ACES

Laboratoire Temps Espace (LTE) as of 2025!

MWL data analysis at SYRTE

Marc Lilley on behalf of the Paris ACES DA team
P. Delva, C. Guerlin, C. Le Poncin Lafitte, F. Meynadier, E. Savalle, P. Wolf

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l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace
CNRS — dépasser les frontières
LNE — Sharing a passion for progress
UPMC — Sorbonne Universités

Outline

A. Mission overview and SYRTE MWL data processing software

- Gravitational redshift test (main focus of our group in Paris)
- ACES Measurement principle
- SYRTE processing software*

B. ADS MWL ground testing data analysis results (show case)

- Static End-to-End performance
- Dynamic End-to-End in common clock mode

C. MWL open issues

* F. Meynadier et al., CQG 3, 035018 (2018).
An MWL simulator and a scientific data exploitation software are also available
P. Delva et al., EFTF proceedings (2012), E. Savalle et al, CQG 24, 245003 (2019)
Theoretical work in L. Duchayne et al, A&A (2009)

Gravitational redshift test (earlier talk by C.S.)

Fractional frequency difference of ground and space clocks

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

Time evolution of proper time as a function of coordinate time

Gravitational potential difference

Velocities

Size of the effect in GR

$$\frac{\Delta U^{s-g}}{c^2} \sim 3.6 \times 10^{-11}$$

With ACES we shall measure the integral of this difference: $\delta(t)$

Deviations from GR

$$(1+\alpha)\frac{\Delta U^{s-g}}{c^2}$$

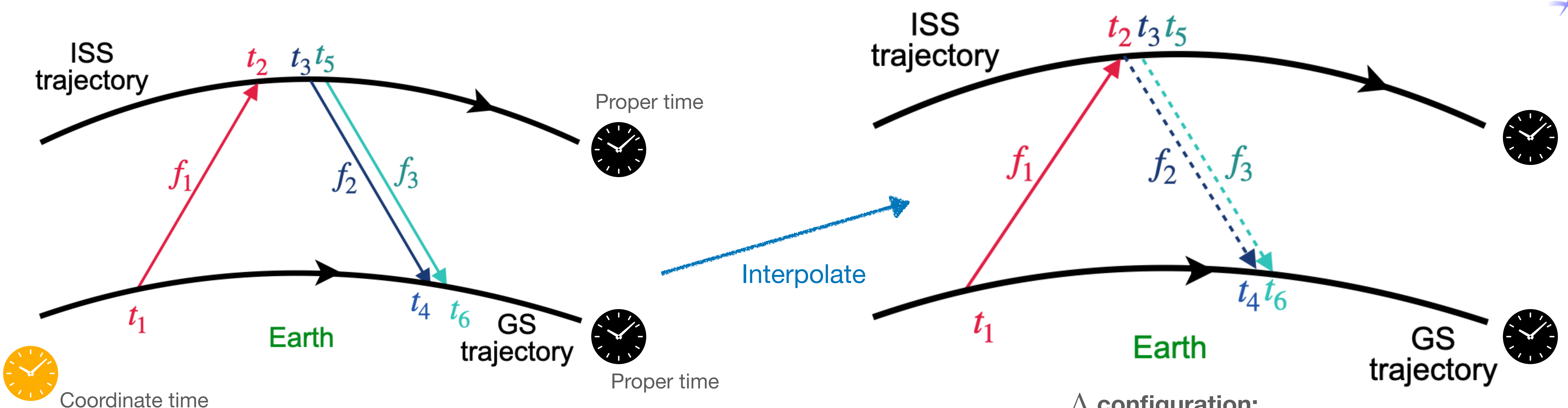
ACES relative frequency accuracy = 10^{-16}

ACES Allan deviation = $10^{-13}/\sqrt{\tau}$

Yields constraints on α at the 10^{-6} level.

The MicroWave Link (MWL) enables the space clock (PHARAO) to ground clock comparisons

ACES measurement principle



Aynchronous measurements

Λ configuration:
Minimisation the error from the uncertainty on ISS orbitography

Pseudo-ranges for Ku band

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

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

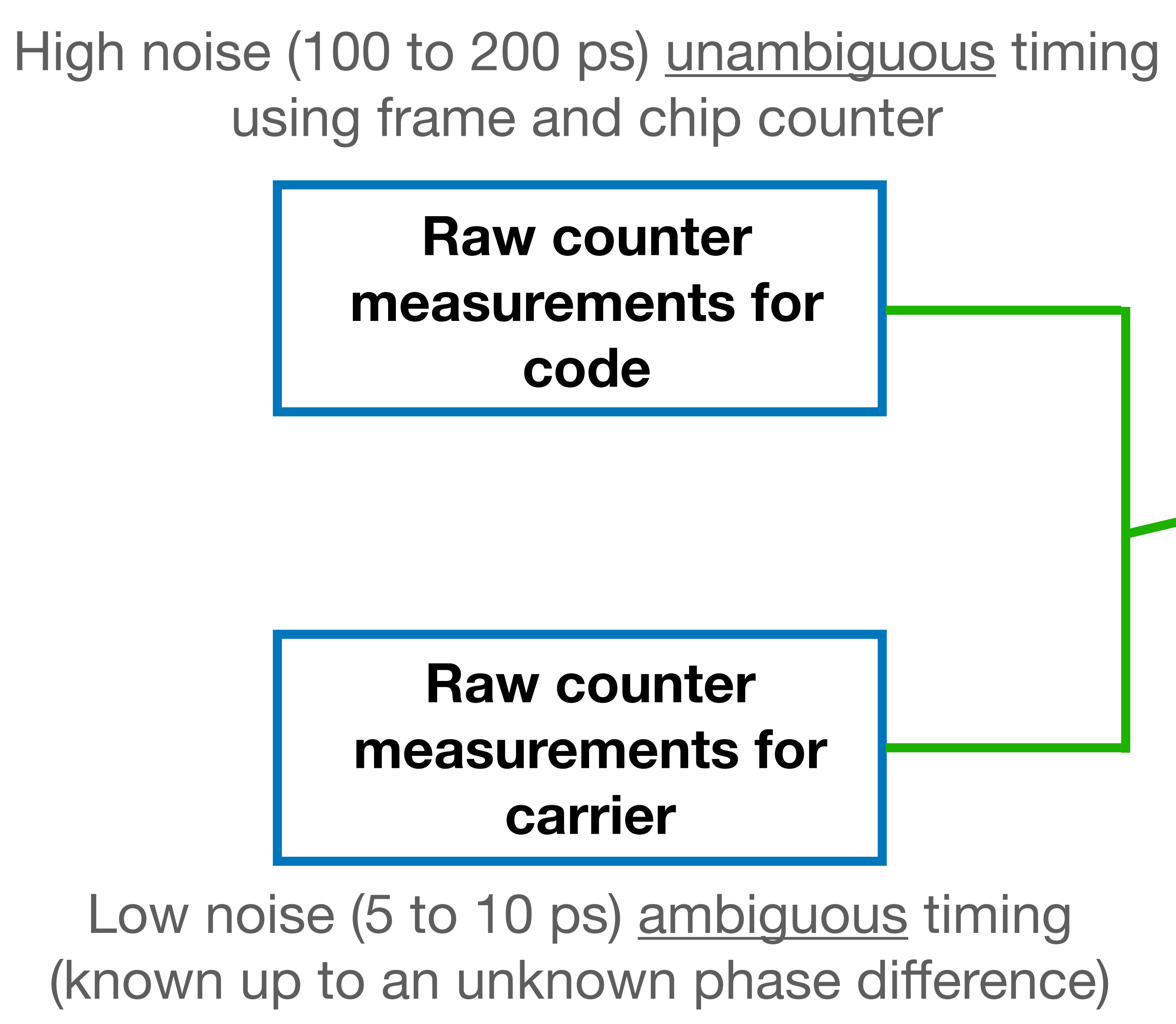
Desynchronisation from the two-way combination in the Λ config

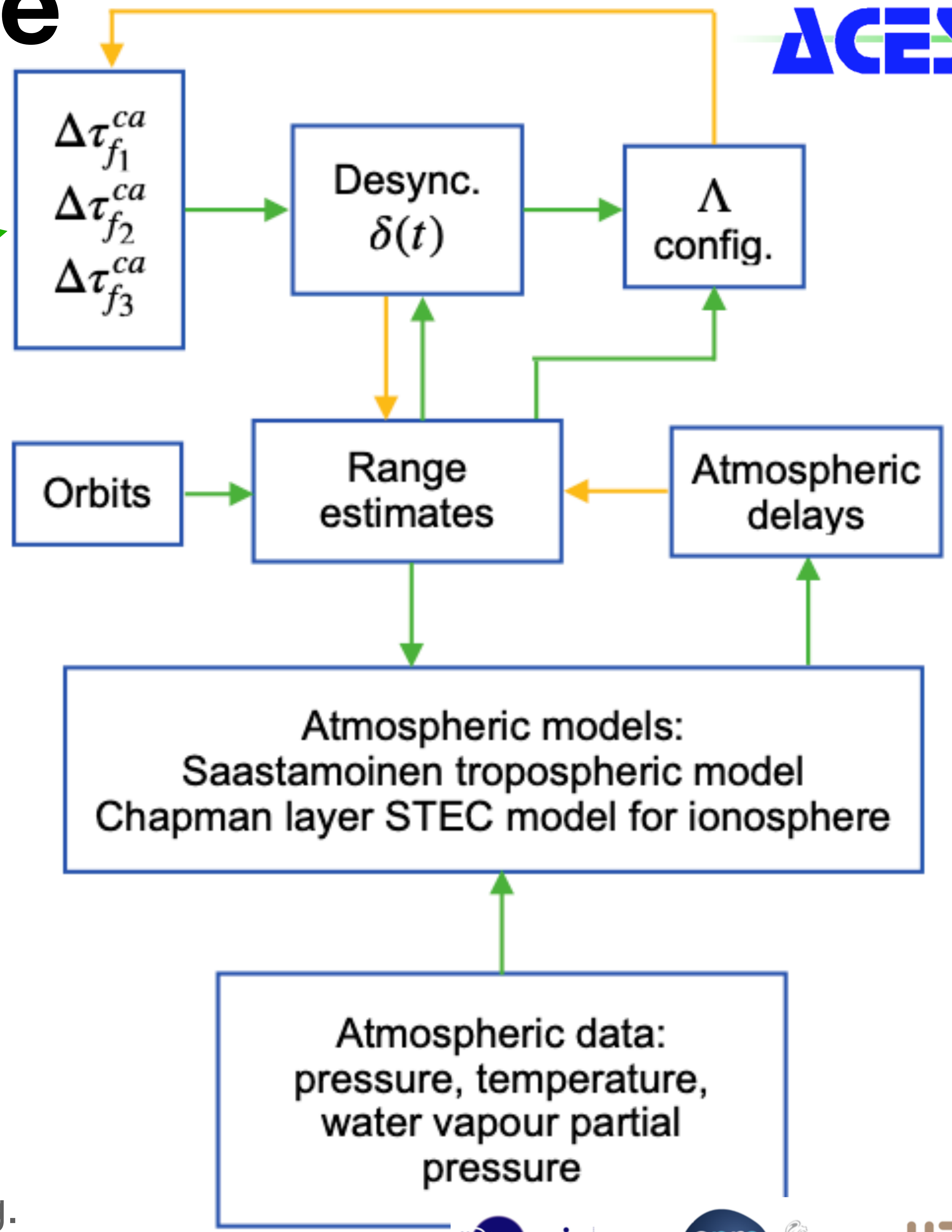
$$\delta(t_2) = \frac{1}{2}\left[\Delta\tau^g(\tau^g(t_4)) - \Delta\tau^s(\tau^s(t_2)) + (T_{34} - T_{12})^g\right] + \Delta^{\text{int}}$$

ACES — ACES — models + orbits

Coordinate transformation to ground clock proper time

SYRTE Processing software

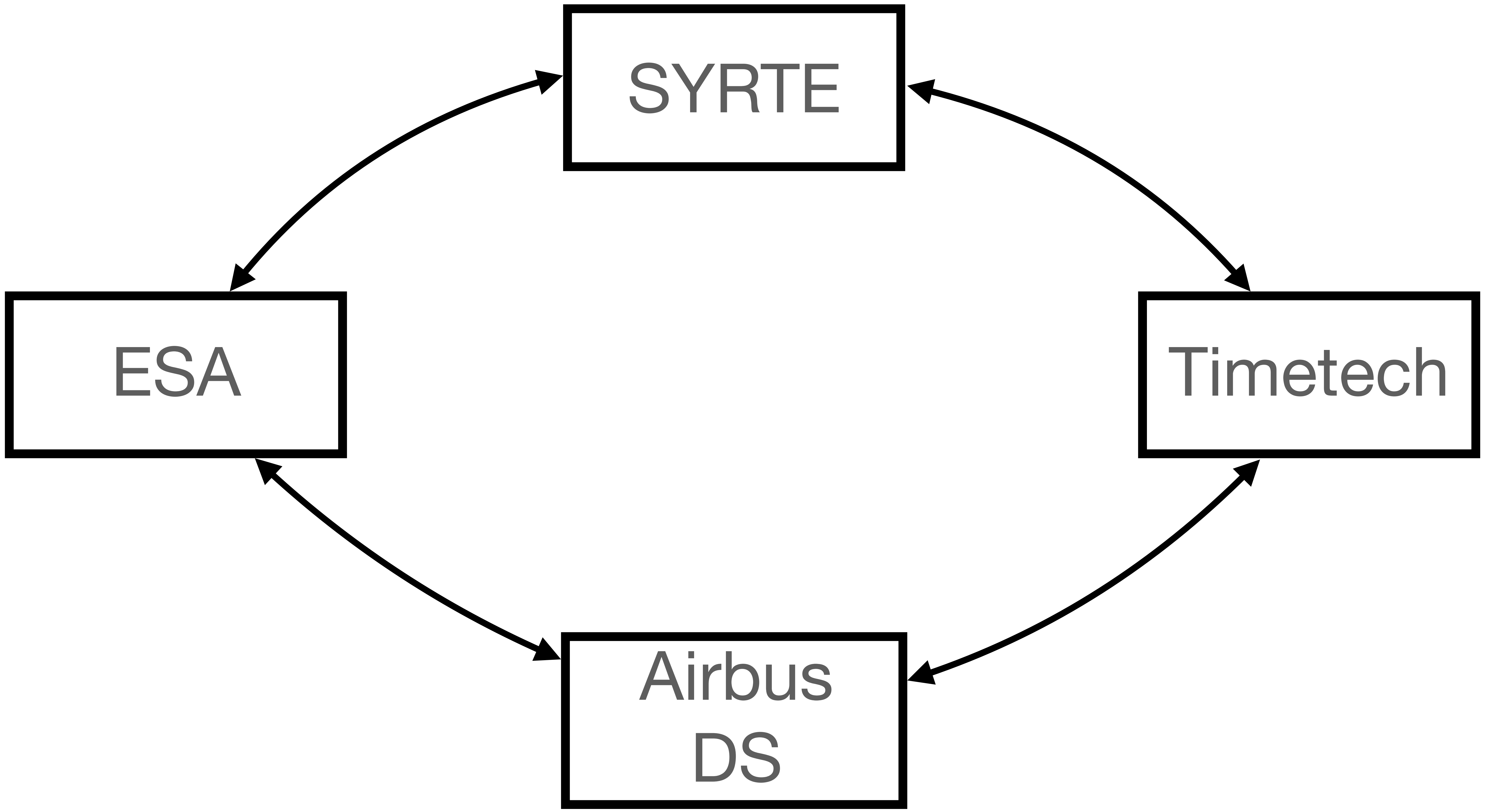




Processing steps

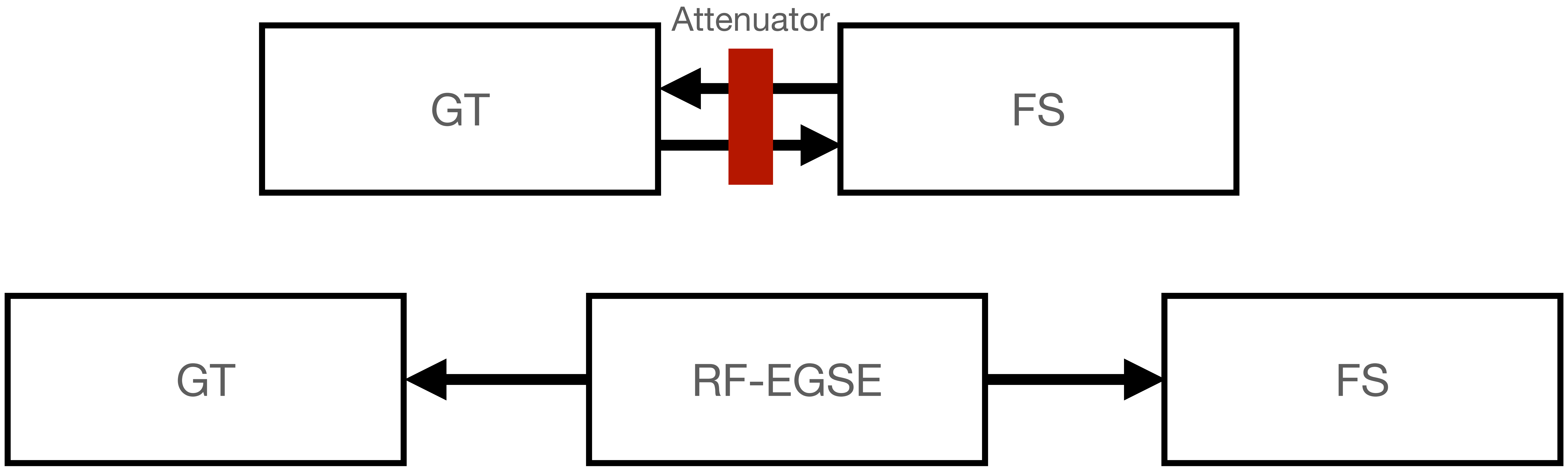
1. Compute pseudo-ranges
2. Compute range (no atmospheric corrections)
3. Compute atmospheric corrections using range
4. Refine range estimates
5. Compute desynch in non-Λ config.
6. Deduce Λ config time shift
7. Shift uplink (or downlink) pseudo range data by Λ time shift
8. Re-compute ranges, atmospheric delays, and desync in Λ config.

E2E data analysis

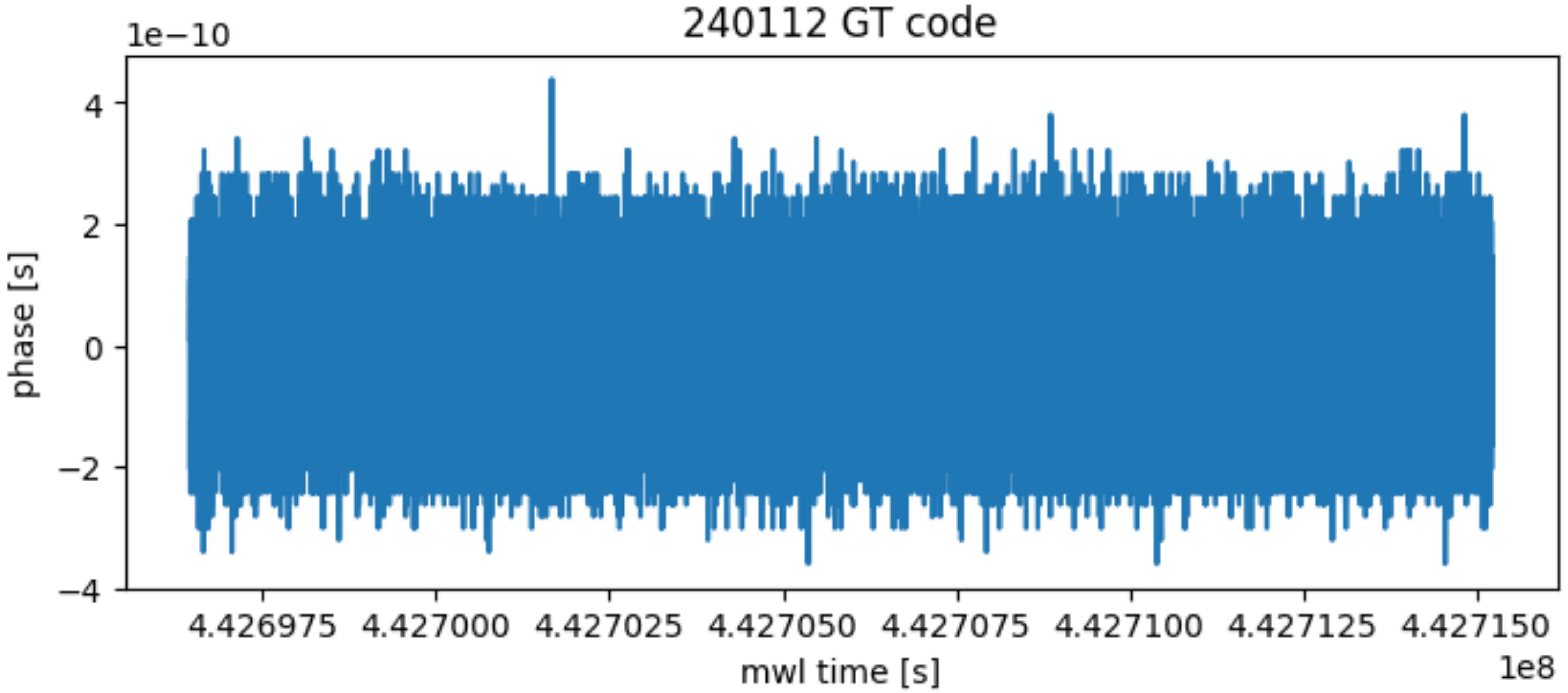


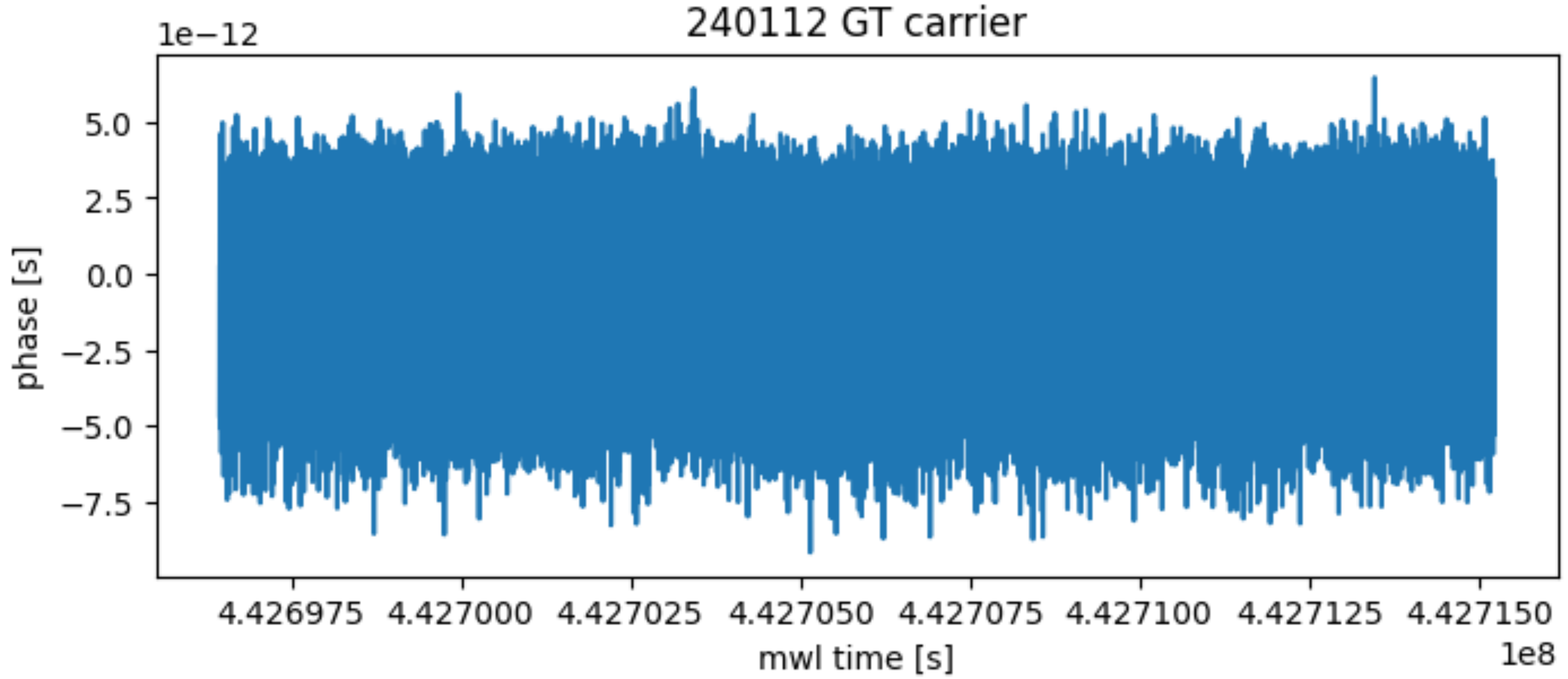
Static End-to-End performance

- Long term time deviation of GT and FS
- Long term linear phase drift of GT and FS
- Two configurations:



Run of 12/01/24 FS to GT (5.2 hrs)



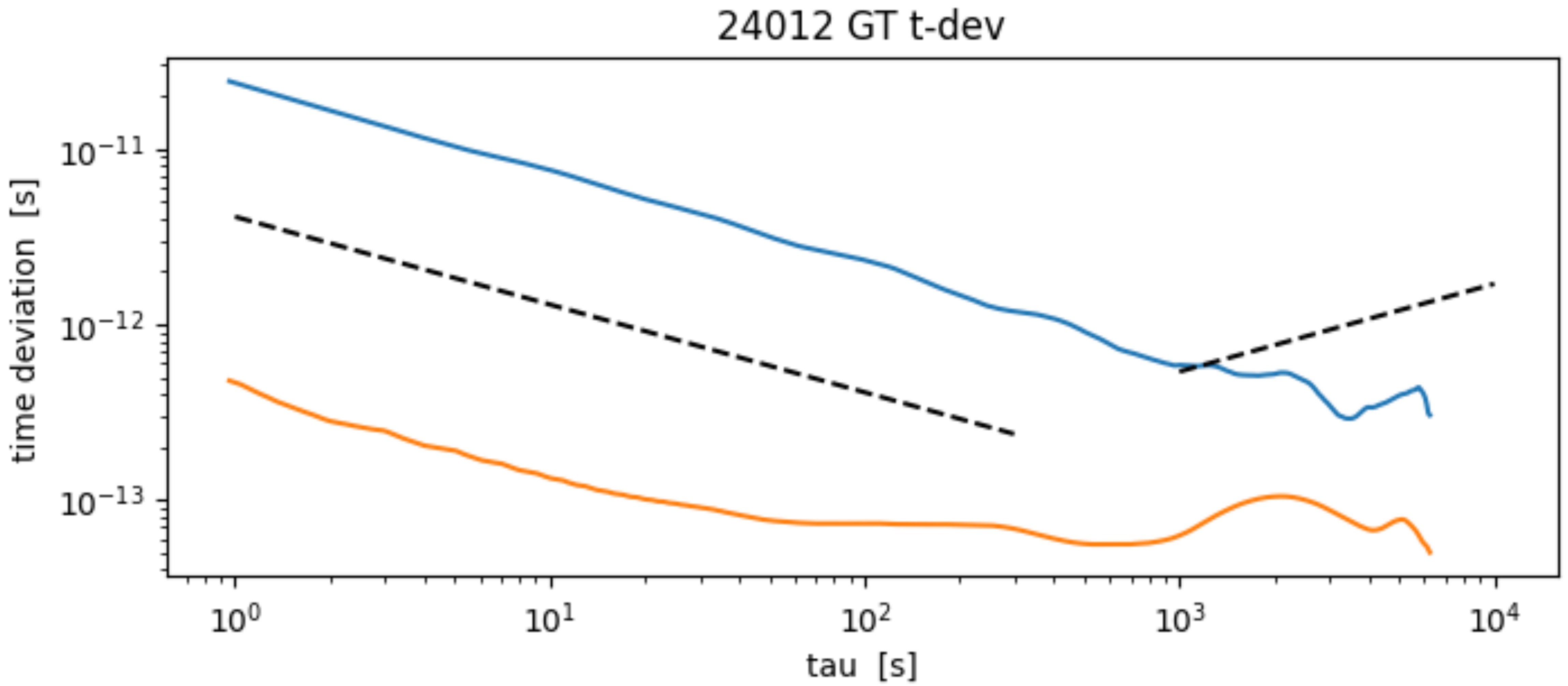


Code noise ~ 400 ps peak-to-peak

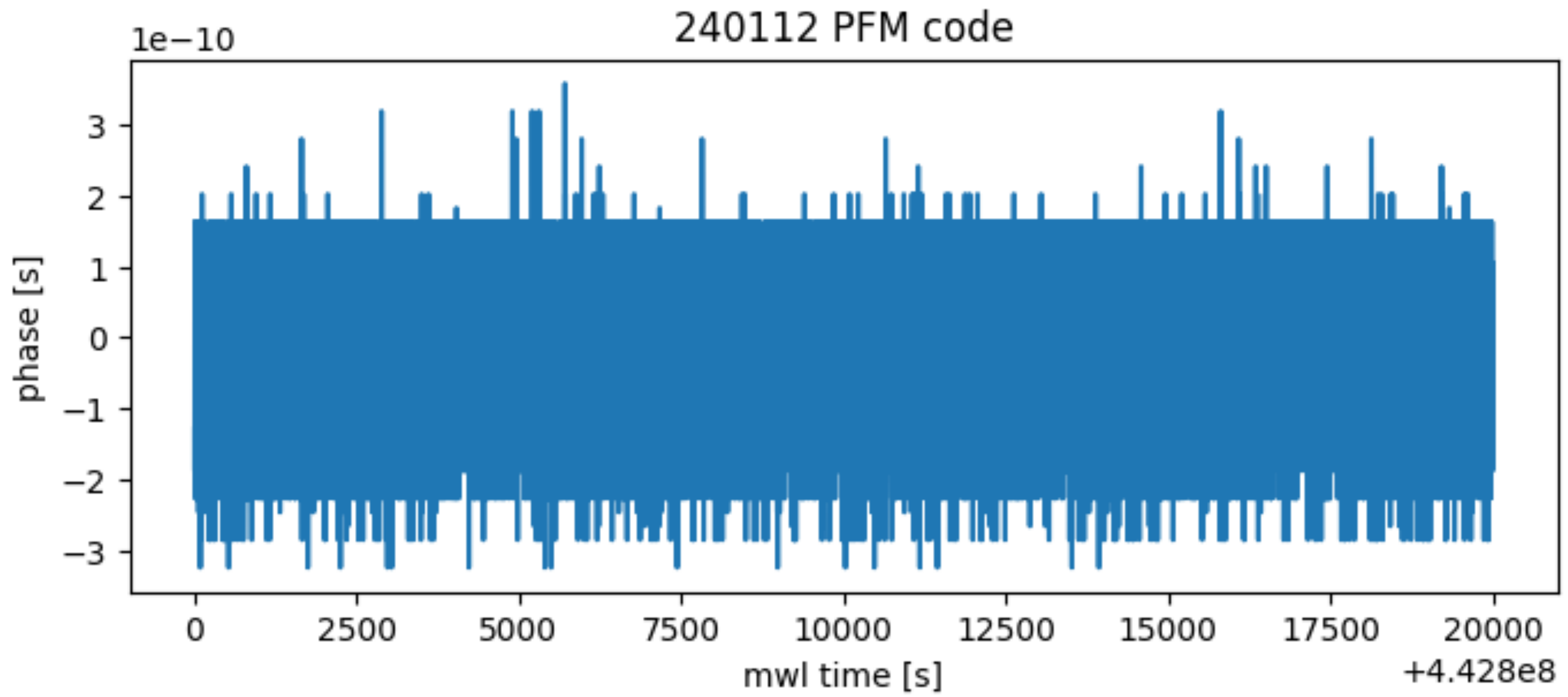
Code drift ~ -1.4E-16 s/s (+/- 3E-17)

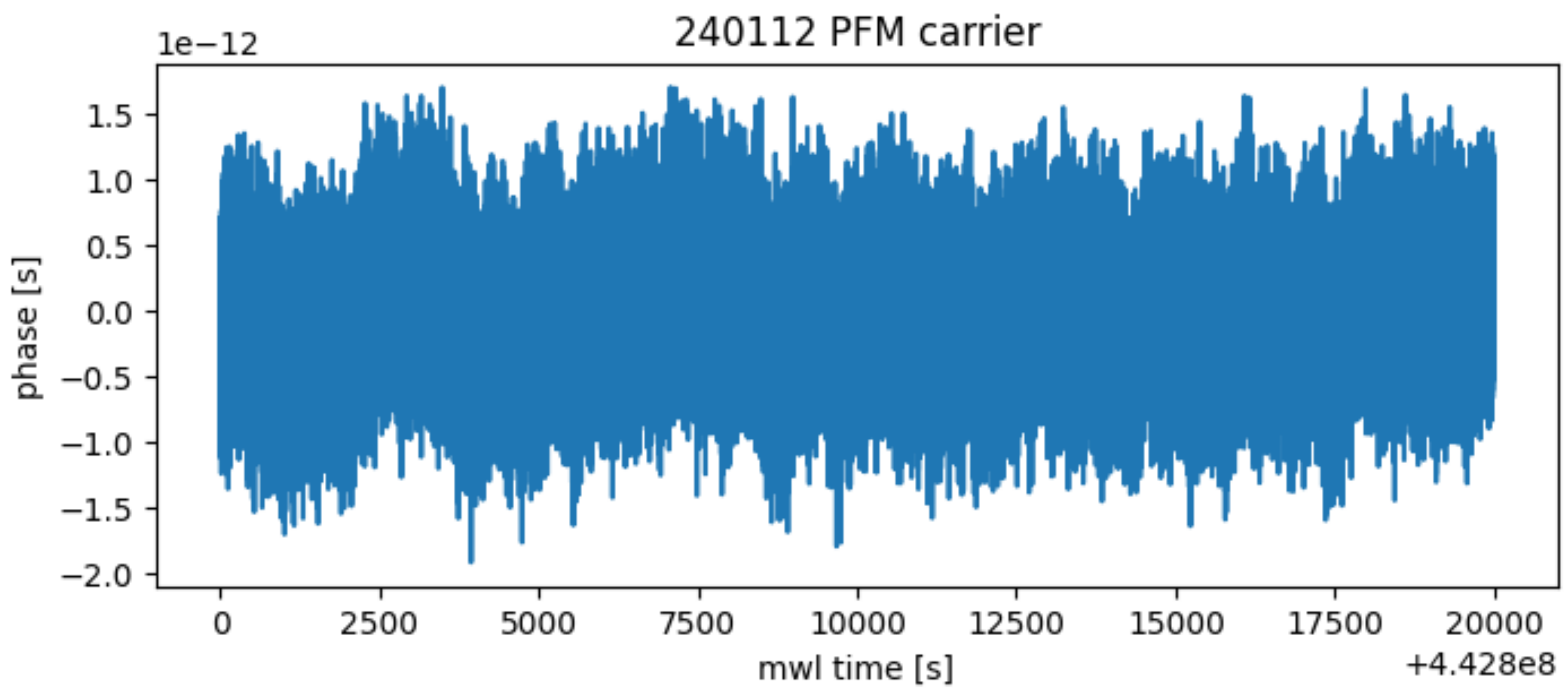
Carrier noise ~ 10 ps peak-to-peak

Carrier drift ~ -1.1E-17 s/s (+/- 6E-19)



Run of 12/01/24 GT to PFM (5.5 hrs)



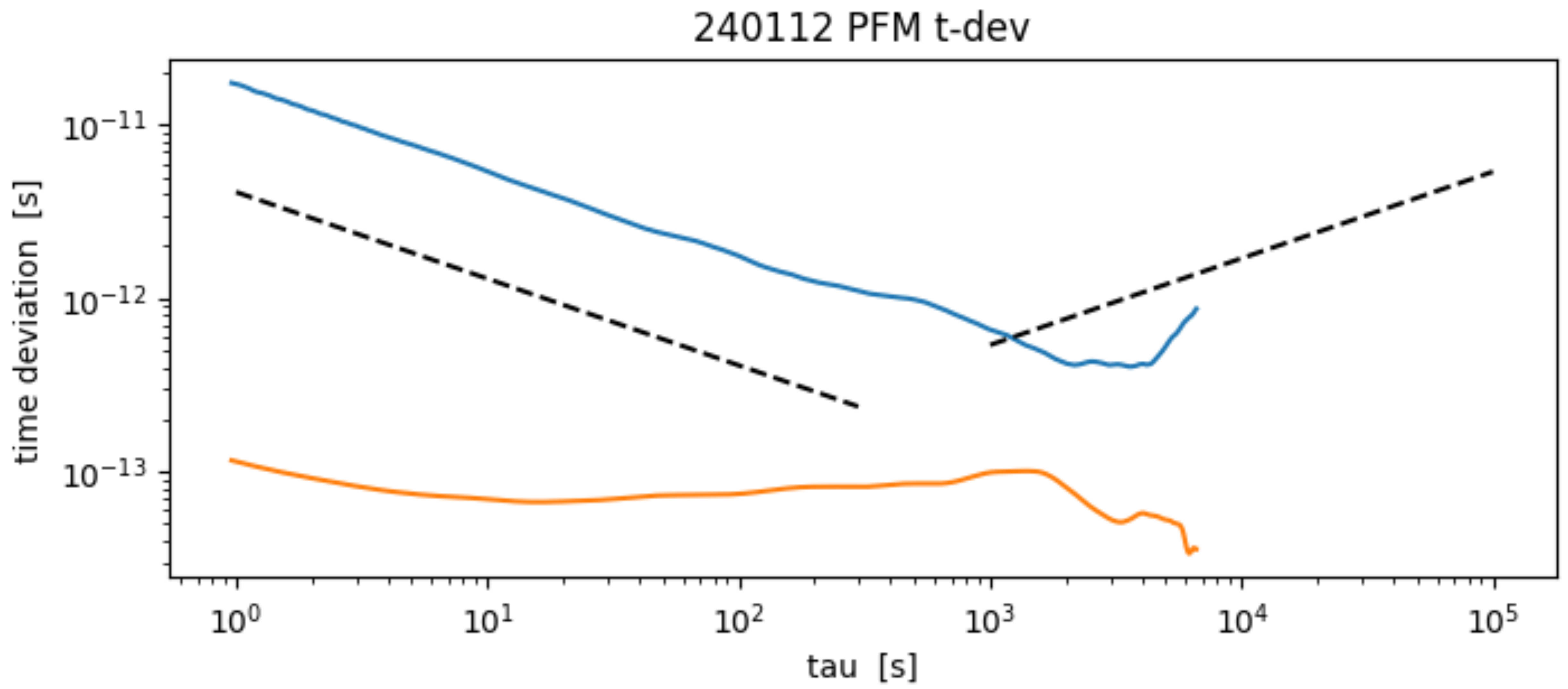


Code noise ~ 400 ps peak-to-peak

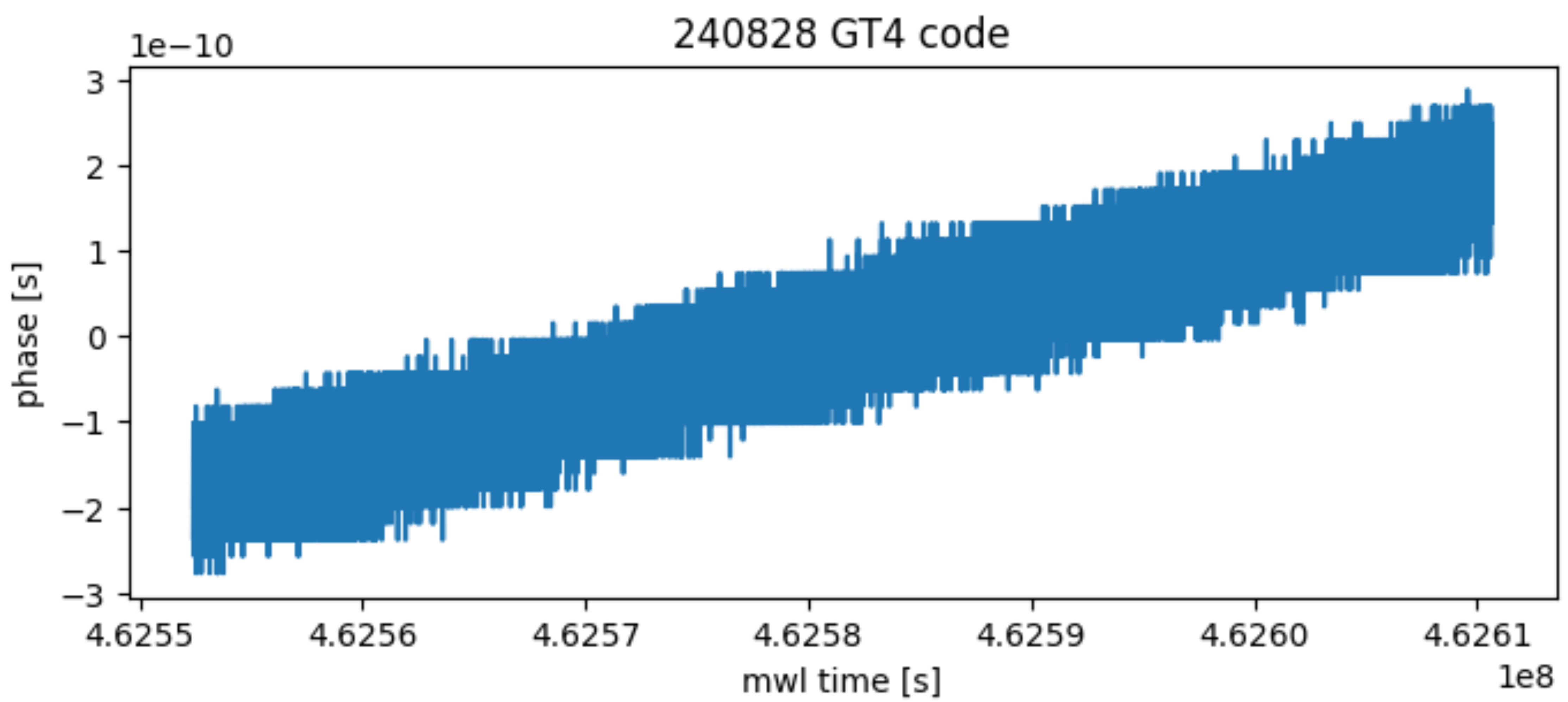
Code drift ~ 3.0E-16 s/s (+/- 2E-17)

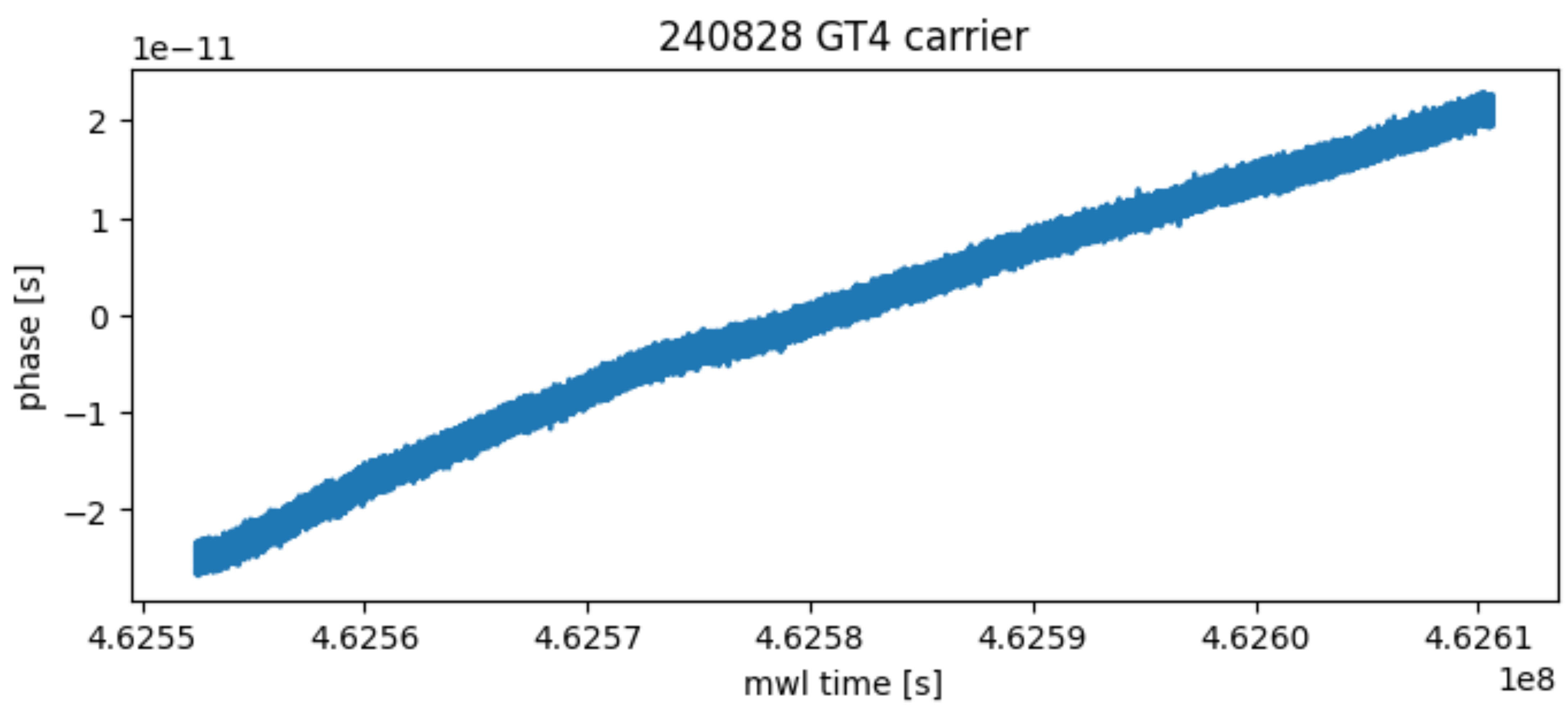
Carrier noise ~ 2 ps peak-to-peak

Carrier drift ~ 4.8E-18 s/s (+/- 1E-19)



Run of 28/08/24 EGSE to GT (16 hrs)



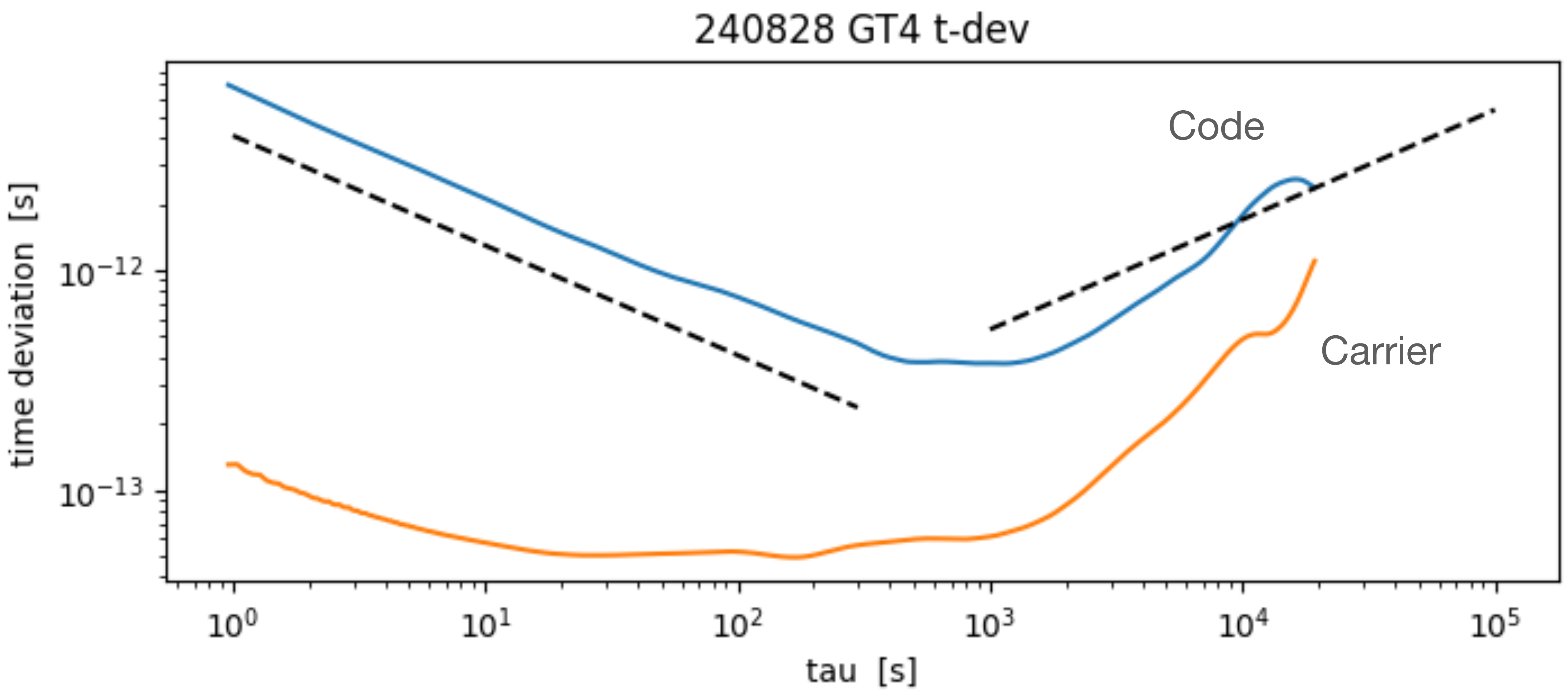


Code noise ~ 200 ps peak-to-peak

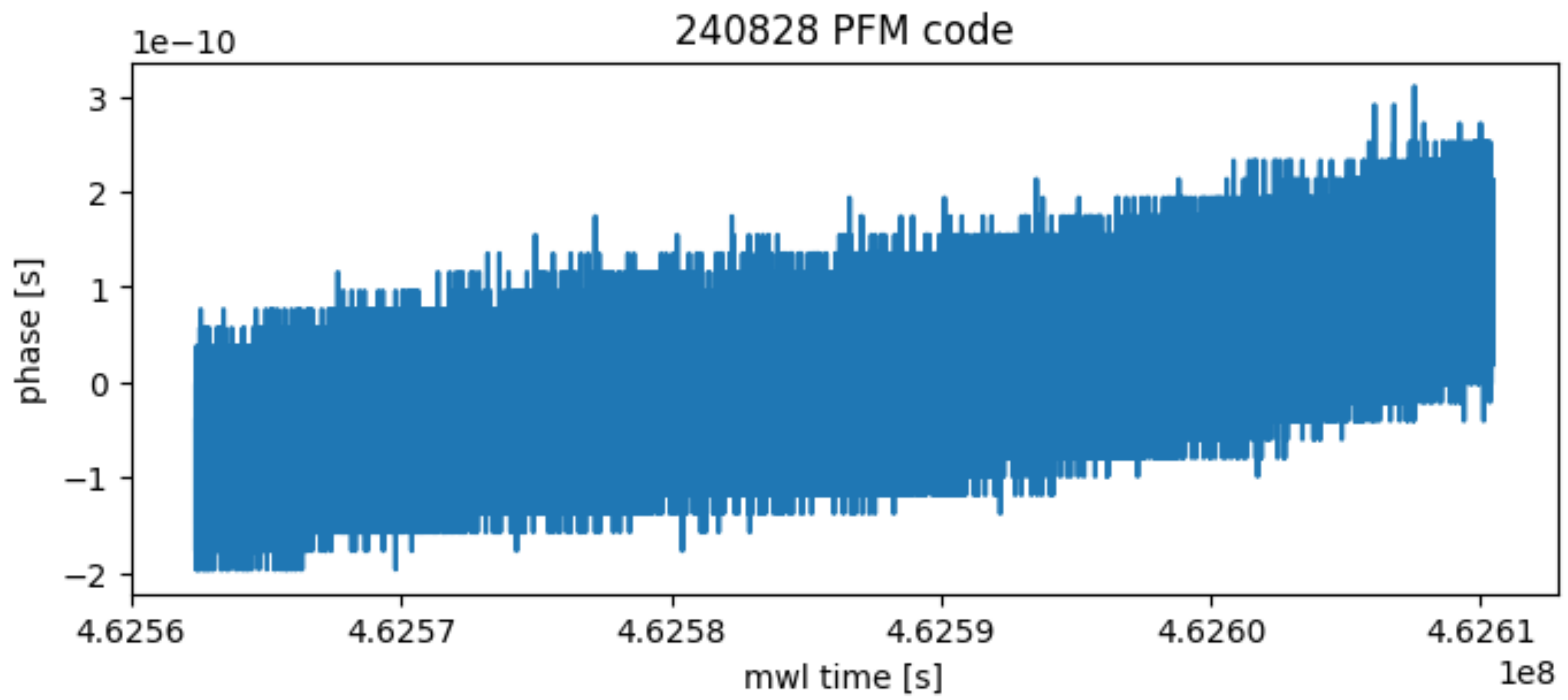
Code drift ~ 6.2E-15 s/s (+/- 1E-18)

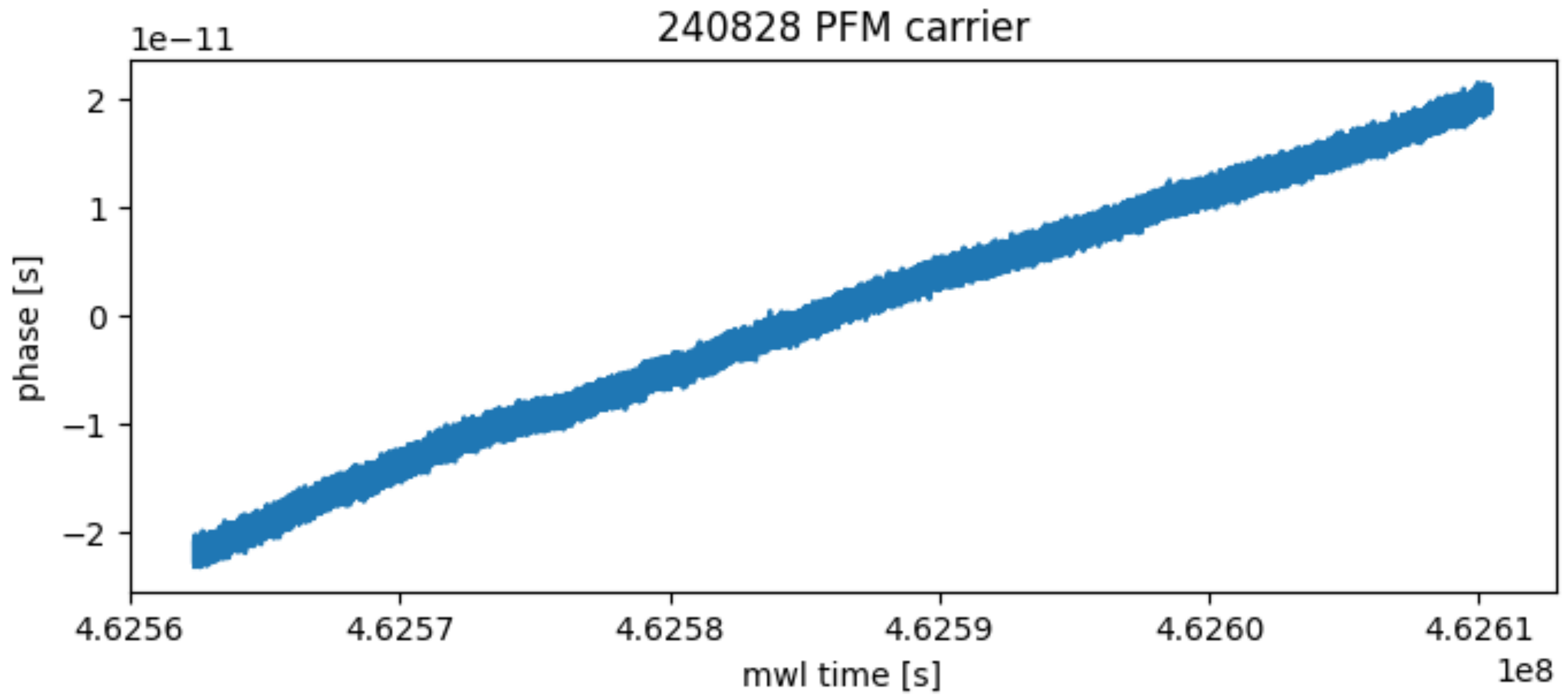
Carrier noise ~ 2.5 ps peak-to-peak

Carrier drift ~ 7.3E-16 s/s (+/- 8E-20)



Run of 28/08/24 EGSE to FS (13 hrs)



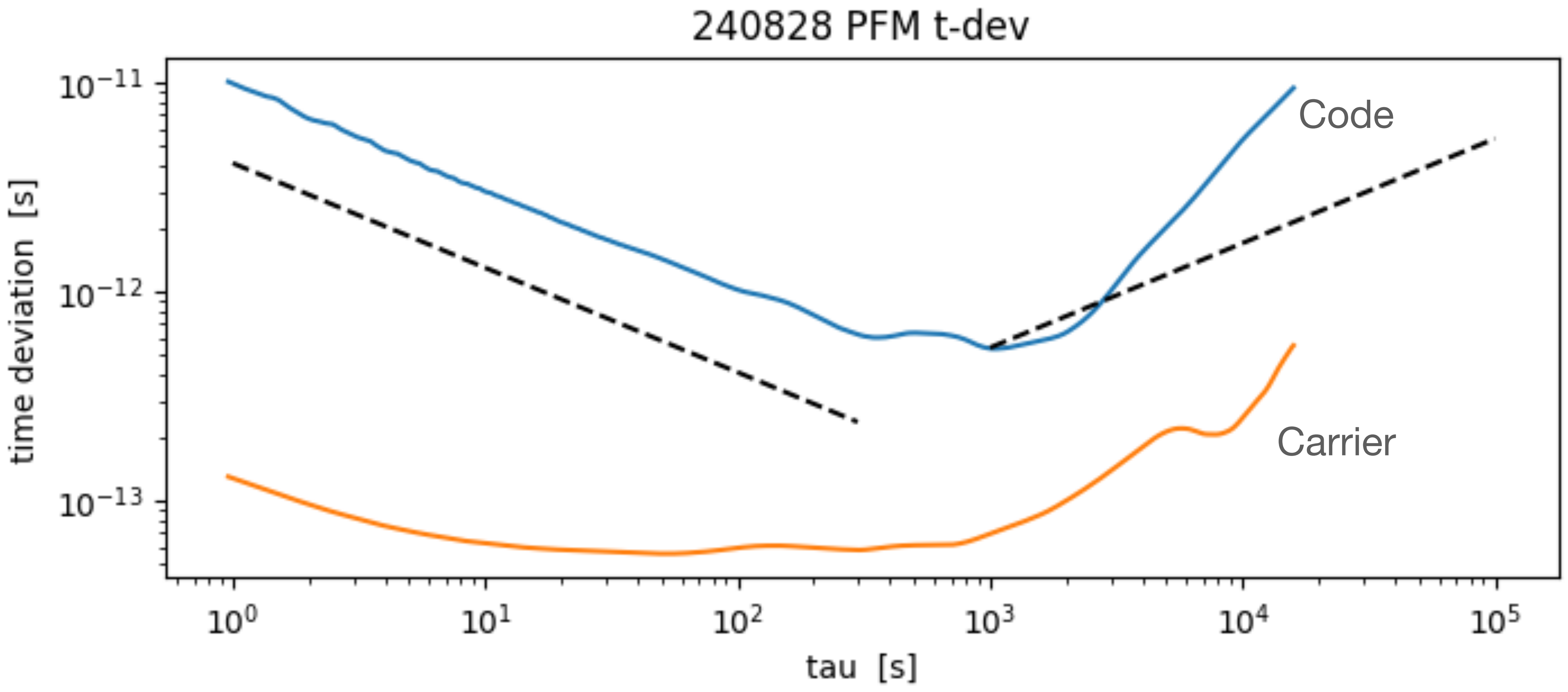


Code noise ~ 200 ps peak-to-peak

Code drift ~ 3.5E-15 s/s (+/- 3E-18)

Carrier noise ~ 2 ps peak-to-peak

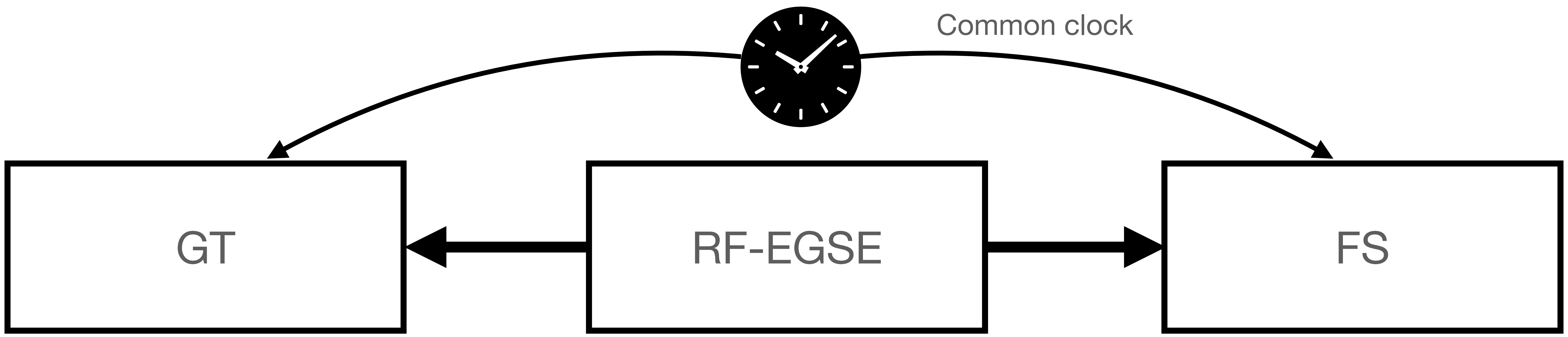
Carrier drift ~ 8.5E-16 s/s (+/- 6E-20)



Take-away on static runs

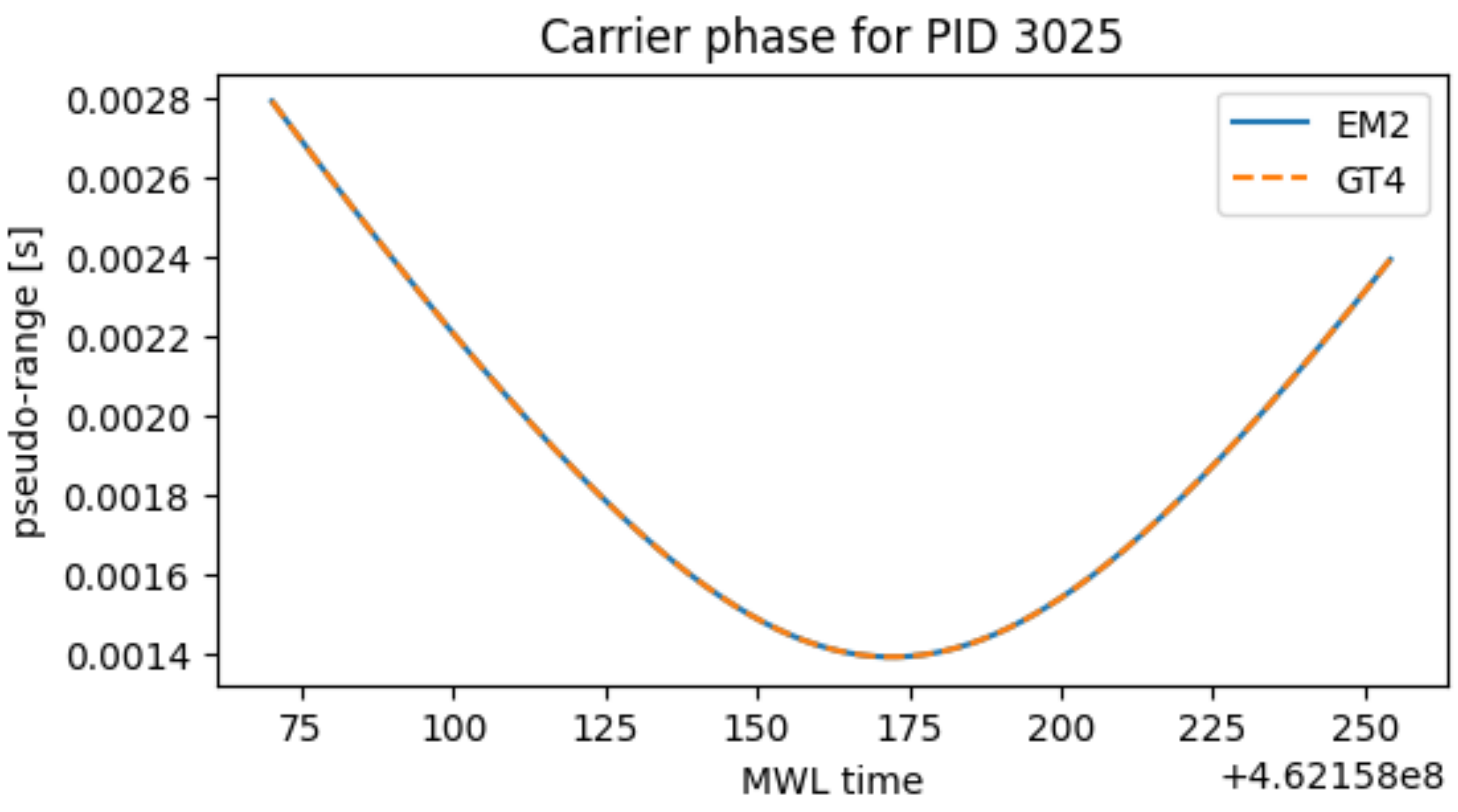
- In the absence of the EGSE, for static runs on the PFM and GT, the residual drift is better than 1E-17 s/s on the carrier for a few hrs of data acquisition.
- In the presence of the EGSE, for static runs on the PFM and GT, the residual drift is at the few times 1E-16 s/s level on carrier for up to 15 hrs. This result has been repeated twice in 2024 (15/03/24 and 28/08/24).
- The larger drift in the presence of the EGSE is consistent with expectations.
- The t-devs on the carrier are in specs on all runs.
- Another very long term measurement on the PFM without the EGSE is necessary in order to make an accurate measurement of the frequency offset.

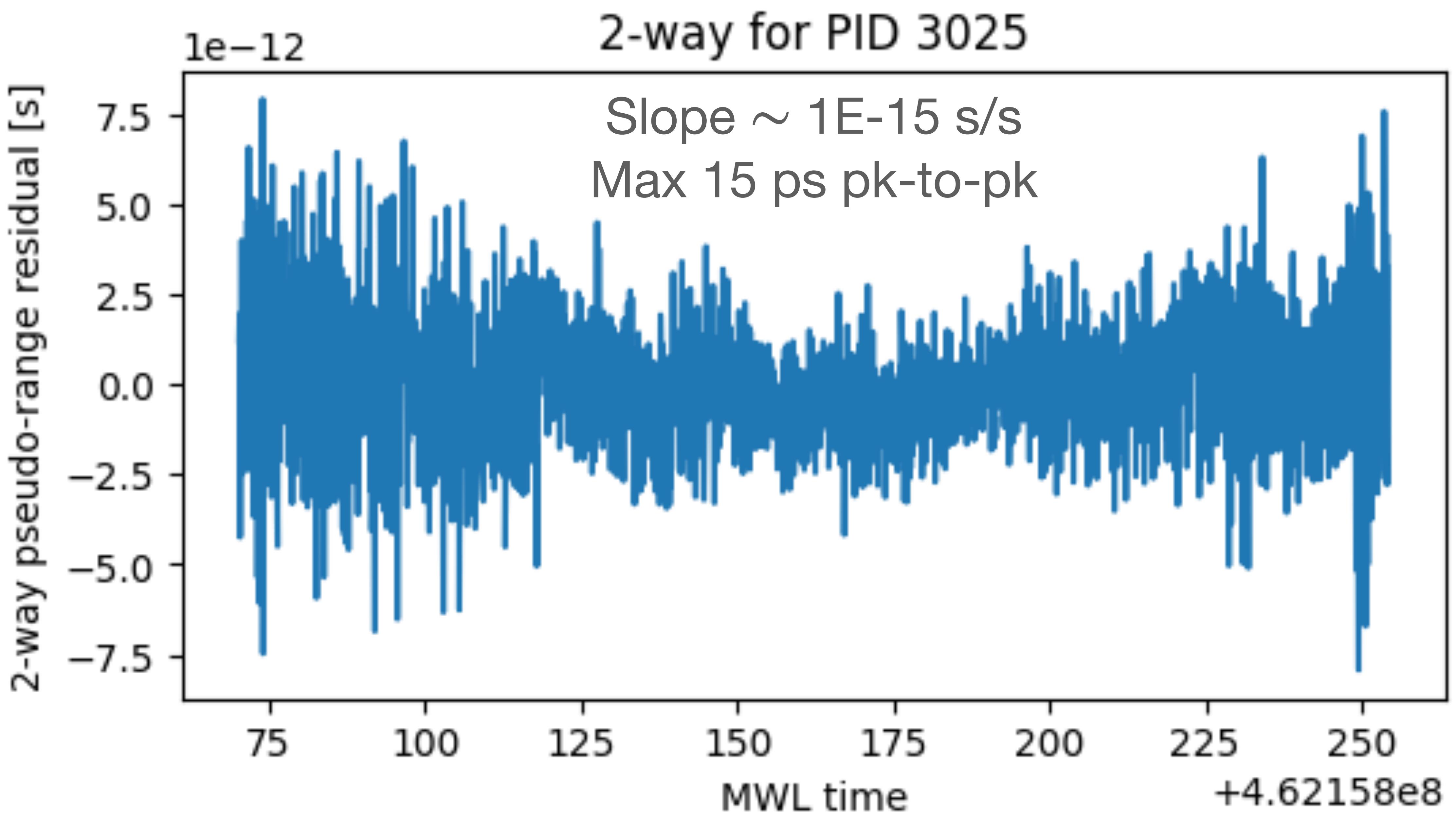
Dynamic End-to-End 24/08/24



- 25 out of 29 good passes (GT and FS locks) for EM2 DLL1 and GT4 DLL1 ✓
- Good two-way performance on each pass ✓
- Ambiguity resolution achieved successfully ✓
- Cycle slip removal on the two-way combination ✓
- 24h t-dev computed ✓

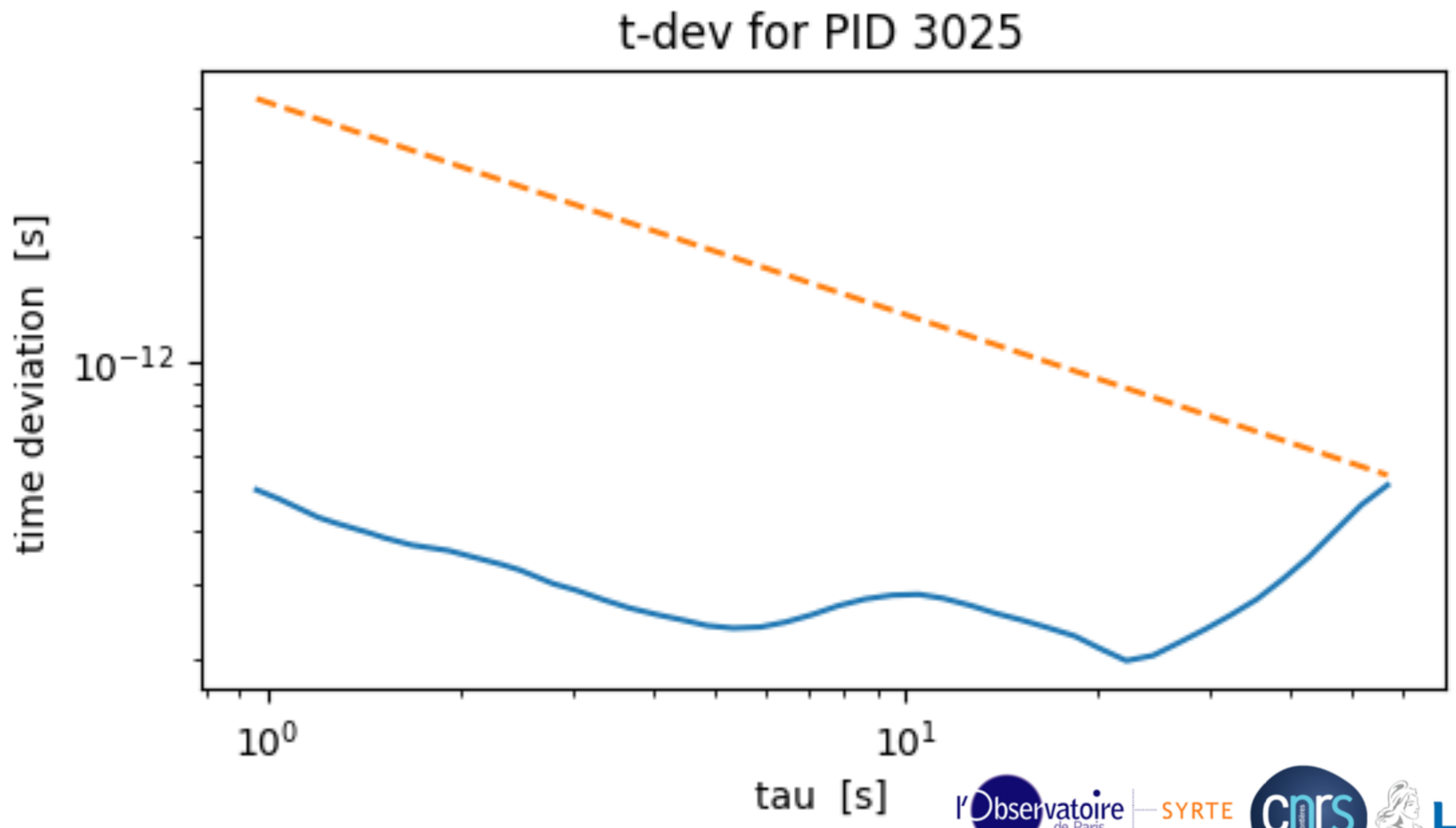
Single pass



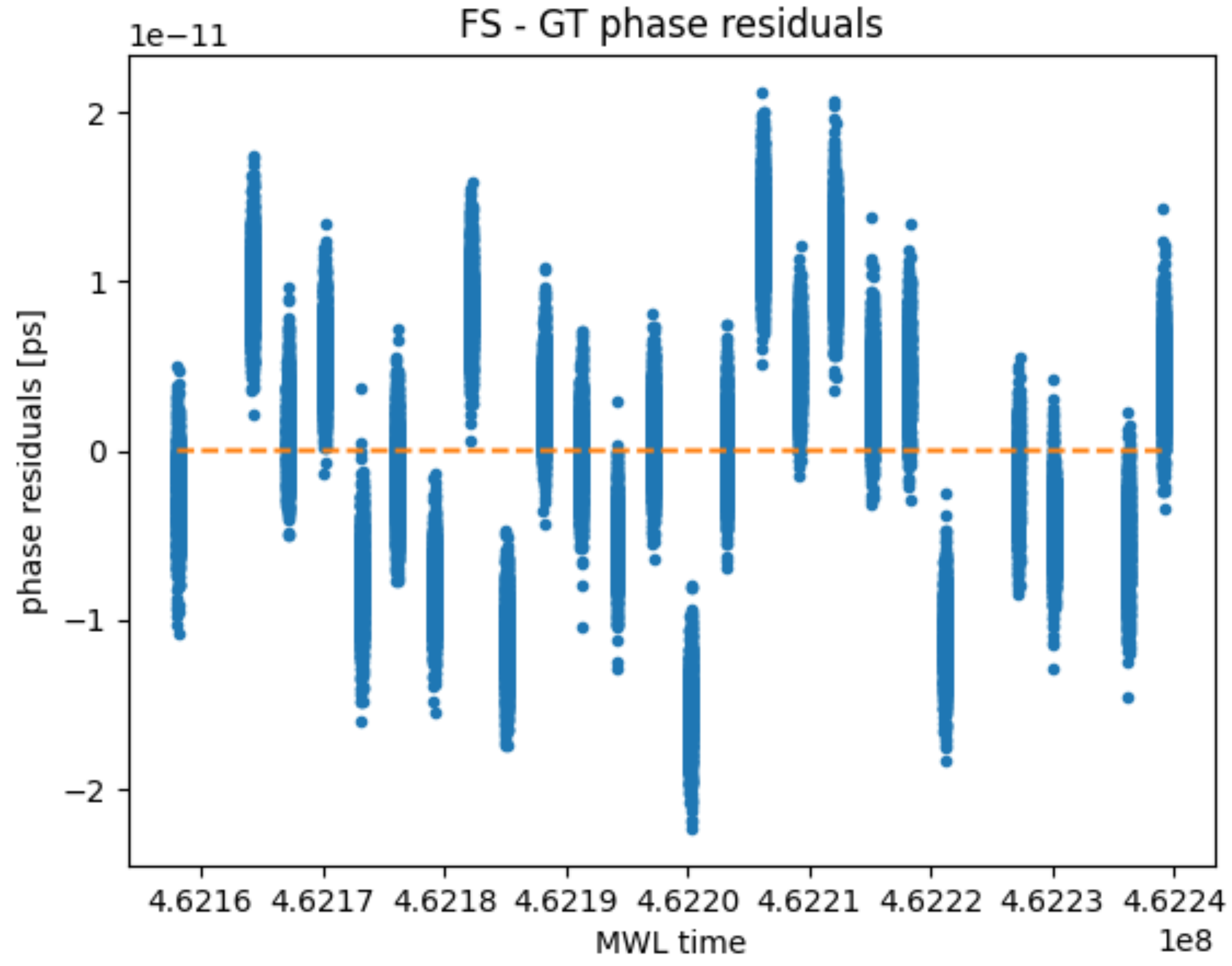


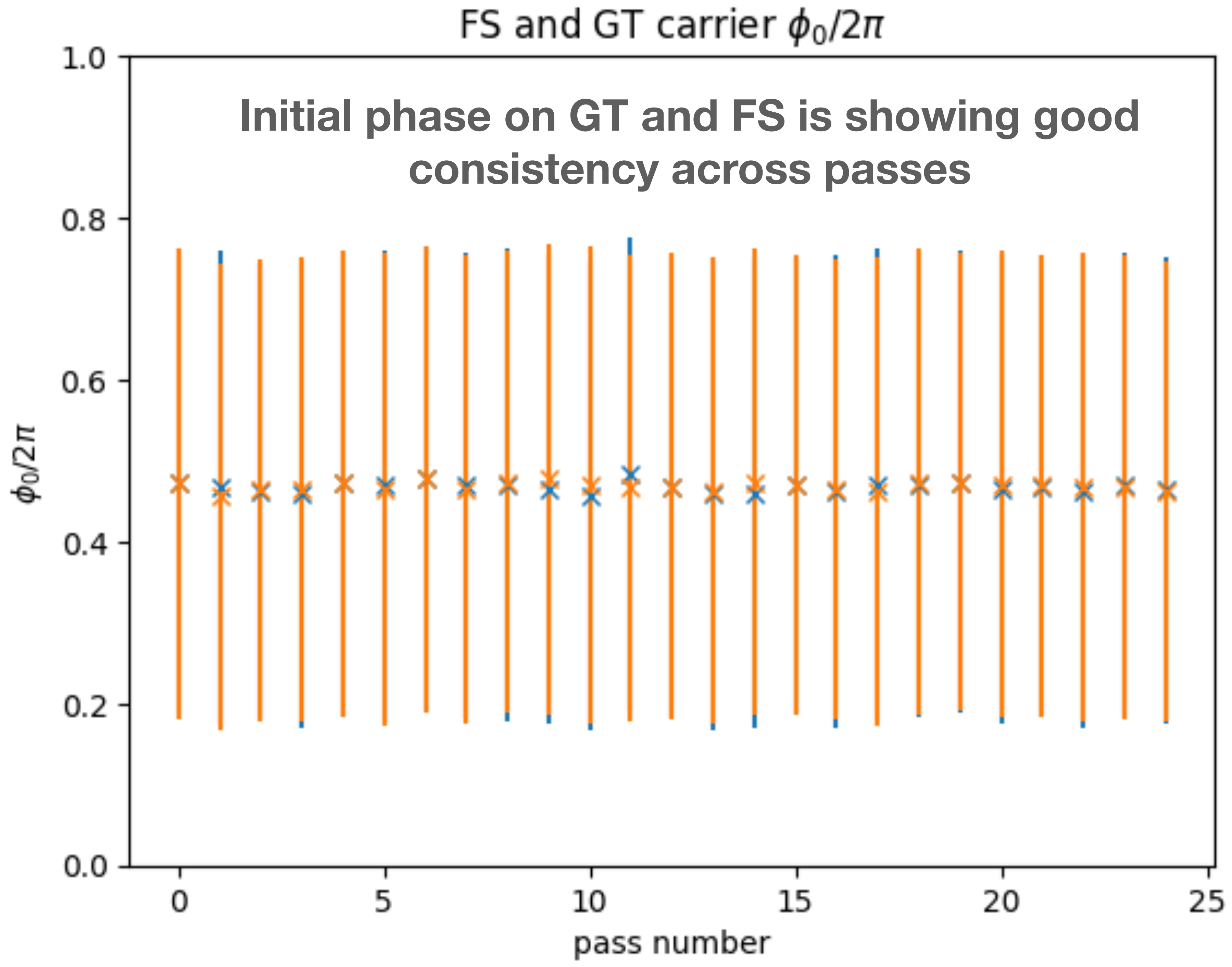
No corrections from any calibration curves were applied.

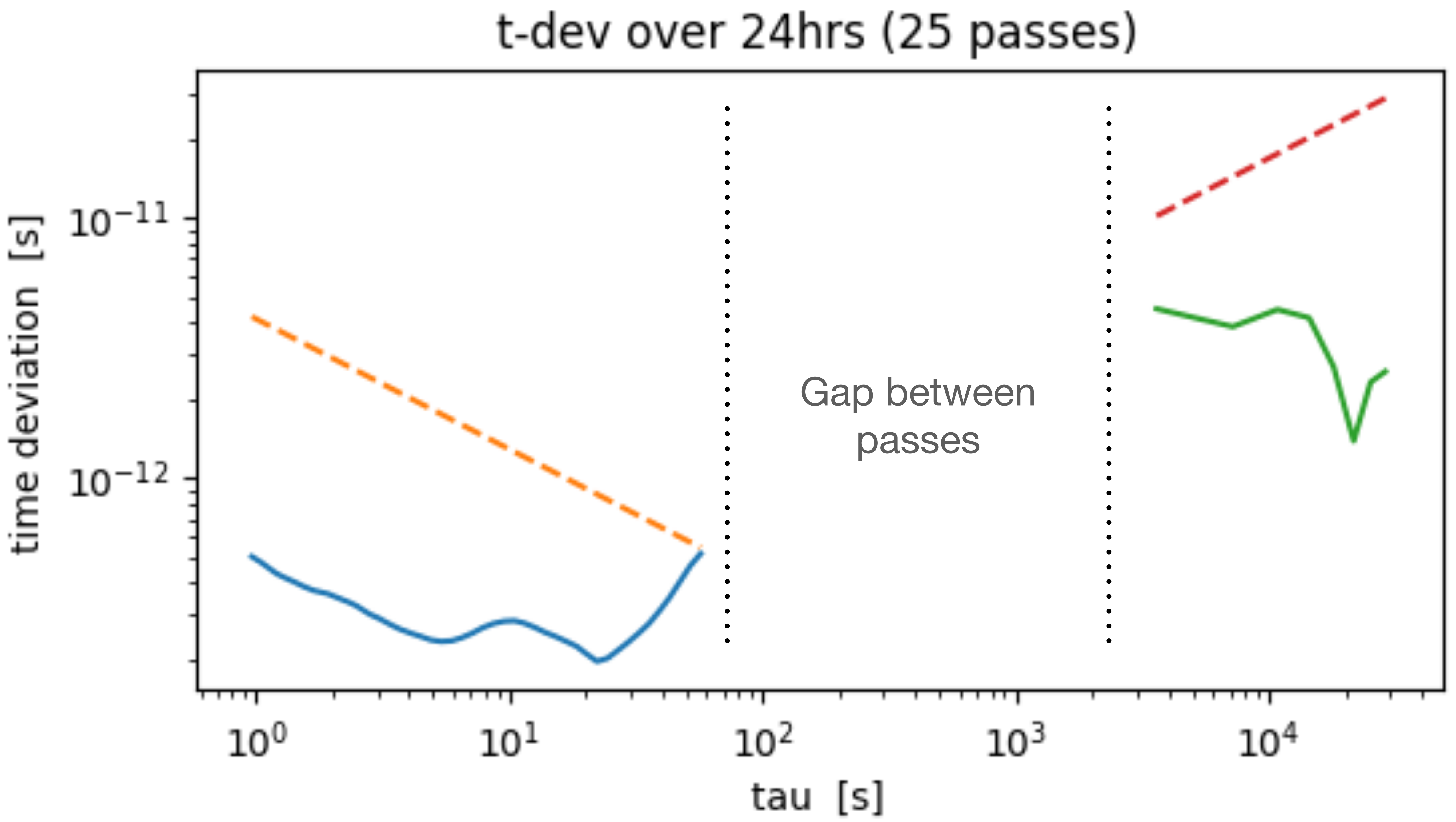
Calibrations curves not yet available!



All passes







Typical peak-to-peak noise = 15 ps
(note: this includes low power regions of the pass)

Phase drift = -5E-20 (+/- 1E-18) s/s

Take-away on Dynamic End-to-End 24/08/24

- This test run was successful, with a good locking statistics: 24 of 29 passes ✔
- The two-way residuals for each pass are within specs ✔
- Carrier cycle slips (not shown) can be consistently identified and removed ✔
- Ambiguity resolution shows good carrier phase continuity ✔
- The t-dev over 24hrs is well within specs ✔
- The residual phase drift over 24 hrs is at the level of 5.0E-20 (+/- 1E-18) s/s ✔

Remaining issues (see earlier talk by L. C. For more)

- **Calibrations**
  - AMPM calibration for PFM (existing data not useable)
  - Group delay calibration for PFM (analysis pending)
  - Temperature calibration for PFM (analysis pending)
  - Doppler rate delay calibration for PFM (existing data not useable)
  - Others…
- **Other major bugs**
  - Dual clock tests (data not understood)
  - Noise spikes at the 100 ps level in many recent Dynamics E2E data sets (now *possibly* solved!)
- **Reproducibility**
  - Reproducibility is unfortunately lacking. The data of 24/08/24 is not representative.

Conclusions

- **SYRTE software**
  - A MWL data simulation software, a MWL data processing software, and an ACES data scientific exploitation software.
  - Both the data processing and data scientific exploitation software will require adjustments (data quality checks, calibrations, carrier cycle slip and outlier mitigation, others…) once a complete set of useable test data is provided in the right format.
- **Test data analysis**
  - Recent static tests show good long term performance
  - A recent dynamic test shows good short performance and good performance over 24hrs
  - A number of calibrations are still pending, some outstanding problems, reproducibility.

If resolved robustly, things could start looking good for ACES.