Preliminary Results of the Vision Based Rendezvous and Formation Flying Experiments Performed During the PRISMA Extended Mission

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Through its participation to the nominal phase of the PRISMA technology mission, CNES has successfully demonstrated rendezvous and formation flying techniques based on new radiofrequency metrology system. CNES went a step further by participating to the extended mission phase and performing a complementary experiment in October 2011. CNES implemented a new on-board software including this time vision based navigation using two cameras accommodated on the chaser satellite. A long range camera providing the “target” bearing angles was used to perform vision based rendezvous with a non cooperative object. A close Range camera that can determine the relative 3D position of a cooperative satellite carrying LEDs was further used as a second metrology stage for proximity operations under 30 meters range. Four rendezvous were performed with success from ranges up to 10 km and destinations down to 50 m. Four series of transitions between RF based and VBS based navigation were exercised satisfactorily during tight proximity control to demonstrate the multi-stage metrology system needed for future formation flying missions. The paper presents the results obtained during this extended phase and outlines the preliminary conclusions.

Introduction

PRISMA is a precursor mission for formation-flying and on-orbit-servicing critical technologies that involves two spacecraft flying in low Earth orbit since June 2010. The mission which is still in operation represents a unique in-orbit test-bed for guidance, navigation, and control (GNC) algorithms, novel relative navigation sensors (GPS, radio-frequency, vision-based), as well as new propulsion systems (high performance green propellant, micro-electro-mechanical components. 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 resulting mission consisted of several hardware and software experiments involving new technologies for propulsion, vision based sensors, GPS and other RF-based navigation, as well as GNC algorithms. OHB-SE as well as DLR/GSOC and CNES have developed their own GNC software for the execution of a series of closed loop orbit control experiments. The nominal mission was

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completed by the end of August, 2011. An extended mission open for contributions from a broader community was initiated right after and CNES participated to it with new experimental objectives. After a summary of the results obtained by CNES with the radiofrequency sensor during the nominal mission, the paper focuses on the experiment based on optical metrology. It will describe the experiment, develop the algorithm design & validation plan (relative navigation for the most part) and present the results obtained during the 4 consecutive weeks of operation along with a discussion of the specific shortcomings. As a conclusion, the paper will highlight the great value of the PRISMA in orbit test bed to validate new technologies through the quick integration of new software components.

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 propulsion system on Mango is based on six 1-N thrusters directed through the spacecraft center of mass and the delta-V capability is approximately 120 m/s. All ground communication is made with Mango. Communication with Tango is made via an inter-satellite link (ISL). The GPS is distributed between the two satellites and GPS messages are transferred from Tango to Mango via the ISL. The GPS navigation software resides within the on-board software of Mango. In this way, relative GPS navigation between Mango and Tango is achieved.

Figure 1. PRISMA satellites: Tango (left) and Mango (right)

PRISMA satellites are operated from OHB-SE premises in Solna, Sweden using one of SSC’s ground antennas in Kiruna, Sweden. The orbit and the antenna result in late afternoon and nighttime passages with up to 10 passages per day. Operations included the initial acquisition, LEOP, Tango separation and the nominal mission phase. The Mission Control Center (MCC) is based on the in-house developed RAMSES ground control software. For approximately five months, between March and July 2011, the mission was operated from DLR/GSOC in order to further support the mission and in this way prolong its operational lifetime. A cloned MCC was set up at DLR/GSOC and personnel were trained at OHB-SE. In addition to the Kiruna antenna, DLR/GSOC also made use of ground stations in Weilheim, Germany and Inuvik, Canada. This allowed for an increased amount of passages and day-time operations.
FFIORD EXPERIMENT

General description

CNES contribution to PRISMA consisted in the Formation Flying In Orbit Ranging Demonstration experiment (FFIORD). The FFIORD experiment cornerstone was a new Formation Flying Radio Frequency (FFRF) metrology sub-system designed for future outer space FF missions and for which in-flight characterization constituted the first objective. FFIORD second objective was to test several Guidance Navigation and Control (GNC) algorithms relying at least on FFRF sensor data and developed to achieve autonomous rendezvous then control of two satellites in close formation.

The FFRF Sensor was developed by Thales Alenia Space with a partnership from CDTI. It is a distributed instrument designed to provide range and Line Of Sight (LOS) measurements at 1 Hz with a typical accuracy of 1 cm and 1°. Its functional principle is inherited from the TopStar GPS using dual frequency S-band signals. Requirements included also the lost in space capability assuming some indirect assistance from the GNC system for signal ambiguity resolution (IAR). Besides, its generic initial design was adapted to fit the accommodation constraints on PRISMA (10 kg and 30 W) and to take into account the formation asymmetric structure composed of a smart chaser satellite (Mango) and a passive target (Tango). In addition, the instrument offers an inter-satellite link (ISL). This capability, not part of the nominal PRISMA communication system, was exercised only for validation.

The other major FFIORD contribution consists of a complex software (designed to take over Mango orbit control) fully developed within the Matlab / Simulink environment. The FFIORD Simulink library was integrated within the GNC core (1 Hz activation) of the whole PRISMA Onboard Software (OBSW) before automatic code generation. The FFIORD GNC software implements its own mode handler and FDIR module together with a set of Navigation, Guidance and Control functions. RF navigation is active whenever the FFRF sensor is active and provides the estimated companion relative state (position, velocity) permanently. Conversely, guidance and control depends on the activity being performed (rendezvous, relative orbit keeping, transfer between two relative states, proximity operations, collision avoidance) and specific algorithms are being triggered in each case. RF based navigation involves an Extended Kalman Filter that estimates the full relative state plus the FFRF sensor direction biases. Guidance functions rely on the Yamanaka-Ankersen state transition matrix for the relative dynamic model.

Synthesis of FFIORD Nominal experiment

The FFIORD nominal mission experiment was run from August 2010 to March 2011 (52 allocated days and 6 m/s budget). The timeline was designed to progressively validate the whole set of functionalities involved in the various maneuvering scenarios. The timeline started with passenger experiments (in parallel with other primary experiments), then it went through primary experiments performed in Open Loop (relying on the GPS based PRISMA Formation Flying services), and finished with long duration Formation Flying operations for a total of 12 days. To get the best benefit of the delta-V budget, the timeline was densely filled with numerous activities including rendezvous, relative orbit-keeping, proximity operations with forced translations and accurate positioning, collision avoidance maneuvering strategies.

*FFRF sensor behavior:* Most of the experimental days were dedicated to the verification of the sensor functionalities and the performance characterization over the 3m to 30 km range in numerous relative attitude configurations. A particular attention was focused on the initialization phase that involves integer ambiguity resolution which success is required to achieve final
accuracy. Experiments allowed to establish the satisfactory sensor behavior in most conditions and identify the operational domain where the finest accuracy of 1 centimeter / 1 degree can be reached.\[10\] The sensor was declared fit for closed loop experiments starting by the end of October 2011.

**GNC performances:** All the 12 days of FFIORD closed loop experiments ran smoothly and the objectives (number of tests, functional behavior, performance) were achieved.\[11\] Rendezvous activities included six approaches from distances of 4-7 km to several tens of meters. Durations went from 7 to 14 orbits and the delta-V usage covered a 7-29 cm/s domain quite in line with expectations. Final rendezvous accuracy went below 20 cm for the closest delivery point at 160 m whereas it was metric for endpoints in the kilometer range. Relative orbit-keeping consisted in maintaining a typical relative distance of 300 m with 20 m radial and cross-track amplitude. This function was activated during 40 orbits for an overall cost of approximately 7 cm/s translating into a mean budget of 1.7 mm/s/orbit. The demonstrated formation keeping accuracy reached an average of 30 cm in cross-track direction and a few meters in radial and along-track directions. Collision avoidance was exercised in two different ways: creating a relative drift between the two satellites or applying a pair of phased maneuvers to obtain maximal radial and normal separations. A total of 5 successful collision avoidance maneuvers were performed with the Mango relative trajectory exiting the prescribed keep-out-zone a few seconds after the maneuver.

**Figure 2. FFIORD experiments.** Left: Rendezvous performed from 6.5 km to 500 m on February 2, 2011 with 8 maneuvers (represented by red squares). Bottom plot shows the accuracy achieved at endpoint [0.07 m, 1.0 m, -1.4 m]. Right: Proximity operations control tracking errors based on POD (blue) and on-board FFRF navigation (dotted red) at 20 m distance on March 11, 2011 with and without sub-pulse mode activated.

The best control accuracy in the FFIORD experiment was demonstrated during the proximity operations activities which included station-keeping and forced translations. To improve the propulsion system resolution (thruster MIB =100 ms), the sub-pulse mode was used with thrusters functioning in a differential way to realize the requested inputs. Station keeping at 80 m and 20 m separations was exercised with quasi-continuous activations of the thrusters (200 s control cycle). As illustrated with the right plot of Figure 2, navigation and control errors based on the reference
POD show accuracy at centimeter level in both bias and standard deviation. The main benefit of the FFIORD experiment onboard PRISMA was the flight demonstration of the FFRF sensor that represents the first metrology stage envisioned for future formation flying missions. Requirements for a coarse accuracy localization system were actually exceeded since proximity operations were run extensively with a centimeter accuracy, hence demonstrating the capability to control a distributed instrument like a telescope, to retarget it and to adjust its focal length.

**FFIORD EXPERIMENT DURING EXTENDED MISSION**

To take benefit of the fully operational test bench and the substantial fuel resources available at the end of the nominal mission in August 2011, OHB-Sweden has solicited proposals at a wide international scale to perform additional experiments during a commercial extended mission phase. CNES responded positively and proposed a new GNC package that would involve this time visual sensors in combination with the FFRF sensor. The presence on PRISMA of two cameras designed for long range and short range observations (developed by DTU) was indeed a unique opportunity to demonstrate two types of operations: (1) validate the transition between RF based and vision based control during final formation acquisition, which is necessary for future formation flying missions, (2) demonstrate vision based rendezvous with a non cooperative object to prefigure future orbit servicing activities such as debris capture. The experiment was implemented in 2011 within a very short time frame since the go ahead was given in May. A new GNC software including the additional navigation functions was then developed with Mathworks® code generation techniques, delivered to OHB-Sweden in August for validation purposes and uploaded on October 10th for the beginning of the operations.

**PRISMA cameras**

PRISMA greatly benefited from the DTU contribution of two Vision Based Sensors (VBS) that enabled to cover the whole spectrum of relative sensing technologies. Using a design derived from the µASC star tracker, these sensors have been specifically tailored to achieve two different and complementary navigation purposes: long distance detection and tracking of a moving target to allow rendezvous (Far Range VBS), accurate relative pose and position estimation of a cooperative target for proximity operations (Close Range VBS).

**Close Range camera (CR VBS):** This camera designed to work in a cooperative mode relies on the presence of light emitting diodes (LED) on the target satellite that deliver a short pulse every second. The Close Range VBS locks on the light of these diodes, extracts the coordinates of all luminous objects and compares the detected pattern with the model stored in the database. In order to increase the measurement principle robustness, the camera optical pass band has been narrowed using a filter centred on the LED wavelength. According to this scheme, an estimate of the target localization is delivered at 1 Hz with a sub-millimetre accuracy for the position and below 1° for the relative pose demonstrated in laboratory conditions at 10 m distance. Some performance degradation can be however encountered in flight given the optical characteristics of some of the satellite components such as the radiator or RF antennas that may degrade the pattern visibility in some particular lighting conditions.
Far Range camera (FR VBS): The Far Range camera is basically a star tracker that is operated in a particular mode. In the Far range mode, the camera processing unit has the capability to detect the luminous objects that do not belong to the star catalogue and that can be robustly spotted as potential orbital targets after a few acquisition cycles given their apparent motion. At long distance, since stars are visible within the same image, the camera will also deliver an attitude quaternion which helps to get rid of the camera bias alignment problem. When range is reduced, the target luminosity increases and obliges some automatic time of exposure tuning to avoid blooming effects (Intermediate mode) which limits the capability to estimate inertial attitude. Therefore, depending on the range, the VBS provides a line of sight that is expressed in either the inertial reference frame, or in the camera reference frame. The specified accuracy is 3 arc seconds at long range and has been verified as such in flight using POD reference data.

OHB-Sweden has performed an extensive characterization of the VBS navigation sensors during the nominal mission and CNES largely benefited from their experience.

Metrology transition experiment

This experiment objective is to exercise the navigation and control process that will be involved in future formation flying missions when transitioning from a coarse metrology stage needed for formation acquisition (FFRF sensor) to a higher accuracy stage required in nominal mode (optical metrology).

Transition between metrologies constitutes a challenge for navigation since the filter must adapt to sudden variations in sensor measurement characteristics and this is particularly true when the bias offset is significant. Figure 5 illustrates such a situation by superimposing Mango Cartesian position derived from both sensors raw measurements around the time of transition on Octo-
ber 31st 2011 (POD from DLR which accuracy is better than 1 cm 3D has been used as reference). Bias variations of 10 cm and 15 cm can be observed on X and Y axes respectively.

**Relative navigation filter and tuning approach:** Relative navigation can be performed in two different modes. In the first mode, we rely on the OHB navigation filter designed for the nominal mission and that is initialized with the FFRF navigation state and covariance. The second mode is based on the CNES navigation filter implemented specifically for the extended mission. The latter one is actually obtained by adapting the already existing FFRF based navigation function so that it can process the measurements from both sensors. This is achievable since their content is basically equivalent (Cartesian coordinates versus distance and line of sight angles). VBS measurements are therefore converted into FFRF like data before they get fed to the filter according to the following formulas:

$$
\begin{align*}
    d &= (x_{vbs}^2 + y_{vbs}^2 + z_{vbs}^2)^{1/2} \\
    x_{LoS} &= x_{vbs} / d \\
    y_{LoS} &= y_{vbs} / d
\end{align*}
$$

(1)

Metrology transition is authorized by the ground after the Close Range VBS sensor has been activated. From this instant, the navigation filter is ready to process VBS measurements whenever
they become available (the validity flag is properly set) and as soon as they get consistent with the expected values given the current uncertainty state. If these conditions are satisfied, the filter ignores right away the FFRF measurements and considers VBS data instead. To handle properly the transition, the filter tuning approach consists in increasing the measurement noise covariance (multiplication by a specific ratio) during a temporary phase before reducing it gradually to the final setting that corresponds to the expected VBS measurement noise uncertainty. This intermediate phase is designed to assure a smooth filter convergence to the new steady state and its role can be considered as a filter reset process except that the state covariance matrix keeps its current value. Position control remains unchanged for the transition and the new navigation regime. The control gains are kept identical as well as the actuation cycle (200 s).

Transition between RF and optical based control was demonstrated 4 times at 20 m and 15 m ranges during proximity operations activities. The scenario first involves a several manoeuvres terminal approach based on RF navigation from a safe relative orbit at 200 m from Target to a station keeping point at 25 m on VBAR. Position control is then activated to allow some precise relative positioning and distance is slowly reduced to reach the desired metrology/navigation handover zone. When the Close Range camera has properly acquired the target, optical navigation takes over and proximity control keeps on for two consecutive orbits. Later, there is a switch back to RF navigation and the active satellite recedes autonomously to the initial safe relative orbit through a 3 manoeuvre transfer (Figure 4.1).

Experiment results. Both FFRF and VBS sensors have been characterized using DLR POD as reference data. The following table synthesizes sensor performance obtained over the 4 repetitions (12 hours altogether between 15 m and 25 m)
VBS instrument showed a very satisfactory behavior since it delivered a reliable measurement set during all the experiments performed from 25 m to 15 m. Compared to FFRF, the VBS sensor delivers a much better quality data on the transverse axes (noise is 5-8 times smaller @15 m). Conversely, range measurement noise appears larger than what is obtained with the FFRF and Figure 5 shows some 10 cm peaks that are likely to correspond to LED false detections. Looking at the VBS image on Figure 4.2, it is easy to understand the metrology challenge in presence of bright reflections on the solar panel periphery and FFRF antennas.

<table>
<thead>
<tr>
<th></th>
<th>X (cm)</th>
<th>Y (cm)</th>
<th>Z (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFRF (bias / noise)</td>
<td>12 / 0.8</td>
<td>11 / 6.2</td>
<td>1.4 / 7.5</td>
</tr>
<tr>
<td>VBS (bias / noise)</td>
<td>0.08 / 2.8</td>
<td>3.3 / 1.5</td>
<td>1.9 / 1.0</td>
</tr>
</tbody>
</table>

Table 1: FFRF / VBS performance comparison @15 m using POD data as reference

Figure 6.1: Navigation error in CNES mode. Transition from FFRF to VBS occurs at 18:38:00.

Figure 6.2: Control error before and after transition into VBS (navigation is in CNES mode).

Figure 6.1 illustrate the type of performance achieved during the 2011/10/31 rehearsal which is representative of the other experiments results. The transition into VBS navigation produces a degradation of performance that is maintained beyond the so-called ”smoothing” phase. The phenomenon is particularly visible on the cross-track component with a 30 cm transient occurring in presence of a 15 cm bias variation.

Performance enhancement with respect to FFRF could not be achieved and the station-keeping control budget was impacted accordingly (>4 cm/s per orbit instead of 3 cm/s under FFRF based control). Experiments were performed with the OHB and CNES navigation modes and control performances were in the same order of magnitude even though the two filters tuning were quite different. Table 2 shows that navigation performance is better in the OHB mode but control does not clearly benefit from this apparent advantage since the estimated relative velocity is very noisy. Conversely, navigation in CNES mode is tuned to offer a better estimation of the
relative velocity and this overshadows its weakness when considering position performance only. To appreciate the navigation and control challenge, it must be outlined that the minimum velocity that can be imparted to the satellite is 0.7 mm/s (mainly in cross track in nominal conditions). This means that the minimum achievable control cycle is about 7 cm (+/-3.5 cm) for a 200 s control period. Control is therefore very sensitive to velocity errors which lead to a very difficult task for navigation tuning specially in presence of temporary bias variations.

Table 2: Navigation and control performance in VBS mode

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Navigation error (cm)</th>
<th>Control error (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>POD as ref</td>
<td>VBS nav as ref</td>
</tr>
<tr>
<td><strong>PROX @ 15 m</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OHB nav (2011/10/24)</td>
<td>Bias [0.8 2.4 3.1]</td>
<td>Bias [2.8 0.1 0.1]</td>
</tr>
<tr>
<td></td>
<td>Std [5.6 1.4 1.2]</td>
<td>Std [14 4.4 5.3]</td>
</tr>
<tr>
<td>CNES nav (2011/10/31)</td>
<td>Bias [2.0 12 6.4]</td>
<td>Bias [4.1 2.4 2.9]</td>
</tr>
<tr>
<td></td>
<td>Std [1.9 3.8 2.0]</td>
<td>Std [14 4.5 5.2]</td>
</tr>
</tbody>
</table>

Given the tight experimental program, little time was unfortunately available between rehearsals to design a better filter tuning and to allow POD data production that was required for an accurate assessment of the navigation performance. Using the collected flight data, some work is currently being pursued through “replay” tests and algorithm adaptation in order to optimize performance. The achieved flight results have shown so far the intrinsic difficulty faced by optical navigation at short range when lighting conditions cannot be totally mastered. In comparison, metrology systems such as the ATV videometer benefit from a tailored environment in the optical target vicinity which is essential to guarantee measurement performance and robustness. Given this far from optimal lighting context, VBS showed anyway a quite impressive behavior.

**Vision based rendezvous experiment**

Mastering vision based navigation provides the ability to rendezvous with non cooperative objects from a long distance and with low metrology resources. This technique is compulsory for the Mars Sample Return mission and will be most useful to future servicing applications such as the active removal of orbital debris. Given the opportunities offered by the PRISMA environment, CNES has logically decided to implement an experiment devoted to the acquisition of knowledge in the development and flight testing of optical navigation.

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 recent years and it has been shown that the application of manoeuvres would provide some distance observability assuming a sufficient knowledge accuracy. More specifically, Woffinden has developed a formulation that allows to characterize the conditions of observability and that outlines the particular benefit of cross-track manoeuvres to improve range observation. A rendezvous approach that takes advantage of this property has been formerly implemented and tested on Prisma by OHB-Sweden. Using VBS Far Range camera, rendezvous has been demonstrated successfully from 30 km down to 50 m. In our experiment, the addition of cross track manoeuvres devoted to range observability was discarded since this was adding an extra delta-V usage that could not be afforded. The co-elliptic approach which lies on the opposite side of spectrum could have been also an alternate option: it was put aside since it did not offer the amount of coupling between navigation and guidance that was part of the analysis goals. Instead, the ap-
proach implemented which is a trade-off between observability and delta-V cost relies only on maneuvers applied nominally in the plane. Some cross-track component was however present from the start to introduce some passive collision capability but this scheme introduces only small corrective thrusts (see Figure 7.2).

**Navigation:** The navigation function developed in partnership with Thales Alenia Space, relies on a dynamic model of the relative motion expressed in Cartesian coordinates (based on the Yamanaka-Ankersen state transition matrix). The filter state includes the Mango satellite relative position and velocity expressed in the predicted Tango spacecraft Local Orbital Frame. This Local Orbital frame is propagated on board and is initialized with some “a priori” absolute state consistent with TLE uncertainty. No estimation of the camera direction bias is implemented since the VBS delivers a valid attitude information at long range.

**Guidance:** On-board guidance relies on a semi-autonomous approach which has proven its efficiency during the previous FFRF-based rendezvous experiments. 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 maneuvers 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 in a progressive manner the real trajectory to the desired one. At least one maneuver is usually computed to reach the waypoint $X_k$ at the specified date $t_k$ (one or two mid course correction maneuvers may be applied later on) and the 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 approach is satisfactory as long as the navigation uncertainty is not sub-

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**Figure 7.1:** Rendezvous trajectory. Top and bottom plots represent respectively the desired in plane and along track / cross track trajectories. Maneuver application times are indicated by stars.

**Figure 7.2:** Rendezvous trajectory: zoom on the last 500 meters
ject to unexpected large variations such that the relative distance could suddenly appear much closer and force the chaser to go backwards to reach the waypoint.

Rendezvous experiment was demonstrated four times. The first test was performed in open loop from 4 km to 100 m for commissioning purposes and relied on OHB-Sweden guidance functionalities with GPS as navigation data. The subsequent tests were performed in closed loop and fully relied this time on CNES navigation and guidance algorithms: one was initiated at 4 km range whereas the next tests started from 10 km. Experiment durations were driven by delta-V considerations but could not be stretched too much for operational reasons: they went from 16 to 20 hours with a maximum 1 m/s allocation for the longer one. 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. To reduce the risk of failure, the experiment was partly cooperative with attitude guidance based on GPS data instead of VBS which allowed to maintain permanently the “target” in the camera field of view.

**Experimental Results.** All tests have been completed successfully with results summarized on Table X. In all cases, target detection was achieved within a few seconds and the solution was regarded as valid by the filter. In long and intermediate regimes, VBS target tracking behaviour was very satisfactory and showed an excellent robustness in presence of bright celestial objects or other satellites crossing periodically the field of view. The flawless VBS performance allowed to reach destination within the allocated budget that was computed from ground simulation with conservative error models for VBS and accelerometer measurements. All experiments showed also that attitude guidance could have relied on VBS data instead of GPS and confirmed *a posteriori* the non cooperativeness capability.

![Figure 8.1: Range profile during rendezvous](image1)

![Figure 8.2: Performance at short range](image2)

The typical relative range profile during rendezvous is shown on Figure 8.1 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. It must be noted that we benefit from two complementary factors: (1) the absolute error is proportional to range and is reduced accordingly when Mango gets closer to the target, (2) the relative range uncertainty gets progressively smaller when manoeuvres are applied. The contribution of the second factor is actually not observable in flight above 2 km and this is consistent with the simulation results given the error assumptions and the specific filter tuning.

Table 3: Summary of rendezvous results

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

Results on Table 3 show that the relative range uncertainty at destination is actually higher than the targeted 1% value (achieved in simulations) and that the performance is getting worse when the destination point is getting closer from Tango. This degradation 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 15 m range as shown on Figure 9.2) 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 gets below 100 m. Even partially filtered out, the effect on navigation accuracy is obviously visible on Figure 8.2 with errors reaching up to 2 m cross track (10% of the cross track motion amplitude).

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. Going any closer in a non cooperative mode is definitely achievable with minor adaptations on the current system design. Conversely, getting safely into the 10-15 meters range constitutes a significant challenge since this requires highly robust image processing techniques 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 navigation.
Anyway, these flight experiments have brought additional evidence that vision based navigation rendezvous in Low Earth Orbit could be a casual technique to perform rendezvous with non cooperative objects and with up to 10% initial range uncertainty. Furthermore, navigation runs in “replay” mode with the collected data indicate that a similar level of performance can be achieved with a range uncertainty as high as 20% while using the same navigation settings. The ability to estimate distance by the application of manoeuvres was also demonstrated at medium range even though cross track manoeuvres were avoided to minimize delta-V usage. In addition, the waypoint guidance approach proved also its efficiency and did not produce a substantial delta-V overhead due to navigation-guidance coupling effects.

Some further work that is still on-going concerns the tuning of the filter in order to improve the distance estimation capability at long range and obtain a better correlation with theoretical results available in the wide literature on Angles-Only Navigation.

**CONCLUSION**

FFIORD experiment during PRISMA nominal mission successfully demonstrated that the major phases of a complete formation flying mission could be autonomously performed using a new radio electric relative sensor and that centimeter positioning accuracy could be achieved at short range. FFIORD additional experiment during the extended mission allowed to get a step further in the mastering of autonomous rendezvous and formation flying techniques by the addition of optical sensors in the loop. 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. Transitions between radiofrequency and optical metrology at short range were also exercised in several scenario to acquire knowledge on the metrology, navigation and control issues that could occur in similar phases during future formation flying missions. The achieved performance at metrology / navigation levels that give a better under-
standing of the potential limitations and improvement possibilities are anyway very 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.

ACKNOWLEDGMENTS

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