METOP PRECISE ORBIT DETERMINATION IN NEAR-REAL TIME WITH GPS

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ABSTRACT *– Metop is an Earth observation mission conducted by EUMETSAT carrying several meteorological instruments. One of these instruments is the GNSS Receiver for Atmospheric Sounding (GRAS) designed to generate atmospheric profiles based on the bending of GPS signals while being occulted by the atmosphere. This data processing requires the orbit determination of Metop to be carried out with a high level of accuracy and within a very restrictive timeliness. This paper focuses on the implementation and performance of the Metop Precise Orbit Determination (POD).*

The Metop POD is based on the navigation signals from the GPS constellation on the GRAS receiver. The requirements imposed by the processing of the sounding signals from the GRAS instrument makes the orbit determination of Metop the most critical processing element in the EUMETSAT Polar System (EPS) meteorological data processing stream. Two main constraints are imposed to the Metop POD. On the one hand the need for precise Metop ephemerides within a very tight timelines leaves a very reduced time span to execute the orbit determination process in near real time. On the other hand the target accuracy to be achieved that fulfils the very severe requirements imposed by the GRAS sounding process.

In the frame of the EPS phase B implementation, GMV has developed the strategy to execute the Metop POD. An orbit determination package has been implemented to demonstrate the feasibility of the Metop POD with the required level of accuracy and within the timeliness constraint imposed by the overall EPS data processing.

KEYWORDS: Earth Observation, Sounding, Meteorology, Metop, GRAS, GPS, Precise Orbit Determination, Near Real Time.

INTRODUCTION

The need for the Metop precise orbit determination arises from the very demanding accuracy requirements within the processing of GRAS sounding data. The orbit determination accuracy demand is derived from the processing requirements themselves while the timelines constraint requirements come from the generic delivery requirements applicable to all instruments aboard Metop.

The processing of GRAS sounding data is based on the Doppler shift experimented by the signal emitted by an occulting GPS satellite while traversing the atmosphere. The high sensitivity of the signal to small perturbations in the atmosphere requires the knowledge of all contributing error sources with very high accuracy, in particular the error in the computation of the velocity has to be limited. The accuracy requirements impose a target of 1m in position and 0.1 mm/s in velocity, being the velocity requirement the most demanding one between the two. Limitations in the estimation of the Metop receiver clock offset can also be expected but they were not defined at the time of closure of this paper, however, accuracy requirements at the nano-second level or below can be expected.

The timeliness constraint requirement establishes a limit of 2h 15m since sensing for the delivery of Metop Level 1b products, which in turns leaves some 12 minutes for the execution of the orbit determination process.

METOP CONFIGURATION

Metop will fly in a sun-synchronous low Earth polar orbit very similar to the one flown by the ERS, SPOT and ENVISAT satellites. This is of great importance as all the experience acquainted during these missions can be applied to the GRAS/Metop Precise Orbit Determination problem.

Metop as the other satellites in its family are all three axes stabilised satellites. This means that the directions of their reference axis are oriented by maintaining certain angles with well-defined directions. This objective is to keep the satellite in its best orientation for the observation of the Earth surface. In the particular case of the Metop POD with GPS is necessary to establish the geometry with respect to the GPS constellation and in particular the position of the navigation antenna, which will conditioned the observability of the GPS satellites and therefore the performance of the orbit determination process.

As shown in figure 1, Metop carries three GPS antennae on board. Two of these antennae are dedicated to capture the sounding signals from the occulting GPS, one along the velocity (Zgva) and another one along the anti-velocity (Zgava). The third antenna (Zgza) is the navigation antenna that actuates as a standard GPS orbiting receiver.

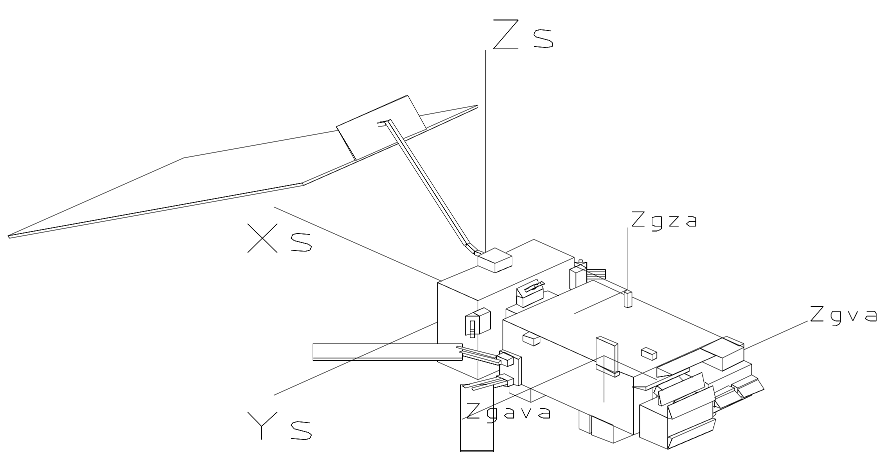


Fig. 1: Metop Reference Frame and GRAS Antennae

ASSUMPTIONS

The main assumptions made during the project were:

1. The accuracy of the GPS precise orbit determination is good enough to achieve the target orbit determination accuracy for Metop.
2. Metop GRAS navigation data rate is 1Hz. Ground station tracking data rate and GPS clocks rates are both equal or lower than 1Hz. The capability to generate Metop clocks with a certain rate is then limited by the rate at which the GPS and station clocks are provided. Also the generation of differences involving a ground station is limited by the data acquisition rate of the ground station
3. The attitude uncertainties in pointing and pointing rate do not impose any limitation in the achievement of the target positional accuracy. Typically, pointing accuracy below 0.2º are expected.
4. GPS orbits and clocks and station tracking are available at the time when the Metop POD is started. NRT availability of state vectors is guaranteed whereas the availability of NRT GPS clocks is subject to GRAS Support Network (GSN) ground station data contents definition.
5. Timeliness constraint of 2 hours and 15 minutes after sensing to deliver products to the users.

DYNAMICAL MODELS

The dynamical model defines the way in which the orbit determination software simulates the behaviour of the satellite evolution with time. It also filters the measurement noise providing a smooth satellite motion. The level of detail in the dynamics modelling depends on the nature of the problem to be solved. In the particular case of the Metop precise orbit determination, the very demanding requirements in accuracy make necessary to exploit the most detailed and accurate models that are available.

There is one factor that makes the Metop POD problem somehow specific. The need for NRT processing restricts the availability of certain type of data to the highest possible accuracy. In particular the knowledge of the solar activity, geomagnetic index and the Earth orientation parameters in known only based on prediction by the time when the process must start. Together with this limitation, the reduced time span for execution of the POD activities restrict the maximum arc length that can be processed in one run. This has the following consequences:

- It is not possible to observe the aerodynamic and solar radiation pressure coefficients for arcs shorter than 6 hours approximately. Not to mention the very poor observability of any empirical acceleration that may also require estimation.
- The sensitivity of the orbit determination to dynamic uncertainties in short arcs is very reduced. However, the stability of the solution requires that the dynamical models be calibrated with long off-line arcs before feeding the coefficients in the short NRT short arcs. Specially the aerodynamic coefficient.
- The uncertainty in the solar and geomagnetic activities do not make desirable to process arcs longer than 1-2 orbital revolutions to avoid the impact of these uncertainties in the propagation of the orbital state.
- The target accuracy makes desirable to include the maximum level of detail in the rest of the models, particularly in the geopotential that contains the terms at high orbital frequencies. Since most models are already implemented in the software package used as reference, for simplicity all models not requiring estimation of parameters have been used, even if their effect is expected to have a very limited contribution to the final accuracy.

According to these considerations, the orbital solution is mainly driven by the 1Hz tracking data while the contribution of the dynamics is limited to the smoothing of the solution between observation points. The following models have been used for the implementation of the GRAS/Metop POD

- Geopotential from EGM-96 truncated to degree and order 70
- Third body perturbations from Sun, Moon and planets

- Frequency dependent solid tides from Wahr
- Ocean tides from Schwiderski
- MSISE-90 air density model with variable frontal area
- IERS direct solar radiation with variable reference area

The aerodynamic and solar radiation pressure coefficients are fixed for the NRT arcs using calibrated values estimated in long arcs. The effect of Earth albedo and infrared and the contribution from estimated 1-c.p.r. empirical accelerations have been neglected.

GPS MEASUREMENTS

A GPS receiver delivers two main types of observations: pseudo-range and carrier phase

The measurement principle for both of them consists in the comparison of signals from the emitter (the GPS satellite) and the receiver (a ground station or an orbiting receiver). However, the details of the each of the measurement principles are different and so is the performance of each of them. Pseudo-range observations also known as code observations are computed from the direct differencing of the reception time and emission time. Carrier phase observations are based on the difference between the transmitted and Doppler shifted carrier phase in the GPS satellite time frame with respect to a reference signal in the receiver time frame.

Adequate simulation models for these two types of observations have to be defined in order to provide the orbit determination algorithm with accurate enough values of the measurement noise and partial derivatives.

The pseudo-range measurement between a GPS satellite and an orbiting receiver is obtained based on the geometrical slant range and different corrections. These latter ones are based on the relativistic effect in the propagation of electromagnetic signals in the presence of a heavy body (Shapiro effect), the difference between the phase centre and the centre of mass, the effects due to clock lack of synchronisation (modeled as receiver and emitter clock errors and estimated in the POD process) and signal propagation (ionospheric correction).

Analogously the carrier phase observations are generated from the geometrical slant range with the same sort of corrections as for the pesudo-range measurements with the specific implementation for carrier phase. The integer ambiguity must also be taken into account to compute the final value of the reconstituted carrier phase observation.

OBSERVATION COMBINATIONS

The purpose of combining observations between satellites and receivers aims to the reduction of the impact of certain errors that affect the estimation process being used. One of the purposes of the study is to analyse the best tracking scenario for the implementation of the GRAS/Metop POD. Hence, the following combinations are considered

Single differences with two GPS satellites, to eliminate the effect of the receiver clock bias

Single differences with ground station, to eliminate the effect of the GPS clock offset. The disadvantage is the implication of the station tracking data in the process.

Double differences with two GPS Satellites and a ground station, which eliminates all clocks in the combination except the one used to time-tag the measurement.

The detail analysis of all these scenarios with simulated data brings the conclusion that in absence of SA, the direct measurements are better suited for the GRAS/Metop POD problem than any of the differenced combination, with the accuracy expected for the GPS positions and clocks. Being the velocity accuracy the most restrictive requirement in study, only the single difference with ground station provided equivalent performance as the direct measurements with slight degradation in performance for the receiver clock estimation.

MEASUREMENT CORRECTIONS

The corrections applied to the processed measurements are the standard in the POD processing of GPS measurements whose details can be found in the literature. These account for antenna phase centre offsets, relativistic propagation, clock corrections and atmospheric delays. In the GRAS/Metop POD problem the advantage of the dual frequency receiver is used to reduce the ionospheric effect (ionospheric-free combinations). The effect of the receiver clock is taken into account by estimation as part of the orbit determination process. The GPS clock offsets are fixed from an off-line GPS constellation precise orbit determination that provides the GPS constellation ephemerides as well.

For observations involving ground stations, the Saastamoinen model is used to account for the tropospheric delay. Station clock bias is also accounted for.

The major concern in the course of the study is the possibility to establish the main sources for errors in the applied corrections and to be able to characterise their level and shape. After a detailed analysis of the error source the derived conclusion appoints the position of the GPS position and clock uncertainties as the main drivers for the errors in the estimation of the Metop position and clock. This is consistent with the fact that the solution is mainly driven by the observations and not by the dynamics in the execution of short arcs.

TIMELINESS CONTRAINT

The timeliness constraint imposes that all EPS products (i.e. meteorological data) must be disseminated to the users in Near Real Time (NRT), within 2h 15min from sensing. This available time can be split in five main contributions:

- Latency time in orbit before dumping: this period of time takes into account that once the measurement has been sensed by the Metop satellite, it must wait until the data dump over the polar station takes place.
- The transfer time from the ground station to the central site including the time required for initial telemetry pre-processing
- POD time, including pre-processing of measurements and post-processing of POD products as well as the POD execution time itself.
- GRAS sounding processing time needed by the GRAS software to process the GPS occultation
- NRT dissemination of the GRAS products to the users.

Taking all these times into account, the POD has to be performed in about 12 minutes including pre- and post-processing of the POD inputs and outputs.

Two main concerns arise in the timeliness analysis. On the one hand to identify the most critical observation that allows the fulfilment of the timeliness constraint and on the other the maximisation of the time for which navigation observations could be accumulated before feeding them to the orbit determination process.

Due to the availability requirements impose to the EPS data processors, the implementation of a pure Kalman filter was discarded as it is very sensitive to local instabilities introduced by badly conditioned observations. The need for a previous non-linear filtering of the most recently received observations lead to the implementation of a batch process that solves non-linearities before including the new dataset into the overall orbit determination process. This can be implemented by extending the orbit determination arc using observations from the past until a sufficient stable solution is obtained, performing then a sequential execution of orbit determination arcs in batch shifting the data window. This process has been designated as sequential batch and implements a traditional Bayesian least squares algorithm.

For the timeliness analysis one needs as input the typical execution time of the above described batch process. Using as reference the software package BAHN, the execution time as a function of the number of processed epochs is shown in figure 2, where undifferenced measurements from a fixed orbit GPS constellation have been used. With observation at 1 Hz delivered by the on-board GPS receiver and an average visibility of the GPS constellation of 6 satellites (3600 observations in 10 minutes) the execution time does not exceed 10 seconds. Even going for long orbit arcs around one hour (21600 observations) it is not expected to exceed 30 seconds of real execution time.

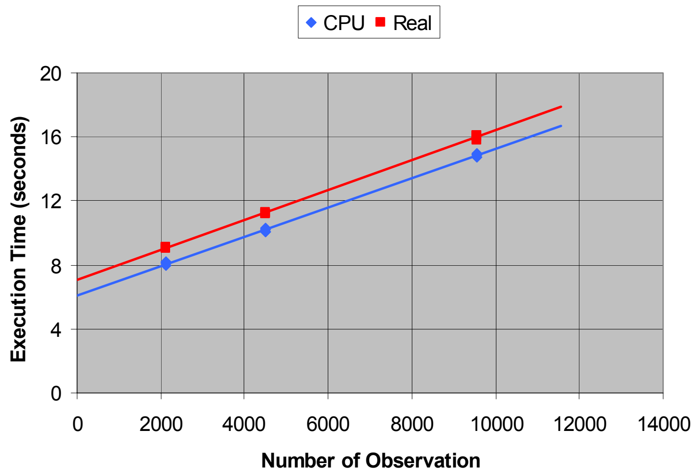


Fig. 2: POD Execution Time

The first state of the timeliness analysis was then dedicated to establish the most critical observation and the maximum duration of the orbit determination arc with respect to the navigation data availability. Figure 3 shows that the most critical observation is always the first one in each orbit determination arc, regardless of the transfer rate to between the ground station and the central site. The lengths of the ramps between peaks depend mostly on the length of the orbit determination arc using observations from the recent past together with the just acquired ones. The worst cases appears when this transfer takes one whole orbital revolution and then all first observation within each arc are at the limit of violation of the timeliness constraint.

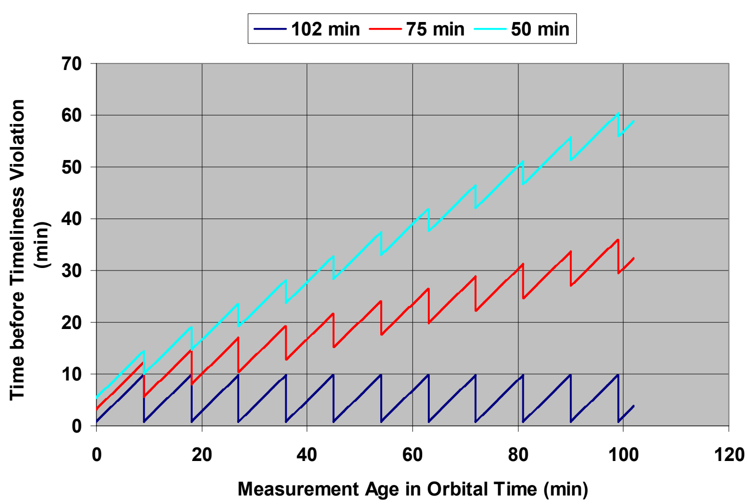


Fig. 3: Critical Observation Detection

Knowing already the criticality of the first observation and the slowest possible data transfer rate, one can establish which is the longest one can wait before processing a whole batch of new observation. This time (as shown in figure 4) is of the order of 10 minutes in terms of orbital elapsed time for the worst case in transfer rate performance.

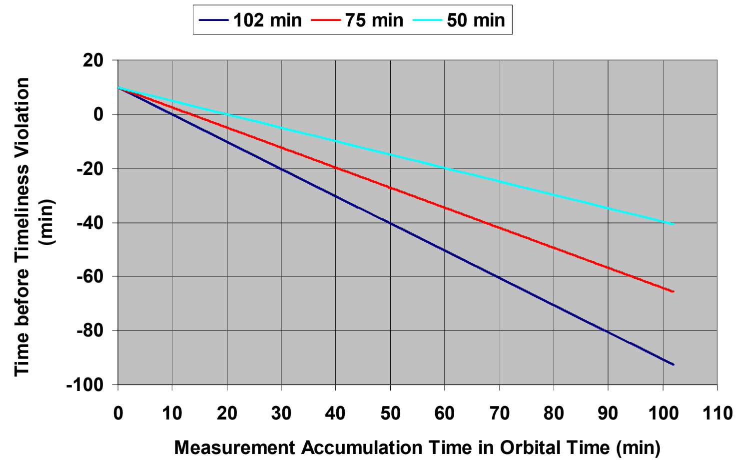
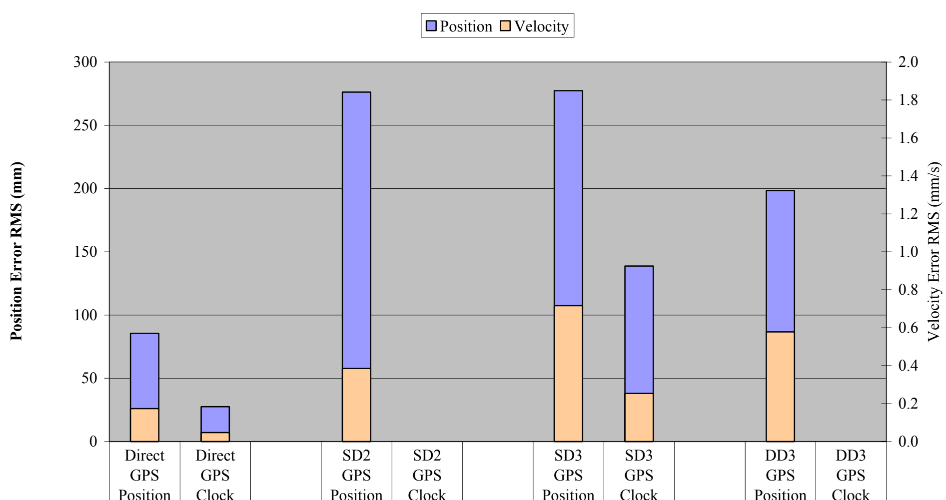


Fig. 4: Maximum Observation Accumulation Time

RESULTS WITH SIMULATED DATA

The use of simulated data was aiming to the implementation of the worst scenario that could be expected in the GRAS/Metop POD problem, looking for the tracking type that better adapts to the input errors and minimises the POD errors.



	Direct GPS Position	Direct GPS Clock		SD2 GPS Position	SD2 GPS Clock		SD3 GPS Position	SD3 GPS Clock		DD3 GPS Position	DD3 GPS Clock
Position	85.514	27.533		276.290	0.000		277.373	138.776		198.429	0.000
Velocity	0.173	0.047		0.385	0.000		0.716	0.253		0.578	0.000

Tracking Type

Fig. 5: Performance vs. Tracking Combination

As shown in Figure 5 the direct measurements (left) filter better the same level of error in the positioning of the GPS constellation, both in terms of position and velocity. The behaviour in the filtering of GPS clock errors is also within specification.

Unfortunately the processing of simulated data are not concluding. The stability of consecutive orbit determination arcs are at the limit of requirements when extreme values for the position and clocks of the GPS constellation are used (i.e. 30 cm in position accuracy and 1.5 ns in clock uncertainty). Overlaps in this situation can reach the meter leading to uncertainties far beyond the requirements. Processing longer arcs can mitigate this problem, but the validation with real data becomes now necessary.

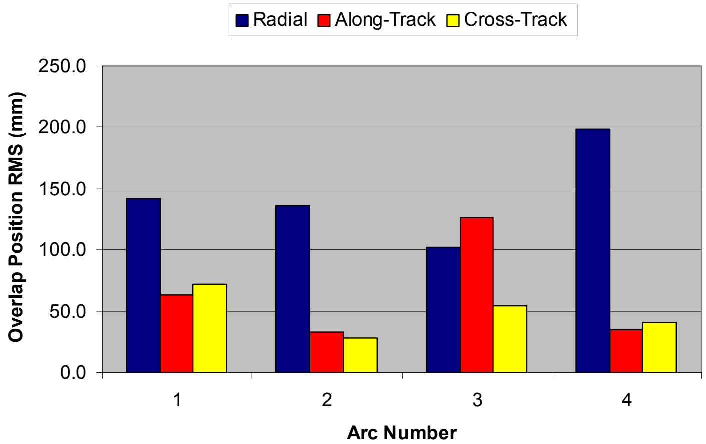


Fig. 6: Worst Case Overlaps

RESULTS WITH REAL DATA

The validation with real data has been performed in two steps. The first one to validate the POD implementation with long arcs, which is also needed for the calibration of dynamical parameters. The second step aims to the validation of the NRT scenario in which short arcs have to be processed. To implement this real data scenario, Topex/Poseidon GPS data has been used. Third party orbits computed in long 5-day arcs with DORIS have also been used for comparison. Since the most critical requirement is imposed to the along track velocity (correlated to the accuracy in radial position), special attention has been dedicated to these components of the comparisons.

The calibration of dynamical parameters requires that the involved estimated coefficients, aerodynamic and solar radiation coefficients, are observable by the processed tracking. Figure 7 shows the evolution of the estimation with the arc length for the aerodynamic coefficient (similar behaviour is encountered for the radiation pressure coefficient). A minimum length of 6 hours is needed to guarantee observability of the coefficients.

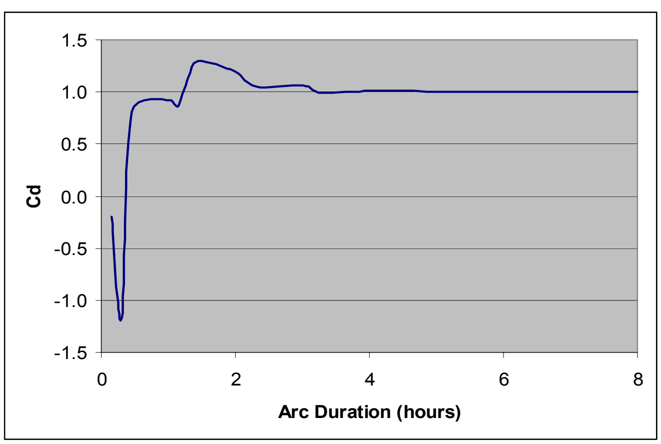


Fig. 7: Aerodynamic Coefficient vs. POD Arc Length.

Figure 8 shows the accuracy of the orbit determination for long arc (12 h). The behaviour is better in the central part of the arc than at the edges. This is a typical behaviour of the least-squares process whose best fit is always located in the middle of the interval because of the better observability of the parameters. The mean accuracy of the radial component of the computed orbits is better than 10 cm in the radial direction which in turn corresponds to 0.1 mm in the along-track velocity component. This guarantees that the implemented POD performs radially within some 5-6 cm of the DORIS orbits, whose accuracy is assumed to be about 5cm radially. Calibration of dynamical parameters is needed to achieve this accuracy.

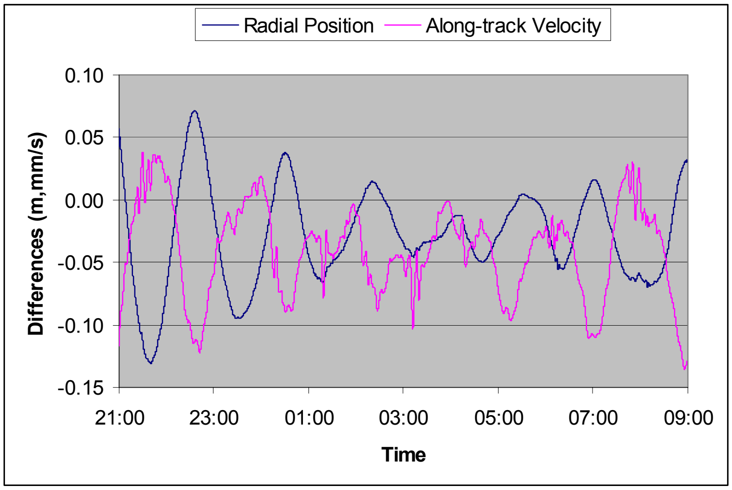


Fig. 8: Topex Accuracy Assessment for Long Arcs

The computation of the NRT arcs can now be performed with confidence in the accuracy of the long arc calibration arcs and the resulting calibrated dynamical parameters. Figure 9 shows the comparison of the sequence of NRT arcs with respect to the calibration orbit. The level of confidence in the resulting estimated orbits is for this NRT scenario about 8 cm radially, assuming some 5-7 cm uncertainty in the reference calibration orbit.

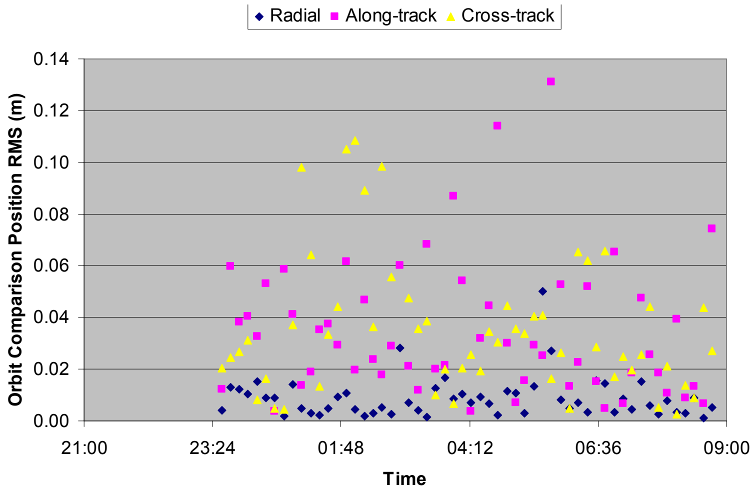


Fig. 9: Topex Orbit Accuracy Assessment

After being confident in the level of accuracy of the orbit it is also necessary to look at the estimation of the receiver clock. This is of great importance if both receiver orbits and clocks are to be used together in a following data processing. Figure 10 shows the estimation of the Topex clock in a long arc (12 hours). Note in the figure the discontinuity around 0:00 h. Time dependent clocks can go through discontinuities without taking any specific action, as the values of clocks are all independent and un-correlated from each other.

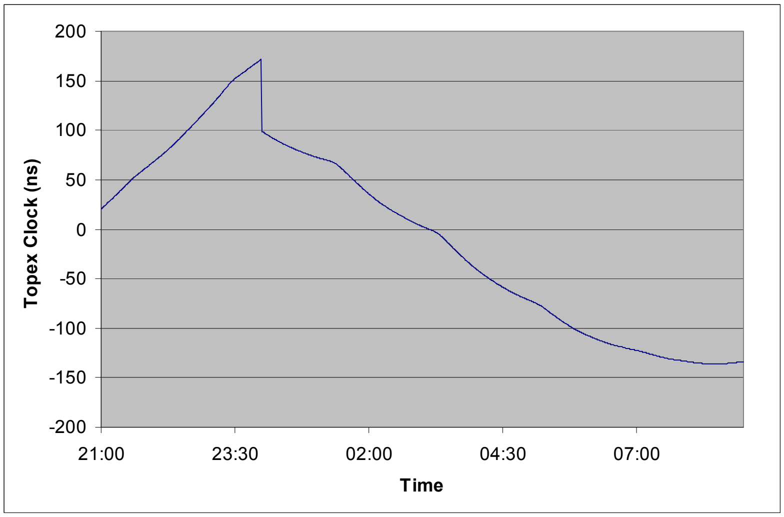


Fig. 10: Topex Clock Estimation in Long Arc

The same comparison performed for the orbit estimation in NRT can be performed for the Topex clock estimates. This is shown in Figure 11 where it is clear that at least an uncertainty of 2ns can be expected.

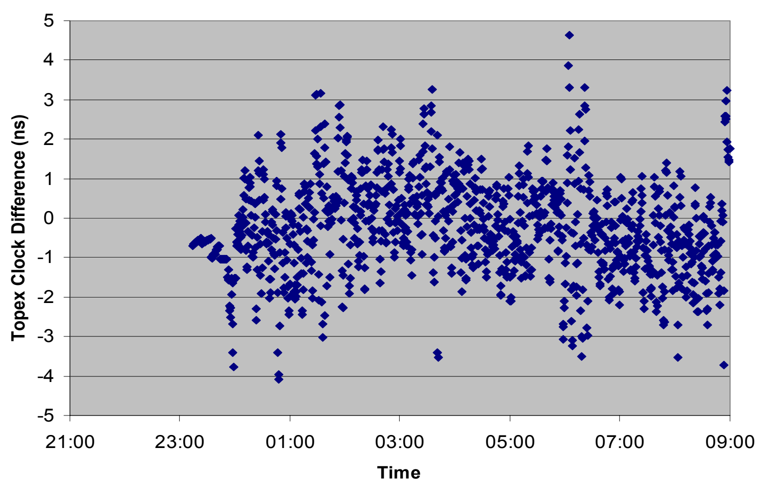


Fig. 11: Topex Clock Accuracy Assessment

CONCLUSIONS

The timeliness constraint, which leaves about twelve minutes for the GRAS/Metop POD, can be easily fulfilled. The processing of real data has demonstrated that even with longer arcs (one orbital revolution = 2 hours for Topex) is still short enough to fulfil the timeliness constraint.

The observability of the Metop orbit dynamical parameters is so limited that constant values can be used for each orbit determination arc. Meaningful calibrated values for the NRT processing must be computed in long arcs.

Although the initial approach for Metop clock estimation was based on a polynomial fit, the processing of real data has proven the need to estimate time dependent clocks in order to follow the trend of the clock with time.

The stability of the sequential execution of several orbit determination arcs, as if it were the operational implementation, has been proven with real data. The stability of the solution in consecutive orbit determination executions is below 10 cm in the radial direction, which in turn guaranties a consistency of along-tack velocity below 0.1 mm/s.

The processing of real data has proven the possibility of computing orbits with the required level of accuracy in NRT. Consistency between consecutive orbits can be found at the centimetre level. Estimated clocks, however, have not been estimated better than an accuracy of 2 ns.

ACKNOWLEDGEMENTS

JPL for their provision of Topex tracking and ancillary data upon request.

ESA/ESOC for their contribution to the development and the provision of licenses to implement the software prototype to execute the study.

EUMETSAT that granted GMV the execution of the GRAS/Metop Precise Orbit Determination Study

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