NEAR REAL-TIME PRECISE ORBIT DETERMINATION FOR LOW EARTH ORBITING SATELLITES

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ABSTRACT

POD (Precise Orbit Determination) is one of the key aspects of most LEO (Low Earth Orbiting) satellites. This becomes critical if additionally timeliness requirements are imposed that lead to an NRT (Near Real-Time) processing scenario. Such is the case for MetOp (Meteorological Operational satellite, the European satellite of the EPS –Eumetsat Polar System– mission) in the processing of GPS (Global Positioning System) data used in the generation of atmospheric sounding profiles by its GRAS (GNSS –Global Navigation Satellite System– Receiver Atmospheric Sounding) instrument.

In GRAS POD, the target accuracy for orbit (10cm) and clock offset (1ns) has to be obtained based on 10-minute datasets and within a few minutes of processing time. Only a sequential algorithm can achieve this.

The selected algorithm is the SRIF (Square-Root Information Filter), which retains the information collected during all previous intervals in the Information Matrix and combines it with the input measurements, using the Householder transformation, to conduct the estimation process.

1. INTRODUCTION

The need for the MetOp (Meteorological Operational Satellite) POD (Precise Orbit Determination) arises from the very demanding accuracy requirements within the processing of the GRAS (GNSS –Global Navigation Satellite System– Receiver Atmospheric Sounding) data. The orbit and clock offset determination accuracy requirements are derived from the processing requirements themselves while the timeliness constraint comes 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 (Global Positioning System) 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 0.1mm/s in velocity, the velocity requirement being the most demanding one between the two. As for the error in the estimation of the MetOp receiver clock offset, it is limited to 1ns.

The timeliness constraint requirement establishes a limit of 2h 15min since sensing for the delivery of MetOp Level 1b products, which in turn leaves some 12 minutes for the execution of the POD process including pre-processing of the observations and post-processing of the generated POD products.

The problem that has to be solved is therefore that of the NRT (Near Real-Time) Precise Orbit Determination of a LEO (Low Earth Orbiting) satellite.

1.1 MetOp configuration

MetOp will fly in a sun-synchronous low Earth polar orbit very similar to the one flown by the ERS (European Remote Sensing Satellite), SPOT (Système Pour l'Observation de la Terre) and ENVISAT (Environment Satellite) satellites. This is of great importance as all the experience acquainted during these missions can be applied to the GRAS/MetOp POD problem.

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

MetOp carries three GPS antennae on-board (see Fig. 1). Two of these antennae are dedicated to capture the sounding signals from the occulting GPS, one along the velocity (GVA) and another one along the anti-velocity (GAVA). The third antenna (GZA) is the navigation antenna that actuates as a standard GPS orbiting receiver, collecting the measurements which will then be used for the GRAS/MetOp POD process.

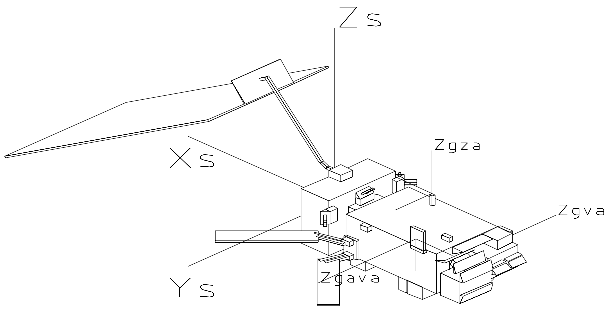

Fig. 1. MetOp Reference Frame and GRAS Antennae

2. THE METOP NRT POD PROBLEM

As for any orbit determination problem, the GRAS/MetOp NRT POD problem consists of estimating a number of parameters based on received measurements and using given dynamical models. The elements of the problem are presented hereafter.

2.1 Measurements

The measurements used for the MetOp NRT POD are the standard ones obtained from the GPS navigation antenna: code-phase and carrier-phase measurements. As it is explained in [1], the measurement principle for both of them consists in the comparison of signals from the emitter (the GPS satellite) and the receiver (in our case, the MetOp orbiting receiver). However, the details of each of the measurement principles are different and so is the performance of each of them. Code-phase observations are made differencing the PRN (Pseudo-Random Noise) code in the received signal with a reference signal in the receiver, while 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 the 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 (which can be easily derived from the code-phase measurement by removing an ambiguity large enough to be computed separately for each measurement) is obtained based on the geometrical slant range and different corrections. These 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 (modelled as receiver and emitter clock errors) 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 pseudo-range measurements with the specific implementation for carrier phase. An integer ambiguity must also be taken into account to compute the final value of the reconstituted carrier-phase observation.

Besides, the GRAS/MetOp POD process can take advantage of the fact that measurements provided by the GPS navigation antenna are dual-frequency, which makes it possible to compute the ionospheric-free combination, both for pseudo-range and carrier-phase measurements.

The measurements introduced into the filter are, therefore, GPS undifferenced pseudo-range (obtained from the code-phase) and carrier-phase ionospheric-free combinations.

The tracking data are input to the POD in 10-minute sets of data at 1Hz. The orbit determination has to be performed for each of these datasets.

2.2 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 modelling the dynamics 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 it necessary to exploit the most detailed and accurate models available.

One factor 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 can only be based on predictions 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 arcs. Specially the aerodynamic coefficient.
- The uncertainty in the solar and geomagnetic activities do not make it desirable to process in batch 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 it 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 frequency. 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 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 (Earth Gravitational Model 1996) truncated to degree and order 70.
- Third-body perturbations from Sun, Moon and planets.
- Frequency-dependent solid and ocean tides
- MSISE-90 air density model with variable front effective area.
- IERS (International Earth Rotation and Reference Systems Service) direct solar radiation with variable cross-section.

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

2.3 Estimated Parameters

The parameters to be estimated in the GRAS/MetOp NRT POD process are:

- The satellite's state vector (position and velocity).
- MetOp clock offset at 1Hz.
- The ambiguities of the carrier-phase measurements.

GPS precise orbits and clocks are an input to the POD process as provided by the GSN (Ground Support Network) and are kept fixed in the POD process.

2.4 Assumptions

The main assumptions made for the POD process are:

- GPS orbits and clocks are available at the time when the GRAS/MetOp POD is started. These data are provided by the GSN as a result of a POD process involving the GPS constellation and a network of fiducial ground stations.
- The accuracy of the provided GPS orbit and clock solutions is good enough to achieve the target POD accuracy for MetOp.
- 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 0.2 degrees is expected.

2.5 Timeliness constraint

The timeliness constraint imposes that all EPS products (i.e. meteorological data) must be disseminated to the users in Near Real Time, 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 occultations.
- NRT dissemination of the GRAS products to the users.

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

The number of epochs to process in each incremental dataset is 600, which corresponds to 6,000 observations (including carrier-phase and code-phase) for an average GPS visibility of 5 satellites.

3. BATCH PROCESSING

One possible method for solving the GRAS/MetOp POD problem is the batch processing of measurements. However, the first approach of processing each of the 10-minute datasets independently is not valid, since the target accuracy cannot be achieved with such a small amount of tracking data.

The way to use a batch method achieving the required accuracy with such small amount of data is to extend 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.

However, this method cannot be used in the scope of the GRAS/MetOp POD because of the timeliness constraints, which are too strict for processing the amount of measurements needed for obtaining the needed accuracy in the solution. A detailed analysis has shown that at least one whole orbit must be processed to achieve sufficient radial accuracy. This represents processing some 60,000 measurements in an iterative process. This cannot be achieved within the tight timeliness imposed.

Therefore, a different algorithm has to be implemented which allows to process just the amount of measurements provided in each dataset and, at the same time, can achieve the target accuracy. The SRIF (Square-Root Information Filter) is such an algorithm, which processes measurements sequentially and keeps in a matrix of reduced size information on the previously processed observations that can be combined with the newly arrived tracking data.

4. SQUARE-ROOT INFORMATION FILTER

SRIF is based on finding the least-squares solution to a system by means of an orthogonal transformation (the Householder transformation) that makes it upper triangular. The system to be solved is formed by the measurements equations, linking the observation partials A, the estimated parameters x and the observation residuals z, plus a new set of equations (one per estimated parameter) which contains the information of a previous state. These fictitious data equations are initialised with the square root of the covariance matrix (hence the name of the filter).

Eqn. 1 shows the measurements equations (subscripts indicate the dimensions of matrices and vectors, m being the number of measurements and n the number of estimated parameters), while Eqn. 2 contains the fictious data equations storing information about the previous intervals.

$$z_{(m)} = A_{(mxm)} \cdot x_{(n)} + v_{(m)} \qquad (1)$$

$$\tilde{z}_{(n)} = \tilde{R}_{(nxn)} \cdot x_{(n)} + \tilde{v}_{(n)} \qquad (2)$$

Although conceptually more complex than the traditional batch method, the implementation of the algorithm is quite simple. Besides, the number of operations to be performed for estimating a given number of parameters with an input set of measurements depends only on the number of parameters and on the size of the dataset. The size of the problem does not increment with time as long as these two figures do not increase.

Given a number of measurements, they are combined with the previous information matrix by means of the Householder transformation T (see Eqn. 3).

$$\begin{bmatrix} \tilde{R} & \tilde{z} \\ A & z \end{bmatrix}_k \xrightarrow{T} \begin{bmatrix} \hat{R} & \hat{z} \\ 0 & e \end{bmatrix}_k \qquad (3)$$

Once triangular, the information matrix $\hat{R}$ can easily be solved for the values of the parameters. In order to process a new observation or a new set of observations, the information matrix has to be propagated to the end of the previous interval, and this is made by combining it properly with the transition matrix of the estimated parameters and performing a new Householder transformation (Eqn. 4). In this way, the information on the previous state is ready for processing the new observation or observations.

$$\begin{bmatrix} \hat{R} & \hat{z} \end{bmatrix}_k \xrightarrow{T} \begin{bmatrix} \tilde{R} & \tilde{z} \end{bmatrix}_{k+1} \qquad (4)$$

From the previous explanation, it can be seen that one of the main properties of the information matrix is that its size does not increment with time, but depends only on the number of parameters being estimated. Therefore, solution of the problem involves the same reduced number of operations each time (as long as the number of estimated parameters does not change). More details on the SRIF algorithm and its application to orbit determination can be found in [2].

4.1 Clock Model

In the case of the GRAS/MetOp POD, the size of the set of observations to be processed simultaneously is configurable. Since observations corresponding to different seconds can be processed in the same step and the MetOp clock offsets have to be provided at 1Hz, some model is needed for this clock.

The selected model is linear (clock offset and drift) plus an optional ECRV (Exponentially Correlated Random Variable), which can be selected through configuration. The two (or three, if the ECRV is selected) coefficients of the model are estimated as part of the POD process and used to interpolate the values of the clock at the required rate.

4.2 Steps in the POD Software

The GRAS/MetOp POD process is carried out in three phases. First, a pre-processing is made in which the following activities are performed:

- Reading of observations from the input file, filtering them in order to keep in memory only those affecting the configured elements within the specified time interval.
- Statistics of the set of applicable measurements and editing of outliers.
- Computation of pseudo-range measurements from the input code-phase observations. Since the ambiguity in these observations is a multiple of around 300km for C/A code and around 30km for P code, it can be easily removed by comparing the input measurements with the orbit propagated in the previous execution of the filter (for initialisation, a moderate-accuracy orbit from the operational system can be used).
- Preliminary estimation of the carrier-phase ambiguities, taking into account all accepted measurements. The figures obtained in the pre-processor will be used as initial values for the estimation of the carrier-phase ambiguities in the filter itself.
- Removal of the GPS clocks, which are fixed, from the measurements, so that they do not have to be considered in the filter itself, thus saving time.

Once the pre-processor has finished these tasks, the measurements are introduced into the SRIF. This is done in batches of measurements of configurable duration. For each of these batches, the needed parameters are estimated.

Finally, after the parameters have been estimated, they have to be propagated into the future, so that initial conditions are present for the next execution of the software. Dynamical parameters are propagated using the propagator inside the software, while the clock offsets are propagated linearly from the last estimated values.

4.3 Tuning the POD

It can be easily understood that the number of parameters that have to be configured in the GRAS/MetOp POD is quite large. However, most of such parameters can be easily configured taking into account the characteristics of the problem to be solved. Such is the case of the dynamic model parameters, or the ones affecting the satellite geometry or the type of the input measurements.

On the other side, there are a number of parameters which will have to be carefully configured, and which may require a certain level of experimentation in order to obtain the values that best fit the specific problem to be solved. Among these parameters are:

- The duration of the observation batches. Since MetOp clock parameters are estimated per batch of measurements, a good clock estimation requires a low value for this duration. But estimation of the rest of the parameters has to be carried out with as many data as possible, so a trade-off between both needs has to be performed.
- The ECRV option in the MetOp clock estimation. From the theoretical characteristics of the MetOp clock, it seems that selection of this option may not be necessary. However, experimentation will have to be carried out with real data from this clock in order to assess the need of selecting it and, if needed, the ECRV characteristic time. For the nominal quality of the clock (as provided by the manufacturer) it seems that a piecewise linear trend for the clock can be estimated for each of the 10-minute datasets. To ensure clock continuity, a constraint in the clock bias with respect to the one estimated in the previous step is to be imposed.

At the time of writing this paper, the experimentation needed for tuning the system had not been completed. Therefore, the results presented hereafter can only be considered as preliminary.

5. RESULTS

The preliminary assessment of the power of this filter has been done using data from Topex/Poseidon. Data from this real mission corresponding to the year 1995, i.e. with SA (Selective Availability) on, have been used for the analysis shown in this paper.

Third party orbits computed in long 5-day arcs with DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) have been used for comparison.

Fig. 2 shows the comparison of the orbit obtained by the POD against the DORIS reference orbit for a long arc computed in batch. The most critical component is the radial one, which, as can be seen, is well under the requirement.

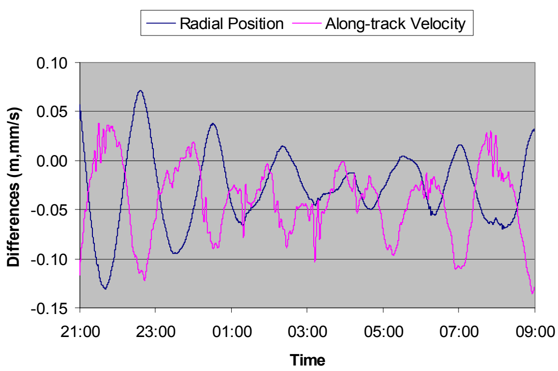

Fig. 2. Topex Accuracy Assessment for Long Arcs

Fig. 2 demonstrates that it is possible to achieve the accuracy requirements with respect to the radial component. The problem remains in demonstrating whether it is possible to obtain the same accuracy while processing short arcs. Using the *sequential batch* scheme describe above, it is feasible if arcs lasting at least one orbit are processed. Fig. 3 shows the comparison of these one-orbit arcs with the long-arc orbit determination with GPS. The approach is suitable what the radial accuracy is concerned, however the timeliness constraint cannot be fulfilled.

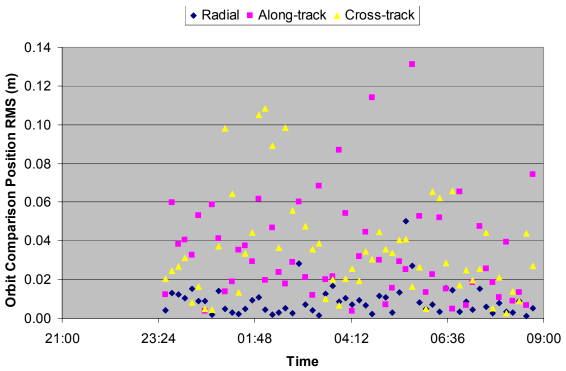

Fig. 3. Topex Orbit Accuracy Assessment

Once confidence in the level of accuracy of the orbit has been gained, it is also necessary to look at the estimation of the receiver clock. This is of great importance if both receiver orbit and clock are to be used together in the processing of atmospheric sounding observations.

Fig. 4 shows the preliminary comparison of the Topex clock obtained in the long-arc orbit determination with the same clock estimated in the short one-orbit arcs. This simple internal comparison indicates that the accuracy of the clock cannot be maintained within the prescribed 1ns, as it is very sensitive to the length of the arc.

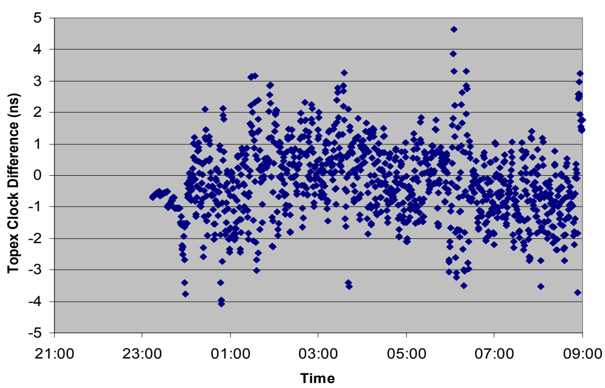

Fig. 4. Topex Clock Accuracy Assessment

Based on these results, the operational GRAS/MetOp POD implements a clock model that should be able to decorrelate the clock errors from any other sources of error (e.g. MetOp orbit), providing a smooth clock evolution with the required accuracy.

6. CONCLUSIONS

The strict accuracy and timeliness constraints imposed on the GRAS/MetOp POD process make it necessary to look for an algorithm different from sequential batch implementing the traditional Bayesian least squares. A sequential filter is needed, and the SRIF algorithm based on the Householder transformation has proven adequate for meeting the requirements of this mission.

Although tuning of the algorithm configuration is still to be done at the time of closing this paper, the preliminary results show that both the target accuracy and the timeliness constraints can be met: orbit accuracy has already been proven, while configuration can still improve considerably the clock estimation.

7. REFERENCES

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