Satellite Clocks Characterization and Monitoring for Global Navigation Satellite Systems

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Abstract

In Global Navigation Satellite Systems (GNSS) the user's position is determined measuring the time of flight of the signals broadcast from satellites, which is proportional to the distance between the user and each satellite of the constellation.

Time and frequency metrology has an essential role in satellite navigation systems: since a distance can be measured from a time, any error on the measure of time leads to an error on the user's position. Hence, it is fundamental to have precise and stable atomic clocks on board satellites.

Therefore the on board clock behaviour has to be continuously monitored and any malfunctioning has to be detected immediately to ensure the adequacy of the timing system to the positioning service and users' needs.

This paper will describe the main methodologies for characterization of onboard clocks and their implementation in a robust software developed at INRIM and also used in the framework of the European project Galileo.

1. Introduction

Nowadays satellite radio navigation systems are more and more employed by different kind of users to determine their position or the location of a certain place. Any satellite navigation system is based on the transmission of signals from a constellation of satellites. Processing the signals received from several satellites it is possible to estimate the position of a user through a least squares adjustment.

All satellites carry atomic clocks to control the timing operations, such as the signals generation and broadcast. Although these clocks are highly stable, a deviation from the reference time scale is possible: in GPS such deviation could be up to 10 ns, leading to a positioning error of the order of 3 m (1σ) [1].

One of the most critical technologies for GNSS developers is the need to fly accurate timing standards, assuring the synchronizations to all satellites clocks and permitting receivers to operate with a low-cost clock. Different clock technologies have been employed in GNSS satellites: Cesium clocks and Rubidium Atomic Frequency Standard (RAFS) are used in GPS, while the European satellite navigation system Galileo will fly Rubidium Atomic Frequency Standard and Passive Hydrogen Masers (PHM). As expected, each clock technology has different features with respect to the others and, most importantly, the space clocks behaviour is different from the one observed on the same type of clocks measured on ground or in timing laboratories. This is due to the clock technology itself, which is differently designed to work on ground or in space, but also to the different operational environment and the complex space-to-ground measurement system: because of these aspects, unexpected phenomena can be noticed on the observed apparent clock. Data from satellite clocks, indeed, often present missing data and outliers [2], as well as periodic fluctuations [3, 4]. All these aspects may complicate the analysis, since clock data from timing laboratories, regularly used by INRIM, are equispaced and usually do not present outliers.

Therefore often, for space clock applications, the typical methods and techniques for clock characterization currently in use in timing laboratories are not sufficient: in fact, the spatial environment where clocks operate as well as the strict requirements of reliability and integrity needed for the navigation systems, require the development of new approaches and algorithms, more suitable for GNSS applications.

To overcome these limitations, INRIM developed the *Clock Analysis Tool,* optimized to deal with atomic clocks for space applications. For this purpose, an existing software used for clock characterization in INRIM laboratories has been adapted to fulfill GNSS needs: it has been enhanced and extended including new routines for the monitoring such as the Dynamic Allan Deviation (DADEV) and Dynamic Hadamard Deviation (DHDEV), commonly used for GNSS satellite clock characterization [5].

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The methodology applied at INRIM for satellite clock characterization is briefly illustrated in section 2 while the clock characterization and monitoring tool will be described in section 3.

2. Satellite Clocks Characterization

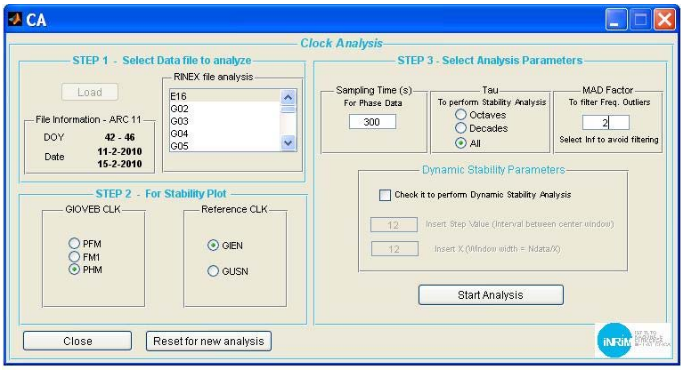
To assess the clocks' behaviour some key parameters have to be monitored. Generally, the satellite clock validation is mainly performed in terms of [6, 7]:

-clock deterministic behaviour: *Phase Offset, Frequency Offset, Frequency Drift*
-clock stochastic behaviour: *Frequency Stability*

The *Clock Analysis Tool* has been developed in MATLAB language to perform the analysis of clocks deterministic and stochastic behaviour.
The *clock phase offset* [8] is the time difference between the lectures of two clocks: in the context of this paper it is the difference between the clock on board the satellite and the reference time scale maintained on the ground.
The *clock frequency offset* [8] is the frequency difference between the onboard clock and the reference frequency. It is the time derivative of the phase offset. The frequency generated by atomic clocks does not remain constantly in agreement with its nominal value: deterministic and stochastic perturbations cause the variation of clocks frequency stability and accuracy. The main deterministic behaviour in atomic clocks is the *frequency drift* [8], that is a systematic variation of the frequency generated by the clock. It may be due to intrinsic changes in the clock itself, to the ageing or to environmental factors [9]. The clock frequency drift can be predicted and removed, using well established features [10]. Among clock deterministic trends often some periodic fluctuations can be observed, mainly due to the clock sensitivity to environment, such as temperature and solar radiation: this kind of analysis will be not addressed in this paper.
The clock signal is also affected by stochastic noises which produce random variations in the oscillator frequency; such noises are typically estimated by means of the Allan Deviation (ADEV), whose use is also recommended in international standards [11]. An alternative analysis can be performed through the Hadamard Deviation (HDEV) [12]. The Dynamic Allan Deviation, as well as the Dynamic Hadamard Deviation, extend the features of ADEV and HDEV (respectively) and add the possibility of identifying and studying clock non-stationarities.

3. Developed Tool for Clocks Characterization and Monitoring

The tool developed at INRIM for clock analysis was optimized in order to deal with typical satellite clock data and was checked with respect to the commercial software STABLE 32 [13] and results were found in complete agreement. Main products for the clock characterization tool are plots generated in an automatic way; such plots allow to monitor in an easy way the clock key parameters and to perform an accurate clock analysis.
To ease the procedure of analysis the tool has been provided with a graphical user interface, illustrated in Fig 1:



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RINEX file analysis
E16
G02
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GIOVEB CLK
○ PFM
○ FM1
● PHM

Reference CLK
● GIEN
○ GUSN

Sampling Time (s) For Phase Data: 300

Tau To perform Stability Analysis
○ Octaves
○ Decades
● All

MAD Factor To filter Freq. Outliers: 2
Select Inf to avoid filtering

☐ Check it to perform Dynamic Stability Analysis
12 Insert Step Value (Interval between center window)
12 Insert X (Window width = Ndata/X)

Fig 1: Clock Analysis Tool

The main steps of the clock characterization tool are described in the following. More details can be found in [2, 6, 14]:

1) *Input data pre-processing*:
The clock phase estimates, extracted from standard files used in GNSS, are firstly pre-processed in order to identify and manage properly potential data gaps and outliers. In fact, often space clocks data may be unavailable since the system ground stations could experience problems in data collection or satellites could be not transmitting for maintenance operations or faults…Clock estimates have to be regularized as for the stability analysis equally spaced data are needed.

Moreover, frequently space clock data present outliers, which have to be identified and removed to allow a representative analysis of clock performances. The solution adopted for outliers detection and filtering is based on a Median Absolute Deviation. The philter on input data can be enabled by the user through the proper panel on the graphical user interface, in which also the philter selectivity can be set according to the user's needs.

2) *Deterministic behaviour analysis*
Averaged frequency estimates are obtained from clock phase data through a time derivative. Then, the main deterministic effect, the frequency drift, is evaluated in order to monitor its evolution over time and to remove such deterministic contribution from clock estimates when the aim is to observe only the clock stochastic behaviour. Different techniques are proposed in literature for frequency drift estimation [10]: the appropriateness of a specific technique is critically dependent on the oscillator model and on the noise present. The tool here described evaluates the frequency drift through a least squares fit. Theoretically the drift could be estimated either on phase or on frequency data, since the relationship between these two quantities is simply a time derivative. This tool has been implemented to evaluate the clock frequency drift estimating the coefficients of a quadratic least squares fit on phase data. This solution has been adopted since satellite clock frequency data may be affected by jumps and outliers: it seemed more convenient to evaluate the phenomenon on phase data, where these events seem to have less impact. Once the clock drift has been evaluated, it is removed from both phase and frequency data by subtracting to the original data sets the estimated quadratic and linear fit respectively. Then the following analysis are performed on both data sets with and without frequency drift.

3) *Stochastic behaviour analysis*
Stability analysis is generally based on the assumption of using equispaced samples. Since data from space vehicles are not always available, very often space clock data present long periods of missing values. The *Clock Analysis Tool* has been designed to extend the approach commonly used for the study of the frequency stability, to deal with the peculiar aspects of satellite clock data [6].

The frequency stability of space clocks is evaluated by means of two independent statistics: first the Allan Deviation is computed on the averaged frequency estimates, then the Hadamard deviation is also determined. Both statistics are evaluated for different observation intervals τ; the number of different observation intervals for frequency stability computation can be set by the user at the beginning of the analysis, through the proper panel on the graphical user interface (Fig.1).

In addition, if one is interested in the evolution of the clock stability over time, also the Dynamic Allan Deviation and the Dynamic Hadamard Deviation are computed if the option of dynamic stability has been selected. Both dynamic analysis are based on the estimate of the Allan and Hadamard Deviation respectively on a sliding window on input data, whose width can be set by the user at the beginning of the analysis.

The results of all the analysis performed by the *Clock Analysis tool* are automatically saved as ASCII files and images in an output folder purposely created during the tool execution. The user can also observe the graphics while they are generated so that he can have an immediate idea of the general clock behaviour; moreover one can analyze the saved plots in order to deepen the analysis focusing on certain periods of data or on particular features. The analysis can be reset and repeated in any moment with different configuration parameters or input files.

4. Conclusion

The tool for clock validation has been expressly developed by INRIM to deal with atomic clocks used in metrological laboratories and then it has been optimized for GNSS applications. The optimization of this tool has been necessary since space clock data can not be treated with the same methods and techniques already in use in metrological laboratories, because of the peculiar features of the clock technology, of the special environment and of the measurement system.

The *Clock Analysis Tool* has been used by the INRIM staff to perform the characterization of the atomic clocks employed in the frame of the experimental phase of the Galileo Project named GIOVE Mission [15]. The tool has been used for the analysis of the clocks flown on board the first two experimental satellites of the Galileo Project, GIOVE-A and GIOVE-B, as well as for the characterization of the clocks of the ground stations. Moreover, it is under consideration the use of such tool in the next phases of the Galileo Project.

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