

Navigation and Control of the PRISMA formation: In-Orbit Experience

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Abstract: This paper presents flight results and lessons learned from the Spaceborne Autonomous Formation Flying Experiment (SAFE) conducted by the German Space Operations Center in the frame of the Swedish PRISMA mission. SAFE represents one of the first demonstrations in low Earth orbit of an advanced guidance, navigation and control system for dual-spacecraft formations. Innovative techniques based on carrier-phase differential GPS, relative eccentricity/inclination vectors and impulsive maneuvering are validated and tuned in orbit to achieve centimeter accurate real-time relative navigation, reliable formation keeping at the meter level and flexible formation reconfiguration capabilities.

1. INTRODUCTION

Distributed systems of cooperating satellites offer the possibility to achieve scientific objectives which are otherwise impossible through traditional solo designs. Spacecraft formations in low Earth orbit (LEO) can realize scientific instruments like synthetic aperture radar interferometers for the generation of high accurate digital elevation models (Krieger *et al.*, 2007), or gravimeters for the determination of the Earth's gravity field on a global scale (Tapley *et al.*, 2005). The range of applications derived from this type of missions is broad and include, among others, Solid Earth Science, Oceanographic Sciences, Geodesy, Earth's Gravity Definition, Reconnaissance Applications, Disaster Monitoring. Tight formation flight, as well as the transient phase to in-orbit rendezvous and docking scenarios, typically requires fully autonomous Guidance, Navigation and Control (GNC) functions on-board the spacecraft. Such autonomy scenarios are not only relevant for future formation flying and rendezvous applications, but are likewise mandatory for proximity operations, in-orbit servicing and robust collision avoidance procedures.

The Prototype Research Instruments and Space Mission technology Advancement (PRISMA) is a precursor mission for such critical technologies managed by the Swedish National Space Board (SNSB) and the Swedish Space Corporation (SSC). The mission objectives can be divided into the validation of sensors/actuators and GNC techniques for formation flying and on-orbit servicing (Bodin *et al.*, 2009). The testbed comprises the fully maneuverable Mango (150 kg) small satellite as well as the passive Tango (40 kg) sub-satellite which have both been launched on June 15th 2010 into a Sun-synchronous orbit at 750km altitude. Mango features a three-axis reaction-wheel-based attitude control and accommodates a hydrazine-based thrusters system that provides delta-V (DV) for orbit control. The system provides thrust in all directions, using six 1-N thrusters that are capable of providing impulse bits of 0.1Ns. These translate to

single velocity increments of ca. 0.6mm/s at begin of life, which can be applied for formation control. A total of 11kg of propellant provides a delta-V capacity of 115m/s. Tango applies a coarse magnetic-based three-axis attitude control and does not have orbit control capability.

Among the key partners of SSC in the development and exploitation of PRISMA, the German Space Operations Center (GSOC) contributes the GPS-based absolute and relative navigation system (baseline relative sensor of the formation), dedicated autonomous formation flying and orbit keeping experiments (about two months of total experiment time), as well as the on-ground precise orbit determination (POD) layer for experiments verification and cross-validation. Altogether these contributions represent one of the first flight demonstrations of a complete GNC system for formation flying spacecraft in LEO (D'Amico, 2010). After a brief description of the navigation and control functionalities, this paper discusses flight results obtained during the first part of the so-called Spaceborne Autonomous Formation flying Experiment (SAFE) conducted in the time frame between September 20th and October 6th 2010. SAFE is intended to demonstrate accurate, safe, robust formation keeping and reconfiguration in LEO, on a routine-basis, employing differential GPS, relative orbital elements, and impulsive orbit control.

2. NAVIGATION AND CONTROL CONCEPT

The design, development, and testing of the GNC subsystem discussed in this paper has been conducted according to stringent functional and performance requirements. The navigation system is intended to serve the needs of the spacecraft baseline platform in terms of formation safety (monitoring and collision avoidance) on one hand, and feed the on-board feedback controllers which constitute the GNC experimental payloads on the other hand. The resulting operational scenarios are quite challenging since the formation safety requires robustness and reliability of the

relative navigation under all circumstances, whereas the formation control experiments require ultimate navigation performance. More specifically the real-time orbit determination shall be robust against erroneous measurements and GPS data gaps, be able to handle orbit (translational) and attitude (rotational) maneuvers of the PRISMA spacecraft, which are characterized by frequent thrusting and non-zenith GPS antenna pointing respectively. From a performance point of view, under the provision of continuous and sufficient GPS data, the estimated absolute position and velocity shall be better than 3m and 1cm/s (3D, RMS). The estimated relative position and velocity of Mango with respect to Tango shall be better than 0.2m and 0.2mm/s (3D, RMS).

In order to fulfill the prescribed requirements, a tailored GPS hardware/software system has been designed for PRISMA (D'Amico *et al.*, 2009). The cold-redundant hardware architecture is identical on Mango and Tango, it is based on two Commercial-Off-The-Shelf single-frequency (L1) Phoenix GPS receivers and two passive GPS antennas which are located at the opposite sides of the spacecraft structure. The GPS measurements collected on Tango are provided to Mango through an Ultra-High-Frequency Inter-Satellite-Link and processed together with the Mango measurements by the navigation software which is integrated into a FPGA-based LEON-3 on-board computer clocked at 24 Mhz. An innovative estimation approach employs a common Extended Kalman Filter (EKF) for the absolute states of the two satellites, which accounts for the interdependency of absolute and relative navigation without the need of an explicit relative state.

In addition to the baseline GPS-based navigation, GSOC contributes one of the primary mission objectives: SAFE. SAFE is intended to demonstrate on-board fully autonomous, robust, and precise formation flying of spacecraft (D'Amico, 2010). In particular the main goals of SAFE are to provide a guidance law implementing a safe collision-free separation strategy, and to provide a robust control algorithm for formation keeping and reconfiguration with an accuracy better than 30m (3D, RMS) for typical separations below 1km. Indeed the design of SAFE motivated the generalization of the concept of relative eccentricity/inclination vector separation. The controller takes advantage of slow varying relative orbital elements and applies an analytical feedback control law to control the relative orbital elements. Compared to other control algorithms, in addition to a minimum number of thrust activations, the implemented strategy shows a high level of robustness and predictability. In fact the size and location of the impulsive maneuvers strictly depends on the desired correction of the relative orbital elements, which in turn is a straightforward function of the nominal formation geometry and the required control accuracy. Such features are considered of utmost importance to simplify mission operations, mission planning and to allow the collection of data from a distributed scientific instrument in orbit.

2.1 Absolute and Relative Navigation

The concept that has been shown to better satisfy the requirements and goals for the PRISMA mission is a combined EKF processing of GRAPHIC (GR) and single difference carrier phase (SDCP) data types (D'Amico *et al.*, 2009). Compared to the other alternatives this concept suffers from a relatively high computational load and complexity, but guarantees good navigation accuracy, robustness to attitude uncertainty and different GPS antenna orientations, simplicity in filter initialization and maneuver handling. The selected filter estimation parameters comprise the 6-dimensional spacecraft state in the Earth Centered Inertial (ECI) frame $\mathbf{x}$, the scalar GPS receiver clock offset $c\delta t$, a fixed number of force model parameters $\mathbf{p}=(C_D; \mathbf{a}_{emp})$, including the aerodynamic drag coefficient C_D and 3 empirical accelerations $\mathbf{a}_{emp}$ in the local orbital frame, and the 12 GRAPHIC float biases $\mathbf{N}$ for each GPS receiver channel. Next to these 23 parameters, which are estimated for each of the co-orbiting spacecraft, we include 3 Mango orbit maneuver increments $\delta\mathbf{v}$ expressed again in the local orbital frame for a total filter size of 49 states. This approach gives the possibility to incorporate the orbit control maneuvers within the navigation process through their direct estimation, and to take into account deficiencies of the maneuver model via dedicated white or colored process noise. Note that we have decided to remove the vertical ionospheric path delay from the estimation state vector. In fact the adopted GPS data types can be considered as ionosphere-free combinations for small inter-satellite separations (<5 km). The selected GPS measurements vector comprises a maximum of 12 GRAPHIC data types taken by the Mango spacecraft receiver, a maximum of 12 GRAPHIC data types taken by the Tango spacecraft receiver, and a maximum of 12 SDCP measurements related to the GPS satellites which are commonly visible by the two spacecraft. The maximum number of processed observations is 36 and provides a high level of redundancy to the filter because GRAPHIC and SDCP observations which involve the same GPS satellites are not independent.

2.2 Relative Orbit Control

We consider an operational scenario with two formation-flying spacecraft in near-circular LEO. Under the assumptions of a Keplerian two-body motion, a circular chief orbit, and spacecraft separations which are small as compared to the chief orbit radius, the fundamental equations of dynamics can be linearized to obtain the familiar Clohessy-Wiltshire (C-W) equations of relative motion (Clohessy and Wiltshire, 1960).

$$\begin{cases} \delta\mathbf{r}_R / a = \delta a - \delta e \cos(u - \varphi) \\ \delta\mathbf{r}_T / a = \delta\lambda - 1.5\delta a(u - u_0) + 2\delta e \sin(u - \varphi) \\ \delta\mathbf{r}_N / a = \delta i \sin(u - \vartheta) \\ \delta\mathbf{v}_R / v = \delta e \sin(u - \varphi) \\ \delta\mathbf{v}_T / v = -1.5\delta a + 2\delta e \cos(u - \varphi) \\ \delta\mathbf{v}_N / v = \delta i \cos(u - \vartheta) \end{cases} \quad (1)$$

Here the relative position $\delta\mathbf{r}$, and velocity $\delta\mathbf{v}$, of the deputy (Mango) is described in the Hill's orbital frame aligned with

radial (subscript R, positive zenith), along-track (subscript T, positive velocity direction), and cross-track (subscript N, positive orbit normal) directions centered on the chief (Tango). Furthermore relative position and velocity are divided by the semi-major axis a , and velocity v , of the chief orbit. The independent variable is the mean argument of latitude u , whereas the integration constants of the C-W equations are recognized as a specific set of relative orbital elements which result from a combination of the Keplerian orbital elements of the co-orbiting spacecraft (D'Amico, 2010). The periodic out-of-plane relative motion (N) is a function of amplitude (δi) and phase ($\mathcal{G}$) of the relative inclination vector ($\delta \tilde{i}$). The periodic in-plane relative motion (R/T) is a function of amplitude (δe) and phase (ϕ) of the relative eccentricity vector ($\delta \tilde{e}$). The along-track motion is characterized by a constant offset and a linear drift given by the relative mean longitude ($\delta \lambda$) and the relative semi-major axis (δa) respectively. Note that throughout the paper the relative mean argument of latitude ($\delta u = \delta \lambda - \delta i \cot i$, being i the orbital inclination) is often used in place of the relative mean longitude. The relevance of this relative orbit parameterization and the resulting enhanced geometrical insight will be more transparent in the next section which addresses the SAFE experiment planning.

The proposed linearized relative motion model offers an ideal mathematical tool to process orbit maneuvers. In particular we can express the relative orbital elements as a function of the instantaneous variation of velocity by inverting the solution of the C-W equations given by Eq. (1) with $\delta \tilde{r} = 0$. The control problem is fully decoupled with respect to in-plane and out-of-plane. A relative orbit control system can be designed to plan and execute correction maneuvers to ensure conformance with predefined nominal relative orbital elements. An arbitrary correction of the relative inclination vector $\Delta \delta i$, can be realized through a single cross-track maneuver of size δv_N , at location u_M , given by (D'Amico, 2010)

$$\begin{cases} \delta v_N = v \|\delta \tilde{i}^{\text{aft}} - \delta \tilde{i}^{\text{bef}}\| = v \|\Delta \delta \tilde{i}\| = v \Delta \delta i, \\ u_M = \arctan(\Delta \delta i_y / \Delta \delta i_x) \end{cases} \quad (2)$$

where the superscripts “aft” and “bef” indicates quantities before and after the execution of the maneuver. The control of the in-plane motion features a closed-loop along-track mode (CL-T) and a closed-loop radial mode (CL-R). CL-T uses pairs of along-track maneuvers only, while CL-R uses also pairs of radial maneuvers, in both cases separated by half an orbital revolution. Overall the maneuver cycle is restricted to a minimum of one pair of in-plane maneuvers and one single out-of-plane maneuver each orbital revolution. The size and location of the individual maneuvers in CL-T mode is computed on-board as follows (D'Amico, 2010)

$$\begin{cases} \delta v_{T1} = v(\Delta \delta a + \Delta \delta e) / 4 \\ \delta v_{T2} = v \Delta \delta a / 2 \\ u_{M1} = \arctan(\Delta \delta e_y / \Delta \delta e_x) \end{cases} \quad (3)$$

whereas size and location of the individual maneuvers in CL-R mode is given by (D'Amico, 2010)

$$\begin{cases} \delta v_{R1} = v(-\Delta \delta \lambda / 2 + \Delta \delta e) / 2 \\ \delta v_{T1} = v \Delta \delta a / 4 \\ \delta v_{R2} = -v \Delta \delta \lambda / 2 \\ \delta v_{T2} = v \Delta \delta a / 2 \\ u_{M1} = \arctan(\Delta \delta e_x / \Delta \delta e_y) \end{cases} \quad (4)$$

The subscripts “1” and “2” indicate the first and second maneuver of the same pair. Once the nominal formation configuration and the desired control windows are fixed by design, the size and locations of the maneuvers are also known and nominally constant during the mission. This characteristic of the control law is of extreme relevance when designing a formation of spacecraft with the aim of minimum complexity and operational effort. The choice of the proper control mode is mission and application dependant. The pro's of the CL-T mode are given by the smaller size of the maneuvers and its capability to correct the semi-major axis. As a consequence the CL-T mode can be used to efficiently reconfigure the formation in along-track direction at an efficient propellant consumption. Unfortunately depending on the constraints posed by the propulsion system, the along-track maneuvers may result smaller than the minimum impulse bit and the controller requests may not be executed in orbit. Furthermore during formation keeping phases each delta-v in along-track direction changes the semi-major axis and introduces unintentional drifts in along-track direction. As a consequence the mean along-track relative motion is characterized by a typical zigzag shape which is continuously corrected in orbit. On the other hand the pro's of the CL-R mode reside in radial maneuvers of larger size (typically two times the CL-T maneuvers) which do not affect the semi-major axis. At the expense of a higher propellant consumption CL-R can be used to accurately control the formation for small reconfigurations at small separations. In the following, key results obtained in flight throughout the conduction of the SAFE experiment are presented.

3. SAFE EXPERIMENT PLAN

This section describes the plan of the first part of SAFE which took place between September 20th and October 6th 2010. Even if this experiment slot was initially meant as a preparatory step to the second and final part of the experiment (March 16th to April 4th 2011), the rapid fulfilment of the envisioned objectives and the flexibility offered by the PRISMA mission operations concept gave the possibility to demonstrate, at an early stage, fully autonomous formation keeping and reconfiguration capabilities based on GPS relative navigation over a wide range of constellation geometries.

The experiment plan is summarized in Table 1 through a list of formation geometries which are meant to be acquired and maintained by the GNC subsystem in chronological order. Duration and commanded controller modes for each formation are indicated. Fig. 1 illustrates the nominal relative motion of Mango w.r.t Tango which corresponds to the prescribed nominal relative orbital elements. First the on-board controller is operated in navigation only mode (N) for one day, and guidance mode (G) for two days. This

operational phase is intended to test and verify the basic GNC functionalities without execution of orbit control maneuvers.

Table 1. Plan of SAFE experiment (first part) between September 20th and October 6th 2010.

ID	Duration [days]							
	1	2	2	1	2	3	3	1
	Controller mode							
	N	G	CL-T	CL-R				
	-	-	A	B	C	D	E	F
$a\delta a$	-0.5	5			0.0			
$a\delta \lambda$	-25	1882.3			0.0			
$a\delta e_x$	-10	55			0.0			
$a\delta e_y$	405	397		400		300	250	200
$a\delta i_x$	-6	-7		0.0		150	125	100
$a\delta i_y$	298	296		300		260	217	173

As a consequence the formation drifts naturally under the influence of the initial relative state conditions (mainly due to the relative semi-major axis), differential gravity (mainly due to J_2 effects) and differential drag (due to the differential ballistic coefficient). After enough confidence has been gained with the behavior of the GNC software, the closed-loop modes are entered for the remaining 13 days. The goal here is to tune the control function by choosing appropriate relative orbital elements dead-bands, setup parameters and by switching the possible control strategies. Most of the ways to change the formation geometry are explored from A to F (cf. Table 1). A is intended to acquire parallel relative inclination

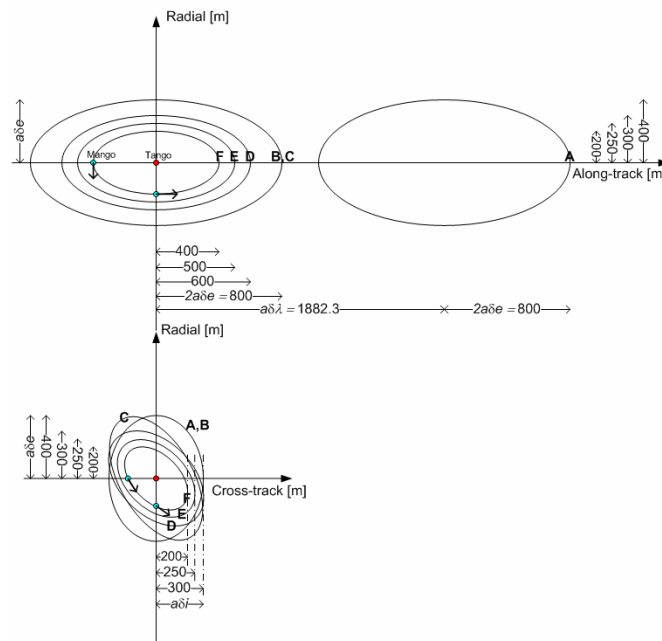


Fig. 1. Nominal formations and relative orbital elements during SAFE. Tango (red) occupies the origin of the Hill's frame. Mango (blue) moves in anti-clockwise direction.

and eccentricity vectors and stop the mean along-track drift at $a\delta \lambda = 1882.3\text{m}$. The reconfiguration to B is intended to demonstrate autonomous rendezvous through the zeroing of the mean along-track separation (in CL-T mode). The subsequent reconfigurations from C to F demonstrate stepwise and simultaneous corrections of non-parallel $a\delta e$ and $a\delta i$ with a reduction of their amplitudes to a minimum of 200m and an enclosed angle of 60° (in CL-R mode). The final geometry corresponds to a minimum separation between Mango and Tango of ca. 150m.

4. FORMATION KEEPING RESULTS

Table 2 summarizes the results obtained from the autonomous maintenance of formations A to F in orbit. Start and end dates, mean and maximum control tracking errors, and on-board DV requests are listed for each formation keeping phase. As a representative example, Fig. 2 depicts the relative orbital elements estimated on-board (at 1Hz) and the control box thresholds (soft: 0.5m, hard: 2m) which trigger the execution of maneuvers during formation D at an average maneuver cycle of one orbit (6000s). For completeness Fig. 3 illustrates the corresponding control errors which are computed as the difference between desired (from Eq. (1)) and actual relative position.

Table 2. Formation keeping results during SAFE.

ID	Time frame [dd/mm hh]		Control errors abs(mean/max) in [m]			DV [mm/s]
	Start	End	R	T	N	/orbit
A	23/09 23	25/09 03	0.3/9	0.6/17	0.2/1	0.75
B	26/09 05	26/09 15	0/2.5	0.7/6	0.2/1	0.67
	26/09 19	28/09 16	0/1.6	0.5/4.7	0.3/2	1.52
C	29/09 02	01/10 00	0/2.4	0.4/9.5	0/0.8	2.18
	01/10 02	01/10 15	0/1.1	0.1/4.2	0/0.8	1.93
D	01/10 22	04/10 17	0/1.6	0/5.2	0/0.9	1.87
E	04/10 23	05/10 16	0/1.2	0.2/3.9	0.1/1	1.62
F	05/10 23	06/10 15	0/1.3	0.3/3.9	0.1/1	1.37
Total (161.2 orbits)						264.3

By definition the error pattern shows osculating effects which are neglected by the linear model. This phenomenon is more evident for larger spacecraft separations and in the orbital plane (cf. formation A in Table 2). The in-plane control errors (R/T) are smaller in CL-R mode (cf. switch from CL-T to CL-R mode in formation B) and are cut by half when the maneuver cycle is decreased from 2 to 1 orbit (cf. two rows of formation C). On the other hand CL-R doubles the propellant consumption for in-plane control (compared with CL-T). This is evident from the DV request per orbit in formation B which is around the minimum impulse bit in CL-T (0.67mm/s), and increases to 1.52mm/s when using radial maneuvers. Consistent with the adopted analytical approach, the average DV request per orbit does not change when the

maneuver cycle is decreased (cf. formation C). As expected the DV requests are proportional to the desired correction of the relative eccentricity and inclination vectors and in turn decrease with the baseline length (cf. DV for formations C to F). In particular Fig. 2 shows clearly how both $a\delta e_x$ and $a\delta i_y$ drifts within the control box in the maneuver cycle due to secular J_2 effects. The orbital corrections required to bring both vectors to the opposite side of the control box are approximately $a\Delta\delta e = a\Delta\delta i = 1\text{m}$, which corresponds to a total DV of approximately 2mm/s per orbit according to Eq. (2) and (4). This is basically confirmed by simulations and flight results. Overall the formation keeping performance fulfils the requirements with margins, demonstrating control tracking errors below 2.5/9.5/2.0 m in R/T/N at steady state for separations below 1km (i.e., B to F). Larger control errors affect formation A with along-track separations between 1km and 2.6km (i.e., 9.0/17.0/1.0 m in R/T/N), which are mainly due to in-plane second order terms neglected by Eq. (1).

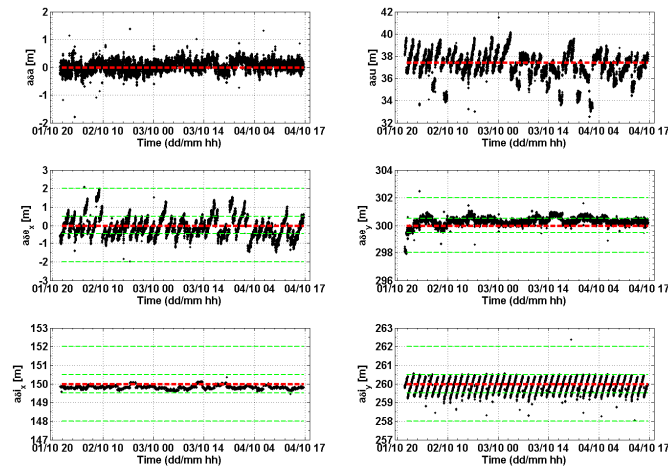


Fig. 2. Actual (black), nominal (red) relative orbital elements and control box thresholds (green) during keeping of formation "D".

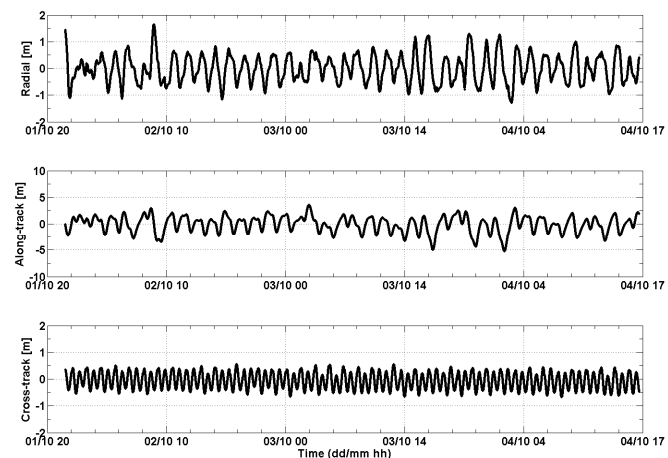


Fig. 3. Control tracking errors during keeping of formation "D" in radial (top), along-track (middle), and cross-track (bottom) directions.

5. FORMATION RECONFIGURATION RESULTS

Table 3 summarizes the results obtained from the autonomous acquisition of formations A to F from the preceding configurations. Desired corrections, convergence times, ideal (from Eq. (2-4)) and on-board (from telemetry) DV requests are listed for each formation reconfiguration. As a representative example, Fig. 4 depicts the relative orbital elements estimated on-board (at 1Hz) and the control box thresholds during the reconfiguration from formation C to D. For completeness Fig. 5 illustrates the corresponding control errors which are computed as the difference between desired (from Eq. (1)) and actual relative position as usual.

Table 3. Formation reconfiguration results during SAFE.

ID	Desired correction [m]			Duration [orbits]		DV [cm/s]	
	$a\Delta\delta e$	$a\Delta\delta i$	$a\Delta\delta u$	R/T	N	Ideal	Real
→A	55	8	8	2	1	3.7	4.4
→B	0	0	1882	6	-	19.8	22.3
→C	0	155	0	-	2	16.3	18.6
→D	100	0	-	2	-	10.5	12.4
→E	50	49.7	-	3	1.5	10.5	13.4
→F	50	50.6	-	2.5	1	10.6	12.4
Total (17.5 orbits)						71.4	83.5

Here the duration of the reconfiguration (triggered by a time-tagged telecommand) is defined as the time necessary to reduce the control tracking errors to a value below the maximum at steady state provided in Table 2 (cf. Fig. 5, right). Typical relative inclination vector (out-plane) convergence times are between 1-2 orbits, whereas relative eccentricity vector (in-plane) convergence times are between 2-3 orbits. It is noted that during this operational phase the maximum allowed correction of the relative orbital elements was set to 100m. If this limit is exceeded the current implementation truncates the size of the maneuver δv at its execution while keeping the originally planned location u_M for simplicity. The side effects of this approach are clearly visible in the along-track reconfiguration to B which takes 6 orbits to converge while requesting 22.3cm/s (against an ideal 19.76cm/s for one orbit convergence time). In this case the controller tried to establish a ca. 190m relative semi-major axis to achieve the desired along-track drift of ca. 1.9km/orbit. The truncation of the maneuvers caused undesired variations of the relative eccentricity vectors which needed to be compensated as well before convergence. Fig. 4 shows instead a nominal reconfiguration of the relative eccentricity vector by 100m in CL-R mode while maintaining the relative inclination vector (cf. $a\delta e_y$ and $a\delta i_y$). It is clearly visible how $a\delta e$ is transferred to its nominal value after a pair of radial maneuvers which do not affect $a\delta a$. As expected the temporary offset of $a\delta u$ lasts half an orbit and is cancelled out after the second maneuver of the pair.

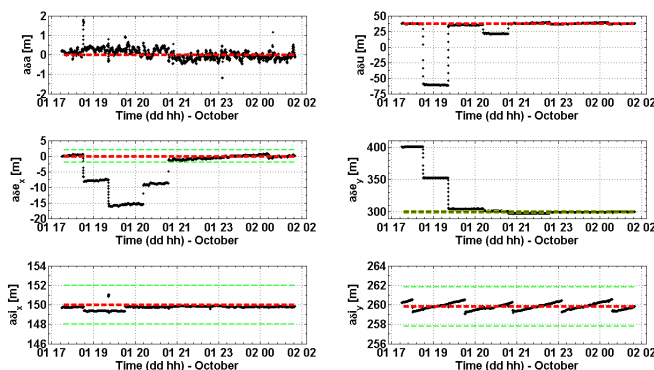


Fig. 4. Actual (black), nominal (red) relative orbital elements and control box thresholds (green) during reconfiguration from formation “C” to “D”.

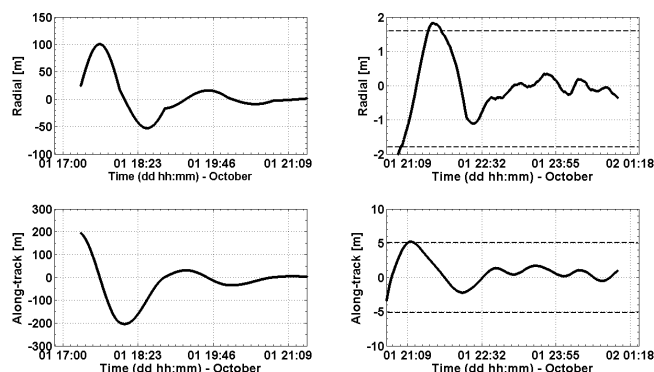


Fig. 5. Control tracking errors during reconfiguration to formation “D” in radial (top) and along-track (bottom).

6. GPS-BASED NAVIGATION RESULTS

The control tracking errors and relative orbital elements discussed in the previous sections are based on the on-board GPS navigation output. This approach is justified since both on-board GPS-based navigation system and on-ground precise orbit determination (POD) layer had been verified, calibrated, and commissioned prior to the conduction of the experiment in the time frame between June and September 2010 (Ardaens *et al.*, 2011). For completeness Table 4 lists the statistics of the GPS-based absolute and relative navigation errors obtained during SAFE.

Table 4. On-board GPS navigation errors during SAFE.

[mean±std]	R	T	N
Mango position [m]	0.36±2.56	0.88±1.14	0.29±0.89
Mango velocity [cm]	0.09±1.08	-0.07±0.68	0.00±0.17
Relative position [cm]	0.03±5.21	0.38±4.97	0.01±3.30
Relative velocity [mm/s]	0.02±0.18	-0.03±0.11	0.00±0.09

The navigation errors are computed through a comparison of the navigation state generated on-board by the GNC subsystem with the POD products generated post-facto on-ground. As shown during the commissioning phase, the reference ephemerides can be used as trustworthy reference since they are affected by errors 5 to 10 times smaller than

the on-board absolute and relative navigation respectively. The demonstrated absolute navigation accuracy is 3.13m and 1.30cm/s, whereas the overall relative navigation accuracy is 8.15cm and 0.24mm/s, for position and velocity respectively (3D, RMS). Although these figures show the compliance of the navigation system to the performance requirements on a routine basis (cf. Section II), it is to be noted that SAFE offers favorable navigation conditions because the GPS antennas are pointing close to the Zenith ($\pm 10^\circ$ ca.) at all times. Other operational phases and experiments during the PRISMA mission are characterized by non-zenith pointing antennas and fast rotations of the spacecraft which are certainly more challenging from a GPS navigation point of view but are out of the scope of this paper.

7. CONCLUSION

This paper has presented flight results gathered during the first part of the GSOC’s Spaceborne Autonomous Formation Flying Experiment (SAFE) in the frame of the Swedish PRISMA mission. A total of six formations have been prescribed via telecommand during a 16-days experiment in order to demonstrate the capability to build arbitrary baselines in space in full autonomy for future remote sensing applications. The reliability, robustness, and performance of the relative GNC functions has been shown to fulfil the requirements with navigation and control accuracies at the centimeter and meter level respectively. The successful conduction of this operational phase paves the way to the second and final part of SAFE planned for March-April 2011.

REFERENCES

- Ardaens, J.-S., D’Amico, S., Montenbruck, O. (2011). Final Commissioning of the PRISMA GPS Navigation System. *22nd ISSFD*, Sao Jose dos Campos, Brazil.
- Bodin, P., Larsson, R., Nilsson, F., Chasset, C., Noteborn, R., and Nylund, M. (2009). PRISMA: An In-Orbit Test Bed for Guidance, Navigation, and Control Experiments. *Journal of Spacecraft and Rockets*, **Vol. 46**, No. 3, pp. 615-623.
- Clohesy, W.H., and Wiltshire, R.S. (1960). Terminal guidance system for satellite rendezvous. *Journal of the Aerospace Sciences*, **Vol. 27**, pp. 653–658.
- D’Amico, S., Ardaens, J.-S., Montenbruck, O. (2009). Navigation of Formation Flying Spacecraft using GPS: the PRISMA Technology Demonstration. *ION-GNSS-2009*, Savannah, USA.
- D’Amico, S. (2010). *Autonomous formation flying in low earth orbit*, Ph.D. Dissertation, Technical University of Delft, ISBN 978-90-5335-253-3.
- Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Werner, M., Younis, M., and Zink, M. (2007). TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, **Vol. 45**, No. 11, pp. 3317–3341.
- Tapley, B., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F., Gunter, B., Kang, Z., Nagel, P., Pastor, R., Pekker, T., Poole, S., Wang, F. (2005). GGM02 - An improved Earth gravity field model from GRACE. *Journal of Geodesy*, DOI 10.1007/s00190-005-0480-z.