IRIDES ESA Executive Summary

SSPO6091

Mission analysis and detailed GNC definition in support of the PRISMA “IRIDES” experiment
GSP Study under ESA Contract Nr. 4000110631/14/NL/MV

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Author:	Thomas Karlsson	AOCS Specialist	2014-12-01
Reviewed by:	Erik Gröndahl	AOCS Engineer	2014-12-01
Checked by:	Susanne Ejdfors Eriksson	Head of Quality and Safety	2014-12-01
Authorised by:	Thomas Karlsson	PM	2014-12-01
Released by:	Thomas Karlsson	DM	2014-12-01

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

No table of figures entries found.

1. THE IRIDES EXPERIMENT

The Swedish PRISMA IRIDES experiment (Iterative Reduction of Inspection Distance with Embedded Safety) encompassed the transfer of the PRISMA MANGO spacecraft to the non-operational and un-prepared CNES PICARD spacecraft with close range rendezvous and inspection. The rendezvous and inspection phases were intended to be performed by on-ground calculated deltaV manoeuvers based on the available relative-navigation data. The intention of IRIDES was to support by in-orbit experiment the development of technology and strategies for space debris monitoring, remediation and on-orbit servicing.

Given this context, the objective of the ESA GSP study with OHB-SE, the operator of the PRISMA MANGO spacecraft, has been to perform guidance, navigation and control (GNC) analysis of the optimal phasing, far range rendezvous and the proximity maneuvers and to perform an operations assessment for the PRISMA IRIDES experiment in preparation for actual implementation and execution of the IRIDES experiment in the timeframe from August till November 2014. Study objectives included the assessment of AOCS sensor utilization, GNC mode selection, upgrade of image processing algorithms, assessment of collision risk, preparation of escape strategies for collision avoidance, and the overall analysis and planning of the step-by-step maneuver sequence, leading to a safe fly-around down to 10m minimum distance, only relying on the available resources on-board MANGO and on ground.

The GSP study was performed partly before and partly in parallel with the in-orbit implementation on-board PRISMA, with an appropriate shift between the study and the implementation. However, during the implementation of the Far Range rendezvous the hydrazine system of PRISMA MANGO was unexpectedly depleted, which affected the course of the study and the in-orbit implementation, since it rendered the remaining overall fuel level insufficient for completion of the actual IRIDES experiment.

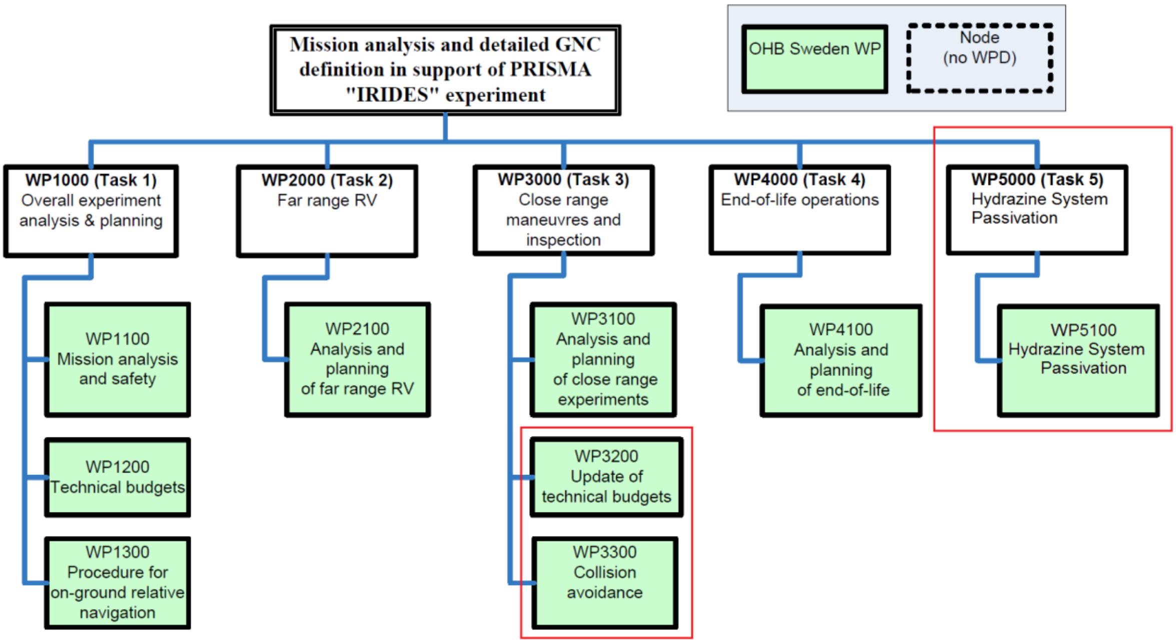

Figure 1-1: Overview of the tasks included in the IRIDES Study

Consequently, some of the work in the GSP study related to rendezvous and inspection detailed planning was redirected towards anomaly investigation, further analysis and lessons learnt. **Error! Reference source not found.** shows an overview of the breakdown of the study into tasks and work packages. As can be seen, the five tasks are subdivided into work packages out of which two (WP3200 and WP3300) were discontinued as a consequence of the hydrazine depletion event, while WP5100 was added for anomaly investigation.

1.1 SPACECRAFT OVERVIEW

The two spacecraft involved in the IRIDES experiment are Mango and Picard, where Mango is the manoeuvrable spacecraft of the PRISMA duo and Picard is a non-operational debris spacecraft in similar orbit as Mango. The two satellites and their sensors are briefly explained below.

1.1.1 Mango

Mango has full 3-dimensional attitude independent orbit control capability and is 3-axis attitude stabilized using star trackers and reaction wheels. The propulsion system on Mango is based on six 1-N thrusters directed through the space-craft centre of mass and the delta-V capability was approximately 200 m/s at the time of the launch. Mango also carries a propulsion system for the new propellant High Performance Green Propellant (HGPG).

For absolute navigation the on-board GPS is used and for relative navigation with Picard, the Vison Based Sensors (VBS) is used. The VBS consists of two optical cameras; one for far range and one for close range images. In addition to the VBS is the Digital Video System (DVS) which can capture high resolution colour images.

Before the IRIDES experiment Mango performed all its formation flying demonstrations against Tango, which was a partially cooperative spacecraft with built in safety features.

1.1.2 Picard

Picard is a French owned satellite that became non-operational in April 2014. It is essentially bigger than Mangos former target spacecraft, and it has a large single solar panel that characterise its shape.

Since it is non-operational, no on-board sensor telemetry can be used for the IRIDES experiment and hence it is a true non-cooperative target. Its absolute position, attitude and tumbling rate is unknown until the inspection could have been performed and the orbit aligning phase (see chapter 2.1) had to rely on public orbit information as TLE’s from JSpOC.

2. EXPERIMENT OUTLINE

The IRIDES experiment covers the three phases; Orbit aligning, Inspection and Deorbit, as shown in Figure 2-1. In the figure, the steps marked *A*, *B*, *C* illustrate the orbit aligning phase where Mango is aligned and synchronised with Picard, and a slow drift from a relative long-track position of ~200 km is safely established. The steps marked D and E depict the first fly-by of Picard where the relative drift is stopped and through which the reduction of the inspection distance is initiated. The deorbit phase is not depicted in the figure, but all three phases are described in the following subchapters.

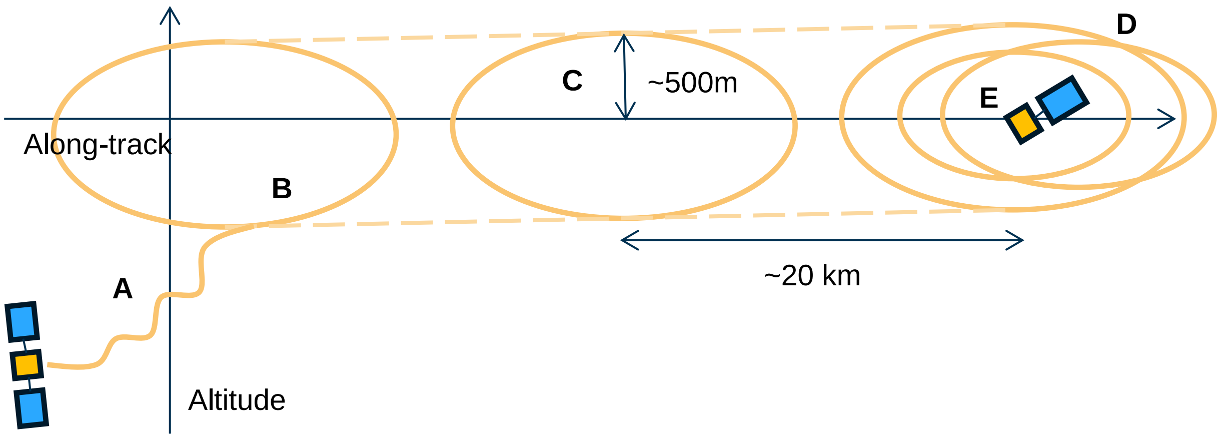

Figure 2-1: Overview of the experiment phases.

2.1 ORBIT ALIGNING PHASE

To perform orbit aligning between Mango and Picard, the major task is to reduce the relative drift of the Right Ascension of the Ascending Node (RAAN) such that the two RAAN's match in a specified time window. When cancelling the relative RAAN drift, the two orbits are equally shaped and only the along-track component within the orbit needs to be matched. This is done in the same manoeuvres as the drift matching manoeuvers, to minimise the use of propellant.

To achieve this in an optimal way the two cross-track and along-track components of the resulting deltaV shall be combined and executed at the equator, which results in 40% efficiency increase compared to having separate manoeuvres. However, since the manoeuvre must be distributed in time over the equator crossing, optimality can only be maintained if it is chopped up into a long series of manoeuvres which are implemented over many consecutive equator crossings. For the IRIDES in-orbit implementation a maximum of 6 minutes and 10 seconds thruster profile duration was implemented at each equator crossing, interleaved over the two propulsion systems.

Optimality is reached only when executing the manoeuvres when the line of apsides resides within the equator plane, i.e. when apogee and perigee occur at the equator crossings, and the aligning campaign had to be distributed over three different occasions when this condition was fulfilled. Further, while executing each sub campaign this condition is self-satisfying and each manoeuvre counter acts the natural drift of the line of apsides and prolongs the duration of each sub campaign.

The in-orbit implementation of the orbit aligning phase was done through a validated procedure repeated each day, which starts with a determination of the true post burn orbit from yesterday. The true post burn orbit is then compared with the expected post-burn orbit from the day before, and adjustments are made to the thruster model. After that the true post-burn orbit is compared with the latest TLE of Picard and a new set of deltaV manoeuvres are calculated and uploaded. The procedure is completed by calculating the next day's post-burn orbit. As Mango approaches Picard, the public orbit information of Picard gets contaminated by the presence of Mango.

2.2 INSPECTION PHASE

The IRIDES inspection constitutes a series of inherently collision free drift manoeuvres that creates fly-by's over Picard at closer and closer minimum distance, and high resolution DVS images were supposed to be captured at the closest distance each time. Each fly-by is preceded by an observation step where the absolute Picard orbit is estimated from VBS images. Figure 2-2 shows an overview of the IRIDES on-ground procedure, where input data from a set of sources is processed to create the input for the absolute Picard orbit determination. When the two spacecraft's absolute orbits are established, fly-by deltaV manoeuvres are generated.

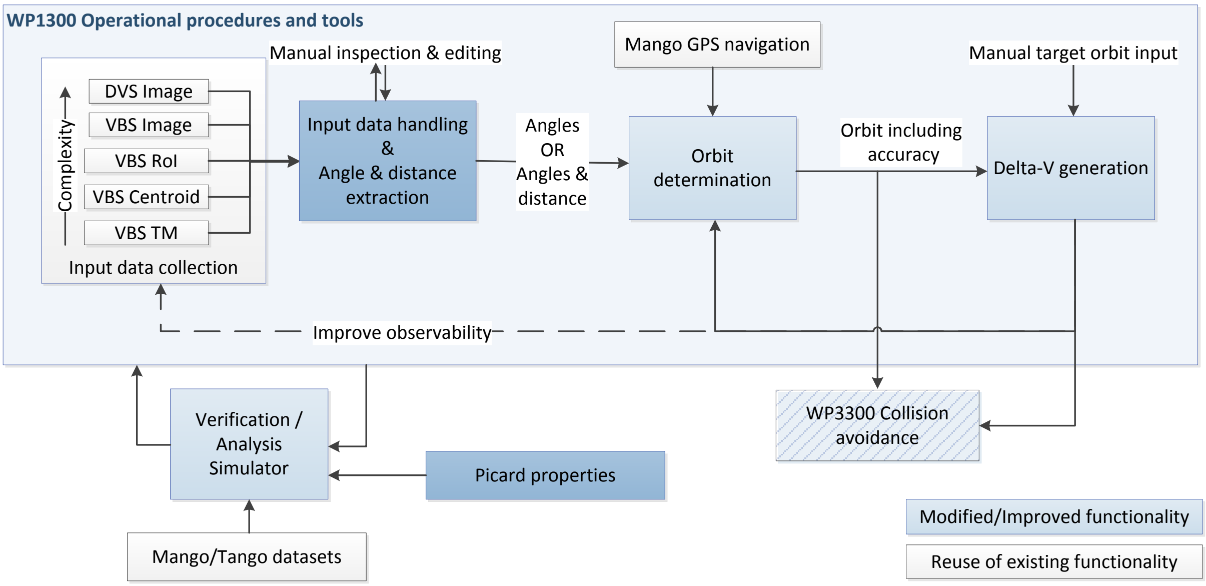

Figure 2-2: Overview of the IRIDES on-ground procedure.

The input data processing is creating two different sets of output; either a long series of angles and distances or a long series of individual 6 degree of freedom (DoF) state vectors. These two outputs are then processed by either an *angles only relative navigation algorithm* or one out of two *filter solvers*, all of which creates an estimated future state of the Mango-Picard formation in the Orbit Determination box in Figure 2-2. These estimated states of the future formation are evaluated within the study to calculate the state error (since the true simulated state is known) as well as a pointing error, i.e. the angle between Mango-Picard vectors for the true state and the estimated state.

As the in-orbit implementation of the inspection was never performed, only on-ground generated images of Picard were used for the study. The methodology and algorithms were then validated against in-orbit images of Tango, captured at the time when Tango was considered the target spacecraft of the formation.

2.3 DEORBIT PHASE

As a consequence of not performing the Picard inspection, new challenges for Mango are being listed as well as planning a deorbit activity to terminate the mission. The most attractive additional activity is to use Mango for a Space Situation Awareness (SSA) activity, since this is an attitude experiment which only requires reaction wheels and the VBS sensor. Foreign object's orbit could be estimated from in-orbit images as an on-ground activity.

For the de-orbit activity, two major strategies are investigated. The first is the traditional strategy to limit the time Mango will spend in orbit before re-entering the atmosphere and the second is to minimize the risk of a Mango collision while still in orbit.

The first strategy means spending the remaining propellant to lower the perigee as much as possible, forming the orbit more elliptical, which will shorten Mango's decay time from about 45 years to 40 years. The other strategy means spending the remaining propellant to instead lower the apogee as much as possible and hence make the orbit more circular, which will reduce the probability of a Mango collision by 22%. Considering this trade-off it is concluded the second strategy is the best deorbit strategy, especially since the first strategy increases the probability of a Mango collision by 37%.

As for the deorbit implementation, it will be conducted in the same manner as the orbit aligning campaign, by dividing the theoretical impulsive manoeuvre into a long series of perigee burns (to lower the apogee), with the same limitations as well.

Before applying a deorbiting manoeuvre it is wise to ensure the manoeuvre will not cause an increased collision risk with another debris object. This is ensured by using a Minimum Orbital Intersection Distance (MOID) algorithm that takes into account the complete public TLE set and searches for objects that potentially can collide with Mango.

The algorithm has a stepwise approach to first filter out objects where the orbits[1] intersect at any point in time and for those orbits that do, look at when in time the two objects occur at these intersection points. At the final step of this procedure it stands clear if any object may cause a collision and if so, the deorbit manoeuvre can be recalculated or applied at another time.

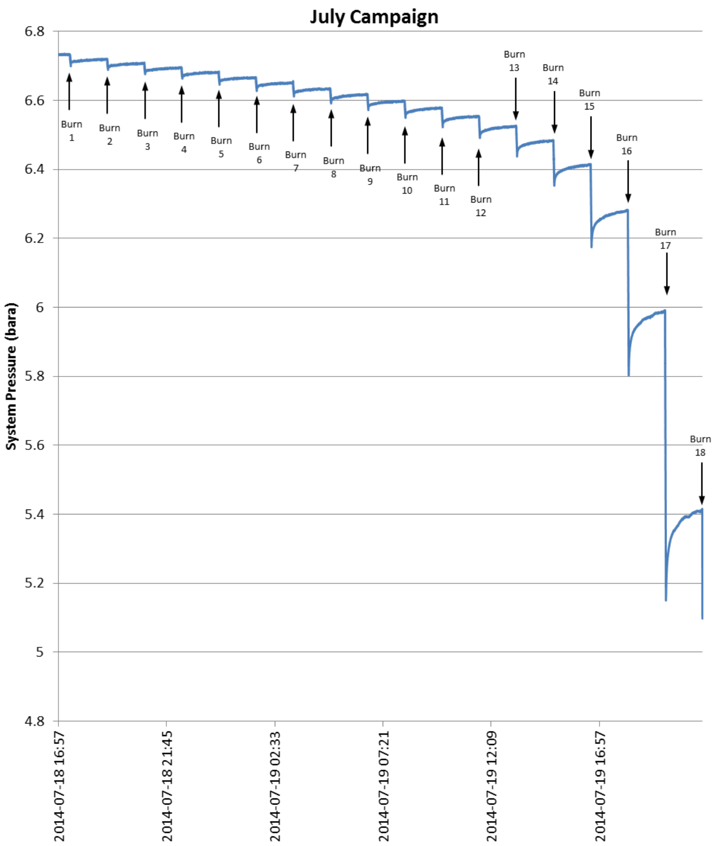

Figure 2-3: Feed line Pressure at hydrazine depletion.

[1] *orbit* shall be interpret as a theoretical tube that encompass the TLE ellipse plus a margin.

3. HYDRAZINE PASSIVATION REPORT

On June 20th 2014, the line feed pressure of the hydrazine system dropped surprisingly while performing manoeuvres of the second orbit aligning sub campaign. At first, this was interpreted as an anomaly since it was not expected to have reached the end of life at this point.

The on-going orbit aligning campaign was immediately stopped and the Mango spacecraft was put in an anomaly state. Telemetry was carefully observed and a series of tests were designed to support (or reject) anomaly hypotheses. However, after thorough investigation it was concluded the hydrazine was depleted and the chase for Picard was over.

This chapter describes the steps to this conclusion.

3.1 TELEMETRY ANALYSIS

The first indication of tank depletion was the telemetry of the feed line pressure that is depicted in Figure 2-3. As this was much earlier than expected it was first interpret as the tank membrane was stuck, and some remaining propellant was trapped inside the tank. Models to accurately predict the end of life point were created and tuned to match the observed telemetry, and it was also attempted to estimate the amount of pressurising nitrogen gas that had passed through the membrane into the propellant side of the system.

3.2 IN-ORBIT TESTS

At first, two in-orbit tests were performed to understand and try release the trapped hydrazine, but as soon as it was concluded this had no effect, the following tests were design to establish the fact that the hydrazine was depleted. The first test was a sloshing manoeuvre where the spacecraft was rotated around the sun direction back and forth, and the later three tests were combustion tests where different thrusters were fired for longer and longer duration.

At the final in-orbit test the pressurising nitrogen gas from the upper side of the tank membrane was detected at one thruster at the end of the feed line, and this was the conclusive indication the hydrazine was depleted and pressurising nitrogen gas had passed through the membrane and reached all the way to the first thruster.

3.3 IN-ORBIT SYSTEM PASSIVATION

As a result of this anomaly investigation, which turned out to be an end of life analysis, it was discovered that the tank membrane leaks pressurising nitrogen gas into the feed line. This was what first caused optimism that hydrazine was trapped by the membrane. However, as this was determined to be nitrogen pressuriser that made the feed line pressure to recover, it was identified as a method of passivation the entire hydrazine system, including the pressurising nitrogen.

The leakage through the membrane accelerates when there is a delta pressure over it and it is estimated to take ten large manoeuvres, separated ten days apart to bring the nitrogen pressure to 1 bar, and which could be done as an additional activity on Prisma.

4. CONCLUSION

Although the PRISMA IRIDES in-orbit experiment itself was never fully carried out, the presented ESA GSP study provided the opportunity to conduct the required mission analysis work, establish the algorithms and procedures for far range as well as close range relative navigation, and overall to prepare for the rendezvous and inspection experiment with subsequent de-orbitation.

The performed work as well as the achieved results are presented in detail in the Final Report. This includes, in particular:

- Perform guidance, navigation and control (GNC) analysis of the optimal phasing, far range rendezvous and the proximity manoeuvres for the PRISMA IRIDES experiment,
- Perform an operations assessment for the PRISMA IRIDES experiment in preparation for actual implementation,
- Upgrade the on-ground image processing algorithms for relative navigation and pose estimation, including generation of representative imagery of the target spacecraft for test purposes and the validation of the algorithms by means of actual in-orbit imagery of the PRISMA TANGO satellite,
- Assessment of safety measures and collision avoidance, including long-term collision risk assessment for the period post IRIDES experiment.

The GSP study also produced an assessment of the anomaly that was encountered in-orbit during the early stage of the experiment and which rendered the experiment infeasible due to insufficient level of propellant. Detailed analysis was carried out to understand the effects leading up to depletion of the membrane tank. This analysis also provided verification for the observed anomaly. Lessons learnt were described in detail in the Final Report.

Lastly, the GSP study also provided recommendations on possible use cases for the PRISMA MANGO platform in subsequent in-orbit activities.