

BOB VAN VALZAH, JULY 9, 2026

# SUB-NANO AT HOME W/GNSS & AI

No Atomics Required

**BACKGROUND**



# BOB CONTEXT

- Retired from low-latency trading June 2025
  - Trading required precise event timestamping
  - No more bosses to give me interesting problems to solve
  - I gave myself a problem to solve: Precise GNSS timekeeping for datacenters
- 
- Fifty slides have more detail than time allows
  - QR code for on-line version at the end
  - Focus on the visuals and the story
- 
- Saw paradoxes mentioned at STAC last fall

# PARADOX ONE

## GNSS Clock



### Key Features

- < 15 ns RMS to UTC (USNO) through GNSS

15 ns

“Call for quote”

## GNSS Lawnmower



30 ps

\$1,575



Art?



Life Imitating art?



Credit: Aaron Foo of FMADIO

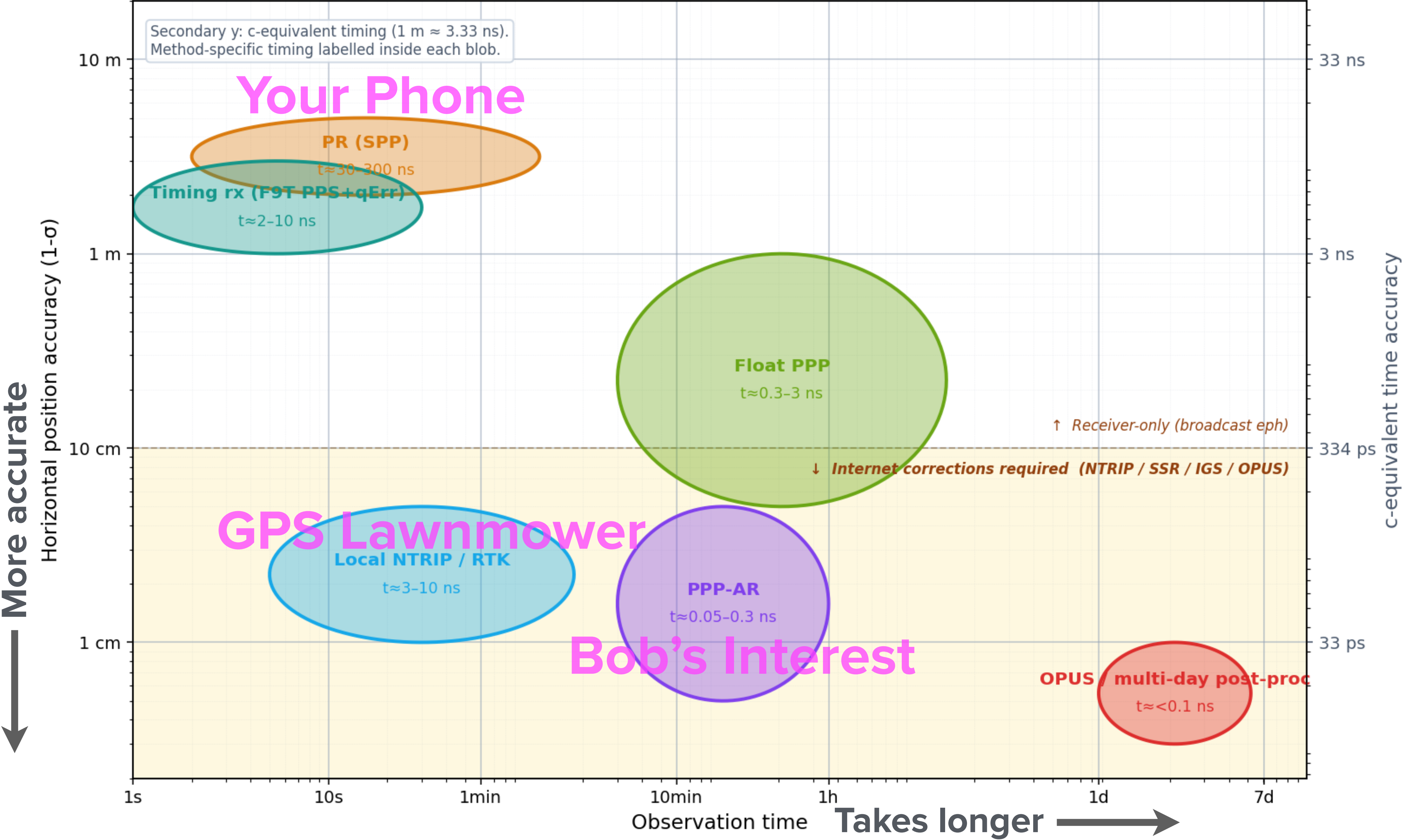


# TERMINOLOGY

- **Deviation & Discipline**
  - It's not kinky sex — it's the way timing experts talk
  - Deviation measures how an unstable clock ticks irregularly
  - Discipline is pushing those ticks back into a stable pattern
- **Position Error  $\propto$  Time Error**
  - GNSS binds position and time together, so errors transfer
- I may say “GPS” when I mean GNSS, Galileo, BeiDou, or GLONASS

# GNSS INTRO

GNSS positioning: observation-time vs accuracy regimes





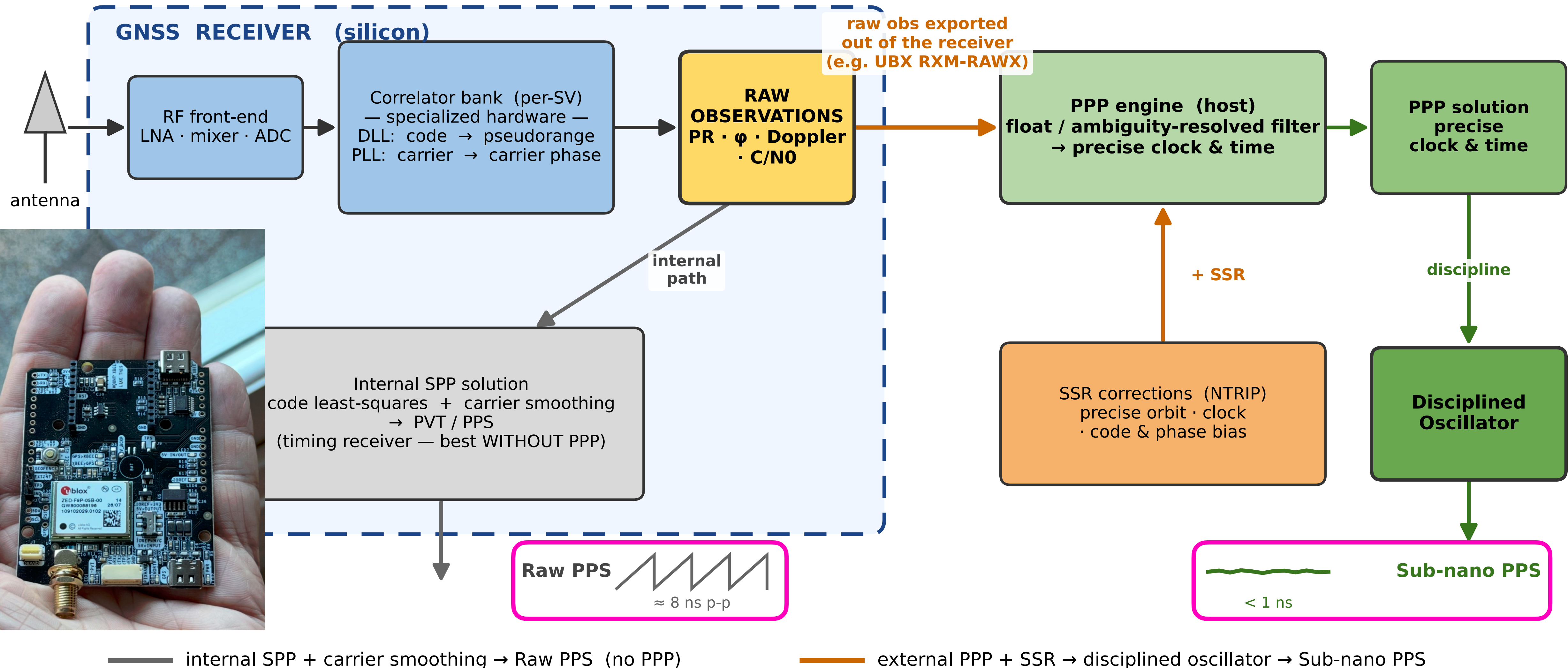
# GNSS POSITIONING TECHNIQUES

|                        | SPP<br>Standard Point Positioning            | RTK<br>Real-Time Kinematic                                                    | PPP, PPP-AR<br>Precise Point Positioning                 |
|------------------------|----------------------------------------------|-------------------------------------------------------------------------------|----------------------------------------------------------|
| How Many Receivers?    | 1                                            | 2, or<br>1 + regional network                                                 | 1 + Hundreds, worldwide                                  |
| Works Where?           | Worldwide                                    | 10 km from base receiver                                                      | Worldwide                                                |
| How Fast? <sup>†</sup> | Seconds                                      | Seconds                                                                       | Offline: hours to weeks<br>Realtime: after 10s of mins   |
| Accuracy               | A few meters<br>~ 15 ns                      | A few centimeters                                                             | Sub-centimeter<br>< 100 ps w/calibration                 |
| Implementation         | Hardware/firmware < \$10                     | Hardware/firmware<br>\$215 each receiver                                      | 32-bit software or service<br>\$310, one receiver needed |
| Notes                  | “Regular old GPS”<br>Uses pseudorange signal | Requires survey-grade antenna, good sky view, dual band<br>Uses carrier phase |                                                          |

<sup>†</sup> Assumes nominal receiver “warmth”



# One set of raw observations → two timing solutions

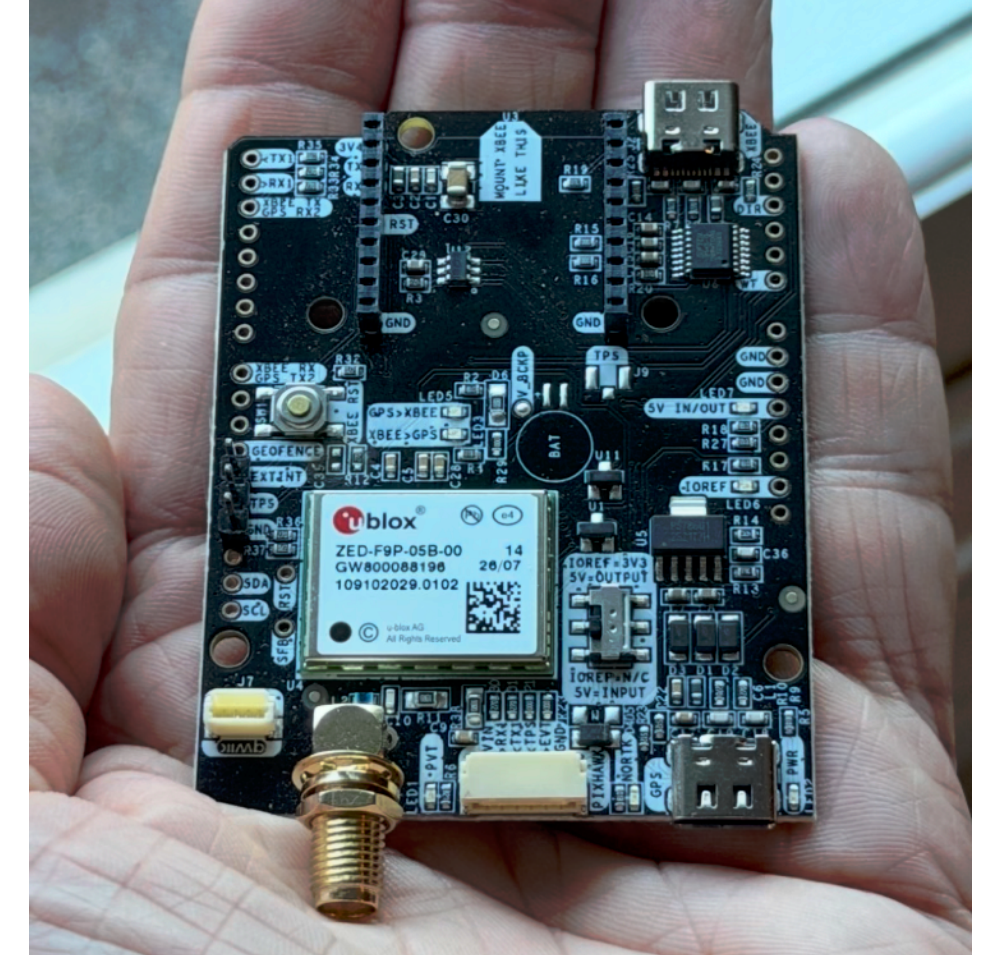


The same raw carrier-phase + code observations either drive the receiver's own SPP fix, or leave the receiver for an external PPP engine fused with SSR. (How PPP turns SSR + raw observations into a precise time fix: later slides.)



# PROJECT KICKOFF

- How to use satellite atomic clocks on Earth?
- Goal: build clocks agreeing to  $< 1$  ns on shared antenna,  $< 2$  ns on two antennas
- Require a fixed antenna position
  - Yes, it's ironic, I'm using GPS when I already know my position
- First survey antenna position, then get time from that
- Combining PPP-AR with fixed position -> Project PePPAR-Fix
- No atomics, no vacuums, no lasers, no cryogenics



# GNSS PRECISION SUPPORTING INFRASTRUCTURE



# HOW DO YOU SYNCHRONIZE ~125 ATOMIC CLOCKS IN SPACE?

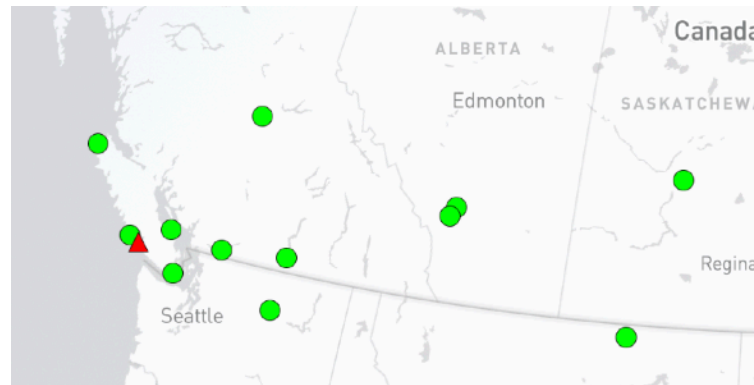
— You don't really try!

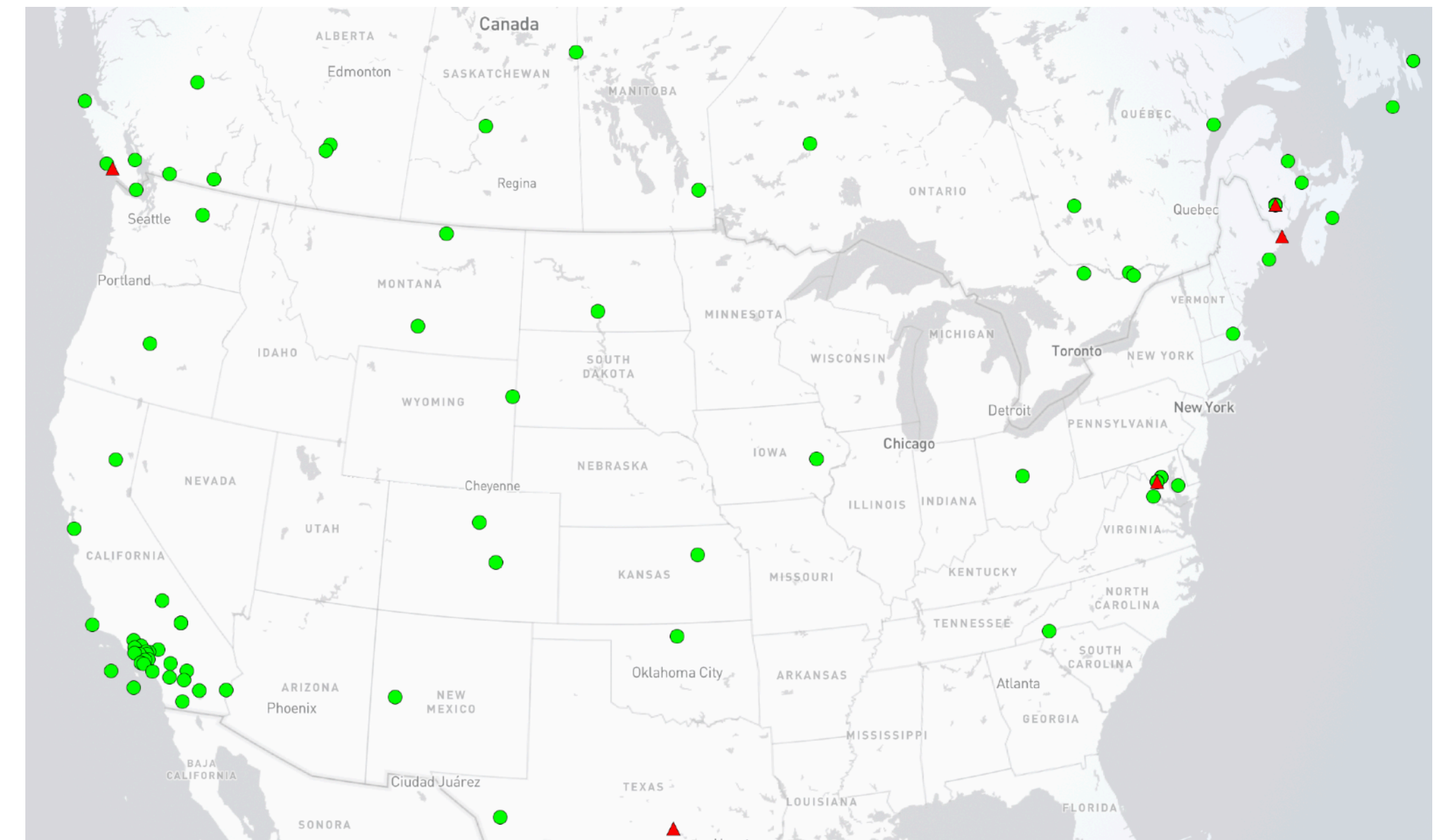
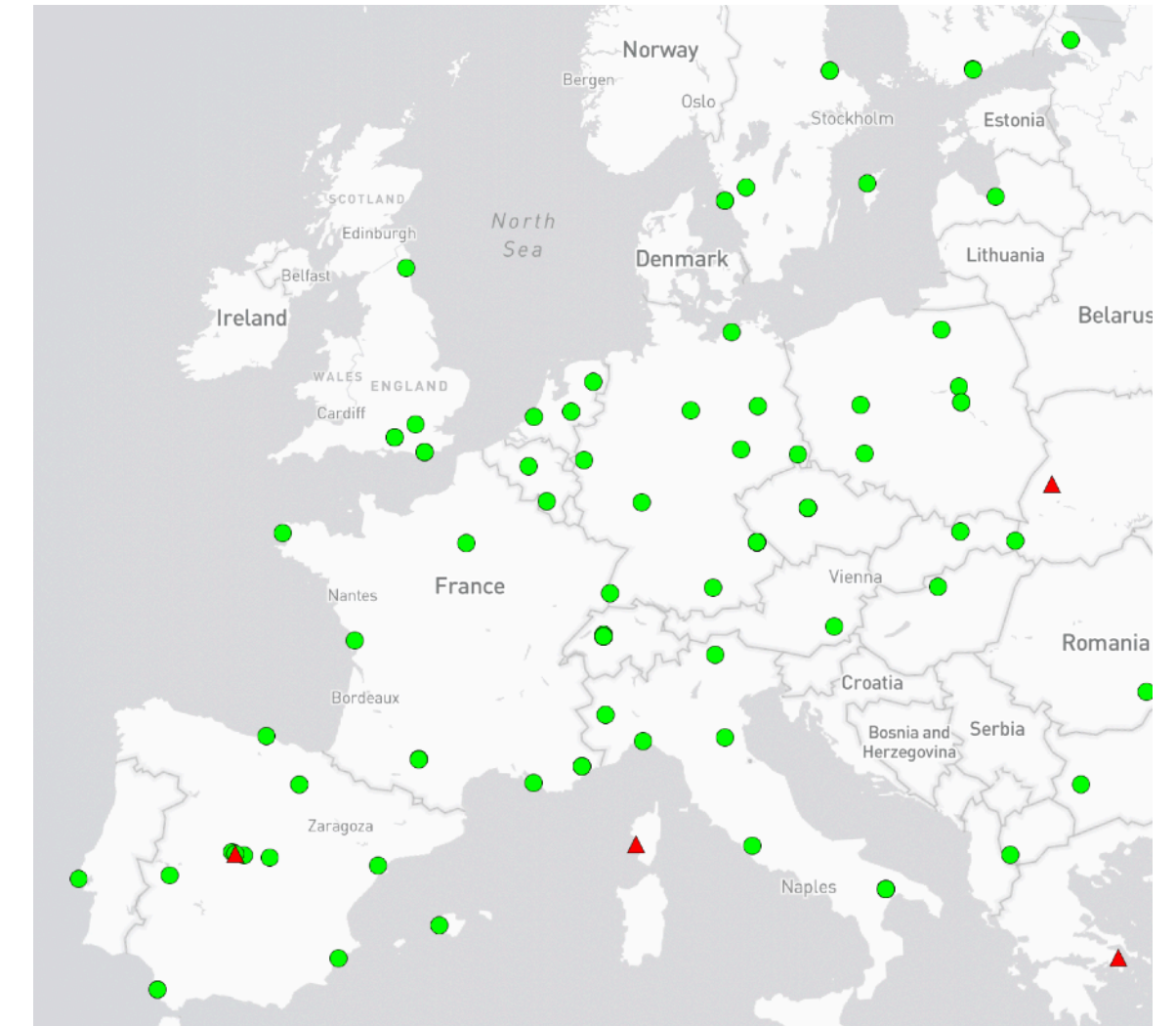
- Let clocks run free, measure error, predict it, broadcast it, receivers apply corrections
  - Same goes for orbits
- Monitoring stations with atomic clocks track sat clock errors
- Prediction quality and available bandwidth limit SPP accuracy to ~1 m, ~3-15 ns

| Constellation | SVs | clock-offset range | worst error (≡ position) | drift / 24 h |
|---------------|-----|--------------------|--------------------------|--------------|
| GPS           | 32  | -607 ... +748 μs   | 748 μs ≈ 224 km          | ≤ 1.9 μs     |
| Galileo       | 30  | -1147 ... +5263 μs | 5.26 ms ≈ 1578 km        | ≤ 10.9 μs    |
| BeiDou        | 40  | -977 ... +967 μs   | 977 μs ≈ 293 km          | ≤ 16.2 μs    |

The “master clocks” are on Earth, not in space

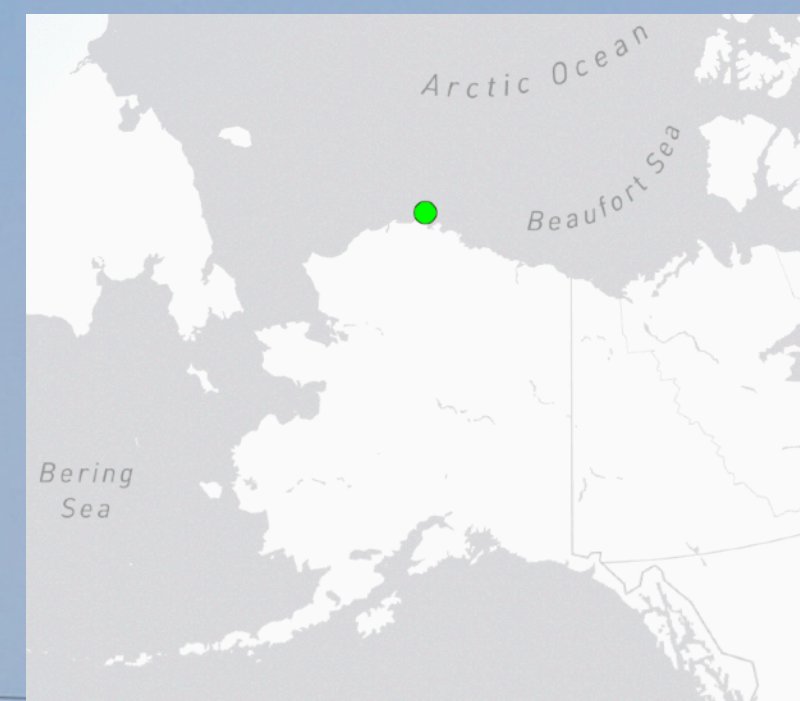
# GROUNDWORK FOR PRECISION GNSS

- **National Metrology Institutes (NMIs), e.g. NPL, USNO, NIST, PTB**
  - **BIPM Time Department**
  - **Constellation “ground segment” or “control segment”**
  - **International GNSS Service (IGS)**
    - **800 monitoring stations worldwide**
    - **100 with atomic clocks**
  - **Global GNSS Analysis Centers (ACs)**
- 
- A map of North America, specifically focusing on the United States and parts of Canada. It shows the locations of GNSS monitoring stations, represented by green dots. The dots are distributed across the western and central United States, including Washington, Oregon, California, Idaho, Utah, Arizona, New Mexico, Texas, and Oklahoma. A red triangle is located on the coast of Washington state, near Seattle. Labels for 'Seattle', 'Edmonton', and 'Regina' are visible. The map also shows the borders of 'ALBERTA' and 'SASKATCHEWAN' in Canada.





# IGS Monitoring Station Barrow, Alaska



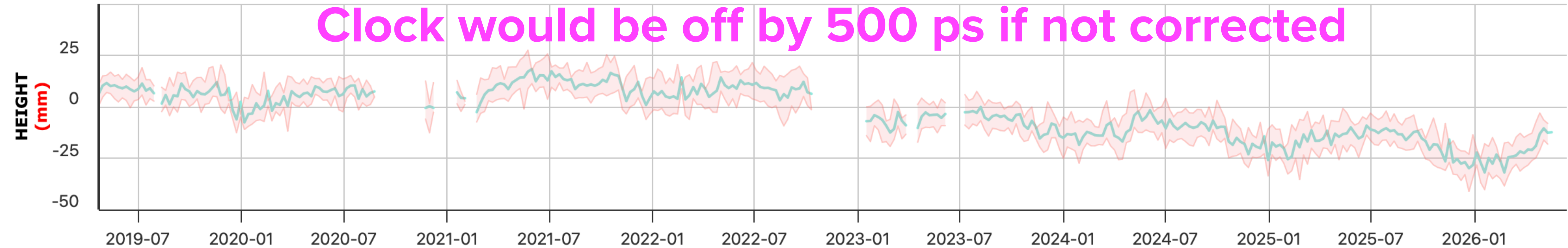
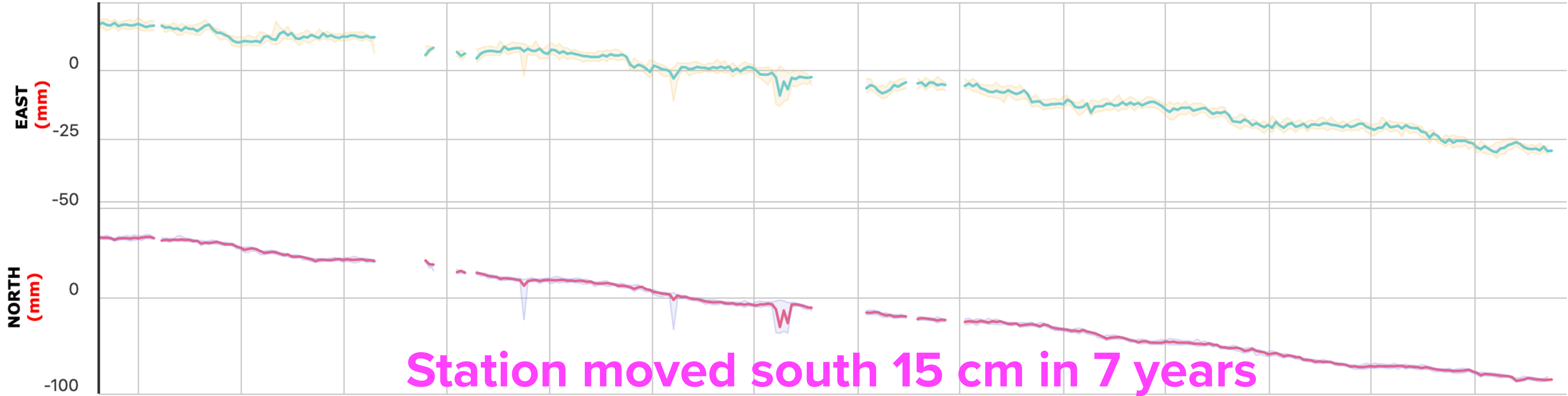


# Position Time Series



Zoom 1m 3m 6m YTD 1y **All**

Apr 22, 2019 → Jun 14, 2026



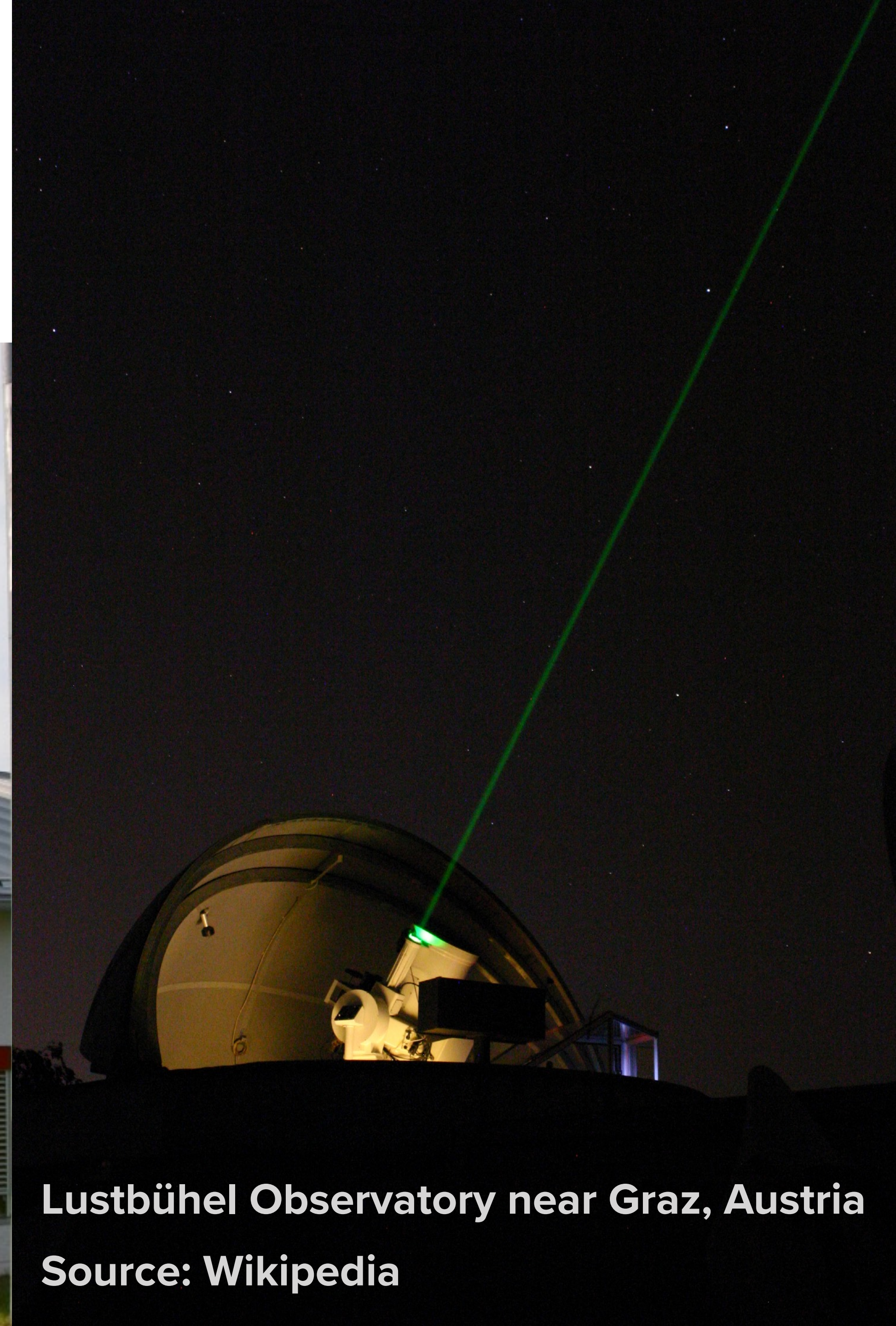
ENV + Sigma Time Series ENV-Detrended Time Series



# SATELLITE LASER RANGING



**Geodetic Observatory Wettzell, Bavaria**  
Source: Wikipedia



**Lustbühel Observatory near Graz, Austria**  
Source: Wikipedia



# GNSS ACCURACY LIMITS



# GNSS SIGNALS & PROCESSING

- Pseudorange code identifies the satellite and anchors absolute time to ~1 ms
- Pseudorange phase resolves time to ~1-10 ns within each ms
- Carrier phase resolves time to ~30 ps within a cycle, but is ambiguous by cycle
  - Very careful corrections and processing provide AR (Ambiguity Resolution)

| Processing Technique    | Position $\sigma$ | Time Stability | Time Absolute Accuracy  | Physical Model    |
|-------------------------|-------------------|----------------|-------------------------|-------------------|
| Pseudorange             | ~1 m              | ~1-3 ns        | ~3-15 ns                | Large beachball   |
| Float PPP Carrier       | ~10 cm            | ~100-300 ps    | sub-ns, w/calibration   | Softball          |
| Fixed PPP-AR-WL Carrier | ~4 cm             | ~40-133 ps     | sub-ns, w/calibration   | Table tennis ball |
| Fixed PPP-AR-NL Carrier | ~1 cm             | ~10-30 ps      | ~100s ps, w/calibration | Green pea         |

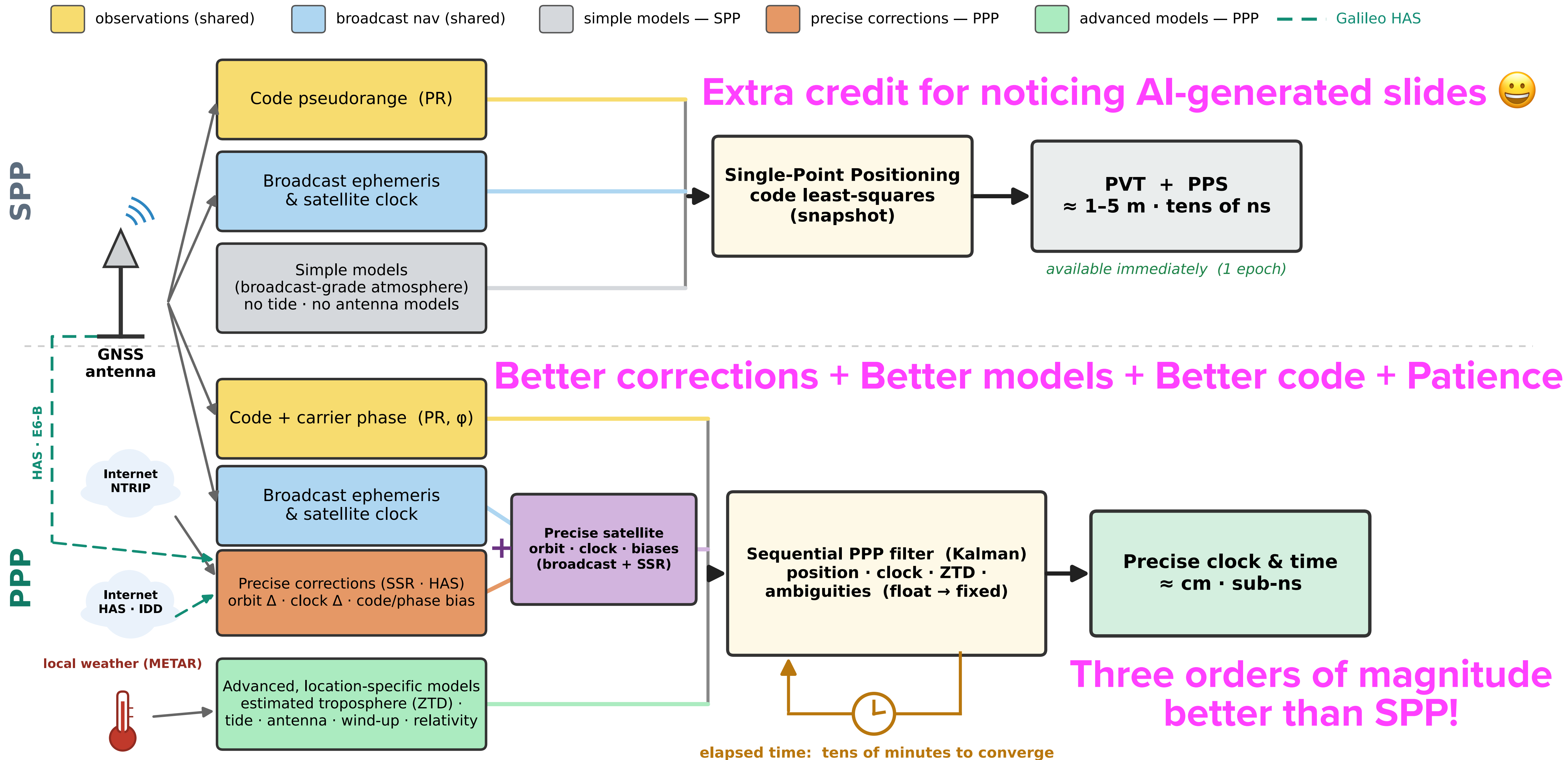


# MATCHING TIME ACQUISITION & TRANSFER

| Time Acquisition | Time Transfer | Accuracy/Precision |
|------------------|---------------|--------------------|
| Internet         | NTP           | Millisecond        |
| GNSS SPP         | PTP           | ~15 ns             |
| GNSS Float PPP   | PPS           | ~1 ns              |
| GNSS PPP-AR      | White Rabbit  | Sub-nanosecond     |



# Two data flows — SPP vs PPP



Matching colours = the same data feeding both flows — PPP builds on the broadcast nav message, not instead of it.  
SSR/HAS orbit/clock are  $\Delta$ -corrections applied on top of broadcast (IODE-matched); code & phase biases are absolute.



# INITIAL PEPPAR-FIX VISION & PIVOT

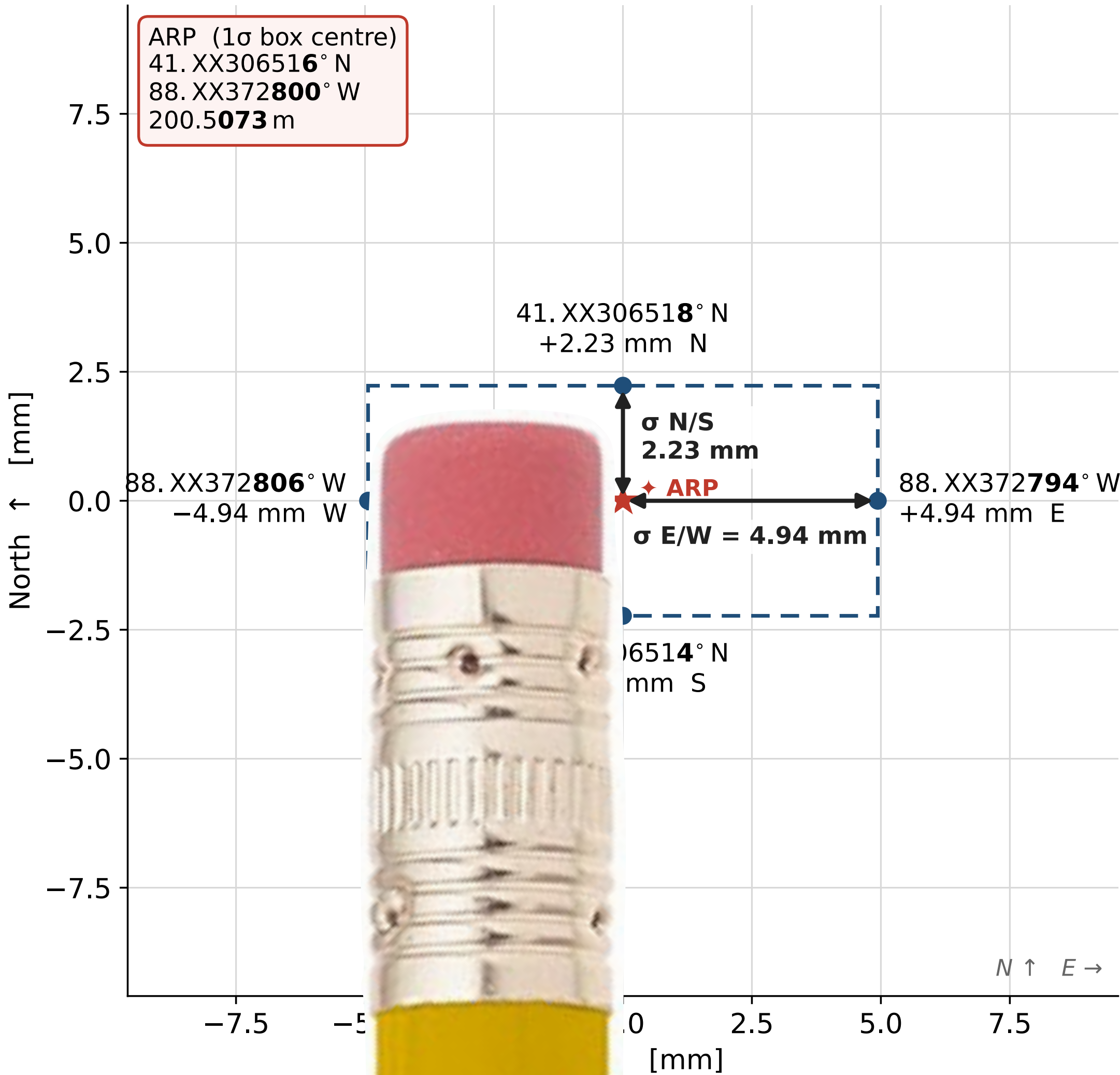
- Existing open source good for post-processing, but scant real-time support
  - Some not maintained well, platform-specific, FORTRAN 😞
- Idea: Write my own real-time PPP-AR solution with AI!
- Solve PPP-AR for position ➡ Solve PPP-AR for time ➡ Discipline oscillator
- Dangerous mix: AI overconfidence + Bob inexperience ➡ Trouble!
  - PPP-AR wouldn't reliably converge on an answer (a position)
  - I didn't know the right answer, so debugging proceeded slowly
- Finally figured out how to do my own antenna position surveys
- Pivoted to require a surveyed position before solving for time
- Gave up on TCXOs and PTP, given far better results with OCXOs and PPS



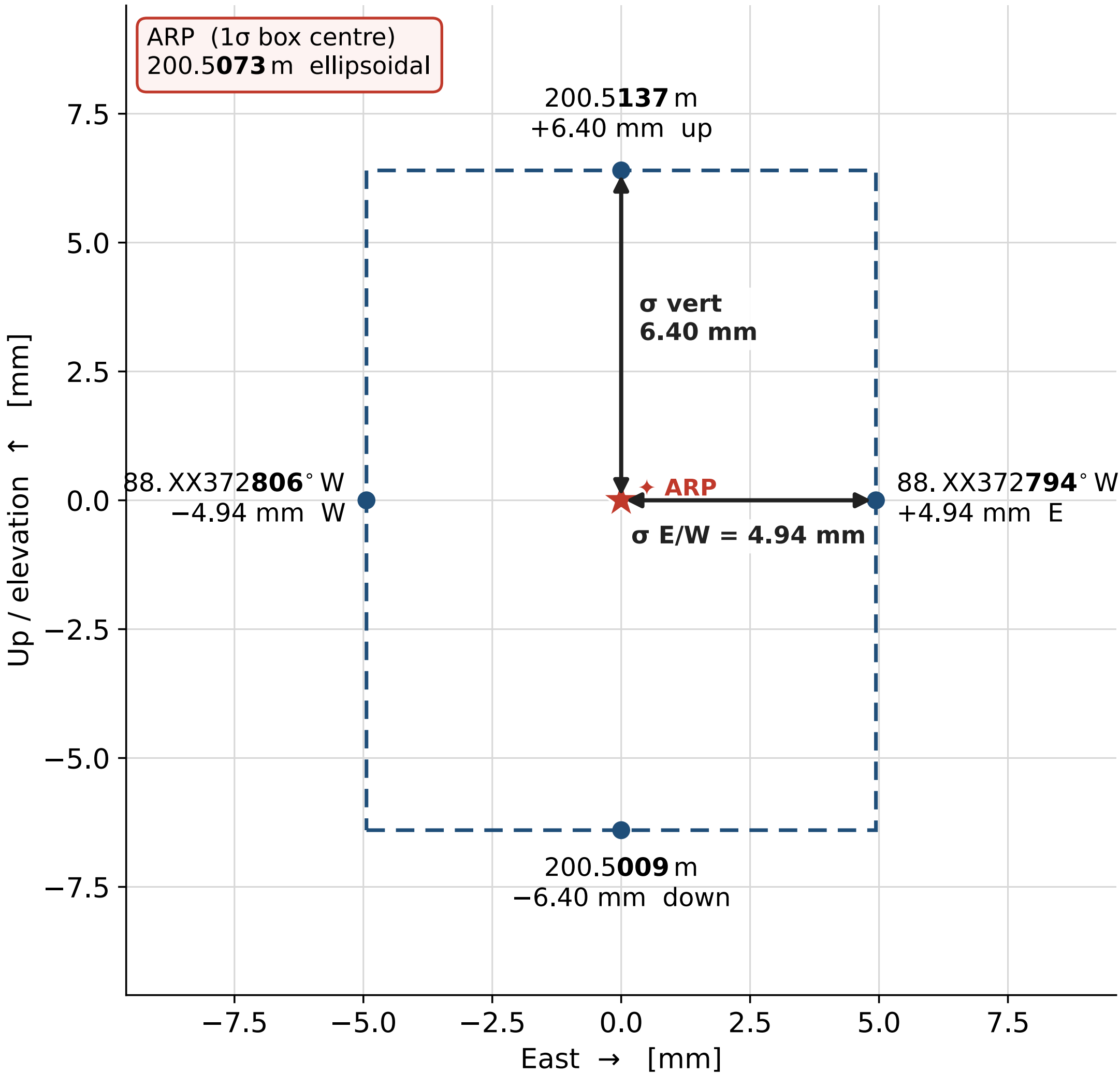
# UFO1 antenna reference point — survey confidence (1σ)

common leading digits in normal weight · **bold** = digits that change across the 1σ range · first two decimals masked (XX)

Plan view (top-down)



Elevation view (from the south, looking north)



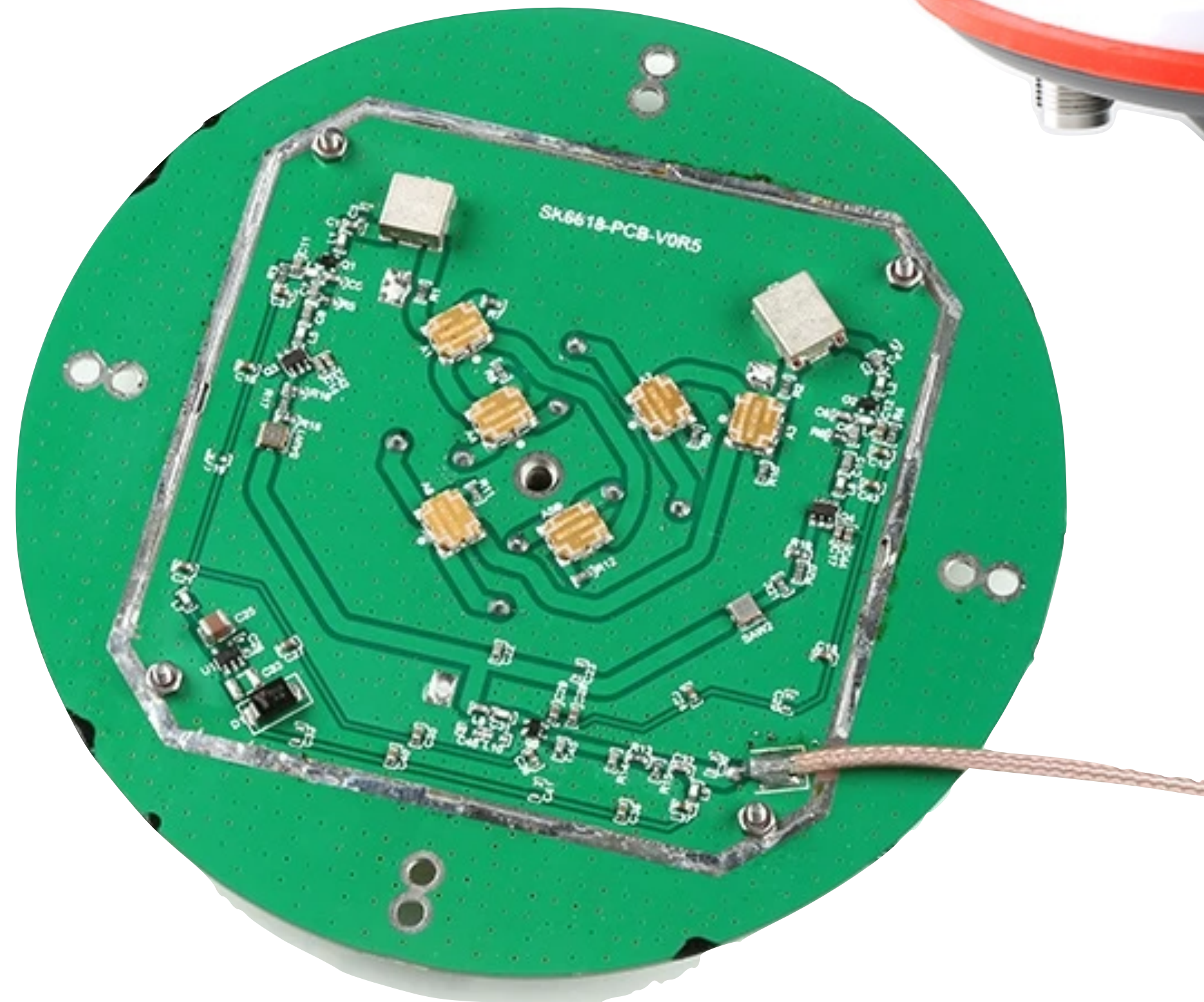
ITRF2020 @ 2020.01.01 · IGS precise · Leica GRX1200 GG Pro reference + SFESPK6618H antenna (NGS-calibrated PCO/PCV)  
1σ = across-day · JPLUS-Static solutions (N/S 2.23 mm, E/W 4.94 mm, vertical 6.40 mm) · cross-checks: PRIDE PPP-AR 2 mm, F9P CORS-RTK 32 mm



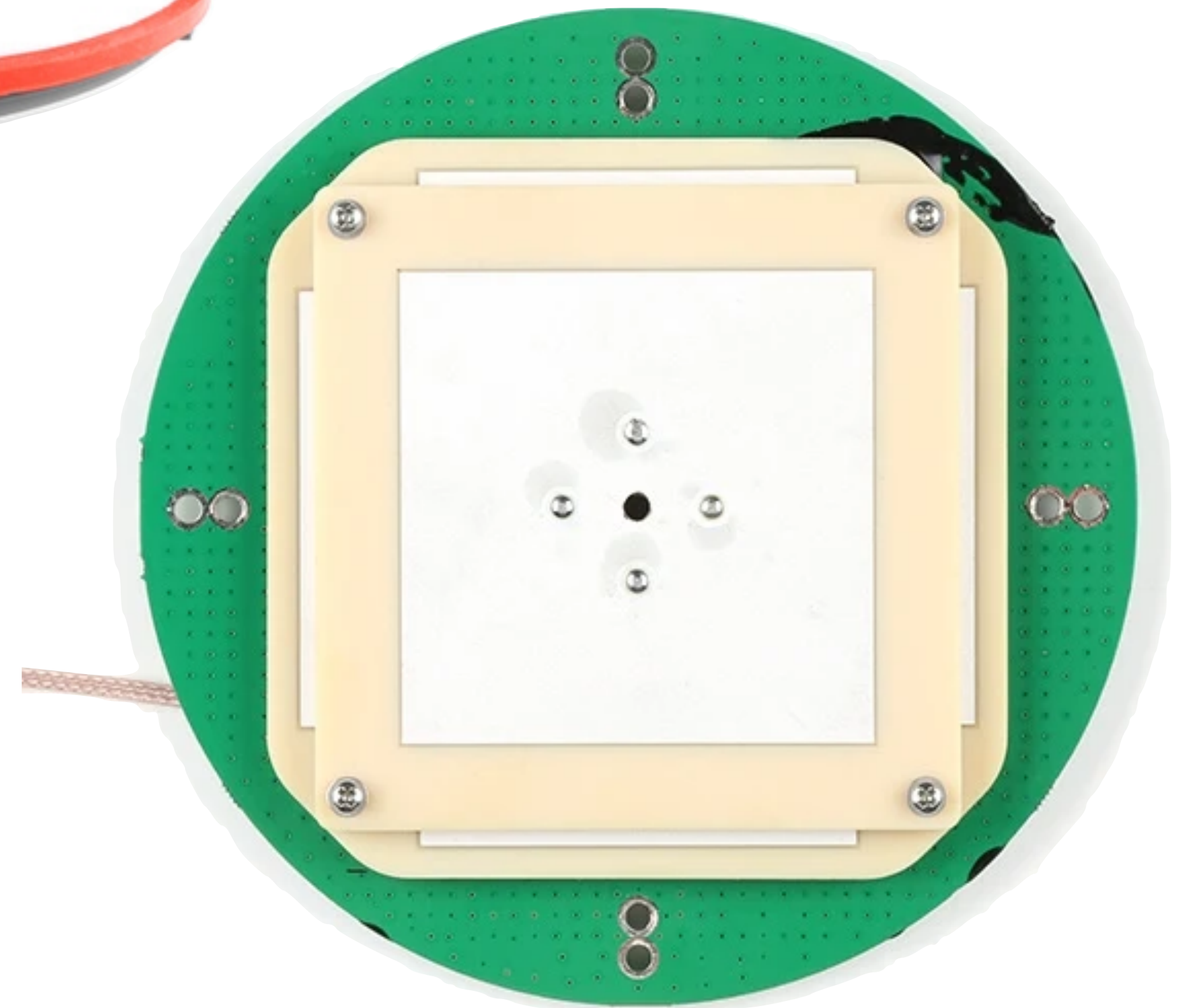
**GNSS ANTENNAS!**



# SURVEY-GRADE “UFO” ANTENNA CONSTRUCTION

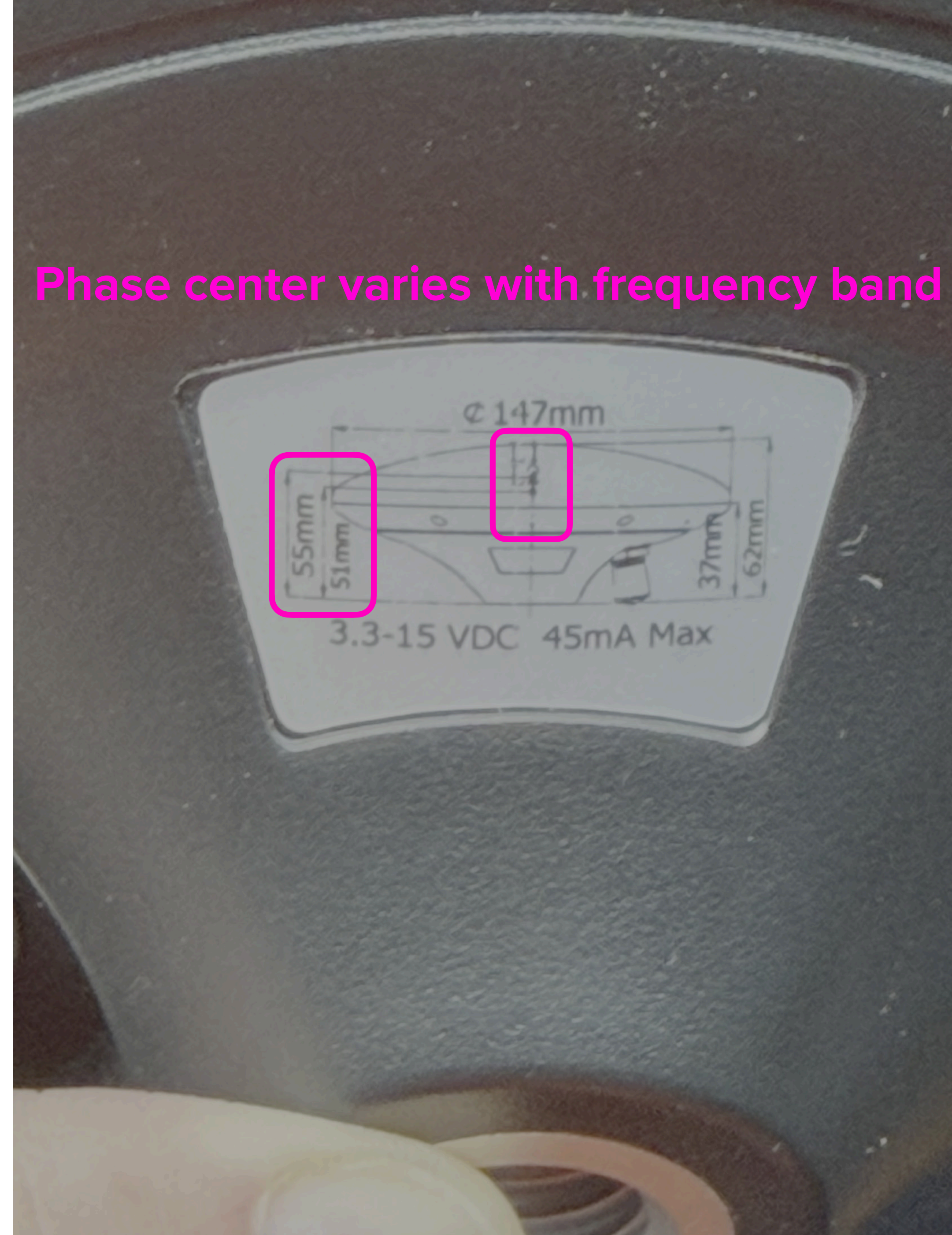
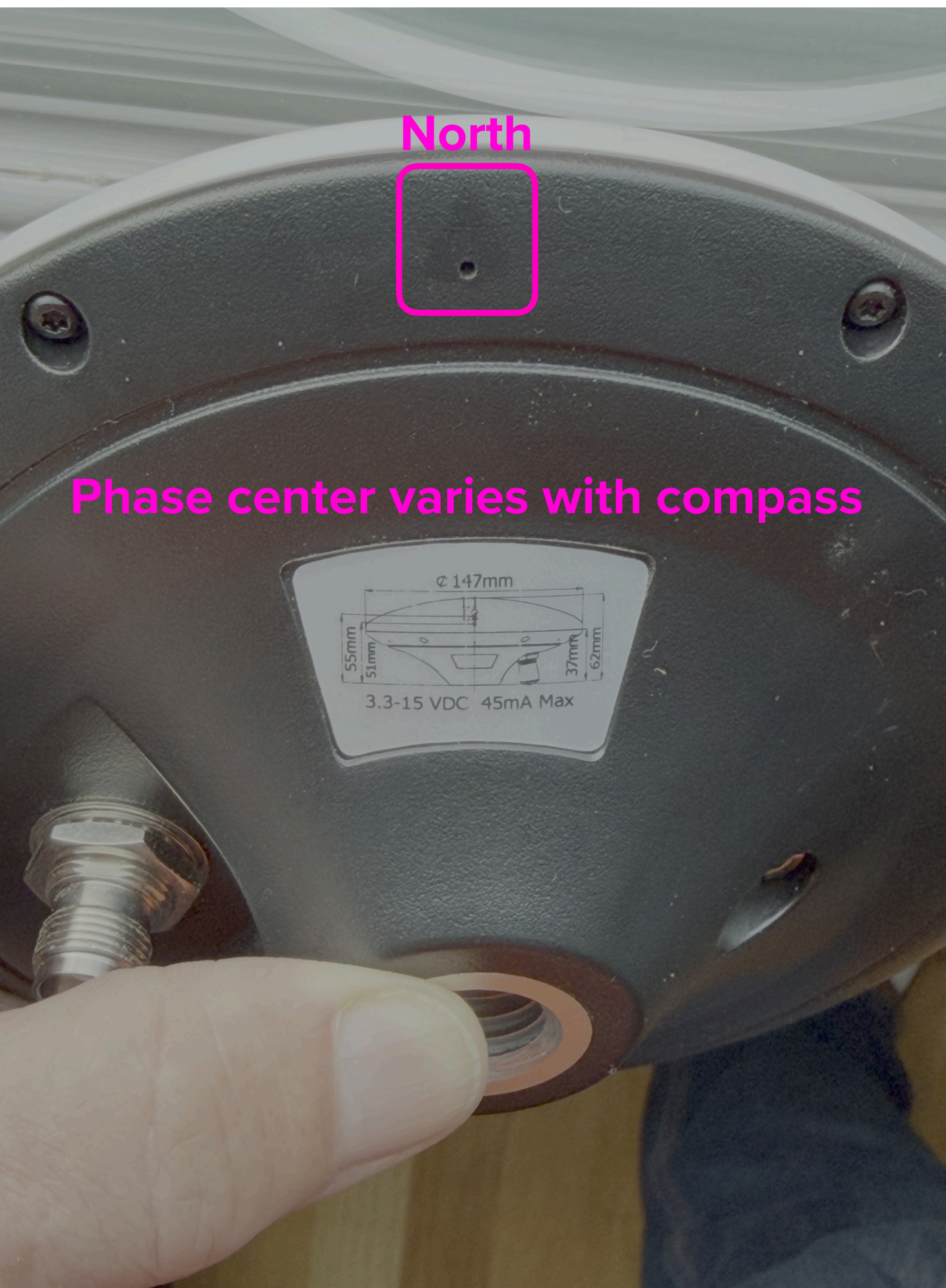


PCB bottom view



PCB top view







MY WIFE IS VERY UNDERSTANDING

Choke Ring Antenna





# CHOKER RING ANTENNA SIZE REFERENCE





# Antenna Calibration Robot



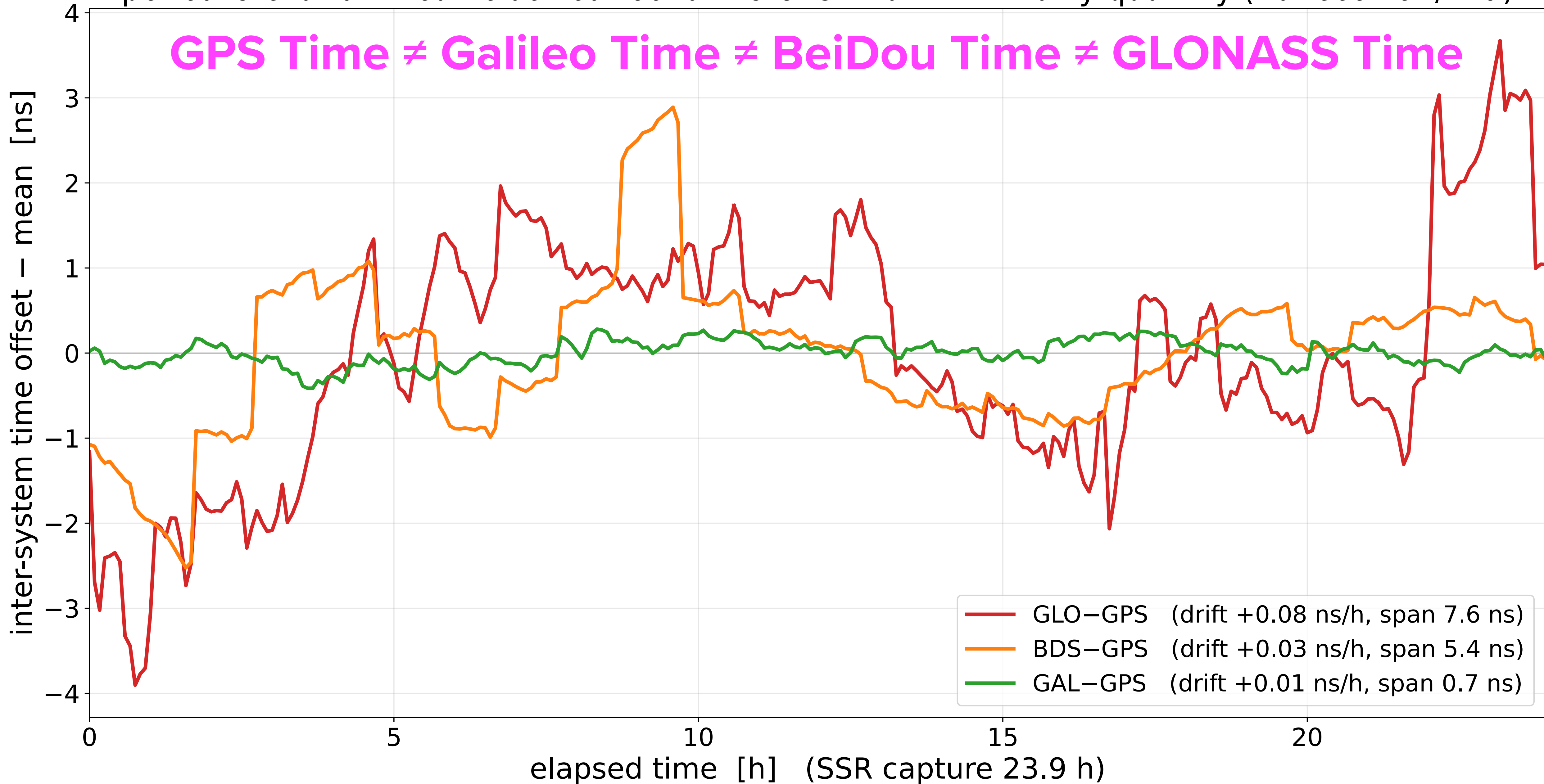
Source: [geopp.de](http://geopp.de)



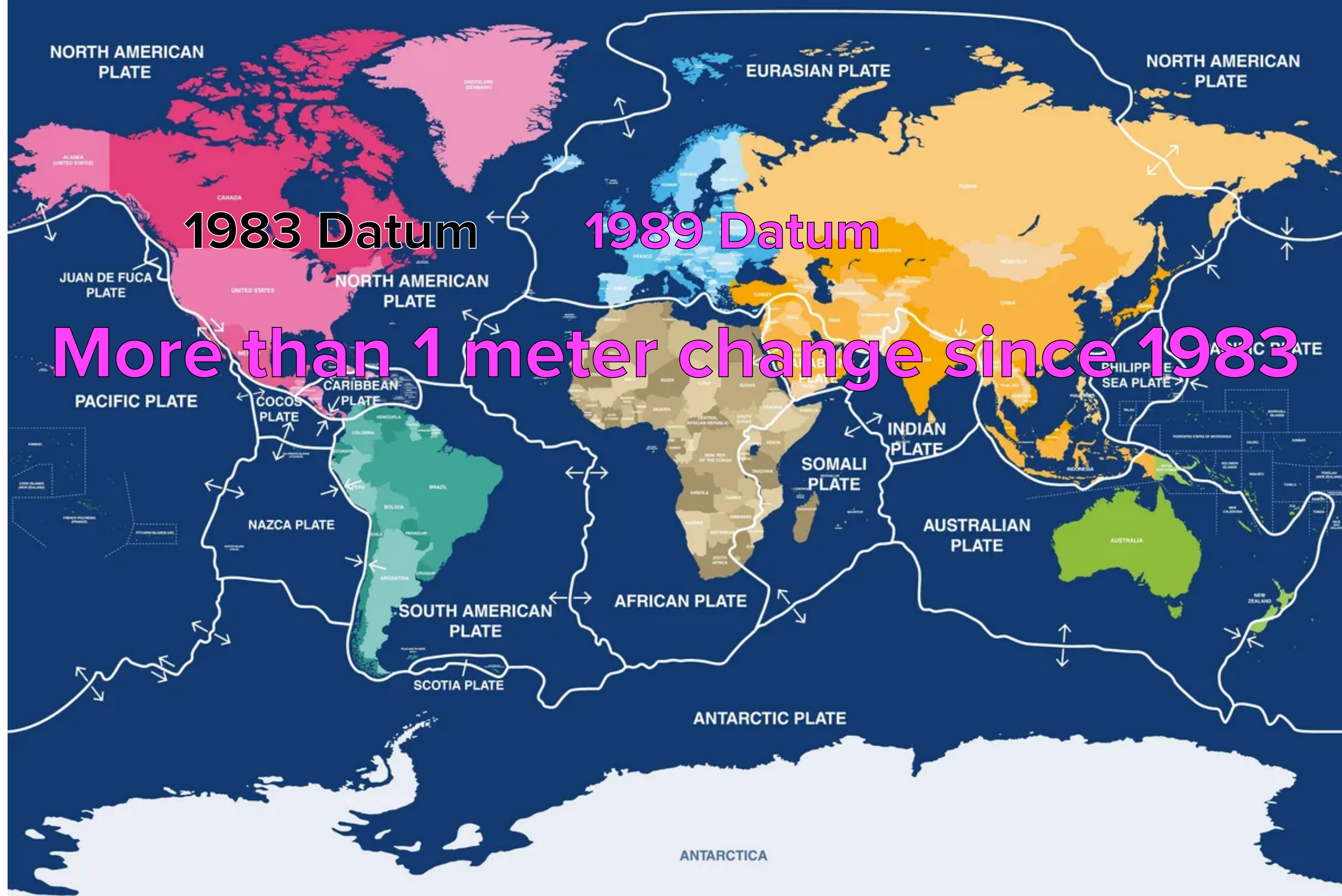
**GETTING BELOW 15 NS IN REAL-TIME**



Inter-system bias drift, straight from the SSR clock stream  
per-constellation mean clock correction vs GPS — an NTRIP-only quantity (no receiver / DO)

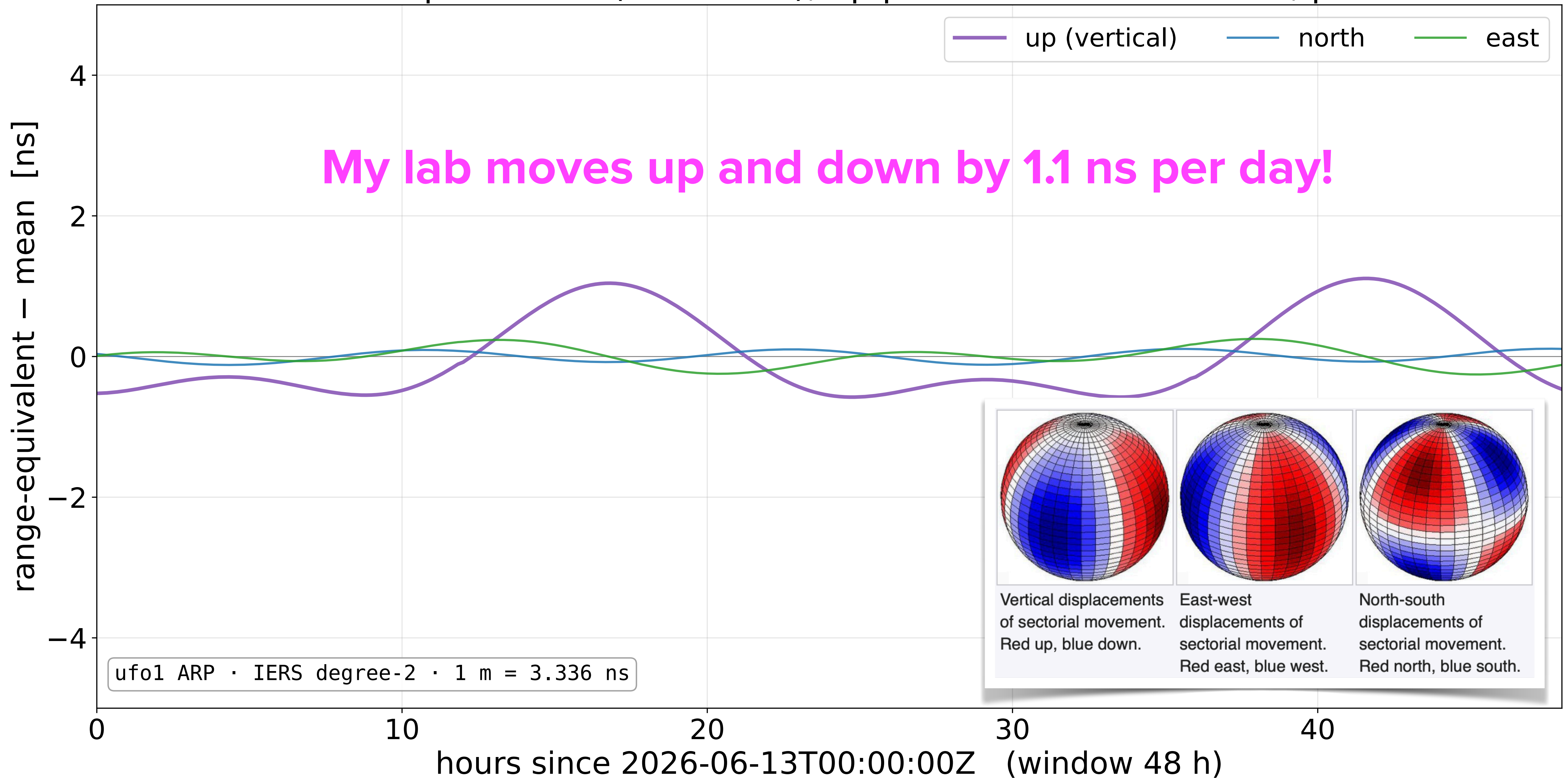








Solid Earth tide as a timing correction — detrended,  $\pm 5$  ns  
deterministic site displacement (no stream); up peak  $\approx 1.11$  ns  $\approx 33$  cm, period  $\sim 12.42$  h





# GETTING BELOW 15 NS IN REAL-TIME

- Instability like PPS sawtooth averages to zero over 24 hours or less
  - Can be ignored until you get below about 15 ns
- However, bias can't be averaged away
- Requirements
  - Survey-grade, low-multipath antenna with good sky view
    - Can't reliably track carrier phase without these
  - Real-time correction streams from GNSS Analysis Centers or Galileo HAS
  - Complex PPP code for Kalman filters and detailed models like solid earth tides
  - Allow 10s of minutes to converge
- Attention to details, e.g. Coordinate Reference System tagging ITRF2020@2026.3164

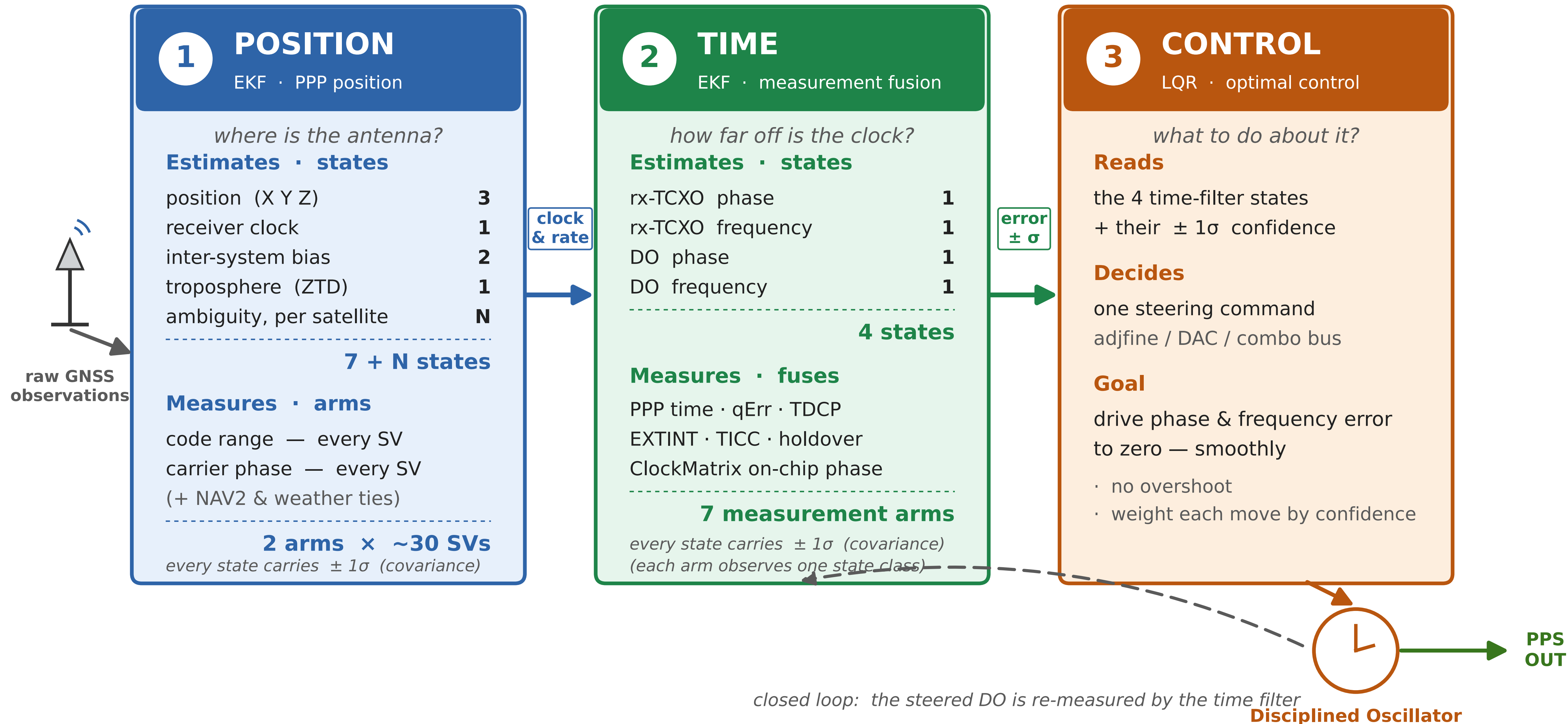


# PRECISION CLOCK ARCHITECTURE



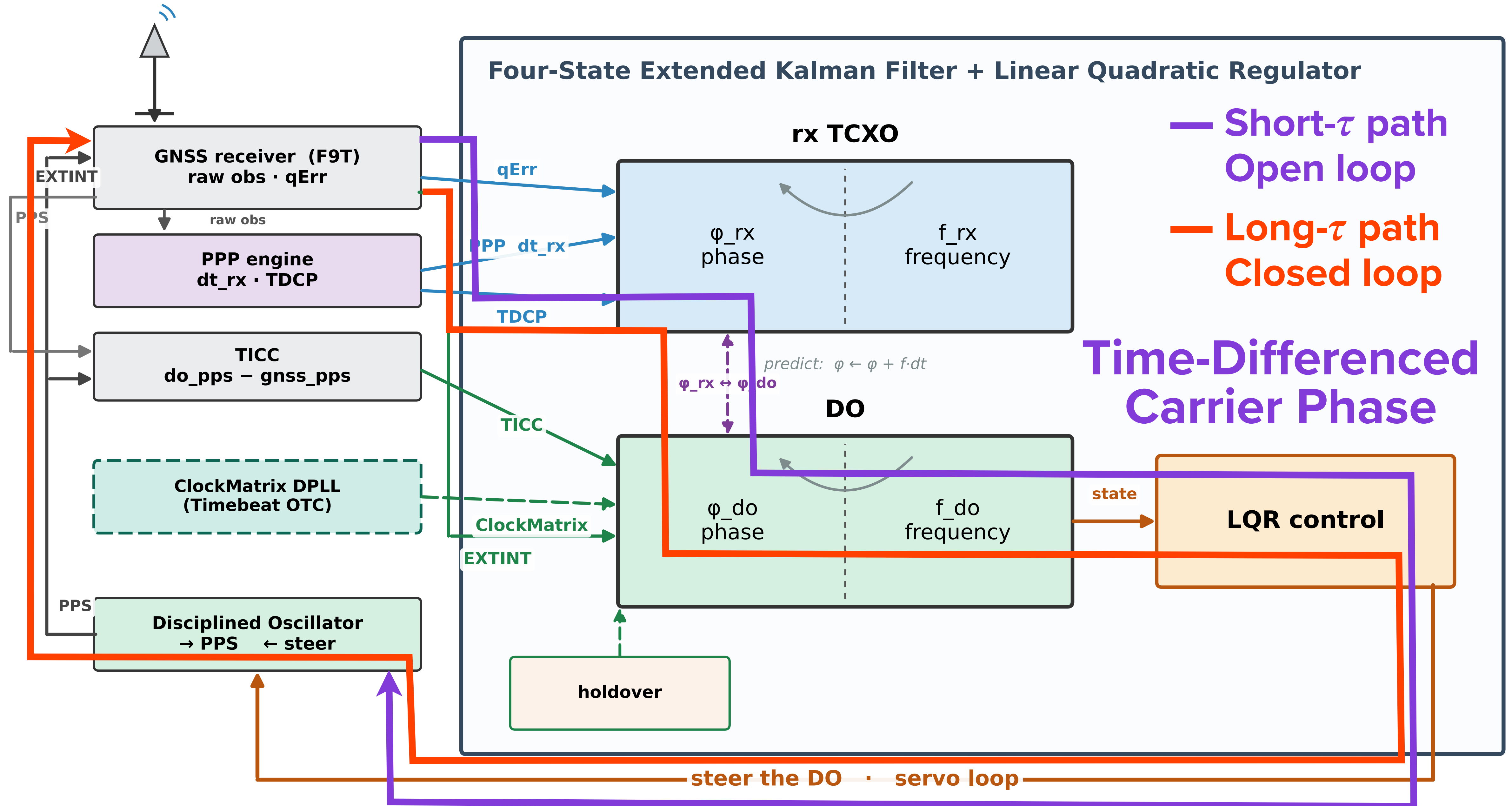
# Estimate the error → then steer it out, gracefully

two Kalman estimators feed one optimal controller — each shown by class of state and class of measurement





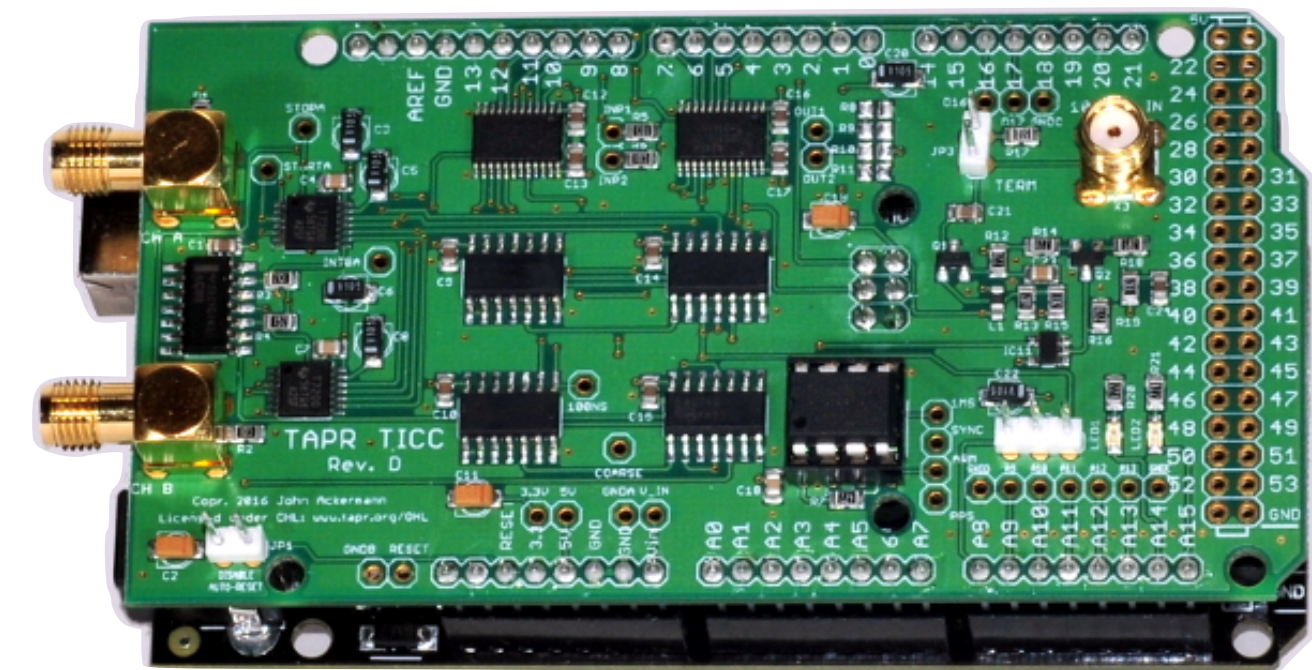
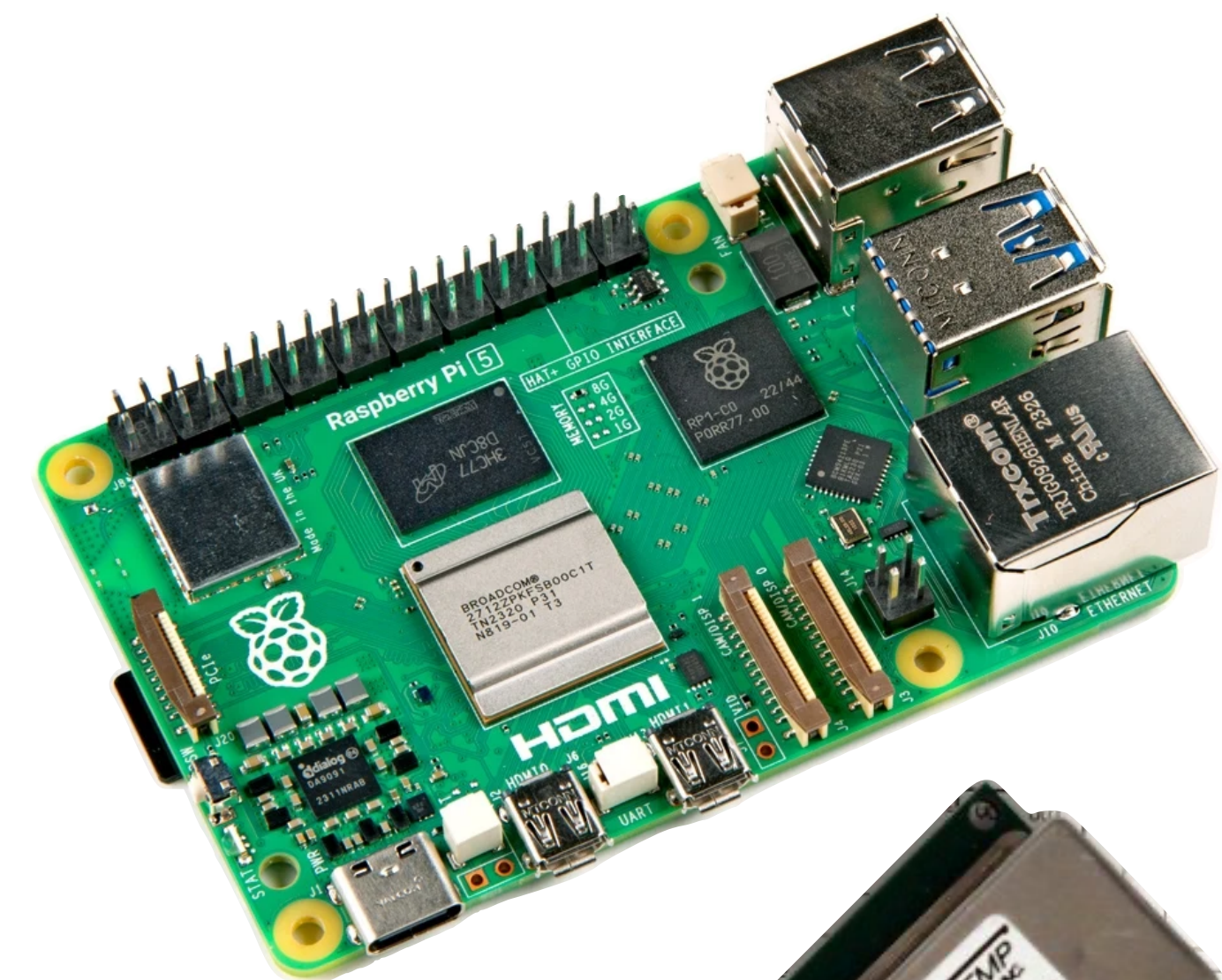
# Fusion Filter Tracking Two Coupled Oscillators and Servo





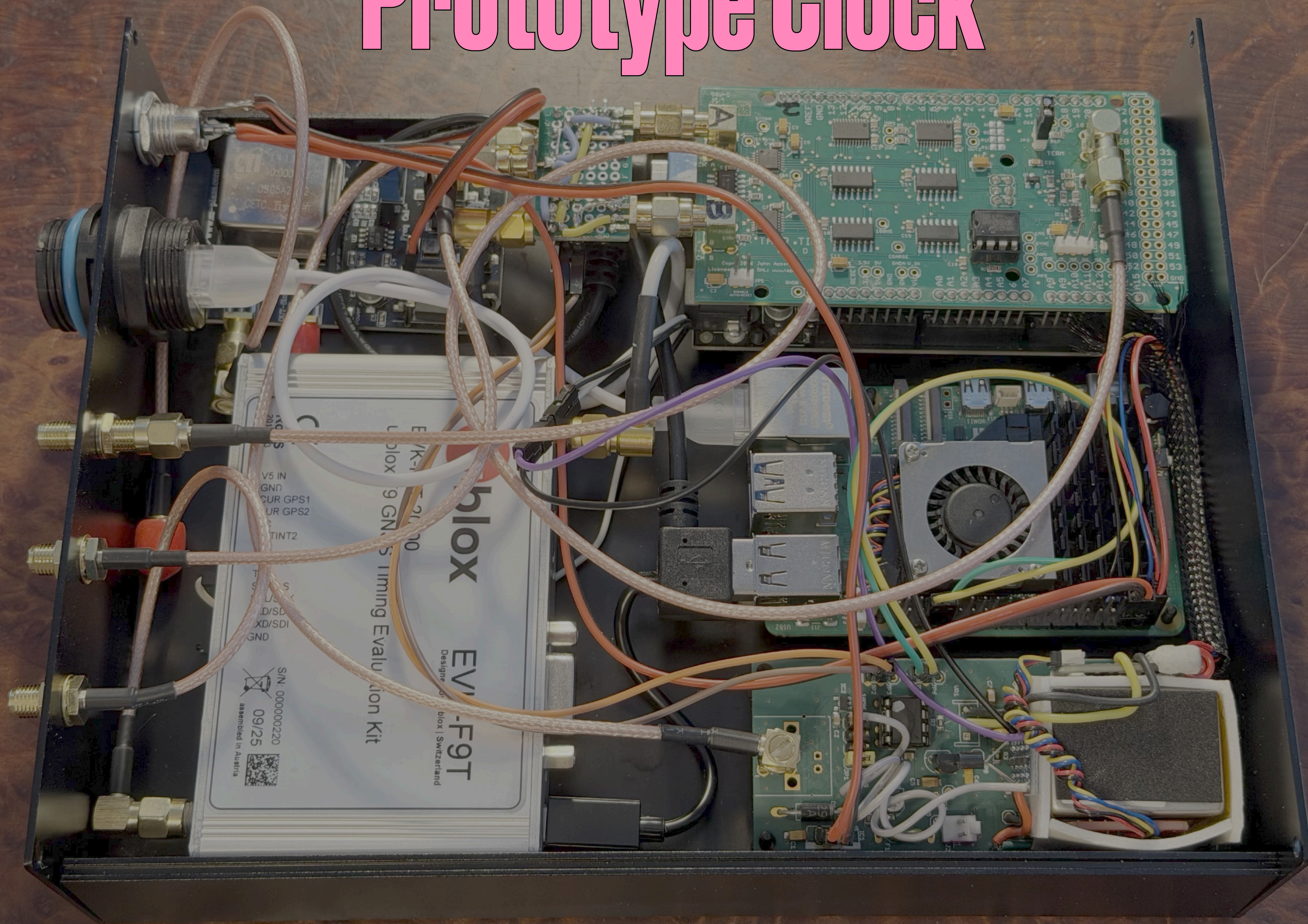
# PROTOTYPE PARTS

- u-blox EVK-F9T: \$350
- Raspberry Pi 5, heatsink, fan, NVMe hat, SSD: \$200
- TAPR TICC: \$250
- TAPR PulsePuppy divider with OCXO for disciplined oscillator: \$100
- Cheap AliExpress OCXO for TICC reference: \$10
- UPS: \$50
- Case: \$35
- Total: \$995





# Prototype Clock



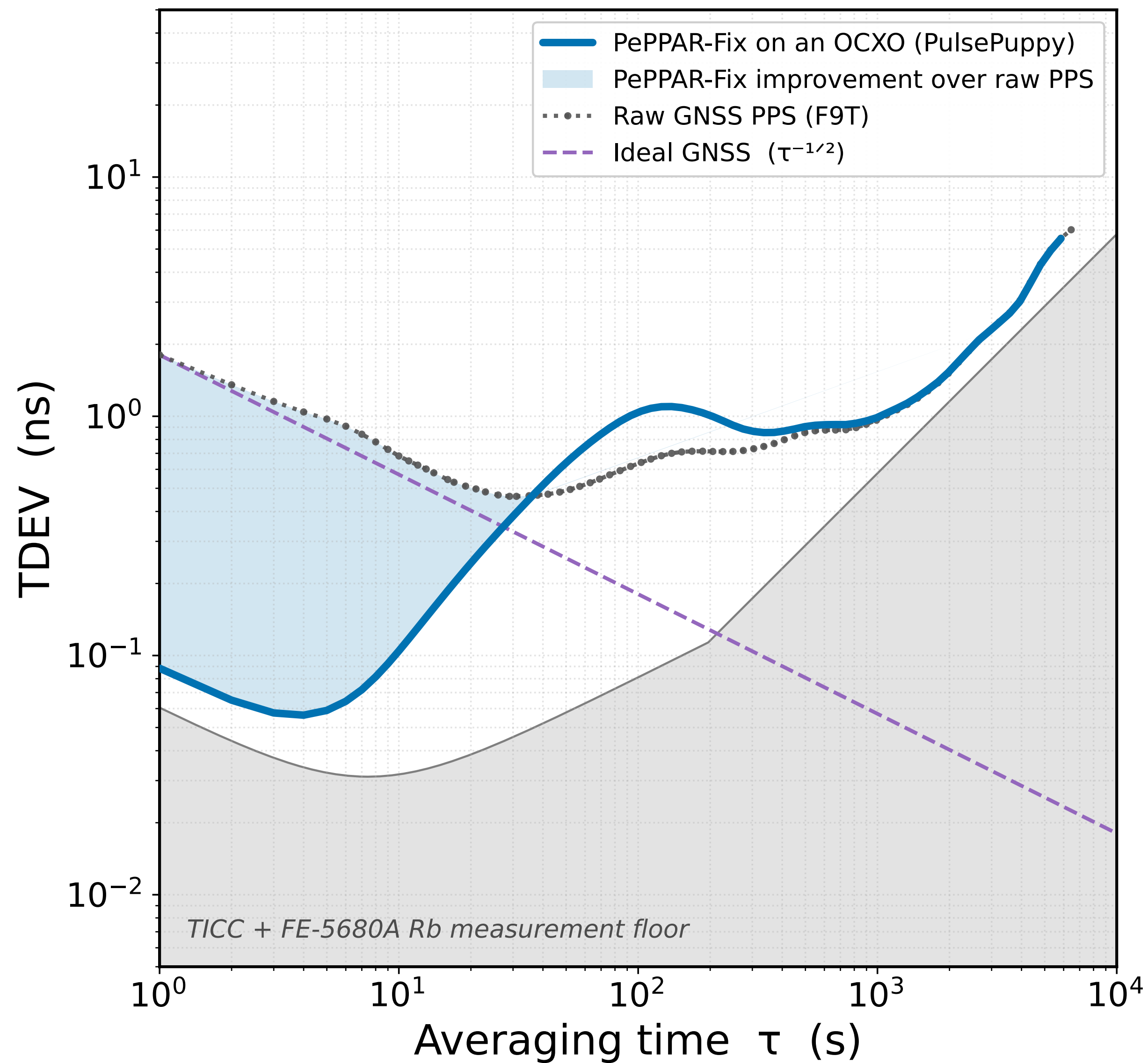


# PROTOTYPE CLOCK PERFORMANCE

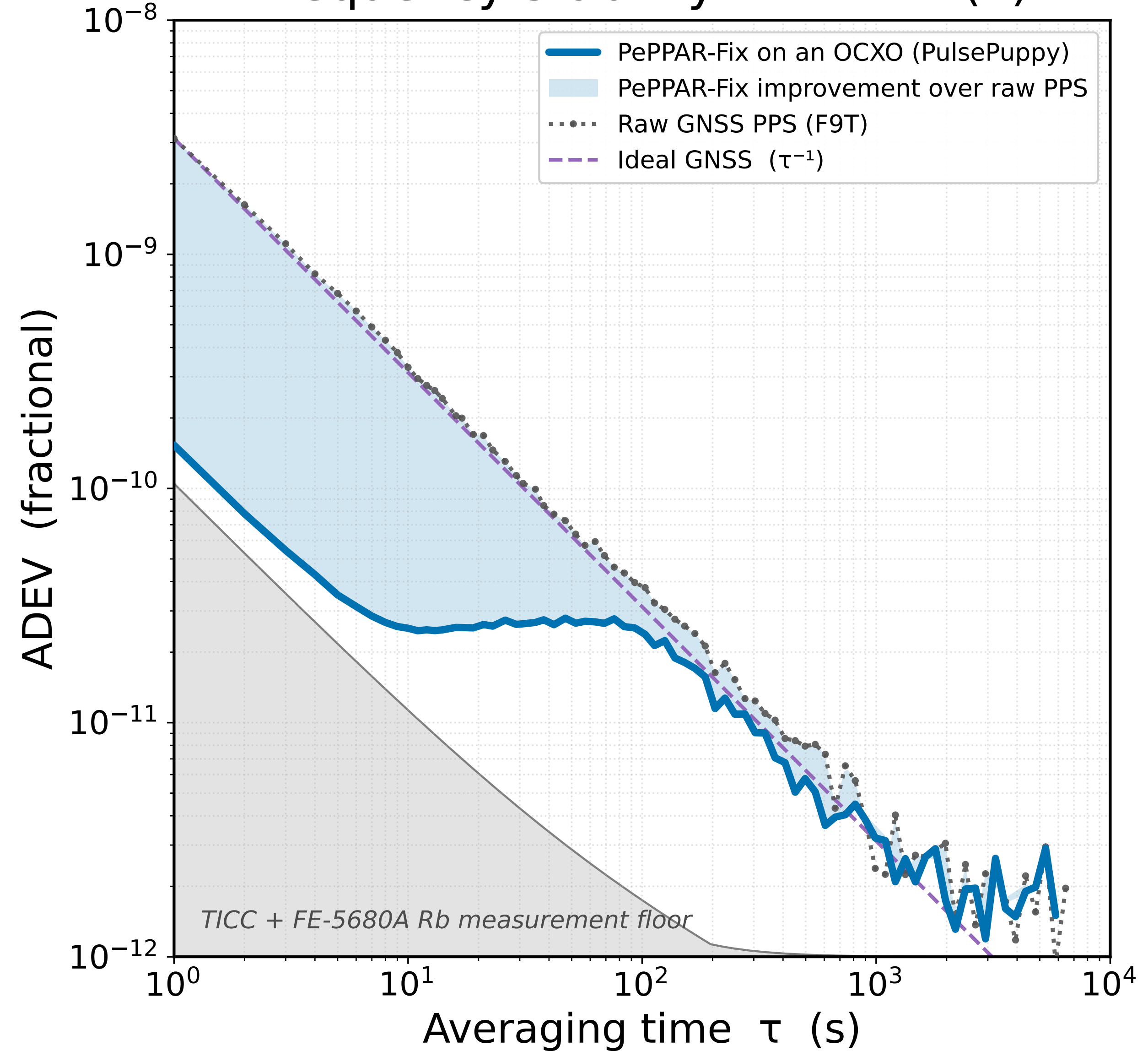


# PePPAR-Fix — the win: disciplined output vs raw GNSS

## Time stability — TDEV( $\tau$ )



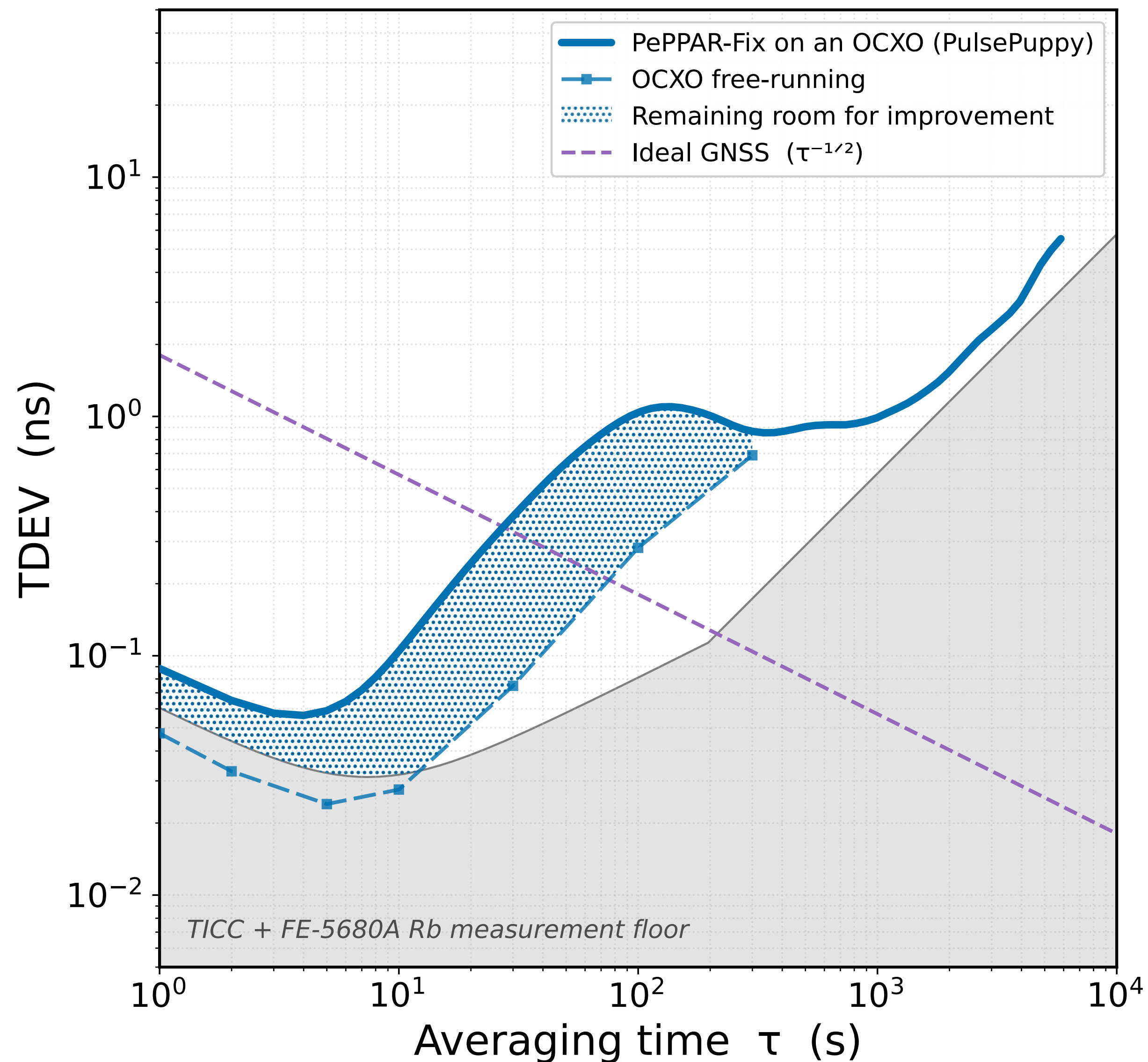
## Frequency stability — ADEV( $\tau$ )



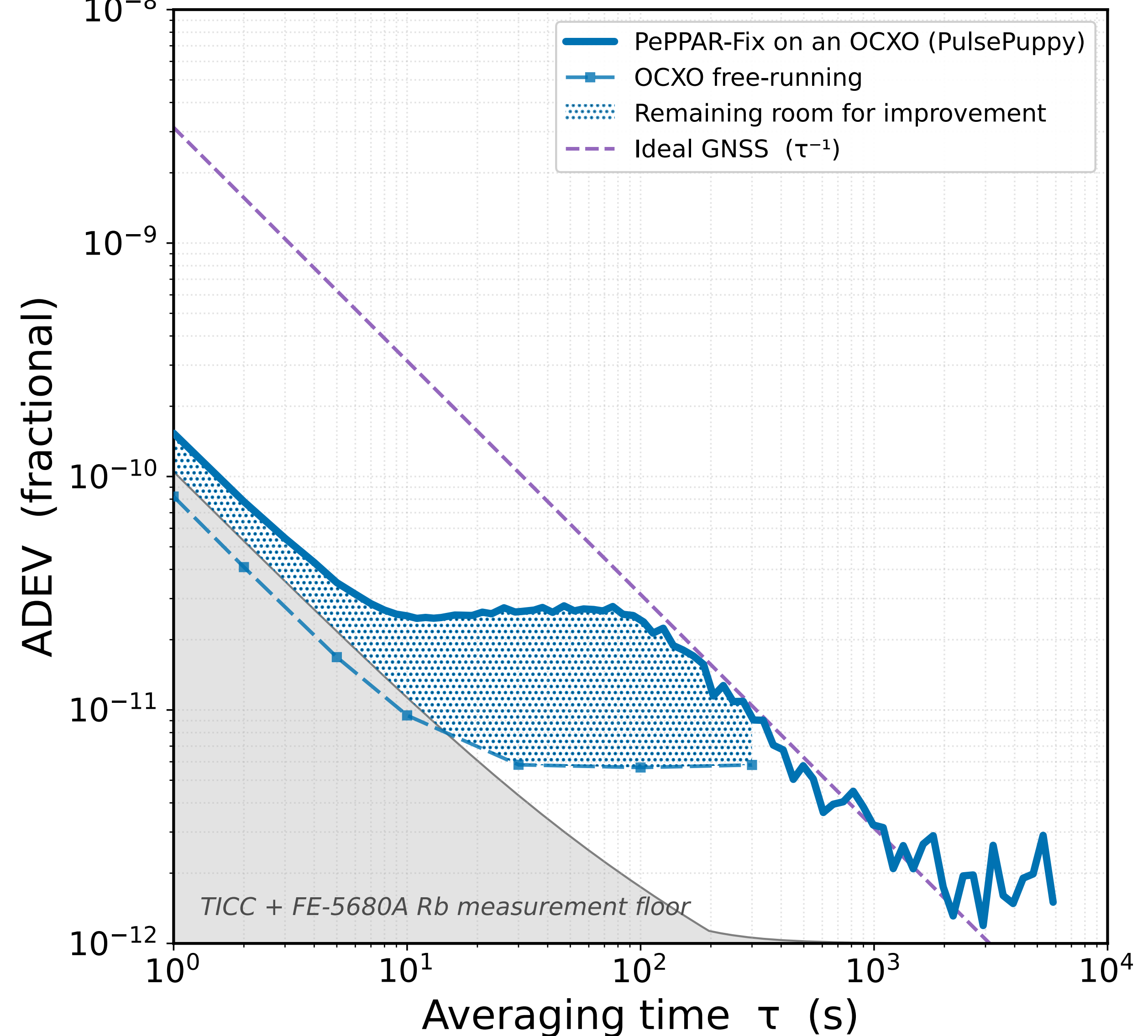


# PePPAR-Fix — the limits: noise floor, free-run oscillator, remaining room

## Time stability — TDEV( $\tau$ )



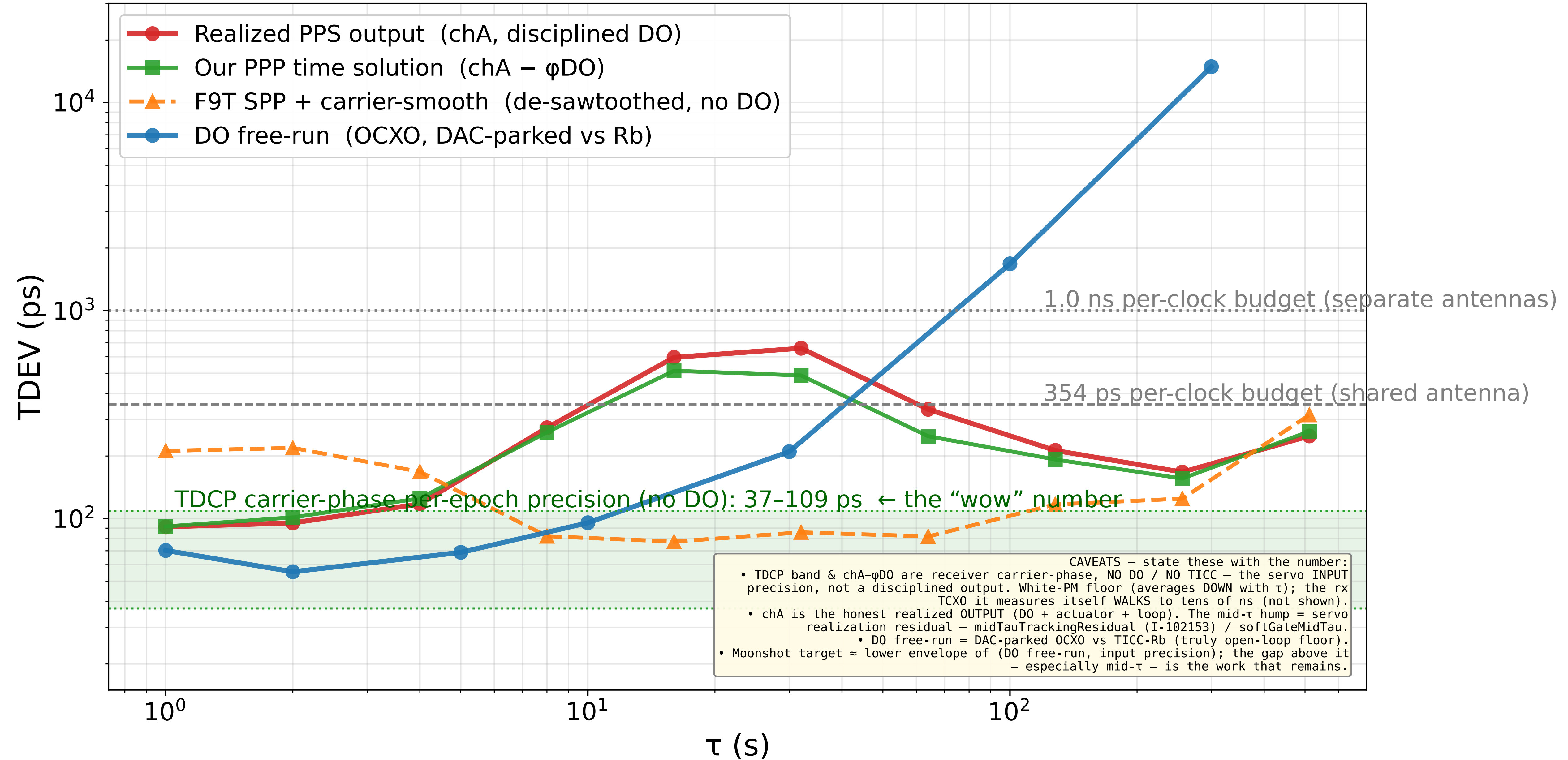
## Frequency stability — ADEV( $\tau$ )





# Servo input precision vs realized output vs DO free-run

## MadHat — F9T-20-00 (L1/L5) + OCXO/AD5693R





**WRAP UP**



# HARD LESSONS

- Know your position before asking new PPP code to solve for it
- Real-time PPP is always harder than post-processed PPP
- Sweat the details like tracking coordinate reference systems
- Hardware details like power distribution and level shifting matter sub-nano

**“People who are really serious about software should make their own hardware”**  
— Alan Kay



**EVEN A BLIND SQUIRREL CAN SOMETIMES FIND AN ACORN**





# AI USAGE NOTES

- Use CLI, not chat, e.g.: `cClaude --dangerously-skip-permissions`
- Runs on sandboxed VM with root access on my time lab
- Multiple, coordinated agents with specialized roles
  - Researching and planning
  - Python coding
  - Managing time lab, running experiments, and running simulations
  - Analyzing data and presenting results
- Key moments are often the exchange of intuition between AI and human
- Sloppy language is sloppy thinking — watch for misnomers
  - Agents read a project glossary on startup and maintain it as new ideas are added



# FUTURE WORK

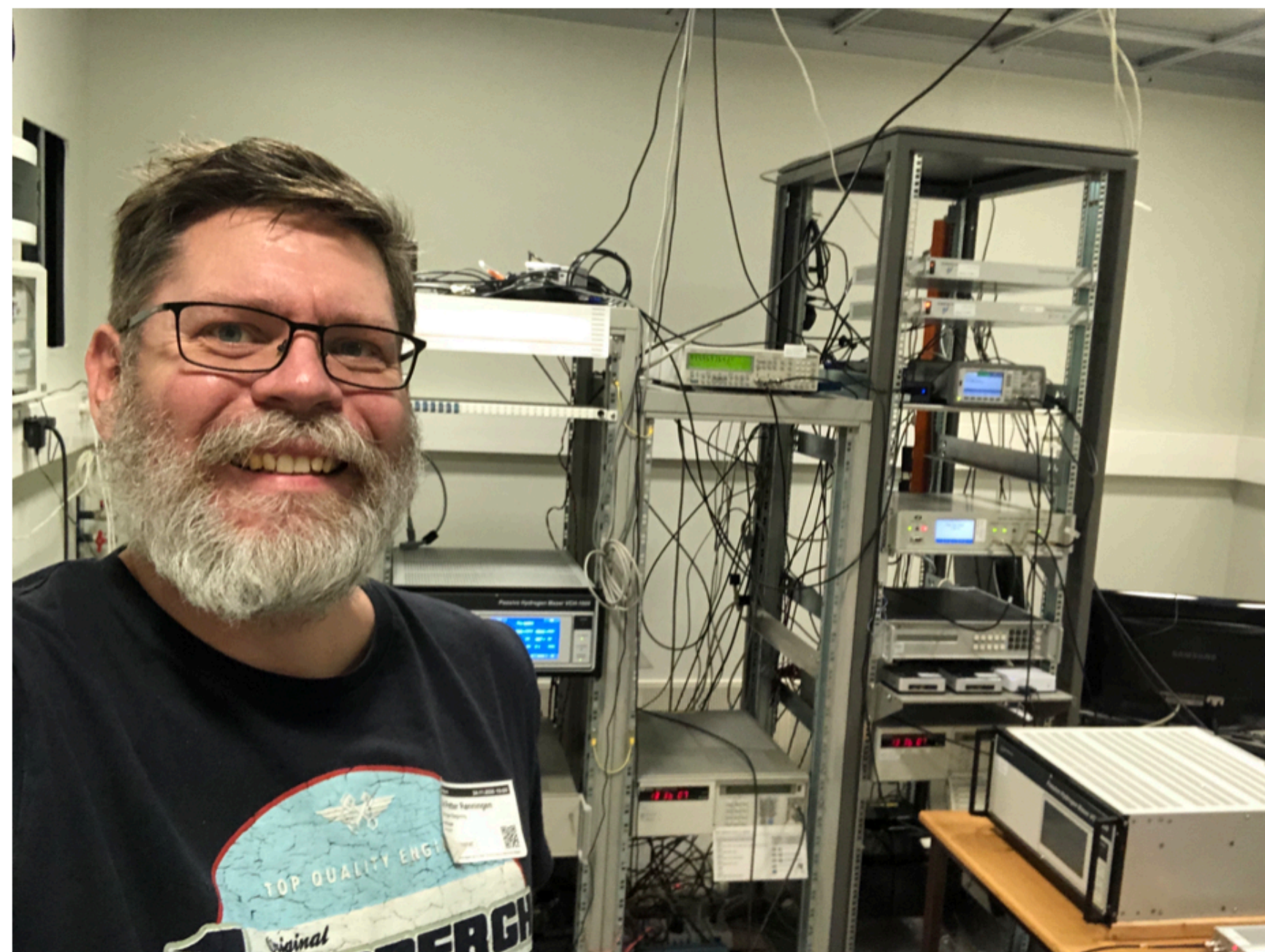
- Push for two-clock, two-antenna agreement to 2 ns
- Use disciplined oscillator to clock GNSS receiver
- More stable oscillators could get down to a few hundred ps
- Make PPP-AR position convergence reliable
- Add support for Timebeat's portable grandmaster
- Low-cost version without TICC, target \$500
- Try newer u-blox GNSS receivers
- Maybe faster update rates like 10 Hz?
- Maybe OSNMA?





# ACKNOWLEDGMENTS

**Ole Petter Rønningen, Time Nut**  
**First PPP GPSDO**



**John Ackermann, N8UR, Time Nut**  
**Inexpensive TIC and divider**





# PRESENTATION SLIDES



**Bob@VanValzah.Com**

**bobvan on GitHub**

**Includes two bonus slides**