Introduction and Report from NIST

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CGSIC, 2020

★ brp1@nist.gov / / ✦ the year of the toilet paper shortage
Theme and scope of this year’s program

- Timing in a challenging and expansive landscape
- Atomic clocks and fundamental science
Civil GPS Service Interface Committee

Timing Subcommittee

Chair: Dr. Bijunath Patla, National Institute of Standards and Technology (NIST)
Co-Chair: Dr. Lin Yi, NASA Jet Propulsion Laboratory (JPL)

21 September 2020
Timing Subcommittee

2:00 pm Central Daylight Time

2:00  **Introduction**  Dr. Bijunath Patla, National Institute of Standards and Technology (NIST)

2:20  **USNO Laboratory Update**  Mr. Stephen Mitchell, U.S. Naval Observatory (USNO)

2:40  **Algorithms and Features of the New GPS System Timescale**  Dr. Michael Coleman, Naval Research Laboratory (NRL)

3:00  **Report From the Jet Propulsion Laboratory (JPL)**  Dr. Lin Yi, JPL, California Institute of Technology

3:20  **Break**  (Reconvene 3:40)
Timing Subcommittee

3:40 Control Algorithm for Resilient Timing  
Dr. Ilya Udovskydchenkov, Lead Electrical Engineer, MITRE

4:00 NIST Network Time Services: Current Status and Future Plans  Prof.  
Dr. Judah Levine, NIST

4:20 Atomic Clocks for Fundamental Physics: Time for Discovery  Prof.  
Marianna Safronova, University of Delaware

4:40 GPS/Galileo Time Transfer with Absolutely Calibrated Receivers  Dr.  
Roberto Prieto, European Space Agency, ESTEC

5:00 Discussion

5:20 Session End
CGSIC 2021
September 20-21, 2021
Union Station Hotel
St Louis, Missouri
Report from NIST

GPS/GNSS

- Time transfer to BIPM
- Subscription-based NIST time service
- Calibrations

Scientific research and data analysis

- Analyze/study data from GNSS timing receivers
- Develop theoretical models for physics/geophysics and resilient timing applications
- Exploring the frontiers of fundamental physics using atomic clocks
Time Transfer with GPS (NIST-PTBB)

**Link Stability: TDEV**

Because mathematicians care less about cantaloupes and more about averaging.

**Two-way time transfer**
*(primary mode of time transfer to BIPM)*

**Ionosphere-free combination GPS**
Calibrations: Group 2 (G2)

- NRC : Ottawa, Canada / Cal_Id:1019-2017
- CNM : Queretaro, Mexico / Cal_Id:1011-2017
- CNMP : Panama / Cal_Id: 1011-2017

Scientists wearing lab coats is an exaggeration.

- Completed
  - NRC : Ottawa, Canada / Cal_Id:1019-2017
  - CNM : Queretaro, Mexico / Cal_Id:1011-2017
  - CNMP : Panama / Cal_Id: 1011-2017

- Ongoing
  - INXE, ONRJ in Brazil
NIST provides frequency and time references to paying customers through its Time Measurement and Analysis Service (TMAS), Frequency Measurement and Analysis Service (FMAS), and NIST Disciplined Clock service (NISTDC). All services are based on GPS common-view measurements.

UTC(NIST) is the reference for all of these services. The NISTDC can provide NIST time at customer sites to within 10 nanoseconds. NISTDC customers include the New York Stock Exchange and the NASDAQ stock exchange – as NIST time is the official reference for U. S. stock markets.
NIST common-view GPS systems are installed at 58 customer sites, located in 23 states and seven sites outside the U. S. Some sites receive NIST frequency only and not time.

The red clocks on the map represent FMAS customers, the blue clocks represent TMAS customers, and the green clocks represent TMAS/NISTDC customers.
Schematic of NIST Disciplined Clock

UTC(NIST) in Boulder, Colorado

Cloud Server

GNSS Receiver

Time Interval Counter

UTC(NIST) – GPS Measurement

GNSS Receiver

Time Interval Counter

NIST Disciplined Clock (NISTDC)

Clock Correction, UTC(NIST) – NISTDC

GNSS Satellites
A locked NISTDC seldom deviates by more than ±10 ns (±0.01 µs) from UTC(NIST).

The peak-to-peak variation over the 6-month interval shown in the graph is ~25 ns, but most data points fall within ±5 ns and the average time offset is less than 0.1 ns, or essentially 0.

The reported time differences between the NISTDC and UTC(NIST) may actually be larger due to uncertainties in the common-view method. These uncertainties (k = 2, or 2σ) typically range from ~10 ns (0.01 µs) in the best case to ~50 ns (0.05 µs) in the worst case. These uncertainties are estimated and reported to stock market clients.
The graph shows the time deviation (stability) of a NISTDC for averaging periods ranging from one hour to about one month.

After averaging for one hour, the stability is about 1.5 ns, dropping below 0.4 ns after one day and below 0.2 ns after one week.

This high level of stability is possible because the time differences between UTC(NIST) and the NISTDC are always compensated for by the common-view corrections.
Galileo versus GPS (NIST-PTBB)

[ RINEX to CGGTTS conversion, see for example, Defraigne, P and Petit, G. *Metrologia* 2015 52 G1 ]
Galileo versus GPS (NIST-PTBB)

- Identical and calibrated receivers at NIST and PTB
- Using GPS P1, P2, Galileo E1, E5

Results

- Constellations have comparable performance
- Difference in accuracy and stability are statistically insignificant
- With noise characteristics resembling white PM

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<thead>
<tr>
<th></th>
<th>GPS</th>
<th>Galileo</th>
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<tbody>
<tr>
<td>$\sigma_y(\tau)$</td>
<td>$\mu = -0.93$</td>
<td>$\mu = -0.91$</td>
</tr>
<tr>
<td>Mod $\sigma_y(\tau)$</td>
<td>$\mu = -1.46$</td>
<td>$\mu = -1.43$</td>
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Studying Earth tide models

Precise point positioning using GPS code and carrier phase

Studying Earth tide models

Spectral decomposition with some of the known peaks identified
Atomic Clock Ensemble in Space (ACES)

- Time and frequency transfer studies (stability: $10^{-13}/\sqrt{\tau}, \tau \rightarrow$ integration time, accuracy $\sim 10^{-16}$)
- Tests of general relativity (gravitational redshift)
- Scheduled launch to ISS in mid 2021 on SpaceX-23

Carrier frequency: 13.5 GHz (up), 14.7 GHz (down)
PN-code modulation: 100 Mcps
Reference signal 100 MHz, UTC (k), 1pps
4 channel; dual frequency
The rise of the planet of the clocks

The SI Second is really important!
- Most accurately realized SI unit ($< 1 \times 10^{-15}$)
- Other units depend on time (length, ampere, candela)
- Two more? (kilogram, mole)

Precision metrology and fundamental science
- Tests of fundamental physics
- Improved timing for high energy physics/astronomy
- Searches for new physics

Advanced clocks will support advanced applications
- Enhanced timing capabilities: femtoseconds vs. picoseconds
- Navigation (ultra GPS) systems
- Sensors, a new type of geodesy?
Fractional Frequency Uncertainty

Evolution of Atomic Clocks: Microwave to Optical

Data representative of their respective clock types

microwave
optical

Al⁺, Ca, Hg⁺,
Sr, Yb optical

10⁻¹⁸ – New state of the art

Evolution of Atomic Clocks: Microwave to Optical
NIST Timescale: Incorporating an optical standard

- AT1 timescale: mainly H masers
- Ensemble frac. freq. stability $\sim$ E-15 over few weeks
- Over this duration, accumulated time error $\sim$ few ns
- Steered out using freq. corrections
NIST Timescale: Incorporating an optical standard

Goals for next generation Timescale:

- Semi-autonomous operation of optical frequency references and optical comb measurement system
- Incorporating a combination of microwave and optical freq. standards on a more regular basis

Acknowledgement

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Victor Zhang

More information regarding:

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NIST timescale
  Jeff Sherman (jeff.sherman@nist.gov)

Two-way time transfer
  Victor Zhang (victor.zhang@nist.gov)
Backup slides.....
Evolution of Atomic Clocks: Microwave to Optical

Fractional Frequency Uncertainty

Year

1.0E-19

Both uncertainty budgets and comparisons

1.0E-18

10^-18 – New state of the art

state-of-the-art Cs microwave

1.0E-17

1.0E-16

1.0E-15

1.0E-14

1.0E-13

1.0E-12

1.0E-11

1.0E-10

Evolution of Atomic Clocks: Microwave to Optical

1) **Redefining our basic physical units**
   Looking to redefine the SI second on an optical transition within the next decade

2) **Probing new physics**
   Testing constancy of fundamental constants
   Searching for dark matter

3) **Clocks, Einstein, and space**
   General Relativity – clock frequencies change $10^{-18}$ for 1 cm altitude change on earth!
   Clocks will need to go to space!
NIST remote frequency and time calibration customers by sector

- Electronics and Instrument Manufacturers: 26%
- Financial Markets / Stock Exchanges: 21%
- U. S. Military: 13%
- Defense Contractors: 13%
- Aerospace: 9%
- Non-Military U. S. Government Laboratories: 8%
- Private Calibration Laboratories: 8%
- Nuclear Energy: 2%
Harmonic traps suppress motional effects, enable long interaction times

**Trapped ions: Al⁺, Hg⁺, Yb⁺, Sr⁺, Ca⁺**

Exc. immunity to environmental effects
Limited S/N ratio – typically one clock ion

**Neutral atoms: Sr, Yb, Hg, Ca**

Need to use tailored optical lattices in 1, 2, or 3D
(Prof. H. Katori, U of Tokyo)
Good immunity to environmental effects
Potential for very high S/N (N > 10,000)

**Dozens of trapped-atom optical clocks worldwide**