# ACES-PHARAO and its two-way Microwave Link

Frédéric Meynadier (BIPM, formerly SYRTE – Observatoire de Paris)

IAG Joint Working Group 2.1 Relativistic Geodesy meeting
10 - 11 October 2018

Bureau International des Poids et Mesures

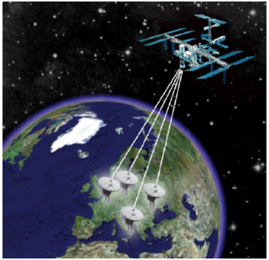
l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

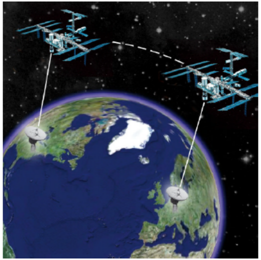
(P. Delva, C. le Poncin-Lafitte, A. Hees,
C. Guerlin, E. Savalle, P. Laurent, P. Wolf)

# The ACES mission

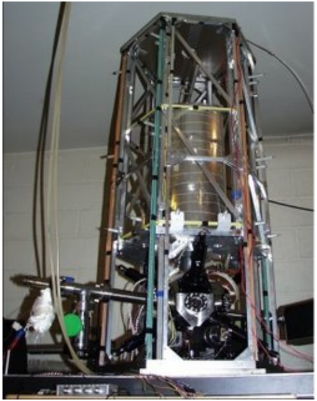
## Objectives

- Realize the best timescale on orbit to date
- Allow time comparison with the best clocks on ground
- Use those comparisons for several fundamental physics tests
- Demonstrate possible applications in intercontinental clock comparisons, in chronometric geodesy, etc. . .



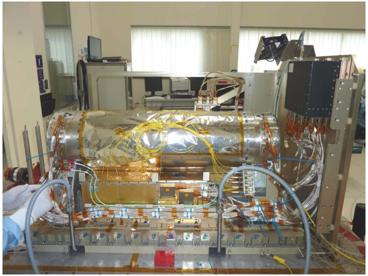


# A cold atom clock in space

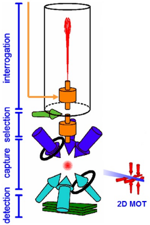


FO2, Rb/Cs fountain (SYRTE)

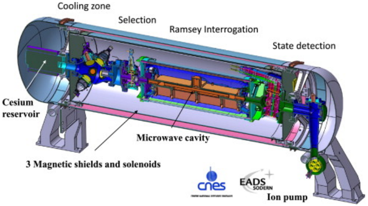
FOM, Cs mobile fountain (SYRTE)



Pharao, Cs beam (CNES, SODERN, SYRTE)

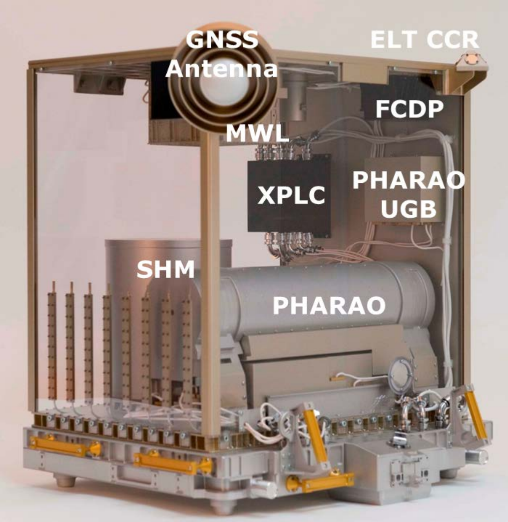



Fountain principle




Pharao schema

# The payload




## Éléments

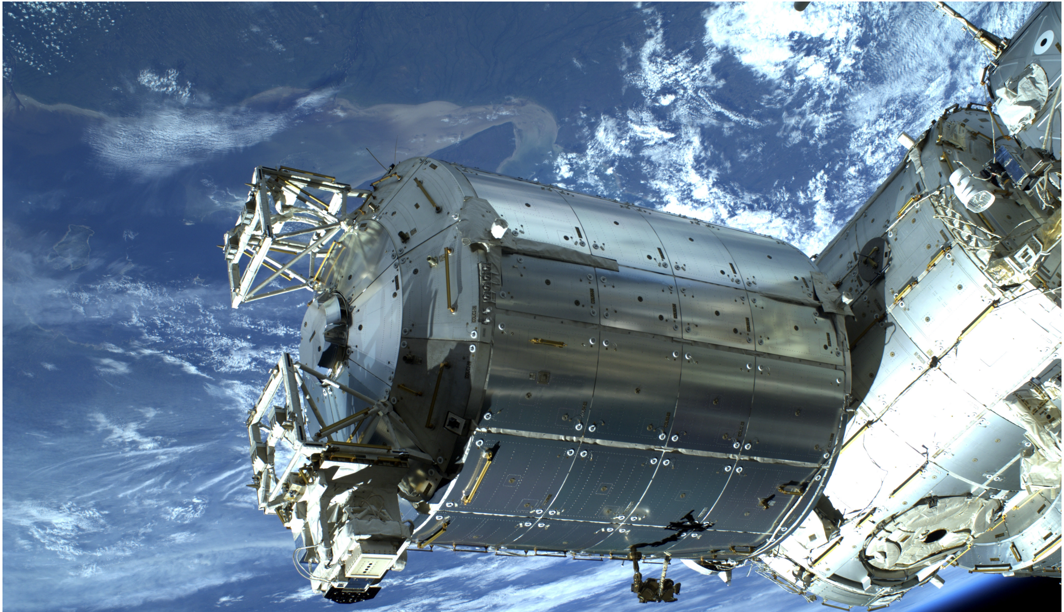
- PHARAO (CNES): Cold atom Caesium beam clock
- SHM (ESA): Active Hydrogen Maser
- FCDP (ESA): Clock comparison and distribution
- MWL (ESA): Microwave link
- GNSS Receiver (ESA)
- ELT (ESA): Laser link
- Support subsystems (ESA)
  - XPLC: Computer
  - PDU: Power supplies
  - Mechanical / thermal subsystem
  - Columbus interface module (ESA / NASA)

# Launch expected in 2020 (SpaceX)

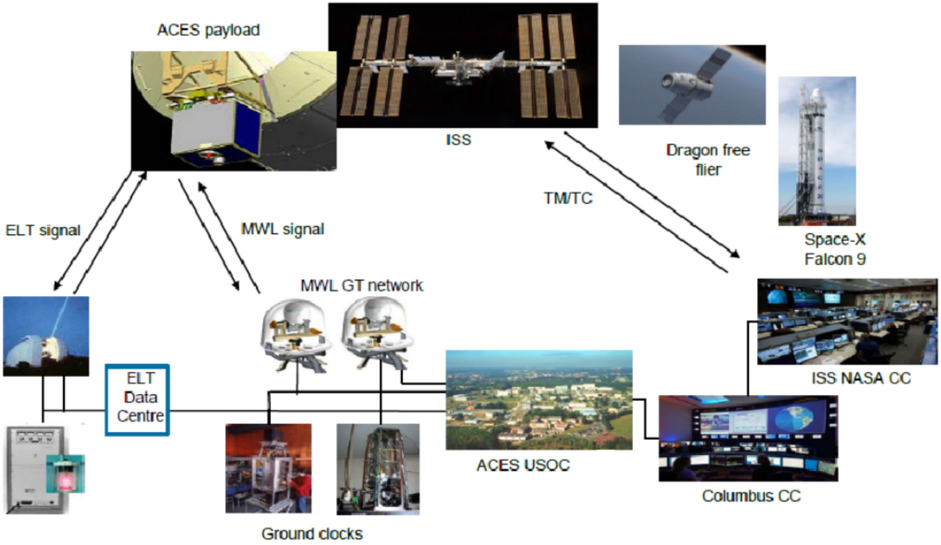
## Falcon9 launcher

## Dragon Capsule

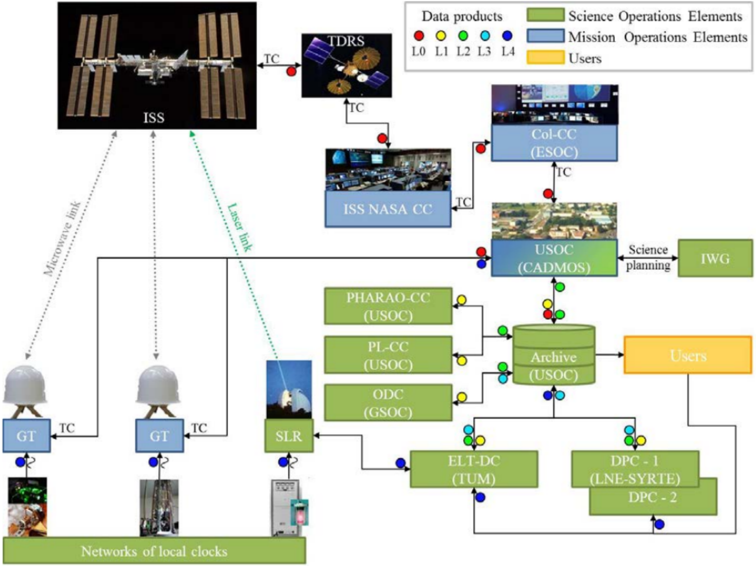
# Colombus module onboard the ISS



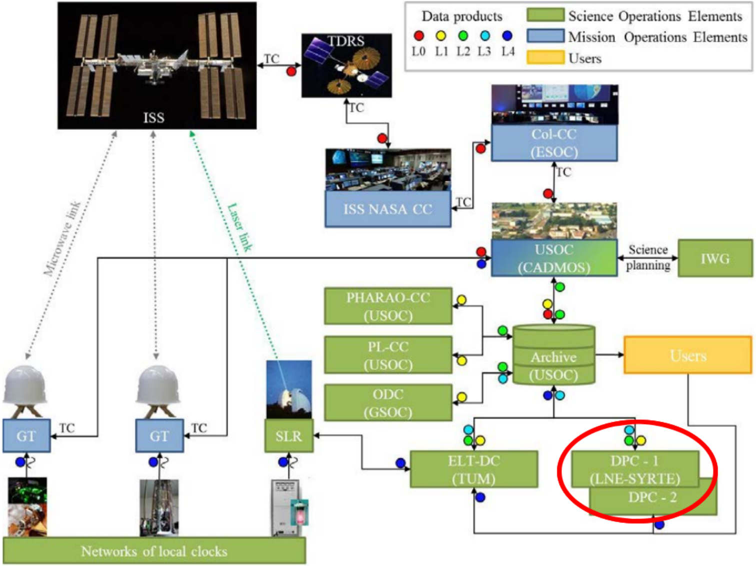
# ACES Mission components



# ACES Ground segment



# ACES Ground segment



# Microwave link principle

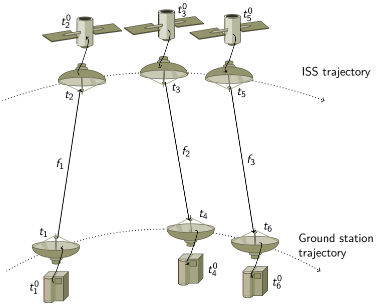
Ku-band uplink: 13.475 GHz

Ku-band downlink: 14.703 GHz

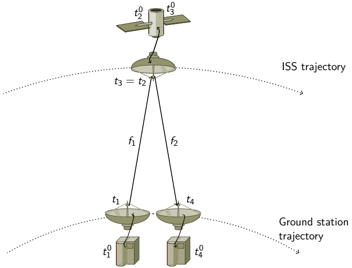
S-band downlink: 2.24 GHz (iono delay)

code: 100 Mcps

The two-way technique cancels out, at first order, the geometric distance and the tropospheric delay



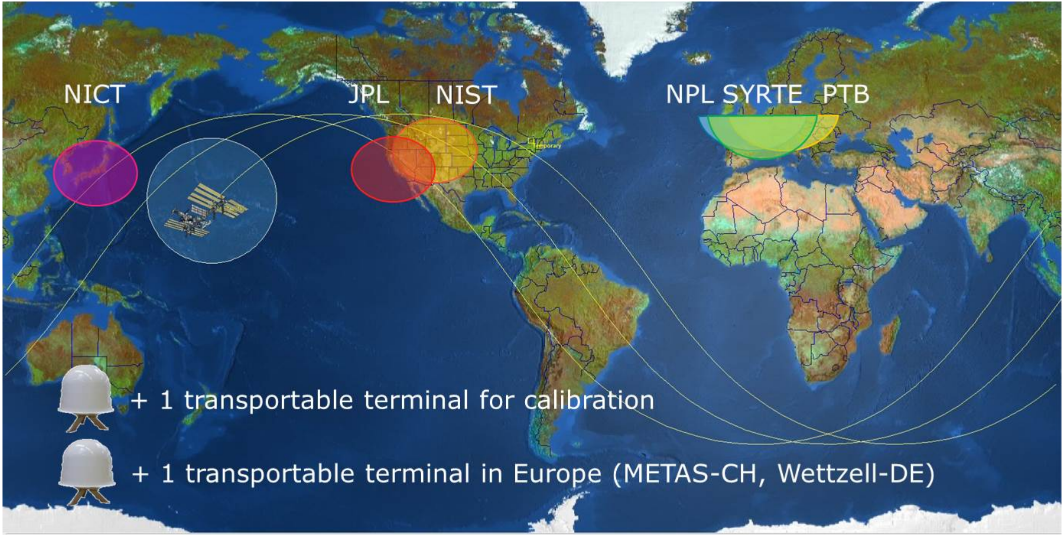

uplink and downlink signals generate 1 measurement every 80 ms




Λ configuration (interpolated)

minimizes the effect of ISS position uncertainty

# Ground terminals localisation



# Development of data processing software in SYRTE

Software has been developed within the "Theory" group in SYRTE – Observatoire de Paris (head: P. Wolf, national coordination: C. le Poncin-Lafitte)

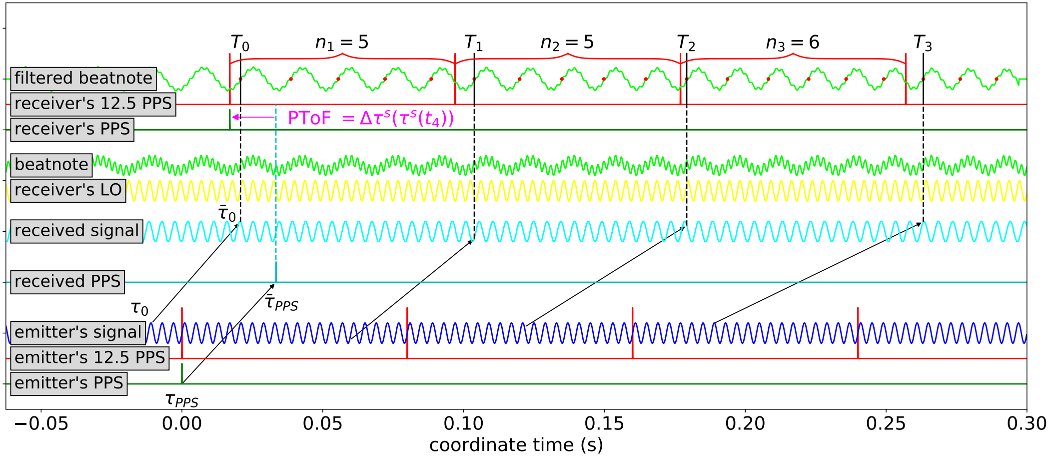
## Processing software

- Early developments $\simeq$ 10 years ago
- First lines of this code written in 2011
- Takes raw data as input and returns desynchronisation (+ TEC, pseudo-range. . . ) between ground terminal and flight segment.
- Validation with an independant simulation, developed by P. Delva

Unexpected issue: bridge the gap between raw data (counter values) and the time transfer equations (which take pseudo-time of flight as input).

Software is considered ready since end of 2017

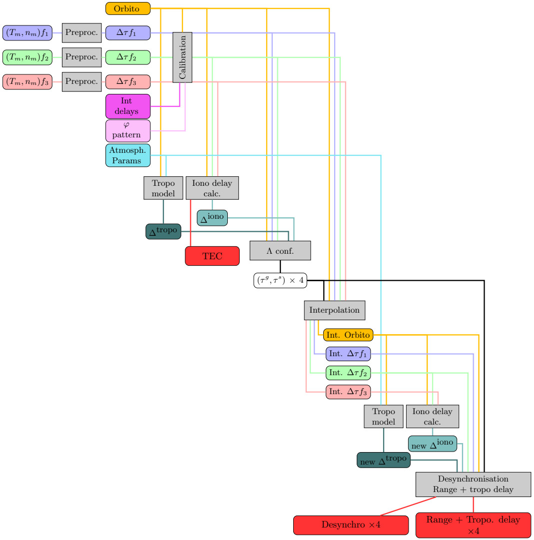
# Microwave link data generation
## as inferred from docs & exchanges with TimeTech



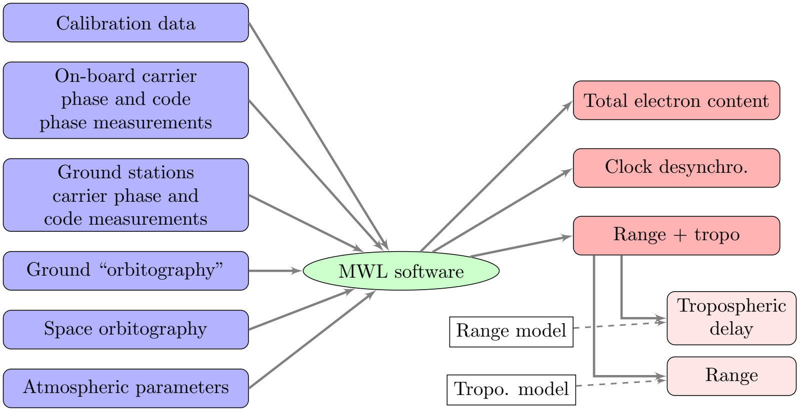
# Global flowchart

Design at module level:

- Process is iterative by nature (need rough idea of clock desynchronisation to get timetags right).
- Need careful choice of interpolation dates and method

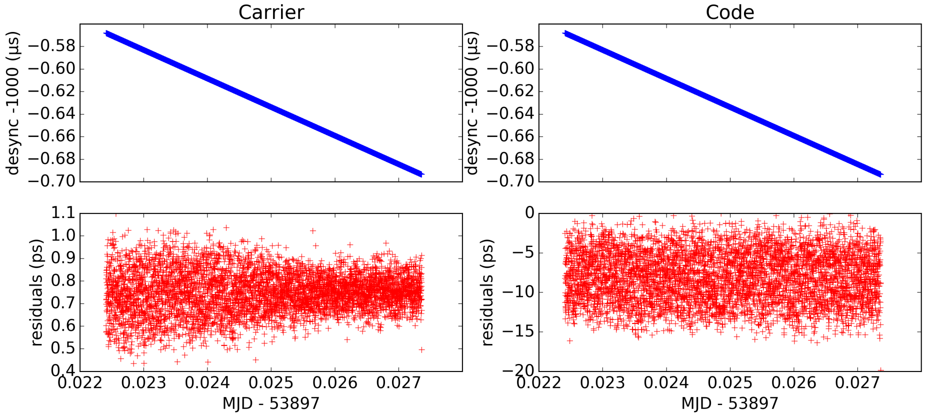


# Global flowchart



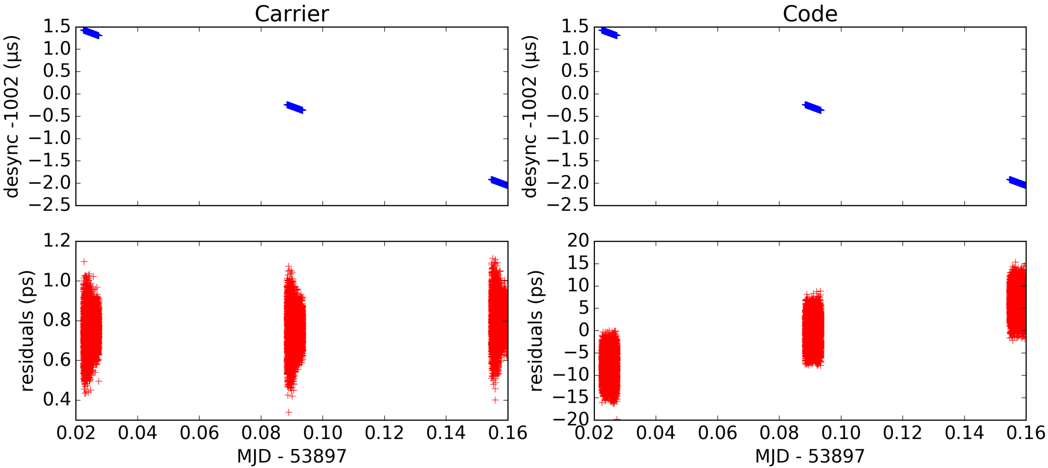

Within a framework that allows robust automated operation, scientific validation, interface with external databases.

# A typical pass




- Top: input desynchronisation (drift = GR)
- Bottom: residuals (theoretical − calculated desynchronisation)
- Noise = counter quantization (= noise floor)

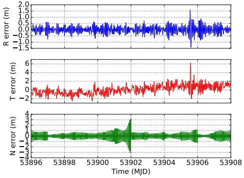
# Major milestone: Carrier disambiguation



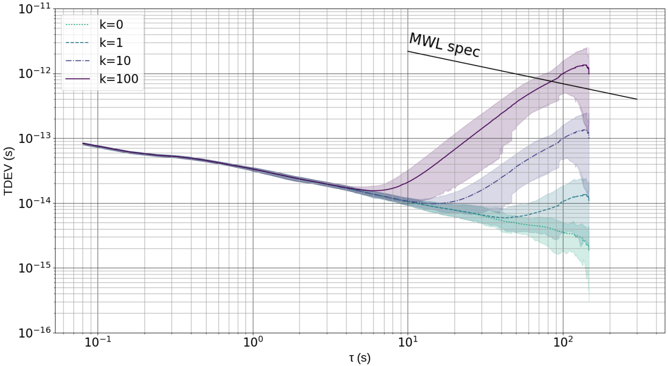

Simulated passes with desynchronisation (1 ms offset + RG drift), code residuals mean values change within $\pm$ 10 ps as expected, but carrier residuals mean values stay stable at the sub-ps level.

# Simulation of ISS orbitography uncertainty impact

ISS orbitography uncertainty estimation




MWL Data proc.




Mean TDEV of desynchronisation residuals for 0, 1, 10 and 100 times the expected ISS orbitography uncertainty (F. Meynadier *et al.* 2018 Class. Quantum Grav. 35 035018)

# If everything goes well. . .

- Gravitational redshift test (*Local Position Invariance* in General Relativity framework)
- Test of fundamental constants stability (comparison between different ground clocks, different atom species)
- Test of space isotropy (*Local Lorentz Invariance*)
- More generally, tests of GR alternatives
- and of course, geodesy

# Specifications (in 2016)

## PHARAO frequency standard

- Systematic effects $< 3 \times 10^{-16}$
- Frequency stability $10^{-13} t^{-1/2}$ for $t < 20d$

## PHARAO + SHM timescale stability

- sub-ps @ 300 s, 40 ps @ 20 d

## Time transfer

- space-to-ground: stability $\simeq 1$ ps @ 300 s (one ISS pass)
- ground-to-ground:
  - common view: a few ps @ 300 s
  - non-common view: stability 7 ps @ 1 day (i.e. freq. comparison $< 10^{-16}$) @ 1d
- Accuracy: 100 ps