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FLIGHT RESULTS FROM THE AUTONOMOUS NAVIGATION AND CONTROL OF FORMATION FLYING SPACECRAFT ON THE PRISMA MISSION

S. De Florio
Department of Aerospace Engineering, University of Glasgow, guest scientist at DLR, Glasgow G12 8QQ, UK,
s.deflorio@aero.gla.ac.uk

S. D'Amico and J.-S. Ardaens
German Aerospace Center (DLR), D-82230 Wessling, Germany

PRISMA is a small-satellite formation flying mission created by the Swedish National Space Board (SNSB) with the Swedish Space Corporation (SSC) as prime contractor and additional contributions from the German Aerospace Center (DLR), the French Space Agency (CNES), and the Technical University of Denmark (DTU). This mission will serve as a test platform for autonomous formation flying and rendezvous of spacecraft. PRISMA comprises a fully maneuverable small-satellite (MANGO) as well as a smaller sub-satellite (TANGO) which have been launched together in a clamped configuration on June 15th 2010 and separated in orbit after completion of all checkout operations. The mission schedule foresees a targeted lifetime of at least eight months. Through PRISMA, novel approaches in the areas of formation flying guidance, GPS based relative navigation, impulsive relative orbit control and space mission operations will have an in-flight validation. DLR's key contributions comprise the on-board GPS-based absolute and relative navigation system, the Spaceborne Autonomous Formation Flying Experiment (SAFE), the Autonomous Orbit Keeping (AOK) experiment as well as the on-ground Precise Orbit Determination (POD) layer. In this paper in-flight results of the PRISMA on-board GPS based navigation system are presented. The on-board navigation performance is estimated through a comparison with the on-ground POD results and is evaluated in terms of accuracy requirements fulfilment and robustness in critical situations (e.g., attitude and orbit control maneuvers, large GPS data gaps). An overview is also given of the innovative and flexible PRISMA operations concept and the DLR's PRISMA Experiment Control Center (ECC).

I. MISSION DESCRIPTION

I.I Mission Objectives

PRISMA[1,2] is a micro-satellites formation mission created by the Swedish National Space Board (SNSB) and Swedish Space Corporation (SSC), which serves as a platform for autonomous formation flying and rendezvous of spacecraft. The formation comprises a fully maneuverable micro-satellite (MANGO) as well as a smaller satellite (TANGO) which are launched together in a clamped configuration and separated in orbit after completion of all checkout operations (Fig. 1-2). The PRISMA mission primary objective is to demonstrate in-flight technology experiments related to autonomous formation flying, homing and rendezvous scenarios, precision close range 3D proximity operations, soft and smooth final approach and recede maneuvers, as well as to test instruments and unit developments related to formation flying.

Key sensors and actuators comprise a GPS receiver system, two vision based sensors (VBS), two formation flying radio frequency sensors (FFRF), and a hydrazine mono-propellant thruster system (THR). These will support and enable the demonstration of autonomous spacecraft formation flying, homing, and rendezvous scenarios, as well as close-range proximity operations.

The experiments can be divided in Guidance, Navigation and Control (GNC) experiments and sensor/actuator experiments. The GNC experiment sets consist of closed loop orbit control experiments conducted by SSC and the project partners which are the German Aerospace Center (DLR/GSOC), the French Space Agency (CNES) in partnership with the Spanish Centre for the Development of Industrial Technology (CDTI), the Technical University of Denmark (DTU), ECAPS (a subsidiary company to SSC), Nanospace (a subsidiary company to SSC), Techno Systems (TSD) and Institute of Space Physics (IRF) in Kiruna.

Table 1 resumes the GNC primary and secondary objectives and the involvement of the different project partners. Table 2 resumes the sensor/actuator primary and secondary experiments and the involvement of the different project partners. In addition to the GPS-based absolute and relative navigation system, which is the baseline navigation sensor for the on-board GNC functionalities, DLR contributes two dedicated orbit control experiments[3,4,5,6]. The primary experiment is named SAFE and implements autonomous formation keeping and reconfiguration for typical separations below 1 km based on GPS navigation.

Primary GNC Related Tests			
Type of control	**Distance range (m)**	**Sensor**	**Prime**
Autonomous formation flying	20-5000	GPS	SSC
Proximity operations[7] Final approach and recede	5-100	VBS and/or GPS	SSC
Collision avoidance and autonomous rendezvous	10-100000	VBS and/or GPS	SSC
Autonomous formation control (SAFE)[8,9]	50-1000	GPS	DLR
RF-based formation flying and forced RF-based motion[10]	20-5000	FFRF	CNES
Secondary GNC Related Tests			
Autonomous Orbit Keeping (AOK) of a single spacecraft[11]			DLR

Table 1: GNC experiments

The required relative position control accuracy is 30 m (3D, RMS). The secondary experiment of the DLR's contributions to PRISMA is AOK which implements the autonomous absolute orbit keeping of a single spacecraft with a required control accuracy of the osculating ascending node of 10 m (1σ).

Primary Hardware Related Tests	
Flight demo of GPS Phoenix receiver	DLR
Flight demo of HPGP Motor[12]	SSC
Flight demo of micro-thrusters motor[13]	Nanospace
Validation of RF Sensor (FFRF)	CNES
Validation of Vision Based Sensor (VBS)	DTU
Secondary Hardware Related Tests	
Flight demo of a Digital Video System	Techno System
Flight demo of a MEMS-based particle mass spectrometer	IRF

Table 2: sensor/actuator experiments

I.II Spacecraft

The MANGO spacecraft (Fig. 1) has a wet mass of 150 kg and a size of 80 × 83 × 130 cm in launch configuration, has a three-axis, reaction-wheel based attitude control and three-axis delta-v capability.

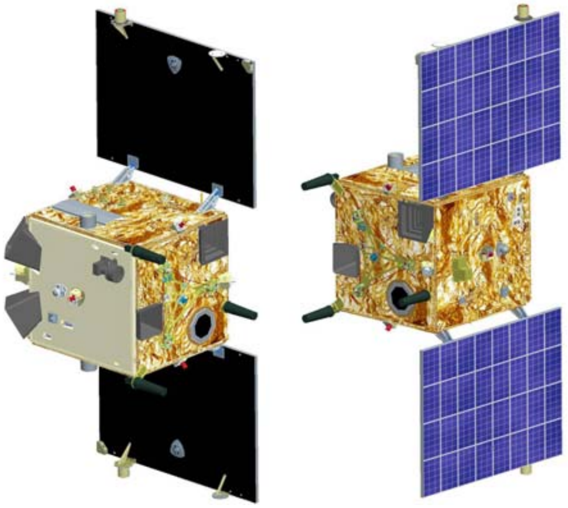

Fig. 1: MANGO spacecraft

The GNC sensors equipment comprises two three-axis magnetometers, one pyramid sun acquisition sensors and five sun-presence sensors , five single-axis angular-rate sensors, five single-axis accelerometers, two star-tracker camera heads for inertial pointing, two GPS receivers, two vision-based sensors and two formation flying radio frequency sensors. Three magnetic torque rods, four reaction wheels and six thrusters are the actuators employed. Electrical power for the operation of the spacecraft bus and payload is provided by two deployable solar panels delivering a maximum of 300 W.

In contrast to the highly maneuverable MANGO satellite, TANGO (Fig. 2) is a passive and much simpler spacecraft, with a mass of 40 kg at a size of 80 × 80 × 31 cm with a coarse three-axis attitude control based on magnetometers, sun sensors, and GPS receivers (similar to MANGO), with three magnetic torque rods as actuators and no orbit control capability. The nominal attitude profile for TANGO will be sun or zenith pointing. Required power is produced by one body-mounted solar panel providing a maximum of 90 W.

Communication between ground segment and TANGO spacecraft is only provided through MANGO acting as a relay and making use of a MANGO-TANGO inter-satellite link in the ultrahigh-frequency (UHF) band with a data rate of 19.2 kbps.

I.III GPS Based Navigation System

DLR/GSOC, besides designing and conducting his own experiments, has assumed responsibility for providing the GPS-based navigation functionality which comprises the provision of Phoenix GPS receivers[14,15,16,17], the GPS based on-board navigation system for absolute/relative orbit determination[4,6,8] and the on-ground POD[19].

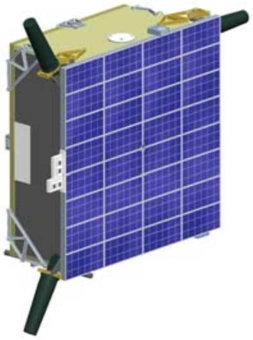

Fig. 2: TANGO spacecraft

In fact the on-board navigation system includes two Phoenix-S GPS receivers and the real-time orbit estimation software with a required absolute (relative) position accuracy of 3 (0.2) m (3D, RMS) in nominal conditions under the provision of sufficient GPS data. The on-ground POD is requested to provide absolute (relative) position accuracies better than 0.5 (0.05) m (3D, RMS).

The Phoenix-S [12] GPS system on MANGO and TANGO will provide pseudorange and carrier phase measurements for the PRISMA navigation system on MANGO. GPS measurements collected on TANGO are transferred to MANGO via the ISL. The navigation system provides absolute position and velocity of the participating spacecraft to be used by the MANGO GNC system as well as the other PRISMA experiments. The GPS system provides also timing information for on-board synchronization. The physical architecture of the GPS system is identical on MANGO and TANGO. For redundancy, two Phoenix-S GPS receivers are available, which are connected to two GPS antennas via a coaxial switch. The dual antenna system provides increased flexibility for handling non-zenith pointing attitudes and antennas may be selected by ground command or autonomously on-board. Only one receiver will be active at any time.

From a functional perspective the primary objective of the GPS-based navigation system addressed here is to perform a real-time reduced-dynamic orbit determination based on raw GPS C/A code and L1 carrier phase measurements. Considering that ionospheric errors dominate the GPS measurements error budget, a suitable combination of raw code and carrier phase is exploited to remove those errors. As a minimum the orbit determination is asked to adjust the spacecraft position, velocity, clock error and carrier phase biases. In order to simplify operations, it is possible to start and initialize the autonomous estimation process from GPS data available on-board. Furthermore the orbit determination is able to detect and reject bad GPS data and be robust against erroneous measurements. The orbit determination is able to bridge GPS data gaps and to handle thruster pulses of the PRISMA propulsion system applied as part of the formation keeping and reconfiguration activities.

Continuous orbit information is important for autonomous on-board GNC applications. As a consequence, orbit prediction is a mandatory function of the navigation system and provides continuous absolute and relative position and velocity information of the co-orbiting satellites. Furthermore the navigation system provides an accuracy measure indicating the expected quality of the orbit results.

II. MISSION OPERATIONS

II.I General Organization

The organization involved in the PRISMA mission operations is divided in two main parts: the mission control team in the Mission Control Centre (MCC) and several experiment control teams corresponding to each project partner's Experiment Control Centre (ECC).

MCC is situated in Solna, Stockholm and the crew consists of one mission manager and (at least) three mission experts. The overall function of the MCC is to schedule and execute the timeline of the PRISMA mission. MCC is also responsible for validation of all incoming data from each experimenter to ensure the safety of the satellite and it is therefore given the authority to reject an experiment if it does not fullfils the satellites' operational constraints e.g. solar aspect angle, delta-V budget, etc. MCC is also given the authority to reschedule the mission time line if necessary. A reason for rescheduling can be rejection of an experiment at a late state when the experiment is not expected to be corrected in time for its deadline.

The ECCs are subdivided in two categories, local ECC situated in direct vicinity to Mission Control Centre and remote ECC situated in the locations of the different mission partners. During the parts of the mission when the experimenter is preparing or executing his experiment, the experimenter will preferably be present at the local ECC, especially in a Go/No-Go experiment. The local ECC has access both to real-time and offline telemetry. The remote ECC can only access telemetry data from the external archive. In the PRISMA mission an external archive is used for all files containing mission project and operations data e.g. telemetry (TM) data, telecommands (TC) logs, documentation, experiment products, POD products, etc. This archive is also used as an exchange data server for all partners in the mission. This provides a static and common interface for all users maintained regardless of the user's location. Other benefits are back-up, version control and reliability of long time post mission storage. The external archive is housed at Parallel Data Centre (PDC) at the Royal Institute of Technology in Stockholm, Sweden.

II.I DLR's ECC

Functional Requirements

The DLR's ECT is situated at Oberpfaffenhofen and makes use of a dedicated Experiment Control Centre (ECC) facility. Primary functional requirements of DLR's ECC are:

1. To provide GPS based navigation procedures to the PRISMA MCC
2. To provide SAFE and AOK experiments procedures to the PRISMA MCC
3. To provide precise orbit determination products according to the functional requirements
4. To provide DLR's mission data archiving

Secondary functional requirements of ECC are:

1. To provide on-board navigation performance analysis results.
2. To provide control performance analysis results.
3. To provide software validation by means of a replay of on-board operations based on history TM data.

Overall requirements in the implementation of DLR's ECC have been compactness, simplicity of structure and high portability.

External and Internal Interfaces

Fig. 3 depicts a scheme of DLR's ECC functional environment. The ECC receives from the GSOC Flight Dynamic (FD) auxiliary inputs necessary to the POD and performance analysis processes. The ECC is connected via the PRISMA PDC data centre to the PRISMA MCC (dotted lines in figure represent indirect connections), to which it sends the TCs procedures and from which it receives the TM data. PRISMA PDC is also the main connection between DLR's ECC and other PRISMA mission ECCs which can access for example to DLR's POD products or GPS-based navigation performance information. Table 3 resumes the data flow involved in the POD and OPS processes.

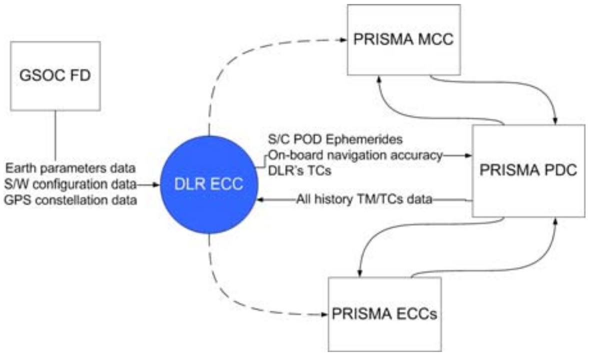

Fig. 3: DLR's ECC functional environment

Process	Inputs	Outputs
POD	TM and TCs POD process auxiliary data	Spacecraft ephemerides On-board navigation accuracy GPS raw data Processed history TM and TCs in a Matlab structure format
OPS	Spacecraft ephemerides Processed history TM and TCs in a Matlab structure format GPS raw data	DLR procedures DLR flight software validation results Experiments control performance analysis results

Table 3: POD and OPS processes inputs/outputs

Architecture

Fig. 4 depicts the general structure of DLR's ECC. The ECC consists of three main processes: the POD, OPERATIONS (OPS) and data ARCHIVE. A Linux and a Windows workstation host POD and OPS respectively, the ARCHIVE is an external mass memory storage device. The POD process is the only one interfaced with the external world and is dedicated to data exchange, pre-processing and to the POD products generation. The POD process runs autonomously 24 hours a day 7 days a week on a time schedule basis.

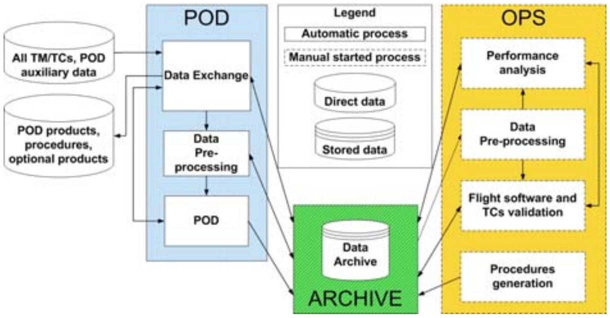

Fig. 4: DLR's ECC general architecture

POD main sub-processes are the precise absolute and relative orbit estimation, fetching of TM data and delivery of POD products and GPS raw data to PRISMA PDC, monitoring of the navigation performance, monitoring and anomaly analysis of the GPS system.

The OPS process includes all the sub-processes required to operate the DLR's experiments for the PRISMA mission and is a manually started process. The OPS main sub-processes are flight software on-board events replay tool, mission scenarios simulation facility and the TM data analysis tool.

Fig. 5 is a scheme of the structure of the replay tool, which is composed by the entire DLR's flight software for PRISMA, and auxiliary modules that feed the flight software modules with data extracted from the history TM packets. The tool, as the entire PRISMA flight software, is built in a Matlab/Simulink environment that provides the top level software and interface description to C/C++ modules that implement the computationally implement intensive core navigation functions.

BSW, GNC and ORB boxes represent the flight software application cores that are implemented as asynchronous tasks with different priority and sample time (respectively 1, 1 and 30 seconds). The boxes named GPS interface (GIF), GPS-based Orbit Determination (GOD) and GPS-based Orbit Prediction (GOP) represent DLR's navigation software modules. GIF performs GPS messages validation, editing and extraction and stores the extracted raw GPS data for access by the orbit determination function. GIF provides also GPS time for on-board time synchronization. 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. In the case that no valid GPS data are available only a time update is performed. GOP retrieves the on-board time, or Spacecraft Elapsed Time (SCET), 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 the SCET. 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. Modules named as Autonomous Formation Control (AFC) and Autonomous Orbit Keeping (AOK) are respectively the formation and absolute trajectory control modules.

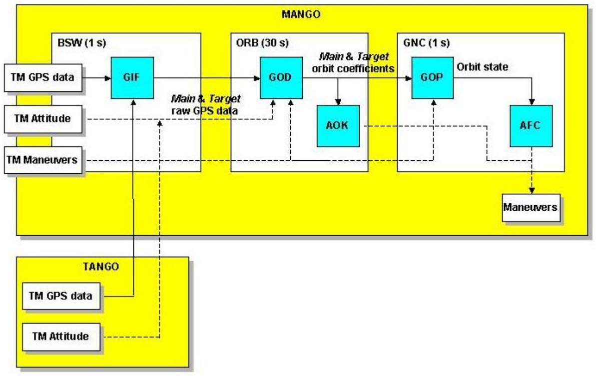

Fig. 5: Top level architecture of DLR's replay tool.

Fig. 6 shows a very basic scheme of the formation flying on-board software development and testing facility of DLR's ECC. The internal architecture is the same of Fig. 5. An orbit propagator developed at DLR/GSOC generates realistic trajectories of MANGO and TANGO. The propagated spacecraft orbits are the input to the Phoenix EMulator (PEM) software that allows a realistic modeling of measurements issued by a GPS receiver in LEO. In case an even more realistic simulation scenario is required, the offline software blocks in charge of numerical orbit propagation and Phoenix receiver emulation are replaced by a 2x12 channels Spirent GSS7700 GPS signal simulator and two Phoenix GPS fully representative of PRISMA flight units. Attitude data come from preset attitude profiles representative of real mission scenarios. Maneuvers generated by the flight software control modules are in a close loop with the orbit propagation module. The on-board software can run on a laptop or on the LEON3 board representative of PRISMA on-board CPU. Common features of the tools developed for the DLR's ECC is a high portability and a user-friendly approach enhanced by graphical user interfaces.

Flight Procedures Generation

DLR has to generate flight procedures for its own experiments and also for the on-board orbit estimation software. The TCs procedure is first validated in DLR's ECC by means of a tool capable of a realistic simulation scenario involving DLR's flight software modules. Once it has been verified that the simulation output is as expected, the procedure TCs procedure is sent to the MCC. Here the procedure is validated by means of a simulation involving the entire PRISMA flight software.

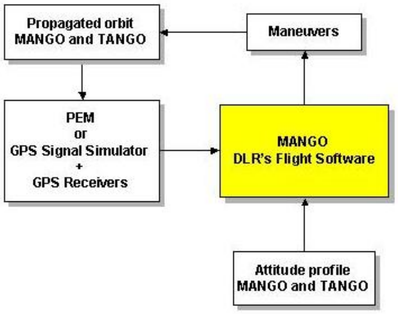

Fig. 6: Top-level architecture formation flight test bed

The results of the simulation performed at the MCC are finally double checked by DLR's ECT.

The TM replay tool of Fig. 5 supports the generation of flight procedures dedicated to the performance enhancement of the on-board GPS based orbit determination software. In-fact it allows to input history telemetry (GPS raw data, attitude, etc.) in the DLR's navigation software. The real navigation software output can be thus reproduced exactly in a simulation environment for a certain time frame. In this way the on-board navigation filter settings given by TCs can be tuned on-ground in order to improve the navigation accuracy performance.

III. MISSION EVENTS AND FLIGHT RESULTS

III.I Operations Plan

The PRISMA[18] mission can basically be divided into commissioning, basic mission and extended mission phases. The first 57 days of the mission foresee the commissioning and initial checkout of on-board equipment, checkout of essential on-board functions and calibration of navigation algorithms such as attitude, rate estimators, and GPS navigation. Most of the commissioning phase operates PRISMA as a combined spacecraft where TANGO is still mated to MANGO. The last slots of the mission timeline in this phase include TANGO separation from MANGO and the subsequent GPS relative navigation calibration campaign.

The basic mission phase starts directly after the commissioning phase and lasts for 235 days. All of the experiments needed to reach the primary mission objectives will be executed during this mission phase. The MANGO and TANGO spacecraft are configured for the different experiments and fly mostly inside the ISL range domain (< 20 km) but sometimes also out of reach of the ISL. Experiments that are expected to go outside the ISL range are placed late in the mission timeline.

The extended mission phase is initiated after completion of all nominal experiments. This should take place in the last 60 days of the mission. In this phase the MANGO/TANGO formation evaporates. The experiments during the extended mission phase in fact include secondary mission objectives and other activities that do not need the presence of the TANGO spacecraft. Before communication with TANGO becomes impossible its transmitter has to be permanently shut down by command from ground. The first part of this mission phase includes also experiments that make use of observations of a vanishing TANGO spacecraft. At the end of this phase, the mission consists of only the MANGO spacecraft. Next section gives an overview of the mission events that took place insofar.

III.II Previous and On-going Events

The PRISMA satellites were successfully launched aboard a Dnepr launcher from Yasny, Russia, on June 15th 2010 at 14.42 UTC[18]. Sixteen minutes after launch, the two PRISMA satellites were released, clamped together in launch configuration, into a nominal dusk-dawn orbit at a mean altitude of 757 km, 0.004 eccentricity and 98.28° inclination. On June 17th 2010, as prescribed by the nominal mission timeline, the PRISMA LEOP has been declared accomplished. The LEOP consists of the initial acquisition of the combined spacecraft (consisting of the clamped MANGO and TANGO) and initial checkout of the power and thermal systems as well as some fundamental GNC functions including the reaction-wheel momentum management function. During LEOP the spacecraft entered the most basic Attitude and Orbit Control System (AOCS) mode named Safe/Sun after having removed the momentum induced by the launch vehicle separation. Safe/Sun makes use of three-axis magnetometers, one pyramid sun acquisition sensors and five sun-presence sensors for attitude sensing. In Safe/Sun the spacecraft is stably sun pointing (i.e., MANGO solar panels are perpendicular to the Sun vector) and rotating around the Sun vector approximately once per hour. The successful conclusion of the LEOP signed the beginning of the Commissioning Phase. During the Commissioning Phase the spacecraft entered the more accurate AOCS modes named Safe/Celestial and Manual. Safe/Celestial makes use of star tracker measurements for attitude determination and orbit information in form of Two Line Elements (TLEs). On July 3rd 2010, after a successful initial Commissioning Phase, PRISMA was put into a safe standby configuration for a period of four weeks. But on July 6th a scaring close approach message was received from the Joint Space Operations Center (JSpOC) in California. An object called COSMOS 2251 DEB, one of the numerous debris resulting from the collision between an Iridium satellite and the COSMOS satellite last year, was dangerously coming closer to the PRISMA clamped spacecraft at a distance of 144 m. PRISMA was waked up to perform an avoidance manoeuvre. Thanks to the joint collaboration of DLR/GSOC and JSpOC a proper collision avoidance maneuver was computed and executed at 19:00 UTC bringing safely the mated spacecraft MANGO and TANGO more than 2 km away from the COSMOS debris.

On 11th August 2010 TANGO was separated from MANGO and stabilised itself in a slowly rotating sun pointing attitude. Everything shown up nominal aboard the small spacecraft and the GPS navigation showed up that the relative trajectory was nominal with a relative distance of about 120 m between the two spacecraft. After a relative drift cancellation maneuver, the initial nominal formation configuration was established.

On 16th August a 5 days GPS calibration phase was started bringing to the improvement of the on-board GPS navigation filter performance. Main goal of this calibration campaign was finding navigation filter settings that could improve the robustness of the relative navigation performance. Robustness in this case means that the filter can keep giving the required relative navigation accuracy in certain operational situation in which the navigation filter is stressed up to the limits of its operability. Common of such situations are TANGO tumbling which impair GPS satellites visibility, South Atlantic Anomaly (SAA) passages in which the GPS receivers are shut down in order to avoid latch-up risks and in which the navigation filter performs only the time update, and finally high thrusting activity that stress the dynamic model of the filter as the orbit maneuvers have to be included in the orbit determination process.

On 20th August the first PRISMA experiment, the in flight validation of the High Performance Green Propulsion System (HPGP) was started and for 4 days a series of firing sequences was executed.

On 24th August the Nanospace thrusters experiment started and ran for 6 days. Though in the first two days it could be verified that all MEMS thrusters responded as expected, it was also discovered that a leakage of gas had most likely occurred on the high-pressure side of the propellant storage and feed system. As a consequence, the delivered thrust could not be verified as planned and the experiment was interrupted.

A slot of four days could be than exploited for testing of new on-board navigation filter settings uploaded in the evening of 25th and further calibration of the GPS navigation.

III.III GPS Based Navigation System Performance

In this section an overview of the on-board GPS based navigation system performance is given. The relative navigation accuracy will be considered in the cases of nominal conditions, SAA passages, TANGO spacecraft tumbling and high thrusters activity.

SAA Passages

As during SAA passages the GPS receivers are shut down for about 20 minutes, the on-board navigation filter is not able to make the measurements update but only the time update, i.e. the estimated trajectory is the result of a numerical propagation that has as initial state the last estimation. Main driver in choosing the new filter settings has been to render the navigation filter more robust in case of prolonged data gaps periods.

Thus a trade-off between navigation accuracy and robustness had to be done. In fact with the new settings the weight of the dynamic model in the orbit estimation has been increased while the weight of the measurements has been decreased. The different behaviour of the filter with old and new settings can be appreciated comparing Figures 7 and 9 while taking in consideration Figures 8 and 10 which shows when are the SAA passages where no GPS satellites can be tracked.

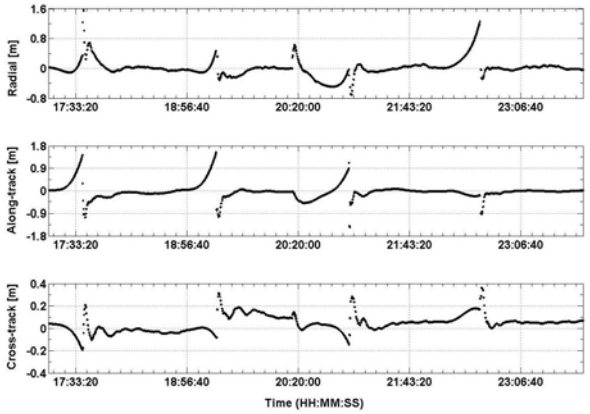

Fig. 7: Relative navigation accuracy, 23rd August

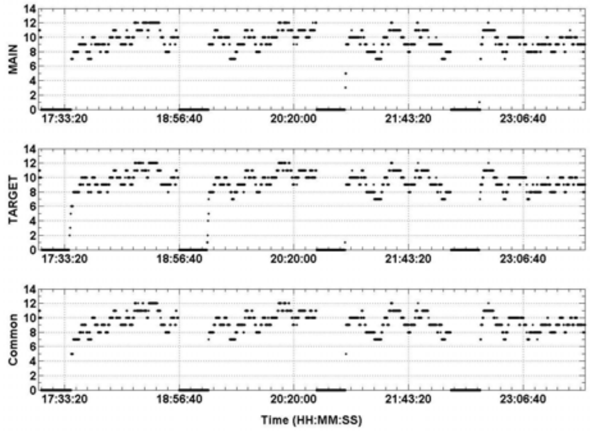

Fig. 8: Tracked GPS satellites, 23rd August

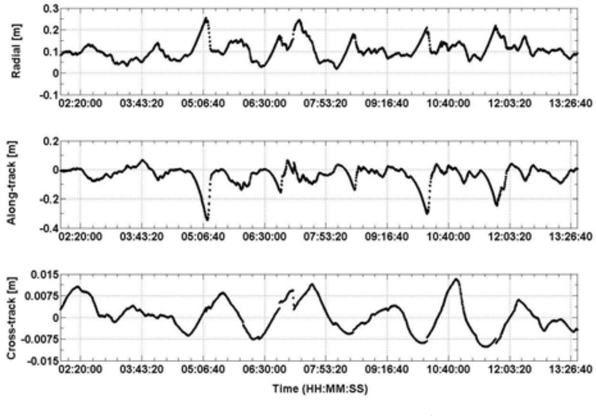

Fig. 9: Relative navigation accuracy, 30th August

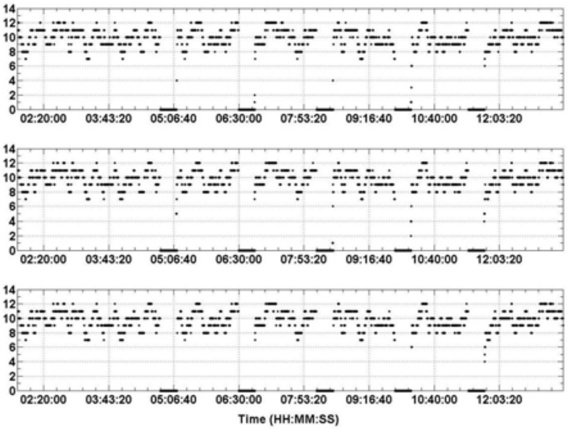

Fig. 10: Tracked GPS satellites, 30th August

The navigation accuracy is evaluated in local orbital frame (R axis in radial, N anti-cross-track and T along-track oriented) with respect to the POD that is accurate at the sub-centimetre level[19]. It can be noticed that the new settings give better behaviour of the navigation filter during GPS data gaps. The fact that the dynamic model has more weight in the estimation process of Fig. 9 is made evident by the strong anti-correlation of the navigation errors in radial and along-track direction.

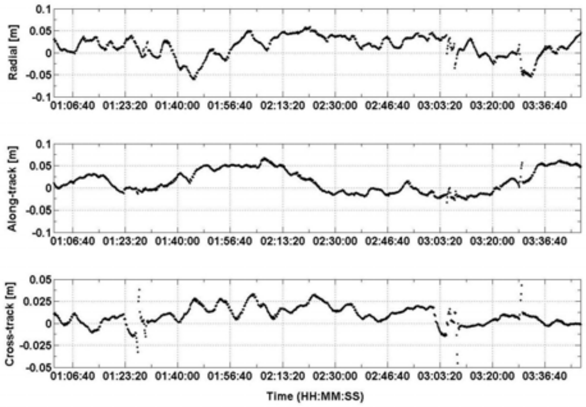

Fig. 11: Relative navigation accuracy, 21st August

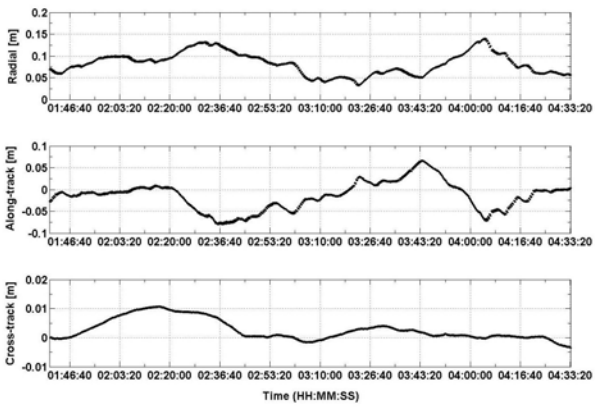

Fig. 12: Relative navigation accuracy, 30th August

Figures 11 and 12 show the different quality of the relative navigation accuracy before and after the filter tuning under nominal conditions, i.e. spacecraft zenith pointing, no GPS data gaps and no orbital maneuvers. The new filter settings provide a smoother relative navigation accuracy which is steady at the sub-decimetre level.

TANGO Tumbling

Fig. 13 depicts the actual yaw, roll and pitch rotations of TANGO with respect to local orbital RTN in the first 15 hours of 26th August. Positive yaw, roll and pitch rotations are clockwise around the respective axes and advancing in their positive directions. Fig. 14 shows the data gap periods and Fig. 15 the on-board relative navigation accuracy in the same time arc. In this extreme case the relative navigation accuracy degrades to the meter level.

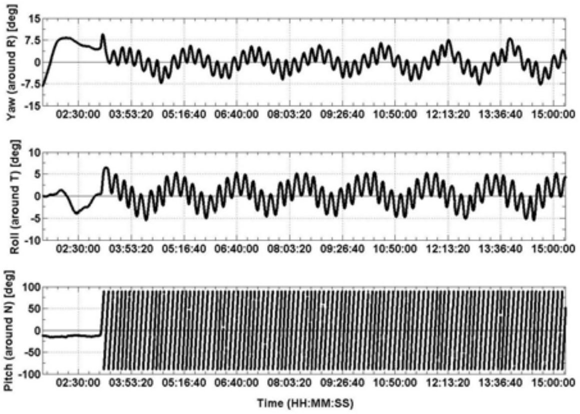

Fig. 13: Relative navigation accuracy, 26th August

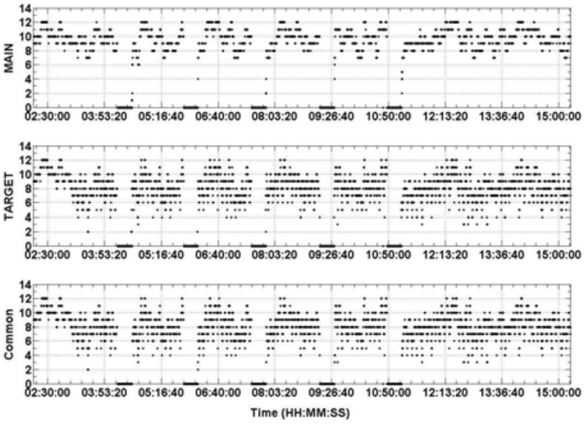

Fig. 14: Tracked GPS satellites, 26th August

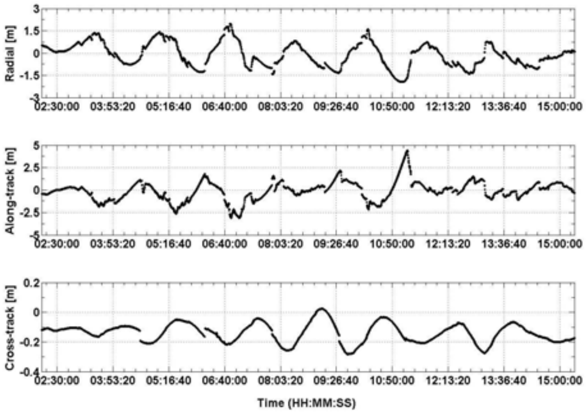

Fig. 15: Relative navigation accuracy, 21st August

Thrusters Activity

Figures 16, 17 and 18 show respectively the number of tracked GPS satellites, the orbital maneuver and the relative navigation accuracy on 4th September. No orbital maneuvers are executed during GPS data gaps. The maneuvers are included in the orbit estimation process and their value is estimated.

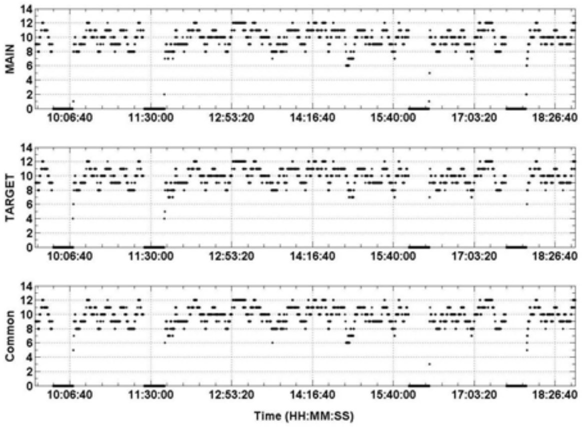

Fig. 16: Tracked GPS satellites, 4th September

Fig. 17 shows the actual executed orbital maneuvers (x markers) and the filter estimation (square markers).

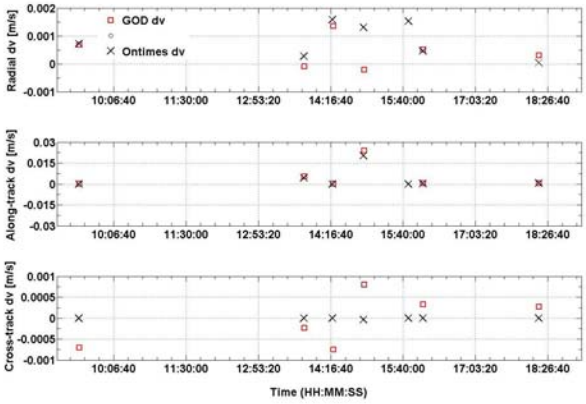

Fig. 17: Orbital maneuvers, 4th September

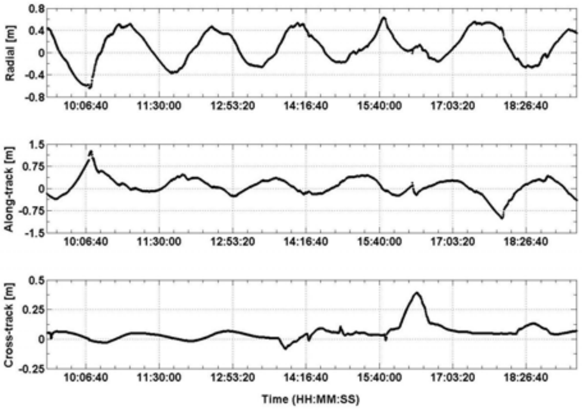

Fig. 18: Relative navigation accuracy, 4th September

IV. CONCLUSION

The PRISMA formation has been launched on June 15th 2010. This mission will serve as a test platform for autonomous formation flying and rendezvous of spacecraft. Novel approaches in the areas of formation flying guidance, GPS based relative navigation, impulsive relative orbit control and space mission operations will have an in-flight validation. An overview of the innovative and flexible PRISMA operations concept and the DLR's PRISMA Experiment Control Center (ECC) has been given. Three months after launch the operations keep going on as scheduled. After the successful LEOP and commissioning phases, the TANGO spacecraft separation, GPS calibration, HPGP experiment and Nanospace thrusters experiment have taken place.

DLR's key contributions comprise the on-board GPS-based absolute and relative navigation system, the Spaceborne Autonomous Formation Flying Experiment (SAFE)[20], the Autonomous Orbit Keeping (AOK) experiment as well as the on-ground Precise Orbit Determination (POD) layer. In this paper flight results of the GPS calibration phase have been shown. The on-board navigation performance is estimated through a comparison with the on-ground POD results that is accurate to the sub-centimetre level. New settings of the on-board navigation filter have been uploaded to the spacecraft in order to improve the reliability and robustness of the on-board navigation system in operational situation in which the navigation filter is stressed up to the limits of its operability. Common of such situations are TANGO tumbling which impair GPS satellites visibility, South Atlantic Anomaly (SAA) passages in which the GPS receivers are shut down in order to avoid latch-up risks and in which the navigation filter perform only the time update, and finally high thrusting activity that stress the dynamic model of the filter as the orbit maneuvers have to be included in the orbit determination process. New filter settings are the result of trade-off between robustness and relative position accuracy that is required to be 0.2 (3D, RMS) under nominal conditions and sufficient GPS satellites visibility.

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