PRISMA RELATIVE ORBIT DETERMINATION USING GPS MEASUREMENTS

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ABSTRACT

The Swedish PRISMA (Prototype Research Instruments and Space Mission technology Advancement) mission is a technologic demonstration from the Swedish National Space Board (SNSB) and the Swedish Space Corporation (SSC). It will provide the demonstration and validation of different sensors, as well as navigation and guidance algorithms, and strategies for rendezvous and advanced formation flying. The aim is to prepare future missions such as Proba-3, Darwin, SMART-OLEV, which rely on formation flying. The launch of the PRISMA satellites is expected in the beginning of 2010.

The mission has two spacecraft, called Main (or Mango) and Target (or Tango). Initially attached at launch, they will first be operated as a single combined unit, and then be separated for the execution of autonomous rendezvous and formation flying experiments.

The on-board GPS-based absolute and relative navigation system is contributed by the German Aerospace Center (DLR). It consists of two redundant single-frequency Phoenix-S receivers on each spacecraft and a dedicated navigation software residing on the Main on-board computer. The DLR's GPS system is not only a sensor and navigation experiment, but it also provides fundamental navigation system functionality for the formation as a whole. Among other experiments, PRISMA supports DLR's Spaceborne Autonomous Formation Flying Experiment (SAFE).

The French National Space Agency (CNES) contribution to PRISMA consists of a Formation Flying RF (FFRF) sensor, funded in collaboration with the Spanish Centre for the Development of Industrial Technology (CDTI), and its dedicated guidance, navigation and control (GNC) software. The FFRF instruments are developed by Thales Alenia Space. This will be calibrated and validated during flight experiment open and closed loops. This contribution is a part of the Formation Flying In Orbit Ranging Demonstration (FFIORD) experiment. The reference for FFRF sensor calibration and validation will be given by the on-ground precise relative orbit determination based on GPS code and phase single-frequency measurements. Although the primary on-ground absolute and relative orbit determination tasks will be performed by DLR during mission operations, a CNES relative precise orbit determination will also be done for backup and internal needs of FFRF sensor calibration.

A pre-flight CNES/ DLR hardware-in-the-loop joint validation of the FFRF and GPS systems was performed, in a context as representative as possible to the PRISMA mission, using a Spirent GPS signal simulator. This article presents conditions of the simulations, the algorithm used and the results of CNES relative orbit determination obtained during this joint validation. The expected orbit determination accuracy is evaluated by comparing CNES precise orbit with the simulated

reference. A comparison is also done with regards to the FFRF relative position solution. The results are in total agreement with the required specifications for the FFRF validation and calibration.

To validate CNES algorithms for PRISMA, an additional test with in-flight GPS measurements from Gravity Recovery and Climate Experiment (GRACE) experiment was performed. GPS flight data collected during GRACE satellites closest approach in the swap maneuver are used in a configuration representative of PRISMA formation geometry. The results presented in this article fully confirm the simulated performance.

1. INTRODUCTION

1.1. PRISMA Mission

PRISMA is a technology demonstration mission for the in-flight validation of sensor technologies and guidance/navigation strategies for spacecraft formation flying and rendezvous. Originating from an initiative of the Swedish National Space Board (SNSB), the Swedish Space Corporation (SSC) is in charge of the mission implementation. PRISMA provides a precursor mission for critical technologies related to advanced formation flying (FF) and On-Orbit-Servicing (OOS).

The mission is to a large extent funded by SNSB while the mission management is with SSC. Contributions to the mission stem from international cooperation partners in agencies, universities and industry. The cooperation partners and their contributions are

1. CNES (France) and CDTI (Spain), providing Formation Flying Radio-Frequency (FFRF) sensors. The sensors are developed by Thales Alenia Space.
2. the Technical University of Denmark (DTU), providing a Vision-Based Sensor (VBS)
3. the German Aerospace Center (DLR), providing GPS receivers and support with guidance, navigation and control (GN&C) functions and a formation flying experiment
4. ECAPS (Sweden) in cooperation with SSC, providing a High-Performance Green Propellant (HPGP) system
5. Nanospace AB (Sweden) in cooperation with SSC, providing a micro-thruster system.

Future formation flying missions of the European Space Agency (ESA) like PROBA-3 and Darwin rely on formation flying technologies as demonstrated by PRISMA. However, the European Space Agency (ESA) is not directly involved in the mission.

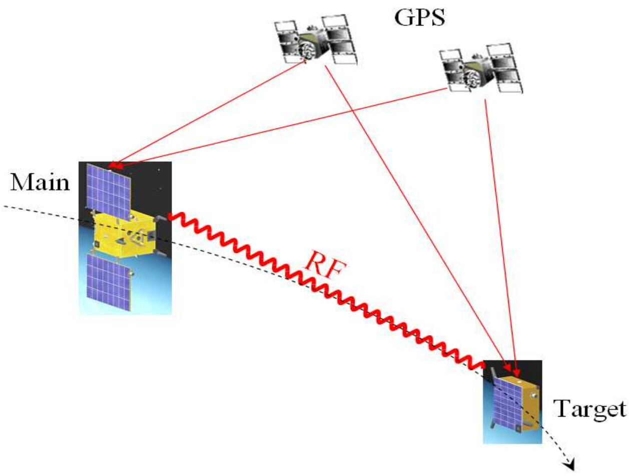

Fig. 1 : PRISMA Main and Target Satellites

PRISMA comprises a fully maneuverable micro-satellite (the Main spacecraft) and smaller sub-satellite (Target) that will be released after initial commissioning. The mission schedule foresees a launch in 2010 of the two spacecraft into a low Earth orbit (LEO) with a targeted lifetime of at least eight months [1] and [2].

The mission objective is to demonstrate in-flight technology experiments related to

- Autonomous Formation Flying
- Homing and Rendezvous scenarios
- Precision Close Range 3D Proximity Operations
- Soft and smooth final approach and recede maneuvers,

as well as to test instruments and unit developments related to formation flying, in particular

- the High-Performance Green Propellant thruster system
- the micro-thruster system
- the Vision-Based Sensor
- the Formation Flying Radio-Frequency sensors.

Secondary mission objective is to test the new developments in the field of Power Conditioning & Distribution Unit (PCDU), Battery Management Electronic (BME), a model project for onboard software and a new Electrical Ground Support Equipment (EGSE). Another secondary mission objective is to demonstrate autonomous orbit keeping of a single satellite (MAIN) close to the end of the anticipated mission lifetime.

1.2. DLR Contribution

In four major areas DLR/GSOC provides significant contributions to the PRISMA mission. These comprise the

1. Spaceborne GPS architecture (four GPS Phoenix flights units and antenna systems)
2. On-board GPS-based navigation software (for real-time absolute and relative navigation)
3. Formation flying experiments (autonomous formation keeping and reconfiguration)
4. On-ground Precise Orbit Determination (POD)

In addition, a guidance and control algorithm for absolute orbit keeping of a single spacecraft will support the respective secondary PRISMA mission objective. Detailed information on the DLR/GSOC contributions are given in [3].

1.3. CNES Contribution: FFIORD Project

CNES contributes to PRISMA mission through the FFIORD (Formation Flying In Orbit Ranging Demonstration) project. FFIORD is in charge of the relative positioning for autonomous formation flying missions: acquisition of formation, navigation in deployment phase, anti-collision.

CNES is responsible for the delivery of the FFRF subsystem, confounded by CDTI, consisting in RF terminals and antennas on both satellites. It will also deliver the FFIORD GNC software that will be integrated on the Main satellite.

CNES contribution also includes the development of the FFIORD ground segment, for telemetry reception and decommutation, FFIORD experiment preparation, data analysis and archiving.

FFRF will be a passenger on PRISMA, which provides an excellent opportunity for its validation, to prepare the future flying formation missions, where it could be used as the main GNC subsystem.

More details can be found in [4].

1.4. FFRF Subsystem Presentation

The FFRF subsystem is developed by Thales Alenia Space (TAS) with relative positioning of 2 to 4 satellites on formation flying, with a range from 3 m up to 30 km.

It has a terminal on each satellite equipped with both transmitter (Tx) and receiver (Rx), which transmits and receives GPS-like navigation signal modulated on 2 S-band carrier frequencies (S1 and S2). Each satellite is also equipped with Rx/Tx antennas.

As for GPS, the system provides pseudo range and two carrier phase measurements, for both frequencies S1 and S2. The pseudo-range measurements are coarse but non ambiguous, whereas the carrier phase are more accurate but ambiguous. The aim of FFRF measurements treatment is to perform the integer ambiguity resolution (IAR) using a wide lane. It allows us to benefit from the good accuracy of phase measurements.

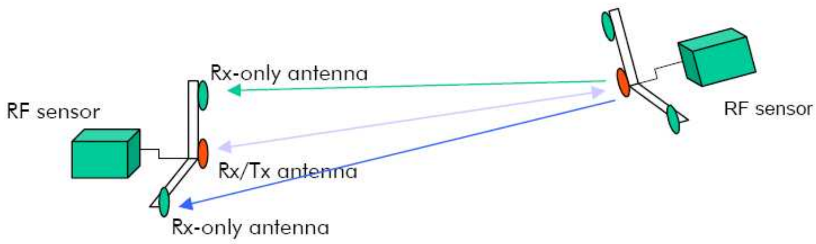

Fig. 2 : FFRF Subsystem Description

The subsystem produces 2 kinds of information:

- distance between two satellites, computed from pseudo-range and phase measurements,
- angular or Line of Sight (LoS), using a differenced method between 2 antennas.

Note that attitude determination is also possible, but for a formation of at least 3 satellites, which will not be the case for PRISMA.

1.5. FFRF In-flight Calibration and Validation

PRISMA will be the first flight for the FFRF subsystem, thus the first opportunity for the validation of the subsystem performances.

Furthermore, FFRF performances are affected by electrical biases and multi path errors. These errors can reach high values and then are likely to cause IAR failures. They need to be reduced from on ground but also in–flight calibrations campaigns.

During flight, DLR will perform the official operational precise reference orbit determination (POD) based on GPS measurements. This will be used for FFRF validation and calibration purpose. However, for particular internal needs, it is interesting to be able to perform a precise orbit determination in CNES, independently from DLR official solution. It will allow us, for example to choose more precisely the comparison period and the measurement arc to be used for relative positioning, and eventually to include attitude or orbit maneuvers. Furthermore, it will enable us to control the estimation hypothesis (e.g. dynamic model used) and to compute the estimation accuracy at the same time, which is necessary for FFRF solution validation. It also makes the post-processing of the result easier, as the ephemeris could be generated with a required time step or on a certain required period.

For the FFRF calibration, the need for accuracy essentially concerns the relative positioning, but not the absolute positioning of each satellite.

The POD ideal precision is one order of magnitude higher than expected FFRF accuracy. That means 1 mm for distance, and 0.1° for LoS. If LoS accuracy seems not to be a problem – for 10 meters distance, 0.1° represents about 2 cm lateral accuracy - , while the distance accuracy is the major challenge of the relative POD with differential GPS measurements.

CNES has developed a specific algorithm for PRISMA relative orbit estimation based on GPS measurements. It is presented in the following chapter 2.

2. CNES RELATIVE ORBIT ESTIMATION FOR PRISMA

2.1. Relative Orbit Estimation with GPS Measurements

Phoenix GPS receiver from DLR, implanted on both Main and Target satellite, is a mono frequency code plus phase GPS receiver. At every time step (10 seconds), it delivers 2 measurements for each couple receiver/GPS in visibility: one pseudo-range (or code) measurement and one carrier phase measurement.

The code measurement is coarse but not ambiguous, whereas the carrier phase measurement is more precise but is ambiguous.

These 2 types of measurement are modeled by Eq. 1 and Eq.2:

Pseudo-Range : $C = D_{geo} + c.(h_{Receiver} - h_{GPS\_emitter}) + d_{iono} + C_{Code} + noise_{Code}$ (1)

Carrier phase : $\lambda_1.L_1 = D_{geo} + c.(h_{Receiver} - h_{GPS\_emitter}) - d_{iono} + C_{Carrier} - \lambda_1.N_1 + noise_{Phase}$ (2)

Where

- D_{geo} is the geometrical distance between GPS emitter and receiver satellite centers of gravity. It depends on the position of the emitter (given by ephemeris) and the position of receiver (estimated).
- $h_{GPS\_emitter}$ and $h_{Receiver}$ are the clock biases of the GPS emitter and receiver. Their values can vary quickly, depending on the quality of the receiver and emitter clock. The emitter clock bias can be obtained from IGS solution website and the receiver clock bias has to be estimated at each step.
- d_{iono} is the ionospheric disturbance on the wave propagation through the ionosphere. It depends on the electronic content along the propagation path and on the wave frequency.
- C_{Code} , $C_{Carrier}$ are some code and phase corrections terms. They take into account correction between the position of antennae and the center of gravity of both emitter and receiver satellites. It also includes relativistic effects, phase windup and antennae phase corrections.
- $\lambda_1.N_1$ is the ambiguity bias of carrier phase measurement: λ_1 is the wavelength of the carrier phase and its value is equal to 19 cm. N_1 is an unknown integer and it is constant during a GPS pass.

- $noise_{Code}$, $noise_{Phase}$ represents noise of code and phase measurement respectively. Typical values for DLR Phoenix receiver measurements standard deviation are 0.5 m for code, 0.7 mm for carrier phase, for a carrier-to-noise (C/N0) level of 42 dB-Hz.

For a batch processing orbit estimation, it is possible to obtain precise ephemeris and clock biases solutions for GPS constellation, that is available on IGS website[6] for example. The estimation principle is then to model each measurement as precisely as possible, using precise modeling of satellite dynamic and measurement function. The estimation of unknown parameters (orbit, parameters of the dynamical model, ambiguities, and clock biases) can then be performed through a least mean square on measurements residuals.

For a precise positioning, the aim is to succeed in solving the ambiguities, so as to take full benefit of the carrier phase precision.

One major problem is the ionospheric delay. This effect is very difficult to model precisely, due to its high variations. This ionospheric delay could contribute several meters of propagation error, which is then widely greater than the wave length λ_1, and becomes a major problem to fix the ambiguity N_1. Keep in mind that Phoenix receiver is a mono frequency receiver, and therefore the classical iono-free combination between carrier phase measurements cannot be used.

One solution to this problem, for relative orbit estimation, is to use Single Differences (SD) measurements between Main and Target. Differencing GPS measurements of Main and Target at a common epoch removes common errors or perturbations affecting the propagation delay, under some conditions. If the baseline is not too long, the ionospheric effects are the same for both satellites, therefore they are cancelled out in the SD measurement.

2.2. CNES POD Algorithm

2.2.1. ZOOM Software

ZOOM is the reference and assessment software for orbit determination in CNES. It includes precise technical subject matters in flight dynamic: physical measurement, filtering, satellite dynamic, orbit estimation and propagation.

ZOOM is the main component of operational precise orbit determination treatments for altimetry and precise localization mission (Jason, SPOT, Envisat, Demeter…).

ZOOM offers a set of elementary tools allowing the user to easily compose algorithms dedicated to a specific treatment.

For PRISMA mission, a dedicated algorithm was developed using mainly ZOOM elementary tools, as well as other specific measurement treatments, which will be presented hereafter.

For this study, we had to face a ZOOM limitation, which is the impossibility to treat the GPS single difference measurements. This new measurement function has been being added since then, and will be used for PRISMA operational POD at CNES, but this article presents the algorithm to work around this limitation, in order to rebuild an equivalent of SD measurement and to benefit from its advantages.

ZOOM can precisely treat a great number of different types of measurement (GPS, Doris, 2GHz network, laser, descending Doppler, Time Group Delay, PVT, generic navigation, etc).

ZOOM can use different filtering methods for orbit estimation. For PRISMA orbit estimation, ZOOM uses a least square filtering algorithm.

A specific script was developed for PRISMA POD. It uses ZOOM components as well as some function developed in SCILAB for some mission specific treatments (measurements pretreatments, result analysis, etc) or functionality not yes integrated in ZOOM.

2.2.2. First coarse pretreatments

The aim of this first step is to prepare the measurement for the orbit determination, to help the filter to converge without rejecting too many measurements. It also gives a first idea of the quality of the measurements.

The main pretreatment is first a coarse estimation of the carrier phase ambiguities, given by the difference between code and carrier phase measurements: These values of ambiguities are affected by ionospheric effect, taken into account twice as shown in the difference of Eq. 1 and Eq. 2.

Some very important carrier phase jumps can be detected at this step, by the analysis of the evolution of "C-L1/lam1" during a same GPS pass, i.e. by using a finite differences method.

2.2.3. Coarse Orbit Absolute Estimation of Main and Target

The estimation first step is to get a coarse absolute orbit of both Main and Target satellites. As already mentioned before, the accuracy of this orbit is not the objective of CNES estimation.

This estimation is done with the use of Code and Carrier phase measurement, without any combination. We choose not to perform any ionospheric-free combination, from code and phase measurement. In addition to orbit elements, the drag and solar radiation coefficients are estimated, as well as floating ambiguities bias and receiver clock bias of both satellites.

ZOOM does not take into account the ionospheric disturbance for this step, so that this disturbance is included in the measurement noise. This reduces the accuracy of the orbit estimation. The validation of the algorithm presented in Chapter 3 will show that an accuracy of about 1 meter can nevertheless be reached on these absolute orbits. Such accuracy is fully satisfactory for an accurate relative Target/Main position estimation.

2.2.4. Relative Target/Main Orbit Estimation

As mentioned before, the single difference measurement function was not implemented in ZOO for this validation. A special treatment of GPS measurements was done to cope with this problem.

The principle was to estimate the emitter clock biases of the whole GPS constellation, assuming that they are equal to Main carrier phase residuals relative to its previous absolute orbit. These clock biases are then introduced in carrier phase measurements of Target. These measurements are then used for Target orbit estimation. This method constitutes a link between both satellites, since one can show that common errors are compensated on carrier phase measurements, in particular ionospheric effect, but also common errors in modeling the measurement function.

Afterward, Target carrier phase measurements are equivalent to single difference phase measurement between Main and Target. It is important to note that this method does not give single difference on pseudo-range measurements at the same time because ionospheric effects are doubled by this method. That is why pseudo-range measurements are only considered with a very low weight compared to carrier phase in the following orbit estimations.

These estimations are done in several steps:

Fine measurements processing

The precision of single difference measurement, due to the elimination of common errors between Main and Target, provides some fine pretreatment on measurements because the detection of phase jump is now possible, based on the analysis of carrier phase residuals relative to the Target coarse absolute orbit estimated on previous step. Jump phase clearly appears and can be corrected. Once this correction is done, a second step is the elimination of wrong measurements, which appear particularly on the beginning and end of a GPS pass. This elimination is simply done by comparison to a threshold.

Fig. 3 and Fig. 4 show the measurement residuals before and after this step. One can clearly see the improvement and the necessity for the future correct estimation of ambiguity. The residuals are reduced to less than one wavelength.

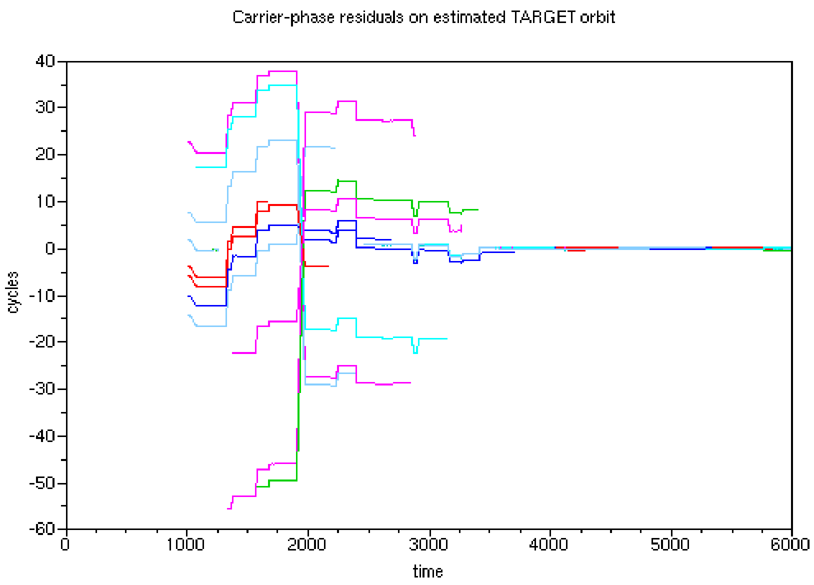

Fig. 3 : Carrier Phase Residuals Before Jump Treatment and Wrong Measurements Removal

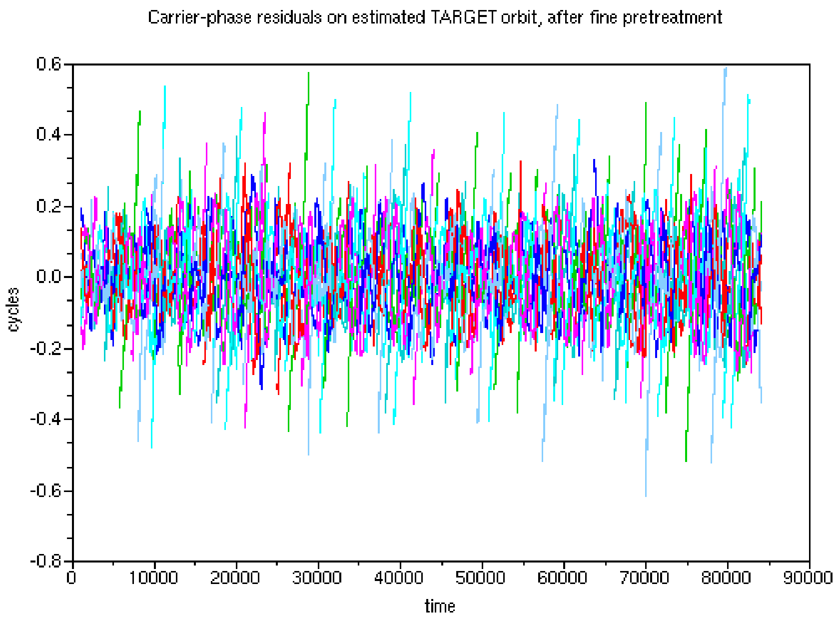

Fig. 4 : Carrier Phase Residuals After Jump Treatment and Wrong Measurements Removal

First orbit estimation with floating ambiguities

First, the drag and solar radiation coefficients are estimated in addition to orbit, floating ambiguities and Target receiver clock bias. After the completion of this estimation, it is possible to attempt the ambiguity fixing. To make sure that the fixing is optimal, the choice was done to carry on the treatment, by trying to improve the dynamical model estimation of Target satellite evolution. Empirical accelerations are the estimated along normal and tangential axes. The evolution of these accelerations is constrained to be constant on local orbital frame on predefined time intervals. The radial acceleration is not estimated, being linked to the tangential one (the observability of both accelerations is not guaranteed).

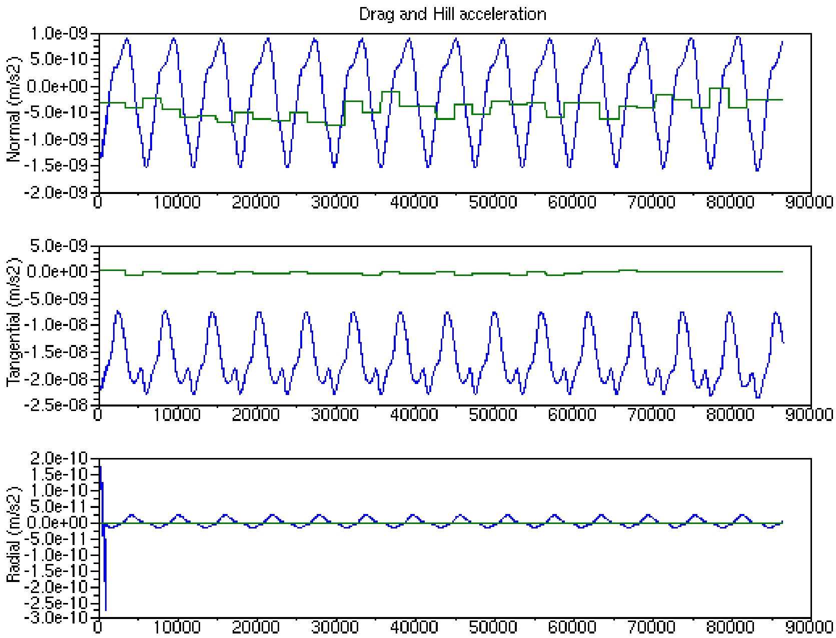

Fig. 5 Estimated Drag and Empirical Acceleration

Integer ambiguities fixing

After the previous step, the residuals are good enough to try the estimation and the fixing of integer ambiguities. As we can see in Fig. 6, an integer number of cycles appears in the gaps between residual of different GPS passes. The integer ambiguity fixing is then easy. Validation has shown that more than 90% of integer ambiguities can be fixed at this step.

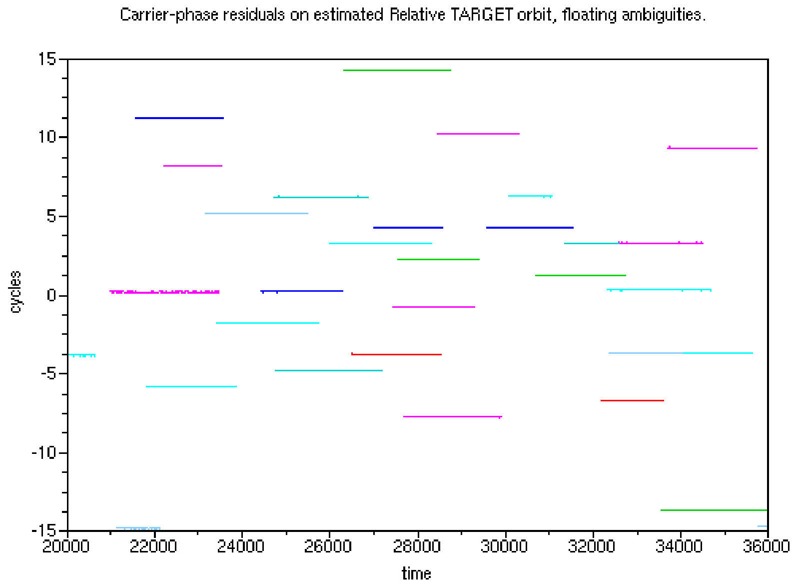

Fig. 6 : Carrier Phase Residuals on Target Relative Orbit, With Floating Ambiguities

Last iteration with fixed integer ambiguities

Once estimated, integer ambiguities are introduced in the carrier phase measurements for a new step of estimation.

This final estimation then benefits from the best accuracy of the carrier phase measurements. The same treatment as before is performed, with the estimation of empirical accelerations.

3. VALIDATION, RESULTS AND DISCUSSION

The validation of this algorithm was done in two steps:

First with simulated measurements as part of DLR/CNES cooperation: This simulation was used for algorithm development and tuning, as well as its performance evaluation, thanks to the reference ephemeris.

A second validation was done with real GPS measurements from in-flight formation of GRACE A and B satellites.

The results of these validations are presented hereafter.

3.1. DLR Simulation for Joint GPS/FFRF Validation

This first validation has been done thanks to DLR/CNES cooperation for GPS/FFRF subsystems validation.

Simulation was done in DLR with Spirent Simulator to generate the GPS measurements. It simulated one day measurements in stable orbit at 700 km altitude for Main and Target. The relative position of Main w.r.t. Target is a mean along-track separation of 500 m, superimposed oscillations of a few hundreds of meters on all components (400 m along-track, 200 m radial and 100m normal).

The nominal attitude is aligned with the local orbital frame, with GPS antennae pointing towards zenith. To be more realistic, a degraded attitude was simulated, by adding of errors on the 3 axis, which comes from a realistic simulation in SSC. These attitude errors are supposed to represent the in-flight uncertainties, due to low accuracy in attitude estimation by magnetometers, particularly on Target. These attitude errors may affect GPS POD, because it has an effect on the GPS antenna position. Furthermore, these attitude estimation errors could contribute to the errors in the comparison between GPS and FFRF solution, since a frame conversion is needed between both solutions.

The dynamical simulation utilized 70x70 earth gravity model, ionospheric perturbation (10 TECU), antenna diagram and offset and GPS ephemeris errors (constant radial bias with a standard deviation of 1.5 m on simulated GPS ephemeris).

DLR provided CNES with RINEX file for GPS measurements, and reference ephemeris of Main and Target, as well as GPS constellation (SP3 format).

Fig. 7 shows the comparison between the Main absolute ephemeris estimation and the reference. The Target comparison shows the same results, which is about 1 meter difference. A bias of 30 cm appears essentially in along track, in addition to an orbital periodic evolution, due to imperfections in the dynamical model estimation.

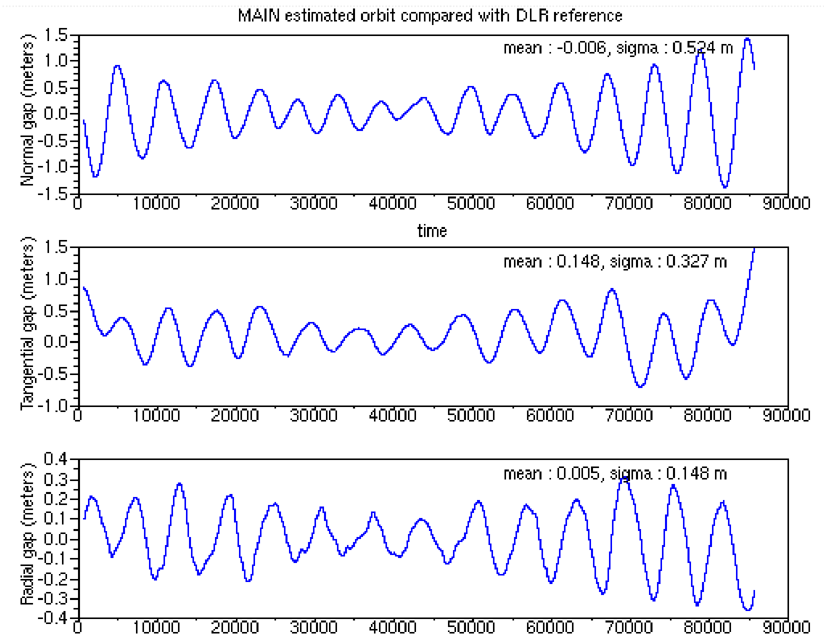

Fig. 7 : Main Absolute Estimated Orbit, Compared To Reference

Fig. 8 shows the relative ephemeris comparison to the reference. The difference is on the order of magnitude of a few millimeters on the 3 axes. We can note that for this case, 100% of the ambiguities were fixed. The residuals can be seen on Fig. 9.

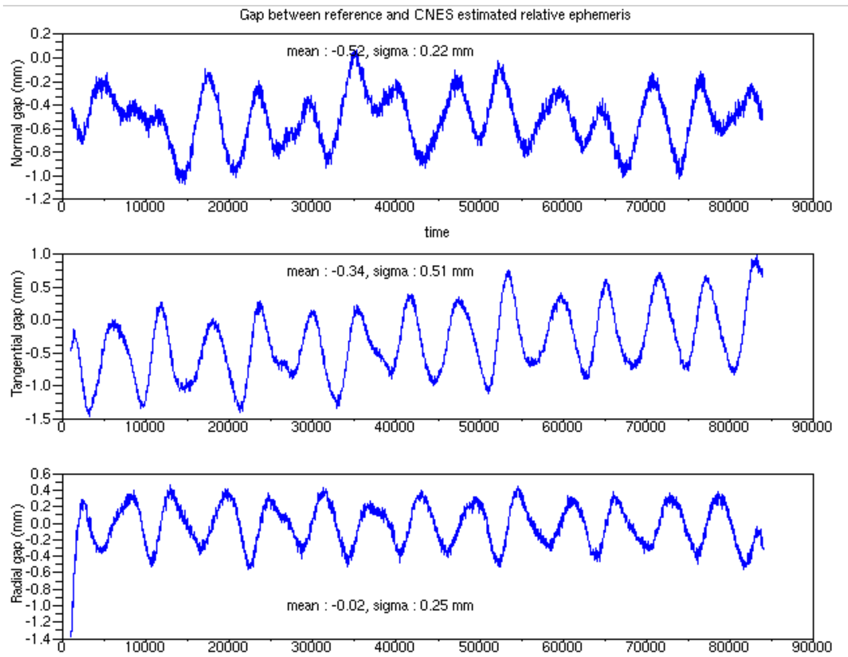

Fig. 8 : Target/Main Relative Estimated Ephemeris, Compared To Reference

Statistics of the comparison are presented in the table 1.

Table 1 : Comparison Between Relative Ephemeris Estimated and Reference, Statistical Values

	Radial (mm)	**Along track (mm)**	**Normal (mm)**
Mean	-0.02	-0.52	-0.34
Standard deviation	0.25	0.22	0.51

The figures are in agreement with the expected accuracy required for FFRF validation presented in chapter 1.5.

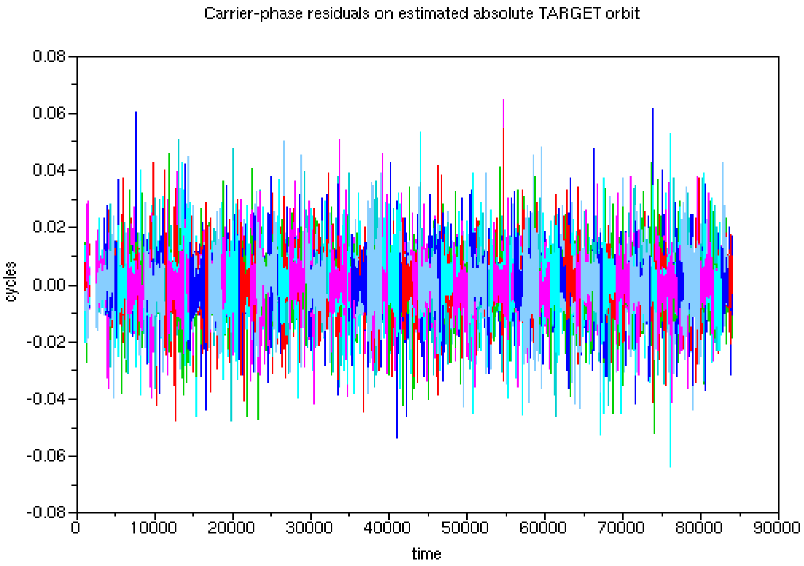

Fig. 9 : Carrier Phase Residuals on Estimated Target Orbit

Comparison with FFRF Solution

In the scope of DLR/CNES cooperation, FFRF measurements were also simulated in CNES using the reference ephemeris. A relative positioning solution was then computed from these measurements. The comparison between FFRF solution and CNES relative POD shows about 5 cm differences (3D R.M.S.). This figure is consistent with the result obtained in [5], where other comparisons are done with DLR real time estimation, DLR POD and reference trajectory.

3.2. GRACE In-Flight Measurements

GRACE stands for Gravity Recovery and Climate Experiment. The mission consists of two identical formation flying spacecraft in a near polar, near circular orbit, with an initial altitude of approximately 500 km. Those spacecraft have nominal separation of 220 km. The primary mission objective is to measure the time varying changes in the Earth gravity field.

Both GRACE spacecraft are equipped with a JPL BlackJack 2-frequency GPS receiver, and an inter-satellite link called KBR for K-Band Ranging. KBR allows performing the baseline measurements with 10 µm accuracy.

As an additional validation for the relative orbit estimation, we found interesting to test our tools and algorithms with these real GPS data.

The GPS measurements files can be retrieved on the PODAAC web site [7], as well as the KBR solution.

We used only the mono-frequency GPS measurements (C1 and LA), while the reference (absolute and relative) ephemeris was obtained using the 2-frequency measurements which enable the removal of the ionospheric delay on both satellites. This 2-frequency resolution is not presented here.

Before that, we had to check the accuracy of our 2-frequency solution with the KBR solution on a long arc of measurements. With an integer ambiguity resolution, the standard deviation on the relative distance errors was 1.5 mm, which validates our 2-frequency solution. We then used it as a reference.

On December 10th, 2005, the 2 spacecraft crossed themselves, and the relative distance varied between 500 m and 20 km during the arc of measurement chosen for this validation. This relative distance is much higher than it was in the previous simulation, but it is still in the FFRF range.

Fig. 10 shows the comparison between CNES relative ephemeris and a bi-frequency solution. More than 90% ambiguities were fixed during the estimation. The order of magnitude is a few millimeters in mean and standard deviation. Regarding the maximum baseline of 20 km, this result is also very satisfying and in agreement to the previous simulated case, with a shorter baseline of only 500 meters.

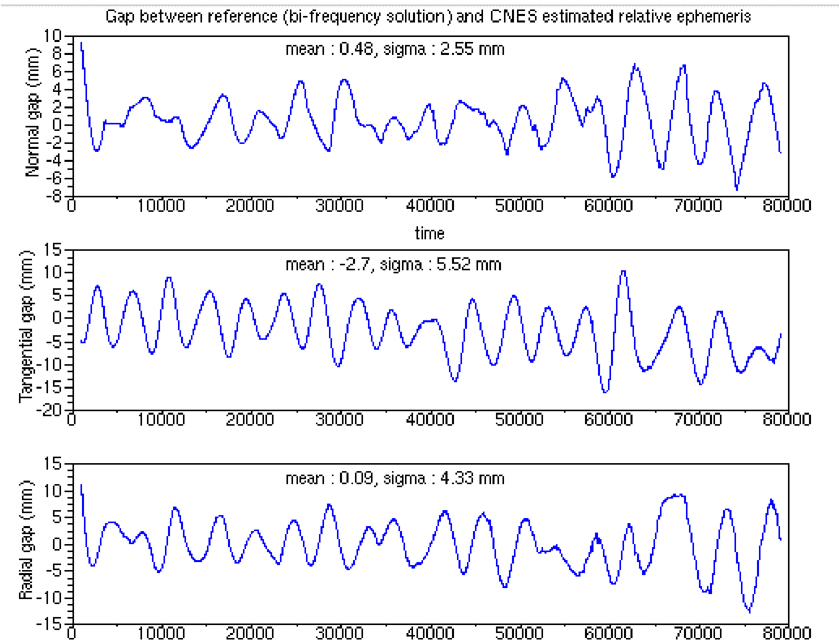

Fig. 10 : GRACE Relative Position Compared to Bi-Frequency Reference Solution

4. CONCLUSION

The CNES relative POD algorithm validations are shown to be one order of magnitude better than the accuracy needed for FFRF validation and calibration. This demonstrates the validity of the algorithm and its performance in some quite favorable formation flying configurations, such as stable orbit (no maneuvers), stable and favorable attitude profile. Indeed, the GPS POD performance may be affected by maneuvers and important attitude motion. The maneuvers reduce the calm measurement duration, and the attitude motion reduces the number of GPS satellites on visibility, as well as the common measurements on both satellites needed for single differences. Some more representative formation flying configurations are foreseen to complete these tests.

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