NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

The use of low-cost GNSS receivers in traceable remote calibration services

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CCTF Technical Exchange

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Commercial Product Disclaimer

As a matter of policy, NIST does not endorse commercial products and identifies them only if necessary for technical clarity. The identification of any commercial equipment does not imply endorsement by NIST.

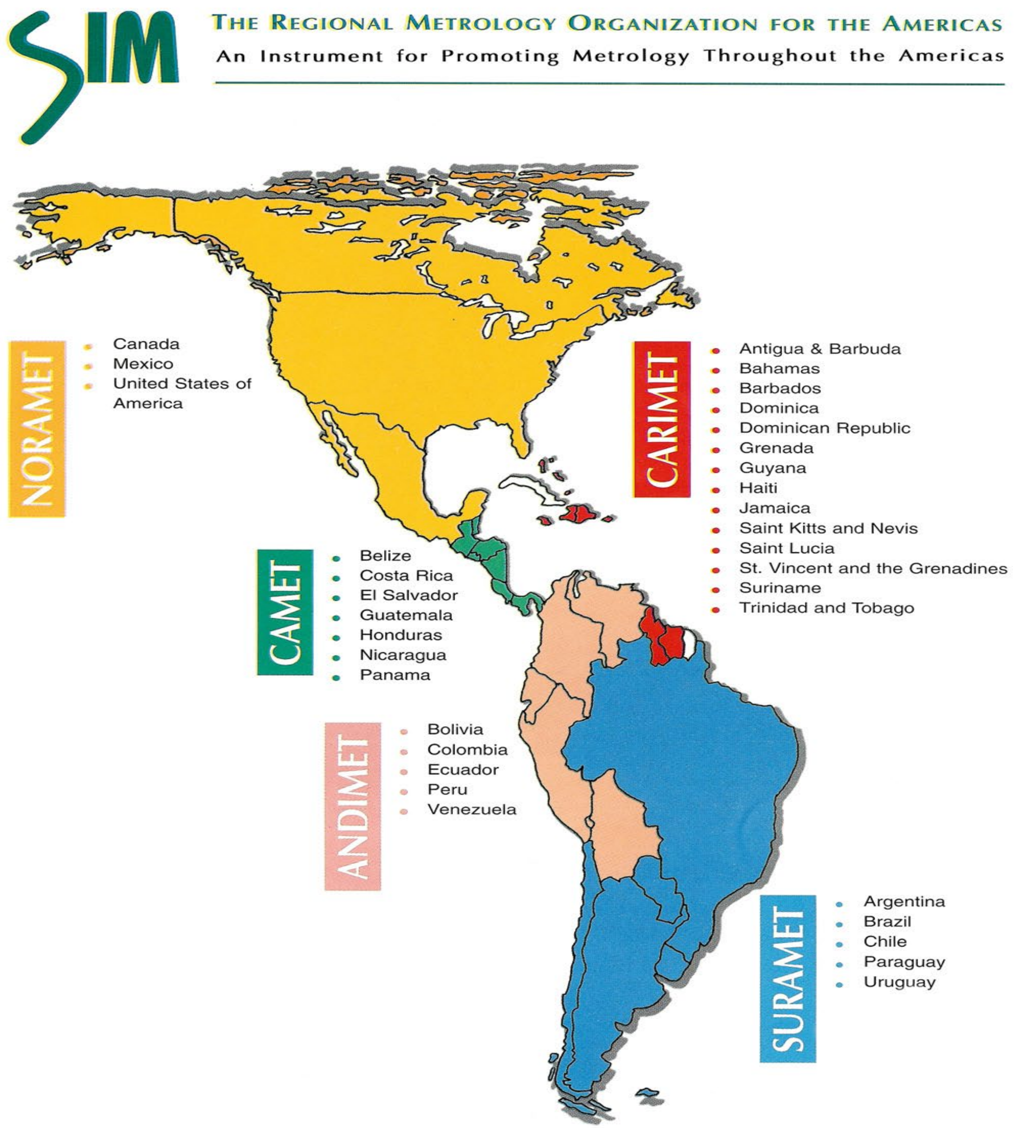
Work with low-cost receivers began with SIM

The goal of the *Sistema Interamericano de Metrologia* (SIM) is to ensure the uniformity of measurements throughout its region.

SIM metrology working groups pursue this goal by collaborating on training programs and technical projects, and by reviewing the quality systems and calibration and measurement capabilities (CMCs) of the NMIs.

They also organize interlaboratory comparisons. These comparisons help NMIs establish traceability and maintain standards that are accurate enough to support their nation's economy. **As of 2004 only 5 SIM countries were contributing to UTC (on Circular-T).**

<u>NIST/CENAM/NRC goal:</u>
To build a network that allowed all SIM NMIs to compare their time standards to those of the rest of the world.



Original SIM System Goals

- To utilize equipment that was ***low-cost*** and easy to install, operate and use, because SIM NMIs typically have a small staff and limited resources.

- To be capable of measuring the best standards in the SIM region. This meant that the measurement uncertainties had to be as small, *or nearly as small*, as those of the BIPM key comparisons.

- To report measurement results in near real-time, without the processing delays of current time-transfer methods.

- To build a democratic network that favored no single laboratory or nation, and to allow all members to view the results of all comparisons.

The “SIM System”

Contents

Tabletop rack

LCD monitor

Measurement system

Pull-out keyboard

Measurement system

Single-board computer

Inexpensive single-frequency GPS receiver (Motorola Oncore VP)

20 ps time interval counter (TIC)

Only three Inputs

GPS from outdoor antenna

1 PPS from time scale or best clock

10 MHz – for TIC timebase

Simple File Format (no RINEX or CGGTTS)

2005-05-19
53509
Division de Tiempo y Frecuencia
Centro Nacional de Metrologia
UTC(CNM)
1 Hz
CAL Time = 2005-05-19/00:00:02
START Res = 27 ps
STOP Res = 27 ps
TIC Delay = -0.27 ns
REF Delay = 12 ns
RX Delay = 70 ns
Mask Angle = 10°
TEMP Rx = 25° C
LAT = 20° 32 min 13.373 s N
LON = 100° 15 min 17.204 s W
ALT = 1917.16 m

```
0010 55.12 - - - - - - - - - 61.43 - - 50.59 - 65.91 - - - 56.1 - 51.28 - - 55.38 - - - - - - -
0020 53.86 - - - - - - - - - 62.26 - - 52.08 - 60.92 - - - 53.25 - 51.81 - - 54.55 - - - - - - -
0030 51.86 - - - - - - - - - 61.18 - - 53.1 - 62.64 - - - 55.22 - - 59.44 - 54.86 - - - - - - -
0040 49.66 - - - - - - - - - 54.59 - - 51.44 - 63.89 - - - 53.34 - - 59.4 - 50.28 - - - - - - -
0050 51.43 - - - - - - - - - 54.67 - - 51.16 - 64.67 - - - 53.54 - - 58.3 - 49.56 - - - - - - -
0100 52.46 - - - - - - - - - 55.13 - - 52.96 - 65.51 - - - 53.09 - - - - 45.59 - - - - - - -
0110 54.3 - 46.17 - - - - - - - 56.19 - - 54.52 - 66 - - - 60.02 - - 50.65 - 52.94 - - - - - - -
0120 54.18 - - - - - - - - - 56.32 - - 58.17 - 62.25 - - - 60.06 - - - - 43.77 - - - - - - -
0130 52.29 - 55.41 - - - - - - - 55.27 - - - - 62.24 - - - 58.85 - - 47.61 - 48.51 - - - - - - -
```

Files are appended every ten minutes and uploaded to servers at NIST, NRC and CENAM.

Header information

Ten-minute data

HHMM Lab(*k*) – GPS Sat[1], …, Lab(*k*) – GPS Sat[11], …

Simple File Format

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Cal.

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Header information

Ten-minute data

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Early SIM Comparisons

SIM Time Scale Comparisons via GPS Common-View

(Table shows results for the 10-minute period ending on 07-07-2005 at 1720 UTC)

SISTEMA INTERAMERICANO DE METROLOGIA		UTC(NIST)	UTC(CNM)	UTC(NRC)	UTC(CNMP)
	UTC(NIST)		-50.08	44.42	
	UTC(CNM)	50.08		95.37	
	UTC(NRC)	-44.42	-95.37		
	UTC(CNMP)				
Last Update (HHMM UTC)		1720	1720	1720	

Table created at 07-07-2005 (MJD 53558) 17:28:55 UTC, and will automatically refresh every five minutes.

Click on time scale names to view **one-way** GPS data, or click on time difference values to view **common-view** GPS data.

Near real-time results
(oldest data are 10 minutes old)

A link to the current SIM grid:
https://sim.nist.gov/scripts/sim_rx_grid.exe

Real-time Comparison Results

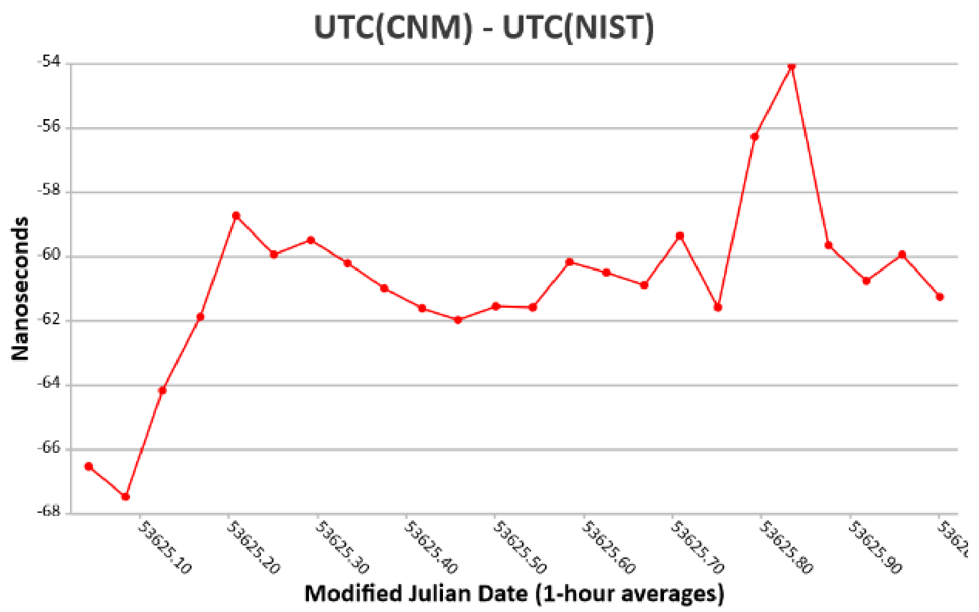
NIST

UTC(CNM) versus UTC(NIST) via Common-View GPS

1 Day Averages | 1 Hour Averages | 10 Minute Averages | Next Date | Last Date | Flip

Laboratory 1	Centro Nacional de Metrologia	**ID Number**	007	**End Date**	2005-09-12
Latitude	20° 32 min 13.373 s N	**Counter Delay**	0.11 ns	**Reference Source**	UTC(CNM)
Longitude	100° 15 min 17.204 s W	**REF Delay**	12 ns	**Mask Angle**	10°
Altitude	1917.16 m	**Receiver Delay**	75 ns	**Receiver Temp.**	27° C
Laboratory 2	National Institute of Standards and Technology	**ID Number**	006	**Baseline**	2198.851 km
Latitude	39° 59 min 44.494 s N	**Counter Delay**	-0.09 ns	**Reference Source**	UTC(NIST)
Longitude	105° 15 min 43.409 s W	**REF Delay**	748 ns	**Mask Angle**	10°
Altitude	1645.60 m	**Receiver Delay**	33 ns	**Receiver Temp.**	24° C

Hours in Common-View	Mean Time Offset (ns)	Range (ns)	Frequency Offset	Confidence (r)
24	-60.85	13.40	$+5.98 \times 10^{-14}$	+0.56



Allan Deviation

Averaging Period (τ) (hours, minutes)	Samples	Frequency Stability
0 h, 10 min	142	4.21×10^{-12}
0 h, 20 min	140	2.58×10^{-12}
0 h, 40 min	136	1.49×10^{-12}
1 h, 20 min	128	7.95×10^{-13}
2 h, 40 min	112	4.09×10^{-13}
5 h, 20 min	80	1.86×10^{-13}

Time Deviation

Averaging Period (τ) (hours, minutes)	Samples	Time Stability (ns)
0 h, 10 min	142	1.46
0 h, 20 min	139	1.37
0 h, 40 min	133	1.37
1 h, 20 min	121	1.28
2 h, 40 min	97	1.57
5 h, 20 min	49	0.98

UTC(CNM) - UTC(NIST)
(common-view tracks from individual GPS satellites)

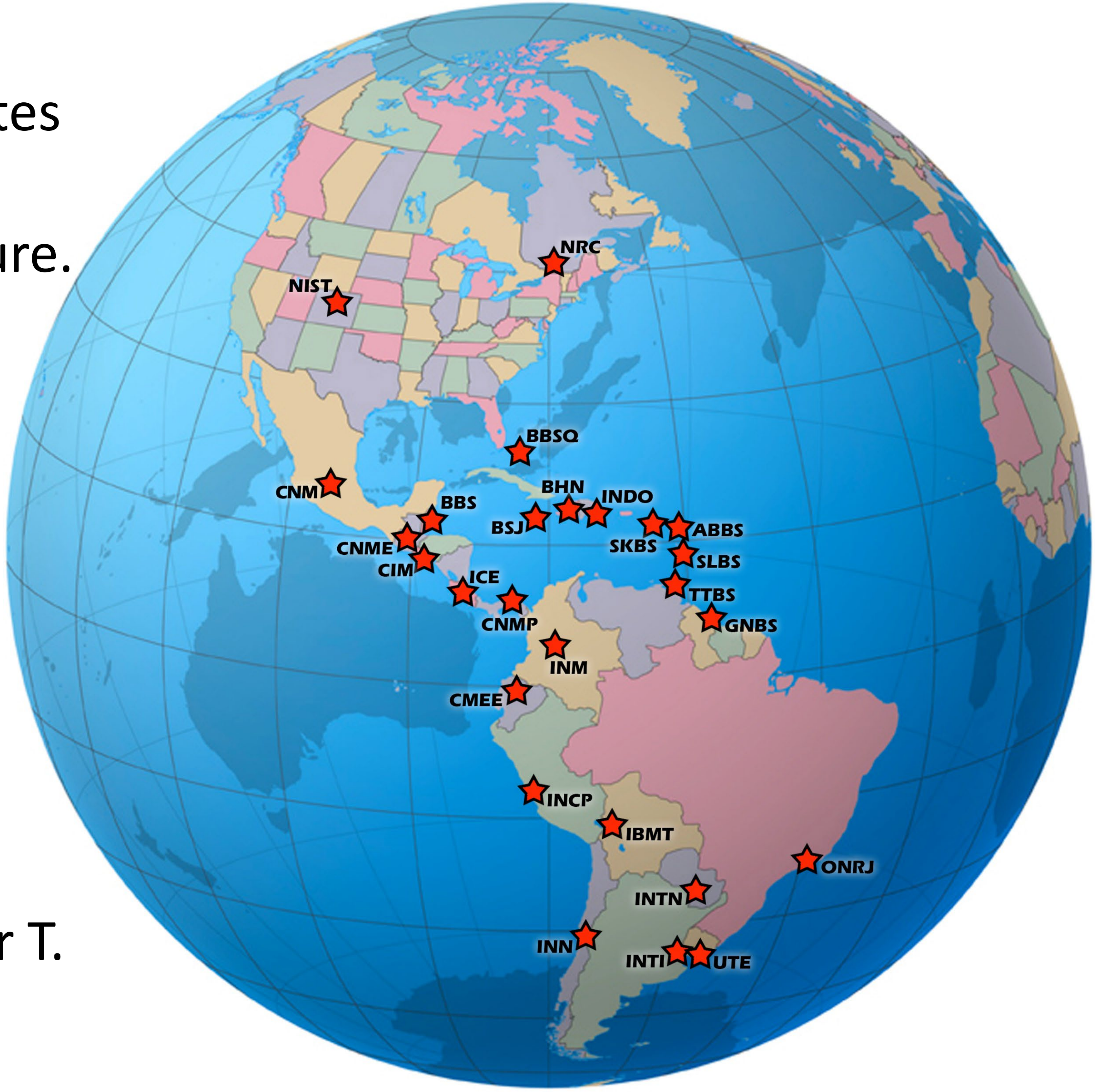
GPS PRN	Minutes (In-View)	Minutes (Common-View)	Range (ns)	Time Deviation	Frequency Offset	Confidence (r)	View Detail
1	450	350	21.62	3.45	$+1.51 \times 10^{-13}$	+0.18	View
2	410	360	25.58	2.19	$+5.79 \times 10^{-13}$	+0.60	View
3	340	270	19.24	2.10	-2.10×10^{-13}	-0.60	View
4	350	280	31.08	2.03	$+1.52 \times 10^{-12}$	+0.86	View
5	---	---	----------	-------	--------------	------	----
6	330	270	18.73	2.06	-4.73×10^{-13}	-0.48	View
7	470	390	34.45	2.60	$+1.44 \times 10^{-13}$	+0.56	View
8	340	290	20.42	1.76	$+2.01 \times 10^{-14}$	+0.16	View
9	400	280	22.90	2.14	$+6.45 \times 10^{-14}$	+0.20	View
10	330	280	31.34	2.25	$+5.22 \times 10^{-13}$	+0.46	View
11	430	290	23.14	2.29	$+9.42 \times 10^{-14}$	+0.48	View
12	---	---	----------	-------	--------------	------	----
13	300	250	18.05	1.90	-3.99×10^{-13}	-0.40	View
14	440	380	22.13	2.64	-1.30×10^{-14}	-0.02	View
15	350	310	28.18	3.20	-4.33×10^{-13}	-0.43	View
16	310	270	13.29	1.58	$+2.11 \times 10^{-13}$	+0.25	View

Growth of SIM

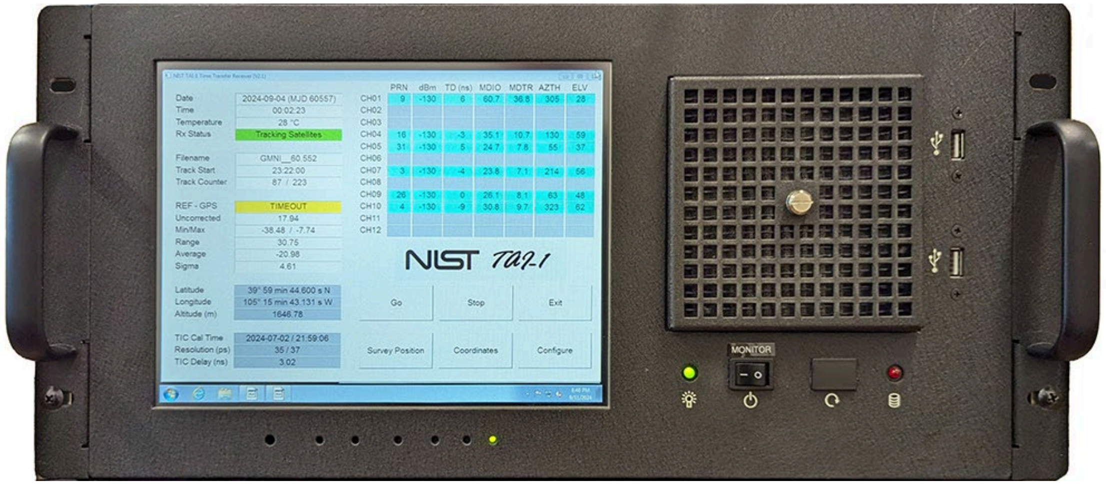
By 2010 there were 16 SIM time and frequency sites
Six sites on Circular-T.
Some labs did not have a good oscillator to measure.

By 2015, there were 23 SIM time and frequency sites, but only 7 on Circular-T.

Barriers seemed to be around hardware/cost (creating and sending CGGTTS files)
...and some labs do not have cesium clocks or timescales, so it was not applicable to join Circular T.



SIM and Circular-T



“TAI-1” system created to help labs submit CGGTTS files to BIPM.

It uses the 12-channel Motorola M12/iLotus receiver and a time interval counter.
Had to deal with the modeled ionospheric correction (MDIO).
Six systems were sent out by the end of 2015.

SIM and Circular-T

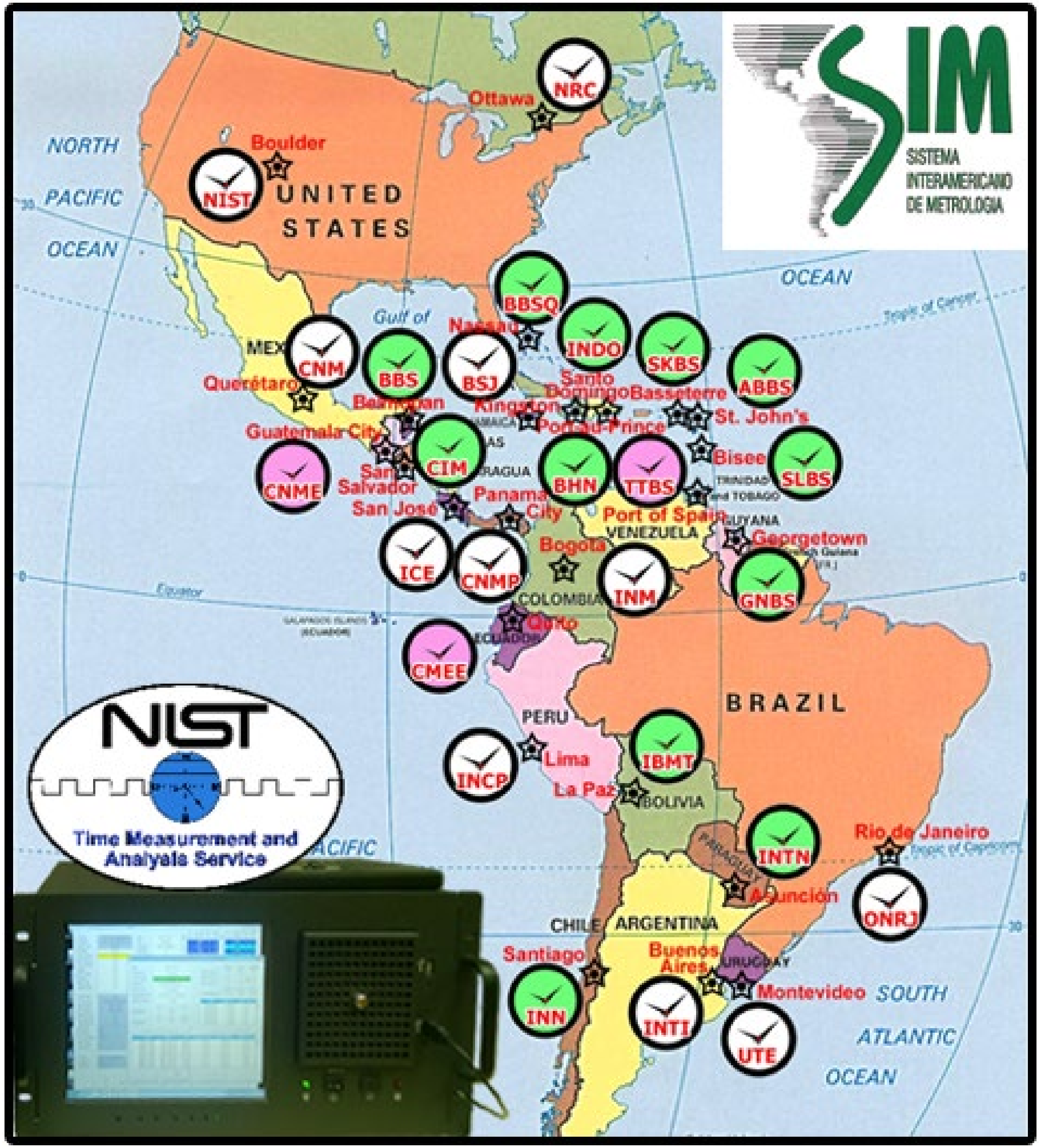
NIST

By 2018 there were 26 SIM time and frequency sites. (current number)

Some have been repaired/retrofit.

Now there are 13 SIM countries on Circular-T.

We get daily SMS messages of comparisons and use them as a time-scale alarm.



White clocks represent labs with cesium oscillator(s) or an ensemble time scale

Green clocks represent labs with Rb oscillators steered to SIMT

Purple clocks represent labs with GPSDOs or undisciplined Rb oscillators

Remote Calibrations

NIST Remote Time and Frequency Calibration Services

TMAS – established in 2007
Time Measurement and Analysis Service
12-channel Motorola M12/iLotus
and time interval counter

<u>44 customers</u>
17 Regular TMAS
27 NISTDC (NIST-Disciplined Clock)
e.g., cal. labs, atomic oscillator manufacturers, stock market data centers, military, aerospace

TMAS service and options

We calibrate the system delays compared to UTC(NIST) before shipping.

Base TMAS provides real-time results via a web portal, time offset uncertainty of ~12 ns and a frequency offset with an uncertainty near 1×10^{-14} after 1 day of averaging.

Monthly calibration reports are sent to customers.

The current cost is $1140/month.

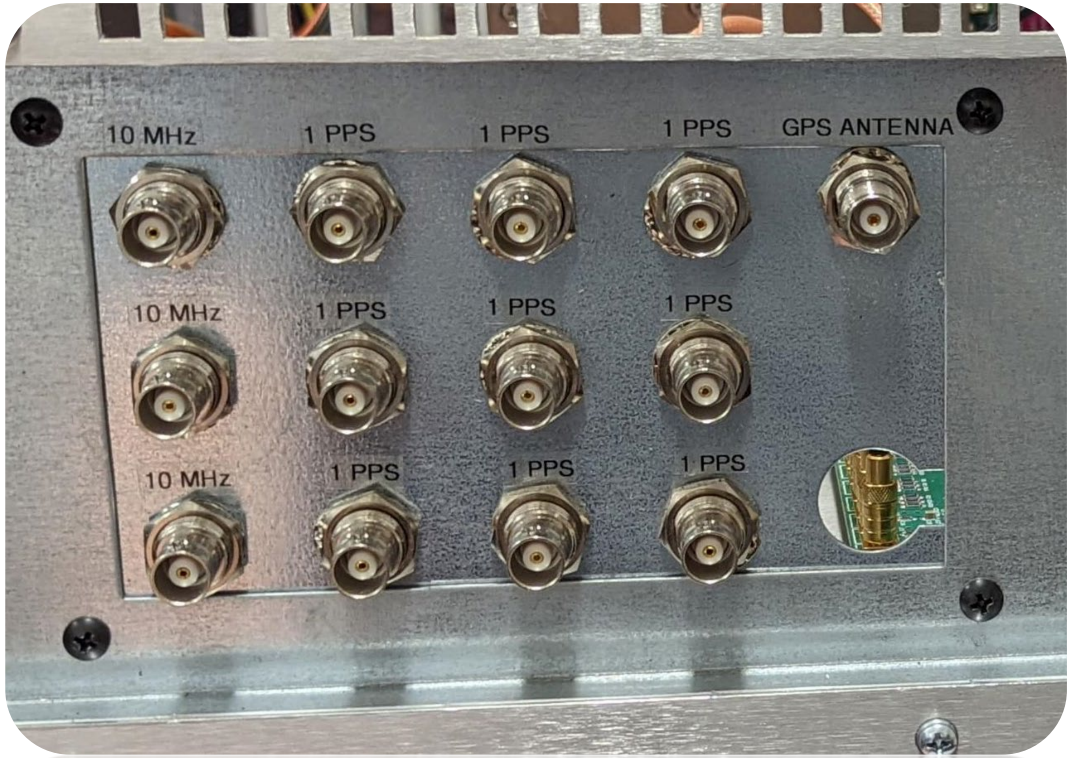
NIST-disciplined clock option includes a rubidium oscillator inside the system which is steered (in frequency) to keep the PPS time output near zero.

NIST-Disciplined Clock (NISTDC)

There are several 10 MHz and 1 PPS outputs from the Rb oscillator (+387/month) or a customer-owned Cs oscillator ($205/month).

A time code option includes an internal NTP/PTP server. (+387/month)

A time code monitoring service checks several customer-set devices by comparing NTP results with the system itself. (+387/month)



Stock Market Timing

NIST

Financial Industry Regulatory Authority, INC. (FINRA) implements rules for traders through the Consolidated Audit Trail (CAT) system.

They name NIST in the procedure: "…business clocks [must be] synchronized to within 50 milliseconds of the National Institute of Standards and Technology's (NIST) atomic clock". High-speed traders want much closer timing.

Stock market data centers drove the increase in NISTDC customers:

- One company put NISTDCs in 8 data centers around the world (NY, NJ, Chicago, Aurora IL, London (x2), Frankfurt, Tokyo).
- A second company has 4 data center locations.
- Multiple exchanges themselves are also customers.

Stock Market Timing

Volume 121 (2016) http://dx.doi.org/10.6028/jres.121.023
Journal of Research of the National Institute of Standards and Technology

Accurate, Traceable, and Verifiable Time Synchronization for World Financial Markets

Michael A. Lombardi[1], Andrew N. Novick[1], George Neville-Neil[2], and Ben Cooke[3]

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[2]Perseus,
New York, NY 10007

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Mike Lombardi won the NIST Condon Award with this paper

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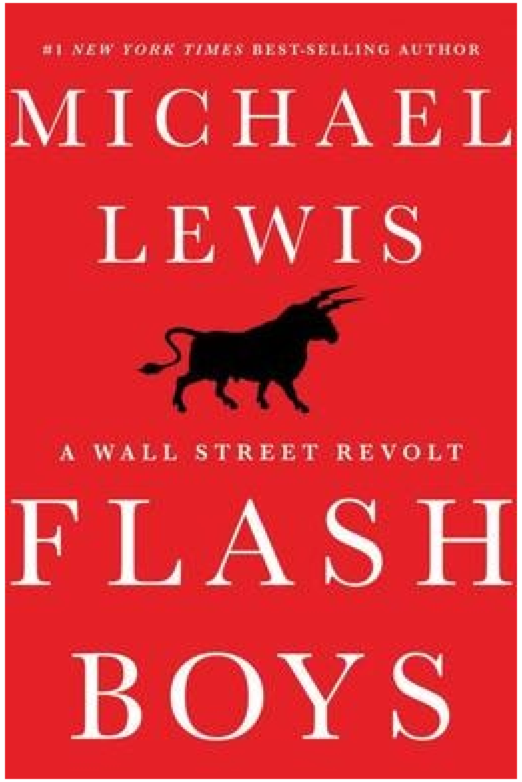

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Where do we go from here?

NIST

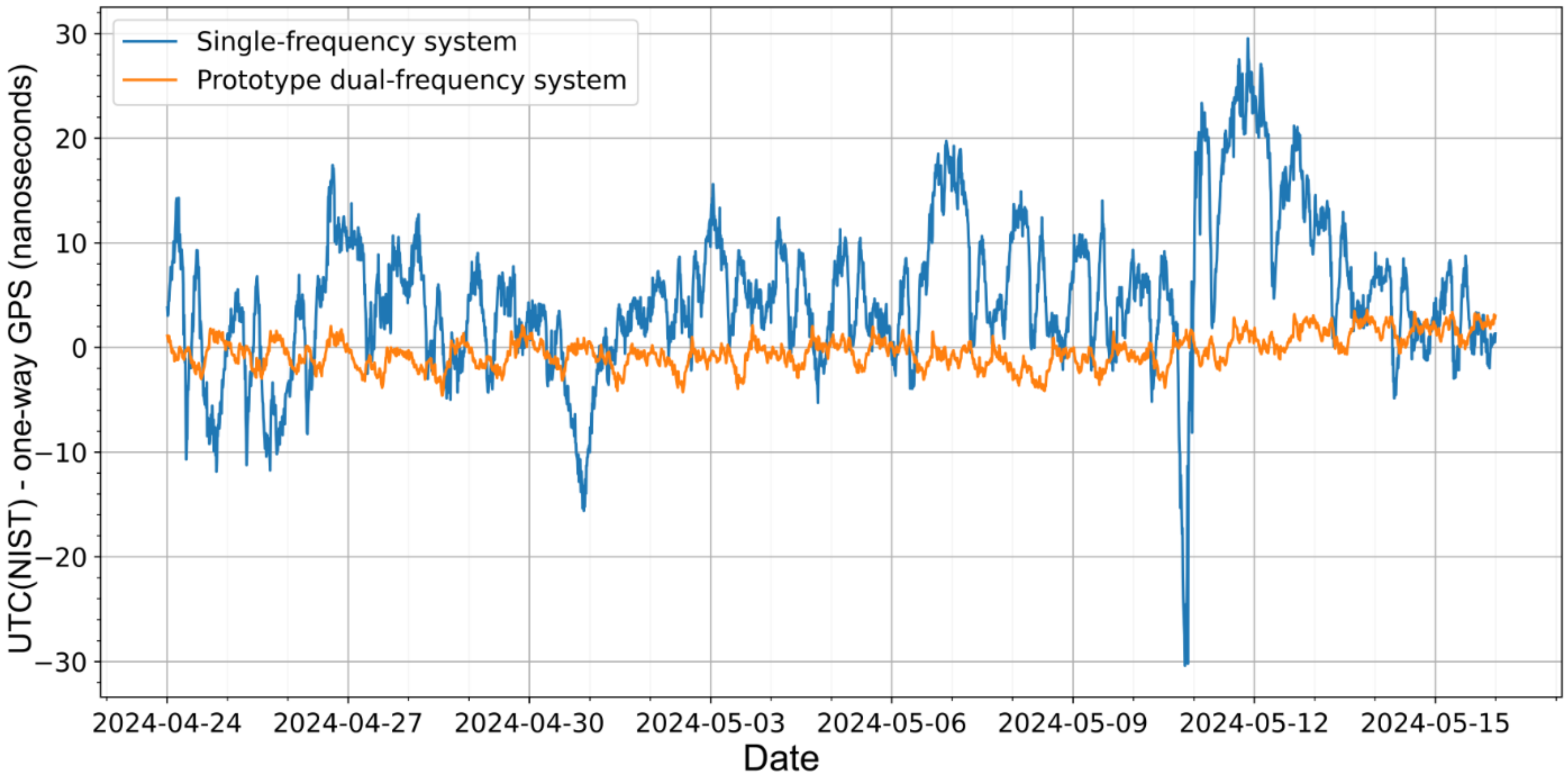
- Some hardware at SIM and TMAS field sites is getting old.
- Low-cost dual-frequency/triband receivers are now available.
- Working on a completely new system to replace SIM/TMAS/FMAS systems.
- Including new variants, like a portable system, which can be used as a traveling receiver for calibrations of GNSS receivers (*eg., CCTF WG concerning traceability to UTC through GNSS signals).

Inexpensive *dual-frequency* GNSS receiver (u-blox F9T):

- Greatly reduces ionospheric effects
- Greatly improves position determination
- Effects due to environment/multipath very low
- On-board comparator (alleviates costly time interval counter)

Improvements to SIM/TMAS

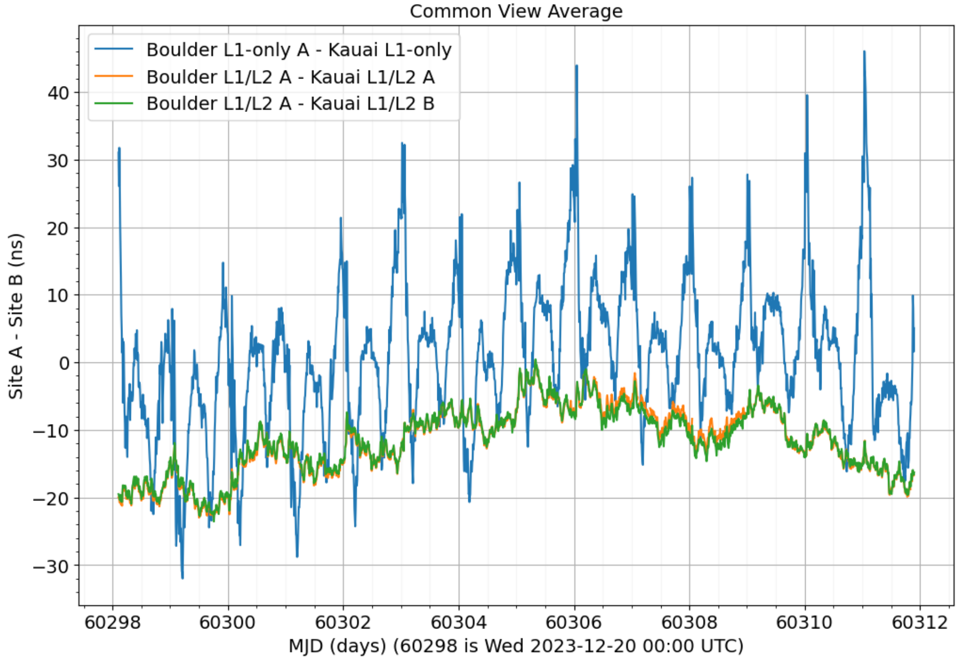
Extreme case of ionospheric effects

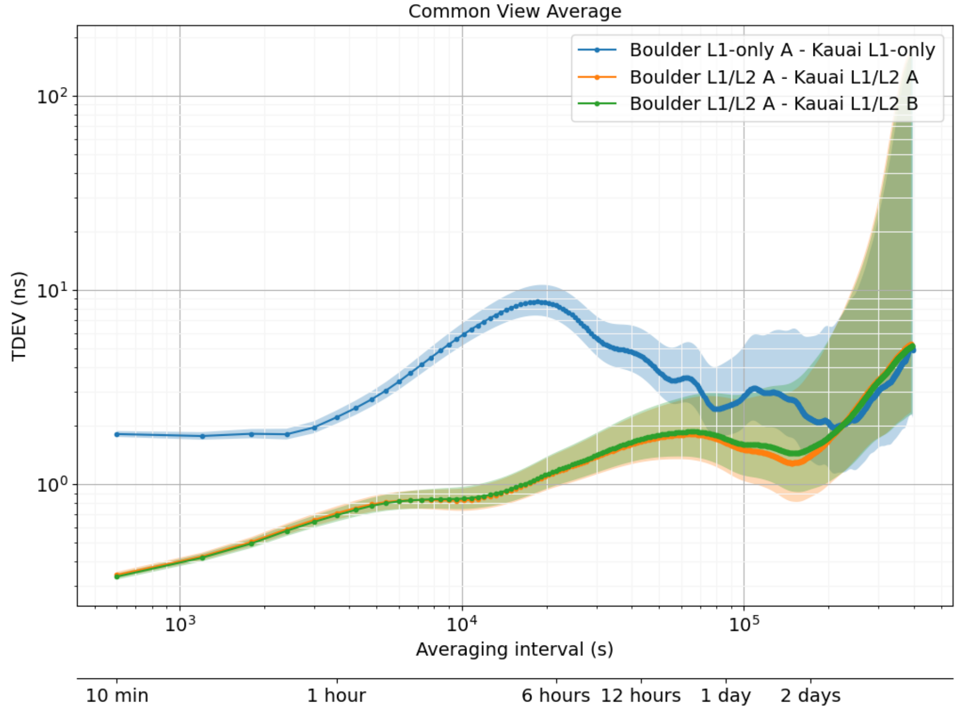


Single-frequency and dual-frequency one-way GPS data compared to UTC(NIST) before and during the solar storm on May 10, 2024.

Improvements to SIM/TMAS

Common-view with very long baseline, to WWVH in Kauai, Hawaii





Very long baseline >5000 km (WWVH)
TDEV at 1 day ~1.6 ns

Improvements to TMAS

TABLE 2 MEASUREMENT UNCERTAINTIES

Uncertainty Component	Assigned Value
U_A, Time Uncertainty	*0.5 ns*
U_B, Calibration	*0.35 ns*
U_B, Coordinates	*0.15 ns*
U_B, Environment	*0.25 ns*
U_B, Multipath	*0.5 ns*
U_B, Ionosphere	*0.25 ns*
U_B, Reference Delay	*0.1 ns*
U_B, Resolution	*0.05 ns*
U_C, k= 2	*1.77 ns*

EFTF June 2024: *Improving the Uncertainty of NIST Remote Time and Frequency Calibration Services*

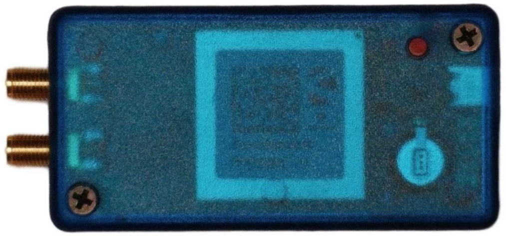
$$U_C = k\sqrt{u_A{}^2 + u_B{}^2} \quad (k = 2, \sim 95\ \%)$$

Future of SIM/TMAS

- Received funds from IAAO to upgrade the SIM systems and some in Afrimets RMO (We have collaborators in Tanzania and Kenya).

- Hope to integrate CGGTTS file generation in ***all*** of the systems, which could help streamline getting more labs onto Circular-T.

- Working with Mosaic-T variants now – Tri-band, CGGTTS, low-cost (< $1000)



Thanks for your attention!