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FLIGHT RESULTS FROM PRISMA FORMATION FLYING AND RENDEZVOUS DEMONSTRATION MISSION

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The PRISMA in-orbit test-bed for Formation Flying and Rendezvous technology was launched on June 15, 2010. The Swedish Space Corporation (SSC) is the prime contractor for the project which is funded by the Swedish National Space Board (SNSB) with additional support from the German Aerospace Center (DLR), the French National Space Center (CNES) and the Technical University of Denmark (DTU). The PRISMA mission consists of two spacecraft: Mango and Tango, launched clamped together and separated in space. The Mango spacecraft is 3-axis stabilized and is equipped with a propulsion system providing full 3D orbit control capability. Tango is also 3-axis stabilized but with a simplified solar magnetic control system, and has no orbit control capability. The mission consists of a series of experiments mainly in the Guidance Navigation and Control (GNC) domain, demonstrating various aspects of formation flying and rendezvous which can be considered key technologies for future missions addressing tasks where multi-satellite technology must be mastered. The spacecraft are equipped with GPS, RF-sensor and Vision Based navigation systems and has three different types of propulsion. The different GNC experiments are conducted by the participating organizations. These consist of Autonomous Formation Flying (based on either GPS or RF sensor), Proximity Operations with Final Approach/Recede Manoeuvres, and Autonomous Rendezvous. Interleafed with the GNC experiments, flight demonstration of the novel motor technologies are carried out. The first two weeks in space were allocated to a thorough system checkout on both spacecraft, with Mango and Tango still clamped together. Tango was then separated from Mango on August 11, after which real formation flying started. The formation control and safety heavily depends on the GPS based relative navigation system. The system has after certain adjustments proven to be stable and accurate down to sub-decimetre level in favourable conditions. By the beginning of September 2010, all essential equipment on the two satellites has been fully commissioned and the initial parts of the Autonomous Formation Flying in closed loop has been initiated. The mission will continue with more and more advance experiments up to a total experiment time of approximately one year. It is expected that propellant will remain after the nominal mission. The possibility exists to extend the mission with other innovative formation flying experiments.

I. INTRODUCTION

The PRISMA formation flying and rendezvous technology mission was launched on June 15 and has passed the early operations and commissioning with flying colours. This paper presents a short recapitulation of the mission description and goals and gives an overview of the project from the launch campaign in Yasny, thought the launch and early operations up to the present status where more complex formation flying experiments just have begun.

The PRISMA mission is a technology demonstration mission with the primary purpose of demonstrating formation flying and rendezvous technology, both in terms of Guidance, Navigation and Control (GNC) software and algorithms, but also in terms of new instruments and operational aspects. For this purpose, PRISMA consists of two spacecraft: Mango and Tango. Both spacecraft are 3-axis stabilized where Mango uses a traditional star-tracker / reaction wheel based control system, while Tango implements solar magnetic stabilization strategy. Mango is equipped with full 3D orbit control capability while Tango does not have any means of controlling its orbit at all. In this way, Tango acts as a rendezvous target for Mango.

The mission also acts as a demonstration flight for several other key technologies and developments at Swedish Space Corporation (SSC), of which the new "High Performance Green Propellant" propulsion system is the most important.

PRISMA is funded by the Swedish National Space Board (SNSB) with additional contributions from the German Aerospace Center (DLR), the French Space Agency (CNES), and the Technical University of Denmark (DTU).

Swedish Space Corporation is the prime contractor for the mission and has been responsible all design, developments, integration and verification activities, with the exception of the GPS-based navigation system (H/W and S/W) by DLR, the Radiofrequency instrument (FFRF) development by CNES and the Vision based instrument by DTU. SSC is also responsible for the operations.

The mission purpose is primarily to demonstrate, via experiments in flight, technology related to either formation flying and rendezvous technology (GNC related or sensors), or propulsion technology. All partners are involved in designing and conducting one or several of these in-flight demonstrations.

For further overview of the mission objectives and mission description, see 1) and 2)

II MISSION DESCRIPTION

The PRISMA mission consists of two satellites: Mango and Tango. The Mango satellite is 3-axis stabilized and has full 3D delta-V manoeuvrability independent of the spacecraft's attitude. A hydrazine propulsion system with 6 thrusters is implemented on Mango and has approximately 120 m/s delta-V capability. The central body of MANGO has exterior dimensions 750×750×820 mm. When deployed, the distance between the tips of the solar panels is 2600 mm.

The Tango satellite has a simplified, yet 3-axis stabilizing, magnetic attitude control system and no orbit manoeuvre capability. The Tango body is 570×740×295 mm.

The wet mass of the two spacecraft is 195 kg. Mango is 145 kg and Tango is 40 kg.

Figure 1 shows an impression of the two PRISMA spacecraft close to each other in orbit.

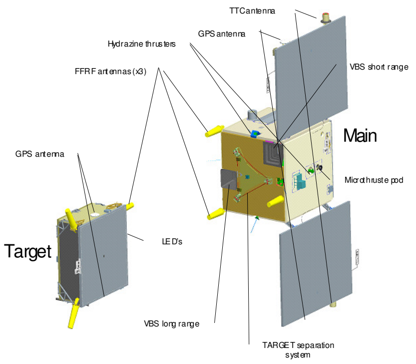

Fig. 1: Mango and Tango layout in flight configuration

PRISMA is launched into a sun synchronous orbit with 725 km altitude and 0600h ascending node. Mango and Tango spacecraft are launched clamped together. Tango is separated from Mango, after an initial commissioning campaign during which all on-board equipment, nominal as well as redundant, is checked out. The separation of Tango is observed with Mango's on-board Digital Video System (DVS).

During the whole mission, ground only communicates with Mango. The TM rate is approximately 1 Mbps. Mango in turn communicates with Tango via an intersatellite link (ISL) with a data rate of 19.2 kbps up to at least 10 km,

After Tango separation, a series of manoeuvring, sensor and motor experiments starts. A detailed description of the mission experiments can be found in 1), 2) and 7). This sequence of experiments is planned in increasing order of complexity and difficulty, and in a way which give an early harvest result for each experiment group in case something would go wrong in the mission.

The primary experiments consist briefly of GNC experiments as in Table 1, and H/W (sensor and actuator) related experiments listed in Table 2.

GNC Experiment Sets	
Passive formation flying	
Autonomous formation flying (AFF)	SSC
Autonomous formation control (AFC)	DLR
RF-based formation flying	CNES
Forced motion	
Proximity Operations (PROX) Final Approach and Recede (FARM)	SSC
Forced RF-based Motion Collision Avoidance	CNES
Autonomous Rendezvous (ARV)	SSC

Table 1: GNC related experiments and responsible organization

Hardware Related Tests	
HPGP Motor Tests	SSC/ECAPS
Microthruster Motor Tests	SSC/Nanospace
Vision Based Sensor (VBS)	DTU
RF Sensor Test	CNES

Table 2: H/W related experiments and responsible organization

The AFF experiment run by SSC can be considered as the hub in the GNC mode architecture, from which the other GNC experiments can be called in.

The most complex functionality is considered to be the VBS autonomous rendezvous (ARV, see 9)) during which the far range detection capabilities of the VBS is examined at up to 100 kilometres and from which a fully autonomous rendezvous with Tango is performed down to sub-meter distance.

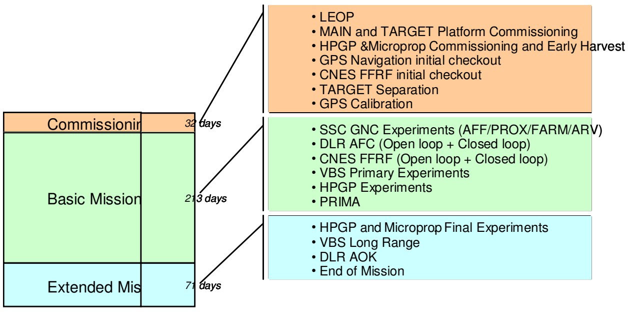

Fig. 2: Overview of the mission timeline and experiment

The mission is planned over a total experiment time of around 320 days, see Fig. 2.

III. THE MISSION STATUS FROM LAUNCH TO PRESENT

III.I Launch campaign and launch

The PRISMA satellites, and the co-passenger, the CNES satellite Picard, were in principle ready for launch on the Russian Dnepr rocket already in the beginning of 2010. However, due to various intergovernmental issues between Russia and Kazakhstan regarding launch authorizations, the launch campaign in Yasny, Orenburg region Russia, did not start until May 20.

Fig. 3: Mango and Tango mated to each other in the background, Picard in the foreground. Mounting into the Dnepr SHM is ongoing

When finally in Yasny, the launch campaign was conducted in a very efficient manner. Due to a very modern and well organized launch facility, but also due to a small and extremely efficient launch team and good cooperation with the Russian/Ukrainian teams. The whole campaign was conducted in 20 days from arrival to final encapsulation by the Dnepr Space Head Module (SHM). Considering that there were two complex satellites, Mango and Tango to pass a complete system and functional check, and that three (!) propulsion systems were pressurized and filled, (the micro-propulsion cold gas system, the HPGP system and the nominal Hydrazine system), assemble the two satellites together and into the Dnepr SHM, this must be considered to be a very efficient launch campaign.

III.II LEOP and Commissioning

On June 15 at 14:42 UTC, the PRISMA and Picard were launched successfully into the specified dawn-dusk sun synchronous orbit on approximately 725 km altitude. The launch injections were exactly as planned and the orbits were very close to nominal.

The first contact was made from the Mission Control at SSC in Stockholm already on the first orbit, around 70 minutes after launch, via the ground antennas at Esrange in the northern part of Sweden. It could quickly be concluded that Mango had started up nominally, deployed its solar panels, and had oriented itself in safe mode to sun and ensured battery charging and good health

The first two weeks in orbit, couple of days, all onboard systems could be checked out. This also included a partial checkout of Tango, still clamped to and powered by Mango. The most important was to conclude that the power systems were healthy with higher than predicted output from solar panels, that the thermal situation was under control, and that the safe mode attitude control and momentum management functions was working robustly. Since PRISMA is an almost fully redundant system on both Mango and Tango, with several cross-couplings and a fairly advanced FDIR implementation, this task took some time and efforts, but it turned out that all systems behaved nominally.

The checkout moved to more and more complex functionalities during the first two weeks. The Star trackers were turned on after a few days and verified to work properly. This enabled the possibility to verify the Safe Celestial attitude mode, essential for all upcoming experiments involving pointing of the Mango satellite, either inertial pointing or pointing to Tango (or any other object).

The plot in Fig. 4 shows the Mango "world plot" where the earth, sun and Tango are located seen from the Mango spacecraft and its coordinate system. The plot is taken during a manoeuvre check and has left the nominal sun-pointing attitude. The Tango position, still clamped on top (+Z) on Mango, is plotted on 90 deg elevation above the X-Y plane, i.e. where it should be. The two eye like figures with the crosses represents the star trackers direction.

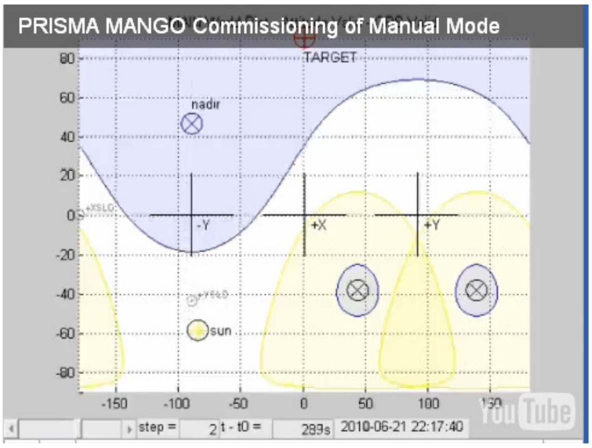

Fig. 4: Mango world plot during a maoeuver check during commissioning. Tango (TARGET) located at +Z, i.e. clamped on top of Mango

An achievement of high importance for the upcoming Tango separation was made already during the commission. The relative navigation between Mango and Tango is based on the GPS navigation hardware/software system implemented by DLR[10, 11, 12]. It could early be concluded that all functional requirements of the GPS-based navigation system were properly met. The GPS messages from Tango are transmitted via the Inter-satellite link to Mango, where the extracted raw single-frequency GPS measurements from the two spacecraft are processed together, achieving a relative positioning accuracy at the sub-decimetre level in real-time. The clamped Mango/Tango configuration offered the unique opportunity to verify the accuracy of the real-time navigation solutions used on-board for GNC purposes and, even more important, the accuracy of the precise relative orbit determination (POD)[13] performed on-ground by DLR. The POD products constitute the baseline verification layer for all GNC experiments conducted in the PRISMA mission. As a demonstration, Figure 5 depicts the comparison between the relative position of the satellites centre of gravity (which is the known true reference in clamped configuration) and the obtained GPS relative navigation results over four hours. Accuracies at the sub-centimetre and sub-decimetre levels are demonstrated post-facto on-ground (Fig. 5, top) and in real-time on-board (Fig. 5, bottom).

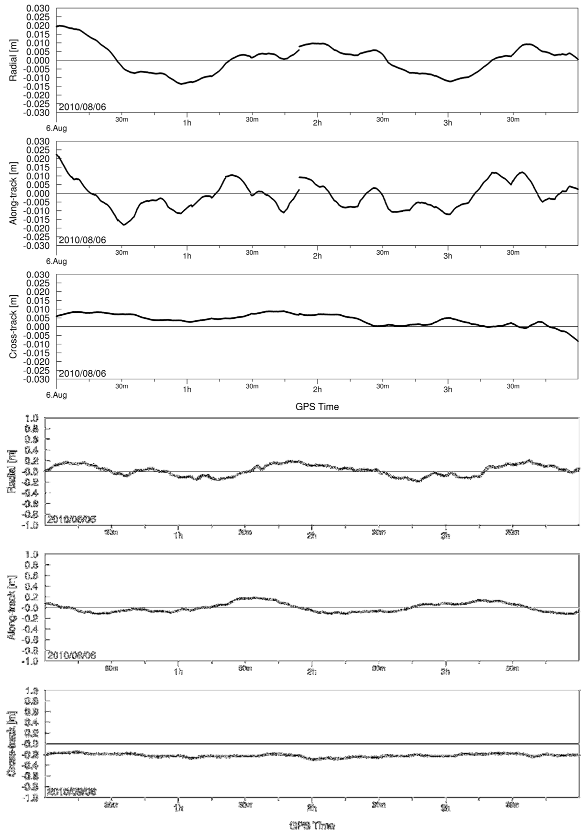

Fig. 5. First relative GPS navigation results with Tango still clamped to Mango. Sub-centimeter level (top) and sub-decimetre level (bottom) relative positioning errors from on-ground POD (top) and real-time navigation system on-board (bottom).

During the first weeks, also the two chemical propulsion systems were commissioned, the Hydrazine and the HPGP. The very high expectation on the newly developed HPGP system was confirmed – thrust could be verified to be as expected, see more in paragraph xxx. The characterization of the thrusters was considered vital in the preparation of the delicate Tango separation activities coming up.

The Digital Video System, a 4 Mpix camera developed by Techno Systems in Naples, was also initiated during the first days, the first picture shows parts of Russia with the still clamped Tango covering a part of the field of view (fig. 6)

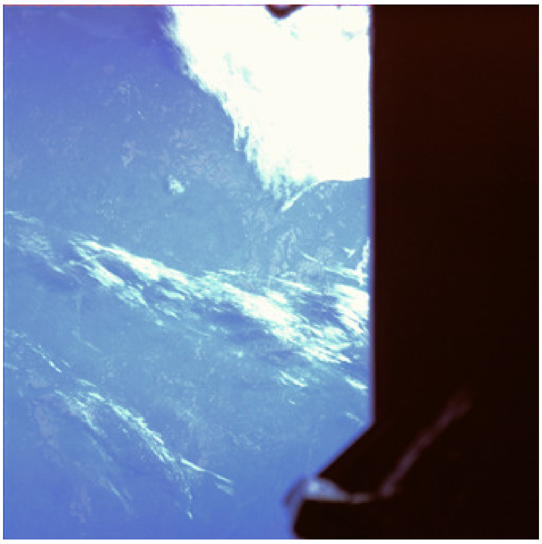

Fig. 6 Russia from Mango DVS camera, Tango to the right.

The whole commissioning period was conducted in only 14 days, an enormous achievement by the Mission control and operators.

III.III Routine operations and Close encounter

The operations went into a routine phase during July in order to allow some vacations to the operations team. (Due to budget constraints, the operations team is extremely downscaled especially for running three shifts Due to the complexity of the mission, the team consists to a high degree of people from the PRISMA system development team, with detailed knowledge about the complex functionality. There are no reserves to call in.)

The routine operations (i.e. to let PRISMA rest in safe mode with very limited monitoring) had only started when an alarm was received from Joint Space Operations Centre, JSpOC:

"*The United States Joint Space Operations Center (JSpOC) has identified a predicted conjunction between PRISMA (SCC# 36599) and SCC# 34544.*"

JSpOC had predicted a collision risk in only 2 days ahead with space debris, with less than 100 m miss distance and with a high uncertainty ellipse around the predictions. A small task force team was called in and together with our partners in DLR/GSOC and JSpOC personnel, an avoidance manoeuvre, consisting of a dV pulse of approximately one dm/s in the right direction, was quickly planned and executed. The actual miss distance became more than 2 km.

III.IV Tango separation

In the first week of August, the preparations for the Tango separation were performed. This operation contained several extremely critical steps and was planned very carefully. This operation had been simulated extensively in the mission simulators in order to prepare for various contingencies. There were many areas to worry about in this operation, among them the following:

- the separation system, function and performance
- the Tango power system and battery capacity
- the Tango attitude control system (ACS) and it's capability to handle the separation rates and tumbling motion, and achieve sun pointing within limited time
- the relative navigation performance and it's capability to establish stable navigation data
- The propulsion system capability to deliver accurate predictable dV impulses

The separation system, a system designed in-house at SSC, has heritage from SSC microsatellites during the 90's, with a few similar systems sold to other projects. It comprises a 3-point system with hooks and clamps that is kept in locked position by a single wire. When the wire is cut, the hooks release the clamps and small springs can push away the opposing part, Tango in this case. Since the original specification in PRISMA prescribed a close to zero separation velocity, the springs were chosen very weak, and the umbilical separation connector was a so called zero-force connector.

The separation sequence was planned in order to direct the separation system dV (predicted to be about 12 cm/s) in such a direction that the along-track separation was small (a few hundred meters per orbit). The along-track drift would then be compensated by a small dV by the Mango S/C. A safe orbit would then be established with small manoeuvres in order to establish an elliptical collision-free orbit around Tango. This strategy would handle the risk posed by e.g. the uncertainty in atmospheric drag coefficients and other perturbing factors.

One set-back just before the Tango separation was the discovery that one of Tango's two battery packs was dead. This led to a crash investigation to find if this was a generic failure expected to appear also on the redundant pack, and which consequences the decreased capacity would have for the upcoming mission events. It was concluded that nothing indicated a generic failure, and that the mission performance was not endangered as long as the redundant battery was alive. It was given GO for separation.

On the afternoon of August 11, the Tango battery was topped up a last time (enabled by an attitude manoeuvre towards the sun), and the command scripts loaded to the onboard queues for initiation of the separation events.

At the next passage, it turned out that the Tango ACS had performed better than expected and that safe sun-pointing attitude with positive contribution to the Tango battery was achieved within single minutes (instead of worst case estimated 50 minutes). It could later be concluded that the tip-off rate of the separation system also had been as expected, i.e. lower than two deg/s.

Just as predicted, Tango drifted along-track with a few hundred meters per second, a motion with was stopped by an accurate dV manoeuvre a few hours later (see fig. 7.

The mission was now into formation flying for real. A safe orbit had been established, with stable relative navigation performance and all systems nominal.

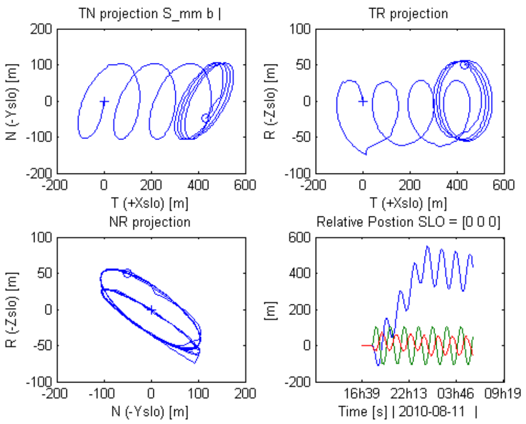

Fig. 7 Relative motion of Mango vs Tango after separation.

The plots in Fig 7 show the relative motion of Mango vs Tango in different projections. A few jumps in the GPS navigation solutions can be seen, that is when the GPS is switched off during passages through the South Atlantic Anomaly.

The separation of Tango from Mango meant also a new thermal configuration for both satellites, especially for Tango - the separation opened up radiator surfaces in parallel with a different power situation. The subsequent thermal checkout demonstrated that the thermal predictions were quite accurate for all configurations.

III.V Tango ACS demonstrates itself

A few days later, Tango ACS[6] also demonstrated the function Zenit pointing, meaning that the slow rotation around the sun vector used adopted in the Tango safe mode was stopped and a real 3-axis pointing with specified antenna pointing to zenith could be maintained. Furthermore, the ACS of Tango was pushed to the limit of its performance – several attitude profiles were uploaded for Tango to follow which was executed very accurately for being a solely magnetic control design. The plots in Fig. 8 below demonstrate parts of this capability.

The demonstration of Tango ACS performance is clearly a main achievement in the mission.

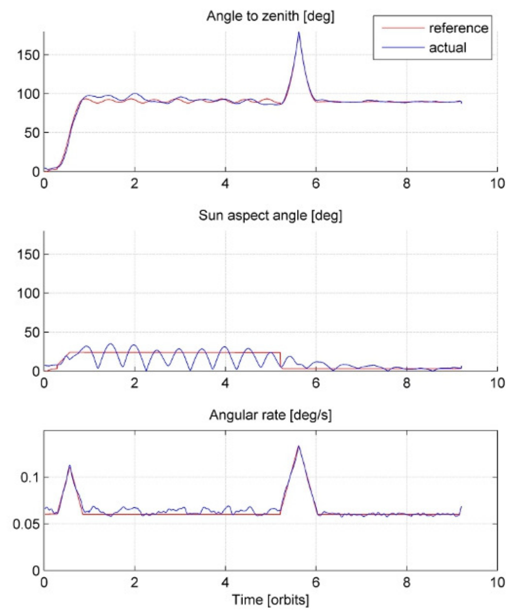

Fig. 8 Tango attitude control performance – result vs commanded reference

III.VI Pictures from the DVS camera

The DVS system took a series of pictures during the separation event, which unfortunately was highly overexposed due to too short experience and evaluation of the different settings options for the camera – the lighting conditions are indeed hard to master.

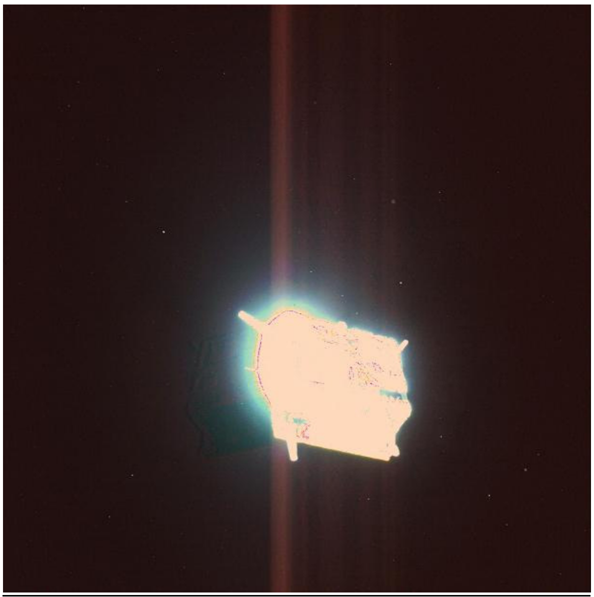

Fig. 9 Tango directly after separation

A few days later, a better picture could be taken from approximately 100 m distance, showing Tango alone against the clack space, and with earth shimmering below.

Fig 10. Tango at 100 m distance

III.VII GPS calibration and performance

An intense period of GPS calibration exercises followed upon the separation event. The first of the DLR's primary experimental slots consisted of a calibration activity dedicated to the characterization and tuning of the GPS-based navigation system. During this experiment the system has been closely monitored under various circumstances which will be encountered during the mission. On one hand the GPS system shall provide the best accuracy to support GNC activities under nominal operations, on the other hand it must be robust and reliable during e.g. frequent orbit control manoeuvres, GPS data gaps, and spacecraft tumbling in a contingency situation. All this could be verified successfully as main outcome of the four days calibration slot.

The post-facto precise relative orbit determination (commissioned during the clamped configuration, cf. Section III.II) has given the possibility to evaluate the real-time navigation errors and, in a second step, tune the navigation filter to obtain the best trade-off between robustness and accuracy. In particular the flight software has been replayed on-ground and fed with the input data (i.e., GPS, attitude and manoeuvre data) generated on-board and available in the telemetry stream. The typical initial and final steps of the tuning process are shown in Figure 11.

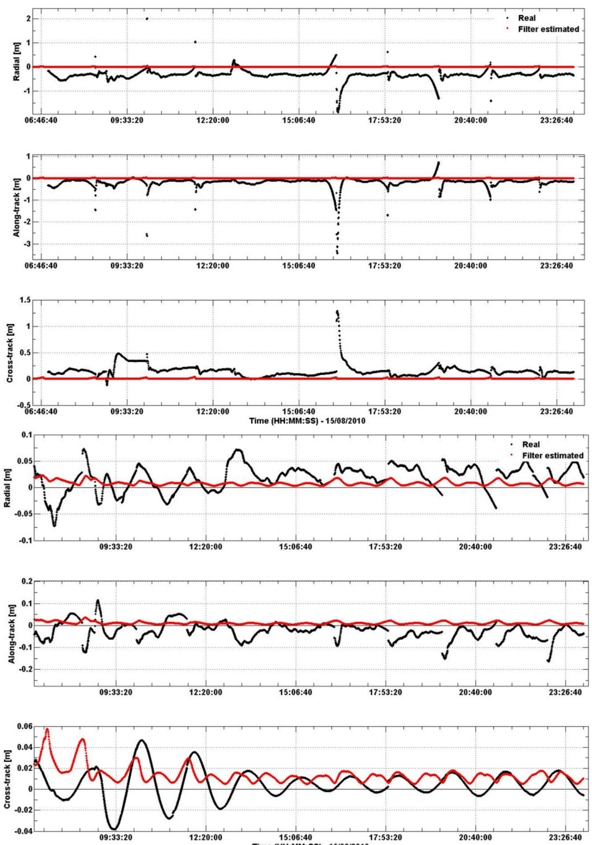

Fig 11. GPS relative navigation error w.r.t. POD (black) and formal covariance (red) before (top) and after (bottom) the tuning process during the GPS

calibration slot. Centimetre level relative positioning accuracy is demonstrated in the presence of frequent data gaps.

A preliminary biased and irregular navigation solution obtained in flight on August 15 (cf. Fig. 11, top) was due to unbalanced filter settings in combination with frequent data gaps over the SAA (South Atlantic Anomaly), where the GPS receivers were switched off. The results after the tuning of the navigation filter (cf. Fig. 11, bottom) show a much smoother error trend over data gaps and a relative navigation accuracy at the centimetre level (one order of magnitude better than before the tuning).

The successful completion of the GPS calibration experiment demonstrates the fulfilment of the prescribed performance requirements and paves the way to the safe and successful conduction of the PRISMA mission.

III.VIII HPGP first test sequence

The in-flight demonstration and performance capability of the HPGP propulsion system[3] incorporates four dedicated test periods during the course of the mission, spread over the mission time. This gives the opportunity to verify performance over time and at different tank pressure (the system works in a blow-down mode).

The first test suite with more than 2000 thruster pulses was carried out during mid August and went exactly according to plan, with pulse durations and duty factors according to the figure below. Approximately 6% of the total fuel of 5 kg was spent on these firings.

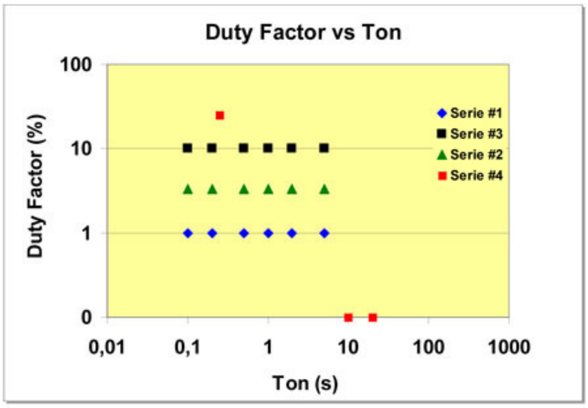

Fig. 12 HPGP first firing test set – duty factors and pulse lengths (Ton).

The evaluation is performed using onboard accelerometers, post manoeuvre evaluation by the DLR-supplied Precise Orbit Determination and the onboard gauging system on pressure and temperature. This initial evaluation indicates that the performance of the HPGP thrusters are just as predicted w.r.t. thrust. Also, the long firings indicate that the specific impulse is also as predicted, i.e. slightly better than for standard hydrazine.

III.IX Micro-thruster system looses pressure

The microthruster experiment has been developed by the SSC subsidiary company Nanospace. The experiment consisted in demonstrating throttelable cold gas microthrusters in the mN range, with highly innovative thruster design etched in silicone wafers and with equally innovative and miniaturized gas management system.

The demonstration of the Nanospace thrusters represented the PRISMA missions first major set-back. When commissioning the system, involving opening up of the miniaturized latch-valve between the gas tank and the pressure regulator and thrusters, it appeared as though the pressure had disappeared. The suspicion that this actually could have happened had already been raised during the early days of the mission. During one 24 hour period 2 days into the mission, a strange behaviour of the onboard momentum management function indicated an external torque on the system. Moreover, the temperature of the Micropropulsion tank dropped slightly in the beginning of this period. The indications are not unambiguous but anyway give ground for the hypothesis that a leak started at this occasion, emptying the tank in 24 hours. An investigation is ongoing for finding the source for the unexpected leak.

Nevertheless, the micropropulsion team managed to demonstrate that the thruster hardware and control electronics functioned as expected, opening and closing microvalves and managing thermal control in the thruster pods. Unfortunately, this potential success could not be manifested in real thrust demonstration due to the non/existing pressure in the tank.

III.X Autonomous Formation Flying

At the writing of this paper, the Autonomous Formation Flying (AFF) experiment by SSC has been ongoing for around one week.

The purpose of the AFF experiment is in short to demonstrate the Mango capability to, autonomously and in closed loop with navigation input from the onboard GPS system, plan and execute fuel-optimal manoeuvres[15] in order to maintain, reorient or shift its relative orbit vs Tango.

The demonstration started on August 27 with a few days of Open Loop checkout, where reference orbits were commanded, but dV manoeuvres calculated onboard were blocked from being executed and instead double-checked vs. commands computed on ground.

After concluding that the onboard algorithms seemed to be robust, on September 1, Mango was fully authorized to make its own decisions on when, how long and in which direction a dV burn was to be applied in order to establish and maintain the constellation geometry commanded from ground. Two reorientations of the constellation were performed on this first day of closed loop control. Both maneuvers were successfully executed, involving changing eccentricity, inclination and along-track distance between Mango and Tango. The later reorientation involved increasing the distance from about 800m up to 5km. The transfer had been designed to take nine orbits and required three short correction pulses of about 0.6 seconds burn time in total (about 3 mm/s correction in total). This was in line with the validation simulations performed for this scenario.

Fully autonomous closed loop control had been demonstrated for the first time. The results of the experiment is described further in detail in another IAC-2010 paper (session C.1.5)

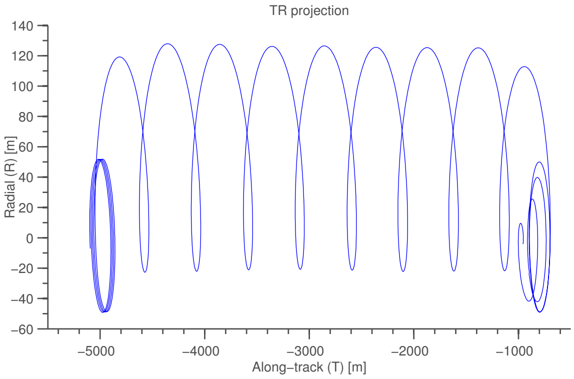

Fig. 13: First two closed loop AFF reorientations, view from the orbit normal.

III.XI The FFRF instrument commissioning

Among the partner contributions, PRISMA accommodates the CNES Formation Flying In Orbit Ranging Demonstration experiment (FFIORD)[5] that will validate new technologies for autonomous rendezvous and close range formation flying of spacecraft. The cornerstone is a Radio Frequency sensory system (FFRF) developed by Thales Alenia Space under CNES and CDTI funding. The system is designed for the future outer space FF missions, and its flight characterization represents the first objective of the CNES experiment. FFIORD also includes a complete Guidance, Navigation and Control system (GNC) that is based on this unique sensor and capable of performing sequential operations like formation acquisition, relative orbit-keeping, precise proximity trajectories and safing manoeuvres upon anomaly detection.

Flight experiments performed so far were devoted to the commissioning of the FFRF sensor as well as the Navigation function. Since August 30th, the subsystem has been put through a series of functional tests and has proven quite resistant to different contingency scenarios (link breakdown, power switching, etc.). Thanks to AFF trajectory control from SSC, the instrument has been tested in a wide spectrum of satellite configurations (range from 30 meters to 10 kilometers, various attitudes with MANGO orbiting around TANGO).

Figure 1 shows the FFRF fine distance measurement over a 14 hour period starting at 1:00 am on September 3rd, when MANGO moves away from TANGO on a corkscrew trajectory. Results are compared with the GPS POD (Precise Orbit Determination) data provided off-line by DLR. Preliminary performances are satisfactory, with a mean bias around 10 cm, and a noise level smaller than 1 cm (STD) outside the SAA (South Atlantic Anomaly where the GPS is off – marked in red).

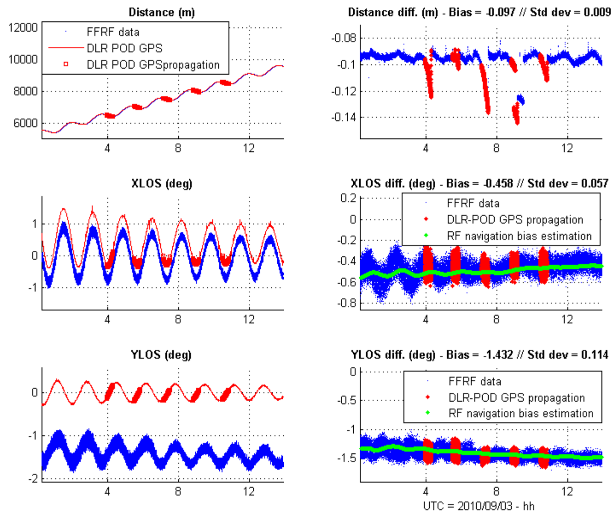

Fig. 14. Distance and LOS measurements from FFRF instrument.

The bias variations are due to internal instrument artifacts (temperature and AGC variations) as well as multi path effects that will hopefully be corrected through instrument calibrations, still to be performed.

Figure 1 shows also the precision of the line of sight (LOS) measurements representing the direction of TANGO with respect to the MANGO satellite. In this scenario, with MANGO flying behind and pointing towards TANGO, the XLOS measurement matches with the in plane component and the YLOS measurement coincide with the across plane component of the vector pointing towards TARGET. Results are equally encouraging with less than 0,01 m (< 0,6 °) bias in the orbit plane and less than 0,025 m (< 1,5 °) bias across the orbit plane. This bias is well estimated by the CNES on board navigation filter (green curve), and can thus be corrected for, leaving only the noise which is less than 0,2° on both axes!

The satisfactory performance of the CNES onboard navigation filter is confirmed on Figure 15, which shows the first real-time estimation of the relative position of MANGO with respect to TANGO. Position error is less than 3 cm along track (X) and less than 12 cm in nadir direction (Z), compared to GPS POD data. The cross-track (Y) error is relatively large, reaching 6,4 m after the application of a delta-v maneuver. However, this error is expected to be reduced significantly once the filter parameters are tuned.

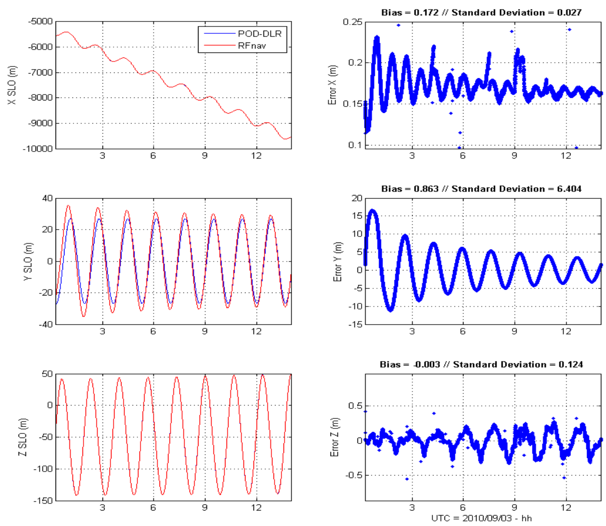

Figure 15: RF Navigation performances

This commissioning session is to be shortly followed by the multi-path calibration of the instrument that will require some specific attitude and relative trajectory profiles. The knowledge of these biases will help to improve the measurement accuracy and will be applied before starting the first FFIORD closed loop formation flying experiments in October.

III.XII Vision Based Sensor

Many of the upcoming advanced GNC experiments by SSC (PROX/FARM, Autonomous Rendezvous) are based on the Vision Based Sensor (VBS)[8], supported by DTU.

At the time of this paper, the evaluation of the VBS cameras (Close and Far range cameras) has just begun, but has not arrived to any advanced results yet. The work is up to now focussing on calibrating gains and settings for the Far range camera in preparations for upcoming experiments.

The Figure 16 shows several overlaid images from the Far range camera of Tango on 850 m during one orbit, where the relative orbit motion can be seen as an ellipse. The dotted line represents the calculated direction to Tango based on relative GPS knowledge.

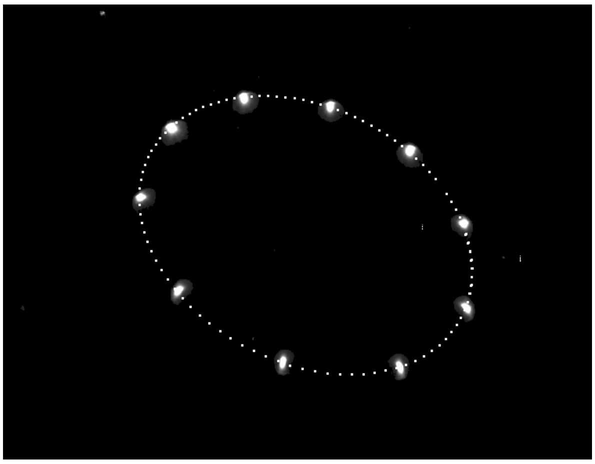

Fig. 16. 10 images of Tango over one orbit seen by the VBS Far range camera (850 mdistance)

IV THE REMAINING MISSION

IV.I The remaining nominal mission

The up-coming experiments according to the planned mission timeline are the following:

- Autonomous Formation Control (DLR)
- Proximity Operations using GPS (SSC)
- FFRF envelope (CNES)
- HPGP 2 (ECAPS)
- FFRF GNC 1 (Closed loop by CNES)
- Proximity Operations using VBS (SSC)
- HPGP 3 (ECAPS)
- Autonomous rendezvous (SSC)
- AFF completion (SSC)
- FFRF GNC 2 (CNES)
- Autonomous rendezvous 2 (SSC)
- FFRF GNC 3 (CNES)
- Autonomous Formation Control 2 (DLR)
- HPGP 4 (ECAPS)
- Autonomous Formation Keeping (single S/C) (DLR)

The planned length of these experiments is approximately 160 days, plus a 30 day period for the single S/C Autonomous Formation Keeping (which will be executed when the formation flying period is declared as finished).

A brief description of the content of these experiments, and the subsequent results, can be followed on the Project web page, www.prismasatellites.se.

IV.II Potential mission extensions

With the good basic performance already proven, there is good ground to believe that the mission will walk through the intended mission timeline without too many unexpected events. In such case, the Mango propulsion systems will still have quite some dV capability left (possibly several tenths of m/s) for extended experimenting in the GNC area. One can in such case envisage different scenarios for such future experiments:

- Extended experiments based on the already existing ones defined by the present main partners SSC, DLR, CNES and DTU.
- Modified experiments, focusing on utilizing the existing experiment GNC S/W from either SSC, DLR and CNES, but with new profiles (extended range, different (re)orientation geometries for formation flying, different rendezvous scenarios, approach vectors, etc etc).
- Completely new experiment profiles based on entirely new S/W in one or several of the domains Guidance, Navigation and Control. Such a scenario is fully possible due to the inherent capability of the PRISMA system to upload and incorporate add-on GNC S/W (after extensive validation in on-ground simulators).

In principle, this opens up the possibility to utilize the PRISMA resources for other organizations interested the formation flying and rendezvous technology, and to suggest potential experiments to be executed on PRISMA after the nominal mission has been finalized.

V. CONCLUSIONS

The PRISMA satellites have been successfully launched and commissioned. Several functions have successfully been tested and proved operational. These functions are e.g.

- the basic platform functions (power, thermal, data handling etc) on both Mango and Tango
- the highly robust GPS-based relative navigation system and the precise orbit determination,
- the basic GNC functions and safe mode autonomy which ensures mission safety
- the robust and versatile propulsion system,
- the flexible onboard S/W allowing for reprogramming e.g. GNC S/W,
- the very promising FFRF instrument performance
- the Mission Control which has proven to master the challenges of planning and executing operations for two closely operating satellites.
- Autonomous formation flying in closed loop which is the hub for all future GNC experiments

As a consequence, the PRISMA mission has proven itself to be as the formidable test bench for advanced formation flying and rendezvous test bench as ever expected.

Additionally, the new HPGP propulsion system has demonstrated the desired performance.

The mission will continue with more and more advanced GNC and sensor experments according to plan.

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