SIMULATION OF THE CLOCK FRAMEWORK OF GAIA

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ABSTRACT

Gaia will perform astrometric measurements with an unprecedented resolution. Consequently, the electronics of the Astro instrument must time tag every measurement with a precision of a few nanoseconds. Hence, it requires a high stability clock signal, for which a Rb-type spacecraft master clock has been baselined. The distribution of its signal and the generation of clock subproducts must maintain these high accuracy requirements. We have developed a software application to simulate generic clock frameworks. The most critical clock structures for Gaia have also been identified, and its master clock has been parameterised.

Key words: Clocks: rubidium; Simulations; Gaia.

1. INTRODUCTION

In this work we present a powerful and highly configurable simulator of generic clock frameworks. This software tool, although focused on Gaia, has been developed as much parameterized as possible, thus being easily adaptable not only to the current design of Gaia (and its possible modifications), but also to almost any space mission. Its objective is to simulate the real performance of an atomic master clock and its several sub-products. It generates a realistic signal for the master clock, including its typical noises. It also simulates its distribution and the generation of clock sub-products from this master signal, using devices such as frequency multipliers, frequency dividers or transmission lines. Finally the resulting clock outputs taken from several nodes of the framework are displayed, both graphically and numerically. These outputs can be used for validating several design issues of Gaia, such as the synchronization lines of the payload, the timing and codification schemes, the time tagging accuracy of the CCD measurements, or the typical deviation between two daily calibrations. The parameters of the master clock and the framework devices, as well as the clock framework structure, are entered using XML files and can be graphically verified.

2. BASIC CONCEPTS

2.1. Specification and Analysis of Clock Signals

The main parameters used to characterise a clock signal are the following:

- Accuracy: The degree of conformity of a measured value to its definition or with respect to a reference.
- Frequency drift: The linear (first-order) component of a systematic change in frequency of an oscillator with time. Drift is due to ageing and to changes in the environment.
- Frequency offset: The frequency difference between the measured value and the nominal (predetermined) value.
- Precision: The degree of mutual agreement among a series of individual measurements.
- Resolution: The degree to which the measurement can be determined.
- Frequency stability: The statistical estimate of the frequency fluctuations of a signal within a given time interval.

The frequency stability cannot be measured by using the classical definition of standard deviation. Instead, a slightly different version of the standard deviation that basically behaves as a filter to many noise components is often used. This analysis tool, the so-called Allan variance (or Allan deviation), can be used to identify noise sources, types of oscillators, and noises of the measurement system. There are two versions of the Allan deviation, Equations 1 and 2 provide their general definition:

$$\sigma_{\mathrm{Std}}(\tau) = \sqrt{\frac{1}{2}\frac{1}{n}\sum_{n=0}^{N-1}\Delta^2\Phi_\tau^2(n)} \qquad (1)$$

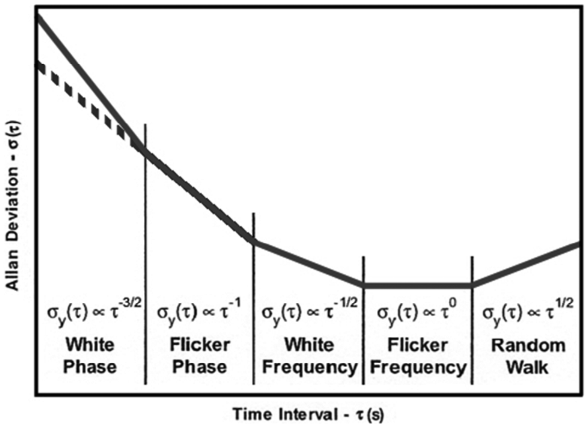

Figure 1. Standard and modified Allan deviations.

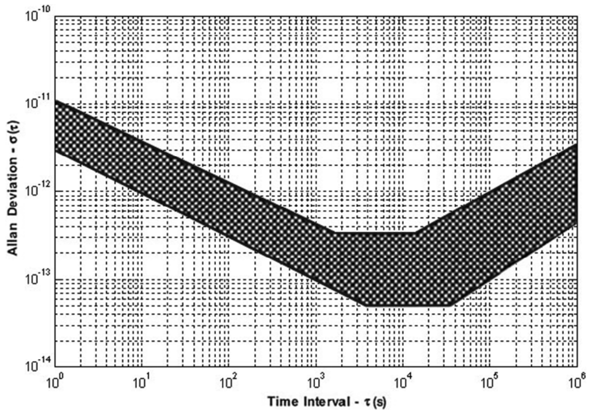

Figure 2. Typical Allan deviation profile of a Rb clock.

Table 1. Typical parameters for a Rb atomic clock.

Parameter	Value
Resonance frequency	6 834 682 608
Output frequency	1 to 15 MHz
Frequency stability	5×10^{-12} over 1 s
	5×10^{-12} over 100 s
	1×10^{-12} over 10 000 s
Frequency drift	1×10^{-13} per day
	3×10^{-11} per month
	5×10^{-10} per year
Ageing	3×10^{-10} per year

$$\sigma_{\mathrm{Mod}}(\tau) = \sqrt{\frac{1}{2}\frac{1}{n}\sum_{n=0}^{N-1} \Delta^2 \langle \Phi \rangle_\tau^2(n)} \qquad (2)$$

In these expressions τ is the measurement interval of the clock phase, $\Delta\Phi$ is the first finite difference of the phase, $\Delta^2\Phi$ is the second finite difference, $\Delta^2\langle\Phi\rangle$ is an average of the frequency stability and n is the number of samples averaged when computing the variance. As shown in Figure 1 the standard Allan variance (dashed line) cannot distinguish between white and flicker phase noise, whereas the modified version (solid line) results in a different slope for each one.

2.2. Rubidium Clocks

The use of a Rubidium (Rb) atomic clock as the spacecraft master clock of Gaia is currently envisaged. For a proper study of this master clock it is necessary to simulate the response of these types of oscillators with their typical noise sources and parameters. Table 1 (Castañeda 2004) lists the typical parameters of a Rb atomic clock, while Figure 2 illustrates its typical Allan variances.

2.3. Simulation of oscillators and clock devices

The output of any generic oscillator can be modelled using

$$V(t) = [V_0 + \epsilon(t)]\sin[\Phi(t)]$$
$$\Phi(t) = 2\pi(\nu_0 + \Delta\nu)t + \pi D\nu_0 t^2 + \phi(t) + \Phi_0$$

where V_0 is the nominal amplitude of the signal, $\epsilon(t)$ is the amplitude noise, $\Delta\nu$ represents the frequency offset of the actual clock from the nominal frequency, ν_0; D is the linear fractional frequency drift rate; $\phi(t)$ is the random phase deviation, modelling oscillator intrinsic phase noise sources, and Φ_0 is the initial phase offset. The basic noise components which contribute to $\phi(t)$ are:

- White phase, which is due to broadband noise from amplifier stages and components.
- Flicker phase, which is a consequence of noisy components.
- White frequency, which is often found when an oscillator is locked to a Ce or Rb standard.
- Flicker frequency, caused by the resonator noise, the active component noise, or both.
- Random walk, which is due to environmental factors such as mechanical shocks, vibrations and temperature fluctuations, which cause random shifts in frequency.

All these noises can be described by power-law noises ($S_\nu \sim \nu^\alpha$). For $\alpha \geq 1$ these noises present a power spectral density that cannot be integrated, thus implying an inherent non-stationary behaviour of the underlying process. Additionally, these noises have another important characteristic: their scale invariance, this is, the power law process is independent of the scale of observation. They can be simulated using the spectral shaping of white noise samples, which can be obtained with the Box-Muller method. This operation can be performed by algorithmic and digital signal processing techniques, such as the Voss-McCartney Algorithm or the Fractional Brownian Motion model.

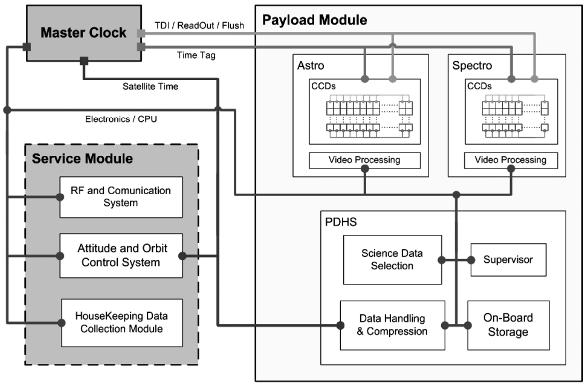

Figure 3. Overview of the clock distribution lines in the payload of Gaia.

Table 2. Main clock signals in the payload of Gaia.

Name	Frequency Range	Requirements
Electronics/CPU	6.4 to 100 MHz	Low
Satellite time	1 Hz	Medium
MC Ticks counter	6.4 MHz	Medium/high
CCD pixel flush	6.4 MHz	High
TDI and readout	50 kHz to 1 MHz	High
Time tags	500 MHz	Critical

3. OVERVIEW OF CLOCKS IN GAIA

In Gaia there will coexist several clock signals which are interrelated. However, all of them are derived from the spacecraft Master Clock. These clock signals control the operation of the instruments (Astro and Spectro), the data processing pipeline and several specific functions of the satellite. We focus on the Payload Data Handling System, and on the effects of non-ideal clock signals. Table 2 summarizes the most relevant clock signals to analyse and their approximate operating frequencies. Their distribution in the payload of Gaia is illustrated in Figure 3.

4. CLOCK FRAMEWORK SIMULATOR

We have developed a generic Clock Framework Simulator able to generate any master clock signal including power-law noises. Its distribution with transmission lines and distribution nodes is also simulated, as well as the generation of clock sub-products using frequency multipliers and dividers. All of these elements add noise to the signal and, additionally, will degrade it, so the final result is quite realistic.

The entire simulator is configured through a stand-alone XML file where we can define not only the structure of the clock framework but also the specific parameters of each device. The clock framework configuration can be validated and reviewed through a graphical interface of our application, a sample of which is included in Figure 4.

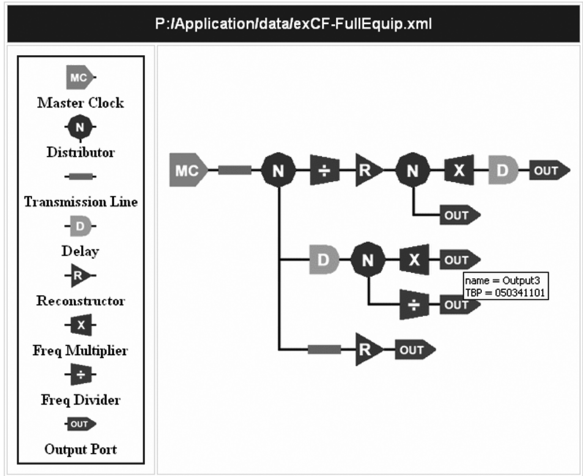

Figure 4. Example of a clock framework configuration as seen with our software tool.

The user can specify the format of the output file to be generated by the simulator, as well as different output nodes (each offering a different format if necessary). Time delays and waveforms can be directly verified with the `.stt` and `.ccl` formats, even directly feeding these data to other simulators. Figures 5 and 6 contain snapshots of the visualisation tools developed for their study. On the other hand, the simulator can directly offer the Allan deviations, offering an `.adv` file that can be plotted with any standard visualisation tool.

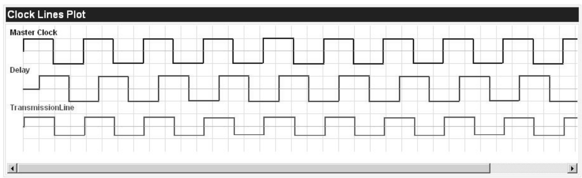

Figure 5. Signal visualisation tool included in our software application.

5. SIMULATION OF THE MASTER CLOCK OF GAIA

Our main objectives included the simulation of a realistic Gaia Master Clock, and the typical deviations at τ = 1 day, 1 second and 1 Astro TDI (736 μs). For this, we had to simulate long periods of time with our tool. The time required to obtain an Allan deviation point is proportional to the Master Clock frequency, so simulation times required to obtain the deviation after 1 day were prohibitively large (up to some years). Taking into account the scale-invariance property of power-law noises, a solution to this problem consists in simulating at lower MC

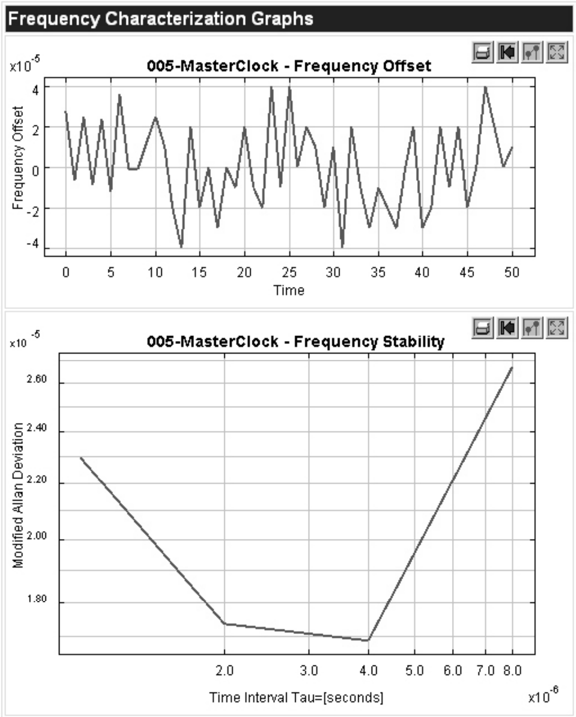

Figure 6. Statistical analysis tools included in our software application.

frequencies with equivalent noise sources (rescaling their effect). With this approach, we split the main simulation into much faster sub-simulations, each with an equivalent Master Clock at different frequencies and thus covering a given τ range. Overlapping their plots we obtain the final Master Clock characterisation shown in Figure 7 (Gordo et al. 2004). From this, we can obtain the desired typical deviations from the nominal frequency:

1. $\sigma = 2 \times 10^{-13}$ over 1 day (1.28 μHz deviated)
2. $\sigma = 6 \times 10^{-12}$ over 1 second (38.4 μHz deviated)
3. $\sigma = 3 \times 10^{-10}$ over 1 Astro TDI period, i.e., 736 μs (1.92 mHz deviated)

6. CONCLUSIONS

We have compiled the models that define a typical oscillator with its corresponding noises, focusing on the Rb atomic oscillator class. Their typical parameters, including the Allan deviation profile, have been identified. Several simulation techniques for generating noisy clock signals have been tested, selecting the best of them for each noise type. Finally, the most relevant clock signals and their possible distribution in Gaia have been identified.

Additionally, a versatile software application has been developed, which is easily configured with XML files. This software can simulate most of the typical clock

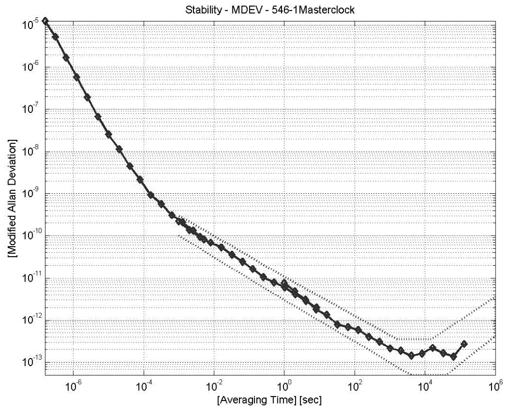

Figure 7. Allan Deviation of the Gaia Master Clock as obtained with our simulator.

frameworks, not only that of Gaia. Graphical user interfaces make possible the verification of the designed clock framework and its parameters. The simulation results, the format of which can be selected, can also be graphically analysed. As a first realistic test of this new simulation tool, the Master Clock of Gaia has been characterised, parameterised and its Allan deviation has been obtained. For this, we have determined the relation between the frequency scaling of the Master Clock and the scaling of its noises. At the end, a realistic Master Clock signal has been generated and the typical deviations after different integration times have been determined.

ACKNOWLEDGEMENTS

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REFERENCES

Castañeda, J., 2004, Clocks in Gaia: effects of a non-ideal generation and distribution of timing data, Master Thesis, UPC

Gordo, J.P., Portell, J., García–Berro, E., Luri, X., 2004, Gaia technical report GAIA-BCN-010, in preparation