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Proba-3: ESA's small satellites precise formation flying mission to study the Sun's inner corona as never before

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ABSTRACT

This paper showcases ESA's Proba-3 mission as a demonstration of how small satellites, in combination with formation flying technology, can achieve relevant scientific goals and perform scientific measurements not possible otherwise, all within a tight cost and programmatic context. The study of the Sun inner corona down to 1.1 solar radius can only be performed by creating in space artificial eclipses with a large distance between a Coronograph instrument and an occulting disk, much bigger than the size of any spacecraft that can fit within a launcher.

Proba-3 will achieve these enhanced scientific observations by controlling two small satellites (~1.5 m cubes in the 200-300kg range) as a 150 m long 'large virtually rigid structure' by maintaining millimetre and arc second relative precision. In effect the paired satellites will fly as a giant virtual satellite creating an 'externally occulted' coronagraph, in which a satellite imager is shielded from glaring sunlight by an occulting disk on the other satellite, forming an artificial eclipse. Precise station keeping for Coronagraphy will be kept for 6 consecutive hours within each 20 hour orbit for a minimum total of 1000 hours of scientific observations over the 2 years of mission lifetime. This will be achieved autonomously, without relying on the ground for active control of the formation.

In addition, Proba-3 will practically demonstrate formation flying technologies enabling other future science missions: station-keeping at different relative distances (from 25 m up to 250 m); approaching and separating in precise formation without losing millimetre precision; the capability to repoint the formation as a virtual rigid body away from the Sun and the combination of station keeping, resizing and re-targeting manoeuvres.

Proba-3 is at full speed in the assembly, integration and verification phase, with the aim of launching Proba-3 in two years' time. The paper describes the overall Proba-3 mission concept and detailed design, the different challenges that were overcome in spacecraft design, formation flying metrology and control, and the need to implement novel verification and operation approaches to achieve the world's first precise formation flying mission.

INTRODUCTION

Formation Flying (FF) is the cornerstone technology required for building in flight large “virtual structures or distributed observatories”. Such application requires FF with high control accuracies. FF missions will avoid the need to pack and deploy large dimension systems, with the associated complexity and the large associated services. They will also improve the achievable relative position accuracy of the different components, with displacements smaller than the thermo-mechanical distortions present in large conventional structures in flight. However, this type of precise FF concepts implies the usage of new and complex technologies to be implemented as a critical element of any eventual target missions. The usage of such critical technologies mandates an extensive and thorough verification of its behaviour prior to mounting it in the target mission. The limitations of the ground verification determine that enough confidence of the behaviour of the formation flying mission will only be obtained by demonstration in flight.

Proba-3 is the ESA project dedicated to the in-flight demonstration of precise formation flying [1]. Proba-3 forms part of the ESA GSTP program, and in that program it is an element of the Proba series of technology demonstration missions. Proba-3 mission is also supported by ESA’s Science Programme as an opportunity mission through cooperation to the Science Operations.

MISSION PURPOSE AND CONCEPT

Overall 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 particular, after completion of the Proba-3 mission the following mission results shall be achieved:

- Sun Coronagraph observation scientific return
- Demonstrate precise formation flying manoeuvres for future science missions
- Mature formation flying metrology
- Demonstrate formation autonomy and robustness
- Validate development approach

Additionally, to maximize the mission return, some additional technology experiments and payloads have been included, in particular:

- Demonstration of rendezvous experiment in highly elliptic orbit.
- Sun Radiometer instrument (DARA)

Enabling Lower Corona Observation

The Sun is a million times brighter than its surrounding corona, so occulting it is essential for coronal studies. But after 40 years of space coronagraphy, the lower corona (<2.5Rsun) remains practically unobserved with satisfactory accuracy, being the stray light due to Sun light diffraction from the occulting disk the most difficult challenge to overcome.

The rare minutes of total Solar eclipses currently present the only opportunities for a seamless view of the corona.

Past experience showed that externally occulted coronagraphs achieve reasonably good diffraction straylight suppression, but due to telescope length limitation and associated optical vignetting, their field of view inner edge is limited.

This is when the concept of formation flying comes into play, being able to build a large giant coronagraph with the occulter disk far away, and capable of producing a nearly ideal eclipse, that allows observation of the Sun corona closer to the solar limb than ever before.

Proba-3, with the occulter disk at 150 m from the coronagraph instrument, is able to provide observations of the white-light corona (540 to 570 nm) and of two narrow-band emissions lines 530.4 nm and 587.7 nm from 1.1 Rsun out to 3 Rsun, and these artificial eclipses are kept during 6 hours every 20 h orbit.

The Coronagraph on Proba-3 is called ASPIICS (“Association of Spacecraft for Polarimetry and Imaging Investigation of the Corona of the Sun”) [3] and is developed by a consortium of European Institutes and Industries from Belgium, Czech Republic, Greece, Italy, Ireland, Poland and Romania. The ASPIICS unprecedented field of view makes it uniquely suited for studies of the solar corona, as it will fill the crucial observational gap between the fields of view of Solar EUV imagers and conventional space coronagraphs (see Figure 1).

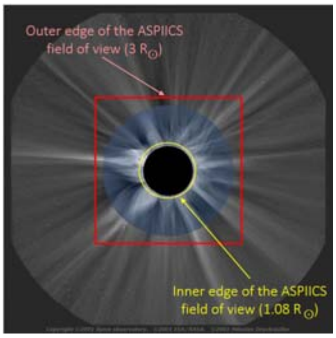

Figure 1: ASPIICS corona observation concept [3]

The top-level scientific objectives of ASPIICS are in first place to understand the physical processes that govern the quiescent solar corona by answering the following questions:

- Nature of the solar corona on different scales
- Processes that contribute to the heating of the corona and the role of waves
- Processes that contribute to the solar wind acceleration.

And in second place, to understand the physical processes that lead to CMEs and determine space weather by answering the following questions:

- Nature of the coronal structures forming CME
- How do CMEs erupt and accelerate in the low corona
- The connection between CMEs and active processes close to the solar surface
- Where and how can a CME drive a shock in the low corona

Precise Formation Flying Demonstration

Creation of large straight "virtual structures" is one of the most promising capabilities of high-precision FF technology. As such, these configurations have been identified as the cornerstone for the development of large "distributed" observatories.

This simple and straightforward concept however, requires being capable of dynamically controlling the vehicles' relative status such that their position difference from the required one is on the millimeter level, and their attitude errors are bounded to the arc-seconds level for long periods of time.

Proba-3, consequently, during the mission operation it will autonomously execute a set of manoeuvres with millimetre level accuracy. Figure 2 shows the top-level pointing and relative positioning performance requirements established to fulfil the FF demonstration objectives [2]:

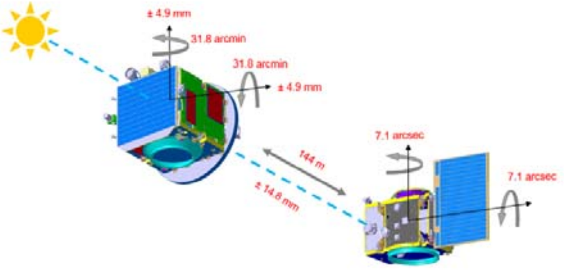

Figure 2: Proba-3 performance Requirements

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 manoeuvres (Figure. 3).

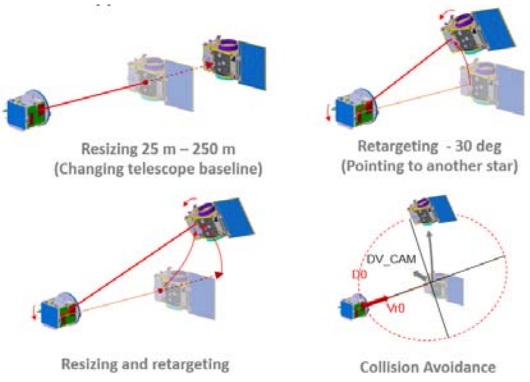

Figure 3: Proba-3 FF Demonstration manoeuvres

PROBA-3 SYSTEM DESIGN

This section is dedicated to present the main areas that have driven the system design..

Orbital derived conditions

The Proba-3 baseline orbit shall be Highly Elliptical Orbit (HEO), in order to have a quiet perturbation environment.

The resulting HEO leads to some relevant issues on mission design and operation:

- Varying orbital conditions: being in a HEO orbit implies that there are significant differences in terms of relative perturbations on the satellites between the apogee and the perigee.
- Long Eclipses: the combination of a HEO orbit and low Sun declinations leads to have a set of periods during the mission lifetime in which the spacecraft are in eclipse for up to 3.5 hours.
- Radiation: spacecraft on HEO orbits being subject to high radiation levels .
- Ground visibility: the combination of HEO orbit, with a period lower than 24 h and the natural evolution of the orbital parameters, leads to a ground contact pattern which is far from cyclical. The visibility passes range from less than 1 h to more than 16 h, and there is a variation of the location of the orbit in which they take place.

Relative metrology accuracy needs

The requirements of the relative control of the spacecraft are very demanding. Their achievement relies on the minimization of the different contributors to the performance error, as follows:

- Alignment needs: the correct alignment of the different units involved in the relative state measurements of both spacecraft is key not only for the final accuracy performances, but to ensure the feasibility of the mission.
- Metrology high thermal stability: maintaining high pointing accuracy and stability requires very low thermo-mechanical deformations of the involved units.
- In-orbit calibration: the required accuracies lead to need to perform in-orbit calibrations between different units involved in the relative state estimation. Thermo-elastic errors only seen in flight need to be identified and appropriately corrected.
- Optical metrology: due to the high accuracy required, optical based metrologies are used. It means that spacecraft need to point to each other to lock the metrology.

Autonomy and Formation management

One of the very particular aspects of the Proba-3 mission is the need to control the two spacecraft simultaneously and in a coordinated way during most of the mission. The spacecraft shall be performing formation flying manoeuvres for different purposes, and they shall be performed autonomously (up to one week of autonomy).

- Autonomous Formation Flying: the implementation of formation autonomy requires a complex on-board logic capable of controlling each satellite on its own and coordinating the action of both spacecraft during the different formation operations.
- Breaking/acquiring the formation: as commented above, being in a HEO orbit the formation has to break before the perigee passage and then re-form again before apogee.
- Safe orbits: in case the spacecraft cannot be controlled in formation, they shall be led to a relative configuration in a safe relative orbit in which they can stay for long periods without the need of mutual coordination.
- Formation Flying Commissioning: In the case of Proba-3, the commissioning also involves testing all the formation flying manoeuvres and associated metrologies before having the formation acquired autonomously.

PROBA-3 MISSION CONCEPT

Proba-3 mission architecture

Proba-3 includes the classical Ground, Space and Launcher segments (see Figure 4).

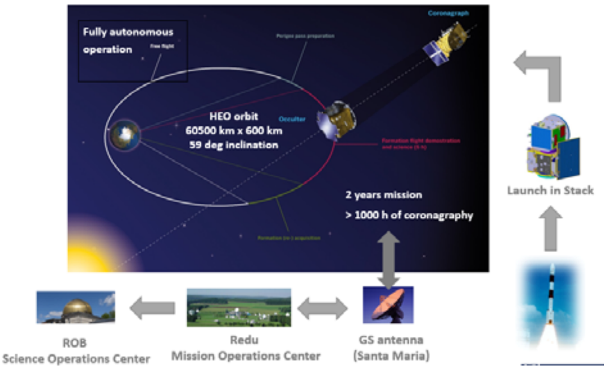

Figure 4: Proba-3 mission architecture

The spacecraft will be launched in stack configuration by direct injection into a highly elliptic orbit with a perigee of 600 km, an apogee of about 60500 km and an inclination of 59º (see Figure 4). The orbital period is 19h 30m. Right ascension of ascending node, inclination and argument of perigee are selected to limit the radiation dose and to allow natural re-entry of the spacecraft after about 30 months. The selected orbit achieves also a good stability and coverage for usage of a single ground station. In a later step the two satellites are separated one from the other.

Proba-3 GS is built upon the heritage from Proba-1, Proba-2 and Proba-V, with high degree of reuse of processes, methods and modules. The Mission Operation Centre is located at Redu (in Belgium) and the Ground Station is located at Santa-Maria in Azores (in Portugal).

The Formation Flying System (FFS), includes the elements necessary to maintain the satellites in the desired relative configuration, and incorporates metrology equipment, control logic, SW and operation management. The FFS uses and must coordinate the two satellites, and the services included in it. One of them is the SC-GNC (developed by NGC Canada), similar to the classical AOCS, which maintains the satellites in the necessary pointing and perform delta-V manoeuvres and includes several modes for allowing high accuracy inertial pointing, target pointing and safe sun pointing, implemented in both satellites.

The thermo-elastic effects on-board the spacecraft have a direct impact on the metrology systems and thus on the system’s formation flying performance. For this reason the metrology equipment of both the CSC and of the OSC are mounted on an optical bench assembly (OBA)

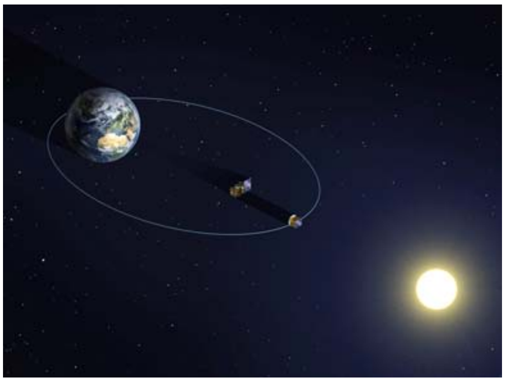

Figure 5: Representation of the Proba-3 HEO

Mission profile

Proba-3 is a complex mission involving two spacecraft that have to perform actions independently and in a coordinated way. In other more “classical” missions with a single spacecraft, the autonomous operation of the spacecraft can be organized around the AOCS modes, which somehow define the different types of activities that the spacecraft is performing, together with the payload operation within a given AOCS mode. This approach is not fully applicable to Proba-3, considering the different levels of Formation and AOCS modes, the different spacecraft operation depending on the phase, the large variety of spacecraft manoeuvres and, what is more important, that the formation flying manoeuvres themselves are somehow part of the “payload” to be demonstrated.

There are several satellite phases that represent the different conditions and configurations in which the spacecraft and formation evolve:

- STACK LEOP and Commissioning Phase
- Formation Flying Operation Phase
- Contingency situations

STACK LEOP and Commissioning

The two spacecraft are launched in a stack configuration, the OSC mounted on top of the CSC, and inserted along the selected orbit detailed previously.

After some commissioning activities, they will be separated from each other, and their relative position starts drifting. The drift will be stopped by impulsive manoeuvers commanded by ground. The ground will also command manoeuvers to be executed at adequate orbital true anomalies to insert the two spacecraft along a safe relative orbit.

The concept of this safe relative orbit is to have the two spacecraft along a relative orbit that is stable enough, such that the safety, in term of collision risk, is ensured for 30 days even if no orbital maintenance manoeuvers are commanded by ground. The two spacecraft are free flying, almost in the same orbit, but with a small difference in the eccentricity vector and the angular momentum vector.

The “dimension” of the safe orbit is characterised by the relative distance at apogee and perigee and depends on the mission needs, and range typically from 1000 meters to 150 meters. The main risk during a long period along the safe orbit is on the contrary to have the two spacecraft drifting from each other due to initial error in the orbital insertion. This will require regular corrective impulsive manoeuvers to limit the use of propellant to return from safe orbit to the nominal operational orbit.

Formation Flying Operation Phase

Formation Flying Phase is the mission main operational phase, in which the spacecraft perform coronagraph observations and formation demonstration manoeuvres. It is performed completely autonomously, only requiring the regular upload of the list of formation operations to be performed sequentially at apogee for the following 7 orbits.

The nominal orbit activity during this phase is very varied, and several manoeuvres could occur, as shown graphically in Table 1 and in Figure 6.

During this phase the formation is no longer in a safe relative orbit but performing the necessary actions to keep the formation in place. Formation flying demonstration manoeuvres and Coronagraphy is performed in the apogee (from point 4 to 6). Rigid formation cannot be kept during the perigee passage since the relative dynamic perturbations are very high and will cost a large amount of fuel.

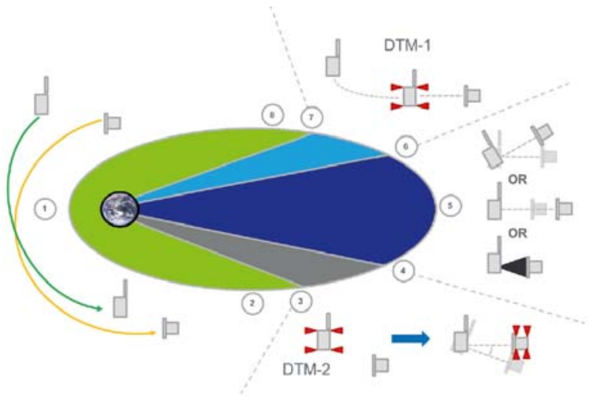

Figure 6: Nominal orbit formation flying phases

Therefore, the concept is to break the rigid formation (point 7) so that during the perigee passage the two spacecraft fly uncontrolled (but inherently safe) pointing to the Sun, acquiring again the formation before the next apogee phase (point 3). The breaking and acquisition of the formation is done by performing a set of impulsive manoeuvres called Direct Transfer Manoeuvres (DTM). There is a DTM-1 performed at point 7 and a DTM-2 performed at point 3.

Table 1. Nominal Orbit Operations

True anomaly	Activity	Attitude
0º	Perigee pass	Sun Pointing
161º	CSC rotates 180º around xRBF	Sun Pointing
163º	Start formation acquisition	The two spacecraft points towards each other Maximum sun off-point of 30º is considered.
169º	Start Apogee Activity	Attitude depends on apogee activity. For retargeting operations a maximum sun off-pointing of 30º is foreseen.
180º	Apogee	
190º	Finish Apogee Activity	The two spacecraft points towards each other. Maximum sun off-point of 30º is considered.
196º	Finish Perigee pass preparation	Sun Pointing
198º	CSC rotates 180º around xRBF	Sun Pointing
360º	Perigee pass	Sun Pointing

Figure 6 also shows two additional manoeuvres (points 2 and 8) to rotate the spacecraft in roll while pointing to the Sun to compensate the effect of the Solar Radiation torque on the spacecraft.

After DTM-2 has finished, the system is ready to acquire formation. For this, certain manoeuvres known as acquisition manoeuvres are required from point 3 to point 4. During these manoeuvres, the CSC and OSC would off-point from the Sun to the position in which the other SC is expected to be.

Finally, during the apogee phase (from point 4 to point 6) the formation flying demonstration manoeuvres and Sun corona observation are performed for a total of 6 h in rigid formation configuration.

Contingency Situations

The on-board computer in each spacecraft monitors at all times the health and proper functioning of the various spacecraft sub-systems to detect failures and anomalies that can be observed at spacecraft level.

Some anomalies or unexpected events, like the loss of a formation flying metrology causing the lack of relative position measurement to feed the navigation function, may not be a direct risk for the spacecraft itself, but a risk for the ability of the formation to be maintained and controlled. Eventually, risk of collision between the two spacecraft must be avoided at all costs.

The formation flying software provides to the on-board software, which is the central authority for system level decision, a number of indicators allowing the safety of the formation to be monitored.

In case of issues at spacecraft or formation flying level that prevents the nominal operational to be maintained, the on-board software triggers a transfer to the safe orbit. It consists in a two points transfer performed autonomously, with the two impulsive manoeuvers executed about 10 hours apart.

The spacecraft executing the transfer depends on which one is healthy. One of the spacecraft might have to go to safe mode, and informs the other through the inter-satellite link.

Special situations that would cause an interruption of the communication between the spacecraft are dealt with by a special logic to ensure that the two spacecraft are not executing the transfer to safe orbit at the same time.

SPACECRAFT DESIGN

Occulter spacecraft (OSC)

The OSC is designed to fly with the same face facing the Sun at all times. For the science operations it acts as an occulting disc, creating a stable eclipse and leaving only the solar corona visible to the Coronagraph instrument located in the CSC. OSC wet mass is about 250 kg, with a size of 1378mm x 1069 mm x 1160 mm. The Occulter spacecraft structure is essentially a cube with all the avionics and instrument equipment mounted on the inner panels, and with the occulter disc on the anti-Sun face.

The OSC is responsible for performing the high accuracy actuation formation control using cold gas milli-Newton thrusters.

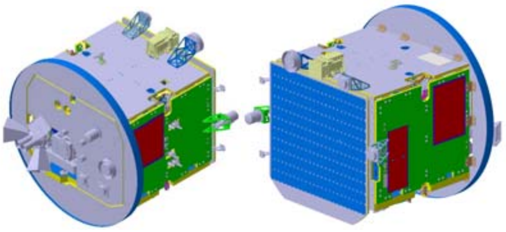

Figure 7: Occulter Spacecraft (OSC)

Coronagraph spacecraft (CSC)

Like the Occulter, the Coronagraph Spacecraft is designed to be always Sun pointing with the same face. CSC wet mass is about 300 kg with a size of 985 mm x 1440 mm x 1238 mm. Particular care in the design of the Solar panel layout is taken due to the fact that the Sun is partially eclipsed by the OSC during Coronagraph Operations. The design of the spacecraft is based on the asymmetric solar sail concept: a rigid support structure is used to position the single solar panel outside the penumbra. During launch, the deployable solar panel is stowed against the rigid support structure. The CSC is responsible of performing the main orbital maintenance impulsive manoeuvres with monopropellant thrusters

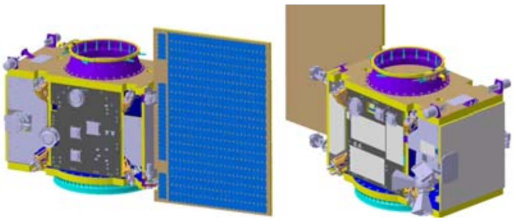

Figure 8. Coronagraph Spacecraft (CSC)

Spacecraft commonalities

The two satellites have been designed with maximum commonality in design and configurations. Both spacecraft share the same power generation and on-board data handling system. Power generation is based on Li-Ion batteries, battery regulated 28 V bus and triple-junction GaAs solar cells. Each spacecraft is equipped with the ADPMS2 on-board computer and power conditioning, which is the workhorse of all previous Proba spacecraft and developed by Qinetiq Space in Belgium. A passive thermal control is implemented in each spacecraft, with the use of thermistors, heaters, radiators and thermal blankets.

The spacecraft include Optical Bench Assemblies (OBA) designed for high thermal stability, including high stability sandwich panels of CFRP and aluminium core, with titanium fittings for attachment of the Units. The benches have a thermal control with heater lines in order to minimize the gradients along the bench.

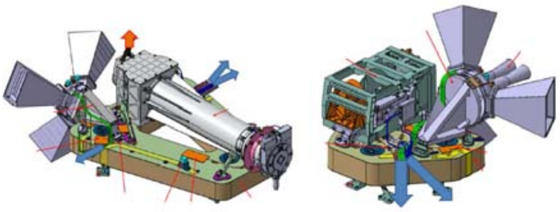

Figure 9: Optical bench on the CSC (left) and on the OSC (right)

Each spacecraft are 3-axis stabilised using a set of four reaction wheels. For attitude determination, a set of 3 star tracker optical heads (STR) are used. Conventional Sun sensors and gyros are used for safe modes. The configuration of formation flying units, AOCS sensors and actuators is presented in Table 2.

Table 2: Proba-3 Spacecraft Configuration

Item	On CSC	On OSC
Formation Flying Units		
High Accuracy Metrology	1 x Corner-cube	Emitter (laser) and Sensor.
Vision Based Sensor	8+8 x IR LEDS	2xWAC 2xNAC
Inter Satellite Link System	2 x Rx-Tx + 4 x antennas	2 x Rx-Tx+ 4 x antennas
GPS	2 x receivers + 2 x Antennas	

Item	On CSC	On OSC
Science Equipment		
Coronagraph Instrument	Optical Detector and electronics	Occulter disk
Absolute Radiometer		In Sun Panel
AOCS		
Star tracker	3 x Optical Heads + 2 x electronics	
Sun sensors	5 (1 Fine and 4 Coarse) redundant cosine sensors	
Rate sensors	Two 3-axes Inertial Rate Sensors	
Actuators		
Propulsion thrusters	2x8x1N Monoprop.	2x12x10mN Cold Gas
Reaction Wheels	Pyramid of 4 units	

FORMATION FLYING TECHNOLOGIES

Details on the Formation Flying System (FFS) required to control the spacecraft formation can be found in [2] [4]. It is built around a core set of novel technologies, units and system, as described in the following sub-sections.

Fine Lateral and Longitudinal Sensor (FLLS)

The FLLS is the highest accuracy metrology on-board Proba-3 and the one providing the performances to achieve the high accuracy pointing and positioning requirements. It is being developed by NEPTEC in UK & Canada and Micos Engineering in Switzerland.

The main functionality of FLLS is to determine the position of the apex of the Corner Cube Retro-Reflector (CCRR) located on the CSC in both the longitudinal and lateral directions, with a goal accuracy of 300 um @ 3σ between 25 and 250 m. The main elements of the of the FLLS are

- Optical Head Unit (OHU) on the OSC OBA
- Laser Control Electronic Unit (LCEU) on the OSC
- CCRR located on the CSC

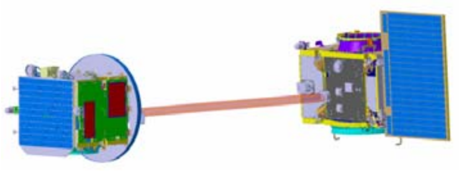

Figure 9: Representation of FLLS Operation

Vision Based System (VBS)

The Visual Based Sensor (VBS), provided by DTU in Denmark, is a metrology unit that is distributed between both SC and provides relative position information. It is composed of the following elements:

- Wide Angle Camera (WAC): Used for first step handover due to its larger FoV.
- Narrow Angle Camera (NAC): Used for the highest possible accuracy.
- Mires: 8 mires forming a light pattern on the CSC.
- Acquisition Mire: Used to ensure synchronization acquisition.
- Synchronization detector: Used to detect the mire blinks and acquire synch on the OSC.

The VBS has 2 modes depending on distance. The long range mode: the VBS tracks only source of light and computes its centroid; and the short range mode: the VBS matches the pattern to compute relative position and attitude.

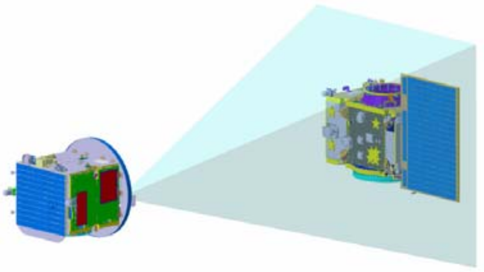

Figure 10: Representation of VBS Operation

Inter-Satellite Link (ISL)

The Inter-Satellite Link subsystem developed by TEKEVER in Portugal has been selected, as an evolution of the GAMALINK (S-band communication software-defined radio) product.

The ISL subsystem is composed of two transceivers and 2x2 antennae per spacecraft. It provides an S-band RF communication and ranging between the two satellites for the following functions:

- Data packets exchange between the two satellites
- Generation of inter-satellite range estimates
- Correlation of ISL clocks (through RF link), as a support for satellites time references correlation

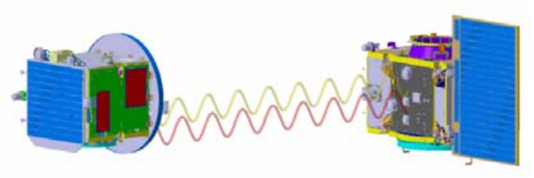

Figure 11: Representation of ISL Operation

Relative GPS navigation (rGPS)

Both spacecraft are equipped with GNSS capabilities for providing absolute spacecraft information (PVT) and enabling advanced relative navigation algorithms (rGPS). Each spacecraft is embarked with redundant GNSS receivers (GNSSR) variant of RSA's PODRIX receiver, developed by RUAG in Austria, supporting L1 and L2, and 2 GNSS antennas capable of tracking GPS L1 and L2.

A relative GPS algorithm is developed by GMV Poland that will process on a single spacecraft (OSC) the GPS measurements obtained by both spacecraft from the same set of the GPS of Spacecraft Vehicles (SV). It provides navigation solution in coarse mode based on pseudo-range measurements, and in fine mode using carrier phase measurements after solving the integer ambiguity of the CP measurements.

Proba-3 orbit goes beyond the GPS constellation, therefore the units are only used during part of the orbit, around the perigee.

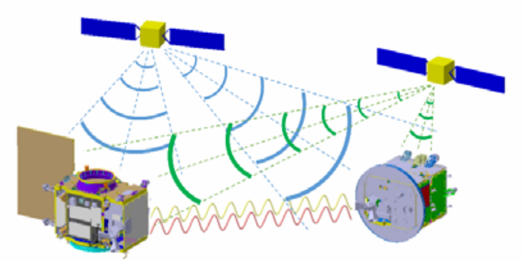

Figure 12: Representation of rGPS operation

CONCLUSIONS

ESA' Proba-3 is world's first precision formation flying space mission with challenging technical requirements. This paper has presented the Proba-3 mission, as a showcase of how novel space mission architectures (i.e. formation flying) can be used to achieve relevant scientific goals with small satellites and within a tight programmatic context.

Proba-3 is at full speed in the assembly, integration and verification phase, with the aim of launching Proba-3 in two years' time. It exemplifies how small satellites can be used to implement novel space mission architectures capable of achieving relevant scientific goals within a tight programmatic environment.

Proba-3 is being implemented by a Core Team of 5 companies led by SENER: QinetiQ Space nv, Airbus Defence and Space Spain, GMV Space and Defence and Spacebel, with the additional contribution of NGC Aerospace Ltd. The payload industrial consortium is led by CSL, in Belgium.

Acknowledgements

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