ASSESSMENT OF GNC IMPACTS OF CHEMICAL PLUME IMPINGEMENT IN THE CASE OF PRISMA "IRIDES" EXPERIMENT

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Abstract: *This paper presents the preliminary analysis of an in-orbit demonstration opportunity to test plume impingement as a viable means to change the attitude state of a space debris based on the Prisma and Picard missions. This technique has been proposed as part of the COBRA concept studied by ESA in collaboration with GMV, Politecnico di Milano and Thales-Alenia Space, as an active debris removal concept relying on the exhaust plume of a monopropellant chemical propulsion system as a means to impart momentum and ultimately modify the orbit of a space debris object in a contactless manner. The feasibility of the experiment is presented as well as its critical areas, no showstoppers are identified.*

Keywords: *plume impingement, attitude control, debris, chemical propulsion, in-orbit demonstration.*

1. Introduction

The COBRA (COntactless deBRis Action) concept was studied under ESA contract and then internally by ESA, as part of ESA´s SysNova technology assessment scheme [1] which uses "technology challenges" and competitions to survey a comparatively large number of alternative solutions. The concept was originally proposed by an industrial consortium made up by GMV form Spain, Politecnico di Milano and Thales Alenia Space from Italy. The concept came first in response to a challenge for mission concepts and technologies capable of providing a contactless Earth-bound object orbit modification system [2][3]. Thus, COBRA is an active debris removal concept studied by ESA's Concurrent Design Facility (CDF) relying on the exhaust plume of a monopropellant chemical propulsion system as a means to impart momentum and ultimately modify the orbit of a space debris object in a contactless manner. An interaction of such kind (intentional or unintentional) has never been studied before in any detail beyond chemical contamination effects. As proposed in COBRA, the effect might be taken as further advantage during a rendezvous and docking phase with an uncooperative object (to complement direct systems such as a robotic arm) in e.g. active debris removal operations.

Recently, relevant concepts for in-orbit demonstration (IOD) using satellites at their end-of-life have been considered. In particular the possibility to perform close proximity operations combined with orbit and attitude modification between two co-flying satellites has been assessed. In particular, recent work has modeled the required performances that would be needed to test such effects with two satellites entering their decommissioning phase, the Swedish PRISMA/Mango spacecraft and the French Picard mission.

The PRISMA mission [4] (originally made up by two spacecraft, "Mango" and "Tango") has successfully demonstrated since its launch in 2010 formation flying with centimeter-accuracy and autonomous rendezvous from 30 km down to 2 m using GPS, vision-based and radio frequency sensors. Following the nominal mission phase supported, the mission is currently entering its final phase where an experiment named "IRIDES" [5] (Iterative Reduction of Inspection Distance with Embedded Safety) is under evaluation. The primary goal of IRIDES will be to perform a rendezvous with, and inspection of, a de-commissioned uncooperative satellite, namely the CNES-owned Picard satellite. The Mango spacecraft (the only currently operational) is maneuvering towards the selected space object. This phase is planned to be completed by August 2014, when the chaser and target orbits will be aligned. The IRIDES experiment, and Mango's transfer to the final disposal orbit, shall then be completed before mid-November 2014 when an eclipse phase starts for approximately three months.

The IRIDES IOD is expected to achieve a relative navigation precision better than 10 m along-track and 1 m in cross-track and radial. This performance, together with the presence of a perfectly functioning propulsion subsystem on-board the Mango spacecraft, and its capability of Picard to determine and control its attitude in presence of an external torque on-board relative sensors, represent a unique opportunity to test in-orbit the COBRA dynamical concept as studied by ESA.

2. Proposed COBRA IRIDES experiment

Mango will orbit around Picard in a spiral orbit in the local horizontal local vertical (LVLH) frame with a certain drift rate towards Picard. An offset in the radial and out of plane directions are maintained so as to ensure intrinsic safety, see Figure 1.

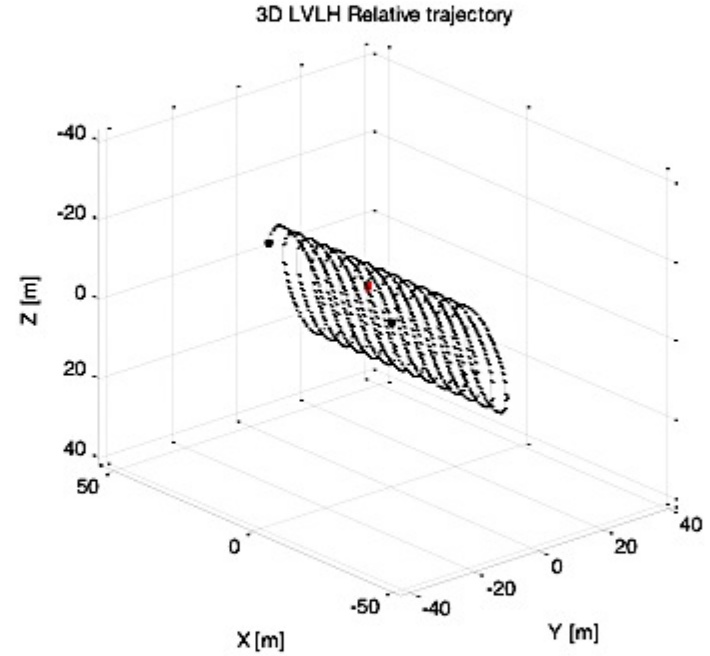


Figure 1. Mango spiral orbit around Picard (10 meters radius, 5 meters drift per orbit)

When the inter-satellite distance is close enough (~10 meters), Mango will point its thrusters towards Picard and perform a small burn (~20 seconds). Optical observations will be performed right before and after the push and the change in the attitude dynamics of Picard due to the plume impingement will be evaluated. The observability of the torque provided by means of the plume impingement during post-processing needs to be determined. Prior to the plume impingement the Mango spacecraft needs to rotate 45° to direct the thruster towards Picard instead of the camera. After the pushing is completed the spacecraft needs to rotate back. During the time required to rotate the spacecraft, perform the pushing and rotate the spacecraft back, no observations can be made of the pose of Picard. On the other hand, long periods of observation are available both before and after the experiment.

Figure 2 shows a schematic overview of the pushing operations timeline. To estimate the torque that operated at the time of the push, the following strategy can be used. The state vector, consisting of the initial orientation, angular velocity and the residual magnetic dipole that was estimated during the initial observation period is propagated forwards to the time of the push. The state vector that was estimated during the final observation period is propagated backwards to the time of the push. If the torque imparted by the pushing is larger than the estimation errors of at the end of the propagation intervals, then the effect of the push can be observed.

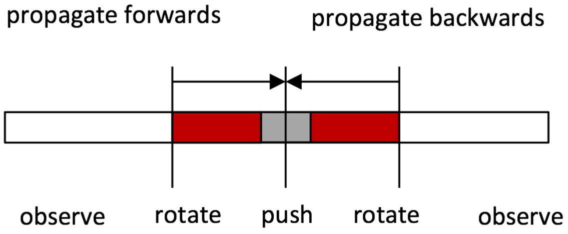


Figure 2. Pushing operation timeline

2.1. Mango Spacecraft

The Mango spacecraft is part of the PRISMA mission [5] and will be the chaser in the COBRA-IRIDES experiment. PRISMA mission was launched been launched on June 15, 2010 in a Dnepr launch vehicle from Yasny, Russia. It shared the launch with Picard, which is the target in the COBRA-IRIDES experiment. The central body of Mango has exterior dimensions 750×750×820 mm. When deployed, the distance between the tips of the solar panels is 2600 mm. There are 2 deployable solar panels (GaAs solar cells) of 1150x850mm. The total dry mass of the spacecraft is 137.815 kg, which should be quite close to the wet mass by the end of the mission.

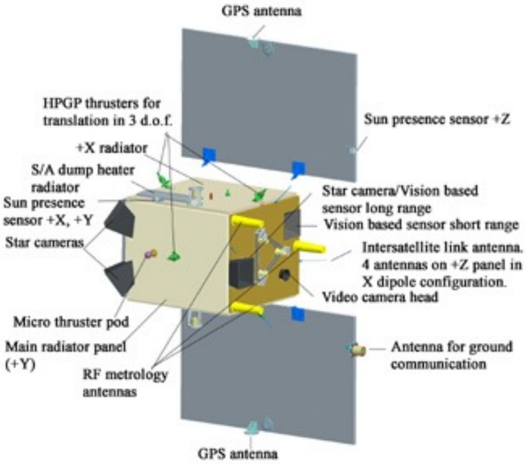


Figure 3: Mango spacecraft diagram

Mango is equipped with three propulsion systems (1N hydrazine, HPGP and MEMS). The system to be used for the experiment is the hydrazine 1N system, which is composed of 6 thrusters and has the capability of providing thrust in opposite directions at the same time, therefore enabling the possibility of compensating the pushing thrust over Picard-

In terms of relative sensors, Mango is equipped with relative GPS, Formation Flying Radio Frequency sensor (FFRF), Visual Based System (VBS) and Digital Video System (DVS). The first two systems are no longer usable, as their counterparts are not present in Picard Spacecraft. Therefore the COBRA IRIDES experiment will rely on the VBS in uncooperative mode and the DVS.The VBS system has been developed by DTU Space of Denmark and is based its successful microASC platform (Star Trackers). It is composed by two optical heads, far range (FR) and close range (CR), and Data Processing Unit for control and data processing. The camera [6] has a detector of 752x580 pixels and a half field of view of 9.15x6.85deg with a focal length of 20.187mm for the far range. The DVS system has been developed by Techno System Developments (TSDev) from Italy [7]. The system is composed by an Optical Unit and a Video Management Unit (H^2VMU). The camera has a detector of 2048x2048 pixels and a half cone field of view of 14x14deg with a focal length of 30mm.

2.2. Picard Spacecraft

Picard mission has been developed by CNES. It was launched back in 2010 together with the PRISMA mission on a DNEPR launch vehicle. The main goal of Picard was to observe the sun (monitor the solar diameter, the differential rotation, the solar constant, etc.). The spacecraft is based on the Myriade platform from CNES composed of a main body of approximately 600x700x800mm plus a deployable solar panel of 600x1500mm. It does not have any propulsion system, hence its wet mass is the same as the dry mass, 144 kg. The momentum of inertia is in the range 12-20 kgm^2.

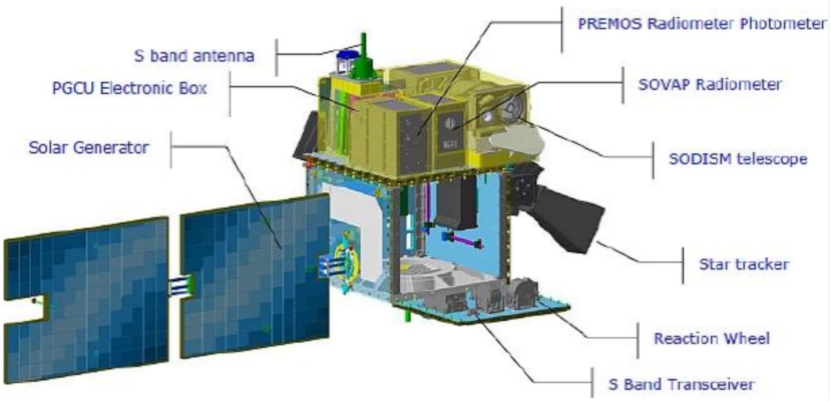


Figure 4: PICARD spacecraft diagram

The spacecraft will be non operational by the time of the experiment and hence it is expected that it will be rotating at a rate between 0.2 and 2 deg/s.

3. Reference trajectory

The reference trajectory for the experiment will be close to the Picard orbit (dawn dusk SSO at 735km altitude). The trajectory of Mango will have a slight variation in eccentricity and inclination vectors with respect to those of Picard, resulting in a spiral trajectory around the target when represented in the LVLH frame (as in Fig. 1 above). This orbit is defined by two main parameters, the characteristic dimension (or diameter of the spiral) and the drift rate space in between spiral arcs). For the COBRA IRIDES experiment it is fundamental to minimize the distance in between the spacecraft at the time of the push so that the effect is maximized. Therefore the characteristic dimension has been selected as small as feasible, 10 meters, taking into account safety considerations. The drift rate has been selected as 5 meters per orbit, as a compromise between safety and number of opportunities to execute the experiment.

3.1. Trajectory constraints

The main constraint on the mission is the beginning of the eclipse session on November 2014. At this stage it is not confirmed if Mango will be continued after this season and hence the experiment should be executed before that date. In terms of ground communications, the use of a station in the north of Europe will provide up to 9 passes per day with a pass duration over 8 minutes. No constraints are envisaged for GPS coverage or attitude profiles (target pointing).

The main constraints comes from the use of the on board cameras. Firstly the Sun exclusion angle must be ensured; secondly the Earth shall not appear on the background of the acquired images in order to ease the image processing. Figure 5 below shows the parts of the orbit where the Earth will be in the field of view (dark blue) or the Sun is below the exclusion angle (yellow).

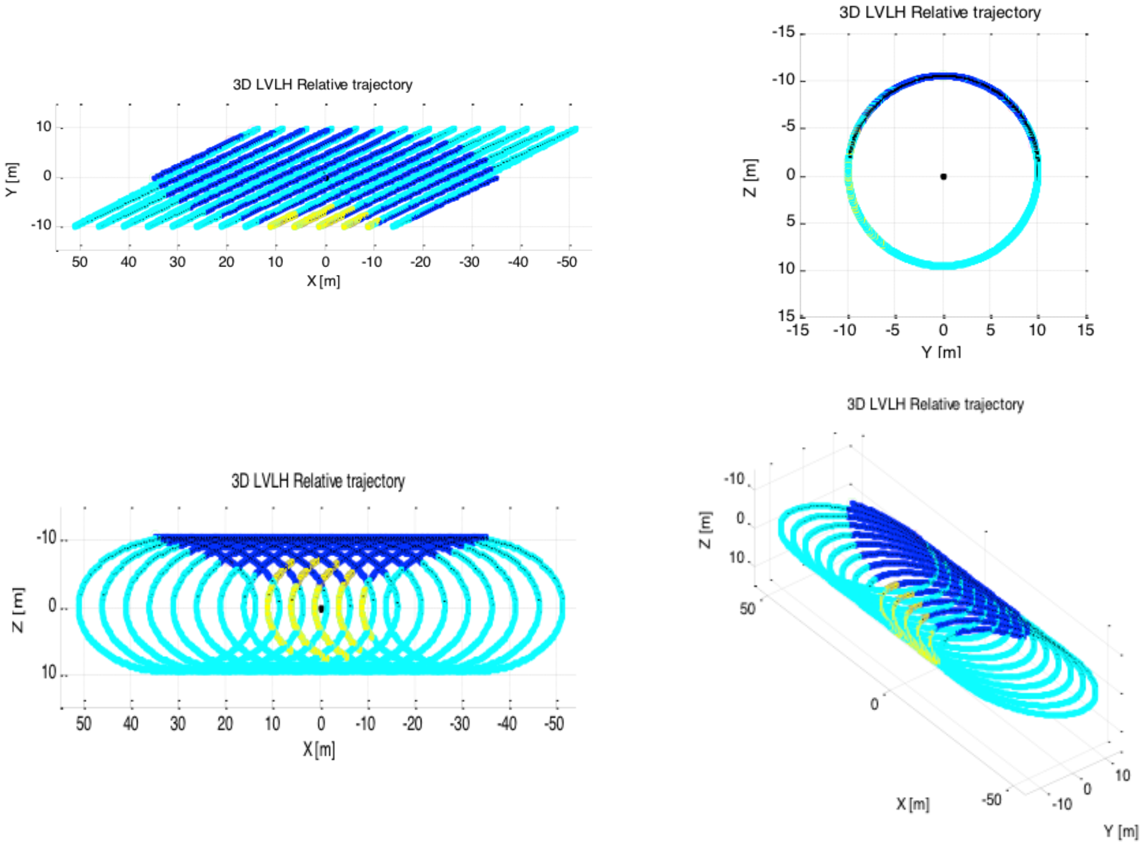


Figure 5. Reference trajectory

Apart from the above constraints, the illumination conditions on the target are also be optimized so that the robustness of the image processing is ensured. This implies that the angle between the Sun, Picard and Mango is lower than 90 degrees. This effectively reduces the part of the orbit during which images can be gathered with good quality to an arc of about 90 degrees (+ZY quarter).

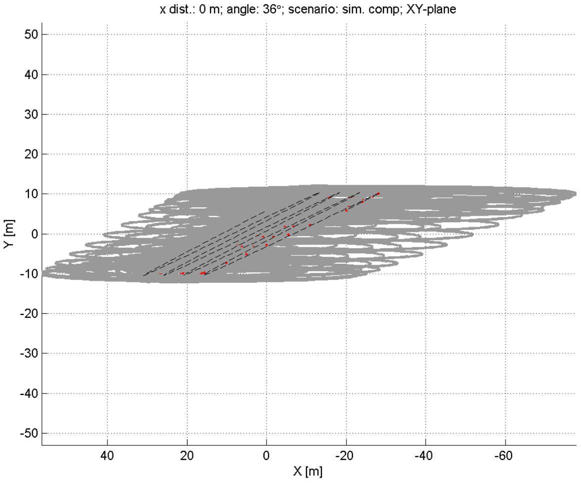
3.1. Safety considerations

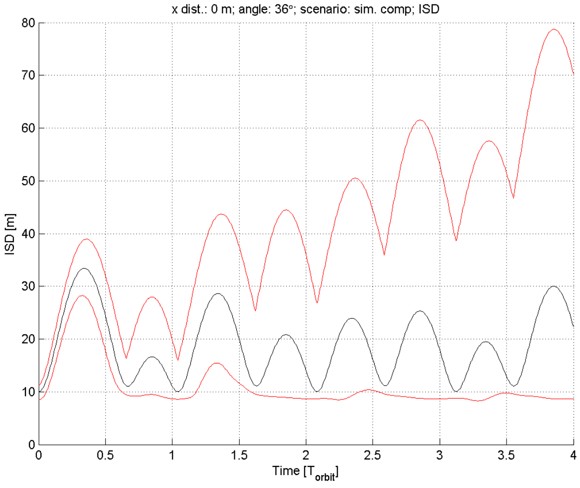
One of the main concerns of an experiment of this nature is the probability of a collision between the two spacecraft, which would generate a debris cloud. Extensive safety analysis has been carried out to asses the possible risks by analyzing the covariances of the trajectories taking into account the navigation, actuation errors, moment at which the experiment is executed (along the +ZY quadrant) and the strategy followed.

The selected reference trajectory offers passive safety, that is, if no actuation is performed there will be no collision due to the offset in the radial and out of plane directions. Furthermore, the safety of the trajectory can be checked will before Mango arrives in the vicinity of Picard along track. Therefore the risk is constrained to the push operations and the resulting relative trajectory. Three main strategies have been investigated to perform the push operations:

- No compensation of the pushing thrust, Mango will enter into a drift trajectory right after the push. In this case the reference trajectory is not maintained, as Mango will fly away from it. Note that the ΔV that will be imparted to Picard is almost negligible.
- Simultaneous compensation of the pushing thrust, i.e., two opposite thrusters are firing at the same time. Reference trajectory is almost maintained.
- Sequential compensation of the pushing thrust, i.e., the ΔV generated by the pushing thruster is compensated by the opposite thruster immediately after the pushing thruster ends its burn. Reference trajectory is almost maintained.

It has been found out that the no compensation strategy can lead to unsafe situations, depending on the point of the orbit at which the experiment is executed. In case this strategy is followed, proper planning will be required and simulation in advance of the resulting trajectory to ensure that Mango enters a escape trajectory. On the other hand, it has been found out that both the simultaneous compensation and the sequential compensation lead to safe trajectories in all the cases. Figure 6 below shows the results of a simultaneous compensation case. The main effect is that the along-track dimension of the probability ellipsoid becomes larger (see the XZ and XY projections). In addition, the radial and cross-track dimensions of the probability ellipsoid increase 180° away from the burn (see the YZ-projection). The distance plot and the plot of the YZ-projection indicate that the trajectory is safe.





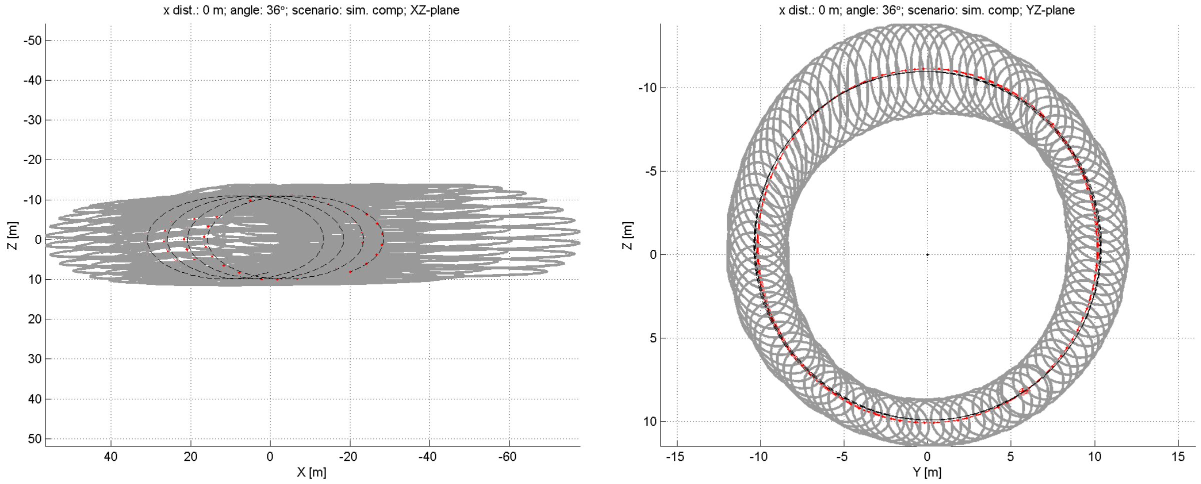


Figure 6. Resulting trajectory for simultaneous compensation

Finally, it has also been investigated the effect of thrusters failure. The most critical situation has been identified as the compensating thrusters working nominally with a failure on the pushing thrusters, i.e. Mango will be pushed directly towards Picard. In all cases the inter-satellite distance decreases to a minimum immediately after the burn stops. In some cases the distance can become as low as 2 meters. The contingency case defined as firing only the compensating thruster should therefore be avoided. Pre-programmed escape maneuver should be executed as soon as the system detects that only the compensating thruster is firing. From this point of view, sequential compensation would offer higher safety as the possible failure could be detected before the compensating thrusters actuates.

4. Experiment effect

The main goal of the COBRA IRIDES experiment is to serve as first step in the demonstration of the COBRA concept for future missions. To this purpose, the change in the angular status exerted by the plume impingement on Picard will be characterized and predicted. The maneuver to impart the plume impingement will be executed and its effects measured, performing therefore the first validation of the concept.

The achieved momentum exchange will be dominated by two main factors, the distance between the spacecraft and the relative attitude of Picard with respect to Mango. Simulations have shown that these will be critical parameters in the experiment execution as the change in angular velocity of Picard can vary by two orders of magnitude depending on the relative attitude from the best scenario where the solar panel is hit (left in Fig. 7) to the worst case in which the solar panel is occulted by the main body of Picard (right in Fig. 7). The effect can be reduced by a factor 4 when the distance to the target is increased from 10m to 22m. The effect of the rotational state of Picard (spin rate and spin axis orientation) has a second order magnitude.

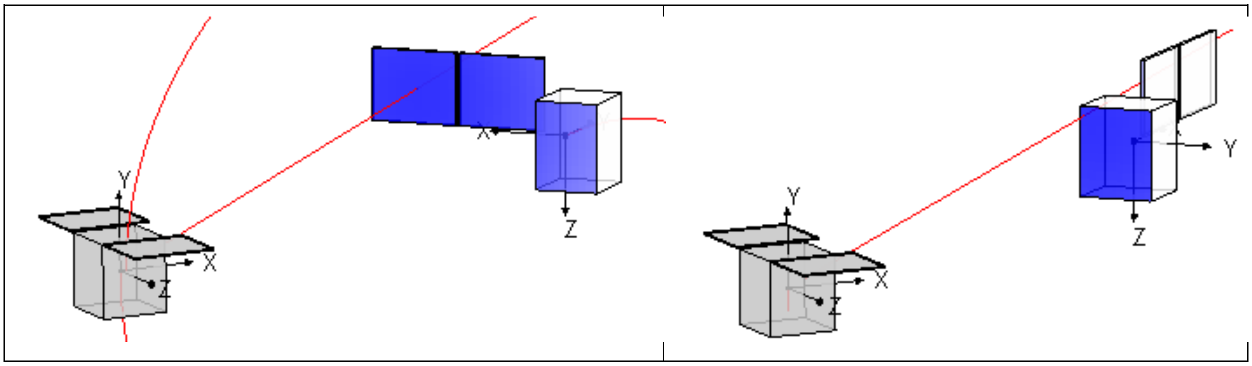


Figure 7. Plume impingement scenarios

This means that the experiment execution time has to be carefully selected, taking into account the attitude dynamics of Picard. Due to the limitations of the sensing system, estimated to be between 0.05 deg/s and 0.1 deg/s, the effect will not be detectable for certain configurations.

5. Experiment timeline

Given the reference orbit, the experiment can be executed in a single day, that is 7 orbits before and 7 orbits after Mango overtakes Picard along track. This gives 9 consecutive orbits during which contact with ground will be available so that the proper telemetry can be analyzed and the required telecommands generated.

It will be divided in two main phases: experiment preparation and experiment execution. During the experiment preparation phase Picard's pose will be determined together with some dynamical parameters of the spacecraft (i.e. remnant magnetic dipole) using image processing and navigation filters. The last known pose will be propagated into the future to select the optimal point at which the experiment will be executed. The exact point of the experiment execution will be that that maximizes the exerted effect. In order to increase the safety this point should be when Mango is in the –X part of the trajectory, so that the push on Picard will increase the drift rate between the two spacecraft.

Figure 9 below shows the proposed timeline for the experiment. Blue 'x' denote optimal observation conditions (good illumination conditions and no Earth on the background) and red circles optimal experiment execution points, dashed vertical blue lines identify the different orbits and the dashed horizontal red line indicates a limit of 15 meters in range. Experiment preparation will take place during orbits 1 to 9 (with data download only after orbit 4). This phase will be followed by three consecutive orbits during which the experiment can be executed, orbits 10 to 12.

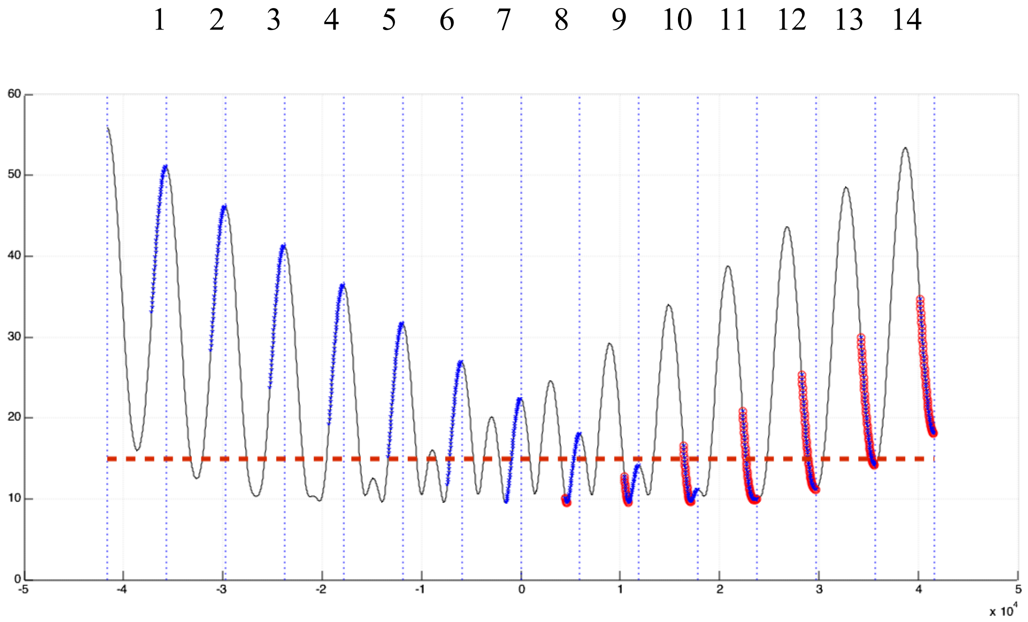


Figure 8. Range evolution during 14 orbits

In the orbit in which the experiment will be executed the spacecraft will start gathering images at high rate before the push. At the specified point the spacecraft will have to perform a rotation to point the thruster in the right direction (offset between the camera boresight and the thruster direction is 45 degrees), perform the thrust itself and rotate back to target pointing to acquire the required images to assess the effect of the experiment on Picard. The data will be downloaded for post processing on ground.

6. Proposed system

In order to perform the experiment several systems are required. The image processing software is the core of the system's experiment in charge of providing the initial input data, that is the pose of Picard. Due to technical and programmatic constraints the full system will be implemented on ground. The acquired images and spacecraft telemetry will be downloaded to ground and processed between communication windows. Due to the dynamical state of Picard (expected rotational speed of up to 2 degrees/s) and the limitations on the image availability (camera output rate), the expected change in the relative attitude from one frame to the following will exceed the capabilities of the automatic tracking system of the image processing software. The process will be initialized manually by an expert analyzing the downloaded images. A navigation filter is then required to provide a first guess to the image processing for subsequent frames. The filter is a sequential kinematic filter both for relative position (Unscented Kalman Filter, UKF) and for relative attitude (second order polynomial filter, DD2).

The initial solution provided by the image processing software will then be fed to a dynamic batch filter. The main purpose of this module is to refine the pose solution, estimate dynamic parameters of the spacecraft and propagate the solution into the future (1 to 2 orbits) to enable the selection of the most optimal point to execute the experiment. Picard will be non operational during the experiment and hence it will be rotating freely. The major disturbance on the attitude dynamics is the magnetic torque, which depends on the remnant magnetic dipole of the spacecraft, not known a priori. Therefore, in order to have an accurate enough propagation this parameter needs to be estimated during the experiment.

These two modules will be run between communication passes during the experiment preparation phase. The orbit before the experiment execution, the propagated pose of Picard will be fed to an experiment effect prediction module to select the optimal moment at which the experiment shall be executed so that the experiment is maximized. The propagated pose and its associated covariances will be used for the evaluation of the effect of the push. Locations at which the expected effect is above the detectability threshold will be pre selected for the experiment execution. Once the experiment execution time has been selected, the required telecommands will be generated for Mango to be uploaded at the next communication window for experiment execution. This telecommands will include the required attitude profiles, the camera commands and the on times for the thrusters.

The last required element of the system is the experiment evaluation module. This module is based on the building blocks of the previous elements. Acquired images will be processed to extract the pose both before the push and right after the push. The solution will be refined and propagated both for forward and backwards to the point at which the push has been executed and the change n angular status of the target evaluated. This operation will be performed completely off line, as the download to ground of the expected number of images could take several orbits/days. A first set of images of the post push situation will be downloaded to ground with high priority to assess the safety of the post push trajectory.

7. Conclusions

The safety of the proposed experiment has been analyzed. Feasible push strategies exist for pushes of 20 seconds and also for larger ones. The final selection of the strategy will depend on the implementation of the on board FDIR. The effect of the plume impingement on the Picard spacecraft has been analyzed as well confirming that potential damage is an issue. In particular, taking into account the level of thrust available and the relative distance between the two spacecraft, no further debris will be generated during the experiment.

Experiment feasibility has been demonstrated, no showstoppers have been identified and critical areas have been highlighted.

8. References

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