Observing the Behaviour of High Stable Galileo Satellite Clocks and Exploring Potential Associated Benefits

Navarro Madrid, P. F., Roldán Gómez, P. J., Calle Calle, J. D., Rodríguez Pérez, I., Cela López, C., M., Laínez Samper, M. D., Romay Merino, M. M., *GMV*

BIOGRAPHIES

Pedro F. Navarro Madrid holds a Master of Science in Mathematics from the University of Murcia (Spain) and Postgraduate studies in Theoretical Physics at the University of Valencia (Spain). He has worked at GMV since 2002 as an engineer in the development of Galileo and later in R&D activities covering both the ground and user segments.

Pedro J. Roldán has a Master of Science in Aerospace Engineering from the Technical University of Madrid and in Meteorology and Geophysics from the Complutense University of Madrid. He has worked at GMV since 2013 in the development of GNSS algorithms, including precise point positioning and orbit determination within magicGNSS and timing algorithms for the Galileo Time and Geodetic Validation Facility.

J. David Calle has a Master of Science in Computer Engineering from the University of Salamanca. He joined GMV in 2008 and he is currently working in the GNSS business unit designing and developing GNSS algorithms, applications and systems. He has been involved in the development of the *magicGNSS* suite and the Galileo Time and Geodetic Validation Facility. He is currently the technical responsible for the development of the Galileo Commercial Service Demonstrator.

Irma Rodríguez is Head of the GNSS Algorithms, Products and Services Division at GMV Aerospace and Defence. She has an MSc in Telecommunication Engineering, from the Universidad Politécnica de Madrid, Spain. Irma has been working in GNSS for almost 15 years and she is currently responsible for a division in charge of, among others, R&D activities in the field of precise orbit determination and high accuracy positioning and integrity, the GMV's *magicODTS* and *magicPPP* services and different projects such as the Galileo CS Demonstrator, the Galileo Time and Geodetic Validation Facility, the G2G Navigation & Metrology Algorithms and the Galileo Reference Center.

Camilo Cela López holds a Bachelor of Science in Physics and Mathematics from MIT. He started working at GMV in early 2017 as a GNSS engineer in R&D activities, mainly related to the *magicGNSS* platform.

María D. Laínez Samper is currently coordinating the GMV research activities in the field of Satellite Navigation, and in particular those related to precise positioning applications. She has also worked in experimentation and verification activities, in the Operational Systems Division, during the preliminary phases of the Galileo Program, and has been the responsible for the clock prediction and navigation message computation modules in the Galileo E-OSPF (Experimental Orbitography and Synchronization Processing Facility).

Miguel M. Romay Merino is the GNSS Business Unit Director at GMV Aerospace and Defence. Miguel leads the GMV Unit that has become one of the strongest groups of GNSS experts thanks to its key involvement in GPS, EGNOS and Galileo. Miguel has been a pioneer in the Galileo Program, collaborating on aspects such as constellation design, precise orbit determination, integrity, performance evaluation, system definition, etc. Miguel is today involved in GMV research activities in the definition of novel GNSS applications and on the design of new generation GNSS.

ABSTRACT

It is quite common to consider GNSS satellites as highly accurate clocks orbiting the Earth and it is with the aid of these orbiting clocks that GNSS users are able to obtain precise positioning solutions. As for any other satellite navigation system, Galileo's satellite clocks are one of the critical technologies in the system. In the particular case of Galileo, each satellite is equipped with four redundant clocks: two primary Passive Hydrogen Masers (PHM) measuring time to within 0.45 ns over 12 hours, which is four times better than the performance of the two secondary Rubidium clocks, accurate to within 1.8 ns over 12 hours, see [Ref. 1.].

Notwithstanding the reported and now identified Galileo satellite clock failures, see [Ref. 2.], the observed behaviour of the Galileo clocks, when operating nominally, seems to be very stable, especially in the short term. The clock stability feature is a key element: on the one hand for the accuracy of the navigation solutions and on the other hand for its non-negligible impact on the system complexity and associated costs.

Clock stability, as well as the navigation solution accuracy, are directly related, together with other factors, to clock predictability. Higher stability implies more accurate predictability, and better predictions mean better ephemeris. Not only better standard ephemeris for navigation solutions, but also better long term ephemeris for assisted navigation. On top of that, better clock stability can also potentially contribute to reduce the complexity of the GNSS ground segment. Standard ODTS (Orbit Determination & Time Synchronisation) approaches implement snapshot strategies for the clock restitution, based on obtaining epoch by epoch estimates of all satellite's and station receiver's clock parameters. This approach implies the management of a large number of parameters in the estimation process, which could be drastically reduced if some information about the physical behaviour of the clocks in the system could be input to the processing filter, for example, if the snapshot estimation strategy could be replaced by a pure model or by a mixed model-snapshot strategy.

This paper is aimed at observing the behaviour of the Galileo satellite apparent clocks, with the purpose of finding interesting features allowing potential improvements in at least the following aspects:

- accuracy of the navigation solutions,
- accuracy of long term ephemeris and
- ground segment complexity.

The results included in this paper are based on the analysis of apparent clocks obtained through accurate restitution by means of ODTS processes, implementing state-of-the-art algorithms and models. Typical trends and anomalous events of the Galileo satellite clocks are going to be described and analysed. Comparisons with other GNSS satellite clocks are going to be shown, and conclusions, driven out of the performed research, are going to be extracted.

INTRODUCTION

The paper is structured into six main sections, describing the performed tasks and carried out analyses for observing the behaviour of the Galileo and other GNSS constellations satellites clocks:

- Apparent Clocks
- Clock Stability Analysis
- Clock Frequency Analysis
- Clock Prediction Analysis
- Covariance Analysis
- Clock Modelling Analysis

The obtained results are going to be shown and assessed in order to determine potential benefits attainable from an optimum utilization of the observed clock data features.

Section "Apparent Clocks" below, is aimed at describing what kind of data have been generated for feeding the clock analyses, how they have been generated, and what can be observed when the obtained clock time series are plotted. The subsequent section, "Clock Stability Analysis", is aimed at showing the stability analyses corresponding to the generated time series. Relevant features of the obtained results will be discussed. In the following section, "Clock Frequency Analysis", the considered satellite apparent clocks will be analysed in the frequency domain, in order to identify whether there are periodic effects in the different GNSS constellations clocks signals or not. Knowing and understanding the satellite clocks signals is helpful for defining smart clock estimation and prediction strategies. Clock prediction attainable performances are going to be addressed in the "Clock Prediction Analysis" section, and the last two main sections, "Covariance Analysis" and "Clock

Modelling Analysis" are intended to, respectively, assessing the impact of the satellite clock lack of knowledge on the global ODTS process uncertainty, and evaluating potential benefits which could be obtained in case pure or mixed clock models where incorporated to the ODTS process.

Potential evolutions of the carried out activities, out of the scope of the present paper, will be suggested in the "Further Work" section, and finally the paper will be closed with the main conclusions driven from the performed research.

APPARENT CLOCKS

The carried out analyses are mainly based on the analysis of "apparent" clocks obtained through accurate restitution by means of ODTS processes, implementing state-of-the-art algorithms and models. The "apparent" clock signal is the addition of the physical clock signal plus a series of other effects, some of them introduced by the ODTS restitution process, which includes: on-board phase stability, receiver noise and orbital residuals, some others not related to the ODTS process, such as thermal effects, which have to be considered when analysing the "apparent" clock signal behaviour.

The ODTS processes executed for the generation of the restituted clock time series were run with magicGNSS, a state-of-the-art ODTS web tool, able to compute multi-constellation GNSS products. See [Ref. 3.] to [Ref. 8.] for further information about magicGNSS. These and other related publications can be found in the magicGNSS website, see [Ref. 9.]. The analysed time period is 120 days long. It stars on DOY 040 in 2017 (corresponding to February 9th) and spans through DOY 160 in 2017 (corresponding to June 9th), about four months.

Each ODTS process was configured to cover a partial period of 6 days, with an overlap of 1 day between consecutive executions. The first and last 12 hours of each process were cut off, for minimising the so called "bathtub" effect, i.e. the effect of the least squares based ODTS estimation process which results in a non-homogeneous distribution of the residual errors, which are typically larger in the extremes of the estimation period, and smaller in the middle. The resulting estimations were joined, and that is how the clock time series were generated.

A summary of the ODTS processed configuration is provided next, showing further detailed information about the estimation process features:

Table 1: *magicGNSS* configuration summary

Constellations	GPS, GLONASS, Galileo, BeiDou
Stations	56 world-wide distributed
Estimation arc duration	6 days
Data Sampling	300 s
Minimum elevation angle	10 deg
Number of iterations	6

The obtained clock time series were adjusted with a low order polynomial (order 2, parabolic fit) which was subtracted from the original time series in order to obtain a "detrended" clock solution, more suitable for a graphic representation. Without the "detrending" operation, the analogous plot would only be able to reflect the low order polynomial behaviour, not allowing the perception of other smaller-scale effects. In some cases, especially for BeiDou and Galileo, the obtained clock time series had discontinuities and gaps. However, the clock time series have not been split into different subsets for avoiding the mentioned discontinuities. Consequently, the associated generated "detrended" clock plots clearly reflect the mentioned discontinuities and gaps. The following figures show the plots of the obtained "detrended" time series. Please note that the X-axis represents the date in MJD(50) format, and the unit for the Y-axis values is the second.

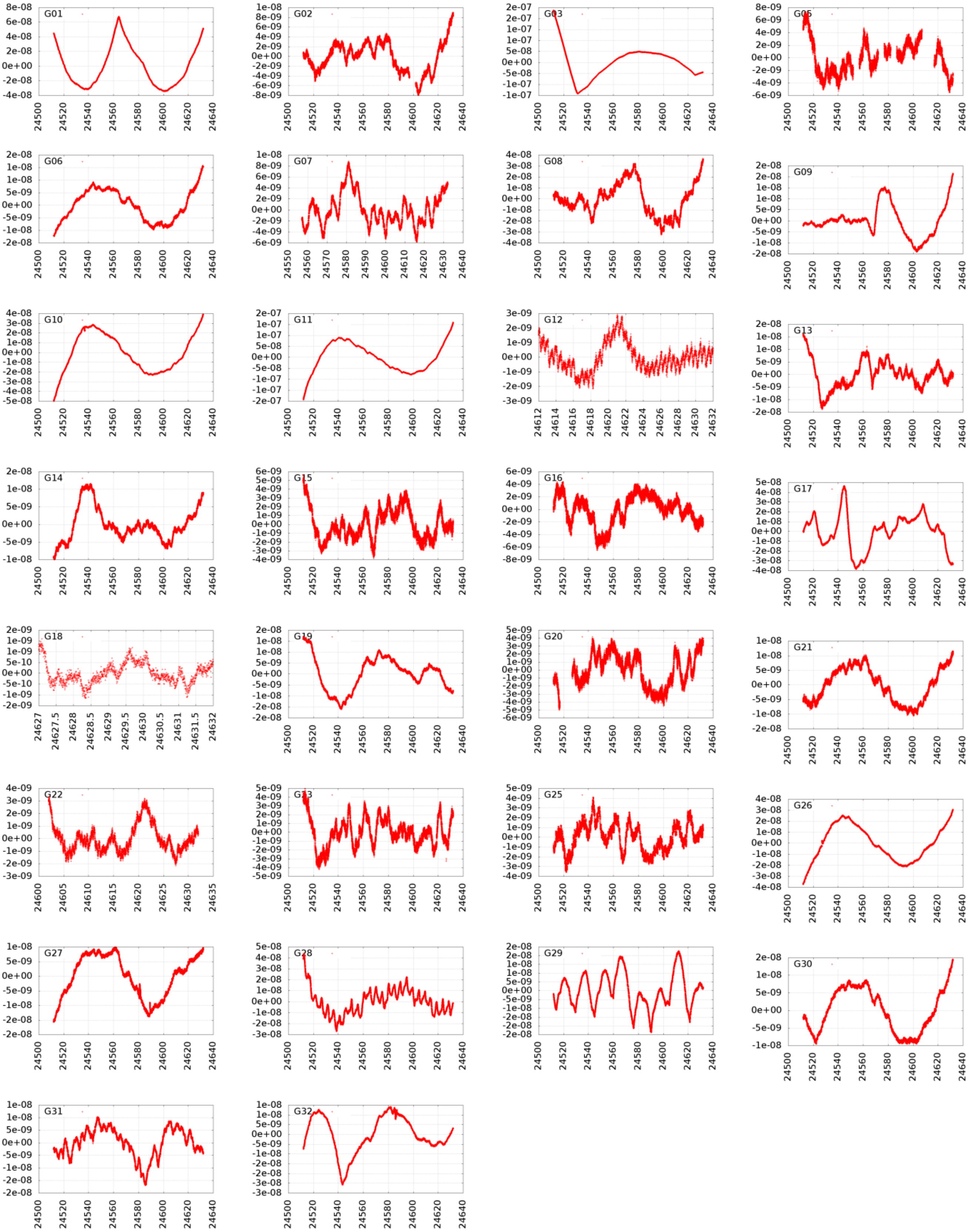


Figure 1: GPS “detrended” clock time series - ~ 4 months

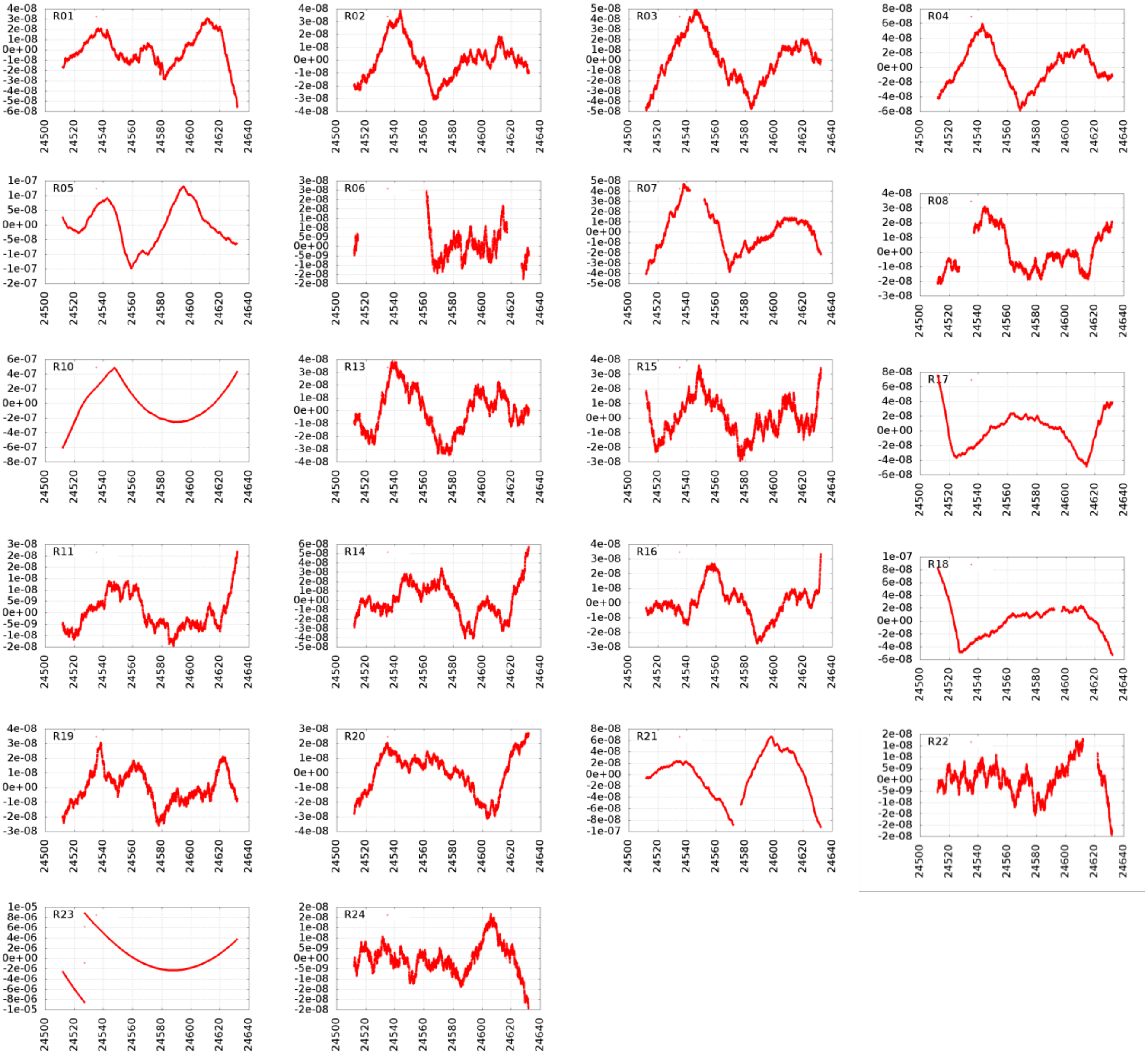


Figure 2: GLONASS “detrended” clock time series - ~ 4 months

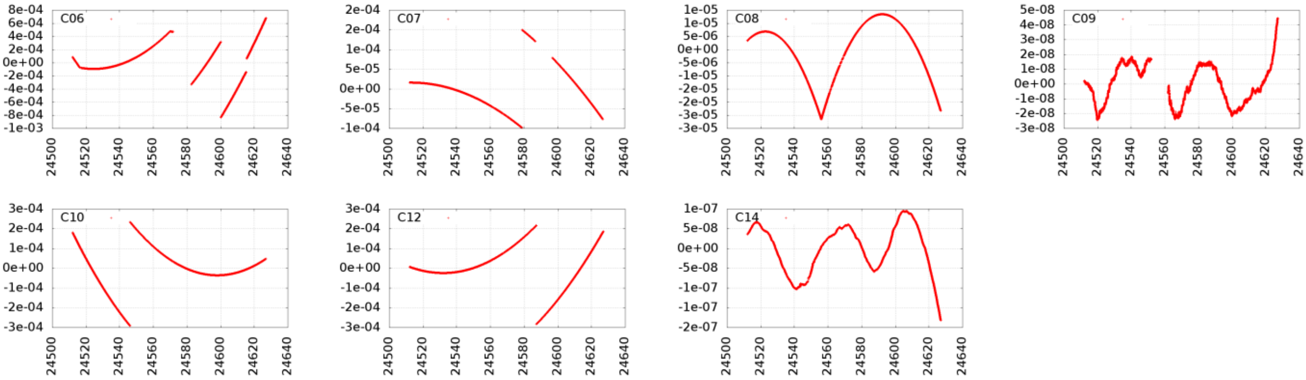


Figure 3: BeiDou “detrended” clock time series - ~ 4 months

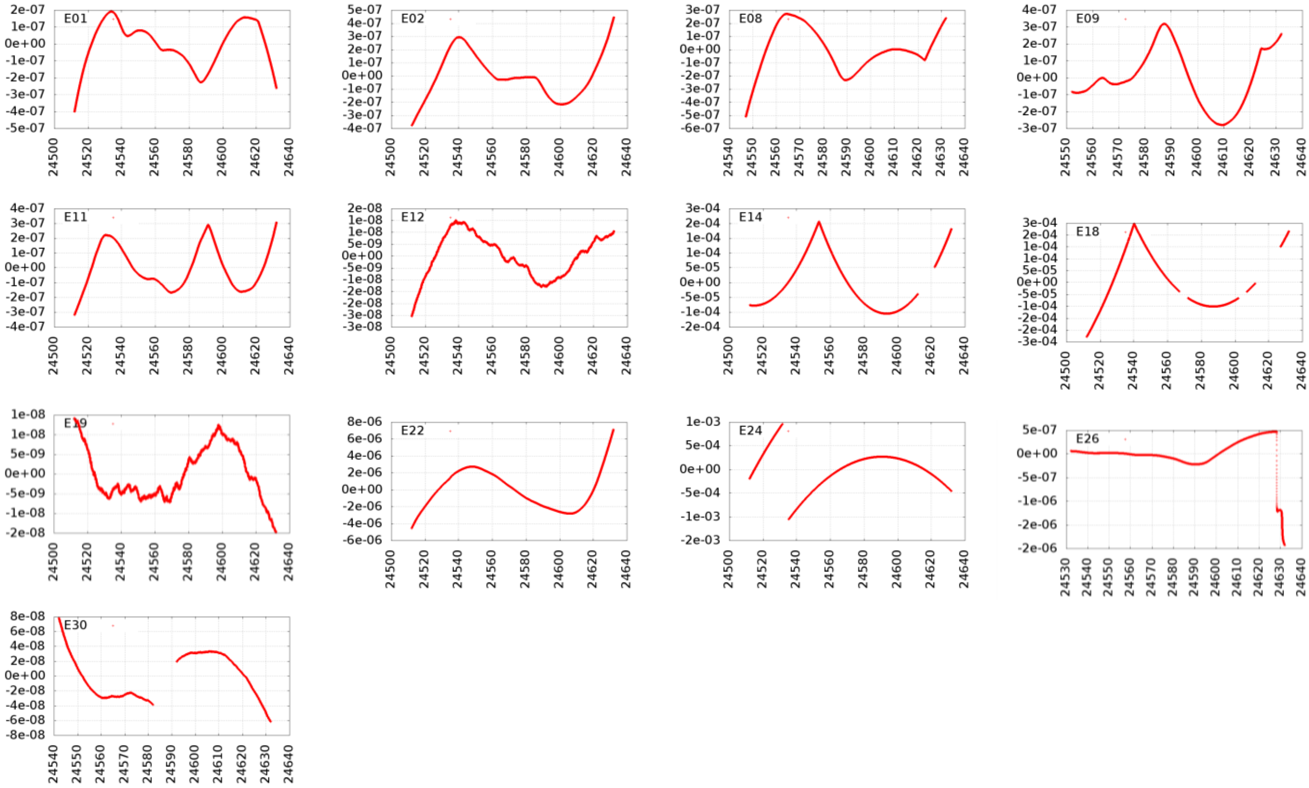


Figure 4: Galileo “detrended” clock time series - ~ 4 months

It is interesting to observe the Y-axis of the previous plots, and see that it is rather large for satellite clocks presenting some kind of discontinuity. It is relatively frequent for BeiDou and Galileo satellites, and also for some GPS satellites. For example the Y-axis magnitude order for C06, C07, C08, C10, C12, E14, E18 and E24 is 1.0e-04 s, whereas it remains about 1.0e-08 s and 1.0e-09 s for almost all GPS and GLONASS satellites. GLONASS R23 does also present a significant discontinuity, and there are two GPS satellites plots showing detrended clocks with Y-axis magnitude orders about 1.0e-07 s: G03 and G11. Regarding GPS, some frequency changes can be observed for G06, G10, G11, G26, G27 and G30. G01 and G03 show clear frequency jumps in the analysed period.

When observed in shorter time periods, the low order polynomial (typically a very smooth parabola, almost a straight line) usually and logically fits much better the clock data set, and the detrended satellite clock data spans in a usually smaller Y-range. The Y-range is related to the statistical dispersion of the clock behaviour, and has a strong dependence on the kind of active frequency standard on board each satellite.

BeiDou satellites are equipped with rubidium (Rb) frequency standards. GLONASS satellites are equipped with caesium (Cs) frequency standards. Each Galileo satellite is equipped with four redundant clocks: two primary Passive Hydrogen Masers (PHM) and two secondary Rb clocks. For the analysed period, all active Galileo satellite clocks were PHM except for E11 and E22, which were Rb. And finally, all current GPS satellites are equipped with Rb clocks, except for G08, which is working with a Cs clock, see [Ref. 19.] . Regarding GPS, it has to be noticed that currently active satellites belong to two different blocks, IIR and IIF, equipped with different generation Rb technologies. The newest GPS satellites are those belonging to block IIF: G01, G03, G06, G08, G09, G10, G24, G25, G26, G27, G30 and G32.

Four examples of “detrended” clock time series, for different satellites with different frequency standards on board are shown below. In the case of GPS, two Rb examples are shown, one for a satellite belonging to block IIR and another one for a satellite in the newest IIF block. Galileo E30 is equipped with a PHM, GPS G08 with a Cs, GPS G01 belonging to block IIF with a Rb and GPS G11 belonging to block IIR also with a Rb. Please note that the y-axis is expressed in seconds (1ns = 1e-09 s ~ 30 cm).

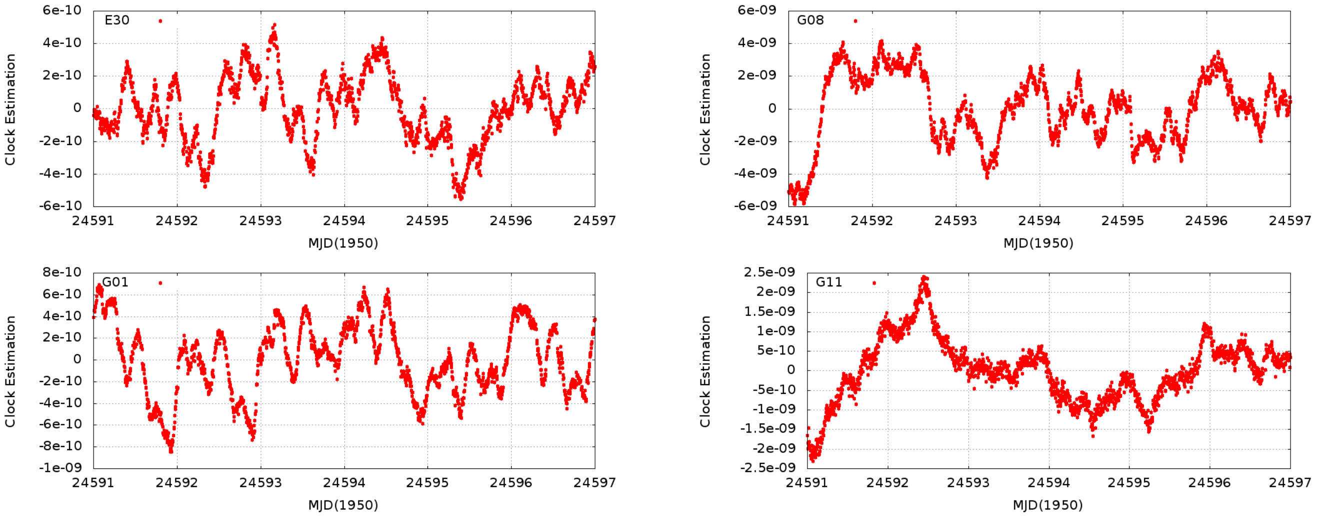


Figure 5: “Detrended” clock time series (s)– 6 days

The analysis of the behaviour of atomic clocks, in short and large time periods, is usually referred as “frequency stability analysis”. That topic is referred in the next section.

CLOCK STABILITY ANALYSIS

Current techniques for clock stability analysis are based on the use of specialized statistical variances which were developed on purpose in order to characterize clock noise as a function of different time periods, usually referred as “averaging times”. Usual statistical parameters, such as standard deviation, were found to be inadequate for clock stability analysis. The standard deviation of a clock data population (set of samples), depends on the number of samples used to determine it. Specific statistical variances, such as the “Allan Variance”, based on using differences of the fractional frequency values (second differences of the phase), started being defined back in the 60’s. These variances, which are not affected by the number of samples of the population, were found to be suitable for the intended purposes, and their introduction set the basis for the current clock stability analyses. Further information about clock stability analysis can be found in [Ref. 10.].

Some basic stability analyses were performed with the GNSS satellite clock time series. In principle, several of the generated sets should have been partitioned, in particular those showing discontinuities, in order to obtain the stochastic characteristics for each one of the considered satellite clocks, which should be constant, both stationary over time and ergodic over the population, for each one of the considered satellite clocks. However we have not split the data sets, and in the cases with discontinuities in the data sets, the obtained stability values are not intended to represent the stochastic characteristics of the considered satellite clocks. They are intended to further illustrate the fact that those discontinuities exist. The obtained results are shown in Figure 7.

For better understanding the clock stability results obtained for the different GNSS constellations satellites, we include Figure 6 below, with stability specifications for the different considered atomic frequency standards: Cs, Rb (RAFS, Rubidium Atomic Frequency Standard) and PHM. Lower Allan Deviation values correspond to higher stability specifications.

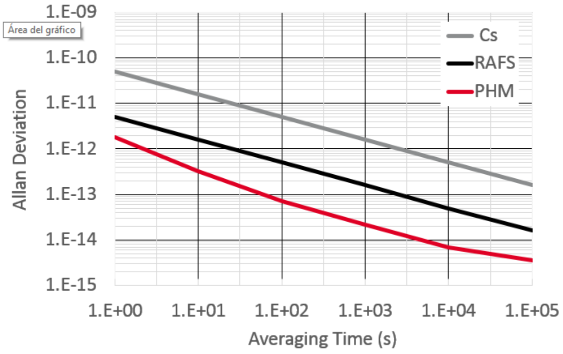


Figure 6: Atomic frequency standards specifications

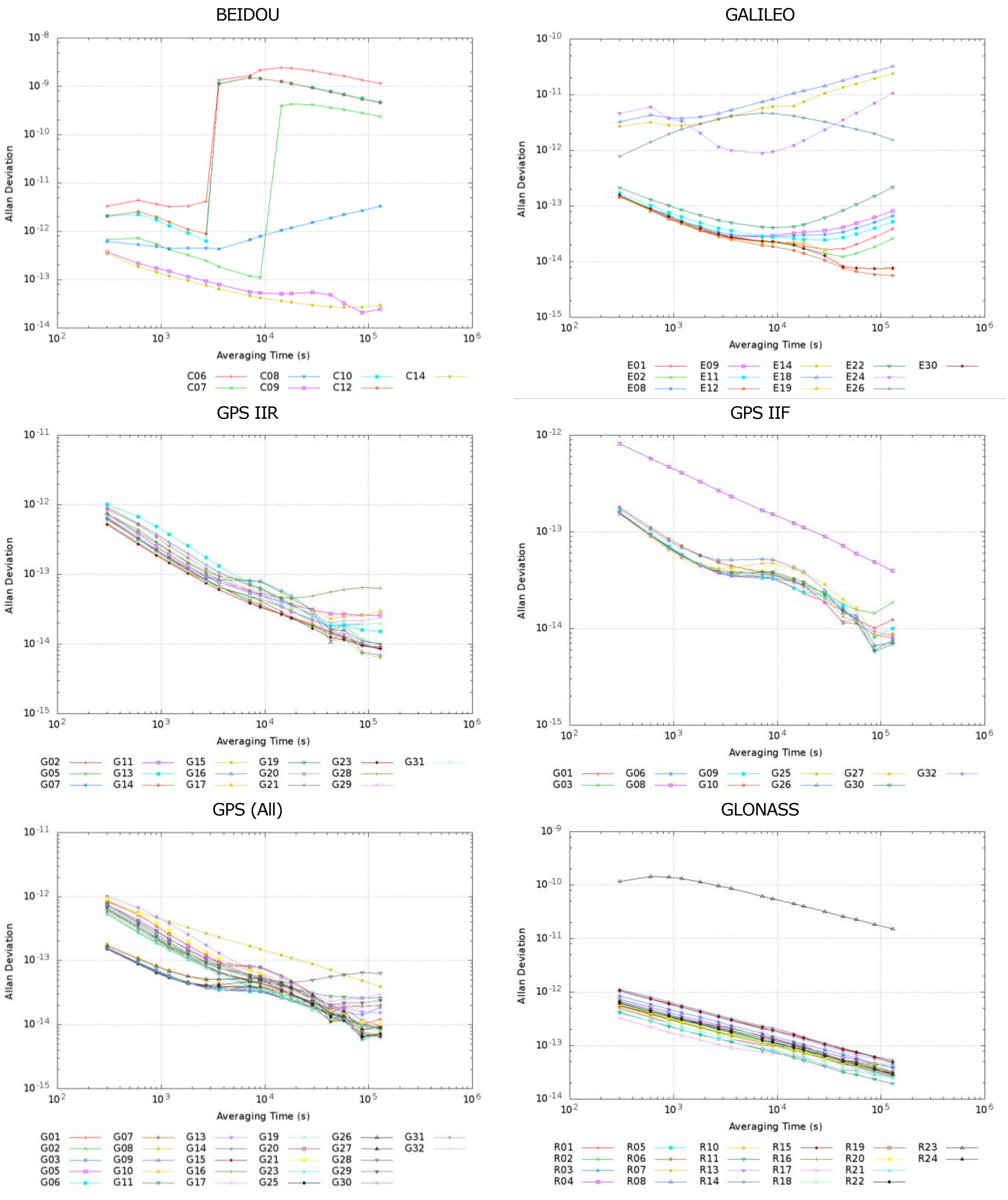


Figure 7: Clock stability analysis – Allan deviation

The clock stability results depicted in Figure 7 above, can be summarised as follows:

Beidou:

- Large discontinuities can be observed for satellites C06, C07, C10 and C12. They are related to phase jumps, as shown in Figure 3.
- A degradation of the satellite C08 long-term stability can be observed. It is related to a frequency discontinuity, as shown in Figure 3.
- Standard ADEV curves are obtained for satellites C09 and C14, the ones showing the smallest Y-axis range in Figure 3.

Galileo:

- Abnormally large ADEV values are obtained for satellites E24, E14, E18 and E26. E24 and E26 present large phase discontinuities, whereas E14 and E18 (which are indeed not operational, they were launched into incorrect orbits and later on moved into more usable orbits, see [Ref. 24.]), present frequency discontinuities. See Figure 4.
- For the rest of the satellites, ADEV for the lower averaging times is in line with the specifications, but for higher averaging times, ADEV values are disperse. Quite large values for higher averaging times ADEV values can be observed with respect to the specifications (E11 and E22 have active RAFS on-boards, all the others have PHM frequency standards) for all of them except for satellites E12, E19 and E30. The reasons for the observed large stability values, especially for the long-term are discontinuities and oscillations already observed in the “apparent clocks” section. The obtained values are coherent with the Y-axis scale range in Figure 4.

GPS:

- No large discontinuities can be observed for any of the considered satellites.
- Three clearly defined blocks can be observed. Satellite G08 is different from all the rest, since its active frequency standard is a Cs clock, and thus its stability is worse. The group of satellites with lower ADEV values for low averaging times (G01, G03, G06, G09, G10, G25, G26, G27, G30, G32) corresponds to the newest block IIF satellites, whereas all the rest belong to older blocks IIR and IIR-M.

GLONASS:

- GLONASS satellites are all equipped with Cs frequency standards. Very similar stability behaviours have been obtained for all of them, except for satellite R23, coherently with Figure 2, in which a large phase jump can be observed for R23.
- ADEV values obtained for GLONASS satellites are slightly worse than for other constellations clocks, using RAFS and PHM frequency standards, for the lower averaging times, but they are quite similar for higher averaging times.

When comparing the results for the different constellations, it can be observed that the best stability values for short averaging times have been obtained for the Galileo satellite clocks (those not affected by phase or frequency anomalies) and for the newest GPS block IIF satellite clocks. This means that, in principle, the best short time clock predictions should be obtained for these satellites. Regarding long time predictions, the difference between the different technologies seems to be smaller, and in this case, the attainable performances seems to be more related to events and discontinuities in the clock operations.

CLOCK FREQUENCY ANALYSIS

The objective of this section is to perform the analysis of apparent clocks in the frequency domain. As it is known (see for example [Ref. 25.]), satellites experience periodic effects along time, which are naturally associated with the fact GNSS satellites follow a periodic orbit around the Earth, with revolution periods of 11h 58’, 11h 15’, and 14h 22’ for GPS, Glonass, and Galileo, respectively. These effects are actually also reflected in the onboard clocks’ behavior, and these (and possibly other periodic effects) are the ones we are going to analyze in this paper.

Two different techniques have been used for the frequency domain analysis: the Fast Fourier Transform (FFT) and the Karhunen-Loève Transform (KLT). The Fourier Transform (FT) is a typical tool for frequency domain analysis and the FFT is its most widely used implementation. The use of the KLT (see [Ref. 26.]) has been introduced in the analysis due to its applicability to more easily identify weak harmonic components.

Although a complete study of the results has been performed for GPS and Galileo, only a representative example of the KLT for each constellation is presented in Figure 8. These examples do only contained the high-frequency components (sub-daily) and the minimum cycle period is 2 hours, which is in fact the sampling rate.

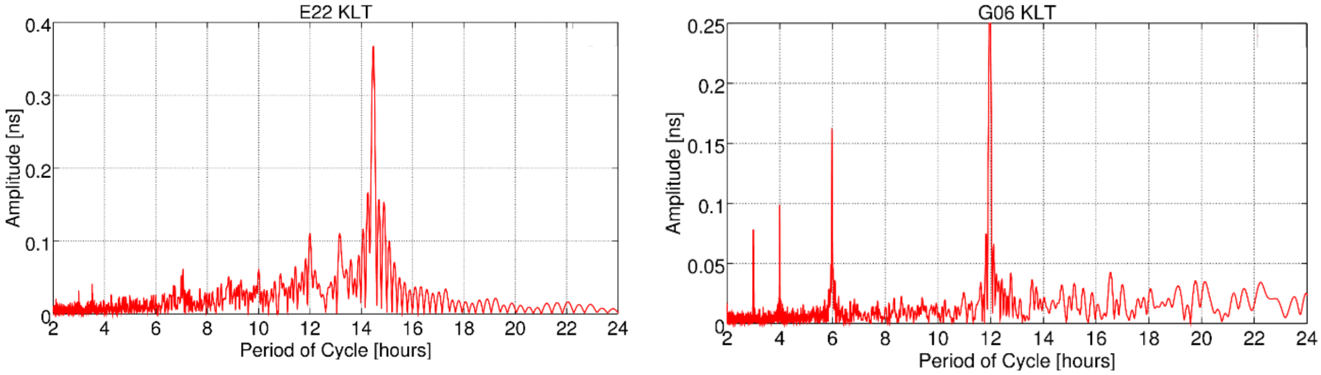


Figure 8: Examples of results of the clock frequency domain

In the case of GPS, there is a clear periodic effect correlated with the orbital period, which could be partially due to thermal effects and to the correlation with the orbit estimation error. The half-period peak could also be related to the second order relativistic correction (associated to J2). In the case of Galileo, the magnitude of the correlation with the orbital period, observed at around 14 hours 22 minutes and submultiples, is not so significant; additionally, we can observe the effect of the correlation with the length of the orbit and clock estimation arc, which is normally multiple of 12 hours, as a periodic effect at this cycle period.

The understanding and characterization of these periodic effects is relevant to improve for clock modelling techniques in ODTS processes as explained in subsequent section “Clock Modeling Analysis”. The frequency of the periodic effects is characteristic of each constellation, whereas the amplitude could be specific for each particular satellite.

CLOCK PREDICTION ANALYSIS

Because of the results obtained in the clock stability analysis section, we have decided to skip the BeiDou constellation satellites, since most of them have shown some kind of anomaly in the previous analyses. Galileo satellites have also shown events and discontinuities, especially affecting the long-term clock behaviour. That is why we have considered them all for the short-term clock prediction analyses, and have just kept the ones without anomalies for the long-term prediction tasks.

The clock prediction analysis has consisted on processing the restituted clock time series in order to build estimation and prediction moving windows covering the whole time series. Fit intervals of 100 minutes, 200 minutes, 12 hours and 24 hours were considered for generating 100-minutes-long predictions (short-term predictions). Fit intervals of 1, 5, 7 and 15 days were considered for generating 100 minutes, 1, 7, 15 and 30 day-long predictions (medium and long term predictions). In all cases, the moving window delta was 1 day long, and both linear and quadratic fit modes were used. Statistical results for the RMS (Root Mean Square), 50% percentile, 68% percentile and 95% percentile have been computed. The clock prediction error presented for each one of the considered satellites has been the lower one obtained for the best fitting model out of the different considered fitting schemes (different fit intervals and regression models). The results have been plotted in Figure 9 below.

Figure 9: Clock prediction analysis

For better interpreting the obtained clock prediction results, they have been summarised in Table 2 below, presenting numerical values for facilitating direct comparisons:

Table 2: Clock prediction analysis - summary

GPS & GLONASS	GALILEO
100-minutes Clock Prediction Error (m)	
Average p50 GPS: 0.13 Average p50 GPS IIF Rb: 0.08 Average p50 GLONASS: 0.31	Average p50: 0.06
Average p68 GPS: 0.16 Average p68 GPS IIF Rb: 0.11 Average p68 GLONASS: 0.41	Average p68: 0.08
RMS (RMS GPS): 0.18 RMS (RMS GPS IIF Rb): 0.11 RMS (RMS GLONASS): 0.19	RMS* (RMS): 0.08
1-day Clock Prediction Error (m)	
Average p50 GPS: 1.13 Average p50 GLONASS: 2.44	p50 E12: 0.44 p50 E19: 0.51 p50 E30: 0.37
Average p68 GPS: 2.18 Average p68 GLONASS: 3.97	p68 E12: 0.83 p68 E19: 0.95 p68 E30: 0.87
RMS (RMS GPS): 3.92 RMS (RMS GLONASS): 3.87	RMS E12: 1.10 RMS E19: 1.14 RMS E30: 2.31
7-day Clock Prediction Error (m)	
Average p50 GPS: 4.20 Average p50 GLONASS: 6.37	p50 E12: 1.53 p50 E19: 1.43 p50 E30: 3.09
Average p68 GPS: 7.20 Average p68 GLONASS: 9.76	p68 E12: 2.29 p68 E19: 2.03 p68 E30: 5.38
RMS (RMS GPS): 14.98 RMS (RMS GLONASS): 14.75	RMS E12: 2.80 RMS E19: 2.47 RMS E30: 9.92

GPS & GLONASS	GALILEO
15-day Clock Prediction Error (m)	
Average p50 GPS: 6.74 Average p50 GLONASS: 10.66	p50 E12: 2.33 p50 E19: 2.12 p50 E30: 9.19
Average p68 GPS: 9.64 Average p68 GLONASS: 16.08	p68 E12: 3.67 p68 E19: 3.27 p68 E30: 14.35
RMS (RMS GPS): 16.11 RMS (RMS GLONASS): 15.66	RMS E12: 4.39 RMS E19: 3.57 RMS E30: 17.50
30-day Clock Prediction Error (m)	
Average p50 GPS: 15.71 Average p50 GLONASS: 18.69	p50 E12: 3.59 p50 E19: 3.64 p50 E30: 22.48
Average p68 GPS: 23.63 Average p68 GLONASS: 17.75	p68 E12: 5.90 p68 E19: 5.99 p68 E30: 27.828
RMS (RMS GPS): 41.14 RMS (RMS GLONASS): 39.82	RMS E12: 8.32 RMS E19: 6.19 RMS E30: 30.59

The obtained results show that Galileo satellite clock prediction errors are similar, and even better than those obtained for other GNSS constellations for relatively short time periods, in the range of the navigation message validity times. Obtained clock prediction errors for 100 minutes prediction intervals are in the cm level: 8 cm (RMS) for operational Galileo satellites, 11 cm (RMS) for block IIF GPS satellites, and 19 cm (RMS) for GLONASS (operating with Cs AFS). For longer time periods, undefined clock anomalies, probably related to operational and/or testing events, not inherent in the clock behaviour, cause the Galileo statistics to degrade. In absence of anomalies and events, the Galileo satellites clock prediction performances are again in the same magnitude order of the ones obtained for other GNSS constellations clocks. Attainable standard clock prediction errors for long prediction intervals would be:

- 1-day-long prediction interval: 2-5 m
- 7-day-long prediction interval: 5-10 m
- 15-day-long prediction interval: 10-20 m
- 30-day-long prediction interval: 20-50 m

Note that as anticipated when performing the GLONASS stability analyses, GLONASS (Cs) clock predictions for short-time intervals are relatively high, whereas long-time predictions are comparable with those obtained for GPS RAFS.

COVARIANCE ANALYSIS

The observed Galileo clocks short-term high stability opens the door to the implementation of clock models in the ODTS process, and thus, to the investigation of potential associated benefits that could be derived from the mentioned alternative implementation. The standard implementation is usually referred to as “snapshot”, and consists of estimating one clock parameter at each epoch, for each one of the satellite and station clocks, which is relatively costly from the computational point of view, and requires good geometrical observability conditions (at least four satellites in view from each station, and four stations in view from each satellite, at all epochs).

Some preliminary covariance analyses were performed in order to assess the impact of the satellite clock lack of knowledge on the global ODTS process uncertainty. The covariance analyses have been carried out with a dedicated analysis tool developed by GMV for the detailed study of the ODTS processes, see [Ref. 14.]. Covariance analysis, though usually optimistic, can provide an analytic “best case” test of the improvement of performances that could be achieved under different circumstances. Figure 10 below contains the results of the covariance analysis performed on orbit determination accuracy. The reference scenario corresponds to a ground network of 17 world-wide homogeneously distributed stations shown and a Walker 27/3/1 Galileo constellation. Please note that even if the covariance tool has been calibrated for rendering significant quantitative results, the provided results are to be qualitative interpreted. Precise accuracy results are strongly dependent on the size, distribution and quality of the tracking stations network, and, for the sake of simplicity and clarity, we have not used those parameters as variables in our analyses. Please note that in Figure 10 below, the covariance estimation for the orbit error is projected into the radial (rad), along-track (at) and cross-track (ct) directions.

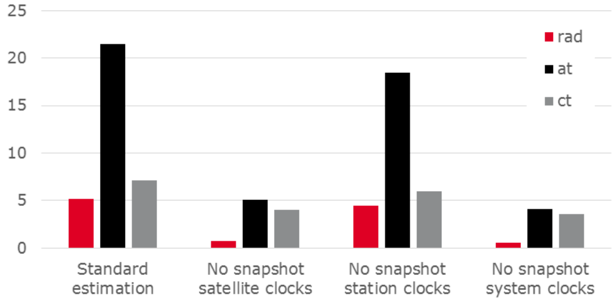


Figure 10: Orbit Estimation Covariance (RMS, cm)

The plot shows that the main benefit is obtained when the satellite snapshot clock estimation is avoided, even if clock estimation remains unknown. The ODTS process uncertainly is significantly reduced when satellite snapshot estimation is kept off, whereas the analogous effect for the stations clock modelling is not as significant. In addition, station clock predictions are not as relevant for navigation purposes as satellite clock prediction, in the sense that only satellite clocks are needed to be predicted for being distributed to navigation users through the navigation messages. Station clock predictions could however be relevant for other purposes.

This means that there is a potential improvement for the ODTS processes, if satellite clocks could be modelled with a simple function (e.g. a quadratic polynomial). The results depicted in Figure 10 above for the “No snapshot satellite clocks” case, represent the theoretical covariance of the expected errors that would be obtained in case it was possible to exactly model the behaviour of all the GNSS systems satellite clocks, which is clearly not the case. In the real scenarios, even the most stable satellite clocks have certain stochastic components, and are affected by other effects, not able to be fit to a model. The final real clock estimation error will be larger or smaller depending on the satellite stability, the fit model, the fit interval length, the correlation with other parameters, etc. but in any case, larger than the theoretical one, since real satellite clocks do not behave as perfect simple models.

CLOCK MODELING ANALYSIS

Notwithstanding the observed short-term high stability of the Galileo PHMs, on-board clocks are not perfectly stable, and “apparent” clock signals are affected by additional effects, besides the strict frequency standard behaviour, such as explained before in section “Apparent Clocks”.

Thus, for the clock modelling analyses with real data, we have considered a simple clock model, and a mixed simple clock model plus snapshot (perturbation around a quadratic function), to be compared with respect to the standard snapshot strategy.

Second order relativistic effects have also been considered, see [Ref. 15.]. The used evolution of a simple quadratic function can be expressed as:

$$b(t) = b_0(t) + b_D(t) + b_s(t)$$

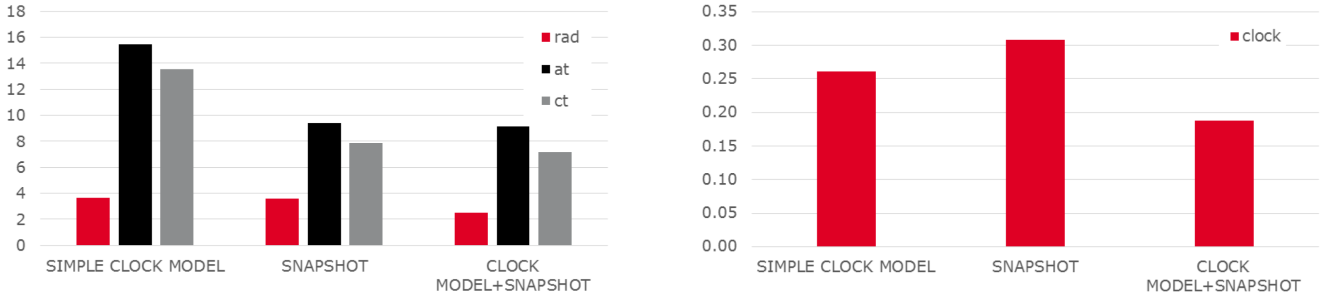
where:

- $b_0(t) = a_0 + a_1 t + a_2 t^2$ is a quadratic function,
- $b_D(t) = -\sqrt{\frac{GM_E}{a^3}}\frac{3a_E^2 J_2}{2c^2} sin^2 i \cdot sin^2(2u(t))$ is the second-order relativistic correction due to the gravitational J_2 coefficient, and
- $b_S(t)$ is a snapshot estimation term constrained to be small (a few cm).

A Galileo-only ODTS process, with a basic configuration of 72h for the arc length, 5 iterations, a sample rate of 5 minutes, with a 17-stations tracking network, was run with three different configurations:

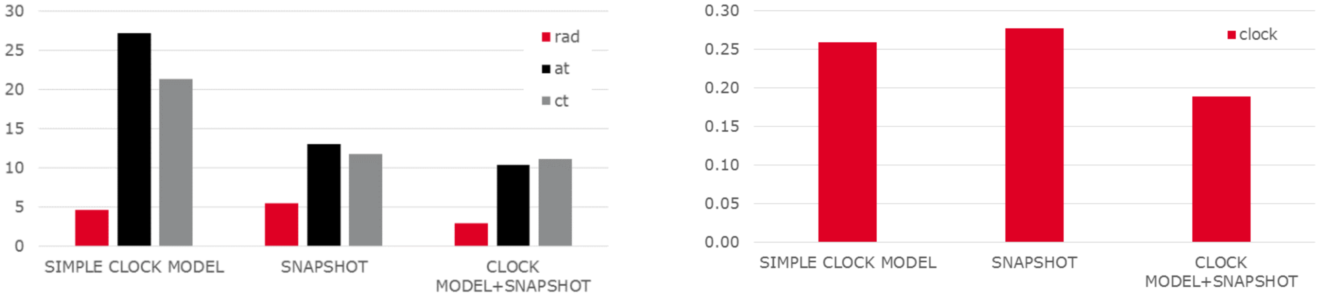
- Simple Clock Model, in which $b_S(t)$ is not considered
- Clock Model + Snapshot, in which $b_S(t)$is considered, constrained to within an order of 10 cm.
- Snapshot, following the standard snapshot mode.

The ODTS orbit and clock estimation and prediction results are shown in Figure 11 below. The reference scenario was generated with a GPS + Galileo ODTS process, with a larger 59-stations tracking network. Please note that for clocks, results are expressed in ns. Prediction results have also been combined and projected in to the Worst User Location (WUL, see Annex A), for better illustrating the effect on the user total positioning error, realistically aggregating both orbit and clock prediction errors.



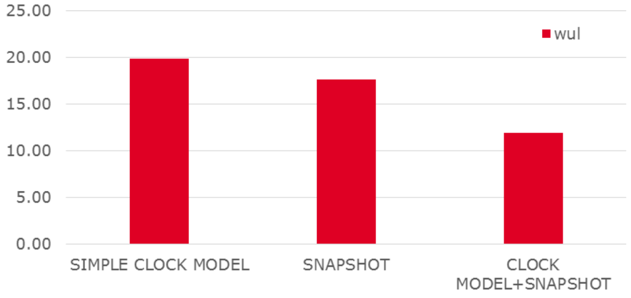
Orbit Estimation Error (RMS, cm)

Clock Estimation Error (RMS, ns)



Orbit Prediction Error (3h, RMS, cm)

Clock Prediction Error (3h, RMS, ns)



Orbit & Clock Prediction Error – WUL Projection (3h, RMS, cm)

Figure 11: ODTS Results

The obtained results can be summarised as follows:

- A pure clock model strategy might degrade the orbit estimation and prediction accuracies when compared with a pure snapshot strategy, whereas the clock estimation and prediction would slightly improve. It can thus be concluded that it would be feasible to estimate Galileo satellite clocks by using a simple quadratic model and still obtain acceptable results. This option would be very interesting for providing robustness in degraded scenarios, for example in scenarios with reduced number of tracking stations.
- Both clock and orbit estimation and prediction might improve, when compared with a pure snapshot strategy, if a clock model plus snapshot mixed strategy was used. This approach is very promising for improving the performances of current high accuracy navigation processes.

Please note that Figure 10 and Orbit Estimation Error in Figure 11 seem inconsistent. In Figure 10, the covariance is significantly smaller for the “No snapshot satellite clocks” case than for the “Standard estimation” case, whereas in Figure 11, the error for the “Simple clock model” case is larger than for the “Snapshot” case. The explanation for the apparent inconsistency lies in the fact that the covariance analysis represents a theoretical approach, whereas the orbit estimation errors depicted in Figure 11 have been generated in real ODTS processes, in which, as previously mentioned, the satellite clocks do not behave as perfect simple models. The correct interpretation of the obtained results is as follows: the ODTS process uncertainty, and thus the ODTS products performance, would improve, in theory, if satellite clocks were able to be modelled. In real ODTS processes, real satellite clocks are not able to be perfectly modelled, and thus, the potential accuracy improvement is not totally reached. However, the use of clock models can have other advantages, beyond accuracy, related to the following two points:

- Just a few parameters are needed to be estimated for fitting a simple clock model
- The computational complexity of the ODTS process is significantly reduced when simple clock models are used, instead of the standard snapshot strategy

These facts imply that ODTS processes are much more robust when clock models are used. This can be especially positive in certain degraded scenarios, for example when using extremely reduced station networks. For illustrating this last assertion, [Ref. 8.] can be consulted, where dedicated analyses with Galileo satellite clocks and networks with as less as 9 stations were performed. It was shown that in scenarios with extremely reduced networks, orbit and clock products generation is feasible, and that the use of clock models significantly improves the attainable performances. The obtained results are summarised in Table 3, and Figure 12 below.

The consistency of the clock bias and orbit products over an overlapped period of 1 day was assessed. Four ODTS processes were carried out; in two of them, the clock bias at each epoch was estimated on a snapshot basis whereas, in the other two executions, a physical clock modelling within the ODTS process was used. The orbit and clock consistency results are shown in Figure 12. The numerical results are summarized in Table 3 for an easier inspection.

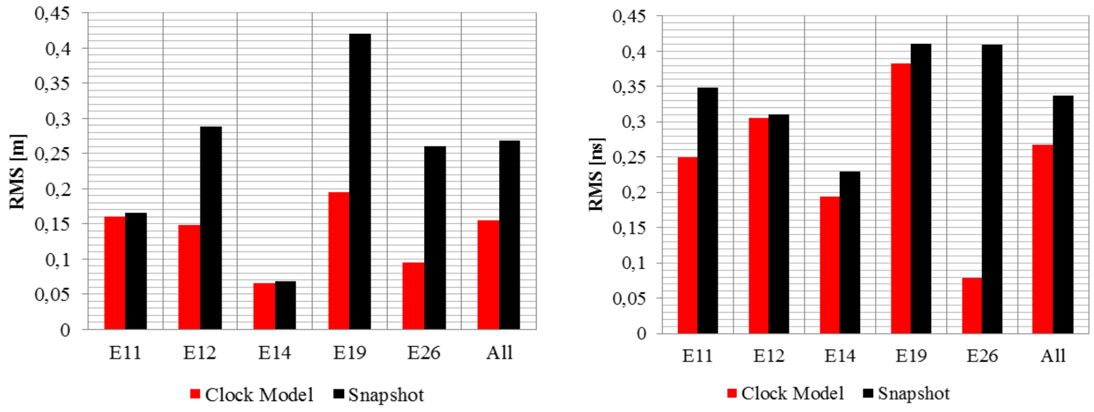


Figure 12: Orbit (left) and Clock bias (right) consistency

Table 3: 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

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.

In scenarios with large networks, with about 50 tracking stations and more, the performances improvement is almost negligible, see [Ref. 8.].

Please note that the clock modelling analysis presented in this section has been carried out ignoring the impact of the jumps, gaps, oscillations and discontinuities observed in previous sections. But the presence of the mentioned irregularities is not to be neglected. In absence of anomalies, Galileo clocks performances are excellent: highly stable, quite predictable and able to be accurately modelled with simple functions, however the realization of those excellent performances is often disturbed by certain events or operations, which cause the clock performances to degrade, especially those for the long term.

FURTHER WORK

Regarding Galileo, we would dare to say that it is possible that the occurrence of operational and/or testing events, not inherent in the clock behaviour, which have shown to cause the Galileo clock performance statistics to degrade, will be largely reduced as the system deployment evolves and matures. In that case, the Galileo satellite clocks analyses presented in this paper would be able to be reproduced, covering a different time span, and more significant results would probably be obtained.

Further clock modelling testing and analysis activities could be carried out, with different configurations, in different ODTS scenarios, for better assessing the advantages and drawbacks of the different considered clock estimation and prediction strategies in the ODTS processes.

CONCLUSIONS

- A series of "apparent" satellite clocks, for GPS, GLONASS, Galileo and BeiDou has been generated, covering a 4-month-long time span
- Discontinuities and jumps were observed for some of the satellite clocks, especially for BeiDou and Galileo.
- Clock stability analyses have been performed, showing results coherent with the different technologies used for the satellite frequency standards, and with the anomalous behaviours observed in the "apparent" clock time series.
- For short averaging times, the newest GPS block IIF and the Galileo constellation satellite clocks, are the ones showing better stability results.
- TBC (frequency analyses)
- Short, middle and long term period clock predictions have been generated and analysed.
- In absence of anomalies and events, the Galileo satellites clock prediction performances are in the same magnitude order or even better than the ones obtained for other GNSS constellations clocks.
- Different ODTS clock modelling strategies have been implemented and tested. Pure simple model, and mixed simple model with snapshot strategy, have been implemented and compared with respect to the standard pure snapshot strategy.
- A pure clock model strategy has been found to slightly degrade the orbit estimation and prediction accuracies when compared with a pure snapshot strategy, whereas the clock estimation and prediction performances have been found to slightly improve.
- This option would be very interesting for providing robustness in degraded scenarios, for example in scenarios with reduced number of tracking stations.
- Both clock and orbit estimation and prediction might improve, when compared with a pure snapshot strategy, if a clock model plus snapshot mixed strategy was used.
- This approach is very promising for improving the performances of current high accuracy navigation processes.
- The obtained results about clock stability, clock predictability and clock modelling, are interesting for supporting the definition of potential future Galileo evolutions.

ANNEX A: PROJECTION INTO THE WORST USER LOCATION (WUL)

The projection of the orbital error into the user direction ε_{OD_user}, see Figure 13, can be bounded as follows:

$$\varepsilon_{OD\_user} < |R| + \sqrt{A^2 + C^2}\left(\frac{R_e}{a}\cos E\right)$$

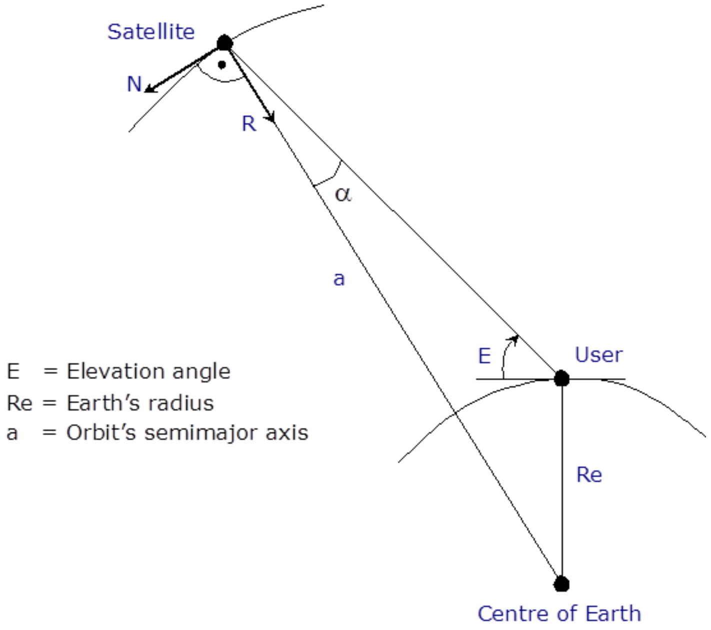


Figure 13: Projection of the orbital error into the user direction

And for the worst user location, for which cos E = 1 (E=0 degrees), we get:

$$\varepsilon_{OD\_user} < |R| + \left(\frac{R_e}{a}\right)\sqrt{A^2 + C^2}$$

Where R is the radial error, A is the along-track error and C is the cross-track error.

Taking into account that the semi-major axis of the GPS orbits is 26,560 km approximately, same for GLONASS is 25,440 km, for Galileo 29,599.8 km and the Earth's radius is 6378.137 km, we get:

$$\frac{R_e}{a}(GPS) \approx 0.24014$$

$$\frac{R_e}{a}(GLONASS) \approx 0.25071$$

$$\frac{R_e}{a}(GALILEO) \approx 0.21548$$

Note that the projection into the WUL is, strictly speaking, more conservative than the projection into a user with 0º elevation angle, since for the WUL projection, the absolute value of the radial error is considered, which is, by definition, larger than its true value considering the actual sign. For coherence with this projection, also the radial error has been considered in absolute value for the projections into the other elevation angle values. In the end, has to be remarked that this strategy is somewhat conservative, and thus its application results into error values which are reasonable, but slightly larger than those which would have been obtained considering the value with its actual sign.

ACKNOWLEDGMENTS

Thank you very much to Dr Valentín de la Rubia for your inestimable support in the paper preparation.

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