GPS NAVIGATION SYSTEM FOR CHALLENGING CLOSE-PROXIMITY FORMATION-FLIGHT

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Abstract: *The PRISMA mission has demonstrated the benefits of employing on-board GPS-based relative navigation for precise formation-flying, allowing the design of low-cost, reliable and accurate sensors essential for precise formation control and mission safety. GPS-based navigation poses some requirements in terms of visibility of the GPS constellation, which are necessary to ensure ultimate performance and which can however be hard to satisfy by some of the upcoming distributed spacecraft systems aiming at embarking such a GPS navigation system. In the paper, the architecture of the PRISMA GPS navigation system is revisited, in order to better support challenging formation-flying missions with non-optimal visibility conditions, such as inertially pointing virtual telescopes or on-orbit servicing missions. The new design foresees the simultaneous usage of a second GPS receiver on each spacecraft to enforce omnidirectional tracking capability, able to provide a large amount of GPS measurements and to achieve real-time relative navigation performance better than 10 cm 3D rms in any situation.*

Keywords: *PRISMA, GPS, relative navigation, formation flying, tumbling spacecraft.*

1. Introduction

The PRISMA technology demonstrator [1] represents a great milestone in the history of autonomous formation flight. Following the launch and the in-orbit separation of the two PRISMA satellites in 2010, key technology and scenarios for formation-flying have been extensively tested and validated for more than two years, constituting an inestimable treasure of know-how for future distributed spacecraft systems. Among the notable achievements of the mission, the GPS navigation system contributed by the German Aerospace Center (DLR) has proven its great value by supporting continuously the formation with accurate and robust real-time navigation. Thanks to its high technology readiness level, the GPS-based navigation could be successfully used to monitor in real-time the safety of the formation, to support on-board autonomous formation guidance and control [2] and has also served as independent reference for the calibration and verification of other sensors.

Overall, the GPS navigation system embarked by the PRISMA satellites demonstrated impressive performance, providing absolute navigation at the meter level and relative navigation accurate at the centimeter level in some favorable cases [3]. Charmed by its performance and maturity, future formation-flying missions able to track navigation signals from a Global Navigation Satellite System (GNSS) will undoubtedly foresee the utilization of such a navigation system to support their objectives and ensure the safety of the mission. On-orbit servicing missions dealing with cooperative targets [4], virtual sensing instruments flying on low-Earth orbit and requiring precise relative control or even the PROBA-3 solar coronagraph flying in high-elliptical orbits [5] are natural candidates to embark a precise GNSS-based sensor.

The main limitation of GNSS-based navigation consists in some obvious requirements in terms of visibility of the GNSS constellation, which can sometimes be hard to fulfill. In fact, precise relative navigation requires all co-orbiting spacecraft of the formation to track the same GPS satellites. In the PRISMA mission, each satellite employed a dual-antenna system, able the select the most favorable hemisphere seen by the antennas. However, this strategy has shown some limitations during the execution of some of the close-proximity formation-flying scenarios exercised by PRISMA. The main reason was that, in some unfavorable situations, the portion of the the sky commonly seen by the antennas of the two spacecraft was insufficient to provide enough measurements for a reliable and robust navigation. The resulting limited amount of measurements is usually not dramatic, but in the peculiar case of forced-motion, the on-board knowledge of the relative dynamics is degraded. Furthermore, some observations are possibly corrupted by multi-path, so that more measurements than usually are necessary to strengthen the relative navigation.

Future formation-flying missions envisioning forced-motion close-proximity operations with tumbling spacecraft or non-optimal antenna pointing would thus need to adapt the architecture adopted in the PRISMA mission by enforcing omnidirectional tracking capability of the spacecraft to improve the common visibility. The paper intends to tackle this issue. After a brief recall of the PRISMA GPS-navigation system, the paper describes the main issues which have been encountered during the mission. The main options available to improve the common visibility are then described and the retained solution is presented, consisting in using two independent GPS receivers covering simultaneously two different hemispheres instead of only one. Minor adaptions of the PRISMA flight software would be necessary to fuse the measurements coming from the different receivers. The architecture presented in the paper is finally validated by highly realistic simulations of typical close-proximity scenarios (v-bar docking and inspection flight) during which the spacecraft are intensively maneuvering and are subject to large variations of attitude.

2. The PRISMA Experience

2.1. Mission Overview

The PRISMA technology demonstrator is a formation-flying platform composed of two spacecraft named Mango and Tango (depicted on Fig. 1). The satellites were injected on June 15th, 2010 into a dusk-dawn, sun-synchronous orbit at 760 km altitude and 98° inclination. After launch, the two spacecraft have been staying in a clamped configuration for initial system checkout and preliminary verification until August 11th, 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 have been conducted within a nominal mission lifetime of about ten months which, in view of the success of the nominal phase, was subsequently extended by several months.

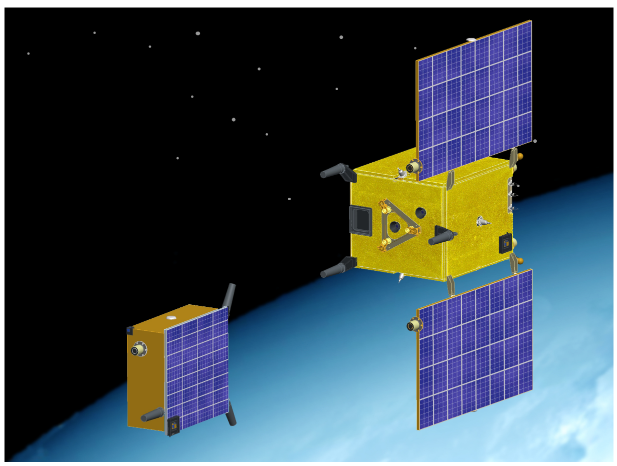


Figure 1: The PRISMA technology demonstrator: Tango (left) and Mango (right) (Image courtesy OHB-Sweden)

The objective of the mission was 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 has been designed and implemented by the Swedish Space Corporation (SSC) (now OHB-Sweden) with international contributions from CNES (France), DLR (Germany) and DTU (Denmark). Key sensor and actuator components comprised a GPS receiver system, two vision based sensors, two formation flying radio frequency (FFRF) sensors, and a hydrazine thruster system. This equipment has enabled the demonstration of autonomous spacecraft formation-flying, homing, and rendezvous scenarios, as well as close-range proximity operations. 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 torquers as actuators.

2.2. PRISMA GPS Navigation System

The GPS navigation system flown on the PRISMA mission is based on a centralized on-board real-time filter, embarked by the main satellite Mango, which processes in real-time measurements coming from the GPS receivers of both spacecraft of the formation. Each satellite is equipped with a cold-redundant set of Phoenix GPS receivers [6]. The receivers of each branch are equipped with a low-noise amplifier (LNA) and cross-connected via a relay to a pair of GPS antennas on opposite sides of the spacecraft (cf. Fig. 2.). In this way, GPS tracking could be ensured in all foreseen attitude modes of the PRISMA formation: during the flight, the active antenna is automatically selected by the spacecraft, depending on the orientation of the antenna, in order to maximize the visibility of the GPS constellation.

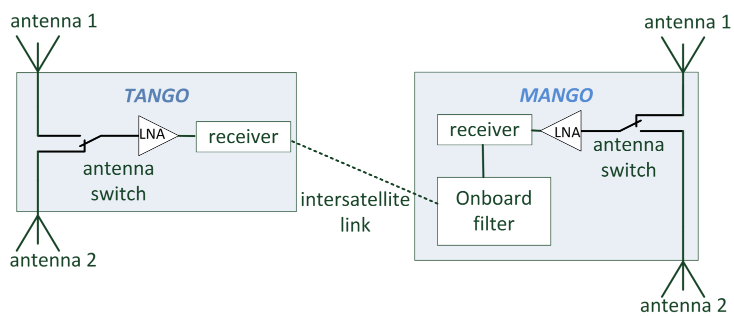


Figure 2: Architecture of the PRISMA GPS navigation system (the redundant branches are not represented)

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 navigation software implements an extended Kalman filter which estimates the absolute inertial position $\boldsymbol{r}_i$ and velocity $\boldsymbol{v}_i$, drag coefficient C_{D_i}, empirical acceleration $\boldsymbol{a}_i$, receiver clock offset δ_i and carrier-phase float ambiguities $\boldsymbol{B}_i$ for both spacecraft. The state is augmented with the estimate $\boldsymbol{m}$ of maneuvers executed by the main spacecraft. The vector $\boldsymbol{B}_i$ comprises the GRAPHIC [7] float biases estimated for all the channels of the receiver and comprises thus 12 elements in case that a Phoenix GPS receiver is employed. As a result, the filter state vector $\boldsymbol{y}$ comprises 49 elements:

$$\boldsymbol{y} = \left[\begin{array}{cccccccccccccc} \boldsymbol{r}_1 & \boldsymbol{v}_1 & C_{D_1} & \boldsymbol{a}_1 & \delta_1 & \boldsymbol{B}_1 & \boldsymbol{r}_2 & \boldsymbol{v}_2 & C_{D_2} & \boldsymbol{a}_2 & \delta_2 & \boldsymbol{B}_2 & \boldsymbol{m} \end{array} \right] \quad (1)$$

The filter time update is done by integrating numerically (using a 5th order Runge–Kutta method) the acceleration provided by an advanced force model, comprising a 20x20 model of the gravity field, a model of the atmospheric density, and taking solar radiation pressure and luni-solar perturbations into account. The filter measurement update is done using GRAPHIC and single-difference carrier-phase measurements. If no GPS measurement is available, only the filter time update is performed, allowing for orbit propagation during data gaps. Further details on the underlying algorithms and software implementation are available in [8].

The GPS navigation system of PRISMA was 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 is believed to go down to the (sub-)centimeter level [3]. 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 on-board navigation. Further details on the ground processing of GPS measurements can be found in [9].

2.3. Relative Navigation Performance

Relative navigation relies on differencing GPS carrier-phase measurements to achieve ultimate performance, which means that the spacecraft of the formation need to track the same GPS satellites. Intuitively, the accuracy and robustness of the GPS relative navigation depends strongly on the number of simultaneous observations (this assertion is however rather difficult to quantify).

The optimal visibility case is achieved when the antennas of both spacecraft are constantly zenith-pointing. Figure 3 depicts an example of such a favorable configuration, in which about 10 GPS satellites are commonly seen in average. In this case, the relative navigation

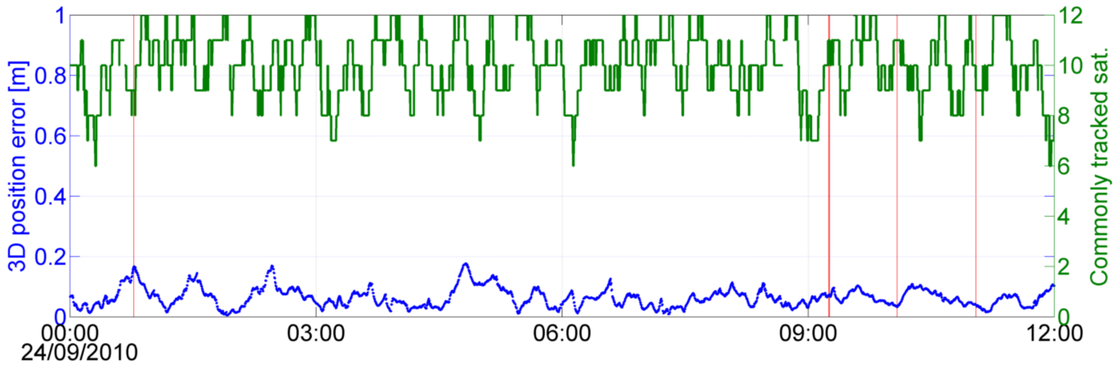


Figure 3: On-board positioning errors and number of commonly tracked satellites in a favorable case (antennas zenith-pointing)

errors amount to 5 cm. In the figure, the red vertical lines represent the execution of maneuvers by Mango. The reference orbits used to assess the on-board navigation errors of Fig. 3 and Fig. 5 were generated using the GSOC POD facility.

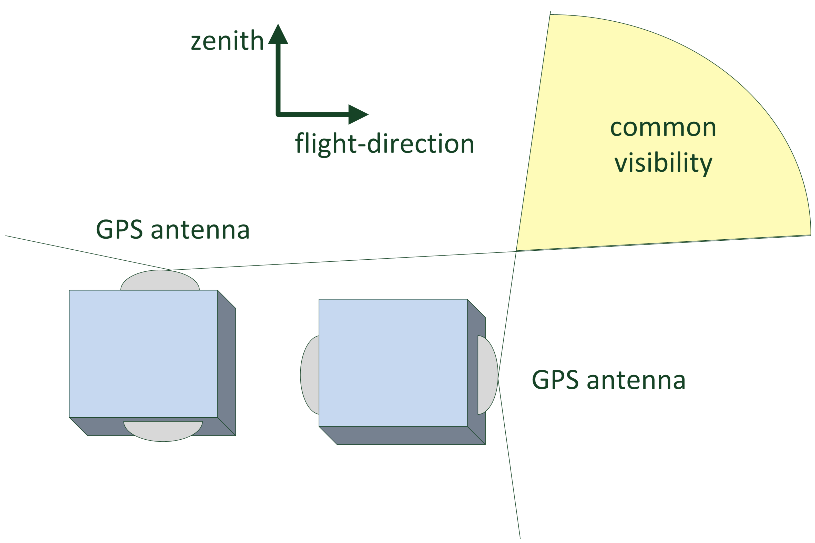


Figure 4: Graphical representation of the worst case common visibility

Maintaining the GPS antenna boresights of both spacecraft to be constantly zenith-pointing is however a strong requirement that can not be always fulfilled by a mission. Other payloads might have more importance (for example orientating the spacecraft for ground communication or setting the orientation of a sensor inertially constant), leading to sacrifice the GPS visibility. Even if the antenna with the best visibility can be selected on-board, the common visibility is reduced to half an hemisphere in the worst case scenario, when the boresights of the active antennas are perpendicular, as depicted in Fig. 4.

This explains the degradation of navigation performance which has been observed during some PRISMA scenarios in which one spacecraft was tumbling. The behavior of the on-board navigation system could be party improved post-facto by tuning the navigation filter, but it was not enough to always ensure accurate and robust navigation. In fact, the main limitation comes from the reduced common visibility. As outlined in the introduction, collecting many differenced measurements is also important to ensure the robustness of the navigation solution during forced-motion and in the presence of multi-path. The PRISMA navigation system is mainly limited by the fact that, even if every spacecraft is equipped with two antennas, only one antenna can be used at any time. In some scenarios where the antenna boresights of the active antennas are perpendicular, the common portion of sky visible by both spacecraft is reduced and the navigation solution derived on-board is weakened. Figure 5 depicts for example the on-board positioning errors encountered in a scenario where the Mango satellite is not zenith-pointing anymore and both spacecraft are separated by a few hundred meters. The scenario was intended to test the FFRF system, for which large rotations of the Mango spacecraft were necessary [10]. It has to be noted that the flight software at this time was affected by some software errors which have been corrected since then. As a consequence, the results presented on Fig. 5 have been reproduced post-facto using a replay tool based on the real input flight data.

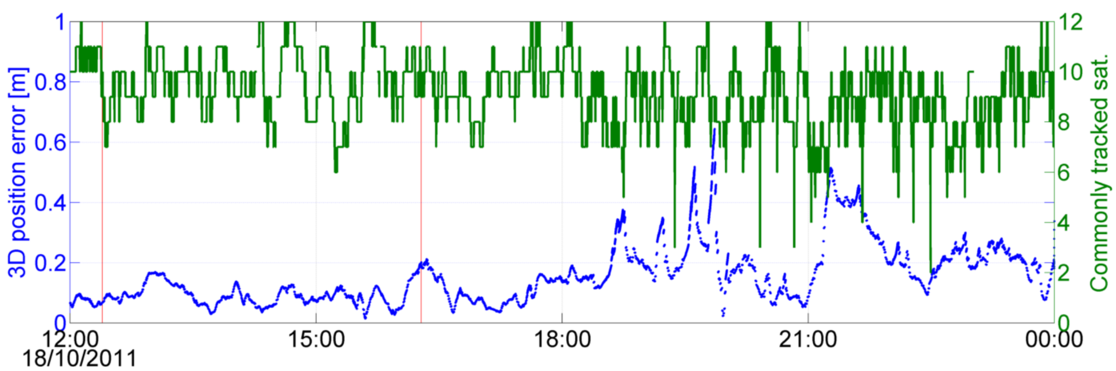


Figure 5: On-board positioning errors and number of commonly tracked satellites in a challenging case (Mango tumbing)

A clear degradation of performance can be observed after 6 pm, when Mango performs large attitude variations, corresponding also to a drop of available common GPS measurements. The relative navigation errors are still below one meter but, for close-proximity activities at few meters separation, such errors might be unacceptable. In addition, it has to be noted that no maneuver is executed in the tumbling phase, so that the observed degradation is simply due to the lower number of commonly seen satellites. In case of close-proximity (i.e. affected by multi-path) forced-motion (i.e. with intense maneuvering) the degradation of the relative navigation could be much worse (c.f. Section 4.2.)! The only way to improve the navigation performance is to ensure that a sufficient number of measurements is always available, and this can be achieved only if the GPS antennas can track at every time in all directions.

Table 1: Typical relative navigation performance encountered in the PRISMA mission

Scenario	GPS satellites	Relative position [cm]				
		R	T	N	3D rms	max
favorable case	9.9	1.7±4.4	1.5±4.2	0.7±2.8	7.1	18
Mango tumbling	8.6	13±8.6	0.0±9.4	-11±8.7	23.5	64

For completeness, the relative navigation performances corresponding to the cases depicted on Fig. 3 and Fig. 5 are summarized in Tab. 1, showing that the relative navigation errors are increased by three in case of non-optimal visibility conditions.

3. Revisiting the PRISMA GPS Navigation System

3.1. Enforcing Omnidirectional Coverage

Omnidirectional coverage of the GPS antenna system is the key to improve the number of commonly seen satellites. Several options have been investigated to use several active antennas simultaneously on a single spacecraft:

- **merging the signals of two antennas**. Antennas are mounted on opposite sides of the spacecraft, like in the PRISMA configuration, but the main difference with respect to PRISMA is that the antenna signals are merged using a power-divider instead of being switched via a relay. For precise navigation, it will also be necessary to link the antenna identifier with the GPS observations (in order to account for the offset with respect to the center of mass and the characteristics of each antenna). This knowledge can be reconstructed on-board post-facto by using attitude and almanac information. This approach presents the advantages of simplicity and can take inspiration from the wrap-around antennas used for sounding rockets which face similar problems [11]. However it comes at the expense of additional difficulties due the possible interferences between the two antennas. It is in fact necessary to ensure that no overlap of the antenna diagrams exists, otherwise both antennas could track the same satellites at the same time, creating destructing interferences. In fact the experience collected during the PRISMA mission has shown that, depending on how it is mounted, an antenna can partially track signals from the back side [3]. This issue might not be too critical for sounding rockets with loose accuracy requirements, but is of real concern for advanced navigation algorithms based on carrier-phase processing. In view of the considerable development and testing efforts necessary to ensure an interference-free dual antenna system, this option has been abandoned.

- **using a multi-antenna receiver**. In this case, the outputs of the antennas are connected directly to a GPS receiver accepting two different antennas as input. Research in this field is very active, especially for GPS-based attitude determination [12], anti-spoofing [13] or novel receiver technology [14]. However, the existing multi-antennas receivers are to our knowledge not yet space-qualified and usually do not expect the antennas to point in opposite directions, so that their firmware would need to be modified.
- **using simultaneously two receivers per spacecraft**. Each spacecraft embarks two active receivers which are running independently. The measurements of the four active receivers of the formation are fusioned in the on-board navigation filter. This option presents also the advantage to double the number of channels to track the GPS satellites, thus increasing substantially the number of measurements. This approach has been retained and is described in the sequel.

3.2. Upgrade for Challenging Close-Proximity Scenarios

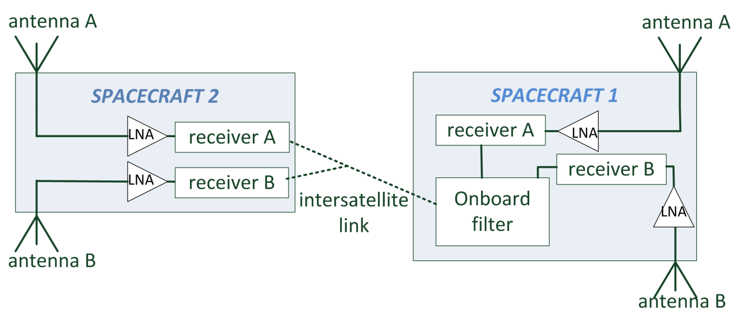


Figure 6: Proposed upgrade of the PRISMA GPS navigation system

Figure 6 depicts the proposed architecture able to provide a full sky visibility for all spacecraft of the formation. No antenna switch is needed anymore, because both receivers embarked by a single spacecraft are constantly linked to a single antenna. In fact, the dual-receiver system is equivalent to a virtual single multi-antenna receiver with twice as much channels. The only difference with a real multi-antenna receiver is that the virtual receiver has two clocks running independently whose offset need to be estimated. This architecture is of course more expensive than the one used for PRISMA. The additional costs are however fully justified in view of the benefits brought by such a solution (cf. Section 4.2.), especially if low-cost commercial off-the-shelf components are used.

The new dual-receiver architecture has little impact on the on-board navigation filter. As already outlined, one simply need to replace the 12-channel receiver of the PRISMA mission with a virtual 24-channel receiver with two clocks. This means that the filter state vector described by Eq. 1 needs to be updated as follows (the modifications are highlighted in blue):

$$\boldsymbol{y} = \left[\begin{array}{cccccccccccccc} \boldsymbol{r}_1 & \boldsymbol{v}_1 & C_{D_1} & \boldsymbol{a}_1 & \delta_{1A} & \delta_{1B} & \boldsymbol{B}_{1AB} & \boldsymbol{r}_2 & \boldsymbol{v}_2 & C_{D_2} & \boldsymbol{a}_2 & \delta_{2A} & \delta_{2B} & \boldsymbol{B}_{2AB} & \boldsymbol{m} \end{array}\right] \quad (2)$$

where δ_{ij} is the receiver clock offset of the j$^{\text{th}}$ receiver of the i$^{\text{th}}$ spacecraft and $\boldsymbol{B}_{iAB} = [\boldsymbol{B}_{iA}\boldsymbol{B}_{iB}]$ is a vector of dimension 24 combining the float ambiguities of both receivers A and B. In the estimation algorithms, it is of course necessary to distinguish the branch {antenna,receiver} used for the measurements, because they have different phase center and clocks offsets. This is trivial in the adopted design, because all the measurements of the channels 1 to 12 are done with one branch, while the measurements of the channels 13 to 24 are done with the other branch. The overall computational load of this upgraded filter is expected to increase, because the size of the filter state is bigger and more measurement updates need to be done. However, some optimization in selecting a subset of measurements could be done if the increased computional load is not acceptable.

4. Performance Validation

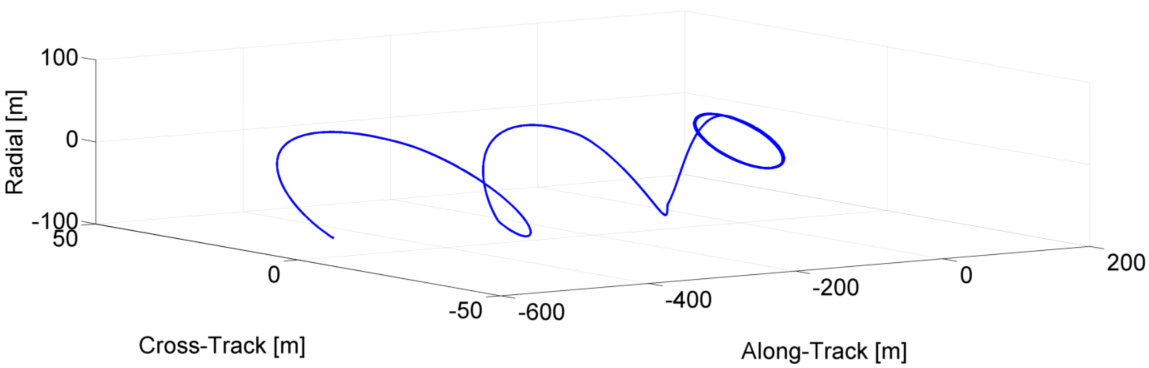
4.1. Simulation Setup

The system performance have been validated in a joint study between the German Aerospace Center and EADS Astrium. The trajectory and attitude data of a formation of two spacecraft flying on low-Earth orbit (550 km height) have been contributed by Astrium. The orbit data have been created by integrating numerically a force model based on a 10x10 gravity field and taking the atmospheric drag into account. The main satellite is actively maneuvering to control the formation. Maneuver execution errors of 4% have been introduced in the simulation. These inputs feed a high-fidelity simulation environment based on the GSOC Multi-Satellite Simulator [15]. This simulator comprises software emulations of the Phoenix GPS receiver, able to simulate the typical output messages of the receivers (navigation data, ephemeris data, raw messages). The messages of the four GPS receivers of the formation are then processed by the upgraded version of the PRISMA flight-software.

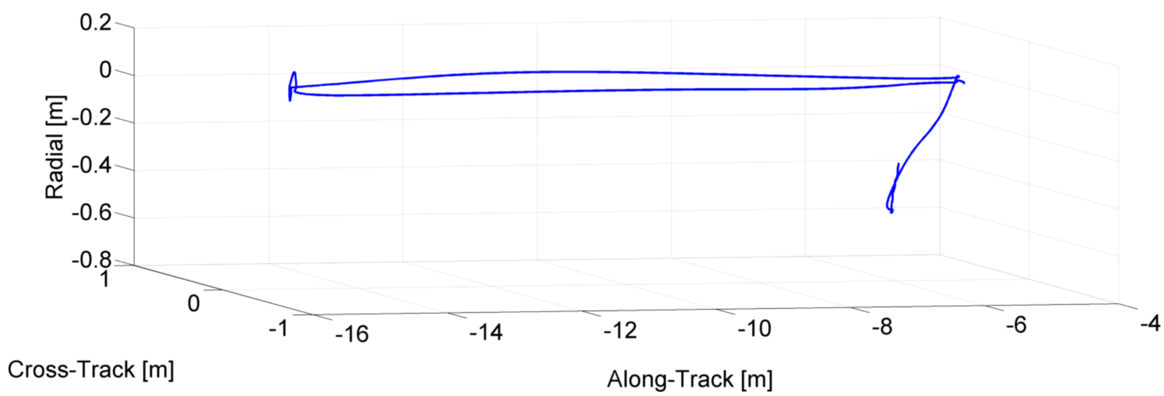
Two challenging formation flying scenarios have been investigated:

- **inspection flight**: a typical scenario for on-orbit servicing. In this case, the main spacecraft flies around a target satellite to observe it. The inspection flight consists in an approach from several hundred meters to create an elliptic relative motion centered on the target spacecraft. During this phase, non-zenith antenna pointing is expected and sparse maneuvers are required.
- **v-bar docking** : also a typical scenario for on-orbit servicing. At the beginning of the test case, the main spacecraft is separated by only 4 m, goes back first to increase the separation up to 15 m and finally approaches the target spacecraft following a straight path aligned to the flight direction. Here the main difficulty consists rather in the intense maneuver activities, because it is required to fight constantly against the natural relative dynamics.

The relative trajectories for both scenarios of the main spacecraft with respect to the target spacecraft are depicted on Fig. 7.



(a) inspection flight



(b) v-bar docking

Figure 7: Relative trajectories during the two selected scenarios

4.2. Simulation Results

The scenarios have been tested using both the original PRISMA flight software and the upgraded version. Figures 8 and 9 depict the observed on-board relative positioning errors and Tab. 2 summarizes the results. The benefit of using simultaneous two antennas is obvious: in average 14 satellites are commonly tracked with a minimum of 7 common observations. The original configuration reaches instead only 5 satellites tracked in average and the number of commonly seen satellites can drop to only 2 common observations.

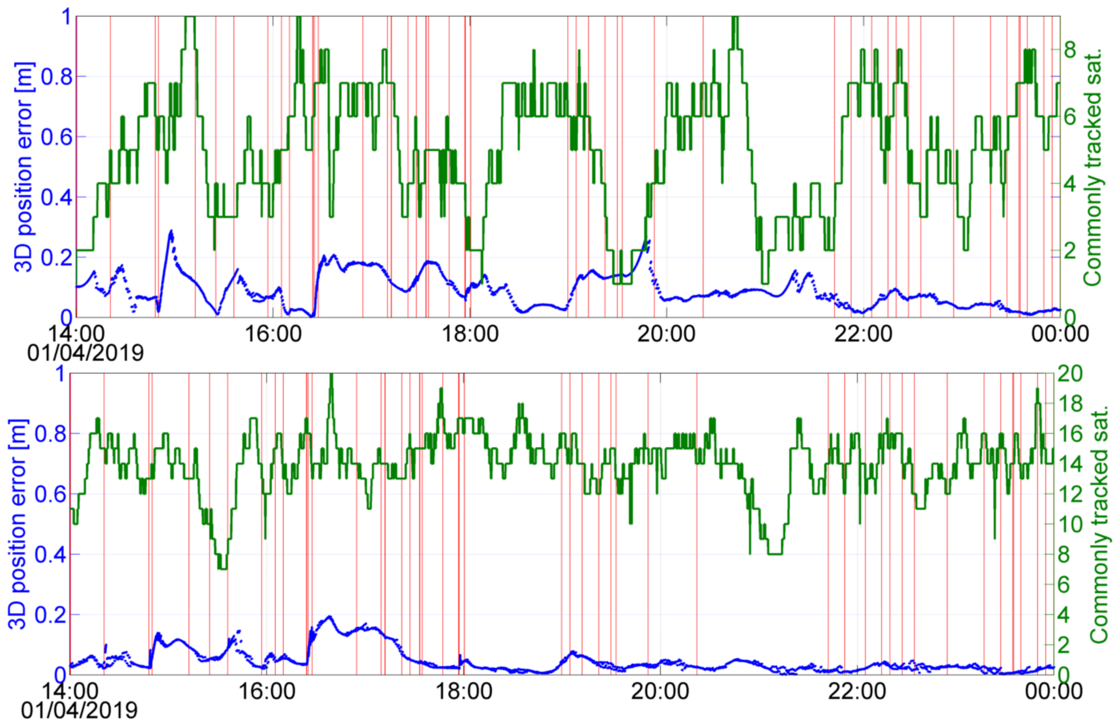


Figure 8: Relative position errors during inspection fight: PRISMA software(top) and upgraded version(bottom)

This difference in terms of available measurements is reflected in the navigation performance, where the upgraded version achieves relative positioning errors smaller than 10 cm 3D rms with maximum errors up to 20-30 cm, while the errors obtained by the PRISMA flight software are twice as large. It has to be noted that the navigation performance observed within the simulations seems to be slightly too optimistic, when comparing with the flight results summarized in Tab. 1. This is probably due to the fact that the force model used for orbit propagation does not account for minor orbital perturbations such as solar radiation pressure, attitude dependent differential drag, luni-solar perturbations, tidal and relativistic effects and higher orders of the gravity field.

In addition, the multi-path is not modeled in the simulation. It is believed that this can have a large impact if only a few measurements are available, because it becomes impossible to know which measurements are correct. If instead 10 satellites are visible, it is unlikely that all the observations are affected at the same time by multi-path, so that the filter will be able to reject the unhealthy measurements.

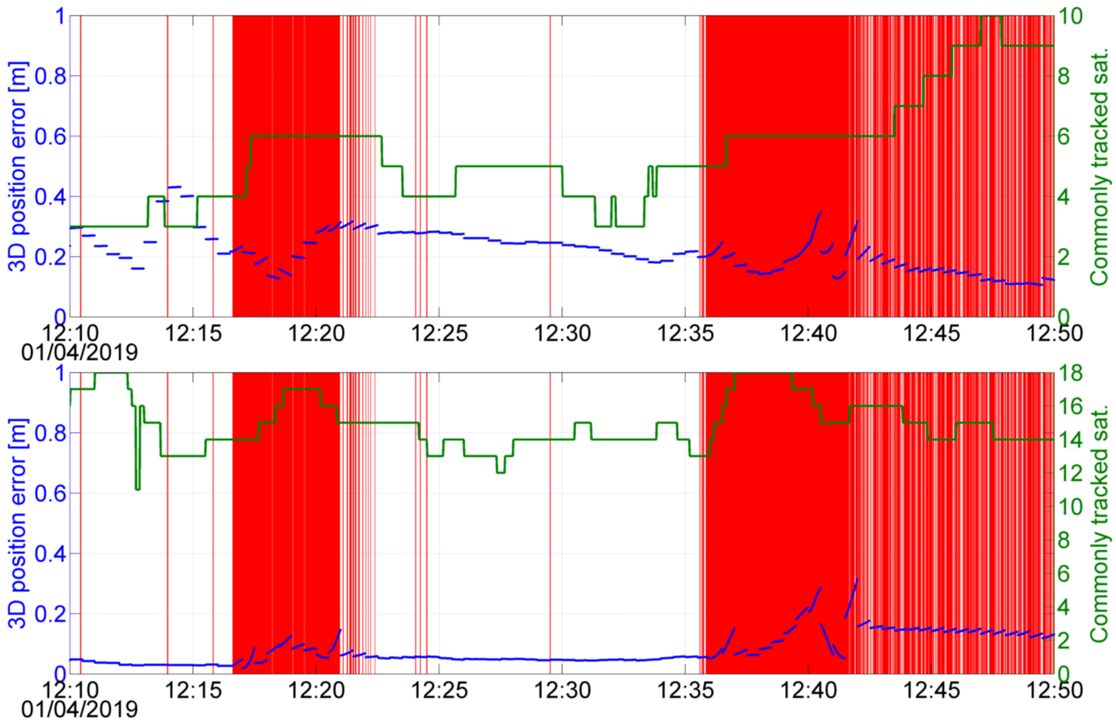


Figure 9: Relative position errors during v-bar docking:
PRISMA software(top) and upgraded version(bottom)

Table 2: Relative navigation performance

Scenario	GPS satellites	Relative position [cm]				
		R	T	N	3D rms	max
inspection flight (original)	5.0	-1.1±6.9	0.0 ±7.0	0.0±2.6	10.2	29
inspection flight (upgraded)	13.9	-0.9±3.9	-0.5±4.1	1.1±1.6	6.1	19
v-bar (original)	5.4	11.7±7.2	5.7±12.7	2.3±11.7	23	43
v-bar (upgraded)	14.9	3.3±4.6	2.0±3.2	-3.9±5.2	9.5	31

5. Conclusion

An upgraded version of the PRISMA GPS navigation system has been presented. This upgrade is intended to support upcoming formations of spacecraft with accurate and reliable GPS-based navigation even in case of forced-motion close-proximity operations, where spacecraft are subject to large variations of attitude and intense maneuvering activities. To that end, the architecture of the navigation system has been modified to enforce omnidirectional tracking of the GPS constellation on each spacecraft. This upgrade allow increasing considerably the number of available differenced measurements, improving the robustness and accuracy of the navigation solution. Overall, simulations representative of challenging close-proximity operations indicate that relative positioning better than 10 cm 3D r.m.s can be achieved in all conditions.

6. References

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