Multi-Static HF Time Signal Analysis for Ionospheric Sounding and TEC Estimation:

4 stations · 9 frequencies · 17 simultaneous paths
Single RX888 SDR + Leo Bodnar GPSDO via KA9Q-radio

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The Phenomena Ladder — What Each Tier Unlocks

Tier	Hardware Setup	Rate Domain (Frequency Stability)	Time Domain (UTC/PPS Sync)
Tier 1	RX888 Alone (~$180)	—	• Station Detection (WWV/CHU/BPM) • Coarse propagation mode • Signal level
Tier 2	RX888 + GPSDO (~$340)	• Carrier-phase Doppler (±0.34 Hz) • dTEC/dt (Ionospheric TEC rate) • Differential dTEC (Cross-frequency consistency)	—
Tier 3	RX888 + GPSDO + PPS on LAN (~$450)	• TID / Terminator / SID detection • Scintillation (S4, σϕ) • GNSS-anchored absolute dTEC	• D_clock (Propagation delay residual) • Mode identification (1F / 2F / E) • Diurnal layer height + storm TEC • D_clock discrimination
Tier 4	RX888 + GPSDO + PPS in HF Stream (~$620)	• All Tier 2 & 3 capabilities available	• Group-delay TEC ($1/f^2$ dispersion) • Sub-ms multipath resolution

TickEdgeDetector — The Measurement Engine

50–57 ticks per minute, per channel

Matched-filter correlation with station-specific templates

Front-edge back-calculation + sub-sample interpolation

SNR-weighted robust median ensemble

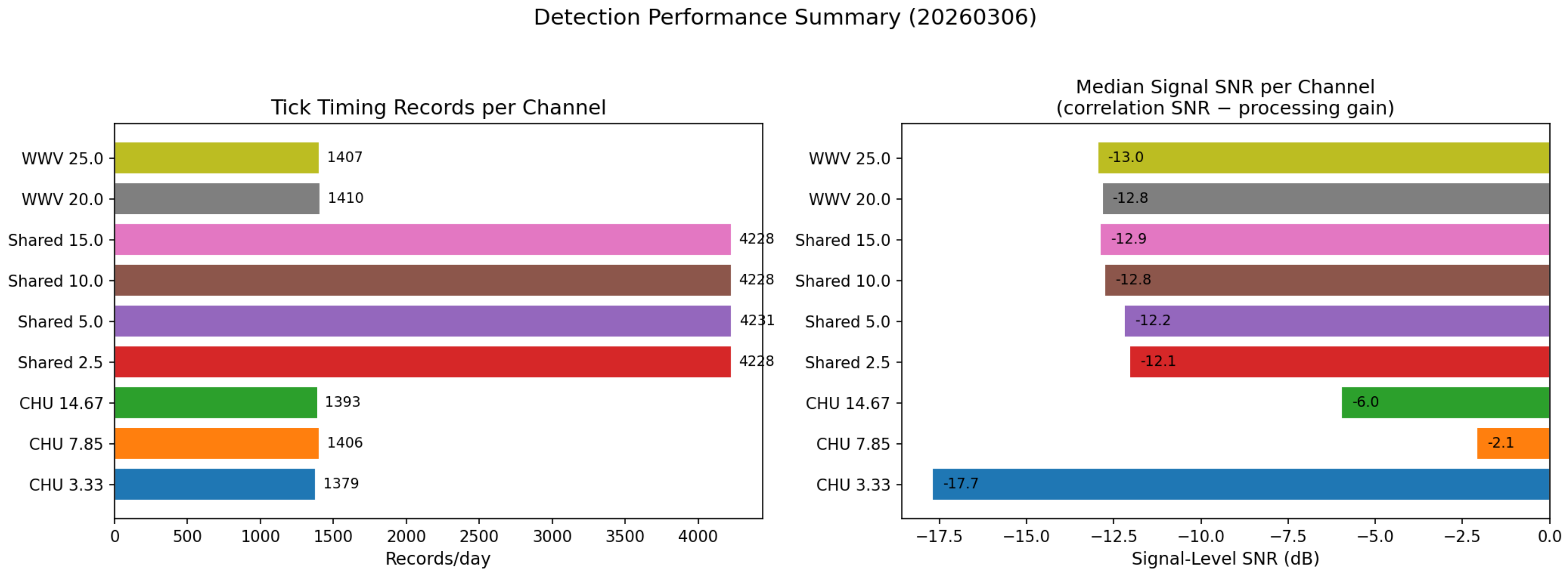
From each tick:

- Timing error (AM domain)
- Carrier phase (IQ domain)
- SNR

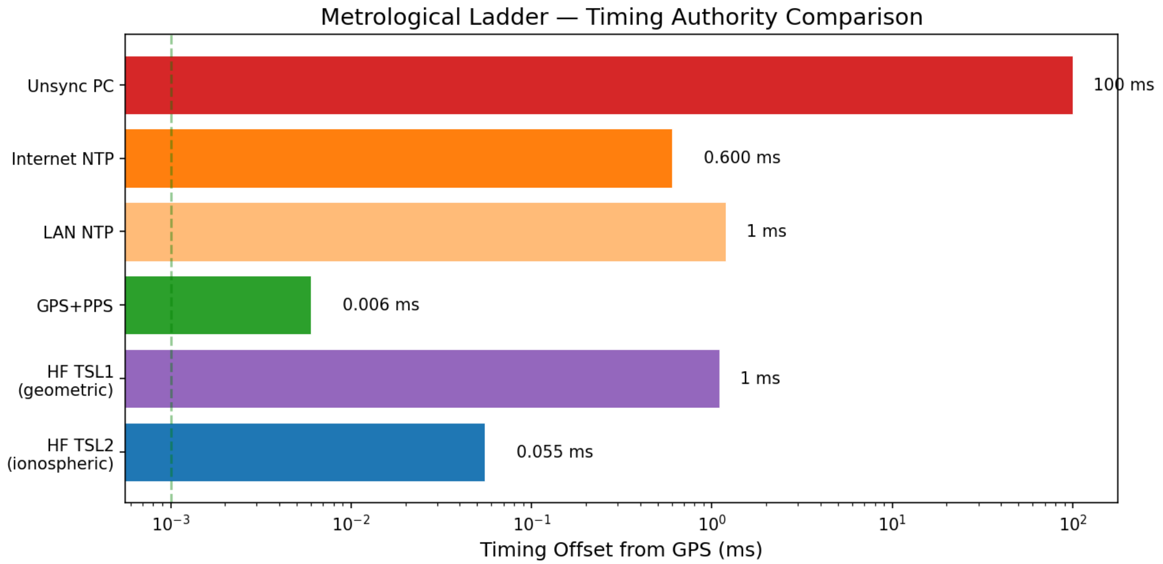
From the minute ensemble:

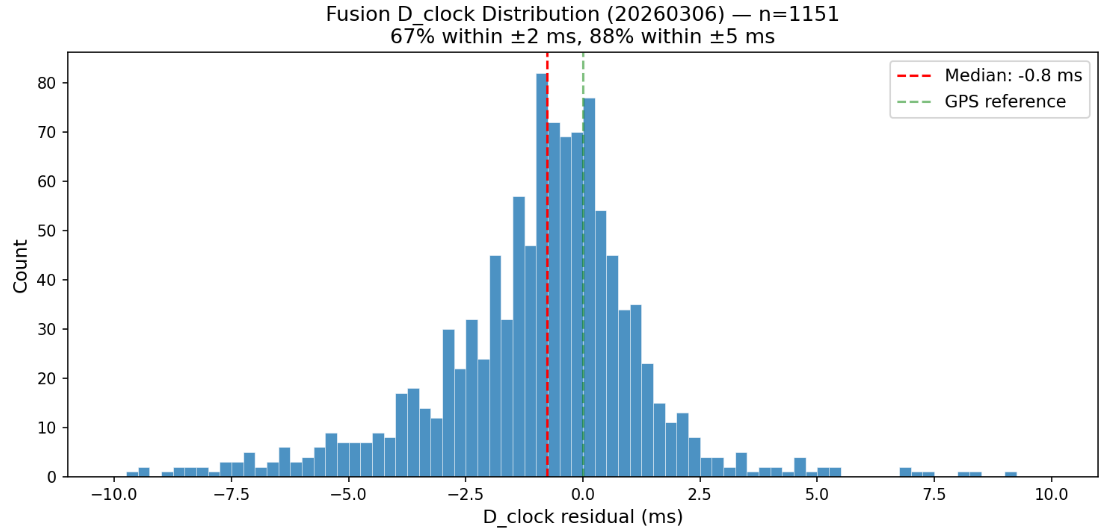
- D_clock — needs UTC (Tier 3+)
- Doppler — needs only GPSDO (Tier 2)
- Mean SNR

Channel	Edges/min	Uncertainty (ms)	D_clock (ms)	Doppler Coverage
CHU 7.85	53	±0.12	+0.79	99.9%
SHARED 10.0	57	±2.1	−0.53	100.0%
WWV 20.0	57	±2.0	−0.72	99.9%



UTC Recovery — Dual Kalman Fusion





The time signals tell us what time it is.

Source	Offset vs GPS	Bound (±)
Internet NTP	−6.0 ms	±4.2 ms
TSL1 (geometric)	+1.1 ms	±0.6 ms
TSL2 (ionospheric)	-0.055 ms	±0.5 ms
GPS+PPS (ground truth)	−0.006 ms	±0.039 ms

HF timing is 100× better than internet NTP

TSL2 has 3.3× tighter bound than TSL1

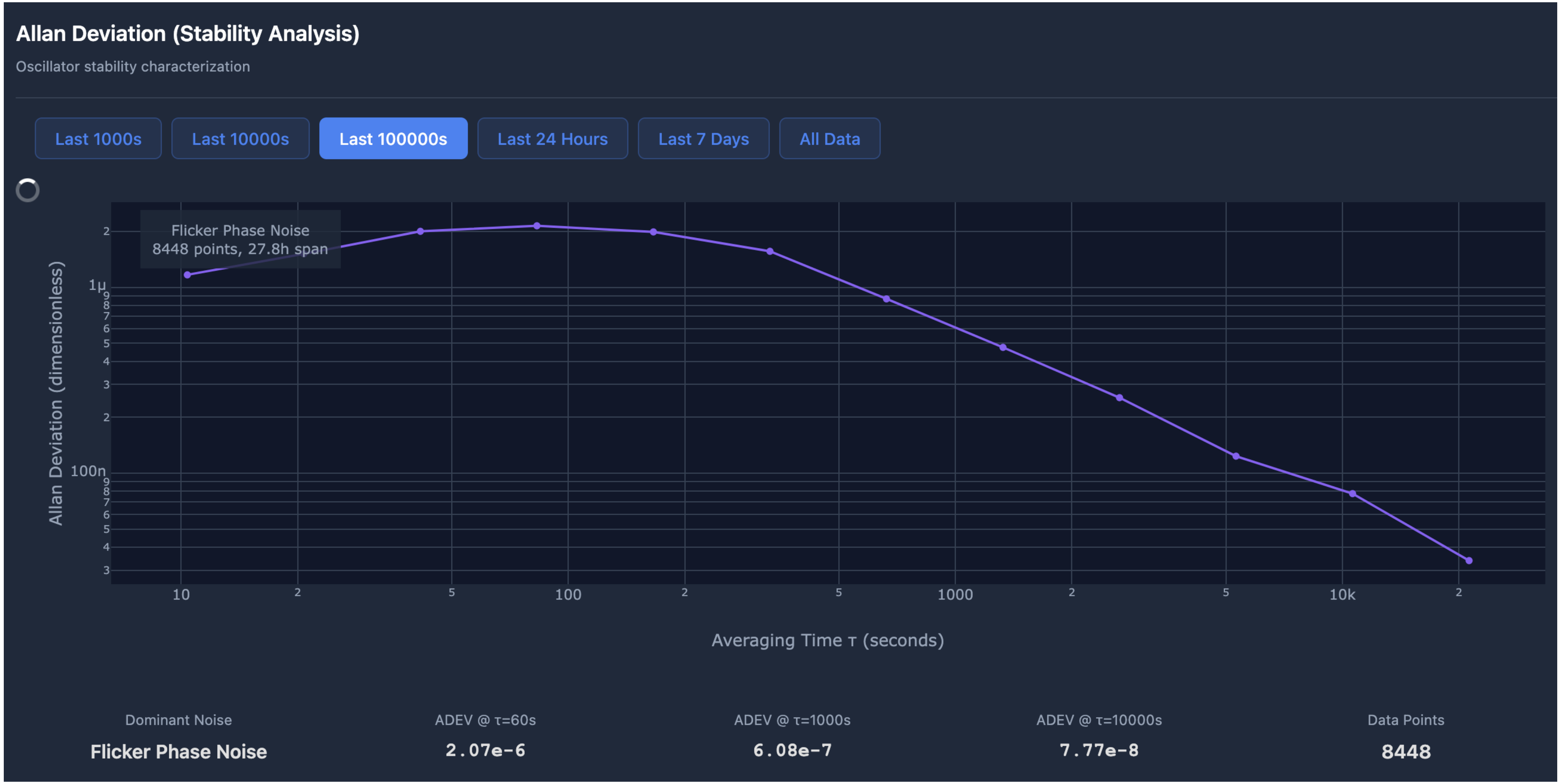
Fusion D_clock: median −0.8 ms, 88% within ±5 ms

A Tier 2 station bootstraps itself to Tier 3

Metrology


Fusion History
Last Hour
Last 6 Hours
Last 24 Hours
Last 7 Days
Custom...
1.5
1
0.5
0
−0.5
−1
−1.5
D_clock (ms)
21:00
Mar 5, 2026
22:00
23:00
00:00
Mar 6, 2026
01:00
02:00
Time (UTC)

Metrology


Allan Deviation (Stability Analysis)
Oscillator stability characterization
Last 1000s
Last 10000s
Last 100000s
Last 24 Hours
Last 7 Days
All Data
Flicker Phase Noise
8448 points, 27.8h span
Allan Deviation (dimensionless)
1µ
100n
10
100
1000
10k
Averaging Time τ (seconds)
Dominant Noise
Flicker Phase Noise
ADEV @ τ=60s
2.07e-6
ADEV @ τ=1000s
6.08e-7
ADEV @ τ=10000s
7.77e-8
Data Points
8448

Shared-Channel Discrimination

Three stations on one frequency — unique characteristics + physics tells them apart

Tick frequency: 1000 Hz (WWV/BPM) vs 1200 Hz (WWVH)

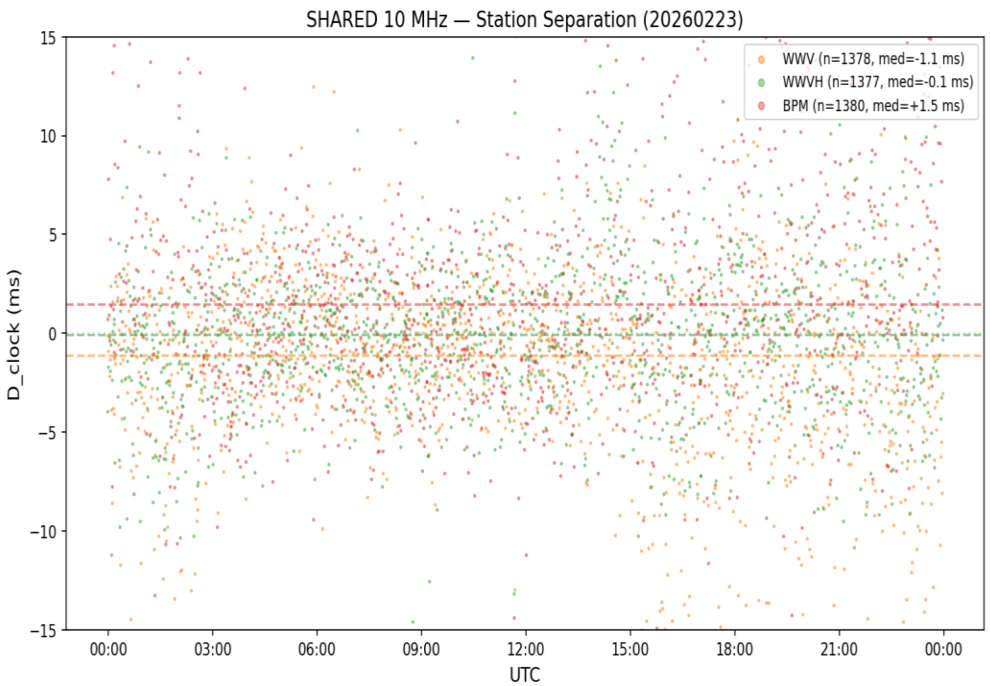
Tick duration: 5 ms (WWV/WWVH) vs 10 ms (BPM)

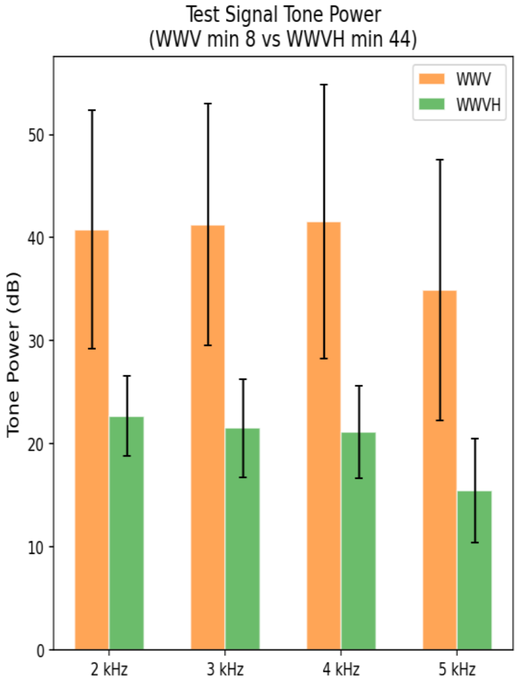
NIST tone schedule: ground truth 14 min/hr

D_clock ordering: WWV < WWVH < BPM
(1,119 km < 6,599 km < 11,564 km)

Test signal: WWV at :08, WWVH at :44
Voices: male at WWV, female at WWVH

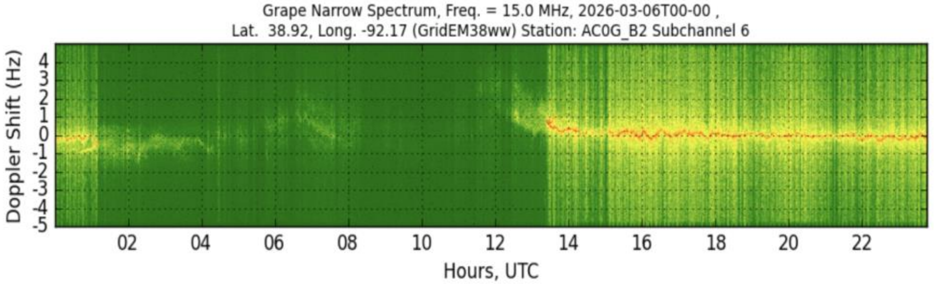
Announcement timing

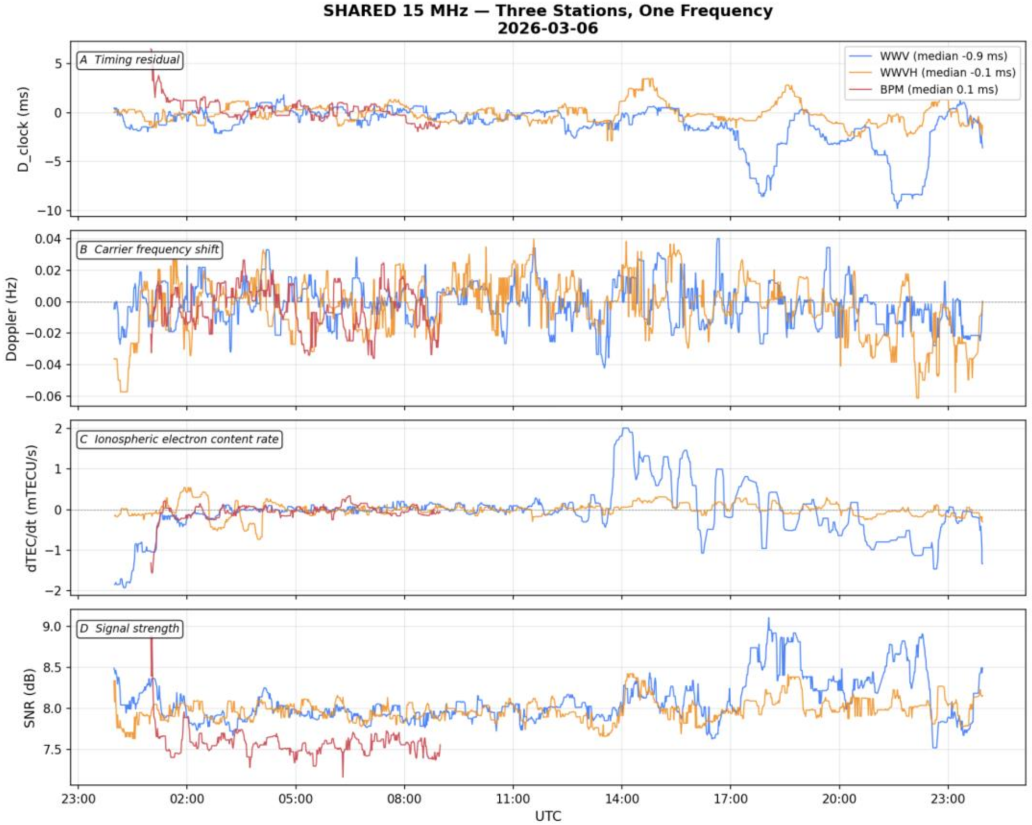


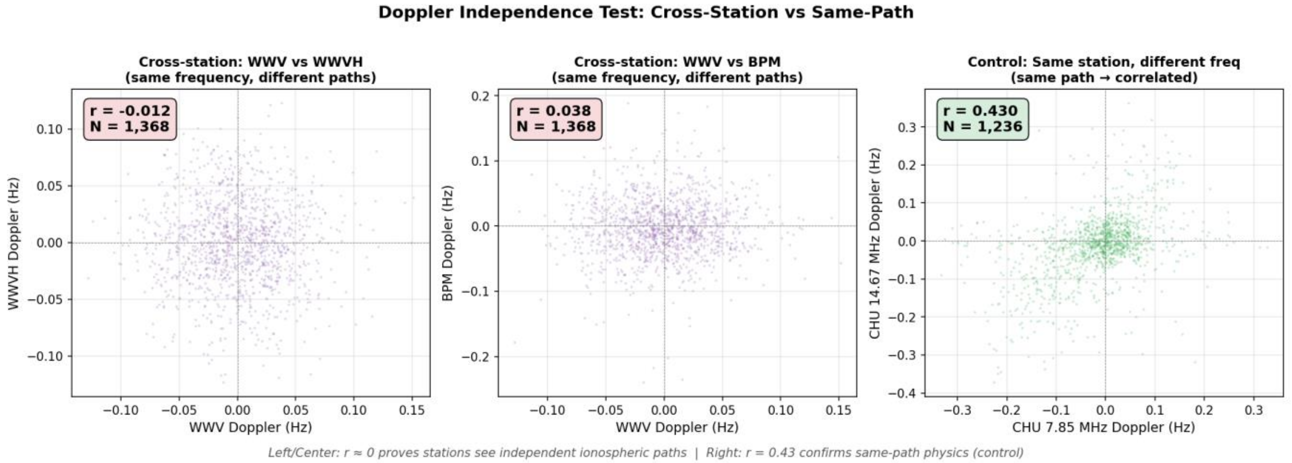


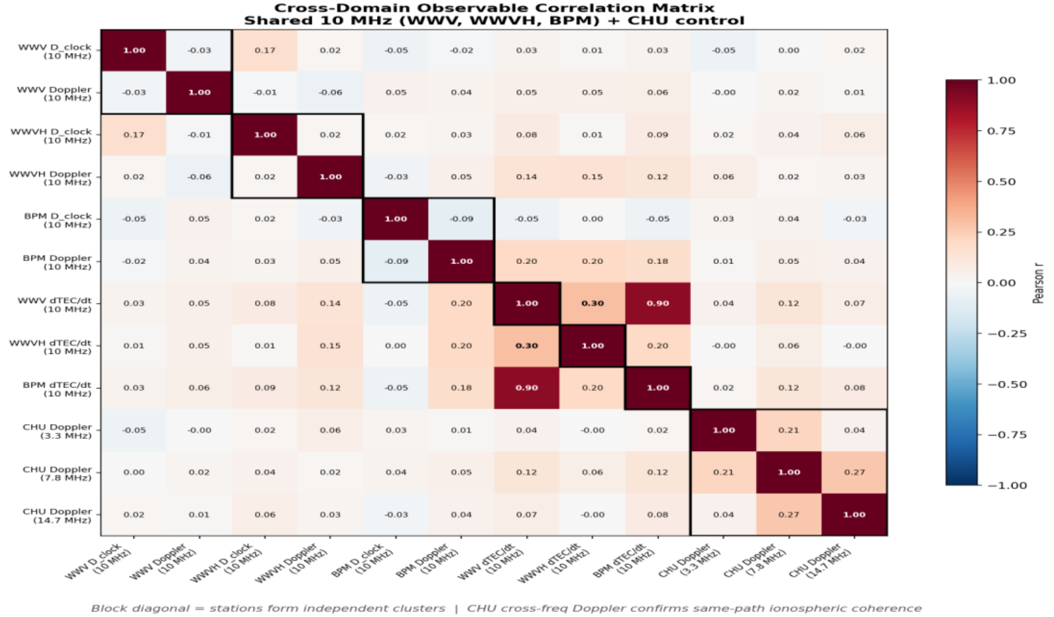
Station	Records/day	Median D_clock	Median SNR
WWV	1,380	−1.12 ms	26.2 dB
WWVH	1,379	−0.08 ms	17.8 dB
BPM	1,380	+1.48 ms	21.1 dB

Three Ionospheric Paths on One Frequency









	WWV D_clock (10 MHz)	WWV Doppler (10 MHz)	WWVH D_clock (10 MHz)	WWVH Doppler (10 MHz)	BPM D_clock (10 MHz)	BPM Doppler (10 MHz)	WWV dTEC/dt (10 MHz)	WWVH dTEC/dt (10 MHz)	BPM dTEC/dt (10 MHz)	CHU Doppler (3.3 MHz)	CHU Doppler (7.8 MHz)	CHU Doppler (14.7 MHz)
WWV D_clock (10 MHz)	1.00	-0.03	0.17	0.02	-0.05	-0.02	0.03	0.01	0.03	-0.05	0.00	0.02
WWV Doppler (10 MHz)	-0.03	1.00	-0.01	-0.06	0.05	0.04	0.05	0.05	0.06	-0.00	0.02	0.01
WWVH D_clock (10 MHz)	0.17	-0.01	1.00	0.02	0.02	0.03	0.08	0.01	0.09	0.02	0.04	0.06
WWVH Doppler (10 MHz)	0.02	-0.06	0.02	1.00	-0.03	0.05	0.14	0.15	0.12	0.06	0.02	0.03
BPM D_clock (10 MHz)	-0.05	0.05	0.02	-0.03	1.00	-0.09	-0.05	0.00	-0.05	0.03	0.04	-0.03
BPM Doppler (10 MHz)	-0.02	0.04	0.03	0.05	-0.09	1.00	0.20	0.20	0.18	0.01	0.05	0.04
WWV dTEC/dt (10 MHz)	0.03	0.05	0.08	0.14	-0.05	0.20	1.00	0.30	0.90	0.04	0.12	0.07
WWVH dTEC/dt (10 MHz)	0.01	0.05	0.01	0.15	0.00	0.20	0.30	1.00	0.20	-0.00	0.06	-0.00
BPM dTEC/dt (10 MHz)	0.03	0.06	0.09	0.12	-0.05	0.18	0.90	0.20	1.00	0.02	0.12	0.08
CHU Doppler (3.3 MHz)	-0.05	-0.00	0.02	0.06	0.03	0.01	0.04	-0.00	0.02	1.00	0.21	0.04
CHU Doppler (7.8 MHz)	0.00	0.02	0.04	0.02	0.04	0.05	0.12	0.06	0.12	0.21	1.00	0.27
CHU Doppler (14.7 MHz)	0.02	0.01	0.06	0.03	-0.03	0.04	0.07	-0.00	0.08	0.04	0.27	1.00

Carrier-Phase dTEC — A Primary Science Product

Bypassing the propagation model noise floor

Group-delay TEC: signal 0.85 ms, noise 6.5 ms → SNR 0.13 (signal buried in the noise)

Carrier-phase dTEC: ~6 mTECU/min sensitivity → SNR 17–330×

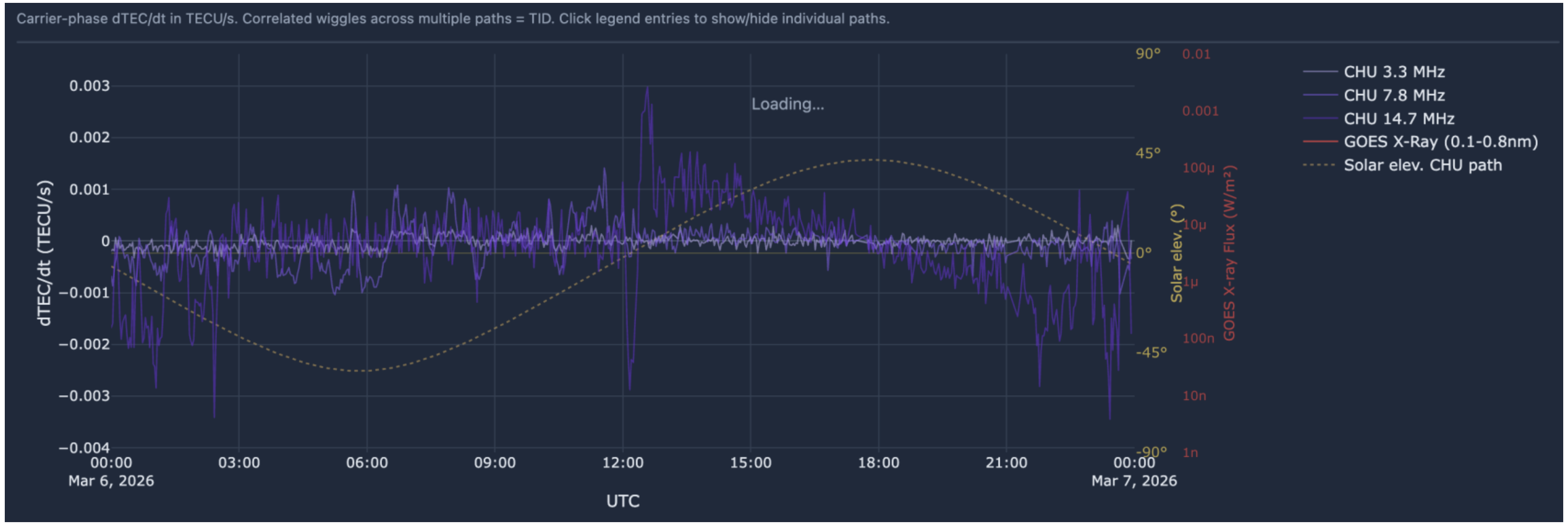
dTEC/dt = −f_D × c × f / 40.3

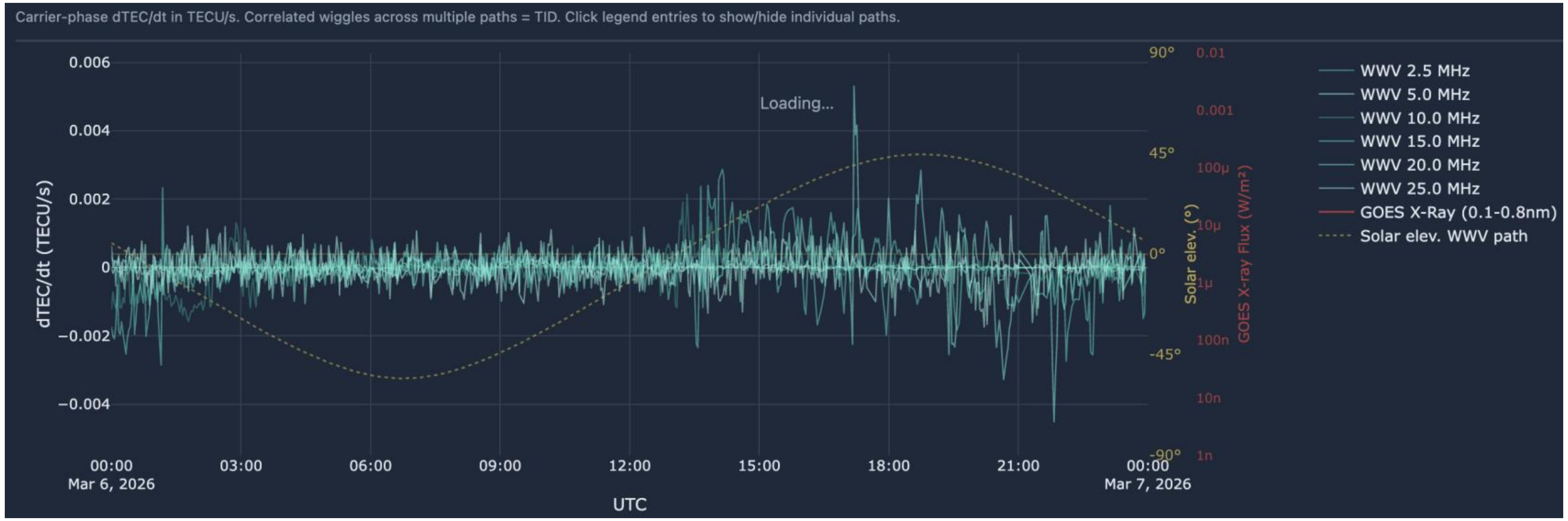
This is a Tier 2 product — needs only the GPSDO

17,045 dTEC records/day (per-minute)

848,599 per-tick records/day (1-second resolution)

GNSS-anchored: ZED-F9P VTEC 41.7 TECU, ±1 TECU





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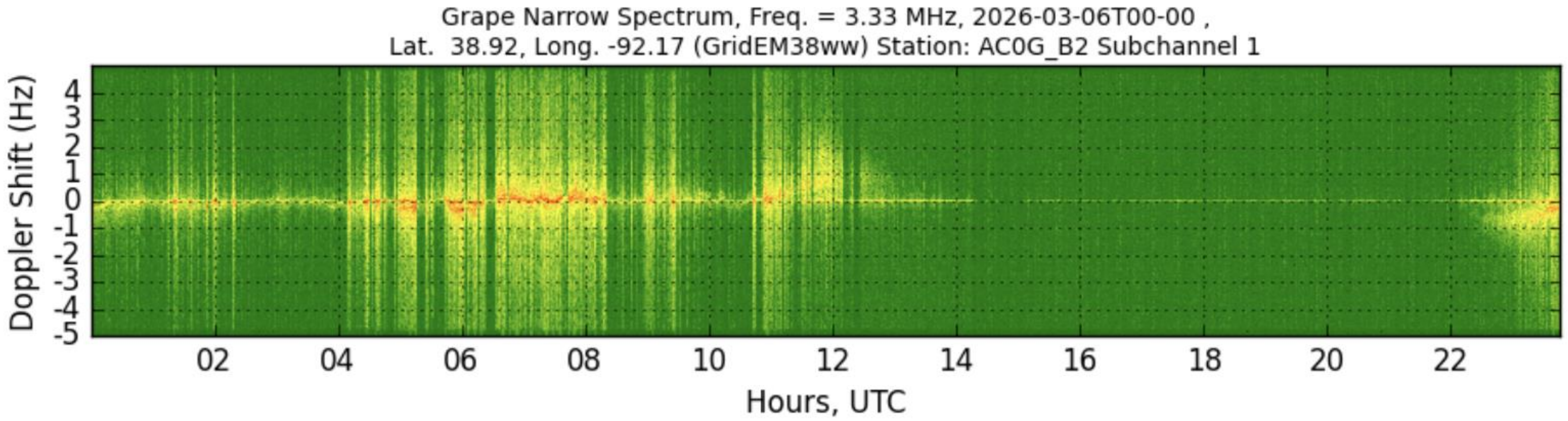

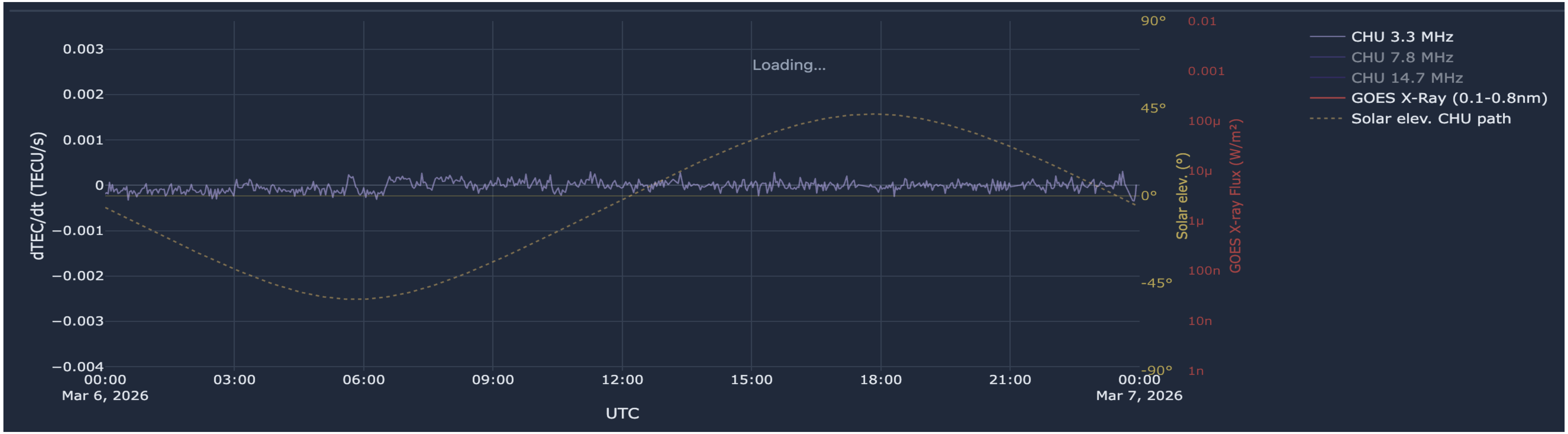

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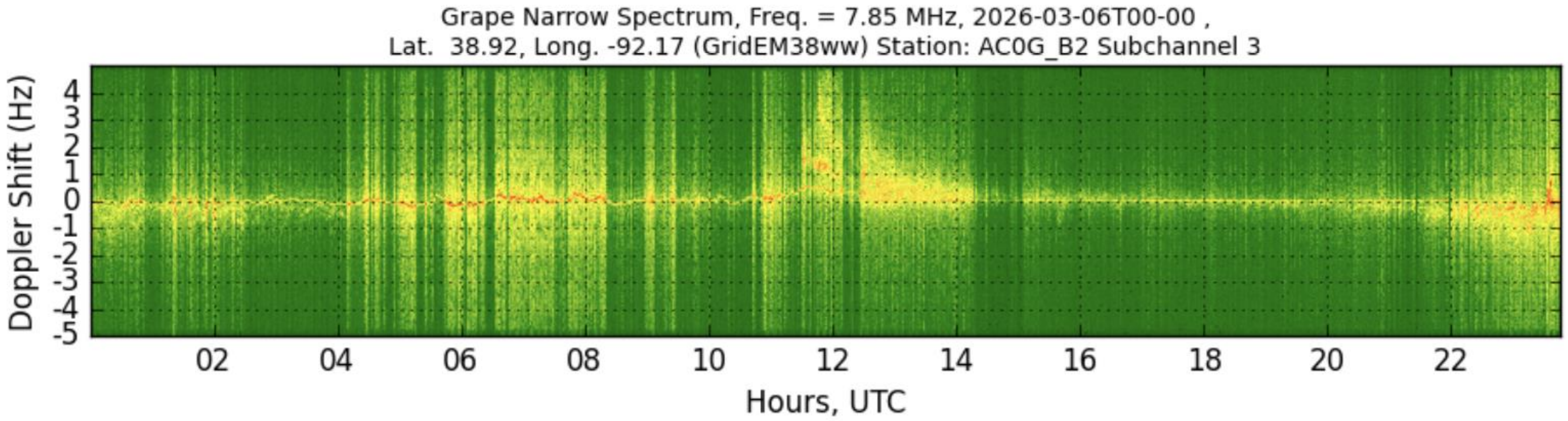

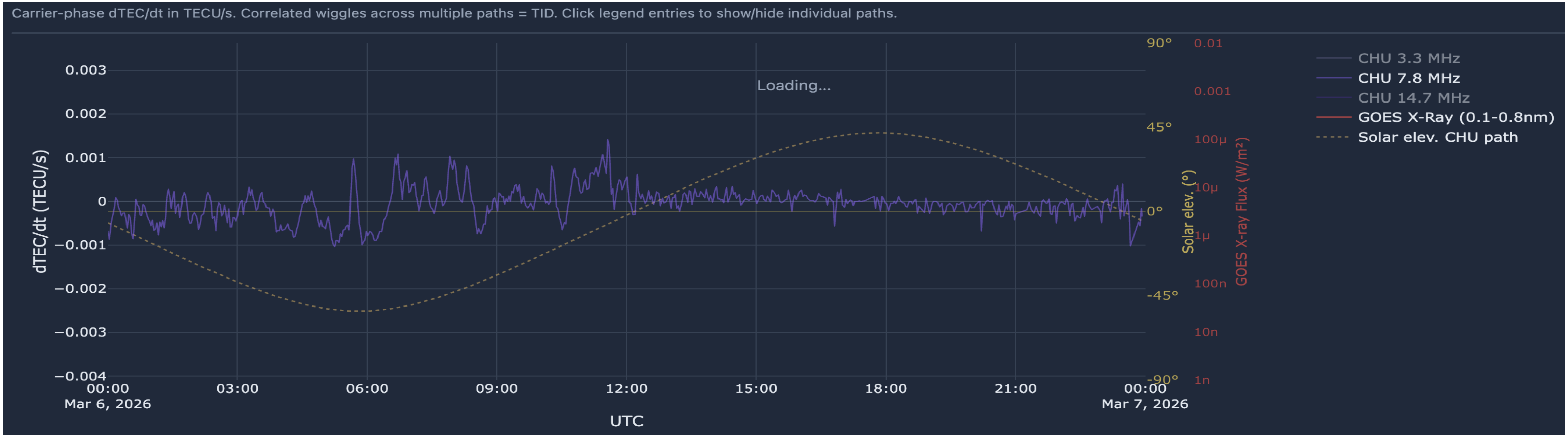

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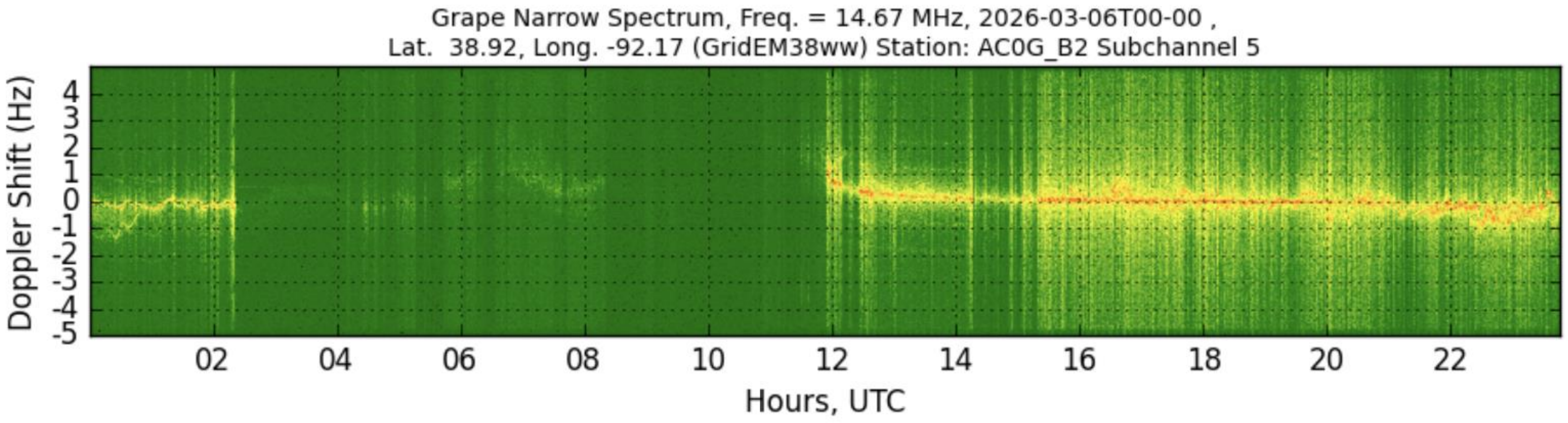
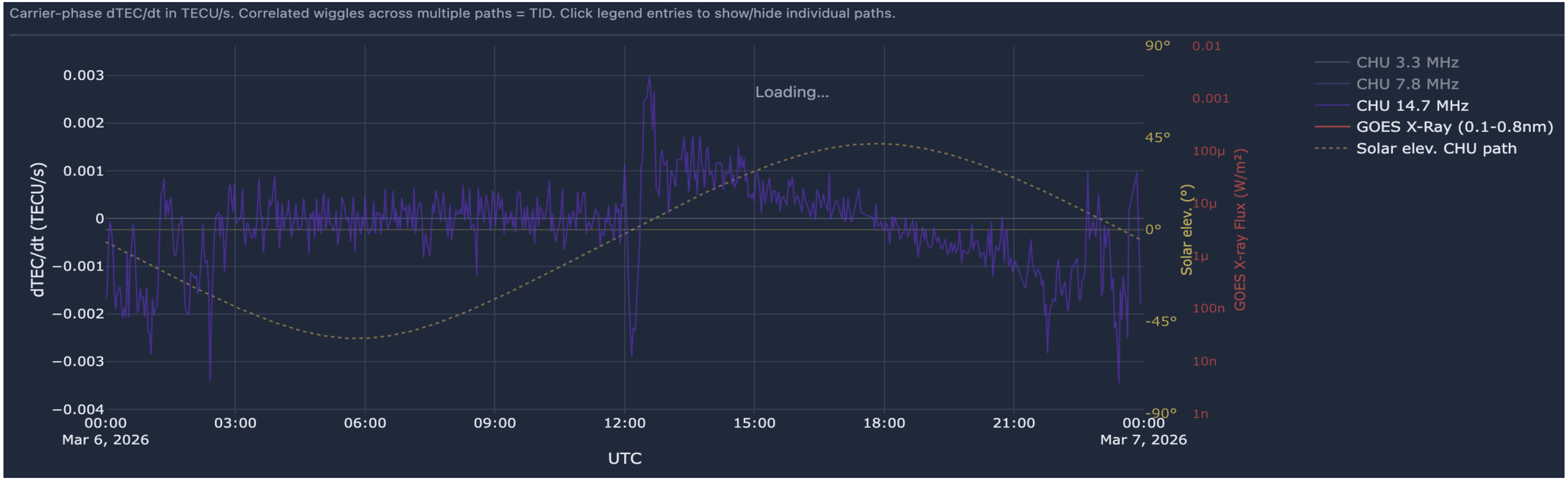




Differential dTEC — Self-Consistency

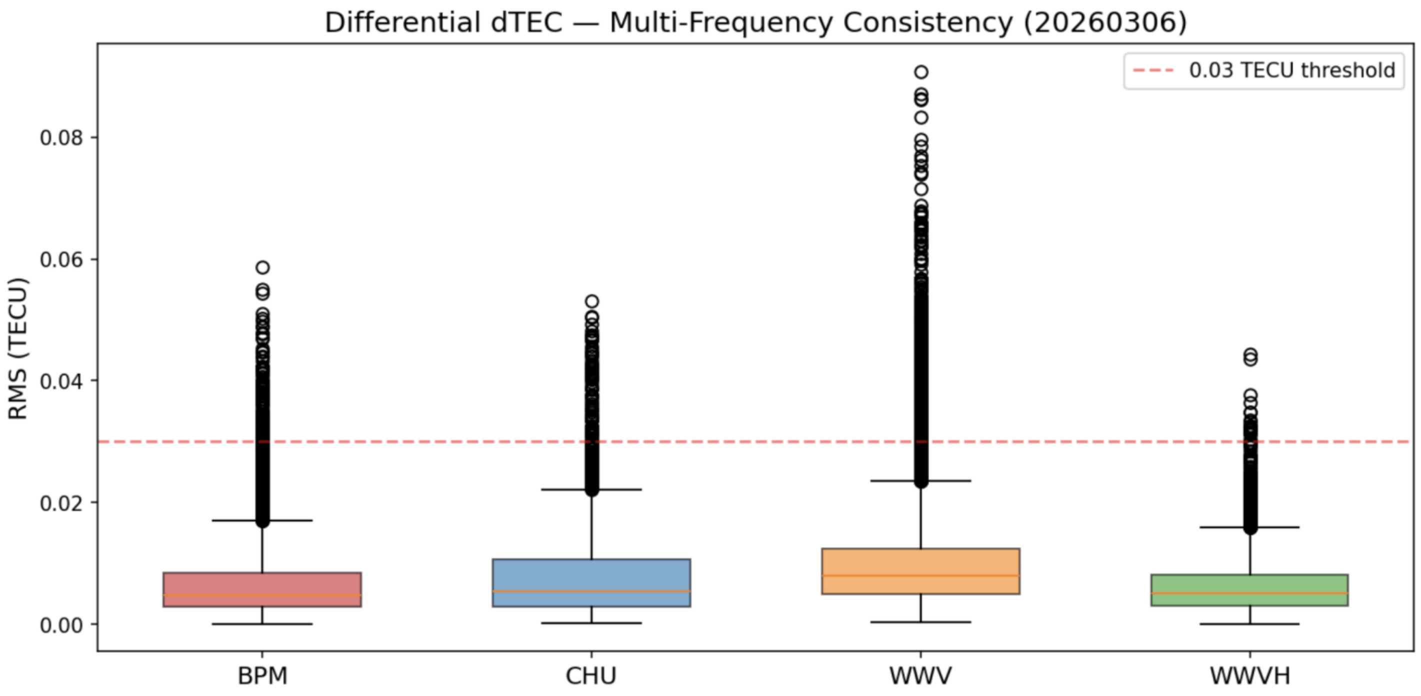
Same ionosphere, different frequencies — do they agree˜

22,474 records/day, all GOOD quality

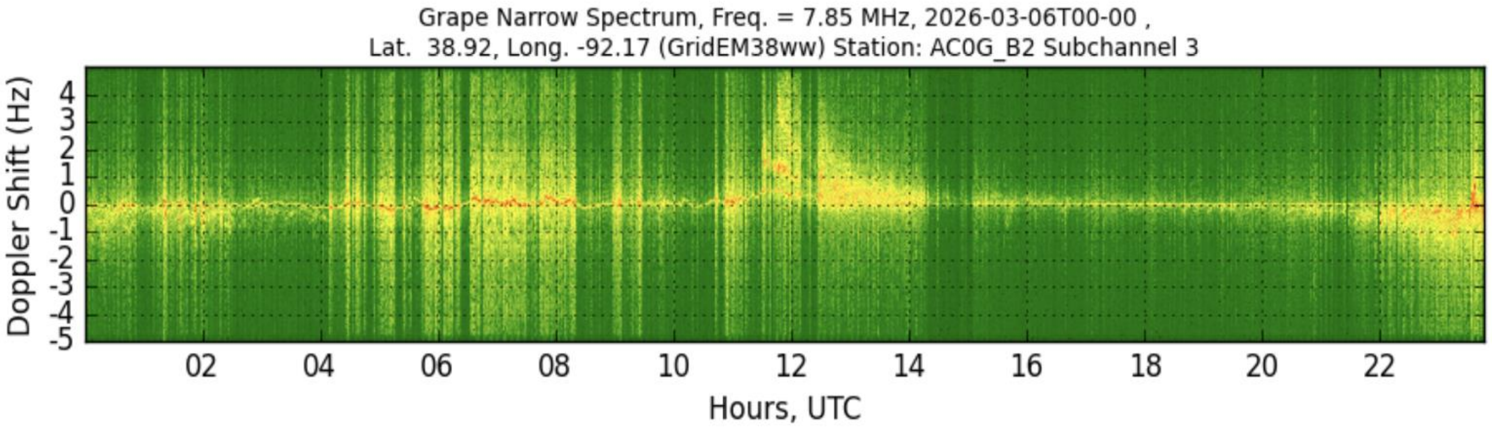
Also a Tier 2 product

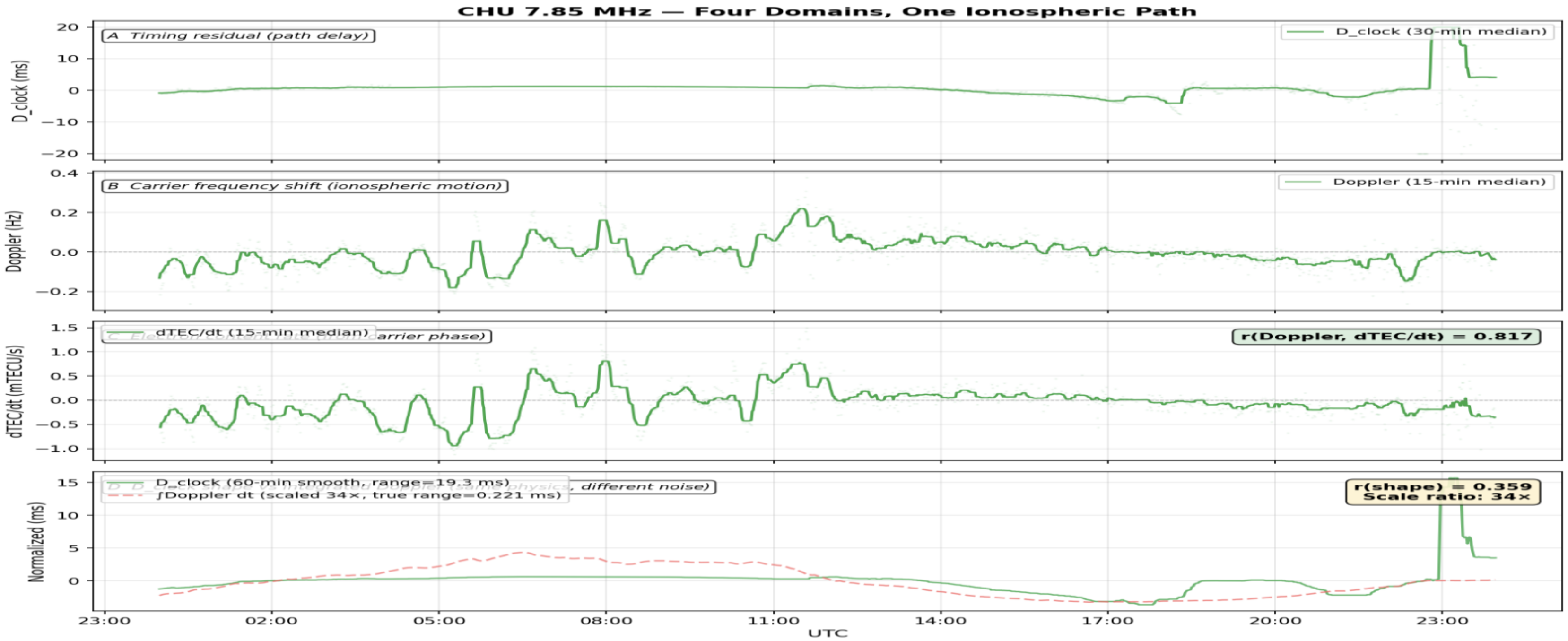
Cross-frequency consistency validates the physics

Station	Widest freq pair	RMS
CHU	3.33 – 14.67 MHz	0.005–0.007 TECU
WWV	2.50 – 25.00 MHz	0.005–0.026 TECU



From Spectrogram to TEC — CHU 7.85 MHz





One ionospheric path, four views

GRAPE spectrogram: Doppler shift visible as carrier frequency offset

Pipeline extracts Doppler → dTEC/dt

Bottom panel: integrated Doppler tracks D_clock shape at 82× finer sensitivity (r = 0.60)

Standard GRAPE data for PSWS upload

What's Next?

Current limits:

Group-delay TEC: below noise floor (SNR 0.13)
VTEC maps from HF alone: noise-dominated
Scintillation: infrastructure ready, awaiting storm

Just deployed:

✅ GNSS-anchored dTEC (ZED-F9P, ±1 TECU)

Under development:

Tier 4: PPS injection into HF IQ stream
Per-path slant correction for GNSS anchoring
Integration with wsprdaemon
Improved web display
Metadata modeling
Signal event data gathering

Network of stations →

Spatial TEC gradients → horizontal structure
TID wavefront tracking (direction + velocity)
Continental-scale passive oblique ionosonde
No transmitter needed — use existing infrastructure

2–4 GPSDO-locked RX888s at one site →

Phased-array angle-of-arrival ($\lambda/2 \approx 15$ m at 10 MHz)
Separate multipath by direction, not just delay
Per-mode Doppler and dTEC on individual ray paths
Scintillation spatial coherence measurements
Same GPSDO → zero relative timing error

Bottom Line

With an RX888 (~$180) and a GPSDO (~$162), you can:

Measure ionospheric Doppler at 99.7% coverage, 24/7

Extract dTEC/dt at ~6 mTECU/min sensitivity on 17 paths

Discriminate three co-channel stations via physics

Self-recover UTC to <1 ms from the time signals

Daily output: 24K timing · 850K phase · 17K dTEC · 22K consistency checks

~$340 of hardware, open-source software, and the time standard stations already on the air
→ a 17-path ionospheric sounder running 24/7

https://github.com/mijahauan/hf-timestd -- UTC time recovery plus physics
https://github.com/mijahauan/ka9q-python -- radiod interface library
https://github.com/mijahauan/ka9q-update -- install and update ka9q-radio and ka9q-web

Acknowledgements and Thanks

Kristina Collins	KD8OXT		Michael Lombardi	K0WWX
Paul Elliott	WB6CXC		Anna Montare	KB3UMD
Nathaniel Frissell	W2NAF		Scott Newell	N5TNL
Gwyn Griffiths	G3ZIL		Sarah Over	KQ4NQO
Phil Karn	KA9Q		Rob Robinett	AI6VN
Dave Larsen	KV0S		Dave Witten	KD0EAG