DOCUMENT

document title/ titre du document

PROBA-3 MISSION REQUIREMENTS DOCUMENT

prepared by/*préparé par*	PROBA 3 team
reference/*réference*	P3-EST-RS-1006
issue/*édition*	1
revision/*révision*	0
date of issue/*date d'édition*	17 September 2008
status/*état*	Issued
Document type/*type de document*	MRD

European Space Agency
Agence spatiale européenne

Distribution/*distribution*

APPROVAL

Title *Titre*	issue *issue*	1	revision *revision*	0

author *auteur*	date *date*	17 September 2008

approved by *approuvé par*	date *date*

CHANGE LOG

reason for change /*raison du changement*	issue/*issue*	revision/*revision*	date/*date*

CHANGE RECORD

Issue: 1 Revision: 0

reason for change/*raison du changement*	page(s)/*page(s)*	paragraph(s)/*paragraph(s)*

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1 INTRODUCTION

1.1 Scope

The scope of this document is to define the mission requirements for the PROBA 3 project and to provide guidelines for the implementation of the mission. This document addresses the background of the mission, the objectives of the mission, technology requirements and the mission elements.

Due to the technology demonstration nature of the project, there is not a single set of quantified driving mission requirements from which all subsequent requirements can be derived. Mission requirements have therefore been included as qualitative requirements and quantified requirements included directly in the System Requirement Document. This document includes also the Formation Flying performances currently required for the future XEUS mission to serve as objectives for the PROBA 3 mission.

1.2 Reference Documents

RD-1	"European Space Technology Harmonisation - Technical Dossier, Formation Flying RF Metrology", TEC-ETN/2007.64, Issue 1.2, 18 July 2008
RD-2	"Error Budgets for Formation Flying Missions", NPD/5022/TD/TR/001 v1.r1.m0, Issue 1.1, 03 March 2008
RD-3	XEUS CDF Final Report, August 2008
RD-4	"PROBA3 Autonomous Rendezvous Experiment Preliminary Definition", P3RVX-DME-COM-PRL02-R, Issue 1, 17 Sep 2008

1.3 Background

Formation Flying (FF) is the operational technique by which separate satellites maintain a desired geometry to achieve the function of a single large virtual spacecraft. FF exploits basic configurations: "rigid" long baseline instruments, synthetic aperture and separation of primary and secondary on a telescope. FF involves new Guidance, Navigation and Control (GNC) functions which allow each spacecraft to be controlled in attitude and position not only in absolute frames but also one in respect to each other. FF requires specific sensors for relative navigation, communication links and high accuracy control. It also requires high stability positioning of each spacecraft and the capability to re-orient in space the constructed geometry.

PROBA 3 is a Formation Flying technology demonstration mission to prepare for future operational FF missions. The mission will cover the design and development and in flight operation of a set of two small satellites, for the full-scale test and validation of Formation Flying (FF) mission architectures and techniques. Various schemes for Formation Flying Management

(FFM), how the set of spacecraft is overall managed, and Mission Vehicle Management (MVM), how is spacecraft is managed to fulfil the FF mission, will be covered.

The mission requirements include requirements coming from the planned XEUS mission, a formation-flying X-ray astronomy mission, and from the science payload, which will consist of a Sun coronagraph instrument distributed over two satellites (the Coronagraph detector and Occulter Disk). In addition, further platform resources will be given to experimental payloads, in order to test related experimental hardware and manoeuvres, such as the Rendezvous Experiment.

See RD-1, Chapter 3 for an overview of future formation-flying missions.

2 DEFINITIONS AND NOTATION

The following definitions assume the notation given in RD-2.

2.1 Formation Flying Definitions

The definition of **nominal formation conditions** is as follows: assuming two spacecraft, the origins of the body-fixed Payload reference coordinate frames (PLF) of each spacecraft are co-linear with some given inertial **target direction vector**, which may be varying in time. The line parallel to the target direction vector which passes through a chosen spacecraft PLF origin is defined as the **target line**. This chosen spacecraft is referred to as the formation centre spacecraft (**FCS**) – usually this satellite is the target or mirror spacecraft. In nominal formation conditions, the two spacecraft PLF reference coordinate frames both have the Z-axis parallel to the target line, and both spacecraft PLF reference coordinate frames are parallel with each other. The roll about the target line for both spacecraft is fixed to the same arbitrary inertial direction. The satellite which is not the FCS is defined as the formation second spacecraft (**F2S**) (see Figure 1). In nominal formation conditions, the distance between the PLF origins is defined as the **nominal ISD** (Inter-satellite distance).

For PROBA3, the Coronagraph instrument aperture is the origin of the Coronagraph satellite PLF reference coordinate frame, which has a +Z axis parallel with the instrument boresight. For the Occulter spacecraft, the PLF reference coordinate frame origin is the centre of the occulting disk, and the +Z axis of the reference frame is perpendicular to the plane of the disk. The Occulter spacecraft is the FCS, and the vector from the Occulter spacecraft reference frame origin to the centre of the Sun is defined as the target direction vector, which is also the +Z axis of the Sun Target reference coordinate frame (STF). Please note that the origin of the STF is also the origin of the Occulter (FCS) PLF reference coordinate frame, and that both spacecraft PLF frames should nominally be parallel to the STF (which also fixes the roll about the target line). The nominal ISD for the Coronagraph instrument and the PROBA3 mission will be 150 metres. For more information on PROBA3 reference coordinate frames, see the SRD.

For nominal formation conditions, the **lateral position error** is defined as the perpendicular distance from the F2S PLF origin to the target line. The **longitudinal position** is defined as the distance between the F2S PLF origin projected on the target line to the FCS PLF origin. The **longitudinal position error** is defined as the difference between the longitudinal position and the nominal ISD (see Figure 2). Please note that for some manoeuvres listed below, the target direction vector (and therefore the target line by definition) and/or the nominal ISD may be changing in time in a pre-defined manner. In addition, please note that the lateral and longitudinal position errors are system-level errors that include a number of different individual errors, such as thermal distortion, sensor measurement error, controller error, static biases, etc.

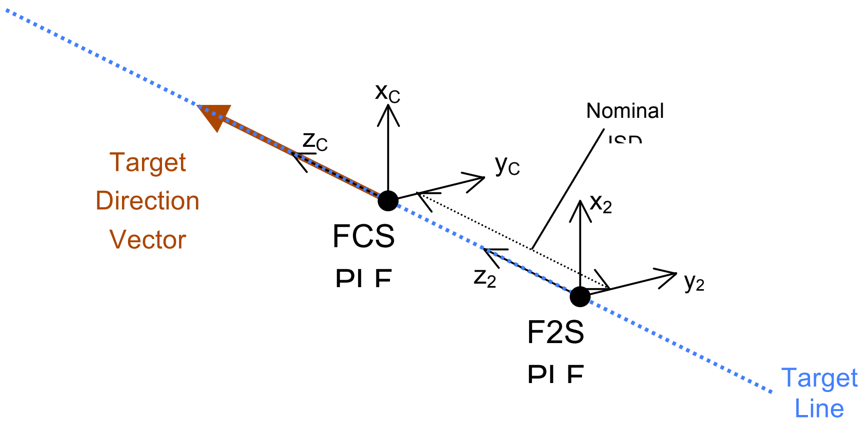

Figure 1: Nominal Formation Conditions

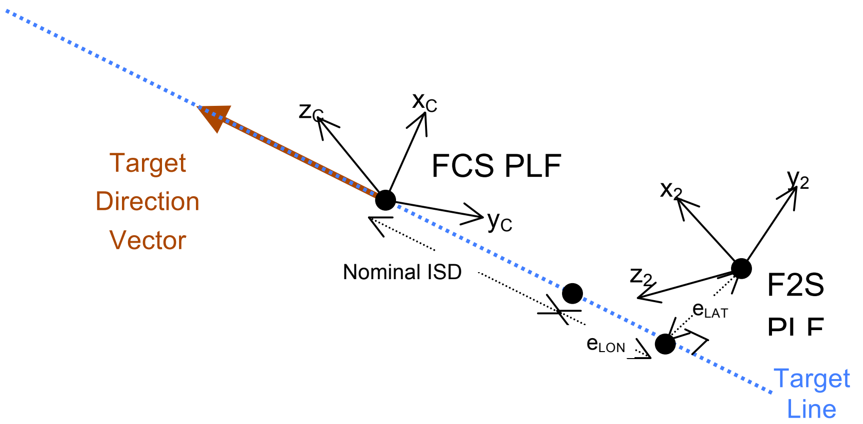

Figure 2: Nominal Formation Conditions, with Lateral and Longitudinal Errors Shown

In the following manoeuvre descriptions, it is assumed one spacecraft will contain the sensing elements of the high-accuracy metrology (HAM) subsystem, and this spacecraft will be designated **SC-A**. Please note that SC-A can be either FCS or F2S. The second spacecraft will be designated **SC-B**.

In manoeuvres designated as a **rigid formation manoeuvre**, the nominal attitude profile for each spacecraft will keep the two spacecraft PLF reference coordinate frames parallel, and the Z-axes of the two PLF reference frames will remain co-linear with the target direction vector. During these rigid formation manoeuvres, the intention is for both satellites to be in such a position as to enable the High-accuracy metrology system to continue operating throughout the manoeuvre. At least one, but possibly both spacecraft will be under active closed-loop positional control throughout these manoeuvres, such that both spacecraft PLF reference coordinate frame origins will be commanded to remain collinear with the target direction vector. These conditions will remain even as the target direction vector (and therefore target line) and nominal ISD may be changing in time in a pre-defined manner.

In manoeuvres designated as a **loose formation manoeuvre**, there are no requirements on the attitude or position during the manoeuvre, only at the start and end of the manoeuvre. This in turn relaxes any requirements for maintaining closed-loop control throughout the manoeuvre, such that metrology systems can lose sight of the other spacecraft for a period of time before reacquiring it. These manoeuvres are intended to reach the final position in a shorter period of time. However, even with these manoeuvres, satellite safety must be taken into account.

The possibility of an inter-satellite link (ISL) between the two spacecraft gives rise to the possibility of **distributed GNC data**, where one spacecraft has access to and makes use of the other spacecraft's real-time GNC data (with some delay due to the ISL latency). GNC data consists of sensor measurements, actuator measurements and possibly even processed data. **Local GNC data** is therefore GNC data produced only on-board. If the ISL is used to transmit control commands to the other spacecraft, the **formation control mode** is defined as **centralised**, while locally-generated control commands are **decentralised.** Hence, the methods of GNC data distribution and formation control mode gives rise to four possibilities: distributed data / centralised control, distributed data / decentralised control, local data / centralised control, local data / decentralised control. Only the last case (local/decentralised) does not explicitly require the use of an ISL for GNC purposes. As SC-A contains the sensing elements of HAM by definition, local data implies that SC-A must generate the control commands, and either execute them (decentralised) or transmit appropriate control commands to SC-B (centralised). Centralised control and distributed data implies that at least one spacecraft may control the other, and possibly both spacecraft may be able to control the other. Although it is feasible for full position, velocity, attitude and attitude rate control to be centralised, for the purpose of the PROBA 3 formation flying experiments it is assumed that centralised control will only refer to position and velocity control, while attitude control will remain decentralised, unless otherwise stated. All manoeuvres are assumed to be operated in a decentralised mode using distributed data unless otherwise stated. All centralised manoeuvre commands are assumed to be generated by SC-A and executed on SC-B unless otherwise stated.

The maximum achievable precision is defined as High-Precision Attitude and Pointing (**HPAP**), and will include requirements on knowledge and control in both position and attitude. The term Formation Station Keeping (**FST**) is used to refer to periods when the nominal ISD and the target direction vector are fixed in inertial space, and when the requirements for HPAP apply and are continuously met. FST is distinct from station keeping in general, which includes FST but also may be used in reference for other types of manoeuvres, for example rendezvous manoeuvres, and covers a wider set of definitions (not fully covered here).

When either the nominal ISD or the target direction vector (or both) are changing in time with respect to inertial space, and the manoeuvre is a rigid formation manoeuvre, the requirements for the maximum achievable precision are down-graded to the set defined as High-Precision during Motion (**HPM**). However, if the ISD and/or target direction vector is considered to be changing at a slow enough rate, the requirements for HPAP may still be applied, depending on the manoeuvre. For example, if the target direction vector is tracking an object such as the Sun whose apparent angle will only change on the order of arc-seconds over the period of the orbit, then HPAP can still be applied. Whether to apply HPAP or HPM (or indeed a separate set of requirements altogether, for example the specific Coronagraph Instrument requirements) will be stated in the individual manoeuvre definitions and requirements.

The term **evaporation** is defined to be any state (i.e. relative positions and velocities of the two spacecraft) from which it is impossible to recover the nominal formation conditions using less than a specified amount of the total initial mission delta-V, in less than a specified number of days. The amount of delta-V and the number of days shall be specified in the SRD. The term **collision** is defined to mean contact between the two spacecraft. The FDIR system will usually maintain a minimum separation between the two spacecraft, in order to avoid potential collisions. This minimum separation can change, depending on the manoeuvre or experiment.

The terms “target” and “chaser” are often used in rendezvous missions, where the chaser is actively pursuing the target spacecraft. For PROBA3, these terms must be used with caution, given that it is possible for either spacecraft to actively move, and either spacecraft can generate GNC commands for itself or the other. Therefore, for PROBA3, the term **chaser** refers to a spacecraft that is active in attempting relative translational motion, deliberately generating pure forces through the use of thrusters. The term **target**, when used in conjunction with the term chaser, refers to a spacecraft that is passive in relative translational motion, i.e. not attempting to generate any pure forces through the use of thrusters. These terms refer to relative motion only where translation is with respect to the other spacecraft or a defined point in space. These terms are undefined for other forced motion, for example orbital manoeuvres. Note that in some cases, it is possible for both spacecraft to be chasers, if they are manoeuvring about some defined point in space. These terms are not fixed to either satellite, and will change depending on the manoeuvre or experiment. Any use of the word “target” in this context must be clearly distinguished from the observational target (e.g. the Sun for the Coronagraph experiments).

See Table 1 below for a summary of the FF definitions given above.

2.1.1 FF METROLOGY DEFINITIONS

Each spacecraft will include a number of different formation flying metrology subsystems. The first metrology subsystem is defined as the long distance, omni-directional, coarse metrology system (**LCM**). This system will be able to work without requiring external initialisation, and can therefore start from a “lost-in-space” condition. This sensor is used to bring the two satellites into approximately nominal conditions, and then initialise the high-accuracy metrology (**HAM**) system. The HAM potentially consists of a chain of sensors, each sensor in the chain is more accurate than the previous, and is used to initialise the next in the chain up to the final, most accurate metrology unit. This final unit will then be used to help achieve the desired formation position knowledge and control requirements.

2.1.2 EXTENSION OF FORMATION FLYING ERROR DEFINITIONS

The definitions given in RD-2 are extended here, for the purposes of defining the XEUS requirements.

- **AAMS** Absolute Attitude Measurement Stability
- **RDMS** Relative Displacement Measurement Stability

In both cases, measurement stability refers to the difference between the average measured error over time interval Δt and the instantaneous error at time t within Δt.

An example of RDMS is given below in Figure 3:

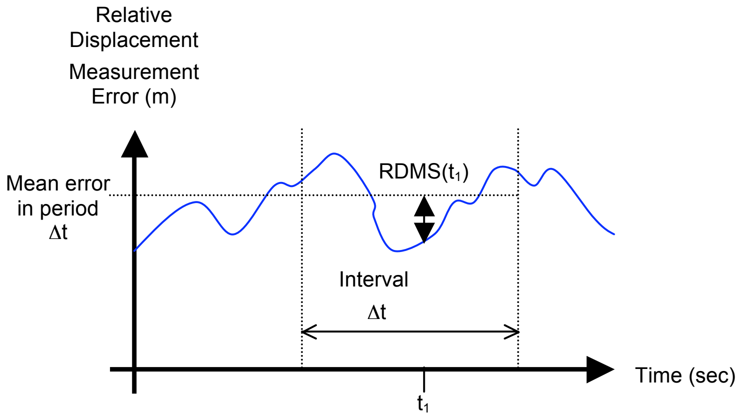

Figure 3: Example of RDMS

2.1.3 SUMMARY OF FORMATION FLYING DEFINITIONS

AAE	Absolute Attitude Error
AAME	Absolute Attitude Measurement Error
AAMS	Absolute Attitude Measurement Stability, over a given time interval
collision	Contact is made between the two satellites
centralised	A formation control mode in which control commands are distributed via the ISL for a single specified spacecraft.
chaser	A spacecraft that is actively translating and generating pure forces with respect to the other spacecraft or a point in space.
decentralised	A formation control mode in which control commands are only generated on-board.

distributed GNC data	GNC data generated on one spacecraft is available to the other, via the ISL
evaporation	Any state (i.e. relative positions and velocities of the two spacecraft) from which it is impossible to recover the nominal formation conditions using less than a specified amount of the total initial mission delta-V, in less than a specified number of days.
formation control mode	Formation control mode is either centralised or decentralised.
FFM	Formation Flying Management, the architecture of the management of set of spacecraft
FST	Formation Station Keeping, when ISD and target direction vector is fixed in inertial space, and the requirements for HPAP apply. *(note that the acronym FSK was not used, in order to avoid any confusion with the common communications acronym for frequency shift keying)*.
HAM	High Accuracy Metrology system.
HPAP	High-Precision Attitude and Pointing, the maximum achievable precision in attitude and pointing knowledge and control, assuming HAM is in use.
HPM	High-Precision during Motion, degraded HPAP requirements when in motion and performing rigid formation manoeuvre.
lateral position error	Perpendicular distance from F2S PLF origin to target line.
local GNC data	Only locally generated GNC data is available for each spacecraft.
longitudinal position error	Distance along target line from nominal ISD to projected position of F2S PLF origin.
loose formation manoeuvre	Manoeuvre where no requirements will be made on manoeuvre positions or rates during the manoeuvre, only at the start and end of the manoeuvre.
LCM	Long distance, omni-directional, Coarse Metrology system.
MVM	Mission Vehicle Management, implementation of spacecraft management functions to fulfil FF
nominal formation conditions	Two satellites, FCS and F2S with parallel PLF reference coordinate frames, each Z-axis co-linear, and with PLF origins separated by the nominal ISD.
nominal ISD	Nominal inter-satellite distance, distance along target line from FCS PLF origin to nominal position of F2S PLF

	origin.
RDMS	Relative Displacement Measurement Stability, over a given time interval
rigid formation manoeuvre	Manoeuvre where two satellite PLF reference coordinate frames are commanded to remain parallel with co-linear Z-axes, and commanded to have the two PLF origins separated by the nominal ISD, throughout the manoeuvre.
target	In terms of "target and chaser", a spacecraft that is not actively translating or generating any pure forces with respect to the other spacecraft or a point in space.
target direction vector	Vector from FCS PLS origin to target (also STF +Z axis).
target line	Line parallel to target direction vector, passes through the FCS PLF origin.

Table 1: Summary of FF Definitions

3 MISSION OBJECTIVES AND REQUIREMENTS

3.1 General Objectives

There is a range of advanced and precise technologies required to enable future formation flying missions. Some of these have been already demonstrated on ground, but the space demonstration of communication-in-the-loop, closed-loop formation flying, even at moderate performance levels has not yet been performed. This step is necessary in view of the complexity at system and operations levels of a formation flying mission and the technical progress still required for the development of future operational missions. The demonstration mission will also achieve the following objectives: the development to TRL-8 / TRL-9 of technology required for satellite FF (GNC, metrology, actuators, …), the development to beta version of SW, the release of tools and facilities and the utilisation of advanced techniques for system engineering, design, development (in particular software) and verification.

It is also an objective of this mission to fly a science payload to "quantify" the mission results. A sun coronagraph has been selected for that purpose. A further objective is to demonstrate as many of the current XEUS GNC requirements on PROBA3 as possible, so that the XEUS mission can re-use high-TRL technologies at lower risk. Finally, it is an objective to perform a rendezvous experiment using only 2D image-based sensors in a highly elliptic orbit, as a prelude to missions such as Mars Sample Return (MSR).

From these objectives, four sets of mission requirements have been derived:

- Requirements associated to generic formation flying, the development of the technology, the tools and facilities and utilisation of the techniques.
- Requirements associated to the Sun-coronagraph mission / payload.
- FF and GNC requirements taken from the most recent XEUS CDF report.

- Requirements associated with the Rendezvous Experiment.

3.2 Formation Flying Requirements

3.2.1 FORMATION FLYING MANOEUVRES

FF manoeuvres are very specific to each mission. The demonstration mission shall demonstrate as far as possible "generic" manoeuvres allowing the demonstration of FF technologies and techniques and the extrapolation to future operational configurations. The following manoeuvres shall therefore be demonstrated:

- **Metrology Test**: Validate the domain of utilisation and the performances of the LCM system and HAM system through a series of pre-defined manoeuvres.
- **Long Range LCM Test**: Increase the ISD up to a specified distance in order to validate the LCM operation up to this distance, and then return the formation to the nominal ISD. This manoeuvre is classed as a loose formation manoeuvre.
- **GNC Sensor & Actuator Characterisation**: All unproven traits of all onboard GNC actuators and sensors that can be tested or characterised in orbit will be listed. A set of formations and manoeuvres will be designed and operated that will individually test and characterise as many of the traits on this list as possible. This list will include (but not be limited to):
    - Metrology sensor maximum and minimum ranges
    - Metrology nominal operation under maximum velocities and angular rates
    - Metrology fields of view
    - Minimum Impulse Bit of untested thrusters
- **GNC System Test**: Validate the complete GNC system through a series of pre-defined manoeuvres.
- **Formation Coarse Acquisition**: Bring the two spacecraft into the nominal formation conditions from any initial set of positions and attitudes. The manoeuvre is complete when the LCM has achieved its final accuracy, and nominal conditions have been achieved to an extent where the HAM system can be initialised. When this manoeuvre has been completed, it should be possible to maintain LCM in its final accuracy while maintaining nominal conditions, or begin the Formation Fine Acquisition manoeuvre. This manoeuvre is classed as a loose formation manoeuvre.
- **Formation Fine Acquisition**: Assuming Formation Coarse Acquisition has been achieved, Formation Fine Acquisition is used to initiate the HAM system, and use it to meet the HPAP requirements. The manoeuvre will be complete when the HAM system is active and returning maximum-precision measurements, and the requirements for HPAP are met. This manoeuvre is classed as a loose formation manoeuvre.
- **Formation Station Keeping Test**: Assuming Formation Fine Acquisition has been achieved, the nominal formation conditions will be maintained with the HAM system active and returning maximum-precision measurements, and with a nominal fixed ISD at

150m. Once the formation has settled, the manoeuvre will be completed once FST has been met for a specified unbroken / uninterrupted period of time. This manoeuvre will be achievable in both centralised and decentralised formation control modes. This manoeuvre is classed as a rigid formation manoeuvre.

- **Formation Resize Close & Far**: Assuming Formation Fine Acquisition has been achieved, the nominal ISD will be either reduced to a specified minimum distance (Close Manoeuvre, see Figure 4 below) or increased to a specified maximum distance (Far Manoeuvre). During the resize, the requirements for HPM will apply. The nominal ISD will then be fixed, and the formation will be allowed to settle. The formation will then be held at FST for a specified unbroken / uninterrupted period of time. The ISD is then returned to its nominal value, during which the requirements for HPM will apply. The manoeuvre is considered complete when the nominal ISD is at 150m, and the requirements for HPAP are met. This manoeuvre will be achievable in both centralised and decentralised formation control modes, and can be either a rigid or a loose formation manoeuvre.

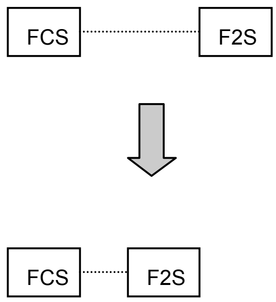

Figure 4: Formation Resize Close

- **Formation Retargeting**: Assuming Formation Fine Acquisition has been achieved, the target direction vector will be slowly rotated, up to a specified final angle from the original. This will necessitate a rotation in inertial space of the formation, maintaining the nominal ISD at 150m. During the retargeting, the requirements for HPM will apply. Once the new position has been achieved, the formation will be allowed to settle (see Figure 5 below). The formation will then be held at FST for a specified unbroken / uninterrupted period of. Once this has been achieved, the manoeuvre is reversed, and target direction vector is slowly rotated and returned to its original direction, during which the requirements for HPM will apply. The manoeuvre is considered complete when the target direction vector has returned to its original position, and the requirements for HPAP are met. This manoeuvre will be achievable in both centralised and decentralised formation control modes, and can be either a rigid or loose formation manoeuvre.

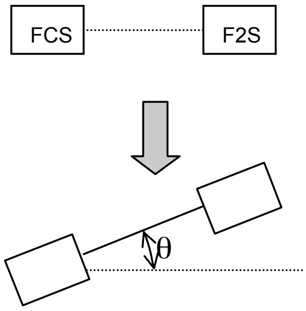

Figure 5: Formation Retargeting

- **Formation Resize and Retarget**: This manoeuvre is a combination of Formation Resize Close and Formation Retargeting. For this manoeuvre, the nominal ISD will be reduced to a specified minimum distance, while at the same time the formation is retargeted up to a specified final angle from the original. During the resizing and retargeting, the requirements for HPM will apply. Once the new position has been achieved, the formation will be allowed to settle. The formation will then be held at FST for a specified unbroken / uninterrupted period of time. Once this has been achieved, the manoeuvre is reversed, and target direction vector is slowly rotated and returned to its original direction while the nominal ISD is returned to 150m, during which the requirements for HPM will apply. The manoeuvre is considered complete when the target direction vector has returned to its original position, the nominal ISD is at 150m, and the requirements for HPAP are met. This manoeuvre will be achievable in both centralised and decentralised formation control modes, and can be either a rigid or loose formation manoeuvre.
- **Formation Perigee Passage**: This manoeuvre will break the formation at the approach to perigee, allow a safe cruise through perigee that guarantees no collision, and then reform the formation. The manoeuvre is considered complete when the LCM has achieved its final accuracy, and nominal conditions have been achieved to an extent where the HAM system can be initialised (i.e. the same exit conditions as for the Formation Coarse Acquisition manoeuvre). Once these conditions have been met, the next manoeuvre to follow should be the Formation Fine Acquisition, in order to prepare for the next formation flying manoeuvre. This manoeuvre is classed as a loose formation manoeuvre.
- **Collision Avoidance Test**: This manoeuvre is used to test the collision avoidance capability onboard, through a series of pre-defined manoeuvres.

3.2.2 SYSTEM AND GNC PERFORMANCE

In orbit performances of FF specific technologies shall be demonstrated by the mission:

- Performances achieved with each metrology (LCM and HAM) will be validated in presence of real conditions of noise and system coupling, and also the combined utilisation of different relative position measurements system will be tested (overlap, transition between metrology systems),
- Control loops will be tested in space environment rather than in simulated environment (including modes transitions, locking, autonomy and, to safe extent, collision avoidance)

and control performances will be validated in real environment conditions including real noise, perturbations and coupling at system level (attitude-position, sensor-actuator, ..) and real precision actuators performances.

3.2.3 MANAGEMENT FUNCTIONS (FFM AND MVM) AND FDIR

At operational level, spacecraft management functions will be tested and validated:

- The strategy for manoeuvring will be verified including the on board autonomy and modes transitions. The performances in real conditions for manoeuvring will be checked (duration of manoeuvre and fuel consumption) and optimised,
- Safe deployment strategies, either autonomous (using inter-satellite communication) or ground controlled will be validated,
- Several strategies for sharing space – ground, and among satellites which will generate the GNC translation commands, shall be tested
- The interface between the Formation Flying on board function and the ground will be developed, tested, validated and exercised, including inter-satellite link and also operators in the loop,
- The formation FDIR will be validated and tuned with a dedicated set of experiments.

3.2.4 METROLOGY SYSTEMS

Inter satellite formation metrology include:

- GPS differential metrology for cm accuracy co-location close to earth,
- LCM metrology for cm accuracy co-location and omni-coverage co-location,
- HAM metrology for high accuracy co-location (down to micrometers).

Metrology technologies will be used depending on the performance requirements and final complexity of the mission. The extent of the demonstration of PROBA 3 shall be sufficient to prepare future missions and validate their required metrology packages, it shall however remain compatible with the programmatic constraints of a demonstration.

3.2.5 INTER-SATELLITE COMMUNICATION FOR COHERENT CONTROL (POSITION AND ATTITUDE) OF THE SATELLITES

FF requires inter-satellite communication. This function depends on the FF architecture, the implementation of the FFM and MVM functions and the needs of relative navigation. The function is assured by Inter-Satellite Links (ISL). ISL technology shall be demonstrated and validated for future missions.

3.2.6 SYSTEM ENGINEERING, DEVELOPMENT AND VERIFICATION TOOLS AND FACILITIES

Formation Flying missions have been so far studied at concept or Phase 0 level and specific technologies are currently at the breadboard stage. However, no team or group of engineers has gone through the complete cycle from system requirements to design of lowest level components and then integration and validation of the whole system. Being the first example of a Formation Flying mission, there is a lot of experience to be drawn during the specification, design and validation process. The engineering process specific to a FF mission shall be revisited and validated and the supporting infrastructure shall also be re-defined. Tools will be developed, correlated and validated, real-time simulator and engineering tool models will be checked against specific but real conditions increasing their confidence and accuracy for later use on operational missions.

Special effort will be devoted to the ground verification of the GNC, FFM, MVM and FDIR functions. These functions will be implemented in SW which will have to be thoroughly tested. System validation will be performed incrementally according to the following scheme exercised on previous PROBA missions:

- the overall system including GNC and management functions will be implemented and tested on a simulation tool such as Mathlab/Simulink. This step will demonstrate that the overall system is properly defined and provides the expected behaviour and performances,
- software will be generated automatically form these tools to create the flight software,
- a System Validation Facility (SVF) will be developed and will support the validation of the flight software in “real time” and simulating the real environment. This facility includes an emulator of the processor to execute directly the real flight software. It includes also TM/TC interface such that it plays the role of a spacecraft simulator and authorises the validation and rehearsal of spacecraft operations,
- as a final step, a hardware-in-the-loop test bench (probably partial) which will allow to validate critical parts of the system including software and hardware units (e.g. metrology, ISL).

3.2.7 FLEXIBILITY

PROBA-3 will have to provide a high degree of re-programmability to correct infant flaws and also to test alternative strategy in the frame of repeated experiments:

- Alternative controlling strategies, autonomy, operational modes transitions will be tested as the mission will be dimensioned to allow retrial of specific Formation Flying actions (manoeuvres, …),
- Various FF control and architectures will be tested: centralised/decentralised control, Formation geometry, modes transitions & locking.
- The on board software shall be organised to allow easy and safe reprogrammability.

3.3 Coronagraph Objectives and Requirements

PROBA 3 will embark on a payload complement. A Coronagraph Instrument is proposed to observe the Sun corona. It requires 2 spacecraft, one spacecraft carries the Occulter Disk and the other spacecraft carries the Coronagraph Detector. In addition to being a first FF user mission, it also intrinsically validates most of the features of 2 spacecraft "inertial" FF missions (albeit with moderate performance requirements compared to some planned missions using interferometers).

The Coronagraph Detector is composed of a single imager which performs high spatial resolution imaging of the corona as well as 2-dimensional spectroscopy of several emission lines from the coronal base out to 3 solar radii (Rsol).

By performing high spatial resolution imaging and 2-dimensional spectroscopy, the Coronagraph Instrument will address the following questions:

- How is the corona heated? What is the role of waves?
- How are the different components of the solar wind, slow and fast, accelerated?
- How are Coronal Mass Ejections (CMEs) accelerated?

In addition, the Coronagraph Instrument will attempt to characterise the topology of the magnetic field in the corona.

3.3.1 INSTRUMENT REQUIREMENTS

Stray light is the main concern for the instrument. During the observing phases, all bright sources (Earth, Moon, etc.) shall be out of a half cone angle of 35° around the optical axis of the Coronagraph Detector. In the same way, they shall be as far as possible from the Coronagraph Detector axis (ideally more than 90°).

The apparent angular radius of the Occulting Disk shall be between 1% and 2% larger than the apparent angular radius of the Sun.

This instrument requires as far as possible continuous unobstructed observation of the sun. The FF performance requirements generated by this instrument are included in the SRD.

3.4 XEUS Performance Demonstration Requirements

3.4.1 XEUS BACKGROUND

The X-ray Evolving Universe Spectroscopy (XEUS) mission is Europe's next generation X-ray observatory. XEUS will be placed in a halo orbit at L2, and consists of two spacecraft – the optics assembly of XEUS will be contained in the Mirror Spacecraft (MSC) while a suite of focal plane instruments will be contained in the Detector spacecraft (DSC). The two spacecraft will be separated by a focal length of 35m, while the effective mirror diameter will be 4m. The main requirement for XEUS is to provide an angular resolution of better than 5 arc-seconds half energy width (HEW).

3.4.2 PROBA3 DEMONSTRATION OF XEUS REQUIREMENTS

PROBA3 will attempt to demonstrate as many of the XEUS GNC requirements as possible, within the constraints of the mission cost and development timeline. In some cases, the XEUS GNC requirements are expected to be difficult or impossible to achieve with PROBA3 expected equipment. Instead, best efforts will be made to meet these requirements, and in the event the requirements cannot be met, a clear justification of the reasons of non-compliance will be given such that XEUS mission designers can benefit from PROBA3 experience.

3.4.3 XEUS GNC REQUIREMENTS

There are two main drivers of the XEUS GNC requirements, as given in RD-3. The first is the lateral position error, and the second is the formation flying contribution to the image quality error budget.

3.4.3.1 Lateral Position Error

The lateral position error is based on keeping a target in the field of view of the NFI, which leads to a lateral requirement of ±1mm (assumed 2σ). The definition of the lateral position error for XEUS is the same as for PROBA3 (see Figure 2), where the F2S PLF acts as the DSC PLF, and the FCS PLF acts as the MSC PLF.

3.4.3.2 FF Contribution to Image Quality

The total image quality budget is 5 arc-seconds (HEW), which is considered to be the root-sum-squared (RSS) summation of a number of different error terms. The FF contribution to the total image quality budget has been allocated as 2 arc-seconds (HEW), which corresponds to 3.8 arc-seconds (2σ) assuming a Gaussian distribution. A margin of 50% gives an allocation of 1.9 arc-sec (2σ) to FF.

This FF contribution in turn is assumed to consist of two major error contributors, due to longitudinal displacement error (Relative Displacement Error, RDE_z) and lateral displacement measurement stability (Relative Displacement Measurement Stability, $RDMS_{xy}$) over a specified period of time. The first contributor affects image blurring, while the second contributor introduces errors in the photon position reconstruction on ground. The FF contribution is approximated by the following equation:

$$\sqrt{\left(\frac{RDE_Z \cdot \Phi}{2F^2}\right)^2 + \left(\frac{RDMS_{XY}}{F}\right)^2} < 9.2\mu\text{rad (1.9 arc-sec)}$$

where F is the focal length and Φ is the effective mirror diameter. The RDE_z is specified to be 3mm (2σ), and hence the $RDMS_{xy}$ must be less than 0.27mm (2σ). This equation assumes that high-frequency lateral stability is small enough to be ignored for PROBA3. Due to the fact that the lateral measurement metrology reference frame is fixed to the spacecraft body, then stability errors in the body attitude measurement will also contribute to the lateral displacement measurement stability. Hence, $RDMS_{xy}$ is assumed to consist of both lateral metrology stability and attitude measurement stability multiplied by the focal length. These two contributors are assumed independent, therefore:

$$RDMS_{XY} \approx \sqrt{(F \cdot AAMS)^2 + \lambda_S{}^2}$$

where AAMS is the absolute attitude measurement stability and λ_S is the lateral metrology stability. Allocating an AAMS of 1.5 arc-seconds (2σ) leaves a lateral metrology stability of 100μm (2σ).

The XEUS exposure time is the driver for the time interval for these long-term stability errors, and is on average 3.5 days. It is not possible to achieve this with the given PROBA-3 24-hour orbit, and therefore the stability time interval shall be 4 hours (TBC). This time period is relatively long compared to the common definition of stability, and implies long-term errors such as mechanical bending due to thermal variations will have an affect. In addition, this long period of time will mean

3.5 Mission Extension Requirements

As a technology demonstration mission, additional funded experiments will be included on-board, in order to test novel techniques and hardware. As the mission progresses, future interested partied may come forward and present further potential experiments. Depending on the validity and funding of the experiment, the mission shall make best efforts to accommodate these experiments, although these additional experiments shall not be major design drivers. This shall require a flexible mission capable of adapting at a late stage of development.

3.5.1 RENDEZVOUS (RV) EXPERIMENT

The general definitions of formation flying and rendezvous regarding two spacecraft are similar, but have subtle differences. For rendezvous, the relative position and velocities between the two spacecraft are controlled, and possibly at certain parts also the relative attitude. The spacecraft are assumed to be on quasi-coplanar orbits, and in general, the only plane of interest is the target orbit plane. The two spacecraft are in close proximity, but at typically larger distances than for formation flying. In addition, rendezvous often precedes docking.

In comparison, during formation flying, the relative position and velocities between the two spacecraft are also controlled, and possibly at certain parts also the relative attitude. The spacecraft are also assumed to be on quasi-coplanar orbits. However, in formation flying, the spacecraft states are directly coupled such that changing the state of one spacecraft affects the state of the other, which is not the case for rendezvous. In addition, a plane is defined for the inter spacecraft positions with an arbitrary orientation space.

Specifically for PROBA3, the rendezvous experiment implies bringing the two spacecraft together into very close proximity (in the order of metres of separation) from some specified separation distance and approximately known initial conditions, while making maximum use of orbit dynamics to reduce propulsion delta-V (this definition is TBC).

3.5.1.1 RV Experiment Description

Given the close similarity between formation flying and rendezvous (RV) operations, it should be possible to demonstrate some aspects of RV operations using the PROBA3 spacecraft.

The RV experiment on PROBA3 shall demonstrate rendezvous using only vision-based 2D sensors to estimate the target's 3D position. The experiment proper will begin when the two spacecraft are at a separation distance of 5km at perigee, with both spacecraft on the same orbit with different true anomalies. The leading spacecraft shall be designated the target and shall be passive during the experiment, while the trailing spacecraft shall be the chaser and shall perform the active manoeuvres. The chaser shall use a vision-based sensor and utilise a-priori knowledge of orbit dynamics to estimate the chaser position and range. The chaser will then use orbit dynamics to minimise fuel consumption and bring the two spacecraft to within 20m at apogee, after 1.5 orbits. The chaser will then carry out a forced translation to a distance of 5m followed by a forced retreat back out to 20m. The two spacecraft will then drift apart, ready to perform a suitable manoeuvre (such as perigee passage) to prepare for further formation flying experiments, thus ending the RV experiment. Throughout the experiment, only measurements from the vision-based sensor, and a-priori knowledge of the initial conditions and relative orbits, shall be used by the RV navigation filter. The experiment shall be conducted in an autonomous manner, with no interaction from ground throughout the experiment.

3.5.1.2 RV Experiment Objectives

The main objectives of the PROBA3 Rendezvous (RV) Experiment have been taken from RD-4 and can be summarised as follows:

- Demonstrate the feasibility of performing realistic and representative operational RV operations in elliptical orbits applicable for future missions.
- In-orbit validation of guidance algorithms for Rendezvous in elliptical orbits, fulfilling typical requirements and constraints of future missions in potential need of this technology.
- In orbit validation of image based navigation algorithms for Rendezvous in elliptical orbits, including far range and close range RV operations.
- In orbit validation of the overall vision-based autonomous RV GNC concept in elliptical orbits.

3.5.1.3 RV Experiment Hardware Requirements

A suitable vision-based sensor shall be included as part of the experiment, which will be capable of sensing specific target light sensors located on the other spacecraft at a distance of at least 5km.

3.6 Expected Mission Timeline

It is expected that all the requirements, manoeuvres and experiments listed above and in the SRD will be achieved by the end of the mission. However, during the mission there will be a priority list, which will list the tasks still to complete in order of priority. It is expected that this list will change with time, depending on the results of the previous manoeuvres and experiments. A preliminary task priority list (TPL) is given below in Table 2. This list assumes the commissioning phase has finished (i.e. that all unit-level and individual spacecraft-level commissioning has been successfully completed), and that the two spacecraft are in approximately the same orbit separated by an approximately constant time offset (i.e. string-of-pearls configuration). This list assumes approximately 85 (TBC) weeks of operation (1 year 8 months), which does not include commissioning or margin.

Under Task: D=decentralised, C=Centralised, L=Loose, R=Rigid. Distances refer to ISD, angles refer to changes in target direction vector from nominal formation conditions, time refers to FST period (min=minutes). Nominal ISD is 150m unless specified.

	Task	**Expected Duration (weeks, all TBC)**	**Remarks**
1	Perigee Passage Manoeuvre	-	This will need to be demonstrated early on, during the first trials of formation acquisition. The manoeuvre is expected to be progressively improved over time, such that the time taken for formation re-acquisition after perigee passage will get shorter with each orbit.
2	Formation Coarse Acquisition + Perigee Passage	3	The initial attempt to complete a formation coarse acquisition manoeuvre. This will go hand-in-hand with the perigee passage manoeuvre. These two basic manoeuvres are repeated to demonstrate consistency, and for analysis.
3	Formation Fine Acquisition + 30 min FST (D)	3	The initial attempt to complete a formation fine acquisition manoeuvre, and to demonstrate meeting the HPAP requirements at 150m. This manoeuvre is repeated to demonstrate consistency, for analysis and in fulfilment of requirement FF-54-R (SRD iss2 rev0).
4	Formation Resize Far to 155m (DR) + 30 min FST (D)	1	First attempt at changing the ISD. Resize Far chosen first, seen as less risky.
5	Formation Resize Close to 145m (DR) + 30 min FST (D)	1	First attempt to reduce the ISD. Interaction with decreasing ISD and FDIR needs to be analysed and validated.
6	Formation Retarget to 5° (DR) + 30 min FST (D)	2	First attempt at Formation Retarget.
7	Coronagraph first light	3	First attempt to gain Coronagraph images, and to demonstrate autonomous Coronagraph manoeuvre. Note that in the following weeks, it is assumed that the “weekend” (2-3 days per week) is devoted to Coronagraph Instrument measurements. Hence, from this point in the timeline onwards, a “week” consists of 4-5 days of the stated task, plus 2-3 days of Coronagraph Instrument measurements.
8	Calibration Manoeuvres	2	Once the basic manoeuvres and science payload have been used for the first time, calibration manoeuvres can be performed to improve the pointing and position performances.

			Although minor calibrations will have already occurred during the previous tasks, this task will allow consolidated calibration with the science instrument in the loop. Once these manoeuvres have been tested and demonstrated, it is expected that they will be performed at regular intervals.
9	Metrology Test Manoeuvres	2	Fulfilment of SRD requirement FF-77-R (SRD iss2 rev0).
10	GNC Sensor and Actuator Manoeuvres	2	Fulfilment of SRD requirement FF-78-R (SRD iss2 rev0).
11	Collision Avoidance & FDIR Test Manoeuvres (low-risk)	2	The set of collision avoidance manoeuvres from requirement FF-75-R (SRD iss2 rev0) that are considered to be low-risk tests.
12	Formation Resize Close to 100m (DR) + 30 min FST (D)	1	Further reduction of ISD.
13	Formation Resize Close to 50m (DR) + 30 min FST (D)	1	Further reduction of ISD.
14	Formation Resize Close to 25m (DR) + 30 min FST (D)	1	First time down to 25m ISD. Fulfilment of requirement FF-58-R (SRD iss2 rev0).
15	Formation Resize Close to 35m (DR) + 1 hour FST (D)	1	Reduce ISD to 35m, to demonstrate HPAP requirements at XEUS nominal ISD. Will also fulfil requirement FF-55-R (SRD iss2 rev0).
16	Formation Coarse Acquisition Manoeuvres	2	Fulfilment of SRD requirement FF-52-R (SRD iss2 rev0).
17	Formation Resize Far to 250m (DR) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-62-R (SRD iss2 rev0).
18	Rendezvous Experiment	3	Fulfilment of SRD requirement FF-106-R (SRD iss2 rev0).
19	Formation Retarget to 15° (DR) + 30 min FST (D)	1	First retargeting to 15 degrees.
20	Formation Retarget to 30° (DR) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-64-R (SRD iss2 rev0).
21	Additional Experiment or further repetition	2	This is a placeholder, for future experiments or for required repetitions of tests, before the loose & centralised combinations of experiments.
22	Formation Resize Far to 155m (DL) + 30 min FST (D)	2	First attempt at Loose formation manoeuvre, with increasing ISD (increasing first, as assumed to be less risky).
23	Formation Resize Close to 145m (DL) + 30 min FST (D)	1	First attempt at Loose formation manoeuvre, with decreasing ISD. Interaction with Loose formation manoeuvre, decreasing ISD and FDIR needs to be analysed and validated.
24	Formation Resize Close to 100m (DL) + 30 min FST (D)	1	Further reduction in Loose manoeuvre ISD.
25	Formation Resize Close to 50m (DL) + 30 min	1	Further reduction in Loose manoeuvre ISD.

	FST (D)		
26	Formation Resize Close to 25m (DL) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-57-R (SRD iss2 rev0).
27	Formation Retarget to 5° (DL) + 30 min FST (D)	2	First attempt at Formation Retarget Loose manoeuvre.
28	Formation Retarget to 15° (DL) + 30 min FST (D)	1	Formation Retarget Loose manoeuvre, with increased angle.
29	Formation Retarget to 30° (DL) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-63-R (SRD iss2 rev0).
30	1 hour FST (C)	2	First attempt at centralised control, also fulfilment of SRD requirement FF-56-R (SRD iss2 rev0).
31	Formation Resize Close to 145m (CR) + 30 min FST (C)	2	First attempt at centralised control with reducing ISD.
32	Formation Resize Close to 100m (CR) + 30 min FST (C)	1	Further reduction in centralised manoeuvre ISD.
33	Formation Resize Close to 50m (CR) + 30 min FST (C)	1	Further reduction in centralised manoeuvre ISD.
34	Formation Resize Close to 25m (CR) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-60-R (SRD iss2 rev0).
35	Formation Retarget to 5° (CR) + 30 min FST (C)	2	First attempt at centralised retargeting manoeuvre.
36	Formation Retarget to 15° (CR) + 30 min FST (C)	1	Formation Retarget centralised manoeuvre, with increased angle.
37	Formation Retarget to 30° (CR) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-66-R (SRD iss2 rev0).
38	Formation Retarget to 30° (CR) + 30 min FST (C), no reaction wheels	1	Fulfilment of SRD requirement FF-67-R (SRD iss2 rev0).
39	Formation Resize Close to 145m (CL) + 30 min FST (C)	2	First attempt at centralised loose control.
40	Formation Resize Close to 100m (CL) + 30 min FST (C)	1	Further reduction in centralised loose manoeuvre ISD.
41	Formation Resize Close to 50m (CL) + 30 min FST (C)	1	Further reduction in centralised loose manoeuvre ISD.
42	Formation Resize Close to 25m (CL) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-59-R (SRD iss2 rev0).
43	Formation Retarget to 5° (CL) + 30 min FST (C)	2	First attempt at centralised loose retargeting manoeuvre.

44	Formation Retarget to 15° (CL) + 30 min FST (C)	1	Formation Retarget centralised loose manoeuvre, with increased angle.
45	Formation Retarget to 30° (CL) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-65-R (SRD iss2 rev0).
46	Formation Resize Close to 145m (CR) + 30 min FST (C), with SC-B generating centralised commands	2	First attempt at SC-B generating centralised commands.
47	Formation Resize Close to 25m (CR) + 30 min FST (C), with SC-B generating centralised commands	1	Fulfilment of SRD requirement FF-61-R (SRD iss2 rev0).
48	Formation Retarget to 30° (CR) + 30 min FST (C), with SC-B generating centralised commands	1	Fulfilment of SRD requirement FF-68-R (SRD iss2 rev0).
49	Formation Resize & Retarget to 145m and 5° (DR) + 30 min FST (D)	2	First attempt at resize & retarget manoeuvre.
50	Formation Resize & Retarget to 100m and 15° (DR) + 30 min FST (D)	1	Further resize & retarget, with greater change in ISD and retargeting angle.
51	Formation Resize & Retarget to 25m and 30° (DR) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-70-R (SRD iss2 rev0).
52	Formation Resize & Retarget to 145m and 5° (DL) + 30 min FST (D)	1	First attempt at resize & retarget loose manoeuvre.
53	Formation Resize & Retarget to 25m and 30° (DL) + 30 min FST (D)	1	Fulfilment of SRD requirement FF-69-R (SRD iss2 rev0).
54	Formation Resize & Retarget to 145m and 5° (CR) + 30 min FST (C)	1	First attempt at resize & retarget centralised manoeuvre.
55	Formation Resize & Retarget to 25m and 30° (CR) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-72-R (SRD iss2 rev0).
56	Formation Resize & Retarget to 145m and 5° (CL) + 30 min FST (C)	1	First attempt at resize & retarget centralised loose manoeuvre.
57	Formation Resize & Retarget to 25m and 30° (CL) + 30 min FST (C)	1	Fulfilment of SRD requirement FF-71-R (SRD iss2 rev0).
58	Formation Resize & Retarget to 145m and 5° (CR) + 30 min FST (C) ,	1	First attempt at resize & retarget manoeuvre with SC-B generating centralised commands.

	with SC-B generating centralised commands		
59	Formation Resize & Retarget to 25m and 30° (CR) + 30 min FST (C) , with SC-B generating centralised commands	1	Fulfilment of SRD requirement FF-73-R (SRD iss2 rev0).
60	Repetition of Rendezvous Experiment	2	Repetition of SRD requirement FF-106-R (SRD iss2 rev0), in order to try new techniques and make use of previous experience. It should be possible to attempt higher-risk manoeuvres at this point.
61	Collision Avoidance & FDIR Test Manoeuvres (low-risk)	1	The remaining high-risk set of collision avoidance manoeuvres in fulfilment of requirement FF-75-R (SRD iss2 rev0).

Table 2: Preliminary Task Priority List (TPL)

4 MISSION RESULTS SUMMARY

In summary after execution of the PROBA 3 mission:

- A set of metrology systems will be validated in orbit (behaviour and performances) and available "off the shelf" for FF operational missions,
- A complete FF GNC including a set of generic FF manoeuvres and configurations will have been analysed, developed and validated in orbit,
- Models of the metrology units and GNC simulators will be available and correlated with flight performances,
- FFM and MVM architecture will have been analysed, implemented and tested in a complete system in orbit,
- A flight software architecture and design suitable for the management of a formation will be validated,
- A development approach including the validation approach and an iteration of the engineering infrastructure will have been exercised,
- The safety and reliability of formation flying will have been demonstrated,
- A first complete dedicated FF mission will have been flown and end to end experience will be available.
- Experience will be gained in attempting to meet the XEUS formation flying performance requirements, which will be valuable for the XEUS mission design team.
- A Rendezvous experiment will be performed, demonstrating the autonomous rendezvous in a highly elliptical orbit using only passive 2D imagery is feasible.
- Scientifically relevant Coronagraph measurements will be made with a performance superior to any current mission.