National Aeronautics and Space Administration

New GPS Carrier Phase Frequency Comparison Capability for JPL's Frequency Standards Test Lab

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Program: FY21 R&TD **Strategic Focus Area: Innovative Spontaneous Concepts**

Objectives:

- To adapt and enhance existing software/scripts written for the Deep Space Atomic Clock (DSAC) mission [1] to now process GPS receivers used by JPL's Frequency Standards Test Lab (FSTL).
- To automate acquisition and processing of several receivers' data in a more streamlined process for two capabilities:
  - ✓ Compare local clock against Coordinated Universal Time (UTC)
  - ✓ Compare local clocks at JPL

Background:

- The FSTL maintains high quality frequency standards and measurement systems to characterize flight oscillators and clocks, and monitor the performance of the Deep Space Network (DSN) timing system. (DSN tracks NASA and many non-NASA space missions.)
- Previous FSTL capabilities:
  - Could already compare local (or DSN) clocks against UTC via GPS code techniques, but GPS code is much noisier in the short term than this GPS carrier phase technique, requiring more time/averaging to achieve the same performance level.
  - Could already compare nearby clocks using laboratory-based measurement systems, but required direct electrical or fiber linkage, rather than via GPS carrier phase which is more flexible across JPL campus.
- A need existed towards streamlining the GPS carrier phase processing to enhance ease of use for the FSTL.

Approach and Results:

First Use: Obtained archived receiver data from national timing labs and did preliminary comparison [A] of our processing against the IPPP technique [2], [3] used by the International Bureau of Weights and Measures (BIPM).

Automation/Streamlining:
- First stage of processing (using JPL's GIPSY orbit and clock products [4]):
  - Now automated for 3 FSTL receivers, with email notifications to monitor progress.
  - Each receiver tracks a local clock to compare with GIPSY's reference clock (i.e. with UTC).
- Second stage of processing: activated upon user request for comparison plots for specific time ranges of specific receivers.
  - Wrote a simple python program that allows for streamlined processing: transfers a parameter file from user's PC to the unix workstation where processing is activated and results are automatically sent back.
  - Tested all steps required for a future graphical user interface.
- Work-estimate of what is needed for upgrading to GipsyX which will replace GIPSY.

Key Findings in Figures:
- Fig. 1: Allan deviation (ADEV) performance of FSTL maser against UTC, as measured by two co-located receivers (red and magenta). **Cyan curve shows that differential measurement reaches a noise-floor of 10^{-16} in a few days.**
- Fig. 2: Pairwise difference curves for receivers [5] located in different states/countries; all tied to clocks that are well-steered to UTC. **These are a bit worse than our co-located, common-clock noise-floor of Fig. 1 (cyan), reaching only 10^{-15} at a few days.**
- Fig. 3: **Preliminary** analysis of NIST-PTBB to reduce clock-noise component of this noise-floor by subtracting a more long-term stable two-way satellite time and frequency transfer (TWSTFT) dataset [6]. Blue curve shows this double difference (with our best day boundary removal algorithm) and it **still doesn't reach 10^{-16} until the high 10^6 seconds**.
  - We attribute this residual noise to long-baseline GPS measurement & processing noise.
  - Green curve shows the same noise-floor using BIPM's IPPP [6] instead of our GIPSY processing. **IPPP shows a bit lower noise-floor, however:**
    - BIPM may have processed NIST against PTBB in one step (using PTBB as the reference receiver).
    - We must follow two-step process, processing NIST and PTBB separately against our GIPSY reference, which can add noise.

Significance/Benefits to JPL and NASA:

1) Enhances FSTL's ability to compare local or DSN clocks against UTC with shorter averaging times
   - Could lead to development of new frequency standards.
   - Example: steer an ultra-low-noise photonic oscillator to UTC quickly enough to counteract the high drift of such oscillators; taking advantage of their ultra-low-noise characteristics.
2) Enhances FSTL's ability to characterize clocks and oscillators across JPL campus
   - Bypasses need to set up fiber links from FSTL's stable clocks to other buildings
   - Example: this processing technique was developed during DSAC ground testing, as a way to characterize the flight-clock during several different environmental testing campaigns in different buildings across the JPL campus.
3) Enabled us to start comparing JPL's GIPSY processing to BIPM's IPPP down near the 10^{-16} to 10^{-17} performance level
   - Data presented is preliminary.
4) Provides more streamlined measurement capability for other missions/tasks.

Fig. 1: ADEV of: JPLP, JPLQ, and difference (common clocks for JPLQ and JPLP)

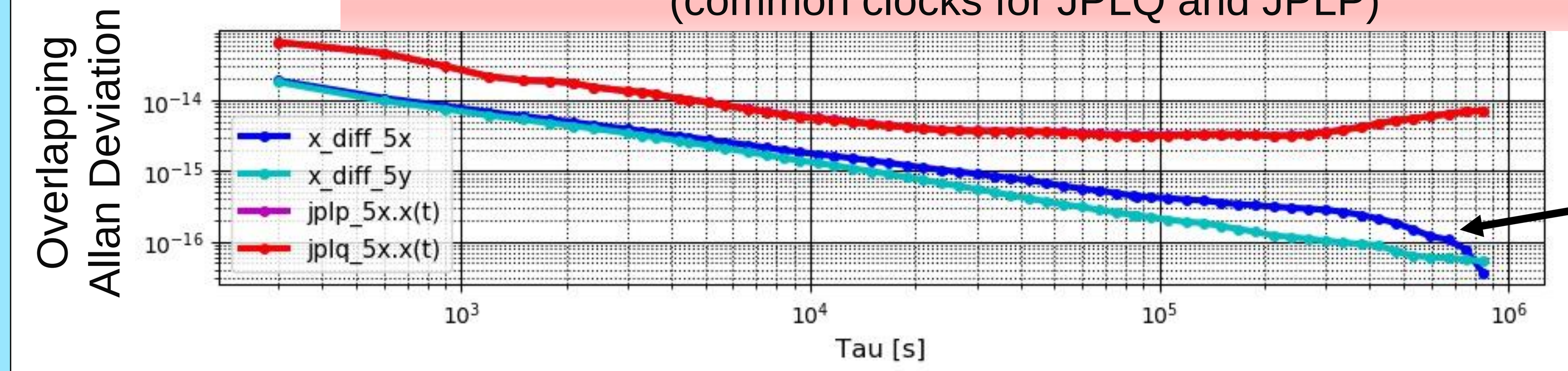


Fig. 2: ADEV of: NIST-PTBB, NIST-USN7, and PTBB-USN7 (all clocks steered to UTC)

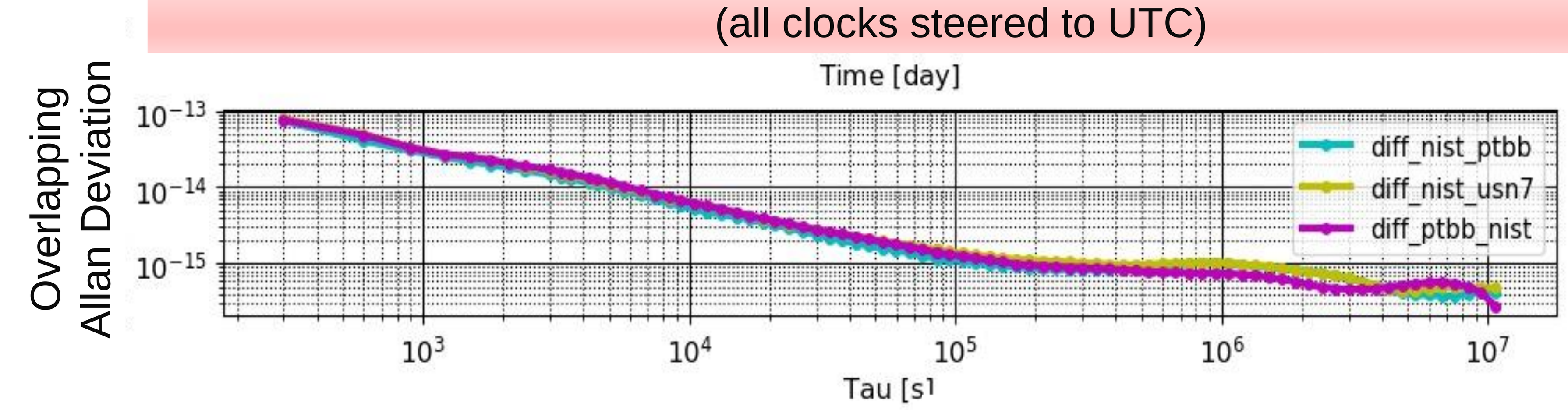
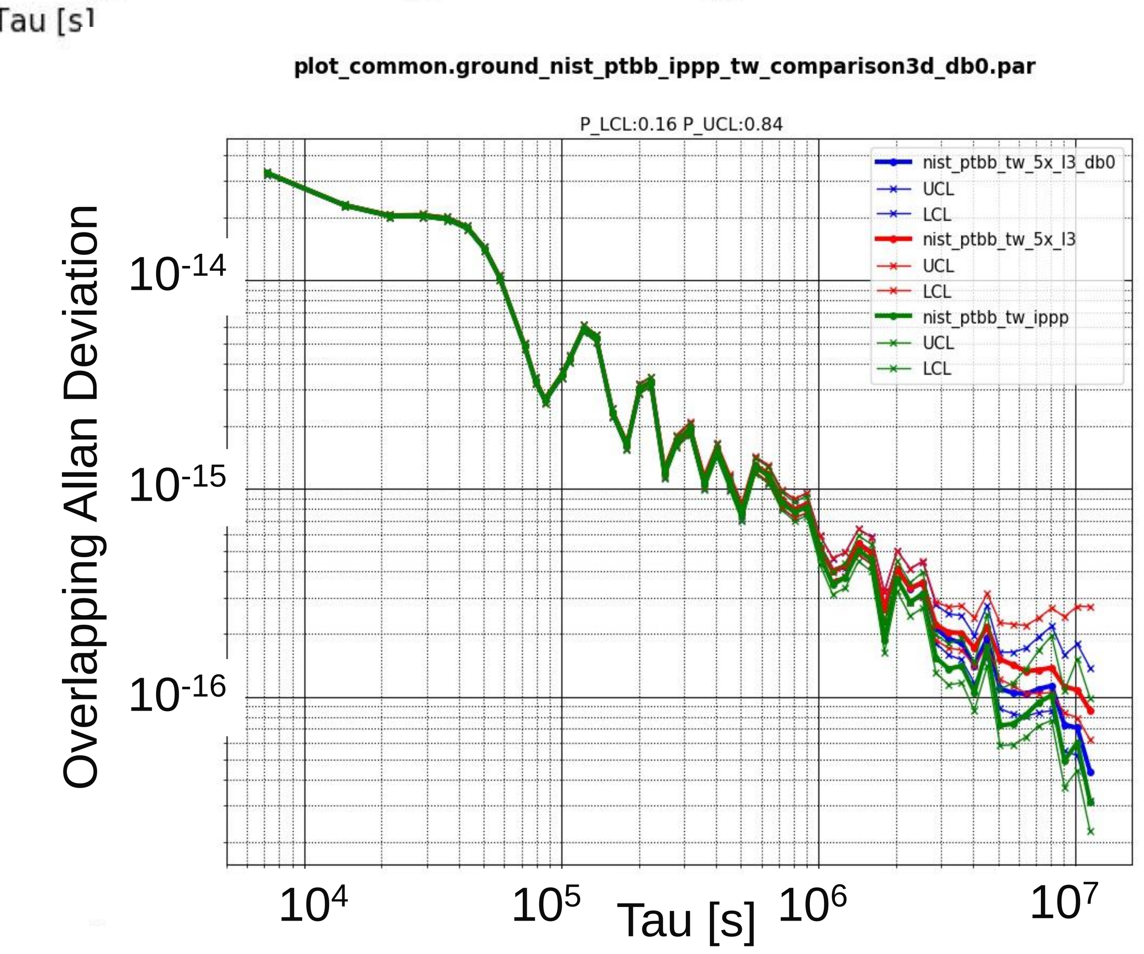


Fig. 3: ADEV of NIST-PTBB: GPS method minus TWSTFT

- Green (IPPP) is a bit better than blue (our technique), but within uncertainty



Publications:

[A] Daphna Enzer and David Murphy "Comparison of GPS Frequency-Transfer Performance between JPL's GIPSY and BIPM's IPPP," *Precise Time and Time Interval Systems and Applications (PTTI),* Long Beach, CA, 2022. **In preparation**

References:

[1] Eric Burt, John Prestage, Robert Tjoelker, Daphna Enzer, Da Kuang, David Murphy, David Robison, Jill Seubert, Rabi Wang, and Todd Ely, "Demonstration of a Trapped-Ion Atomic Clock in Space," *Nature* **595** (July 2021): pp. 43-47.
[2] Gérard Petit, Amale Kanj, Sylvain Loyer, Jerome Delporte, Flavien Mercier, and Felix Perosanz, "1 × 10−16 Frequency Transfer by GPS PPP with Integer Ambiguity Resolution," *Metrologia* **52**, no. 2 (Apr 2015): pp. 301-309.
[3] Gérard Petit and Frédéric Meynadier, "IPPP Links for UTC: Comparison to Existing Techniques," in *Proceedings of the 52nd Annual Precise Time and Time Interval Systems and Applications Meeting (PTTI)*, virtual conference (January 25–28, 2021): pp. 71-86.
[4] Willy Bertiger, Shailen Desai, Bruce Haines, Nate Harvey, Angelyn Moore, Susan Owen, and Jan Weiss, "Single Receiver Phase Ambiguity Resolution with GPS Data," *Journal of Geodesy* **84** (Mar 2010): pp. 327-337.
[5] Data from International GNSS Service, Daily 30-second observation data, Greenbelt, MD, USA:NASA Crustal Dynamics Data Information System (CDDIS), Accessed July 23, 2021, Subset obtained: 2019-12-27 to 2020-10-26 at http://cddis.gsfc.nasa.gov/Data_and_Derived_Products/GNSS/daily_gnss_o.html.
[6] Data used were submitted by laboratories for UTC, and processed by the BIPM.

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