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# PROBA-3 Rendezvous Experiment Design and Development[1]

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**Abstract:** PROBA-3 is a technology demonstration mission with, among others, the aim to develop up to Technology Readiness Level (TRL) 8 / 9 the technology required for Formation Flying (FF): GNC, metrology, actuators, etc. In the context of this mission, and for its strong synergies with the Rendezvous (RV) required technology, a dedicated Rendezvous Experiment (RVX) has been designed and developed to upgrade the TRL of that RV technology and demonstrate the feasibility of vision-based RV as a valuable option for this type of scenarios.

## 1. Introduction

Recent years have seen a growing interest towards the development of the GNC functions associated to RV and Formation Flying (FF) scenarios, motivated by the need of increasing the Technology Readiness Level (TRL) of different technologies required to successfully accomplish several of the future planetary and science missions. Moreover, different sources (for instance, [1]) have demonstrated the benefits of running planetary RV in non-circular orbits, since though circular relative motion is simpler, and better known and tested (from ISS-ATV experience, see in [2] a film showing the automatic approach and docking of ATV and ISS), elliptical option is being identified as interesting for a cost-effective mission delivering heavy vehicles for planetary exploration.

On the other hand, data fusion is of paramount importance for having a robust enough mission design in RV scenarios. Particularly important is the selection of a reliable set of sensors for measuring the *relative* motion, since for close distance between the two satellites (up to few tens of km, as a maximum) Navigation function must be based on it, instead of estimating two absolute motions (which is

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[1] The results in this paper were obtained in the frame of the PROBA-3 development phase B2.

the Navigation approach for longer distances). Several sensors combinations are possible, being those based on optical devices, on one hand, and on radiofrequency signals, on the other, the two best suited candidates.

This article presents the design and development of a Rendezvous Experiment (RVX) to be flown by PROBA-3 mission. This RVX is based on only-camera measurements (images) taken on a target in free flight, though controlled in attitude. The main advantage of this solution is that it is simpler and hence more robust than if considering additional sensors for relative motion, since no data fusion is required for estimating relative motion.

The work presented in this paper is part of the activities performed by DEIMOS Engenharia and FFCUL (Portugal) in the frame of the PROBA-3 Phase B2. Contents are as follows: Section 2 presents the generals about the PROBA-3 RVX, including mission constraints and RVX main drivers and objectives. Section 3 presents the design of a nominal RVX profile compatible with the imposed constraints. Section 4 presents the relative navigation system the RVX relies on, while Section 5 presents some results of the first analyses performed on RVX.

## 2. Generals about PROBA-3 Rendezvous Experiment

A set of **demonstration objectives and requirements** is foreseen for the PROBA-3 technological experiments. Among them, those envisaged for the RVX are 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;
- Consolidation and maturation up to flight level of a GNC architecture and concept for RV in elliptical orbits

As additional set of drivers for the RVX design, the following guidelines should be followed in the PROBA3 context when devising the RVX:

- The experiment shall be totally complementary, without duplicating effort and results;
- The experiment should not imply major constraints in the PROBA3 baseline;
- The experiment shall make maximum re-use of available equipment and resources;
- The experiment shall not represent a risk to the mission.

Apart from these guidelines, a set of **mission constraints** provided the ‘legal’ playground for RVX design. These constraints are mainly a consequence of RVX being an experiment housed by a mission whose main objectives are not linked to the technological experiments themselves. In a general program (i.e. not experiment basis) the user of specific equipment would impose all relevant H/W and S/W requirements to ensure its efficient and safe use. On the other hand, for an experiment the equipment may be pre-selected based on other system needs. This is the case of RVX, for which some of the major constraints come from the fact that the Visual Based Sensor (VBS) the RVX is based on is a sensor that will be used by the mission for other purposes different from RVX.

The following bullets briefly present the collection of constraints the RVX design had to respect from design stage:

- RVX shall be designed considering the VBS on the Occulter SC (OSC), acting as chaser for RV, and with the boresigh oriented along $X_{OGFF}$.
  VBS bore sight is oriented to maximize possible system usage, since all of other VBS users required camera to be mounted in this face. Conversely, the light pattern to be imaged in the Coronagraph SC (CSC), acting as target for RV, will be placed in $-X_{CGFF}$ face. See figure below for a graphical representation of the mounting geometry and these two body (i.e., attached to the satellites) reference frames (OGFF and CGFF).

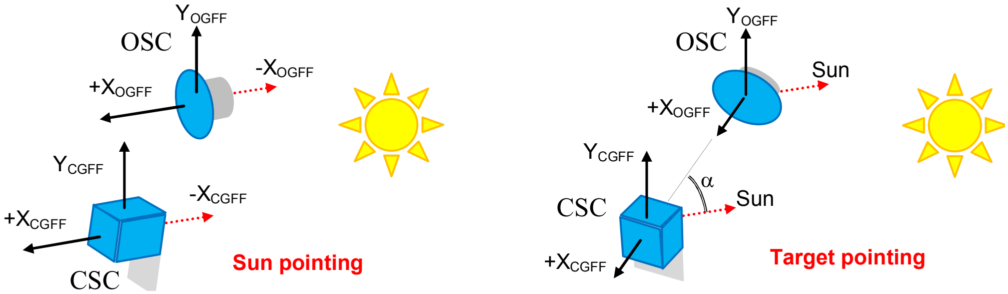

**Figure 1 PROBA-3 SCs Sun pointing requirement**

- RV experiment shall consider a maximum target pointing period of 6 hours per orbit when the maximum offset between the $X_{OGFF}$ and the Sun direction is within +30º in the $X_{GFF}$-$Z_{GFF}$ plane and +30º in the $Y_{GFF}$-$X_{GFF}$ plane.
  This requirement limits both the time per orbit that both satellites may be out of Sun pointing, to 6 hours, and the maximum allowed rotation from Sun pointing condition, to 30º. Considering that orbital period is about 19.7 hours, 6 hours for target pointing represents a stringent requirement for the de-pointing of satellites, acquisition of relative navigation and the corresponding execution of manoeuvres.
  One other important limitation imposed by these requirements is a maximum rotation from Sun pointing of 30º, either in the $X_{OGFF}$ - $Z_{OGFF}$ plane, either in the $X_{OGFF}$ - $Y_{OGFF}$ plane. Considering that camera is installed in the OSC with its boresight oriented towards $+X_{OGFF}$ and that the beacons are installed in the face $-X_{CGFF}$ of the CSC, a maximum allowed offset from Sun pointing of 30º means that CSC must always be well behind the OSC, with respect to the Sun. This limitation is illustrated in figure below.

- <u>RVX shall not make use of ISL to receive or communicate with the companion satellite</u>.
  The consequence of this requirement, imposed for robustness sake, experiment fidelity with respect to an eventual RV mission, and simplicity of design and development of the RVX, is that target (CSC) will implement an off line sequence of attitude manoeuvres enabling the relative navigation during a target pointing condition, by 'showing' the beacons to the camera in the chaser (OSC), actively controlled by RVX SW. This translates into a requirement of the maximum dispersion that can be afforded by RVX profile in order to allow a successful acquisition of beacons after a blind period.

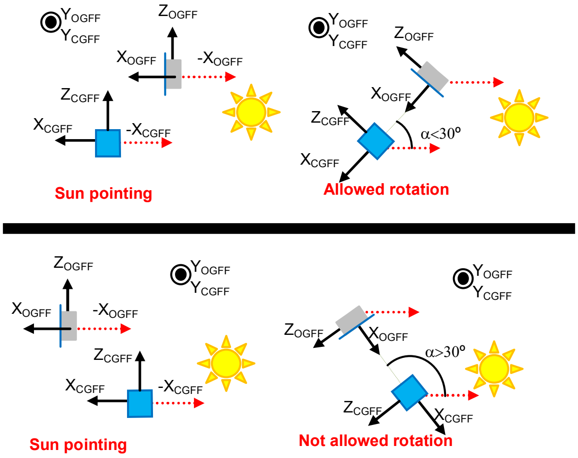

**Figure 2 PROBA-3 pointing constraints: allowed (above) and not allowed (below) rotations**

These constraints and drivers imposed a real challenge to the design of a feasible RVX profile, since the stringent pointing constraints, combined with the expected dispersions between manoeuvres due to relative navigation errors, made necessary the conception of a manoeuvring strategy guaranteeing the control of dispersions while keeping the RVX Δv within reasonable margins.

## 3. Design of a feasible RVX profile

As a consequence of the drivers, guidelines and constraints explained above, any sequence of concatenated Δv manoeuvres making part of a feasible RVX profile should fulfil following conditions, in order to be compatible with constraints:

- **Avoid as much as possible an evolution of angle OSC-CSC-Sun above 30º**. The reason for this driver is that only for angles smaller than this limit it is possible a relative navigation between OSC and CSC through the commanding of a target pointing manoeuvre to acquire the mire pattern in CSC from the VBS camera in OSC.

- **Design passive safe manoeuvres**. This means that the designed Δv manoeuvres must generate a non-drifting motion, in this way fulfilling the passive safety constraints from the RVX profile design stage.
- **Avoid as much as possible large time intervals between two consecutive manoeuvres**. Typical expected relative navigation velocity errors (in the order of 1mm/s at distances OSC-CSC of some few hundreds of meters) generate a huge dispersion if propagated only for few hours. As a consequence, nominal manoeuvres of RVX profile must either consider short periods between consecutive manoeuvres, either allow the possibility of commanding as many mid-course manoeuvres as needed to counteract the generated dispersion.
- **Design nominal manoeuvres as close as possible to Sun pointing condition**. In this way, time out of Sun pointing condition is minimised, since in this case it would be possible to command the manoeuvre while in Sun pointing, i.e., with CSC-OSC-Sun aligned along the same direction.
- **Minimise, as much as possible, manoeuvre cost**. Cost of manoeuvres if not in typical v-bar approach (which is the typical configuration for taking advantage of the relative orbit dynamics in elliptical orbits) might generate an extra-cost of the RVX, i.e., typical two-boost manoeuvres are more expensive if not in typical v-bar jumps. This issue is to be taken into account.

After combining all these factors, a design process for this sequence of manoeuvres was conceived as follows:

- The RVX profile will be composed of a sequence of **way points**, defined by the orbital position (i.e., true anomaly) and the relative position.
- Starting at a given way point, and for a given transfer time (i.e., time between two consecutive way points), compute a Δv (jump) manoeuvre respecting two criteria:
    - Chaser goes back to CSC-Sun line at next way point, that is, OSC is again (same as at the first way point) aligned with CSC and Sun, in this way allowing the execution of the next manoeuvre in Sun pointing (not requiring target pointing for VBS navigation);
    - Resulting motion between the two way points is non-drifting, i.e., passive safety driver is met by manoeuvres design. As a consequence, range at the second way point is a consequence of initial range and transfer time: in other words, imposing transfer time, non-drifting motion, and the condition of having OSC-CSC aligned with Sun at every way point, range is not a free parameter, but a consequence of these conditions.
- For each transfer time (i.e., for each potential way point), compute the corresponding relevant parameters allowing the selection of the most suitable manoeuvre; these parameters are:

  - Range, i.e., maximum distances acquired during transfer between the two way points;
  - Maximum angle OSC-CSC-Sun during transfer between the two way points;
  - Cost of manoeuvre;
- In view of these results, select the new way point by choosing a transfer time, and as a consequence of it, an orbital position and a range.

From the point of view of Mission Analysis, the imposed pointing constraints make RVX feasible only at epochs in which Sun declination on the orbital plane is small, i.e., when Sun crosses the reference orbital plane. From a dedicated study performed in the course of the PROBA-3 phase-2, it resulted that this happens only along apogee-perigee direction, hence this is the Sun position that will be assumed in the design of the RVX profile.

By running this design process, the RVX nominal profile was designed as follows:

- **Far Range Jump Apogee to Pre-perigee**: assuming satellites aligned with Sun direction at 150m at apogee, a jump manoeuvre takes OSC to a distance of almost 750m some 127º in true anomaly before perigee (i.e. $\nu$=233º).
- **Far Range Jump to Perigee Passage**: in terms of range it does not seem to provide any evolution, however, this manoeuvre allows passing the perigee fulfilling the two conditions above, i.e., angular distance to Sun pointing smaller than 30º and non-drifting condition. Final true anomaly and distance is 32º and 737m, respectively.
- **Far Range Jump Post-perigee to Previous Apogee**: during this phase, satellites aim at a distance of 609m just 11º before the apogee. Since the manoeuvre starting this phase is commanded quite close to perigee, associated $\Delta V$ is very high (around 150mm/s for a manoeuvre lasting around 40 minutes), however the cost of delaying this manoeuvre to an orbital position farther from perigee would be the exponential increase of dispersions and, as a consequence, the eventual loss of experiment, caused by eventual angular distances from Sun pointing bigger than 30º.
- **Far Range Forced Motion Around Apogee**: this is the first forced motion included in the profile, aiming at bringing OSC at a distance of only 50m from CSC, starting from around 600m. This forced motion occurs with Sun, CSC and OSC aligned, i.e., in principle satellites will not need to command a target pointing manoeuvre to allow VBS navigation. This phase is designed as a typical forced motion phase in RV profiles, i.e.:
  - A first acceleration phase until reaching the intended relative velocity between OSC and CSC;
  - A second phase, in which satellites approach at a constant relative velocity (in this case, 5cm/s, as compromise design value between fuel cost and phase duration);
  - A final exponential deceleration phase, in which relative drift is nullified at 50m distance.

- **Close Range Jump Apogee to Pre-perigee**: this is exactly similar to the corresponding far range manoeuvre, except for the initial (and hence, final) distance: now OSC evolves from an initial distance of 50 at apogee, to 202m at 233º. This phase requires the smallest manoeuvre of all the RVX profile: only 4mm/s, to be completed in less than 1 minute.
- **Close Range Jump to Perigee Passage**: similar to the corresponding far range phase, but for shorter distances, this phase takes OSC through perigee to a true anomaly of 50º and practically the same range. Again, as a consequence of the shorter distance with respect to the similar far range phase, the cost of this manoeuvre is much lower: 20.8mm/s against 73mm/s in the far range case.
- **Close Range Jump Post-perigee to Pre-apogee**: similar to the corresponding far range phase, final distance and true anomaly for this phase are 166m and 169º, respectively, needing a manoeuvre of 42mm/s.
- **Close Range Forced Motion Around Apogee**: during this forced motion phase, OSC approaches CSC along the Sun pointing direction, from 166m to only 10m. Same sub phases as in corresponding far range phase are present in this one: acceleration, constant drift phase (at 3cm/s) and exponential deceleration, completed in almost 2 hours.
- **Station keeping at 10m distance**: just to test the typical RV phase previous to eventual docking or capture, a station keeping phase at 10m during 1 hour will keep relative distance around apogee at a very cheap cost, in terms of fuel.
- **Retreat to 150m distance**: finally, a retreat phase is needed to go back to PROBA3 nominal configuration at 150m. This phase is completed as forced motion, in the same way as the other forced motion phases explained above.

Next figures show graphically the most relevant parameters of RVX nominal profile.

- Figure 3 shows the evolution of the relative position between OSC and CSC during RVX nominal profile execution in the Local Vertical, Local Horizontal [3] (LVLH) reference frame. As it can be seen, it is easily distinguishable the two different ranges at each of the two sequential orbits composing the nominal profile. Manoeuvres are denoted by a red line.
- Figure 4, on the other hand, shows the main two advantages of this profile: first of all, it is always possible to perform a manoeuvre (including those mid-course manoeuvres intended for dispersion counteracting) during RVX execution, since all main (i.e., attached to way points) are commanded with OSC & CSC aligned with Sun, and evolution between way points does not impose large angular excursions from this configuration. Second, the designed manoeuvres are passive safe by design, since they do not impose any difference in the semi major axes of both satellites, unless (obviously) during forced motion phases.

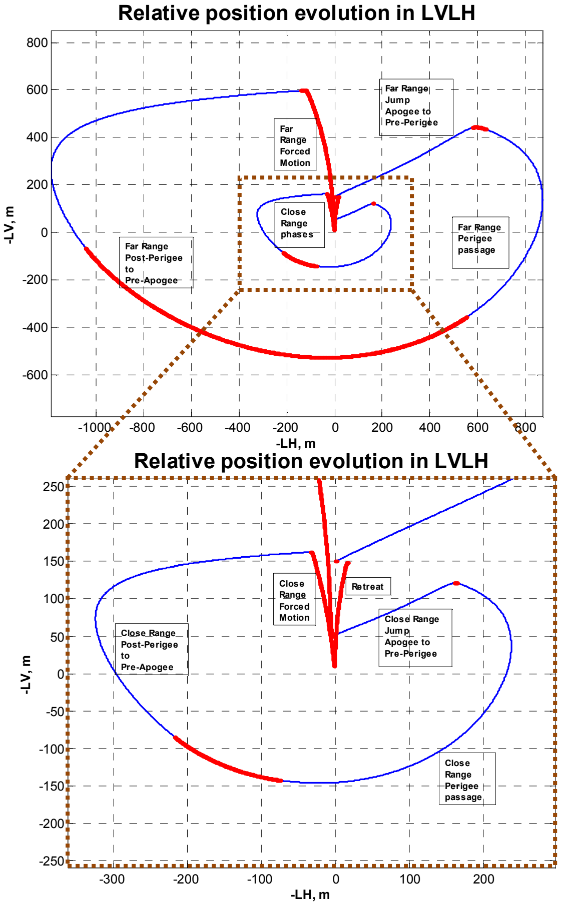

Figure 3 Reference RVX profile in LVLH axes: zoom on close range below

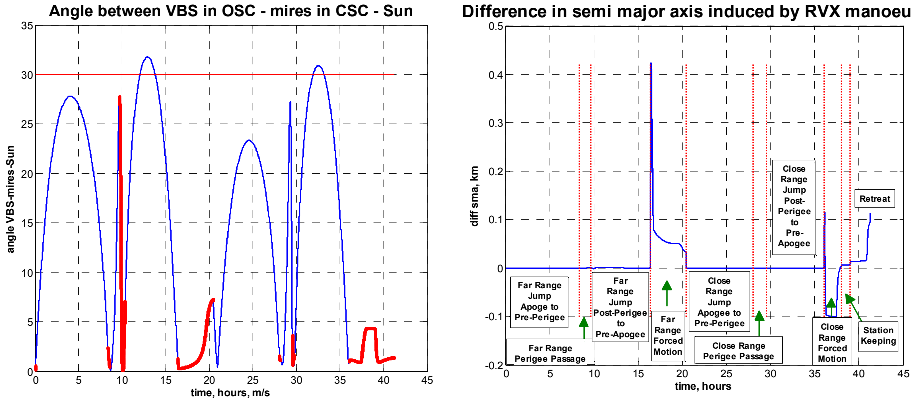

Figure 4 Evolution of angles between VBS-mires-Sun during nominal profile in the left; semi major axes difference evolution along nominal profile phases in the right

## 4. Vision based relative navigation in PROBA-3 RVX

As stated above, the only relative motion sensor used by RVX is a camera (VBS) mounted on OSC. This camera, by taking images of a light pattern installed in CSC, enables the processing of the corresponding raw image and the subsequent derivation of the relative position estimation.

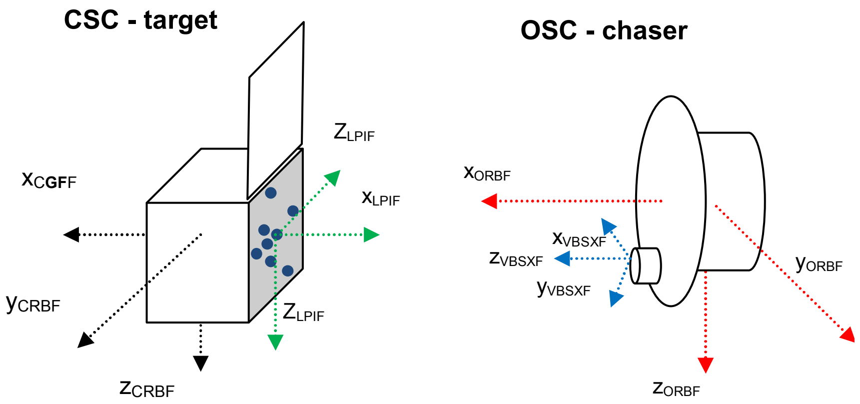

**Figure 5 Schematics of relative sensing between OSC and CSC during RVX**

As it can be seen in Figure 5, a camera mounted on OSC will take images of a set of beacons installed on CSC, and arranged to ease the estimation of both relative position (including range, when distance allows for it) and relative attitude.
However, since VBS will have additional usages within PROBA-3 different from RVX, a process for consolidating a unified set of VBS requirements satisfying all users was carried out. Some of the most relevant requirements on VBS for RVX are:

- **Operational Range for VBS shall be between 10m and 2km**. Any RV sensor must be prepared to work with the highest possible accuracy in a wide range of distances. During former phase B1 required operational range extended up to 5km, however due to the constraints imposed on the SC pointing, and some other mission-related constraints, this number was decreased down to 2km.
  This does not mean that camera has to provide fully resolved images for the complete operational range: for longer distances, it is enough to detect a blob of beacons (or a sub-pixel light) in order to derive LOS measurements; only for closer ranges it is necessary to derive distance measurements from fully resolved beacons.
- **Line of sight (LOS) accuracy at 150m of 5” (1σ)**. RVX Navigation filter is based on the estimation of relative motion (position & velocity) taking as inputs only a set of LOS measurements to a pre-defined (known) pattern of

mires. The required accuracy applies to the error of the measurement with respect to the structural reference frame of the sensor (i.e., accounting neither for calibration errors, nor for location / orientation errors with respect to SC frames).

- **Field of view shall be 10ºx10º**. This value is a compromise between VBS accuracy (the narrower the FOV, the more accurate the sensor) and operational considerations (the narrower the FOV, the more complex the acquisition of a target pointing profile and the image-tracking of a identified set of beacons). On the other hand, this value represents a generous margin allowing relative navigation from a Sun pointing condition for wider RVX intervals.
- **Maximum CSC rotation from nominal of 20º**. In the same direction as the requirement above, this one allows the minimisation of the CSC attitude manoeuvres previous to a relative navigation interval.
- **Measurement frequency > 1Hz**. In order to improve estimation filter performances, it is necessary to feed it with as many processed images as possible. This 1Hz rate is in the order of magnitude of typical RV scenarios; slower rates might also work properly, with no big impact on GNC performances. However, IP algorithms are not particularly demanding for this beacons-like scenario; on the other hand, GNC has been tested in a LEON3 @ 70MHz with very light computational weight. As a consequence, 1Hz was selected as a compromise between GNC accuracy and resources allocation.

## 5. PROBA-3 RVX GNC analysis

With the objective of testing what RVX GNC performances can be expected, a complete simulation was run with the GNC system defined as explained above closing the loop.

The developed RVX GNC was integrated in DEIMOS Rendezvous Functional Engineering Simulator (RVD-FES) for six degrees of freedom, high fidelity simulation of environment effects and closed-loop testing. The simulator, besides single simulations, allows performing Monte-Carlo analysis. Following bullets present the setup of the simulator:

- Dynamics, Kinematics and Environment
    - Earth central gravitational field plus 4th order model for gravitational harmonics.
    - Solar radiation pressure considering S/C geometry and attitude
    - Atmospheric drag force and torque
    - Third body gravity pull
- GNC equipment
    - Eight 10 mN thrusters on OSC, with optimal thrust assignment (simplex). Ton-Toff thrusters detailed model consider realistic MIB, dynamic response, misalignment errors and thrust noise.

- Camera – IP chain was simulated by a performance model, providing the sensed (with errors) positions of light beacons in VBS focal plane for every given simulation conditions.
- Star tracker, with bias and noise errors.

Results are shown in following plots.

Figure 6 shows the evolution of relative position in LVLH frame (target, i.e., CSC, is always placed in [0,0]; plot shows the relative motion of chaser, OSC, around target) while Figure 7 provides the evolution of relative velocity along with the required & commanded manoeuvres; note the order of magnitude (tens of mN) of those manoeuvres. Finally, Figure 8 shows the error in the estimation of the relative velocity, which is the key performance parameter to improve in a RV scenario, since it greatly determines the errors in the execution of manoeuvres and hence, the level of dispersions in relative position to be counteracted during profile evolution.

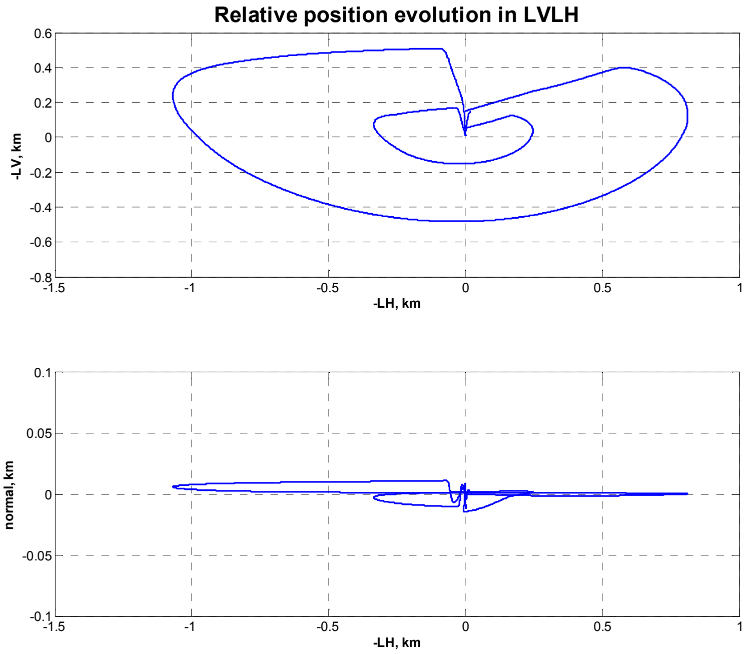

**Figure 6 Evolution of relative position in LVLH frame**

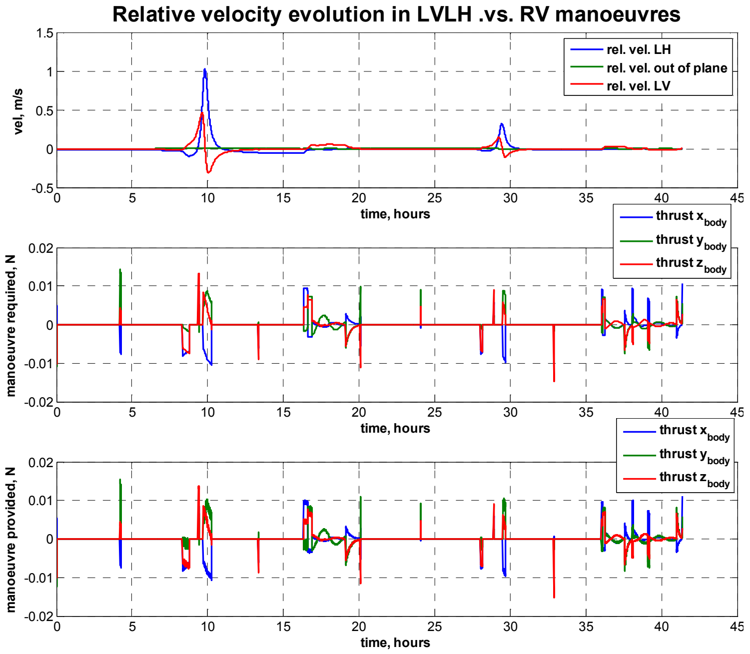

Figure 7 Evolution of relative velocity in LVLH frame and manoeuvres along time

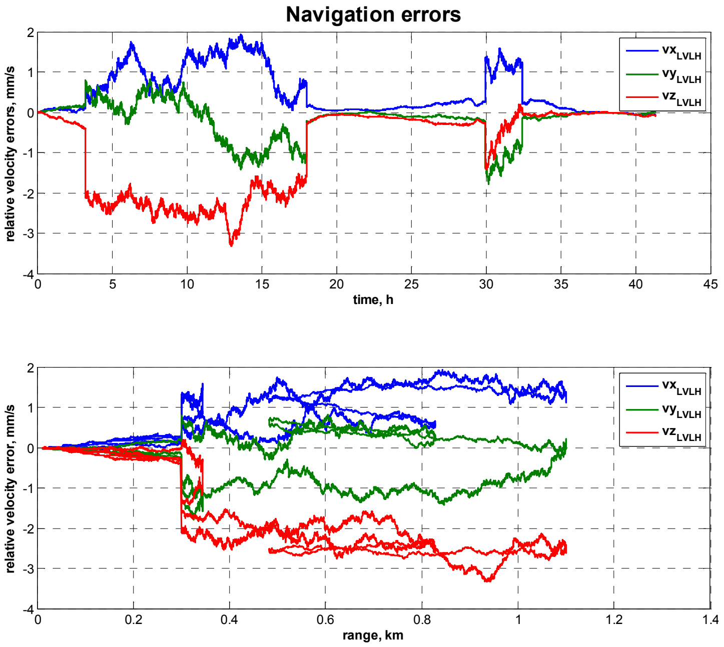

Figure 8 Evolution of relative velocity navigation error along time (above) and with respect to distance OSC-CSC (below)

## 6. Summary and Conclusions

This paper presents the design in its current stage at phase B2 of a Rendezvous Experiment to be flown by the PROBA-3 mission. After a presentation of the major mission requirements and constraints, RVX design has been detailed in terms of reference profile and relative navigation strategy. Finally, a one-shot simulation is shown demonstrating the feasibility of the RVX as it is conceived now. The main idea to be retained is that PROBA-3 mission will certainly allow the upgrade up to TRL 8 / 9 of the RV related GNC algorithms and technologies required to perform autonomous RV in elliptical orbit.

## References

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3 K. Yamanaka, F. Ankersen, "New State Transition Matrix for Relative Motion on an Arbitrary Elliptic Orbit", Journal of Guidance, Control, and Dynamics, Vol. 25, No 1, Jan-Feb 2002, pag 60–66