PROBA-3 MISSION

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***Abstract:** Proba-3 is the ESA mission devoted to the demonstration of precise Formation Flying technology. Precise Formation Flying will allow small spacecraft, flying with a fixed relative geometry, to synthesize giant structure-less instruments. Proba-3 consist of two satellites keeping a formation from 25 to 250 meters controlling relative position with about one millimeter accuracy. The spacecraft will autonomously manage the formation and take mission critical decision with no ground supervision. The metrology sensors chain will allow formation acquisition and relative position determination maintenance with micrometric precision. Periodic in flight automatic calibration will compensate the systematic deformation induced by the space environment. The formation flying verification on ground is complicated by the impossibility of testing the two satellite system in representative environment. The paper details the mission objectives and the challenging requirements. It describes the overall mission design and in particular the formation flying technology demonstration plan. The main mission novelties are highlighted and the mission autonomy, formation flying sensors and algorithms and verification approaches are introduced. The PDR performance results are presented. In the conclusions the paper presents the potential exploitation of the Proba-3 demonstration for future missions.*

***Keywords:** Formation Flying, Autonomy, Technology Demonstration, Rendez-Vous.*

1. Introduction

PROBA is a space program managed by ESA for the in-orbit demonstration of platform and payload technologies. Proba-3 aims to demonstrate Formation Flying (FF) technology.

The mission consists of two small spacecraft of 320 kg and 180 kg flying in a formation with relative position control accuracy of less than 1 mm. The two spacecraft will be controlled in space as if they were two parts of a rigid structure (e.g. telescope optics and detector). This virtual rigid structure will be commanded to rotate and point to any desired direction. It will also be possible to set the relative distance of the two spacecraft from 25 to 250 meters (i.e. change the focal length).

In order to complete the end-to-end validation of the formation flying technologies, a scientific instrument, a coronagraph, has been selected with the goal of taking pictures of the inner solar corona. The coronagraph system is distributed over the two satellites; one carrying the detector and the second one carrying the Sun occulter disk. The Proba-3 satellites are named according to the hosted payload element: Coronagraph SpaceCraft (CSC) and Occulter SpaceCraft (OSC). Figure 1 show the OSC and CSC spacecraft.

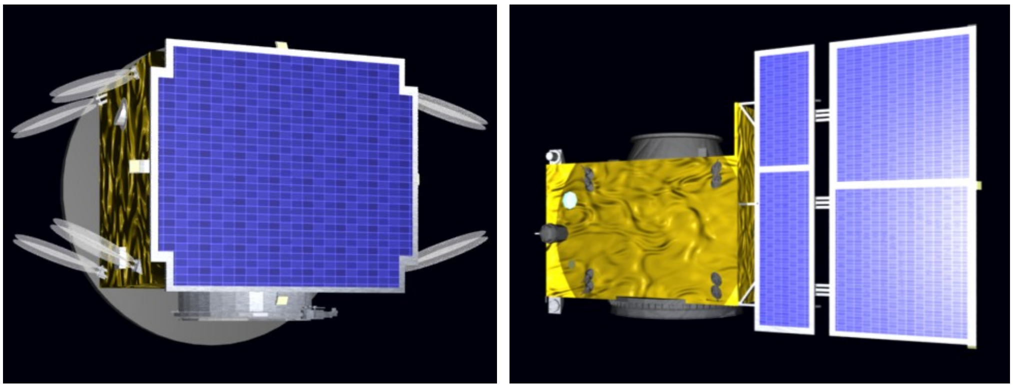

Figure 1: Occulter SpaceCraft (left) and Coronagraph SpaceCraft (right)

The formation flying demonstration requires a low gravity gradient region that will be achieved around the apogee of a highly elliptical orbit. The selected orbit has perigee height of 600 km and 60,530 km apogee. The formation is broken and reacquired every 19.5 hours, since it cannot be maintained at perigee. The Proba-3 spacecraft are designed to execute autonomously this orbital routine with no support from ground.

Proba-3 has successfully passed ESA Preliminary Design Review in late 2012. During the phase B, the mission has been developed by a large consortium with a Core Team of companies lead by SENER and completed with GMV Aerospace and Defence, QinetiQ Space nv, EADS CASA Espacio and Spacebel. SENER is the designated mission prime for CDE phase.

2. Proba-3 Mission Objectives

Proba-3 mission has the goal to demonstrate in-flight Formation Flying key technologies and obtain scientific results from a coronagraph science payload, including also dedicated rendezvous demonstration in elliptical orbit. After completion of the Proba-3 mission the following mission results are expected:

- **Validated formation flying control algorithms.** A complete FF Guidance Navigation and Control (GNC) including a set of generic FF manoeuvres and configurations will have been analysed, developed and validated in orbit. Experience will be gained in attempting to meet future formation flying mission performance requirements.
- **Mature formation flying metrology.** A set of new metrology systems will be validated in orbit in term of behaviour and performances. A complete metrology chain will be available “off the shelf” for future FF operation
- **Demonstrate formation autonomy and robustness.** Autonomous FF distributed architecture will have been analysed, implemented and tested in a complete system in orbit. The safety and reliability of formation flying will have been demonstrated.
- **Advanced assembly, integration and verification approach and tools.** A development approach including the validation approach and an iteration of the engineering infrastructure will have been deployed and exercised. Models of the metrology units and GNC simulators will be available and correlated with their actual flight performances.

- **Scientific return**. Scientifically relevant coronagraph measurements will be made with measurements inside the inner corona superior to any current or past mission and a solar radiometer will fly as secondary payload.
- **Relative dynamics experiments.** Proba-3 will incorporate 6DOF formation control with thrusters, realistic collision avoidance demonstration and rendezvous experiments.

It is important to remark that Proba-3 mission design is completely driven by the need to fulfil Formation Flying demonstration objectives. Mission and system requirements are mainly derived by the Proba-3 technology demonstration mission envelope, in particular the need to constrain the budget and maximise PROBA platform reuse. Figure 2 illustrates the Proba-3 spacecrafts acquiring formation.

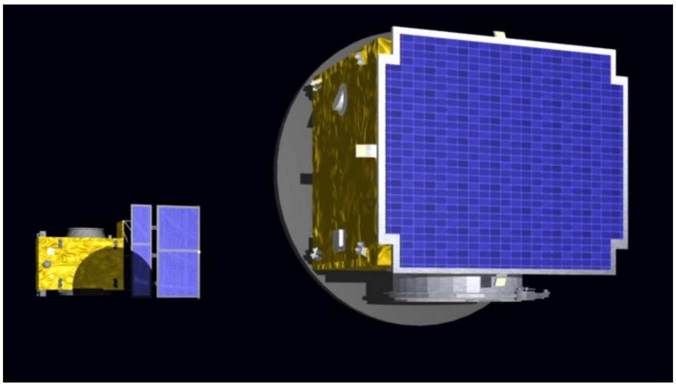

Figure 2: Proba-3 spacecraft acquiring formation

3. Proba-3 Mission Challenges

Few European missions have already exercise formation operations in low earth orbit.

The German TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission is composed by two large Earth Observation satellites, of 1350kg each, flying Synthetic Aperture Radars. The satellites were launched on June 2007 and June 2010 into 514 km altitude circular orbit. The mission uses relative GPS navigation to control the formation with typical distances between 250 and 500 m. TanDEM-X autonomously control the formation with an accuracy of 10m (1σ) [1], while typical ground-in-the-loop formation accuracy is about 30 m (1σ).

The Swedish Prisma mission consists of two small satellites: Mango of 150 kg and Tango of 40 kg. The satellites were launched in stack configuration in June 2010 into 725 km altitude circular orbit. The mission uses relative GPS, Radio Frequency Sensor and Vision Based sensor navigation to demonstrate different formation manoeuvers from few kilometers distance, down to ~2 m. The autonomous formation control, exclusively performed by the Mango spacecraft, achieved decimetre level accuracy [2].

Proba-3 mission is meant to go a step further and to demonstrate the Formation Flying technology that will enable virtual structure build up. Several are the challenges for achieving this ambitious goal. Proba-3 will autonomously execute a set of manoeuvers with millimeter level accuracy. In particular Proba-3 will demonstrate formation station keeping at different relative distances, from 25m to 250m. The mission will exercise formation resize between 25m and 250m, formation retargeting up to 30º and combination of station keeping, resize and retargeting maneuvers (Figure 3).

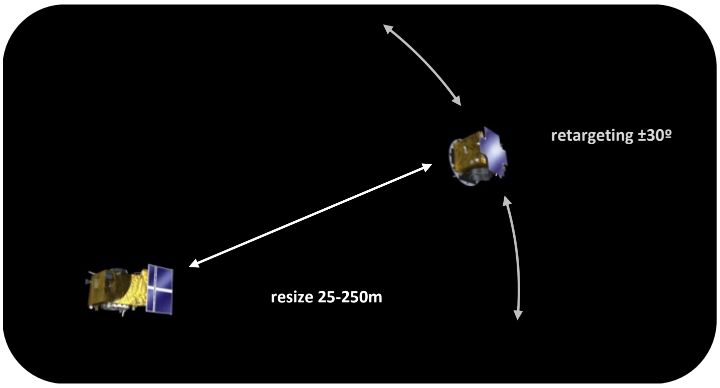

Figure 3: Proba-3 FF Demonstration maneuvers

In order to achieve the objectives above, Proba-3 will tackle several challenges as described below.

Proba-3 formation flying demonstration shall extend over several hours and cannot be achieved in low Earth orbit where the high gravity gradient would require high thrust authority and large propellant quantities to maintain the formation. Therefore, the two spacecraft will be launched into high elliptic orbit and FF will be exercised during the apogee phase. Then, since formation cannot be maintained at perigee, formation break and reacquisition is required every orbit.

In case of off-nominal situations, the spacecraft will autonomously manage the formation and will need to take mission critical decision with no ground supervision.

The satellites will not only worry about collision but also about formation evaporation. Very energetic collision avoidance maneuvers may lead in few orbits to large separation between the satellites. This separation needs to be limited otherwise excessive mission time and resources to re-acquire the formation will be needed.

During Formation Flying operation periods, GPS measurement will not be available. Proba-3 will embark a dedicated metrology sensor suite capable of acquiring the formation and providing relative position determination with micrometric precision. The metrologies sensors' field of view limitation, will force the spacecraft to point to the companion satellite to acquire relative navigation.

Sun off-pointing will cause thermo-elastic deformations and periodic in flight autonomous calibration will be mandatory to compensate them.

End-to-end formation flying verification on ground is impossible in the required formation range and in a representative environment. The Proba-3 approach for Formation flying performance verification is to use a dedicated software-based bench.

4. Proba-3 System Design

Proba-3 mission is organised into four system modes: STACK, MANUAL, OPERATIONAL and PARKING. STACK and MANUAL modes are used for commissioning and contingency while OPERATIONAL and PARKING are used for nominal operations. In particular OPERATIONAL and PARKING modes are high autonomy modes requiring minimum ground intervention. Figure 4 depicts an overview of the system modes with nominal and contingency mission transitions.

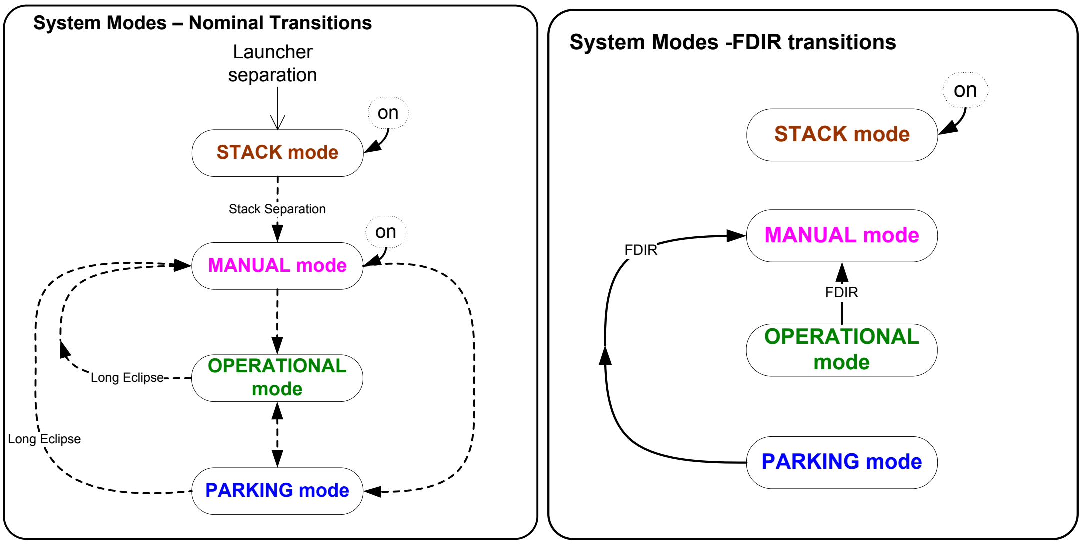

Figure 4: System Modes Overview Diagram

System modes are detailed in the next sections.

4.1 STACK Mode

The OSC is sitting on top the CSC that is connected to the launcher interface. After launcher separation, the spacecraft will boot in STACK mode. CSC will be the only active satellite while OSC will stay passively connected to the CSC. CSC will detumble the stack, acquire and maintain sun pointing. Very limited autonomy is implemented onboard while in STACK mode. Ground is individually commanding the spacecraft via tele-command. Commissioning of the CSC and OSC will start in stacked configuration. This first commissioning will include spacecraft subsystems functionalities and performances of star trackers (STR), GPS, thrusters and reaction wheels (RW). The non-formation guidance and navigation modes will also be tested. The spacecraft separation into safe relative orbits will be performed at a defined orbital position, with the correct attitude and correct thermal environment. Following separation, the two spacecraft will be held with actuators inhibited for a given amount of time, to allow reaching adequate separation distance.

4.2 MANUAL Mode

System MANUAL mode is entered for the first time after the two satellites separate from the stacked configuration. While in MANUAL mode, CSC and OSC spacecrafts will acquire and point the Sun waiting for commands from ground.

Continuous Inter-Satellite Link (ISL) communication between the two spacecraft is foreseen to allow formation commissioning. In particular the approach for the incremental commissioning of the relative metrology sensor follows the principle of the “accuracy chain”. First less accurate metrology is commissioned. Then next element is commissioned up to the highest accuracy sensor that is the scientific instrument.

MANUAL mode is also the boot mode while the spacecraft are separated. It will be the spacecraft safest configuration and will be used in case of problem and to limit the power consumption during long eclipses.

4.3 OPERATIONAL Mode

After successful commissioning, the complete mission is carried out in the OPERATIONAL mode. OPERATIONAL mode will be entered around apogee when nominal conditions are met: power and equipments are nominal, inter satellite distance is between 100 m and 200 m and relative navigation solution accuracy is better than 15 m and 2 mm/s. This means that if the system is in MANUAL mode, ground shall plan and command a sequence of manoeuvres to enter into the OPERATIONAL mode acquisition boundary. In OPERATIONAL mode the designed orbital routine for the Proba-3 nominal operation is rather complex and consists of four different phases detailed in the following list:

- During *Formation Acquisition Phase* (2h), the formation flying metrologies are acquired while the spacecraft are drifting. Formation is then acquired with the two satellites at a distance of about 150 m.
- Then in *Apogee Operation Phase* (6h), the formation flying demonstration and experiments activities takes place. Formation flying demonstration counts on different manoeuvres to be exercised. Experiments include different GNC software modes and risky operations like realistic collision avoidances scenarios.
- After apogee phase, in *Perigee Pass Preparation Phase* (2h), perigee pass manoeuvre is executed to ensure no collision risk at perigee and formation reacquisition at next apogee entry.
- Finally *Perigee Pass Phase* (9.5h) is the longest phase centred around perigee. In this phase the satellite are free flying and pointing towards the sun. Absolute and relative navigation solution is obtained below about 5,000 km from GPS receivers. Relative position is then propagated up to next formation acquisition phase.

CSC will host the formation metrology sensors and provide the measurements to the OSC. The OSC will process the measurement and command the nominal formation changes along the four phases of the operational sequence. Maximum autonomy is implemented onboard. Ground is only providing mission timeline information every 4 days. The timeline includes a plan for one week.

4.3 PARKING Mode

The PARKING mode represents a formation stand-by mode, where the two spacecraft are maintained on slightly different orbits. PARKING mode may be entered in case of operations problems or to perform maintenance activities. For instance, in case of empty operation timeline the FF software will autonomously command the two S/C to go to PARKING mode. While in PARKING orbit the propellant consumption is minimised and nominal operation recovery is feasible within one or two orbits. In PARKING mode, the two spacecrafts will repeat the same main operation sequence every orbit. The sequence is composed of four phases:

- In *Apogee Parking Operations Phase* (2h), the two spacecraft point towards each other and acquire relative navigation using formation flying metrologies. CSC executes the first parking orbit maintenance manoeuvre. Relative navigation is acquired and “go ahead” for free drift phase is given. This phase last about one two hours.

- During *Descending Orbit Free Drift Phase* (8h) the two spacecrafts drift up to the beginning of the GPS visibility at perigee. No manoeuvre is executed. Relative state is propagated.
- In *Perigee parking operations Phase* (1,5h) the Relative GPS navigation is acquired. CSC executes the second orbit maintenance manoeuvre before the end of GPS visibility. Relative GPS navigation is performed after the manoeuvre and “go ahead” for free drift phase is given. This phase last about one and a half hour.
- The last phase is the *Ascending Orbit Free Drift* (8h) where the two spacecrafts drift up to the beginning of the Apogee parking operations. No manoeuvre is executed.

Transition from OPERATIONAL to PARKING and back is part of the system autonomy.

5. Proba-3 Mission Timeline

Proba-3 nominal mission lifetime is two years. The mission is composed by three main phases:

- LEOP, lasting less than 2 days.
- Commissioning, lasting about 2 months.
- Nominal Operations, lasting about 22 months.

It will be possible to extend the operations up to the maximum mission duration of about 2.5 years depending on launch date. At the end of the operation phase Proba-3 is decommissioned waiting for its passive re-entry into the atmosphere.

Within the Proba-3 nominal operations, the operation priority is addressed according to the objective importance: FF demonstration first, then science and finally experiments.

5.1 FF Demonstration

The fulfilment of FF mission objectives depends on the execution of FF demonstration tasks. The demonstration will start with small scale (few meters) rigid resize and retarget tests. The objective of these tests is to assess the initial accuracy of the uncalibrated system. Then calibration manoeuvres will be executed. Dedicated manoeuvres will allow metrology and GNC equipments performance characterization. Prior to the execution of full scale formation manoeuvres, collision avoidance manoeuvres will be demonstrated. Formation resize (from 25 to 250 m) and retarget (from -30º to +30º) will be finally demonstrated. This will include station keeping operations at different ISDs. The *rigid* manoeuvre objective is to demonstrate operations foreseen from future formation flying missions. In particular space telescope or interferometer mission will perform part of their scientific observation during rigid manoeuvre. Rigid manoeuvres will require well defined trajectory, the highest accuracy metrology system and formation control with maximum level of performances. *Loose* manoeuvre objective is intended to demonstrate service operation and in particular move from point A to point B in order to perform an additional operation (e.g. station keeping or start a resize or retargeting manoeuvre).

5.2 Coronagraph Science

A total of 167 orbits are needed in order to complete the planed minimum 1,000 hours of coronagraph observations. The science payload on Proba-3 consists of a distributed coronagraph system . The coronagraph system is composed by a Coronagraph Instrument and four Shadow Position Sensors (SPS) mounted on the CSC and an Occulting Disk and six Occulter Position Sensors mounted on the OSC. The coronagraph instrument will take images of the inner solar corona with observational parameters never achieved before. Broad and narrow band images as well as polarisation measurements will be possible. The Proba-3 spacecraft will fly during the apogee phase in station keeping configuration at about 150 m inter satellite distance. Coronagraph science operations will last about 4.5 months. The planning of these operations mainly depends on the availability of the dedicated downlink ground antenna.

5.3 Experiments

Three experiments are currently considered within the Proba-3 mission. Additional experiments may be included in the mission at the beginning of phase C. The experiments include: 6DOF Control with Thrusters, Rendezvous Experiment and Realistic Collision Avoidance & FDIR Test Manoeuvres.

Future interferometer mission will avoid the use of ball bearing reaction wheels to limit the internal vibration. Within the *6DOF Control with Thrusters* experiment, Proba-3 will repeat formation manoeuvres controlling the relative spacecraft position and attitude only with the thrusters.

Mars sample return mission is considering high elliptic orbit as option for the rendezvous between the canister and the return ship. The Proba-3 *Rendezvous Experiment* is aimed to the demonstration of the rendezvous in high elliptic orbit.

The most feared and critical failure in a formation flying mission is the collision event. Any test performed with no collision risk involved could not be fully representative. The *Realistic Collision Avoidance & FDIR Test Manoeuvres* will validate in flight the collision avoidance system by entering the Proba-3 spacecraft in a real collision path.

Among these experiments, the highest priority is given to the *6DOF Control with Thrusters experiment* due to its lower risk. The lowest priority is given to the *Realistic Collision Avoidance & FDIR Test Manoeuvres* due to its higher risk.

6. Proba-3 Mission Novelties

Proba-3 mission will validate several novel algorithms, equipments and processes. The novel algorithms include distributed system autonomy, formation flying algorithms and the rendezvous in high elliptic orbit GNC. Coarse lateral metrology system and fine lateral and longitudinal sensor are developed specifically for formation flying applications and will be validated in flight by Proba-3. The distributed vision based sensor derived from the one applied in Prisma mission will be upgraded including autonomous optical synchronization functionality. The use of relative GPS will be brought to the extreme level acquiring and propagating measurement obtained only at perigee. Coronagraph instrument payload will exercise first class science, peeking into the inner corona of the Sun. Proba-3 will adopt the consolidated PROBA verification approach and adapt it to the formation dimension. In particular the software verification tools used in previous PROBA will be adapted to verify the formation system. Software verification is particularly critical in Proba-3,

given the difficulties to test Proba-3 in the formation range and environment on ground.
Details on the distributed system autonomy, FF algorithms & technologies and the validation & verification approach follow.

6.1 Distributed System Autonomy

Proba-3 System Autonomy requires two safety levels: Spacecraft Safety and a Formation Safety. The following Table 1 provides an overview of the needed level of autonomous safety for the different mission phases.

Table 1: Autonomy on different mission phases

Mission Phase	Spacecraft Safety	Formation Safety
LEOP	Autonomous 4 hours	None
Commissioning	Autonomous 24 hours	Ensured from Ground
Operational	Autonomous 4 days	Autonomous

In the following sections the spacecraft safety, formation safety and FDIR concept are introduced.

6.1.1 Spacecraft Safety

Spacecraft Safety will be ensured by dedicated spacecraft Safe Configuration in STACK and MANUAL system modes. It will ensure power and safe thermal control and will guarantee ground communications to allow ground to investigate the failure. It will be maintainable for long periods of time minimising fuel consumption and will be fully reliable (i.e. fully tested on ground). Spacecraft Safe Configuration is requested to cope with all non autonomously recovered failures from all spacecraft subsystems. The goal is to prevent spacecraft degradation or loss. After any entry into a spacecraft Safe Configuration, ground is the responsible for analysing and recovering from the source of the failures, and the spacecraft safety software actions. As failure could happen at any time during mission, Spacecraft Safe Configuration is required to be executed at any time. Spacecraft Safe Configuration is also designed to guarantee a minimum functionality from all subsystems to avoid spacecraft loss.

6.1.2 Formation Safety

In Proba-3, Formation Safety is guaranteed by design. After each orbital maneuver, relative navigation is performed to ensure the correct orbital evolution. In case of failure during formation flying activity that prevents the system to maintain the formation, *Orbital Reconfigurations* are triggered. Any orbital reconfiguration involves a loss of formation and increased propellant consumption. It therefore reduces mission time and requests ground intervention to recover to operational modes. FDIR design will therefore minimize the use of these orbits trying to recover failures without losing operational modes. This is particularly important for Collision Avoidance Manoeuvre that leaves both spacecraft in a situation where formation recovery requires a considerable amount of propellant. Orbital reconfiguration will use two types of orbits: *Safe Orbit* and *Drifting Orbit*.
Safe orbits are passively safe trajectories that require no formation orbit control for long periods of time. They have the following characteristics:

- Any of the spacecraft can execute Safe orbit acquisition.
- Two impulsive manoeuvres are required to acquire the orbit, using nominal navigation based on GPS.
- No additional maintenance manoeuvres are required once the orbit has been acquired.
- They are designed to be safe for at least two weeks.
- Ground intervention is required to recover the formation.

Availability of good relative navigation data is of critical importance to enter safe orbits. In order to command safe orbit acquisition the relative position navigation accuracy shall be better than 20 m and the relative velocity navigation accuracy better than 20 mm/s.

Drifting orbit is the result of Collision Avoidance Manoeuvres (CAM) execution. CAM are designed with the objective of avoiding a collision, and making it in such a way that no collision will happen in subsequent orbits. In Proba-3, the CAM is designed to ensure the safety of the System up to two months.

CAM is triggered whenever the inter-satellite position/range and velocity/range-rate measurements cross some pre-defined threshold values during operational part of the orbit a CAM is triggered to avoid collision.

CAM is also executed in case of ISL reconfiguration time out. ISL loss could mean that the companion spacecraft has entered a spacecraft Safe Configuration after an On Board Computer (OBC) failure (reset or reconfiguration). Such spacecraft reconfiguration, depending on the relative distance and velocity, may lead to a collision. For this reason, whenever the ISL is lost unexpectedly, a timer is started. When the time exceeds that of an ISL reconfiguration, the system assumes that the companion OBC recover action in progress. Therefore a CAM is triggered to avoid potential collision. As baseline, 20 minutes are considered as maximum acceptable ISL blackout.

CAM is the last formation recovery action. All cases that cannot be solved by safe orbit entry will be solved by CAM triggering.

6.1.3 FDIR Concept

FDIR concept set up the basis for the organization, architecture and implementation aspects of the distributed system autonomy in Proba-3 mission. As usual in any FDIR design in space missions FDIR design is divided in different levels according to the criticality of the failure and the envisaged recovery action. Five different FDIR level, according to recovery actions, are defined:

- **L0 FDIR No Recovery Action:** when the recovery is autonomously performed by unit or function.
- **L1 FDIR Unit/function recovery:** Recovery action on the same unit but performed by the FDIR. In particular **L1a** is defined for **Hardware Failure** and **L1b** for **Software Failure**.
- **L2 FDIR Unit/function reconfiguration:** Unit or function is substituted by a redundant or a functional redundant one by the FDIR.
- **L3 System Recovery:** System and Spacecraft mode change up to a safe configuration from any failure that endangers mission and is not recovered at previous FDIR levels. FDIR mode is analysed in the present document. After L3 recovery, Ground is responsible for recovering operational modes after any L3 FDIR action. Within L3 failures, **L3a** is used for **System recovery** including subsystem failure (excluding OBC) and unresolved L0,L1 and L2 failures that

leads to a system hazardous situation. **L3b** is dedicated to **OBC recovery,** intended as any recovery action to be taken at OBC using either HW traps or SW checks that lead to a L3 system recovery.

- **L4 Collision Avoidance Recovery:** In case there is a risk of collision a CAM is requested by formation FDIR leading to drifting orbit.

Summary of the FDIR level definition is presented in Figure 5.

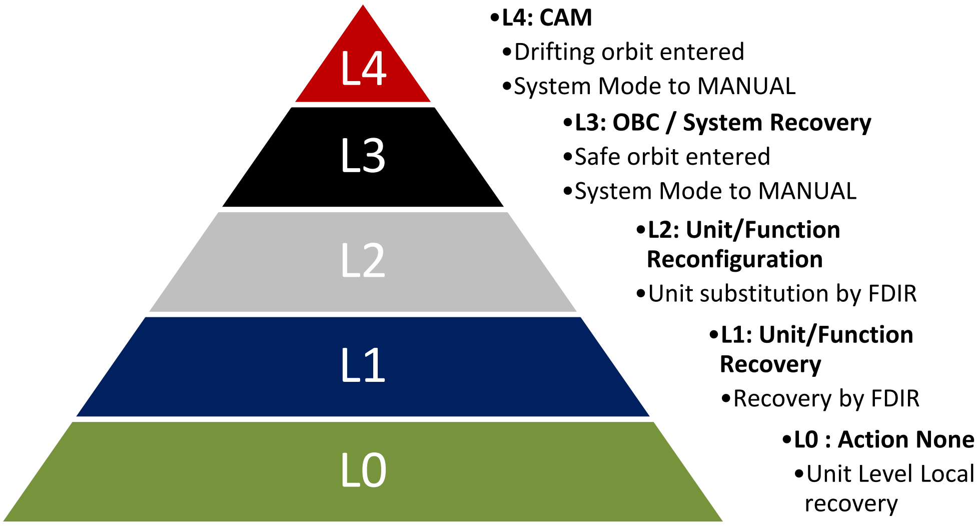

Figure 5: FDIR recovery action level

The FDIR main principle is that lowest-level isolation and recovery is attempted first. This approach minimizes the impact in the system operation. For example, unit-level recovery is attempted first, before reconfiguration of the GNC modes or higher level modes (such as spacecraft or System modes).

Figure 6 depicts the FDIR recovery order. In particular three reset attempts are indicated within L1 recovery, before a redundant unit reconfiguration action at L2 level.

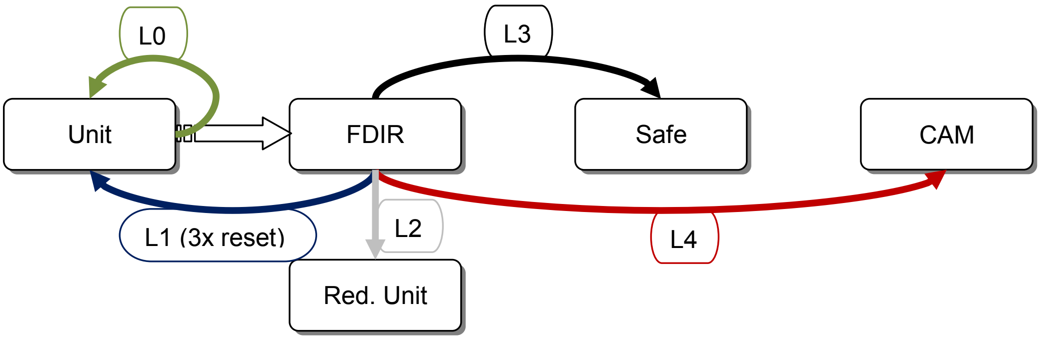

Figure 6: FDIR recovery order

6.2 FF Technologies and Algorithms

Proba-3 will validate in orbit novel Formation Flying metrology sensors that will allow the acquisition of the metrology chain. The metrology chain consists on GPS, Coarse Lateral Sensor (CLS) and Fine Lateral and Longitudinal Sensor (FLLS) to finally acquire the Coronagraph Instrument (CI).

In Proba-3 the relative GPS sensors will be commissioned first. The way to commission it, will be to downlink the absolute GPS data of the CSC and OSC spacecrafts and calculate on ground the same solution obtained in flight. Since solar radiation pressure coefficients are hard to estimate on ground, several orbits will be devoted to the characterisation of this perturbation. Once the relative GPS is commissioned, its propagated solution will be used to commission the CLS. No manoeuvres will be performed from the perigee GPS navigation to the CLS acquisition, in order to have the maximum propagation accuracy. CLS lateral measurements and GPS longitudinal measurements will be used to acquire and commission FLLS. Finally FLLS will be used to acquire and commission the Coronagraph Instrument (CI). Incremental sensor commissioning approach is depicted in Figure 7.

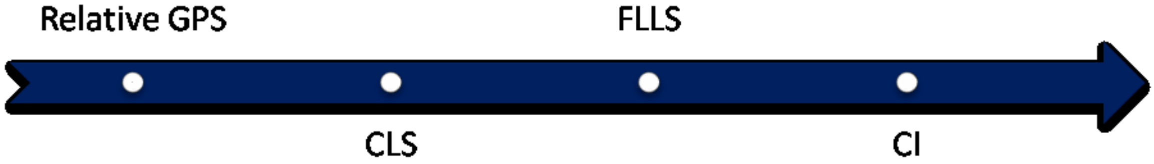

Figure 7: Incremental Sensor Commissioning Approach

The metrology elements operational range and accuracy are indicated in Table 2. In particular CLS and FLLS will be validated in flight by Proba-3 and requires a special attention in this section.

Table 2: Proba-3 metrology chain

Metrology Element	Operational Range	Accuracy (1σ)
GPS	At perigee	7.5 cm (at perigee), <10m when propagated up to at apogee entry.
CLS	+/-13m @ 150m (lateral) 25-250 m (longitudinal)	1 mm (lateral) @150m
FLLS	±20.5mm (lateral) 25-250 m (longitudinal)	21 μm (lateral) 30 μm (longitudinal)

6.2.1 Coarse Lateral Sensor

Coarse Lateral Sensor is the second level in the chain of Proba-3 relative metrology. The CLS allows enough LOS precision to acquire the fine/ranging metrology. CLS working principle is the following: (1) a defocused laser beam is sent towards a corner cube located on the companion satellite; (2) the laser bounce on the corner cube and is retro-reflected to the sensor lens, which images the light on a detector; (3) a filter blocks all unwanted light; (4) the detector captures the images; (6) an electronic unit records the images and localizes the return light bright spots; (7) this unit computes the centroid and forwards this information as output via a RS422 communication link. The CLS prototype is shown in Figure 8 (left).

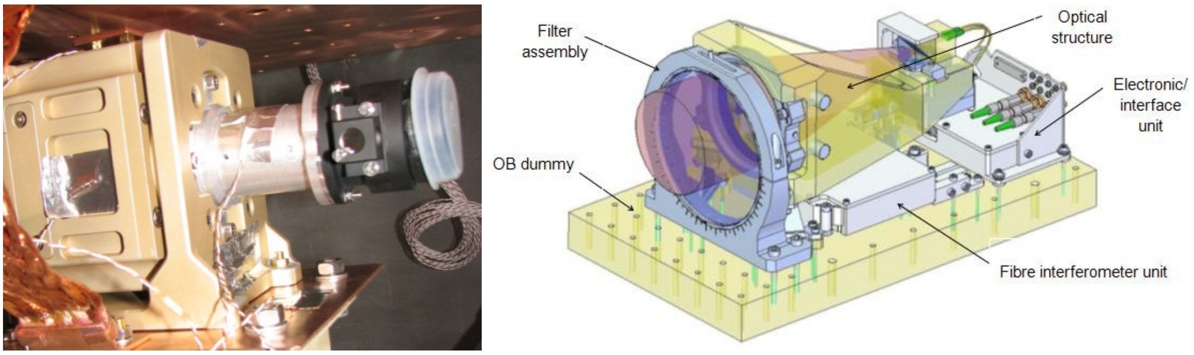

Figure 8: CLS prototype from Centre Spatial de Liége (left) and FLLS design from QinetiQ (right)

6.2.2 Fine Lateral and Longitudinal Sensor

Fine Lateral and Longitudinal Sensor is the third and last level in the chain of Proba-3 relative metrology. FLLS working principle is the following: (1) a laser pulse train is generated and split in two parts; (2) one part is transmitted to a corner cube located on the other satellite, whilst another is sent via a reference arm of the interferometer, prior to recombination of the two sets of pulse trains; (3) the reflected light is received back at the optical head; (4) part of the received light is split and sent to the lateral position sensor; (5) the remaining light is mixed with the reference and sent to the distance detector; (6) distance is finally computed from the interference between the signal and reference beams. QinetiQ SIPOD has been selected as baseline FLLS for Proba-3. Figure 8 (right) shows the FLLS Optical Head design.

6.2.3 FF algorithms

The FF algorithms are designed to combine and propagate the available metrology sensors measurement and execute the commanded timeline. The estimation of the performances of the formation flying demonstration will rely on the highest accuracy element of the metrology chain.

The Formation Flying station keeping maneuver, at about 150 m relative distance, will be validated using the coronagraph instrument. In particular the coronagraph instrument images and the shadow position sensors readings will be combined with the orbital data and the other GNC sensors telemetry (STR, SAS, etc) and post-processed on ground. The obtained information on the relative position of the spacecrafts will be used as reference to estimate the FLLS performances and validate the FF algorithms. FLLS will be calibrated to a very high level of accuracy using coronagraph instrument data. FLLS measurement will be used by ground and combined with orbital information and the other GNC sensors telemetry (STR, SAS, etc) to derive a filtered solution that will be used as reference for the performances analysis of Formation Flying resize and retargeting maneuver. Figure 9 depicts the metrology sensors validation approach.

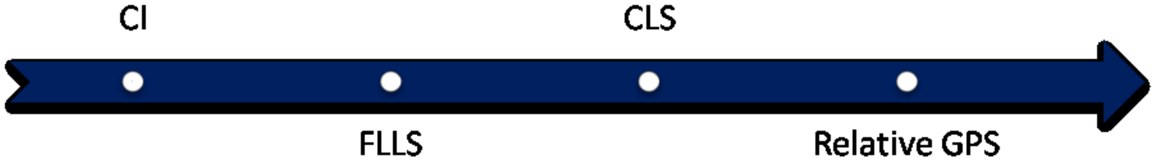

Figure 9: Metrology Sensor Validation Approach

For rendez-vous experiments it is foreseen to use relative GPS and FLLS measurements post-processed on ground to validate VBS sensor. Given the relative distance between the spacecrafts during the experiments, FLLS and GPS data will only be available during a reduced time frame. Outside these period VBS measurements will be used. The metrology sensor data will be combined with the orbital data and the other GNC sensors telemetry (STR, SAS, etc), post-processed on ground and used as reference for the rendez-vous algorithms performance estimation.

6.3 Software Validation and Verification Approach on Ground

The Proba-3 software will follow a modular design development and validation approach with complete reuse of prototype software and lowest level verification philosophy.

The design and main functional verifications is based on Matlab/Simulink^{TM} Functional Engineering Simulator and Verification tool developed in phase B. This tool contains high fidelity models of the sensors, actuators and the dynamic environment. The developed GNC modules are validated in the FES and auto-coded to flight software. The formal system and software verifications is performed on a dedicated software based test bench. This real time environment contains a high fidelity Proba-3 onboard computer and data handling system models. Limited set of tests is repeated in the Avionic Test Bench (ATB) and in the System Test Bench (STB). STB is assembled combining two ATB and is used to test formation aspects. Finally a subset of the avionics test is repeated on the two satellites.

7. Proba-3 PDR Results

During phase B, simulation campaign was performed to support the Proba-3 system performance budget analysis. Table 3 reports the Proba-3 PDR budget. Different performance is obtained for station keeping and maneuvers. For station keeping High-Precision Attitude and Position (HPAP) budget is applicable while for maneuvers, High-Precision during Motion (HPM) budget is defined. Performances are provided for Relative Displacement Error (RDE), Relative Velocity Error (RVE) and Relative Displacement Measurement Stability (RDMS).

Table 3: Proba-3 Formation Flying Budget at PDR

Error	HPAP Value	Remarks	HPM Value	Remarks
RDE [mm]	0.66 1.73 2.58	ISD <40m ISD <160m ISD <250m	3.26	25m<ISD<250m
RVE [mm/s]	-	-	0.02	25m<ISD<250m
RDMS [mm]	0.15	over 4h in post-pro	-	-

PDR results indicates that the above performances can be further improved by increasing the STR bias stability, reducing the thermo-elastic drift of the satellite and calibrating in flight the system with more accuracy.

These measures will be implemented in Phase C.

8. Conclusion

FF technology demonstration is a milestone for future small and large scale *virtual structure* mission. Virtual structure will allow small spacecrafts, flying with a fixed relative geometry, to synthesize giant structure-less spacecraft or instruments. Example of virtual structure missions are:

- Solar corona missions, where one satellite is used to eclipse the Sun.
- Two elements space telescopes, composed by a lens-spacecraft and a receptor-spacecraft separated tens of meters.
- Multi-element space interferometer missions, composed by several telescope flyers and a central combiner.
- Multi-spacecraft SAR topographic levelling missions, composed by a fleet of several small satellites.

The paper provides a description of the Proba-3 FF technology demonstration mission that has successfully completed the phase B. Special emphasis has been put on the main mission novelties. PDR results indicate that millimetre level formation control is achievable. These promising results highlight the feasibility of this very challenging technology demonstration.

9. References

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