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PROBA-3 PRECISE ORBIT DETERMINATION BASED ON GNSS OBSERVATIONS

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ABSTRACT

ESA's PROBA-3 mission[1] will demonstrate high-precision formation-flying of a pair of satellites in a High Eccentric Orbit (HEO) with new developed in-orbit technologies. It is a solar coronagraph science experiment consisting of two spacecraft, where the telescope of the solar coronagraph is mounted on one spacecraft, while the other spacecraft is maneuvered to block the solar disk as seen from the coronagraph spacecraft. The launch of the spacecraft is expected in late 2020. The PROBA-3 spacecraft pair will fly divided between periods of accurate formation flying, when payload observations will be possible, and periods of free flight. Each spacecraft will be able to maneuver itself. The typical separation distance between the spacecraft will be about 150 m. As the second spacecraft carrying the occultation disk is maneuvered relative to the primary spacecraft with the coronagraph on-board both spacecraft are considered to fly in the same orbit.

ESA's Navigation Support Office (NavSO), located at the European Space Operations Centre in Darmstadt, Germany will use this ESA mission to test, analyze and demonstrate advanced concepts for spacecraft precise orbit determination (POD). This paper will provide an overview of the expected performance for absolute- and relative satellite POD for the PROBA-3 mission, based on simulations conducted in the preparation for this mission.

Figure 1: Principle of PROBA-3 solar coronagraph science experiment

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INTRODUCTION

Each of the two PROBA-3 spacecraft will have a GNSS receiver on-board with the capability of tracking multi-frequency (dual freq.), multi-signal and also multi GNSS constellation (Galileo and GPS). In addition, the GNSS equipment consists also of two antennas on each satellite, a high gain antenna, which will point towards the Earth during the Apogee phase of flight and a patch antenna, pointing away from the Earth, which will be used during the perigee phase of the flight. PROBA-3 will fly below the altitude of the GNSS constellations during the perigee phase and above the altitude of the GNSS constellations during apogee phase. Taking into account the recent developments related to the interoperable GNSS Space Service Volume (SSV), which is supported by all GNSS providers, the PROBA-3 mission can be considered as an ideal case to demonstrate the benefits of an interoperable GNSS SSV on end-user level.
With a perigee altitude of about 600 km and an apogee altitude of about 60,530 km PROBA-3 provides a perfect test platform to demonstrate the availability of GNSS signals in space, in terms of signal reception and signal strength, covering a very large altitude range, very different geometry conditions and also dynamics of the satellites in terms of velocity conditions.

In this paper, the main focus will be on the analysis of the visibility conditions and respective link-budget considerations for PROBA-3 in order to develop the most realistic scenarios. The results of the PROBA-3 Precise Orbit Determination (POD) should be considered as initial results. The POD related performance aspects will be addressed on a later stage of the project.

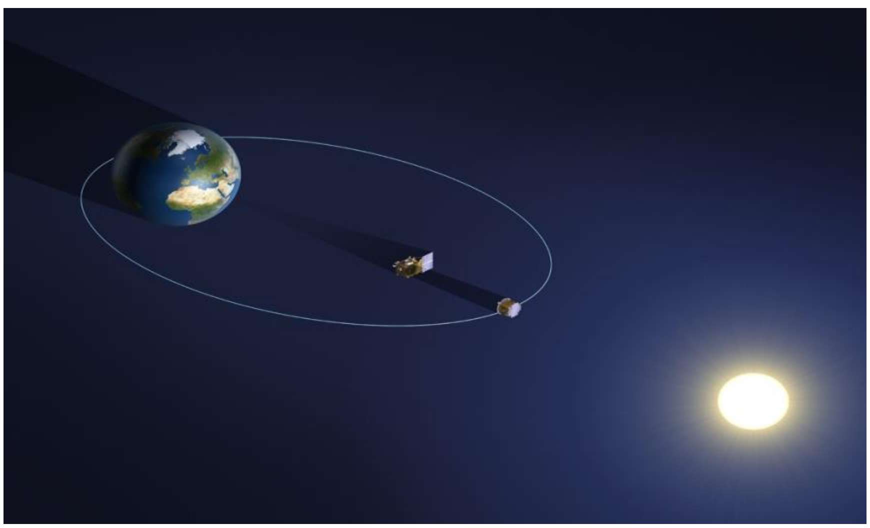

Figure 2: Orbit configuration for PROBA-3 solar coronagraph science experiment geometry

GNSS SIGNAL AVAILABILITY ANALYSIS

The general situation related to the relative geometry between GNSS satellites and space user satellites is outlined in Figure 1. As can be seen, the geometrical visibility conditions are strongly depending on the orbit altitude and also on the possibility to use signals from the Main Lobe and also the 1st Side Lobe in the Link-Budget calculations.

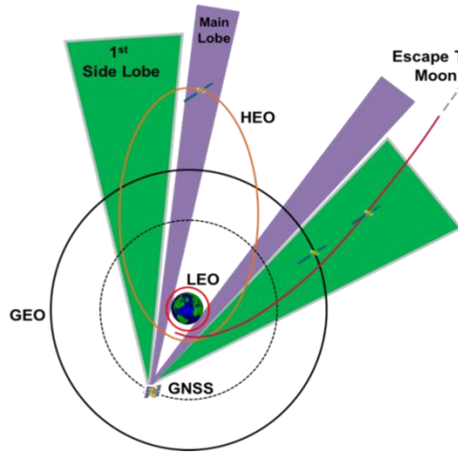

Figure 3: Relative geometry between GNSS constellations and space user for visibility analysis

GNSS signal availability simulations setup for PROBA-3

In order to accurately assess the expected GNSS signal availability in space for the Proba-3 mission, it is important to have realistic assumptions and the associated simulation setup. The setup adopted for this study is hereafter described. The orbital elements for the Proba-3 satellites are defined in Table 1.

Table 1. Proba-3 satellites - orbital elements.

Osculating elements	Proba-3 master / chaser
a	36943 km
e	0.8111
i	59 deg
ω	188 deg
Ω	152 deg
ϑ	0 deg / -0.016 deg
Altitude at perigee	601 km
Altitude at apogee	60529 km
Relative separation at perigee	2 km
Relative separation at perigee	0.2 km

As each Proba-3 satellite will carry a dual-frequency multi-constellation (Galileo and GPS) receiver, only the Galileo and GPS nominal constellations, as defined in the Space Service Volume (SSV) Booklet[2], were used for this analysis. The nominal constellations consist of a total of 24 satellites for Galileo deployed into 3 orbital planes and 27 for GPS deployed into 6 orbital planes.

In order to evaluate the GNSS signals availability, an accurate link-budget analysis has been carried out. This has the objective of evaluating the GNSS signals carrier-to-noise ratio CN0 received by Proba-3 along its orbit, and to determine whether these signals can actually be acquired and tracked by the on-board receivers. For this reason, several parameters have to be defined and also several assumptions have to be made for the link-budget calculation. The parameters and assumptions are described in the following part.

For the GNSS Effective Isotropic Radiated Power (EIRP), the ICG agreed values as defined in the SSV Booklet have been adopted in the simulations. These values were derived in a very conservative approach, and are hence to be considered as the minimum power the constellations are actually emitting in space. Concerning the power values for the signals Galileo E1 and E5a and for GPS L1 and L5, the ICG agreed values, as outlined in the SSV Booklet have been used in the scope of this study.

Also results from a NASA experiment were used, by which the antenna patterns of the various GPS blocks for L1 was measured from space, by means of a single frequency receiver on board a geostationary satellite. The GPS Antenna Characterization Experiment (GPS ACE)[3 4], for which the data are available online, were used to reconstruct the EIRP for the GPS L1 frequency and were used in this study for the GNSS signals availability analysis. This solution will be referred in the text and graphics as *ACE*.

In addition to the ICG and ACE EIRP, in 2014 Lockheed Martin[5] published the legacy and improved GPS antenna patterns for the L1 and L2 for the different satellites. From these values, it has been possible to derive the expected improved EIRP and use the L1 values in our simulations. The reconstructed EIRP values adopted in the frame of this study are shown in Figure .

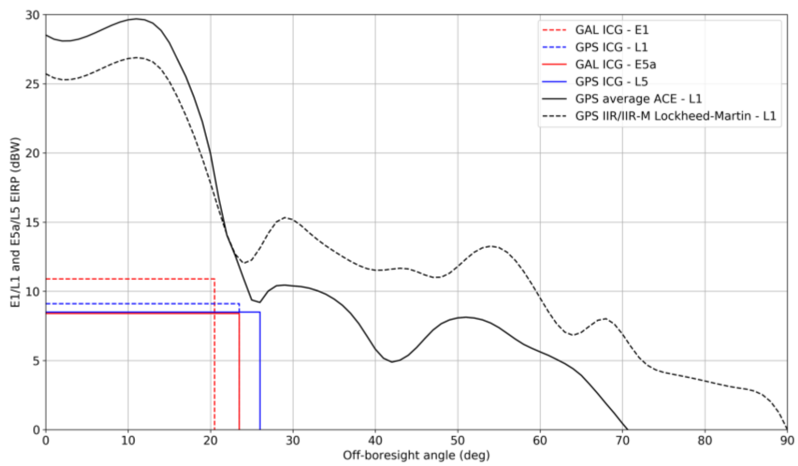

Figure 4. Galileo E1 and E5a and GPS L1 and L5 ICG, ACE and Lockheed Martin EIRP values as a function of the off-boresight angle.

As can be observed in Figure the ICG values are very conservative and in addition, they only account for the emitted signal main lobe, and they disregard the secondary lobes, as shown by the sudden drop of power represented by the vertical lines. The GPS ACE L1 EIRP (computed as the mean of all the values) shows a much higher primary lobe, more than 20 dBW higher at the peak, and also shows that a significant amount of power is emitted in the off-boresight directions, with more than 0 dBW up to 70 degrees. A similar pattern is visible for the Lockheed Martin L1 EIRP, which shows a good consistency with the ACE values. The main lobe for the Lockheed Martin pattern is 3 to 4 dB lower than the ACE pattern, but on the other hand it has higher secondary lobes (about 5 dBW higher), with EIRP values above the 0 dBW up to 90 degrees. However, it is shown later in this analysis, that the exactly the secondary lobes are extremely important for the SSV GNSS signals availability and therefore allowing receivers to track GNSS signals at extremely high altitudes, in particular above the GNSS MEO constellations. An important note on Figure , regarding the ACE EIRP. NASA provides the antenna patterns in the off-boresight range 16-90 degrees. Below 16 degrees the signal is obstructed by the Earth. For completeness of the antenna patterns, the ACE gap has been filled with the GPS L1 Lockheed Martin pattern, scaled to match the boundary value at 16 deg. This is a simple assumption, not based on real measurement, that will not affect the results presented in this study. Because of the Earth blockage, this range of signal can only reach the LEO part of the Proba-3 orbit, where the CN0 of the signals are in any case higher than the defined acquisition and tracking thresholds, even for the ICG EIRP patterns.

For what concerns the receivers' link-budget parameters, the Proba-3 satellites in our simulations have been equipped with two GNSS antennas. As the satellites attitude is nadir-pointing we have implemented a Low-Gain (LG) patch antenna pointing in the zenith direction and a high-gain antenna (HGA) pointing in the nadir direction. The two receivers' antenna patterns are shown in **Figure 5**. The reason for this choice is because the satellites in a highly-eccentric orbit will be flying below the Galileo and GPS orbits for the LEO part of the orbit (600 km altitude), while for the rest of the orbit they will be above them, with an apogee high of 60000 km. In the LEO region, a standard GNSS receiving antenna will be enough to allow the receiver to acquire and track the GNSS signals, as they will have a high CN0. On the other hand, as soon as Proba-3 flies above the GNSS constellations towards the apogee the GNSS signals CN0 will drop significantly. Hence a high-end HGA with about 9 dBi gain in the boresight direction is needed to increase the CN0 as much as possible as in the apogee region the GNSS CN0 levels become extreme, as it will be shown in the next section.

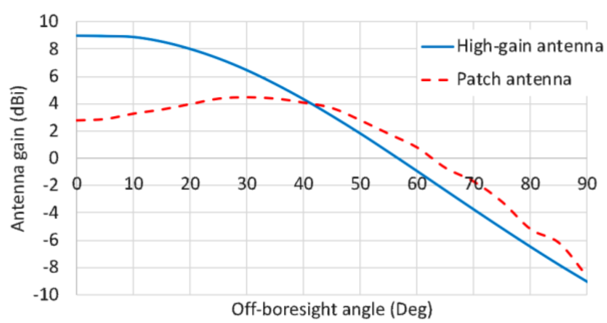

Figure 5. Proba-3 receiver antenna patterns. Nadir-pointing patch antenna pattern and zenith-pointing high-gain antenna pattern.

Concerning the tracking and acquisition CN0 for the Proba-3 receiver, two parametric thresholds have been chosen, respectively 20 and 30 dBHz. For simplicity, the acquisition and tracking CN0 thresholds have been assumed to be equal. The results for both conditions are presented. The four simulated scenarios are shown in Table 2.

Table 2. Proba-3 simulated scenarios configuration.

	Galileo EIRP	GPS EIRP
Scenario #1	ICG E1	ICG L1
Scenario #2	ICG E5a	ICG L5
Scenario #3	ICG E1	ACE L1
Scenario #4	ICG E1	Lockheed Martin L1

All results and statistics reported in the following section are based on a simulation duration of 5 days (6 Proba-3 orbital revolutions). The link-budget calculation approach, as described in the SSV Booklet has been adopted within this analysis.

GNSS signal availability results

This section contains the results for the four simulated scenarios. The following four figures show the GNSS signals availability for the four scenarios, for 2 entire orbital simulations, starting and ending at the perigee of the Proba-3 orbit. A common and expected pattern that can be observed in all these figures is that at the perigee there is a high signal availability which then quickly drops towards the apogee. At the perigee the availability contribution is mainly due to the zenith pointing patch antenna, while the HGA contribution becomes significant when Proba-3 reaches the altitude of the GNSS constellations and above them. Two main limiting factors play a role in the scares availability around the apogee: 1) the Earth occultation, which blocks the GNSS signals main lobe and 2) the limited power in the secondary lobe, which in most cases is not enough to guarantee coverage at high altitudes.

The results of ICG scenarios #1 and #2 in Figure **6** and Figure 7 show a very limited coverage at the apogee due to the lack of secondary lobes in the simulated EIRP. For E1/L1 (scen#1) a maximum of 2 satellites per constellation are in view around the apogee with a CN0 of 20dB-Hz and a maximum of 3 satellites per constellation for E5a/L5. Even an interoperable solution (Galileo+GPS) would guarantee a minimum of 4 observations in limited period of times, leaving many gaps at apogee. If the CN0 threshold is set to 30 dB-Hz the availability is inexistent once Proba-3 flies higher than the GNSS constellations.

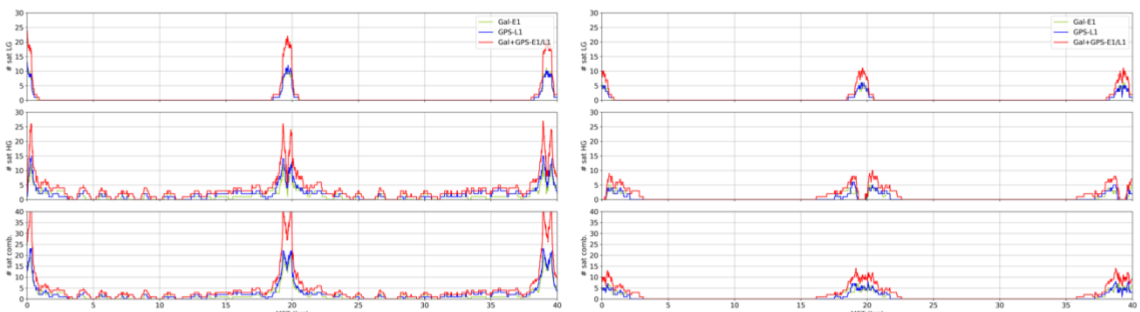

Figure 6. Scenario #1 GNSS signal availability for a CN0 receiver threshold of 20dB-Hz on the left and 30dB-Hz on the right. Galileo ICG E1 and GPS ICG L1 EIRP have been used.

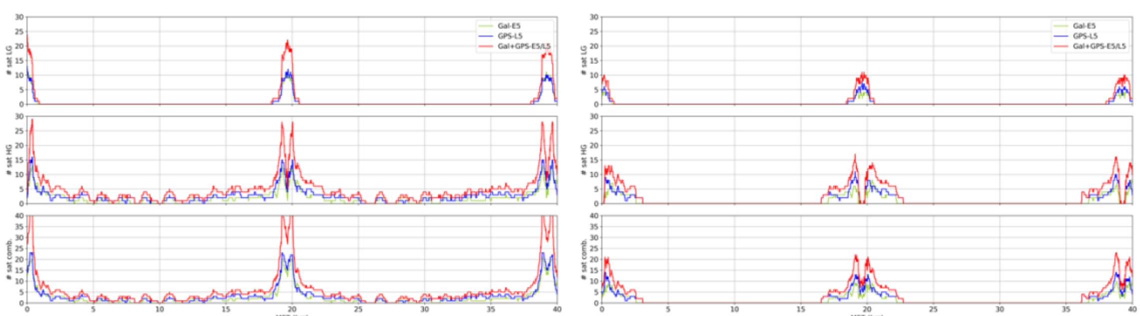

Figure 7. Scenario #2 GNSS signal availability for a CN0 receiver threshold of 20dB-Hz on the left and 30dB-Hz on the right. Galileo ICG E5a and GPS ICG L5 EIRP have been used.

On the contrary, when a realistic EIRP is used, the results are substantially different. This is the case for GPS when the ACE or the Lockheed Martin EIRPs are used, as shown in Figure **8** and Figure 9. For scenario #3, when the ACE pattern is in use, the CN0 of the signals reaching Proba-3 is much higher, and this guarantees a 100% coverage with a minimum of 10 signals available all over the orbit for the 20 dB-Hz threshold. On the other hand, if the receiver is capable of tracking only 30 dB-Hz the signals availability will significantly drop, to a maximum of one or two satellites at most around the apogee, with a lot of data gaps. In any case, this more realistic EIRP pattern shows that with a more advanced receiver, capable of tracking weaker signals, it is possible to achieve full coverage for the Proba-3 mission. It also demonstrates how conservative the ICG EIRP is.

Scenario #4 in Figure 9 shows the GNSS signals availability when using the GPS Lockheed Martin EIRP pattern. As already shown Figure the Lockheed Martin pattern has a lower main lobe but higher secondary lobes. This is directly visible in the plot, where for 20 dB-Hz a minimum of 14 signals are available all over the orbit, while for 30 dB-Hz a minimum of 2 signals (with an average of 5 around the apogee) are guaranteed. This shows the fundamental concept that more power in the secondary lobes is directly linked with a better signals availability at altitudes higher than the MEO GNSS constellations.

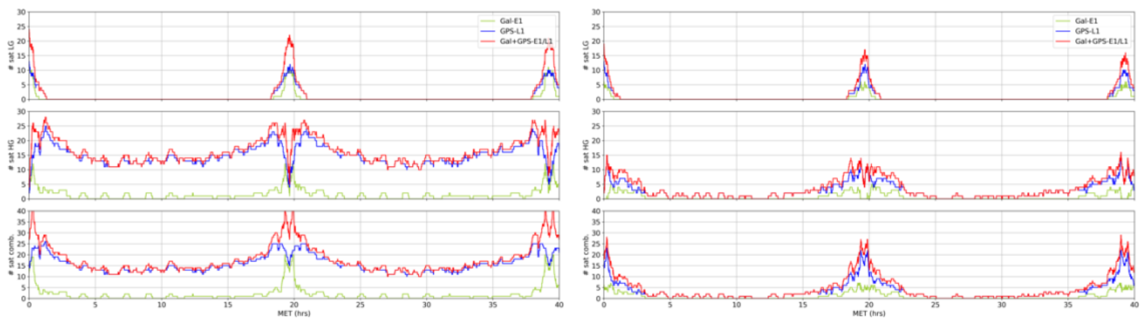

Figure 8. Scenario #3 GNSS signal availability for a CN0 receiver threshold of 20dB-Hz on the left and 30dB-Hz on the right. Galileo ICG E1 and GPS ACE L1 EIRP have been used.

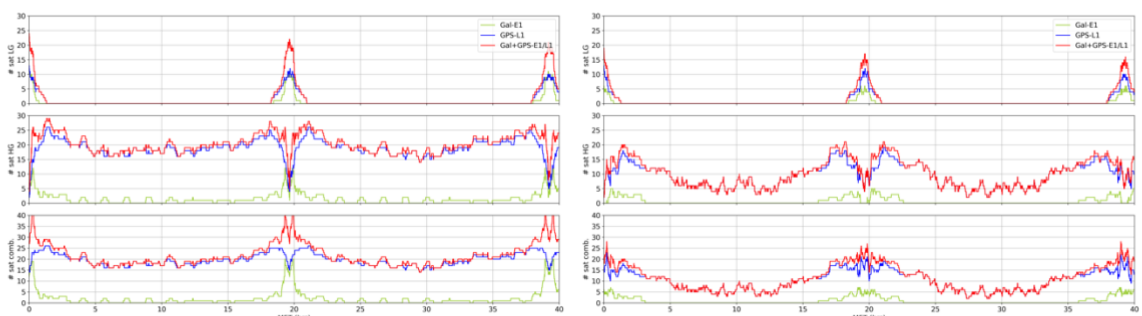

Figure 9. Scenario #4 GNSS signal availability for a CN0 receiver threshold of 20dB-Hz on the left and 30dB-Hz on the right. Galileo ICG E1 and GPS Lockheed Martin L1 EIRP have been used.

Table 3 summarizes and compares the GPS signals availability in the apogee area for the two CN0 thresholds.

Table 3. Number of available GPS signals during the apogee phase.

	$CN0_{min}$ = 20 dB-Hz	$CN0_{min}$ = 30 dB-Hz
ICG L1	0 – 2	0
ICG L5	0 – 3	0
ACE L1	10 – 16	0 – 3
L.M. L1	15 – 22	2 – 13

Table 4 is a summary of the figures of merit for the various Proba-3 scenarios simulated in this paper, and computed consistently with the SSV Booklet. The table reports the average GNSS signals availability (AVG) and the Maximum Outage Duration (MOD) for at least 1 or and at least 4 signals available. The average gives an indication of how many signals are in view throughout all the orbit, while the MOD defines what is the longest gap in the observations, in minutes.

Table 4. Figures of merit for the different scenarios: GNSS signals availability average and maximum outage time for at least 1 / at least 4 signals.

			AVG-1sign (%)		MOD-1sign (min)		AVG-4sign (%)		MOD-4sign (min)	
CN0 (dB-Hz)			**20**	**30**	**20**	**30**	**20**	**30**	**20**	**30**
Scenario #1	**Gal.**	**ICG E1**	67	33	71	792	10	10	1077	1077
	GPS	**ICG L1**	78	21	88	957	11	9	1057	1062
	Combined		88	33	55	792	28	18	705	996
Scenario #2	**Gal.**	**ICG E5**	81	27	57	878	14	13	1026	1026
	GPS	**ICG L5**	87	32	85	808	18	17	919	941
	Combined		94	32	46	808	48	27	506	873
Scenario #3	**Gal.**	**ICG E1**	67	33	71	792	10	10	1077	1077
	GPS	**ACE L1**	100	79	0	88	100	30	0	830
	Combined		100	79	0	88	100	33	0	800
Scenario #4	**Gal.**	**ICG E1**	67	33	71	792	10	10	1077	1077
	GPS	**L.M. L1**	100	100	0	0	100	96	0	43
	Combined		100	100	0	0	100	96	0	43

PRECISE ORBIT DETERMINATION ANALYSIS

Precise Orbit Determination setup and processing

Based on the GNSS signals availability described in the previous section, a Precise Orbit Determination (POD) campaign was set up. Galileo E1 and GPS L1 code and carrier-phase observations have been simulated for a reference orbit of Proba-3, for the two satellites. The same orbits, attitude, signal structure and link-budget parameters have been chosen for the POD simulation as defined in the previous section. The E1/L1 signals have been chosen as they provide results that are more conservative than E5a/L5, in terms of signals availability, and because the same frequency is available for GPS for the three L1 scenarios, with different EIRP patterns. A realistic white noise has been added to the observations, with a standard deviation of 20 cm for the code and 2 mm for the phase observations. All GNSS and receivers' clock biases have been set to zero and no ionosphere has been considered. The duration of the simulation is one Proba-3 orbital period (19.6 hours) starting and ending at the perigee, with GNSS observations sampled every 10 seconds.

The simulated GNSS observations have been processed using the dynamic Least-Square-Adjustment approach. Small perturbations in the dynamics of the satellites have been introduced in order to simulated a more realistic scenario. The initial state vector and 3 empirical piecewise constant parameters in the radial, along- and cross-track directions have been estimated in order to absorb the dynamical perturbations. Additionally, the receivers' clocks have been estimated epoch-wise.

Different approaches can be selected to treat the observations. If more than one frequency is available, the signals could be combined in an ionospheric-free linear combination. Even though this is the most frequently chosen approach, it has the limitation that when either one signal is not available the linear combination cannot be formed and hence useful observations are discarded. In addition, at high altitudes such as the SSV zone, no atmospheric effects are present and the linear combination is not useful. The GRAPHIC linear combination, which is the ionospheric free linear combination of code and phase measurements on the same carrier has been used in this analysis, as it eliminates the ionospheric delays and keeps the observations on different carriers independent. The RAW approach, where no linear combinations or differentiation of signals is applied, would be the best solution, but it requires a deeper and more detailed analysis and is not treated in this paper, and will be treated in a future dedicated study.

The POD analysis conducted in the context of this paper is at a preliminary stage, and serves to understand 1) what is the impact of the GNSS signal availability on the POD performances and 2) what are the difficulties and limitations of the POD approach on such a high and eccentric scenario with limited observations. The reader should focus on the relative accuracies between the presented scenarios and not on the absolute accuracies achieved in this analysis.

The POD results are presented for the three scenarios shown in Table 5.

Table 5. Proba-3 POD simulated scenarios configuration.

	Galileo EIRP	GPS EIRP
Scenario ICG	ICG E1	ICG L1
Scenario ACE	ICG E1	ACE L1
Scenario LM	ICG E1	Lockheed Martin L1

Precise Orbit Determination results

The results of the POD processing of the Proba-3 Galileo + GPS observations are presented here in terms of absolute and relative orbital accuracy.

Figure 10 shows the orbital difference between the solutions based on the different GNSS availability and the reference orbit, a-priori known and used to generate the observations. As it is clear from the graphics, the ICG solution, which is the one with less observations around the apogee (see Figure **6**) performs badly with respect to the other two solutions. Having only a few (20 dB-Hz) or no (30 dB-Hz) observations available around the apogee the LSE approach cannot absorb the perturbations leading to significant errors in the absolute positioning. On the other hand, if more observations are available, which is the case of the ACE and LM solutions, the absolute orbital accuracy is three times better, because the parameters can be more accurately estimated (especially the empirical accelerations around the apogee).

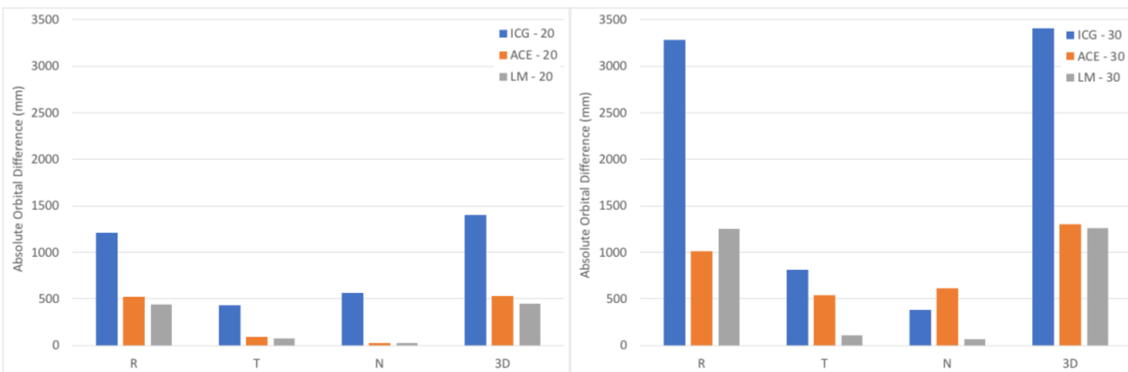

Figure 10. POD absolute orbital difference RMS for the different scenarios for a CN0 threshold of 20 dB-Hz on the left and 30 dB-Hz on the right.

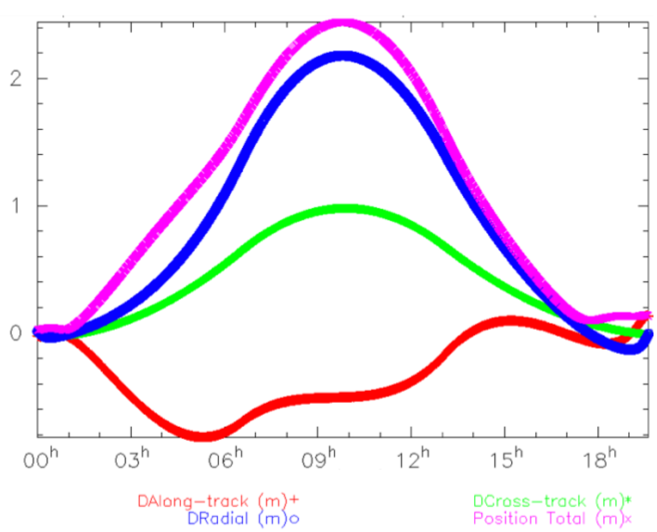

Figure 11. POD absolute orbital difference as a function of the mission elapsed time for the ICG solution with CN0 threshold of 20 dB-Hz.

Again, it can be noticed that higher secondary EIRP lobes (see LM) leads to a slightly improved absolute positioning accuracy, even though only marginal with respect to the ACE solution. This again proves that higher secondary lobes are fundamental for the SSV navigation and orbit determination. Figure 11 shows POD absolute orbital error along the Proba-3 orbit for the ICG solution with CN0 of 20 dB-Hz. This clearly shows that the estimated orbit drifts away from the reference orbit in the apogee area, due to the limited number of GNSS observations in that area, while it accurately models the orbit at the perigee, where significant more observations with better geometry are available.

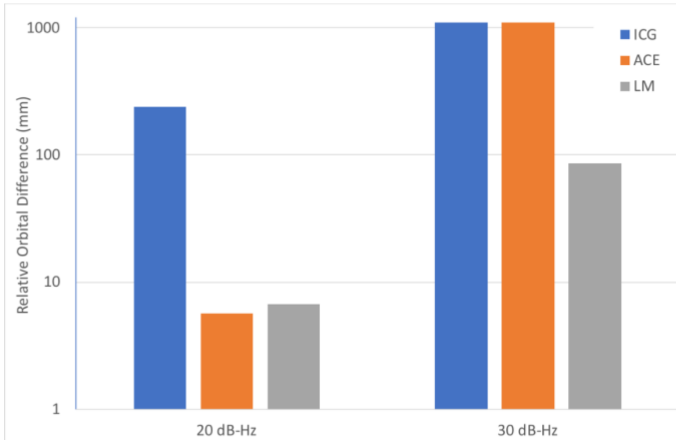

Figure 12. POD relative orbital difference RMS for the different scenarios for the two CN0 thresholds.

In Figure 12 it is possible to observe the accuracy in the relative positioning that can be achieved with different GNSS availability patterns. In this case, the relative distance between the two Proba-3 spacecraft has been selected as a reference and compared against the relative distance of the estimated orbits. It is clear that also in this case the more observations are available, the better the relative accuracy that can be achieved. In case of a receivers' CN0 threshold of 20 dB-Hz the difference between the ICG and the other two solutions is significant, by a factor of 20. When the CN0 threshold is set to 30 dB-Hz and the GNSS availability at the apogee is limited for both ICG and ACE solutions, the relative accuracy is degraded. ACE and ICG solutions are at the same level because, as outlined in Figure **6** and Figure **8**, the GNSS availability is very limited or non-existent. In this case only the higher secondary lobes of the EIRP provide enough signal strength to guarantee a better GNSS signals availability and hence better relative and absolute positioning accuracies.

CONCLUSION

Concerning the GNSS Signal Availability analysis for PROBA-3, it has been confirmed that the results from ICG are very conservative, because only the main lobe is considered. The GPS L1 ACE estimated antenna pattern (main lobe + side lobe) is considered as being consistent with the data sheets from Lockheed Martin and provides a significant improved GNSS signal availability for PROBA-3 compared to ICG. A receiver capable of acquiring and tracking a signal level of 20 dB-Hz CN0 will have GNSS signal availability of more than 4 GNSS satellites for the entire PROBA-3 orbit.

Concerning the Precise Orbit Determination analysis and related POD accuracy aspects, the GNSS observations selected for the initial POD are considered as sub-optimal from an accuracy point of view, but very well suited to show the impact of GNSS signal availability to the POD accuracy. The initial POD results demonstrate already the orbital accuracy improvement that derives from the higher number of GNSS signals available, in terms of absolute and also relative orbit accuracy for the PROBA-3 mission. POD based on the RAW approach is considered as optimal and will assure the availability of all the GNSS observations to the process and therefore improved orbit accuracy both absolute and relative.

With the analysis presented in this paper some important lessons have been learned. Especially the dynamical parameterization commonly adopted for POD and also the method for the numerical integration of this highly eccentric Proba-3 orbit will have to be carefully tested and evaluated, to avoid numerical instability.

As future activities, the simulated scenarios will be further improved in order to better understand the POD-related issues with the focus on the achievable accuracy and also to prepare for the actual Proba-3 mission processing campaign.

ACKNOWLEDGMENTS

We would like to thank all the agencies who contributed to the Space Service Volume booklet, who has been used as a reference and term of comparison throughout all the work performed in the context of the Proba-3 study.

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