EndRun TECHNOLOGIES
"Smarter Timing Solutions"

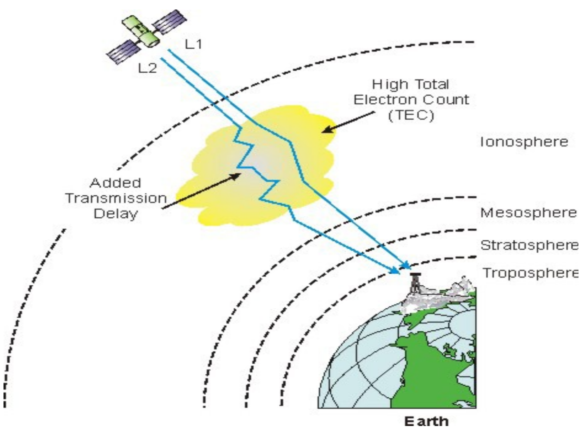
Real-Time Ionospheric Corrections *Option*

For use with GPS Time & Frequency Standards

Our Time and Frequency Standards, both Rackmount and Module versions, can be configured with the Real-Time Ionospheric Corrections (RTIC) Option for optimal performance. The RTIC Option uses proprietary algorithms within EndRun's L1 GPS timing receiver to measure and remove ionospheric delays in real-time that optimize stability and accuracy. This unprecedented real-time capability was previously only available with expensive dual frequency L1/L2 GPS receivers.

Ionospheric Delay and Impact To GPS Time-Transfer

The largest contributor to GPS time-transfer error is the delay of the satellite signals as they pass through the ionosphere, a layer of ionized particles a few hundred kilometers above the Earth's surface. The ionization is caused by solar radiation phenomena, and is maximum a little after local noon and minimum a little after local midnight. The GPS signal delay through the ionosphere is proportional to the ionization level, expressed as Total Electron Content (TEC). Data transmitted from the satellites contains a model that receivers may use to partially compensate for this delay. This model, however, provides only a coarse compensation for night-to-day variations in the ionosphere. It is unable to compensate for the much shorter-term variations in the ionospheric delay caused by various types of solar "storms", and it cannot keep up with the day-to-day variations. As such it was never intended to achieve more than about a 50% improvement over not compensating for the ionospheric delay at all.



Our Proprietary Solution

The GPS code modulation and carrier phase delays are affected differently as they propagate through the ionosphere. By recognizing a few other aspects of this behavior, EndRun developed an algorithm to directly quantify the delay through the ionosphere, and for resolving the code phase and carrier phase bias. The bias information enables real-time measured delay compensation in our single-frequency, L1 receiver. *To our knowledge, this capability is unique to EndRun Technologies.*

The algorithm is effective when the receiver is operating at a stationary location with continuous tracking of at least one satellite at all times. After a 24-hour initialization period it begins producing real-time ionospheric delay measurements, with full accuracy of those measurements achieved after several days. Under quiet ionospheric conditions, this option improves the accuracy and stability of the timing outputs by as much as a factor of three at observation intervals between 3,000 and 100,000 seconds. During a major ionospheric storm event, the improvement may be much greater. It is very difficult to achieve this stability over these observation intervals by another method, as only a high-performance Cesium frequency standard is stable enough to act as a filter for the timing errors caused by the GPS broadcast model.

Performance Verified at National Institute of Standards and Technology (NIST)

To characterize the performance gain of the RTIC Option , a Meridian II was sent to NIST, where its 1PPS output was monitored continuously relative to UTC(NIST) for over 30 days. The ionospheric delay corrections calculated using the broadcast ionospheric model, along with the real-time corrections computed using the RTIC Option, were logged. With these logs, the NIST timing measurements were post-processed to determine what the performance would have been if the RTIC Option had not been active, and the broadcast model had been used instead. The following table shows the difference in stability between the two delay compensation methods of the Meridian II - one with the RTIC Option and one without. Also shown, for comparision, is the stability of two levels of HP 5071 Cesium standards.

KEY BENEFITS

- Real-time measurement and removal of ionospheric delays.
- Improves frequency stability: $<4 \times 10^{-14}$
- Improves time domain stability by 50% (<2.5 nanoseconds STD).
- Compensates for disruptive ionospheric events (solar storms).
- Tighter absolute calibration.
- Exceeds stability of the standard 5071 cesium.
- Costs much less than dual frequency L1/L2 alternatives.

PRODUCT MODELS

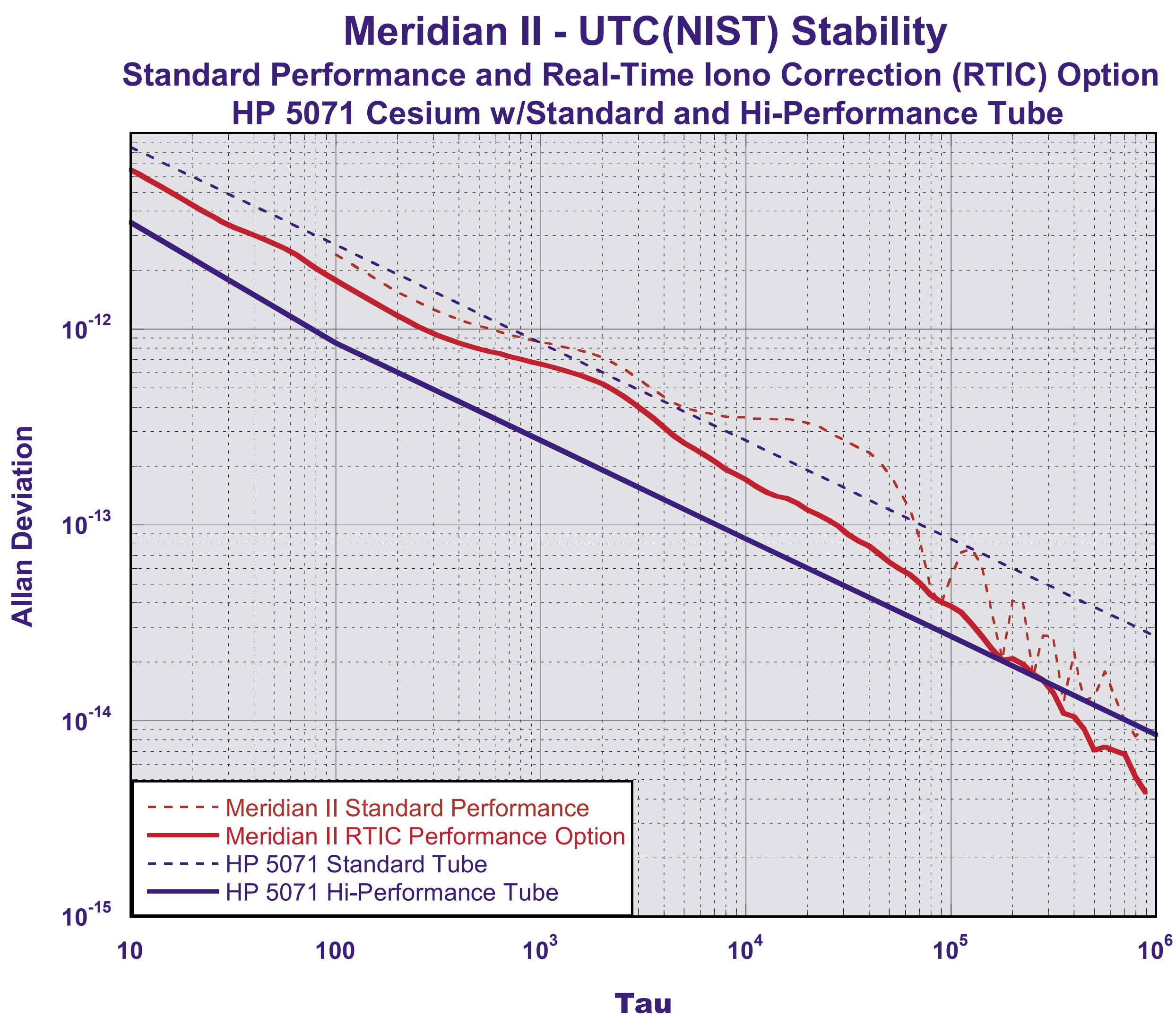
Following are the models capable of being configured with the RTIC Option.

- Meridian II Precision TimeBase
- Tycho II Precision TimeBase
- RTM3205 Precision Timing Module
- Ninja Precision Timing Module

Real-Time Ionospheric Corrections Option

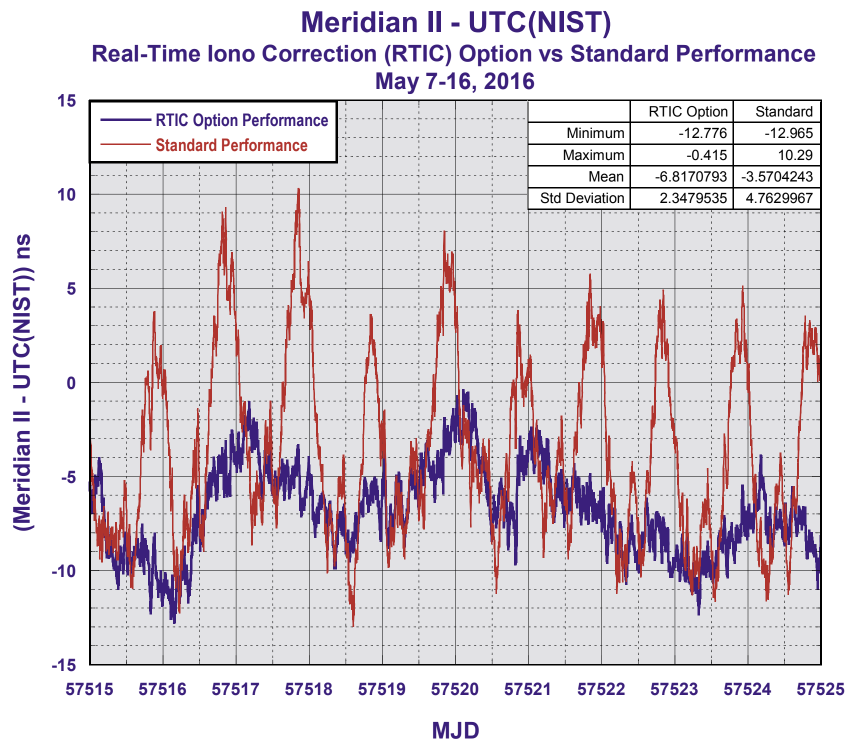
	Meridian II*	Meridian II RTIC Option*	HP 5071 Std Tube	HP 5071 Hi-Perf Tube
Allan Deviation				
1000 sec	8.5×10^{-13}	7.5×10^{-13}	8.5×10^{-13}	2.7×10^{-13}
3000 sec	7.0×10^{-13}	5.0×10^{-13}	4.9×10^{-13}	1.6×10^{-13}
10,000 sec	5.0×10^{-13}	1.8×10^{-13}	2.7×10^{-13}	8.5×10^{-14}
30,000 sec	3.5×10^{-13}	1.2×10^{-13}	1.6×10^{-13}	4.9×10^{-14}
100,000 sec	6.0×10^{-14}	4.0×10^{-14}	8.5×10^{-14}	2.7×10^{-14}

* Oscillator Options US-OCXO or US-Rb are required to meet these specifications.

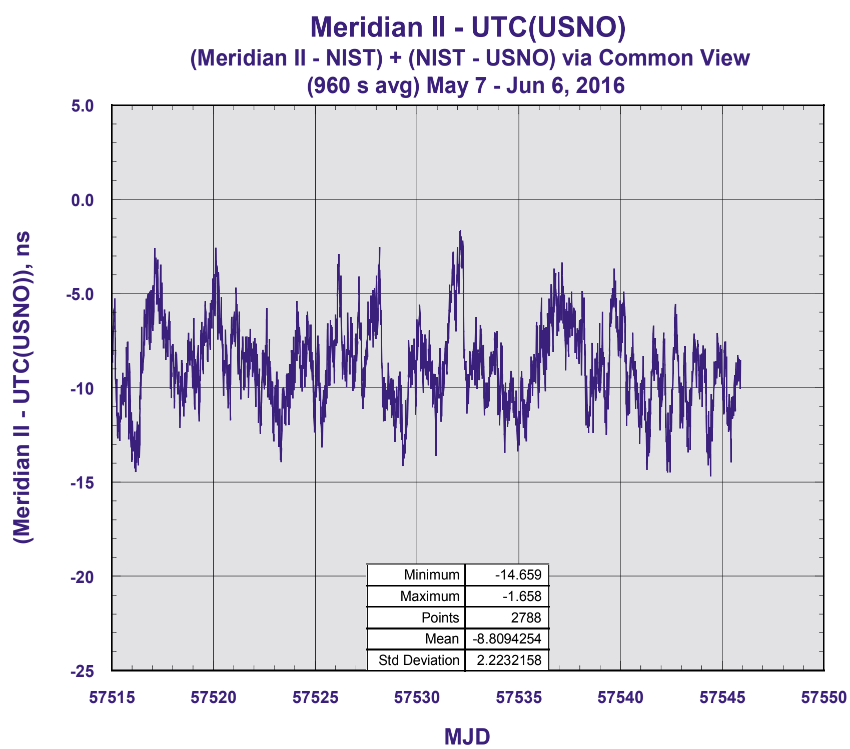


The above Allan Deviation plot shows that the performance improvement gained with the Real-Time Ionospheric Corrections (RTIC) Option is largest for observation intervals around 40,000 seconds. With the RTIC Option, the stability of the Meridian II is superior to the HP 5071 Cesium frequency standard with standard beam tube for all observation intervals, and it surpasses the stability of the HP 5071 with the high performance beam tube option at around 250,000 seconds.

Real-Time Ionospheric Corrections Option



The above shows a phase plot of the Meridian II with the RTIC option active (blue) compared to what the Meridian II performance would have been using the GPS broadcast model (red). Throughout the 10-day test period referenced to UTC(NIST), the RTIC option demonstrated substantial improvement to stability and accuracy through real-time ionospheric delay measurements and real-time compensation.



The above phase plot of the Meridian II with the RTIC option is referenced to UTC(USNO). Through the 30 day test period, the Meridian II 1 PPS output had an impressive standard deviation of 2.22 nanoseconds that is unmatched by any other single band GPS based instrument.

Real-Time Ionospheric Corrections Option

Meridian II and Tycho II Precision TimeBases
Stability Specifications

System Oscillator Stability (Allan Deviation)

Tau in Seconds	MS-OCXO	HS-OCXO	US-OCXO	US-Rb
1	3.0x10^{-12}	1.0x10^{-12}	4.0x10^{-13}	1.5x10^{-11}
10	3.9x10^{-12}	1.3x10^{-12}	5.0x10^{-13}	5.0x10^{-12}
100	3.0x10^{-12}	1.7x10^{-12}	8.5x10^{-13}	1.4x10^{-12}
1000	2.0x10^{-12}	1.5x10^{-12}	8.0x10^{-13}	7.0x10^{-13}
10000	4.0x10^{-13}	4.0x10^{-13}	4.0x10^{-13}	4.0x10^{-13}
100000	6.0x10^{-14}	6.0x10^{-14}	6.0x10^{-14}	6.0x10^{-14}

System Oscillator Stability (Allan Deviation) with RTIC

Tau in Seconds	MS-OCXO	HS-OCXO	US-OCXO	US-Rb	Cs*	HP-Cs*
1	3.0x10^{-12}	1.0x10^{-12}	4.0x10^{-13}	1.5x10^{-11}	1.2x10^{-11}	5.0x10^{-12}
10	3.9x10^{-12}	1.3x10^{-12}	4.5x10^{-13}	5.0x10^{-12}	8.5x10^{-12}	3.5x10^{-12}
100	3.0x10^{-12}	1.7x10^{-12}	8.5x10^{-13}	1.4x10^{-12}	2.7x10^{-12}	8.5x10^{-13}
1000	2.0x10^{-12}	1.3x10^{-12}	7.0x10^{-13}	6.0x10^{-13}	8.5x10^{-13}	2.7x10^{-13}
10000	2.0x10^{-13}	2.0x10^{-13}	2.0x10^{-13}	2.0x10^{-13}	2.7x10^{-13}	8.5x10^{-14}
100000	4.0x10^{-14}	4.0x10^{-14}	4.0x10^{-14}	4.0x10^{-14}	8.5x10^{-14}	2.7x10^{-14}
1000000					1.0x10^{-14}	1.0x10^{-14}

*NOTE: 5071A Cesium Control Module specifications always include RTIC.

Ninja and RTM3205 Precision Timing Modules
Stability Specifications

System Oscillator Stability (Allan Deviation)

Tau in Seconds	MS-OCXO	HS-OCXO	US-OCXO
1	3.0x10^{-12}	1.0x10^{-12}	6.0x10^{-13}
10	3.9x10^{-12}	1.3x10^{-12}	6.0x10^{-13}
100	3.0x10^{-12}	1.7x10^{-12}	8.5x10^{-13}
1000	2.0x10^{-12}	1.5x10^{-12}	8.0x10^{-13}
10000	4.0x10^{-13}	4.0x10^{-13}	4.0x10^{-13}
100000	6.0x10^{-14}	6.0x10^{-14}	6.0x10^{-14}

System Oscillator Stability (Allan Deviation) with RTIC

Tau in Seconds	MS-OCXO	HS-OCXO	US-OCXO
1	3.0x10^{-12}	1.0x10^{-12}	6.0x10^{-13}
10	3.9x10^{-12}	1.3x10^{-12}	6.0x10^{-13}
100	3.0x10^{-12}	1.7x10^{-12}	8.5x10^{-13}
1000	2.0x10^{-12}	1.3x10^{-12}	7.0x10^{-13}
10000	2.0x10^{-13}	2.0x10^{-13}	2.0x10^{-13}
100000	4.0x10^{-14}	4.0x10^{-14}	4.0x10^{-14}

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