Operational Flight Dynamics System for PROBA-3 Formation Flying Mission

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This paper describes the Flight Dynamics System for PROBA-3. Previous PROBA missions were demonstrating the on-board autonomy capabilities of the spacecraft and hence did not include any FDS on ground. However, PROBA-3 aims to validate the automatic formation flying of two satellites. The high level of activity performed on board imposes some heavy requirements to the ground segment in general, and to the Flight Dynamics System in particular, that forces them to deviate from the standard design of this system. Besides, the FDS is also in charge of evaluating the performances of the on-board formation flying system.

Key Words: Proba-3, Flight Dynamics, Formation Flying

Nomenclature

$\bar{r}$	:	position
$\bar{v}$	:	velocity
Ω	:	angular velocity
Subscripts		
OSC	:	Related to Occulter Spacecraft
CSC	:	Related to Coronagraph Spacecraft

1. Introduction

PROBA-3 is the fourth ESA mission of the PRoject for On-Board Autonomy (PROBA), aimed at the demonstration of European on-board technology. It is intended to validate in-orbit formation flying techniques and technologies with the scientific aim of observing the Sun's corona during a mission lifetime of 2 years. The mission is composed by two spacecrafts (coronagraph and occulter) on a high-elliptic orbit, building a virtual telescope during scientific operations near the orbit apogee. This requires very precise formation flying of the two objects distant 150 m from each other around the apogee.

2. Generic Flight Dynamics Functionality

PROBA-3 mission has very demanding performance requirements for the on-board Guidance Navigation and Control (GNC) system, which is in charge of controlling the formation flying through a dedicated system, FFS.

However, the monitoring of the system on ground also imposes some particular requirements on the flight dynamics system (FDS). This system covers the following functionalities:

- Orbit determination, focused on the relative distance between the two satellites, being this critical for the mission objectives.
- Orbit and events prediction, which has to account for the on-board controlled phases for the formation flying.
- Manoeuvre optimisation: whereas routine formation flying (FF) and collision avoidance manoeuvres (CAM) between both satellites are automatically computed on board, FDS is responsible for the manoeuvre computation for initial formation acquisition, recovery from CAM and formation resizing.
- Collision risk evaluation between the two satellites is being performed as part of the manoeuvre computation and will be evaluated accounting for both misperformance and failure to execute any manoeuvre in a commanded batch.
- On-ground FFS calibration, based on the telemetry analysis and the results of the orbit determination, FDS shall perform the calibration of the on-board software in particular for the perigee pass and formation acquisition manoeuvres. Additionally, the flight formation performance analysis in terms of relative orbit and attitude will be also carried out within this system.

3. PROBA-3 Orbit

PROBA-3 will be located in a High Eccentricity Orbit (HEO) in order to perform Sun coronagraphy around the apogee. Whereas the ideal orbit to perform such a mission would be a halo around L1, the HEO orbit apogee allows representative environments for most of the intended demonstrations, requiring only reduced launch capabilities with respect to the orbit around the Lagrange point[1)].

Table 1 shows the reference orbit parameters for the PROBA-3 orbit.

Table 1. Orbital elements

Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Inclination	59º
RAAN	84º
Argument of Perigee	188º

3.1. Nominal orbit managed from FFS

During the six hours around the orbit apogee, between approximately 170 and 190 degrees in true anomaly, the two satellites are flying in formation. In this phase, both satellites are intended to behave as a solid body, pointing towards the Sun and separated by a constant distance of 150 m, with the OSC interposing its disk-shaped body between the CSC and the Sun. The CSC is flying without internal perturbation, while the OSC uses the Cold Gas Propulsion thrusters (providing a thrust of a few mN) to keep the formation shape.

FFS on-board is managing different inputs from the GNC and several instruments (in particular the Fine Longitudinal and Lateral Sensor, FLLS, and the Coarse Lateral Sensor, CLS) to compute the relative position. The fine metrology is available in the CSC and the actuation during the formation has to be performed by OSC, so the on-board software must compensate the delays of the inter-satellite link (ISL) and synchronise the on-board time (OBT) of the two satellites. After the data synchronisation, the final estimation of the relative position and velocity is implemented as a Kalman Filter, using the Yamakara-Ankersen formulation for the dynamic modelling of the relative motion, and computing and commanding the required ΔV to keep the formation[2)].

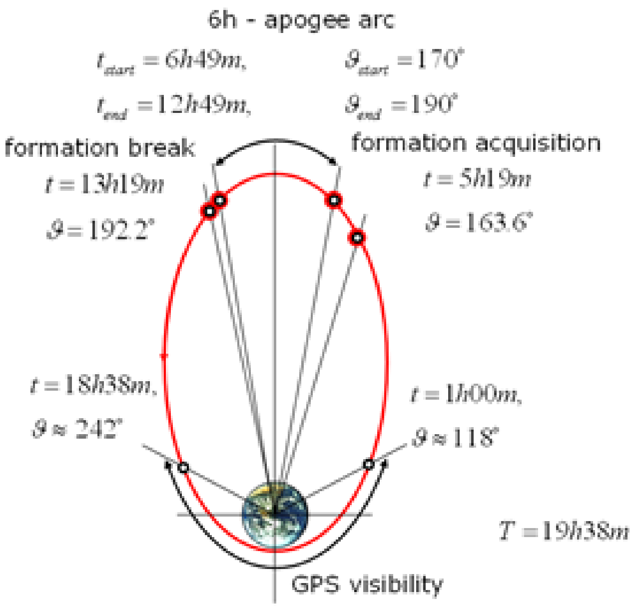

Fig. 1. PROBA- 3 nominal routine orbit.

At the end of the formation flying phase, the CSC becomes the controlled spacecraft. The formation is broken by a manoeuvre performed by the monopropellant thrusters (1N) in the Coronagraph satellite during the first half hour after the end of the apogee arc. At this time the FLLS still maintains the lock between the two satellites, so precise knowledge of their relative position is available on-board.

This manoeuvre is computed as the first Direct Transfer Manoeuvre (DTM) for the formation reacquisition in the next orbit, but it also aims to ensure a safe perigee pass for the two satellites. Therefore, any actuation errors in this manoeuvre is compensated by a cold gas manoeuvre performed right after the first DTM. This strategy also ensures the maximum inter-satellite distance during the perigee pass[3)].

For about two hours around the perigee, the system is within GPS visibility range. Relative GPS data is used for the navigation, so at the end of the perigee pass (true anomaly close to 118 degrees), the relative position is known with an error slightly above 2 cm (1σ) and an estimated bias close to 4 cm (1σ). This accuracy is needed for the formation reacquisition performed with the second DTM, about one hour before the start of the formation flying phase.

3.2. Orbit prediction

Orbit prediction is highly influenced by the formation flying performed on board. First of all, not every orbit is intended to be used for coronagraphy, so the Flight Dynamics system needs to ingest the mission plan in order to know in advance when the FFS will be active.

Considering that the two satellites are autonomously manoeuvring during the nominal orbits in which science is to be performed, none of them can be propagated independently from the other. Furthermore, the perigee pass preparation and formation acquisition manoeuvres implemented by the CSC introduce a dependency between the orbit propagation and the manoeuvre computation modules within the ground system.

After a perigee pass (true anomaly equal to zero), the orbit must be propagated until the start of the formation acquisition phase (defined either by the time after the perigee or by the true anomaly of the CSC). The manoeuvre shall be modelled using the same algorithms used by FFS for the two point transfer manoeuvre that would be implemented on-board. Since in this phase the OSC is not being controlled, the final state of the formation acquisition phase is well defined. Any correction that could be performed on-board in closed-loop to the second thrust of the manoeuvre would lead to the same state after the reacquisition, so only minor errors in the predicted CSC estimation are expected during this manoeuvre. Furthermore, after the manoeuvre calibration performed on ground in the first orbits, it is expected that these errors should decrease during the mission.

The next orbital phase consists in the formation flying. CSC is free-flying during this segment, so its orbit can be directly propagated. However, it has to be considered that, during the formation flying, the OSC shadow is being projected on the CSC and therefore, the area of this satellite affected by the solar radiation pressure is much lower than the total surface opposed to the Sun direction.

The OSC orbit propagation during this phase can be performed in two different ways: the simpler one, which should be accurate enough for the obit prediction required by the event computation, is based on the assumption that the FFS is controlling the OSC within the required accuracy and, therefore, the nominal formation is being kept. Following this approach, the OSC orbit can be replaced by a kinematic evolution based on the following equation:

$$\begin{aligned} \bar{r}_{OSC} &= \bar{r}_{CSC} + \lambda \cdot \frac{\bar{r}_{Sun} - \bar{r}_{CSC}}{|\bar{r}_{Sun} - \bar{r}_{CSC}|} \\ \bar{v}_{OSC} &= \bar{v}_{CSC} + \bar{\Omega}_{Sun} \times \lambda \cdot \frac{\bar{r}_{Sun} - \bar{r}_{CSC}}{|\bar{r}_{Sun} - \bar{r}_{CSC}|} \end{aligned} \quad (1)$$

where λ represents the distance between the two satellites in the formation (nominally 150 m).

An alternative to the kinematical solution for the OSC orbit is based on the reuse of the algorithms implemented on-board. Whereas the FFS is working in closed-loop and, therefore, it is not possible to accurately predict its behaviour, the Yamanaka-Ankersen formulation[4) can be used to predict the expected ΔV evolution of the OSC's cold gas thrusters during the formation flying. This approach is not needed for the orbit prediction, but would provide a nominal manoeuvre profile that can be compared with the one performed on-board to evaluate the FFS performances.

After the formation break, both objects will be orbiting without internal perturbations until the perigee pass preparation manoeuvre performed by CSC. FFS algorithms aiming to perform a two point DTM until the formation acquisition are mimic in the Flight Dynamics system. However, the orbit prediction cannot account for any thruster misperformance at this stage, so no cold-gas correction is assumed after the monopropellant thrust. As per the formation acquisition manoeuvres, the calibration performed on-ground aims to correct the errors in the thruster actuation, so this error in the orbit prediction should eventually disappear.

During the perigee pass both satellites' orbits can be propagated separately. Whereas in the first stage of the mission a mid-course manoeuvre (MCM) was expected to be performed after the perigee and the end of the GPS coverage in order to prepare the second DTM[1)], this approach was later discarded by further analysis in favour of the cold-gas correction[3)]. Nevertheless, the FDS shall be able to simulate this intermediate manoeuvre in case the difference with the on-board estimated position and the propagation is above a certain threshold.

3.3. Orbit determination

The orbit determination function in the Flight Dynamics System implements a batch weighted least square method[5)]. For PROBA-3, one of the main objectives of this function is ensuring the mission safety calibrating the automatic manoeuvres based on the accurate knowledge of the orbital evolution. Hence, the main performance requirements imposed on this feature are related to the accuracy of the relative orbit determination.

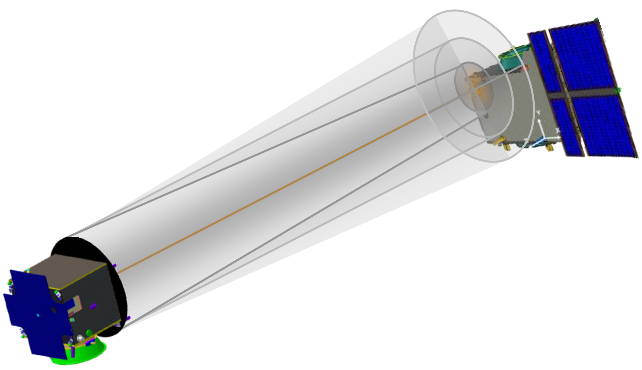

Fig. 2. Satellites in formation configuration. FLLS field of view can be seen pointing from the OSC base to the CSC corner.

According to these requirements and the orbital apogee height, the first question that arises is whether an 8-byte representation of the state vectors around the apogee would be good enough, considering that at this range, the numerical error would be in the order of 0.5 μm. The most accurate observations are provided by FLLS (Fig. 2) with a standard deviation of 50 μm (1σ), i.e. two orders of magnitude above the numerical errors. Therefore it has been preferred to keep the standard implementation of the propagation function, obtaining the relative states by differentiation of the absolute state vectors rather than integrating the inertia forces of the relative motion between the two satellites.

Due to mission constraints, only one ground station at Redu (Belgium) will be allocated for PROBA-3. The length of the passes vary from several hours (with visibilities during the apogee) to few minutes (perigee passes). This means that for most low height visibilities there will be not enough time to receive all the data required by the FDS, process it and prepare the commands to the satellite.

The orbit propagation performed during the determination differs from the orbit prediction algorithms explained in the previous section. During the formation flying phase, the actual OSC orbital state has to be reconstructed, not using any theoretical kinematic evolution or a simplified model to preliminary estimate the manoeuvres. The cold gas actuation telemetry has to be processed beforehand to generate the set of pulses performed by the OSC during the whole apogee pass, so it can be included in the dynamical propagation of the S/C as impulsive manoeuvres with their computed ΔV. A single calibration factor shall be used for all these pulses, since it would be impossible to estimate the cold gas actuators performances otherwise.

One of the main challenges of the orbit determination function for PROBA-3 comes from the amount of data that has to be processed and the different sources to be managed:

The station at Redu is providing Doppler and pointing angles. However, the coverage of one single station with respect to the orbital period is very low and the provided tracking too coarse for the mission accuracy requirements.

One of the main sources of data for the orbit determination will be the GPS telemetry. For about two hours around the perigee, the PROBA-3 satellites will be in visibility of the GPS constellation. Raw GPS data shall be available at the Flight Dynamics system, so pseudo-range and carrier phases can be used in the determination process. Whereas the GPS service provider for this mission has not been selected, typical values of the GPS orbit and clock accuracy permit achieving absolute errors of 1 m in real time and 10 cm within the first 10 hours[6)].

However, considering the short distance between the two satellites and that each of them is carrying its own GPS antenna, it is possible to perform double differences in the pseudo-range and phases in order to use them in the orbit determination process. By making these differences, the uncertainty of the GPS clock (and, therefore, one of the main sources of error in the estimation) is removed from the equations and the GPS orbital errors are mostly removed as well (except for a minor effect depending on the difference of the visibility angles between the two PROBA-3 satellites and each GPS spacecraft).

Considering that the main requirements on the determination process focus on the relative position, the usage of double-differences seems optimal for this problem.

However, it imposes several constraints to the GPS on-board receivers. The most relevant of them forces the synchronisation of the observations taken in both CSC and OSC in order to properly compute the differences. Failing to obtain both measurements exactly at the same epoch would force the interpolation of one of them, which would introduce the clock noise back into the problem, degrading the accuracy of the solution.

Multipath errors can be partially filtered by the on-board antenna ignoring the Left Hand Circular Polarized (LHCP) signals – reverse polarization coming from an uneven number of bounces, or signals weaker than the others. Further multipath observations processed on ground by the orbit determination system should be eventually rejected by the batch least-squares method, comparing the observation residuals with the weighted RMS of the observations corresponding to the same type.

Despite of the good accuracy of the DGPS data, it will be only available around the perigee, so it cannot be used to evaluate the formation acquisition manoeuvres or the formation flying phase. The metrology instruments telemetry, in particular the FLLS observations, will also be incorporated to the orbit determination process. This instrument, which is also used in closed-loop by FFS, provides a very accurate measurement of the distance between the two satellites, split in the longitudinal and lateral axes.

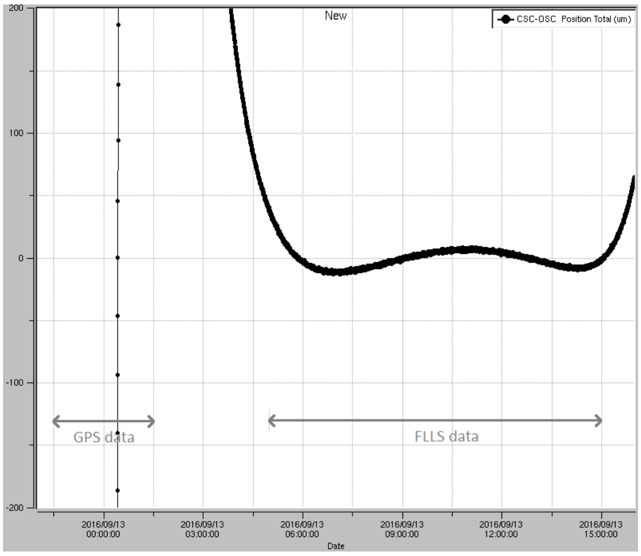

Fig. 3. Uncertainty of the relative position between the two satellites after the orbit determination. Only the GPS navigation solution was used during this simulation.

As shown in the previous figure, the inclusion of relative observations within the orbit determination process, even when it is performed estimating the absolute orbits, highly increases the accuracy of the relative distance between the two satellites.

The main drawback of using these observations within the orbit determination system is the dependency of the solution with the satellite attitude. Since the star trackers provide a very accurate pointing, it will be processed in the FDS to use the provided attitude as an input to computation of the nominal FLLS measurements in the orbit determination function.

The FLLS lock will be available between the formation acquisition and the perigee pass preparation manoeuvre half an hour after the formation break. However, in order to have some observability of this manoeuvre before it is corrected by the cold gas thrusters, the FDS needs some data in this interval. The only source of measurements available at this stage comes from the ISL. According to the manufacturer specification, a pseudo-range with 0.75 m error can be obtained from this link. ISL will also be used during the apogee as backup for the longitudinal measurement from the FLLS, with the CLS or the coronagraph camera providing information of the lateral displacement of the formation.

4. Manoeuvre Optimisation

Being part of the PROBA missions, the on-board autonomy is a key feature of these satellites. As explained before, the formation break and reacquisition is automatically triggered on-board, but the space segment is also prepared to perform other manoeuvres, mostly related to the reconfiguration of the formation, either autonomously or with very little ground intervention.

The FDS is designed to optimise and prepare several manual manoeuvres to be commanded to the satellites, but also to compute the manoeuvres automatically performed on board in order to predict orbital events and assess the performance of the system and update the thruster calibration for the on-board system to consider in future manoeuvres.

4.1. Automatic manoeuvres

Besides the nominal manoeuvres performed every orbit, there are some formation flying experiments that permit a reconfiguration of the formation and the system is prepared to automatically execute them upon ground request[3]:

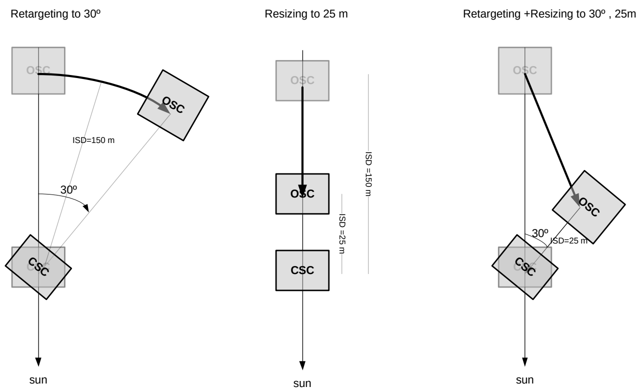

Fig. 4. Rigid formation reconfiguration manoeuvres.

- Resizing: aims to modify the inter-satellite distance from the nominal formation station-keeping to an alternative value (nominally, 25 m). This plan includes the initial resizing at apogee, a 30 minutes station-keeping, perigee pass and formation reacquisition.
- Retargeting: similar to the previous one, but instead of changing the inter-satellite distance, it intends to modify the

pointing direction of the formation, with an angle of up to 30 degrees with the nominal Sun direction.
- Simultaneous retargeting plus resizing.
- Six degrees of freedom (6DoF) manoeuvre (thrusters only).

Whereas the previous manoeuvres are computed on board and executed in closed-loop with the sensors telemetry, their nominal impulses are also calculated in the flight dynamics and, once the manoeuvre telemetry is available on ground, assessed as part of the Performance Evaluation Tool (PET) included in the FDS system.

Additionally to the formation reconfiguration manoeuvre, the PROBA-3 satellites Failure, Detection, Isolation and Recovery (FDIR) system on-board will ensure that the two satellites are safe for at least four days in case of a single failure. This FDIR system can trigger a Collision Avoidance Manoeuvre, placing the two satellites in a drifting orbit. FDS cannot predict these manoeuvres, but they will be evaluated as part of the orbit determination and manoeuvre reconstruction functions.

4.2. Commanded manoeuvres

FDS is also in charge of computing the manoeuvres whenever the space segment enters a non-nominal state that prevents the on-board software from automatically acquiring a routine orbit. In particular, the following events shall be managed by the FDS:
- Correction of injection errors: the manoeuvres to be performed by the satellites (still in stack configuration) to achieve the nominal orbit after launch.
- Drift stop manoeuvres after CAM or stack separation: keeping the two satellites in a safe orbit configuration until the problem that triggered the FDIR is corrected from ground. Nominal inter-satellite distance of this safe orbit is 1 km.
- Initial formation acquisition or recovery after CAM: these manoeuvres aim to leave the two satellites at nominal formation range in order to start (or reacquire) the routine operations. This recovery has to be performed in several steps: first shrinking the safe orbit dimension from 1000 to 250 m. After an orbit dedicated to assess the previous manoeuvre batch, a second step will reduce the distance to the nominal 150 m. Another orbit determination will be performed and any further manoeuvre to achieve the nominal state shall be computed before setting the satellites in normal mode.
- End of life manoeuvres: Before the system passivation, the FDS will be in charge of computing the manoeuvres to place the two satellites in orbits in which they cannot collide. A first estimation of the re-entrancy time in the Earth atmosphere will be performed as part of this computation.

Whereas initially the flight dynamics was intended to include a complex software for the manoeuvre optimisation, the constraints finally required by the mission (at least in the current stage) would permit a more relaxed approach for this component.

Since there will be a full orbit dedicated to ground operations between different manoeuvre batches, the main constraint with respect to the station visibility would be having one pass long enough (or two passes with enough separation) to permit performing an orbit determination and refining the next set of manoeuvres. This condition shall be easily achieved without imposing any mathematical constraint to be included in an optimisation process with the manoeuvre time and ΔV.

Besides the station visibility, the reaction wheel rate has to be monitored during the manoeuvres, since the torque provided by these wheels is quite low and therefore they can be easily saturated. Whereas the manoeuvre time can be selected to minimise the satellite slews required to perform the manoeuvre in the required direction, it is also possible to perform a wheel off-loading together with the manoeuvres. As above, this constraint can be easily monitored and decoupled from the manoeuvre computation without being included in the optimisation problem.

Therefore, considering that the imposed constraints can be independently evaluated, it is possible to notably simplify the manoeuvre optimisation, directly computing the ΔV and thruster actuation.

4.3. Collision risk evaluation

As part of the manoeuvre optimisation process, the FDS shall evaluate the safety of the constellation for every set of manoeuvres commanded from the system. The main concern regarding the mission integrity is the risk of collision between the two satellites, but also the constellation evaporation, defined as a separation between the two spacecrafts such as the formation recovery is not possible with the available resources[1)], has to be considered.

The flight dynamics system will include the ***closeap*** component, in charge of computing the risk of collision given the two satellite orbits and their covariance evolution[7)], both computed during the orbit propagation. The Alfriend and Akella algorithms[8)] are used within this component to provide the probability of collision.

The FDS will calculate this risk for the nominal orbit evolution assuming that the computed manoeuvres are performed without any problem, but the collision probability will be also analysed in case of failure to execute any single manoeuvre commanded within a batch, taking into account that the on-board software is implemented so that such a failure will automatically abort any further commanded manoeuvre.

Additionally, the FDS will also analyse the case of manoeuvre misperformance, simulating several cases between severe under-performance (around 50%) up to a 10% over-performance (both configurable at software level).

5. Ground calibration

Besides the aforementioned manoeuvre (and thruster) calibration, the FDS is required to support the calibration of different on-board parameters to optimise the FFS performances during the mission.

The two satellites are launched in a stack configuration, as shown in Fig. 5. During the LEOP and the first orbits of the commissioning phase, the satellites will remain together, activating all the instruments. The advantage of this configuration is that all the elements are kept in a well-known geometry that facilitates the estimation of any constant biases of the relative instruments. In this stage, the FDS is required to process the GPS data in order to correctly initialise the rGPS software on board, estimating any mounting or systematic bias in the antenna that would lead to an error in the relative position estimation during the formation flying.

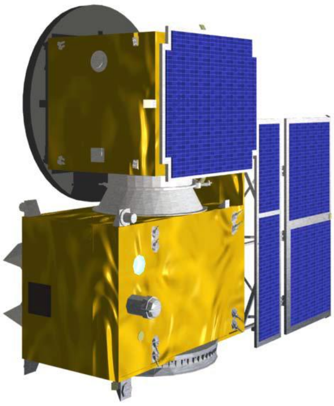

Fig. 5. Satellites in stack configuration.

The centre of mass (CoM) position and the inertia matrix of each satellite will be measured on ground and tabulated as a function of the mass for its usage both on-board and in the flight dynamics system. However, the analysis of the torques and angular rates generated by the reaction wheels would permit both the calibration of the wheels and, to some extent, the verification of the mass properties of the satellite.

One of the main limitations of the platform, in particular for the CSC, comes from the reaction wheels. As explained above, they provide a relatively low torque, but the shadow of the OSC on the CSC displaces the centre of pressure for the solar radiation with respect to the CoM. This generates a perturbation torque during the formation flying that has to be compensated by the wheels, and forces them to be de-saturated every orbit. In order to prevent the constant off-loadings, the CSC performs two roll manoeuvres per orbit, rotating 180 degrees right after the perigee-pass preparation manoeuvre and before the formation reacquisition. Considering the nominal orbit evolution, the solar radiation perturbation torque in the CSC can be roughly predicted for all the mission lifetime. This torque law could be also corrected based on the actual telemetry from the wheels in order to predict if any further de-saturation will be required before the next station pass.

6. System automation

Previous PROBA missions intended to demonstrate the on-board autonomy of the system and did not include any flight dynamics system in the ground segment. Given the complexity of the PROBA-3 system, this was not a possibility for this particular mission. However, in order to reduce the cost of operating the system, the FDS has to be heavily automated, trying to minimise the manual intervention of the operator except in cases when some decision has to be taken, in particular when selecting among different manoeuvre profiles after a manoeuvre computation.

In order to achieve this level of automation, the FDS scheduler has a direct interface with the mission planning system (IMPS) of the ground segment, which includes the flight dynamics operations in the planning and directly triggers the execution of generic flight dynamics sequences without human interaction.

7. Conclusion

PROBA-3 flight dynamics system includes all the typical functions provided by any FDS for a generic mission. However, the formation flying imposes some additional requirements on the orbit management functions, considering that the automatic manoeuvres performed on-board have to be accounted for in the orbit prediction and calibrated during the orbit determination.

In order to achieve a high level of automation on board, some parameters that are usually provided by the satellite manufacturer are intended to be calibrated in flight by the FDS based on the telemetry, aiming to improve the performances of the on-board system.

Furthermore, FDS results are intended to be used for the evaluation of the formation flying performances by comparing them with the nominal formation laws and the data retrieved from telemetry, making this system a key function to evaluate the success of the PROBA-3 mission.

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