



ACES: first results

Atomic Clock Ensemble in Space

**Marc Lilley on behalf of the ACES collaboration
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This talk in the context of this conference...



Several talks on modifications of gravity with

- Applications to astrophysics (c.f. Langlois)
- Applications to late time cosmology (c.f. Noui)
- Applications to tensions in cosmology (c.f. Kalife)

Many other ways to test various aspects of Einstein's theory

- Gravitational waves (c.f. Cogeze)
- Test of the equivalence principle (free-fall experiments)
- *Test of the gravitational redshift (using precise clocks)*
- *etc.*



Talk overview



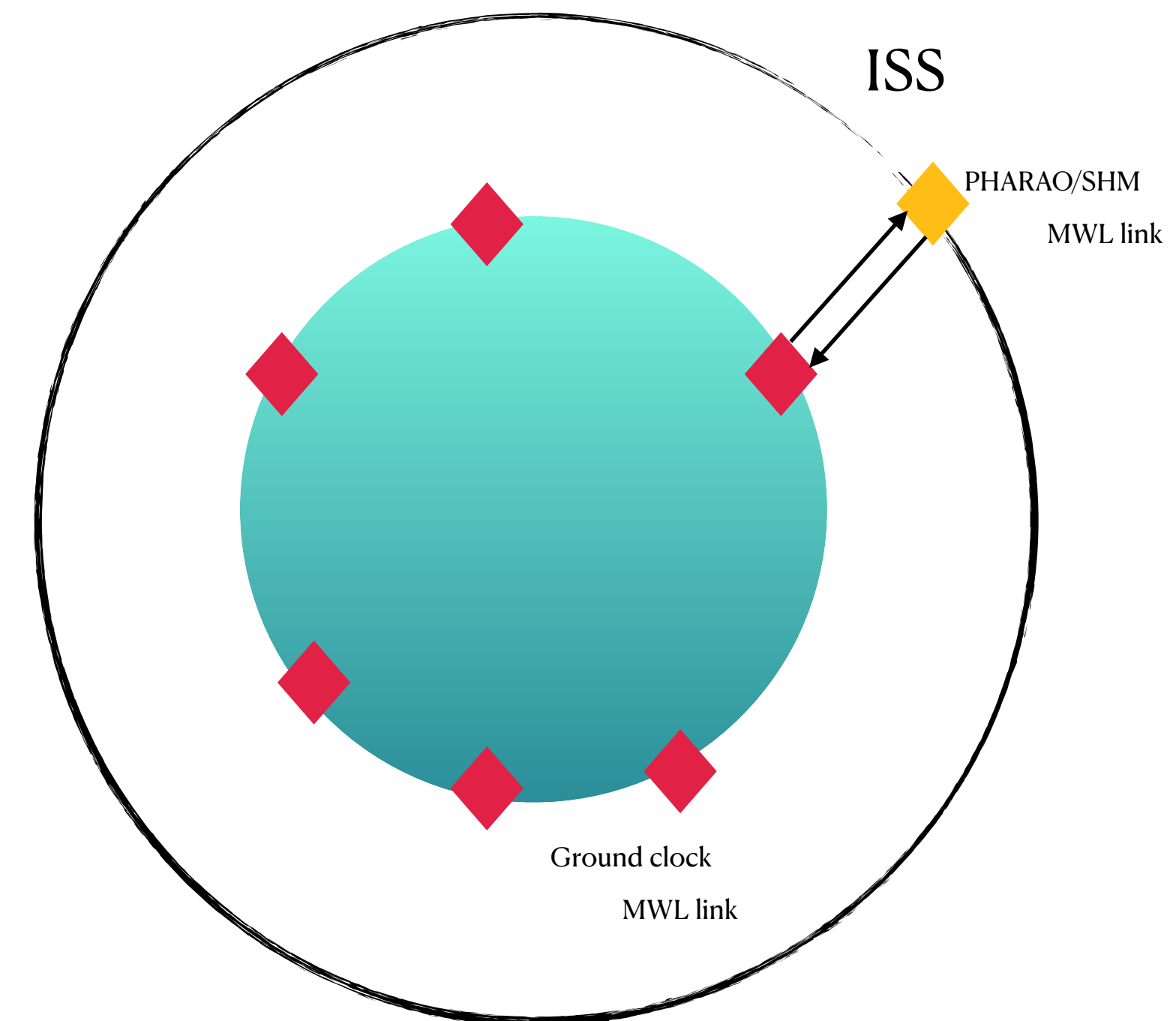
- Mission overview and status
- Measurement principle
- LTE data processing pipeline
- Validation using common views
- In-orbit measurement vs GR
- How to constrain deviations from GR using ACES
- Some preliminary results



Mission overview in brief



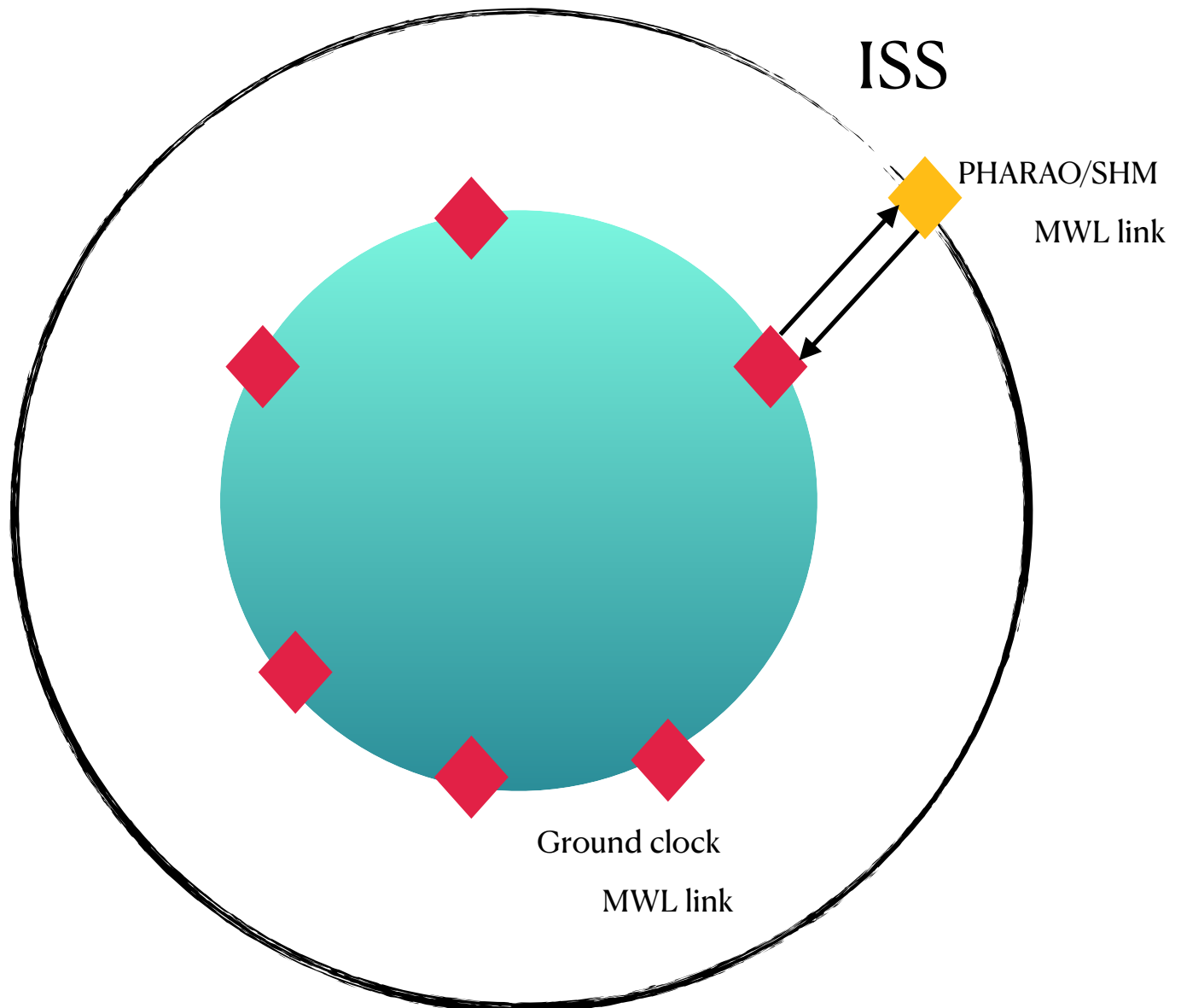
- 1 flight module on the ISS containing PHARAO/SHM and the MWL
- PHARAO is a cold atom Cesium clock (most stable and accurate clock ever put in space)
- SHM is a Space Hydrogen maser
- 9 ground terminals installed in EU, UK, US, Japan each containing a MWL and wired to atomic clocks.
- Via the MWL, ACES compares ground clocks to PHARAO using 2-way measurements.
- Launched on April 21 2025. Commissioning phase still ongoing.
- Main objectives:
 - Test of the gravitational redshift
 - Inter-comparison of ground clocks
 - Demonstrate atomic clock operation in space





Operational status

- GT003 and GT101 (mobile) at Paris Observatory **OK**
 - GT007 at NPL (UK) **OK**
 - GT002 at JPL (California) **OK**
 - GT001 at NIST (Colorado) **OK**
 - GT004 (Germany) **OK**
 - GT005 (Japan) **Not online**
 - PHARAO **OK**
 - SHM **NOK**
- on the ISS*



Measurement stretches of 300 seconds
for each GT for each ISS orbit



Gravitational redshift test



Fractional frequency difference of ground and space clocks

$$y_m(t) = \frac{d\tau^g}{dt} - \frac{d\tau^s}{dt} = \frac{1}{c^2} \left[\Delta U^{s-g}(t) + \frac{v_s^2(t)}{2} - \frac{v_g^2(t)}{2} \right]$$

Evolution of proper time as a function of coordinate time

Gravitational potential difference

Second order Doppler

ACES measures the integral of this frequency difference, the desynchronisation $\delta(t)$

Size of the effect in GR: $\frac{\Delta U^{s-g}}{c^2} \sim 4.4 \times 10^{-11}$

Current constraint: $|\alpha| \leq 2.5 \times 10^{-5}$
[Delva *et al* 2018]

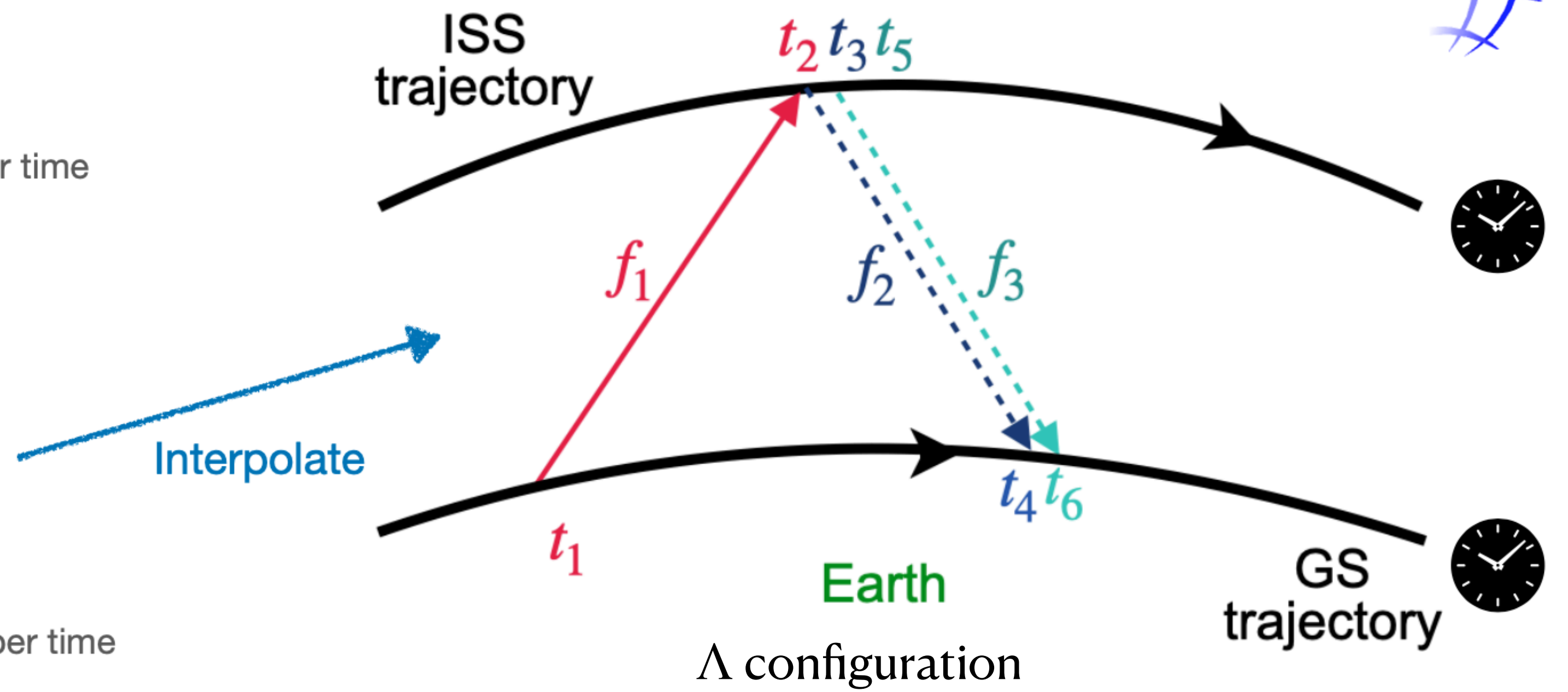
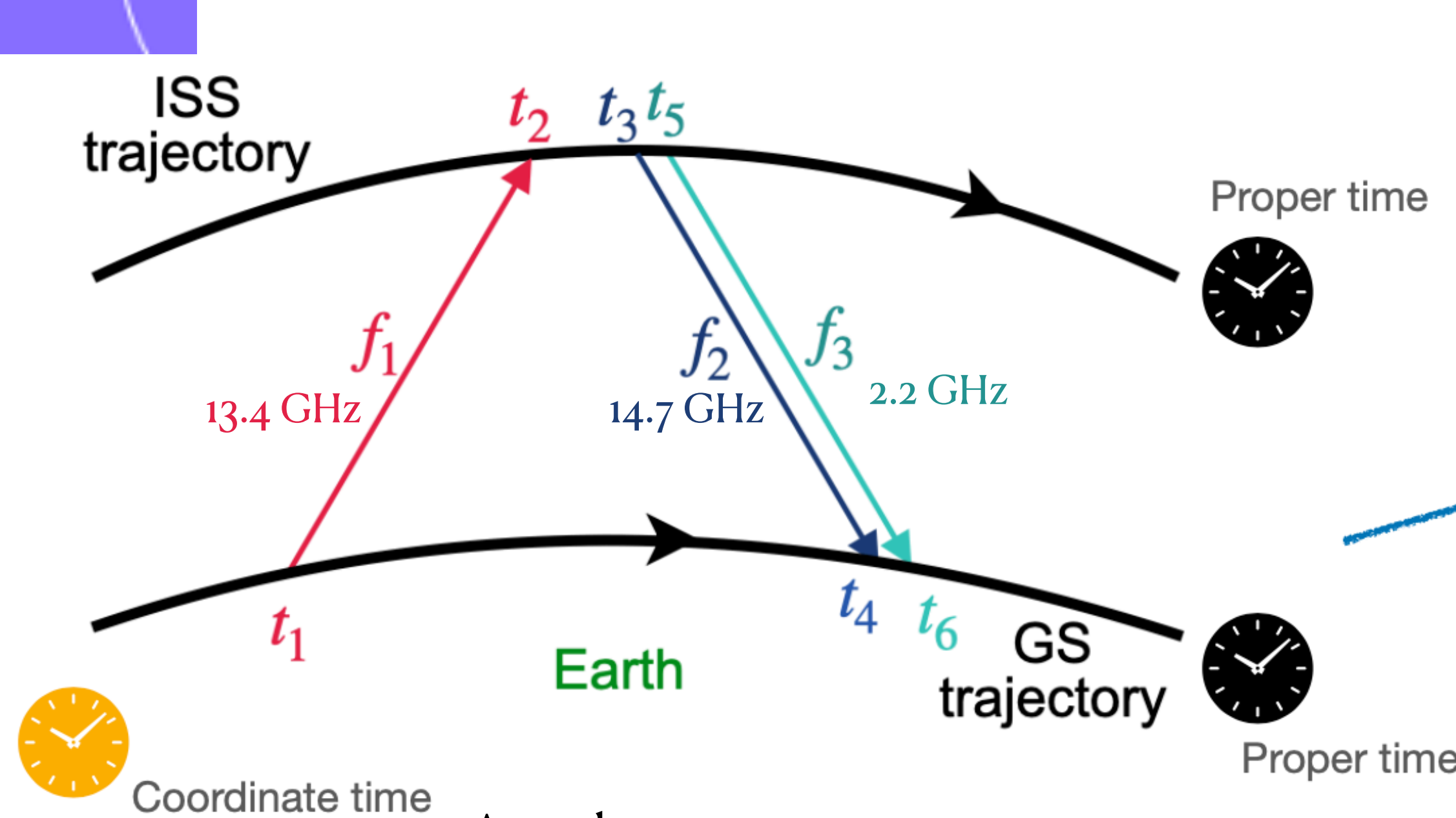
Deviations from GR are parameterised as: $(1+\alpha) \frac{\Delta U^{s-g}}{c^2}$

ACES relative frequency accuracy: 10^{-16}
 Statistical uncertainty : $10^{-13}/\sqrt{\tau} \rightarrow 10^{-16}$ after 10 days
 Yields constraint on α at the 10^{-6} level.

Confirmed in simulations by Savalle *et al*, 2019, Enzer & Yu, 2025



ACES measurement principle



Pseudo-ranges using f_1 and f_2

$$\Delta\tau^s(\tau^s(t_2)) = \tau^g(t_1) - \tau^s(t_2)$$

$$\Delta\tau^g(\tau^g(t_4)) = \tau^s(t_3) - \tau^g(t_4)$$

f_3 is used to measure $\Delta\tau^{\text{iono}}$

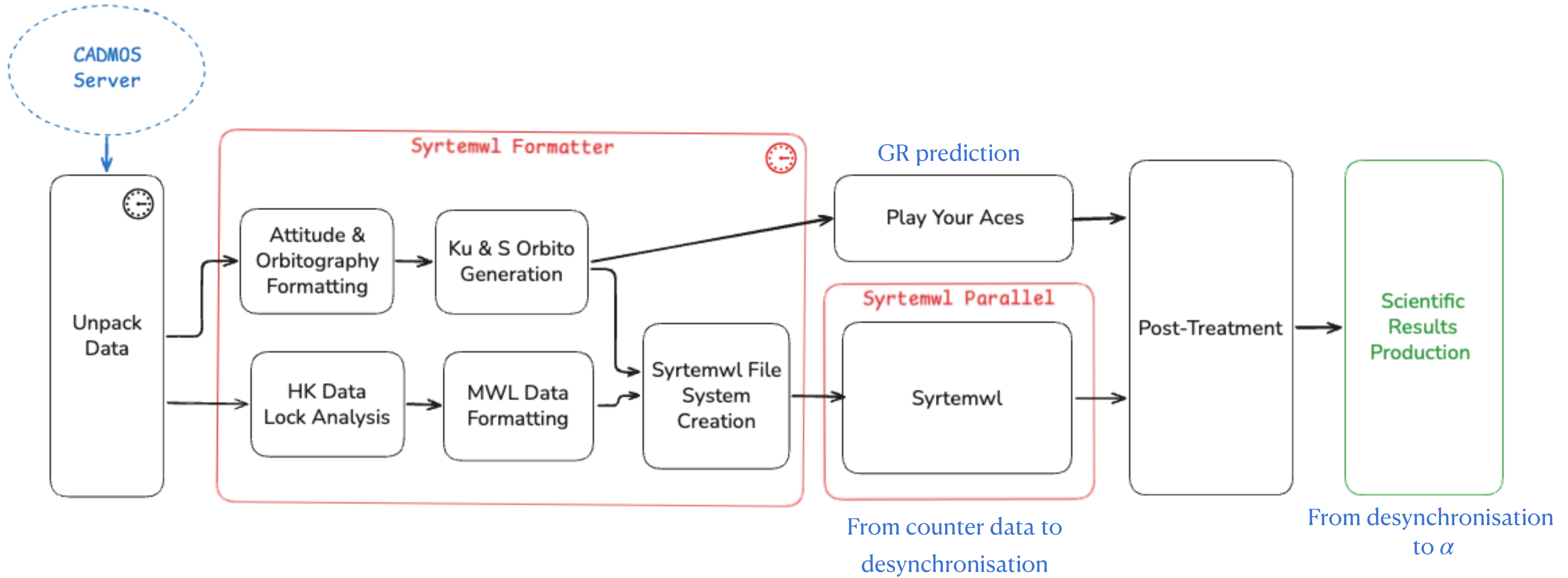
Desynchronisation from the 2-way combination in the Λ configuration

$$\delta(t_2) = \frac{1}{2} [\underbrace{\Delta\tau^g(\tau^g(t_4))}_{\text{ACES}} - \underbrace{\Delta\tau^s(\tau^s(t_2))}_{\text{ACES}} + (T_{34} - T_{12})^g] + \Delta^{\text{int}}$$

ToF using models and orbits



LTE processing pipeline





systemw1



Data Processing

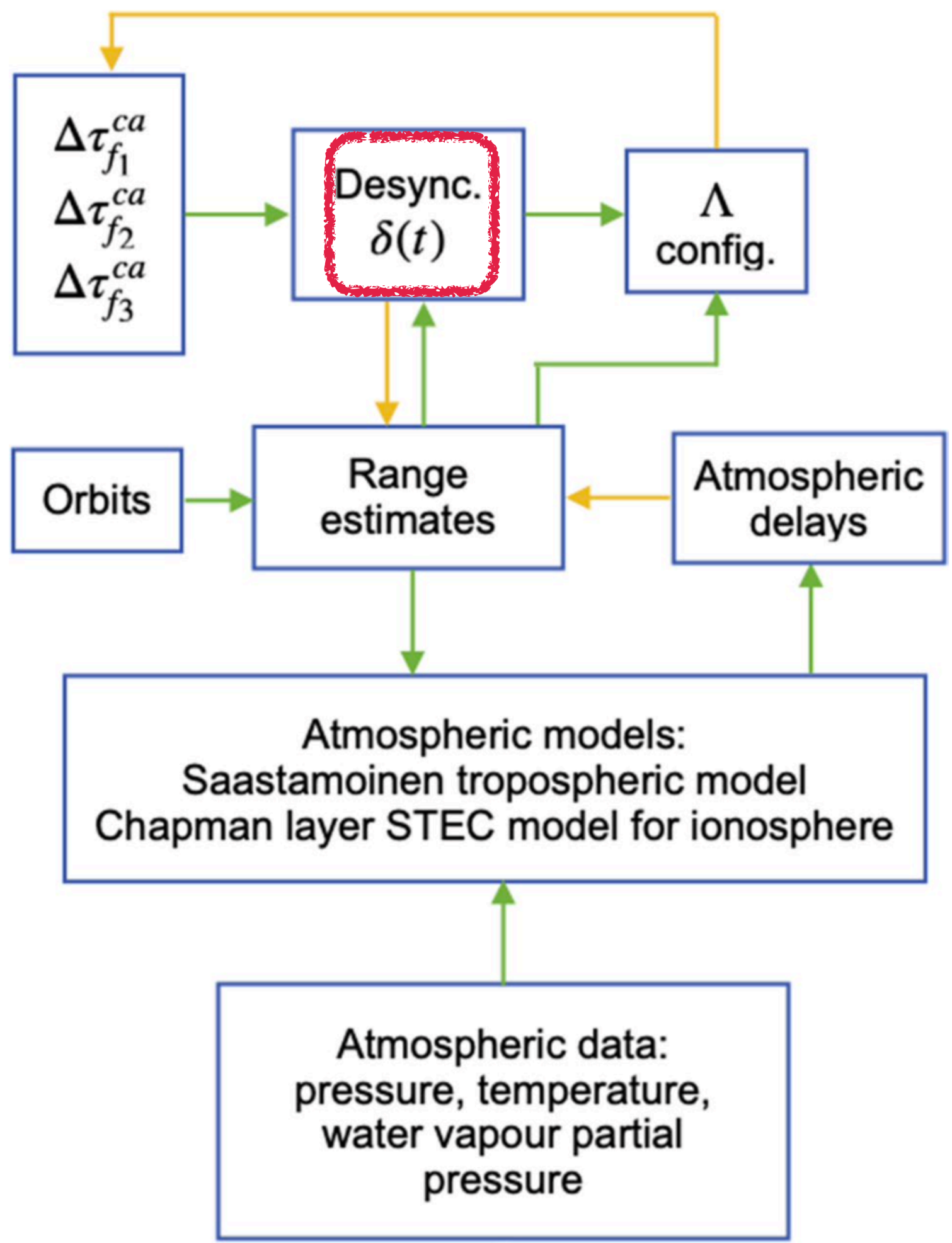
High noise (100 to 200 ps) unambiguous timing using frame and chip counter

Raw counter measurements for code

Raw counter measurements for carrier

Low noise (5 to 10 ps) ambiguous timing (known up to an unknown phase difference)

Use code to fix carrier ambiguity (34 ps)



PlayYourAces

GR Prediction

ISS orbitography
ground stations positions

GR model

noise model

simulated data

[Savalle et al, 2019]

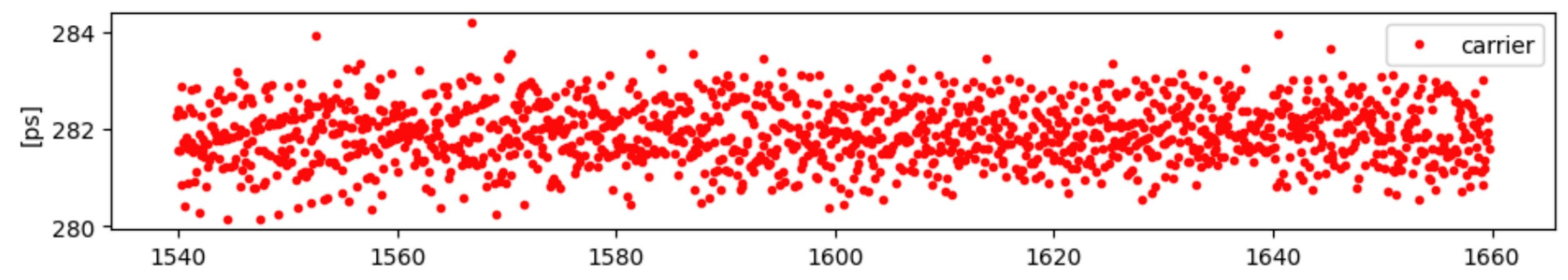
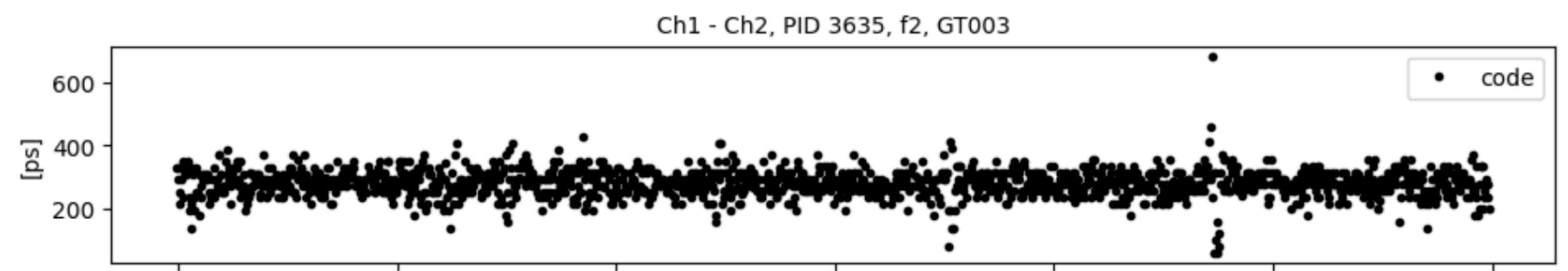
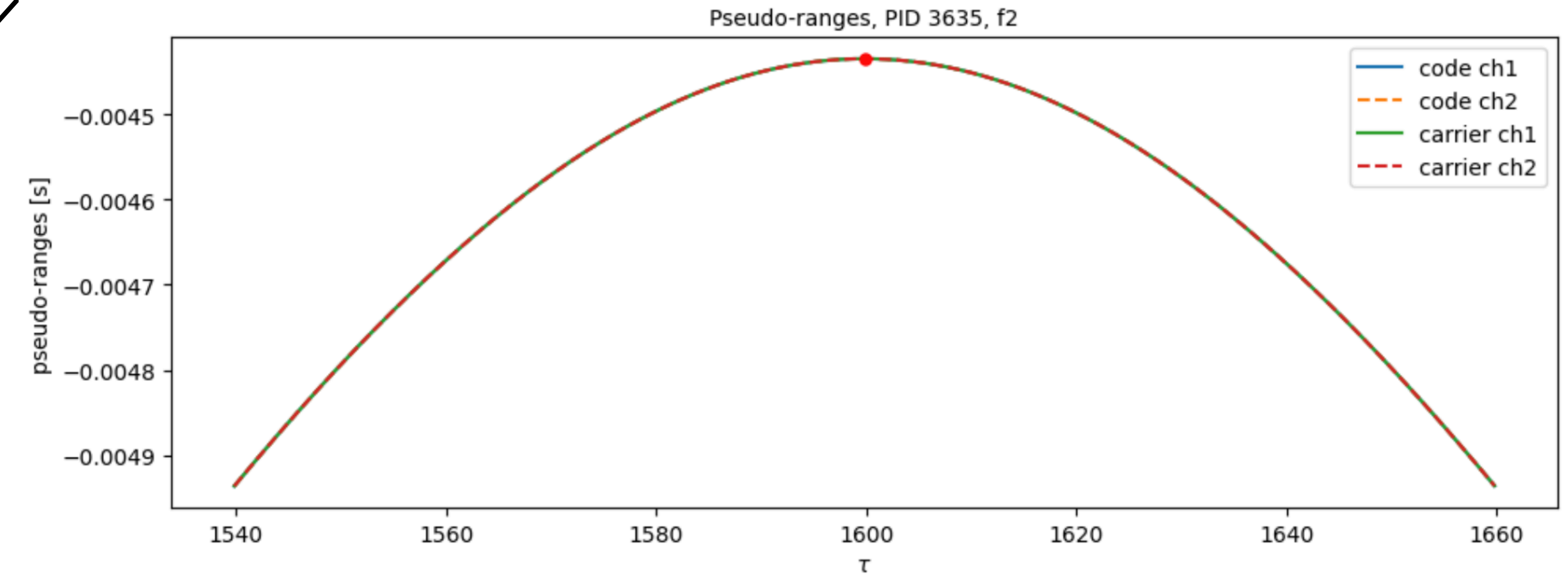
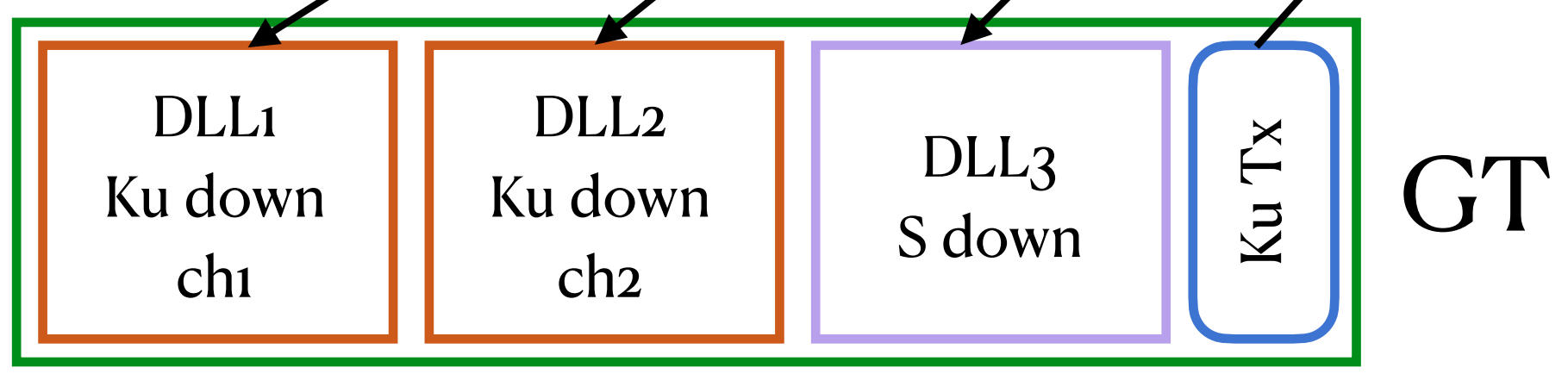
[Meynadier et al, 2018]



MWL validation: common view with the same GT



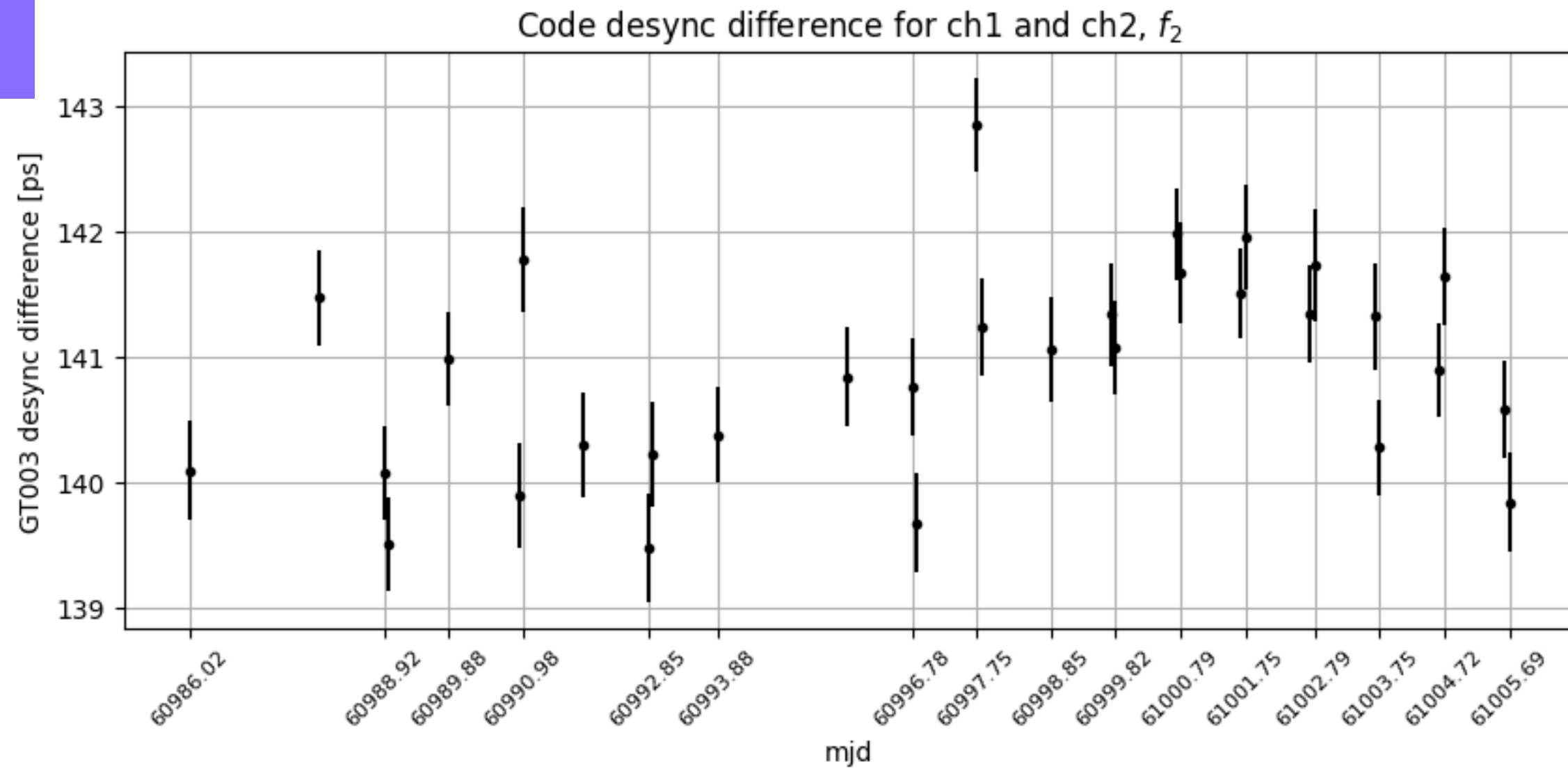
Ku: 13 to 14 GHz
S: 2.4 GHz



Code noise per pass is 150 ps pk-to-pk
Carrier noise per pass is 4 ps pk-to-pk

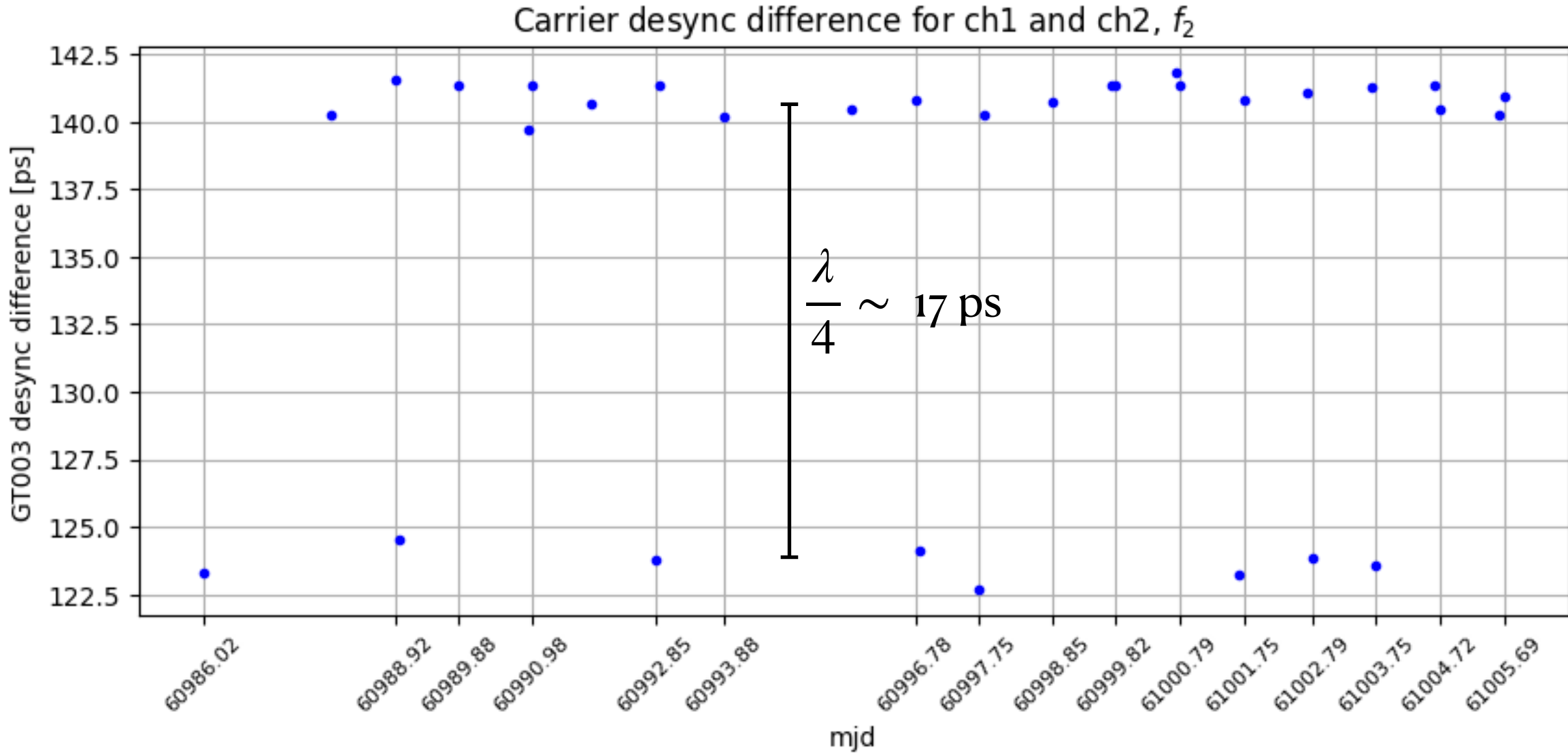


MWL validation: common view with the same GT



Mean $\delta(t)$, one point per pass, for **code**.
 4 ps variation from pass-to-pass

NB: lots of common mode effects



Mean $\delta(t)$, one point per pass, for **carrier**.
 0.5 ps variation from pass-to-pass (excluding ambiguity errors)

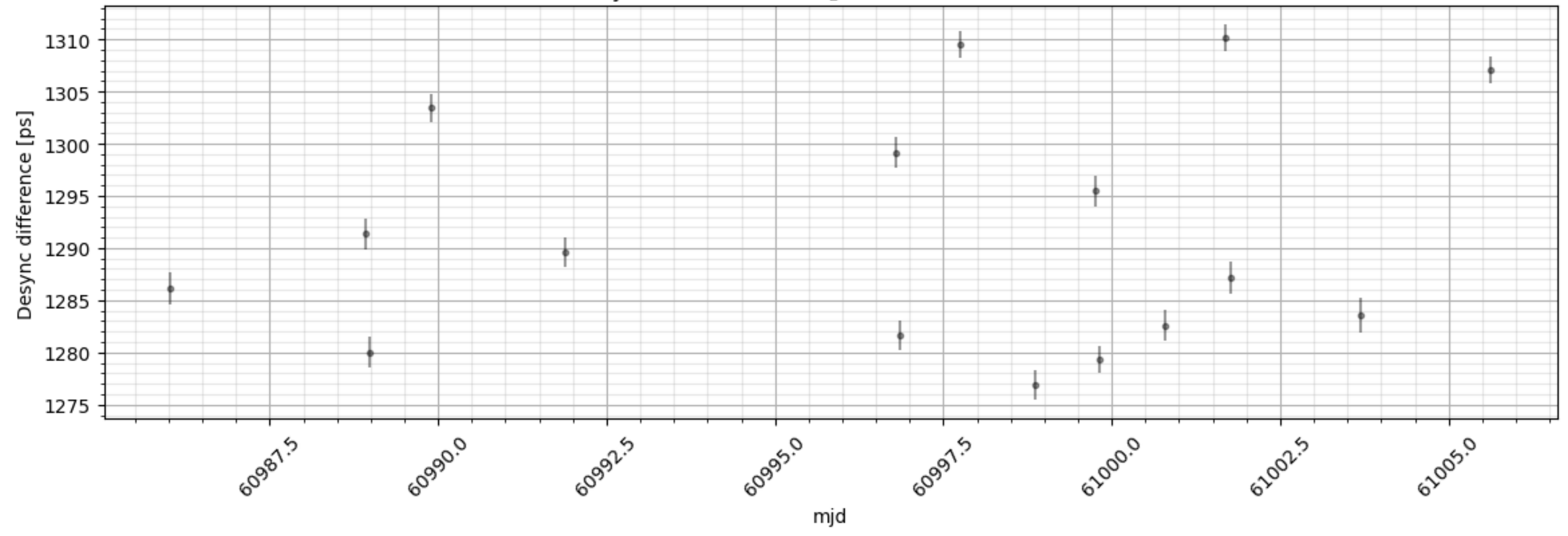
Carrier ambiguity resolution is not yet fully under control because of noise non-stationarities, calibration uncertainties, etc.



MWL validation: common view, colocated GTs



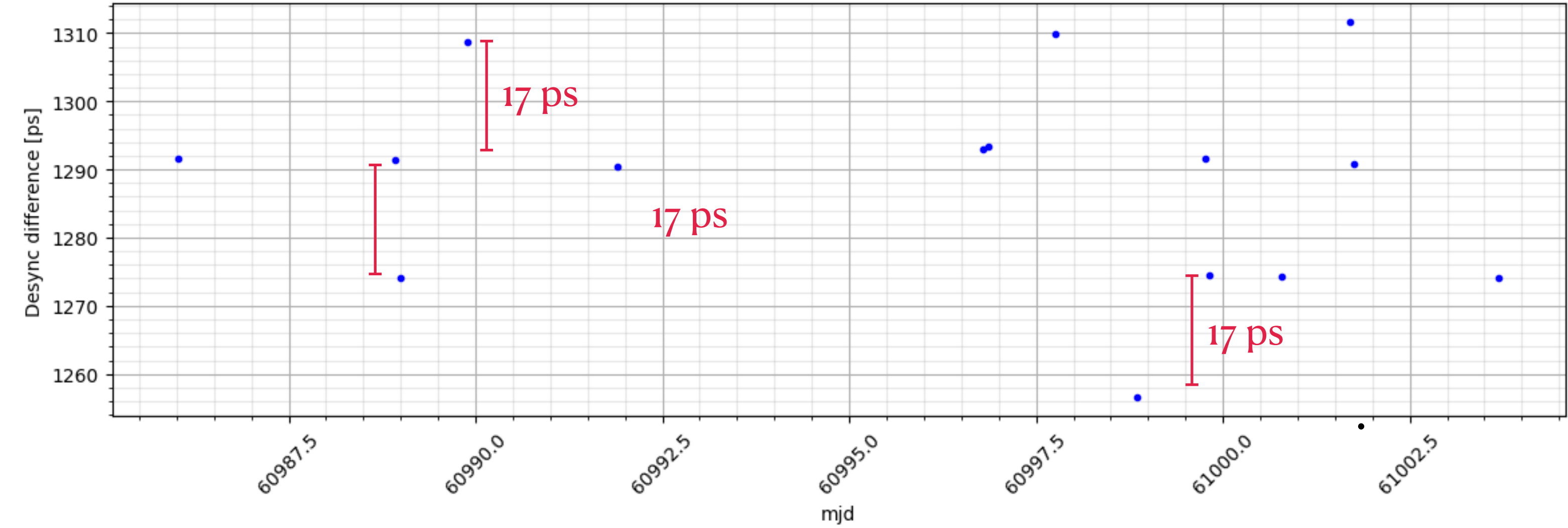
Code desynchronisation for f_2 , GT003-ch1 and GT101-ch2



GT101 (mobile GT) and GT003 are colocated at OP

Code $\delta(t)$ spread from pass-to-pass is 35 ps.

Carrier desynchronisation for f_2 , GT003-ch1 and GT101-ch2



Carrier $\delta(t)$ spread from pass-to-pass is a multiple of 17 ps.

With carrier ambiguity errors solved, it drops to 5 ps.

For a typical 10 day measurement period, using code, the frequency error is $\sigma_{MWL} \sim 10$ ps over 10 days.

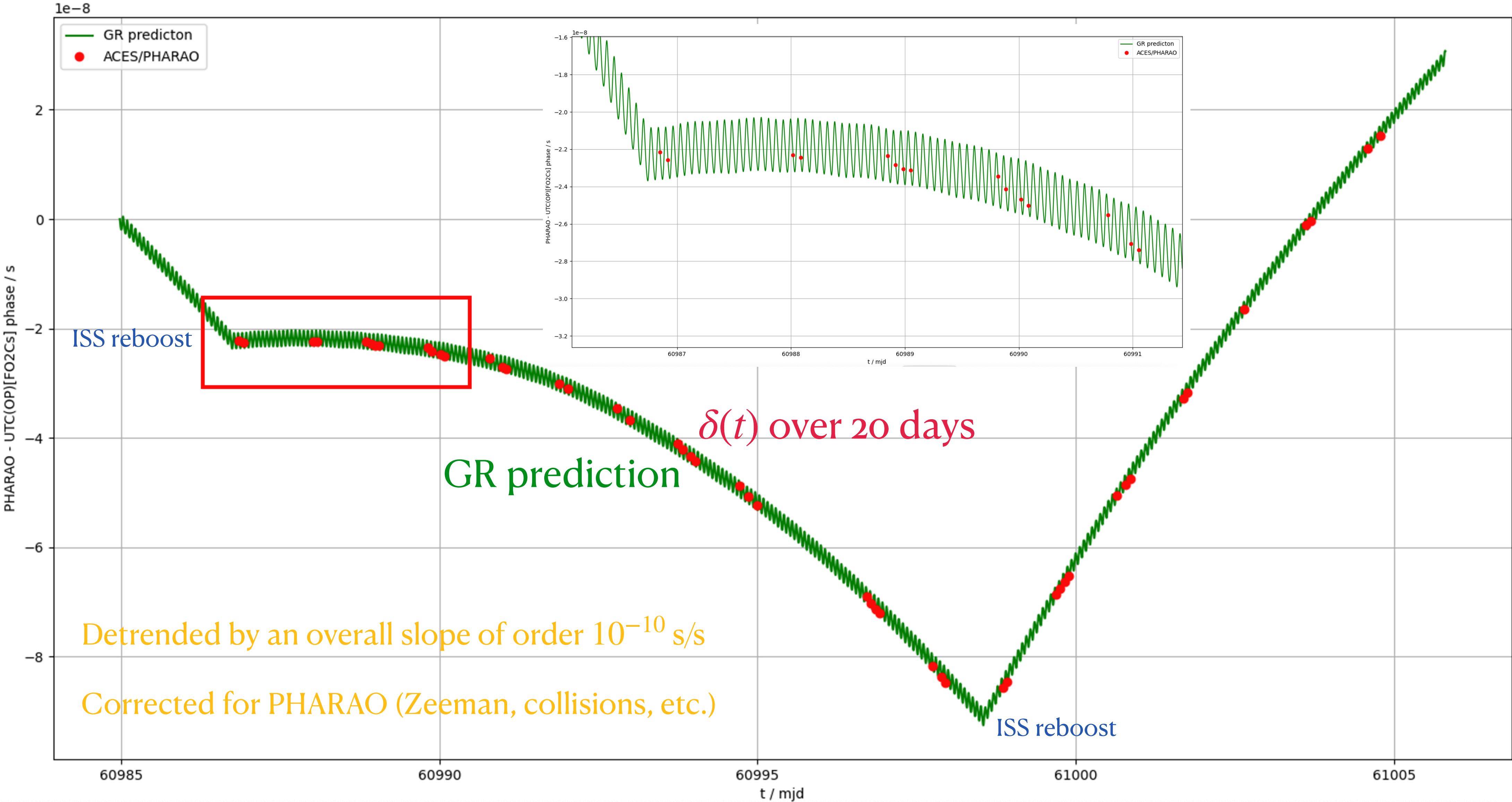
Translates in a frequency error $\sim 10^{-17}$

MWL not limiting for ACES, but...

... this is a *lower limit* on MWL noise (pending fiber link measurements).



In-Orbit measurement over 20-day period



Constraining α



$$y_m^{\{i,j\}} = y_0 + y_Z + y_{BBR} + y_{rec} + K v_i + \rho_i R_j$$

$y_m^{\{i,j\}}$: Measured fractional frequency difference (GR subtracted)

y_0 : Unperturbed fractional frequency difference (includes α)

y_Z : Zeeman shift (given)

y_{BBR} : Black body radiation shift (given)

y_{rec} : Recoil shift (given)

ρ_i : Collisional shift

K : Doppler coefficient

R_j : Atomic density ratio (set)

v_i : Atomic velocity (set)

- Operate PHARAO in various $\{v_i, R_j\}$ configurations.
- Run ACES and determine $y_m^{\{i,j\}}$
- Solve for $\{y_0, K, \rho_1, \rho_2, \rho_3, \dots\}$ for each GT channel and ground clock.



Computing $y_m^{\{i,j\}}$

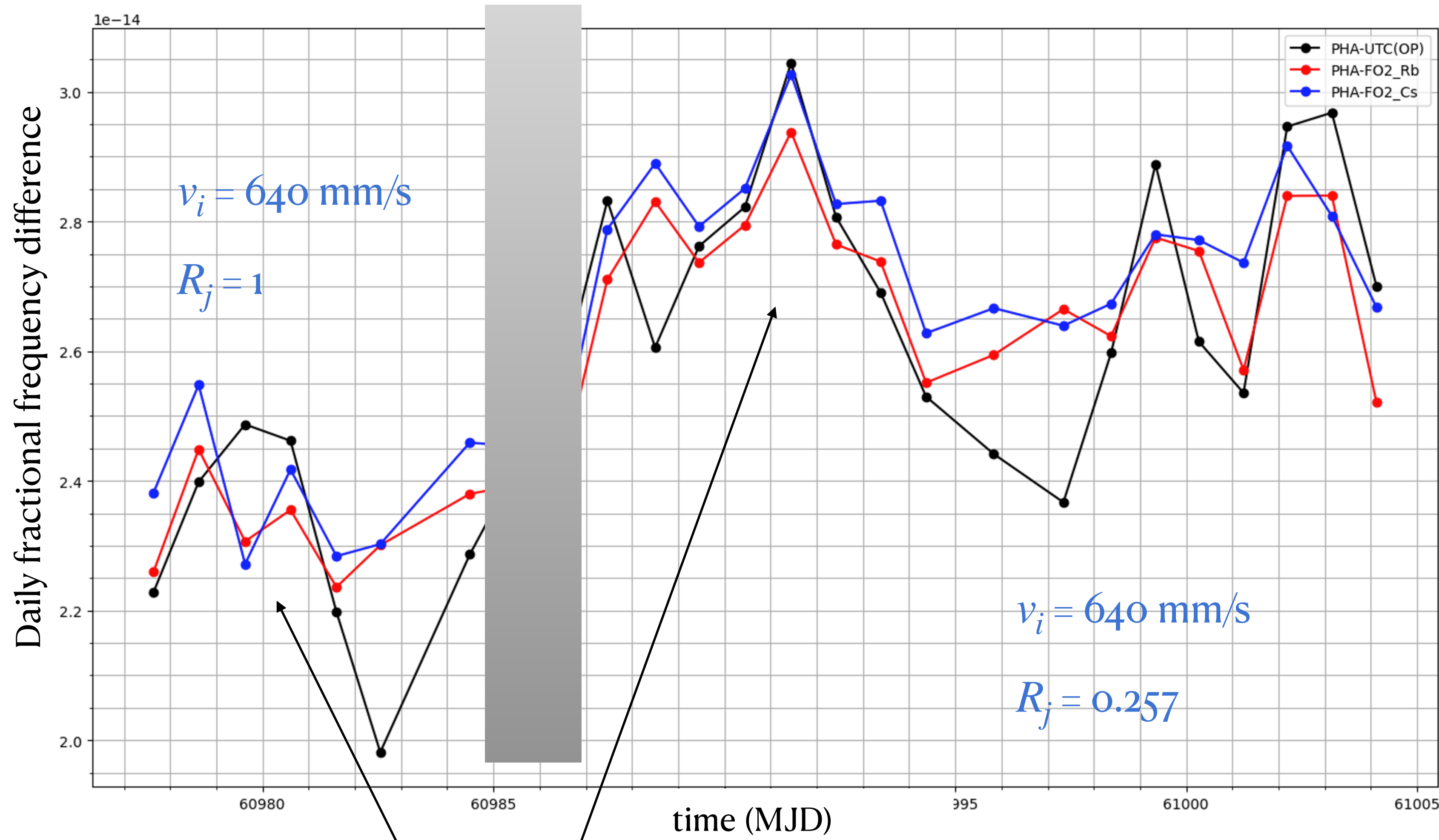


For each $\{i,j\}$ pair, corresponding to a PHARAO atom velocity and density ratio:

- Run ACES for a measurement period (typically 1 to 2 weeks)
- Process ACES data to obtain desynchronisation in phase, $\delta(t)$.
- Compress to one point per pass and one point per day.
- Compute day-to-day relative frequency difference and average to obtain $y_m^{\{i,j\}}$.
- Error estimation on $y_m^{\{i,j\}}$:
 1. Orbit errors at the 20 cm from DLR assessment (requirement is 8 m).
 2. MWL errors current *lower limit* at the 10^{-17} in fractional frequency (from common views).
 3. PHARAO vs ground clock $\frac{\delta f}{f}$ uncertainty at the $\sim 4 \times 10^{-16}$ level, see below.



Space/ground $y_m^{\{i,j\}}$ for 2 measurement periods



Compare PHARAO to:

- UTC (OP)
- Rb fountain (OP)
- Cs fountain (OP)

Infer an uncertainty on fractional frequency difference $\sim 4 \times 10^{-16}$ for PHA-FO2 (before PHARAO corrections, velocity, collisions, etc.)

Many such runs are needed to get an estimate for α at the 10^{-6} level.



Outlook

- Still a lot of work to do.
- All GTs are gradually coming online
- Still too many hiccups at operational level (too many to list)
- Carrier ambiguity resolution
- Carry on with data analysis in different PHARAO configurations
- Fiber link measurement campaign to assess MWL noise
- Cumulate data to reach the target uncertainty of 2×10^{-16}

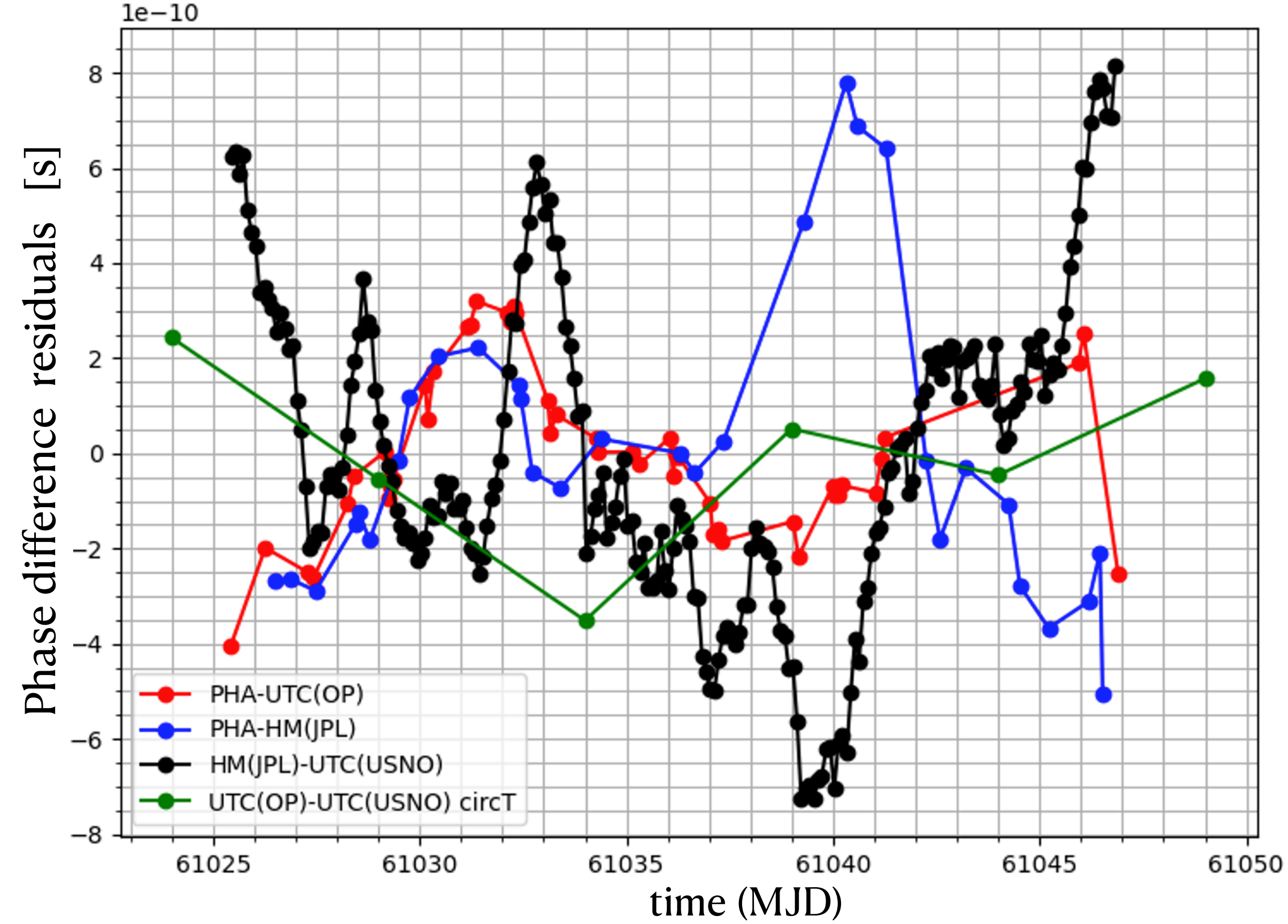
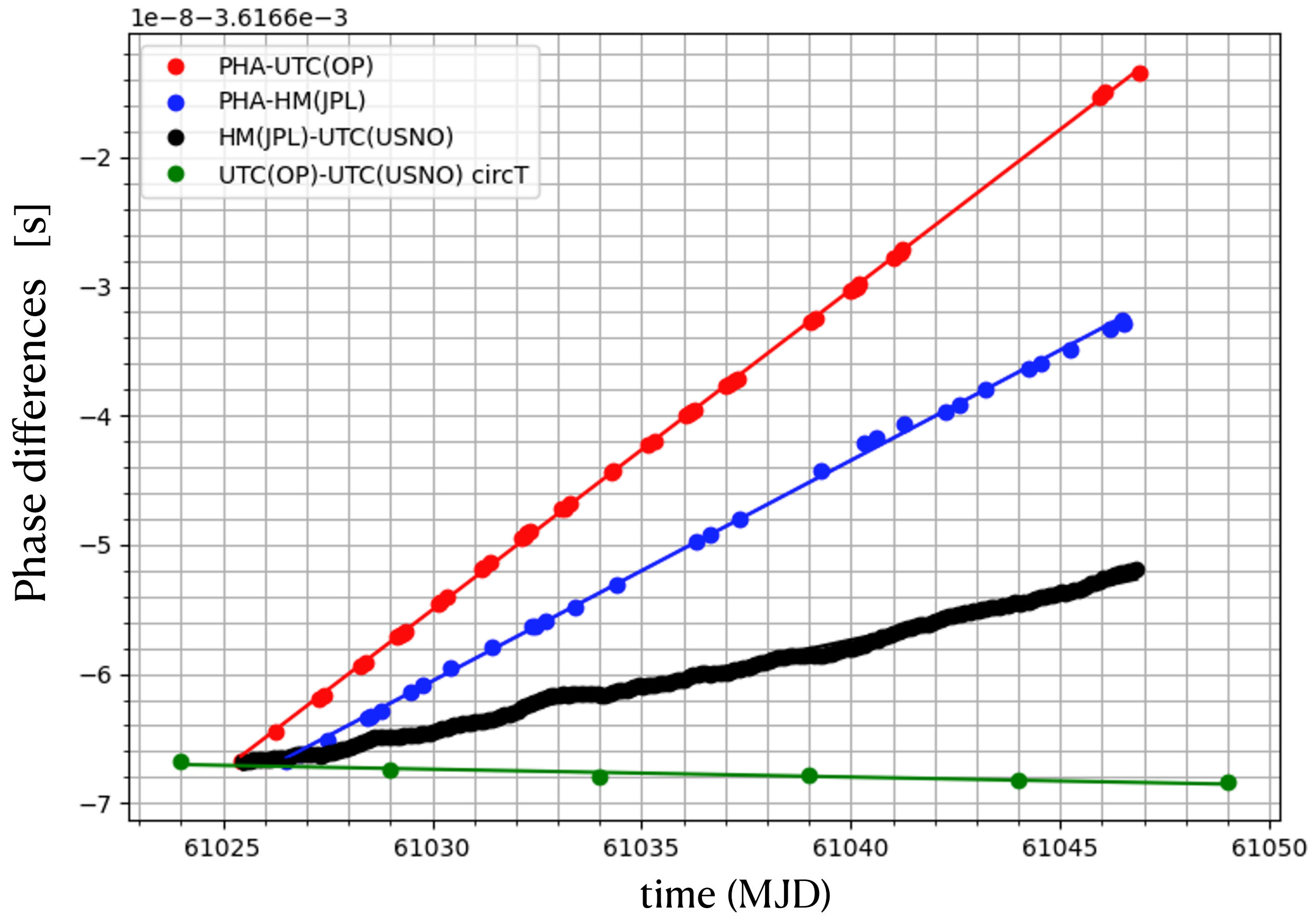
Backup



Intercontinental clock comparison



First rough test



$UTC(OP) - UTC(USNO) = -7.01 \times 10^{-16}$ from BIPM Circular T

$UTC(OP) - UTC(USNO) = -9.26 \times 10^{-16}$ from ACES



Calibrations



Several instrumental effects induce unwanted shifts on the phase, and must be corrected for.

Antenna corrections:

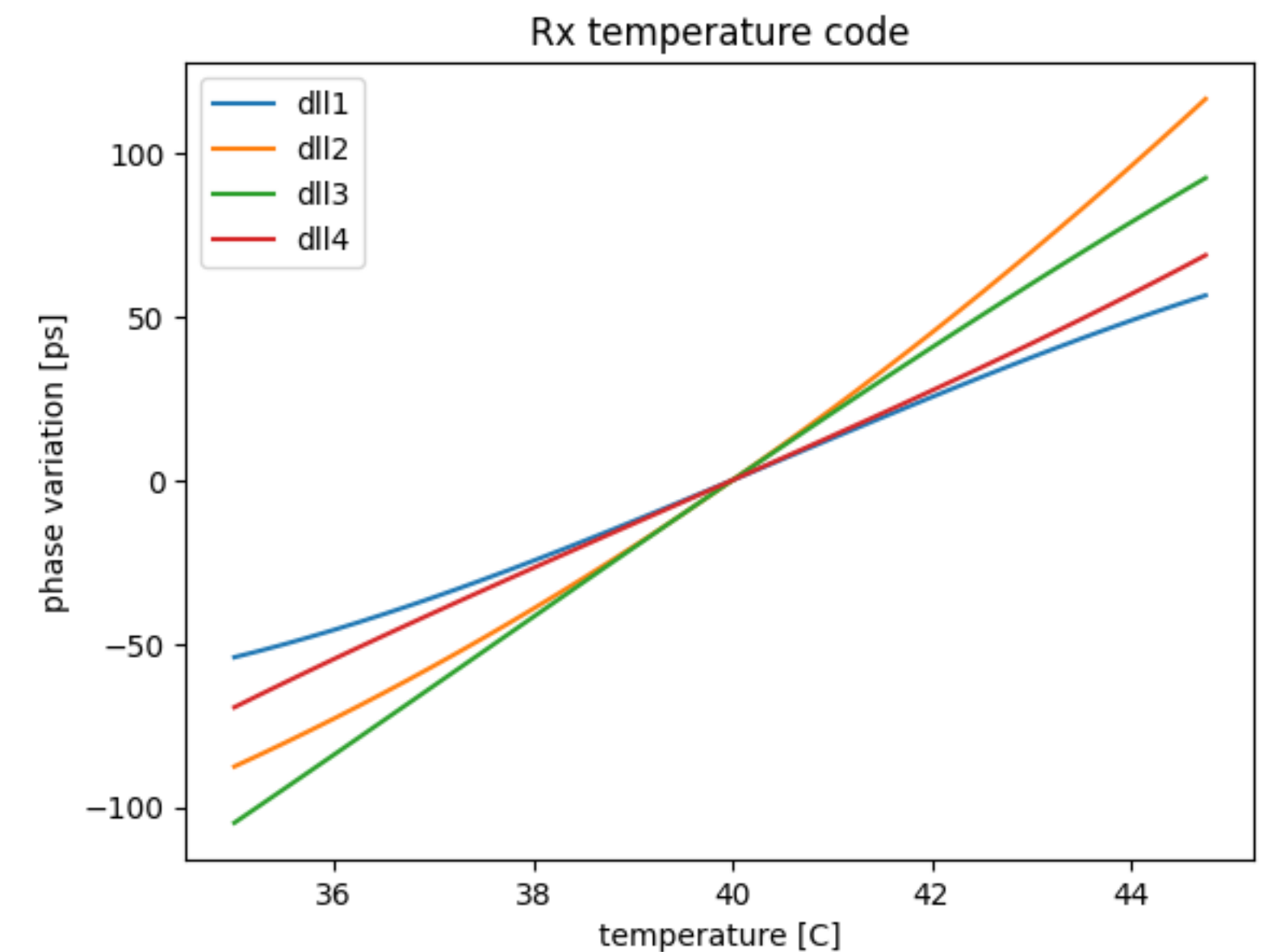
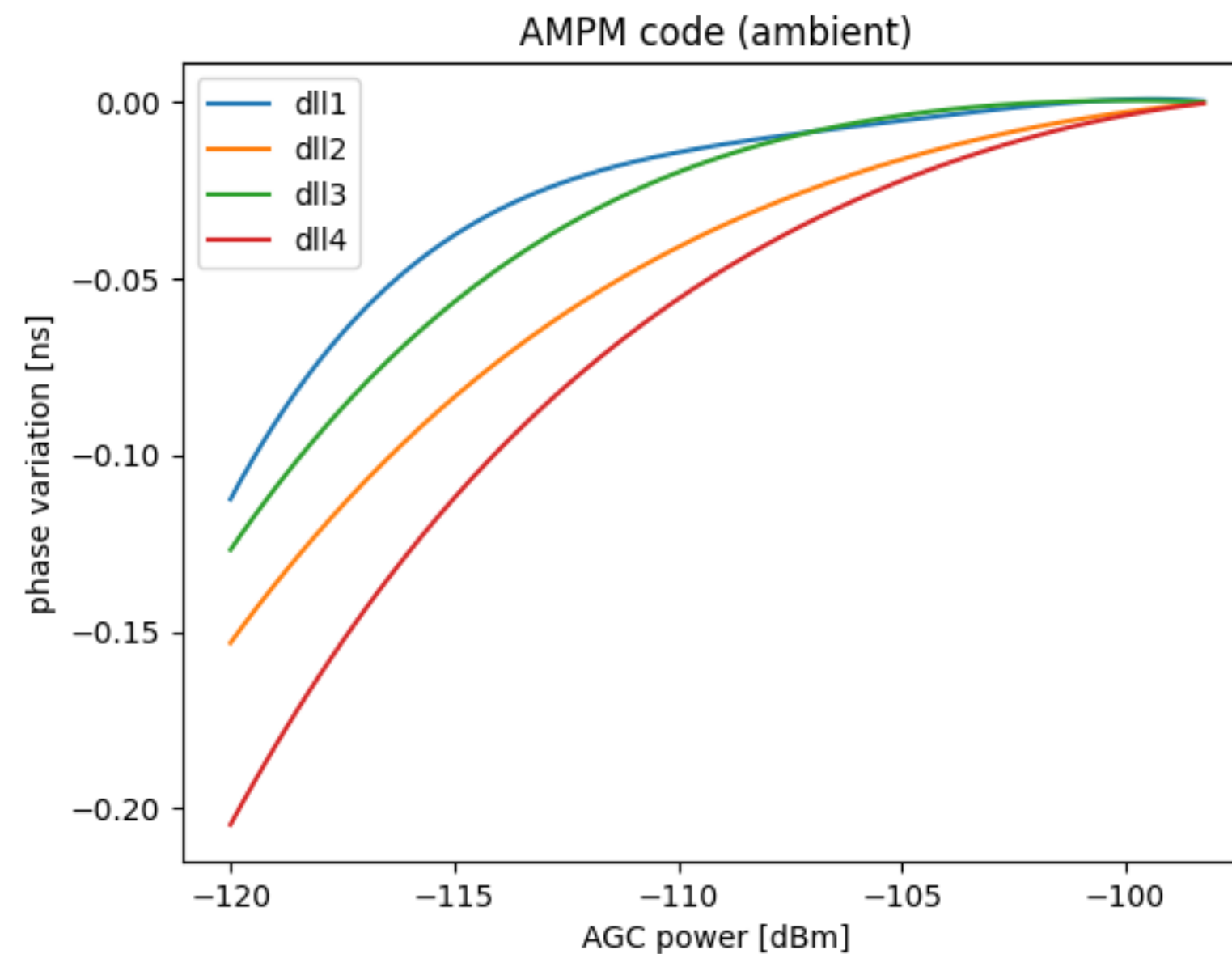
- Ku S offset (large)
- Phase windup (small)
- Phase pattern (small)

Impact of the dynamics on the DLL measurements:

- Group delay, induced by the Doppler (small)
- Doppler rate (small)

Instrumental effects:

- AMPM: impact of the received power on phase (large)
- Temperature variations (large)



PHARAO

- Zeeman effect: impact of B field on the atom transition of the clock ($\sim 10^{-13}$)
- Black body radiation: ambient thermal radiation induces a frequency shift ($\sim 10^{-14}$)
- Recoil shift: caused by atomic collisions with photons ($\sim 10^{-16}$)
- Atomic density ratio: Atomic density is N/V , difficult to estimate, but the ratio of 2 states can be precisely known (from 0 to 1).
- Collisional shift: induced by interactions between atoms during interrogation
- Doppler coefficient: relates the atom velocity to a frequency shift/broadening induced by the Doppler effect.