USNO Report
to the
CGSIC Timing Subcommittee

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• The Secretary of the Navy shall direct the U.S. Naval Observatory to:
  – Develop and maintain the standards for Precise Time and Time Interval (PTTI) services, earth orientation parameters, and the celestial reference frame for the DoD Components
  – Provide representation to PNT committees and working groups, as necessary

Maintain the Master Clock for the DoD Community
USNO Master Clocks

• Master Clock
  Washington, DC
  – ~100 High Performance Cesiums
  – ~30 Cavity-Tuned Masers
  – 4 Rubidium Fountains

• Alternate Master Clock
  Shriever AFB
  – 12 High Performance Cesiums
  – 4 Cavity-Tuned Masers
  – 2 Rubidium Fountains in test mode
Network Time Transfer

- **USNO provides NTP to ~37 million unique users/week**
  - 15 thousand requests/second serviced
- **Provides authenticated NTP to DoD/USG users**
- **NTP servers synchronized to multiple master clocks over IEEE 1588 (PTP)**
- **R&D efforts**
  - *Develop next-gen security methods for NTP*
  - *Utilize open-source software for PTP synchronization*
  - *Employ PTP over satcom links*
UTC - UTC(Lab)
Yearly Root Mean Square (RMS)
USNO Contribution to GPS

USNO

NGA

GPS Master Control Station

Monitor Stations

Satellite Signal

Timing Links

Timing data

EOP

Data

Time and Frequency Signals

USNO AMC

(Alternate Master Clock)
GPS Timing and USNO’s Contribution

• **GPS Time is a Navigational Timescale**
  – No leap seconds, fixed to UTC on January 6\textsuperscript{th}, 1980
  – 18 seconds off from UTC now
  – Intelligent average of system clocks
    • Satellite and ground clocks

• **USNO utilizes a specialized set of calibrated GPS timing receivers to track GPS**
  – We compute the offset of GPS System Time to UTC(USNO) and deliver this to the USAF

• **USAF 2\textsuperscript{nd} Operations Squadron (2SOPS) uses this data to accelerate GPS Time to match UTC(USNO)**
  – There are no time or frequency steps in GPS Time, only steps in the acceleration
• GPS delivers timing bias and frequency offsets to convert from GPS Time to a prediction of UTC(USNO)
  – This information is contained in the GPS navigation message in Subframe 4, Page 18 (SF4P18)

• USNO developed monitoring guidelines and is actively monitoring the integrity of the SF4P18 data

• Additionally, work is underway to publish resiliency recommendations for User Equipment to ensure User Equipment will not use bad UTC data from GPS
GPS Week Rollover

- GPS Time is defined in the legacy GPS navigation message to cover finite period of 1024 weeks due to its 10 bit representation
- GPS started on Jan 6, 1980
- The first GPS Time Epoch ended on Aug 21/22 1999.
- GPS Time is presently in its second Epoch which will end on April 6, 2019
- It is up to the user and user receiver to resolve this week number ambiguity
- The Modernized Navigation message has a 13-bit week number, which for all practical purposes will not encounter a rollover
GPS Time Delivery, 30-day Averages

GPS Time and GPS Predicted UTC(USNO)
1 month smoothed

- GPS - UTC(USNO) modulo 1s
- GPS Predicted UTC - UTC(USNO)
GPS Timing, More Recent History

GPS Time and GPS Predicted UTC(USNO)
1 month smoothed

- nanoseconds

Year
2013 2013.5 2014 2014.5 2015 2015.5 2016 2016.5 2017 2017.5 2018

-1 -0.5 0 0.5 1 1.5

GPS - UTC(USNO) modulo 1s
GPS Predicted UTC - UTC(USNO)
**GPS Timing Instability**

**Figure:** Monthly RMS of Daily Solutions

- **Orange Line:** GPS - UTC(USNO) modulo 1s
- **Blue Line:** GPS Predicted UTC - UTC(USNO)

**Axes:**
- **Y-axis:** nanoseconds
- **X-axis:** Year

**Legend:**
- 1990
- 1995
- 2000
- 2005
- 2010
- 2015

**Graph Description:**
This graph illustrates the monthly root mean square (RMS) of daily solutions for GPS timing instability. The data is represented from 1990 to 2015, showing the fluctuation in GPS timing deviations from UTC(USNO) modulo 1 second and the difference between GPS predicted UTC and UTC(USNO). The graph indicates a gradual decrease in RMS values over time, suggesting improvements in GPS timing stability.
Recent GPS Timing Instability

Monthly RMS of Daily Solutions

- GPS - UTC(USNO) modulo 1s
- GPS Predicted UTC - UTC(USNO)
Precise Timing Applications

Communications

Power Grid

Financial

Scientific

GPS/USNO Provided Timing Service is Critical to the Modern World’s Infrastructure
GPS + other GNSS Added Benefit

- **Increased reliability and availability of Position, Navigation, and Timing**
  - Especially for users in challenging environments such as urban canyon users

- **Requires coordination between navigational timescales**

- **USNO and Galileo to broadcast the difference between their navigational timescales**
  - Galileo GGTO, GPS-GALILEO Time Offset
  - Parallel operational measurements with combined receivers
    - Shared and Compared
    - System running in test mode

- **Bias Measurements being actively measured by USNO**
USNO Additional GPS III support

• USNO will act to coordinate GPS Time with other Global Navigation Satellite Systems Time and provide a correction message to GPS (GGTO)
  – USNO is presently providing both GLONASS and Galileo time differences in support of special CNAV testing (not presently being broadcast)
  – USNO is moving into an operational phase coordinating the Galileo to GPS Time Offset (GGTO) information with Galileo system

• Also supporting OCX, USNO will work with USAF for the determination of the GPS satellite and reference stations inter-signal and inter-frequency biases
  – This is needed to ensure that average constellation biases are removed in a consistent way to ensure accuracy for timing user community
GPS to GNSS Time Offset (GGTO)

- CNAV Message Type 35 contains the GPS-to-GNSS Offset (GGTO) for various systems
  - Current schedule for broadcast is 2022 with OCX
- GALILEO and GLONASS daily average GGTO solutions are computed and monitored daily
- Last step is to finalize GNSS receiver calibrations
- GNSS simulator calibration procedures are being validated and tested to ensure consistency and accuracy
  - Latest repeat calibrations demonstrate very good consistency
Notes:
- Improved zero-crossing techniques and output signal measurements were used after 11/19/2015 for more accurate calibration results.
- Impedance mismatch in the calibration equipment was removed by 7/06/2017.
GPS - GALILEO Time Offset
Measured by USNO Combined Receiver
GPS - GLONASS Time Offset
Measured by USNO Combined Receiver
GPS - GLONASS Time Offset
Measured by USNO Combined Receiver

Year
nanoseconds

2016 2016.2 2016.4 2016.6 2016.8 2017 2017.2 2017.4 2017.6 2017.8
Future Emphasis for Reliable Sub-Nanosecond Timing

1. Stable Timescale Reference
2. Carrier Phase Analysis for GNSS
3. Environmental Control
4. Redundant Independent Receiver Systems
5. Multipath Reduction
6. Calibration, and Recalibration
7. Impedance Matching / Cable Reflections
8. Equipment Design
9. Inter-frequency Bias corrections
Clock Development

- **Rubidium Atomic Fountains**
  - Use 6.8GHz transition in laser-cooled rubidium
  - 4 fountains in operation in Washington, DC for the past 6.5 years

- **Next generation: optical clocks**
  - Use transition with frequency of hundreds of THz
  - Calcium has good properties to make a robust clock

Schematic of thermal beam optical clock

Two of the USNO rubidium fountains
Other Activities

• USNO also measures the Earth Orientation Parameters, including the Earth’s rotational angle UT1, for GPS and other users

• USNO serves as the rapid service/prediction center of the International Earth Rotation and Reference Systems Service (IERS)

• USNO maintains the Astronomical Almanac with Her Majesty’s Nautical Almanac Office in the UK
Summary

- **USNO specializes in real-time timekeeping**
  - *UTC realization*
  - *Dissemination*
  - *Monitoring*
  - *Device and analysis R&D*

- **Thank you!**

- **Questions?**