USNO Report to the CGSIC Timing Subcommittee

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US Naval Observatory (USNO)
September 24, 2018

DODI 4650.06 (2016)

- ***The Secretary of the Navy, through the Oceanographer of the Navy:***
  - ***Develop and maintain the standards for Precise Time and Time Interval (PTTI) services, earth orientation parameters (EOP), and the celestial reference frame (CRF) for the other DoD Components***
  - ***Provide representation to PNT committees and working groups, as necessary***
  - ***Maintain the master time and frequency standard for DoD and the underlying timing reference for coordinating all U.S. Government PNT systems***

Maintain the Master Clock for the DoD Community

- **3.2.4 GPS Timing**
  - USNO provides GPS with the underlying UTC timing reference necessary for precise PNT operations. USNO operates a primary and backup Master Clock system from its headquarters in Washington, DC and the Alternate Master Clock facility co-located with the GPS Master Control Station (MCS) at Schriever Air Force Base in Colorado Springs, CO. The USNO Master Clock system is made up of an ensemble of more than 90 precise atomic clocks that are fully traceable to the internationally accepted standard for timing, promulgated by the International Bureau of Weights and Measures (BIPM). USNO uses an ensemble of specialized GPS timing monitor station receivers to continuously monitor the GPS signal and provide the GPS MCS with these precise timing data. Details about obtaining calibration of GPS timing receivers and traceability to UTC can be found at http://www.usno.navy.mil/USNO/time

USNO Master Clocks

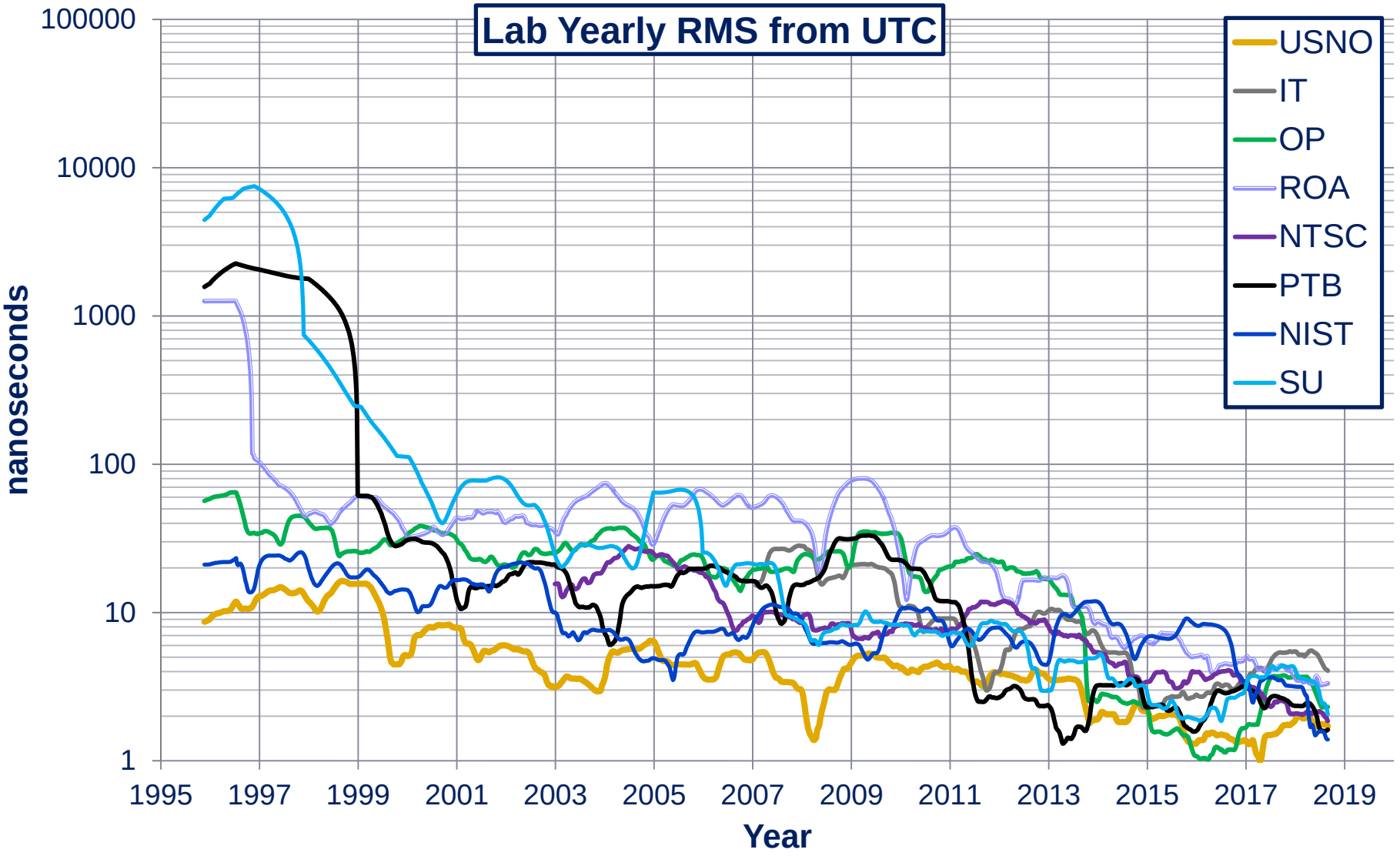
- ***Master Clock Washington, DC***
  - ***~100 High Performance Cesium***
  - ***~30 Cavity-Tuned Masers***
  - ***4 Rubidium Fountains***

- ***Alternate Master Clock Schriever AFB***
  - ***12 High Performance Cesium***
  - ***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 sat-com links*

UTC - UTC(Lab)
Yearly Root Mean Square (RMS)



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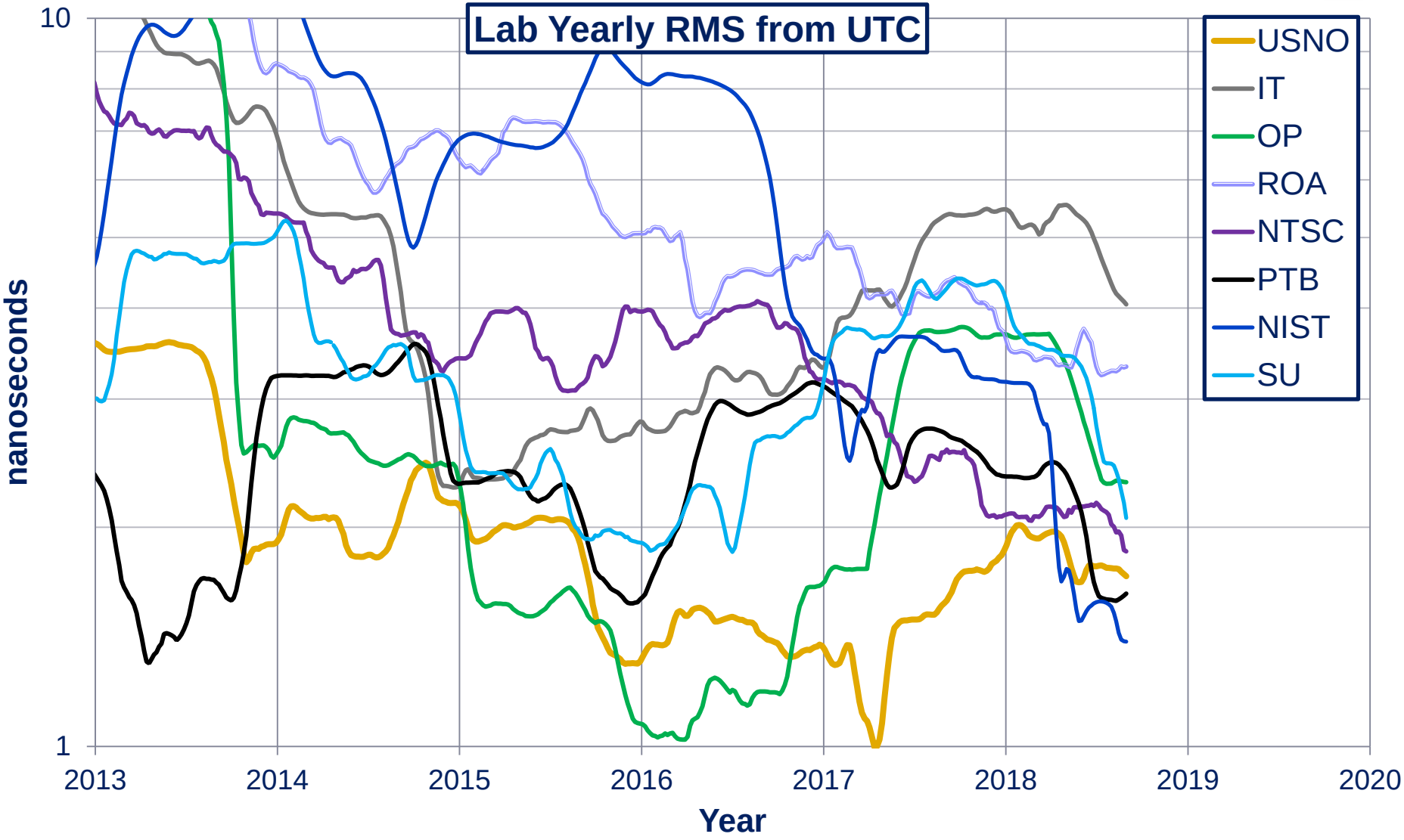

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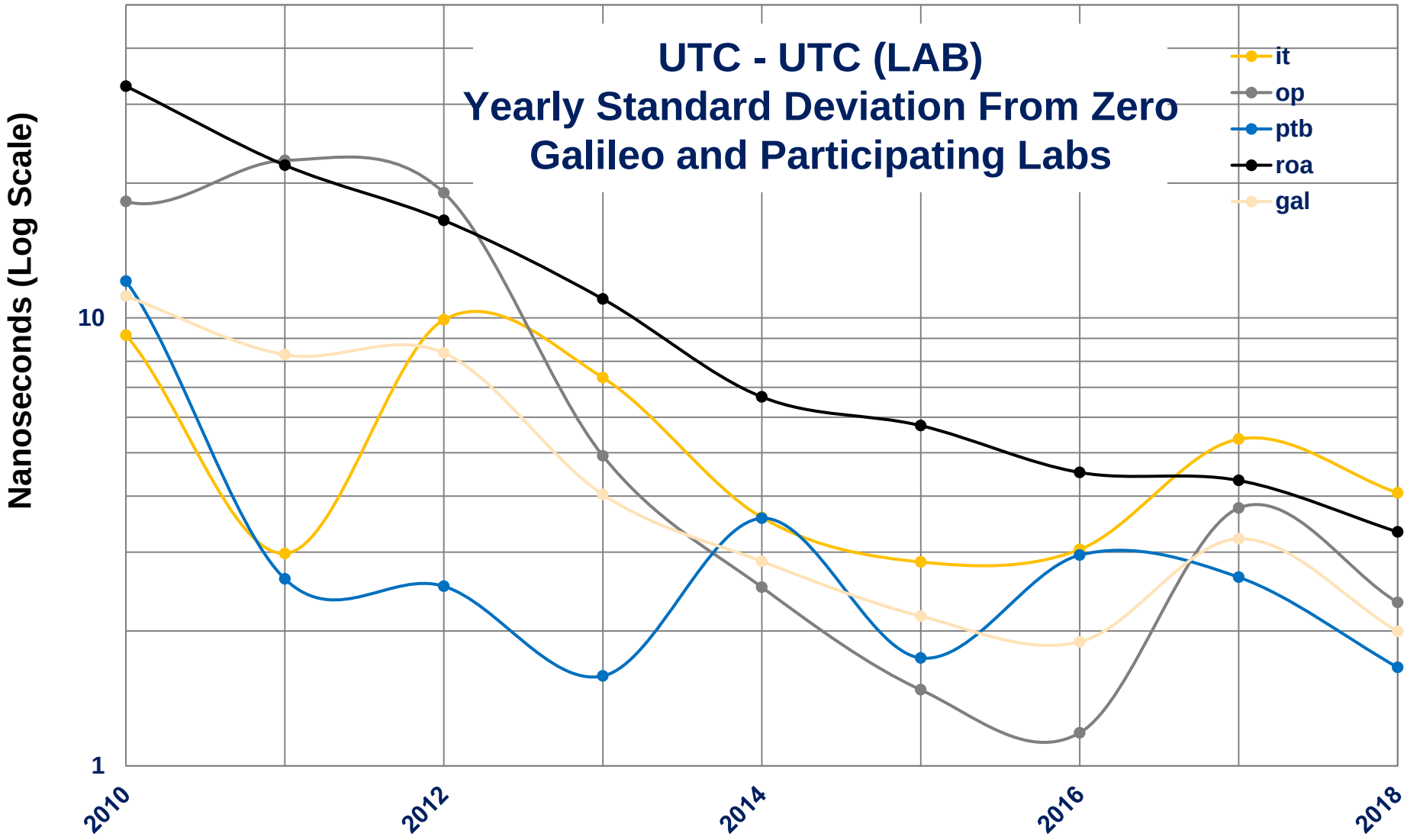
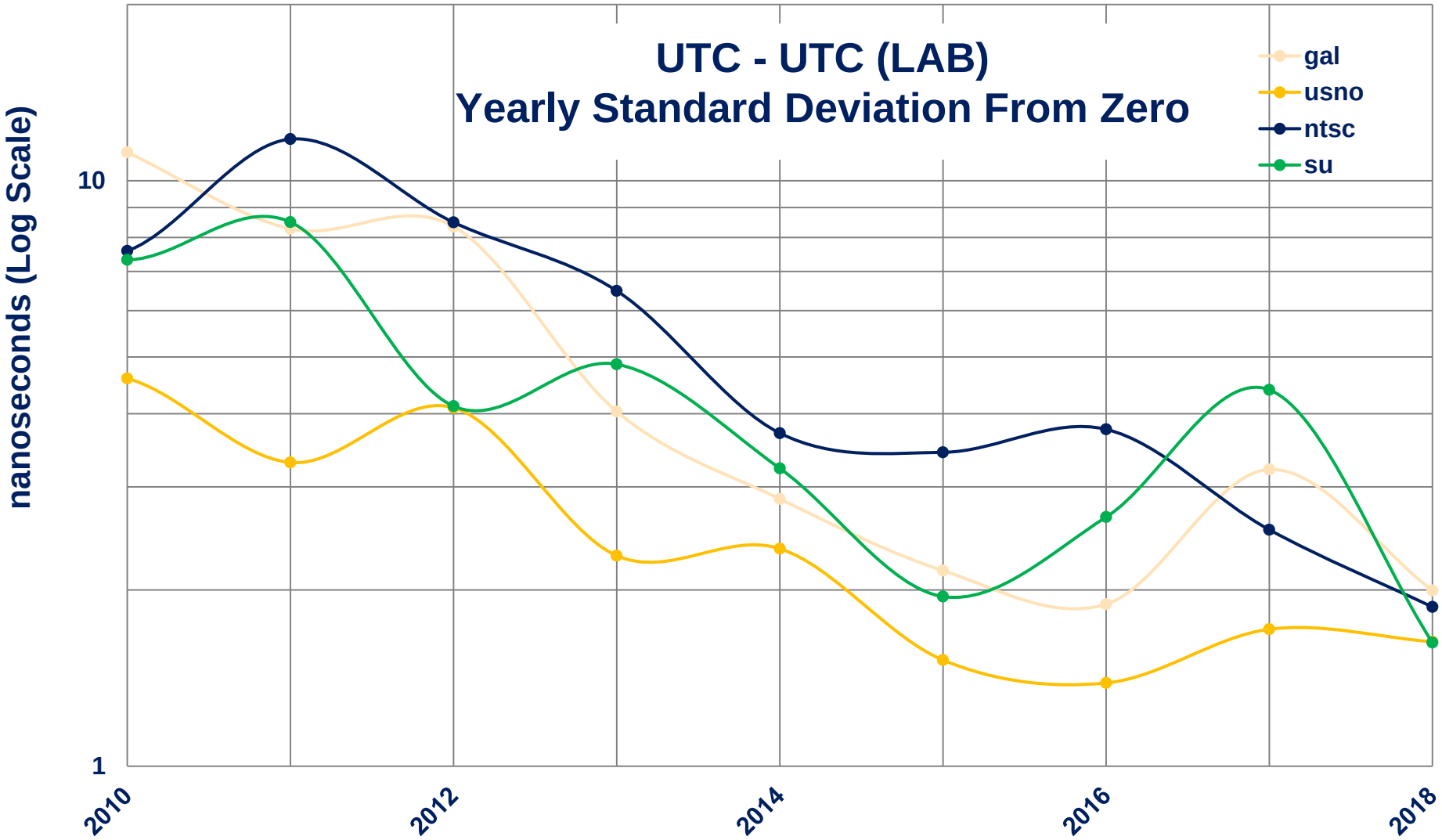

UTC - UTC (LAB)
Yearly Standard Deviation From Zero
Galileo and Participating Labs
Nanoseconds (Log Scale)
10
1
2010
2012
2014
2016
2018
it
op
ptb
roa
gal

UTC - UTC(Lab)


UTC - UTC (LAB)
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gal
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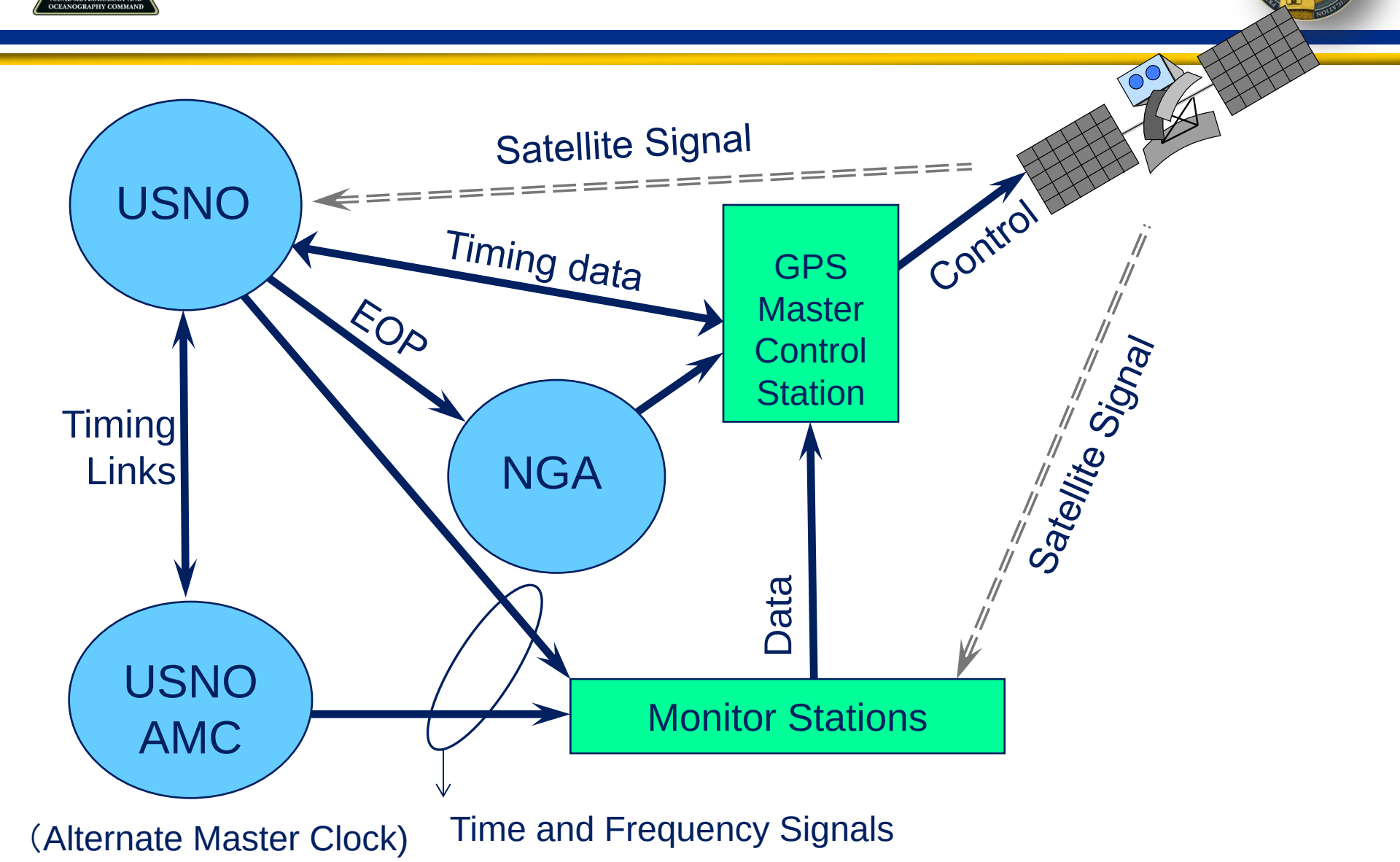
USNO Contribution to GPS



GPS Timing and USNO's Contribution

- *GPS Time is a Navigational Timescale*
  - *No leap seconds; fixed to UTC on January 6th, 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 2nd 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*

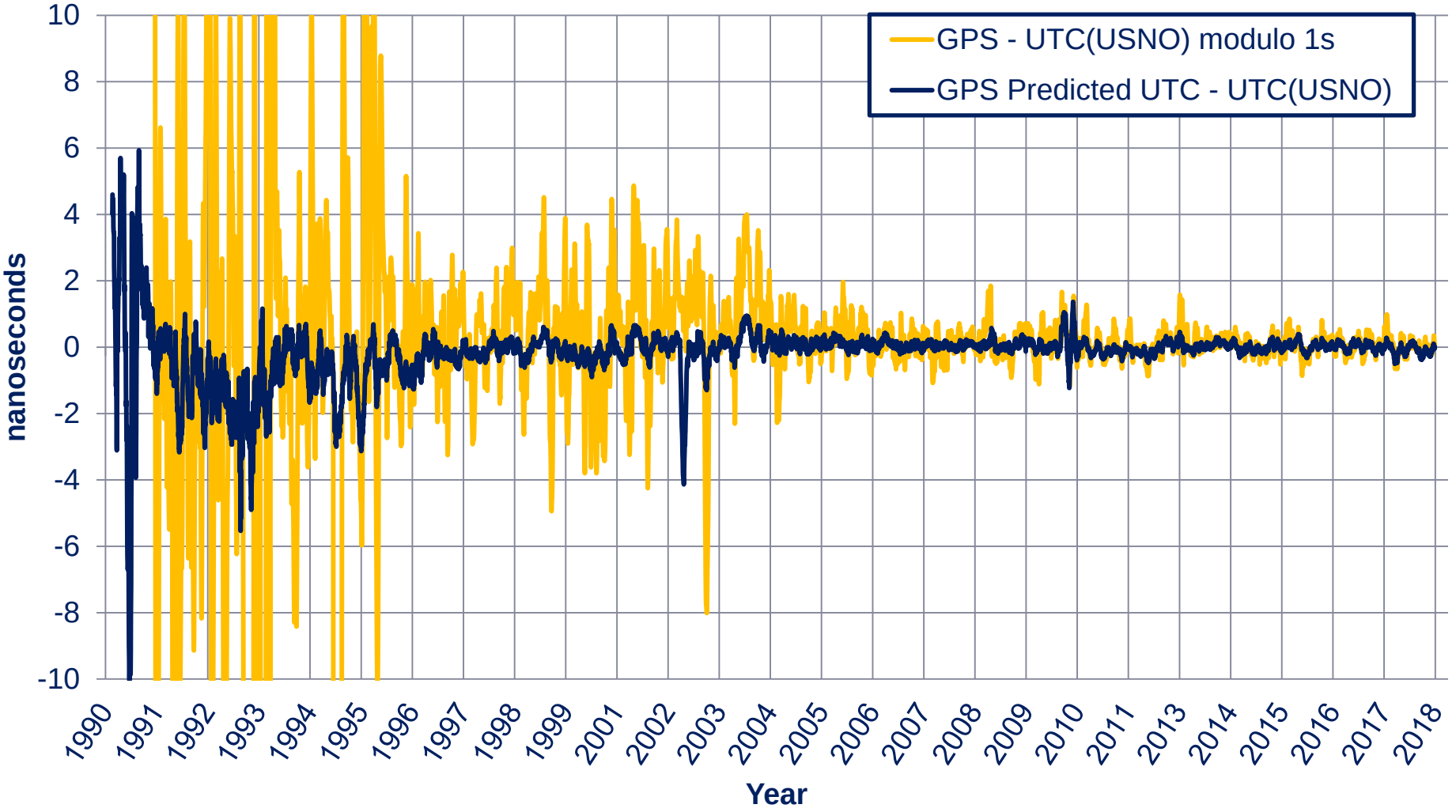
GPS Subframe 4 Page 18

- *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*

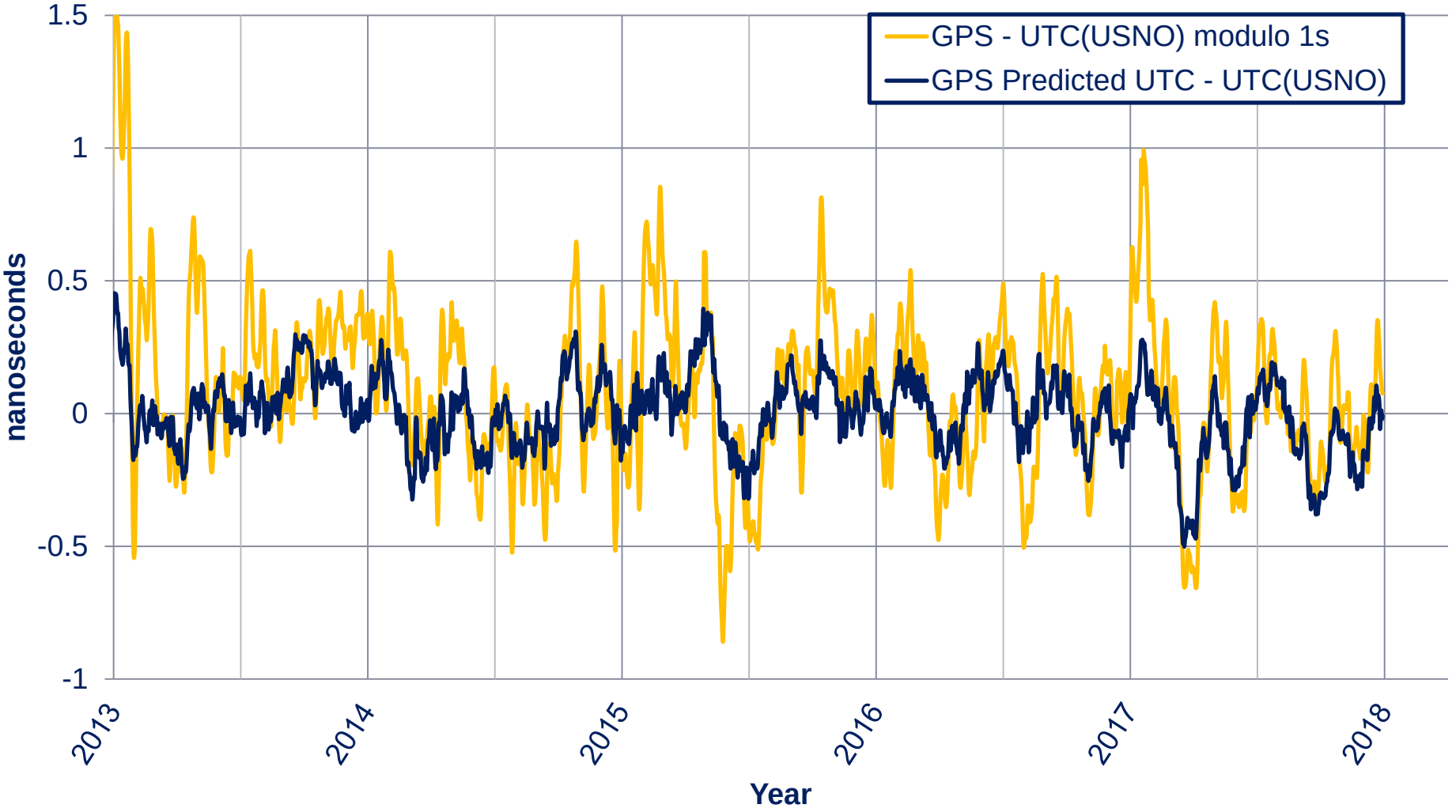
GPS Week Rollover

- *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 receiver manufacturer to resolve this week number ambiguity (some receivers will not transition gently)*
- *The Modernized Navigation message has a 13-bit week number, which for all practical purposes will not encounter a rollover*
- *GPS simulator to test receiver response to rollover (start a few hours before rollover)*

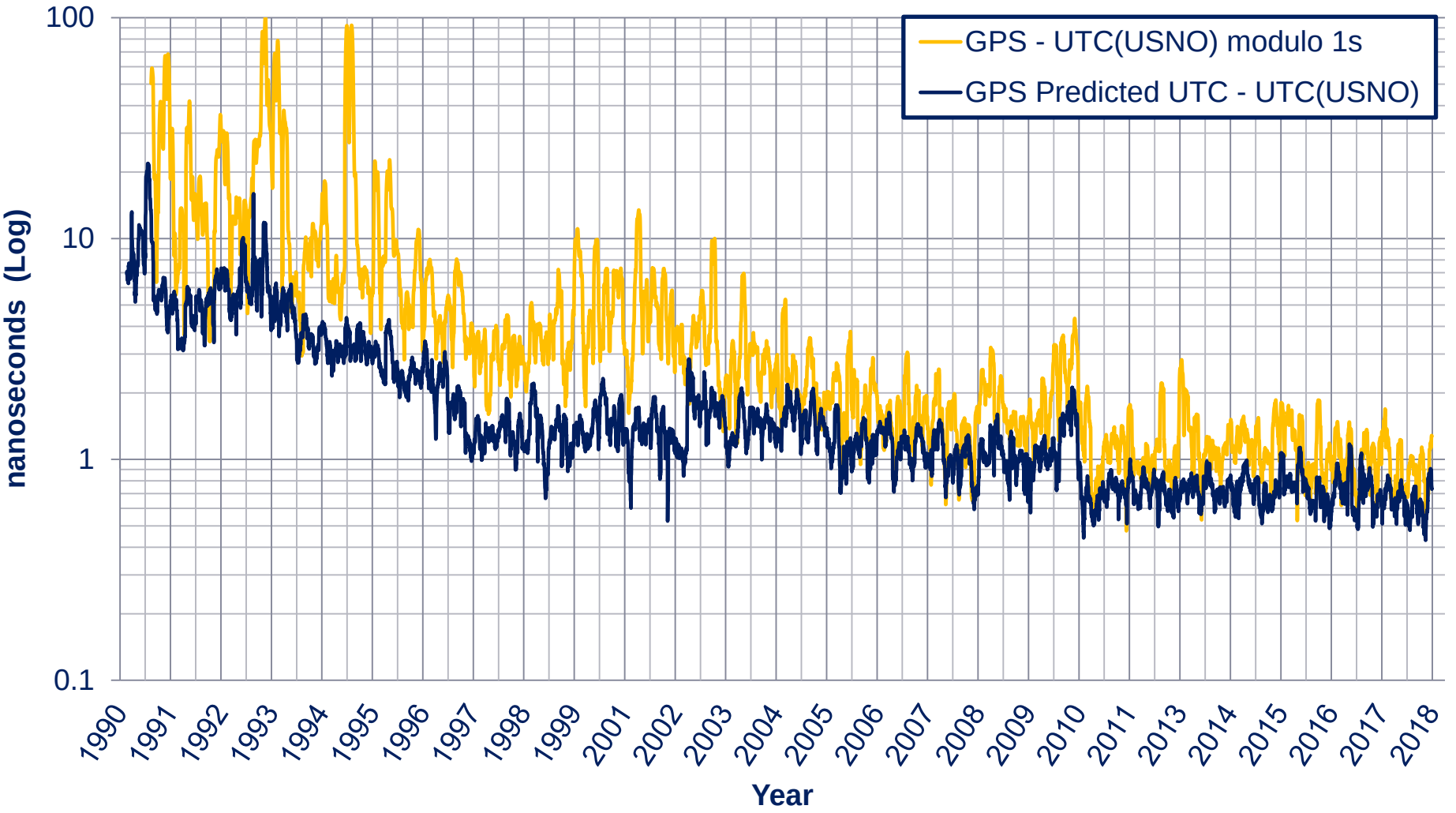
GPS Time Delivery, 30-day Averages



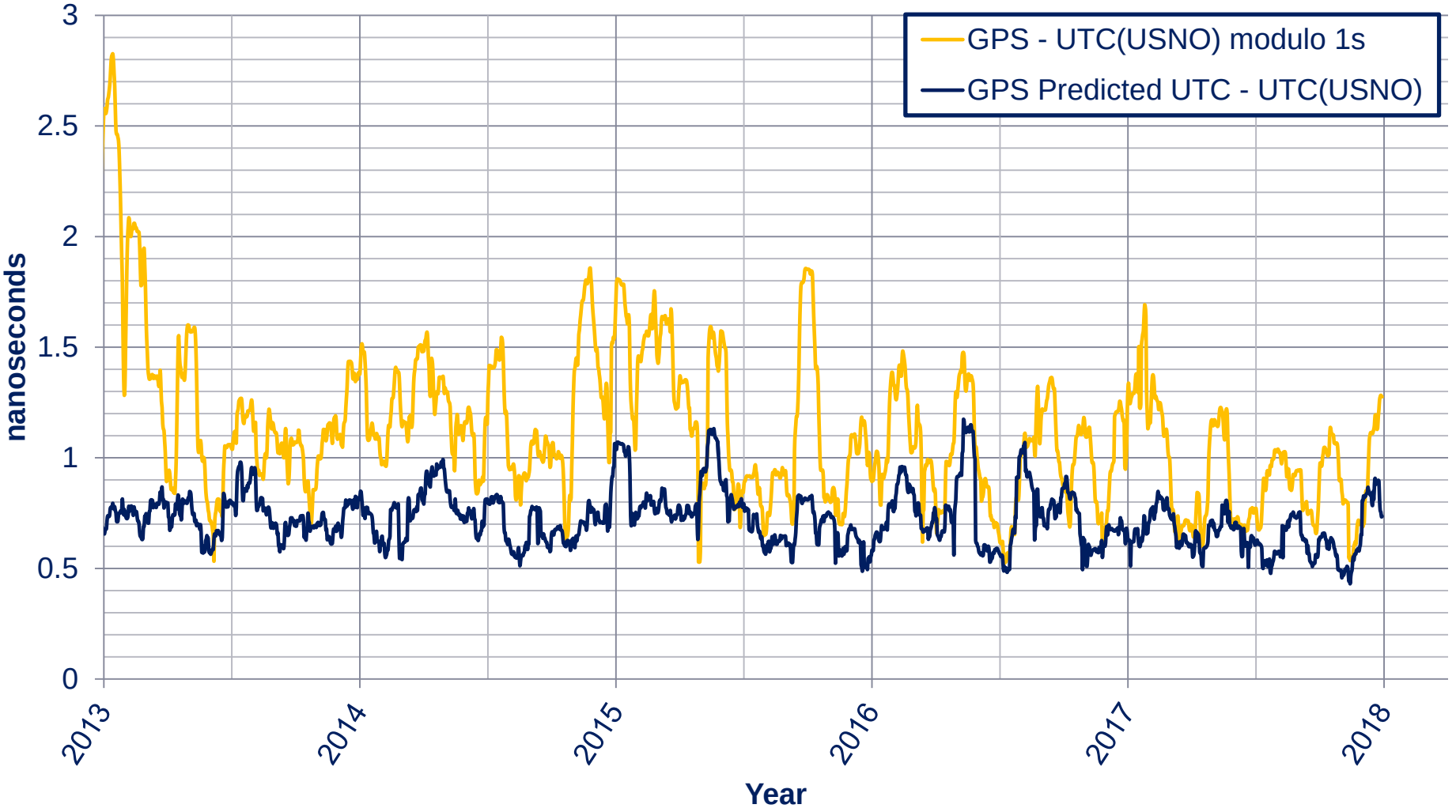
GPS Timing, More Recent History



GPS Timing Instability



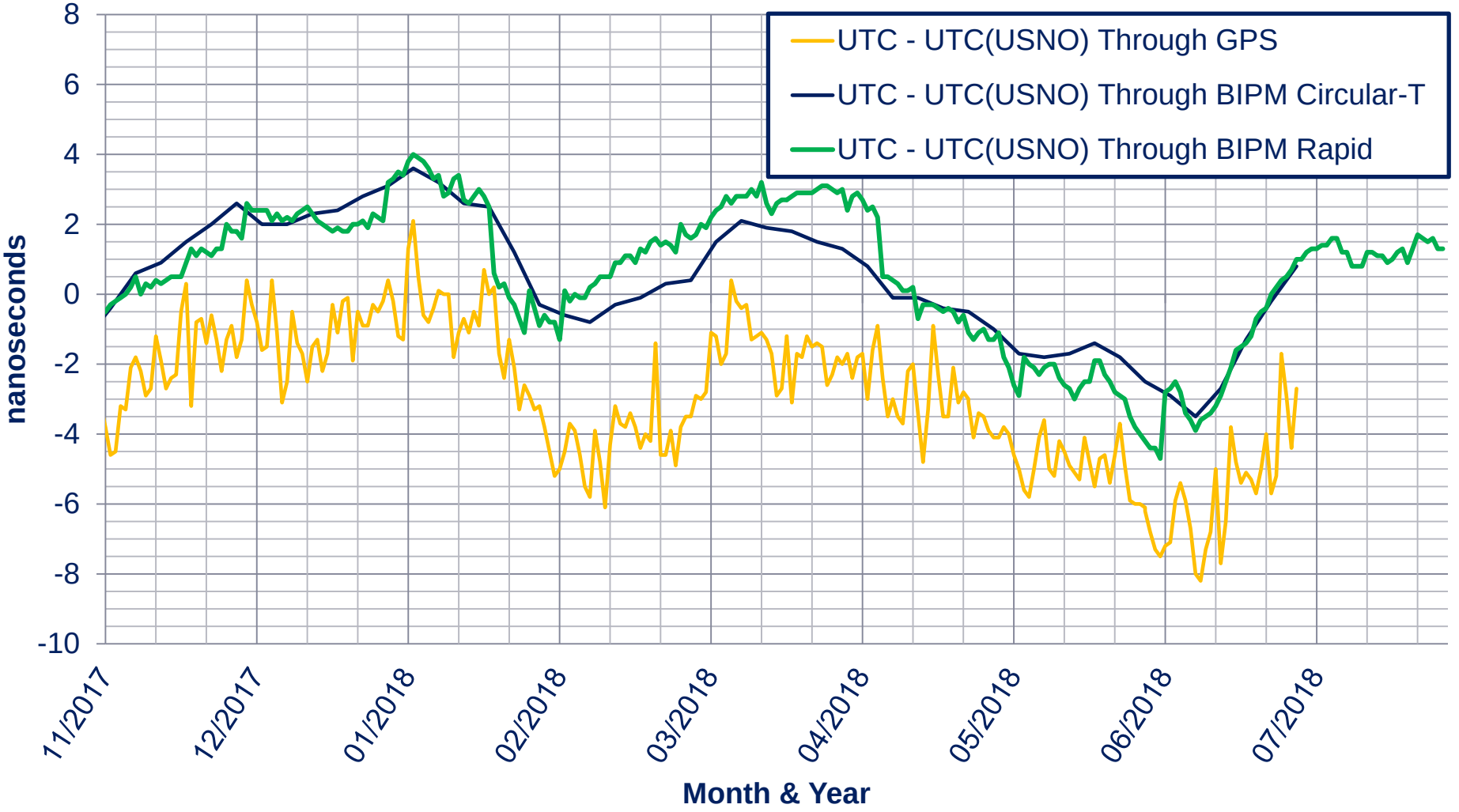
Recent GPS Timing Instability



Receiver Calibrations

- ***Absolute calibration***
  - ***Multiple GPS timing receivers on CA, P1, and P2***
  - ***Goal: to provide better representation of UTC(USNO) through GPS***
    - ***At least quarterly re-calibrations on receivers to prevent drifts from GPS receivers***
  - ***Live-sky includes antenna calibrations (passive element, active element, cable delays)***
  - ***Additional GPS offset provided to 2SOPS***
    - ***Requires small increments as to not introduce large jumps (<500ps a week)***

Recent USNO Receiver Calibrations



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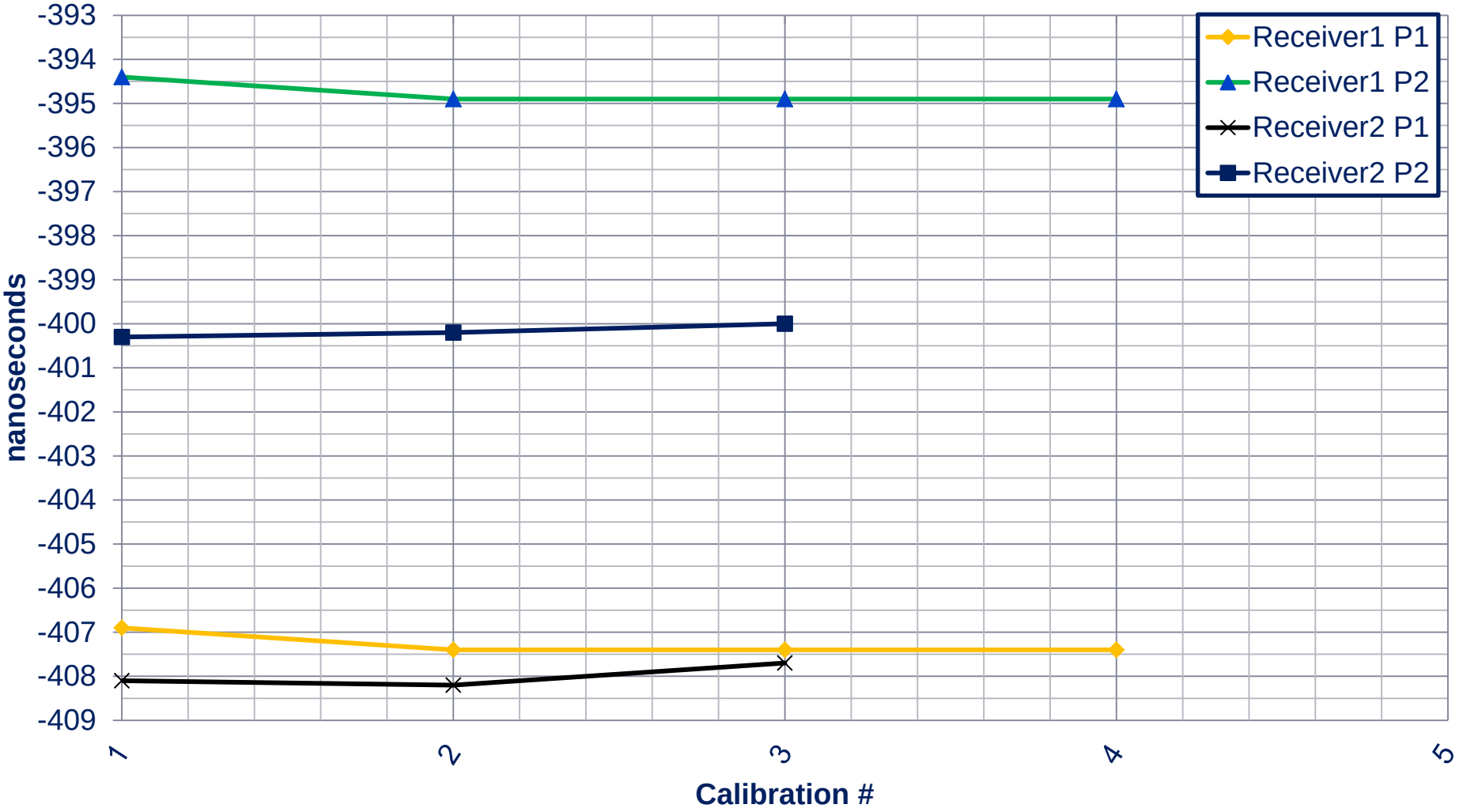


Precise Timing Applications

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)

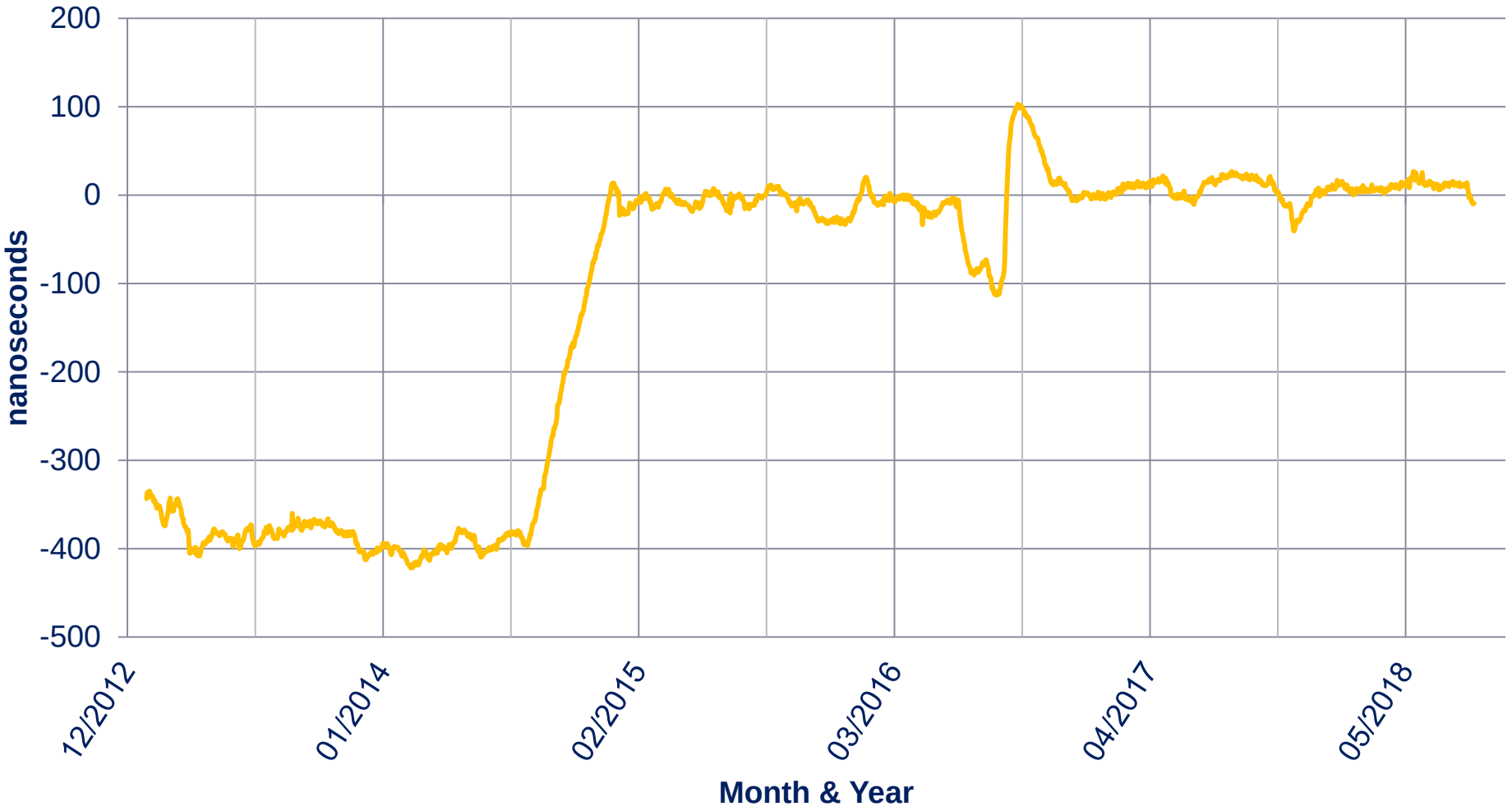
- *CNAV Message Type 35 contains the GPS-to-GNSS Offset (GGTO) for various systems*
  - *Current schedule for broadcast is 2022 with OCX*
- *GALILEO and GLONASS daily average GGTO solutions are computed and monitored daily*
- *Last step is to finalize GNSS receiver calibrations*
- *GNSS simulator calibration procedures are being validated and tested to ensure consistency and accuracy*
  - *Latest repeat calibrations demonstrate very good consistency*

GALILEO GGTO

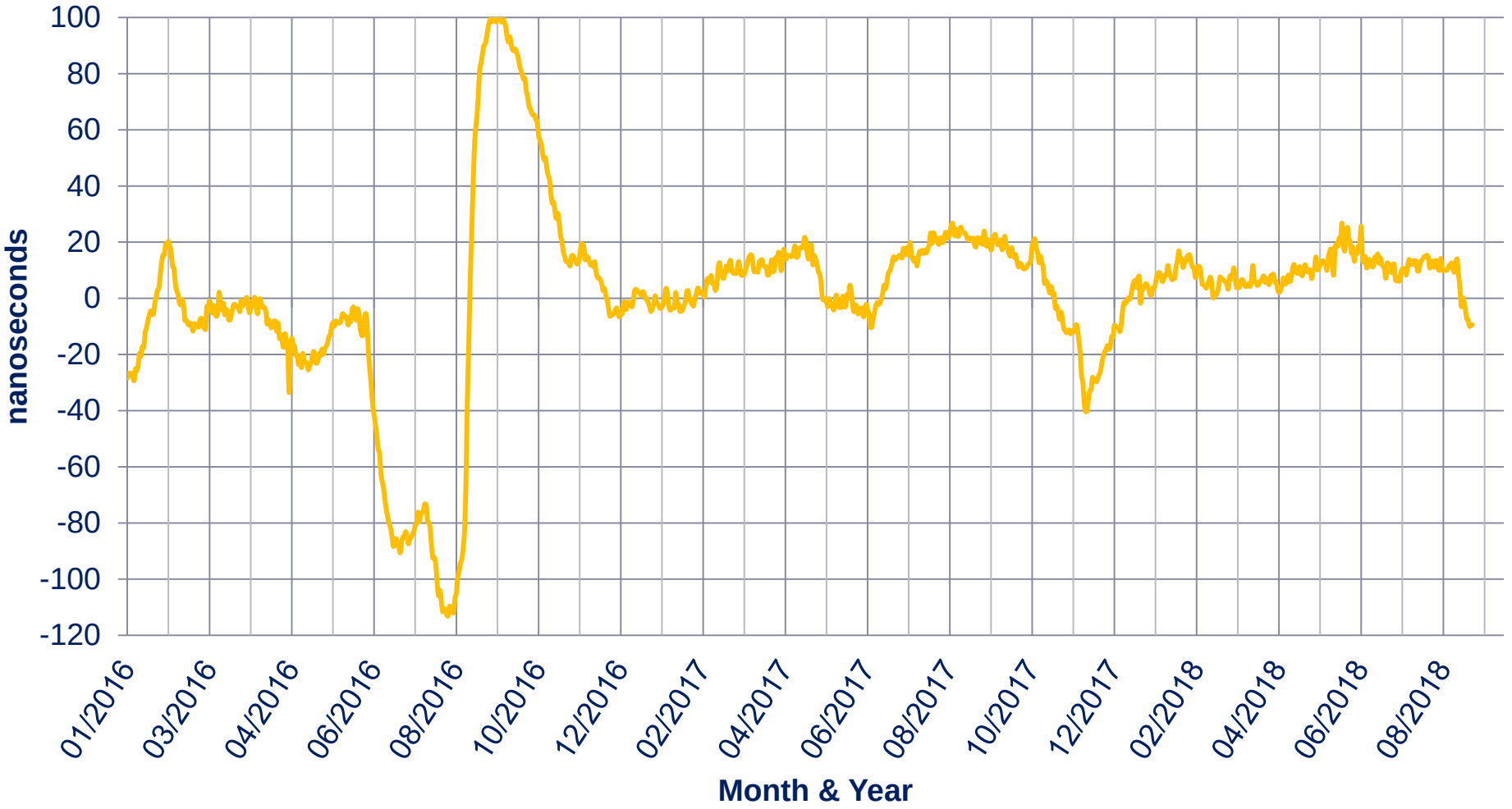
GPS - GALILEO Time Offset

Measured by USNO Combined Receiver

GLONASS GGTO



GLONASS GGTO (from 2016 – 2018)



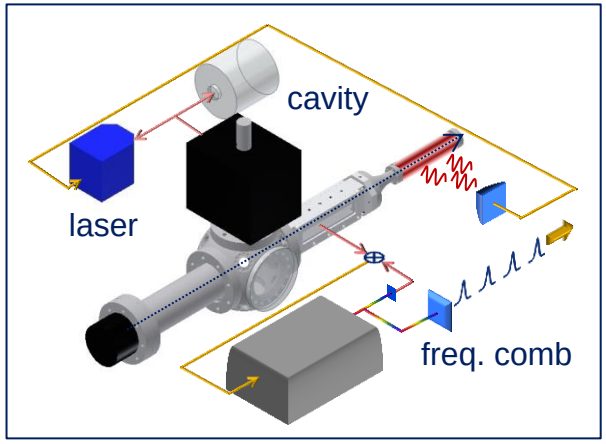
Future Emphasis for Reliable Sub-Nanosecond Timing

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***

two of the USNO rubidium fountains



schematic of thermal beam optical clock

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

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?*