Advanced GNSS Algorithms and Services Based on Highly-stable On-board Clocks

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BIOGRAPHIES

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Irma Rodríguez has a MSc in Telecommunication Engineering, from the Universidad Politécnica de Madrid, Spain. She is Head of the GNSS Algorithms and Products Division within the GNSS Business Unit of GMV, being responsible for a division in charge of, among other activities, the GMV's *magicODTS* and *magicPPP* services, the Galileo CS Demonstrator and the Galileo Time and Geodetic Validation Facility.

ABSTRACT

The on-board GNSS clock technology has evolved greatly in the last years, moving from the initial Caesium atomic clocks, to the latest Rubidium (Rb) and Passive Hydrogen-Maser (PHM) clocks. Both Rb and PHM technologies have proven to be highly predictable clocks, which opens the door to a series of improvements or modifications with respect to the "classical" Orbit Determination and Clock Synchronisation (ODTS) algorithms that would not only lead to the consequent and quite evident performance improvement, but it may also pave the way for the provision of advance services such as extended long-term predictions or an autonomous navigation service implemented on-board.

The most common approach for any ODTS process is to estimate the satellite orbits and clock parameters by means of a Weighted Least-Square or a Kalman Filter processing, but whereas the satellite orbits are integrated by using a dynamical model with at most 15 parameters, the estimation of the satellite clock parameters is based on an epoch-by-epoch estimation of all clock parameters without taking into account any physical behavior of the satellite clocks. This means that the values of a clock bias at different epochs are considered independent of each other, regardless of their stability. This classical epoch-by-epoch clock estimation approach has the advantage of being somehow "insensitive" to the typical stochastic behavior of the atomic clocks and to clock jumps, whereas the clear disadvantage is that no a-priori information regarding the clock stability is used within the estimation process.

The explanation for this clock estimation approach is that traditionally the stability of the on-board clocks was such that no deterministic model could match the clock behavior to the necessary accuracy level. In this regard, the Galileo satellites are equipped with Passive Hydrogen Masers clocks, which have shown excellent short-term performance only comparable to the Rubidium clocks (Rb) clocks on-board of the GPS Block IIF satellites.

This aforementioned high clock stability makes it feasible to accurately parameterize those satellite clocks with a model within the ODTS process, reducing the number of snapshot parameters to be estimated, which will allow to reduce the computational burden, increase the robustness of the estimation process of the other parameters, increase the prediction performances validity and reduce the required ground tracking network, since a continuous satellite tracking by several stations would no longer be required. Furthermore, the clock stability does not only enable the improvement in the performance of the ODTS algorithms, but it would also increase the prediction performance validity of the predicted clocks in the navigation messages.

The scope of this paper is to perform a preliminary assessment of the potential station network reduction and clock prediction performance improvement based on the usage of physical clock modelling within the ODTS processing.

INTRODUCTION

Currently, one of the main factors which drive accuracy of an orbit and clock determination process is the size of the station tracking network. In this regard, the typical reference network used for achieving centimeter-level ODTS accuracy is normally larger than 60 stations. In order to support this statement, the size of the reference networks used both by IGS' Analysis Centers [Ref.6] and the main high accuracy private service providers have been analyzed and summarized in the following tables:

Table 1: IGS' Analysis Centres typical network size

Analysis Centre	Reference Network size
CODE	240
NRCan	80
ESOC	150
GFZ	200
JPL	80
MIT	300
NGS	200
SIO	290

Table 2: Main High Accuracy Service Providers network size

Service Provider	Reference Network size	Source
FUGRO	>100	[Ref.7]
TRIMBLE	100	[Ref.8]
VERIPOS	74	[Ref.9]

This typical network size represents a considerable burden in terms of deployment and maintenance which could be drastically reduced by means of clock modelling within the ODTS process.

The current state-of-the-art GNSS ODTS processing estimates satellite orbits and clock parameters in a batch processing mode. The satellite orbit are propagated using models of all dynamics and physics involved in the satellite motion (integrating the equations of motion), which require no more than 15 parameters per satellite. On the other hand, the clock parameters are obtained from an epoch by epoch estimation of all satellite and station receiver clock parameters, usually called snapshot estimation. This approach introduces a huge number of parameters to estimate, dismissing any knowledge of the physical behavior of the satellite or station clocks, even for atomic clocks which have proven to have a high degree of performances in terms of frequency stability, such as PHM (as the ones on-board the Galileo satellites) and the latest Rb clocks (as the ones carried by the GPS IIF satellites).

Table 3: GNSS clocks characteristics [Ref.2]

GNSS	Block	Type	Accuracy	$\sigma_y(1s)$	$\sigma_y(1day)$	$dF/F/^{o}C$	kg	V(l)	W	year
GPS	I	Rb		6.0E-11	9.40E-14	2.00E-12	5.9	13.6	25	1
	I, IIA	Rb	5.00E-12		1.37E-13	1.00E-13	5.9	13.6	25	1
	I, IIA	Cs	3.00E-12	1.0E-11	1.36E-13	5.00E-14	12.7	10.3	22	3
	IIR	Rb	5.00E-12	3.0E-12	1.50E-14	7.00E-14	5.3	4.5	15	10
	IIF	Rb	5.00E-12	2.5E-12	5.00E-15	5.00E-14	6.1	4.8	39	12
	IIF	Cs	2.00E-12	1.0E-11	6.00E-14	1.00E-13	15.1	12.7	33	10
GLO	I	Rb								
	I	Cs	1.00E-11	5.00E-11	5.00E-13	5.00E-13	39.6	83.3	80	1
	M	Cs	1.00E-11	2.00E-11	1.00E-13	2.00E-13	52.0	149.0	90	3
	K	Cs	1.00E-11	2.00E-11	1.00E-13	1.00E-13	32.0			
	K*	Cs	1.00E-11	1.00E-11	6.00E-14	5.00E-14	16.0			
GAL	I	Rb	5.00E-10	5.0E-12	3.00E-14	5.00E-14	3.4	2.6	35	12
	I	PHM	2.00E-13	1.0E-12	3.00E-15	3.00E-14	18.0	28	60	12

By following the aforementioned approach, although it has the advantage of insensitivity to the typical stochastic behavior of the atomic clocks or to clock jumps, the advantages that the a-priori knowledge of their stability could bring to the estimation process are left aside.

Despite the GNSS clock characteristic information shown in Table 3, based on each atomic clock technology, a good knowledge of the properties of each GNSS clock is necessary to properly model them in the ODTS estimation processes. The identification of systematic patterns (e.g. periodicities) is crucial, together with the clock stability properties and the estimated amplitudes of the noise components. In this regard, several limitations must be taken into account:

- The clock values are contaminated by the estimation noise. For example, if the clock is an PHM, the error in the clocks derived from GNSS observations dominates the frequency stability measures, hiding the underlying clock characteristics.
- The clock data is not absolute, but is based on offsets between different clocks. A solution is that one of the clocks in the comparison is considered a 'noise free' standard.
- It is possible that clock modelling is not feasible, in terms of performance improvement, for all the GNSS clocks. Rather to those which are a-priori suitable to be modelled (Rb and PHM).

The GNSS clock values have contributions from several effects not related to the atomic clock itself, but originated by the different elements participating in the generation, propagation, tracking and processing of the GNSS signals. These corrections must be taken into account, and fall into two different categories:

- Systematic effects: Constant biases or periodic signals. They have to be estimated with the appropriate deterministic model.
- Random or high-frequency effects: They cannot be modelled using a deterministic formulation. It can be assumed that they are absorbed in the noise types, namely [Ref.4]:
    - White phase noise.
    - Flicker phase noise.
    - White frequency noise.
    - Flicker frequency noise.
    - Random walk frequency noise

Although there are several statistical functions that characterize the level of noise of the clocks, the most widely used measure is the Allan variance, which can be expressed using the phase values as:

$$\sigma_y^2(\tau) = \frac{1}{2\tau^2} E\{[x_{k+2} - 2x_{k+1} + x_k]^2\}$$

The Allan variance may be estimated for intervals of different length τ, so that it probes the clock stability at different scales. The Allan deviation (ADEV) is the square root of the Allan variance, and it is commonly used instead of it.

The following figure shows a typical example of the apparent clock stability for the different GNSS constellations in terms of their ADEV, where "G" stands for GPS, "R" for GLONASS, "E" for Galileo, "C" for BeiDou and "J" for QZSS.

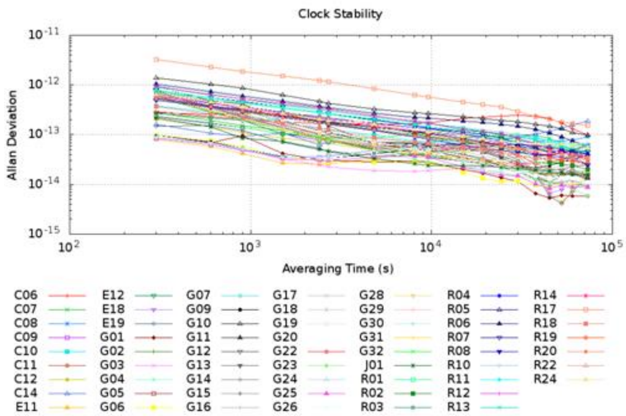

Figure 1: GNSS ADEV based on *magicGNSS'* estimations

The aforementioned example helps to confirm the atomic clock technology stability characterization included in Table 3.

Prior to any physical clock model implementation, a theoretical ODTS covariance analysis was performed. This analysis is described in the following section.

COVARIANCE ANALYSIS

In order to deeply analyse the ODTS processes, and in order to understand how the estimation errors are managed by the ODTS filter, a Precise Orbit and Clock Determination Covariance Analysis Simulation tool (ODTS Covariance Simulator) was developed by GMV [Ref.5]. This tool is able to simulate the behavior of the ODTS estimation errors with a high degree of realism, for different input data quality and different 'a priori' ODTS filter information constrains. Both the magnitude and the nature of the errors are considered.

The ODTS Covariance Simulator allows studying the ODTS covariance matrix for different scenarios, in particular for those for which no real data exists, by accurately modelling the stochastic error associated to the ODTS process and the data quality.

It takes into account geometry aspects, data quality and quantity aspects, parameters to be estimated and the estimation process. The tool reproduces with a high fidelity the classic GNSS ODTS stochastic process. Its main characteristics are:

- The satellite constellation can be defined by the user.
- It works with ground stations data and/or with Inter Satellite Ranging, being possible to define tracker and tracked satellites.
- The user can define the ground station network.
- The visibility conditions can be configured. Masking angles when using ground stations, and tracker and tracked visibility angles when using Inter-Satellite Ranging.
- It is able to process code and/or phase measurements, the user can define the characteristics of these measurements.

The ODTS Covariance Simulator's orbit propagator includes all major perturbations: Earth gravitational field, third body, solar radiation pressures, etc. The perturbations to be considered can be defined by the user. The tool provides estimation accuracies for:

- The satellite orbital elements, and other dynamic parameters such as the solar radiation pressure coefficients
- Arc dependent bias per station
- Satellite clock biases, estimated epoch by epoch
- Station clock biases, estimated epoch by epoch
- Phase ambiguities
- Tropospheric zenith delay, estimated at user defined time intervals.

The aforementioned tool has been validated using real data and comparing results with those computed with GMV's *magicGNSS.*

In order to obtain an initial estimation of the impact of clock modelling on the accuracy of the ODTS process, a dedicated covariance analysis has been carried out using the ODTS Covariance Simulator. The accuracy of the ODTS process has been measured using 2 different sets of reference networks of 23 and 7 GNSS stations respectively:

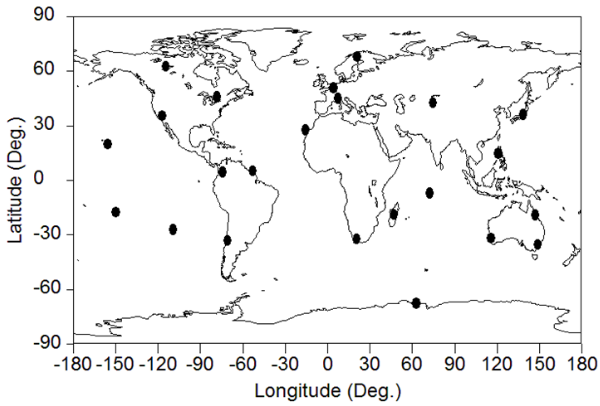

Figure 2: 23 station network

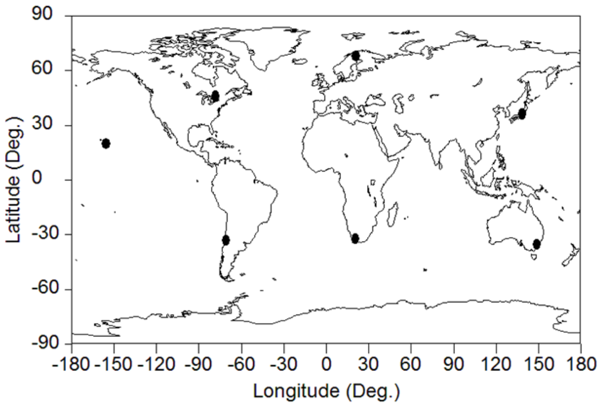

Figure 3: 7 station network

, and under the following conditions, where "U" stands for unconstrained, "F" for fixed, "TC" for tightly constrained and "LC" for loosely constrained:

Table 4: Covariance analysis clock modelling scenarios

Scenario ID	Size	Station Clocks	Satellite Clocks	Ambiguities
SC-001	23	U	U	U
SC-002	23	F	U	U
SC-003	23	TC	U	U
SC-004	23	LC	U	U
SC-005	23	U	F	U
SC-006	23	U	TC	U
SC-007	23	U	LC	U
SC-008	23	F	F	U
SC-009	23	TC	TC	U
SC-010	23	LC	LC	U

Scenario ID	Size	Station Clocks	Satellite Clocks	Ambiguities
SC-011	23	U	U	F
SC-012	23	U	U	TC
SC-013	23	U	U	LC
SC-014	7	TC	TC	U
SC-015	7	U	TC	U

The results of the performed covariance analysis are shown in figure below:

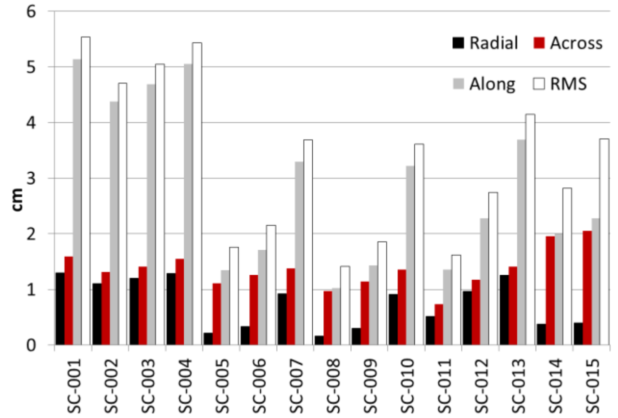

Figure 4: Orbital error

It can be observed that:

- Fixing or constraining the station clocks does not significantly improve the ODTS process accuracy.
- Fixing or constraining the satellite clocks does significantly improve the ODTS process accuracy, as well as fixing or constraining the ambiguities, even if the number of stations is significantly reduced.
- When the satellite clocks are fixed or constrained, fixing or constraining the station clocks does not significantly improve the ODTS process accuracy.

The performed analysis shows the potential improvement margin to be obtained in an ODTS process, based on the implementation of physical clock models in the ODTS filter. The final improvement to be obtained will depend on the actual stability of the clocks and how well they can be fitted into the selected models. Other considerations that are worth being taken into account for getting the right conclusions out of the performed analysis are mentioned next:

- The accuracy of the ODTS process is limited by the measurements noise, the fact the phase measurements ambiguities have to be computed and the fact that the systems clocks have to be synchronized.
- The station clocks are much more observable than the satellites clocks (the inverse geometry of the satellites 'observing' the station clock is much

better that the direct geometry of the stations observing the satellites).

IMPLEMENTED MODEL

As mentioned before, GNSS orbit and clock determination is currently based on estimating each satellite or station clock bias as an independent parameter at each observation epoch (snapshot estimation). As a result, the number of parameters to be estimated within the ODTS process becomes huge. So, in order to attain a good accuracy it is necessary to process big amounts of data, and in particular to use a large number of tracking stations, as shown in Table 1 and Table 2. However, in doing snapshot estimation we are wasting a non-negligible part of the information provided by the measurements. In fact, the behavior of a clock bias can be modelled as a simple clock model (linear, quadratic or harmonic) to account for the clock's deterministic behavior, plus a residual component whose amplitude does not exceeds a few ns for a GNSS satellite atomic clock to cope with the random or stochastic components, as shown in the figures below, where the deterministic component (quadratic model) of the apparent clock has been removed:

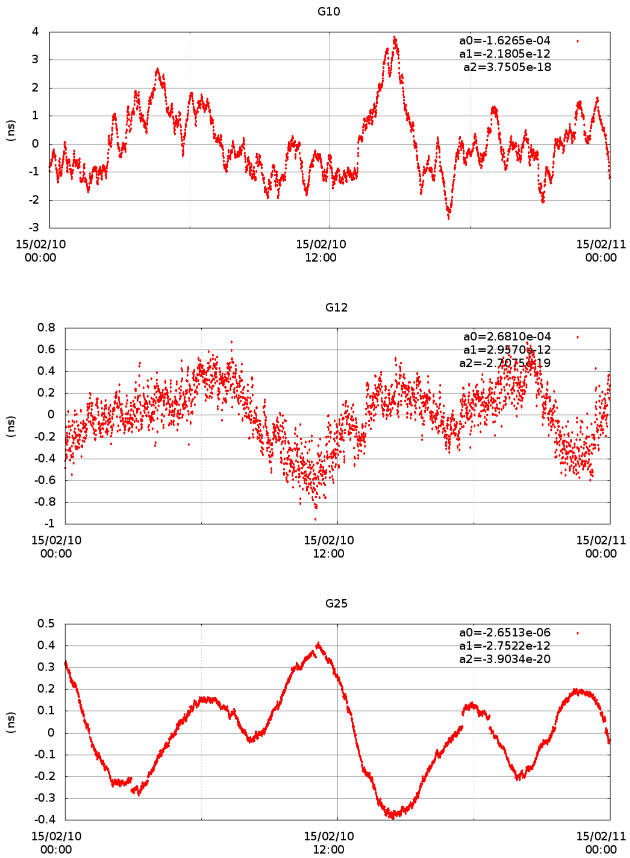

Figure 5: Detrended GPS clocks for G10 (IIA), G12 (IIR), G25 (IIF)

Additionally, atomic clocks may show jumps and other anomalies that must be checked for before deciding the type of modelling to be used.

The residual term is the sum of two parts:

- Stochastic behaviour, due to random noise, whose characteristics depend on the clock and are usually analysed by means of the Allan deviation as mentioned previously.
- Systematic effects due to variations in the temperature of the satellite payload, steering corrections, unmodelled relativistic corrections, etc. [Ref.2] [Ref.3]

Hence, the variability shown by the apparent clock is much smaller than that of a white noise with large variance, the latter being the underlying stochastic model of the typical clock snapshot estimation.

As a general principle, if we constrain the clock estimation to follow a more restrictive and deterministic pattern, we should expect an improvement in the accuracy, as the same amount of information is used to resolve a smaller number of variables. In the same way, the existing level of performances could be achieved with a smaller station network.

In defining an improved clock estimation based on the previous considerations, the target is reducing the 'freedom' of the estimated clocks as much as possible without introducing modelling errors. The minimal model consists of a linear or quadratic function, which requires just two or three parameters per clock (though an harmonic component may also be considered). But this restriction is excessive for most satellite clocks (as shown in Figure 5), and in general it is necessary to model the residual part of the clock. For the latter, there are two directions to follow:

- In the first place, find suitable models to compute the systematic effects beforehand, so that the variations left to the estimation are as small as possible. If no a priori model can be determined, at least parametrize them with a few additional parameters (e.g. sine and cosine terms with orbital frequency).
- Secondly, add a correction term that accounts for the stochastic behaviour and the un-modelled effects. The simplest approach is to use snapshot estimation for this term, which is much more constrained in magnitude than in the standard case. In principle, it would be better to introduce a stochastic model based on the clock noise characteristics, but this could be quite difficult to implement in practice, for different reasons.

In summary, we can introduce the following clock estimation variables, divided in two parts:

- Global model:

$$b_G(t) = a_0 + a_1 t + a_2 t^2 + \cdots$$

- Snapshot model, $b_S(t)$, which is constrained to the level of nanoseconds or a fraction of nanoseconds.

The value of the clock bias at each epoch is the sum

$$b(t) = b_{SYS}(t) + b_G(t) + b_S(t)$$

The term $b_{SYS}(t)$ represents the systematic corrections to the clock (relativistic corrections, thermal effects, etc).

The aforementioned physical clock model has been implemented in *magicGNSS'*, enabling the execution of a set of preliminary tests to assess the potential performance improvement of clock modelling within the ODTS process.

The implemented clock model is the sum of a quadratic function $b_G(t) = a_0 + a_1 t + a_2 t^2$ plus a snapshot correction constrained depending on the stability of the clocks processed (a fraction of nanosecond in most cases). Additional systematic effects such as thermal or additional relativistic effects have not been analysed in the scope to the current paper.

It is worth mentioning that the aforementioned physical clock model does not intend to model thermal effects on the atomic clock's behavior no additional relativistic effects, as the scope of this paper is considered as a preliminary assessment of the practical potential performance ODTS improvement when using physical clock models.

CLOCK MODELLING RESULTS

One of the main objectives of this paper is to analyse the feasibility of reducing the required ground GNSS tracking network while maintaining the overall ODTS performances. In this regard, 2 different reduced tracking networks have been defined, as a subset of IGS's tracking network:

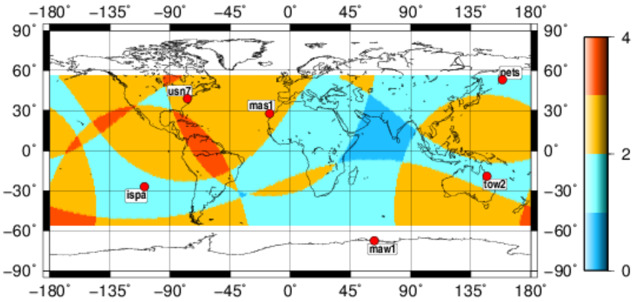

Figure 6: 6 GNSS station network

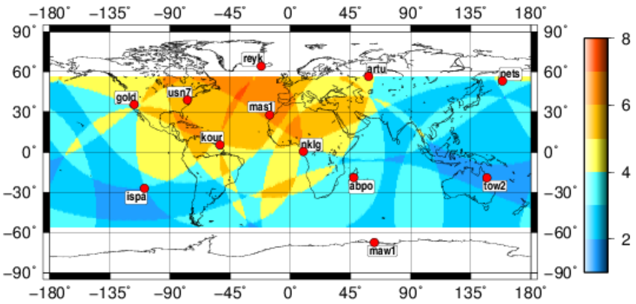

Figure 7: 12 GNSS station network

The selected dates correspond to the days 9 and 10 of February 2015. Table 5 contains the comparison of the orbit and clock estimates obtained by magicGNSS versus IGS' final products.

Table 5: Orbit and clock determination errors wrt IGS

Processing type	Clock error (ns)		Orbit error RMS 1D (cm)	
	6 stations	12 stations	6 stations	12 stations
Snapshot	0.507	0.264	21.32	6.62
Model + constrained snapshot	0.434	0.267	16.54	5.64

It's important to acknowledge that the ODTS performances did not seem to improve when introducing a physical clock model in a 50 station scenario. This may lead to believe that underlying effects affecting the clocks, such as thermal or relativistic should be modelled prior to applying a physical clock modelling within the ODTS processing.

The clock prediction error over a 20-day period has been analysed for the 6 station network scenario, both with and without physical clock modelling within the ODTS process. The performances versus IGS' final estimates are included in Figure 8.

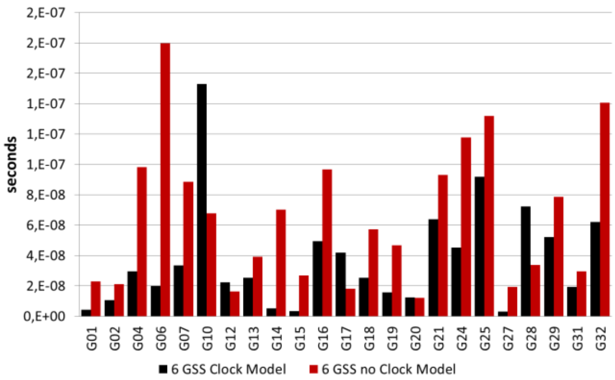

Figure 8: 20-day RMS clock prediction error

This preliminary test shows that it is possible to improve the accuracy of the orbit and clock determination when using reduced networks, by using even a quite simple model. Furthermore, the long term clock predictions have also been improved when using a simple clock model within the ODTS process.

The previous results only accounted for GPS satellites, however, the PHM clocks on board the Galileo satellites surpass the GPS ones (except maybe for the IIF ones) in terms of stability and predictability as shown in Figure 1. In this regard, an additional test was carried out to assess the potential performance improvement that the proposed clock modelling algorithm could bring to the Galileo System.

In order to perform this analysis a reduced subset of 9 stations from the IGS's tracking network has been defined trying to achieve a global coverage.

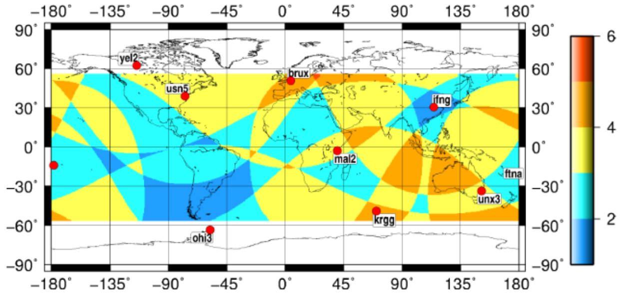

Figure 9 GNSS station network with 9 stations

A period of time of three days from July 5 to July 7 2015 has been processed. The estimated clocks for E11 and E26 included in Figure 10 (being the behaviour of the remaining Galileo satellites analogous) shows the stability and predictability of the clocks and their potential modelling as a physical constrained model.

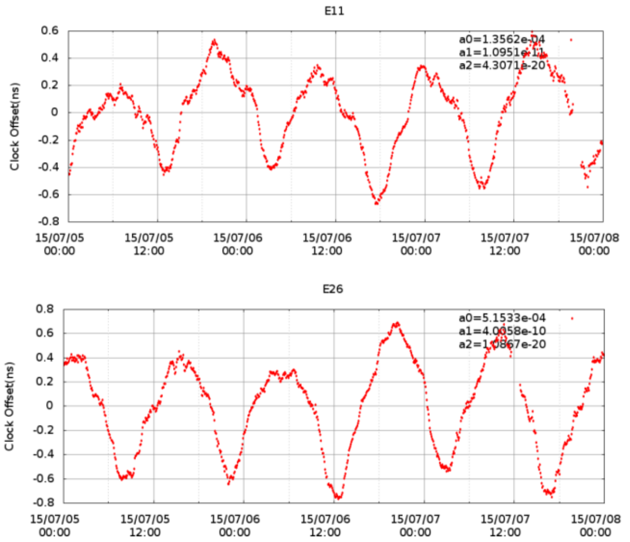

Figure 10 Detrended Galileo clocks for E11 and E26.

The consistency of the clock bias and orbit products over an overlapped period of 1 day has been assessed. Four ODTS processes have been carried out; in two of them, the clock bias at each epoch has been estimated on a snaphot basis whereas, in the other two executions, a physical clock modelling within the ODTS process has been used.

The orbit and clock consistency results are shown in Figure 11 Figure 12 respectively. The numerical results are summarized in Table 6 for an easier inspection.

Table 6 Orbit and clock consistency (figures)

Processing type	Orbit Error (cm)	Clock Error (ns)
Model + constrained snapshot	15,5	0,27
Snapshot	21,6	0,34

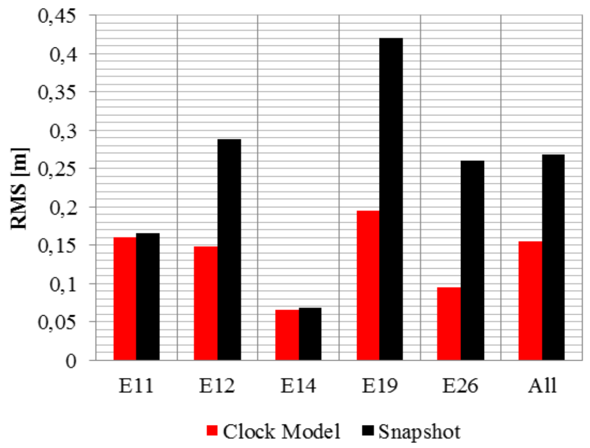

Figure 11 Orbit consistency

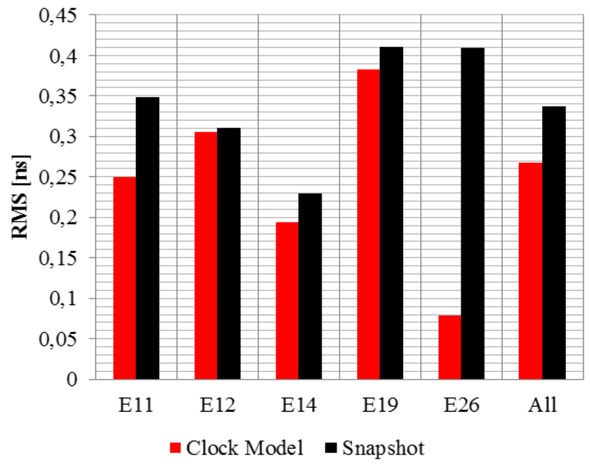

Figure 12 Clock bias consistency

The obtained results show that a significant enhancement of the accuracy of the Galileo's orbit and clock bias estimation can be achieved when considering a physical clock modelling within the ODTS with reduced tracking station networks. This improvement is mainly driven by the stability and predictability of the on board clocks in the Galileo constellation.

FUTURE WORK

This first approach to physical clock modelling has been focused on station network reduction and improving the clock prediction performances, based on such networks for GPS satellites. It is foreseen to extend this analysis to the additional GNSS constellations, in particular to Galileo as they carry the most precise atomic clocks ever in space.

The impact of physical clock modelling in different ODTS aspects, such as integer ambiguity resolution is also to be tackled.

Additional potential ODTS improvements such as the usage of multi-frequency techniques (estimating the ionosphere within the ODTS process) instead of the classic iono-free double frequency combination, and the non-gravitational force modelling (especially for the new GNSS constellations) need to be analyzed.

CONCLUSIONS

Several conclusions can be inferred from the analysis and results presented throughout the paper:

- The current GNSS clocks stability clears the path for potential performance improvements based on the additional information provided due their modelling feasibility.
- Physical clock modelling in ODTS processing have shown promising results when using a reduced network for GNSS Precise Orbit Determination (POD) determination.
- Thermal or additional relativistic effects may need to be properly understood and modelled prior to applying a physical clock modelling within the ODTS processing.
- The adequateness of physical clock modelling within the ODTS process may be driven by the target requirements or applications: Network reduction, prediction improvement, etc.

ACKNOWLEDGMENTS

We greatly appreciate the efforts done by IGS, the International GNSS Service, and in particular the Multi GNSS Experiment (MGEX), to generate high quality data and products and make them available to the GNSS community in a timely and reliable way, together with raw data for the different GNSS constellations.

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