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Proba-3: Challenges and Needs for Sub-Millimetre Autonomous Formation Flying

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Abstract

Proba-3 is the ESA's precision formation flying space mission. Encompassing two satellites flying together in a highly elliptic orbit, they focus on creating a "large virtual rigid structure", maintaining sub-millimetre and arc second relative position and pointing accuracy. One (the Coronagraph spacecraft) will take pictures of the Sun corona while the other (the Occulter spacecraft) will create an "artificial eclipse", allowing observations with an accuracy higher than ever before. The mission also intends to set the bases and develop the technologies for future "virtual" telescopes, capable of achieving focal distances much larger than the ones that can be obtained with rigid structures.

The mission is designed to autonomously perform complex sequences of activities every single orbit, which lasts 19.6 hours. Even though the main activities will be performed during the low-disturbances apogee phase, one the main challenges of the mission relies on the amount of activities that have to be performed every revolution, as well as the different needs depending on the mission phase. The spacecraft dynamics forces to execute two point transfer manoeuvre before and after every perigee in order to guarantee that the spacecraft will not collide during the "non-controlled" phase of the orbit. Moreover, due the small size of the satellites, the units, metrologies and payload have to be managed specifically depending on the needs, so that the power budget is not exceeded.

1. Introduction

Creation of large straight "virtual structures" is one of the most promising capabilities of high-precision formation flying technology. As such, these configurations have been identified as the cornerstone for the development of large "distributed" observatories.[1]

This simple and straightforward concept however, requires being capable of dynamically controlling the vehicles' relative status such that their position differ from the required one in sub-millimetre distances, and their attitude errors are bounded to the arc-seconds level for long periods of time. For this purpose, Proba-3 mission is dedicated to the demonstration of precise formation flying activities.[2] It 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 is also supported by ESA's Science Programme as an opportunity mission through cooperation to the Science Operations.

Proba-3 is a mission not only intended in demonstrating formation flying capabilities, but also with a scientific objective. The FF activities done range from adjusting of both the inter-satellite distance, as well as the SC pointing

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(individually, and as a whole), to executing evasive and collision avoidance manoeuvres. However, the system is designed so that it is also possible to perform measurements of the Sun corona: the occulter SC will be placed in between the Sun and and the coronograph instrument in the companion, so that pictures of the Sun corona can be taken with Sun occultation factors tighter than ever before.

The space segment of the mission consists of the Coronagraph Spacecraft (CSC) which houses the coronagraph instrument and the corresponding Occulter Spacecraft (OSC) which includes the occulting disk. OSC wet mass is about 250 kg, with a size of about 1.4 m x 1.1 m x 1.2 m. The OSC 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 formation control actuation using cold gas milli-Newton thrusters.

The CSC is designed to point its coronagraph instrument towards the Sun on a continuous basis. CSC wet mass is about 300 kg with a size of about 1 m x 1.5 m x 1.2 m. The solar panel layout is designed to be, when deployed, outside the penumbra created by the other satellite in coronagraph operations. During launch, the deployable solar panel is stowed against the rigid support structure.The CSC is responsible for performing the main orbital maintenance manoeuvres with mono-propellant thrusters.

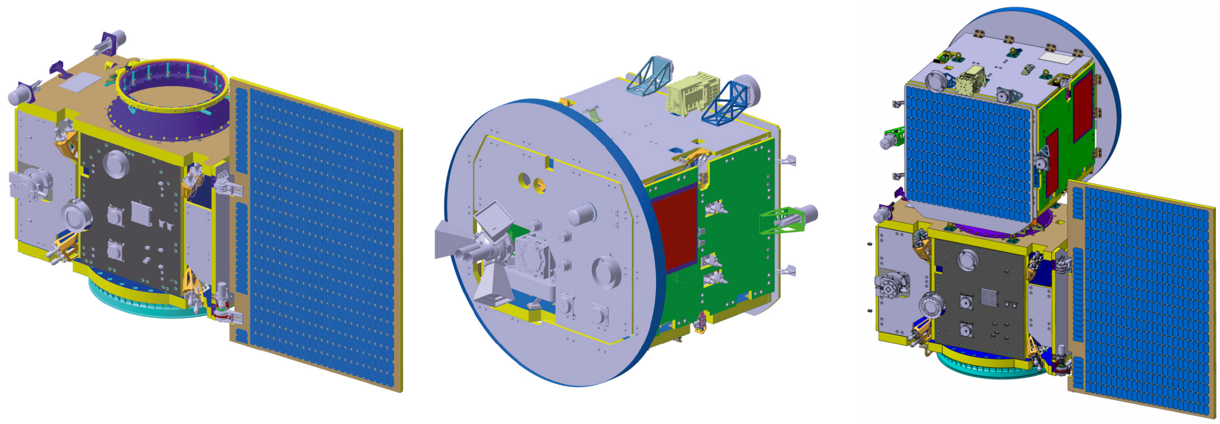

Figure 1: External view of the Coronagraph spacecraft (CSC, left), the Occulter spacecraft (OSC, center), and both SC in STACK configuration (right)

In formation flying missions, the activities have to be done not only by one spacecraft, but by a system formed of two (or more) different vehicles in continuous communication with each other. In case of Proba-3, this inter-satellite link, is performed by a radio-frequency system, used to "close the loop" and allow operations using information from the companion in real time. All this has to be done in a fully autonomous manner, without any ground support or surveillance for 8 days. For this, the OSC takes the role of "master", managing and commanding all the operations to be done by itself and the coronagraph ("slave"). When in non-operational configurations however, both spacecraft must be capable of surviving without its companion, while allowing ground control to configure and manage them individually.

This imposes the development of a complex on-board functional logic in order to obtain a consistent and robust mission strategy. Three different software entities running at different frequencies are working in cooperation, each one in charge of different aspects: "Platform" software, focused on the management of the units, failure recoveries and mission level needs; a "Formation Flying GNC" software, in charge of the formation flying activities (including impulsive and continuous manoeuvres); and a "Spacecraft GNC" software, taking care of the standalone aspects of the spacecraft (absolute attitude and position). Each one of them can be independently configured, potentially allowing more than 1000 different combinations. In order to design, develop and verify such a complex system and to ensure the correct interaction amongst all the entities, state machines based simulators, as well as a Functional Engineering Simulator and a Software-based Test Bench are developed.

The present paper lists, as per Proba-3 development experience, the most relevant aspects that have to be considered when defining a formation flying mission. Besides, the way the Proba-3 most remarkable challenges in the functional design have been solved is presented, together with the means developed for checking the consistency of the proposed solutions.

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2. Formation Flying Challenges and Needs

The Proba-3 development has served to identify a series of needs and challenges that every mission should meet and overcome in order to be capable of executing formation flying manoeuvres in space during large periods of time. These aspects have to be considered on top of the nominal space mission's requirements so that the final system is capable of successfully executing the desired activities.

The identified elements do not only affect to the mission requirements definition, but also guide the design process, put constraints to the solutions, and can enforce the selection of certain technologies.

2.1 Formation Flying Missions Needs

The most relevant **needs** that should be considered for the design of a system capable of performing formation flying activities are here enumerated:

- **Performances**: Two SC can be considered to be creating a "virtual rigid structure" if their dynamics are coupled in a very accurate way. Due to this, the performances imposed to the SC relative position and attitude are one of the main drivers for the definition of a formation flying mission. In particular, different performance requirements may have to be considered depending on the conditions at which the SC are put. Proba-3 main performance requirements are shown in Table 1.

Table 1: Proba-3 Pointing and Positioning Requirements

	Requirement	Value
Absolute Attitude	Pointing	7.1 arc-sec
	Pointing stability (10s)	2.6 arc-sec
Relative displacement error	@ 40 m distance	2.2 mm
	@ 150 m distance	4.9 mm
	@ 250 m distance	8.1 mm
	Relative velocity error	0.15 mm/s

- **Coupled dynamics**: Due the stringent performance requirements, a control capable of simultaneously managing position and attitude is needed. This increases the complexity of the AOCS and GNC on-board.
- **Flexibility**: Formation flying activities should not be limited to placing the SC in a specific relative state. The distance between satellites, the relative and absolute orientations, etc. should be adjustable. Hence, the system definition needs to be as flexible as possible to provide this capability.
- **Low Disturbances**: Even though it is not a need but a desirable feature, spacecraft are much easier to control in regions with reduced disturbances. Beside this, a slow evolution of the formation relative state would be desirable, as well as the existence of these conditions during large operation times. For this, the SC have to be placed in orbits such that the SC dynamics are slow and the disturbances are minimised (e.g. orbits around L2 points).

  Considering this need, Proba-3 spacecraft are placed in a Highly Elliptical Orbit (HEO, see Table 2 for the desired orbit characteristics after launch). These type of orbits are the simplest and cheapest orbits (considering the launcher capabilities) providing a low disturbance environment during large periods of time. However, operating in them introduce some extra challenges that have to be overcome, as explained in section 2.2.
- **Cooperation**: In order to enable formation flying activities, the vehicles need to be capable of cooperating one with each other. Non-cooperative operations in which one vehicle reacts to the activities done by other are also possible, but increase the complexity of the system.
- **Communication**: Communication between actors is required to fulfil the cooperation need described above. This is not only for sharing information, but also for allowing one of the vehicles issuing the requests, while the other(s) is only following the received instructions. This can be also used to detect failures on board if communication with the companion is lost.

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Table 2: Proba-3 Orbit Parameters (launch conditions)

Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Semi-major axis	36942.96 km
Eccentricity	0.8111
Inclination	59 deg
RAAN	153.8 deg
AoP	188 deg
Orbital Period	19h 38 min

- **Synchronisation**: If two or more spacecraft are executing activities in a cooperative manner, it is important that they are synchronised so that their operations are executed in an predictable way. Having entities operating independently from others always increases the complexity of the problem. Moreover, having two systems independently changing their dynamic states can lead to coupling in the actuations, resulting in the generation of undesired feedbacks which a divergent evolution.[3]
  Besides, the activities have to occur following an order. Therefore, both SC have to share a common time base so that the activities that are planned for the future happen following the correct sequence.

- **Actuation**: In order to maintain the desired relative state, continuous adjustment of the SC state is needed. Therefore, the system has to be designed so that continuous actuations are possible. This is something typically done for the attitude of space systems, but continuous orbital corrections are not so usual. Besides, given the stringent performances required for the formation flying activities, all the actuations have to be calculated on-board and on-line (i.e. "live"). This is an approach completely different from the typical one, where the orbital correction manoeuvres are computed on ground, validated and afterwards uploaded to the SC.

- **Relative State Awareness**: When operating with other entities, it is relevant to keep track of the relative state between vehicles. For this, the provision of specific metrologies has to be considered. Different levels of accuracies could be advisable depending on the specific formation flying activities and needs.

  For Proba-3, beside the AOCS, specific metrology technologies have been developed in order to meet the mission requirements:

  – Vision Based System: A system composed of two cameras capable of identifying the SC features and beacons at different ranges, capable of providing information about relative position and attitude.
  – Fine Lateral and Longitudinal System: A very sensitive laser ranging instrument capable of providing information about the distance and relative position of a the companion.
  – Inter Satellite ranging: Using the RF technology that enables the communications between SC, this unit provides and estimation of the distance between them computing the signal travel time.
  – Relative GPS: Precise relative positioning systems as used on ground have been developed in order to allow their real-time execution on the on-board computer.

- **Autonomy**: Due to the need of continuous actuation, it is not possible to have ground in control of the SC: transmission and computation latencies as well as the accuracy needed do not allow to have ground calculating the SC orbital correction manoeuvres for formation flying periods. Autonomous on-board operations are therefore needed.

  Beside this, Proba-3 has the extra requirement of being capable of actuating for one week without ground contact, which further increases the complexity of the operations.

- **Controllability**: Even though the system has to operate in an autonomous manner, the possibility of having ground controlling the SC has to be always granted. This is to allow the execution of several activities such as commissioning or recoveries from a SAFE configuration.

- **Distributed actuations**: In case a failure occurs, both SC have to be capable of detecting this situation and executing the required actions to ensure the safety and survival of the mission. Therefore, all the actors may need to be capable of performing decisions and actuations.

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2.2 Formation Flying Missions Challenges

Besides the previously presented needs, during the development of Proba-3, some aspects have been identified as the main drivers and **challenges** that need to be overcome for formation flying missions. As can be seen, some of the previously mentioned needs are also challenges due the impact they have on the system:

- **Two (or more) satellites**: The complexity of a system composed of two space vehicles is not double the nominal, but much higher. Interfaces, number of units, coupled dynamics, relative states... make the system much more complex than when considering one vehicle design, implementation and operations.

  Beside this in Proba-3, the existence of 3 vehicles have to be considered in the design: the STACK for LEOP conditions, and after the separation, CSC and OSC. The presence of a STACK configuration is not a typical way of proceeding, but reduces the cost and complexity of the mision deployment.

- **Performances requirements**: The more stringent the requirements, the most challenging the operations are. Given that one of the needs of formation flying activities is being capable of operating the SC with high accuracies (see Table 1), this is an inherent challenge for this type of missions.

- **Special Orbit**: Due the need of low disturbances, special orbits may be needed. In particular, if elliptical orbits are selected, the different parts of the orbital period will have different conditions, not only dynamically, but environmentally (e.g. varying radiation levels), which increases the complexity of the mission.

- **Activities per orbit**: Executing formation flying activities means that there is at least a region of the orbit in which continuous operations and orbital corrections manoeuvres are needed. However, other parts of the orbit could be less active. This means that a lot of different activities and processes need to be foreseen for every rotation.

- **Autonomy**: Besides being a need for formation flying capable systems, the provision of a sufficiently autonomous system may be itself a challenge as well as a need. Autonomous systems have the benefit of not having an operator in the loop, but increase the complexity of the on board logic. Since the system has to be capable of managing everything without requiring any external intervention, all the potential activities, transitions, and contingencies need to be identified a priori for the definition of an on-board system capable of executing all the required activities.

- **Actuators design**: Typical orbit control systems (not considering the orbit raising ones) are designed considering that they will be used in for specific orbit correction activities, and not in a continuous manner. This means that the propulsion subsystems' design may have limitations or constraints (minimum impulse bit, maximum duty cycles, temperatures, etc.) not compatible with the continuous actuations required for formation flying activities.

- **Safety**: The operations of two spacecraft in close proximity encompasses a collision risk that has to be managed. For this, specific procedures and evasive manoeuvres need to be put in place.

- **Low Cost**: In general, reduced costs are always desirable. In particular, for formation flying missions, the benefit of having low cost systems is the possibility of replacing faulty units, or having a large amount of vehicles capable of operating in a cooperative way between each other, each one of them providing different capabilities.

- **Reduced Budgets (size, power)**: One of the main consequences of being low cost projects, is that the system budgets are limited as well. Operations and system designs have to consider the limited amount of mass, power generation and propellant that can be carried. Beside, the use of complex systems should be limited in order not to increase the complexity of the activities and minimise the failure occurrence probability.

- **Eclipses**: The shadows that can be projected by one of the SC onto the other is one of the aspects that could affect the design. Having another SC in close proximities could reduce the amount of Sun illumination received. Beside this, HEO orbits can suffer from different eclipse periods depending on the location of the shadow region with respect to the orbit shape (as illustrated in Figure 2). This affects both to the thermal and power generation subsystems.

All the previously mentioned elements do not only affect the mission definition, but also guide the way the operations and different phases of the mission have to be executed. Next, the way some of these needs and constraints have been overcome in Proba-3 is presented.

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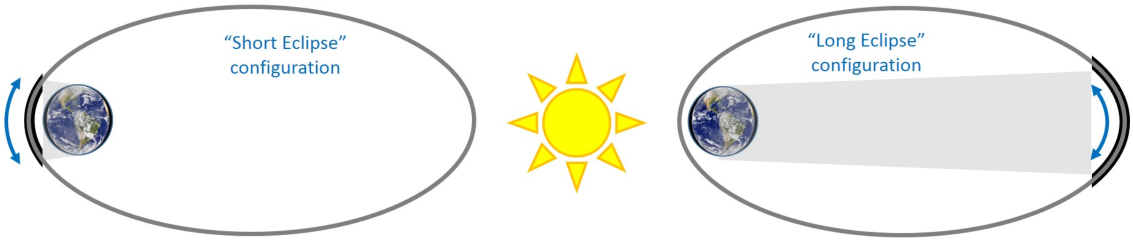

Figure 2: Different type of eclipses existing for high elliptically orbits

In case of Proba-3, the needs and challenges that have been found to be more relevant are the **performances**, imposing a specific **mission implementation** and affecting to the amount of activities that have to be executed, the need of ensuring the **safety** of the SC during all the operations, and the large **autonomy levels** imposed to the system.

The solutions adopted to overcome each one of these critical aspects are presented next.

3. Formation Flying Mission Implementation

The previously mentioned needs and challenges, in case of Proba-3, are translated into the definition of different **mission phases**. Given the complexity and different aspects that have to be considered, the mission is constructed following an incremental approach.

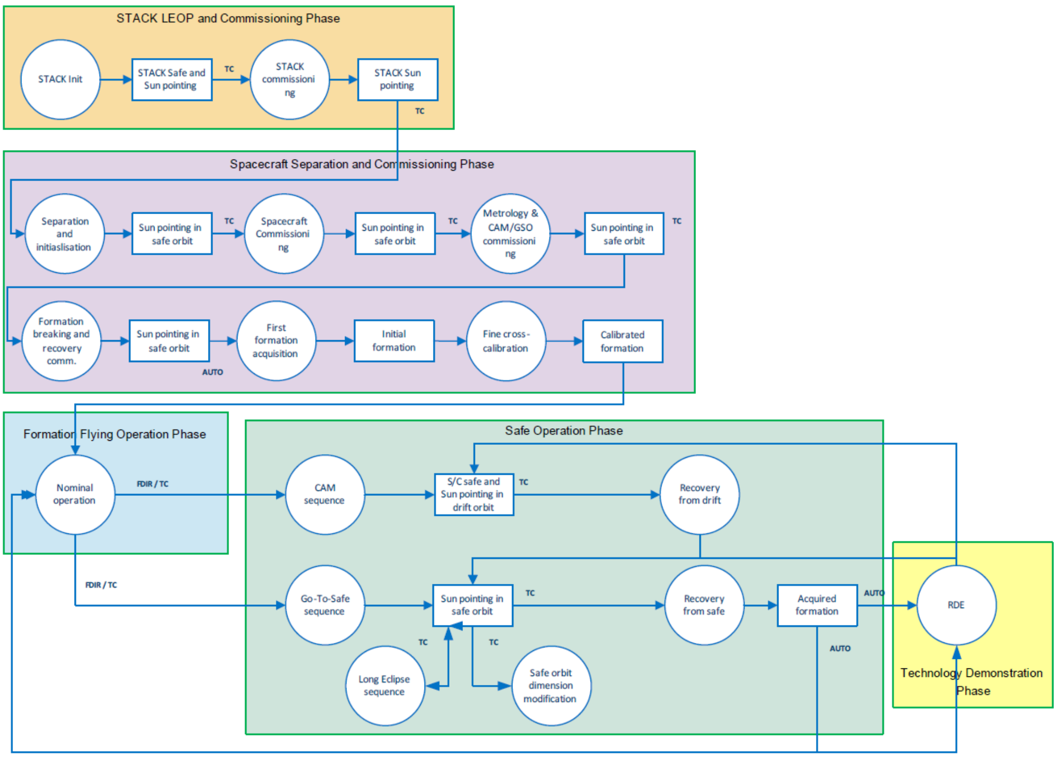

Figure 3: Phases of the Proba-3 mission

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 due to the different spacecraft operations, 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.

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The approach is then to build the space segment operation based on a hierarchy of three elements:

- **Mission Phases**: these are the high-level phases in which the mission is formally divided (see Table 4). For example, LEOP and Commissioning phase is separated from the operational phase. In this phase, it is also distinguished between nominal operational, where the minimum set of mission objectives need to be fulfilled, and the extended operational phase, which includes the possibility of executing further experiments.
- **Satellite phases**: during the mission the spacecraft goes through distinct phases in which the objective of the spacecraft varies as shown in Figure 3 (coloured boxes correspond to the satellite phases). It is totally different what is expected from a spacecraft in STACK (launch) configuration, from what is expected during commissioning or during nominal operation phase. These phases define the different states in which the mission can be at spacecraft level. Some of them are present only once, while others can be entered and exited several times.
- **Sequences**: these are lists of steps that shall be followed at space segment level to achieve a given goal. Sequences are contained within a spacecraft phase to guide the spacecraft through the different states and actions that allow to complete the required operations. The sequences can be executed either automatically by the SC, or through the direct commanding from ground.

More details about the relation existing between mission phases, satellite phases and sequences are provided in Table 4. This list of phases and sequences define how the complete mission is handled and executed either by the on-board software or/and by ground commanding.

Table 3: Proba-3 Mission phases, satellite phases and sequences

Mission Phase	**Satellite Phase**	**Sequence**
Launch and Early Operations Phase	STACK LEOP and Commissioning Phase	Init. sequence STACK after launcher
		STACK Commissioning sequence
Commissioning Phase	Spacecraft Separation and Commissioning Phase	Init. sequence after SC separation
		Spacecraft Commissioning sequence
		Metrology and CAM/GSO commissioning sequence
		Formation breaking and recovery commissioning sequence
		First acquisition sequence
		Fine cross-calibration sequence
Operational Phase and Extended Operational Phase	Formation Flying Operation Phase	Nominal coronagraphy sequence
		Nominal FF manoeuvres sequence
	Safe Operation Phase	CAM sequence
		Go to Safe sequence
		Long eclipse sequence
		Recovery from drift sequence
		Recovery from safe sequence
Extended Operational Phase	Technology Demonstration Phase (experiments)	RDE sequence
Post-Operational Phase	De-orbiting Phase	Passivation and de-orbiting sequence

One peculiarity of the Proba-3 mission is the fact that the orbit in which the different mission phases are executed needs to be also considered. However, it is not the absolute orbit the one that is relevant for the mission, but the trajectories that the SC fly one around the other. The so called "relative orbits". The main trajectory around the Earth will be maintained (or slightly modified due the impulses generated for the formation flying), but the SC will need to change their relative orbits depending on the activities to be done.

Proba-3 SC are launched in a STACK configuration (see Figure 1), while after some commissioning activities, SC are separated. Once separated, the SC can be in different relative orbits and, depending on this, some activities will be possible or not. Therefore, when considering the execution of specific sequences, the relative orbit in which the SC are placed need to be considered as well. SC will perform all their activities modifying their relative orbits, and not affecting to the main orbit around Earth.

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This means that both satellite phases and type of relative orbits are linked: in case the spacecraft has to stop executing certain activity and has to change to a different phase, relative orbit management will be required as well. These transitions may need to occur autonomously (e.g. in case of failure or unexpected dynamical situations, the SC may need to autonomously decide go stop the formation flying operations and change to a safe phase) or manually (e.g. when coming from safe operation phase to formation flying operation phase, the manoeuvres will be provided by ground).

In particular, three type of relative orbital configurations are defined for Proba-3:

- **Drifting orbits**: This is the orbit entered after STACK separation or if an evasive manoeuvre is performed. When in this type or orbital configuration, SC drift apart one from each other. Specific stop manoeuvres are needed in order not to lose the mission.
- **Safe orbits**: These orbits are used to "park" the vehicles when a failure has occurred. They keep the SC in a situation in which they do not drift apart, but the collision risk is fully avoided for a specific amount of time (30 days) while the corresponding recovery activities are performed. These are also used for periods in which the nominal operations cannot be continued (e.g. during Long Eclipses seasons). Figure 4 illustrates the path followed by one of the SC around the companion when in this type of relative orbit.
- **Nominal orbits**: These is the orbital configuration that allows the execution of formation flying activities.

When the SC are in orbits different from the nominal, the execution of formation flying activities is not possible due the difference in the dynamic evolution. Nonetheless, some activities can be performed to calibrate the instrument. All the commissioning of the relative meteorologies and payloads take place in SAFE orbits specifically adjusted for this purpose.

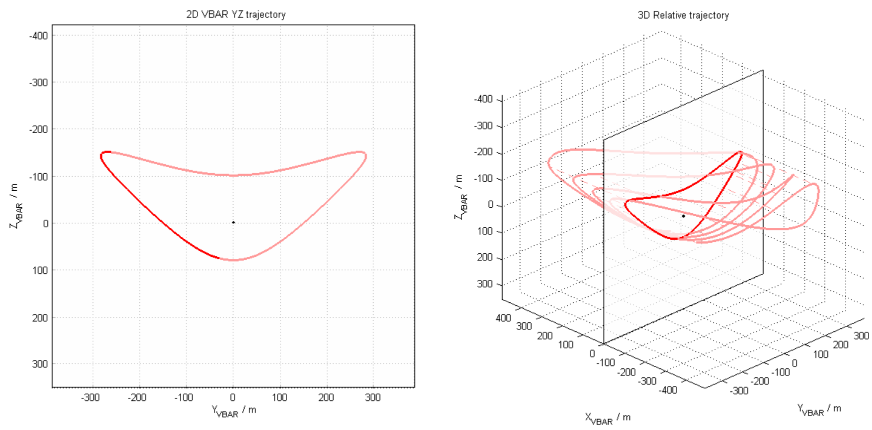

Figure 4: Shape of the relative trajectory described when SC are in Proba-3's Safe orbit (by courtesy of GMV)

4. Solving the Safety Challenge

Beside defining different type of orbits for the different mission and spacecraft phases, it may be necessary to also split the orbits in different regions or phases in order to guarantee the safety of the spacecraft.

In order to perform formation flying manoeuvres, the SC need to have the possibility of accurately controlling their position and orbit without effort. For this, they actuation capability needs to be such that they can overcome the trajectory imposed by the orbital dynamics, to adjust their relative position to the desired one. Depending on the orbit, the activity to be done, and the position inside it, this is not always possible.

4.1 Safety in nominal orbits

Due the shape of HEO orbits, the perigee arc would be much more demanding in terms of force needs if relative position were to be controlled with high accuracy. As a result, the Proba-3 formation flying activities are restricted to a

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region close to the apogee in which the low disturbance requirement is met.

For the rest of the mission, SC are left flying free in a collision risk-free relative trajectory. This means that the SC have to execute two point transfer manoeuvres in every nominal orbit, so that their trajectories are separated not to collide during the perigee arc. This forces to split the orbits in regions, where different activities take place.

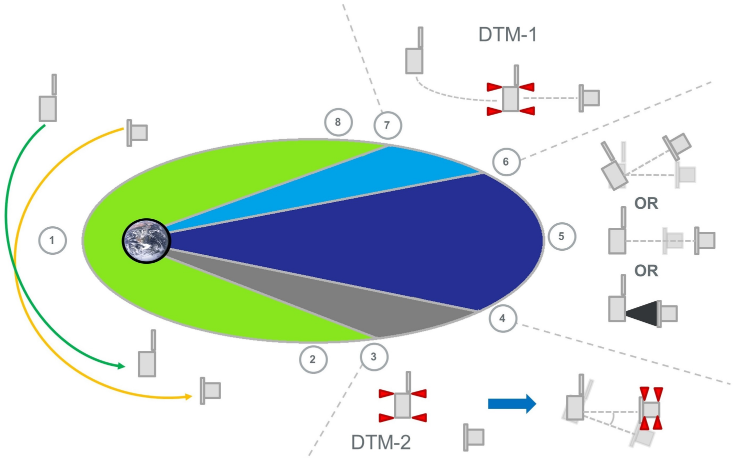

Figure 5: Activities that have to be performed every Operational orbit of the Proba-3 mission

This safety requirement, is introducing a remarkable amount of activities that have to be executed every orbit. Even though, these are activities required to avoid the SC producing a collision, in case a collision risk is identified, or a specific sequence (such as formation or metrology re-acquisition) fails, the possibility of executing contingency manoeuvres is always possible. The execution of these manoeuvres has to be possible, and also affects to the amount of activities that have to be executed on-board as explained in 4.3.

In particular, as shown in Figure 5, the Proba-3 nominal orbit configuration is split phases. The next steps are performed on each one of these phases:

Table 4: List of different manoeuvres and activities performed by Proba-3 satellites during one nominal orbit

Event	True Anomaly	Activity	Remarks
1	0 deg	Perigee Pass	Sc flying free in Sun pointing attitude
2	161 deg	CSC rolls 180 deg	SC acquire the required attitude
3	163 deg	Formation acquisition	Second impulse of the TPT
4	169 deg	Apogee activity start	Depending on the orbit, formation flying activities are executed here onwards
5	180 deg	Apogee	-
6	190 deg	Apogee activity end	End of the formation flying activities
7	196 deg	Perigee pass preparation	Second impulse of the TPT
8	198 deg	CSC rolls 180 deg	SC are put "upside-down". Afterwards, SC are left flying free

Note that in the table above, events 2 and 8 correspond to activities that are not directly linked with the safety of the mission, but are required to guarantee a good behaviour of the system. Due the non-symmetrical shape of the CSC (see Figure 1), a considerable amount of angular momentum is stored in the attitude control system due the Solar Radiation Pressure. In order to diminish this, both SC are rotated "upside-down" twice every orbit: one before and one after apogee arc. Beside, one reaction wheel de-saturation activity is done once per orbit, before the beginning of the formation flying activities, in order to ensure that the system is left at the ideal conditions.

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4.2 Safety in non-nominal orbits

When the SC are placed in non-nominal orbits, some activities have to be also performed to ensure the survival of the SC. The activities done will not be as much as when in nominal orbits, since the SC are following safe relative trajectories, but angular momentum maintenance activities are still required. Due to this, both "roll flips" and reaction wheel de-saturations are happening as well in a planned manner.

Besides, periodic orbital adjustment manoeuvres could be required in order to correct deviations and to still ensure that the SC relative trajectories are safe. All this illustrates that the safe configuration of Proba-3 mission is not as in others in which the SC is put to a minimum consumption status, pointing to the Sun and left flying uncontrolled, but that specific activities are still required.

4.3 Transitions from nominal to non-nominal orbits

Other aspect relevant for the safety of the system, is the execution of the relative orbit changes. These changes are performed either to take the system to a safe configuration (from nominal orbit to safe or drifting orbit), or to recover the system and continue nominal operations.

It is particularly important the amount of activities that have to be done when a SC fails. In this situation, it is no longer possible to guarantee the safety of the configuration, since one of the SC is no longer capable of performing the required orbital corrections. Therefore, both the healthy and safe SC have to perform a series of activities:

1. SC failed enters safe configuration:
    - De-activates systems, enters a low consumption configuration and points to Sun using robust sensors
2. Healthy SC detects that companion has failed
3. Healthy SC computes on-board and autonomously, the evasive manoeuvre to be launched
4. Healthy SC checks the safety of the trajectory computed. If not safe, a different one is used.
5. Healthy SC executes the relative orbit correction manoeuvre deemed safe enough
    - Depending on the conditions and criticality of the failure, a safe or drifting orbit will be entered
    - If a drifting orbit is entered, the drift has to be stop afterwards (by ground).
6. Point the SC to Sun and enter a configuration in which it waits ground to take control of the system to recover the functionalities failed.

All the previous steps have to be performed autonomously. This illustrates the complexity imposed by the safety needs, and illustrates one of the reason why both SC have to be equipped with propulsion subsystems: so that both of them are capable of executing orbit correction manoeuvres, required for safety and contingency purposes.

5. Solving the Autonomy Need

As introduced, autonomy is one of the needs associated with formation flying missions. Due the performances required, it is not possible to control the SC from ground in a dynamic way. Therefore, all the activities done in orbit have to be computed and executed on-board with no ground control contact. This includes not only the formation flying activities done in operational orbit, but the formation re-acquisition, two point transfer manoeuvre calculation, and all the collision avoidance manoeuvres in case needed.

This level of autonomy, in the case of Proba-3, is even increased, since the mission has to be capable of performing its activities for periods without any type of ground contact lasting up to 8 days. This is for the nominal part of the mission. For other phases, ground will be in charge of the execution of the manoeuvres (e.g. return from safe orbit sequences).

In order to solve this need, and considering the different actors, the mission autonomy is divided in two parts: the mission related autonomy and the orbit related autonomy.

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5.1 Autonomy of mission activities

In Proba-3, different levels of autonomy are foreseen depending on the mission phase. At the beginning of the mission, most of the activities will be controlled and executed by ground. However, when the Operational Phase is reached, the control of the system will be fully passed to the on-board resources.

Three different levels of autonomy are identified, which are associated to specific SC modes as shown in Figure 6:

- **SAFE mode**: In this mode, the SC is configured to a minimum consumption survival state. Only the mandatory resources are used, while the formation flying activities are stopped. This mode is the first one entered upon SC activation, or after the occurrence of a failure, and it is used to ensure the survival of the SC. Only the survival related autonomous activities are executed.
- **MANUAL mode**: This is an intermediate mode, in which the SC is capable of performing certain autonomous activities (such as angular momentum management), but control is mainly from ground. This mode is used when the SC is not faulty, but needs to perform certain activities (e.g. commissioning), or when it is waiting for the companion to recover from a failure.
- **OPERATIONAL mode**: In this mode the SC is configured so that it performs all the activities required for the nominal mission. It is typically linked to the nominal orbit, and depending on the SC role (master or slave), will configure the SC either to command requests or to follow the instructions provided by a companion.

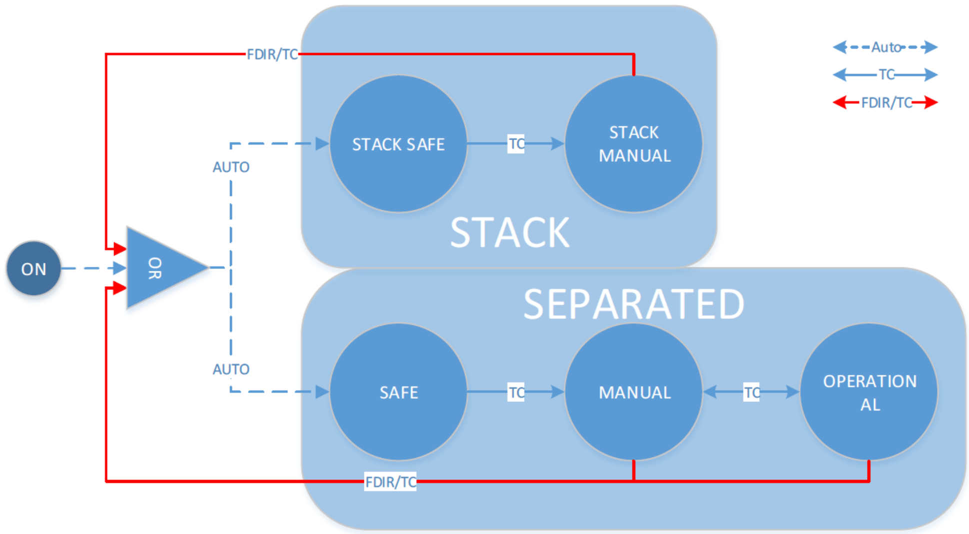

Figure 6: SC modes defined for Proba-3. Different modes exist depending on the SC being in STACK or separated

Each one of these modes has its own characteristics and requirements, and will be used depending on the phase of the mission. Note that the modes are defined for each SC individually. This means that every SC can be at a different mode even though the mission is at a specific phase. This is specially relevant for the failure recovery, where one SC can be at SAFE mode, while the other is in MANUAL.

Even though each SC can be at a different mode, not all the combinations are allowed: having one SC in OPERATIONAL mode, executing all the nominal activities, while the other is in SAFE due to a failure is not safe. Therefore if one SC performs a SC mode change, the companion would need to perform the corresponding change, either autonomously if safety is endangered, either requested from ground as for for the recoveries of nominal configurations.

This allocation allows both direct ground commanding and autonomous actuations. However, when the system is at the fully autonomous configuration (OPERATIONAL mode), it shall be capable of continuing its operations with reduced amount of ground contacts (for Proba-3, weekly contacts are foreseen). For this, the concept of Mission TimeLine (MTL) is defined.

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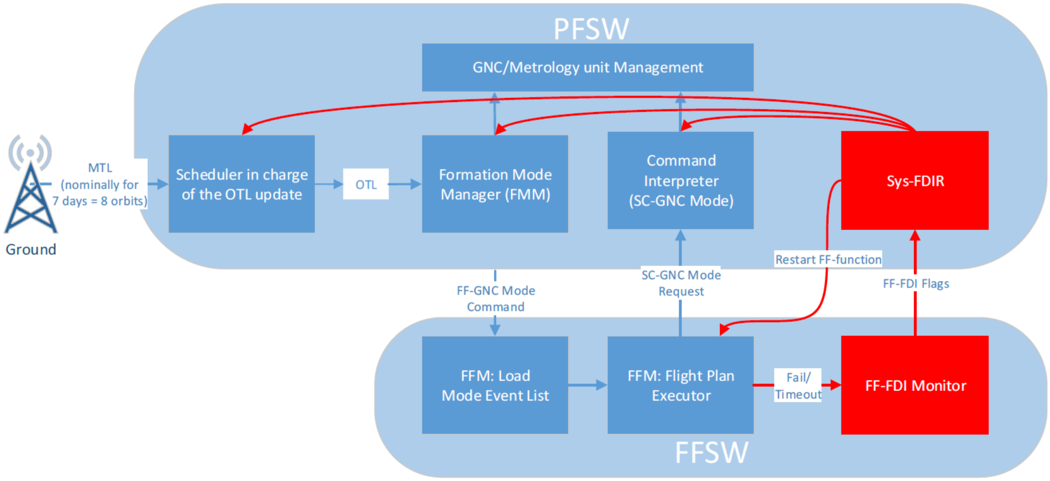

Figure 7: Mission Time line approach

Ground will provide to the SC a list of activities to be executed in the next 7 days. This information is managed by a specific module of the Platform Software, in charge of decoding and configuring the system in such a way that the corresponding activities are executed. The Mission TimeLine is split in several Orbit TimeLines (OTL), which are provided to the Formation Mode Manager every perigee. In case ground contacts are not possible, a default OTL will be issued in order to continue the nominal operations as much as possible.

5.2 Autonomy of orbital activities

Once a specific Orbit TimeLine is provided, the Formation Mode Manager is in charge of requesting the different activities to be executed inside that specific orbit. The activities are collected inside Formation Flying Modes. Each one of the FF mode defines a "Flight Plan" or list of steps that configure the system (local and companion SC) so that the different activities are executed. All the activities shown in Figure 5 are defined as sequences of activities inside specific flight plans. With this, through the definition of different Flight Plans, all the activities inside one orbit can be allocated.

For example, the FF mode in charge of preparing the formation for Apogee activities ("apogee preparation mode") executes the next activities:

1. Corrects the roll of the SC (for solar radiation pressure accumulation reduction).
2. Using propagated relative navigation information, points the SC one to each other to acquire relative metrology while ensuring some panels are not illuminated.
3. After update of the relative state, computes the orbit correction manoeuvre (if needed).
4. Executes the orbit correction manoeuvres.
5. Points the SC one to each other again to evaluate the new dynamic state (also, not illuminating some panels).
6. Adjusts the SC pointing to leave them in a condition such that the formation acquisition manoeuvres can begin.

At every perigee, a new OTL is received by the FMM. Based on this information, the corresponding FF-GNC modes are loaded when required. This configures the system, not only considering the activities to be done during the apogee arc, but also during the rest of the orbit. Figure 8 shows the FMM logic executed depending on the received OTL.

Note that this is the way the contingency activities (at orbital level) are executed as well. If the System FDIR detects a failure that requires some kind of orbital correction (e.g. collision risk, companion SC not responding, etc.), it will either re-start the FF modes, or will directly request a specific contingency FF mode so that the SC executes and evasive manoeuvre. This has to be executed in a coordinated manner so that only one SC executes the contingency activities, which is achieved thanks to the existence of a data link between SC: if one of them reports a failure or stops communicating, the System FDIR can take the corresponding decisions (as proposed in the communication need in section 2.1).

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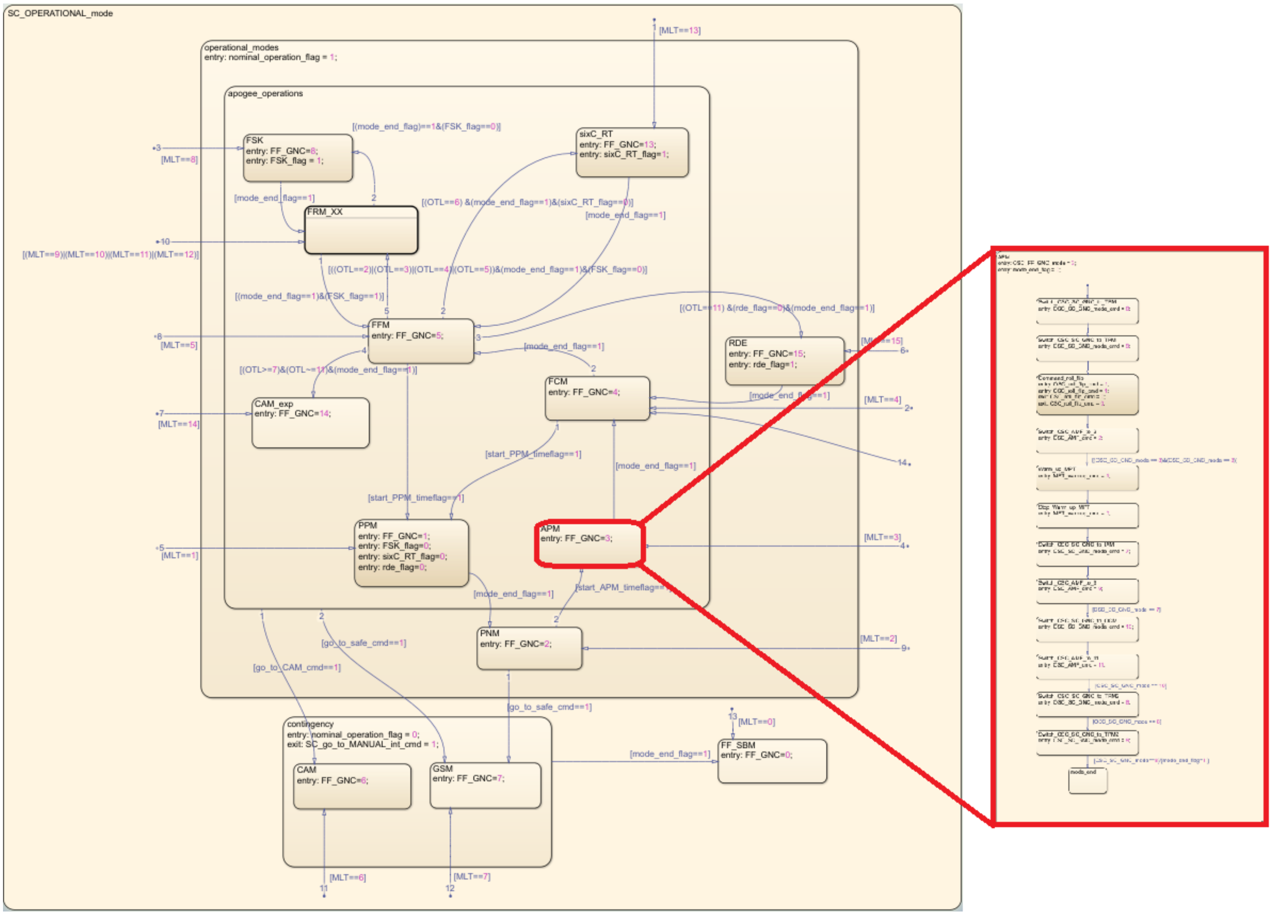

Figure 8: Example of the transition logic for the different FF-GNC modes when in OPERATIONAL mode. Each one of the boxes correspond to a different FF-GNC mode and its associated flight plan

5.3 Autonomy of units management

When the system is completely autonomous, not only the orbital activities have to be managed, but also the rest of resources on board: units, subsystems, metrologies... For this, specific procedures need to be put in place.

Beside the clear distinction between actuators and sensors, management of the different entities is organised depending on how they are used. Those units which are required for the activities done by the SC as a "standalone" entity (e.g. attitude determination, Sun direction computation, etc.) are activated whenever the functionality using them is activated. However, those more "specialised" units such as the metrologies, follow a different activation approach.

Metrologies are power consuming units used in very specific regions of the orbit. Therefore, it is not required to have them activated for long periods of time. Beside this, due the stringent accuracy imposed to them, they typically require a "settling time" so that the thermal environment is adjusted to the calibrated conditions and they can provide maximum performances. Therefore, they cannot be activated "just before" they are required. Since they need to be prepared in advance, these units will be activated based on the future activities that will be executed.

For this, the PFSW is in charge of preparing and configuring the units as in needed, depending on the active value of the the OTL associated to the current orbit. This results in having certain units that will be managed depending on the active functionalities on-board, while others will be completely de-coupled, managed based on position inside the orbit as reflected in Table 5.

For the actuators, a similar procedure is considered: those actuators that do not require any preparation activity are armed upon mode requests, while others will be activated based on direct requests depending on the activities that are expected to be done.

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Table 5: Units on Proba-3 and associated activation and de-activation mechanism

Unit	Type	Activation	De-activation
Sun Sensor	Sensor	SC mode	SC mode
Star Tracker	Sensor	SC-GNC mode	SC-GNC mode
Rate sensors	Sensor	SC-GNC mode	SC-GNC mode
Inter Satellite Link	Metrology	SC mode	SC mode
GPS	Metrology	Altitude	Altitude
Vision Based System	Metrology	Time before apogee	Time after apogee
Fine Lateral and Longitudinal System	Metrology	Time before apogee	Time after apogee
Shadow Position Sensor	Metrology	OTL + Time	Time
Reaction wheels	Actuator	SC mode	-
Mono-propellant thrusters	Actuator	Direct request	SC mode
Cold Gas thrusters	Actuator	FF-GNC mode	FF-GNC mode

5.4 Onboard logic testing

Due the complexity and the number of actors implicated in the Proba-3 operations, the logic management all the system has to be defined and explained in a clear, consistent and unique way so that all the actors involved in the project development have the same source of information.

For this purpose, in order to define a the mission management logic in a clear and straightforward way, a specific set of documents has been generated in the frame of Proba-3 project. These documents constitute what it is known as the "Mission Folder", in which the mission logic, restrictions, sequences, associated constraints and procedures are defined. These documents constitute the basis for understanding the activities that are executed on board, and are used to derive the use cases containing logic to be implemented on-board.

All these logics and restrictions are tested using a tool specifically created in Matlab® STATEFLOW. This System State Simulation Tool (S^3T, see Figure 9) allows to check whether the transitions, sequences and information flow envisioned in the Mission Folder is correct before actually deriving the corresponding on-board software use cases.

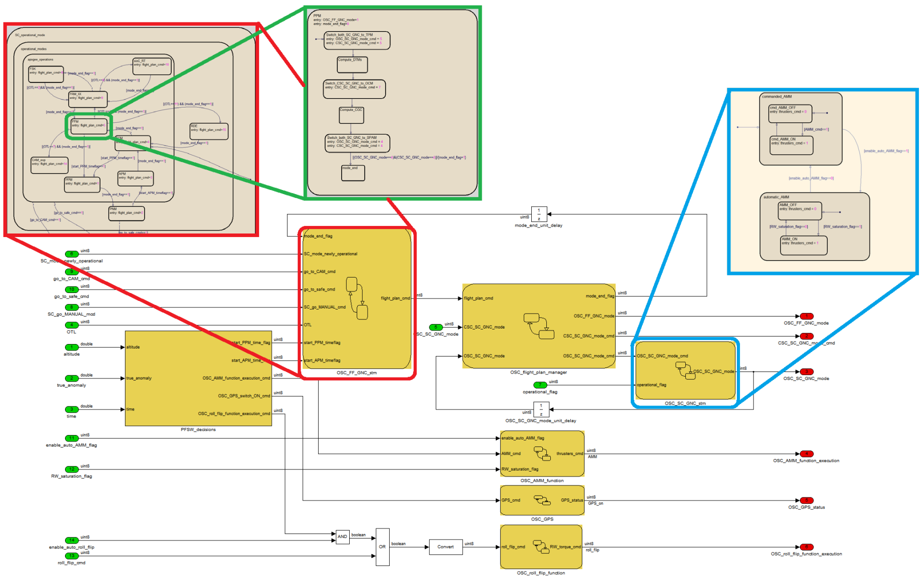

Figure 9: System State Simulation Tool, S^3T

This S^3T tool is a simulator whose intention is to implement and test the different state machines that are required for the mission control. This simulator is used to check the correct behaviour and coupling of the different logics defined,

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and it is different to the typical AOCS verification dynamics simulators, focused on the verification of the performances requirements.

6. Conclusions

The development of formation flying missions in space presents a good opportunity to further enhance the possibilities of space systems. However, they present specific challenges that have to be tackled in the preliminary phases of the mission definition. Probably the most remarkable challenges are the need of executing several different activities with two spacecraft cooperating, as well as the autonomy required for this while fulfilling the safety requirements. This forces to define specific mission procedures, as well as to have a very tunable and modular software and GNC, capable of encompassing all the activities that have to be performed.

In Proba-3, these has been achieved through the definition of different elements with different autonomy, each one in charge of managing different aspects of the mission. This modularity, even though provides a large flexibility when considering the execution of different activities, increases the complexity of the system, since increases the number of combinations that can exist. Therefore, specific procedures and logics need to be put in place for the on-board logic definition and testing.

The Proba-3 project is settling the basis for the development of future sub-millimetre formation flying missions, and the solutions here presented should serve as a reference for the identification of those aspects potentially affecting to the mission scenario, as well as for the selection of the most suitable design solutions.

7. Acknowledgments

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References

[1] Luis Peñin, José Ibarz, Yann Scoarnec, Victor Marco, Diego Rodríguez, Agnes Mestreau-Garreau, Damien Galano, and Karim Mellab. Proba-3 mission: Creating an artificial solar eclipse every day by spacecraft flying in formation. October 2018.

[2] Luis F. Peñin, Damien Galano, Karim Mellab, Victor Marco Gomez, and Agnes Mestreau-Garreau. Engineering six-hour solar eclipses with formation flying. *Room, The Space Journal of Asgardia*, 18:72–77, February 2018.

[3] Joost Veenman, Daniel Serrano, Raúl Sánchez, Alex Cropp, Luigi Strippoli, and Rafael. Contreras. Formation flying control design for the proba-3 phase C/D. May 2017.