2016 Report on GPS Time Transfer Activities at NIST

Michael Lombardi
NIST Time and Frequency Division
lombardi@nist.gov

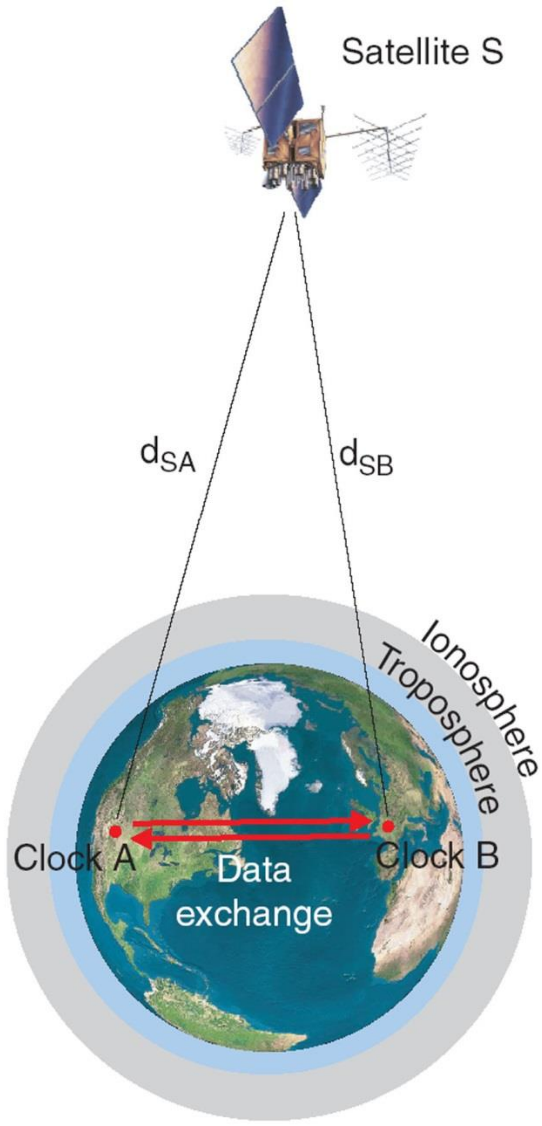
56th CGSIC Meeting – Timing Subcommittee
Portland, Oregon
September 12, 2016

Outline

- ✓ The Use of GPS in Delivering NIST Time to Our Customers
- ✓ GPS Time Transfer Links for Contributions to Coordinated Universal Time (UTC)
- ✓ Space Clock and GPS Time Transfer Research at NIST
- ✓ Issues in GPS Time Noted at NIST in 2016
- ✓ Summary

The Use of GPS in Delivering NIST Time to Our Customers

NIST distributes frequency and time to its customers via Common-View GPS Measurements

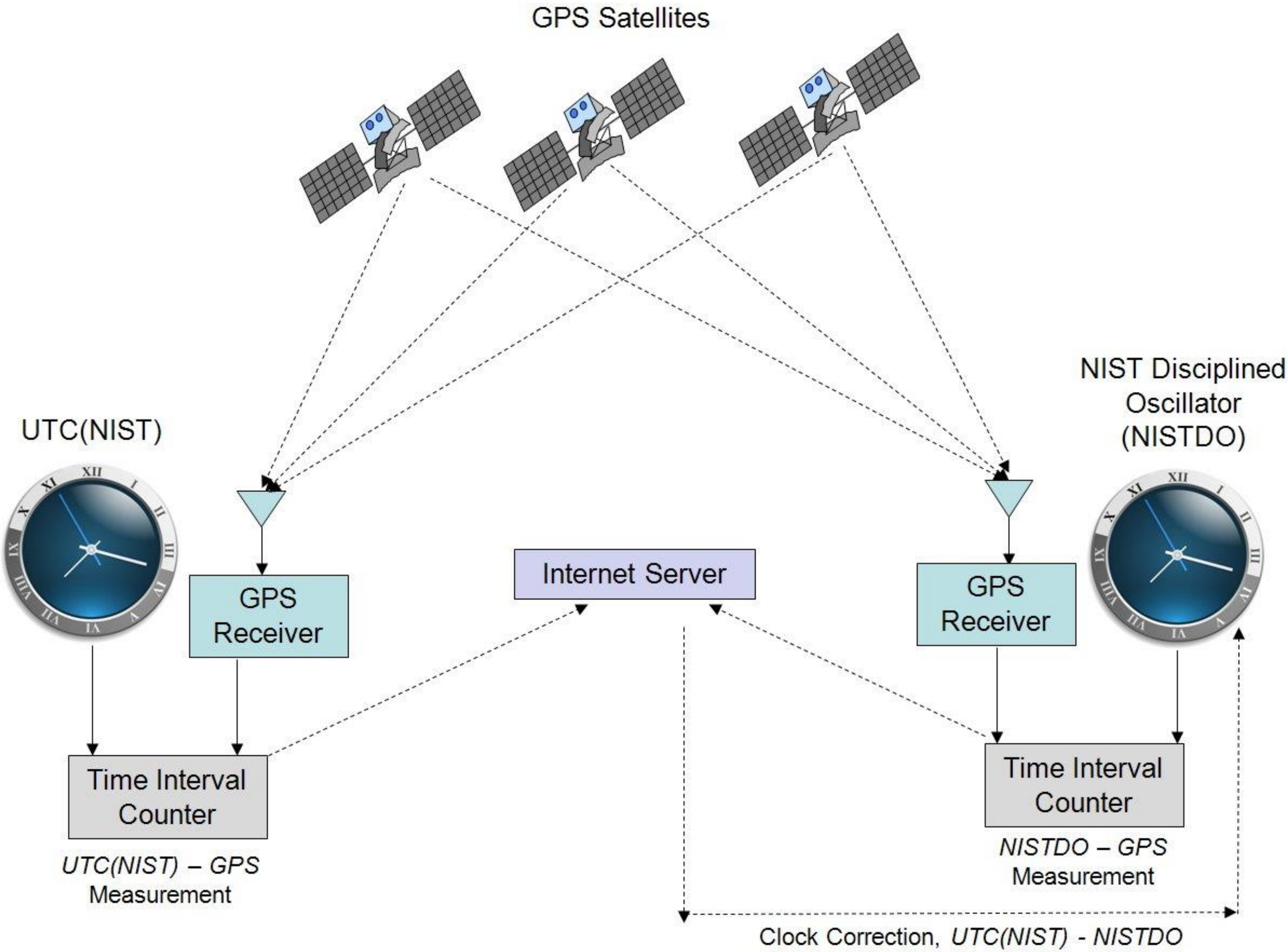


- ✓ NIST provides common-view GPS measurement systems to its remote calibration customers. These systems allow customers to compare their clocks to NIST by using the GPS satellites as a "relay".
- ✓ The common-view data is processed in real-time and shows the difference between the NIST clock and the customer's clock. Customers can then show traceability to the International System (SI) of units through NIST.
- ✓ Several common-view services are offered that:
  - Report frequency uncertainty to the customer (FMAS and TMAS)
  - Report time uncertainty to the customer (TMAS)
  - Lock the customer's clock to the NIST time scale (NISTDO)

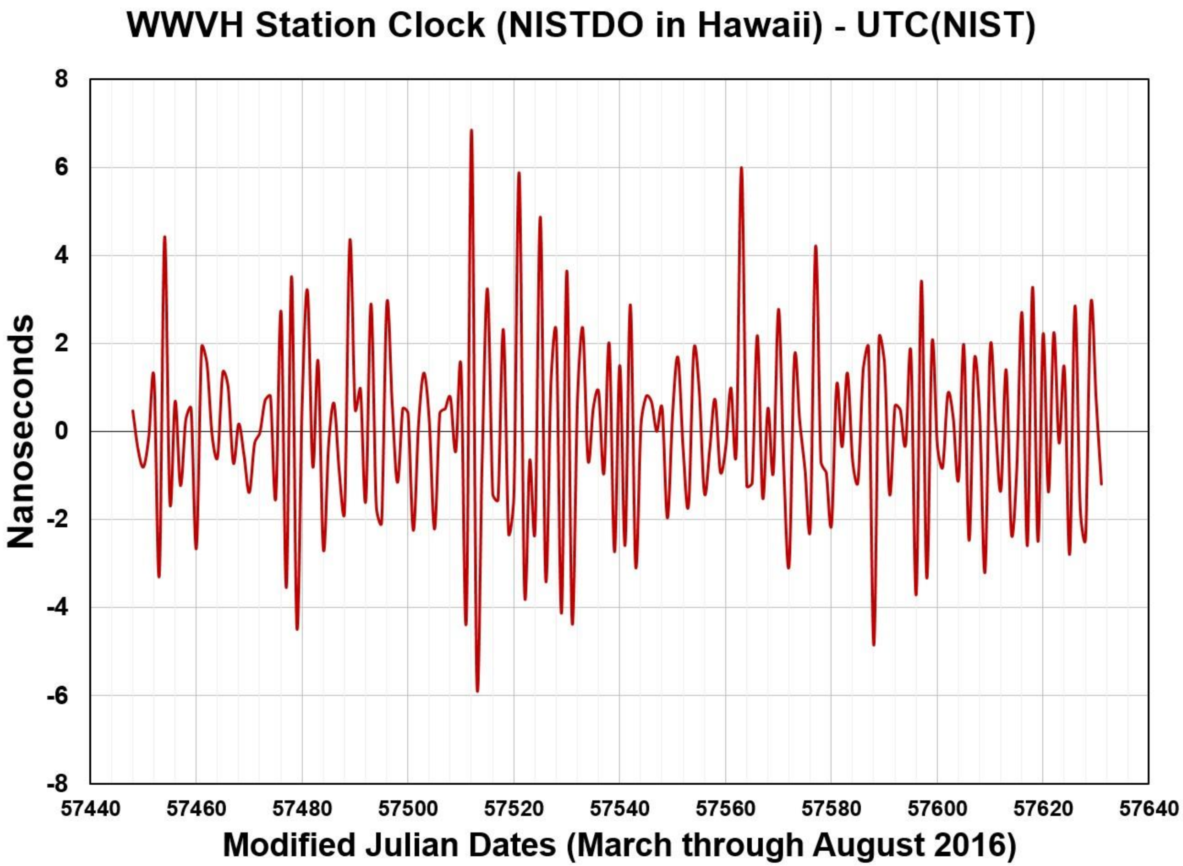
Map of Common-View GPS Systems Maintained by NIST

(76 total systems deployed, 51 at customer sites and 25 in SIM Time Network)

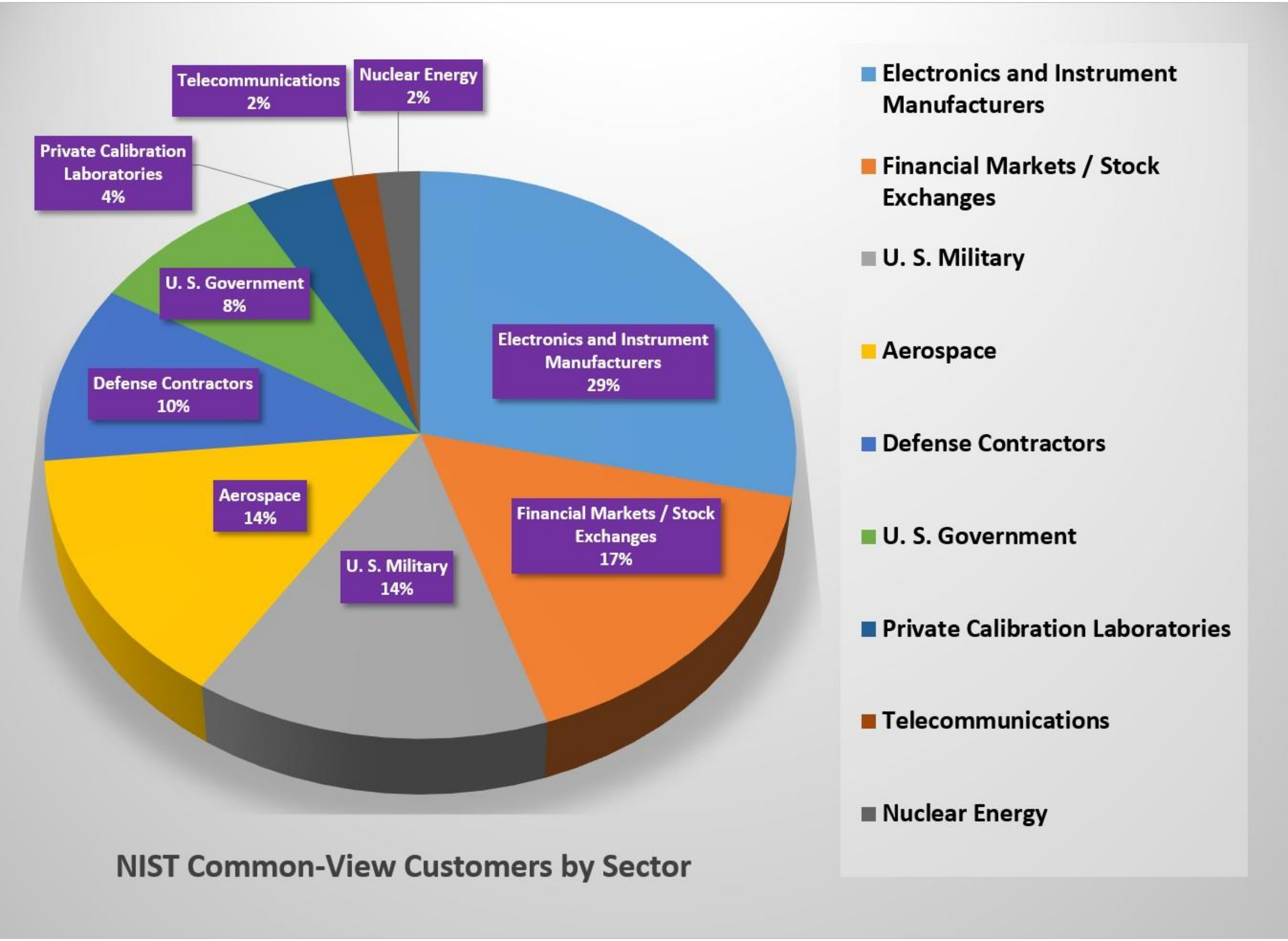
How a NIST Disciplined Oscillator (NISTDO) Works



A NISTDO is the station clock at WWVH in Kauai

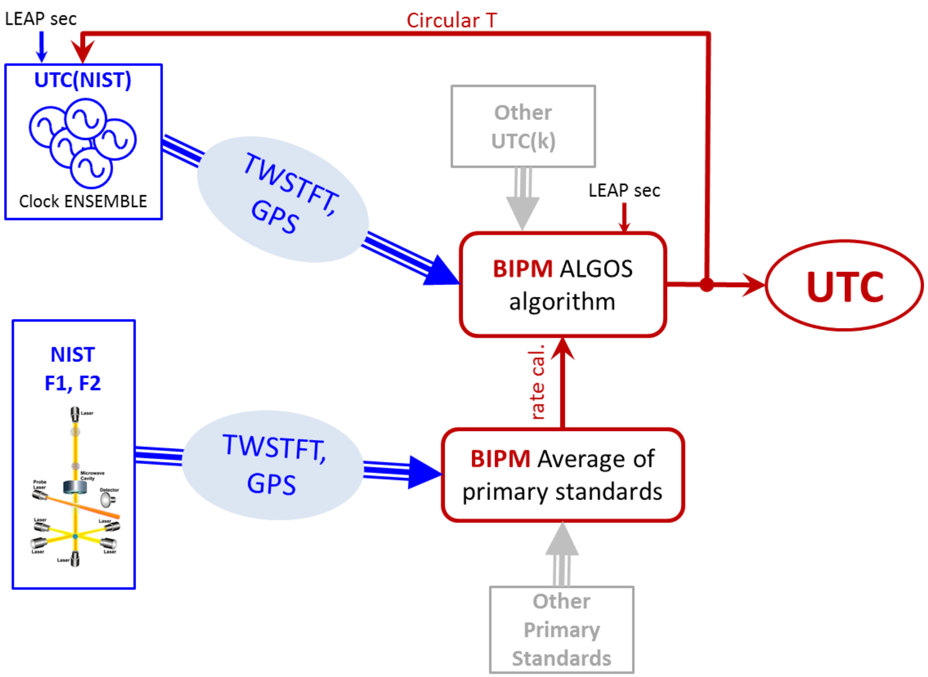


- ✓ A NISTDO (based on cesium) is the station clock at shortwave radio station WWVH in Hawaii.
- ✓ The Boulder-Kauai baseline is long (5324 km) and Internet access at WWVH is through a satellite and is not always available.
- ✓ Even so, the average time offset is near 0 and peak-to-peak time variations are usually within ±10 ns of UTC(NIST) in Boulder.


Telecommunications
2%
Nuclear Energy
2%
Private Calibration Laboratories
4%
U. S. Government
8%
Electronics and Instrument Manufacturers
29%
Defense Contractors
10%
Aerospace
14%
Financial Markets / Stock Exchanges
17%
U. S. Military
14%
Electronics and Instrument Manufacturers
Financial Markets / Stock Exchanges
U. S. Military
Aerospace
Defense Contractors
U. S. Government
Private Calibration Laboratories
Telecommunications
Nuclear Energy
NIST Common-View Customers by Sector

GPS Time Transfer Links for Contributions to Coordinated Universal Time (UTC)

How NIST Contributes to UTC



- ✓ NIST maintains and operates the U. S. time standard, UTC(NIST) and the U. S. primary frequency standards, cesium fountain devices known as F1 and F2.

- ✓ The UTC(NIST) time scale consists of an ensemble of hydrogen masers and cesium clocks. It is a local realization of Coordinated Universal Time or UTC, which is computed by the International Bureau of Weights and Measures (BIPM) in France. UTC is the official world time scale.

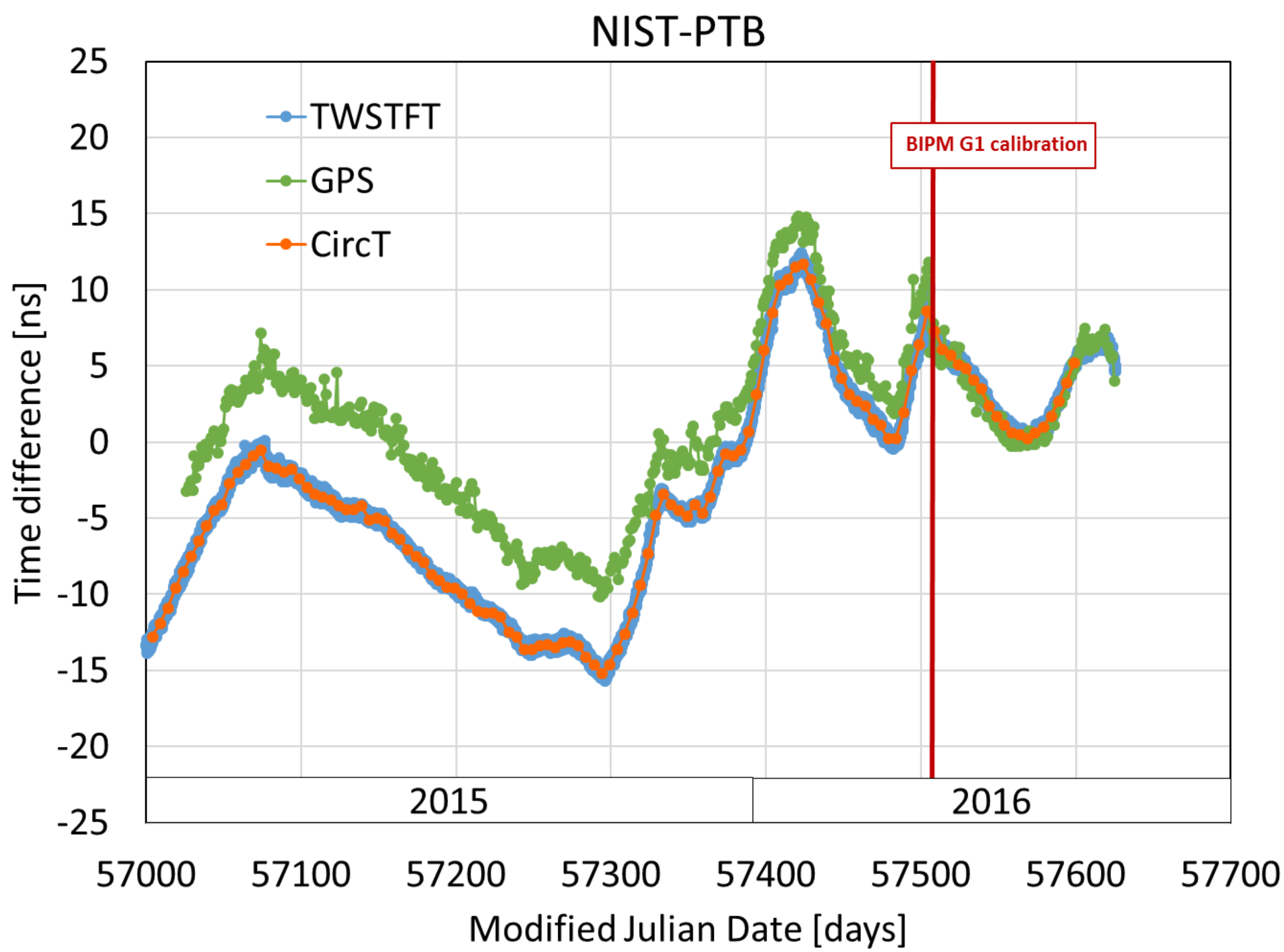
- ✓ The primary time transfer link between NIST and UTC is based on two-way satellite time and frequency transfer (TWSTFT) measurements that utilize geostationary satellites. The backup link utilizes various forms of common-view GPS measurements.

Comparisons with PTB (NIST's link to UTC)

GPS: A comparison to PTB via code-based, common-view, ionosphere-free GPS time transfer (the backup NIST link to UTC).

TWSTFT: A comparison to PTB via two-way satellite time and frequency transfer (the primary NIST link to UTC).

CircT: The official NIST-PTB comparison results as reported by the BIPM's monthly *Circular-T* document.



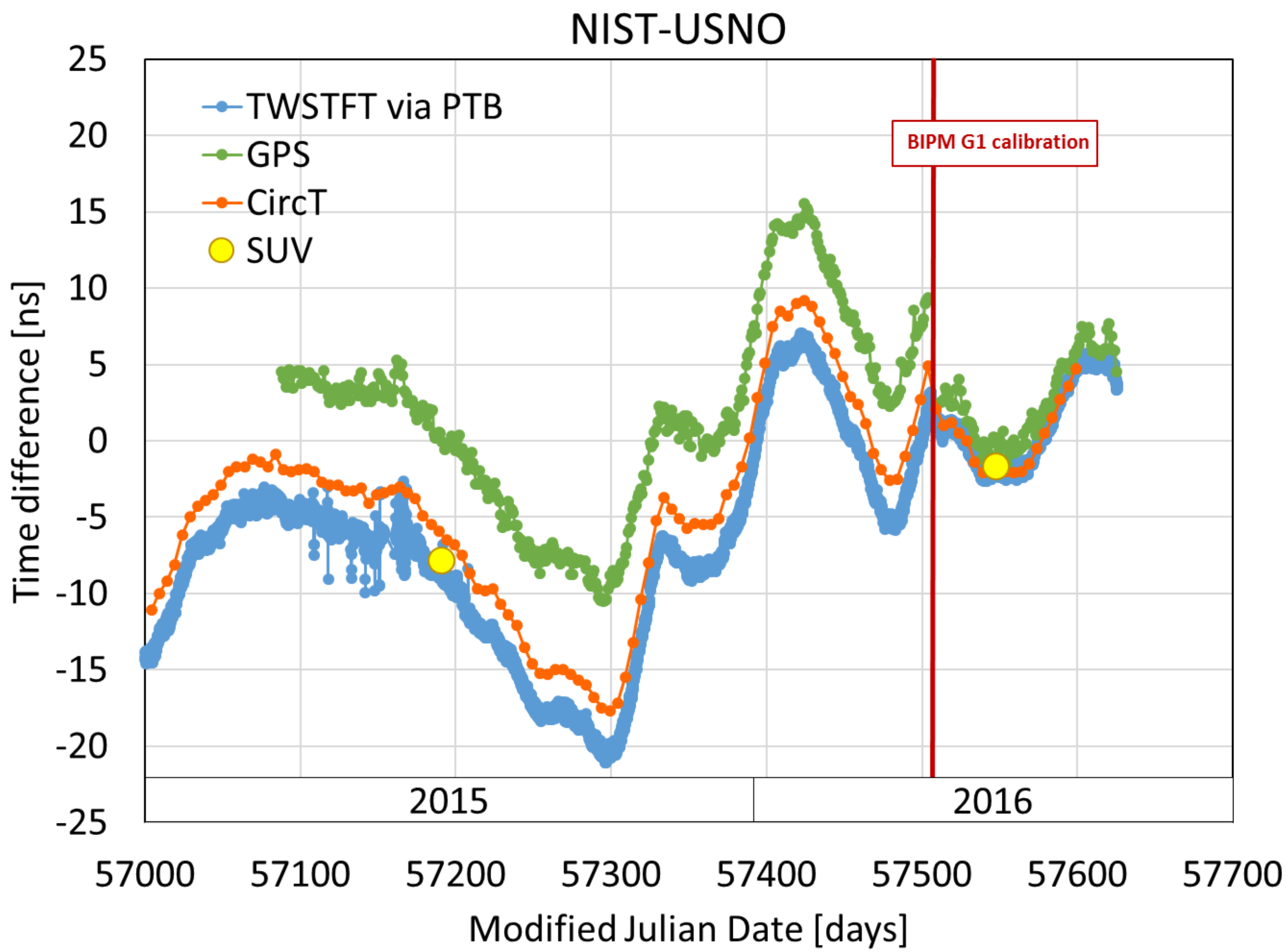
NIST Comparisons with USNO

GPS: A comparison to USNO via code-based, common-view, ionosphere-free GPS time transfer.

TWSTFT: A comparison to USNO via two-way satellite time and frequency transfer.

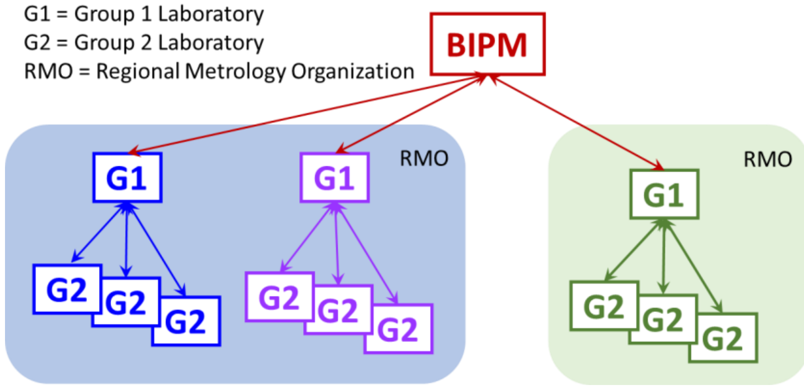
CircT: The official NIST-USNO comparison results as reported by the BIPM's monthly *Circular-T* document.

SUV: Calibration results from TWSTFT mobile Earth station owned by USNO, and periodically driven to NIST in Boulder, CO.



NIST and USNO are Group 1 Labs in the SIM Region

NIST is now responsible for the calibration of national metrology institutes within the SIM region that contribute, or will contribute in the future, to UTC.



NIST	**(Boulder, CO, USA)**
CNM	(Queretaro, Mexico)
CNMP	(Panama City, Panama)
INTI	(Buenos Aires, Argentina)
INXE	(Rio de Janeiro, Brazil)
NRC	(Ottawa, Canada)
ONRJ	(Rio de Janeiro, Brazil)
INM	(Bogota, Colombia)
INCP	(Lima, Peru)

USNO	**(Washington, DC, USA)**
APL	(Laurel, MD, USA)
IGNA	(Buenos Aires, Argentina)
NRL	(Washington, DC, USA)
ONBA	(Buenos Aires, Argentina)

NIST Calibrations of Group 2 Laboratories

FALL 2016

✓ Trip 1: COMPLETED!
NRC (Ottawa, Canada)

Trip 2:
CNM (Queretaro, Mexico)
CNMP (Panama City, Panama)

SPRING 2017

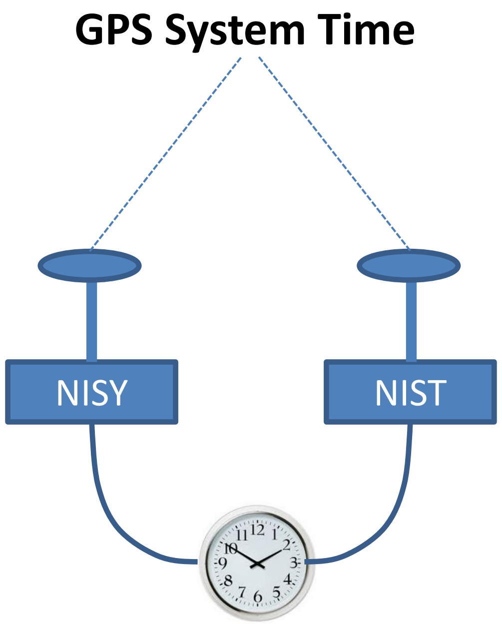
Trip 3:
INTI (Buenos Aires, Argentina)
INXE (Rio de Janeiro, Brazil)

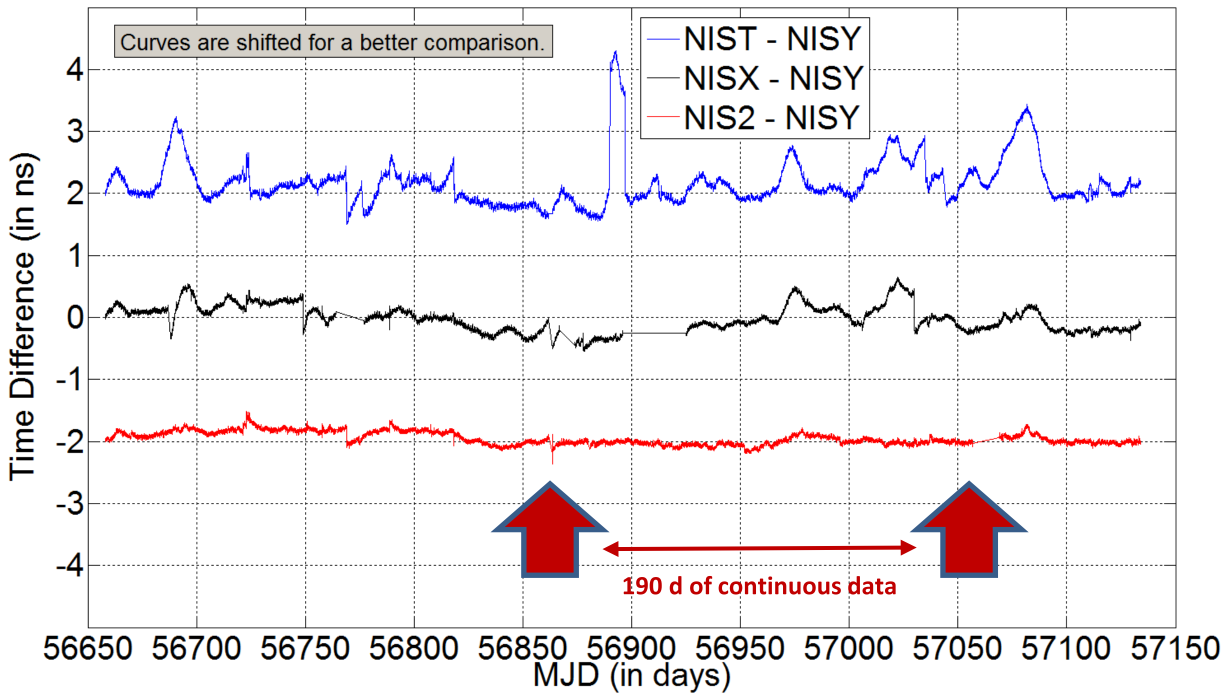
ONRJ (Rio de Janeiro, Brazil)

NIST Traveling Calibration System

GPS Time Transfer Research at NIST

NIST Research in GPS Carrier-Phase Time Transfer[1]

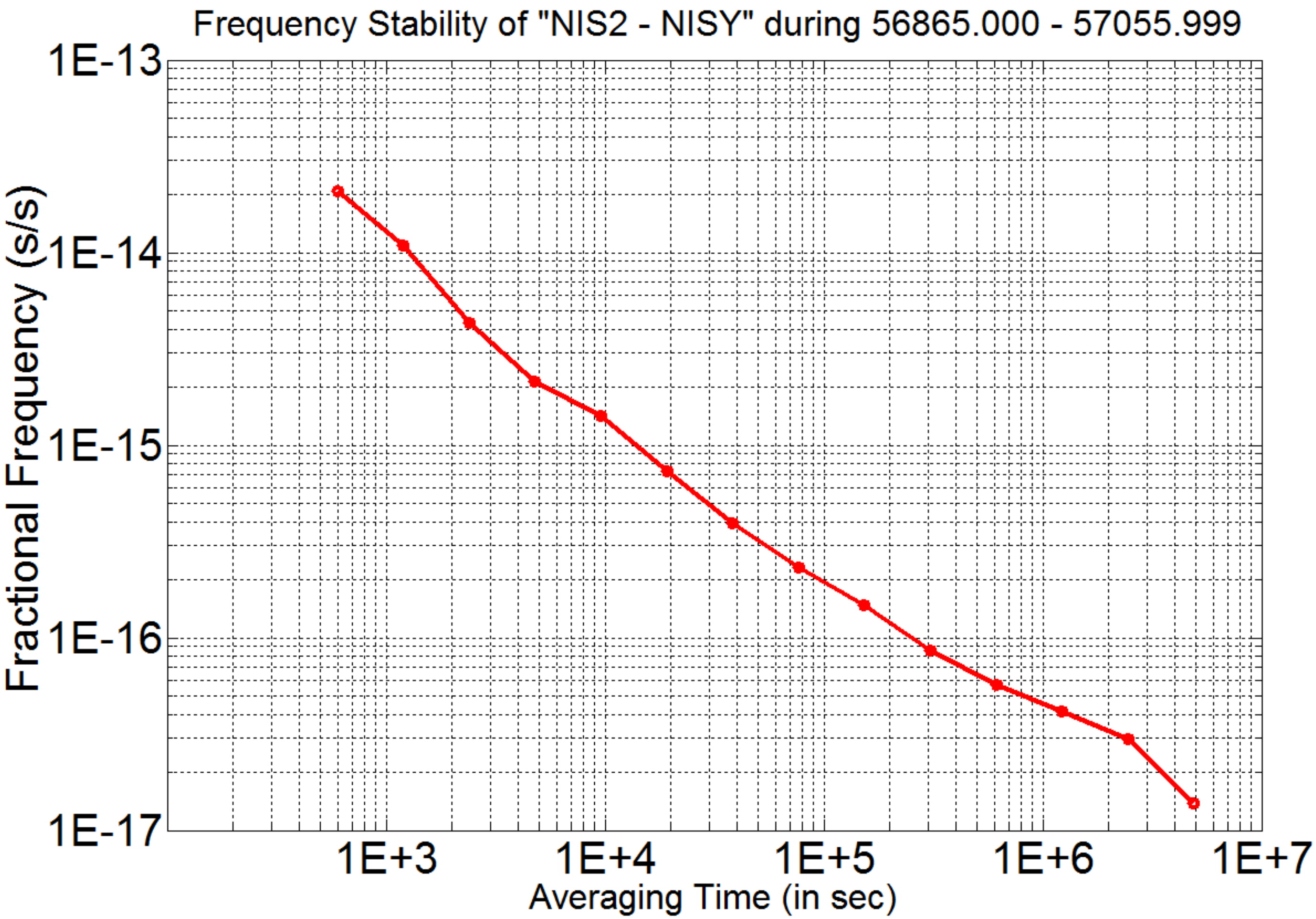




- ✓ The time difference between two receivers can reach 1.8 ns (peak-to-peak), over 1.3 years (blue curve). This poses a challenge for the long-time GPS timing, if sub-nanosecond accuracy is needed.
- ✓ The smallest time difference between two receivers is 0.3 ns (peak-to-peak), over 1.3 years (red curve).

[1] Jian Yao and Judah Levine, *NIST Journal of Research*, vol. 121, pp. 372-388, 2016.

Best GPS Time Transfer Stability at NIST (common clock)[1]



- The frequency stability of GPS CP time transfer is 1.5×10^{-15} at 3 hours, 2.1×10^{-16} at 1 day, 5.0×10^{-17} at 10 days, and 1.3×10^{-17} at 60 days.

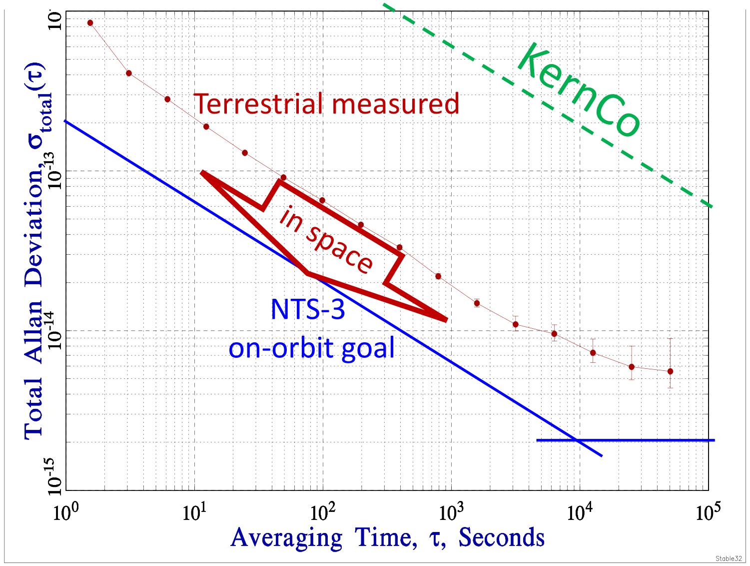
[1] Jian Yao and Judah Levine, *NIST Journal of Research*, vol. 121, pp. 372-388, 2016.

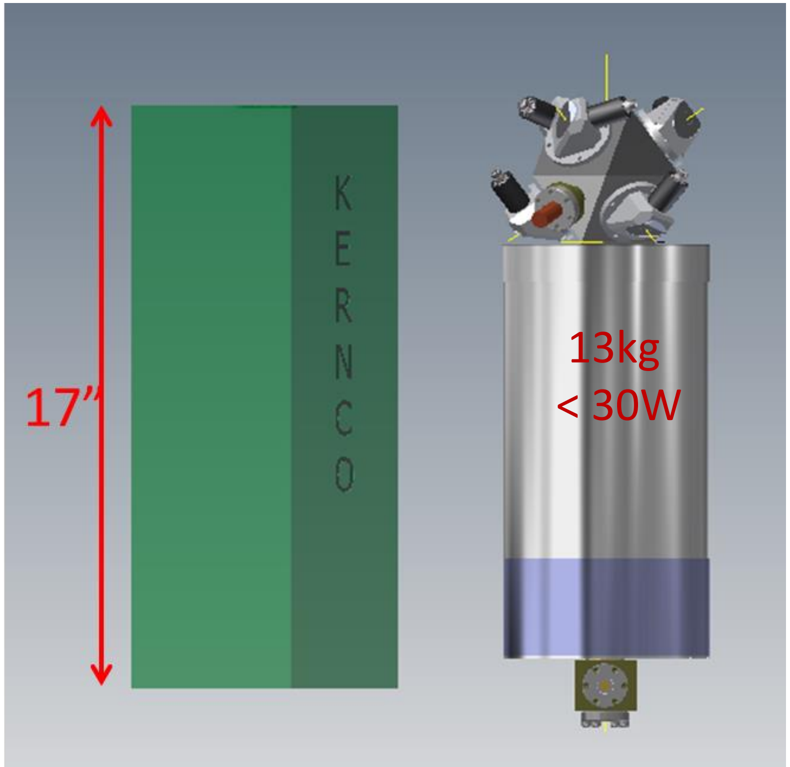
NIST R&D in Space Clocks

NIST is involved in the Air Force Research Lab program to support the Navigation Technology Satellite 3 (NTS-3), as well as possible future clocks for GPS.

New Laser-cooled Atomic clock

The current clock technology is unlikely to be significantly improved





Volume ~ 1.3 * legacy KernCo

NIST GPS-Related R&D also includes:

- **Data processing to reduce time transfer uncertainties**
  - Doppler-aided navigation: including Doppler information from RINEX files
  - Development of filtering techniques to combine carrier-phase data and Doppler information

- **Atomic Clock Ensemble in Space (ACES) mission support**
  - Development of Precise Point Positioning (PPP) algorithm to accurately determine the position of the International Space Station (ISS) to allow for the best frequency transfer between ground stations and ISS.

- **Tests of General Relativity**
  - Noise estimation and analysis of pseudorange data to better understand the acceleration noise of spacecrafts used in various test missions

- **Studying the effect of lunar and solar tidal perturbations on the frequency of GPS clock**
  - Prediction and eventual verification with cool-atom clocks on orbit

Issues in GPS Time Noted at NIST in 2016

Various Legacy Receivers and GPSDOs have or will fail due to the GPS Week Rollover Problem

Oncore Version	Firmware Date	Base Date	Failure Date	Fails to	Accepts "@@Ac" date command
UT 2.2	04/24/98	01/01/98	**08/14/16**	12/29/96	No
UT+ 3.2	08/23/00	01/01/00	**> 2038**	n/a	Yes
VP 8.8	09/24/97	01/01/03	**08/15/21**	12/30/01	Yes
VP 10.0	09/24/97	01/01/99	**08/13/17**	12/28/97	Yes
VP 10.0	09/24/97	01/01/00	**08/12/18**	12/27/98	Yes
VP 10.0	09/24/97	01/01/03	**08/15/21**	12/30/01	Yes
VP 10.0	09/24/97	01/01/09	**08/06/27**	01/21/08	Yes
VP 10.0	09/24/97	01/01/16	**08/13/34**	12/28/14	Yes
iLotus	09/06/06	01/01/05	**> 2038**	n/a	Yes

GPS Week Rollovers
4/7/2019
11/30/38

1999

2000

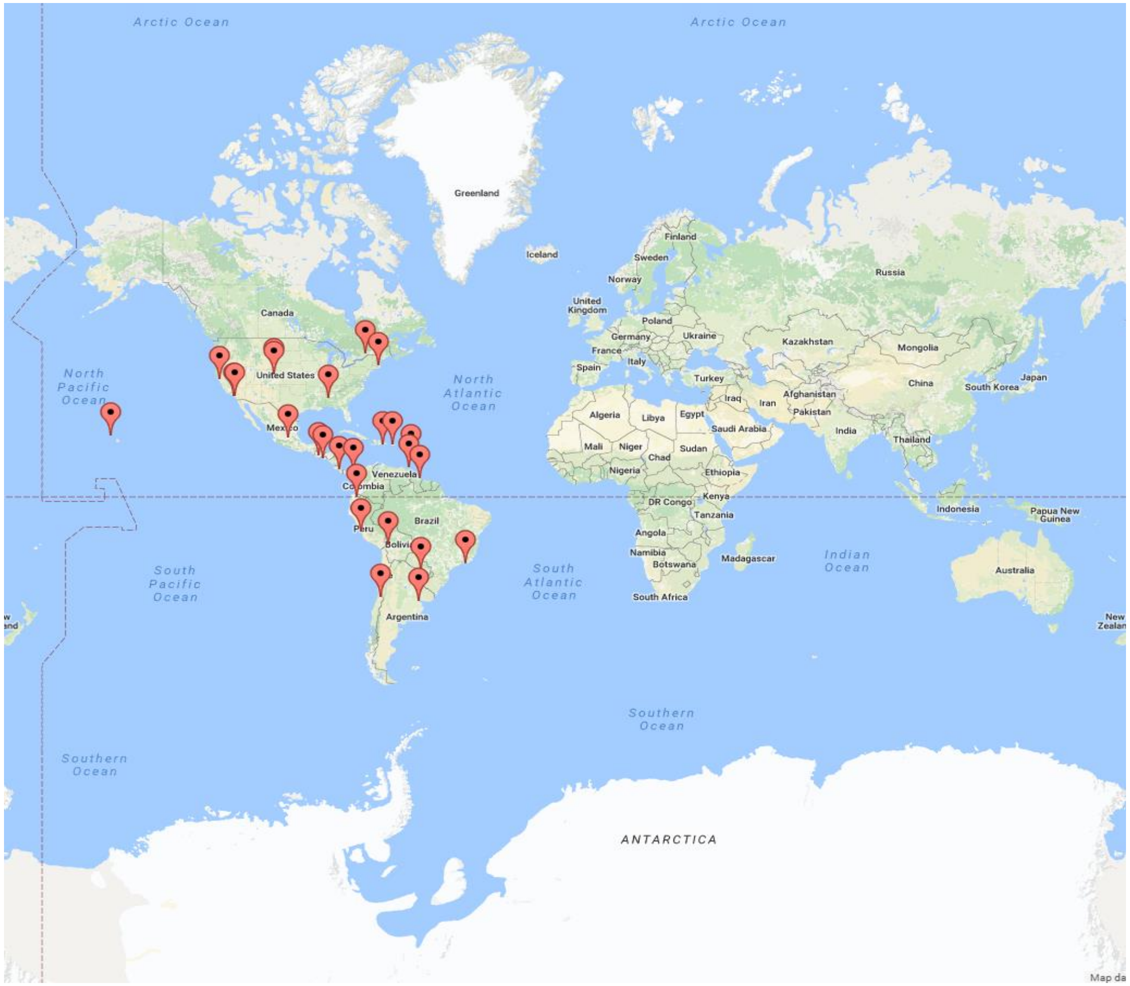
2003

2009

GPS Timing Error of January 26, 2016

- ✓ An error in the UTC offset parameter was broadcast by 15 of the GPS satellites resulting in an approximate 13 microsecond time error.
- ✓ NIST received text message alarms from its systems that monitor the remote customer data, and reported the error to 2 SOPS within a few hours after it occurred (we were one of the first GPS users to report the problem).
- ✓ We were able to look at data from approximately 80 L1-band GPS timing receivers, located at customer sites and at the NIST laboratories in Boulder. Only about 10 were not affected.
- ✓ Common-view links were only affected if one of the two receivers involved was showing the offset. If both were bad or both were good, there was no effect.
- ✓ We plan to report some rudimentary analysis of this incident and its effect on NIST services at the ION/PTTI meeting in January 2017.

Locations of some of the receivers monitored by NIST that were impacted by the GPS timing error of January 26, 2016



Latitude Range: -34.59^0 to $+45.45^0$.
Longitude Range: -157.86^0 to -43.23^0.

ION PTTI Meeting

(January 30 – February 2, 2017 in Monterey, California)

A very good venue for the discussion of GPS and other GNSS timing studies is the ION Precise Time and Time Interval (PTTI) meeting. The proposed sessions for the January 2017 meeting include these GPS-related topics:

- **Advances in GNSS Time Transfer**
- **The Role of PTTI in Improving GNSS Invulnerability, Reliability, and Performance**

Plus, many other areas where GPS time is utilized will be discussed, including:

- **Consumer Market Applications**
- **Electric Power Distribution**
- **Telecommunications**
- **Financial Sector Time Stamps**

The deadline for abstract submissions is October 3rd, about three weeks from today. Please visit this link for more information:

www.ion.org/ptti/

Summary

The use of GPS time and frequency information is an essential part of the services offered by NIST to the general public and many of NIST's scientific research programs. The four groups listed below have each contributed to the work described in this report.

Atomic Standards
S. Römisch – Leader
T. Parker
B. Patla
J. Savory
V. Zhang

Primary Frequency Standards
S. Jefferts – Leader
N. Ashby
S. Barlow
Y. Dudin
J. Shirley

Time and Frequency Services
J. Lowe – Leader
M. Deutch, WWV/WWVB
M. Lombardi
A. Novick
D. Okayama, WWVH

Network Synchronization
J. Levine – Leader
J. Yao