# ACES Micro-wave Link data analysis status update

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## Overview

The Atomic Clocks Ensemble in Space (ACES-PHARAO mission [4]), which will be installed on board the International Space Station in 2016, will **realize in space a time scale of very high stability and accuracy**. This time scale will be compared to a ground clock network thanks to a **dedicated two-way MicroWave Link (MWL)**. For that purpose **our team is developping advanced time and frequency transfer algorithms**.

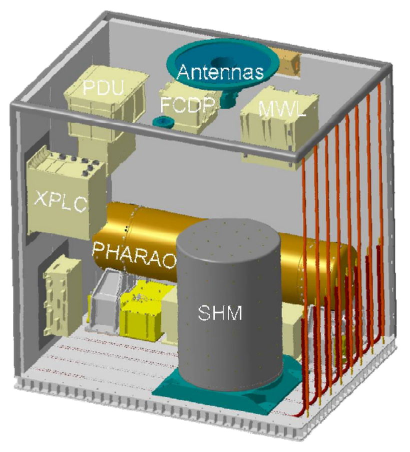
The altitude difference between the ACES-PHARAO clock and ground clocks will allow to measure the **gravitational redshift** with unprecedent accuracy, as well as looking for a **violation of Lorentz local invariance**. Several ground clocks based on different atomic transitions will be compared to look for a **drift of fundamental constants**. Moreover, the mission will pave the way to a new type of geodetic measurement: the gravitational redshift will be used to measure gravitational potential differences between distant clocks, with an accuracy around 10 cm.

## The ACES mission and its microwave link

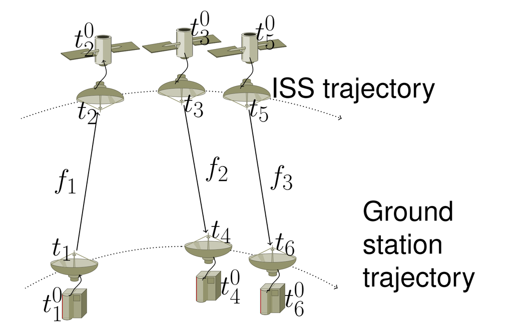
The ACES payload includes :

- 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 onboard timescale
- a MicroWave Link (MWL) using both code-phase and carrier-phase measurement.

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.




*The ACES payload*




*The MicroWave Link (MWL): one uplink (Ku-Band) and two downlinks (Ku and S-Band). MWL hardware developed by TimeTech GmbH.*

## Expected performances

The **projected stability of the atomic clocks of ACES** can be expressed in term of Allan deviation (fig.A). The performance of the MicroWave Link can be compared in terms of time deviation (Fig.B). Quantitatively, expected performances are:

- Relative frequency stability (ADEV) should be better than $\sigma_y = 10^{-13} \cdot \tau^{-1/2}$, which corresponds to $3 \cdot 10^{-16}$ after one day of integration (see fig.A)
- time deviation (TDEV) should be better than $2.1 \cdot 10^{-14} \cdot \tau^{1/2}$, which corresponds to 12 ps after one day of integration (see fig.B)
- Absolute frequency accuracy should be around $10^{-16}$

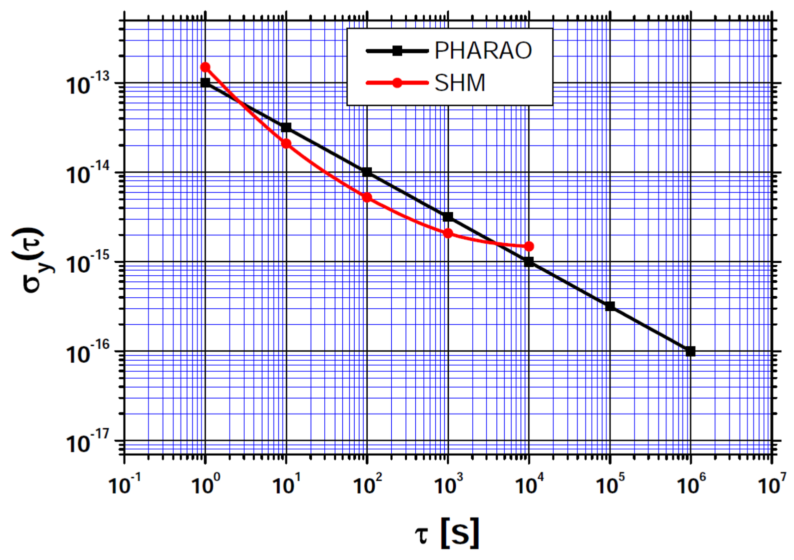



*fig.A: PHARAO (Cesium clock) and SHM (hydrogen maser) expected performances in Allan deviation.*

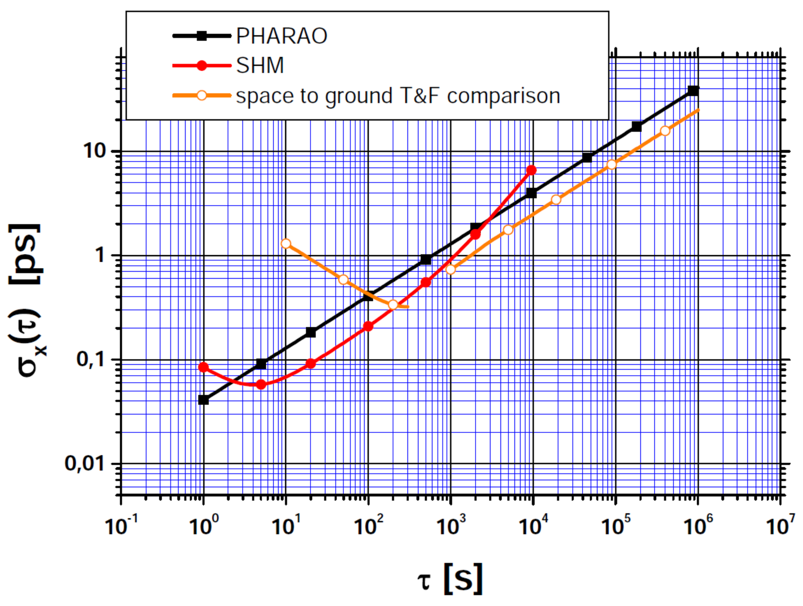



*fig.B: Performance objective of the ACES clocks and the ACES space-ground time and frequency transfer expressed in time deviation.*

## Two-way Measurement principle

The MicroWave Link 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 **$\Lambda$-configuration minimizes the impact of the space clock orbit error** on the determination of the desynchronisation [3].

We sketch on fig.C the space-time diagram of the two signals at $f_1$ and $f_2$ in a $\Lambda$-configuration. We define the **observables used by the Syrte Team (ST observables) by $\Delta\tau(\tau_e) = \tau_e - \tau_r$, where $\tau_e$ is the local time of emission of the signal and $\tau_r$ the local time of reception**. It can be linked to **desynchronisation**:

$$\text{desynchronisation } (t_2) \equiv \tau^s(t_2) - \tau^g(t_2) = \frac{1}{2}\left(\Delta\tau^g_{\text{mo}}(\tau^g(t_4^0)) - \Delta\tau^s_{\text{mo}}(\tau^s(t_2^0)) + [T_{34} - T_{12}]^g\right) \tag{1}$$

where $t$ is coordinate time, $\Delta\tau_{\text{mo}}$ are the ST observables corrected for the delays in the cable between the clock and the antenna at transmission and at reception, $s$ and $g$ stand for *space* and *ground* respectively, $T_{ij} = t_j - t_i$ and $[.]^g$ is the coordinate time to the ground clock proper time transformation.

The **time-of-flights** $T_{34}$ and $T_{12}$ 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.

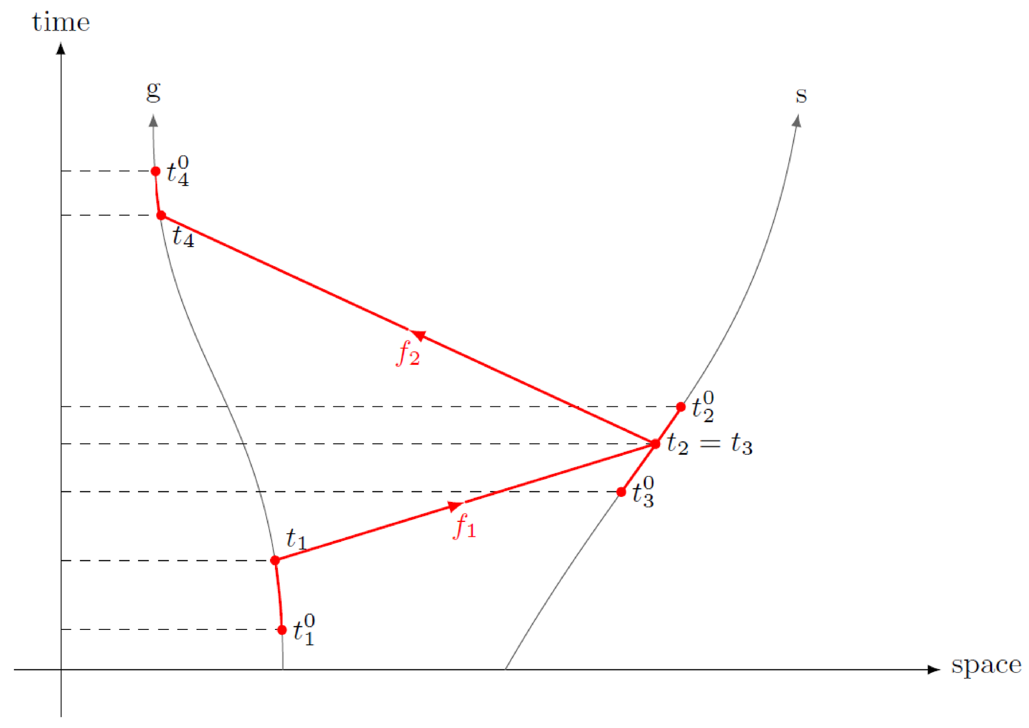


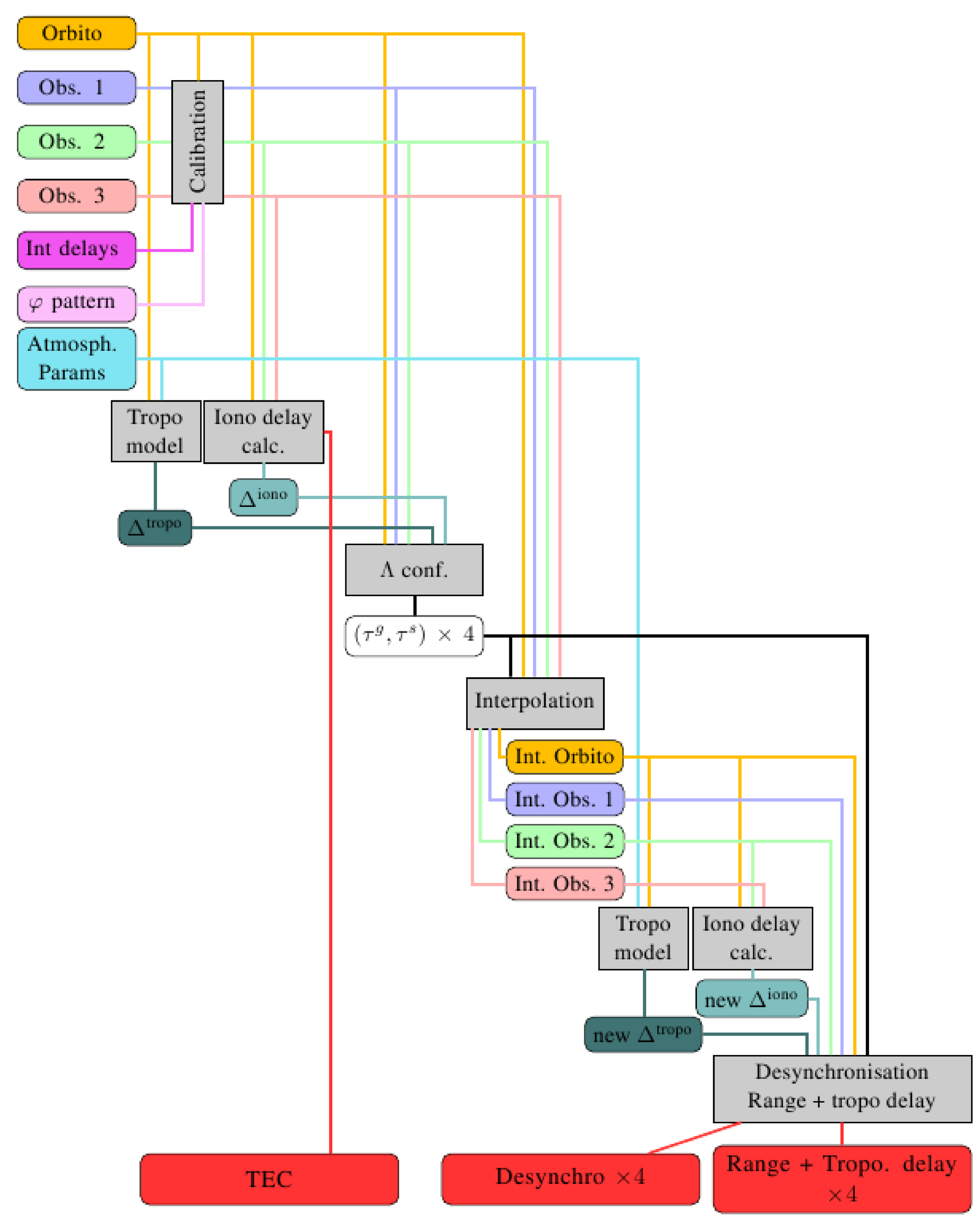

*fig.C: Signal $f_1$ is generated at coordinate time $t_1^0$, is emitted by the ground antenna at time $t_1$, received by the space antenna at $t_2$ and arrives at the receiver modem at $t_2^0$. For signal $f_2$ the sequence is $(t_3^0, t_3, t_4, t_4^0)$. The $\Lambda$-configuration interpolation is such that $t_2 = t_3$.*

## Data processing software

Our team is currently developping a **prototype of the data processing software**. It will be used :

- as a guideline for Astrium who will implement the industrial-grade data processing in the ACES ground segment
- by our team, to achieve the highest possible accuracy in post-processing.

The core algorithm has been largely inspired by Loïc Duchayne's PhD thesis [2].

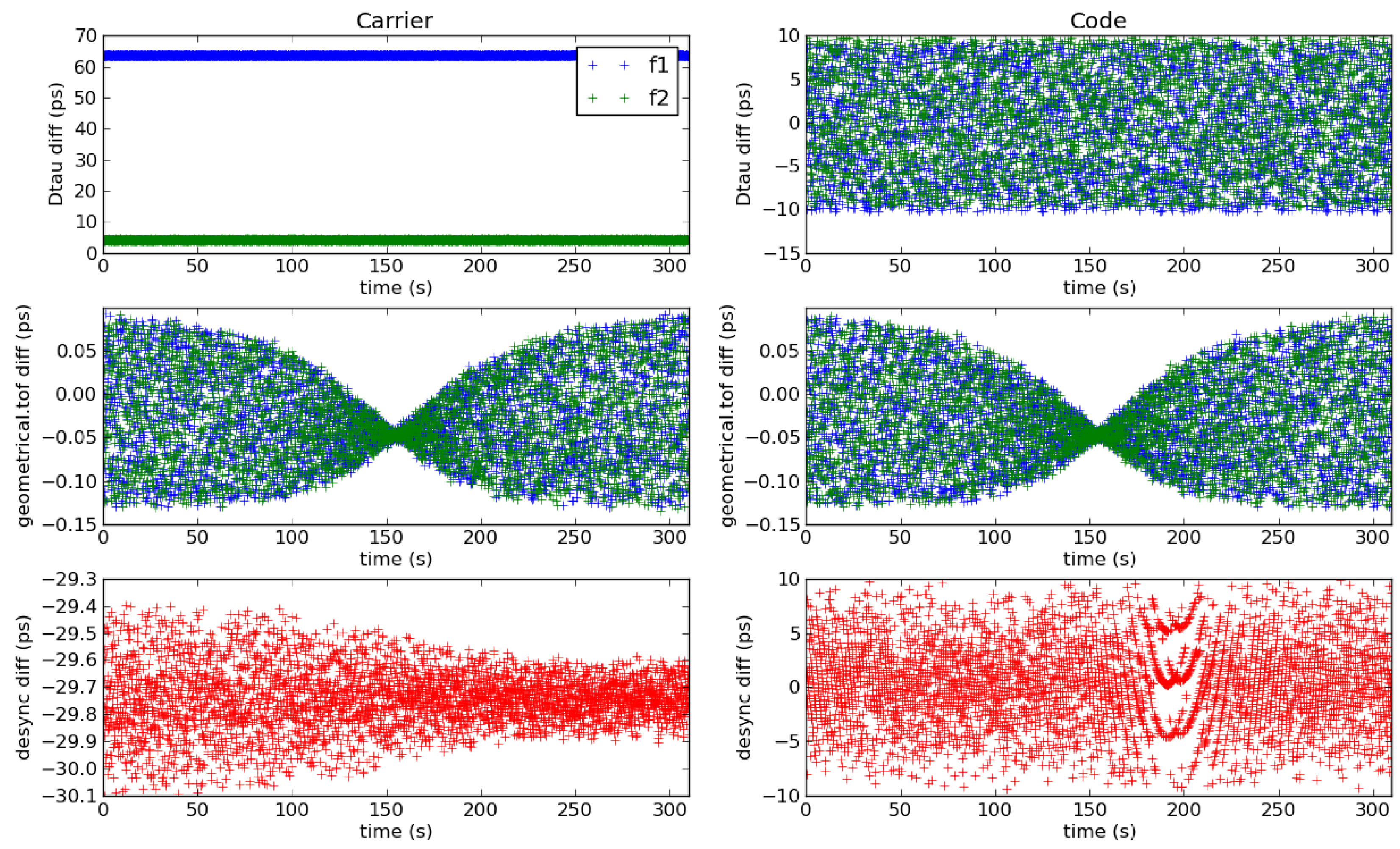



*Right: overall flowchart of the data processing software. Inputs are in the top-left corner and scientific products are at the bottom (red squares).*

## Simulation and analysis: First results

The basic observables of the modem developed by TimeTech (TT observables) are different from the observables used by the Syrte Team (ST observables). The link between TT and ST observables is detailed in [1]. In order to test the data processing software, **we wrote a simulation that generates TT observables as well as ST observables**. The simulation is as much as possible independent from the data processing software.

Here we plot the **differences between simulated input quantities and quantities recovered by the data analysis software** for: the ST observables recovered from the TT observables (Dtau diff), the time-of-flights and the desynchronisation, which is the final scientific product (see eq.(1)). Atmospheric delays and the lambda configuration are not yet implemented.




## References

[1] P. Delva et al. "Time and frequency transfer with a microwave link in the ACES/PHARAO mission". In: *Proceedings of the EFTF*. 2012. eprint: `1206.6239`.
[2] L. Duchayne. "Transfert de temps de haute performance : le lien micro-onde de la mission ACES". PhD thesis. Observatoire de Paris, 2008.
[3] L. Duchayne, F. Mercier, and P. Wolf. "Orbit determination for next generation space clocks". In: *A&A* 504 (2009), pp. 653–661.
[4] C. Salomon, L. Cacciapuoti, and N. Dimarcq. "Atomic Clock Ensemble in Space:. An Update". In: *International Journal of Modern Physics D* 16 (2007), pp. 2511–2523.