COBRA EXECUTIVE SUMMARY

COBRA EXTENSION OF IRIDES EXPERIMENT

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1.0	07/07/2014	36	First official issue of the document.

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1. INTRODUCTION

1.1. PURPOSE

This document is one of the deliverables of the "COBRA" extension of the "IRIDES" experiment project (ESA Contract No 4000110632/14/NL/MV), devoted to the definition of a follow on experiment within the IRIDES framework to demonstrate de COBRA concept. In more detail, this document is the output of WP100, "Management" under GMV responsibility.

The purpose of this document is to provide an executive summary of the activities carried out during the course of the project and summarise its results.

1.2. SCOPE

In the frame of the "COBRA" extension of the "IRIDES" experiment project, experiment definition, risk analysis and experiment operational plan definition is to be carried out (see [AD.1] and [AD.2] for details). During the second phase of the project the detailed definition and implementation of the image processing software is to be performed together with the definition of the operational plan and the next steps. The scope of the present document is limited to report a summary of the activities carried out during the course of the project and summarise its results.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1: Applicable documents

Ref.	Title	Code	Version	Date
[AD.1]	COBRA extension of IRIDES experiment	GSP-SOW-13-702	1.0	10/12/2013
[AD.2]	GMV EXPRO PROPOSAL COBRA-IRIDES	GMV 10010/14	1.0	17/01/2014

2.1.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2: Reference documents

Ref.	Title	Code	Version	Date
[RD.1]	COBRA Experiment Analysis	GMV.COBRA.D1	1.0	16/04/2014
[RD.2]	COBRA risk analysis	GMV.COBRA.D2	1.0	16/04/2014
[RD.3]	COBRA operational analysis	GMV.COBRA.D4	1.0	

2.2. ACRONYMS

Table 2-3: Acronyms

Acronym	Definition
BSD	Berkeley Software Distribution
BSP	Binary space partitioning
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CHU	Camera Head Unit
DKE	Dynamic and Kinematic Environment
DLT	Direct Linear Transformation
DVS	Digital Video System
ECEF	Earth Centered, Earth Fixed
ECI	Earth Centered Inertial

Acronym	Definition
GNC	Guidance Navigation and Control
GPS	Global Positioning System
LOS	Line of Sight
OBT	On Board Time
PPS	Pulse Per Second
RMS	Root Mean Square
SRP	Solar Radiation Pressure
TBC	To Be Confirmed
VBS	Visual Based System

2.3. DEFINITIONS

Table 2-4: Definitions

Concept / Term	Definition

3. EXPERIMENT SUMMARY

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 which uses "technology challenges" and competitions to survey a comparatively large number of alternative solutions. The concept was originally proposed by an industrial consortium led by GMV form Spain with 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. 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 dynamics of a space debris object in a contactless manner, either to control its attitude dynamics or to deorbit it. 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 capture phase with an uncooperative object (to complement direct systems such as a robotic arm) in e.g. active debris removal operations by reducing the tumbling rate of the target before capture.

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. The COBRA IRIDES experiment is one of these concepts. The main goal will be to demonstrate the COBRA concept making use of two already flying missions, the Swedish PRISMA/Mango spacecraft and the French Picard mission.

Mango spacecraft will approach Picard and fire its engines towards it to impart a change in angular momentum. The momentum exchange will be characterised by taking indirect measurements with Mango's on board sensors, the visual cameras VBS and DVS.

The experiment will make use of the same relative trajectory as IRIDES, a spiral orbit around the target with a radius of 10m and a drift rate of 5m per orbit. In this trajectory the minimum distance to the target will be 10m, repeated in several consecutive orbits along one day of operations (14 orbits).

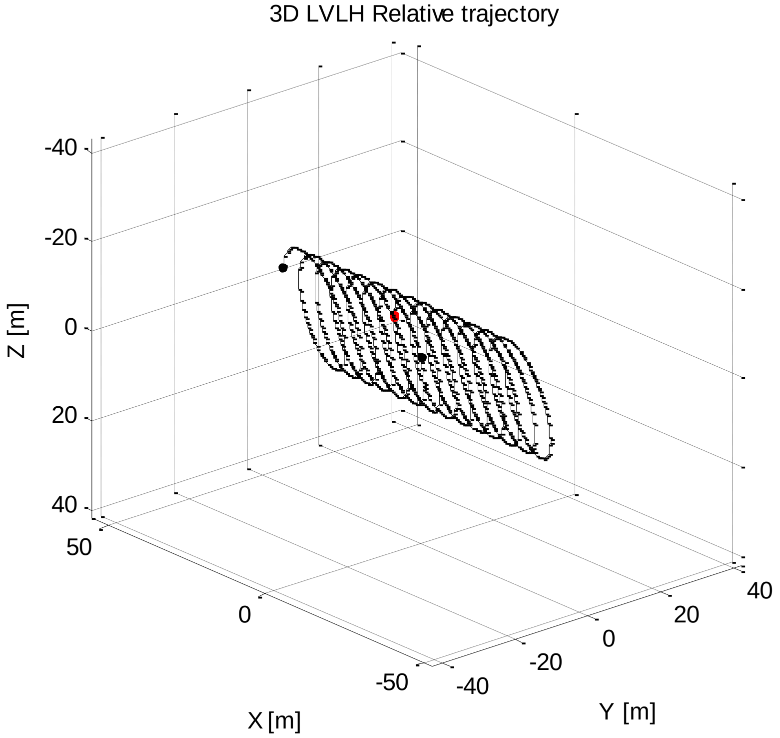

Figure 3-1: Reference trajectory

The actual firing of the thrusters will take for 20 sec in one of the orbits around the target (minimum distance). Measurements with the relative sensors will be taken during the orbits preceding the push itself and during some orbits after, to be able to assess the change in dynamics. Meassuremetns taken in advance will be also used to estimate the dynamics of the target and find the optimal point in time to execute the experiment, minimum relative distance and relative attitude of the target to maximise the momentum exchange.

The experiment is divided in two phases:

- experiment preparation, orbits 6 to 9 in Figure 3-2 below, devoted to the gathering of images of the target, estimation of its attitude dynamics and relative orbit and selection of the experiment execution time
- experiment execution, orbit 11, 12 or 13 (three consecutive attempts), devoted to the acquisition of images at high rate before the push, execution of the push and acquisition of images after the push to determine the change in the dynamics of the target

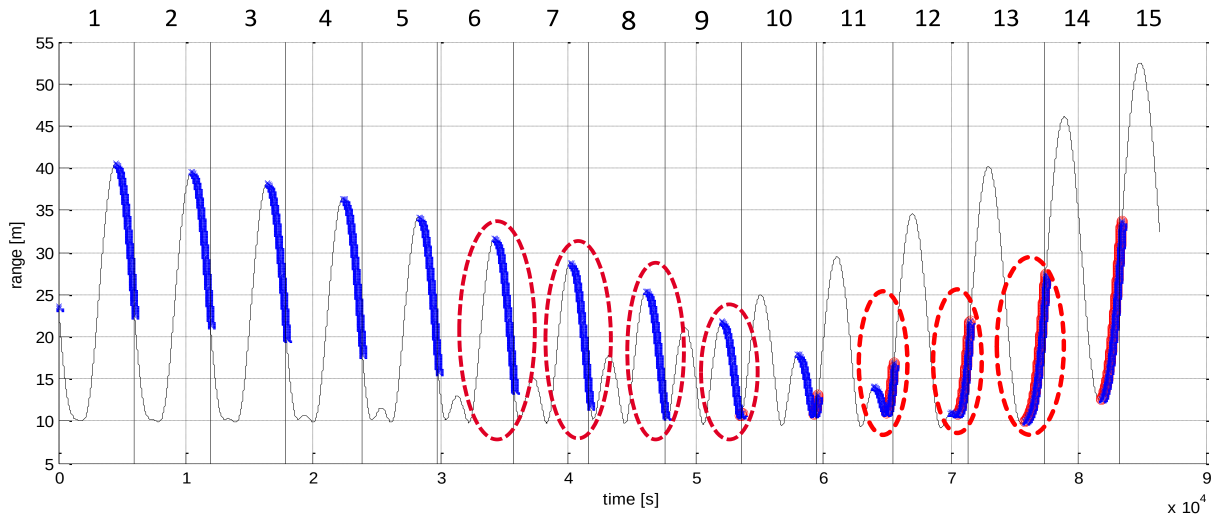

Figure 3-2: Range vs time for reference trajectory

4. REVIEW OF THE PRISMA MANGO AND PICARD SPACECRAFT CHARACTERISTICS

The **Mango** spacecraft is part of the PRISMA mission and will be the chaser in the COBRAIRIDES 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.

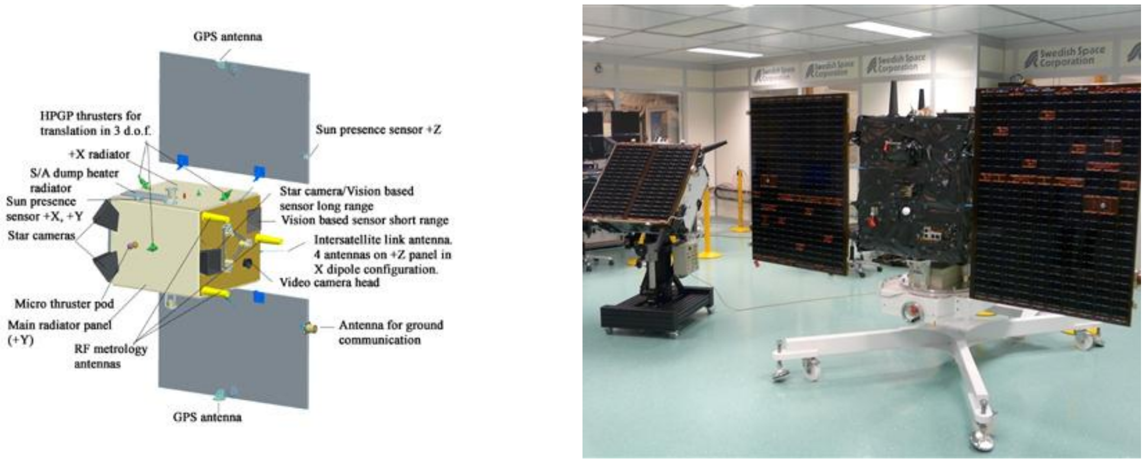

Figure 4-1: Mango Spacecraft (diagram left, picture rignt)

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 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. The system is composed by an Optical Unit and a Video Management Unit (H2VMU). The camera has a detector of 2048x2048 pixels and a half cone field of view of 14x14deg with a focal length of 30mm.

Figure 4-2: VBS (left) and DVS (right)

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.

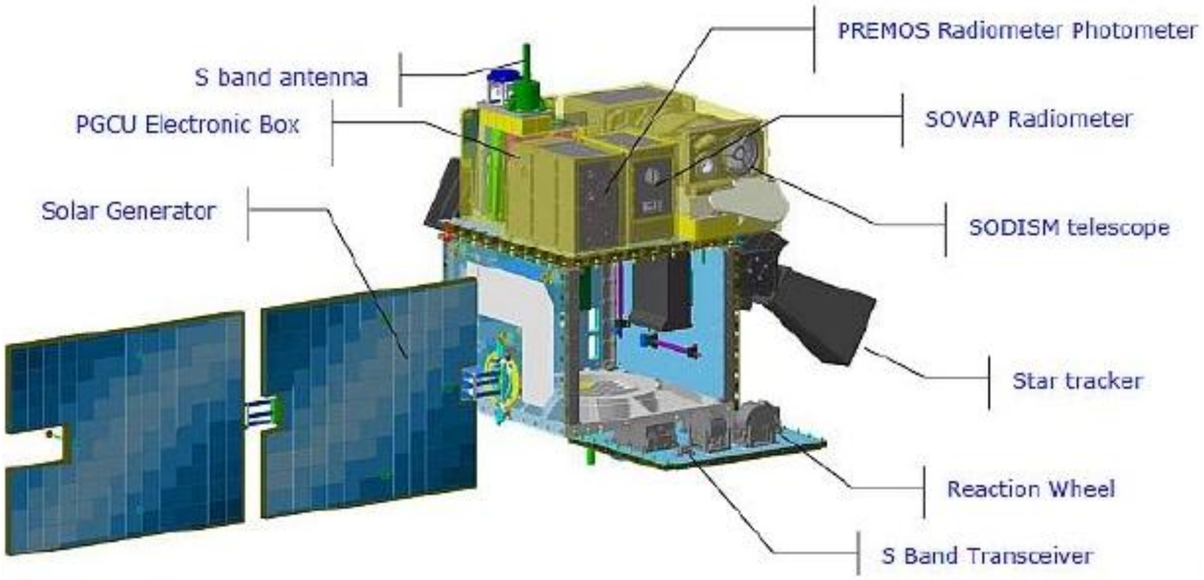

Figure 4-3: Picard diagram

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.

The COBRA experiment is expected to take place between August 2014 and November 2014. Picard current orbit as obtained from TLE (almost dawn dusk SSO orbit at 735km) has been propagated using NAPEOS GMV Software to assess the mission constraints mainly in terms of eclipse times and contacts with ground from that orbit.

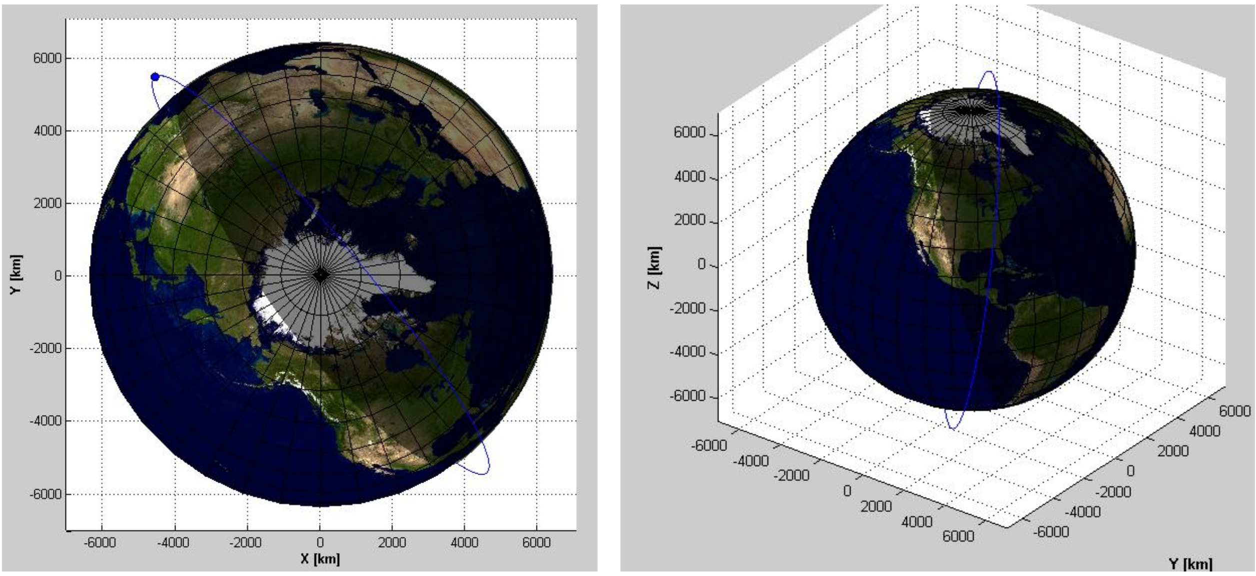

Figure 4-4: Orbit on the 01/11/2014

5. PLUME IMPINGEMENT MODEL

Plume impingement model has been implemented to predict what the effect of the experiment will be.

5.1. PRESSURE MODEL

The pressure field due to plume impingement on the surface of the target is computed in polar coordinates (r,θ), as a function of the characteristics of the thrusters such as plume semi-divergence angle and thrust level. The pressure model has been implemented using the model by Fehse:

$$P(r,\theta)=\frac{\phi_0}{r^2}e^{\frac{-\theta^2}{2\theta_0^2}} \tag{5-1}$$

polar coordinates (r,θ) represent respectively, the distance from the nozzle exit area and the deviation angle from the plume centerline. The parameter ϕ_0 represents a constant of the thruster and it depends on the plume semi-divergence angle θ_0 and the thrust level T:

$$\phi_0=\frac{T}{\pi}\frac{1}{\int_0^{\pi}e^{\frac{-\theta^2}{2\theta_0^2}}\sin(2\theta)d\theta} \tag{5-2}$$

The pressure field depends then only on the characteristics of the thruster, on the relative distance and on the angle with respect to the plume centerline. The physical properties of the target and the plume impingement mechanism do not have any effect on the pressure distribution on the surface of the target.

5.2. THERMAL MODEL

In analogy to the pressure model implementation, the thermal flux profile generated by the plume impingement on the surface of the target is computed in polar coordinates, as function of the characteristics of the thruster. The reference model is the heat flux model by Trinks:

$$q(r,\theta)=H_0\left(1+\frac{r}{r_0}\right)^{-2}\left(2e^{-\frac{\theta}{\theta_0}}-e^{-\frac{2\theta}{\theta_0}}\right) \tag{5-3}$$

Where H_0 and r_0 are experimental constants of the thruster and θ_0 is the plume semi-divergence angle.

5.3. MODEL OF THE DYNAMICS

5.3.1.1. Target

The model simulates the attitude and orbital dynamics of the target spacecraft. The forces and torques acting on the spacecraft as result of the interaction with the plume are computed starting from the pressure field, considering the different impingement mechanisms, taking into account for the different contributions given by diffuse and quasi-specular reflection.

The force due to pressure acting on each surface element of the target is computed by means of the following equation:

$$dF_i=-P(r_i,\theta_i)\cdot dS_i\left[(1-c_s)\hat{S}_i+2\left(c_s\cos\theta_i+\frac{1}{3}c_d\right)\hat{N}_i\right]\cos\theta_i \tag{5-4}$$

Where the subscript "i" indicates the i-th surface element, with $\hat{S}$ denoting the direction of the plume impinging on the surface and $\hat{N}$ represents the normal to the surface. θ is the angle between the plume and the direction orthogonal to the surface. Finally, C_s and C_d are respectively the coefficient of specular and diffuse reflection.

5.3.1.2. Chaser

The relative dynamics of the chaser with respect to the target is simulated in order to take into account for changes in the relative position during the thrusting phase due to both drifting on the relative trajectory and to deviations with respect to the initial orbital path due to the effects of the plume interaction.

5.4. IMPLEMENTATION AND RESULTS

The model has been implemented n Matlab/Simulink and has been successfully validated against the data provided in the COBRA CDF Report. Some differences exist at close range due to the shockwave that is generated, but for COBRA application the inter satellite distance will be around 10 and hence no problem is envisaged. A second model has also been implemented, optimising the code for running time to allow it use in the experiment effect prediction tool, to be run between comms passes.

A large set of scenarios has been analysed to assess the possible effect of the plume impingement, as a function of the relative distance, relative attitude, surface properties, initial target rotational speed and orientation of the spin axis. The following figure summarises the results for one of the tests (SC1 is an scenario were the solar panel of Picard is impacted perpendicularly, SC2 corresponds to an scenario where the solar panel is hidden and SC3 corresponds to a simetrical scenario wrt SC1, i.e the solar panel is visible but the plume is directed to the other side of the spacecraft.

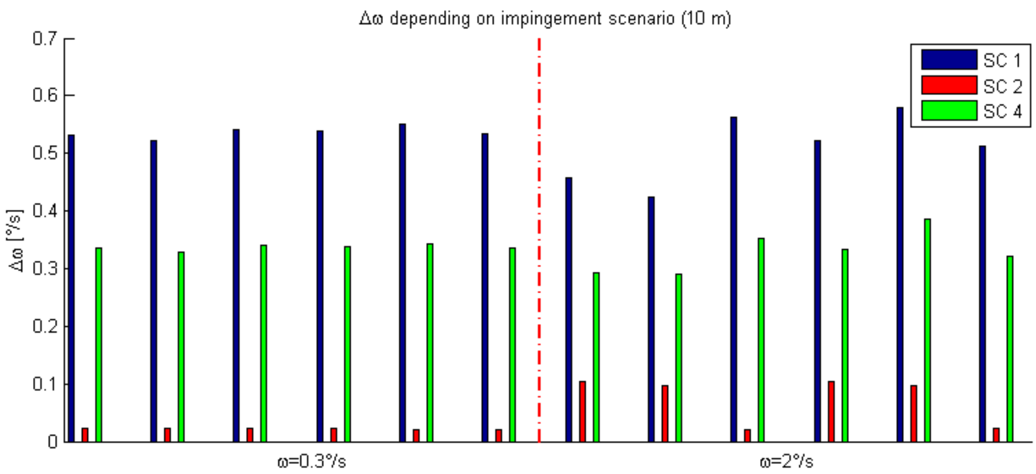

Figure 5-1: $\Delta\omega$ fro 20secburn at initial relative distance=10 m

As a conclusion it can be stated that there is a large variability in the results, both in terms of the change in magnitude of the angular velocity and the change in orientation of the angular velocity vector. The main driver is the relative attitude. Configurations in which the solar panel cannot be impacted lead to a lower momentum exchange. The inter satellite distance has also a significant influence, while the influence of the spin rate and the spin axis orientation is of second order.

6. SAFETY ANALYSIS

Experiment safety analysis has been carried out in the frame of the experiment definition phase. The safety analysis has focus in two areas:

- Potential damage to Picard due to the plume impingement
- Collision risk due to the push strategy

6.1. POTENTIAL DAMAGE TO PICARD S/C

With the limited information available related to the construction details and materials of Picard and the results from the plume impingement model in terms of pressure field and heat flux distribution, and analysis has been performed on what could be the impact on Picards surfaces. The failure modes identified are:

- Rupture of MLI
- Separation of MLI
- Interaction with SSM
- Interaction with solar cells
- Flexure of solar panel
- Impinging heat flux

Large safety margins have been found in all the cases, therefore it can be concluded that theproposed experiment will not pose any risk to Picard experiment.

6.2. EXPERIMENT SAFETY ANALYSIS

The current proposal for the COBRA IRIDES experiment relies on the reference trajectory of the IRIDES experiment. This trajectory is considered safe if no actuation is performed. Mango will approach Picard in a relative orbit with certain offset both in the radial direction and in the out of plane direction. Therefore the only safety concern is related to the push operation and the resulting trajectory. In the following sections a safety analysis is presented for different actuation strategies.

Simulations have been performed to assess the safety of the resulting trajectory after the push for four different scenarios: no compensation of the pushing burn, simultaneous compensation, sequential compensation and only compensation. J2, SRP and drag have been taken into account.

After analysis of the results it can be concluded that:

- Not compensating the push leads to a rapid increase of the ISD immediately after the push, such that the chaser quickly moves out of the ideal range of the camera for determining the attitude of the target. In some cases, the chaser returns to the vicinity of the target with a smaller minimum ISD than the original safe orbit. In general, the dimensions of the safe orbit decrease, meaning that the circular projection on the YZ plane becomes an ellipse of which the minor direction is smaller than the original dimension of the safe orbit. This means that not compensating for the push can only be made safe if the push is designed as an escape manoeuvre.
- For 20 second burn durations the behaviour of the simultaneous compensation and the sequential compensation is very similar, and the distance after the push is fairly low. The main difference is that sequential compensation requires twice the amount of time to perform, such that images after the push will be available later with respect to the simultaneous compensation. On the other hand, sequential compensation can be performed using the standard on-board software of Mango, while simultaneous compensation would require low-level commanding of the thrusters and modification of the on-board software. For both scenarios the possibility of a thrust failure exists, either of the pushing thruster or of the compensating thruster. The pushing burn should be prepared in such a way that the push alone would lead to an escape trajectory. This means that during the preparation of the experiment the trajectory of Mango with respect to Picard should be checked to ensure that it is a safe escape trajectory. If the pushing thrust fails, the thrust should be switched off as quickly as possible, i.e., as soon as it is detected that only the compensating thruster is active.

- The firing of only the compensating thruster should be avoided. Firing the compensating thruster only leads to a rapid decrease of the ISD, which in many cases leads to an unsafe situation.

Figure 6-1 shows the results for one case for simultaneous compensation. In the distance plot the black line indicates the nominal distance and the red lines indicate the 3σ boundaries. In the trajectory plots the original safe orbit is indicated in a dotted black line, the trajectory resulting from the experiment is red and the 3σ probability ellipsoids are indicated in grey.

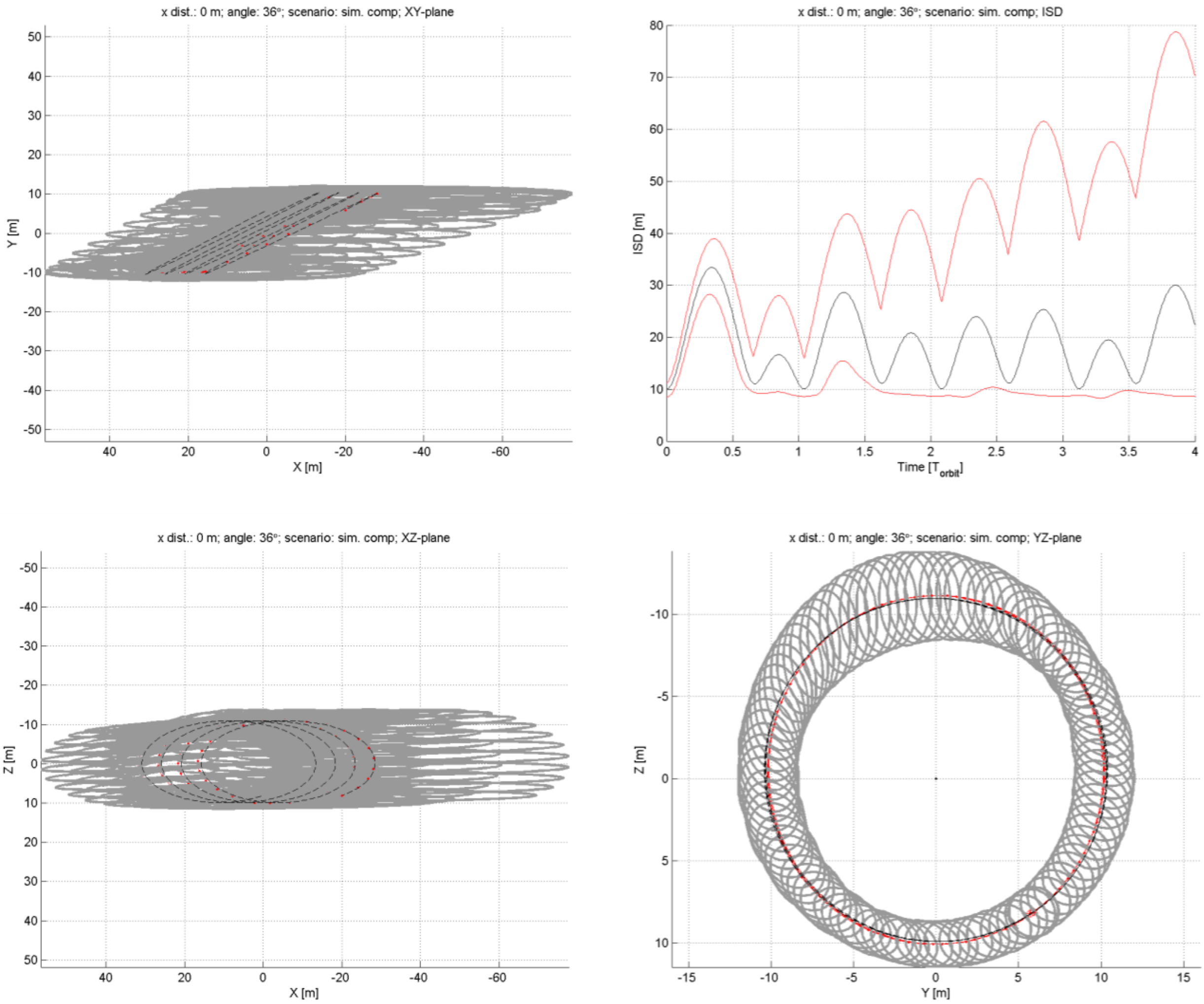

Figure 6-1: Simultaneous compensation 20 sec burn

7. IMAGE PROCESSING

The COBRA experiment will rely on the information gathered by the Mango relative sensors (VBS and DVS) both for the planning and execution of the experiment and for the analysis of the results. The available relative sensors are visual cameras, hence image processing has to be developed in order to extract the relative pose of the target with respect to Mango and be able to provide relative navigation information and dynamic characterisation of the target. For the purposed of the COBRA experiment the VBS has been selected as the main sensor for all the experiment phases. DVS will be used as well for the experiment effect analysis, acquiring images just before and just after the push. The image processing is to be performed off line from ground.

Geometrical edge-based features method (CAD model of the target available) has been selected, as it shows robustness against illumination conditions, image noise and are particularly suited when the target object is low textured, such as in our debris removal context.

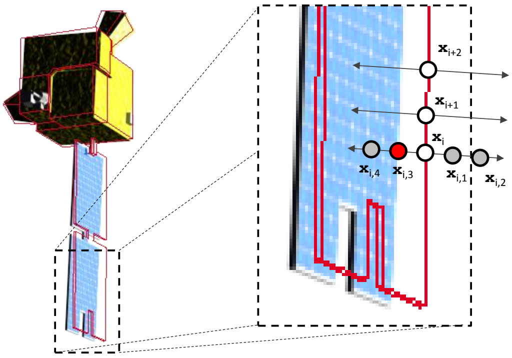

Figure 7-1: Edge tracking from control points

It shall be noted that the IP software accuracy is mainly driven by:

- Initialisation errors, the software will try to minimise the error between the image and the projection of the 3D model over that image. There are limitations on the amount of error from which the software will be able to recover. This means that if the change in pose in between two consecutive images is too large, an initial guess will have to be provided to the software for each individual image
- Distance to the target, basically linked to the resolution of the image
- Relative attitude, if the image does not provide depth information, large errors will be found (i.e. frontal image, solar panel not visible). In the following image it can be seen how peaks in the error correspond to configurations where the solar panel is seen from one side.

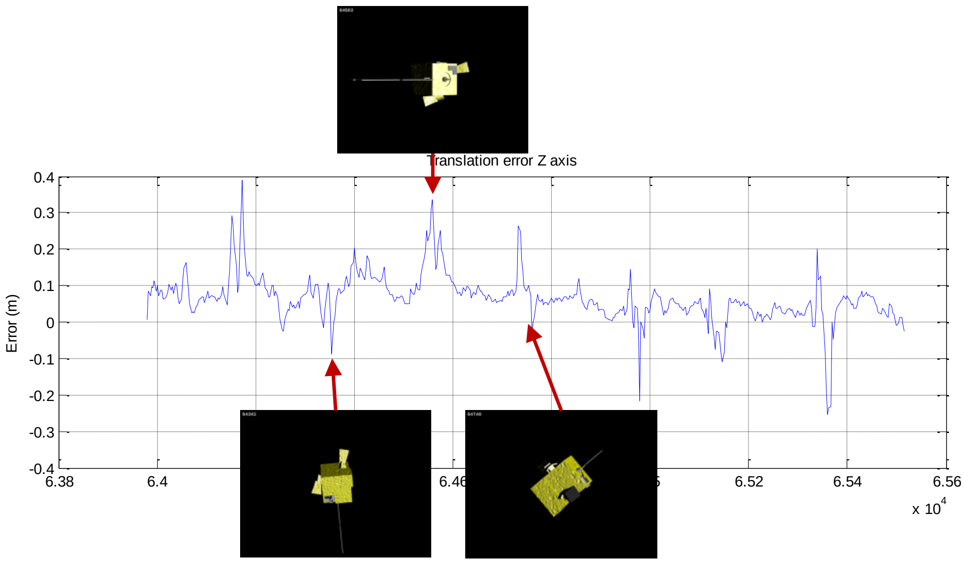

Figure 7-2: Translation error for z-axis and corresponding images.

The software has been implemented in C++ and tested under different constraints obtaining good results. Most of the tests have been based on the use of synthetic mages generated over the reference trajectory for the COBRA IRIDES experiment. Some tests have been also performed using real images from the VBS camera with Tango spacecraft as target:

- Manual initialisation, IP needs an initial guess of the pose to be initialised. This will be provided by manually analysing the first 2-3 images of each batch. A tool has been implemented to support this process. Accuracies of under 1cm across LOS and under 30cm along LOS have been obtained. In terms of attitude, errors below 0.5 deg have been obtained in all axis
- Experiment preparation, IP will be initialised manually and will be supported by navigation filters to provide guess for subsequent images (45s between images and the dynamics of the target avoid the use of automatic trackin feature). Accuracies of 0.1m across LOS and 0.5m along LOS have been obtained. In terms of attitude, errors below 2 deg have been obtained in all axis
- Experiment execution, IP will be initialised manually and make use of automatic tracking for subsequent images (acquisition rate of 3s). Accuracies of 0.05m across LOS and 0.4m along LOS have been obtained. In terms of attitude, errors below 2 deg have been obtained in all axis
- Tango images, real Tango images from the PRISMA-HARVD experiment have been used to check the behaviour of the IP software. As can be seen in the image below, it provides a good matching between the model and the real image.

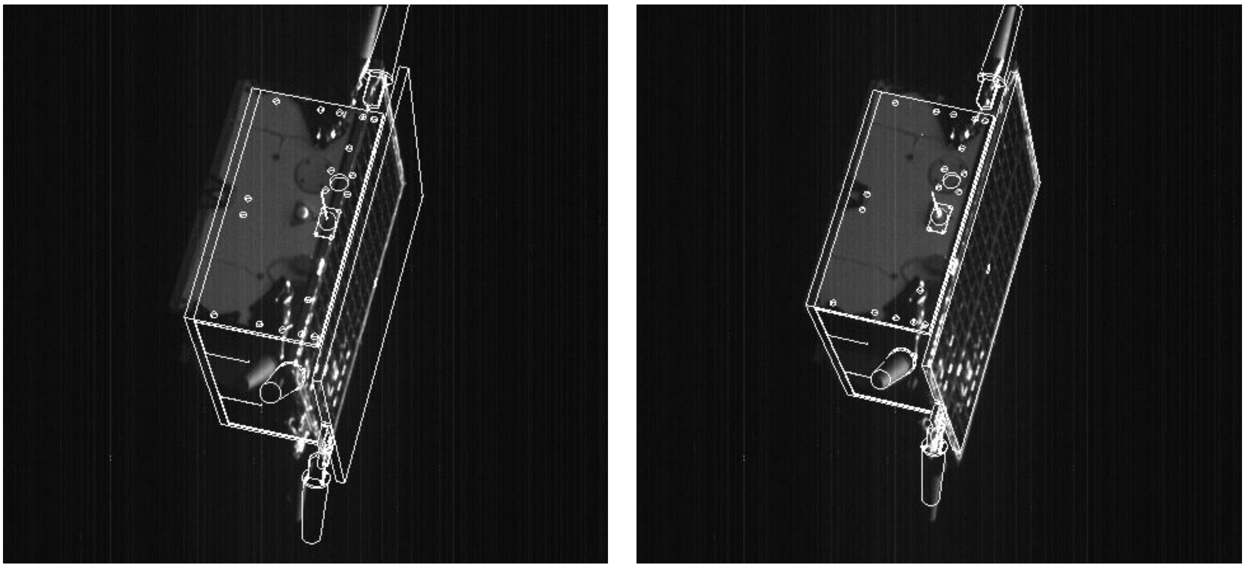

Figure 7-3: Matching after a perturbed initialization. Left, perturbed image; right, converged solution.

8. SYSTEM DEFINITION

In order to support the experiment execution different systems will need to be implemented and integrated. At the core of the system will be the image processing software, supported by different filters both to extract the first solution and to refine it while determining critical parameters for orbit propagation. An experiment effect estimator will be required to decide the precise moment when to execute the experiment and post processing software to assess the effect of the experiment.

8.1. EXPERIMENT PREPARATION PHASE

The following figure summarises the required systems for the experiment preparation phase.

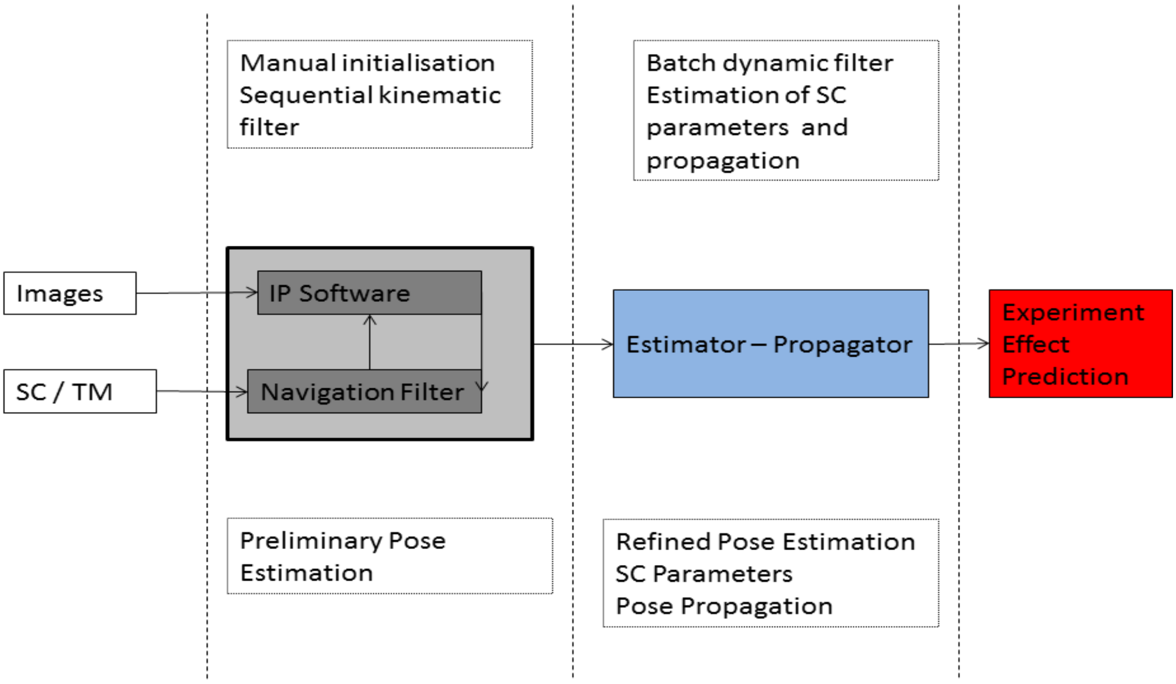

Figure 8-1: Experiment preparation system

8.1.1. IMAGE PROCESSING MODULE

The image processing module will be composed by the image processing software and the supporting navigation filters to provide it with an accurate initial guess for each image.

Due to the image acquisition rate (45s) and the target dynamics (rotational speeds of up to 2 des/s) it will not be possible to use automatic tracking for the image processing, as the difference in pose from image to image will be too large, especially in terms of relative attitude (changes of up to 80deg could be expected in the worst case, while the limit for tracking is in the range of a few degrees, depending on the range an axis considered.

Therefore navigation filters for both relative estate and relative attitude are required to provide the image processing software with a good enough initial guess for each image to be processed. Obviously the filters will need to be initialised. In the first pass it will be required to process several images by hand in order to support the initialisation.

The relative position filter is based on a sequential Unscented Kalman Filter (UKF), while the attitude filter is based on a second order polynomial filter DD2. This filter is similar to an unscented Kalman filter offering better robustness by the use of sigma points.

8.1.2. ESTIMATOR PROPAGATOR

Once the image processing solution has been provided it will be fed to a dynamic batch dynamic filter. The main goal of this filter is to enable the accurate propagation of the pose into the future for experiment execution time decision. This will be achieved mainly by fitting the image processing solution and by estimating dynamic parameters. This same filter will be used for the post processing of the experiment data.

This module will be used in each orbit during the experiment preparation and will be fed with all the data available till that moment (image processing solution and spacecraft telemetry). It will both estimate and propagate the relative dynamics and will also estimate the main perturbation parameter, the magnetic dipole.

8.1.2.1. Experiment effect prediction

The experiment effect prediction module will take as input data the propagated pose of the target with its associated uncertainties and will run over it a simplified plume impingement model to assess the effect of the experiment along this relative trajectory. Points in which the effect is over a certain threshold (change in angular velocity of 0.05-0.1 deg/s TBC) will be selected as possible points for the execution of the experiment.

This module is based on the improved plume impingement model. The amount of cases to be run will be extremely large, around 6000, and therefore it has been necessary to optimise the code for reduced run time.

8.1.2.2. Telecommands generator module

The last required module is the one devote to the generation of the telecomands required for the experiment execution. It is assumed that GMV will not be responsible of writing the actual telecomands, the operator of the spacecraft will assume that responsibility (and most probably will not delegate it), by GMV will be responsible to provide the inputs required to build up the required telecomands. Three types of telecommands are envisaged:

- Attitude profile. During the orbit in which the experiment is to be executed, the attitude of the spacecraft will need to change from target pointed (either autonomous or time tagged) to thrusters target pointing and back to target pointing during the quarter of the orbit in which the experiment is executed.
- Camera control. It will be required to define when to switch on the camera and define the acquisition rate for the two different observation phases. It may also be required to define the images to be downloaded at the next communications window to check the safety of the post push trajectory.
- Thrusters on commands. It will be required to define which thrusters to use and the on time of the thrusters. This will basically depend on the final strategy selected and the safety approach.

8.1.3. EXPERIMENT EXECUTION

The following figure summarises the required systems for the experiment execution phase.

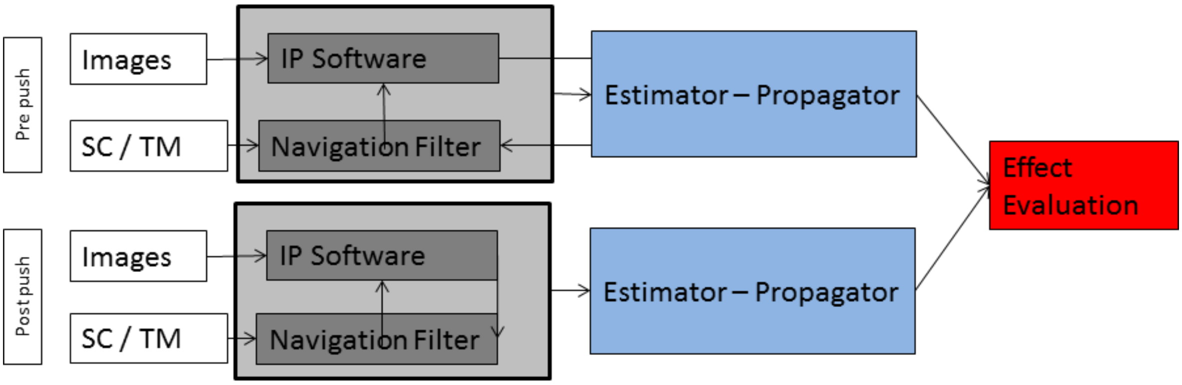

Figure 8-2: Experiment execution system

Most of the systems required for the experiment execution phase will be reused with minor modifications from the previous phase.

8.1.3.1. Image processing module

This module will be reused from the previous phase. The only modification will be that the need for navigation filters to support the image processing may not be required if the image acquisition rate is high enough.

It shall be analysed if the use of DVS images will provide any benefit for the experiment evaluation. In case of positive answer, the software will need to be adapted and tuned to the DVS parameters.

8.1.3.2. Estimator Propagator

This module will be reused from the previous phase without modifications.

8.1.3.3. Effect evaluation

Two options exist for this module, both based on the estimator propagator module:

- Run the estimator propagator over the two sets of image processing solution, pre and post push, and propagate the solution both backwards and forward till the moment of the push. At this point the torque equation can be evaluated.
- Modify the estimator propagator and include the plume impingement torque as one of the parameters to be evaluated.

9. SYSTEM SIMULATION

System simulation has been carried out at this stage, obtaining satisfactory results, though some tuning of the filters should be performed in the next phase of the project.

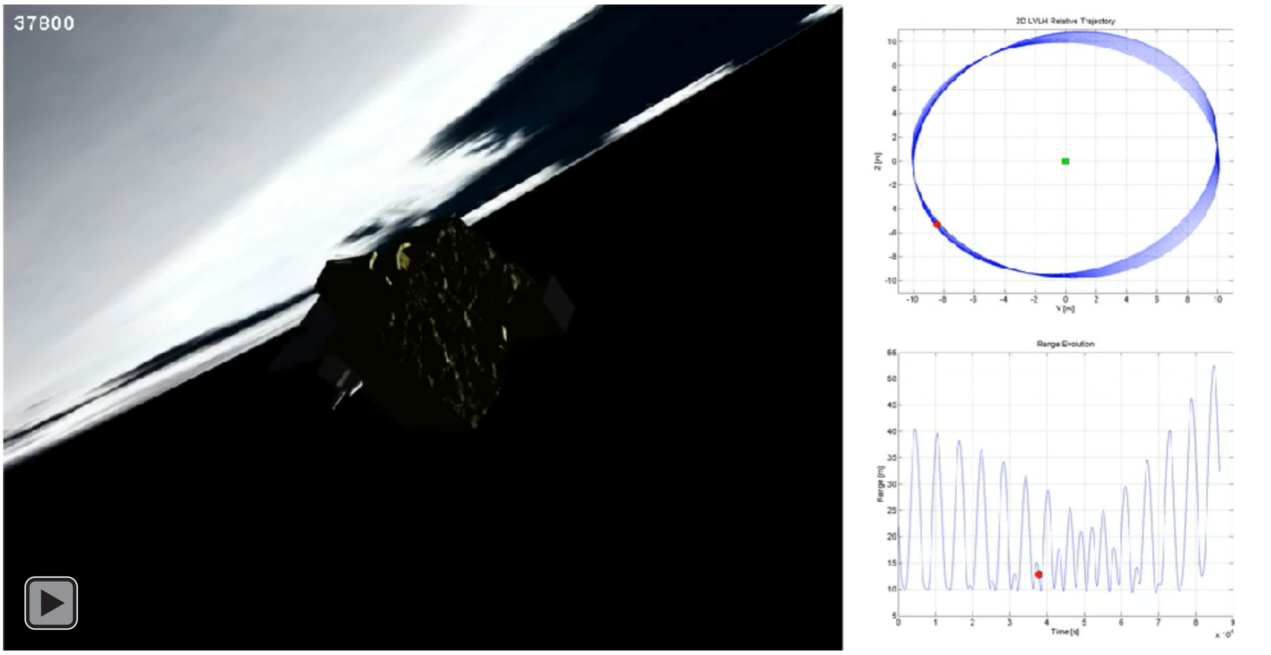

Figure 9-1: Camera view animation for reference trajectory

9.1. IMAGE PROCESSING FOR EXPERIMENT PREPARATION

The following figures present the results obtained by the image processing module when fed with the initial guesses provided by the supporting navigation filters for four consecutive orbits.

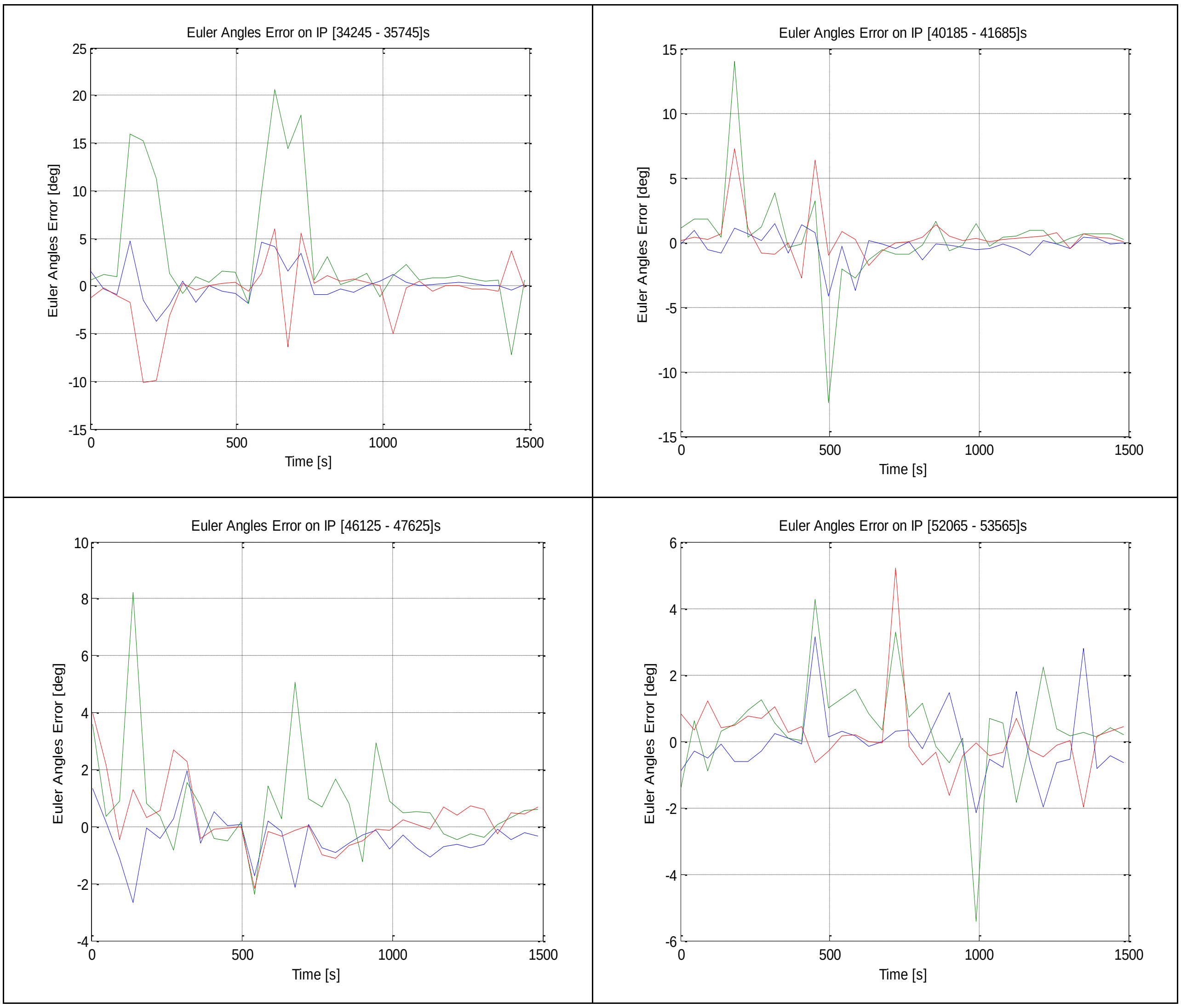

Figure 9-2: Estimation Error Image Processing on attitude of Body Picard wrt Camera Frame [deg]

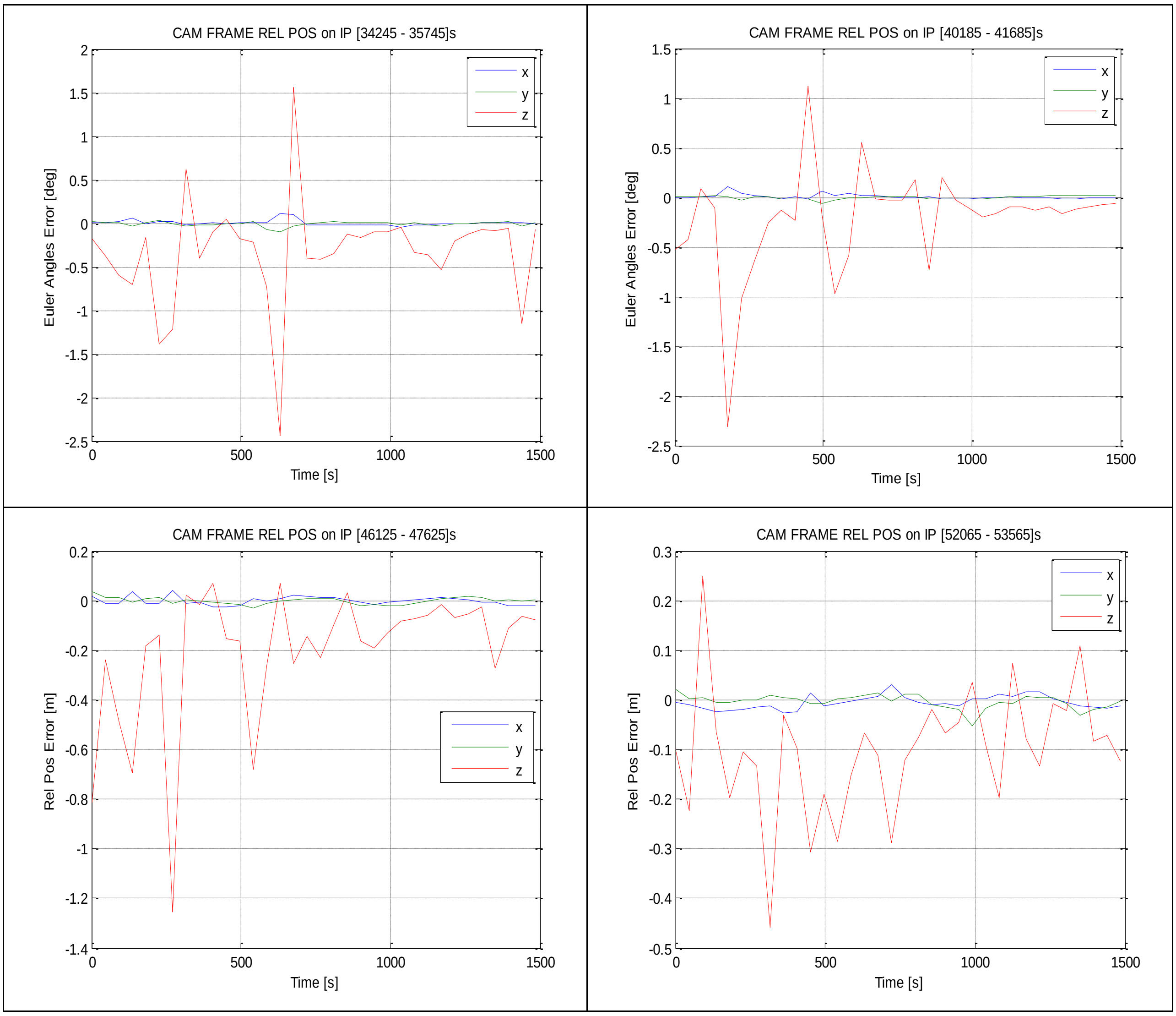

Figure 9-3: Estimation Error Image Processing on Relative position of Picard in Camera Frame [deg]

The results shown in Figure 9-2 and Figure 9-3 are referred to the error between the attitude and position computed by the Image Processing module and the correspondent real Euler angle and position values coming from DKE.

In figure above some peaks of error can be observed in the image processing solution due to particular Picard poses. These results will be monitored in real time during the experiment execution, and if a too bad result is encountered, manual re-initialisation will be implemented to reduce the errors.

9.2. ESTIMATOR PROPAGATOR

During the first phase of the experiment (experiment preparation) the main objective is to exploit camera measurements and Mango state estimations to predict Picard behaviour. The information will then be used to predict the trajectory and attitude of the target and select the most suitable time to begin the following phase (experiment execution). This module has been tested over the reference trajectory with the following main results:

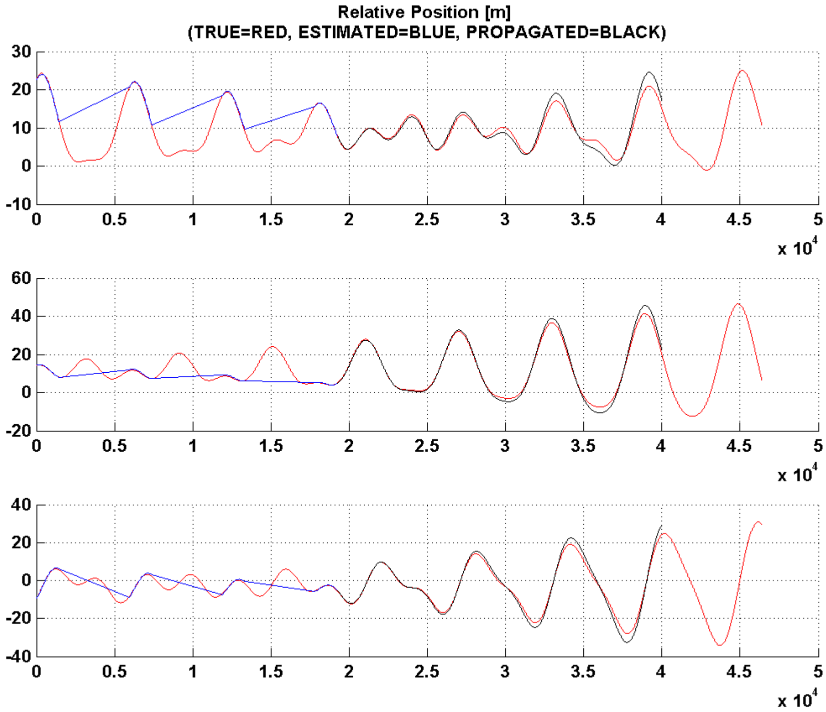

Figure 9-4: Picard relative position [m] (TRUE=RED, ESTIMATED=BLUE, PROPAGATED=BLACK)

Figure 9-5 and Figure 9-6 present Picard attitude quaternion and Picard attitude Euler angles.

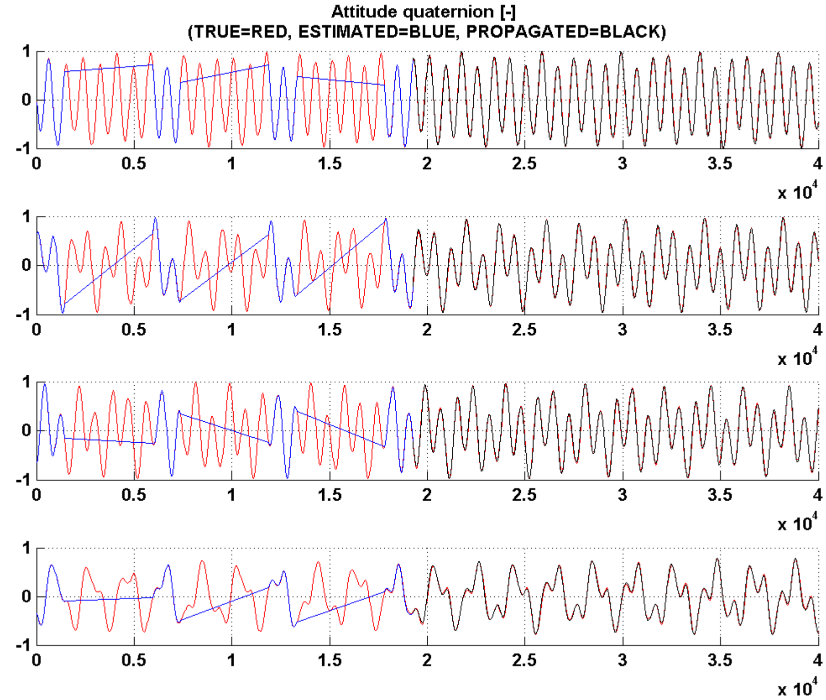

Figure 9-5: Picard attitude quaternion [-] (TRUE=RED, ESTIMATED=BLUE, PROPAGATED=BLACK)

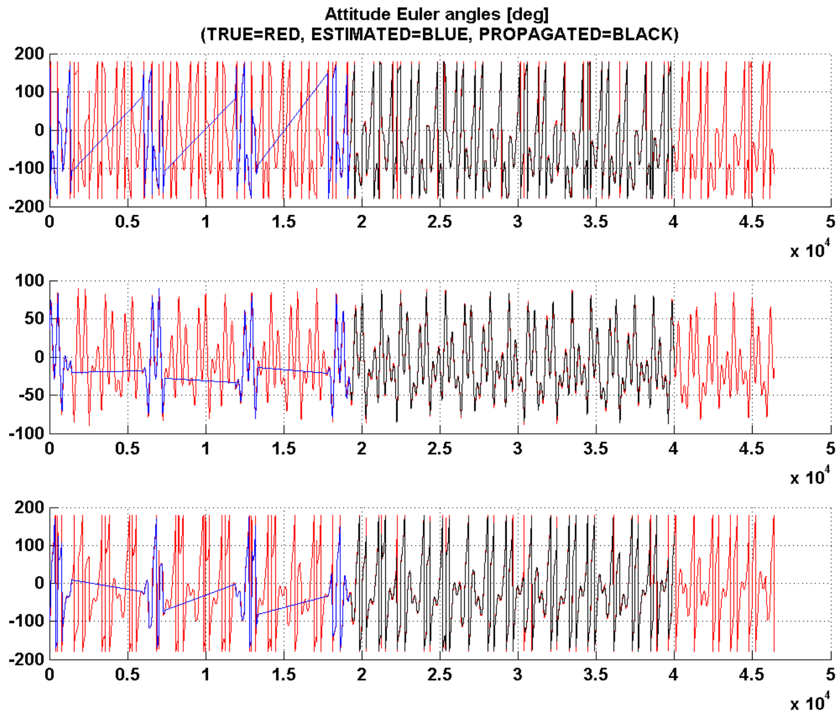

Figure 9-6: Picard attitude Euler angles [deg] (TRUE=RED, ESTIMATED=BLUE, PROPAGATED=BLACK)

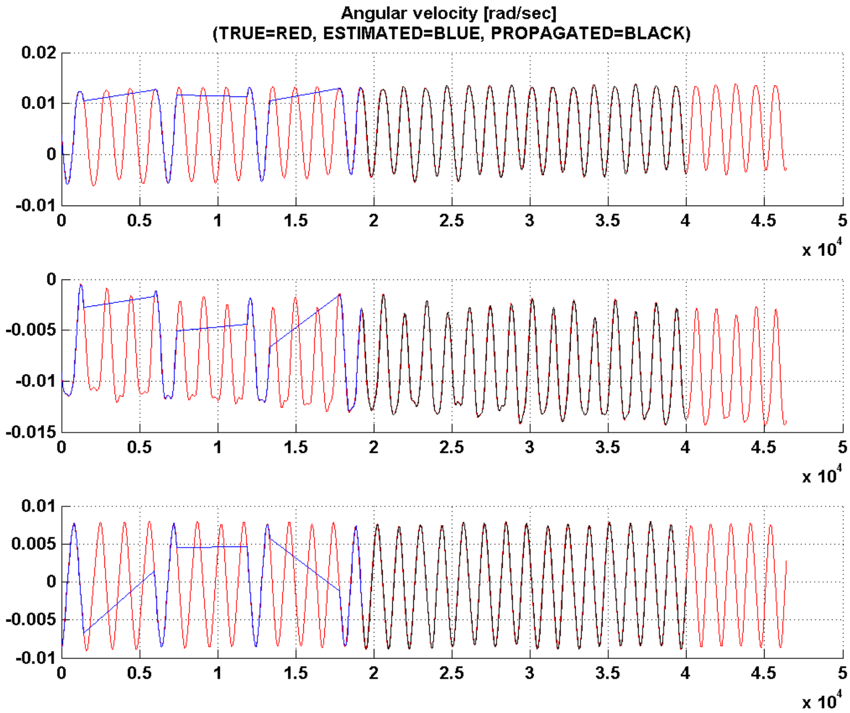

Figure 9-7: Picard angular velocity [rad/s] (TRUE=RED, ESTIMATED=BLUE, PROPAGATED=BLACK)

In the simulations reported measurements will be available till second 19260 while the experiment should be executed between second 29760 and 31260. With the present tuning the filter is able to provide the required performances for attitude prediction, though further tuning and testing should be performed.

9.3. EXPERIMENT EFFECT PREDICTION

The prediction of the experiment effect will provide an estimate of the plume impingement effect, measured as an attitude rate change of Picard. The purpose of this operation is to select the time at which the experiment shall be performed to ensure that the experiment is successful, i.e. the effect will be measurable. This FoM consists in the norm of the vector defined as the difference between the angular velocity before and after the 20 seconds pushing action (module in deg/s).

The operational condition analyses results showed that the temporal window in which it is possible to perform the experiment is almost 25 minutes. In order to have time to take images before and after the experiment, the pushing phase shall be centred in that window, within an interval of 10 minutes. This is the time in which the experiment can be performed, so it is the time in which the relative position and attitude condition should be analysed in order to decide the optimal timing, considering the maximization of the selected FoM.

The system has been tested taking as input the propagated trajectory from the estimator propagator. The trajectory has been sampled at 10s intervals and 100 evaluations of the plume impingement model has been carried out per point. The results are shown in the following figure, for a nominal case and a case in which the knowledge of the relative attitude has been worsen to 40deg.

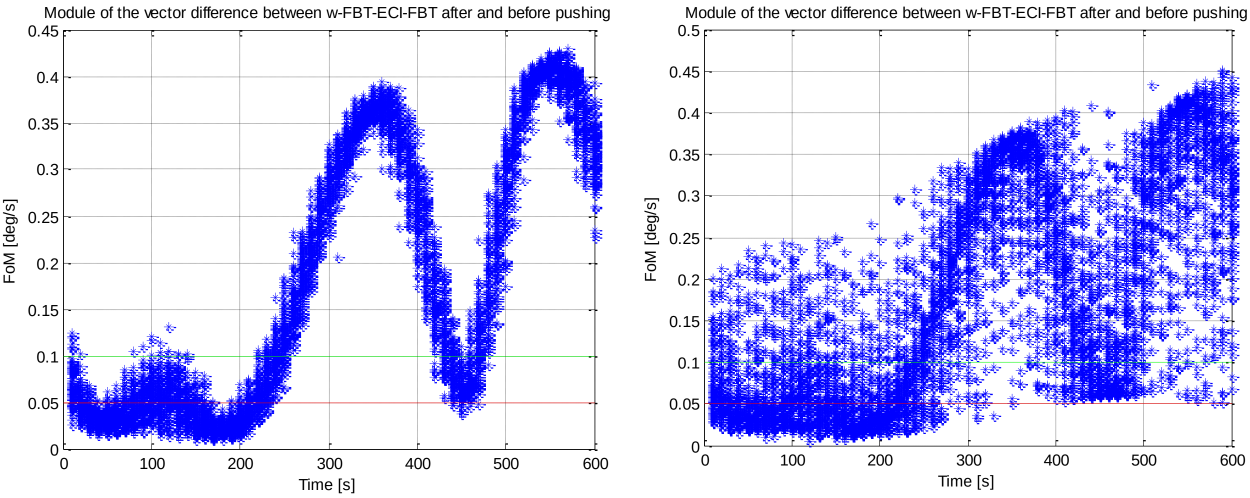

Figure 9-8: FoM evolution during the 10 minutes window [1-σ of 3 deg in attitude on the left and 1-σ of 40 deg in attitude on the right]

Figure 9-8 shows that there are two major factors that directly affect the target attitude and the selected Figure of Merit. As expected, there is a tendency that increases the value of the FoM. This is due to the progressive reduction in range of the relative trajectory. The second factor is the relative attitude. This factor could lead to very high differences in the FoM at the same relative distance between target and chaser. Indeed at second 350 the range is 13.5 m and at second 450 the range is 12.5, however at second 350 the FoM is almost 8 times higher than the FoM at second 450.

The red line is considered to be the lowest value of the FoM that could be measured; the green line represents a conservative estimation of this value. To properly select the experiment timing, it is important to see if there are any temporal windows in which in every possible case (also with large error of attitude estimation) the imparted effect will be measurable. The percentage of the cases in which the FoM is higher than the minimum threshold gives exactly this information.

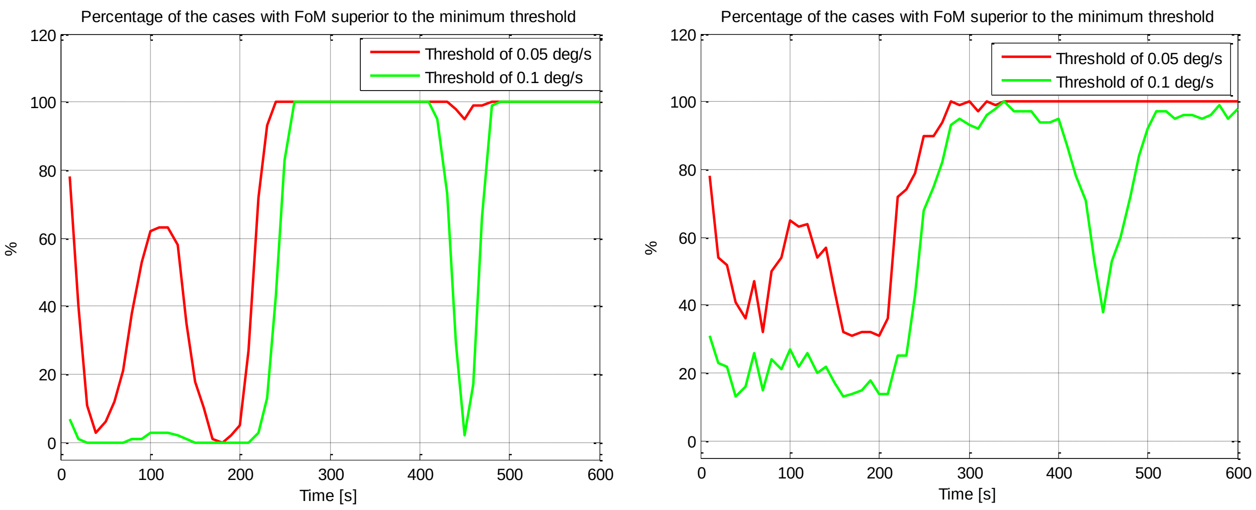

Figure 9-9: Statistics of the FoM [1-σ of 3 deg in attitude on left , 1-σ of 40 deg in attitude on right]

It is possible to notice from Figure 9-9 that if the dispersion is higher, the chance to obtain a 100% possibility of success (FoM higher than the detectable threshold) is reduced, especially considering the conservative green line threshold.

From Figure 9-8 and Figure 9-9 there are two interesting temporal windows for the experiment, from 300 s to 400 s and from 500 s to 600 s. Even if a poorly estimated attitude is assumed (figures on the right), both of these intervals maximize the chances of success in the detection of the target attitude change.

9.4. SYSTEM SENSITIVITY

The estimator propagator module is to be used to estimate the angular velocity of the target before the push and right after the push. The experiment execution will take place over one quarter of an orbit (around 1500s) and will be divided in three phases:

- Pre-execution observation campaign
- Push execution
- Post execution campaign

Enough measurements shall be acquired both before and after the execution of the push, hence the experiment execution window has been constrained to 10 minutes centered in the execution arc, that is, at least the first 7.5minutes will be devoted to image acquisition as well as the last 7.5 minutes. The experiment execution itself is expected to last for only 5 min including the 20 burn.

The IP solution with image acquisition rate at 1 every 3 seconds has been fed to the estimator propagator and the accuracy of the solution in terms of angular velocity assessed. In this case the estimator propagator has been used without SRP and drag perturbations. The exercise has been repeated for the three orbits in which the experiment could be executed.

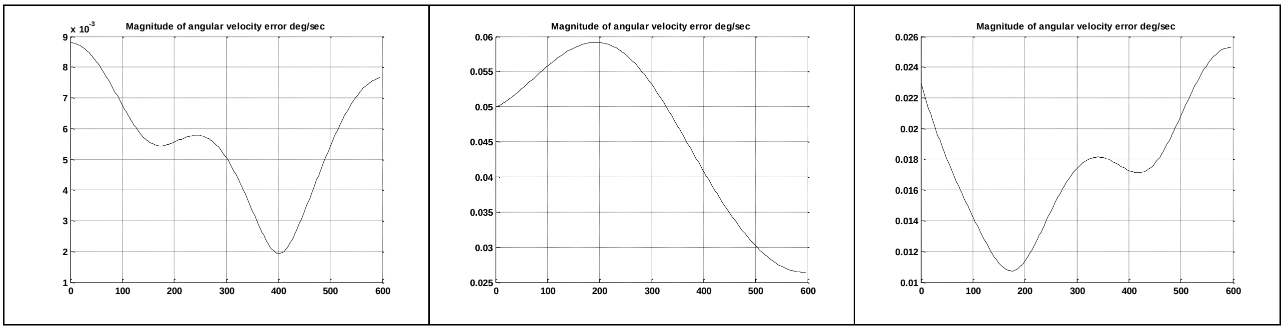

Figure 9-10: Angular velocity error for orbits 11-13

As can be observed, a maximum error of 0.057deg/s could be expected. Some margin should be taken over this figure i.e. increasing it to 0.1deg/s. Analysing again Figure 9-9, it can be seen that there are still two windows of opportunity to execute the experiment and be able to detect the effect with a 90% confidence level for the worst case of attitude prediction.

A quick test has been carried out for the extreme case in which only 4 images will be avaialbe before the push:

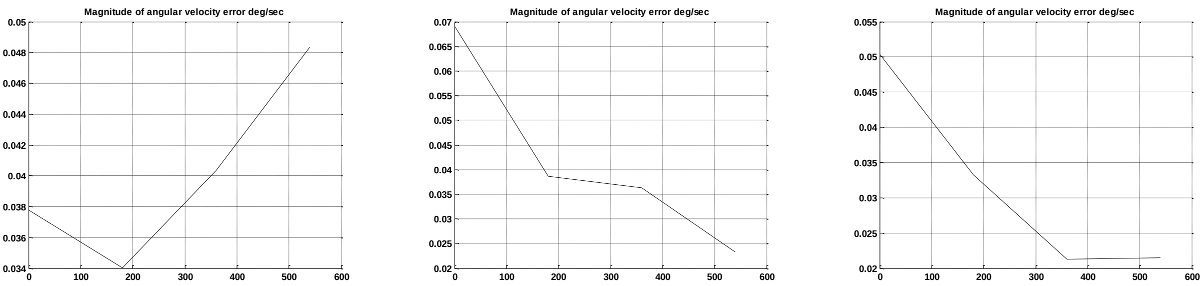

Figure 9-11: Angular velocity error with for images (orbits 11-13)

As can be seen in the images above, there is a general loss of sensitivity, being it reduced to about 0.07 deg/s, which in principle could still be OK. The main issue is that with only 4 images before and after the push, it should be checked that the relative attitude will be OK also from the point of view of image processing, i.e. it would be desirable to maximise the quality of these four images so an accurate solution can be obtained from the IP.

10. PRELIMINARY OPERATIONS PLAN FOR COBRA EXPERIMENT

10.1. EXPERIMENT DEFINITION

10.1.1. REFERENCE TRAJECTORY

The reference trajectory of the COBRA IRIDES experiment is based on the trajectory of the IRIDES experiment with a characteristic dimension of 10m and a drift rate of 5 meters per orbit.

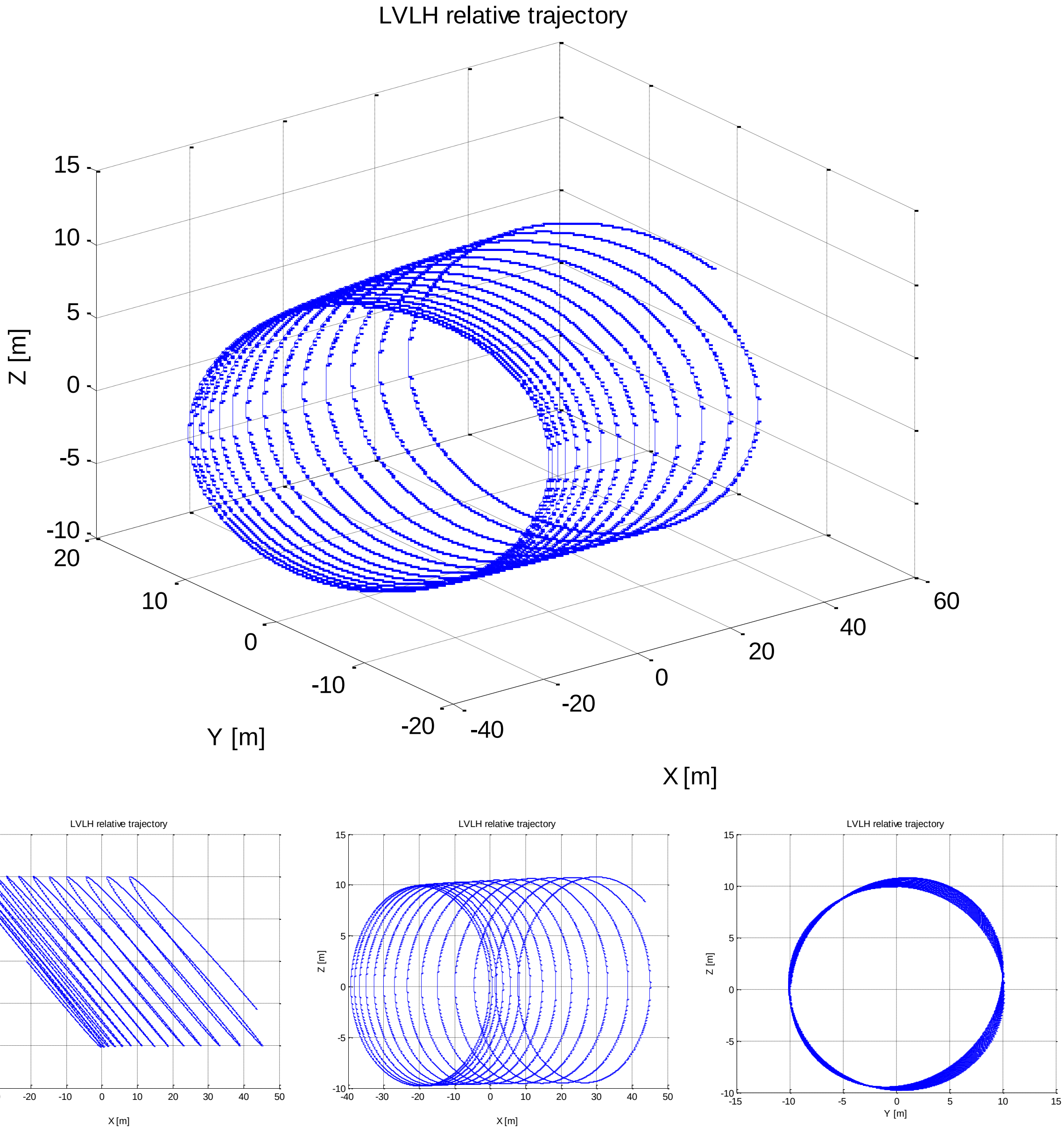

Figure 10-1: Reference trajectory

Analysis has been carried out including SRP and drag perturbations over the reference orbit. data provided by CNES and OHB has been used. As can be seen in the figure above, there is a clear effect of these two perturbations in the reference orbit when compared to the reference trajectory used during the first part of the study. The main effect is I the drift rate. As can be seen in the bottom left figure, the drift rate decreases with time, getting to almost cero after 14 orbits. This implies that the computation and execution of the orbit insertion manoeuvre shall have these effects into account, so that the drift rate is more or less 5m per orbit at the beginning of the day and still positive at the moment of the execution of the experiment.

When looking at the experiment timeline, figure below, no real impact is expected, as the range to the target varies insignificantly with respect to the original trajectory and the number of opportunities is still maintained.

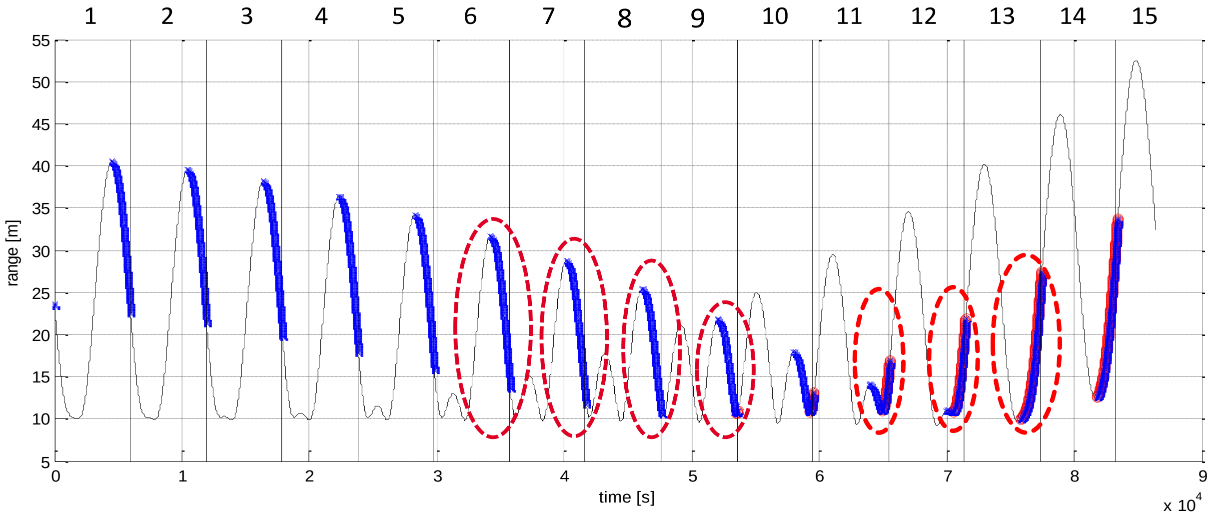

Figure 10-2: Range evolution over the reference trajectory (blue 'x' denote optimal observation conditions and red circles optimal experiment preparation and execution points)

The safety analysis has also been revisited in view of these perturbations. The conclusion has been that in the scenario of simultaneous compensation (baseline proposed) no significant impact has been found, i.e. it is considered a safe approach.

10.1.2. EXPERIMENT TIMELINE

The experiment is to be divided into two phases; experiment preparation and experiment execution.

The experiment preparation will consist on a series of orbits during which the pose of Picard will be observed with the camera so that is behaviour can be predicted to select the most suitable point in subsequent orbits to execute the experiment. During this preparation phase an observation period of a quarter of an orbit will be used (best illumination conditions and no Earth n the background). The images are to be downloaded to ground for processing.

Once a significant number of images have been acquired and downloaded (33 images per orbit during at least 4 orbits), the pose is propagated and the point of experiment execution is selected. The proper telecommands are to be prepared and uploaded at the next communications window.

It is expected to have up to 9 consecutive communication windows per day. Therefore the experiment preparation and execution should be limited to 9 orbits as follows:

- 4-5 orbits for preparation
- 1 blank orbit
- 1-3 orbits for experiment execution (nominal plus back ups)

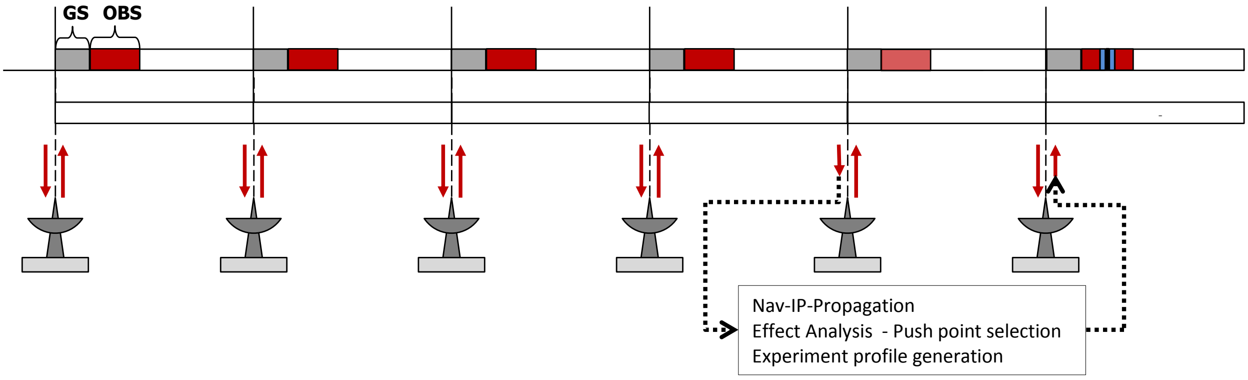

Figure 10-3: Experiment timeline

An open point at this stage is the synchronisation of the communication window with the observation period. In order to maximise the amount of images downloaded to ground in a single orbit, it would be desirable that the observation period starts right after the communication window closes, so that almost one orbit is available to extract the images from the camera for download at the next communication window.

Small tune up manoeuvres (cm/s) could be performed to ensure this synchronisation. The manoeuvre will consist in a two point transfer at true anomalies separated by 270deg.

On the other hand, some tests have been run with the estimator propagator using only 3.5 batches of images, i.e assuming that all images in orbits 1, 2 and 3 will be available but only half of the images gathered during orbit 4. Initial testing indicated that there is a very small impact on the performances of the filter when these images are mission. More detailed analysis should be performed to se a threshold for the amount of images that are required in the last orbit (synchronisation with ground) before deciding the implementation of a synchronisation manoeuvre.

10.2. OPERATIONAL PLAN

The total ΔV for the push operation is in the order of 6cm/s (including pushing burn of 20 sec plus the corresponding compensating burn, with no margins) plus some 10cm/s for tune up of the trajectory. ΔV fro orbit insertion has not been considered.

It is assumed that the push burn and the compensating burn will be executed simultaneously.

At this point it is assumed that the experiment will be executed one time. If more propellant is available, it would be desirable to execute it more than once.

10.2.1. TIMELINE

The following table below summarises the characteristics of the proposed experiment and manoeuvres to be executed, including the envisaged sensors and actuators to be used, and the ideal ΔV budget and time schedule.

The experiment execution is expected to last for one day, 14 orbits.

Orbit	Step Description	Start Condition	End Condition	Experiment Sensors	Actuators	Estimated delta-V	Estimated Time
Experiment preparation							
1	Approach towards Picard, VBS images acquisition for future download. No comms with ground	COBRA–IRIDES reference orbit acquired centered at X+30m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s

Orbit	Step Description	Start Condition	End Condition	Experiment Sensors	Actuators	Estimated delta-V	Estimated Time
2	Approach towards Picard, VBS images acquisition for future download. No comms with ground	COBRA–IRIDES reference orbit centered at X+25m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
3	Approach towards Picard, VBS images acquisition for future download. No comms with ground	COBRA–IRIDES reference orbit centered at X+20m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
4	Data download Processing of available data Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X+15m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
5	Data download Processing of available data Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X+10m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
6	Data download Processing of available data Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X+5m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
7	Data download Processing of available data Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X+0m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
8	Data download Processing of available data Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X-5m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s

Orbit	Step Description	Start Condition	End Condition	Experiment Sensors	Actuators	Estimated delta-V	Estimated Time
9	Data download Processing of available data Computation of experiment execution time an preparation of TC Approach towards Picard, VBS images acquisition for download at next comms window	COBRA–IRIDES reference orbit centered at X-10m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera	As per nominal PRISMA GNC system	0 m/s	5948s
Experiment execution							
10	Upload of experiment TC Data download Processing of available data Experiment execution VBS (and DVS TBC) images acquisition pre and post push for download at next comms windows	COBRA-IRIDES perturbed orbit centered at X-15m aprox	1 orbit after, slightly perturbed COBRA–IRIDES reference orbit	Mango nominal GNC system VBS camera DVS camera TBC	As per nominal PRISMA GNC system Propulsion system	0.0547 m/s	5948s
11	Back up orbit for execution Upload of experiment TC Data download Processing of available data Experiment execution VBS (and DVS TBC) images acquisition pre and post push for download at next comms windows	COBRA-IRIDES perturbed orbit centered at X-20m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera DVS camera TBC	As per nominal PRISMA GNC system Propulsion system if not used in prev orbit	0.0547 m/s if not executed in previous orbit	5948s
12	Back up orbit for execution Upload of experiment TC Data download Processing of available data Experiment execution VBS (and DVS TBC) images acquisition pre and post push for download at next comms windows	COBRA-IRIDES perturbed orbit centered at X-25m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera DVS camera TBC	As per nominal PRISMA GNC system Propulsion system if not used in prev orbit	0.0547 m/s if not executed in previous orbit	5948s
Experiment post processing							

Orbit	Step Description	Start Condition	End Condition	Experiment Sensors	Actuators	Estimated delta-V	Estimated Time
13	Processing of available data Free drift wrt Picard, VBS images acquisition for download at next comms window TBC	COBRA-IRIDES reference orbit centered at X-30m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera TBC	As per nominal PRISMA GNC system	0 m/s	5948s
14	Processing of available data Free drift wrt Picard, VBS images acquisition for download at next comms window TBC	COBRA-IRIDES reference orbit centered at X-35m aprox	1 orbit after, same condition	Mango nominal GNC system VBS camera TBC	As per nominal PRISMA GNC system	0 m/s	5948s
					Total	**0.0547 m/s**	**8.3285s** **14 orbits** **23.13hr**

Table 10-1: Experiment timeline

For the experiment preparation it is envisaged to have two experiment operators during the orbits with ground coverage and three during the orbit for experiment execution.

The following table provides a first allocation on the times required for the different operations to be executed between communication passes (around 1.5 hours once the communication window itself has been taken into account).

Activity	**Allocated time**
Experiment preparation	
Data acquisition	Real time
Image processing initialisation (processing of 1 to 3 images by hand)	5 min
Image processing (automatic with expert supervision)	5 min+10 min margin
Estimation – propagation (automatic)	15 min
Total	35 min
Experiment execution	
Data acquisition	Real time
Image processing initialisation (processing of 1 to 3 images by hand)	5 min
Image processing (automatic with expert supervision)	5 min+10 min margin
Estimation – propagation (automatic)	15 min
Experiment effect prediction (automatic)	15 min
Experiment execution time selection (supervised)	10 min
Telecommand input preparation (supervised)	5 min
Total	65 min
Post processing	
	No requirements

Table 10-2: Operations time allocation

In terms of telemetry, the images gathered by the VBS and the DVs should be downloaded together with the telemetry of the spacecraft, mainly navigation and attitude solutions. Initial estimation of the data volume has been performed and indicates that is in line with system capabilities.

11. CONCLUSIONS

The COBRA IRIDES experiment has been defined during this phase of the project, together with the definition and implementation of the required systems to run the experiment. This phase should be followed by a consolidation phase in which the remaining open points are closed and an implementation phase in which the different systems are integrated with OHB elements.

The main open point at this stage is the image acquisition rate of the VBS. In the present study it was assumed that the camera has the capability of acquiring images at a rate of up to one image every 3 seconds and store them locally for later transmission to the DHS of the spacecraft at the know rate of one image every 180s. This led to the definition of an acquisition rate of one image every 45s during the preparation phase and one image every 3s during the execution phase. After the final presentation it has been verified that this assumption is not correct, every image has to be transferred to the DHS before the next one can be acquired. This would reduce the acquisition rate to one every 180s.

A solution to overcome this issue is to reduce the compression quality factor. So far a factor of 95% has been used, which is quite high for the purposes of the experiment. Image processing can be performed with images with a quality factor of 75% (and even lower), which will divide the size of each image by a factor of four, making it possible to recover the initial acquisition rate of an image every 45s for the experiment preparation phase. For the experiment execution phase the reduction in the number of images leads to a reduction in the sensitivity of the system. If the original acquisition rate of 180s is used, the sensitivity is reduced from 0.057deg/s to 0.07deg/s, which in principle is tolerable. But this sensitivity is directly related to the relative attitude (IP accuracy). If a bad configuration is encountered during this phase it may be possible that the sensitivity is even worse, hence it will be desirable to have a higher sampling time. This can be achieved by using the VBS at 45s or by using the DVS (TBC).

END OF DOCUMENT