

TIME AND FREQUENCY TRANSFER WITH THE ESA/CNES ACES/PHARAO MISSION



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Joint Discussion 7 - Reference Frames
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An international metrological space mission

- A time scale in space of **high stability...**

- better than $\sigma_y = 10^{-13} \cdot \tau^{-1/2}$ (in frequency)
- better than $\sigma_x = 2.1 \cdot 10^{-14} \cdot \tau^{+1/2}$ (in time)

- ...and **accuracy** $\sim 10^{-16}$

- **International cooperation** of more than 150 people

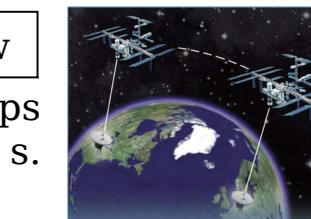
- PI: LKB/ENS, Neuchâtel Obs., SYRTE/Paris Obs.
- Space agencies: ESA, CNES
- Industrial: EADS/Astrium, EADS/Sodern, TimeTech, ...

- Main **scientific objectives**

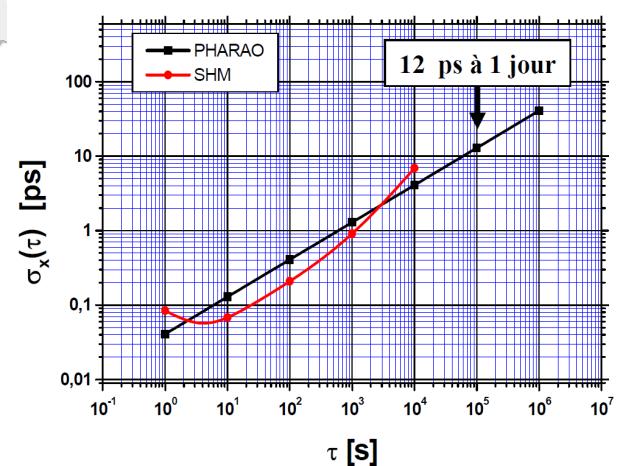
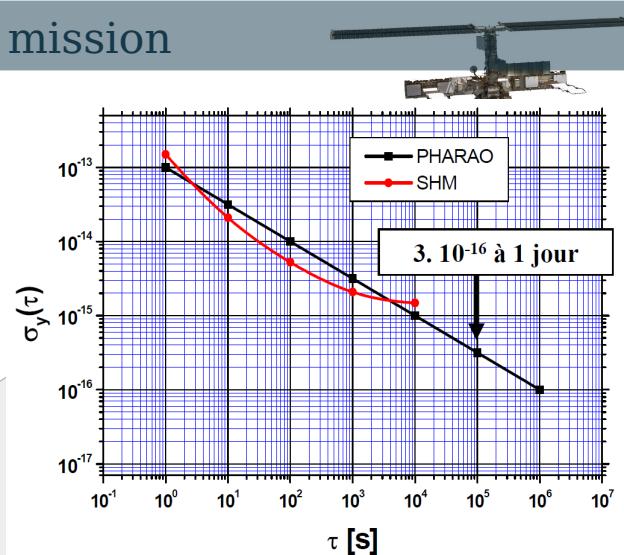
- Atomic clock and microwave link performances in a space environment
- Distant clock comparisons
- Equivalence principle tests
- Relativistic geodesy



Common view
Stability ~ 0.3 ps
 $\text{@ } 300\text{ s.}$



Non common
view
Stability ~ 7 ps
 $\text{@ } 1\text{ day}$





- What is a time transfer ? Compare distant clocks to determine their **desynchronisation**

- The MWL :

- **Three signals** of different frequency (1 up, 2 down)
- One signal = carrier + code
- Asynchronous link → choice of the configuration by interpolating

- **ST** (Syrte Team) observables (six):

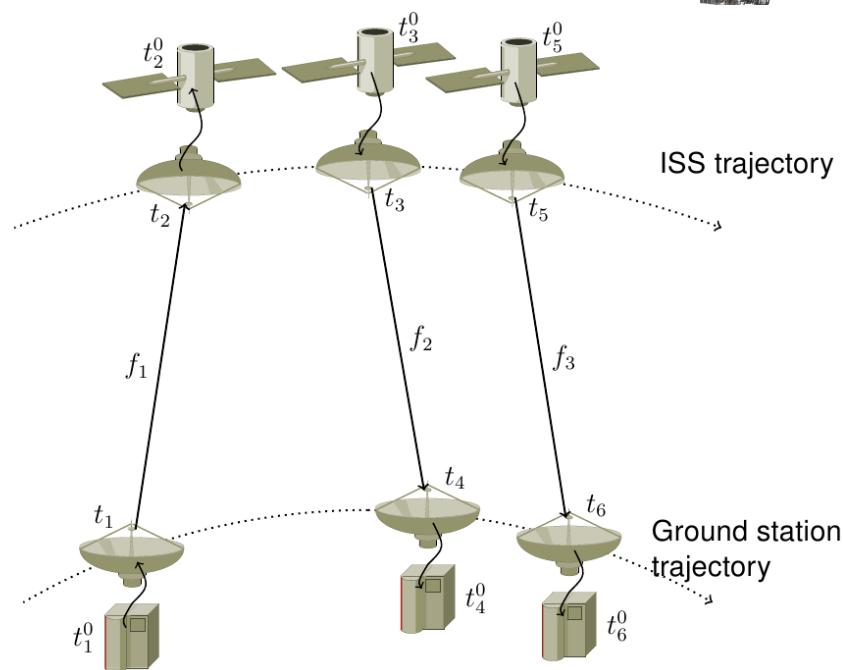
- Time difference between the locally generated code/carrier and the received one

$$\tau^s(t_2^0) - \tau^g(t_2^0) = -\Delta\tau^s - [T_{12} + [\Delta_{Tx} + \Delta_{Rx}]^t]^g$$

Desynchronization

ST observable

Time of flight (from orbitography)



$$f_1 \simeq 13.5 \text{ GHz}$$

$$f_2 \simeq 14.7 \text{ GHz}$$

$$f_3 = 2.24 \text{ GHz}$$



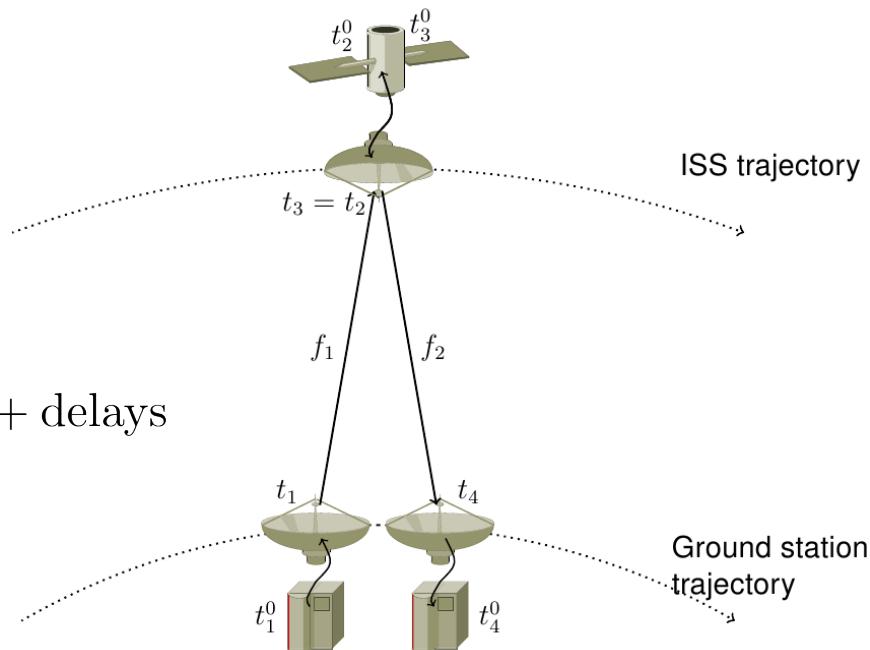
- **Lambda configuration :**

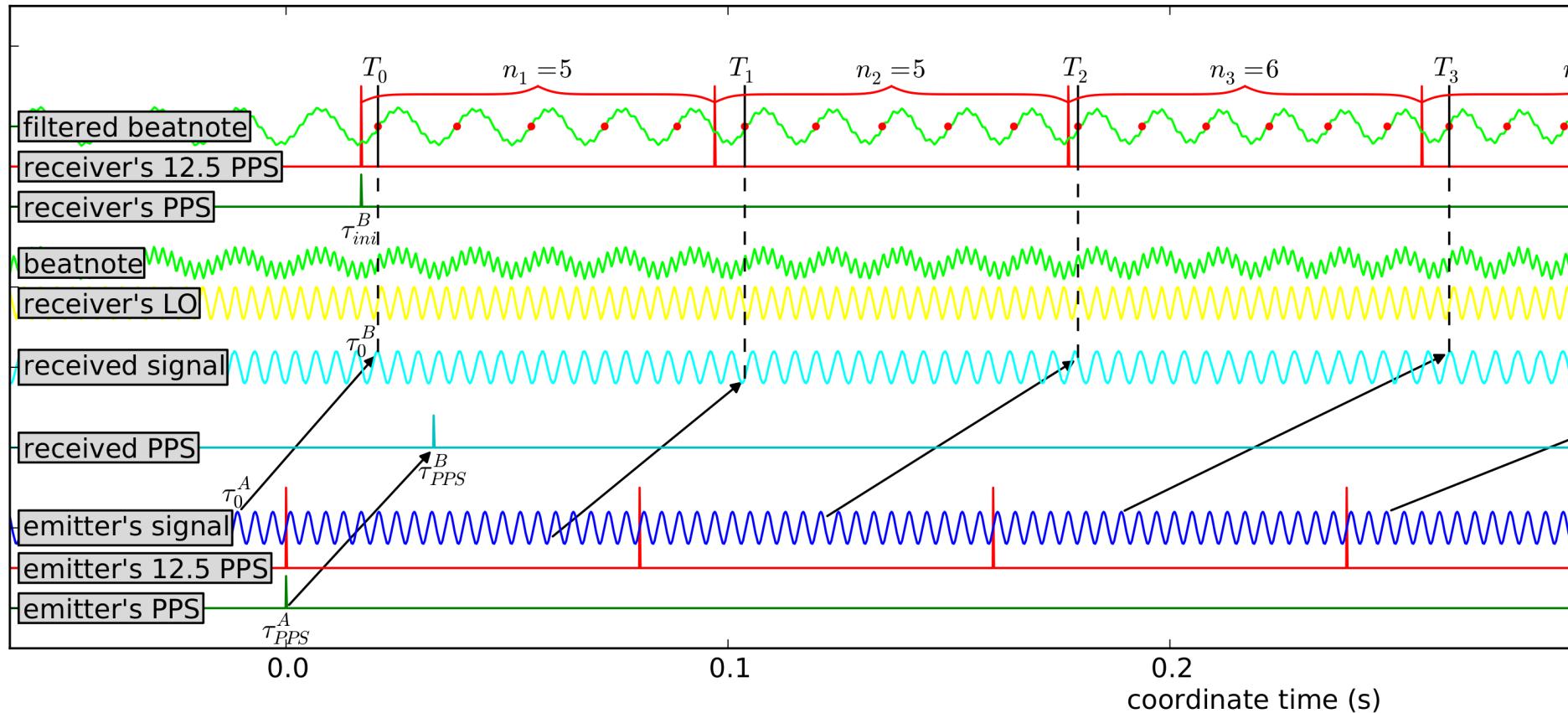
- Interpolate data so that $t_2 = t_3$
- Minimize error due to ISS orbitography (Duchayne et al., A&A 504(2), 2009)
- Different than the 2-way configuration

$$\tau^s(t_2) - \tau^g(t_2) = \frac{1}{2} (\Delta\tau^g - \Delta\tau^s + [T_{34} - T_{12}]^g) + \text{delays}$$

- **Atmospheric electronic content**

- Ionospheric delay depends on signal frequency and STEC
- Data from downlinks → STEC





ST observables : time difference between the locally generated code/carrier and the received one (in receiver time)

$$\Delta\tau_m^B(T_m) = \Delta\tau_{m-1}^B(T_{m-1}) \pm \frac{n_m}{f_{\text{emi}}} + \left(\frac{f_{\text{L.O.}}}{f_{\text{emi}}} - 1 \right) (T_m - T_{m-1})$$



- **Relative accuracy** of ST observables during one passage
(for frequency transfer) :

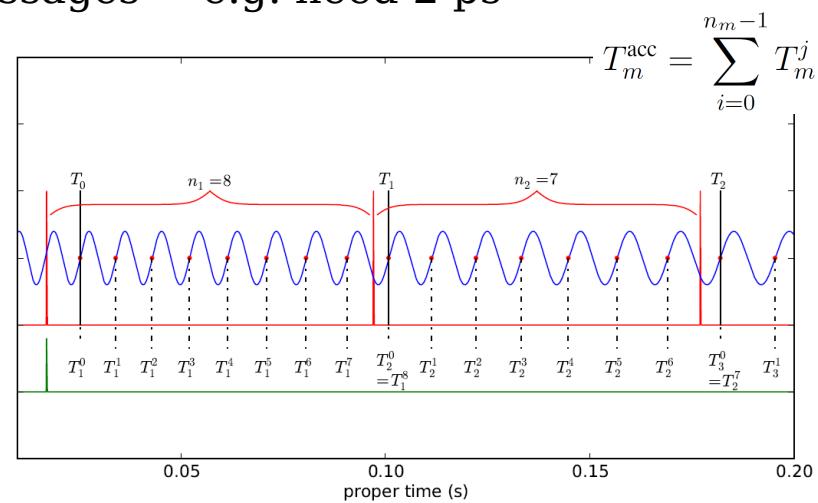
$$\delta(\Delta\tau_m) = \left| \frac{f_{\text{L.O.}}}{f_{\text{emi}}} - 1 \right| \cdot \delta T_m$$

$\sim 10 \text{ ns}$

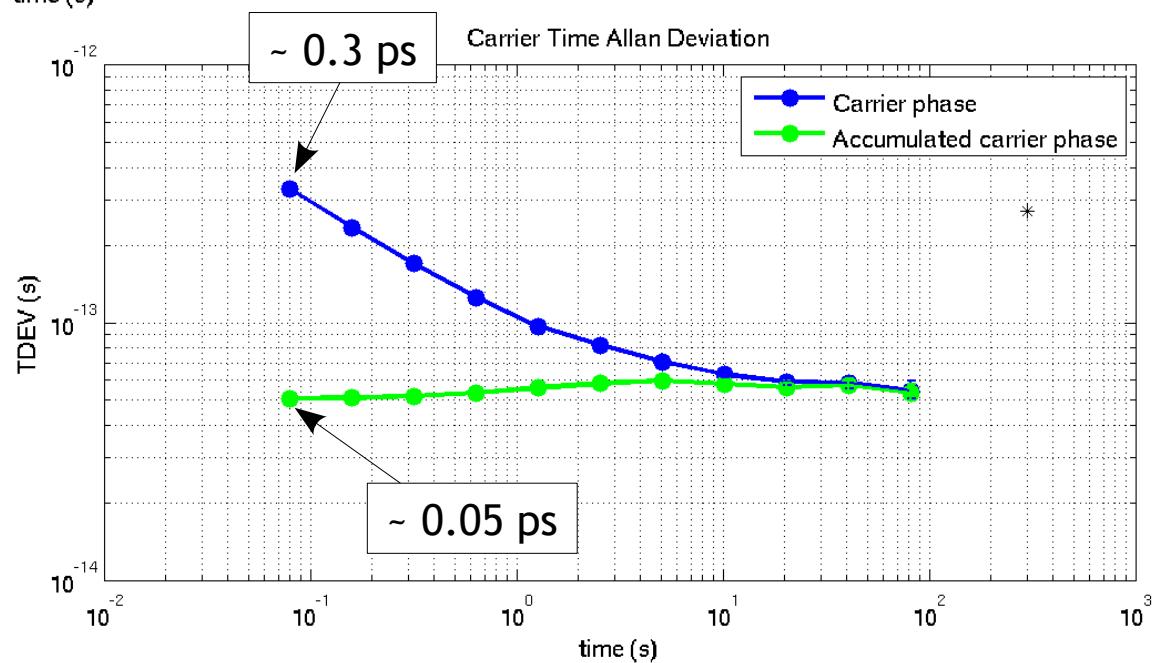
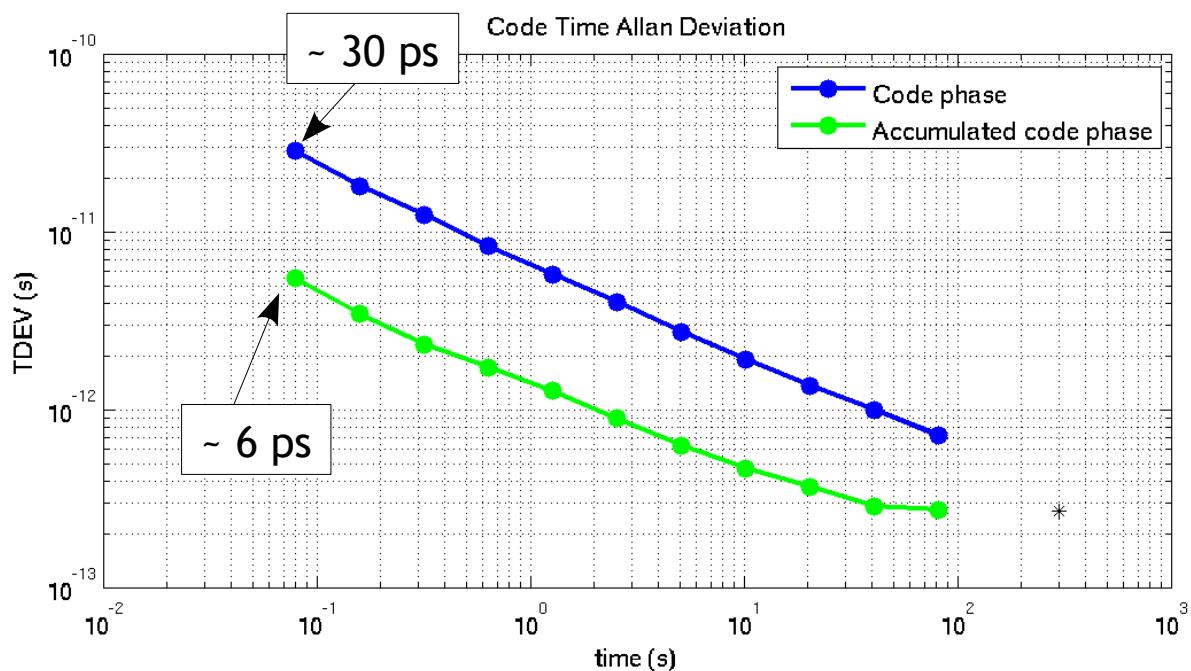
$\frac{195 \text{ kHz}}{100 \text{ MHz}} \cdot 10 \text{ ns} \sim 20 \text{ ps (code)}$
 $\frac{729 \text{ kHz}}{13.5 \text{ GHz}} \cdot 10 \text{ ns} \sim 0.5 \text{ ps (carrier)}$

- **Initial term determination** ($\Delta\tau_0$)

- From PPS which is unambiguously linked to UTC
- PPS and code are synchronised → precise PPS determination
- Absolute accuracy on $\Delta\tau_0$ (for time transfer) : 20 ps
- Problem : bridge the gap between two passages → e.g. need 2 ps for a gap of one orbital period
- Solutions :
 - accumulated phase latch ?
 - Carrier phase → phase ambiguity...



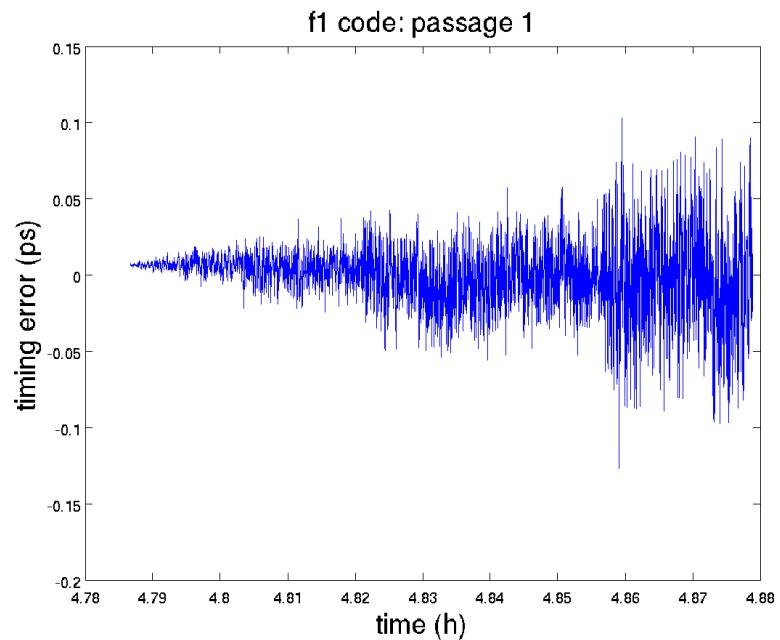
Pre-processing and link performance (2/2)



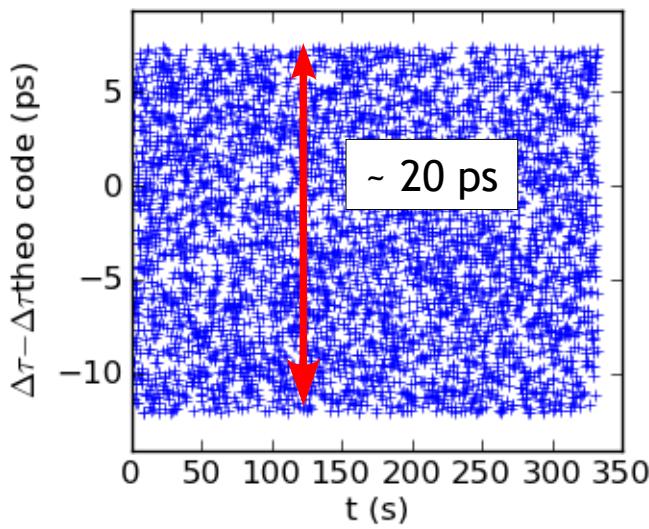
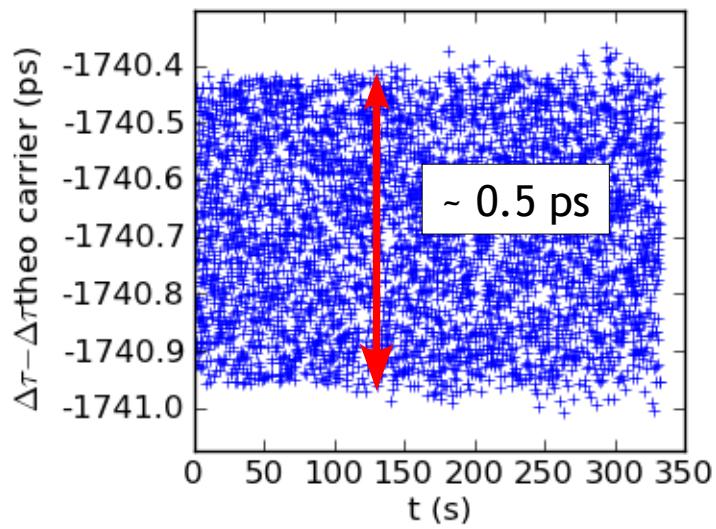
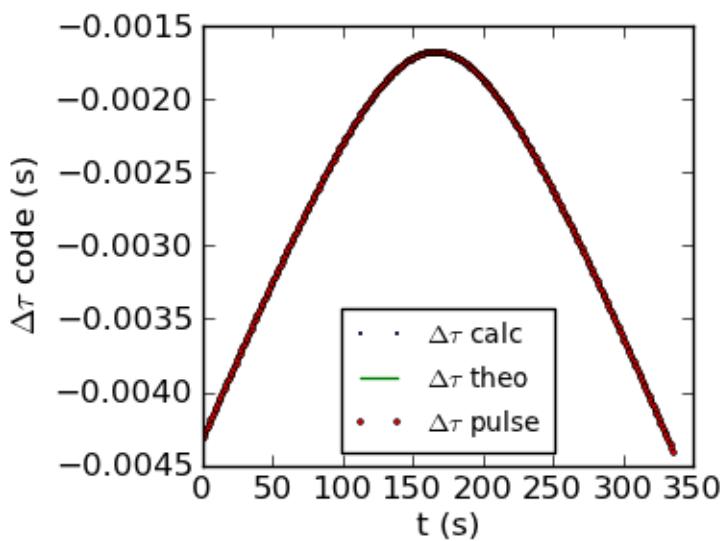
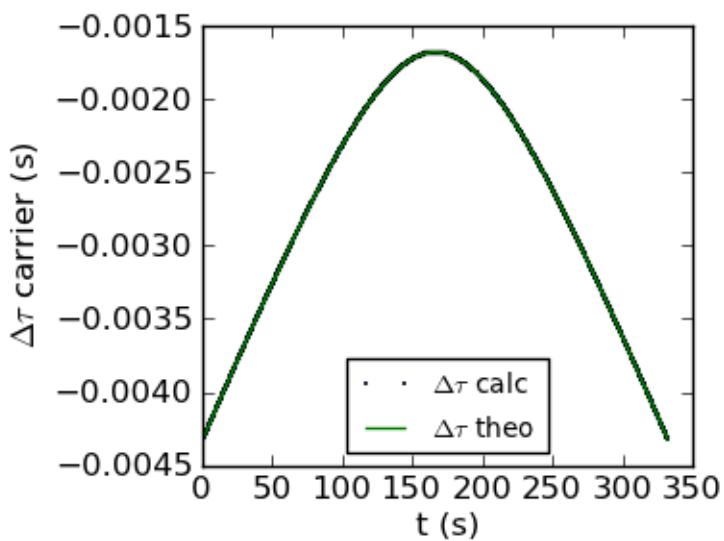


- ISS orbitography + station coordinates in Terrestrial Reference Frame
→ transform to Celestial Reference Frame (inertial)
- clock modelization for ISS & GS (e.g. noise)
- Solve time transfer between the two terminals
- Generate TimeTech observables & theoretical values

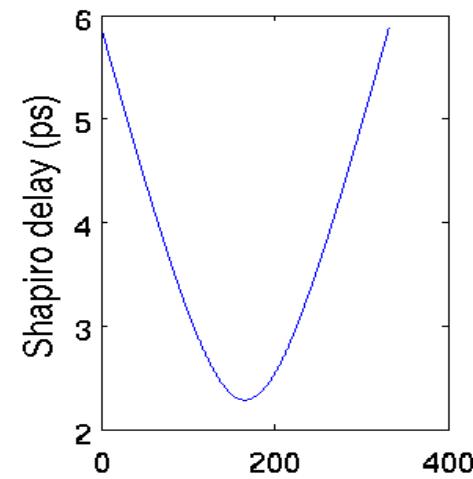
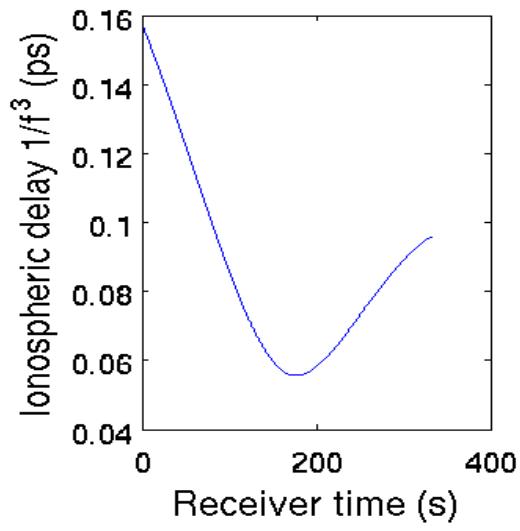
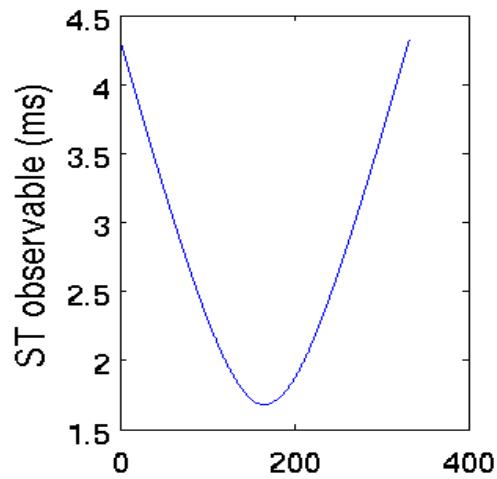
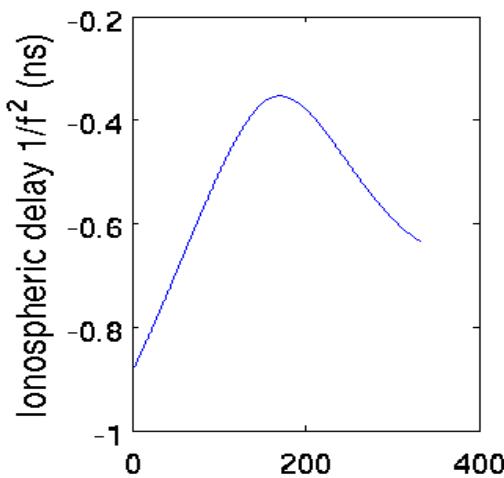
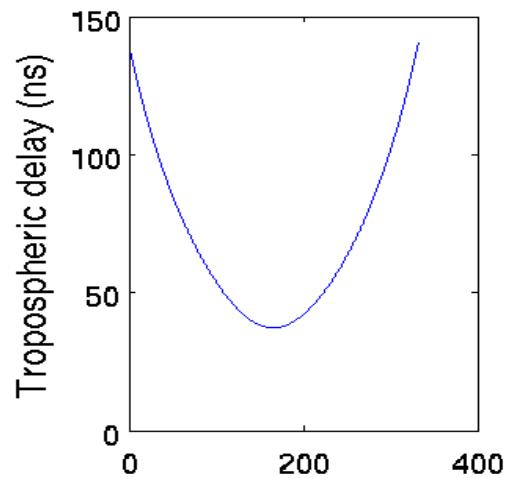
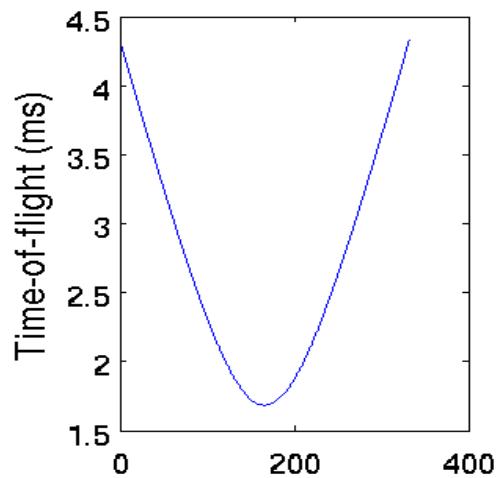
ST observables reconstructed after pre-processing of TimeTech data minus theoretical ST observables : residuals are due to cumulated numerical sampling errors



Independant pre-processing

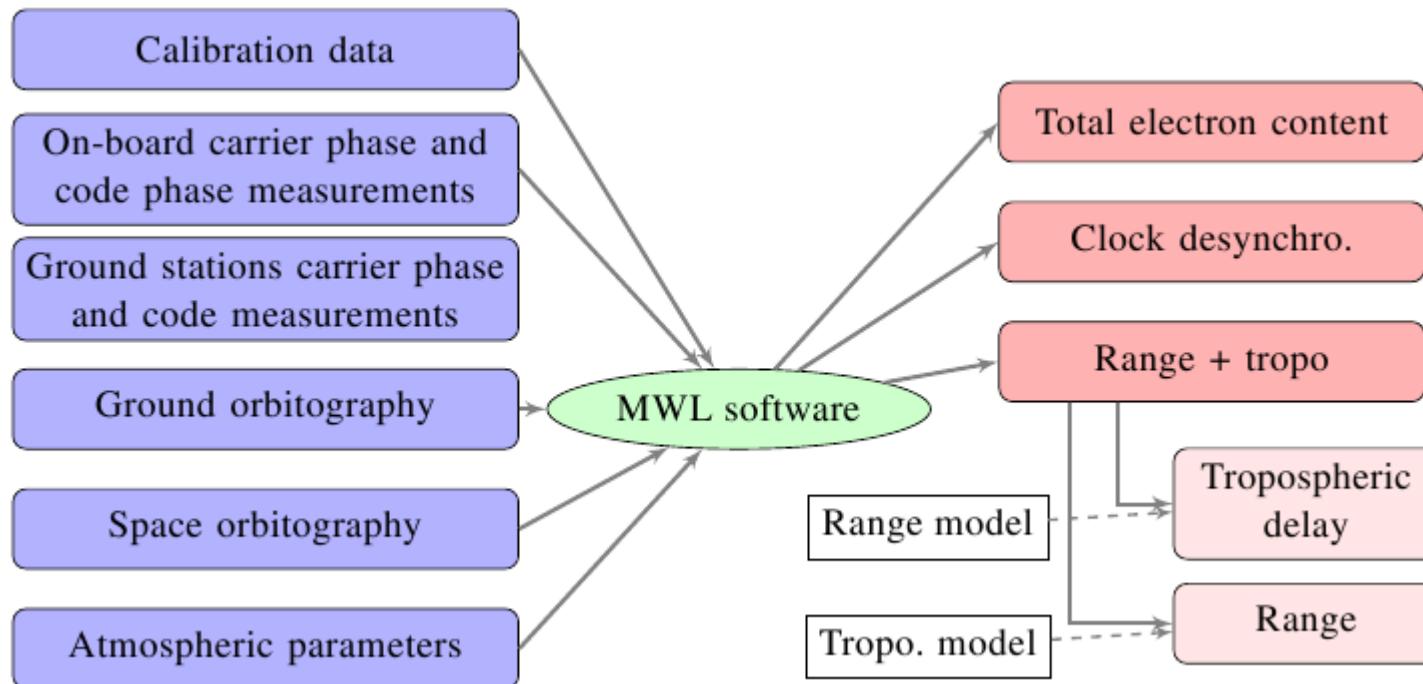


Time transfer model

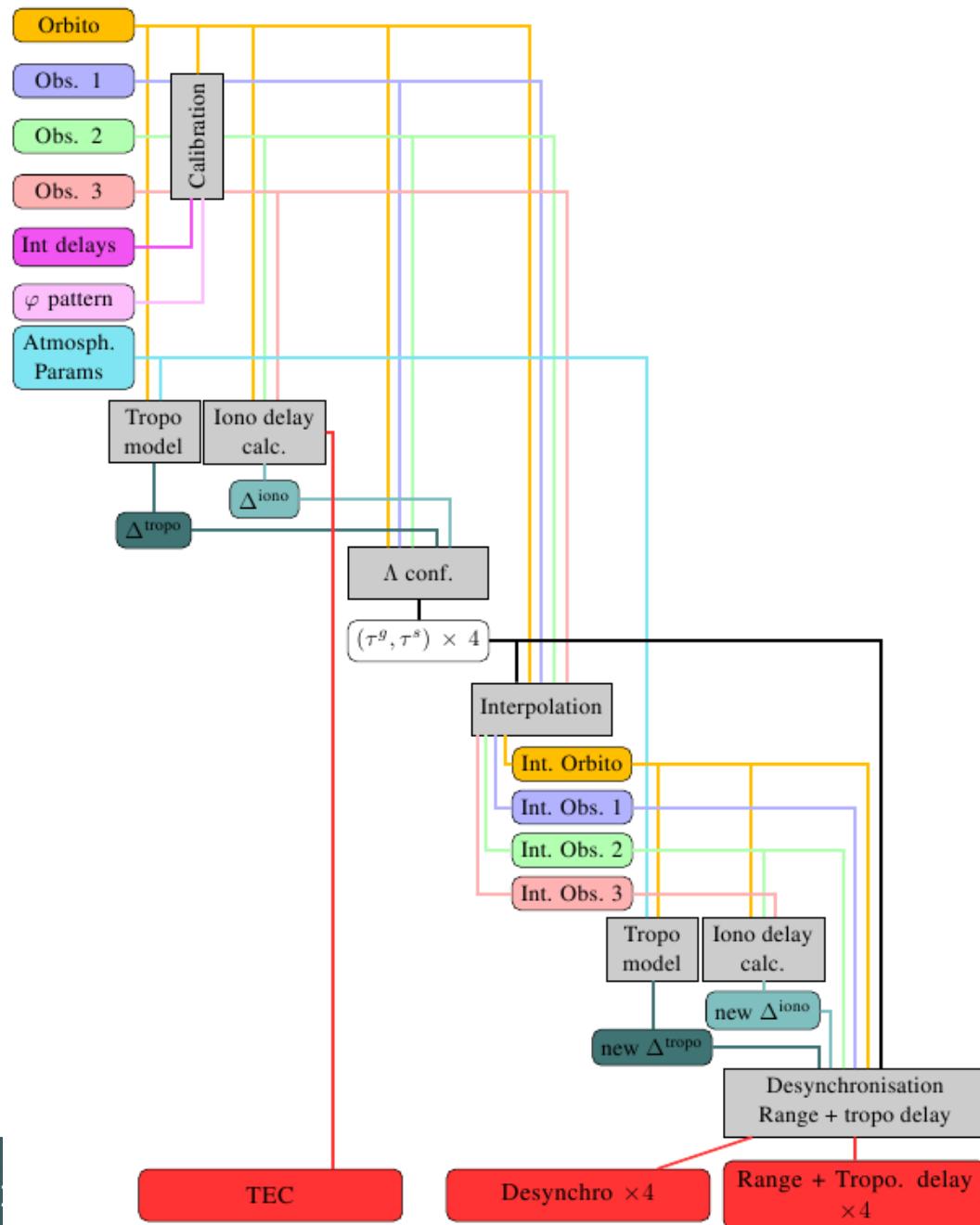




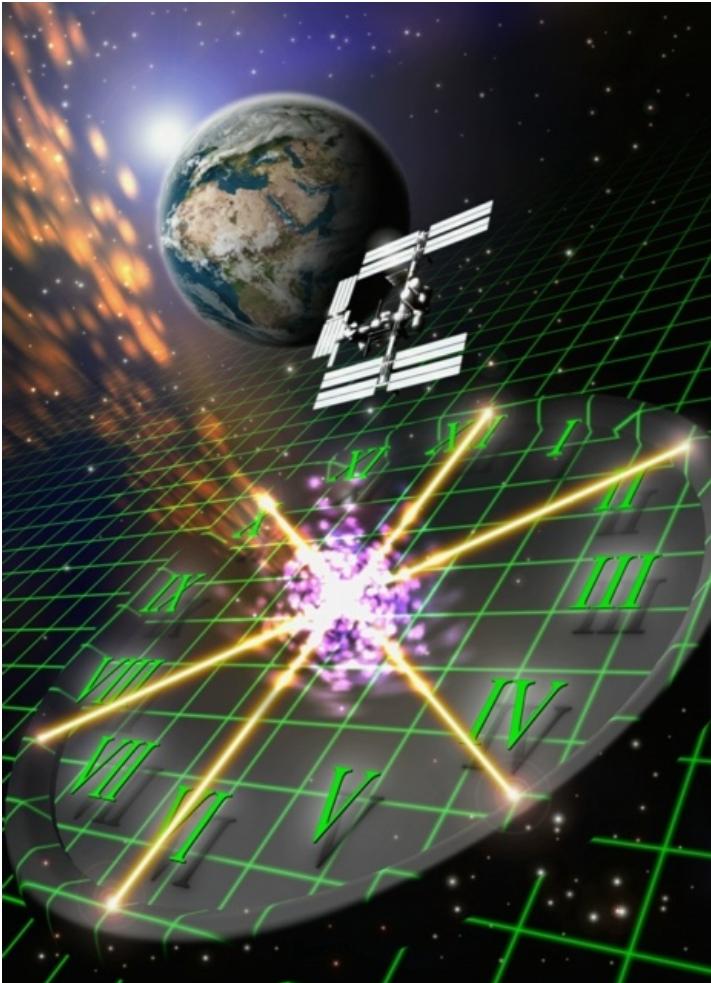
- Data analysis : file naming, data classifying, file formats, conventions...
- Inputs and outputs :



Software design



Conclusion



- ACES/PHARAO is a key mission for fundamental physics in space
- Independent Data analysis centers are very important for a complete understanding and cross-checking of observables
- Progress :
 - Link between TimeTech observables and Syrte Team observables understood
 - Simulation to generate TimeTech observables and theoretical observables
 - Software for pre-processing of data finished and tested
 - Data analysis software : design done, writing and testing in progress
- MWL end to end test in progress (TimeTech)

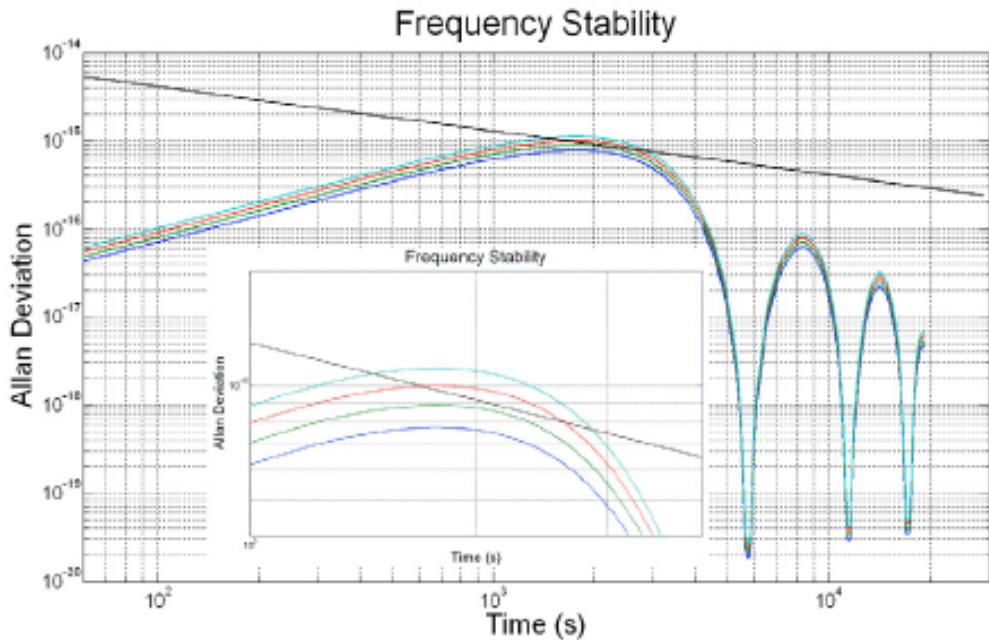


Fig. 7. Modified Allan deviations of the redshift error for $X = 14, 16, 18, 20$ m.

Duchayne et al., A&A 504 (2009)

- « Naive » estimate give 1m for 10^{-16} relative accuracy
- Relativistic frequency shift : grav. Redshift + 2nd order Doppler effect → errors partly cancel
- Hill and white noise model give :
 - 8 m for radial errors
 - 16 m for tangential errors
 - 1,4 km for normal errors
 - Plus constraints on the Lambda configuration and calibration delays