New, Robust, High-Performance, Commercial GPS Timing Receiver

56th CGSIC, ION 2016
Portland, Oregon
September 12, 2016

Bruce Penrod

EndRun
TECHNOLOGIES

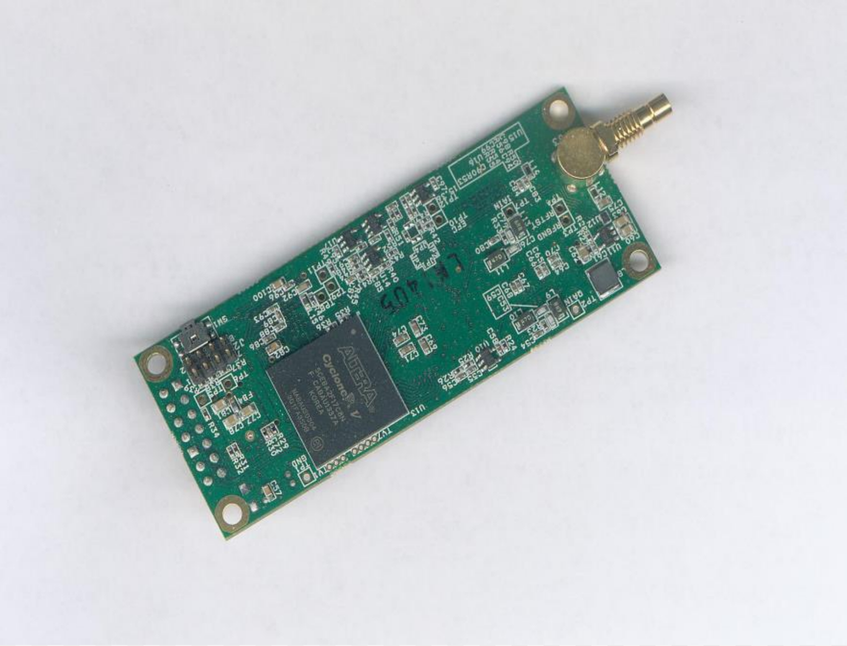
Why Develop a Purpose-Built GPS Timing Receiver?

- Re-purposing inexpensive, mass-market navigation receivers has its problems:
  - No visibility into how exceptions, outliers, week rollovers, etc. are handled
  - Current focus is on Multi-GNSS
  - Time-to-first-fix and high-fix-density priorities not our priority
  - Product life cycles are short

- *With current FPGA and ARM microprocessor technologies, a much better GPS timing receiver can be realized in a small footprint and manufactured at reasonable cost, even in low volumes.*

New, Robust, High-Performance, Commercial GPS Timing Receiver
(In production since August 2015)

- In-House, US-made, GPS L1- only design using COTS components
- Optimized for Ultra-Precise Time and Frequency Transfer Performance at a fixed location
- Implements Comprehensive Demodulated Data Sanity Checking, TRAIM and Weighted SV Measurement Ensembling
- Innovative, Real-Time Ionospheric Correction Option achieves Time Transfer Performance comparable to L1/ L2 receivers



EndRun
TECHNOLOGIES

Applications –
Precision GPS Time and Frequency Products

- Ultra-Low Phase Noise (< -110 dBc @ 1Hz) 10 MHz References for LO synthesis in satellite earth stations
- Low Jitter Reference Clocks for “direct-to-digital” capture of RF signals
- Precise Synchronization (< 10 ns) for secure communications
- Laboratory frequency standards
- Research

Applications –
TCP/IP Network Synchronization Products

- Network Time Protocol (NTP) Servers
- IEEE-1588 Precise Time Protocol (PTP) Servers
- Database Transaction Timestamping
- Stock Market Trade Timestamping
- Algorithmic / High-Speed Stock Trading

Key Implementation Strategies for Robustness

- GPS ICD parity check is weak, erroneous data demodulated from low elevation SVs can pass parity.

- Use Only Satellites whose data is *Continuously Parity Error-Free*

- Perform Consistency / Sanity Checking of Demodulated Data
  - Make use of a priori known values, and relationships between values, to detect inconsistencies.
  - Range check all critical values where possible.
  - Subframes 1, 2 and 3 (Ephemeris of the transmitting SV)
  - Subframes 4 and 5 (Almanacs for all SVs, UTC, Iono)

- Use Timing Receiver Autonomous Integrity Monitoring (TRAIM)

- Use Weighted Ensembling of SV measurements using elevation, URA, noise

Robust Data Checking – Subframes 1, 2 & 3 (Ephemeris, Alerts, Health)

- These are examples of common sense strategies to minimize exposure to both random errors and control segment errors:
  - ✓ Verify TOW from HOW modulo 30 seconds is correct for the subframe ID being received.
  - ✓ Verify TOW has appropriate relationship to the previous subframe TOW.
  - ✓ Per ICD, verify IODC from subframe 1 and IODEs from subframes 2 & 3 match.
- Ephemeris is re-transmitted every 30 seconds, random data demodulation errors do not persist, errors affect a single SV
- TRAIM effective in mitigating

Robust Data Checking – Subframes 4 & 5 Consistency Checking (Almanacs, UTC Parameters, Ionospheric Model)

- Perform Consistency Checking during parsing as first step to help neutralize erroneous data:
  - ✓ Buffer a complete, 12.5 minute, parity-error-free data set from the *highest* SV, and verify groups of critical parameters *before any part of the buffered data is transferred to working memory.*
  - ✓ Per ICD, verify that all received almanac reference time-of-week t_{oa} values for the individual SVs match to ensure that all share the same almanac reference week number WN_a, which is only transmitted once.
  - ➢ *Reject the entire 12.5 minute Subframe 4 & 5 data set if not the case.*
  - ✓ Verify that the UTC reference time (WN_t / t_{ot}) matches the Almanac reference time (WN_a / t_{oa}).
  - ➢ *Reject the entire 12.5 minute Subframe 4 & 5 data set if not the case.*

    (This simple test is enough to reject the Jan 26th control segment UTC offset blunder.)
- The UTC and Ionospheric Model parameters are critical to accurate UTC time transfer.
- TRAIM ineffective in mitigating.

Robust Data Checking – Subframes 4 & 5 Sanity Checking (UTC Parameters and Ionospheric Model)

- Now Perform Range / Sanity Checks (consistency checks are not enough)
  - Range / Sanity check the UTC parameters: A_0, A_1, Δt_{LS}, Δt_{LSF} , WN_{lsf}, DN:
    - A_0 and A_1 must be consistent with the ICD maximum difference between GPS and UTC time of 1 us.
    - Δt_{LS} and Δt_{LSF} must have a reasonable relationship to each other, and to a historical Δt_{LS} record.
    - If a Leap Second is pending, WN_{lsf} and DN must match a possible Leap Second insertion day.
    - *Reject the entire 12.5 minute Subframe 4 & 5 data set if anomaly detected.*
  - Range / Sanity check the Ionospheric Model coefficients: $\alpha_0 – \alpha_3$, $\beta_0 – \beta_3$:
    - Calculate the intermediate Amplitude and Period parameters, that are used to calculate the delay.
    - Check their reasonableness at the equatorial and polar regions, where they reach their extreme values.
    - *Reject the entire 12.5 minute Subframe 4 & 5 data set if anomaly detected.*
- Require that the UTC reference time is current in order to apply the UTC correction to GPS time.

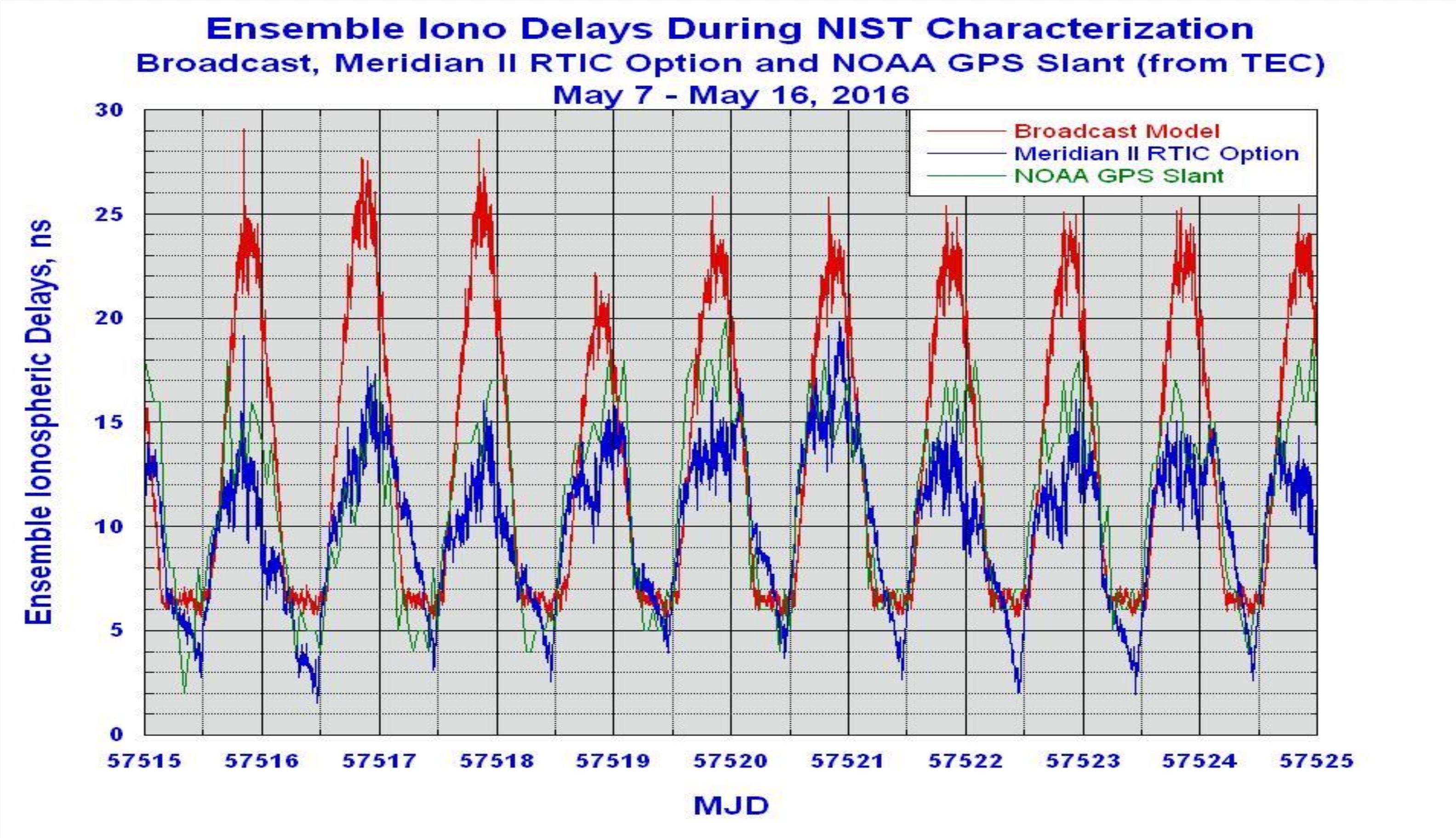
  (This simple test is enough to reject the Jan 26th control segment UTC offset blunder.)

EndRun
TECHNOLOGIES

An Innovation – High Performance, Real-Time Ionospheric Correction (RTIC)

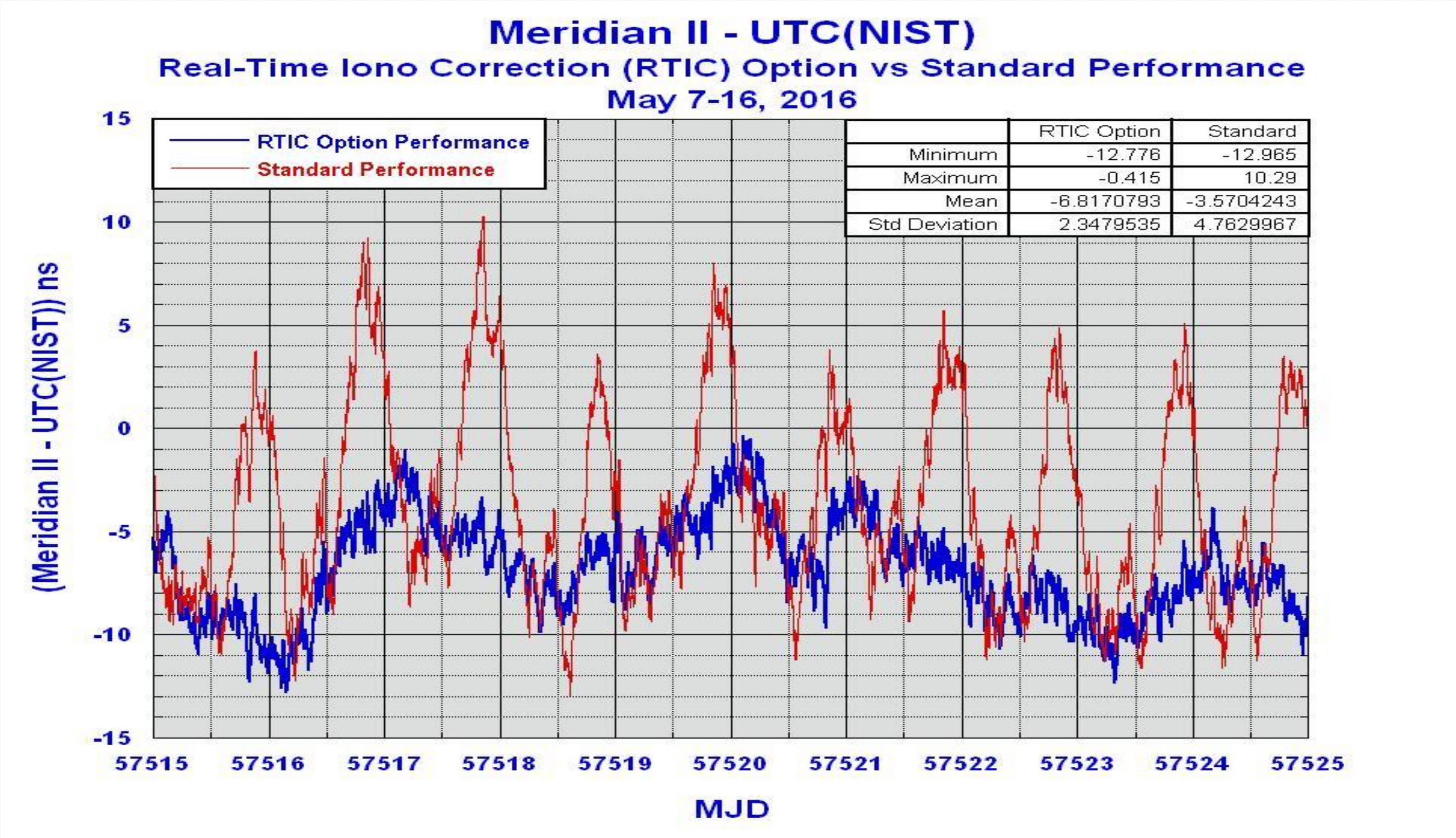
- Largest component of the GPS time transfer error is due to the ionospheric delay model.
- New, Proprietary Algorithm uses L1channel *Code and Carrier Phase Divergence* to make more accurate, *Real Time Ionospheric Delay Measurements.*
- Requirements of the Algorithm:
  - Static installation with good view of the sky
  - 24-hour initialization period
- Advantages over L1/L2 receiver:
  - ✓ Much lower cost for both receiver and antenna
  - ✓ No Differential Channel Bias calibration required
  - ✓ Less susceptible to loss-of-lock (cycle slips) during ionospheric scintillation due to *codeless L2 mode*
- Algorithm performance characterized via data collected at NIST (Boulder), May 6 -- June 6, 2016. (Thank You Victor Zhang)

High-Performance, Real-Time Ionospheric Correction – Ensemble Ionospheric Delays at NIST (Boulder)



EndRun
TECHNOLOGIES

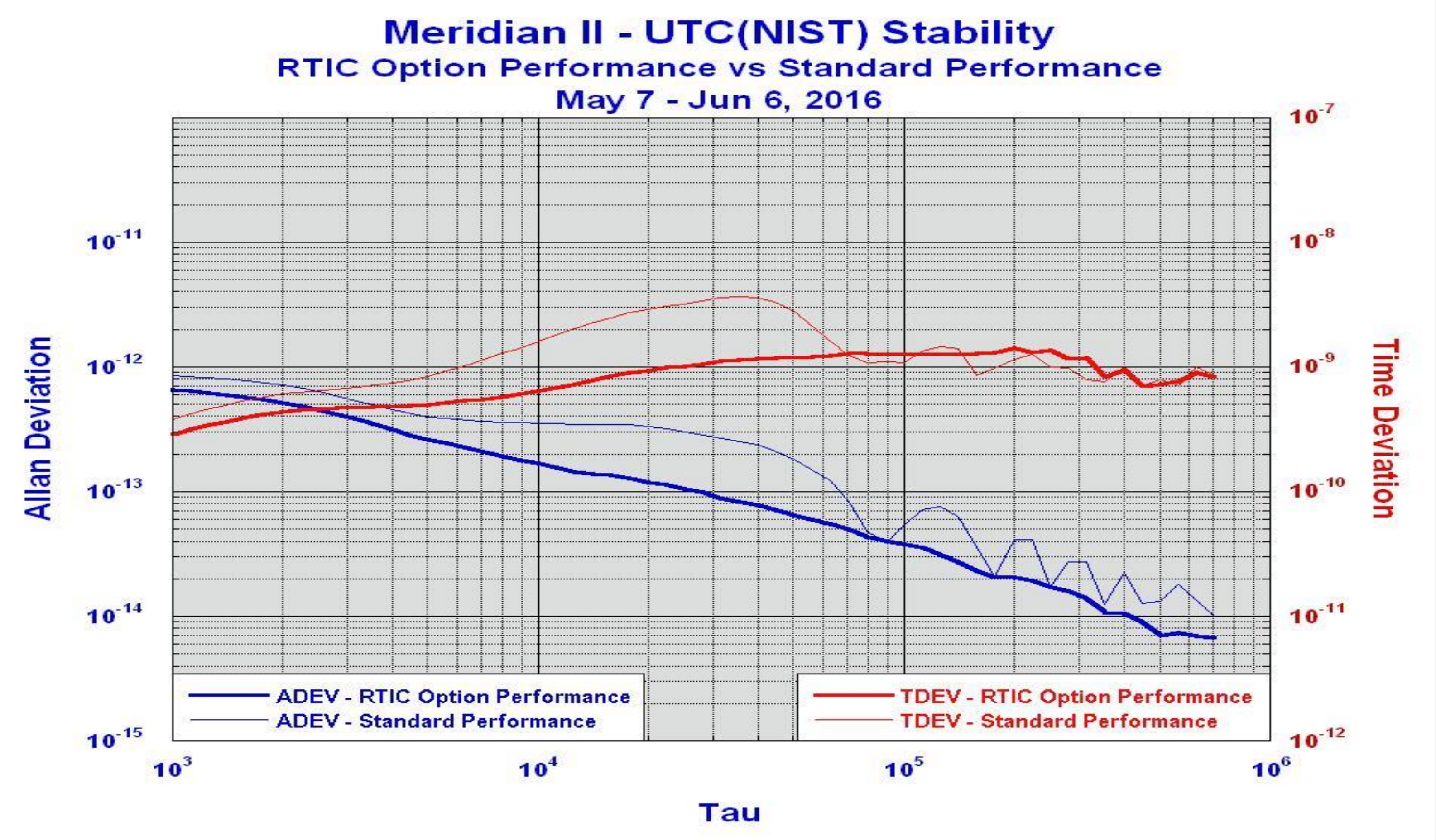
High-Performance,
Real-Time Ionospheric Correction –
1PPS Timing vs UTC(NIST)



	RTIC Option	Standard
Minimum	-12.776	-12.965
Maximum	-0.415	10.29
Mean	-6.8170793	-3.5704243
Std Deviation	2.3479535	4.7629967

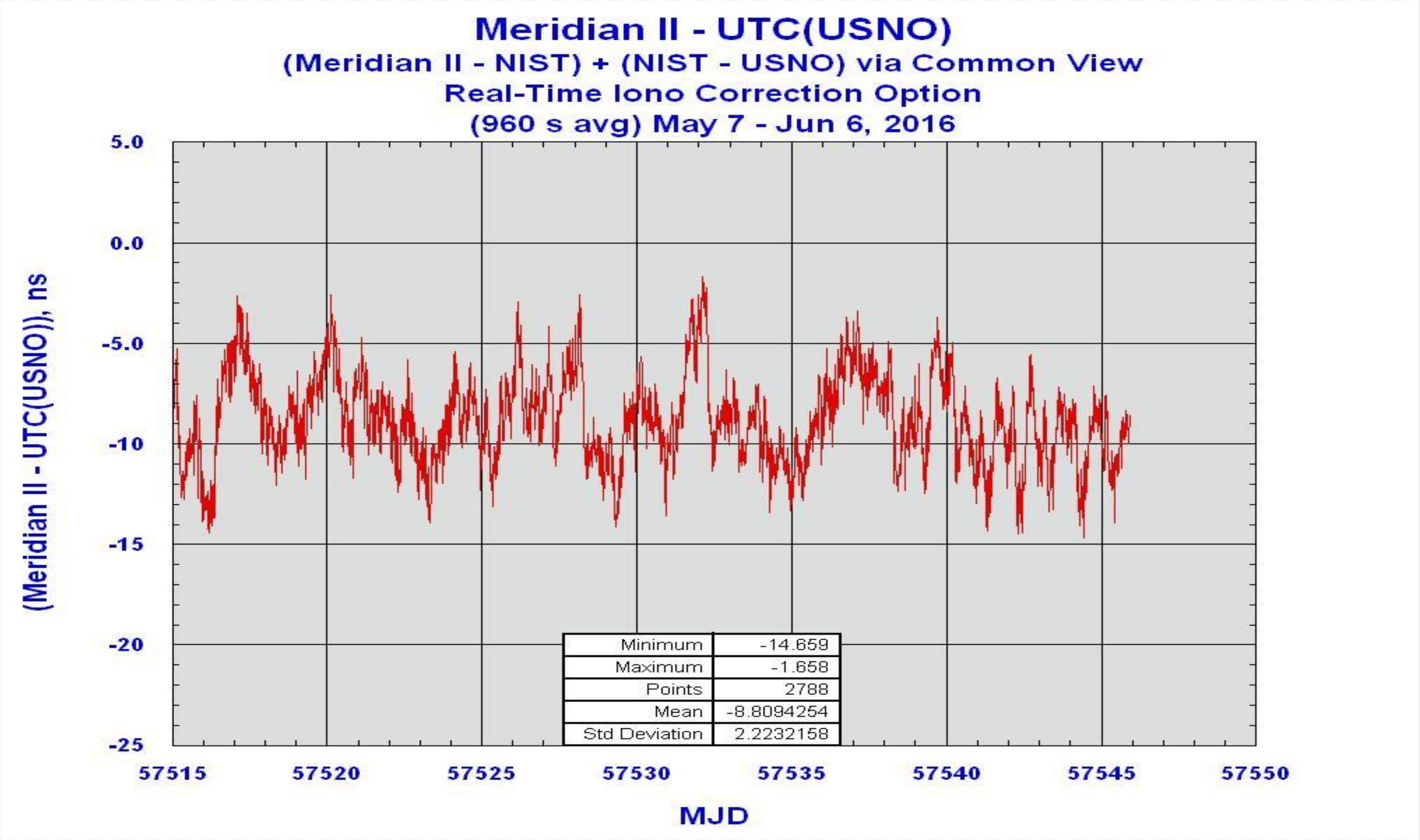
EndRun
TECHNOLOGIES

High-Performance, Real-Time Ionospheric Correction – 1PPS Stability vs UTC(NIST)



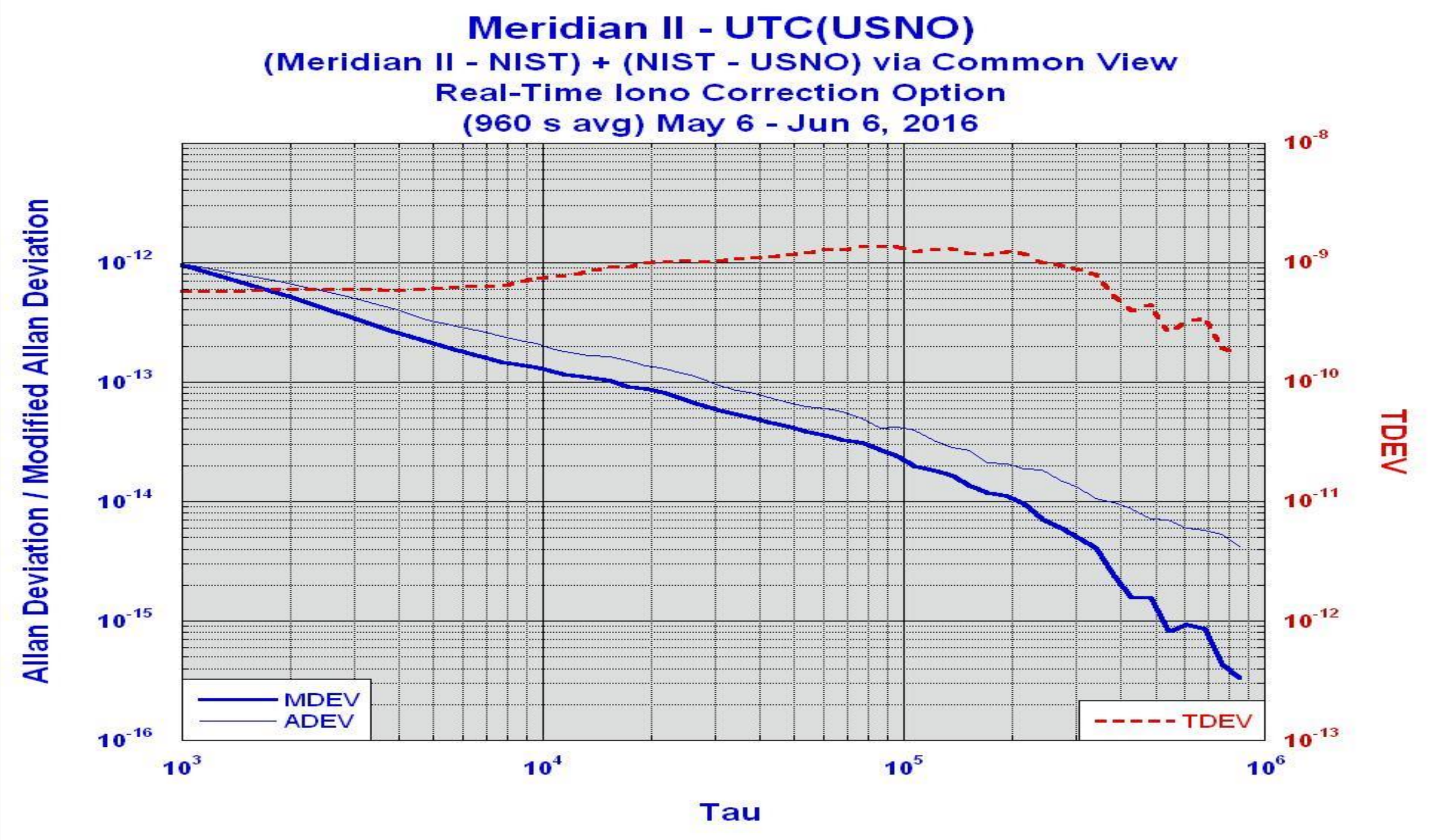
EndRun
TECHNOLOGIES

High-Performance, Real-Time Ionospheric Correction – 1PPS Timing vs UTC(USNO)



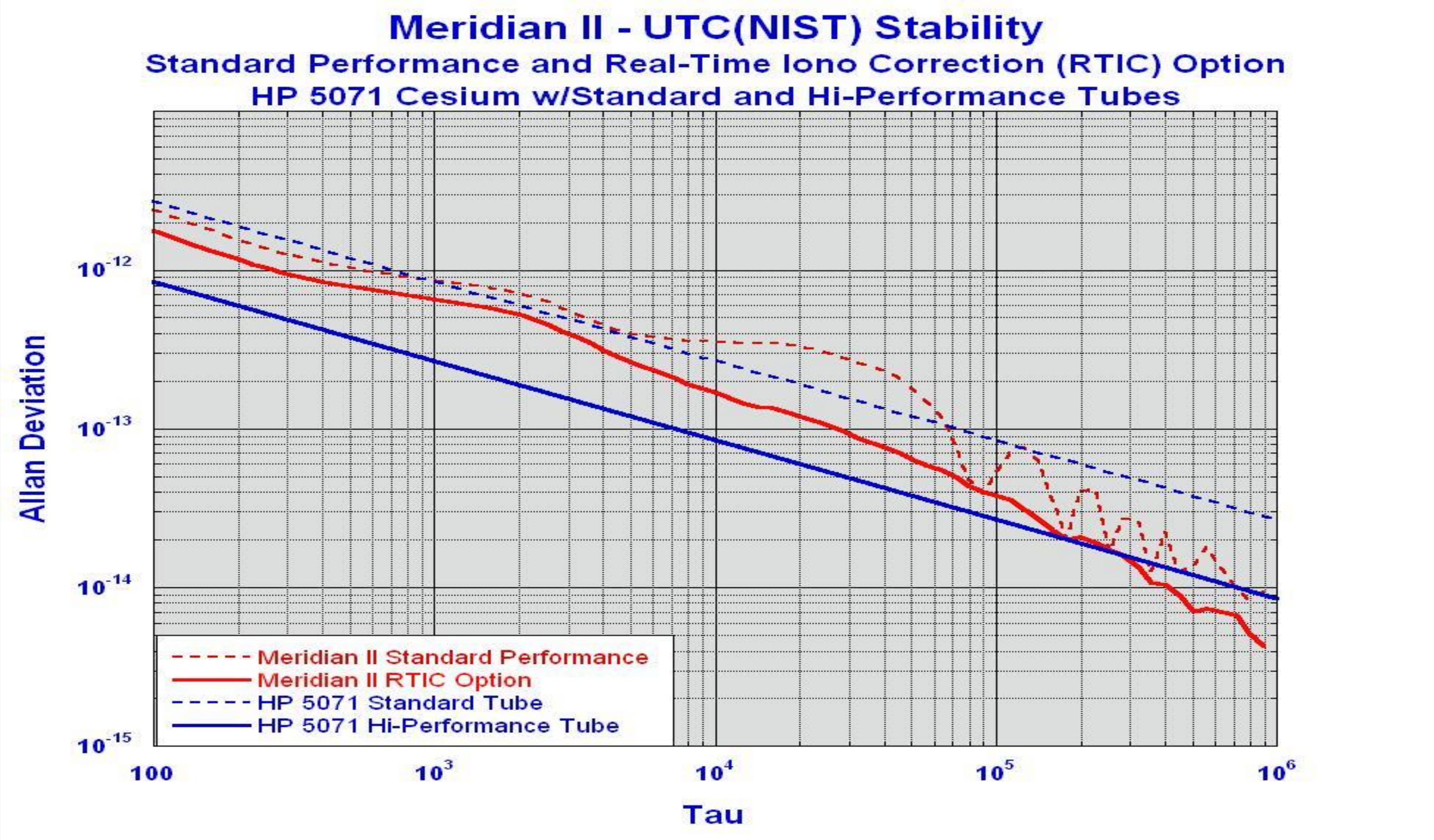
EndRun
TECHNOLOGIES

High-Performance, Real-Time Ionospheric Correction – 1PPS Stability vs UTC(USNO)



EndRun
TECHNOLOGIES

High-Performance, Real-Time Ionospheric Correction – 1PPS Stability vs HP 5071 Cesium



EndRun TECHNOLOGIES

Thank You for Your Attention.

- Contact:
  - bmpenrod@endruntechnologies.com
  - www.endruntechnologies.com