TIME AND FREQUENCY TRANSFER WITH A MICROWAVE LINK IN THE ACES/PHARAO MISSION

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ABSTRACT. The Atomic Clocks Ensemble in Space (ACES/PHARAO mission), which will be installed on board the International Space Station (ISS), uses a dedicated two-way microwave link in order to compare the timescale generated on board with those provided by many ground stations disseminated on the Earth. Phase accuracy and stability of this long range link will have a key role in the success of the ACES/PHARAO experiment. SYRTE laboratory is heavily involved in the design and development of the data processing software: from theoretical modeling and numerical simulations to the development of a software prototype. Our team is working on a wide range of problems that need to be solved in order to achieve high accuracy in (almost) real time. In this article we present some key aspects of the measurement, as well as current status of the software's development.

1. THE ACES-PHARAO MISSION

The ACES/PHARAO mission is an international cooperation of more than 150 people, PI laboratories being SYRTE at Paris Observatory, LKB at ENS, Neuchâtel Observatory, and leading space agencies are the European Space Agency and CNES, the French space agency. Many industries are involved, the main ones being EADS/Astrium, TimeTech and Thales. The payload will be installed on board ISS and will realize in space a timescale of very high stability and accuracy. To reach this goal, the ACES payload includes a cesium atomic clock (PHARAO), an active hydrogen maser (SHM), a GNSS receiver for precise orbit determination, a Frequency Comparison and Distribution Package (FCDP) for local comparison of the on board clocks and generation of the on board timescale. This timescale will be compared to a ground clock network thanks to a dedicated two-way microwave link, using both code-phase and carrier-phase measurement. The main scientific objectives of the mission are 1. to demonstrate the high performance of the atomic clocks ensemble in the space environment and the ability to achieve high stability on space-ground time and frequency transfer, 2. to compare ground clocks at high resolution on a world-wide basis using a link in the microwave domain where the link stability should reach around 0.3 ps after 300 seconds of integration in common view mode and 3. to perform equivalence principle tests. It will be possible to test Local Lorentz Invariance and Local Position Invariance to unprecedent accuracy by doing three types of tests: a test of gravitational red-shift, drift of the fine structure constant and of anisotropy of light.

2. THE MICROWAVE LINK

The MicroWave Link (MWL) will be used for space-ground time and frequency transfer. A time transfer is the ability to synchronize distant clocks, *i.e.* determine the difference of their displayed time for a given coordinate time. The choice of time coordinate defines the notion of simultaneity, which is only conventional. A frequency transfer is the ability to syntonize distant clocks, *i.e.* determine the difference of clock frequencies for a given coordinate time. Here we suppose that all clocks are perfect, their displayed time is exactly their proper time. Proper time τ is given in a metric theory of gravity by the relation

$$c^2 d\tau^2 = -g_{\alpha\beta} dx^\alpha dx^\beta \,, \tag{1}$$

where $g_{\alpha\beta}$ are the components of the metric tensor, c the velocity of light in vacuum, $\{x^\alpha\}$ the coordinates, Einstein summation rule being used.

MWL is composed of three signals of different frequencies: one uplink at frequency $f_1 \simeq 13.5$ GHz, and two downlinks at $f_2 \simeq 14.7$ GHz and $f_3 = 2.2$ GHz. Measurements are done on the carrier itself and on a code which modulates the carrier. The link is asynchronous: a configuration can be chosen by interpolating observables, the so-called Λ-configuration, which minimizes the impact of the space clock orbit error on the determination of the desynchronisation (Duchayne et al., 2009). We define the SYRTE Team (ST) observables by $\Delta\tau = \tau_e - \tau_r$ with τ_e the proper time of emission of the signal and τ_r the proper time of reception. It can be linked to desynchronisation by

$$\tau^s(t_2) - \tau^g(t_2) = \frac{1}{2}\left(\Delta\tau^g_{\mathrm{mo}}(\tau^g(t^0_4)) - \Delta\tau^s_{\mathrm{mo}}(\tau^s(t^0_2)) + [T_{34} - T_{12}]^g\right) , \tag{2}$$

where t is coordinate time, $\Delta\tau_{\mathrm{mo}}$ are the ST observables corrected for the delays in the cable between the clock and the antenna at transmission and at reception, $T_{ij} = t_j - t_i$, $[.]^g$ being the transformation from the coordinate time to the ground clock proper time obtained from Eq. (1). T_{34} and T_{12} are the coordinate time of flight and can be calculated from the known orbits of the clocks, accounting for the tropospheric, ionospheric and Shapiro delays. The observables from the two downlinks can be used to determine the Total Electronic Content (TEC) of the atmosphere along the line-of-sight, in order to correct for the ionospheric delay. The two-way configuration cancels the tropospheric delay, which does not depend on the signal frequency at this level of accuracy. The basic observables of the modem developed by TimeTech (TT observables) are different from the ST observables. At the emitter and the receiver are generated a PPS signal (one Pulse Per Second), a 12.5 PPS (one pulse every 80 ms, the period of measurements), and a periodic signal (either code at 100 MHz or carrier). When received, the periodic signal is mixed with a local oscillator signal not far from the received frequency, and filtered to obtain the low frequency part of the beatnote. The beatnote frequency is around 195 kHz for code and 729 kHz for carrier. The receiver modem records the time of the first ascending zero-phase of the beatnote signal after the 12.5 PPS signal, and it counts the number of ascending zero-phase during one 80 ms sequence. The link between the TT and ST observables is detailed in Delva et al. 2012.

3. DATA ANALYSIS AND SIMULATION

The SYRTE team is developing an independent data analysis software to be able to perform a pre-processing of the raw data and a complete scientific analysis. This software is written in Python language. In order to test it, we wrote also a simulation that generates (noisy) TT observables, as well as theoretical ST observables. This simulation is written in Matlab language, and is as much as possible independent from the data analysis software. Current status of our implementation includes several effects as

- ISS orbitography + ground stations coordinates in ITRF, with transformation into ICRF,
- Clock modeling for ISS & ground stations, with basic noise simulation,
- Time transfer modeling between the two terminals,
- Generation of TimeTech observables, together with theoretical values against which calculated values will be compared.

Current work concerns the modeling of multipath effect and the attitude of ISS and of the ACES-payload. For the multipath, we use a simplified model where the emitted signal finds two paths to reach the receiver : one path goes in straight line from the emitter to receiver, the other one is reflected once somewhere on the path. This second path is heavily attenuated and is considered to be a perturbation of the main signal. We only consider the code signal (as opposed to carrier). For the attitude problem, we are currently implementing some new Python classes linking the attitude of ACES-payload with ITRF.

4. REFERENCES

Duchayne, L., Mercier, F., Wolf, P., 2009, "Orbit determination for next generation space clocks", A&A, 504, pp. 653–661.

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