BOB VAN VALZAH

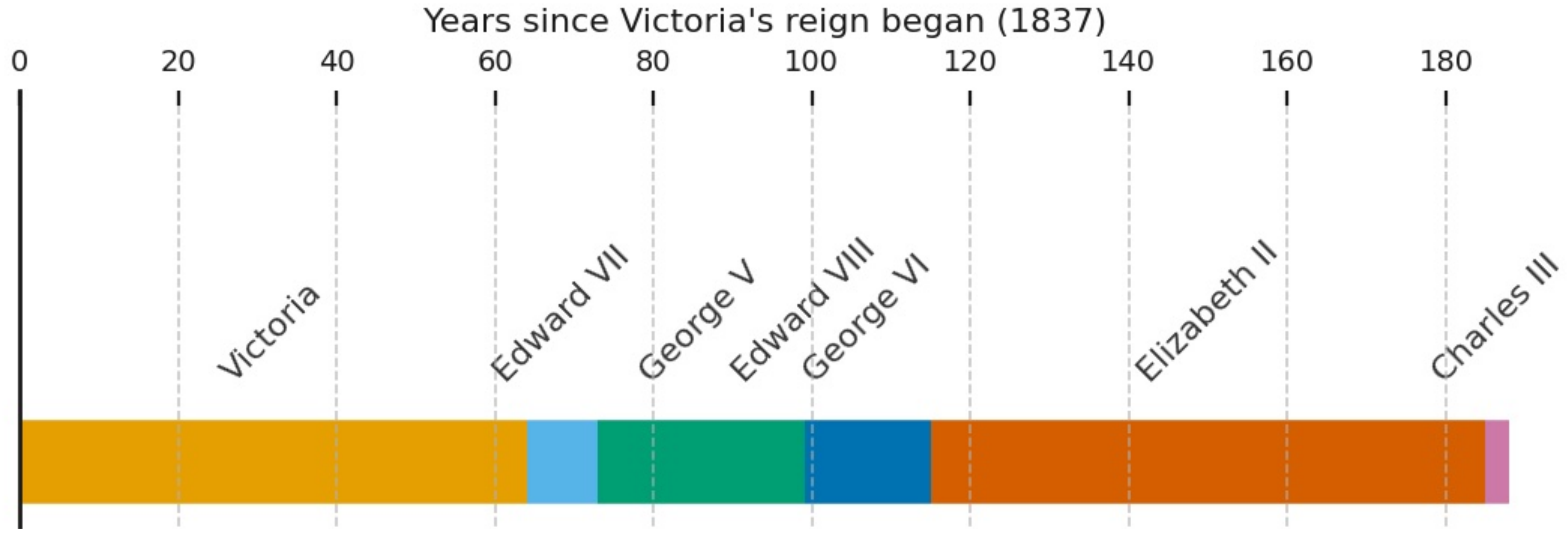
THE LAST NANOSECONDS TO UTC

Or … Bob goes down the (white) rabbit hole

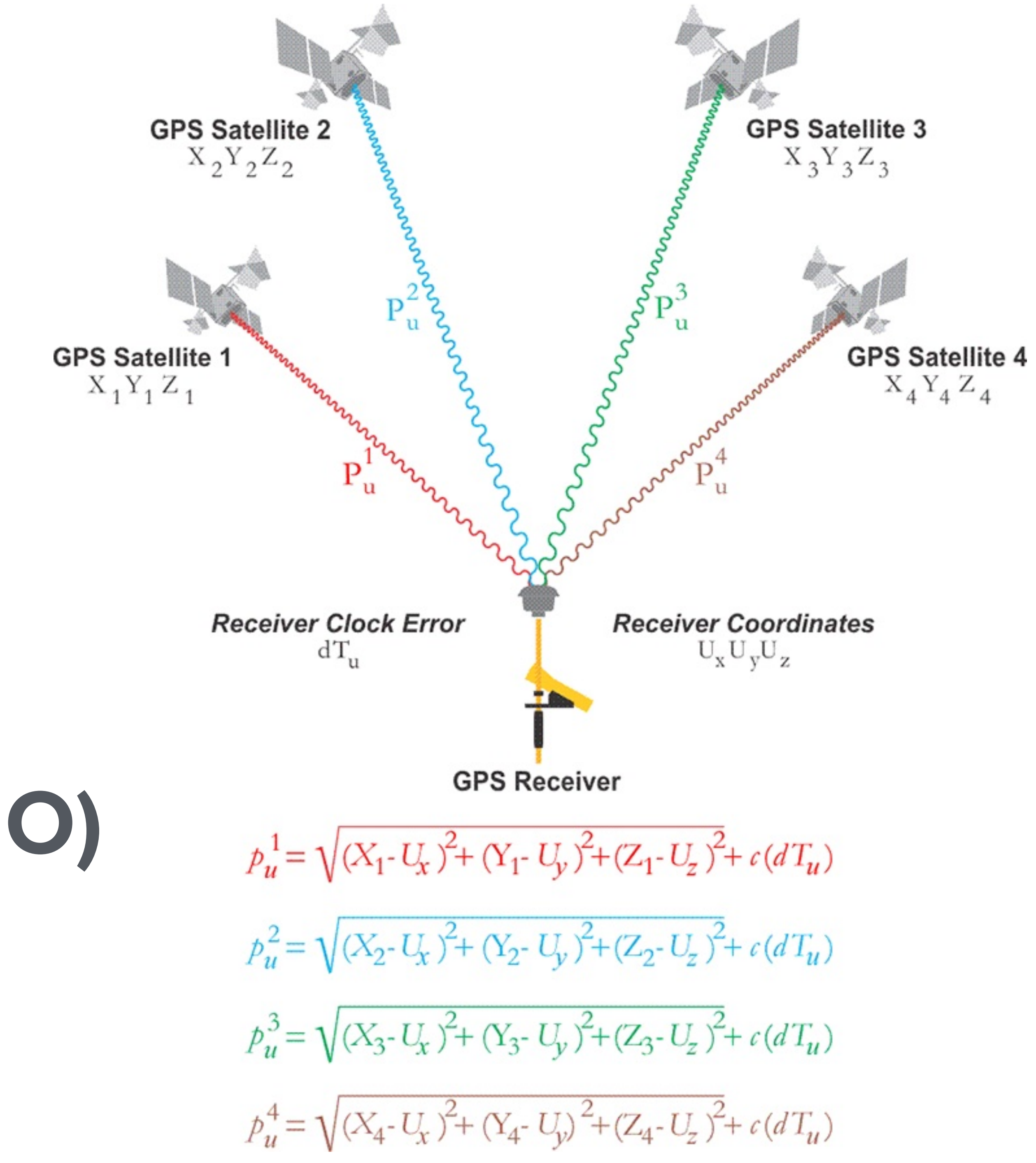
CLOCKS & TIMESCALES

- Not digital circuit clocks, “Time-of-Day” Clocks
  - Tick rate, relative to standard like Earth's rotation or orbit, or atomic resonance

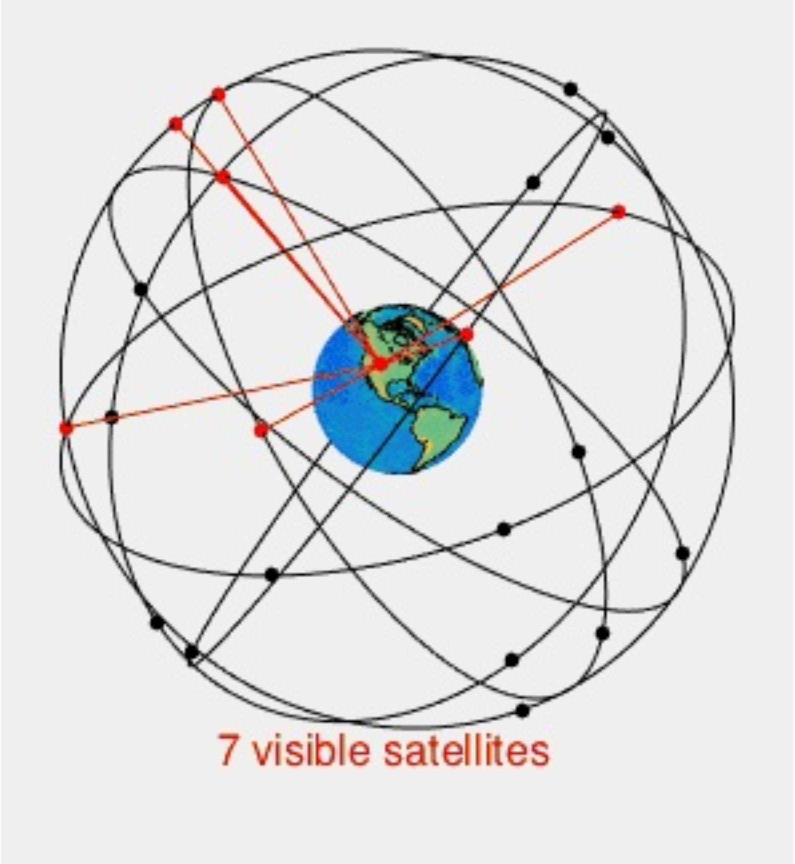
  - Count ticks to get elapsed time to one-tick resolution
  - Define a first tick, an epoch, to get a timescale
- Timestamps taken on a timescale



GNSS 101



- ~24 GPS satellites in 12-hour orbit, ≥ 4 always visible
- Synchronized atomic clocks on all satellites, traceable to UTC(USNO)
- GNSS signals give UTC time and orbit
- GNSS receiver gets UTC and positions of four satellites
- Receiver solves four equations with four unknowns: latitude, longitude, elevation, UTC
  - Produces 1 PPS at top of UTC second



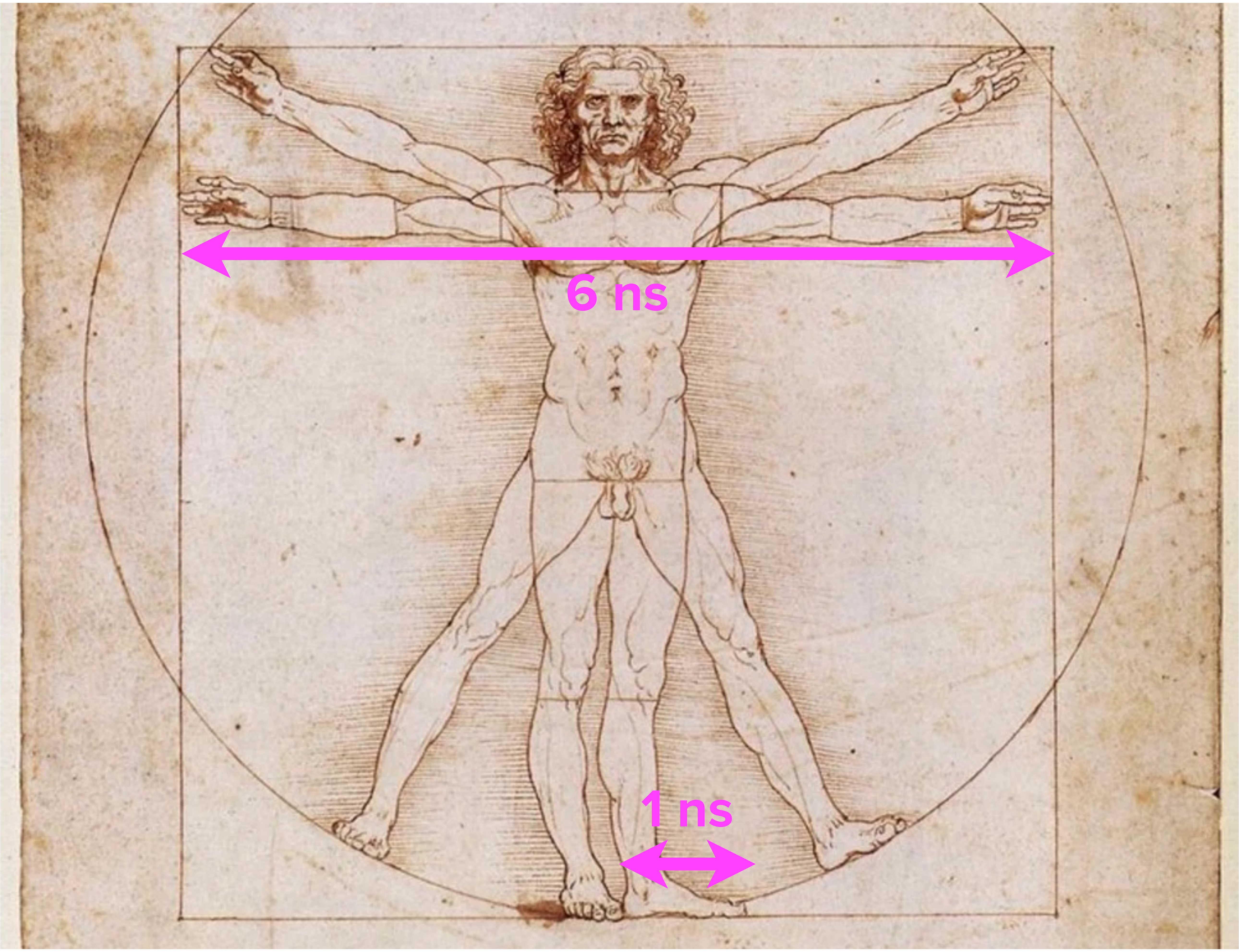
- Glossing over details like leap seconds, UTC vs gpstime

- Errors in position equivalent to errors in time


LATENCY BY MANHATTAN BLOCK
900 ns
250 ns
Very Roughly:
1 µs East/West
1/4 µs North/South

LATENCY BY BODY PARTS

Relating distance and time



Free space latency shown

PARADOXES

PARADOX ONE

GNSS Clock

Key Features

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

15 ns

“Call for quote”

GNSS Lawnmower

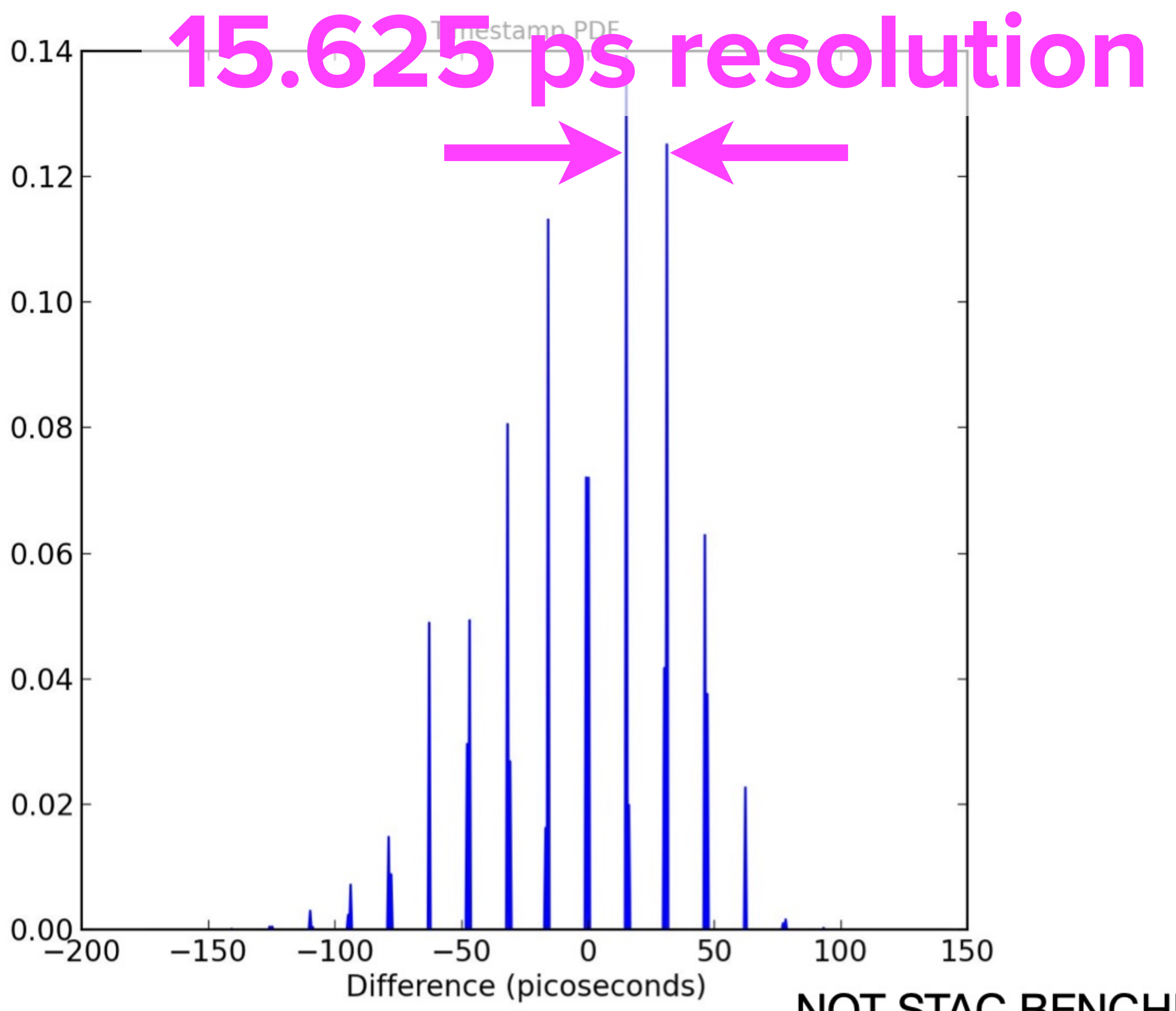
30 ps

$1,575

PARADOX TWO

Key Features

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



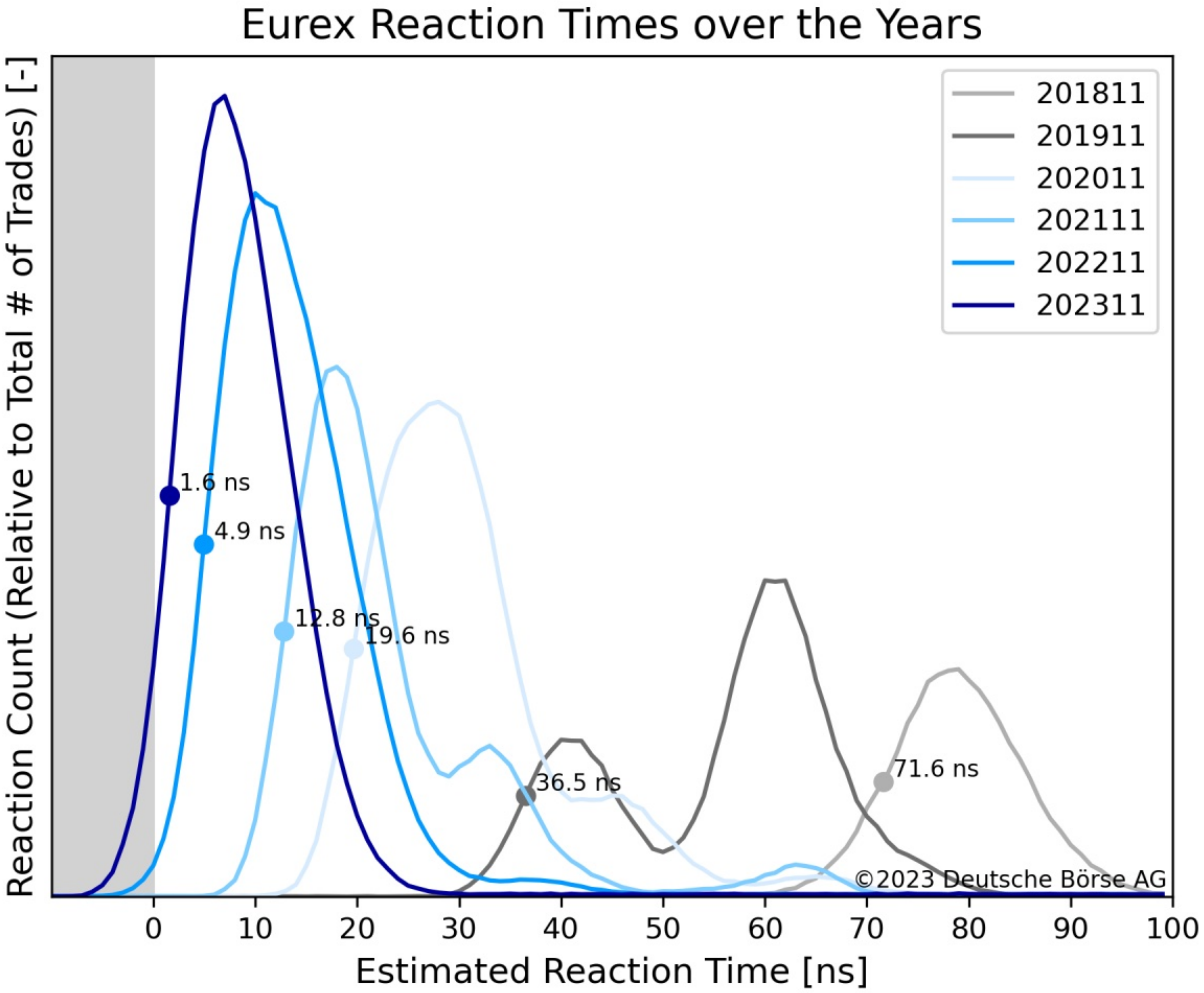
NOT STAC BENCHMARKS

Acquiring UTC vs Network Timestamping: Three Orders of Magnitude


Equinix Campus
Secaucus, NJ
Sync any pair of 7130 ports
to 200 ps over 1/2-mile
campus, but sync to UTC
only +/-15 ns RMS
NY5
NY6
NY2
NY4
NY3
Equinix NY5 Data Center
Equinix Data Center
Secaucus Rd
Enterprise Ave S
Hartz Wy
Jefferson Ave
Metro Wy
Image Landsat / Copernicus

PARADOX THREE

Market reaction times much less than UTC sync error

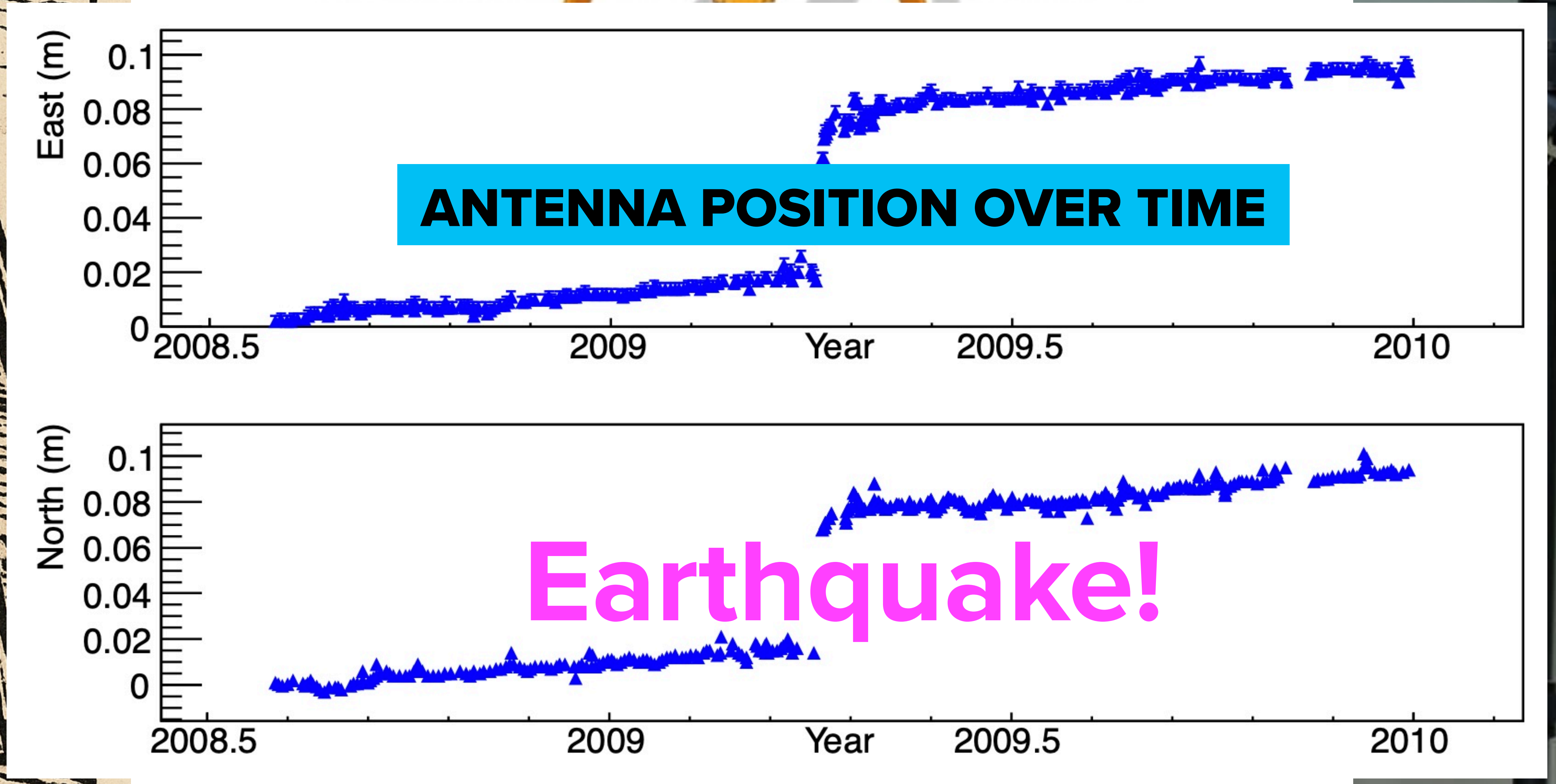


Stefan Schlamp via LinkedIn

HOW DID WE GET HERE?

Post-processing is the secret!

POSITIONING ACCURACY



MARKET SIZE

PRECISE POSITION

~92% consumer & automotive

GNSS market: €260 B in 2023

NAVSTAR GPS

PRECISE FREQUENCY

PRECISE TIME

NOT TALKING ABOUT

- Not talking about host timestamping accuracy
- Not talking about a slave host following a GM accurately
- Not talking about host timestamps at all (parallel instruction retirement variance > PTP sync variance)
- Not talking about GNSS clock holdover
- Not talking about elapsed time on a single clock, that's just frequency stability, insignificant for typical trading durations
- Not talking about MiFID 2 compliance
- Not going to FUD you with spoofing and jamming

What's Left?

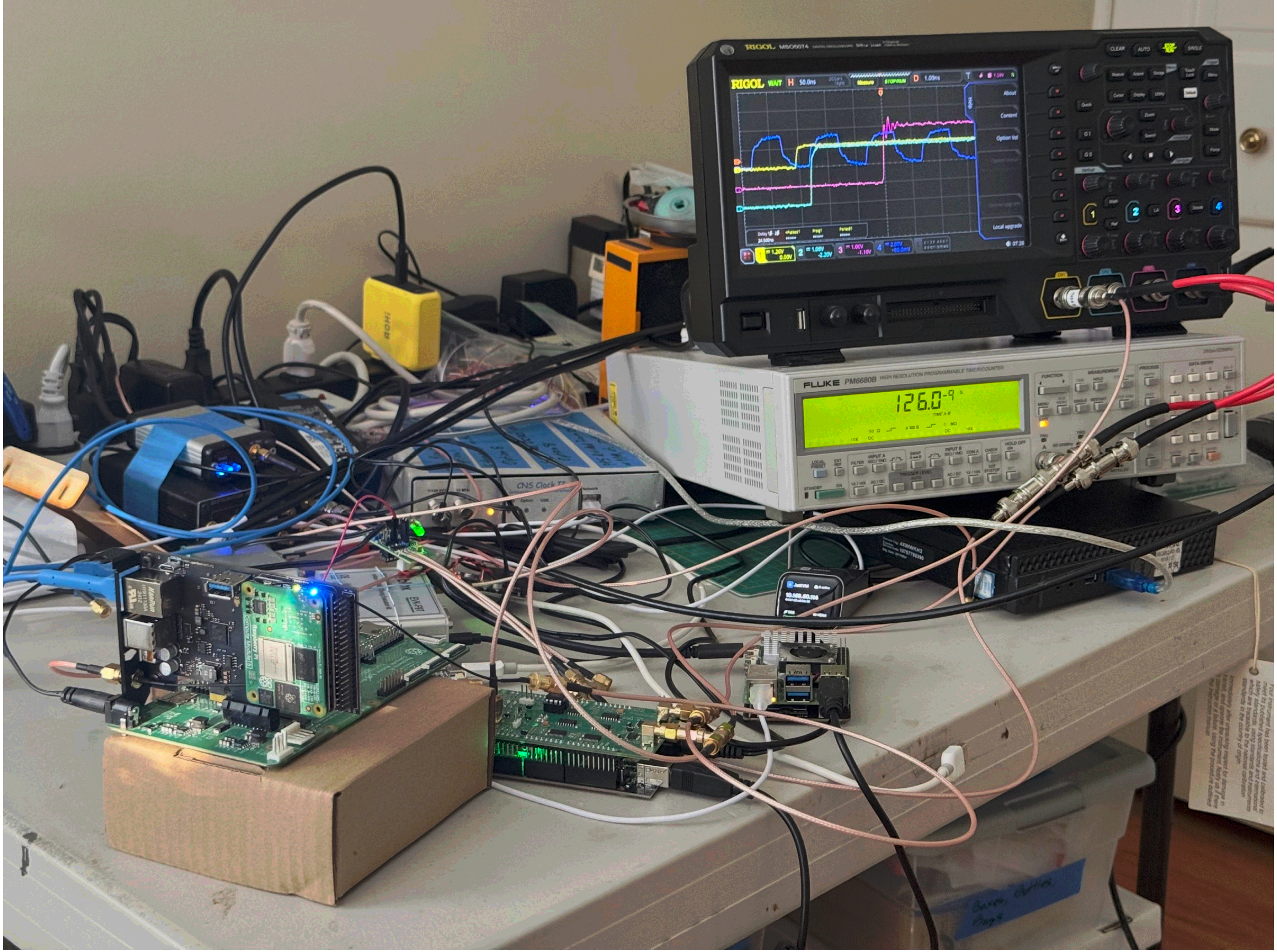
How close can network timestamps get to UTC?

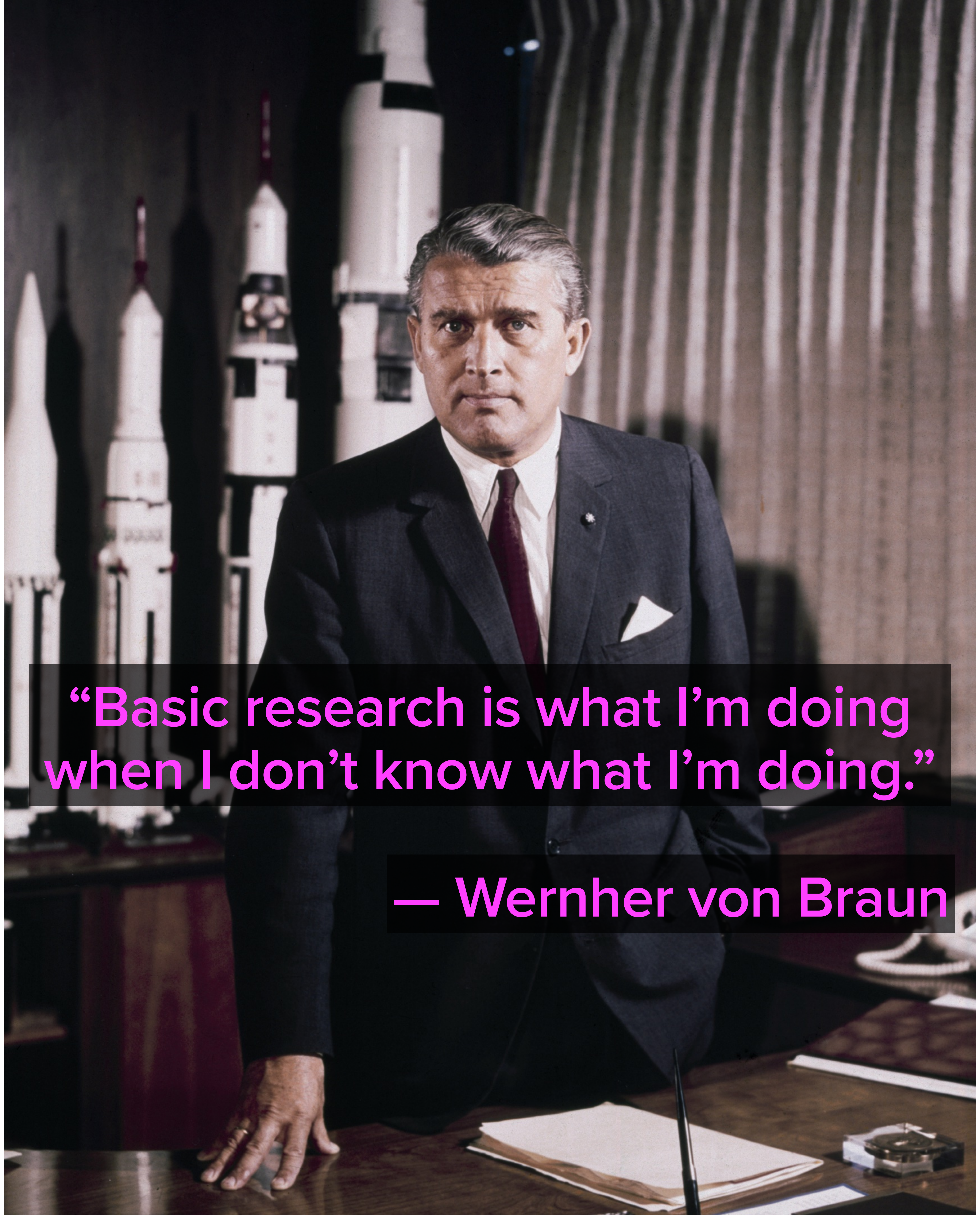
RESEARCH IN RETIREMENT

Is Sub-Nanosecond UTC Sync Possible?

Literally, no.

Practically, yes!


RIGOL
FLUKE PM6680B
126.0-9


"Basic research is what I'm doing when I don't know what I'm doing."
— Wernher von Braun

WHY SUB-NANOSECOND IS HARD

- Digital systems intentionally hide time between cycles
- It's a problem in the analog domain
- Impractically-high clock rates
  - Would still be quantized
- Expensive lab equipment, if available at all
- How to calibrate/test what you build yourself?
- Picoseconds since epoch >> 64-bits
- Create your own datatypes and math for picoseconds
- Basic research completed by national labs, VLBI, CERN, etc.
- R&D for trading applications remains

Clock Resolution (Period)	Clock Frequency
100 ns	10 MHz
10 ns	100 MHz
1 ns	1 GHz
100 ps	10 GHz

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CERN Accelerating science

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News › Press release › Topic: At CERN

Voir en français

OPERA experiment reports anomaly in flight time of neutrinos from CERN to Gran Sasso

23 SEPTEMBER, 2011

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UPDATE 8 June 2012

Neutrinos sent from CERN to Gran Sasso respect the cosmic speed limit

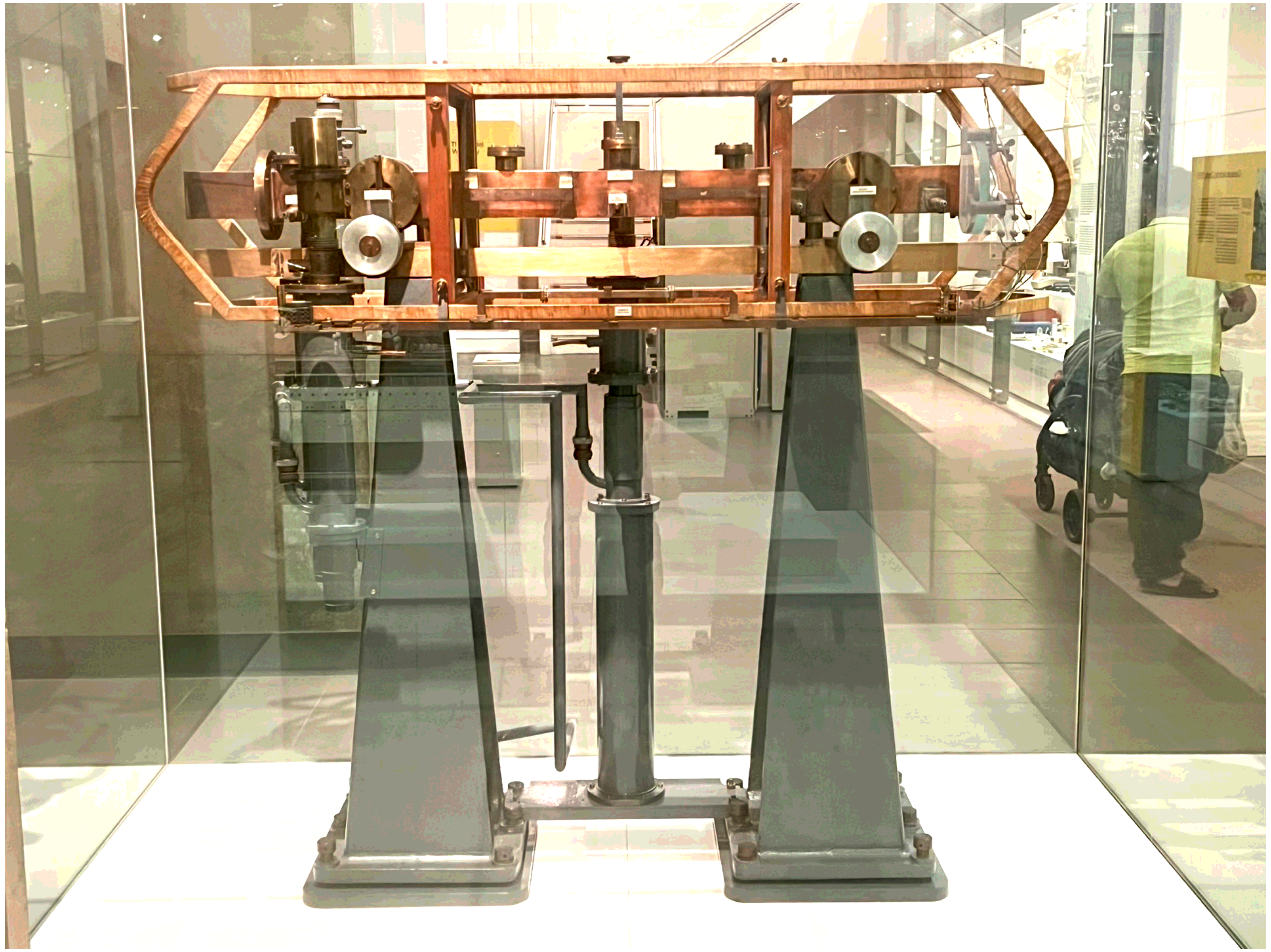
At the 25th International Conference on Neutrino Physics and Astrophysics in Kyoto today, CERN Research Director Sergio Bertolucci presented results on the time of flight of neutrinos from CERN to the INFN Gran Sasso Laboratory on behalf of four experiments situated at Gran Sasso. The four, Borexino, ICARUS, LVD and OPERA all measure a neutrino time of flight consistent with the speed of light. This is at odds with a measurement that the OPERA collaboration put up for scrutiny last September, indicating that the original OPERA measurement can be attributed to a faulty element of the experiment's fibre optic timing system.

"Although this result isn't as exciting as some would have liked," said Bertolucci, "it is what we all expected deep down. The story captured the public imagination, and has given people the opportunity to see the scientific method in action – an unexpected result was put up for scrutiny, thoroughly investigated and resolved in part thanks to collaboration between normally competing experiments. That's how science moves forward."

In another development reported in Kyoto, the OPERA experiment showed evidence for the appearance of a second tau-neutrino in the CERN muon-neutrino beam, this is an important step towards understanding the science of neutrino oscillations.

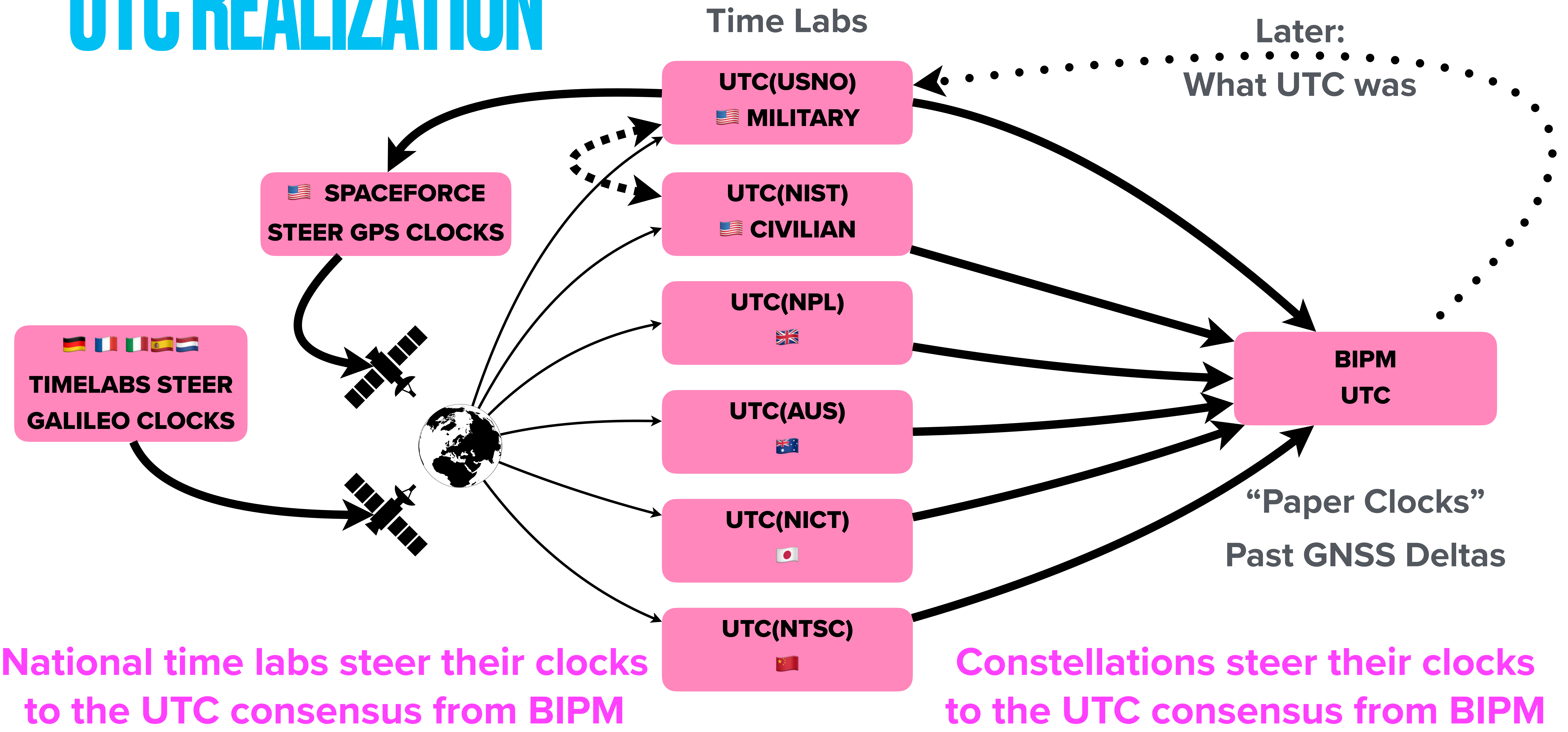
UTC 201

NATIONAL TIME LABS



- E.g. National Physics Lab in Teddington
- Very stable frequency standards
  - Hydrogen maser
  - Cesium fountain
  - Optical lattice
- Precise GNSS receivers
- Time comparison with other labs
- Each lab has own “realization” of UTC, e.g. UTC(NPL), UTC(USNO), etc.
  - These are *predictions* of what will be UTC, when published by BIPM
- National labs steer their ensembles to match other lab’s and UTC

UTC REALIZATION



4 - Relations of UTC with predictions of UTC broadcast by GNSS.

For this edition of *Circular T*:

σ_GPS = 5 ns
σ_GLO = 7 ns
σ_GAL = 5 ns
σ_BDS = 5 ns

HOW BIPM DEFINES UTC

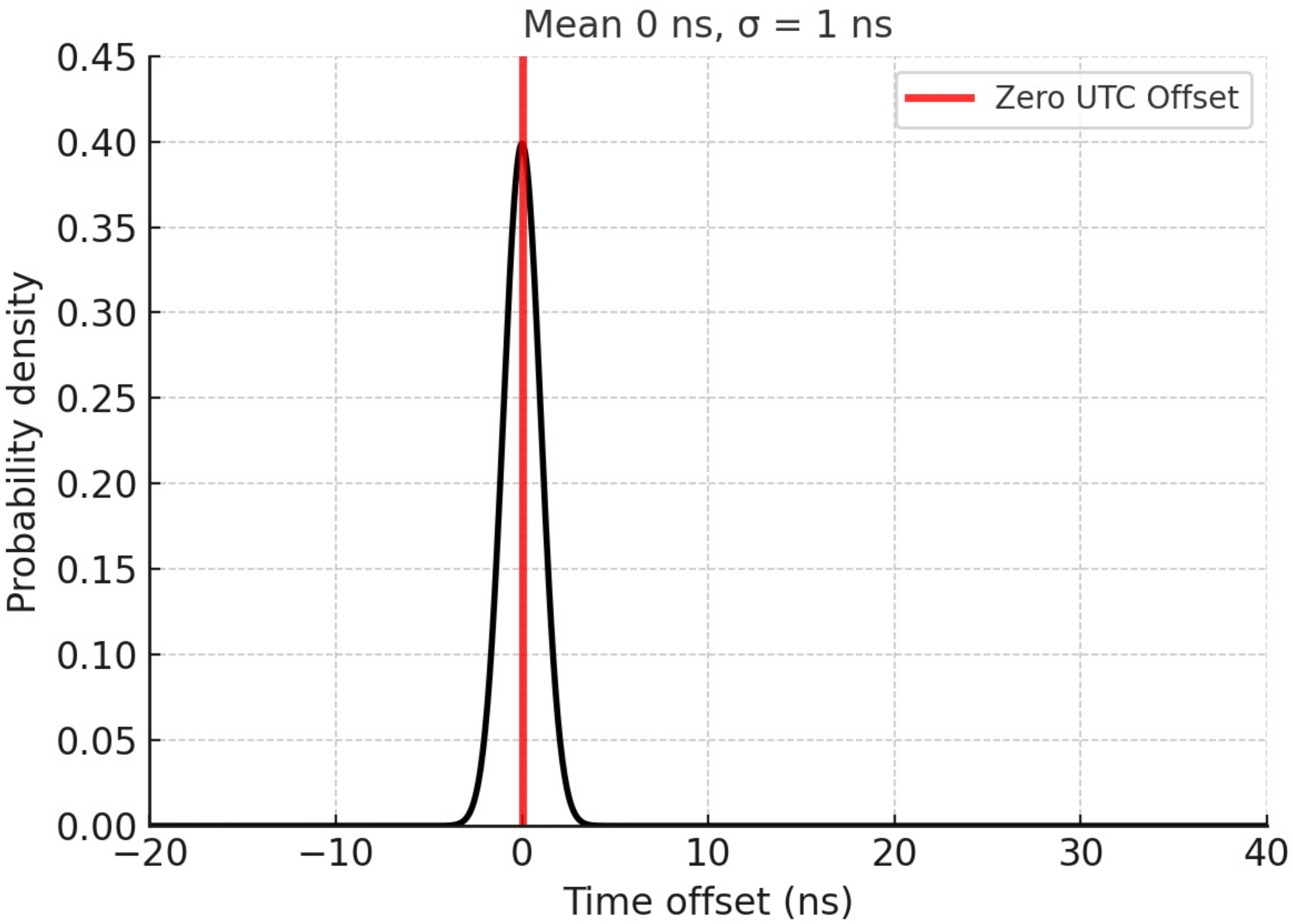
DATE 0h UTC	MJD	UTC-bUTC_GNSS /ns			
		GPS	GLO	GAL	BDS
2025-07-28	60884	-0.5	-6.1	3.4	-0.6
2025-07-29	60885	0.7	-5.3	2.8	-0.4
2025-07-30	60886	1.1	-5.1	-0.4	-0.6
2025-07-31	60887	1.4	-6.4	0.3	-0.3
2025-08-01	60888	0.8	-6.0	0.5	-0.4
2025-08-02	60889	0.4	-5.1	0.2	-1.1
2025-08-03	60890	1.6	-5.4	-0.1	-1.5
2025-08-04	60891	2.4	-8.2	-0.1	-1.1
2025-08-05	60892	2.4	-6.3	-0.3	-0.6
2025-08-06	60893	0.2	-4.9	-0.7	-0.7
2025-08-07	60894	-0.9	-6.0	-0.6	-1.5

GNSS UNCERTAINTY (“ERRORS”)

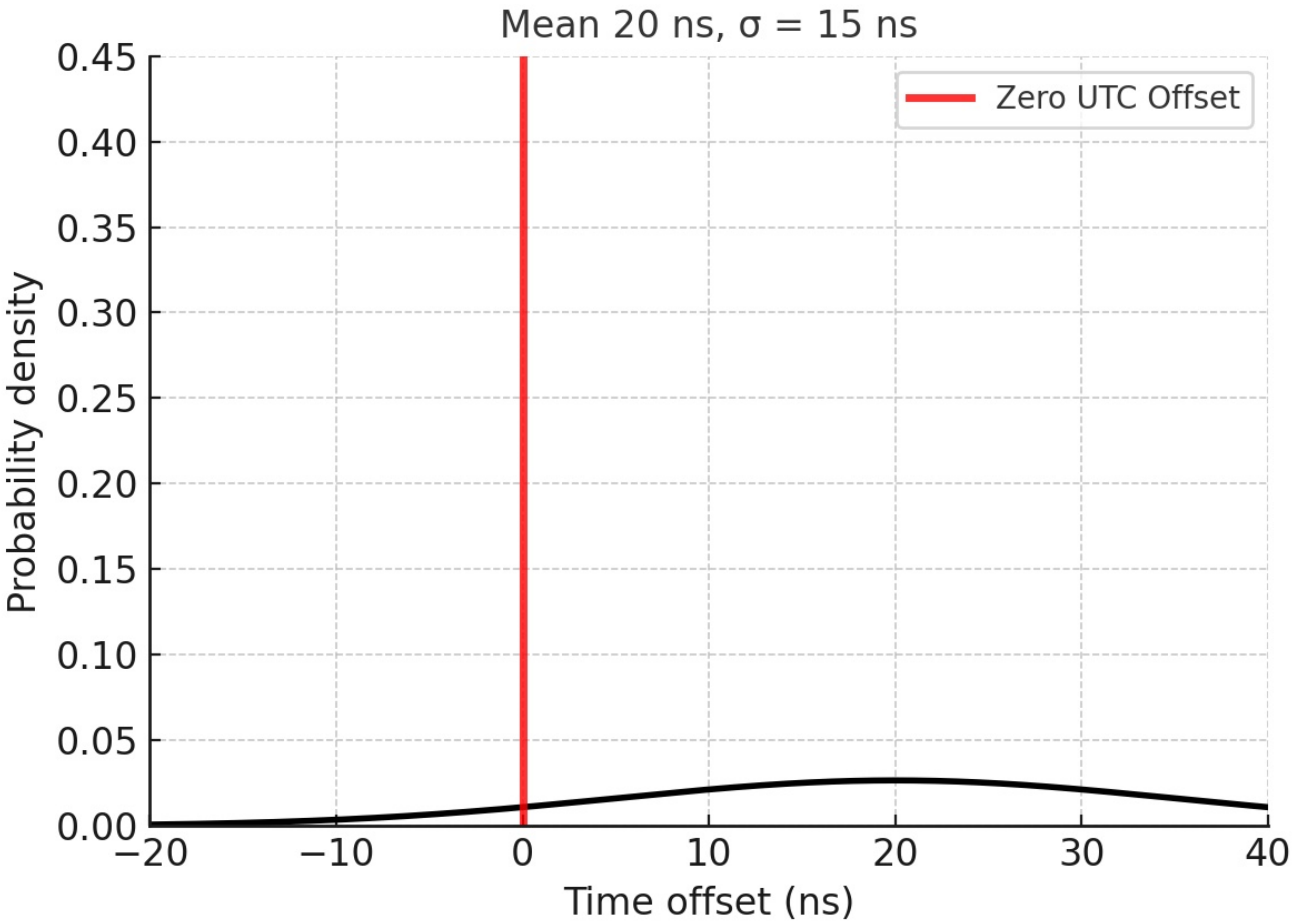
GNSS UTC UNCERTAINTY

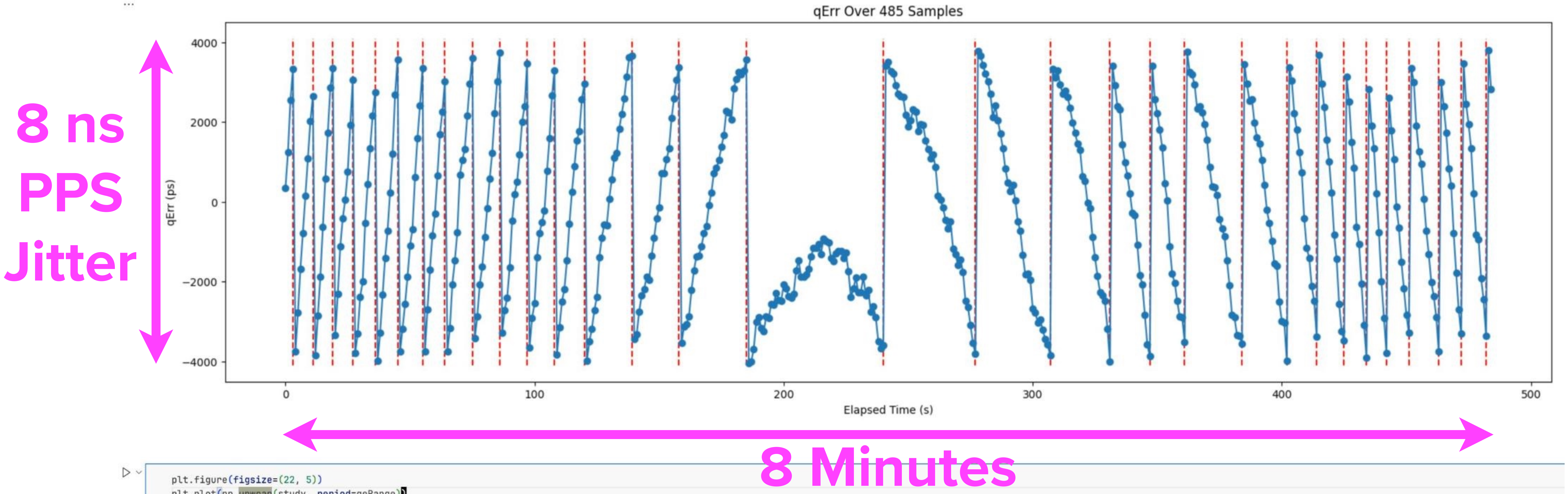
- Mean offset from UTC
  - A 1-foot error in antenna position or height is a 1 ns error in UTC
  - Incorrect antenna cable length compensation
  - Frustrations: No datacenter roof access, “community” antennas
- Instantaneous UTC error
  - PPS “Sawtooth Error” a.k.a. quantization error
    - PPS edge sync’d to GNSS module clock (typ. < 100 MHz)
  - Ionospheric
  - Tropospheric
  - Satellite clocks
  - Satellite orbits

Probably what you want



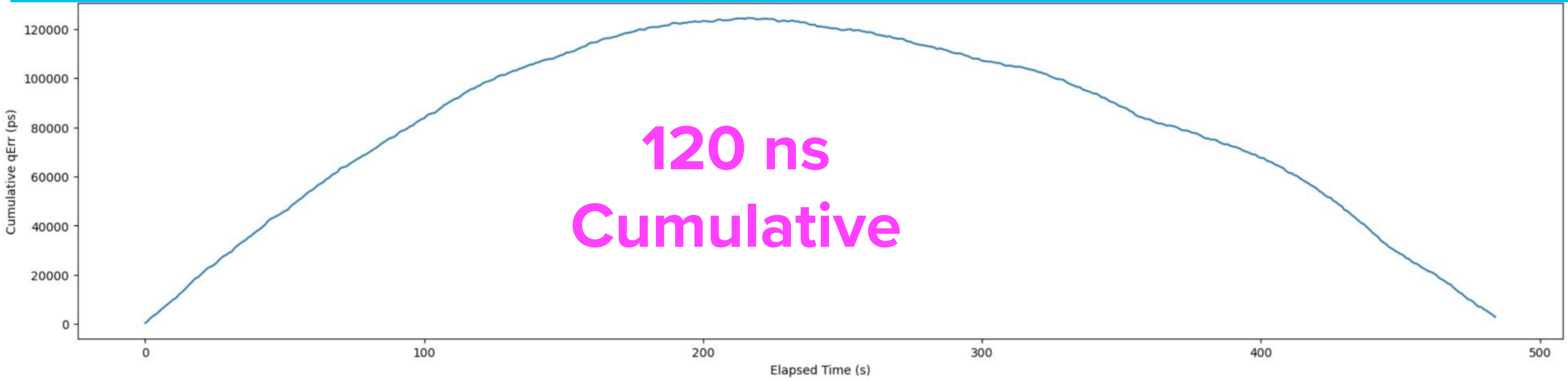
Probably what you have






```
plt.figure(figsize=(22, 5))
plt.plot(np.unwrap(study, period=qeRange))
```

LESSON LEARNED: WHEN YOU COMPARE GPS TIME TO QUARTZ TIME, YOU'VE BUILT A VERY EXPENSIVE THERMOMETER

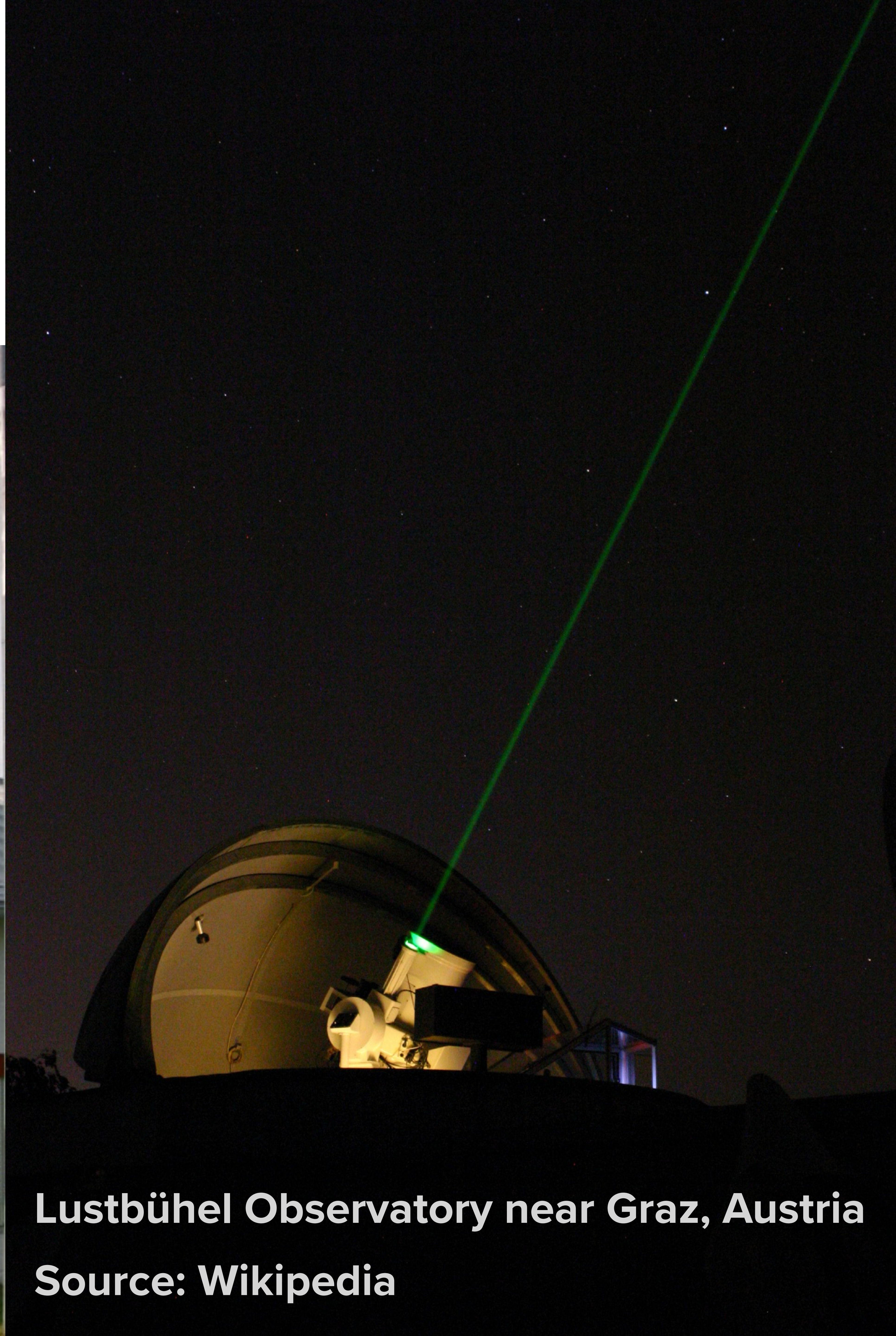


Impact of u-blox F9T qErr Corrections on TDEV(τ)
2 ns
1 ns
900 ps
800 ps
700 ps
600 ps
500 ps
400 ps
300 ps
200 ps
100 ps
90 ps
σx(τ)
1 s
10 s
100 s
1000 s
τ
Uncorrected
Corrected
Not a STAC Benchmark
Instrument: TAPR TICC
Reference: Geppetto GPSDO with OH300 5ppb OCXO
RMS Jitter Floor of TAPR TICC

SATELLITE LASER RANGING

Geodetic Observatory Wettzell, Bavaria

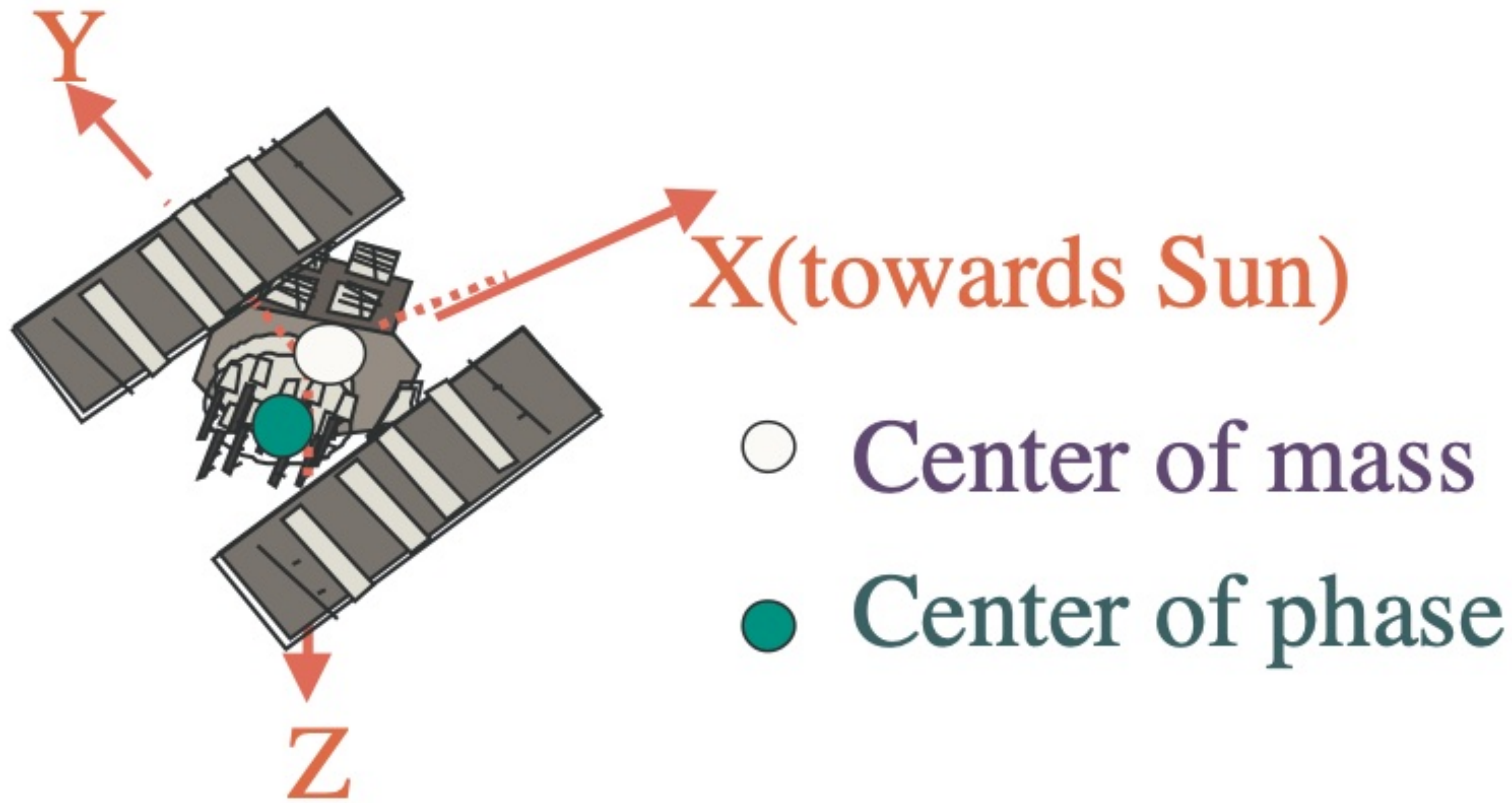
Source: Wikipedia



Lustbühel Observatory near Graz, Austria

Source: Wikipedia

EVEN CONSIDER ANTENNA VS CENTER OF MASS



Relative GPS antenna phase center offsets adopted by IGS in satellite body fixed reference frame (m)

	X	Y	Z
Block II/IIA:	0.279	0.000	1.023
Block IIR :	0.000	0.000	0.000

Figure 2: IGS conventional (relative) GPS satellite antenna phase center offsets in satellite body fixed reference frame, used up to Nov. 4, 2006 (GPS Week 1399) and consistent with the relative *igs01.pcv* and *igs01.atx* PCV's.

SECRETS OF THE GPS LAWNMOWER

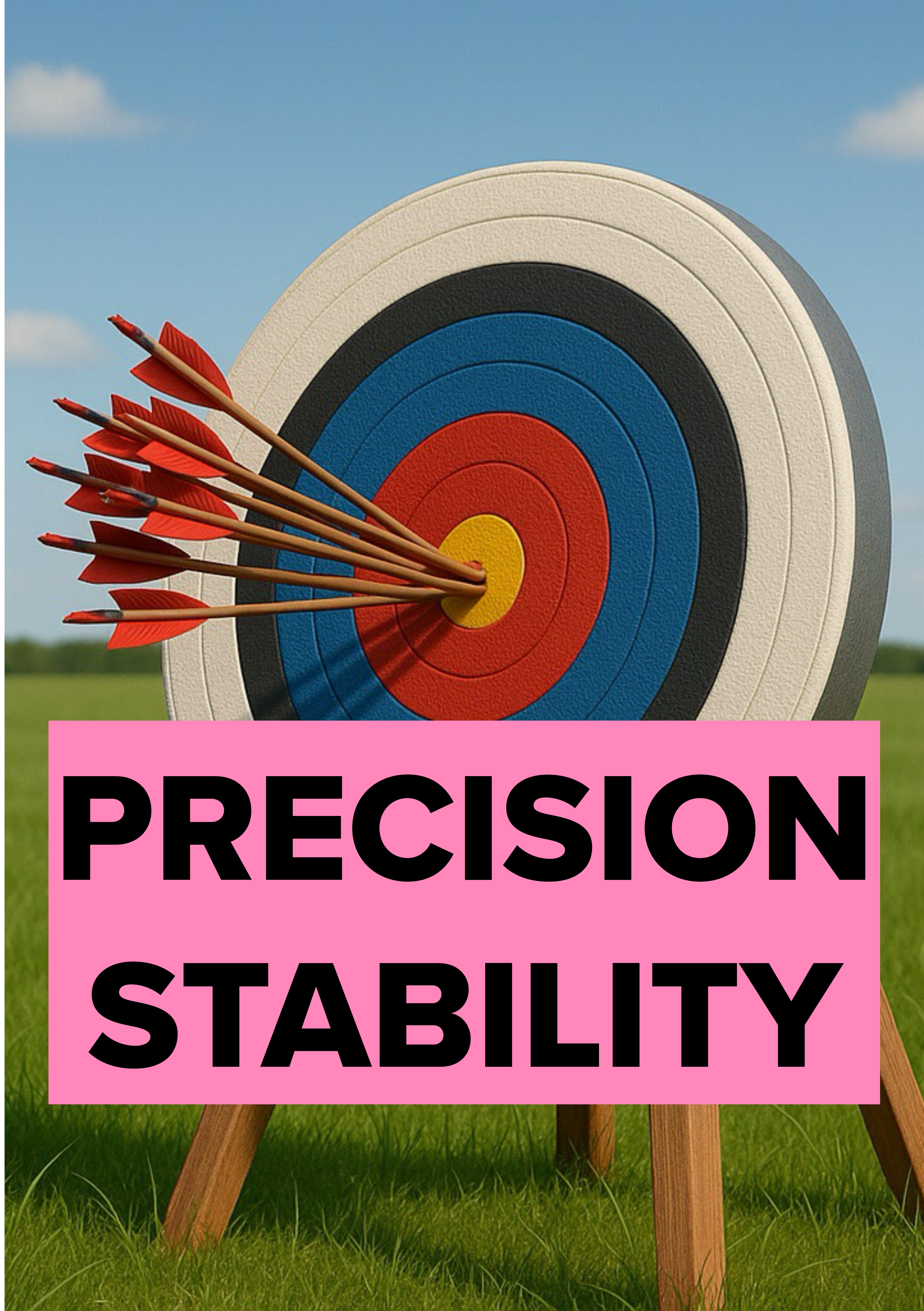
- Fixed “RTK Base” measures current GNSS errors
- Sends current corrections to “RTK Rover” (lawnmower)
- Observation over time and post processing
- GNSS augmentation
  - RTK corrections
  - Terrestrial radio
  - Satellite
  - Internet
- Precise Point Positioning (PPP)
  - Calibrated hardware observing raw GNSS signals over 24-hours
  - Post processing raw signals gives RTK Base its position to centimeter accuracy

STABILITY

LUCKY SHOT?

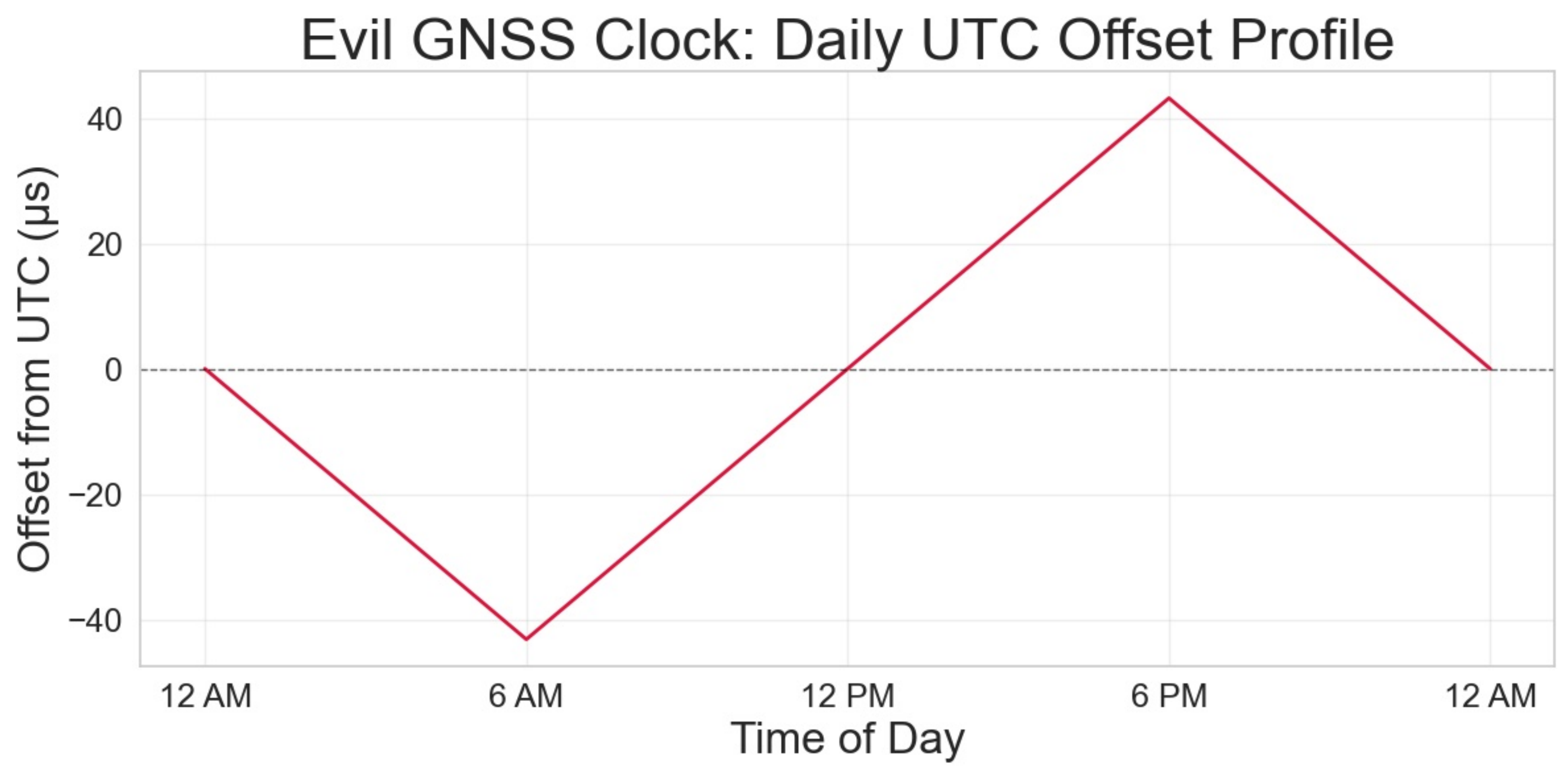
PURE SKILL

TIMING ANALOGY



INSTANTANEOUS ACCURACY VS MEAN ERROR

- Imagine an evil GNSS clock reversing fast and slow
- Runs 1 ns per second fast between 6 am and 6 pm
- Runs 1 ns per second slow between 6 pm and 6 am
- Mean error over the day: Zero!
- A day still has exactly 86,400 seconds, but was 43.2 µs ahead or behind
- Twelve hour reverse makes the point, but could reverse more quickly
- Reversing every minute, still would have 30 ns peak error
- Would be very hard to notice
- GNSS clocks all agree on length of day, but time may vary +/- 15 ns or more



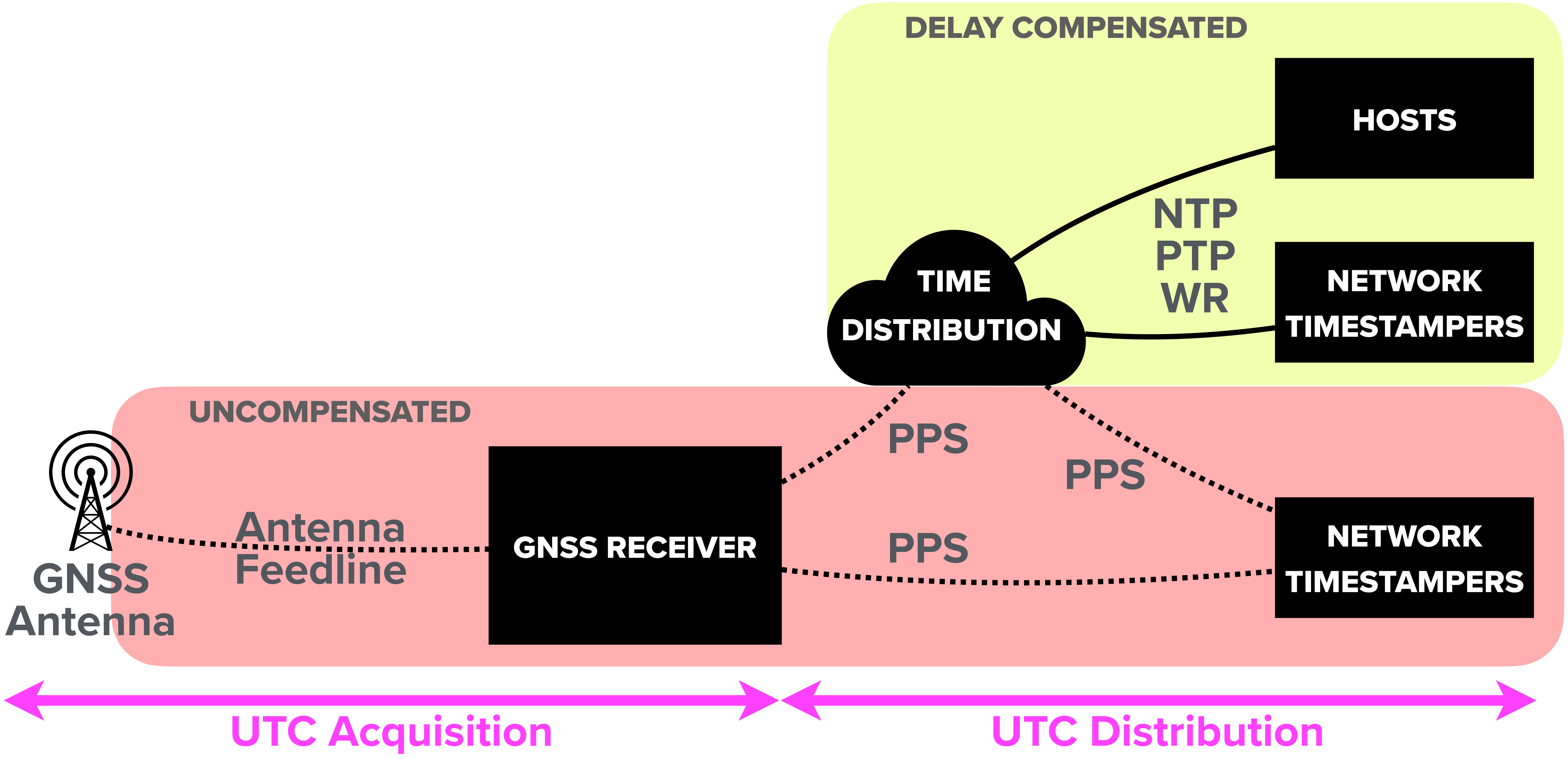
MEASURING

	TIME	FREQUENCY
MEASURE ONCE	Instantaneous Time Error (seconds)	Fractional Frequency Error (PPM)
REPEATED MEASUREMENTS	Time Stability TDEV(τ) MTIE(τ) Time Deviation Mean Offset	Frequency Stability ADEV(τ) Allan Deviation

If you’re taking 1e12 timestamps/day, you care about stability!

UTC DISTRIBUTION

UTC ACQUISITION & DISTRIBUTION DELAY COMPENSATION



NTP and PTP assume symmetric delay, WR handles asymmetry

UTC DISTRIBUTION ACCURACY (1 σ)

Note log scale, 10 orders of magnitude!

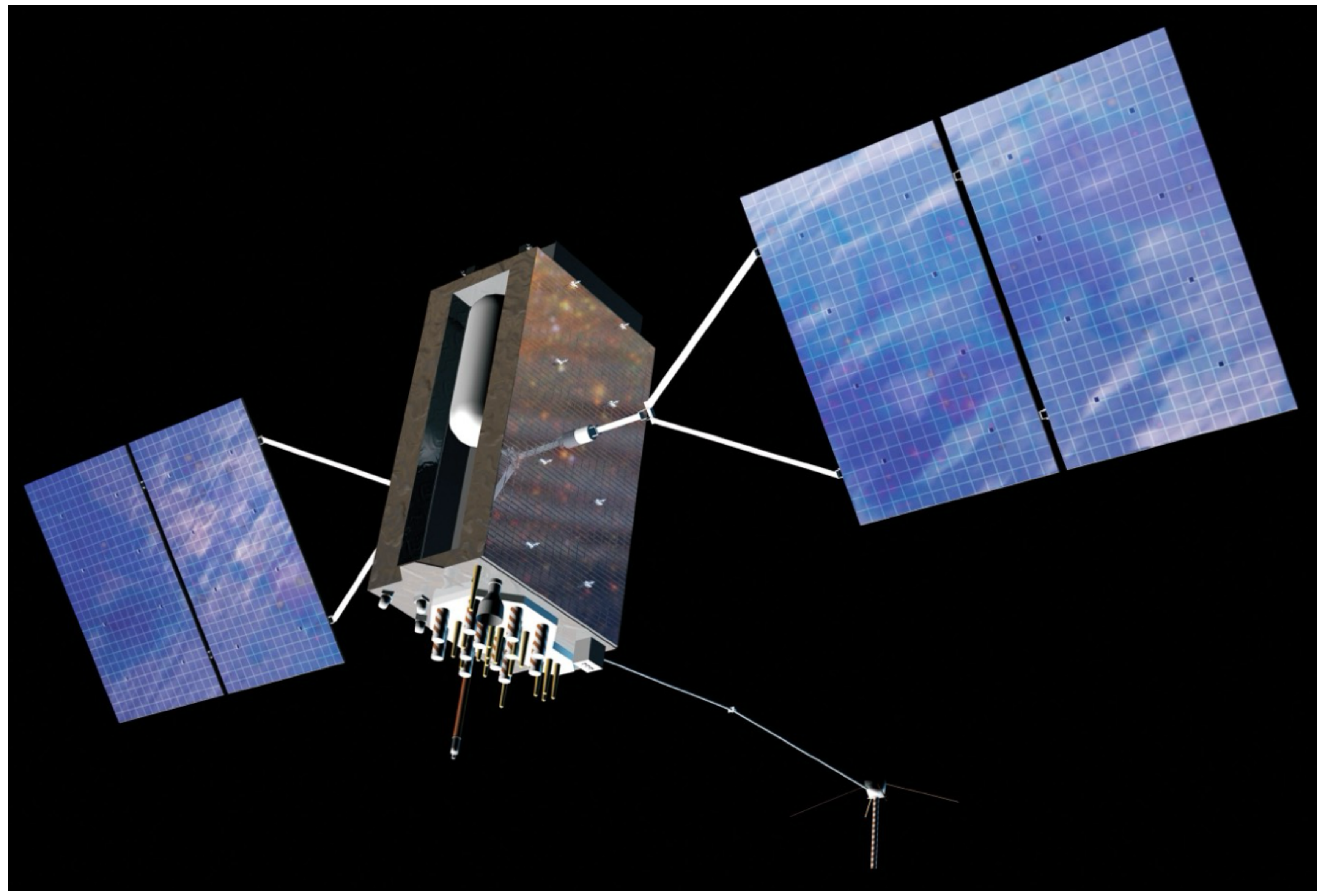
TESTING GNSS CLOCK ACCURACY

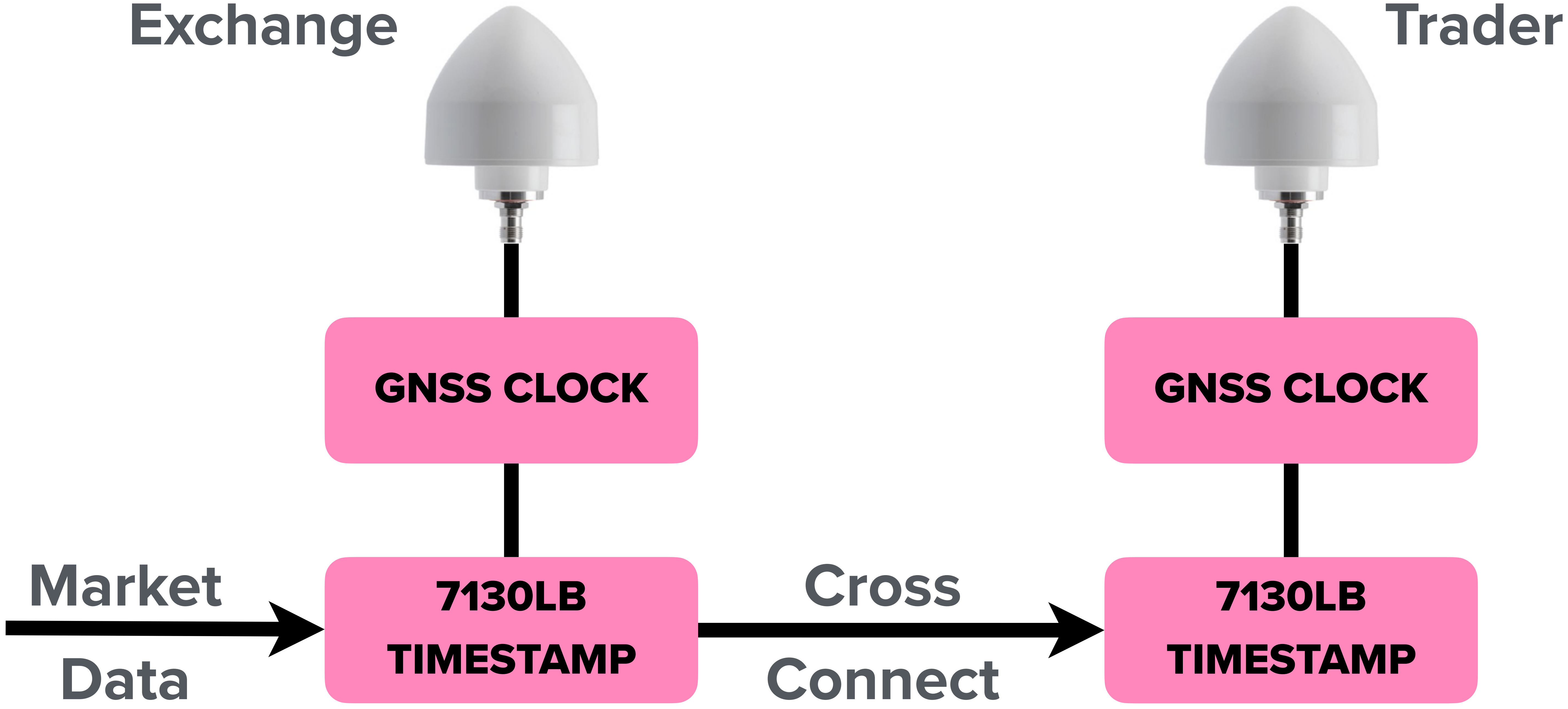
STAC-TS BENCHMARKS

- Network Capture, for example, Arista (nee Metamako) 7130
  - External sync
  - Port-to-port sync
  - MetaWatch delivers 15.625 ps resolution
  - Resolves time as though it had a 64 GHz clock
    - But it doesn't really

- GNSS Clocks
  - Holdover test protocol established
  - No work on UTC accuracy AFAICT

ACQUIRING UTC USING UTC

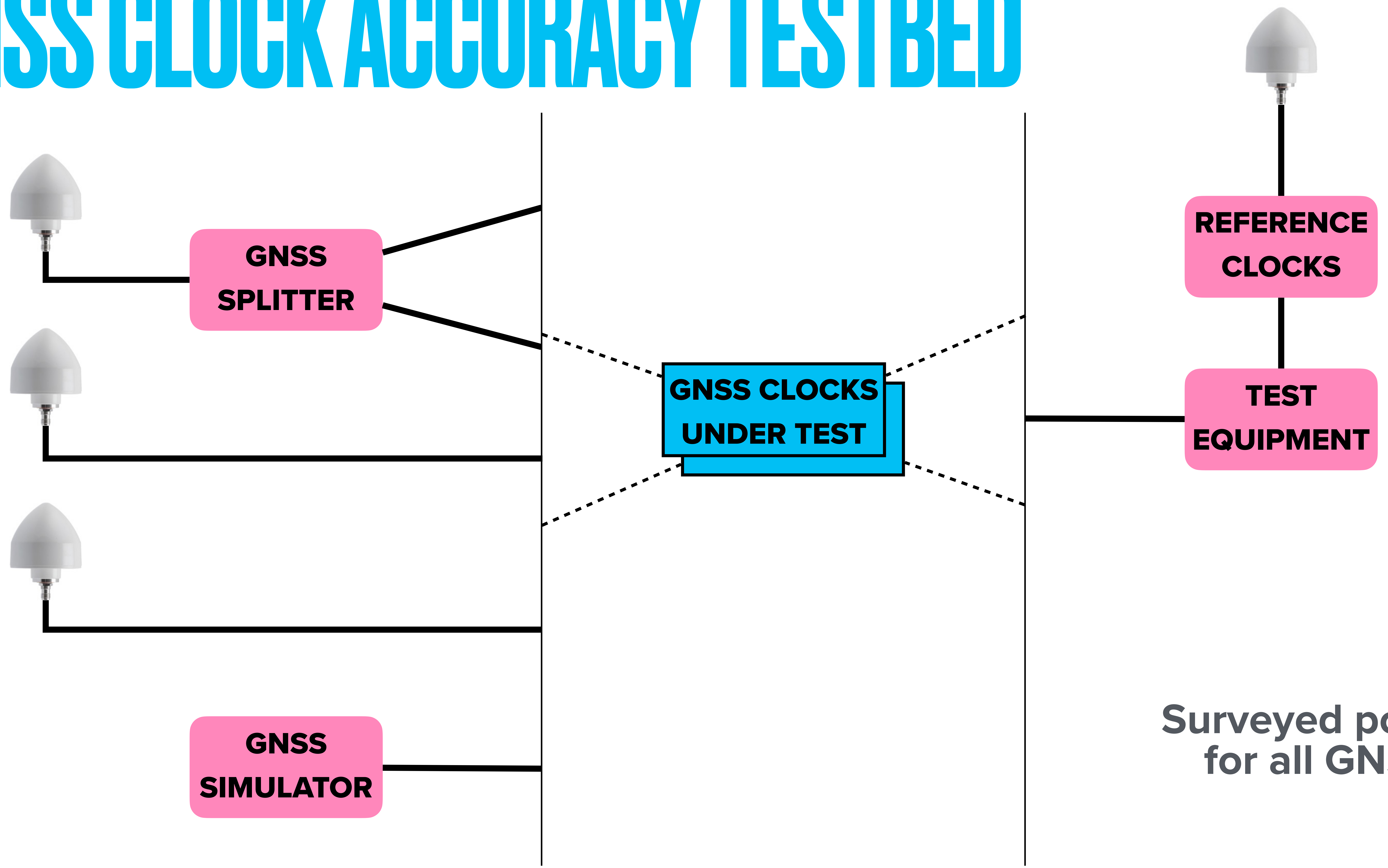




$$\begin{array}{r} \text{Trader Timestamp} \\ -\text{Exchange Timestamp} \\ \hline \text{s/b Positive Constant} \end{array}$$

Image: U.S. Air Force

GNSS CLOCK ACCURACY TESTBED



Surveyed positions known for all GNSS antennas


Comparing TDEV for Two u-blox F9Ts with Common Anntenna and qErr Corrections Individually and to Each Other
F9T-Bob
F9T-PT
F9T-Bob vs F9T-PT
Not a STAC Benchmark
Instrument: TAPR TICC
Reference: Geppetto GPSDO with OH300 5ppb OCXO
RMS Jitter Floor of TAPR TICC
7 ns
6 ns
5 ns
4 ns
3 ns
2 ns
1 ns
900 ps
800 ps
700 ps
600 ps
500 ps
400 ps
300 ps
200 ps
100 ps
90 ps
1 s
10 s
100 s
1000 s
10000 s
$\sigma_x(\tau)$
τ

UTC ACQUISITION IN DATA CENTERS

DATA CENTER GOOD/BAD

- Building structure blocks internal GNSS antennas
- Data center operator may not allow roof access or external antennas
  - Effectively forcing use of GNSS signal feed they provide
- May not have accurate antenna location
- May not know antenna feedline length

- Only good thing: Data centers move slowly, if at all

- UTC mean offset calibration possible with an “atomic backpack”


WARNING
DANGER
DANGER
HIGH VOLTAGE 1KV
ELECTRIC SHOCK HAZARD
REMOVE POWER BEFORE
REPAIR OR ADJUSTMENT


GUINNESS

FUTURE WORK

FINAGLE'S VARIABLE CONSTANT

"The correct answer minus your answer."

REDUCING MEAN OFFSET FROM UTC

- Easier than reducing instantaneous time error
- Zero antenna position error
- Known antenna feedline delay
- Known receiver delay to PPS
- Known antenna calibration
- Standard deviation of instantaneous errors sets target for mean offset

- And also building a Proof of Concept GPSDO with sub-nanosecond σ

WRAP UP

“FOR EVERY COMPLEX PROBLEM THERE IS AN ANSWER THAT IS CLEAR, SIMPLE, AND WRONG”

– H.L. MENCKEN


OAS
Kress

TAKEAWAYS

- Saw two clocks in my lab stay within 550 ps of each other
  - Mean offset to UTC left for future work
- Mean offsets to UTC below 5 ns can’t be measured with GNSS
  - But mean offsets to GNSS time well below 5 ns are possible
- Accuracy below 10 ns may not matter for host timestamps
- STAC-TS protocols for holdover testing are good
  - But let’s talk if you care about instantaneous UTC accuracy testing too
- GNSS clock vendors have room to improve with modern GNSS receiver modules
- Consider where your time distribution network is not length-compensated
- Traders care more about short-term time stability than long-term frequency stability
- Evaluate GNSS clock accuracy with TDEV(1 s) and MTIE(1 s)

BEST PRACTICES

- Run GNSS clocks in fixed-position mode, not survey-in
- Choose antenna sites with good sky view and few multipath reflection points
- Use dual-band (e.g. L1/L5) receiver and antenna
- Measure antenna feedline length and configure it in GNSS clocks
- Spoofing defense: Use NTS encryption to public servers
  - Use ntpsec in favor of ntpd
- Check your clocks against others, e.g. matching engine timestamps
  - Plot min delta for every 5000 ticks or 5 minutes
- Use symmetry of radio and fiber latency to check clocks across sites

NOW GO SET YOUR CLOCKS...

ACCURATELY!