FINAL COMMISSIONING OF THE PRISMA GPS NAVIGATION SYSTEM

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Abstract: *The primary relative navigation system of the PRISMA technology demonstration mission is based on GPS. The PRISMA satellites have been launched in June 2010 and, since their separation in August, have been successfully conducting a multitude of autonomous formation flying and on-orbit servicing experiments. The onboard navigation system relies on GPS measurements to provide in real-time accurate absolute and relative navigation. The output of the GPS-based navigation system is used to feed the numerous on-board feedback controllers and the safety monitoring and collision avoidance functions. As a consequence the navigation system has to provide the utmost accuracy to the experimental payloads and, at the same time, be robust and reliable to support fault detection isolation and recovery tasks. The commissioning of the GPS navigation system is therefore a crucial milestone for the mission. It has to be ensured that the on-board navigation solution is always reliable even in the presence of hardware anomalies and that the navigation performance satisfies the mission requirements. The performance assessment is done using precise orbit products generated by a ground facility for GPS-based precise orbit determination which needs, in turn, to be also commissioned. The paper summarizes the commissioning activities performed to validate both precise orbit products and onboard navigation and presents key flight results to illustrate the overall system performance.*

Keywords: *PRISMA, GPS-based Navigation, Precise Orbit Determination.*

1. Introduction

The successful launch of the PRISMA satellites on June 15th, 2010 kicked off the era of autonomous formation flying in Europe. PRISMA is a precursor mission for critical technologies for formation flying and on-orbit-servicing. The objective of the mission is to enable the validation of sensor and actuator technologies related to formation flying and the demonstration of experiments for formation flying and on-orbit servicing. PRISMA is designed and implemented by the Swedish Space Corporation (SSC) with international contributions from CNES (France), DLR (Germany) and DTU (Denmark). Key sensor and actuator components [1] comprise a GPS receiver system, two vision based sensors, two formation flying radio frequency (FFRF) sensors, and a hydrazine thruster system. This equipment enables the demonstration of autonomous spacecraft formation flying, homing, and rendezvous scenarios, as well as close-range proximity operations.

The PRISMA spacecraft are named Mango and Tango and were injected into a dusk-dawn, sun-synchronous orbit at 757 km altitude and 98.2° inclination. After launch the two spacecraft have been staying in a clamped configuration for initial system checkout and preliminary verification (cf. Fig. 1) until August 11th, the date of the spacecraft separation. The successful separation of the spacecraft was the starting point of the formation flight, during which various experiment sets for formation flying and in-orbit servicing are being conducted within a mission lifetime of about ten months. Spacecraft operations are performed remotely from Solna, near Stockholm, making use of the European Space and Sounding Rocket Range (Esrange) ground station in Kiruna in northern Sweden.

The Mango and Tango spacecraft belong both to the class of small satellites. In contrast to the highly maneuverable Mango spacecraft, Tango is a passive and much simpler spacecraft. The Mango spacecraft implements a three-axis, reaction-wheel based attitude control and three-axis delta-v capability. The Tango spacecraft applies instead a coarse three-axis attitude control based on magnetometers, sun sensors, and GPS receivers, with three magnetic torque rods as actuators.

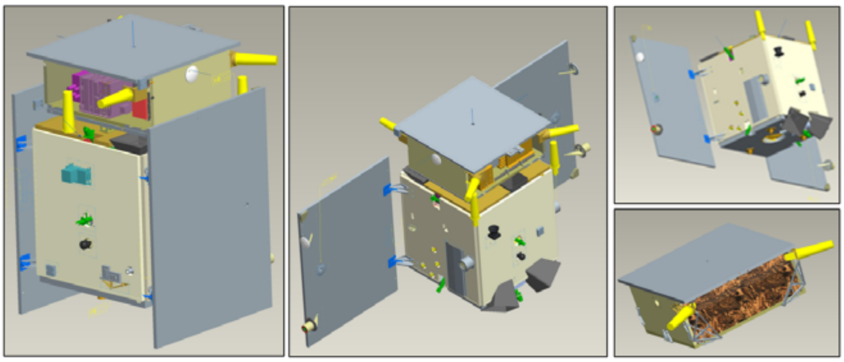

Figure 1. PRISMA clamped configuration after launch (left), with the Mango solar panels deployed (center), and the individual Main (right-top) and Tango (right-bottom) spacecraft when separated. Courtesy of SSC.

The onboard GPS navigation system is contributed by DLR and provides the primary reference for absolute and relative position measurements. GPS-based orbit products are in addition intensively used for the validation and calibration of other relative navigation sensors. Each of the PRISMA satellites is equipped with a cold-redundant set of Phoenix GPS receivers [2]. The receivers are each equipped with a low noise amplifier and cross-connected via a relay to a pair of GPS antennas on opposite sides of the spacecraft (Fig. 2). In this way, GPS tracking can be ensured in all foreseen attitude modes of the PRISMA formation. During the flight the spacecraft select automatically the antenna to be used, depending on the orientation of the antenna to maximize GPS constellation visibility. This automatic antenna switch is only possible when attitude estimation is available onboard.

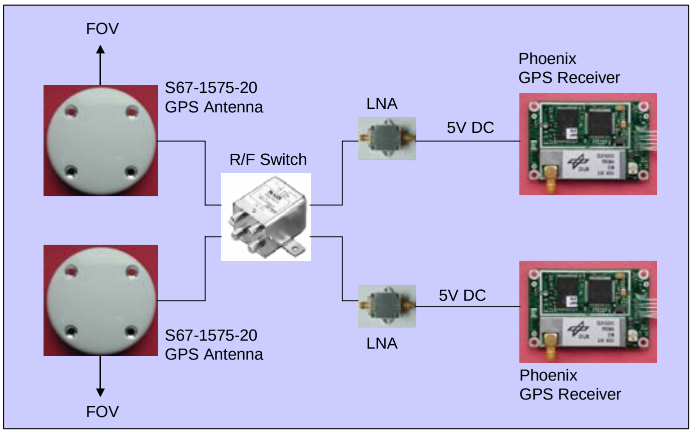

Figure 2. Phoenix GPS system on Mango and Tango.

As part of the GPS navigation system, Mango embarks an advanced onboard real-time navigation filter [3] able to bridge data gaps. The filter processes the raw measurements provided by the receivers to deliver in real-time accurate absolute and relative navigation solutions at the meter and decimeter levels respectively. The GPS measurements from Tango are transmitted in real-time via an inter-satellite link to Mango. The GPS navigation system of PRISMA is finally complemented on ground with a facility for precise orbit determination (POD) located at the German Aerospace Center (GSOC) premises, which serves as verification layer for the routine monitoring of the performance of the GPS navigation system and as ultimate reference for the knowledge of position. The POD facility uses more advanced techniques to generate routinely highly accurate orbit products. The resulting relative positioning accuracy goes down to the (sub-)centimeter level. Even if they share the same source of measurements, namely the GPS observations, the on-board navigation and on-ground orbit products differ greatly in their processing techniques, so that the orbit products can be utilized as independent reference to analyze the onboard navigation.

The paper focuses on the result of the commissioning of the GPS navigation system, which took place formally right after the separation of the spacecraft in August 2010. Additional flight results coming from the first months of operations are sometimes included to help the reader gaining a better overview of the system capabilities under various conditions.

2. Hardware Check-out and Verification

The first commissioning activities conducted after the launch of the spacecraft have been dedicated to the verification of the GPS hardware system [4]. It has been checked that the GPS receivers on Mango and Tango in the main and redundant branches, i.e. a total of 4 receivers, were working properly and that the desired antennas could be successfully automatically selected. At a hardware level, the commissioning focused on the tracking capabilities and on the overall performance of the GPS receivers. The fact that the spacecraft have been flying in a combined configuration has given the opportunity to compare the receiver performance in an environment affected by multipath effects (before the separation) and free from multipath (after the separation). A close look at the combined spacecraft configuration (Fig. 1, middle) and especially at the position of GPS antennas shows that Mango is almost not affected by the presence of Tango (because the Mango antennas are located on the edge of the solar panels), while Tango undergoes heavy multipath effects due to the presence of Mango. This is clearly visible on Fig. 3, which depicts the map of carrier-to-noise ratio in the +X antenna frame of Tango before and after the separation, where the irregular variations of signal strength are due to multipath effects. In addition, shadowing effects are also clearly recognizable, for example the effects of two of the long cylindrical FFRF antennas (painted in yellow on Fig.1) at 210° azimuth.

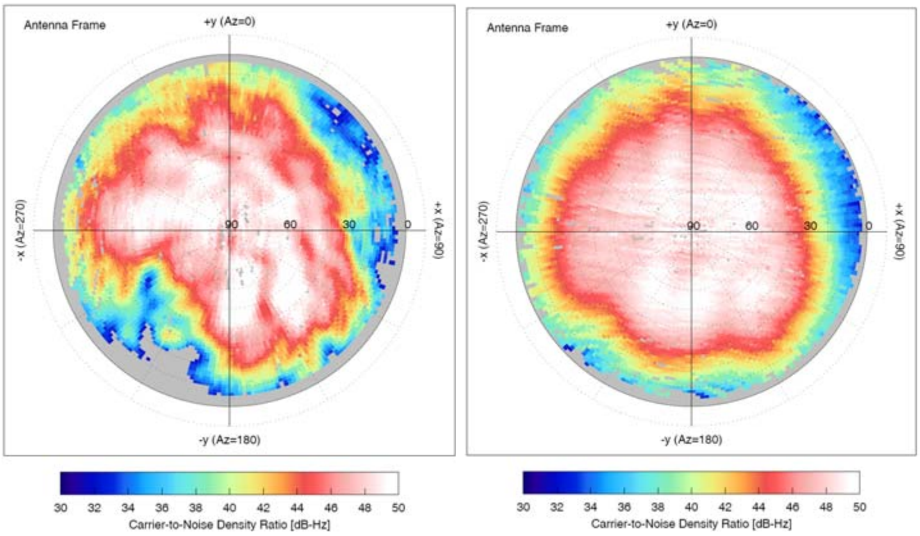

Figure 3. Carrier-to-noise ratio in the antenna (+X) frame of Tango before (left, August 6th, 2010) and after (right, August 21st, 2010) separation.

Similarly, plotting the carrier-to-noise ratio against the elevation (Fig. 4) shows a dramatic improvement of the diagram after the separation. On the contrary, the same plots for Mango do not exhibit any important difference after the separation. They rather show that Mango is *always* affected by multipath (cf. Fig. 5, which shows that the diagrams after separation are less smooth than the ones of Tango). This is probably due to the peculiar configuration of the antennas mounted on the solar panels, which can receive signals reflected on the main spacecraft body. Analyses have even shown that this configuration allows surprising tracking capabilities, where the GPS constellation can be seen from behind when the antennas are pointing towards the Earth [5]. The absence of measurements below 5° elevation (Fig. 4 and Fig. 5) are due to a feature of the Phoenix receiver which rejects all measurements below a certain elevation mask and to the fact that the antennas were zenith-pointing on August 6th and 21st.

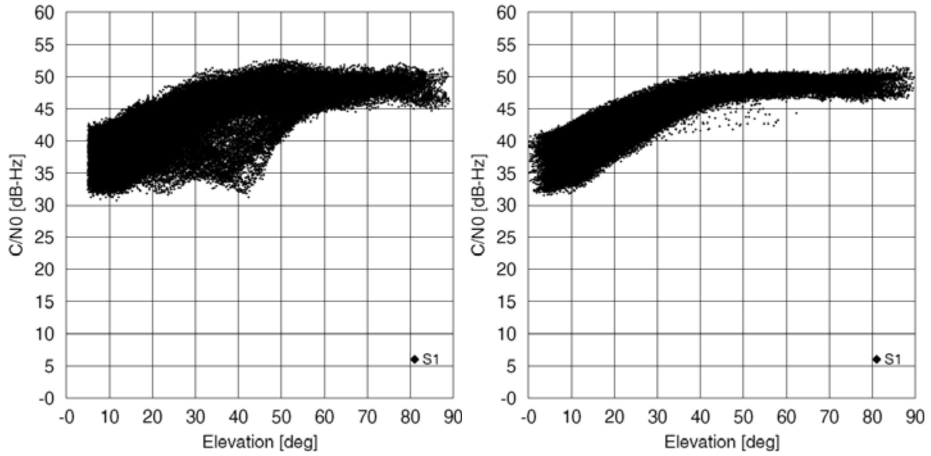

Figure 4. Carrier-to-noise ratio against elevation of the (+X) antenna of Tango before (left, August 6th, 2010) and after (right, August 21st, 2010) separation.

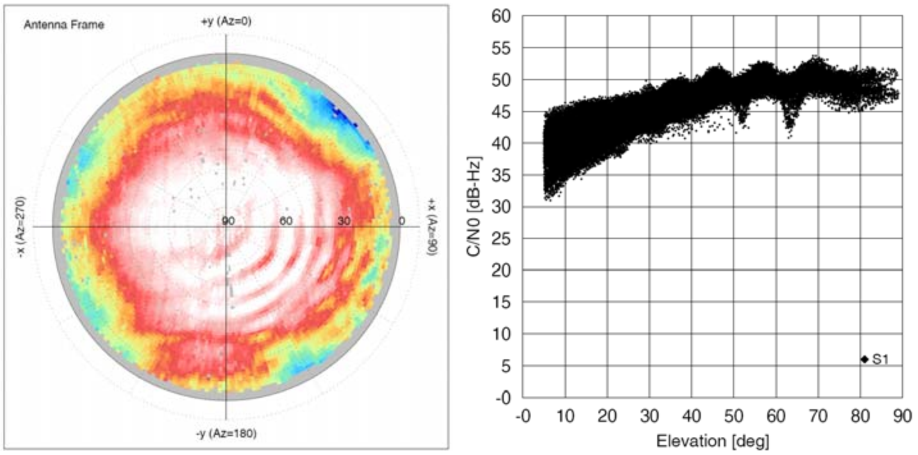

Figure 5. Carrier-to-noise ratio in the antenna frame (left) and against elevation (right) of the (+X) antenna of Mango after separation.

Overall the Phoenix receiver demonstrates excellent tracking capabilities. Thanks to its twelve channels, the receiver tracks on average 10 satellites when the antenna is zenith-pointing (Fig. 6). This makes it very suited to relative navigation, where a high number of commonly tracked satellites is needed. The noise affecting the measurements has been found to be compliant to the values obtained during the pre-flight validation tests done on ground with a Spirent GPS signal simulator [6] (50 cm for C/A code measurements and 0.7 mm for the carrier phase measurements at a representative carrier-to-noise level of 42 dB-Hz).

Special attention has been paid to the hardware reliability. The special role played by the GPS navigation system in the formation safety excludes the possibility of any serious hardware failure. Being based on a low-cost commercial platform, the Phoenix receiver is however not radiation tolerant. Some radiation events (latch-ups) have been detected during the first half year of the mission in the vicinity of the South Atlantic Anomaly, where the density of protons is known to be much higher than its average value. The fact that the Phoenix is prone to latch-ups was anyway known before the launch, thanks to the experience gained in the PROBA-2 mission, which carries as well a Phoenix receiver [7]. The frequency of events in the PRISMA mission (one single event latch-up per receiver every 15 days) is surprisingly much lower than what is observed for PROBA-

2, which seems to indicate that the models of the Phoenix receivers used in PRISMA (so called Phoenix-S receivers) are more resistant to the exposure to radiations. The fact that none of these events was destructive makes these types of anomaly of low criticality. A latch-up can indeed be easily and quickly detected onboard. The recovery is simply done through a restart of the receiver, which can be performed autonomously by the spacecraft Fault Detection, Isolation and Recovery (FDIR). The warm-start procedure offered by the Phoenix allows a recovery of the navigation solution within a few minutes (typically 2-3 minutes) after the latch-up. Sporadic hardware anomalies have been in addition encountered and identified during the first months of the mission (faulty pseudoranges tagged as valid, handling of broadcast ephemerides during acquisition phases) and will be corrected in the next future via a patch of the firmware.

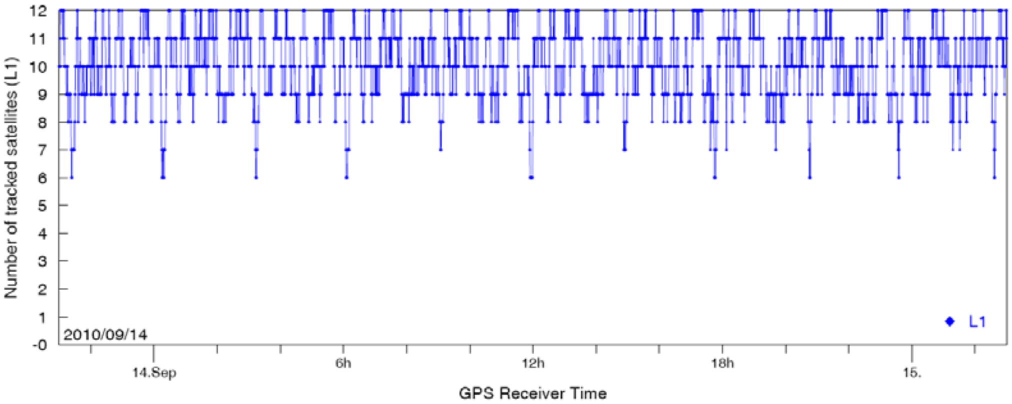

Figure 6. Number of tracked satellites on Mango in zenith-pointing mode (Sept. 14th, 2010).

At a first glance, relying on Commercial-Off-The-Shell receivers (as primary relative positioning sensors) for the mission safety might appear risky. This reliability problem is mitigated in the PRISMA mission by the presence of the real-time navigation filter running on the onboard computer, which is able to bridge data gaps. Thanks to this strategy, the main concern regarding the safety of the formation is no more the probability of hardware failures of the GPS receivers but rather the ability to detect them onboard quickly and to recover autonomously.

3. Commissioning of the GPS-Based Precise Positioning

3.1. Facility for Precise Orbit Determination

The PRISMA POD facility is based on the DLR's in-house GPS High precision Orbit determination Software Tools (GHOST) [8]. This software suite is already used routinely to support many missions (GRACE, CHAMP, TerraSAR-X, TanDEM-X, PROBA-2) and has already proved its high-readiness level as well as its ability to provide reliable and accurate orbit products.

The data processing for precise orbit determination follows the scheme depicted on Fig. 7. First the raw GPS measurements are processed with the Single Point Positioning for Low-Earth Orbit (SPPLEO) program to derive a kinematic navigation solution. The output of the kinematic single point positioning is a discrete set of navigation points affected by errors at the meter level. Second, this kinematic solution is filtered dynamically using a batch least square process, called PosFit, which relies on accurate models of the spacecraft dynamics. Third, a precise orbit determination is done using the previously computed coarse orbit solution for data editing. During the data editing, the coarse reference is used to assess the quality of raw measurements and to select the healthy observations. The program for Reduced Dynamics Orbit Determination (RDOD) implements a least square filter which processes ionosphere free combinations of pseudorange and carrier phase measurements (so called GRAPHIC measurements [9]) to generate orbit products accurate at the meter level for single-frequency receivers. Finally, a filter for relative navigation of satellites

(FRNS) provides accurate relative positioning using the precise orbit products of Mango and Tango as references for data editing. The filter makes use of double difference carrier phase measurements to achieve ultimate relative positioning accuracy. The double difference carrier phase integer ambiguity is solved using the LAMBDA method [10].

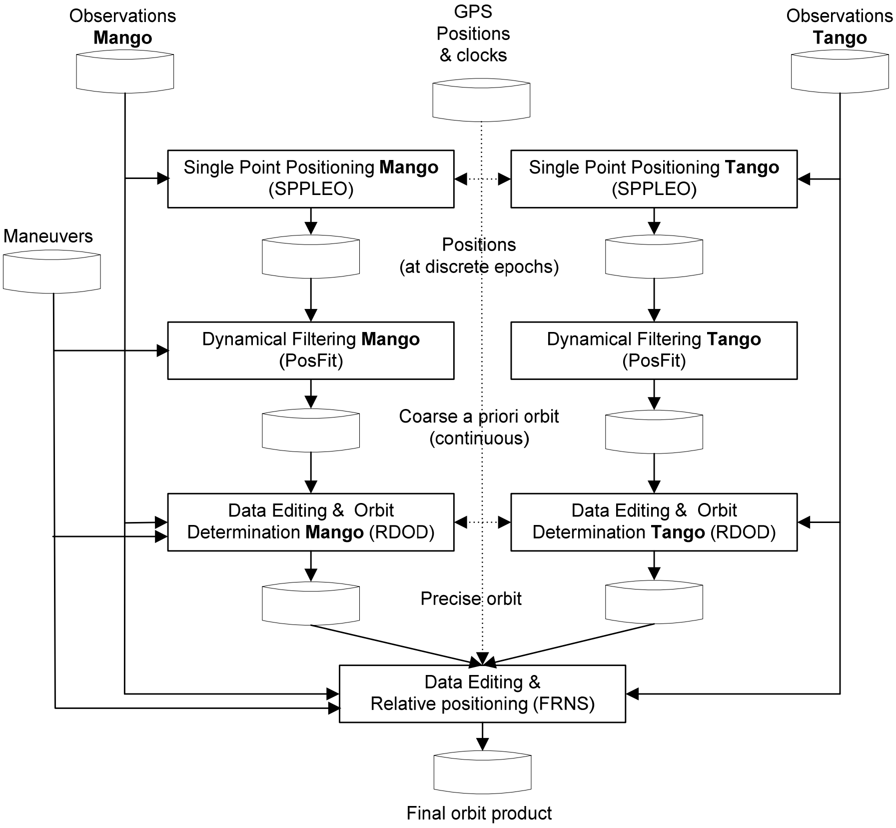

Figure 7. Schematic view of the POD chain.

As depicted on Fig. 7, the POD process requires external data which are either downloaded from the Internet (GPS orbits and clocks, Earth orientation parameters, history of the solar flux,...) or extracted from the spacecraft telemetry data (spacecraft attitude, maneuvers, antenna used to collect the GPS measurements). For simplicity, the spacecraft antenna phase center variations (which can amount to several mm) are not taken into account in this mission.

The PRISMA mission offers many technical challenges when compared with typical space missions: complex and rapidly varying attitude profile, dense thrusting activities, frequent switching of antennas. This unusual complexity makes the routine generation of precise orbit products difficult. In particular the process for relative positioning based on the resolution of double difference integer ambiguities is extremely sensitive. Even if this method provides outstanding results for most of the time, it has been recognized that the scenarios used in the PRISMA mission are sometimes too challenging. For example the large rotations of the spacecraft, during which the number of commonly tracked satellites decreases rapidly, makes the method fail. In order to cope with the high computational load that would be required by the LAMBDA method when processing all ambiguities of a one day arc in a batch estimator, the relative positioning is instead done using an extended forwards-backwards Kalman filter instead of a batch least-square filter [11]. This approach makes it very sensitive to any perturbation of the orbit model. In particular the bridging of data gaps can be successfully done only in the absence of maneuvers during this data gap. These considerations have triggered the implementation of an intermediate mode based on float ambiguity estimation. In this mode the carrier phase ambiguities have float values which are simply estimated as part of the state vector in the Kalman filter. This method is more robust but comes at the cost of a degraded accuracy and is thus used only if the integer ambiguity can not be used successfully.

3.2. In-flight Performance Assessment of the Precise Positioning Products

The GPS receivers are the only absolute positioning sensors of the PRISMA satellites. As a consequence, any direct evaluation of the quality of the absolute orbit products is impossible. It is assumed that the accuracy of the absolute positioning achieved in the PRISMA mission is similar to the one obtained with single-frequency receivers exhibiting a similar noise of the measurements and flying on similar orbits. In particular, being equipped with the same receiver and flying at almost the same altitude and inclination, the PROBA-2 satellite is an ideal reference. Based on satellite laser ranging measurements, it has been demonstrated that the error affecting the orbit products of PROBA-2 should be below 50 cm [12]. The performance of the absolute orbit determination for PRISMA should be similar or even slightly better since the spacecraft attitude is known more accurately on PRISMA (in fact the GRAPHIC residuals obtained during the orbit determination are roughly 25% smaller in the case of PRISMA (Fig. 8)). The figure demonstrates in addition that the noise of the pseudorange measurements amounts to 50 cm (since the plotted noise of the GRAPHIC measurements is only half of the noise of the C/A code).

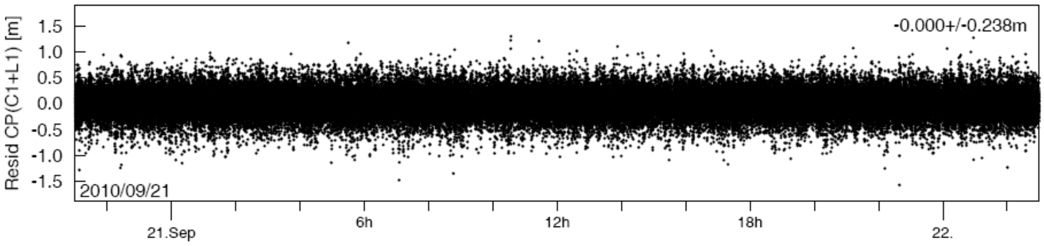

Figure 8. Residuals of ionosphere-free code-carrier combination of Phoenix GPS measurements (Sept. 21st, 2010).

Anyway the quality of the absolute positioning is only of limited relevance for the PRISMA mission. What counts is rather the quality of the relative positioning. The PRISMA satellites embark sensors and technologies for relative navigation which need to be precisely cross-validated. Even if the investigations done during the validation of the POD facility promise relative positioning accuracy at the sub-centimeter level [13], they were still based on simulations. The real world comprises instead much more unknowns which cannot be satisfactorily simulated, like multipath effects or variations of the antenna phase center. Fortunately the PRISMA mission offers a unique opportunity to assess independently the performance of the GPS-based relative positioning, namely the fact that both spacecraft were flying in a clamped configuration before their separation. From an orbit determination point of view the combined satellite is a single big spacecraft comprising two GPS systems (receivers + antennas). In order to assess the performance of the relative orbit determination, it is sufficient to apply the algorithms for precise relative positioning to the same spacecraft using the two different GPS systems (the position of the center of mass of the combined spacecraft is of course different and needs to be properly accounted for). Since the precise relative positioning generated by the POD facility provides the position of the spacecraft center of mass, the position difference between the orbit products should be theoretically always zero.

Figure 9 depicts the results of the relative positioning done using the two GPS systems of the same spacecraft. Overall the accuracy is at the millimeter level. A clear bias of 7 mm is observable in cross-track direction, which might be due to a slightly incorrect knowledge of the antenna offsets in the body frame of the combined spacecraft. This discrepancy has been however considered as negligible in view of the mission needs. During the early phases of the mission, it was decided to power off the GPS receivers over the South Atlantic Anomaly to avoid any additional trouble due to the handling of possible latch-ups. This strategy results in several data gaps (represented by gray vertical bands on Fig. 9) which give a good indication about the propagation error introduced during data gaps (about 2 cm in 20 minutes).

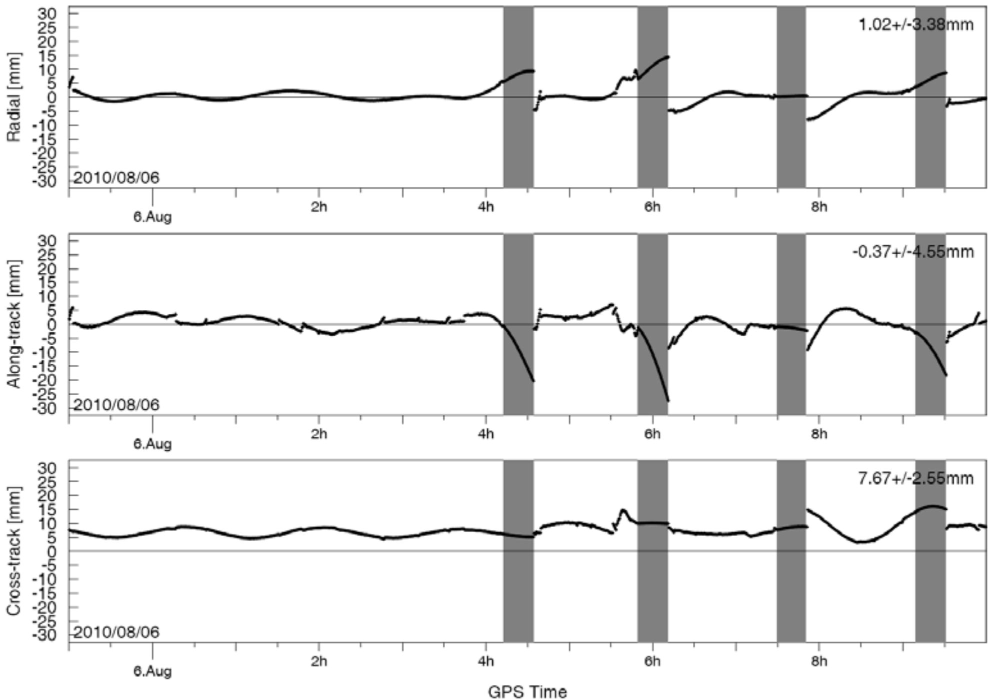

Figure 9. Relative positioning of the combined spacecraft (Aug. 6th, 2010).

The performance of both relative positioning techniques (using integer ambiguity resolution or float ambiguity) have been evaluated during the combined configuration and are summarized in Table 1. The relative positioning error using float ambiguity amounts to several centimeters, which is still sufficient to validate routinely the onboard navigation.

Table 1: Relative positioning error [m]

	Radial	Along-track	Cross-track
integer ambiguity	+0.001 ± 0.003	+0.000 ± 0.005	-0.004 ± 0.003
float ambiguity	+0.003 ± 0.022	- 0.010 ± 0.045	-0.015 ± 0.015

This analysis provides the most representative results of the relative positioning performance to be expected during the flight. However the configuration is still not fully identical to the formation of separated satellites. The main difference is due to the fact that only the attitude estimation onboard Mango was available for the combined spacecraft. This is not a big issue because in the clamped configuration both spacecraft share exactly the same attitude but this means that Tango benefits from the accurate attitude sensors of Mango (star trackers). In reality the attitude estimation onboard Tango has a poor accuracy (several degrees of errors) because it is done using only Sun sensors and magnetometers. As a consequence the results collected during the combined phase might be slightly too optimistic. On the other hand the combined spacecraft suffers from an environment heavily affected by multipath (cf. previous section), which could degrade the performance, even if the performance of the relative navigation is much less affected by this phenomenon because the multipath affecting the carrier phase cannot exceed one fourth of the wavelength.

3.3 Routine Generation of Precise Orbit Products

Precise orbit products have to be delivered on a daily basis during the mission to support the scientific exploitation of flight data. This means that, in addition to the pure performance assessment, the commissioning of the ground processing of GPS data needs to ensure that the POD facility is able to cover all mission phases, even if the conditions for successful GPS-based positioning are unfavorable (like poor visibility or intense maneuvering). The POD facility described in section 3.1 has been designed to generate automatically daily orbit products. However their ultimate validation cannot be automated and thus requires a human-based quality verification. Operationally this is done by checking the residuals of the GPS measurements as well as the estimated un-modeled accelerations, whose typical values have to come from flight experience. When the integer ambiguity resolution is chosen, the percentage of ambiguities successfully solved is also a criterion to assess the quality of the relative positioning products. Practically, the residuals of the single difference carrier measurement should be below 10 mm (cf. Fig. 10), the estimated relative empirical should not exceed a few nm/s² and more than 90% carrier phase ambiguities should be successfully solved in order to consider the relative positioning as successful. If one of these criteria is not achieved, the data arc is reprocessed by estimating float ambiguities. The values of the residuals of single difference carrier phase measurements obtained during the precise orbit determination (Fig. 10) might be surprising considering the noise of the carrier phase measurements (1 mm) exhibited by the Phoenix receiver. This is mainly due to attitude estimation errors and to the fact that the phase center variations are not modeled in the POD process.

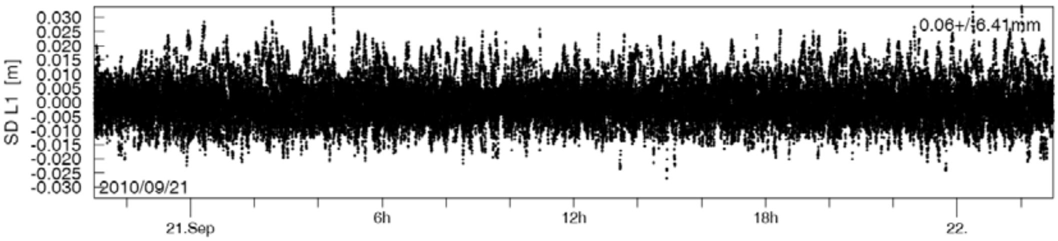

Figure 10. Residuals of single difference carrier phase measurements (Sept. 21st, 2010).

The POD activities performed during the first months of the mission have demonstrated that precise relative positioning using integer ambiguity fixing can be done operationally even in the case of intense maneuvering or rapid rotations of the spacecraft but is likely to fail in some challenging cases [5]. Table 2 summarizes the percentage of daily orbit products generated using either integer ambiguity or float ambiguity over several months, between August 19th, start date of the basic mission phase, and December 22nd, date of the Christmas break during which the GPS telemetry data are deactivated. The few cases in which no relative positioning product could be generated correspond mainly to mission periods where no attitude data was available because one of the two spacecraft was flying in safe mode.

Table 2: Utilization rate of relative positioning methods over 126 days

relative positioning method	orbit products [%]
integer ambiguity	74.6
float ambiguity	20.6
none	4.8

Table 2 shows that, despite the great complexity of the formation flying scenarios used in the PRISMA mission, precise relative positioning using integer ambiguity fixing has been successfully used during almost 75% of the mission.

4. Commissioning of the Real-Time Onboard Navigation

4.1. PRISMA Onboard Navigation Filter

The onboard GPS-based navigation filter runs on Mango and processes the raw measurements coming from the receivers to provide accurate absolute and relative navigation in real-time. The software has been designed and tailored to run on an onboard computer with limited resources (LEON3 clocked at 24 MHz). To that end the navigation software has been split in three different modules running at different frequency (cf. Fig. 11, where the number between brackets is the sample time of the block).

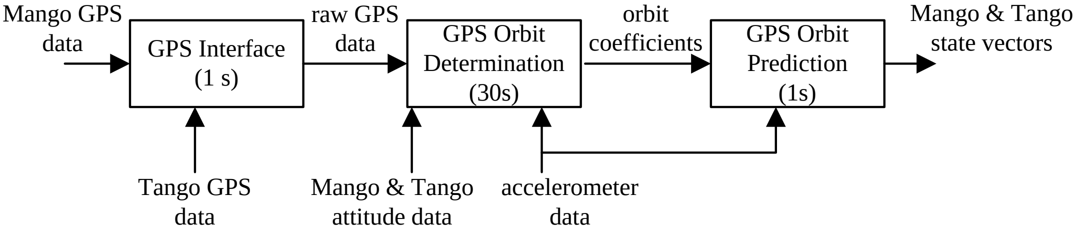

Figure 11. Architecture of the onboard software.

The GPS interface (GIF) is running at 1 Hz and receives the messages from the operational Phoenix-S receiver on Mango and on Tango with a sample time of 10 s. GIF performs message validation, editing, and extraction and stores the extracted raw GPS data for access by the orbit determination function. GIF provides to the onboard software the GPS time for on-board time synchronization. GPS raw measurements are read by the module for GPS-based Orbit Determination (GOD). GOD comprises the complete orbit determination task which provides the absolute trajectories of Mango and Tango. To this end, both time and measurement updates of an Extended Kalman Filter (EKF) are executed. The absolute position and velocity, aerodynamic drag, empirical acceleration, receiver clock offset, and the GRAPHIC float ambiguities of the 12 receiver channels are estimated for both spacecraft. The complete filter state is finally augmented by the estimation of the maneuvers executed by Mango and is thus a vector of dimension 49. The filter uses an advanced dynamical model comprising a 20x20 gravity field, a Jacchia-Gill atmospheric density model and taking the luni-solar pertubations and the solar radiation pressure into account. In the case that no valid GPS data are available only a time update is performed. GOD requires as input antenna, attitude and maneuver data to compute the GPS antenna offset with respect to the center of mass and account for past thruster impulses. The history of a-priori maneuver data is derived from accelerometer measurements. As a result, GOD outputs Mango and Tango orbit parameters which are also stored internally. The GPS-based Orbit Prediction (GOP) subsystem retrieves the on-board time and the orbit coefficients which have been generated by GOD. These parameters are used to compute 1 Hz updates of the Mango and Tango position and velocity at onboard time. In the case that orbit maneuvers have been executed in the past interval, GOP generates a new set of orbit coefficients which is used internally until a new set is provided by GOD. Additional details about the flight software and the underlying algorithms can be found in [3] and [14].

4.2. Post-facto Analysis of Flight Data using the Replay Tool

The commissioning activities have been supported on ground by a dedicated Replay Tool which helps understanding the behavior of the navigation software and facilitates the tuning of the filter. Based on the simulation environment used to develop and validate the flight software (Matlab/Simulink®), the Replay Tool replaces simply the simulation part (orbit and attitude propagation as well as models for the sensors and actuators) with dedicated functions for reading real flight data. As depicted on Fig. 12, the other parts of the simulation environment remain identical, making possible the playback of spacecraft telemetry for offline analyses. In this case, the flight software is fed with the same inputs as during the flight, which allows reproducing post facto the behavior of the software and which gives the possibility for dedicated debugging. The navigation performance is analyzed based on the precise orbit products generated by the POD facility.

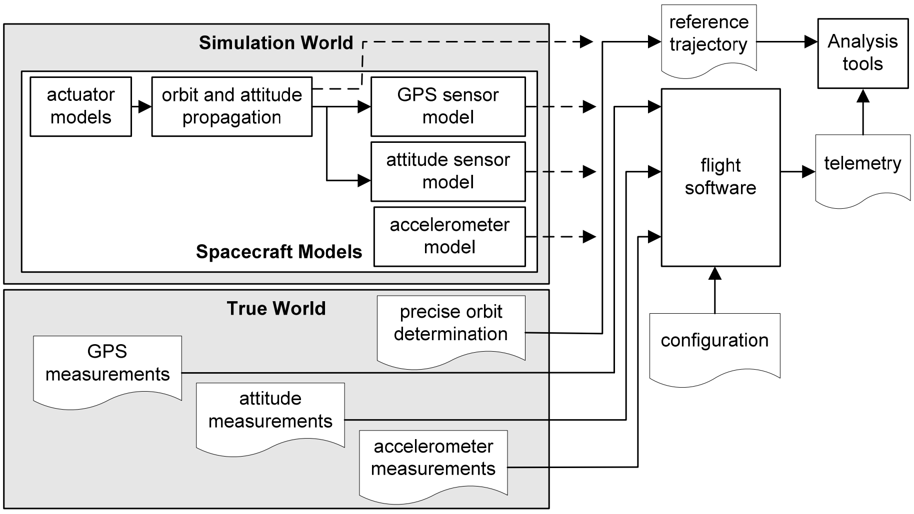

Figure 12. Schematic view of the Replay Tool.

The tuning of the flight software is also possible by replacing the filter settings used during the flight with new values gained after post-facto analyses.

4.3. Calibration of the Onboard Navigation

The first analyses done after the separation of the spacecraft showed that, functionally, the filter behaved as expected. However the comparison done with the precise orbit products revealed a pronounced degradation of the relative navigation in the presence of long data gaps, especially if maneuvers are executed during the data gaps.

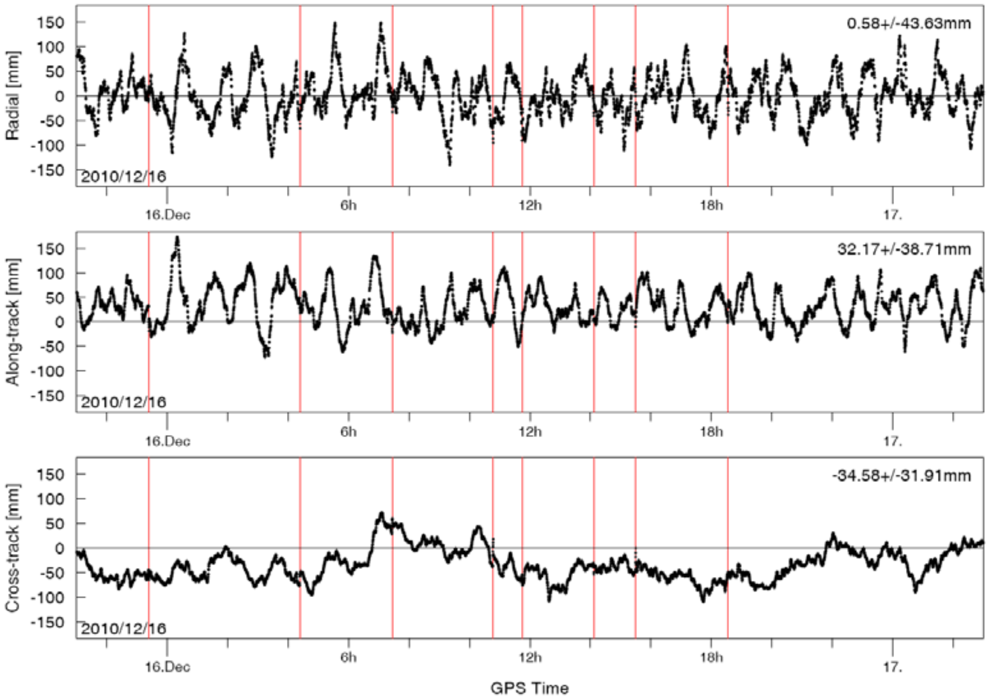

Figure 13. Onboard relative navigation error under nominal conditions (Dec. 16th, 2010).

An unexpected high jump of the relative navigation (120 m) during a one hour data gap was for example observed on August 12th, 2010, which can be critical for the safety of the formation. This large relative navigation error was due to the fact that the default settings were based on simulation results [15] and intended to provide the best navigation accuracy for absolute and relative navigation. The best navigation performance is obtained when using large values for the variance of the estimated empirical accelerations, which allows the filter absorbing all the mismodeling of the dynamics. Fig. 13 shows for example that these settings provide outstanding relative navigation at the sub-decimeter level under nominal conditions, i.e. with zenith pointing antennas, no hardware anomalies, few data gaps and sporadic maneuvers (represented by red vertical lines on the figure). It has been recognized that, in the absence of measurements, this strategy is too dangerous since it can results in unrealistically high estimated empirical accelerations. In the current design of the onboard filter, these estimated empirical accelerations are not set to zero during the propagation phases (i.e. during the GPS data gaps), which can lead to large navigation errors. As a consequence, these filter settings, called *performance* settings, can be used only during continuous operations of the receivers or in the presence of short data gaps (up to a few minutes). On the other hand, constraining the estimation of empirical accelerations increases the overall robustness of the solution but leads to a clear degradation of the performance. These so called *trade-off* settings have been obtained after post-facto analyses using the Replay Tool. However, the resulting robustness comes at the cost of a degradation of the absolute navigation which then violates the mission requirements in term of performance. As a consequence, it has been decided to use the *trade-off* settings only during the first weeks of the mission, when the receivers were powered-off during each passage over the South Atlantic Anomaly and when the FDIR was not able to restart quickly the GPS receivers in case of hardware anomalies. The *performance* settings were instead used only once the decision was taken to use continuously the receivers (September 20th, 2010).

Table 3. Comparison between the navigation performances using two different settings

Performance settings (September 24th – October 6th, 2010)			
	Radial	*Along-track*	*Cross-track*
Position [m]	+0.354 ± 2.713	+0.885 ± 1.185	+0.305 ± 0.898
Velocity [m/s]	+0.000 ± 0.012	+0.000 ± 0.005	+0.000 ± 0.001
Rel. position [m]	+0.003 ± 0.061	+0.003 ± 0.060	+0.011 ± 0.038
Trade-off settings (September 9th - September 12th, 2010)			
	Radial	*Along-track*	*Cross-track*
Position [m]	-0.377 ± 98.34	-16.35 ± 215.4	+0.309 ± 8.896
Velocity [m/s]	+0.018 ± 0.141	-0.003 ± 0.101	-0.004 ± 0.013
Rel. position [m]	-0.107 ± 0.308	-0.114 ± 0.287	-0.201 ± 0.295

Table 3 demonstrates that absolute navigation at the meter level and relative navigation at the sub-decimeter level can be reached when using the *performance* settings. In the presence of long data gaps, the *trade-off* settings increase the robustness of the relative navigation, whose accuracy is slightly degraded but is still close to the mission requirements (50 cm 3D RSS), but lead to a heavy degradation of the absolute navigation which violates the performance requirements (2 m RSS). Considering the importance of the safety and the irrelevance of the absolute navigation for the PRISMA mission, this compromise has been considered acceptable to mitigate the non-nominal GPS data gaps encountered at the beginning of the mission.

4.4. Long Term Analyses

The fact that the onboard navigation is routinely monitored throughout all the mission phases gives a unique opportunity to analyze deeply the behavior of the navigation filter during the numerous challenges offered by formation flying and close proximity scenarios of the PRISMA mission. The main technical challenges for the onboard navigation filter comprise the long data gaps, intense spacecraft maneuvering, large attitude rotations and presence of hardware anomalies. Contrary to their behavior with long data gaps, the *performance* settings are shown to be robust and quite accurate during dense thrusting activities. Figure 14 depicts for example the behavior the relative navigation during a forced relative motion requiring extremely frequent maneuvers (up to 0.1 Hz, represented by the red vertical lines). The figure shows that the relative navigation error does not exceed 1m when the spacecraft is using its thrusters almost continuously.

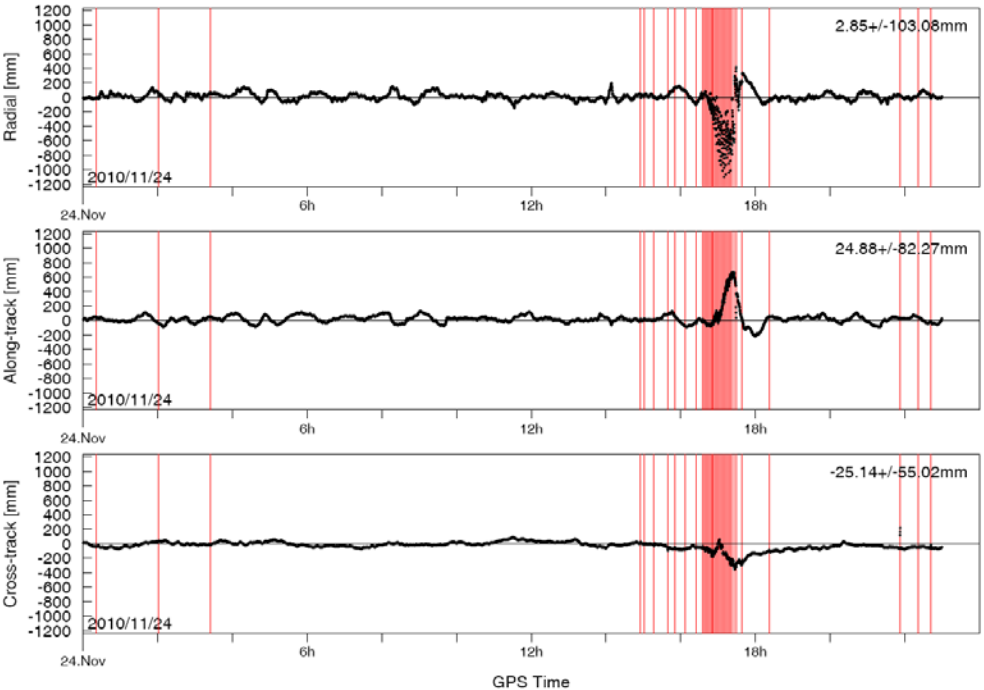

Figure 14. Onboard relative navigation error during intense maneuvering (Dec. 2nd, 2010).

Two software anomalies have been otherwise detected during the first months of operations. Sudden jumps of the relative navigation have been observed right after antenna switches (represented by green vertical lines on Fig. 15). This problem is still under investigation and could be related onboard to a wrong provision of the information of antenna offsets to the filter. In this case the filter would get few measurements affected by an error equivalent to an antenna offset (more than two meters for Mango) which could result in a sudden discontinuity of the solution followed by a re-convergence of the filter.

Another small anomaly, more critical but much less frequent, has been detected only after several months of operations: a jump of several hundreds of meters of the relative navigation in the vicinity of a maneuver. The investigations have shown that this anomaly is due to the fact that the current firmware of the GPS receivers can not handle too many broadcast ephemerides during the acquisition phase after a reboot, resulting in a simultaneous sudden shift of 90 ?s of the carrier phase measurements for all the channels. This hardware anomaly is most of the time successfully detected by the onboard filter, simply by verifying that the variation of carrier phase bias between two consecutive measurements stays below a reasonable threshold. Unfortunately this check was disabled in the original filter design when maneuvers were executed, in order to allow for unnaturally high variations of carrier phase measurements. This approach resulted in a high relative navigation error every time that a simultaneous shift of carrier phases (represented blue dot on Fig. 16) occurred exactly when a maneuver was executed (red line on Fig. 16).

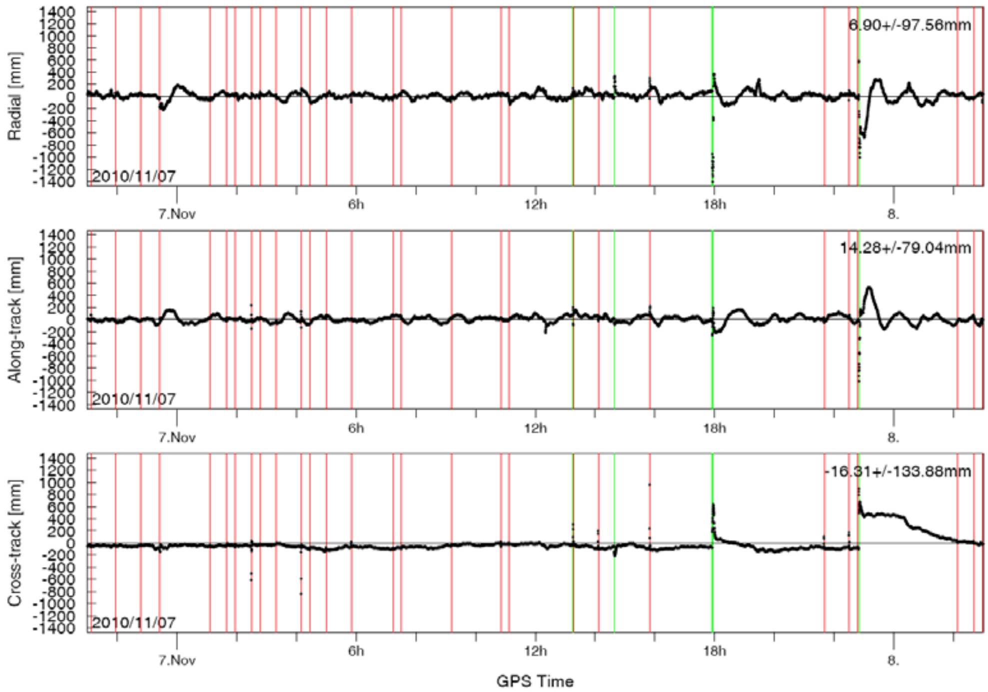

Figure 15. Jumps of onboard relative navigation during antenna switches (Nov. 7th, 2010).

This anomaly could be successfully investigated, understood and reproduced with the Replay Tool. After having been validated on ground (cf. Fig. 16), a patch of the flight software was applied on January 24th, 2011 to fix this anomaly.

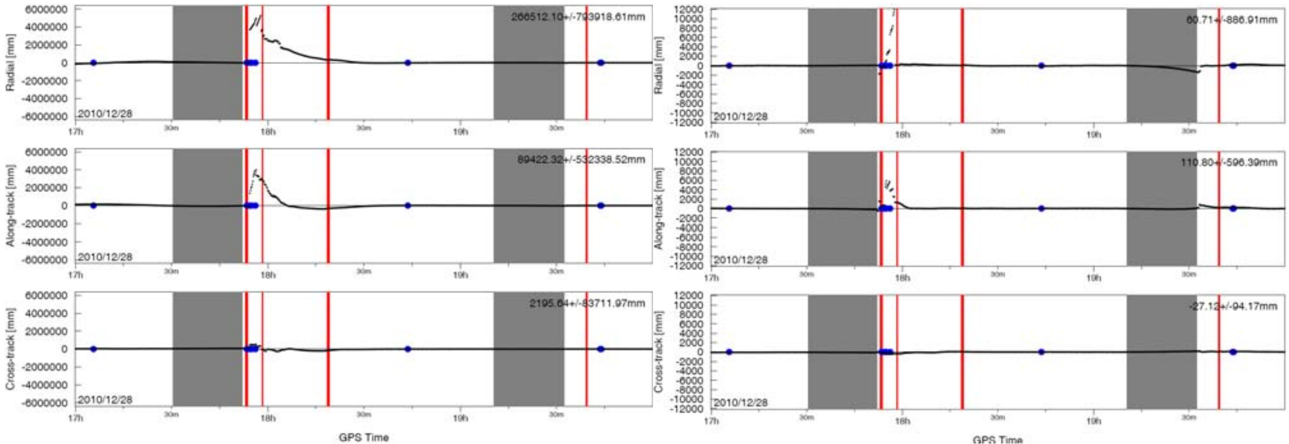

Figure 16. Onboard relative navigation error during hardware anomaly (Dec. 28th, 2010) with original flight software (left) and patch flight software (right).

5. Conclusion

The successful commissioning of the GPS navigation system of the PRISMA mission demonstrates that GPS-based navigation is well suited for autonomous formation flying in low Earth orbit. In particular, thanks to its high technology readiness level, the GPS navigation system can be used for autonomous monitoring of the formation safety and may serve as real-time relative positioning sensor for close proximity (up to several meters) operations.

The low-cost Phoenix GPS receivers used in the mission are shown to provide excellent tracking capabilities and high measurement quality, which make them well suited to GPS-based absolute and relative navigation. The use of Commercial-Off-The-Shelf technology qualified for space applications raises of course the problem of tolerance against radiations. The flight experience gained during the first half year of the mission shows however that the radiation events on the Phoenix receivers are not destructive, so that their effects can be mitigated by implementing a proper onboard strategy for rapid fault detection and recovery and by complementing the GPS receivers with an onboard filter able to bridge short data gaps. Minor reliability issues have been otherwise detected during the mission and will be corrected via a patch of the firmware.

The on-ground post-facto generation of precise orbit products, essential for the cross-validation of other experimental relative positioning sensors, has been successfully commissioned. Ultimate relative positioning accuracy is achieved using the resolution of integer double difference carrier phase ambiguities. The performance analyses done during the commissioning have shown that the resulting relative positioning is accurate at the (sub)-centimeter level. About 75% of the orbit products have been generated in 2010 using this method, which is still very sensitive to any perturbations. As a consequence, another more robust but less accurate method, based on the estimation of float ambiguities, is used to generate relative positioning products with accuracy better than 10 cm when the integer ambiguity fixing fails. The resulting accuracy is still sufficient to monitor routinely the health of the onboard navigation.

Accurate absolute and relative navigation is provided in real time by the onboard filter, which processes directly the GPS raw measurements from the receivers. The navigation performance has been verified using the precise orbit products generated on-ground. Under nominal conditions, absolute navigation at the meter level and relative navigation at the sub-decimeter level can be expected. The filter is shown to be robust in all challenging conditions encountered during the mission, but is per design very sensitive to long data gaps. Robust but poor filter settings have been derived during the commissioning to cope with the mission phases affected by numerous data gaps. Minor software anomalies have been observed, which have either been fixed via a software patch or are currently under investigation.

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