# VISION BASED RENDEZVOUS EXPERIMENT PERFORMED DURING THE PRISMA EXTENDED MISSION

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***Abstract***: *A demonstration of autonomous rendezvous based on angles only navigation was performed by CNES in October 2011 during the PRISMA extended mission phase. Within a short timeframe, a new on-board software was implemented in the chaser satellite to process measurements from a long range camera and achieve optical navigation in a non cooperative context. An extensive phase of algorithm tuning and scenario validation followed to optimize the fuel usage and ensure a satisfactory system robustness. This effort was rewarded by the successful of four rendezvous rehearsals from ranges up to 10 km and destinations down to 50 m. The paper describes the system architecture, the guidance and navigation functionalities along with the experiment design. Flight results obtained during this extended phase are presented along with an analysis of the experiment and performance shortcomings. The demonstration confirms anyway the potential of optical navigation for future rendezvous missions with non cooperative objects.*

**Keywords**: vision based navigation, autonomous rendezvous, flight experiment

## 1. Introduction

Vision based navigation constitutes an attractive technique when rendezvous with potentially non cooperative objects is to be achieved. Such a problem was identified during the Mars Sample Return studies when mission design came up with the need to capture an orbiting sample in Mars orbit. The capability to detect, track and approach a completely passive object would relax design constraints and increase the chances of mission success. This technique was therefore the object of considerable interest and work at the turn of the century. Today, new missions devoted to either the lifetime prolongation of orbital assets or the removal from orbit of large and potentially hazardous debris are being conceived by several space organisations [1]. For most of these applications, the cooperativeness of the object to be approached is not guaranteed if not definitely impossible. Using optical navigation constitutes therefore a valid approach that increases the spacecraft rendezvous capabilities with full or partial autonomy. This technique has also a great potential since it does not rely on complex and sophisticated instrumentation. The use of light passive and possibly low cost optical cameras in the visible or infrared domain simplifies the equipment accommodation task and represents an attractive solution for missions with stringent budget and reliability requirements.

The main challenge of vision based navigation comes down to the ability to estimate the full relative state relying on direction angles only. This problem has been addressed by numerous studies in the past. More recently, some literature has shown some progress in different areas such as the characterization of the conditions that provide range observability [2], the representation of the relative dynamic motion throughout more intuitive differential orbital parameters [3] and the development of methods to capture the relative trajectory characteristics when the size remains unknown [4]. Vision based navigation is becoming a very promising technique but very few flight experiments have been performed so far to demonstrate its potential. This trend has recently changed with the flight opportunities offered by the PRISMA mission [5] and several experiments have been performed by the different mission partners.

The work presented in this paper concerns the demonstration of autonomous rendezvous with a non cooperative object that was performed in the October – November 2011 timeframe during the PRISMA extended mission. The experiment benefited from the presence of two satellites that played the roles of chaser for the active one and target for its passive companion. The chaser carries several cameras from the Danish Technical University (DTU) and particularly a Vision Based Sensor (VBS) that allows to implement far range optical navigation [6][7]. This sensor has been previously used by OHB-Sweden in 2011 to conduct a MSR like experiment with object detection, orbital parameters determination and rendezvous from a 30 km distance [8]. The work performed by CNES benefited from the available VBS utilization experience and the effort was devoted to the autonomous rendezvous issues. The first challenge consisted in the development of an algorithm package including guidance and navigation capabilities that had to be integrated in the PRISMA on-board software. The major difficulty came from the very tight schedule that severely constrained the whole development / validation activity since three months elapsed between the project start and the software delivery. The good knowledge of the complete PRISMA system acquired during the primary mission facilitated the development task that consisted in an upgrade of the already delivered software [9]. In addition, the use of a model based design approach and code generation technique was of tremendous help. The angles only navigation function that is implemented does not feature any novelty: it relies on a representation of the relative motion in Cartesian coordinates based on the Yamanaka Ankersen state transition matrix [10]. An extended Kalman filter processes the VBS measurements to reduce progressively the relative state uncertainty that is initialized in accordance with the standard TLE accuracy. Since filter performance strongly depends on the manoeuvre profile, a particular attention is drawn to the design of the guidance strategy. This introduces another challenge of this work that comes from the limited delta-V budget allocated for the whole experiment. The goal is to maximize the number of rendezvous rehearsals compatible with a total budget of 3 m/s while maintaining a sufficient interest from the GNC point of view. The proposed program includes finally four rendezvous rehearsals with initial ranges up to 10 km and getting as close as 50 m from the target. The adopted solution consists in a guidance strategy relying essentially on manoeuvres in the orbital plane. A large amount of work concerned the trajectory design along with the tuning of the navigation filter that represents a difficult exercise. In order to privilege robustness, a conservative approach was taken in the selection of the navigation settings and this was rewarded by success in all rendezvous trials. The work is pursued after flight operations by a thorough analysis of the potential discrepancies between simulation and flight results along with a characterization of the VBS performance using Precise Orbit Determination (POD) data based on GPS. In addition, the capability to "replay" the experiment on the ground using flight telemetry is intensively used to evaluate different navigation tunings and compare performance with alternate algorithms.

The paper presents in the next section the main characteristics of the PRISMA system while the add-on GNC functionalities are described in the third section. The design of the experiment plan with a special focus on the preparatory steps are described in the fourth section. The presentation of the flight results with a discussion on the navigation performance and some analysis of the

VBS camera behaviour is given in the fifth section. Finally, the conclusion summarizes the different experiment achievements and opens perspectives for future work.

## 2. Overview of the PRISMA system

PRISMA is a demonstration mission for formation-flying and on-orbit-servicing critical technologies that involves two spacecraft launched in low Earth orbit in June 2010 and still in operation. Funded by the Swedish National Space Board, PRISMA mission has been developed by OHB Sweden with important contributions from the German Aerospace Center (DLR/GSOC), the French Space Agency (CNES), and the Technical University of Denmark (DTU).

The PRISMA space segment consists of a small satellite Mango (150 kg), and a microsatellite Tango (40 kg). Mango has full 3-dimensional attitude independent orbit control capability and is 3-axis attitude stabilized using star trackers and reaction wheels. Tango does not have any attitude control capability and is equipped with a solar magnetic attitude control system still providing 3-axis stabilization. The nominal propulsion system on Mango is based on six 1-N hydrazine thrusters directed through the spacecraft center of mass and the overall delta-V capability is approximately 120 m/s. Several novel metrology technologies are accommodated to conduct various rendezvous and formation flying experiments. A semi autonomous Formation Flying Radio Frequency (FFRF) metrology system [11] is distributed on the satellites and is used during dedicated CNES experiments. Both satellites are also equipped with Phoenix GPS receivers from DLR and Mango hosts a GPS relative navigation that constitutes the backbone of the formation safety system. GPS data is further processed on the ground by DLR to deliver Precise Orbit Determination (POD) files that are essential in the offline characterization of sensor and system performance. Mango embarks also two Vision Based Sensors (VBS) from DTU that are further described later in the section. This work is actually based one of these instruments to implement optical navigation. Finally, Mango is equipped with accelerometers that give quite accurate measurements during the application of thrusts and this constitute a valuable feature to achieve angles only navigation.

The PRISMA satellites are operated from Sweden using a ground antenna located in Kiruna and a Mission Control Centre (MCC) in Solna. The orbit configuration and the single antenna result in late afternoon and night-time passages with up to 10 passages per day. Experiments run by partners typically require the PIs presence in the MCC even for autonomous activities and critical operations such as the terminal optical rendezvous were scheduled within the visibility period.

The camera used for the experiment belongs to a set of four Camera Head Units (CHU) embarked on Mango and based on the microASC star sensor design. Two cameras are actually used as standard star trackers to offer the minimum level of redundancy required in rendezvous operations. The two remaining CHUs correspond to the VBS instruments that have been specifically tailored to achieve different and complementary navigation purposes. The Close Range VBS designed to work in cooperative mode is capable to estimate the relative attitude and position of Tango satellite through the extraction of Light Emitting Diodes patterns – to achieve this goal, it carries an optical filter as well as iris and electronic shutters. The Far Range VBS also equipped with an electronic shutter is capable to detect and track a moving target from several tens of kilometres to a few decametres. It constitutes therefore the adequate instrument to perform vision based rendezvous with a non cooperative object.

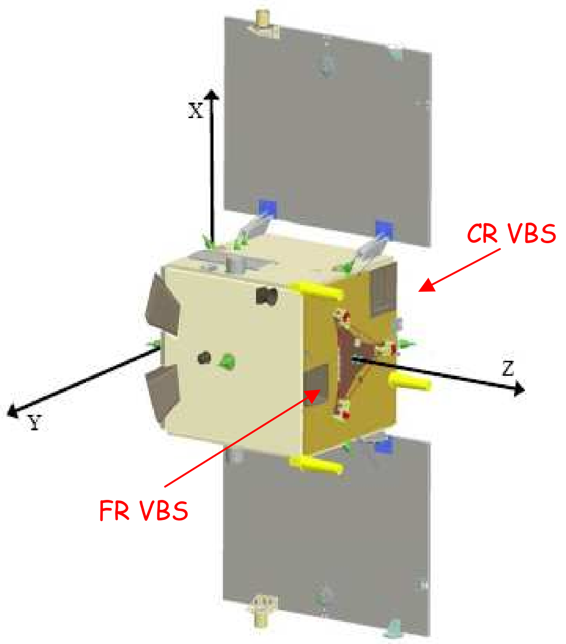


**Figure 1.1: Mango satellite:** Cameras and FFRF antennas (yellow cylinders) are located on the Z face of the spacecraft.

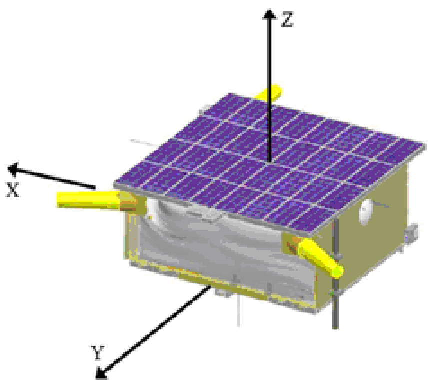


**Figure 1.2: Tango satellite:** it is covered with patterns of LEDs on all faces but the solar panel for close proximity navigation (CRVBS)

The Far Range camera behavior relies upon a dedicated software in the Data Processing Unit that runs in different modes depending on the lighting conditions. At long range, the software has the capability to detect the luminous objects that do not belong to the star catalogue. These objects can be robustly spotted as potential orbital targets after a few acquisition cycles given their apparent motion and the brightest is usually selected as the most likely candidate. In this far range mode, stars are also visible in the field of view and the camera will be capable to deliver an attitude quaternion which helps to get rid of the camera alignment biases. When range gets smaller, the target becomes brighter and the activation of the electronic shutter is necessary to avoid blooming effects. In this mode (Intermediate range), the capability to estimate inertial attitude starts being impacted and the conversion of the line of sight in the inertial frame relies on star tracker measurements. At short range, the target becomes a large object in the field of view and the camera processor uses some image processing algorithm to extract characteristic satellite feature and estimate the direction of its center of mass. Given the stringent lighting conditions, the robustness of this process is potentially weak and direction biases are likely to be observed. Finally, the Far range camera is working in a stand alone mode and this constitutes a limitation since it cannot benefit from the navigation function knowledge.

**Table 1: FRVBS main parameters**

| Item | Value | Unit |
|---|---|---|
| Half field of view | [9.15 6.85] | deg |
| Camera resolution | [752 580] | pixel |
| Pixel size | $[8.6\ \ 8.3].10^{-6}$ | m |
| Focal length | $20187.10^{-6}$ | m |

Given the camera characteristics indicated in Table 1, the camera angular resolution is 80 arcsecs which corresponds to about 4 meters in lateral position at 10 km range. Conversely, this position resolution gets down to 4 cm for a distance of 100 m but the object image is 25 pixels wide assuming no blooming effect.

## 3 – Description of the dedicated rendezvous system

### 3.1 - System Architecture

The new rendezvous system benefited from the existing on-board software that was developed for the PRISMA primary mission and devoted to the FFRF sensor utilization [9]. This software, built with a model based approach and code generation tools (Matlab/Simulink$^{TM}$ environment), allows to take over the whole satellite control during dedicated rendezvous or formation flying experiments. The provided GNC modules include a RF navigation function, several guidance algorithms to cover the different tasks from rendezvous to proximity operations, a dedicated control function to achieve accurate forced positioning. The function activation / transition is managed by a mode handler that monitors the system behaviour and performs FDIR action for a limited set of functional anomalies (the processing of the critical ones is handed over to the higher FDIR level that can also interrupt the current task if necessary). The provided GNC software focuses on relative positioning and relies on the platform attitude estimation / guidance and thruster command services.

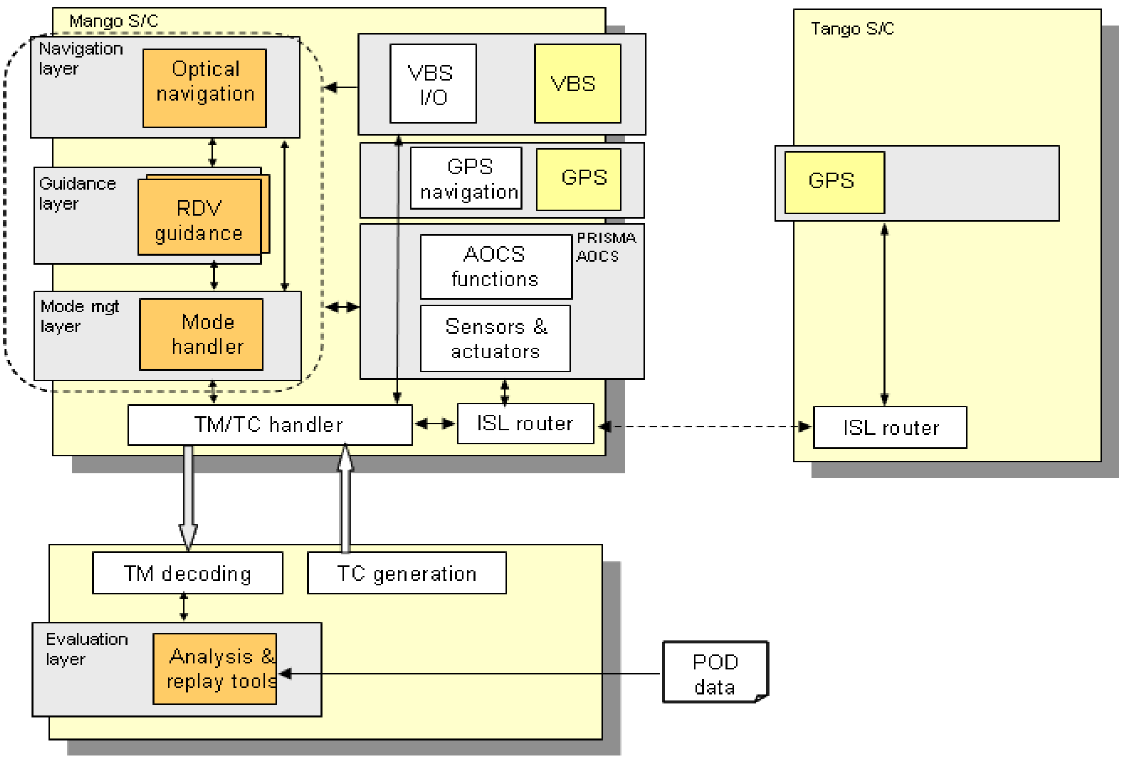


**Figure 2: Rendezvous architecture**

The design approach for the additional experiment consisted in upgrading this software while maximizing the re-use of existing functionalities. First, interfaces had to be updated to benefit from the cameras inputs. For the vision based RDV experiment, a new navigation functionality based on angles only was added to the software. Conversely, rendezvous guidance relied on some already available manoeuvre computation algorithm that was modified to cope with the relative position uncertainty magnitude [12]. As for the mode handler, it remained untouched but with a different parameterization. The experiment was implemented under high pressure since the project started in May 2011. The use of Matlab/Simulink™ tools allowed to deliver the software to OHB-Sweden in August 2011 for validation purposes and it was finally uploaded on October 10th for the beginning of the operations. The system is completed by a series of ground tools for flight telemetry offline analysis that relies on the POD files for performance evaluation. A "replay" tool based on the same navigation function allows to check the on-board behaviour and diagnose potential discrepancies. Further investigation can be performed by using alternate tunings and navigation algorithms.

*Limitation*: The design of the rendezvous experiment is based on a major assumption concerning the knowledge of the target orbital position. In the general problem of rendezvous with a non cooperative target that is affected by a large uncertainty on some orbital parameters (ex: an orbiting sample on a Mars orbit), the first estimation step consists in narrowing the uncertainty by collecting observations of the target line of sight while using the chaser orbit as reference. This initial estimation process can be performed on the ground for the most part to take advantage of complex and accurate dynamic models. Here, this experiment focuses on the terminal phase when the autonomous relative navigation gets possible and benefits from reasonably good initial guesses of the target position and chaser relative state. Such a situation is actually representative of a rendezvous in LEO with a debris which estimated orbital position is available as TLE bulletins.

### 3.2 Optical navigation

The rendezvous experiment relies actually on two different algorithms located respectively in the flight software and in the ground toolbox.

The algorithm used in flight was developed throughout some R&D activities with an industrial partner (Thales Alenia Space) that were on-going when the decision to perform the experiment was taken. For computing efficiency, it is based on a full decoupling of position and attitude estimation. Attitude estimated states are provided by the PRISMA services whereas optical algorithm focuses on the estimation of the satellites position. This algorithm relies on a dynamic model of the relative motion that is expressed in Cartesian coordinates. The model is based on the Yamanaka Ankersen state transition matrix to take into account orbit eccentricity. The filter state carries a 6 state vector that contains the chaser relative position and velocity expressed in the predicted target Local Orbital Frame

Given the camera capability to measure the inertial attitude along with the target line of sight, the introduction of two measurement biases in the filter state vector has been a low priority and was finally not considered. The navigation function is an extended Kalman Filter that processes the two angular measurements provided by the camera. Here, the observation equation involves the conversion of the estimated relative position into the camera frame and this requires an adequate knowledge of the Local Orbital Frame attitude. This attitude is therefore provided by an on-board propagator implemented by an add-on function which is initialized with some “a priori” absolute state. Since this propagator is not integrated in the filter, it does not benefit from any state update and the attitude is therefore subject to some drift.

The state noise covariance (Q) is configured and permanently updated to take into account several uncompensated perturbations: (1) non linear phenomena due to the simplified dynamic model and particularly the Earth oblateness J2 effect that is proportional to range according to Table 2, (2) orbit curvature which effect is also range dependent, (3) knowledge error on the target orbital parameters that produce inaccuracies in the transfer matrix computation and a varying bias in the Local Orbital frame attitude, (4) manoeuvre execution error that is considered dependent on the manoeuvre magnitude according to Table 3.

**Table 2: J2 contribution error for a 10 km range**

| axis | ax | ay | az |
|---|---|---|---|
| uncertainty m.s-2 | $4.4\ 10^{-4}$ | $4.1\ 10^{-5}$ | $5.8\ 10^{-4}$ |

**Table 3: manoeuvre execution error model**

| dV magnitude | a < 2 mm/s | 2 mm/s< a <2cm/s | a > 2 cm/s |
|---|---|---|---|
| Relative uncertainty | 20% | 6% | 2% |

Another multiplicative coefficient which value is range dependent according to a tabulated law has been introduced to amplify the overall state noise uncertainty and capture non linear effects which impact is not strictly proportional to range.

The measurement noise covariance (R) is supposed to convey the uncertainty affecting the camera azimuth / elevation measurements and the typical order of magnitude is the pixel size (400 µrad). However, the tuning of this matrix needs to be updated to include error contributing terms that are not correctly represented in the predicted measurement uncertainty. Kalman filter theory assumes that the function used to predict the measurement and its Jacobian are perfectly known but this assumption is not rigorous since the H errors is strongly dependent from the relative distance. A corrective coefficient ($R_{coef}$) that is range dependent is therefore introduced to increase the uncertainty. Attitude uncertainty represents an additional term that will affect the accuracy of the predicted measurement and it must be added as well before applying the corrective factor. In addition, the initial values of the R and Q matrices are tuned such that the range uncertainty remains constant before the application of manoeuvres.

The second algorithm represents an adaptation of the already existing navigation function that processes the radio-frequency sensor measurements [13]. This filter focuses on the relative dynamic motion and carries a 8-state vector that contains the same set as the previous filter and two additional states for direction biases. The relative state is propagated differently with respect to the previous one: it is obtained by difference of the satellite absolute states that are integrated independently with a dynamic model including the J2 gravity term and perturbations such as atmospheric drag. Conversely, the state covariance propagation still relies on a simpler dynamic model based on the Yamanaka Ankersen formulation. When the relative state is updated, the chaser absolute state is recomputed using the target absolute state as reference. In addition, the function that produces the predicted measurement performs first a curvilinear correction of the relative position to account for the orbit curvature. In this algorithm, the target absolute state is integrated in open loop which causes some possible error in the attitude of the Local Orbital Frame. The dominant error comes from the estimation of the target true anomaly which produces a direction offset in the orbital plane. The first bias state is used to cancel this offset whereas the second bias state takes care of potential azimuth error (Figure X). The filter tuning principle is similar to the previous one with some exceptions: the magnitude of the state noise covariance can be reduced due to a more accurate modelling of the relative dynamics. This algorithm has been implemented in the last phase of the project and could not be included in the final software for lack of validation. However, it is available in the ground processing toolbox to perform comparisons of navigation algorithm behaviour using telemetry data.

### 3.3 Rendezvous guidance

On-board guidance relies on a semi-autonomous approach which has proven its efficiency during the previous FFRF based rendezvous experiments [14]. The trajectory is not elaborated by the on-board system but predefined on the ground as a list of waypoints which spacing is properly chosen considering the expected range uncertainty profile. In addition, the chaser is told when to apply the different manoeuvres that will be computed on board using the navigation solution. The chaser will aim at the waypoints without trying to achieve precisely the full state (position, velocity) at the corresponding date. The waypoints are actually used as attractors to bend progressively the real trajectory to the desired one. At least one manoeuvre is usually computed to reach the waypoint $X_k$ at the specified date $t_k$ but in some cases the application of mid coarse correction manoeuvres may be requested to improve accuracy. The manoeuvre computation is based on the Yamanaka-Ankersen state transition matrix. When date $t_k$ has expired, guidance ignores the current waypoint and starts aiming at the next one. This “fixed” approach remains satisfactory as long as the navigation uncertainty is not subject to unexpected large variations such that the relative distance could suddenly appear much closer and force the chaser to go backwards to reach the next waypoint. Efficiency can be actually achieved by allowing the guidance algorithm to skip a waypoint in case of some large variation of the estimated range.

## 4. Experiment description

### 4.1. Experiment plan

The goal is to maximize the number of rendezvous trials compatible with a total budget of 3 m/s while maintaining a sufficient interest from the GNC point of view. The vision based rendezvous experiment includes four different trials which characteristics are summarized on Table 1. The first trial is dedicated to the commissioning of the navigation function and is performed in open loop to avoid any negative interaction with guidance. Here, the desired rendezvous profile starting from a 4 km range is followed with an OHB-Sweden guidance functionality that relies on GPS on-board navigation. Assuming a successful first trial, the subsequent tests are designed with the navigation function coupled to the CNES guidance algorithm. The first closed loop test is initiated also at 4 km range to allow some performance comparison with the open loop commissioning test whereas the next ones start from 10 km. Two destination ranges are selected: 100 m for tests #1,#2,#3 and 50 m range for the last test (#4) since navigation at close range is considered more risky. Experiment durations are driven by delta-V considerations which lead to stretch the rendezvous duration. they go from 16 to 20 hours with a maximum 1 m/s allocation for the longest one.

**Table 4: Rendezvous characteristics**

| Id | Date | Initial range (m) | Final range (m) | Navigation type | Duration (hrs) | Number of waypoints |
|---|---|---|---|---|---|---|
| 1 | 2011/10/13 | 4000 | 100 | O/L | 16.2 | 7 |
| 2 | 2011/10/21 | 4000 | 100 | C/L | 16.2 | 7 |
| 3 | 2011/10/27 | 10000 | 100 | C/L | 18.5 | 9 |
| 4 | 2011/11/03 | 10000 | 50 | C/L | 19.5 | 9 |

During all rendezvous, the attitude guidance mode is "Target pointing" which aligns a particular body axis (parallel to the camera bore sight) with the estimated target direction. To simplify the on-board software interfaces, the target direction is actually coming from GPS navigation instead of the CNES vision based navigation function. Given the expected performance of the navigation, this adaptation does not constitute a simplification of the problem and this will be confirmed by flight results.
In all tests, the initial uncertainty was 10% for range, 100 m for radial / cross track components and up to 5 cm/s for velocity coordinates. For consistency, Mango initial relative state was chosen on the envelope of the uncertainty domain centred on the a priori relative location.

## 4.2 Trajectory design

The design of the rendezvous profile is driven by two contradictory requirements: (1) ensuring a sufficient range observability, (2) minimizing the fuel usage. This issue was first analyzed using the Woffinden [2] criterion that allows to evaluate the efficiency of manoeuvres from the range observability viewpoint. Range becomes observable when a manoeuvre causes some angular deviation with respect to the natural motion. The larger the angular deviation θ, better is the reduction of uncertainty δρ and the limiting factor is the angular resolution ε of the camera. This observability index is given by Equation 1, assuming a perfect knowledge of the manoeuvre and no uncertainty on the others states.

$$\frac{\delta\rho}{\rho} = \frac{\varepsilon}{\sin\theta} \qquad (1)$$

With such a criterion, cross-track and radial manoeuvres appear equivalent whereas the along-track manoeuvre provides a better range observability in the long run. When considering a generalization of the Woffinden criterion that takes into account both manoeuvre error and initial relative state uncertainty, the balance is definitely in favour of the croos track manoeuvre since it is much less affected by the along track rate uncertainty.

In addition, manoeuvres in the cross track direction provide some angular deviation without changing the relative motion in the orbital plane and this constitutes a valid advantage from the safety point of view. However, this approach implies to apply pairs of manoeuvres in opposite directions to cancel the cross-track motion and this is definitely not cost effective. Fuel efficiency being the priority, it has been decided to design a rendezvous trajectory that does not rely on cross-track manoeuvres for range observability. Some cross-track motion is however imposed from the start with some variations at the end but this scheme introduces only small corrective thrusts. The profile for rendezvous #3 (10 km initial range) includes 9 waypoints and is illustrated on Figures 3.1 and 3.2 for a typical simulation run.

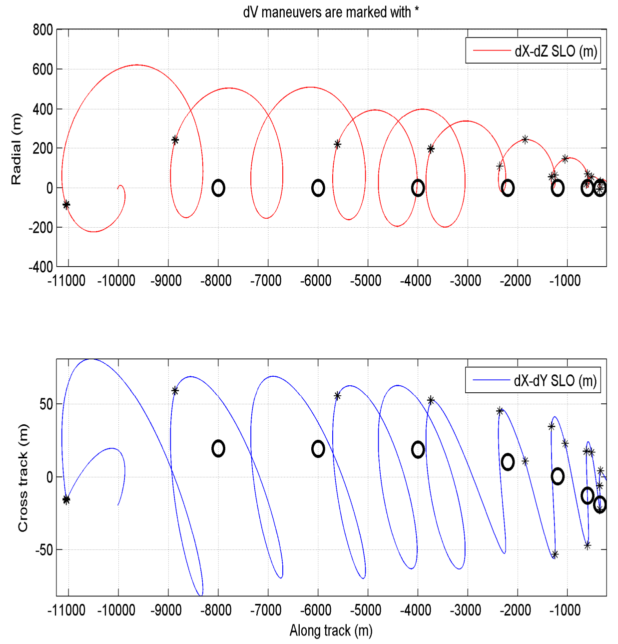


**Figure 3.1**: **Illustration of trajectory profile**. Top view represents the along track / radial plane while bottom view is the along track / cross track plane – manoeuvres are represented by stars and waypoints by circles

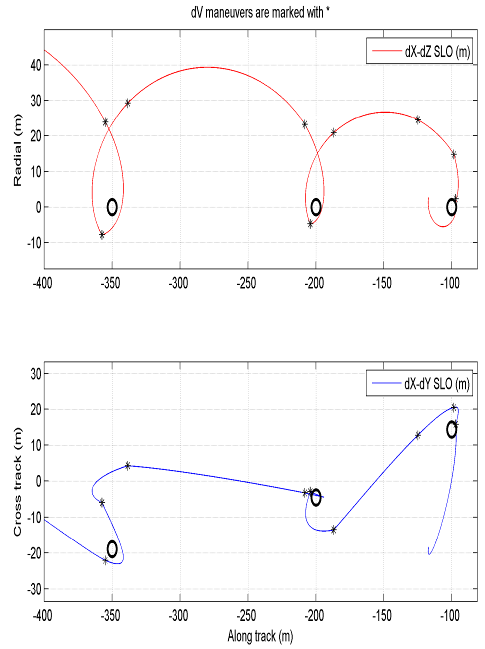


**Figure 3.2**: **Zoom on the profile final part**. The final waypoint is defined to put the chaser on a stable relative orbit on with 20 m amplitude on cross track and radial axes.

## 4.3 Preparation

The scenarios have been validated and tuned through an extensive Monte Carlo campaign. In this analysis, the first objective was to guarantee the rendezvous success while ensuring the lowest possible fuel usage. The reduction of dispersions was therefore the key driver in this exercise and this led to the selection of conservative navigation settings. In particular, range observability was voluntarily neglected since the observed impact on the trajectory and budget dispersions was rather positive. Series of Monte Carlo simulations with the following varying parameters were considered:

- initial target true anomaly (0.3 deg)
- chaser relative state (δa: 40 m, aδe: 40 m, aδi: 40 m)
- camera imperfections (1 pixel noise (1σ) – no bias – 3% data loss)
- manoeuvre execution error 5% and accelerometer error 2%.

Variations of the chaser initial state (except the along track separation that was chosen fixed) served to tune the rendezvous starting point from the delta-V dispersion point of view and account for some realization error in the initialization phase. As far the navigation is concerned, the considered initial uncertainty was 12% and 10% for range (respectively 4 km and 10 km rendezvous), 100 m for radial and cross track components and 10 cm/s for position rates.

## 5. Flight Results

### 5.1. Result overview

All tests have been completed successfully with results summarized on Table 5. In all cases, target detection is achieved within a few seconds and the solution validity is confirmed by the filter. In far and intermediate range regimes, VBS functional behaviour is satisfactory and shows a good robustness in presence of bright celestial objects or other satellites crossing periodically the field of view. Optical navigation convergence is slower than expected but acceptable and does not interfere with the execution of the guidance profile. Another satisfaction is the respect of the deltaV budget that stays close to the expected value and confirms the relevance of the scenarios validation approach.

**Table 5: Summary of rendezvous results**

| Experiment | Duration (hours) | Range accuracy (%) | Expected Delta V (cm/s) | Real Delta V (cm/s) |
|---|---|---|---|---|
| RdV from 4 km to 100 m (OL) | 16.2 | 1.8% | N/A | N/A |
| RdV from 4 km to 100 m (CL) | 16.2 | 2% | 54 | 42.6 |
| RdV from 4 km to 100 m (CL) | 18.5 | 3% | 98.5 | 86.8 |
| RdV from 4 km to 50 m (CL) | 19.5 | 5.5% | 74 | 73.6 |

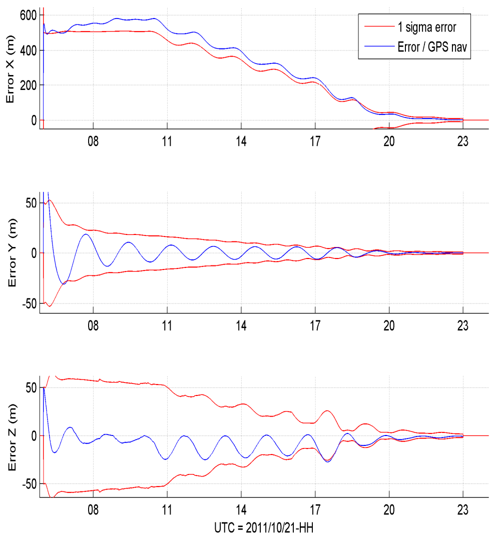


**Figure 4.1: Relative position profile during RDV #2 (range from 4 km to 100 m)**

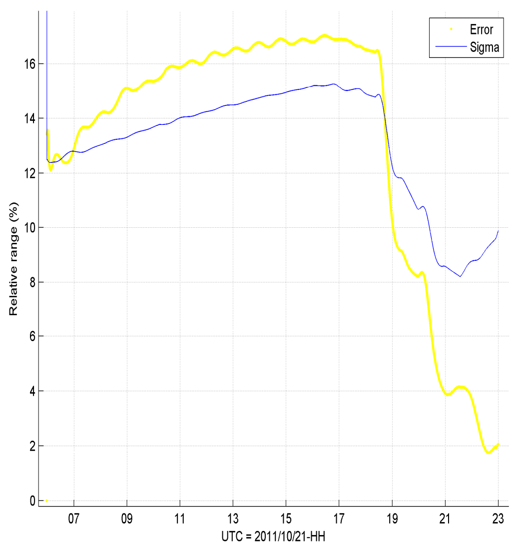


**Figure 4.2: Relative range uncertainty during RDV #2 (range from 4 km to 100 m)**

The typical relative range profile during rendezvous is shown on Figure 4.1 with a comparison of true and estimated data. The range uncertainty is slowly reduced when approaching the target and reach the metric level at a few tens of meters. We benefit from two complementary and favourable factors: (1) the absolute error is proportional to range and is reduced accordingly when Mango gets closer to the target, (2) the range observability improves at shorter distance when manoeuvres are applied. The contribution of the second factor becomes observable in flight above 2 km and this is consistent with the simulation results given the error assumptions and the specific filter tuning. However, the range uncertainty at destination is higher than the targeted 1% value (it is typically in the 2-3% range).

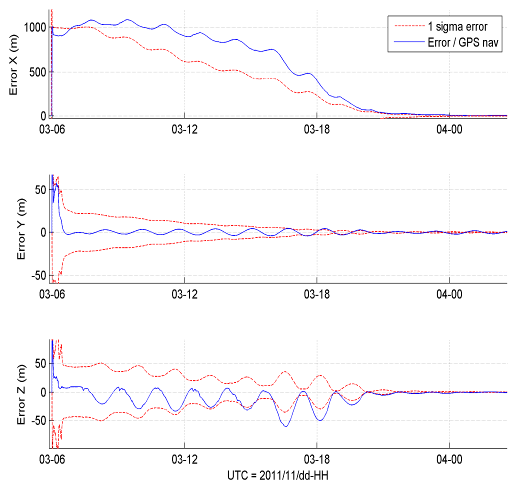


**Figure 5.1: Relative position profile during RDV #4 (range from 10 km to 50 m)**

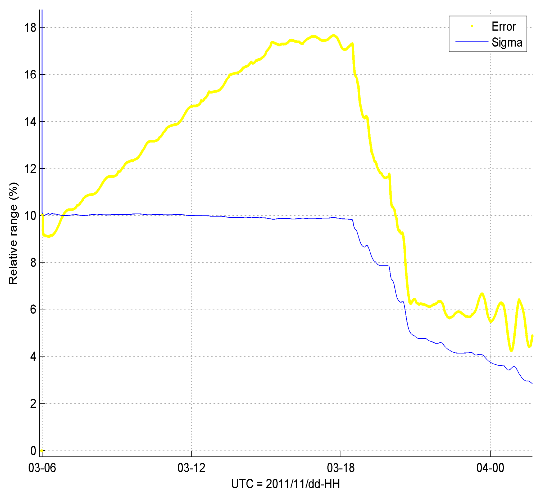


**Figure 5.2: Relative range uncertainty during RDV #4 (range from 10 km to 50 m)**

Even though the trajectory remains within the 3 sigma envelope (Figure 4.1 and 5.1), the range relative error is increasing during the first orbits from 10% to 18% whereas this phenomenon is not observable in the range covariance that remains steady before the filter starts benefiting from the manoeuvres. This shows clearly that the state covariance does not capture properly the magnitude of uncertainties and this could be due to larger accelerometer errors, VBS degraded performance or larger error on the attitude of the Local Orbital Frame. Accelerometer responsibility is quickly discarded since the on-board GPS navigation confirms an accuracy in the 1% range.

### 5.2 VBS behaviour

At long range, VBS instrument behaviour is examined by using the following criteria: (1) the measurements validity ratio (measurements rejected by the instrument itself), (2) the measurement difference with respect to an external reference (the "reference" measurement is reconstructed using relative position from POD and attitude estimation data), (3) the number of erroneous measurements (the measurement is flagged as valid but it is related to a wrong target), (4) the availability ratio of VBS attitude measurements

**Table 6: VBS behaviour and filter robustness**

| Scenario Id | Measurement validity ratio (%) | Angles difference (std dev) | Attitude availability ratio (%) | Wrong measurements |
|---|---|---|---|---|
| #1 | 61.2 | (3.7e-4 – 4.5e-4) | 15.4 | 1 |
| #2 | 95.9 | (7.2e-4 – 8.1.e-4) | 10.9 | 6 |
| #3 | 98.5 | (2.6e-4 – 3.7e-4) | 58.4 | 4 |
| #4 | 96.4 | (5.3e-4 – 3.4e-4) | 39.9 | 46 |

The angle difference cannot be regarded as a measurement error since the reference measurement is corrupted by two types of errors: (1) attitude estimation error when the VBS instrument does not deliver any attitude, (2) data time synchronization. An illustration of this signal is given on Figures 7.1 and 7.2; Even though this information cannot be used to characterize the VBS accuracy, it represents an adequate means to check the measurement consistency. In all scenarii, the difference standard deviation remains close to the VBS pixel size (4.26 $10^{-4}$ rad) which confirms the assumptions made during the design phase. In addition, the VBS erroneous measurements are rejected by the filter and do not affect the navigation performance. The VBS has therefore no responsibility in the relative range uncertainty profile.

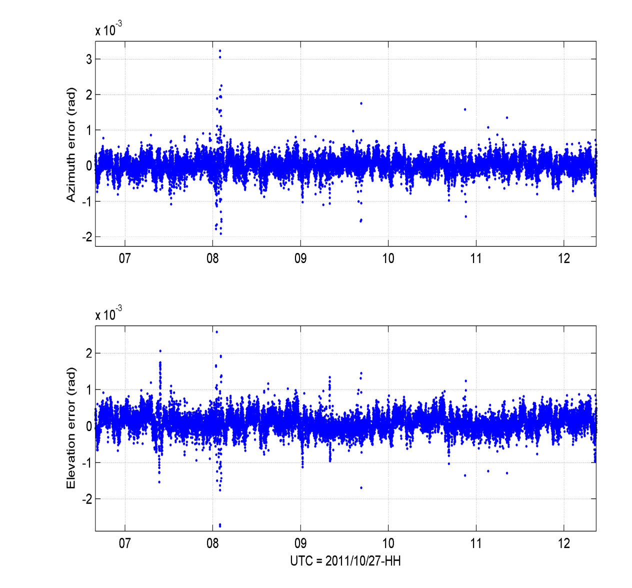


**Figure 7.1**: Difference between true and predicted measurements (POD) over a 6 hours period during scenario #3. Larger amplitudes appear when manoeuvres are applied and produce some sudden attitude variation. Most of this error is due to the time synchronisation of both signals.

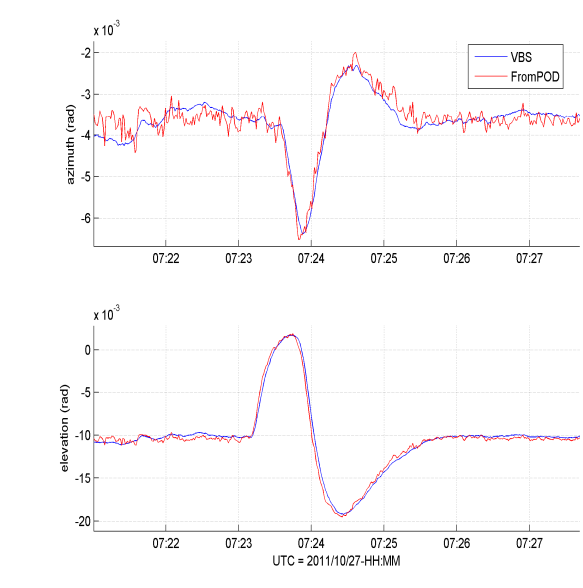


**Figure 7.2**: Display of true (blue) and predicted measurements (red) over a time period with manoeuvre application. Both signals remain consistent during the manoeuvre but some slight phase shift is visible which cause an increase of the signal difference.

Navigation performance degradation at short range can be easily explained when considering the direction measurement principle implemented within the Close Range VBS. At short range, Tango satellite occupies a significant area in the field of view (up to 50 pixels at 50 m range as shown on Figure 6.2) and direction biases can be expected due to the difficulty to perform an accurate extraction of the blob barycentre and a fair determination of the satellite centre of mass. Quick bias variations may also occur if the sensor gives a particular weight to bright target areas such as the RF antennas (perfectly visible on both sides of the satellite). Figure 9.1 illustrates this impact by comparing the VBS measured direction with the "true direction" reconstructed with POD (this comparison is only relevant at short range since attitude estimation errors affect the reconstructed reference). Error variations up to 1° and 0.4° can be observed respectively on the azimuth and elevation axes when range approaches 50 m. Even partially filtered out, the effect on navigation accuracy is with errors reaching up to 2 m cross track (10% of the cross track motion amplitude).

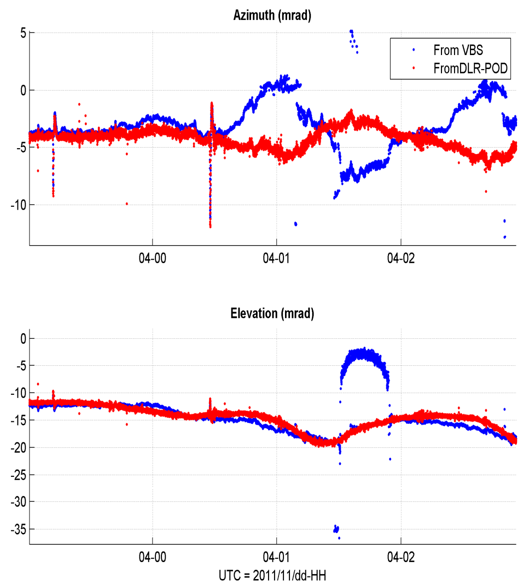


**Figure 6.1: Difference between direction angles from VBS and reconstructed from POD data.** *This signal is a valid representation of VBS measurement error at short range (beyond 04-00)*

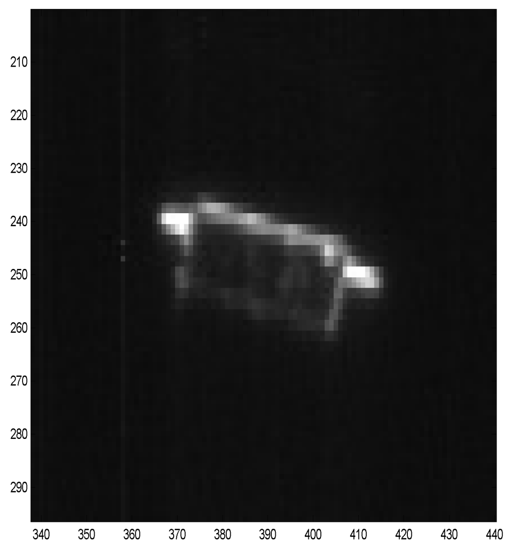


**Figure 6.2: Target appearance at 50 m range.** *Zoom on a Far range VBS image taken on November 4th 2011. Bright objects on both sides correspond to FFRF antennas.*

This expected performance limitation shows the need to rely on additional image processing capabilities with some model based oriented techniques and preferably implemented in the on board computer for higher design flexibility. However, getting safely into the 10-15 meters range constitutes a significant challenge since this requires a high level of robustness and most probably lighting control capabilities. Until proven otherwise, the use of an alternate metrology system like a Lidar still represents the most reasonable option for close range navigation.

### 5.3. Post flight analysis

A detailed analysis has been performed to fully understand the level of performance. Using flight data and ground replay tools, results have been reproduced and allowed to confirm that the relative range increase was caused by an initial error of about 0.4° on the Local orbital frame attitude (replay with a perfect attitude cancelled quasi totally this phenomenon). The same tool was used to check the navigation robustness in presence of larger initial uncertainties and convergence was still ensured with range errors up to 20%.

Further investigations were performed to assess the impact of periodic optical data loss with ratios up to 40% per orbit like in eclipses. Figures 8 show a superimposition of results with and without data loss: a 20% data loss has a negligible impact on the real and estimated errors when using the same navigation settings (Figure 8.1). Conversely, the 40% ratio has a significant impact on the range covariance and range error: performance shown on Figure 8.2 looks actually better since it is obtained with a minor modification of the algorithm (addition of a curvilinear transformation before computing the predicted measurement). The robustness of the algorithm and its applicability to more realistic flight scenarii is therefore suggested.

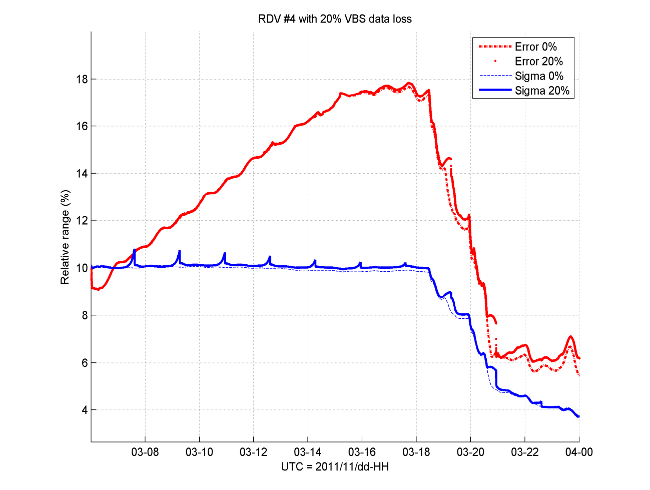


**Figure 8.1: Replay simulation with 20% data loss per orbit (short eclipse)**

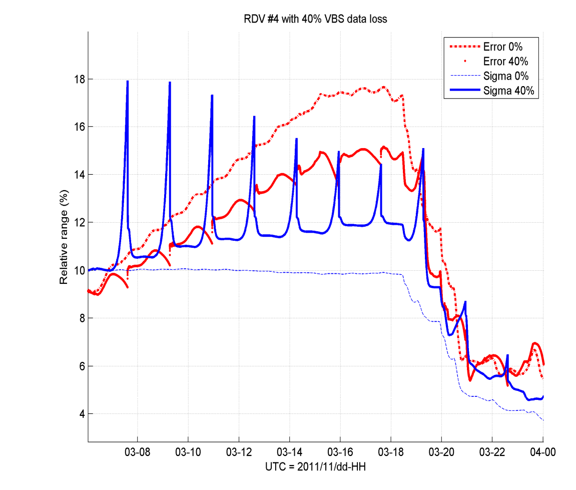


**Figure 8.2: Replay simulation with 40% data loss per orbit (long eclipse)**

The benefit of the curvilinear correction is blatant on Figure 8.2 and further improvement has been achieved through the use of the alternate navigation algorithm including the Earth oblateness J2 effect along with the estimation of the Local Orbital frame attitude bias. The filter tuning becomes globally easier but not trivial since the range dependency of the covariance coefficients is still required. The comparison of the different navigation methods with the flight telemetry is still underway and will be published in a next paper. This work is showing anyway the potential of the flight collected data and the ground assessment tools that allow to perform exhaustive analyses and qualify new algorithms.

## 6. Conclusion

This flight experiment presented in this paper has brought additional evidence that vision based navigation rendezvous in Low Earth Orbit represent a valid technique to perform rendezvous with non cooperative objects. Within a short timeframe, a new on-board software including angles-only navigation and guidance functionalities was developed and exercised successfully during four consecutive rehearsals performed with realistic conditions of uncertainty. Collected results were analyzed with accurate GPS navigation information which allowed to evaluate the performance of the main components and particularly the navigation algorithm. In addition, complementary runs in replay mode showed the robustness of the technique and its potential of improvement through some limited adaptation.

This work allowed to identify several issues that will need some further consolidation for future applications. The first remark concerns of course the instrument which capabilities drive the performance of the whole navigation system. Throughout the various rehearsals, the VBS camera performance proved to be quite in line with expectations in the far and intermediate range regimes and the conservative assumption of one pixel accuracy (80 arcsecs) was never infirmed. Conversely and not surprisingly, entering the 100 m and below regime proved to be too challenging for this instrument given the stringent lighting conditions and robustness requirements for the image processing functionalities. Improvement could be anyway achieved at all ranges through a better data interaction of the camera with the navigation system.

The second issue is linked to the fuel minimization constraint which impacted the navigation performance through a selection of a non optimal guidance profile and conservative navigation settings. The improvement of range observability through the application of manoeuvres could not be observed in flight above a few kilometres range whereas simulation showed that it could be achieved early on with less fuel efficient trajectory profile and settings. The uncertainty profile was acceptable for an experiment but would definitely appear too risky in the scope of a real mission. In this context, the waypoint guidance approach proved anyway its efficiency and did not produce a substantial delta-V overhead due to navigation-guidance coupling effects.

The third remark concerns the tuning of the extended Kalman Filter that appeared to be a difficult and time consuming task given the range dependency of the uncompensated non linear perturbations and the need to adapt the covariance matrices in a non intuitive fashion. This effort was definitely augmented by the selection of a simple relative dynamic model that did not capture some significant effects like the Earth oblateness and the orbit curvature. Runs in replay mode have shown the level of improvement that can be achieved when adding these features in the relative dynamic model both from the performance and filter tuning points of view.

Nevertheless, ground analysis showed that the navigation function implemented on-board and based on the Yamanaka Ankersen relative dynamic model could still perform satisfactorily in situations where permanent visibility cannot be achieved (eclipses). This preliminary assessment clearly indicates the potential of this technique for an utilization on any type of orbit.

Vision based rendezvous in a non cooperative mode that may be required in future orbital debris removal activities or Mars Sample Return mission has been demonstrated several times up to 10 km. The achieved performance at metrology / navigation levels give a better understanding of the current limitations and also improvement possibilities that appear quite promising. In addition, this experiment has proven the high potential of the VBS cameras developed by DTU and derived from already well known star trackers. Furthermore, this flawless experiment that was developed in a very short time frame has clearly demonstrated the great capability and flexibility of the PRISMA test bed environment as well as the unbeatable efficiency of code generation techniques.

## 7. Acknowledgements

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## 8. Conclusion

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