectory. It is also important the image acquisition rate is adjusted appropriately to the timeframe of the relative motion in order to capture a sufficient amount of images. Different methods are considered depending on the rate of the images.

The object characterization phase is not considered part of the flight experiment since it is entirely ground based and is instead seen as a follow-on activity.

## 5. CONCLUSIONS

This paper has presented the IRIDES experiment currently in progress within the PRISMA mission. The experiment demonstrates On-Orbit Inspection and associated GNC functionalities including VBS based relative navigation with respect to a non-cooperative target (Picard). To this end, it is believed that the experiment and the demonstrated capabilities will contribute to a general downplay of perceived difficulty and complexity of multi-vehicle operations by providing the appropriate TRL evidences.

The proposed strategy will allow for a close approach with embedded safety between Mango and Picard, where the final minimum relative distance depends on the evaluated achieved Vision Based navigation performance. With a performance close to what has been achieved during previous PRISMA experiments, the final safe relative distance could be as close as 10 m allowing for image capturing fidelity of the rendezvous object where a pixel would represent 4x4 mm with the Vision Based Sensor and 3x3 mm for the digital video system.

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