



USNO Report to the CGSIC Timing Subcommittee

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US Naval Observatory (USNO)
September 12, 2016***



DoD Directive 4650.05 (2008) and 4650.07 (2012)



- ***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**
 - 68 High Performance Cesiums
 - 29 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

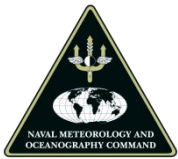




Network Time Transfer



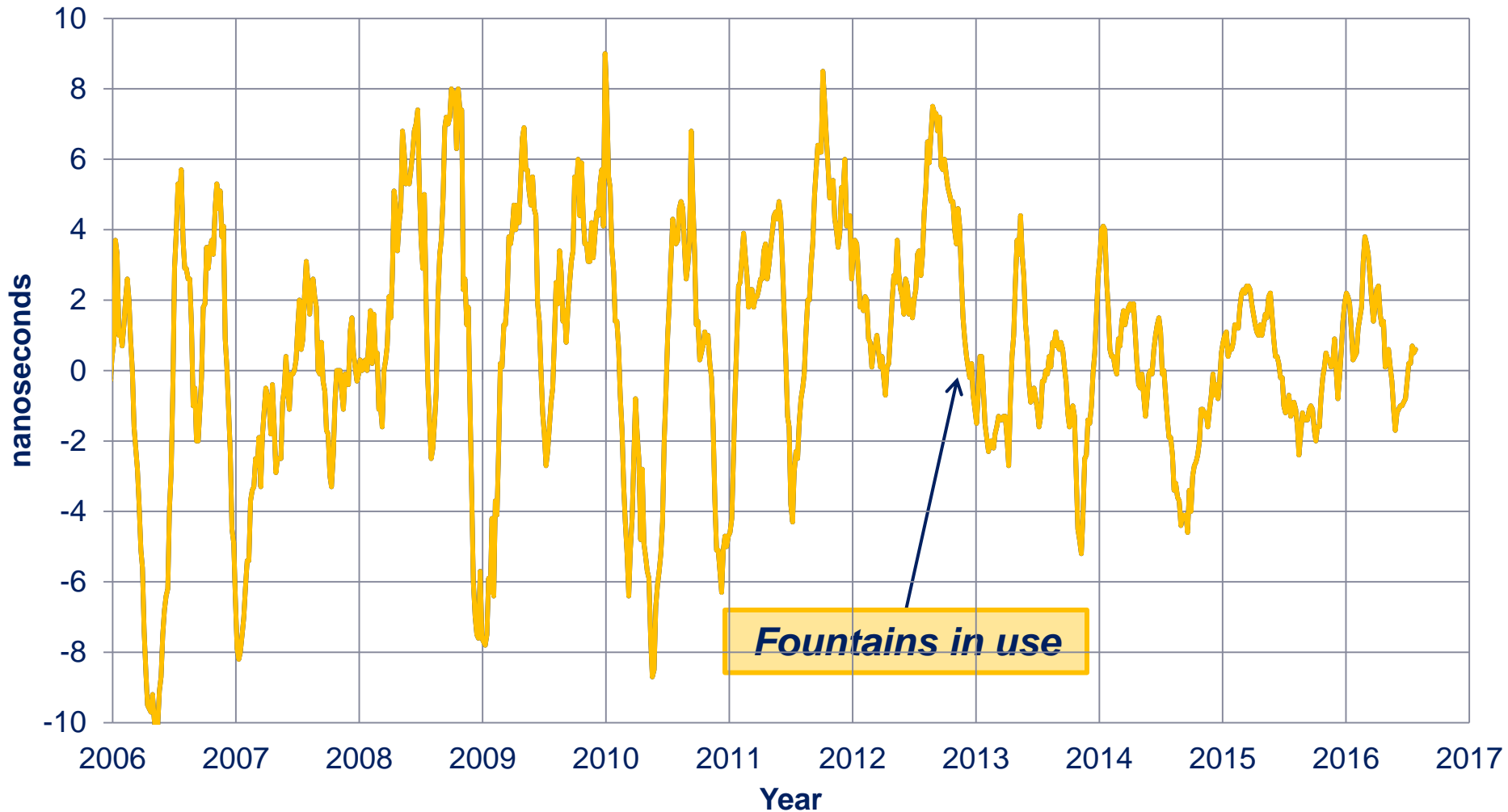
- ***USNO provides NTP to ~37 million unique users/week***
 - ***6-7 thousand requests/second serviced***
- ***Provides authenticated NTP to DoD/USG users***
- ***NTP servers synchronized to multiple master clocks over IEEE 1588 (PTP)***
- ***R&D efforts***
 - ***Develop next-gen security methods for NTP***
 - ***Utilize open-source software for PTP synchronization***
 - ***Employ PTP over satcom links***

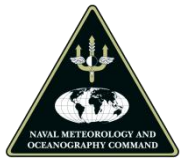


USNO Master Clock and UTC before/after Fountains

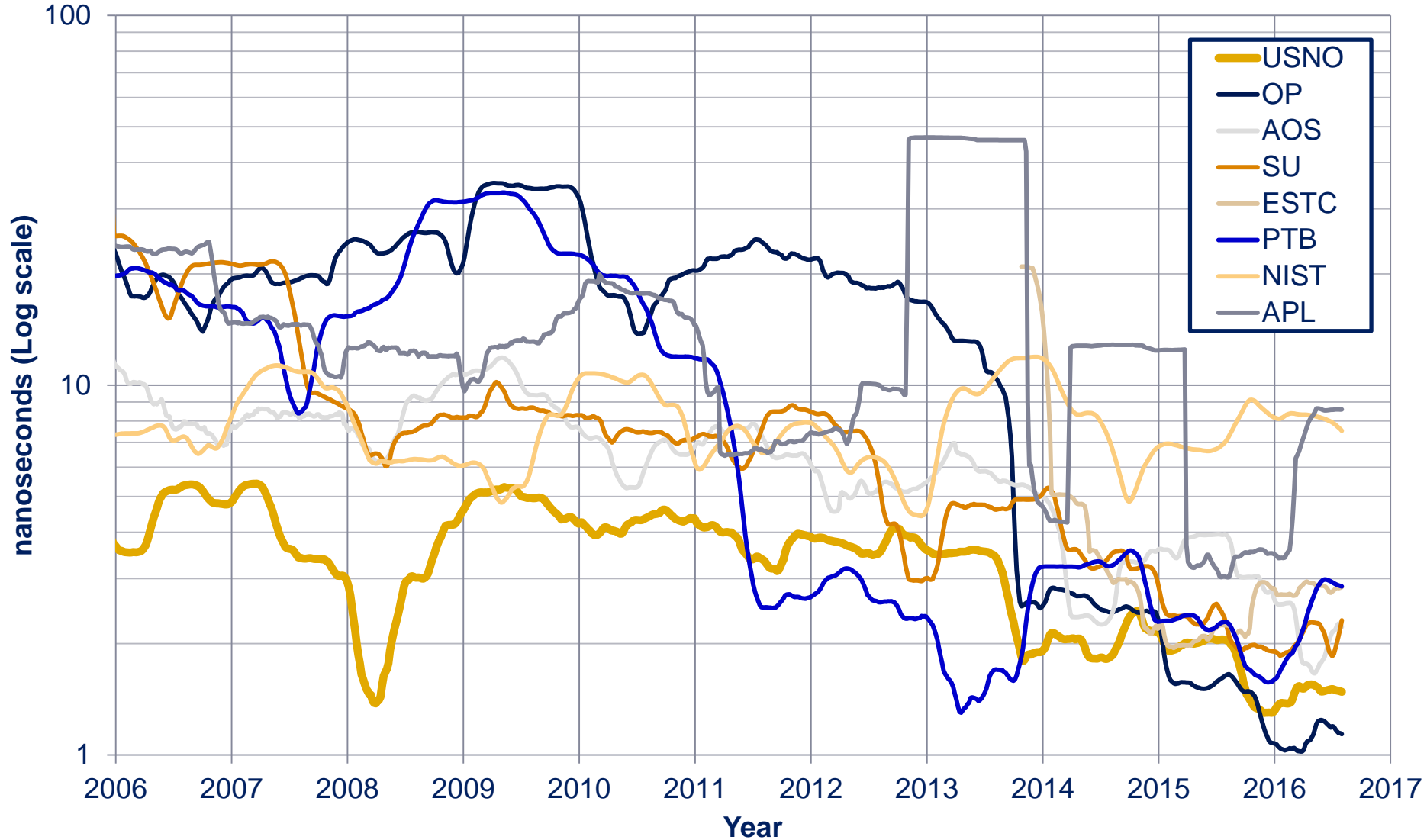


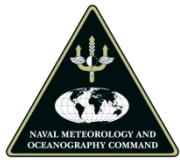
UTC - UTC(USNO)



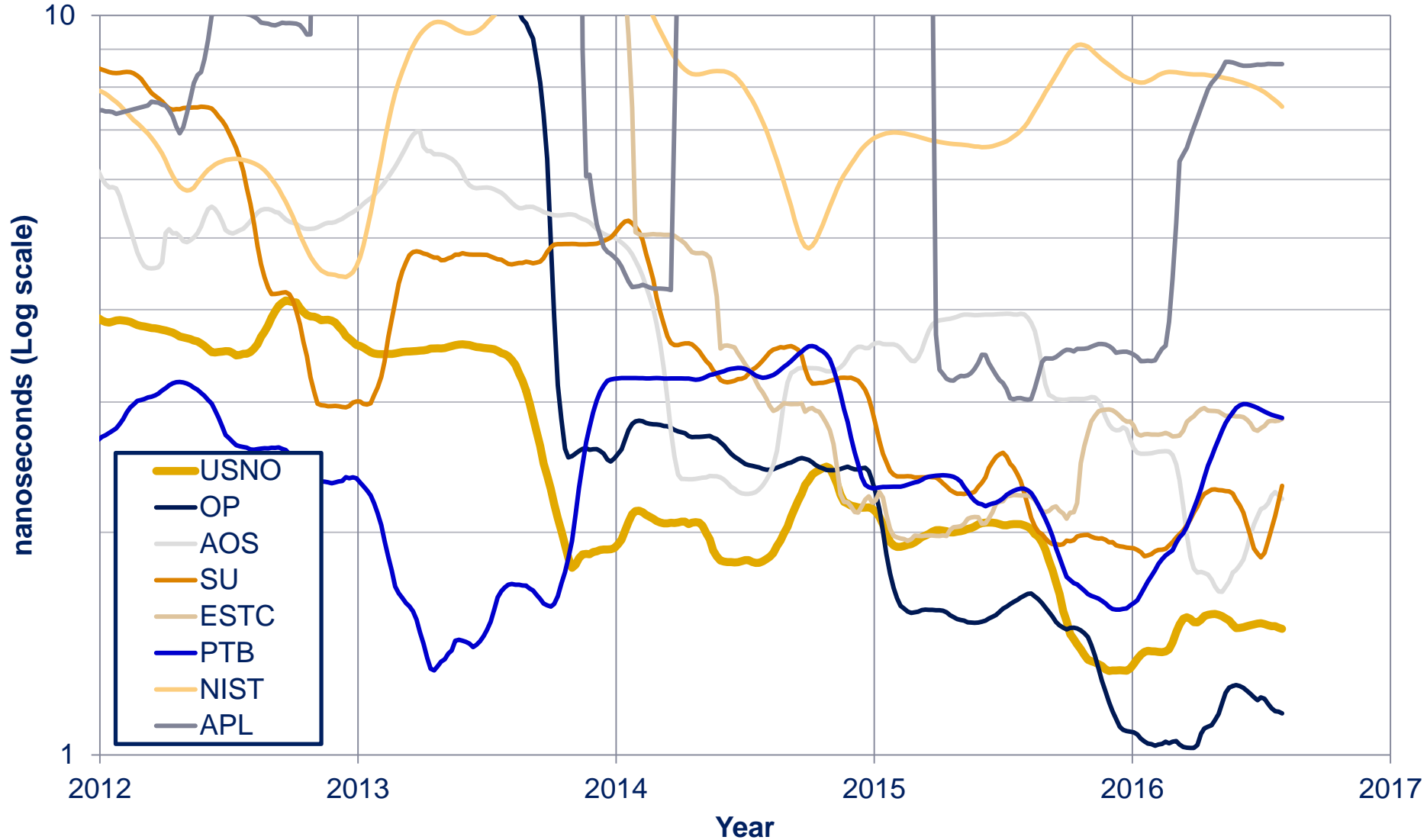


UTC - UTC(Lab) Yearly Root Mean Square (RMS)



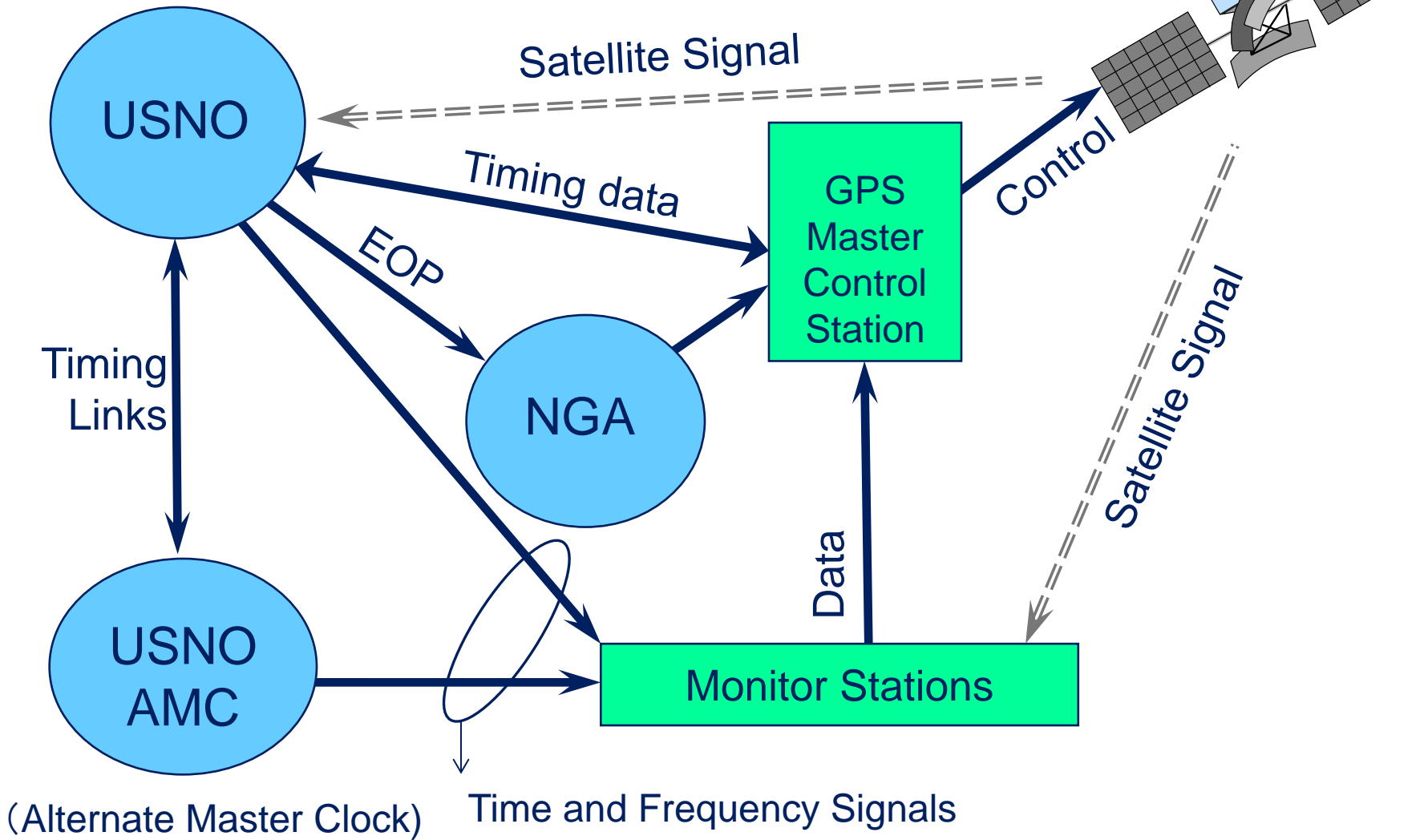


UTC - UTC(Lab) Yearly Root Mean Square (RMS)





USNO Contribution to GPS

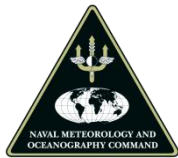




GPS Timing and USNO's Contribution



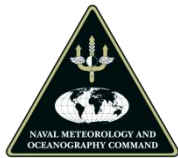
- **GPS Time is a Navigational Timescale**
 - **No leap seconds, fixed to UTC on January 6th, 1980**
 - **17 seconds off from UTC now, 18 after December 31st, 2016**
 - **Intelligent average of system clocks**
 - **Satellite and ground clocks**
- **USNO utilizes a specialized set of calibrated GPS timing 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)***
- ***An error in the GPS ground segment resulted in erroneous SF4P18 being broadcast by about half the constellation***
- ***As a result, 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***

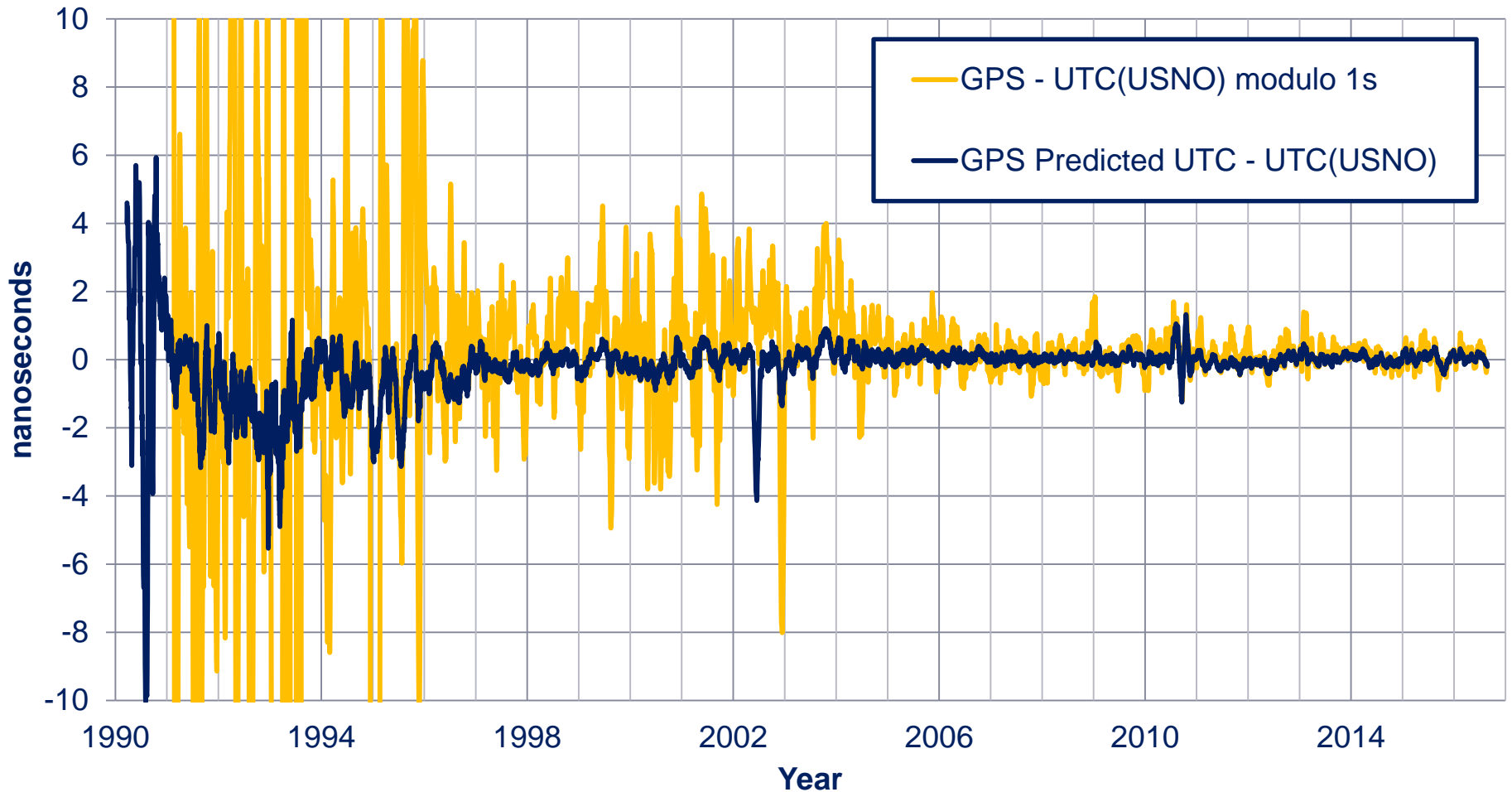


GPS Time Delivery, 30-day Averages



GPS Time and GPS Predicted UTC(USNO)

1 month smoothed



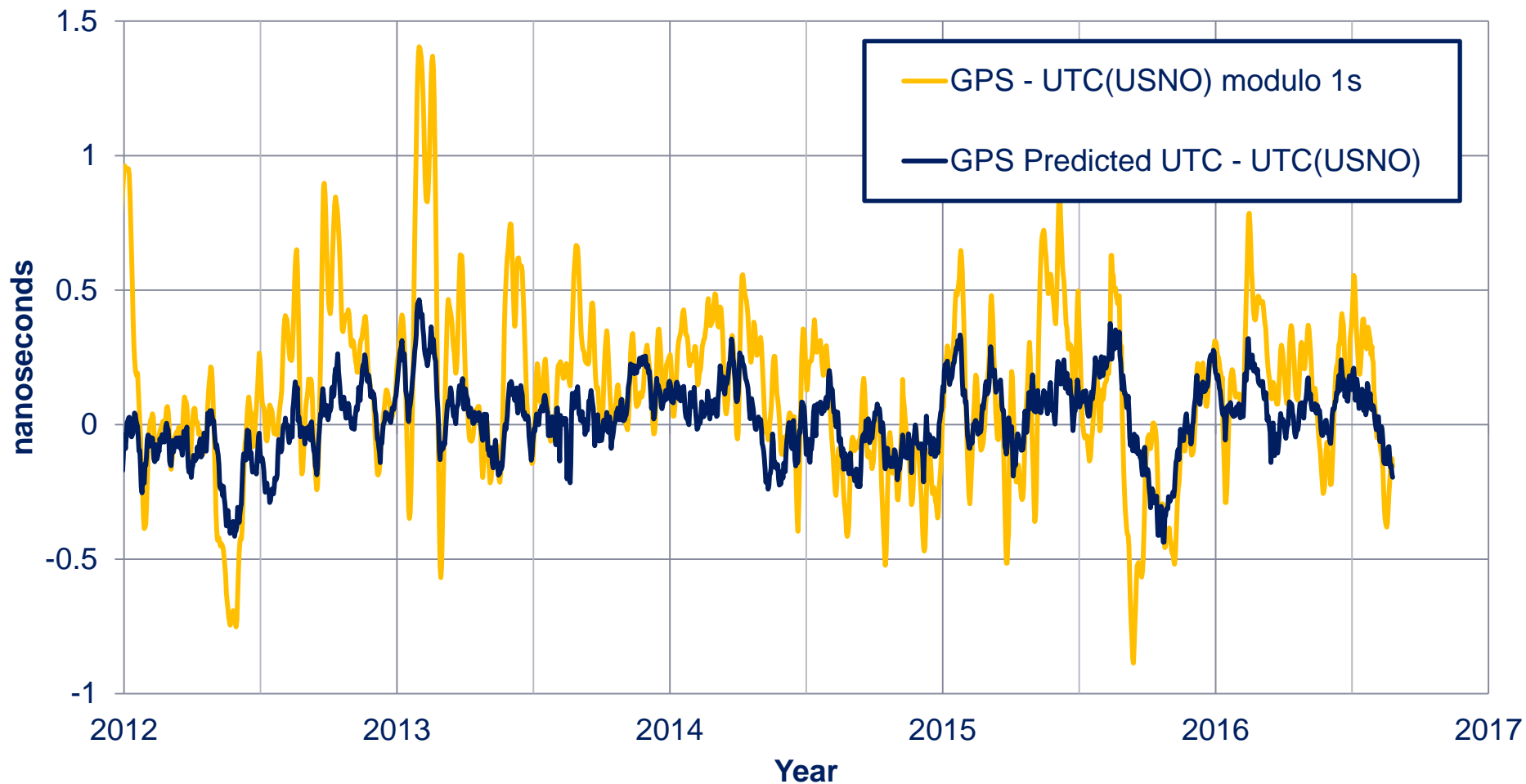


GPS Timing, More Recent History



GPS Time and GPS Predicted UTC(USNO)

1 month smoothed

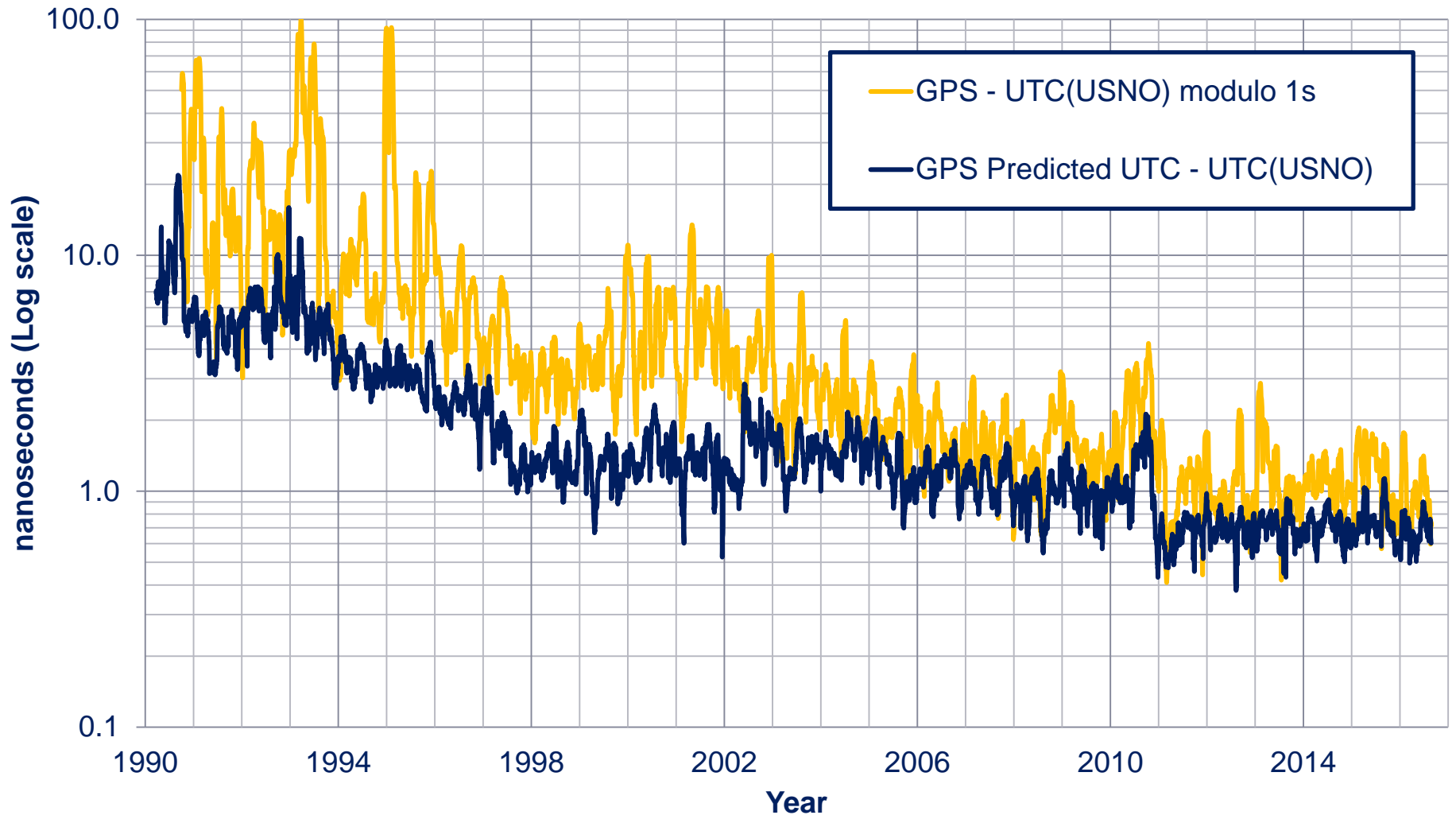




GPS Timing Instability



Monthly RMS of Daily Solutions

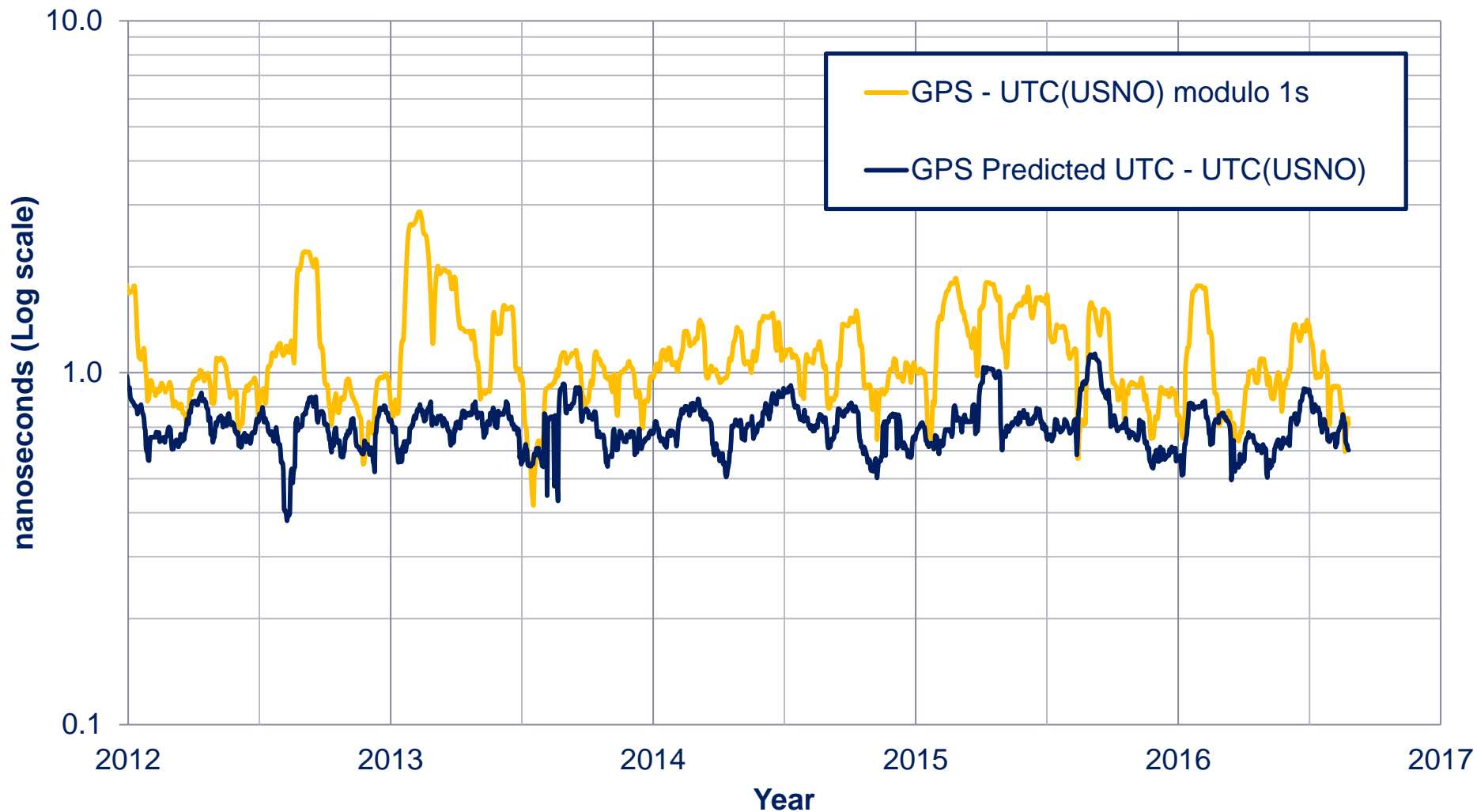




Recent GPS Timing Instability



Monthly RMS of Daily Solutions





Precise Timing Applications



Communications



Power Grid

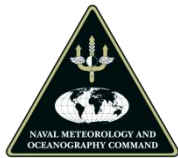


Financial



Scientific

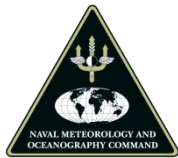
GPS/USNO Provided Timing Service is Critical to the Modern World's Infrastructure



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***
 - ***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***



Receiver Calibration – Multiple Tests



Comparison with old data

Code	11/19/15 Delays (ns)	<u>11/19/15 - 7/22/16 Δ(ns)</u>	10/30/15 Delays (ns)	<u>10/30/15 - 7/22/16 Δ(ns)</u>
CA1	-36.610	0.088	-36.675	0.023
P1	-36.688	-0.173	-36.640	-0.126
L2C	-37.776	-0.265	-37.896	-0.385
P2	-37.783	-0.128	-37.905	-0.250
L5	-44.234	0.147	NA	NA

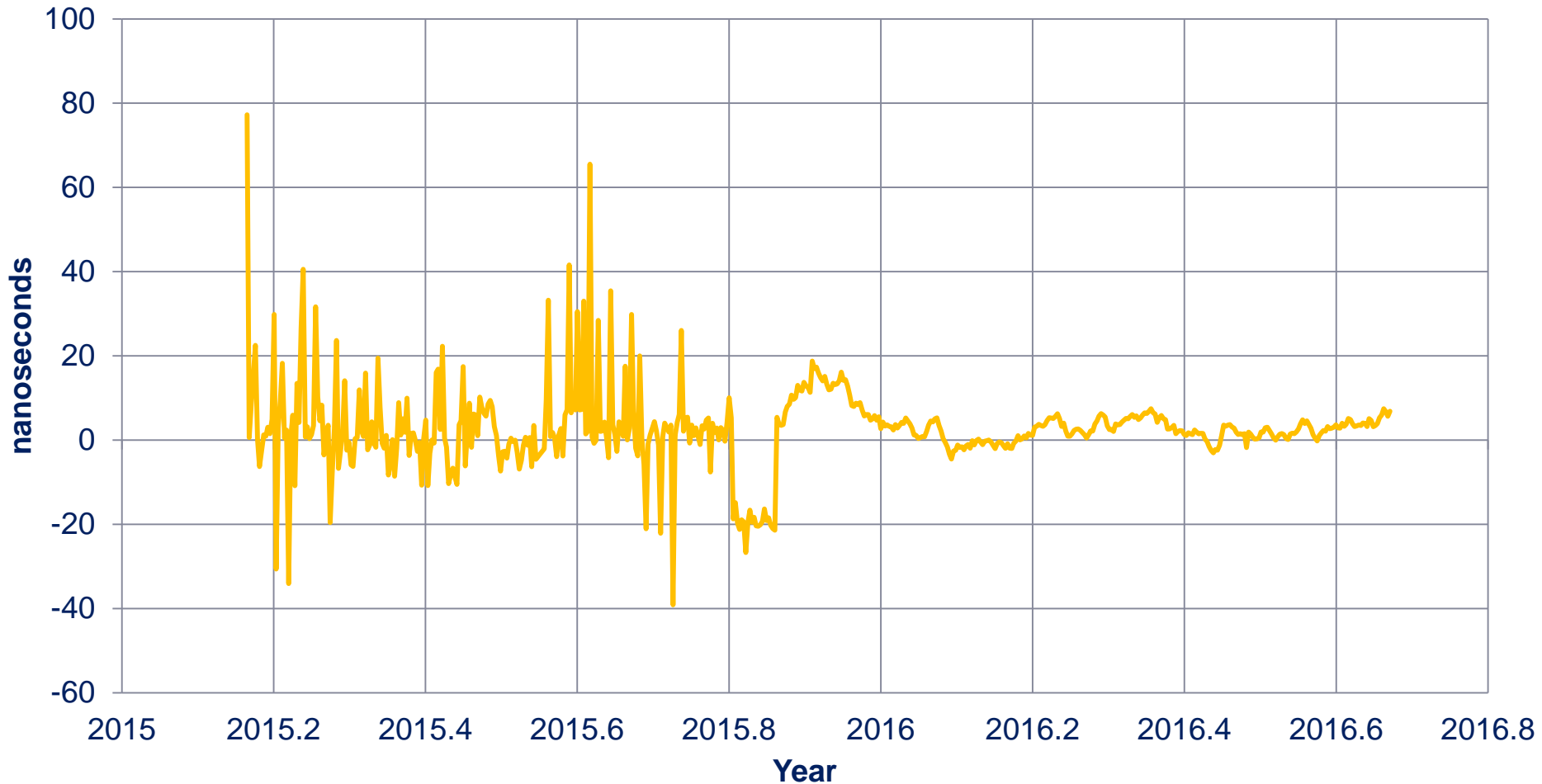
Note: Test setup on 10/30/15 and 11/19/2015 were different from test on 7/22/2016. However, repeatability of results are less than 1ns.



GALILEO GGTO



GPS - GALILEO Time Offset Measured by USNO Combined Receiver

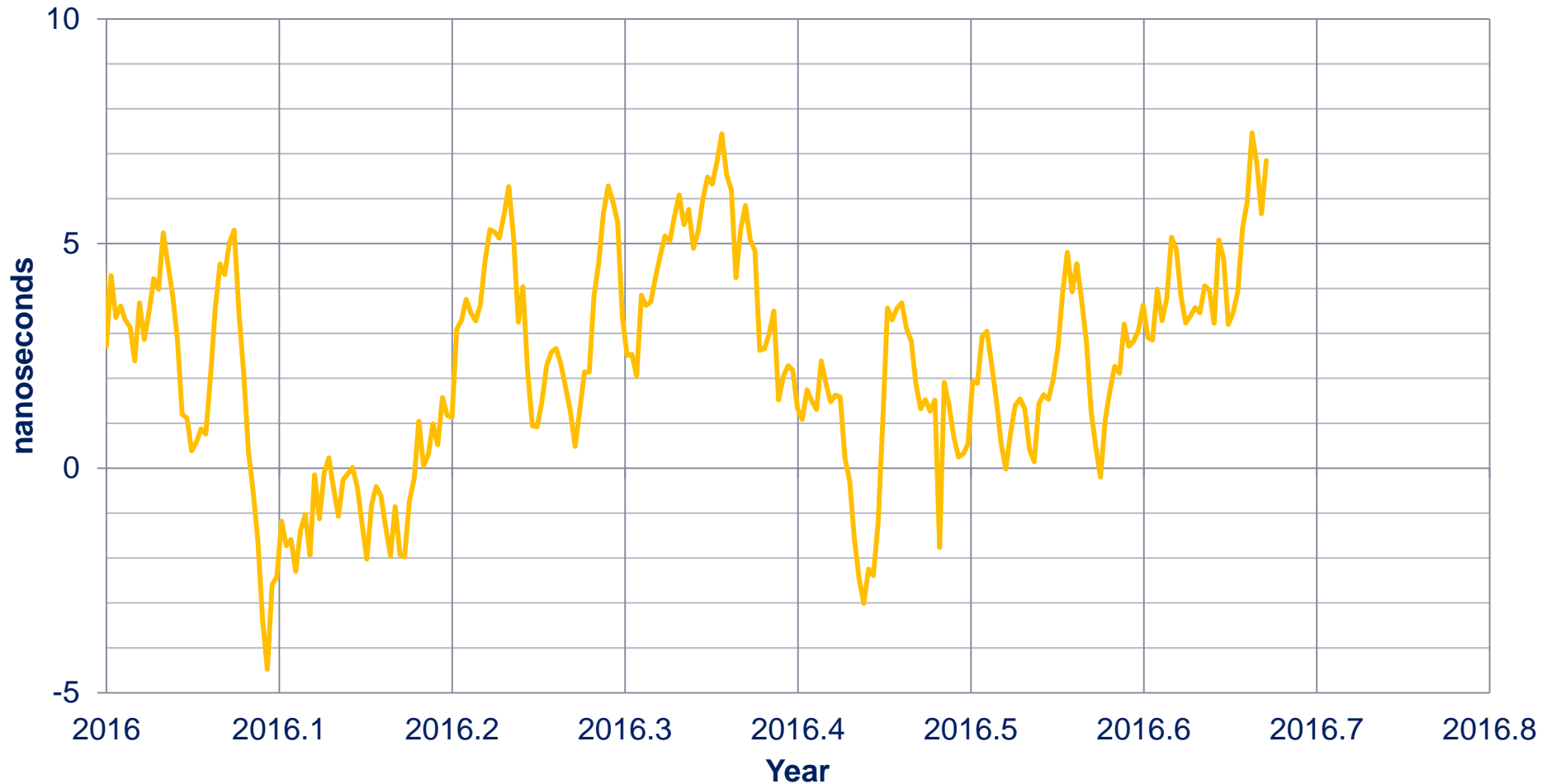


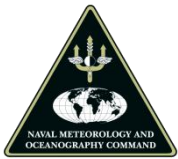


GALILEO GGTO



GPS - GALILEO Time Offset Measured by USNO Combined Receiver

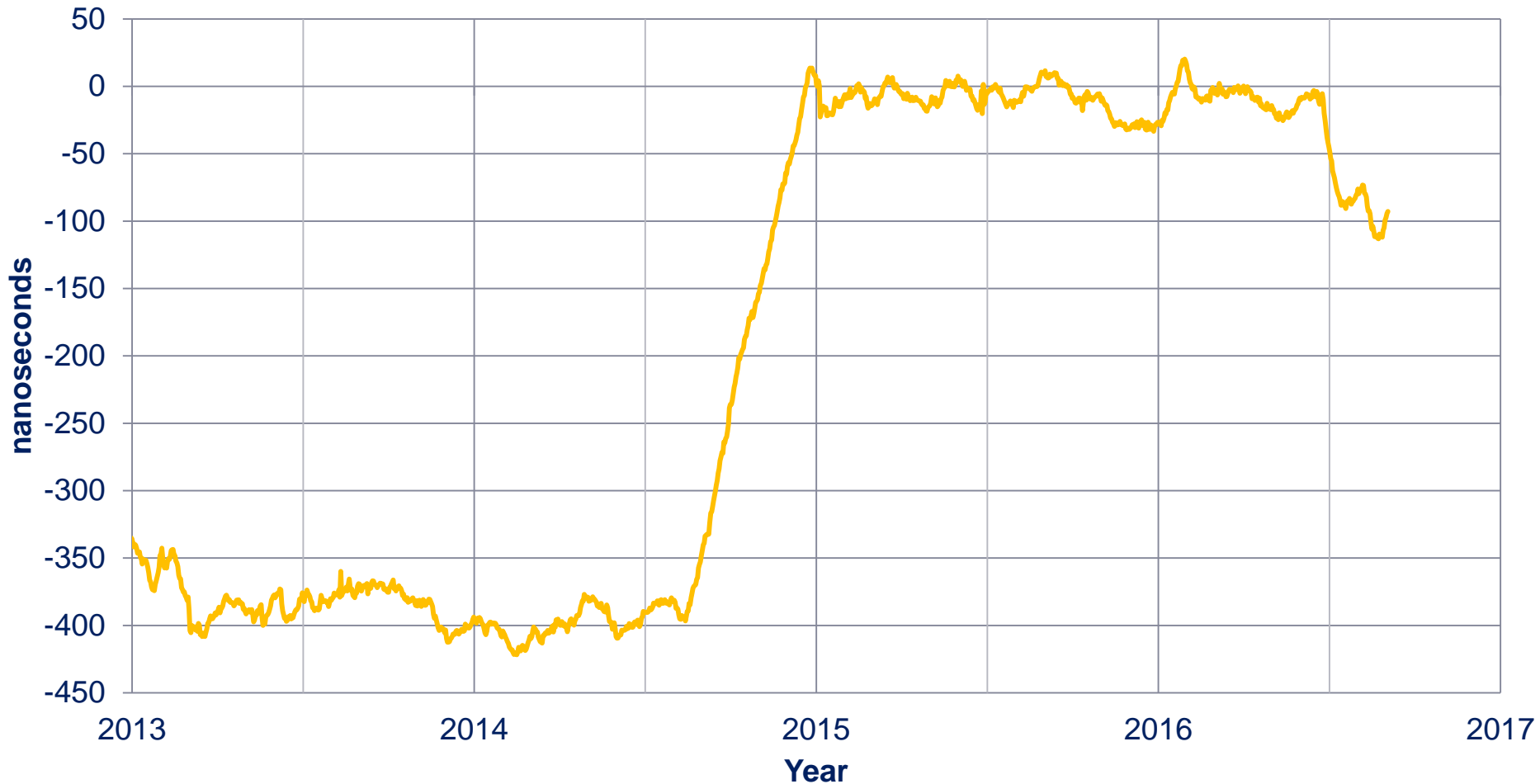


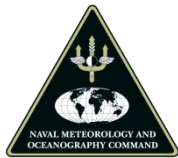


GLONASS GGTO



GPS - GLONASS Time Offset Measured by USNO Combined Receiver





Future Emphasis for Reliable Sub-Nanosecond Timing



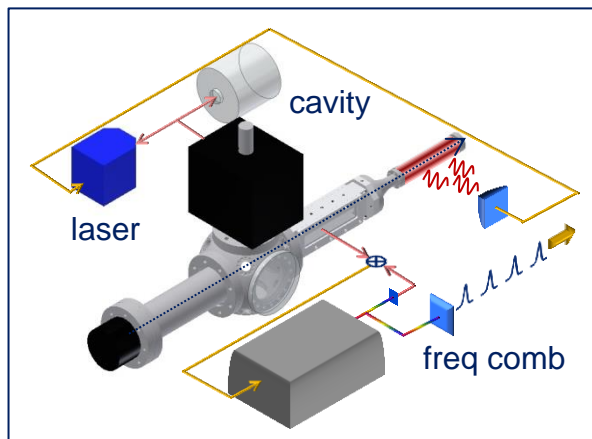
- 1. Stable Timescale Reference***
- 2. Carrier Phase Analysis for GNSS***
- 3. Environmental Control***
- 4. Redundant Independent Receiver Systems***
- 5. Multipath Reduction***
- 6. Calibration, and Recalibration***
- 7. Impedance Matching / Cable Reflections***
- 8. Equipment Design***
- 9. Inter-frequency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

- **Rubidium Atomic Fountains**

- **Use 6.8GHz transition in laser-cooled rubidium**
- **4 fountains in operation in Washington, DC for the past 5.5 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?***