GRAS NRT PRECISE ORBIT DETERMINATION: OPERATIONAL EXPERIENCE

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ABSTRACT

EUMETSAT launched the meteorological satellite MetOp-A in October 2006; it is the first of the three satellites that constitute the EUMETSAT Polar System (EPS) space segment. This satellite carries a challenging and innovative instrument, the GNSS Receiver for Atmospheric Sounding (GRAS). The goal of the GRAS instrument is to support the production of atmospheric profiles of temperature and humidity with high accuracy, in an operational context, based on the bending of the GPS signals traversing the atmosphere during the so-called occultation periods.

One of the key aspects associated to the data processing of the GRAS instrument is the necessity to describe the satellite motion and GPS receiver clock behaviour with high accuracy and within very strict timeliness limitations. In addition to these severe requirements, the GRAS Product Processing Facility (PPF) must be integrated in the EPS core ground segment, which introduces additional complexity from the data integration and operational procedure points of view.

This paper sets out the rationale for algorithm selection and the conclusions from operational experience. It describes in detail the rationale and conclusions derived from the selection and implementation of the algorithms leading to the final orbit determination requirements (0.1 mm/s in velocity and 1 ns in receiver clock error at 1 Hz). Then it describes the operational approach and extracts the ideas and conclusions derived from the operational experience.

1. INTRODUCTION

Precise orbit determination (POD) has been one of the key aspects of most low Earth orbiting satellites. The precise orbit determination of these satellites is a well-known and documented problem and its solution based on the processing of GPS signals is also well understood. In previous missions like Topex/Poseidon or Jason it was possible to obtain very accurate orbits by processing long orbit determination arcs with a moderate data rate. Notably, in the orbit determination problem of these satellites the receiver clock bias is a parameter whose estimation is limited to be reduced and, therefore, discarded.

MetOp is the first meteorological satellite for which POD has become a key aspect of the mission with orbit determination and clock estimation requirements comparable to other missions but with remarkable specific aspects. First of all, the timeliness constraint imposed to the delivery of the meteorological products imposes a tight restriction in the amount of time that can be devoted to orbit determination and when this processing time is available as well as the latency of the provided products. The second difference is that the estimation of the receiver clock bias must really isolate the clock behaviour from all other effects that might be absorbed in its estimation process. The GRAS clock offsets are further used in the GRAS occultation process and therefore must represent the actual clock behaviour free from any contaminating effects.

2. GRAS OPERATIONAL POD

The main operational constraint that also makes the GRAS POD different from other missions is the data availability restriction imposed by the EPS ground segment architecture. The EPS ground segment provides the GRAS PPF with a stream of 3-minute data slices that must be processed sequentially. The processing of such small datasets does not represent any technical problem in itself, but the accuracy requirement cannot be fulfilled based only on each independent 3-minute dataset. Thus, the use of batch algorithms for parameter estimation was proven not adequate in preliminary phase B studies. Although batch algorithms can process the 3-minute datasets in the specified time, accuracy requirements impose the processing of much larger number of measurements spanning over several orbital periods. This represents a processing overhead that prevents completion within the imposed timeliness requirement. The timeliness requirement is expressed in terms of the delivery of the level 1b meteorological products before 2 hours and 15 minutes after sensing. In the EPS operational context, this means that a batch-based orbit determination process spanning several orbits to achieve the required accuracy would take longer than the actual time available for orbit determination.

As a consequence, a sequential processing scheme was selected to solve the problem. The chosen algorithm is based on the so-called Square-Root Information Filter

(SRIF), which makes use of the Information Matrix to store the parameter estimation data in combination with the Householder transformation to conduct the estimation process. The Information Matrix accumulates and retains all the information collected during all previously processed intervals of measurements that will be needed for the next interval. The size of the Information Matrix does not increase with the number of measurements, but depends only on the number of parameters being estimated.

In the particular case of the GRAS POD, the satellite state vector, the aerodynamic and solar radiation pressure coefficients and the GRAS clock have to be estimated. Existing dynamical models represent the dynamical parameters to be estimated with a high level of detail. The modelling of the GPS measurements to achieve this is also a well-known problem whose modelling has been widely described in the literature. However, this has been one of the key aspects leading to the successful configuration of the orbit determination software. The GRAS receiver delivers very raw data in the telemetry stream. Understanding how to convert this raw data into information - like carrier-phase and pseudo-range - suitable for orbit determination has been one of the key aspects during the GRAS commissioning phase.

The clock offset estimation has also been one of the most interesting aspects during the commissioning of the GRAS PPF. The quality and stability of the clock fulfils the manufacturer's description (Allen deviation of 10-13 for any 1 to 100 seconds integration interval) and exceeds all expectations from the POD point of view, especially when compared with the receiver clock from other analysed missions. This has great interest from the science processing point of view and also from the operational point of view. The ability to select adequate and simple clock models (in practice linear piecewise model to represent the clock behaviour) as part of the sequential orbit estimation adds great stability to the estimation process, which in turn simplifies the operational set up that leads to the successful extraction of the satellite ephemeris and a clean estimation of the GRAS clock offsets. These can then be fed into sounding process without any further post-processing since the clock residuals compared to the estimated linear model do not exceed 50 pico-seconds in any case.

As most of the commissioning period for the GRAS PPF is almost over, some conclusions can already be extracted from the acquired knowledge and the learnt lessons. Sequential processing based on SRIF has proven suitable for GRAS precise orbit determination, both in terms of accuracy and timeliness. It has proven very efficient in processing the GRAS data at full rate (1-3 Hz) allowing the direct estimation of the precise trajectory and the high rate receiver clock offsets, simplifying in this way the software integration as part of the GRAS PPF. The initial performance comparison with respect to least-squares long arc solutions indicate agreement below 0.05 mm/s even during periods of low GPS visibility and reduced tracking data quality. Further analyses from the algorithm and operations points of view are still being conducted to fully qualify the performance of the GRAS precise orbit determination.

2.1 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 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 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 Figure 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 POD process.

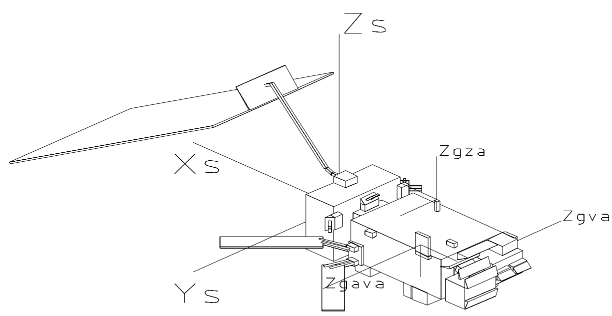

Figure 1. MetOp Reference Frame and GRAS Antennae

3. THE METOP NRT POD PROBLEM

As for any orbit determination problem, the GRAS 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.

3.1 Measurements

The measurements used for the MetOp NRT POD are the standard ones obtained from the GPS navigation antenna: pseudo-range 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. Pseudo-range 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 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 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 and carrier-phase ionospheric-free combinations.

The tracking data are input to the POD in 3-minute sets of data with pseudo-range running at 1Hz and carrier phase data running at 3Hz. Orbit determination has to be performed for each of these datasets.

Unlike other commonly used receivers, the GRAS receiver produces data that is not synchronised. In the GNNS world is common to process data that contains pseudo-range and carrier phase data for all PRN in the field of view sampled. The GRAS receiver produces all pseudo-range of the PRN in the filed of view simultaneously but not at the same epoch as the carrier phase. In addition, the sampling rate of pseudo-range and carrier phase are different and the time between consecutive samples may vary slightly from sample to sample.

3.2 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 POD:

- Geopotential from GRACE truncated to degree and order 100.
- Third-body perturbations from Sun, Moon and planets (JPL DE200 ephemeris).
- 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.

3.3 Estimated Parameters

The parameters to be estimated in the GRAS 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.

3.4 Assumptions

The main assumptions made for the POD process are:

- GPS orbits and clocks are available at the time when the GRAS 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.

3.5 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 less than 12 minutes, including pre- and post-processing of the POD inputs and outputs.

The number of epochs to process in each incremental dataset is 180, which corresponds to 3600 observations (including carrier-phase and pseudo-range) for an average GPS visibility of 5 satellites.

4. PROCESSING ALGORITHMS

4.1 Batch

One possible method for solving the GRAS POD problem is the batch processing of measurements. However, the first approach of processing each of the 3-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 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.

4.2 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.

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

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

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).

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

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.

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

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].

4.3 Clock Model

In the case of the GRAS 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.

4.4 Steps in the POD Software

The GRAS 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.
- 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.

5. THE FINAL APPROACH

Up to this point the description of the system has been based on the theoretical behaviour of the system. As already described in [5] preliminary results of the systems were obtained with reference data from Tompex/Poseidon. The final approach however is quite different since the operational scenario where the software is operated and the data behaviour are quite different. The operational deployment of the GRAS POD has focused on two main aspects: the analysis of the navigation data from the GRAS instrument and the definition of the POD setup such that is stable and robust to cope with all possible situations during automatic operation.

5.1 Data analysis

The understanding of the navigation data is essential to implement the second step for the operational configuration. There are three items to look at when considering the inputs for POD: the carrier phase data, the pseudo-range data and the GRAS clock. In most cases the clock is not an essential part of the process since it is reduced and discarded; in the GRAS POD this is a fundamental magnitude since it has to be accurately estimated as is it used as part of the GRAS data production during the sounding process.

In the initial stages of the GRAS instrument operations several teams were looking at the quality of the data produced by the instrument. The POD was looking particularly at the navigation data and its statistical quality; also at the accuracy of the algorithms to be applied to correct for dynamical and geometrical effects. The POD process implements those corrections that re not part of the processing of the raw telemetry; the POD needs to apply the centre of mass corrections, the GRAS antenna corrections, the relativistic effects and the GPS clock offset.

The most important finding during this analysis can be summarised in three points: the high quality of the carrier phase data, the extreme short term stability of the GRAS clock and the odd behaviour of the pseudo-range data.

The carrier phase data shows the expected behaviour with noise levels about the millimetre and also with very low levels of multi-path, even for low elevations. Only in some areas where the satellite solar array produces low elevation reflections one can observe a minimum level of multi-path. Unexpectedly, the algorithms delivering the carrier phase signal leave a huge unresolved ambiguity. Although the carrier phase is expected to have integer ambiguities in L1 and L2, the actual value of the ambiguities is about 10^{10}, which is too big to be handled directly by the POD process. This required the implementation of a ‘coarse ambiguity’ removal step in the POD data pre-processing.

The behaviour of the pseudo-range data is different from the one expected. Whereas it shows a very low short term noise at high elevations, the global behaviour over a whole pass shows a behaviour difficult to explain. This behaviour was observed in the post fit residuals of a least-squares orbit determination process and in the analysis of the L3-P3 residuals. Figure 2 shows the mentioned behaviour that systematically appears in all pseudo-range passes. It is remarkable the sinusoidal pattern and the big amplitude a low elevations shown by the pseudo-range data. This is still under investigation by the GRAS engineers.

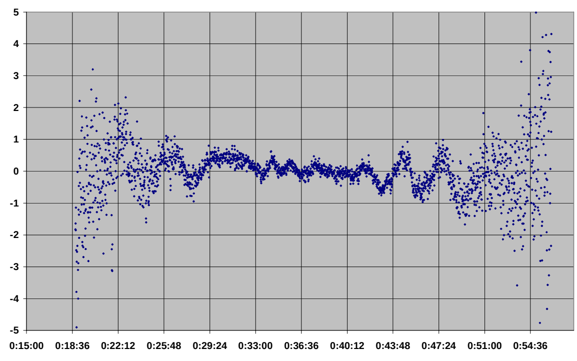

Figure 2. L3-P3 residuals typical behaviour

From the statistical point of view, the pseudo-range data show good behaviour with averages adequate for orbit determination and a global noise level in the vicinity of 0.7 m.

The most interesting result of the GRAS data analysis comes from the clock behaviour. The preliminary analysis of the clock estimation using a least squares filter showed that the clock noise was better than all expectations. Figure 3 shows the post fit clock residuals, that are a re good indication of the actual clock noise.

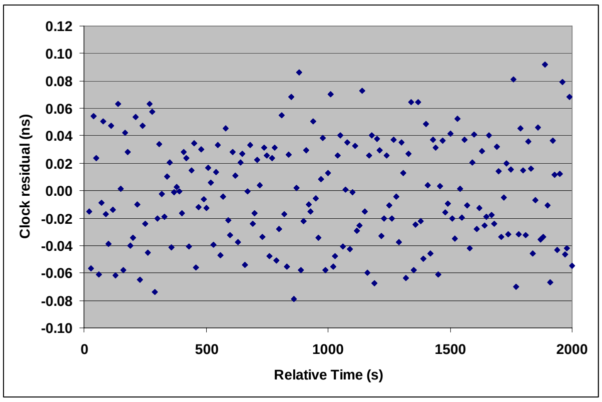

Figure 3: Post fit clock residuals

One of the main consequences of this high stability of the clock is that the sequential process can estimate a linear clock model over the typical size of the processing batch. This will permit the de-correlation of the clock from other effects, thus allowing the estimation of the clock free of other effects that may be absorbed by the clock estimation process. The standard deviation of the above residuals is 0.03 ns; this means that a linear model for the clock will not introduce an error higher than 0.1 ns at 3-sigma. This is one order of magnitude lower than the clock estimation requirement of 1 ns.

5.2 Orbit determination validation

The process is similar as the one implemented in [5]. First of all a least-squares based orbit determination was performed with synchronised data running at 0.1 Hz both in pseudo-range and carrier phase. The purpose of this step is to assess the adequacy of the data processing models in an scenario that is well understood from experience with other satellites (e.g. Topex and Champ). Overlap comparisons and different configurations were used to assess possible effects coming from the data. In the end the most suitable configuration is selected to generate the reference solution. For the different periods of data being analysed, reference orbit and clocks estimations are based on 3 days worth of data synchronised and sampled at 0.1 Hz. The reference solutions are then series of state vector estimates at 60 second spacing (interpolated with an 8th degree polynomial) and series of GRAS clock offsets at 10 second intervals.

In a second step, the SRIF based orbit determination process is configured. The way to assess its accuracy and stability is to compare the obtained solution with the reference orbit and clock from the reference orbit determination. Assuming that the long arc solution is the best possible estimate of the trajectory, the comparison of the SRIF based solution with the reference is expected to provide a good approximation of the sequential orbit determination performance.

Additionally, comparison of the least squares solution with other centres was performed. Two centres, ESOC and DLR, contributed to this comparison. From the two, DLR was more interesting because the data source and the POD software were completely independent, whereas ESOC used the same software package as EUMETSAT for the POD process. Figure 4 shows the differences in metres between the orbit computed by the DLR and the one computed by EUMETSAT using the least squares process.

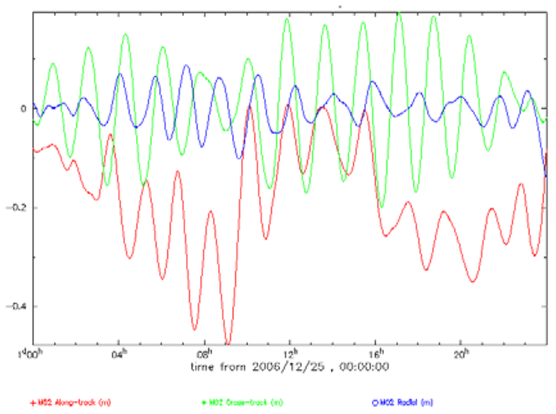

Figure 4: EUM vs. DLR orbit comparison

The most remarkable aspects of this comparison is that the averages of the radial and cross-track differences are common (zero difference). This is an indication that the dynamical models and reference systems are compatible. The one cycle per revolution differences may come from different GPS ephemeris and clocks together with different observation processing algorithms. The 0.2 m along-track offset cannot be explained without further knowledge of the details of the process by DLR, although it is not of particular relevance for the GRAS processing where the radial component is the critical one.

5.3 The operational SRIF

All elements described so far contribute to the understanding of the GRAS POD problem. However, the final step of setting up the system to perform the orbit determination in the sequential scenario needs to be described in detail.

Sequential estimation is a known problem and the SRIF algorithm has been used for POD purposes in a number of cases. The main difference in the GRAS context is that the system must work autonomously for long periods of time and therefore the system and its configuration must be robust enough to react properly when receiving anomalous data. This has been one of the most difficult problems to solve in the setting up of the system.

The initial intended approach was to configure the SRIF in the same manner as one would configure the least squares algorithm. In this approach both carrier phase and pseudo-range contributed to the process in the same way as in the least-squares. At the time when this was attempted and with the low knowledge of the data at that point, it was not possible to obtain a configuration that would converge to the actual solution and would stay converged, more when anomalous observations were inserted into the filter. During the analysis, it was observed that pseudo-range data at full rate could produce acceptable orbit results with a configuration that was more robust than the one running with carrier phase and pseudo-range together. The drawback of this approach is that the clocks could not be estimated with sufficient accuracy, even if the clock model was extended over the 3-minutes orbit determination batch. Figure 5 show the process converge based on pseudo-range only and the attainable accuracy with this set-up.

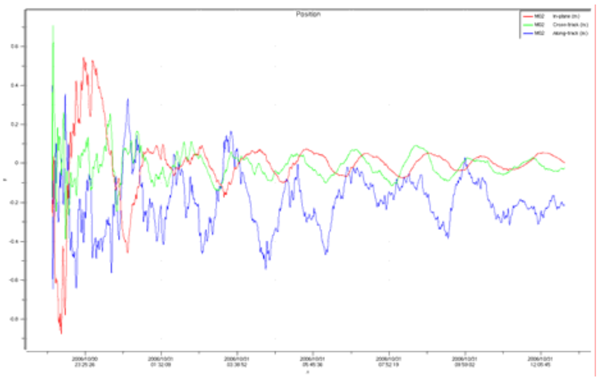

Figure 5: SRIF solution convergence

Figure 6 shows the assessment of the GRAS clock estimation accuracy based on a process involving pseudo-range only. It is quite clear that this process leaves a potential error in the estimation of the order of 2-3 ns which is much higher than the accuracy required for the GRAS product processing.

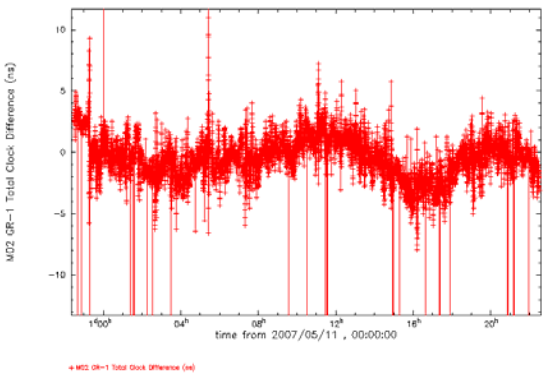

Figure 6: SRIF clock solution with pseudo-range

The process with pseudo-range only leaves a good quality orbit and a poor clock. This can be mitigated with a second step in the orbit determination process. This is implemented fixing the orbit obtained with the pseudo-range and re-computing the GRAS clock offset with carrier-phases. This second step has proven to be stable and produces much better clocks as shown in Figure 7. Note that both Figure 6 and Figure 7 shoe difference between the SRIF based solution and the reference solution. The outliers come in general from the reference solution that implements a snapshot approach for the clock. These outliers can be easily reduced using a low pass filter.

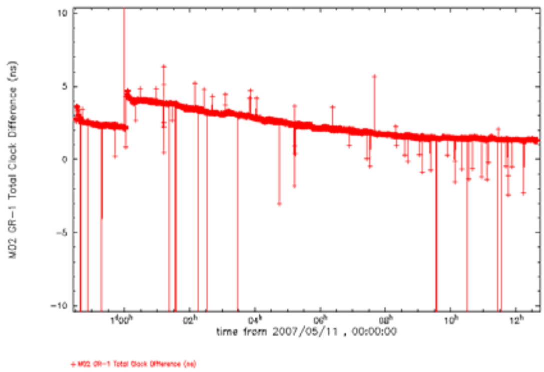

Figure 7: SRIF clock solution with carrier-phase and fixed orbit

There are two aspects in this solution that must be taken into account. First that the GRAS processing requires clocks whose solution is very stable between epoch, rather that very accurate. This is important because the solution shown in Figure 7 would be adequate for GRAS processing even if the clock has an offset about 3 ns. The second one is that there is a strong correlation between the carrier phase ambiguity estimation and the GRAS clock estimation. This correlation is removed differently in the sequential and batch processes and cannot be completely removed in the sequential case. This is the consequence that the batch process uses all available data (basically 20 minutes for each pass) to estimate the ambiguity while the sequential filter estimates the ambiguity accumulating the data as it arrives. The information available to eliminate the correlation in the sequential case is therefore less.

5.4 Key configuration aspects

The GRAS Pod is based on a generic software component derived from the generic ESA software package NAPEOS. This has permitted that the final set up has been obtained by configuration of the software and without implementing in the POD process any elements which are specific for the GRAS scenario.

There are two configuration items that play the key role in the accuracy and robustness of the sequential estimation.

The weighting and editing criteria of the pseudo-range data is very important. Because of the odd behaviour of the pseudo-range data, it is not possible to configure the system assuming that the noise distribution corresponds to a normal distribution. In fact, if the configuration assumes such principle, the very high residuals at the beginning and end of the passes causes in some cases a big push to the estimation process that degrades the solution to unacceptable values. The SRIF filter is configured to reject all observations whose residual is bigger than 0.7 m once converged. This leaves a population that is sufficiently accurate to yield an orbital solution within the prescribed limits. The clock needs to be further estimated with the phases.

The second configuration element that needs to be taken into account is the amount of history that the filter retains in the process. As in any other sequential filtering, the process cannot retain all the information from the beginning of the process because then the absence of system noise would cause that the observations no longer add information and the filter diverges. This is implemented in the SRIF algorithm as a time constant that makes the information from past observations fade according to an exponential law. Selecting this time constant is a trade off between convergence and solution noise. This time constant has been obtained empirically for the pseudo-range based solution to be in the vicinity of 90000 seconds. The interpretation of this figure is basically that the filter will retain the information from the last day of data.

5.5 Way forward

Essentially the way forward in the GRAS POD is to produce a configuration that uses simultaneously carrier phase and pseudo-range, to obtain the best possible solution of both orbit and GRAS clock. Again the difficulty of this task does not reside in the setting up of the filter itself but in doing it in such a way that is accurate and robust enough regardless of the data arriving to the filter.

The preliminary steps in this direction have already been taken and a provisional configuration for this setup is already available. In this setup the correlation between the different estimated parameters is really strong. To obtain all the information from the carrier phase one has to weight it sufficiently with respect to the pseudo-range; this is assign 0.7 m to the pseudo-range and 0.03 m to the carrier phase as in the least squares case. Without any other configuration measures, this weighting causes the filter to diverge strongly. Looking at the evolution of the estimation one can see that the correlation between the clock and the carrier phase ambiguity estimation has a strong effect in the estimation of the orbital radius, which in turn affects the estimation of the drag coefficient. This makes the orbit drift strongly along-track and then the whole process diverges.

The basic configuration for this POD scenario is completely different from the pseudo-range only one. The key aspect in this new setup is that the pseudo-ranges should not be discarded. In the pseudo-range only scenario the pseudo-range define the solution whereas in the joint scenario the solution is driven by the carrier-phase and the function of the pseudo-range limits to the definition of the average distance to estimate the ambiguity. In this case, instead of rejecting all pseudo-ranges whose residual is bigger than 0.7 m, the configuration retains all pseudo-range and just rejects those whose residual is bigger that 6 times the RMS of the whole population. Just a few pseudo-ranges are discarded.

A second aspect of the joint tracking scenario configuration is the amount of history retained by the filter. Using the value of 90000 s as in the pseudo-range case causes the filter to accumulate to much information and diverge. A value about 6000-9000 s (i.e. one to one and a half orbits) seems optimum.

Finally, one needs to improve the weighting of the pseudo-range with respect to the carrier phase. Leaving it to 0.7 m causes that the convergence is somehow slow and the process does not fully converge. Setting the pseudo-range weight to 0.5 m improves the convergence significantly and the final converged state is better. The drawback is that the pseudo-range noise maps slightly in the clock estimation. Probably there is some further improvement in this area to obtain the final configuration.

Figure 8 shows the orbit solution using simultaneously carrier phase and pseudo-range. The first assessment of this solution indicates that the radial accuracy is similar to the one obtained with pseudo-range only, but the along-track and cross-track differences (compared to the least squares reference solution) present a remarkable improvement. First the along-track offset of 0.2 m seem to have disappeared and the cross-track difference oscillates between ±0.1 m rather than between ±0.2 m.

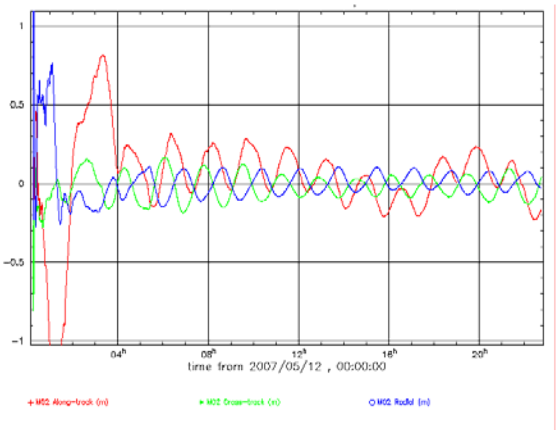

Figure 8: SRIF orbit solution with carrier-phase

The clock estimation also improves with respect to the pseudo-range only process; of course not very much with respect to the estimation with carrier phase and fixed orbit. Figure 9 shows the accuracy assessment of the clock estimation. After convergence the correlation between carrier phase and clock prevent from an estimation that does not differ from the reference one, still the evolution is smooth enough for the GRAS processing even with some additional noise introduced by the pseudo-range weighting.

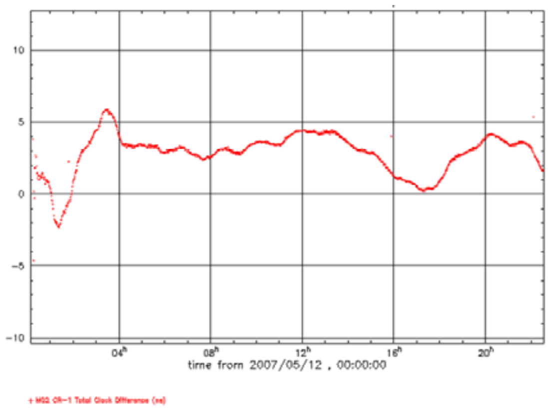

Figure 9: SRIF clock solution with carrier-phase

6. CONCLUSIONS

The strict accuracy and timeliness constraints imposed on the GRAS POD process made it necessary to look for an algorithm different from sequential batch implementing the traditional 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.

Preliminary studies proved the adequacy of the algorithm to meet the strict accuracy and timeliness requirements. These have been confirmed by the implementation in the final operational scenario, where the GRAS POD is performing according to the expected accuracy and GRAS products are disseminated based on the solutions from the sequential filter.

The configuration of the GRAS POD has been one of the most complex tasks in the GRAS data processing tuning. Not because of the complexity of the filtering process but because of the necessity to produce a robust setup capable of executing continuously under all possible data conditions.

There are still some activities to be undertaking until a final configuration of the system is achieved. Mainly the simultaneous processing of pseudo-range and carrier phase requires additional tuning until a dependable enough configuration is obtained. In addition further understanding of the pseudo-range behaviour may be advisable. The pseudo-range data seems to a have a potential that is not fully exploited with the current algorithms.

7. REFERENCES

1. Parkinson B. W., Spilker J. J., *Global Positioning System: Theory and Applications*, American Institute of Aeronautics and Astronautics, Washington, DC, USA, 1996.

2. Bierman G. J., *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York, New York, USA, 1977.

3. Martínez Fadrique F., Luengo Herrero O., *GRAS Precise Orbit Determination. Final Report, Issue 1.0*, GMV S.A., Madrid, Spain, 2001.

4. Martínez Fadrique F., Luengo Herrero O., *MetOp Precise Orbit Determination in Near Real Time with GPS*, GMV S.A., Madrid, Spain, 2001.

5. Sancho Rodríguez-Portugal, F., Martínez Fadrique F., Águeda Maté, A., Damiano, A., *MetOp Near Real-Time Precise Orbit Determination for Low Earth Orbiting satellites*, GMV S.A., Madrid, Spain, 2004.