RESULTS OF PRISMA / FFIORD EXTENDED MISSION AND APPLICABILITY TO FUTURE FORMATION FLYING AND ACTIVE DEBRIS REMOVAL MISSIONS

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Keywords: Formation flying, flight results, lessons learned

ABSTRACT

Several experiments have been performed by CNES during the extended PRISMA mission which started in August 2011. A first session in October 2011 addressed two objectives: (1) demonstrate angles-only navigation to rendezvous with a non cooperative object, (2) exercise transitions between RF based and vision based control during final formation acquisition. A complementary experiment in September 2012 mimicked some future astrometry mission and implemented the manoeuvres required to point the two satellite axis to a celestial target and maintain it fixed during some observation period. In its first section, the paper presents the experiment motivations, describes its main design features including the guidance and control algorithms evolutions and provides a synthesis of the most significant results along with a discussion of the lessons learned. In the last part, the paper evokes the applicability of these experiment results to some active debris removal mission concept that is currently being studied. The analysis focuses on the re-use of demonstrated functionalities and collected metrology data to maximize ground simulation representativeness and help to extrapolate the level of achievable performances in a different mission context.

1. Introduction

Formation flying and autonomous rendezvous are expected to flourish in the years to come. Formation flying (FF) still constitutes the leading approach to build large dimensions instruments while getting free from most launchers payload accommodation constraints. However, despite the exciting perspectives offered for scientific observation, formation flying suffers from a severe prejudice: its implementation appears too expensive and far too complicated. Given the technological challenges and the new paradigms involved, FF mission concepts are expected to remain in the waiting room, as long as the whole set of required equipment and functionalities have not been flight proven. Technology demonstrations represent therefore the key to break the conservatism and pave the way to more ambitious missions. As regards autonomous rendezvous, several applications are currently pushing the technology in the non cooperative direction. Orbit servicing ideas have been around for years and the active debris removal trend is now bringing new challenges from the GNC, metrology and obviously capture point of views. An important achievement was obtained by the DARPA Orbital Express technology mission that demonstrated satellite servicing. However, dealing with non cooperative targets (from debris to asteroids) requires the mastering of robust navigation techniques likely based on a combination of passive and active sensors that need to be flight qualified.

PRISMA mission launched in June 2010 constitutes the most recent and significant step in the advancement of formation flying and rendezvous techniques, by the integration of a large variety of navigation and guidance algorithms along with new sensors and actuators, the test of numerous flight tasks and the demonstration of complex operations in a routine manner [1]. From the formation flying perspective, several significant contributions were achieved. First of all, the validation and utilization of two new metrology/navigation systems: (1) the Radio Frequency sensor (FFRF) representing the first metrology stage of future outer space missions and cornerstone of the FFIORD experiment, (2) the relative GPS metrology system devoted to LEO or MEO applications. Both systems behaved
successfully at functional and performance levels within their operating ranges and enabled a wide spectrum of manoeuvre tasks including forced positioning at short range with 1 cm accuracy (FFRF based). Beyond the flight validation of numerous GNC techniques, a major achievement is the demonstration of long duration proximity tasks in complete autonomy that allows to weaken the psychological barrier associated to the risk of collision. In the rendezvous domain, the most striking accomplishment was the OHB-S demonstration of vision based capabilities such as target search, orbit determination and alignment, approach from 30 km to 50 m [3]. This “première” remarkably outlined what can be expected in the future from angles-only navigation in presence of non cooperative targets. Other experiments involved also autonomous rendezvous phases based on GPS (or FFRF) but these capabilities were already demonstrated in the formation flying functional domain. Finally, proximity operations were also performed with a camera working in cooperative mode that could constitute a precursor of low cost vision based RDV sensor.

Since all experiment objectives were already accomplished, the extended mission that started in August 2011 constituted an excellent opportunity for CNES to push the PRISMA system to its limits. The work presented in this paper constitutes a modest effort to bridge the gap a little further between what can be achieved today in flight and what is expected in future technology or real missions. Three different experiments were approved for implementation: (1) demonstrate angles-only navigation to rendezvous autonomously with a non cooperative object as a continuation of OHB-S work but with a different navigation algorithm, guidance approach and constraints (particularly from the fuel usage point of view) [4], (2) exercise transitions between RF based and vision based control at short range to emulate the final formation acquisition phase when switching to finer metrology stages is required [5], (3) accomplish formation manoeuvres that would be required in future FF missions illustrated by the NEAT / µ-NEAT mission concepts [6][7] - this involves the pointing of the formation to a selection of celestial objects belonging to the actual mission catalogue.

In the next section the paper presents en overview of the PRISMA system, its current capabilities and nominal mission main achievements. The subsequent sections include a description of the three experiments performed during the extended mission. The paper will synthesize for each experiment the objective, the design with a special focus on the GNC issues and the flight results. Next, the paper attempts to show how more challenging missions can actually benefit from the PRISMA experiments: first from the already GNC functions that can be re-used with some potential adaptation, and also from the large amount of collected data that is usable to extrapolate system behaviour with different spacecraft and environment characteristics. Finally, the conclusion summarizes the main achievements obtained so far and opens perspectives for future work.

2. PRISMA system description and limitations

The PRISMA space segment launched in June 2010 on a 700 km sun-synchronous orbit consists of a small satellite Mango (150 kg), and a microsatellite Tango (40 kg) [8]. 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 centre of mass and the delta-V capability is approximately 120 m/s. All ground communication is made with Mango and communication with Tango is made via an inter-satellite link (ISL). The flight system is developed by OHB-Sweden but includes several hardware / software contributions from European partners. DLR provided GPS receivers on both satellites, a relative navigation system and a dedicated experiment software to perform autonomous formation keeping [9]. DTU delivered a set of Vision Based Sensors (VBS) that enable optical navigation in non cooperative mode and cooperative mode [10][11]. CNES provided a new Formation Flying Radio Frequency (FFRF) metrology sub-system designed for future outer space FF missions and some on-board GNC software to perform a variety of formation flying experiments. PRISMA metrology and propulsion system are further described to illustrate their capabilities and limitations in the context of the extended mission.

The FFRF Sensor is a distributed instrument designed to provide range and Line Of Sight (LOS) measurements at 1 Hz with a targeted accuracy of 1 cm and 1°. Its functional principle is inherited
from a GPS receiver using dual frequency S-band signals [12]. Its operating range is 3m-30 km and its behaviour has been characterized in flight over most of that domain. In its current design and accommodation, its main limitation comes from its sensitivity to multipath that may lead to initial range biases up to 1 m and bearing bias variations in the 0.5° range for 30° attitude changes. During the nominal mission, this instrument allowed anyway to achieve the various formation acquisition and formation-keeping objectives and demonstrate forced positioning with 1 cm stability [13].

The Vision Based Sensors (VBS) which design is derived from the µASC star tracker have been specifically tailored to achieve two complementary navigation purposes: long distance detection and tracking of a moving target (Far Range VBS), relative position/attitude estimation of a cooperative target (Close Range VBS).

The Close Range camera (CR_VBS) detects the signal of light emitting diodes (LED) located on Tango satellite. CCD coordinates of all luminous objects are extracted and the detected pattern is compared with the model stored in database. To improve robustness, the camera optical pass band is narrowed using a filter centred on the LED wavelength but the whole satellite remains visible. The instrument operates up to 40-50 meters and delivers a localization estimate at 1 Hz with an accuracy that depends on the lighting conditions (a sub-millimetre accuracy for the position and below 1° for the relative pose was achieved in laboratory conditions at 10 m distance). In the nominal mission, this instrument allowed OHB-Sweden to achieve forced positioning with 1 cm accuracy at 10 m range [1].

The Far Range camera (FR_VBS) is a star tracker operating in a particular mode. In Far range mode, the camera processing unit is capable 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 range, since stars are visible in the field of view, the camera can deliver an attitude quaternion that helps to get rid of the camera bias alignment problem. At smaller range, the target luminosity increases and the activation of the electronic shutter is necessary to avoid blooming effects (Intermediate mode) which limits the capability to estimate inertial attitude. At short range, the target becomes a large blob 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 centre of mass. Given the stringent lighting conditions, the robustness of this process is potentially weak and direction biases are likely to be observed.
The Phoenix GPS receivers allow to perform on-board relative navigation with an accuracy in the 10 cm range and this information is used to perform some FF experiments and ensure PRISMA formation safety in all circumstances. In addition, the raw GPS measurements processed on the ground allow to perform Precise Orbit Determination (POD) and reach a relative accuracy in the sub centimetre range.

The propulsion system used for the FF and rendezvous experiments relies on 6 hydrazine 1N thrusters with a 0.7 mm/s Minimum Impulse Bit at the mission start. Most maneuvers require the use of at least 2 thrusters which push the effective MIB in the 1 mm/s range. This resolution level outlines the challenge of reaching centimeter positioning accuracy and this constituted an important performance limiting factor during the experiments with FFRF and CR_VBS.

3. Experiments performed during the extended mission

3.1 Experiment #1: Rendezvous with angles only navigation

This experiment was performed in October-November 2011 to acquire expertise in the field of vision based navigation that represents an attractive technique to rendezvous with non cooperative objects since it can rely on low cost and passive equipment (cameras in the visible or infrared domain). The 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. The implementation implied the on-board software modification to cope with new interface (cameras) and to accommodate the optical navigation function.

Optical navigation: The implemented algorithm is based on a full decoupling of position and attitude estimation. Attitude estimation is provided by PRISMA services whereas optical navigation focuses on the determination of the satellites position. The algorithm relies on a dynamic model of the relative motion expressed in Cartesian coordinates and based on the Yamanaka Ankersen state transition matrix [14]. The Extended Kalman Filter carries a 6 state vector associated to the chaser relative position and velocity expressed in the LVLH frame attached to target (no bias measurement state was included since the camera can provide attitude information as well). The LVLH frame attitude is provided by an on-board propagator which is initialized with some “a priori” absolute state. Since the propagator is not integrated in the filter, it does not benefit from any state update and the attitude is subject to some drift that is taken into account in the filter tuning.

Here, the filter tuning is a critical activity since it must properly capture the range dependency of the state and measurement noise covariance. State noise covariance is configured and periodically updated to capture several uncompensated perturbations: (1) non linear phenomena due to the simplified dynamic model, (2) orbit curvature, (3) knowledge error on the target orbital parameters that produce some LVLH frame attitude bias, (4) manoeuvre execution error. Measurement noise covariance is also adapted to take into account attitude uncertainty as well as errors on the observation transfer function coefficients that depend on the range uncertainty.

Rendezvous 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 predefined on the ground as a list of waypoints which spacing is properly set considering the expected range uncertainty profile. In addition, the ground defines the dates of the different manoeuvres to be computed on board using the navigation solution. The chaser aims at the waypoints without trying to reach precisely the full state (position, velocity) at the corresponding date. 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. Manoeuvre computation is based on the Yamanaka-Ankersen state transition matrix. When date \( t_k \) expires, 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.

Experiment description: The vision based rendezvous experiment includes four different trials performed with a 3 m/s total delta-V budget. The first one devoted to optical navigation commissioning starts from a 4 km range and is performed in open loop: guidance relies on some OHB-S module based on GPS navigation. 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 tests whereas next trials 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. During all rendezvous trials, the attitude guidance mode is “Target pointing” which aligns a particular body axis (parallel to the camera bore sight) with the estimated target direction. For each test, 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.

The rendezvous profile design was driven by two contradictory requirements: (1) ensuring a sufficient range observability, (2) minimizing the fuel usage. Range observability criteria first established by Woffinden [15] show the higher benefit of cross track manoeuvres over those applied in the orbital plane. However, pairs of manoeuvres in opposite directions must be applied which increase the fuel expense. Fuel efficiency being the priority, the rendezvous trajectory was designed without cross-track manoeuvres except for the introduction of some initial cross-track motion to prevent any risk of collision. The typical profile (RDV from 10 km) includes 9 waypoints and is illustrated on Figures 2.1 for a typical simulation run.

**Figure 2.1 Illustration of trajectory profile. Top view is the along-track/radial plane whereas bottom view is the along-track/cross-track plane. Manoeuvres are represented by stars and waypoints by circles.**

**Figure 2.2: Target appearance at 50 m range. Zoom on a Far Range VBS image taken on Nov 4th 2011. Bright objects correspond to FFRF antennae.**

Flight Results: All tests have been completed successfully with results summarized on Table 1. 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. In addition, the delta-V budget stays close to the expected value and confirms the relevance of the scenarios validation approach.

The typical relative range profile during rendezvous is shown on Figure 3.1 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. Two complementary and favourable factors come into play: (1) the range dependent absolute error is reduced 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 two non nominal phenomena were observed: (1) the range relative error increased during the first orbits from 10% to 18% whereas range covariance remained steady (2) the range uncertainty at destination was higher than the targeted 1% value (it is typically in the 2-3% range). The use of ground replay tools allowed to investigate the first anomaly and establish that it was due to an 0.4° initial error in the definition of the LVLH frame attitude (replay with a perfect attitude confirmed the disappearance of this phenomenon). This error value not captured in the state covariance was quite pessimistic since it corresponds to a 50 km along-track Tango position error. Navigation performance degradation at short range was easily explained by the Close Range VBS measurement limitations. At 50 m range, Tango satellite is about 50 pixels wide and direction biases build up due to the difficulty to perform an accurate extraction of the blob barycentre (and a fair determination of the satellite centre of mass). At this range, error variations up to 1° and 0.4° can be observed respectively on the azimuth and elevation axes. Even partially filtered out, their impact reach up to 2 m cross track (10% of the cross track motion amplitude).

Table 1: 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>

Figure 3.1. Relative position error in LVLH frame during RDV #4 (range 10 km to 50 m)  
Figure 3.2. Range error uncertainty during RDV #4 (range from 10 km to 50 m)
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.

A post flight analysis has been performed to fully understand the level of performance and show its applicability to more realistic flight scenario. Using flight data and ground replay tools, the navigation robustness has been evaluated in presence of larger initial uncertainties and convergence was still ensured with initial range errors up to 20% (Figure 4.1). Others investigations were also performed to assess the impact of periodic optical data loss with ratios up to 40% per orbit as in eclipses. With the same navigation settings, the 20% data loss impact was negligible whereas some minor modification of the algorithm (addition of a curvilinear transformation before computing the predicted measurement) allowed to handle the 40% loss case and improve actually the overall performance.

![Figure 4.1. Replay simulation with 20% data loss per orbit (short eclipse)](image1.png) ![Figure 4.2. Replay simulation with 40% data loss per orbit (long eclipse)](image2.png)

This work allowed to identify several issues that will need some further consolidation for future applications. First of all, the behaviour of the VBS instrument proved to be quite satisfactory in the far and intermediate range regimes and the conservative assumption of one pixel accuracy (80 arcsecs) was never infirmed. Conversely, the shot range behaviour (50 m – 100 m) was below expectations due to the stringent lighting conditions and the lack of robust image processing functionalities (the absence of a coarse distance measurement inferred from the object size had a negative impact). This outlined the tough challenge to be faced by optical navigation in this region. Second, range observability through the application of manoeuvres was not observed in flight above a few kilometres range although simulation showed it could be achieved early on with a less fuel efficient trajectory and more aggressive filter settings. The position uncertainty profile that was acceptable for an experiment would definitely appear too risky in the scope of a real mission. The use of cross-track manoeuvres with sufficient magnitude is therefore a requirement. Finally, the EKF tuning appeared to be a difficult 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.
3.2 Experiment #2: Metrology transition experiment

This experiment motivation was the exercising of navigation and control processes to be involved in future formation flying missions when a transition from a coarse metrology stage to a higher accuracy stage (usually an optical sensor) is required. In the PRISMA context, coarse metrology is represented by the radio-frequency sensor (FFRF) that delivers range and line of sight measurements whereas the presumably finer sensor is the Close Range VBS. The latter one delivers relative position in Cartesian coordinates and can provide relative attitude as well. Transition between metrologies constitute 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 this situation with 10-15 cm bias variations on along track and cross track axes when transitioning from FFRF to VBS).

Relative navigation based on optical data was performed in two different modes. The first one relied on the OHB navigation filter designed for the nominal mission and updated to accept inputs from the FFRF navigation (state and covariance) at initialization. The second mode is based on the CNES navigation filter implemented specifically for the extended mission. It is actually obtained by adapting the already existing FFRF based navigation function so that measurements from both sensors can be processed. 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.

To handle the transition that is triggered when the VBS measurements get available, 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. In the meantime, position control remains unchanged with same control gains and 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. Initially on a safe relative orbit at 200 m range Mango is driven to a station keeping point at 25 m on VBAR in RF navigation mode. Using forced position control, range is slowly reduced to reach the desired metrology/navigation handover zone. When Close Range VBS...
has acquired the target, optical navigation takes over and forced position control goes on for two consecutive orbits. Soon after, navigation is switched back into RF mode and Mango recedes autonomously to the initial safe relative orbit.

**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)

<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>

VBS instrument delivered a reliable measurement set during all 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 and Figure 5 shows some 10 cm peaks that are likely to correspond to LED false detections.

Figure 6.1 illustrate the type of performance achieved during the 2011/10/31 rehearsal which is representative of the other experiments results. Transition into VBS navigation produces some performance degradation that is still observable 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 was not achieved and station-keeping delta-V 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 3 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 which compensates its weakness when considering position performance only. Since the minimum impulse is 0.7 mm/s (mainly along cross track), the minimum achievable control cycle is about 7 cm (+/-3.5 cm) for a 200 s control period and is very sensitive to velocity errors. In that context, navigation tuning constitutes a quite difficult job especially in presence of temporary bias variations.
Table 3: Navigation and control performance in VBS mode

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Navigation error (cm) POD as ref</th>
<th>Control error (cm) VBS nav as ref</th>
<th>Control error (cm) POD as ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROX @ 15 m</td>
<td>Bias Std</td>
<td>Bias Std</td>
<td>Bias Std</td>
</tr>
<tr>
<td>OHB nav (2011/10/24)</td>
<td>[0.8  2.4  3.1]</td>
<td>[2.8  0.1  0.1]</td>
<td>[4.1  2.4  2.9]</td>
</tr>
<tr>
<td></td>
<td>[5.6  1.4  1.2]</td>
<td>[14  4.4  5.3]</td>
<td>[14  4.5  5.2]</td>
</tr>
<tr>
<td>PROX @ 15 m</td>
<td>Bias Std</td>
<td>Bias Std</td>
<td>Bias Std</td>
</tr>
<tr>
<td>CNES nav (2011/10/31)</td>
<td>[2.0 12 6.4]</td>
<td>[0.2 1.1 1.6]</td>
<td>[2.2 11 8.2]</td>
</tr>
<tr>
<td></td>
<td>[1.9  3.8  2.0]</td>
<td>[2.2  5.3  2.9]</td>
<td>[2.5  6.0  3.3]</td>
</tr>
</tbody>
</table>

Within 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. Flight results have shown anyway the challenge faced by optical navigation at short range when lighting conditions cannot be totally mastered. Obviously, future formation flying will rely on more robust measurement techniques that will make the navigation job much easier and guarantee higher positioning performance. Despite its intrinsic limitations, VBS instrument can demonstrate a reliable behavior in tailored conditions and some experiments performed by OHB allowed to reach 1 cm level accuracy [1].

3.3 Experiment #3: Mimicking µ-NEAT formation manoeuvres

The experiment was inspired by two formation flying astrometric missions (NEAT and µ-NEAT) that have been proposed to ESA with different scales: NEAT as an M-class mission with a 1m telescope and µNEAT as an S-class mission with a 0.3m telescope. µ-NEAT can search and characterize giant3 planets, i.e. Neptune’s mass and heavier, in the Habitable Zone around these stars, whereas NEAT can detect even smaller planets down to an Earth mass. NEAT/µ-NEAT concepts are based on a simple optic system with one off-axis parabolic mirror (Telescope) and a focal plane located at the distance that allows a correct sampling of the point spread function (Detector). The differential astrometry measurement is performed by an external metrology system that can calibrate the detector response with a micro-pixel accuracy. Main characteristics of NEAT / µ-NEAT are the following: (1) L2 Lagrange point mission: 5 years (NEAT) / 3 years (µ-NEAT), (2) Spacecraft distance: 40 m (NEAT) / 12 m (µ-NEAT), (3) Up to 20 reorientation manoeuvres per day (200 targets to be visited 50 times), (4) Observation duration between 30min and a few hours, (5) Telescope pointing accuracy: 3 arcseconds, (5) Detector positioning accuracy: 2 mm on all axes (NEAT) / 1 cm (µ-NEAT), (7) Average angle distance between 2 pointing directions: 10°

Figure 7: schematics of the NEAT spacecraft concept
**Formation configuration:** The set-up is tailored to approach the µ-NEAT configuration but with some necessary adaptation to cope with the large gravity gradient of the LEO environment and the PRISMA system limitations in terms of positioning and attitude accuracy. In addition, the active satellite (Mango S/C) will play the Telescope role whereas the passive one will represent the Detector. The experiment focuses on the Detector spacecraft manoeuvres and particularly the translational part plus the observation period. The intent is to be representative in terms of manoeuvre geometry and duration as well. Relative distance is therefore 12 m whereas final accuracy target is in the 10 cm range during the observation phases. Manoeuvre success will be evaluated using on-board attitude and Precise Orbit Determination (POD) data. In addition, the manoeuvre completion is to be illustrated by VBS or DVS images of the Detector spacecraft (Tango) and the celestial target whenever visible. In the experiment context, Mango is located in the plane defined by the Sun, Tango, targeted star triplet and the apparent angle between Tango and the targeted star is 3.8° (0.8 m transversal bias at 12 m). Tango nominal pointing imposes the solar panel to be parallel to the orbital plane with expected variations in the 10-15° range.

![Formation configuration diagram](image)

**Figure 8.1: Inertial formation configuration**

**Figure 8.2:** Illustration of Tango S/C attitude configuration and related constraints for the Mango relative position.

**Limitations and constraints:** The experiment was designed to satisfy the following requirements: (1) perform relative control using as much as possible radio frequency metrology (FFRF); (2) achieve the best possible control performances in the various pointing configurations, (3) point to a selection of NEAT scientific targets that are potentially visible with on board instruments. Since its magnetic actuation system offers low flexibility, Tango S/C attitude is kept quasi fixed during the whole experiment. To avoid antenna switch or accuracy degradation by large multipath biases, Mango relative position must remain in a 30° half angle cone around the axis of one of Tango RF antennae. The antenna is then selected to maximize the number of observable celestial targets.

The experiment design had to take into account additional geometrical and operational constraints. First, the targets located in the acceptable zone (60° max inclination with respect to the orbital plane) could not be observed permanently due to the periodic Earth occultation. Since occultation avoidance would have introduced large magnitude orientation manoeuvres and degraded the navigation, it was decided to maintain the pointing during the occultation periods while guaranteeing for each target some minimum observation time. Second, the observation plan had to be designed to minimize the simultaneous blinding of the two Mango S/C star trackers (a target threshold is 25 minutes to avoid a degradation of the attitude knowledge). In this experiment, such a blinding condition is due to occur...
when Earth gets in the back of Mango S/C. Given a list of celestial targets that satisfy the previous requirements, the only available leverages to maximize star tracker availability resides in the sizing of the observation/manoeuvre durations and in the sorting of the manoeuvres. Figure 9 shows the sequence of manoeuvres that was actually designed to observe the set of NEAT targets over a period of 3 orbits during the first experiment session.

**Guidance & Control aspects:** In previous PRISMA experiments so far, position guidance and control was designed only for motions defined with respect to a local orbital frame attached to Tango S/C centre of mass. Forced trajectories were defined as combinations of station-keeping points and linear segments whereas control design relied on a model of the relative dynamic motion (Hill equations) and the use of LQR technique with feed-forward terms. GNC software had therefore to be adapted to allow inertial motion definition, generation of the appropriate guidance profile and potential improvement of the control performance. In order to keep this evolution effort within the experiment limited resources, the selected solution consisted in keeping the same guidance and control paradigm and converting instead the desired inertial motion into its equivalent in the local orbital frame. Under this constraint, a fixed position in the inertial frame corresponds to a circular trajectory in the local orbital frame. In the general case, this trajectory is parallel to the orbital plane and is defined by two parameters: the radius of the circle $R$ (inter-satellite distance) and the cross-track distance (projection of the target direction vector along the normal to the orbital plane).

The guidance module accepts a trajectory input profile defined as a combination of linear segments and station keeping points with associated dates and produces a 6D position/velocity setpoint at 1 Hz cycle. After adaptation, this module can work in LVLH or inertial mode. If inertial mode is selected, trajectory inputs coordinates are assumed to be inertial and the setpoints are then computed in the inertial frame before being converted to the LVLH frame and delivered to the control module. This approach was further generalized to allow the definition of a rotating frame with respect to the LVLH frame by providing a single rotation vector. This allows to perform either circular or helix trajectories in any given plane and at any rate.

Relative position control is based on a discrete LQR algorithm using a Linear Time Invariant relative dynamic model (Clohessy-Wilshire equations). The control structure is expressed as follows:

$$u = -[K_p, K_v]X + [M_p, M_v]X_d + G$$

where $K$, $M$ and $G$ represent respectively the 3x6 regulator gain matrix, the 3x6 input matrix and the 3x1 feed forward vector to compensate for quasi constant perturbations such as differential drag and solar radiation pressure. This LQR algorithm can be designed to precisely follow any type of trajectory profile assuming the selection of the appropriate set of gains. In this experiment, the trajectory profile converted in the local orbital frame is a combination of circular arcs and portions of helices that correspond respectively to the observation periods and the re-pointing phases. This would imply to carry two sets of gains and swap them when entering or exiting each observation phase. For the sake of simplicity, a single set of gains was actually implemented with the focus on the observation phase (circular trajectory). Here, the period of activation is set to 100 s.

**Control accuracy and propellant usage:** Assuming perfect navigation, control accuracy is driven by two main variables: the control rate and the thrust Minimum Impulse Bit (MIB). Mango S/C MIB is 0.7 mm/s at the beginning of the mission (100 ms minimum pulse duration for a 1 N thruster and a 140 kg satellite mass). Fortunately, the thrust is smaller at the time of experiment due to the tank pressure reduction and this allows to select a control period of 100 s. An estimate of the delta-V budget required to maintain Mango S/C on a circular trajectory in LVLH frame can be obtained by integrating the expected perturbations while assuming a continuous thrust. The cost per orbit to maintain Mango S/C on a 12 m radius circle with no cross-track bias is respectively 4.8 cm/s and 9.6 cm/s on the along-track and radial axes. Taking into account some loss of efficiency due to the thrusters skewing, the expected budget ends up in the 16-17 cm/s range.

**Experiment sessions:** The experiment was decomposed in two consecutive sessions performed on September 20th and 21st 2012. Each session starts with a control handover by CNES when Mango S/C is in the vicinity of its companion and radio frequency navigation is initialized. Next, some forced
translation along VBAR allows to reduce the distance to 14 m and control is switched into inertial mode. The duration allocated to formation inertial pointing is purposely limited to 3 orbits for fuel saving considerations. The sequence is therefore completed five hours later and control is switched back into LVLH mode. At the end of the scenario (a few minutes later), control is handed over to OHB-S and Mango S/C is driven back to some parking orbit. The first session sticks as much as possible to the NEAT/µ-NEAT mission concept and involves real celestial targets from the NEAT catalogue – it relies also on FFRF navigation that is the candidate metrology for outer space missions. The scenario includes a sequence of 9 target time slots representative of a typical mission day except for the observation phase that is obviously downsized. Each target time slot lasts 2000 s including a 1400 s observation phase and a 600 s re-pointing manoeuvre.

<table>
<thead>
<tr>
<th>Man Id</th>
<th>Manoeuvre magnitude (°)</th>
<th>Translation magnitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.8377</td>
<td>5.41</td>
</tr>
<tr>
<td>2</td>
<td>21.7218</td>
<td>4.44</td>
</tr>
<tr>
<td>3</td>
<td>28.5856</td>
<td>5.74</td>
</tr>
<tr>
<td>4</td>
<td>18.7034</td>
<td>3.84</td>
</tr>
<tr>
<td>5</td>
<td>24.7205</td>
<td>5.02</td>
</tr>
<tr>
<td>6</td>
<td>21.7623</td>
<td>4.45</td>
</tr>
<tr>
<td>7</td>
<td>16.1635</td>
<td>3.34</td>
</tr>
<tr>
<td>8</td>
<td>21.2071</td>
<td>4.34</td>
</tr>
<tr>
<td>9</td>
<td>23.8714</td>
<td>4.85</td>
</tr>
</tbody>
</table>

Figure 9.1: Sequence of manoeuvres to maximize star tracker availability. The map origin corresponds to the zenith direction at the orbit ascending node. Vertical axis coincides with the orbital plane.

Figure 9.2: Manoeuvre characteristics associated to the Figure 9.1 sequence.

The second session involves a different and shorter set of targets (4) that includes this time the Moon for illustration purposes since the magnitude of NEAT targets is too faint for a direct observation with the cameras when the companion satellite is in the cameras field of view. The time slot is now 3000 s for the NEAT targets (2200 s for observation and 800 s for the re-pointing manoeuvre) whereas it is extended to 9000 s for the Moon observation. Control relies this time on relative GPS navigation to relax the experiment constraints and to offer some comparison benefits. In both sessions, the manoeuvre sequence has been optimized to limit the star tracker masking by the Earth and its impact on the attitude estimation performance.

Results overview: Both experiment sessions were monitored carefully during the various passages and no anomaly prevented them to run until completion. Fuel usage was particularly scrutinized and it always remained in line with expectations (about 30 cm/s per orbit). Control performance was being assessed using three navigation references: RF navigation, on board GPS navigation and Precise Orbit Determination (POD). POD is usually the most accurate reference when the pointing of both satellites is quasi constant in LVLH frame and a 1 cm (1 s) 3D accuracy is achievable. Conversely, navigation conditions get far from optimal in inertial pointing and some noticeable performance degradation was actually observed in both experiments with POD not properly reconstructed during 50% of the inertial pointing phase. Control performance presented on Table 4 concern only the observation phases: the time slots associated to the re-pointing manoeuvres are ignored when computing the error signal statistics (mean and standard deviation parameters).
Table 4: Summary of experiment performances

<table>
<thead>
<tr>
<th>Session</th>
<th>Delta-V (cm/s)</th>
<th>Control error (cm) RF nav as ref.</th>
<th>Control error (cm) GPs nav as ref.</th>
<th>Control error (cm) POD as ref. (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>65.2</td>
<td>N/A</td>
<td>Bias [-9.35 8.03 -5.87] Std [5.87 15.83 11.57]</td>
<td></td>
</tr>
</tbody>
</table>

Bold figures correspond to performances observed with the navigation function used in the control loop. These figures do not reflect the actual positioning performances that take into account the navigation error budget and that are usually provided by POD. This data when available could not be blindly trusted given the poor GPS measurement conditions.

The first session based on RF navigation allowed to obtain the best control performances during the observation periods. These were actually close to the performances obtained during previous station-keeping experiments in LVLH frame where control stability was in the 2 cm range [12]. The relatively good behaviour despite higher gravity gradient perturbations can be explained by the MIB reduction. Figure 10.2 illustrates the sub optimal control behavior during the re-pointing manoeuvres with control errors increasing up to 20 cm. However, this large error is quickly reduced during the first control cycle of the observation phase. As regards the total propellant budget, it looks rather high for 3 orbits (almost 1 m/s) but most of it is due to the large amplitude re-pointing manoeuvres. Considering the observation phases only, this budget goes down to roughly 18 cm/s per orbit.

![Figure 10.1: Desired trajectory in inertial frame and RF navigation solution](image1)

![Figure 10.2: Control error observed by RF nav, GPS nav. and POD during the 1st session](image2)

The second session based on GPS navigation benefited from better conditions since both re-pointing manoeuvres and observation periods were longer. However, coarser control performances as illustrated on Table 4 were observed due to some GPS navigation degraded behaviour. There is no apparent impact on the propellant budget that it is about 30 cm/s less than the first session but this saving is explained by the smaller magnitude of the re-pointing manoeuvres and their longer duration. The observation phases average budget is still around 18 cm/s per orbit. Here, the design was driven by the illustration objective (the moon is chosen as target) and not the navigation / control performance. This choice allowed to take numerous Moon images that illustrate quite effectively the inertial pointing capability (Figure 11).
4. Applicability to others missions: rendezvous and inspection of a non cooperative object

Motivation: CNES is currently running system studies about the active removal of multiple debris that focus mainly on the capture concept and the vehicle overall architecture (X-OTV). To consolidate these studies, some internal R&D effort is devoted to the design of a representative numeric simulator that enables to analyse in detail some of the critical phases and particularly the proximity operations prior to debris capture. Whatever the capture concept that may rely on rigid links (ex: robotic arm) or flexible ones such as harpoons or nets, the chaser will have to approach the debris, manoeuvre at short distance for inspection purposes and probably remain fixed in the debris body frame to limit the relative motion prior to capture. Different sensor suites can be envisioned for these different phases: passive devices like camera in the visible / infra red domain or active sensors such as LIDARs. The simulator purpose is to emulate the different scenario, implement the associated perception and GNC algorithms and characterize their constraints from the guidance strategy, robustness and also computing load point of views. Given the numerous commonalities with experiments performed on PRISMA, it appeared relevant to rely on this heritage for the simulator development (sensor model design and algorithm reuse).

Description of the scenario and setup: Among the different possible scenarii, we highlight here the option relying on a camera in the visible domain to approach the debris from several kilometres down to about 100 m and a low resolution LIDAR for all the subsequent proximity operations. In this preliminary study, the chaser satellite and space debris characteristics are identical to Mango S/C and Tango S/C respectively: same propulsion system, same camera for long/medium range navigation. The sole evolution concerns the addition of a LIDAR instrument that can provide an instantaneous depth image of the scene (flash LIDAR). We actually consider a camera model with characteristics similar to the Dragon Eye from Advanced Scientific Concept Inc that offers a128x128 resolution on a 45° FOV [17]. Given the small target size, the FOV was actually scaled down to 30°. The scenario context is described here-after:

- The debris is located on a 700 km low eccentric polar orbit and the epoch is selected to provide a 25% eclipse ratio.
- The chaser is driven by ground operation at about 10 km range from the debris and the initial uncertainty is [1500 km, 200 m, 200 m] for both objects absolute position when autonomous navigation is started
- Rendezvous consists in approaching the debris with angles only navigation over a 12 hours period while remaining on a collision free trajectory down to the 100 m range where the LIDAR instrument can take over. The trajectory profile is designed such that the distance to VBAR axis remains always above a safe threshold (from 100 m at long range to 20 m at short range).
- After LIDAR navigation hand over, the chaser is driven to a point on VBAR at 30 m behind the debris with a 3 manoeuvres transfer. Next, the distance on VBAR is reduced to 15 m through a 15° forced translation.
- For inspection purposes, the chaser performs two forced revolutions around the debris at twice the orbital rate (about 3000 s). The first one is performed in the orbital plane while the next one is located in the plane defined by the along-track and cross-track axes. The two revolutions are phased such that they take place during Sun-lit periods (before and after one eclipse).

**PRISMA heritage:** The PRISMA/FFIORD heritage is twofold (GNC algorithms, metrology data). Given the various developments performed for PRISMA nominal and extended experiments, most of FFIORD GNC algorithms are reused with slight adaptation or tuning.

**Table 5: FFIORD heritage overview**

<table>
<thead>
<tr>
<th>Scenario phase</th>
<th>FFIORD heritage</th>
<th>New development</th>
</tr>
</thead>
</table>
| Medium range operations   | - Angles only navigation algorithm  
- RDV guidance  
- VBS model updated using flight data collected | N/A                            |
| Short range operations    | - Metrology transition handler  
- LIDAR navigation (position only)  
- Guidance  
- Forced position control | - LIDAR model  
- LIDAR data processing algorithm |

**Angles only navigation:** Angles only navigation relies on an alternate algorithm that was implemented but not used during flight experiment #1 since it was not sufficiently validated. Nevertheless, it was available in the ground processing toolbox to perform comparisons of navigation algorithm behaviour using telemetry data. This algorithm constitutes an adaptation of the already existing navigation function that processes the radio-frequency sensor measurements (addition of tabulated functions to express the range dependency of the state and noise covariance) [16]. The filter tuning principle is similar to the one used during the flight experiment with some exceptions: the magnitude of the state noise covariance can be reduced due to a more accurate modelling of the relative dynamics.

**VBS model:** such a model was previously developed for one of the FFIORD experiments and its representativeness level was satisfactory. However, the flight experiment allowed to identify some phenomena that affected the performance at different ranges (false detection, temporary bias due to CCD blinding effects) that were considered relevant enough to be included in the model. An error pattern was actually built from the collected metrology data and directly added to the current model output with a range dependent coefficient.

**LIDAR navigation and transition logics:** The LIDAR navigation function processes the 6D relative position/attitude measurement set provided by the LIDAR perception layer which is further described in the sequel. The navigation function relies on the same flight algorithm used to process the FFRF and later on the Close Range VBS measurements (metrology transition experiment). In its current version, the filter processes only the relative position information since it does not run any relative attitude states. Filter tuning is of course adapted to take into account the specific LIDAR error model. Navigation is performed at 1 Hz.

**Guidance and Control:** The guidance algorithm developed for the µ-NEAT pathfinder experiment allows to generate linear trajectories in a frame that is rotating with respect to the LVLH frame (it was flight demonstrated for the inertial frame case). The same algorithm is used therefore to specify the circular trajectories around the debris: the first rotation to be performed in the orbital plane is obtained by requesting a fixed position in a rotating frame that is defined by 3 parameters (the rotation axis coordinates multiplied by the orbital rate). The FFIORD LQR control algorithm that includes a model of the dynamics in the LVLH frame is reused as well to follow the different trajectory profiles. To improve control performance, the feed forward gains are updated for each type of profile and their
computation requires the modelling of the system with augmented states that represent the evolution of the desired position/velocity in the LVLH frame. Control activation period is 50 s.

For this study, the new simulator functionalities to be developed were the model of the LIDAR instrument and the associated perception algorithm to be embedded in the GNC suite. In this preliminary version, these two modules were developed but not integrated in the simulator due to their high computational load. The LIDAR model that generates depth images of the scene relies on ray tracing techniques. These images are then used by the data processing algorithm to extract the relative 6D coordinates while taking into account the satellite CAD model. These two models were used to consolidate the range dependent error model that was elaborated analytically and described herebelow for the Tango S/C case. The ranging error model considered is: 10 cm bias, 5 cm (1 σ) noise for all ranges. An approximation of the 3D error model is given here below for a 15 m range irrespective of the target attitude.

<table>
<thead>
<tr>
<th>Error type</th>
<th>X &amp; Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias (m)</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>1 σ Noise (m)</td>
<td>0.06</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Presentation of results: This scenario which total duration is 66000 s has been run several times and we present here-after the typical performances obtained during the subsequent phases: rendezvous with angles only navigation, final approach after transition into LIDAR navigation, inspection with forced revolutions around the debris.

The new trajectory profile offers a better range observability due to the presence of cross track maneuvers (the amplitude is first increased to 100 m and later decreased to 50 m then 20 m). The filter performance shows a satisfactory behaviour with a range error ratio going quickly down to 2-3% and remaining at that level until the LIDAR handover. The impact of the 20% data loss due to eclipses is minimal and is only observable at short range with peaks on the range uncertainty ratio (Figure 12.2).
Figure 13.1: LIDAR image of Tango S/C seen at 15 m range with a 30° FOV

Figure 13.2: Delta-V usage during inspection phase (red parts = revolutions around target)

Figure 14.1: Inspection profile with 2 revolutions at twice the orbital rate at 15 m distance

Figure 14.2: Position control error in LVLH frame during the inspection phase

Evolutions are being implemented to include the LIDAR numeric simulator in the loop and evaluate position control performance during station-keeping phases in the reference frame of the slowly rotating debris. The next step will consist in implementing vision based navigation for the short range operations and compare the achievable performance with respect to LIDAR. These preliminary results show anyway that the combination camera + LIDAR constitute a relevant approach to perform rendezvous and proximity operations prior to capture. They illustrate also the applicability of the PRISMA/FFIORD experiment output.
5. Conclusion

PRISMA extended mission enabled CNES to pursue its demonstration effort that was initiated in the formation flying domain and focused on radio-frequency navigation. Three new experiments were performed to exercise more challenging tasks in formation flying as well as autonomous rendezvous and this involved the addition of optical sensors in the loop.

The first experiment brought additional evidence that vision based navigation in Low Earth Orbit represent a valid technique to perform rendezvous with non cooperative objects. Four consecutive rehearsals with ranges up to 10 km down to 50 m were successfully performed under realistic conditions of initial uncertainty. Using collected flight data, complementary runs in replay mode have also shown the technique robustness in presence of data loss and larger uncertainty as well as its potential of improvement through some limited adaptation.

The second experiment involved transitions between radiofrequency and optical metrology at short range in several scenarii to acquire knowledge on the metrology, navigation and control issues that could occur in similar phases during future formation flying missions. Even though the second stage was not a real FF sensor candidate, the successful experiment allowed to exercise in the real world the filter tuning tasks and increase the maturity level of the software involved.

The third experiment enabled to emulate the type of manoeuvres that will be required in future astrometry FF missions represented by the NEAT/µ-NEAT concepts. The formation was pointed successively to a set of celestial targets and the configuration was maintained fixed during time slots representing observation phases with a control stability better than 4 cm (1σ). Under such stringent environmental and operational constraints, the good functional behaviour and performance level constitutes a blatant illustration of the margins that should be available when going on a higher orbit and using finer equipment for both metrology and actuation.

This paper has evoked the benefit of these experiments for future applications and illustrated particularly their relevance for the active debris removal domain. Here, a representative mission scenario spanning the rendezvous and inspection phases was implemented on a numeric simulator that was built within a short timeframe using the output from three experiments: (1) the GNC system relied entirely on functional bricks developed and already flight validated (2) the collected metrology data allowed to improve the fidelity of the sensor models. Simulation results and preliminary discussion were presented to illustrate this continuing work and outline the value of PRISMA/FFIORD heritage.

Finally, as regards formation flying and specifically challenging missions such as NEAT, another possible work axis may consist in reusing the RF metrology data in order to extrapolate the system behaviour during the formation acquisition and re-pointing phases with different spacecraft and environment characteristics. This modest effort would allow to anticipate the achievable level of performance with the current technology on less perturbed orbits and participate to the promotion of these missions. Nothing will replace however the demonstration of positioning accuracy down to the millimetre range as it is envisioned for the future Proba3 technology mission [18].

References


