PROBA-3 formation flying guidance navigation and control

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Abstract

PROBA-3 is an ESA technology demonstration mission devoted to the validation of the novel technologies required by future Formation Flying (FF) missions. The PROBA-3 mission and in particular its Guidance, Navigation and Control (GNC) architecture are being defined within the currently running Bridging Step after phase A. The Bridging Step includes evaluation and consolidation of the results of the two previous phase A studies before the start of the project phase B foreseen for the end of 2008.

This paper describes PROBA-3 GNC including requirements, GNC architecture and design, and to a lesser extent, the calibration process. A key feature of the GNC is a design that allows the verification of different types of control architectures (functions allocations), facilitating the change in the level of centralisation of the control. The paper also includes the definition and description of the different GNC modes, the sensors and actuators to be used at SC and at FF level, and the way they are going to be used. Emphasis is put on the flexibility of the system for maximisation of technology demonstration.

Keywords

Proba-3; Formation Flying; GNC.

1. Introduction

Verification of FF on-ground has been demonstrated to be complex and not fully representative of the space environment. In-flight verification of FF technology is clearly needed before its implementation in a full scale target application mission. This need for in-flight verification has been identified several times for many applications, including the initial concept of the SMART-2 initiative (ESA's initiative initially intended for the demonstration of LISA Drag Free and DARWIN FF technology), ST-3 (FF and interferometer demo mission by JPL), PRISMA (Sweden), and others. Finally ESA's efforts in FF demonstration are being focused in the PROBA-3 mission.

PROBA-3 GNC introduces the capability for demonstration of a number of key technologies including the execution of most of the identified formation flying manoeuvres and reconfigurations to be needed in future virtual structure missions like XEUS and Simbol-X and to some extent Darwin. PROBA-3 GNC is being designed to maximise its capability for introducing additional experiments and concepts in FF.

Two parallel Phase A studies for PROBA-3 were performed during 2006 and 2007, and have been followed by a Bridging Step activity to consolidate the results, and to prepare for the preliminary design to be completed during the coming phase B.

In this environment, an industrial team led by SSC has been organized for the Bridging Step and the subsequent phases of PROBA-3 in which SENER+GMV as one integrated team is taking the responsibility of the Formation Flying System of the mission, integrated in the project core team with Verhaert, QinetiQ and EADS-CASA. Within the Formation Flying System, GMV takes the lead of the FF-GNC.

2. PROBA-3 baseline mission

PROBA-3 will allow the verification of generic formation configurations valid for multiple types of target missions. It will include capability for formation acquisition from a range of initial conditions, resize maneuvers, formation rotations of different types, combination of resize and rotation, precision formation flying., etc. In addition, a Sun coronagraph instrument is intended to be flown distributed between the two spacecraft: the Occulter spacecraft will mount a round disk that will be used to generate a stable eclipse on the second spacecraft embarking the Sun corona sensor. The Coronagraph satellite will be maintained in formation with the Occulter at a distance of about 150 m with very good accuracy in longitudinal and lateral position.

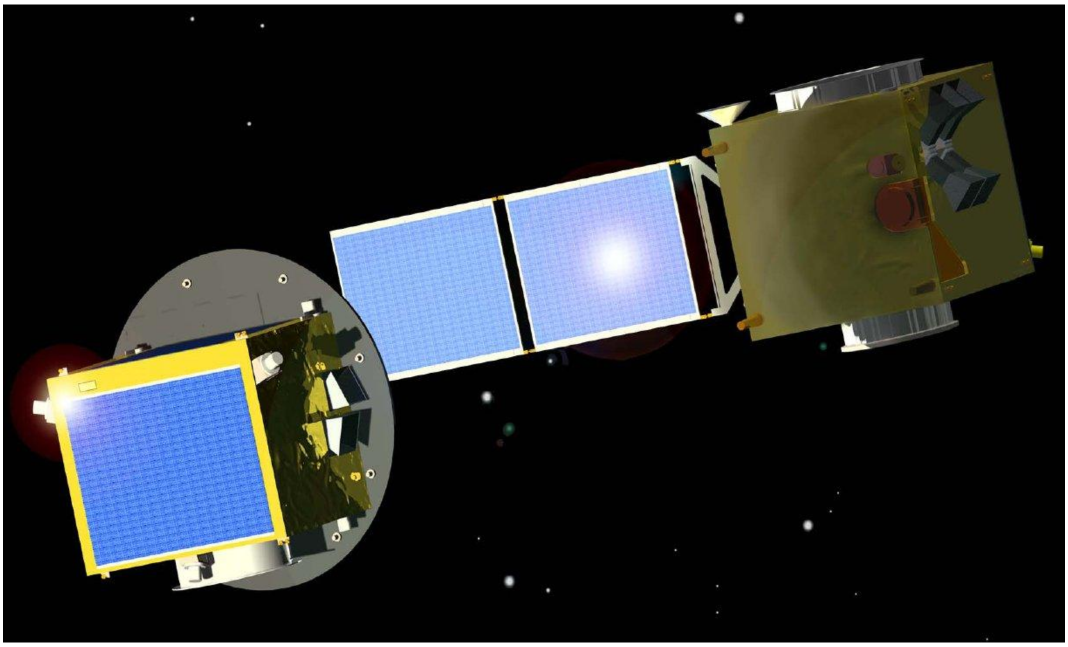

Fig. 1: PROBA-3 artistic view (source: SSC)

In order to exercise these FF capabilities while maintaining a reduced cost, PROBA-3 will avoid expensive Lagrange point or Earth trailing orbits and it will be injected in a terrestrial highly elliptic orbit with 24 hours period (800 x 71200 km). Two main options remain open for the satellites injection: One in which the two PROBA-3 spacecraft will be injected from PSLV directly into operational orbit by their own means without the intervention of an additional propulsion module, and a second one in which the launch with Vega will require the use of such propulsion module. The current GNC architecture has the flexibility to support both scenarios.

The nominal mission lifetime will be two years. Due to the high perigee perturbations, FF will only be performed near apogee. The PROBA-3 GNC will autonomously compute, execute and control the formation change between the precise formation at apogee and the loose perigee pass configuration. Every single orbit requires a significant injection manoeuvre before the perigee, and another injection manoeuvre after the perigee pass for re-acquisition of the formation to be used for the new apogee region (Fig. 2). Disturbances and errors force the implementation of a mid-term correction to be executed one hour before the final formation acquisition. The perigee pass will also be used for obtaining the desired formation configuration change between experiments, such that the new experiment configuration is directly obtained at the beginning of the FF orbit segment.

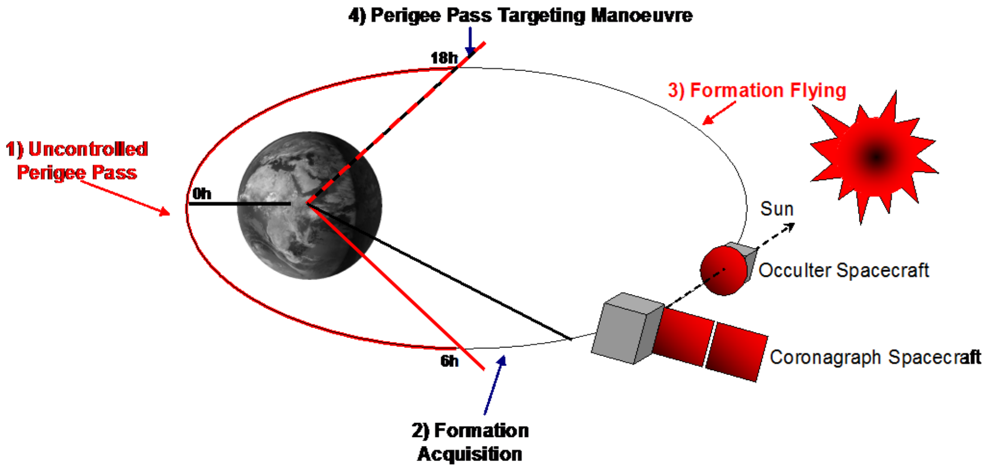

Fig. 2: PROBA-3 orbit activities schematic

The PROBA-3 GNC will also include collision and evaporation avoidance capability, structured in several levels, in coordination with the spacecraft safe mode, and in general with the GNC and the system Faliure Detection Identification and Recovery (FDIR).

3. Formation flying requirements and constrains

The PROBA-3 mission is devoted to the in-flight verification of the FF technology. It does not focus on a specific target mission, on the contrary it intends to verify technologies that could be needed for as many future FF missions as possible, under the constrains and limitation of a low-cost demonstration mission.

Ideally, PROBA-3 GNC should be designed to comply with a common set of requirements from the list of candidate target missions. However, for practical reasons, PROBA-3 is being designed with focus on verification of XEUS requirements, in combination with the requirements derived from the coronagraph payload.

XEUS is an X-ray virtual telescope mission that requires two spacecraft flying at a distance of 35 m with a maximum longitudinal error of 0.3 mm and lateral error of 1 mm [1]. The Sun Coronagraph instrument requires relative position at about 150 m with accuracy that is coupled between longitudinal and lateral errors, the later to be always smaller than 3.4 mm, even without longitudinal error, and this accuracy to be increased when a longitudinal error is allowed. In the coronagraph phases the Inter-Satellite Distance (ISD) is driven by the need for relative apparent angle of the occulter disk has to be between 1% and 2% larger than the Sun apparent radius [2].

Within the bridging step new Proba-3 requirements have been provided by ESA. These requirements have been revisited and allocated into “experiments” in which they will be exercised.

In addition to the requirements derived from the accomplishment of the mission, PROBA-3 is intended to incorporate alternative or “bonus” requirements for verification of special FF concepts.

The FF-GNC principal requirements from [3], [4], [5] and [6] are summarised in Table 1.

Table 1. FF-GNC Principal Requirements

Nº	Type	Description
1	Main	Proba-3 shall acquire the formation from a range of initial conditions (separation up to 100 km).
2	Main	Proba-3 shall demonstrate high accuracy formation flying. This requirement includes the verification of the formation at several ISDs, with accuracies needed for meeting the XEUS and Coronagraph requirements
3	Main	Proba-3 shall experiment FF during a minimum of 6 hours per orbit.
4	Main	Proba-3 shall perform perigee pass reconfiguration once per orbit. Executing maneuver to break the formation before the perigee and acquire it again after pass.
5	Main	Proba-3 shall perform resize maneuvers with intermediate formation maintenance of several hours, from 25m to 250m Inter-Satellite-Distance (ISD) and reverse. Resizing to be performed in rigid mode (maintaining formation during maneuver) and loose mode (no need to maintain formation properties during the maneuver).
6	Main	Proba-3 shall perform formation “Retargeting” (rotation of up to 30º from the original direction) in rigid and loose mode.
7	Main	Proba-3 shall demonstrate centralised FF GNC. One satellite commanding the complete formation.
8	Main	Proba-3 shall be capable of sharing relative metrology data. Capability of distributing the sensors measurement to be used onboard the other satellite.
9	Main	Proba-3 shall be a high autonomous mission. One full week operations without ground intervention.
10	Main	Proba-3 shall perform centralized and decentralized collision avoidance system to maximize mission safety and success.
11	Bonus	Proba-3 shall demonstrate advanced FF by combining different manoeuvres (Resizing plus Retargeting).
12	Bonus	Proba-3 shall demonstrate formation coning manoeuvre. One spacecraft describing a cone wit respect to the other.
13	Bonus	Proba-3 shall perform a Navigation with Camera experiment.
14	Bonus	Proba-3 shall simulate a Darwin formation rotation. Simulating additional satellites.
15	Bonus	Proba-3 shall be capable to fly host GNC experiments. Capability of implementing “host” GNC as an experiment controlled by the FF-GNC system.
16	Bonus	Proba-3 shall perform a collision avoidance experiment.
17	Bonus	Failures Tests experiments.

Table 2 and Table 3 report the most demanding position and attitude requirements.

Table 2: Main Position Requirements.

Error	Longitudinal 35m [mm]	Lateral 35 m [mm]	Longitudinal 150m [mm]	Lateral 150 m [mm]
RDE	0.3 (Xeus)	1 (Xeus)	0.3 (Xeus)	3.25 (Coron)
RDME	0.3 (Xeus)	0.17 (Xeus)	0.3 (Xeus)	0.73 (Xeus)

RDE = Relative Displacement Error, RDME = Relative Displacement Measurement Error from [3]

Table 3: Main Attitude Requirements.

Error	LOS [arcsec]	Around LOS [arcsec]
AAE	8.0 (Coronagraph)	600 (Xeus)
AAME	1.0 (Xeus)	60 (Xeus)
AAS	0.75 (Coronagraph)	60 (Coronagraph)

AAE = Absolute Attitude Error, AAME = Absolute Attitude Measurement Error, AAS = Absolute Attitude Stability

4. PROBA-3 GNC architecture and design

The GNC design for the PROBA-3 mission adds a new layer of complexity to the single satellite GNC design: the formation level. It is requested that one satellite could be able to control the complete formation sending control commands to the other satellite via the Inter-Satellite Link (ISL). The controlling satellite can either have the capability to perform relative navigation onboard or to receive metrology measurements from the companion satellite. This centralised control can be carried out by either one or the other satellite.

To design the PROBA-3 GNC system it was decided to separate it into two levels: formation and spacecraft. Being the Formation Flying GNC (FF-GNC) responsible for the formation level and the Spacecraft GNC (SC-GNC) responsible for the spacecraft level. Fig. 3 shows this two-layer GNC architecture.

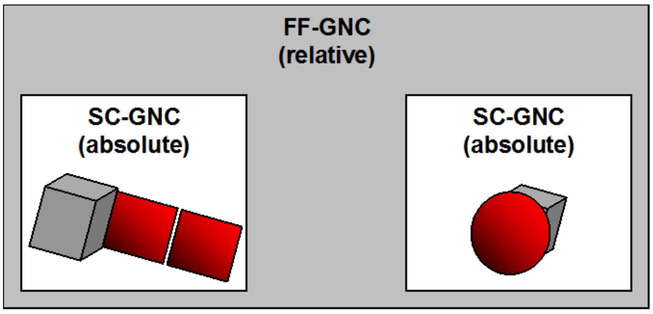

Fig. 3: Proba-3 GNC levels: FF and SC

In particular the FF-GNC is in charge of the relative formation state, corresponding to the relative attitude and position of the two satellites. The FF-GNC processes the relative sensors' measurements either available onboard or received via the ISL, for the determination of the relative position, and it establishes the actions required for acquiring and maintaining the relative trajectories. The FF-GNC also evaluates the need for relative attitude control, computing the equivalent absolute attitude and commanding the SC-GNC to point it.

The SC-GNC includes the functions for determining and controlling the absolute spacecraft state. On top of this the SC-GNC is handling the low-level interfaces with the sensors and actuators.

This means that it is in charge of executing the actuation commands coming from the FF-GNC and it performs sensors reading. The SC-GNC functions are quite similar to the classical AOCS.

This separation implies that each satellite will have the capability to implement FF-GNC software to be able to control the formation. This architecture guarantees a full redundancy of the formation control function.

Formation Flying Sensors and Actuators

The sensors' configuration design selected at this stage of the project includes four levels of formation sensors accuracy.

- Metre-level. The lowest accuracy level, provided by the FF Radio Frequency sensor (FFRF), is required for formation acquisition from a "lost in space" configuration. FFRF provides omni-directional coverage in a range of 100 km. For its versatility FFRF is also used for continuously monitoring the relative position of the satellites and trigger collision avoidance.
- Centimetre-level. The next accuracy level is provided by Relative GPS (RGPS). The low perigee of the PROBA-3 orbit allows to get GPS signal visibility once per orbit. The GPS measurements of the two satellites are combined by the onboard navigation system to provide cm-level relative position information after each perigee pass.
- Millimetre-level. Millimeter-level relative position information is obtained using Coarse Lateral and longitudinal Sensor (CLS). The sensor operational range is 250 m with a field of view of 9º.
- Sub-Millimetre-level. Finally a Fine Lateral and longitudinal Sensor (FLS) provides sub-mm-level relative position information. The operation range of this fine metrology is limited to few mm in position.

The CLS and FLS are embarked onboard the Coronagraph satellite and constitutes the main sensors for FF demonstration. The FFRF and RGPS are present on the Coronagraph and Occulter spacecraft. Additionally the Occulter spacecraft embarks a Vision Based System (VBS) to provide redundancy to the CLS.

Due to the coupling between attitude and relative position, very accurate absolute attitude knowledge is required. For this reason each satellite is equipped with three very precise Star Trackers (STR). The STR are mounted in a pyramidal configuration to improve the attitude determination performance in the target line. The selected configuration guarantees that 2 STR are always in use, and provide errors in the target line close to the STR LOS errors. Sun Acquisition Sensors (SAS) and Gyros to be used for safe mode complete the sensors set.

The full list of selected sensors is shown in

Table 4.

Table 4: Summary of the Sensors Configuration on the Proba-3 Spacecrafts

Sensors	Coronagraph	Occulter
FFRF	1 plus 1 redundant electronics	1 plus 1 redundant electronics
CLS	1 CLS Sensor	1 CLS Reflector 1 VBS camera (for CLS redundancy)
FLS	1 FLS Sensor	1 FLS Reflector
STR	3 units mounted in pyramid configuration	3 units mounted in pyramid configuration
SAS	3 internally redundant	2 internally redundant
GPS	1 plus 1 redundant receiver	1 plus 1 redundant receiver
GYROS	5 one-axis systems	5 one-axis systems

PROBA-3 actuators have been selected to provide three different levels of actuation. Table 5 reports a summary of the PROBA-3 actuators.

- N-level. Two sets of four 1N monopropellant thrusters provide redundant N-level thrust capability over 4 degrees of freedom (DOF) with a privileged direction. This propulsion system is mounted only on the Coronagraph spacecraft. The N-level thrust is used mainly for orbit injection and perigee maneuvers, but it can also be used for high thrust collision avoidance maneuvers.
- mN-level. The baseline for main formation control has been selected to be 10mN cold gas thrusters. The Coronagraph mounts two sets of 8 thrusters for redundancy while the Occulter is only mounting one set of 8 thrusters. Analyses have been carried out during the bridging step to verify that the thrusters satisfy the requirements on Minimum Impulse Bit and authority for formation control.

Table 5: Summary of the actuators configuration

Actuator	Coronagraph	Occulter	Function
1N Monoprop THR	2 redundant set of 4 Monopropellant (4DOF)	None	Orbit injection, perigee maneuvers and high thrust collision avoidance
10 mN Cold Gas THR	2 redundant set of 8 thrusters (6DOF)	1 set of 8 thrusters (6DOF)	Formation Flying manoeuvres, CEAM, RW unloading, Acquisition and safe mode
μN EP THR	2 dual-ended 50-500μN EP thrusters (2DOF), partially redundant	16 x 10-1000μN CG thrusters in 4 clusters (6DOF), partially redundant	Micropropulsion demonstration and fine FF demonstration
RW	4 x (1Nms) in pyramidal configuration with a priviledged	4 x (1Nms) in pyramidal configuration with a	Attitude control

	direction	priviledged direction	

- μN-level. Both satellites embark μN thrusters for μ-propulsion demonstration and fine FF demonstration. In particular the Coronagraph is equipped with two dual ended Electric Propulsion (EP) thrusters providing 50-500μN on 2 DOF. The Occulter is equipped with four cluster of four Cold Gas (CG) thrusters proving 10-1000μN on 6 DOF. Both systems are partially redundant and they will enhance the experimentation capability with continuous control and simultaneous actuation.

For attitude actuation, 4 reaction wheels are mounted in pyramidal configuration to maximize momentum capability along the axis where the environmental torque from the solar panel actuates.

4.1.SC and FF GNC Modes

The overall architecture of GNC modes reflects the SC and FF levels. Modes are structured for Composite, Single SC and Formation configurations. With composite it is meant the assembly formed by the Coronagraph, the Occulter and, if required, by the Propulsion Module (PRM).

The Composite configuration covers the time span from the composite separation from launcher to the deployment of the formation. The formation deployment is intended as the separation of the Coronagraph and Occulter satellites in the final orbit.

In the Composite configuration the Coronagraph SC-GNC will take the lead to perform the transfer to reach the final orbit. The three SC-GNC modes are:

- The Sun Pointing Mode (SAM) executed to orient the Coronagraph solar panel towards the sun during the cruise. This mode is also used as Safe Mode.
- Inertial Attitude Mode (IAM) executed to acquire an inertial attitude before performing orbital maneuvers.
- Orbital Control Mode (OCM) executed to perform orbit maneuvers
- In the Individual configuration the two spacecrafts are operated and commanded regardless of the fact that they are or might be part of a formation. Individual configuration may take place in several occasions:
- During the satellite deployments,
- During commissioning and/or troubleshooting.
- If the satellites reach evaporation (they are outside the ISL range)

- When the mission control decides to maintain the SC in a non formation waiting for a decision to be taken.
- The Coronagraph and Occulter SC-GNC are active and they can execute Sun Acquisition Mode (SAM) or Inertial Attitude Mode (IAM)/Orbital Control Mode (OCM). These modes are basically the same of the Composite configuration but executed by single spacecraft. Also the FF-GNC is active and running in Collision and Evaporation Avoidance Mode (CEAM) mode.
- The CEAM mode is entered when an FDIR alarm triggers a safety risk for the formation (possibility of collision or possibility of evaporation, or failure in a critical system). This mode can be considered as a FF-GNC mode and a SC-GNC mode since both GNC will have collision avoidance capability.

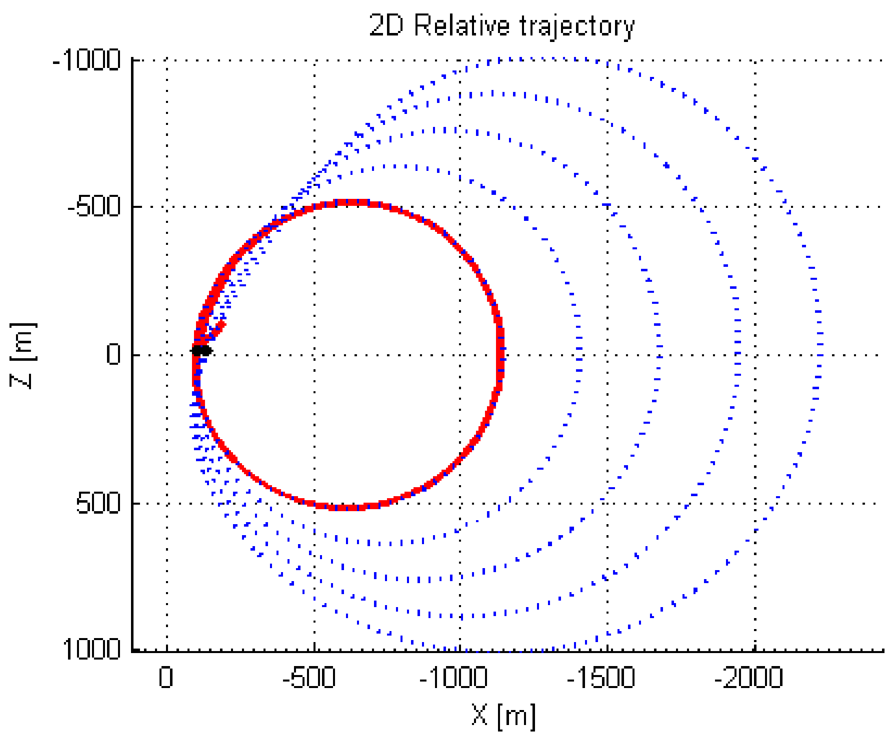

Fig. 4: FF-GNC FSB: Tandem formation (continue line) and natural drift (dotted line).

The Formation configuration can be considered the nominal PROBA-3 configuration. To fulfil the mission objective the FF-GNC may be executed in several modes:

- The Formation Standby Mode (FSB) has been designed to guarantee that the spacecraft do not collide nor separate too much from each other. In FSB mode one spacecraft is monitoring the state of the constellation and performing maneuvers to acquire or maintain a tandem formation around the other one. Stand-by formation path in Local Vertical local Horizontal Frame (LVLH) is reported in Fig. 4.

- Formation Coarse Mode (FCM). This mode is executed to bring the two spacecraft in a controlled configuration starting from a random configuration.
- Formation Fine Mode (FFM). This mode is executed to acquire fine formation using the fine metrology sensors.
- Formation Reconfiguration Mode (FRM). In this mode all formation reconfigurations would be performed, including low and high accuracy formation flying maneuvers.
- Perigee Pass Mode (PPM). During every perigee pass the formation will follow a predefined formation evolution where one satellite will execute three maneuvers: at perigee entry, during the free drift (1h before acquisition) and at formation acquisition.
- Experiment Mode (EXP). This mode is intended for introducing special FF-GNC experiments, such that the control of the formation can be acquired by this mode without the need to replace the rest of modes. This can include specific guidance, navigation and control laws and software, which can be loaded in flight and replaced while the formation is controlled by the other modes.

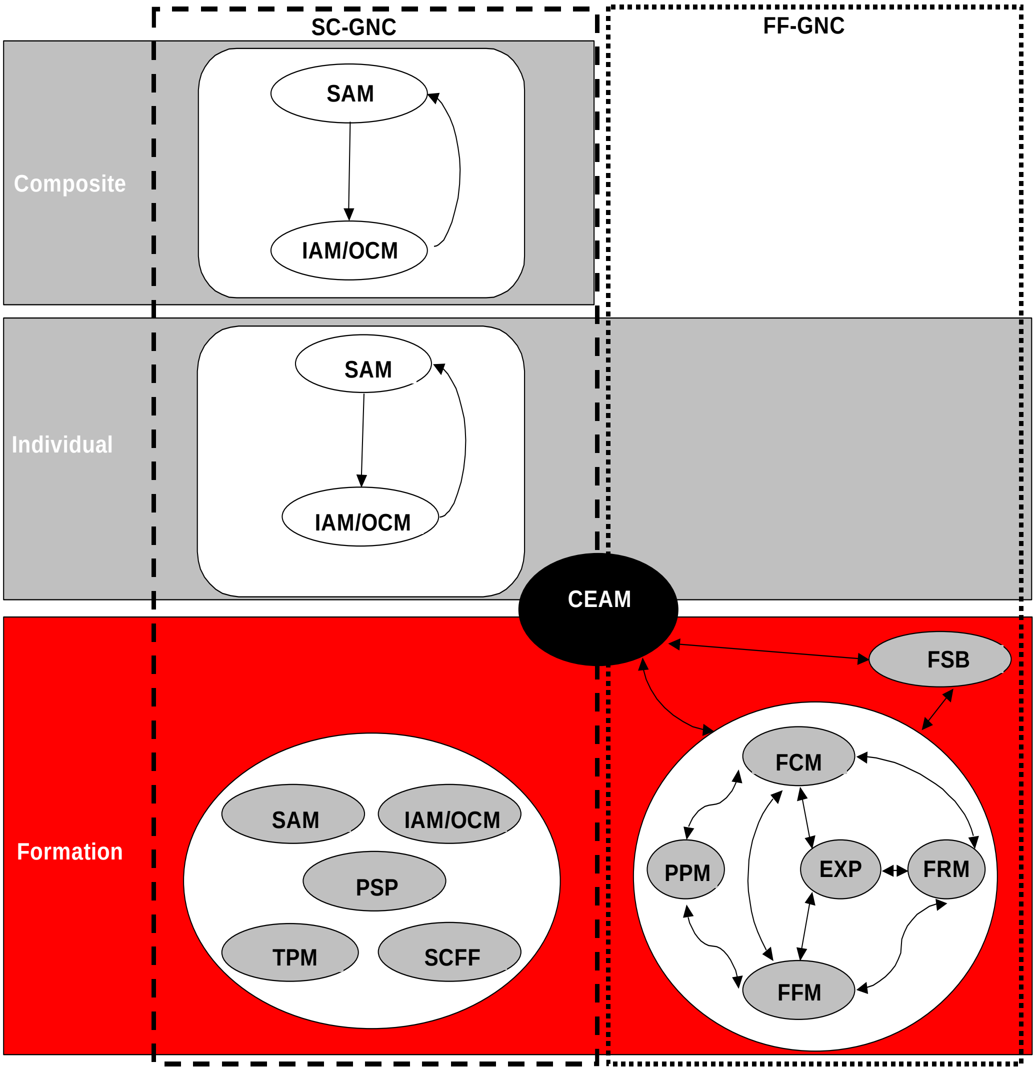

Fig. 5: Formation and SC Modes

Figure 5 shows a schematic of the SC-GNC modes in parallel with the FF-GNC.

On the SC-GNC side two modes have been added in the formation configuration: the Target Pointing Mode (TPM), Precise Sun Pointing mode (PSP) and the Spacecraft Formation Flying Mode (SCFF).

- The TPM is executed by the SC-GNC to point one spacecraft in the direction of the other such that proper relative measurements can be acquired.
- The PSP is executed by the SC-GNC to accurately point the Sun. Accurate sun pointing is required by the Coronagraph experiment. For this mode the position of the Sun is retrieved onboard from ephemeris.
- In the SCFF mode, the SCs are just executing the commands that the FF-GNC sends to each one. This mode is required to allow centralised GNC commanding.
- Modes configurations and acronyms are included in Table 6.

Table 6: Formation Configuration GNC modes combination

FF-GNC	SC-GNC	Description
FCM	**IAM / TPM / SCFF / PSP**	Formation Coarse Mode. Includes formation acquisition and coarse controlled formation up to cm level. SC control can be in IAM, TPM or SCFF.
FRM	**IAM / TPM /SCFF /PSP**	Formation Reconfiguration Mode. Performs formation resizing and re-pointing and other types of formation manoeuvres.
FFM	**IAM / SCFF / PSP**	Formation Fine Mode. Precise metrology for longitudinal and lateral position in mm and sub-mm range..
PPM	**SAM / IAM / TPM**	Perigee Pass Mode. Implements the Perigee Manoeuvres and the perigee coasting.
FSB	**SAM / IAM /TPM**	Formation Stan-By. The formation is entered/maintained in stable tandem configuration.
EXP	**IAM / TPM / SCFF**	EXPeriment Mode. Special Mode devoted for implementation of ancillary experiments
CEAM	**SAM / IAM / TPM**	Collision and Evaporation Avoidance Manoeuvres are executed to bring the formation in FSB.

Most of the active equipments in the formation, as well as the FF processing core is centralised in the Coronagraph satellite, which is the satellite with higher power capabilities. The mode architecture is structured in a modular way with capability for complex configurations and activity share between the Coronagraph and the Occulter and in particular:

- Centralisation-decentralisation capability, with the allocation of functions between the FF-GNC and the SC-GNC.
- Master-Slave allocation and freedom to swap the centralized functions from one satellite to the other.
- Control actuation allocation between satellites, with centralized manoeuvres as baseline. This Chaser-Target like formation control is expected for Xeus, and most of the distributed telescopes configurations.
- Experiments with distributed control actuation between satellites. Each satellite implements 6 DOF for this purpose.

4.2.Navigation Architecture

PROBA-3 navigation is the key issue to fulfill the demanding FF requirements imposed by Xeus and the Coronagraph mission. The proposed navigation is customised as a function of the sensors configuration, such that its may be optimised for the type of sensors (dynamics, measurements, errors, etc). The most likely implementation approach would be Extended Kalman filters with simplified mechanisations, and adequate initialisations at each start. The following navigation architecture is proposed.

Each satellite receives absolute position information from the GPS sensor at perigee. The GPS output is processed onboard to obtain a precise orbit determination. The absolute position and velocity of the satellite is then propagated along the orbit. During nominal operation absolute position computation and propagation is only needed onboard the master satellite (nominally the Coronagraph). Absolute position information is also used to accurately determine the Sun vector in inertial frame by means of numerical ephemeris. It has to be mentioned that during Coronagraph experiment inertial pointing attitude cannot be followed since the satellite displacement in the orbit induces a change of about 100 arcsec in the Sun vector direction.

Several different relative navigation filters are envisaged for PROBA-3. Each filter uses different sensors' measurements. The selection of different filter instead of a single filter fed by all the sensors is mainly driven by the following consideration:

- Single filters tend to be more instable (according to GMV's experience).
- Single filters are much more demanding in term of CPU load.
- Single filters even if theoretically could provide better performances, from prototyping activities provide the same results than dedicated filters
- The following relative state filters are proposed for the Coronagraph:
- GPS Relative PosVel filter. This filter receives Occulter and Coronagraph GPS data during perigee pass and computes the relative position of the Occulter. The relative position is then propagated when GPS information is not available.
- Coarse1 Relative PosVel filter. This filter receives FF-RFS data and smoothes the noise and outputs relative position of Occulter in body frame.
- Coarse2 Relative PosVel filter. This filter receives Line Of Sight (LOS) and range data from the CLS. In case the range information is not available from the CLS (depending on the final CLS sensor selection), the FF-RFS's one is used. The filter outputs the Occulter relative position in body frames. Attitude knowledge is needed to remove the coupling effect linked to the CLS measurements.
- Coarse3 Relative PosVel filter. This filter receives FF-RFS data but processes only the range information, the LOS information is retrieved from a Visual Based System (VBS) embarked on the Occulter. This mode is used in medium and long range, which is when the VBS provides the LOS. The filter outputs the Occulter relative position in body frames and is used as Coarse2 back up in case of CLS failure.
- Fine Relative PosVel filter. This filter receives LOS and range data from FLS. In case the LOS information is not available from the FLS (depending on the final FLS sensor

selection), the CLS's one is used. The filter outputs Occulter relative position in body frames. Attitude knowledge of both satellites is needed to remove the longitudinal displacement of the sensor components due to attitude mispointing.

The Coronagraph navigation architecture is shown in Fig. 6. In the diagram the metrology coming information from the Occulter is depicted in with a white background.

The various filters for absolute and relative positions are checked for consistency at several levels (e.g. Sensor output, intermediate results, filtered state, etc). Both spacecraft will have symmetrical architectures. Coronagraph will pass the metrology to the Occulter via the ISL. Fig. 7 shows the navigation architecture of the Occulter, where the metrology passed from the Coronagraph is shown in white labels. The advantage of a symmetrical system is that it enables a centralised formation control performed either by the Coronagraph or the Occulter. Duplicating the system also adds redundancy, although it is not strictly needed since the Coronagraph on board computer is fully redundant. The exploitation of this redundancy for contingency case will anyway be possible.

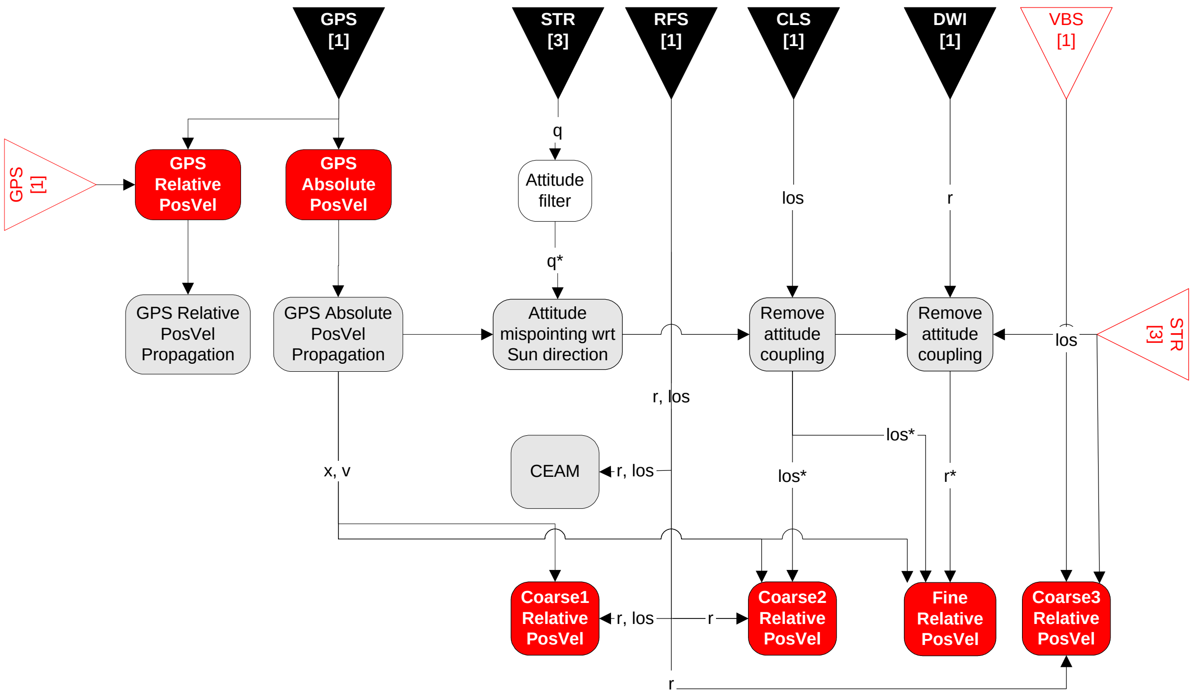

Fig. 6: Coronagraph Navigation Architecture. In this diagram CLS is not providing range and FLS is not providing LOS data.

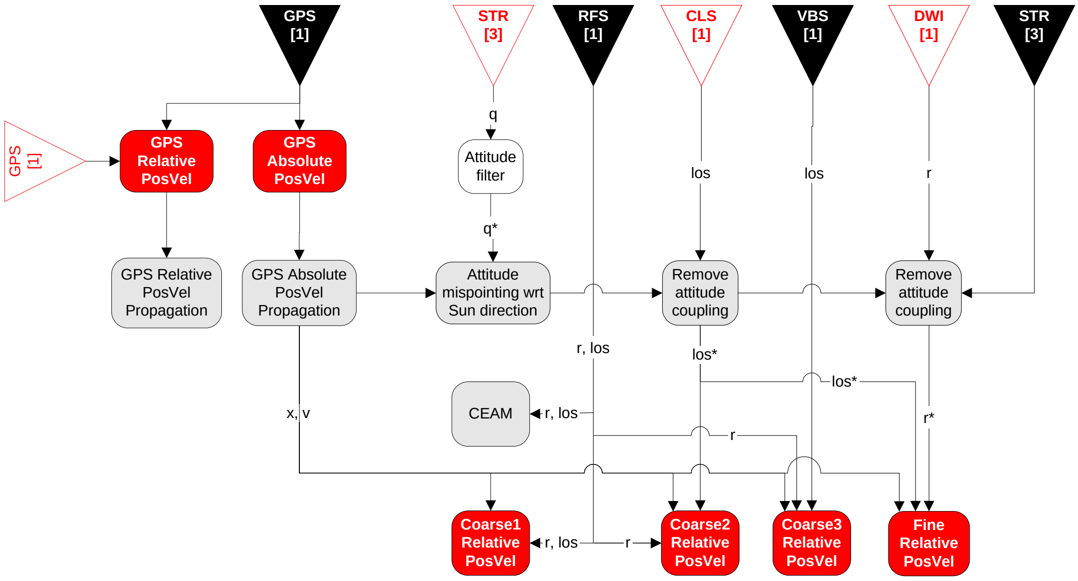

Figure 7: Occulter Navigation Architecture. In this diagram CLS is not providing range and FLS is not providing LOS data.

4.3.FF-GNC Metrology Calibration Process

From the Bridging Phase resulted that a very accurate calibration of the PROBA-3 sensors is mandatory to fulfil the Xeus and Coronagraph FF requirements [8]. The baseline calibration technique is described hereinafter.

The fist step consists on pointing the Coronagraph camera towards an inertial direction in the sky with good star pattern. The Coronagraph instrument is sensible enough to detect stars. This allows computing on ground the attitude of the spacecraft starting from the Coronagraph images and comparing it to the attitude retrieved from the STR. This results in the calibration of any eventual Coronagraph pointing error.

The second step consists on aligning the Coronagraph and the Occulter and turn on the Occulter Position Sensors (OPS). The OPS are LEDs that are placed on the disk of the Occulter spacecraft. By observing the position of the LEDs it is possible to retrieve with very high accuracy the relative pointing direction of the Coronagraph spacecraft towards the Occulter. This information is used to calibrate the LOS measurements of the metrology sensors.

The step two is then repeated at different ISDs. The components related with linear an angular calibration biases are finally determined by comparing the calibration measurements obtained at different distances.

5. Conclusion

This paper provides a description of the PROBA-3 FF-GNC . The paper starts from an overview of the requirements split into two levels: main and bonus. Then the FF-GNC architecture is presented covering the baseline sensors and actuators, the FF modes, the navigation architecture and finally the calibration technique.

With the objective to facilitate the incorporation of many new experiments, the PROBA-3 FF-GNC includes a baseline configuration that will provide all the means and infrastructure for accomplishing the baseline requirements of the mission, while the verification of additional requirements or alternative concepts will be performed via ancillary experiments, to be incorporated even at a late stage in the project development.

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