EVALUATION OF CARRIER-PHASE GNSS TIMING RECEIVERS FOR UTC/TAI APPLICATIONS

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Abstract

USNO evaluated several carrier-phase GNSS timing receivers to determine their suitability to support UTC/TAI applications. These receivers were subjected to thermal testing, power cycle retrace testing, and long-term stability evaluation. The goal is to identify candidate replacement receivers for the USNO to be used for UTC/TAI applications, including the common-view technique for both GPS and GLONASS monitoring. Test results are reported in this paper.

INTRODUCTION

As part of the U.S. Naval Observatory (USNO) mission to maintain precise traceability of UTC (USNO) to the various international timescales, the USNO Time Service Department GPS Division periodically evaluates new Global Navigation Satellite Systems (GNSS) products **[1]**, including GNSS timing receivers. Over the course of several months at the end of 2007, the USNO GPS team evaluated several new timing receivers with tests focusing on code and carrier-phase tracking stability, receiver sensitivity to temperature, solution consistency across cold-starts, and repeatability of the receiver's internally generated time reference. These tests incorporate the necessary prerequisites for a receiver to be defined as a carrier-phase GNSS timing receiver. This testing phase will continue over the course of 2008, during which USNO will examine other important characteristics such as long-term hardware reliability, tolerance of RF power fluctuations, and long-term solution stability. This paper reports the results of the first block of tests for the following four receivers: Ashtech Z12T, Septentrio PolaRx2eTR, Javad Lexon-GGD, and the NovAtel PROPAK-V3. Of these four, the Ashtech Z12T is a USNO legacy Standard Positioning Service (SPS) timing receiver and, as such, is used as the benchmark for the other three receivers.

DEFINITION OF A TIMING RECEIVER

For the purpose of this paper, it is important to distinguish a GNSS timing receiver from other receiver classes. A receiver is a timing receiver if it fits within one of the following two definitions:

i. A receiver that uses the GNSS pseudorandom noise code as a reference and outputs a timing signal, usually 1 pulse-per-second (1PPS) and/or a frequency source, from a steered oscillator to measure against a local clock

ii. A receiver that, for each satellite signal, makes code-phase and/or carrier-phase measurements that are traceable to an externally provided time and/or frequency signal.

The second definition includes the timing receivers that facilitate common-view and carrier-phase time transfer, which are the primary interest of this paper. In order to be used for time comparisons, such receivers should be calibrated to obtain the absolute value of the receiver's electrical delays. Calibration allows the use of the raw measurements, which are based on a receiver's internal reference point, to obtain clock comparisons which are, instead, referenced to an external event, usually a given voltage on the rising edge of a pulse (1 PPS) derived from the clock frequency. It is, therefore, important to understand what is considered to be the internal reference of a given receiver, and how it relates to the external timing reference signal **[2].**

In principle, this calibration value is only valid at the environmental temperature within which it was measured. In practice, however, if the thermal coefficient of a receiver is below the receiver's measurement noise floor, for a given operational temperature range, no dynamic modification to the calibration point needs to be applied. Conversely, if a receiver's thermal coefficient is large, peak performance may only be obtained by collecting environmental telemetry in conjunction with the receiver measurements, to dynamically adjust the receiver's calibration point.

RECEIVER RESPONSE TO THERMAL VARIATIONS

To investigate the sensitivity of a receiver's group delay to temperature, the receivers were operated in an environmental test chamber while cycling the temperature within a fixed range. In conjunction with the test receivers, data were collected from a reference receiver, which was operated in a thermally stable laboratory. A common antenna was used for all receivers, and the receivers shared the same external frequency-reference signal (e.g., 10 MHz) and time-reference 1PPS signal. By differencing the raw time-aligned pseudorange and carrier-phase data, all common noises are removed and the residuals, therefore, provide good approximations to each receiver's sensitivities to temperature. The hardware test configuration is illustrated in Figure 1.

As shown in Figure 1, a signal switch (denoted in the figure as MUX) and a time-interval counter provided a monitor of each receiver's output timing pulses; however, the data which the reported results are based upon were taken from each receiver's ASCII RINEX or binary to ASCII collections. Custom processing tools were written to column-format the RINEX files, extracting all C/A, P1, P2, L1, and L2 bands. With the intermediate files in place, residual data were created per receiver, per band, per measurement epoch, per SV. Bin averages of the residual data were combined for all SVs within a given epoch. Figures 2a-e display the bin averages of code and carrier delays versus temperature for each receiver.

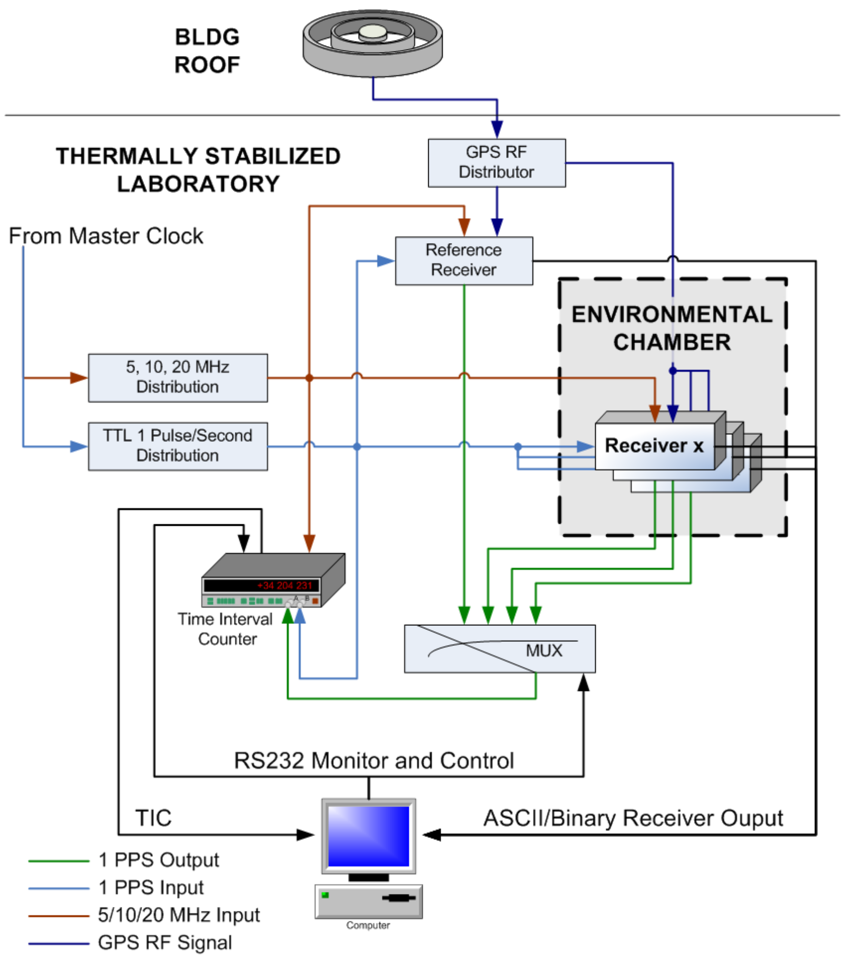
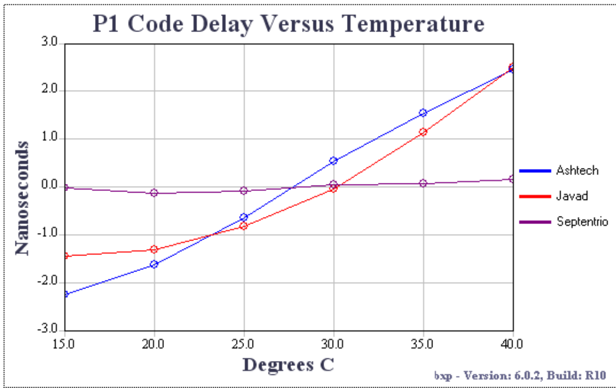


Figure 1. Hardware configuration for receiver thermal testing.

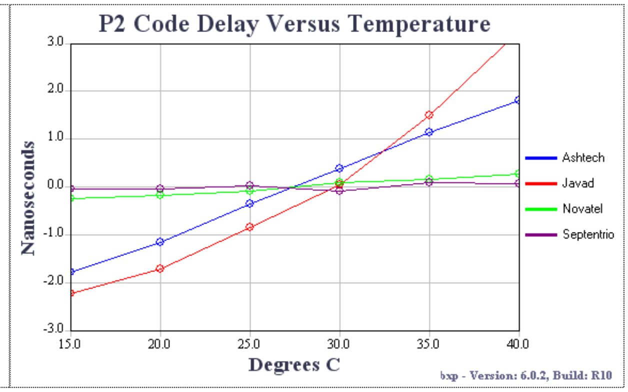
Figures 2a, b, and e show an impressive level of temperature insensitivity in code measurements (i.e. C/A, P1, and P2) for both the NovAtel PROPAK-V3 and the Septentrio PolaRx2eTR. Note, however, that the NovAtel PROPAK-V3 does not output a P1 measurement, and is, therefore, absent from Figure 2a. For the carrier measurements (L1 and L2), in both bands, the Ashtech Z12T yields the flattest response. It is interesting to note that the Septentrio PolaRx2eTR receiver, while fairly consistent across the three code bands, shows a change in sign in its temperature coefficient between the L1 carrier and L2 carrier phase measurements. Additionally, the magnitude of its L2 response is about 8 times that of its L1. The temperature coefficients for all the receivers are provided in Table 1.

POWER-CYCLE RETRACE AND TICK-TO-PHASE REPEATABILITY

Using a GPS constellation simulator and reference signals (10 MHz and 1PPS) from the USNO Master Clock, experiments were conducted to test the integrity of each receiver's internal tick-to-phase relationship. This was done by imposing calibrated phase differences between the supplied reference signals while monitoring the receiver's measurements of the GPS simulator's signals. Simultaneously, consistency across power cycles was verified to ensure that each receiver under test repeatedly selected the appropriate cycle of the 10 MHz reference for use as its internal reference for all pseudorange measurements.



(a)



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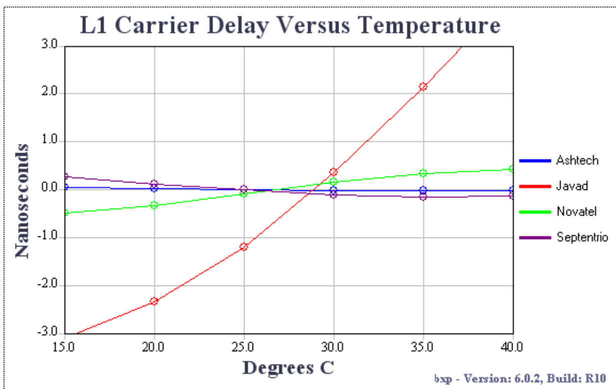

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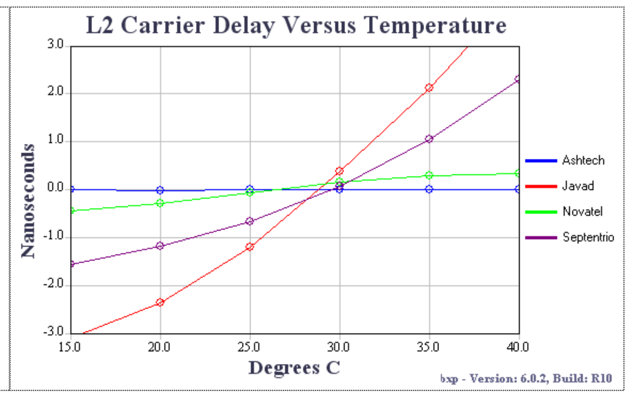

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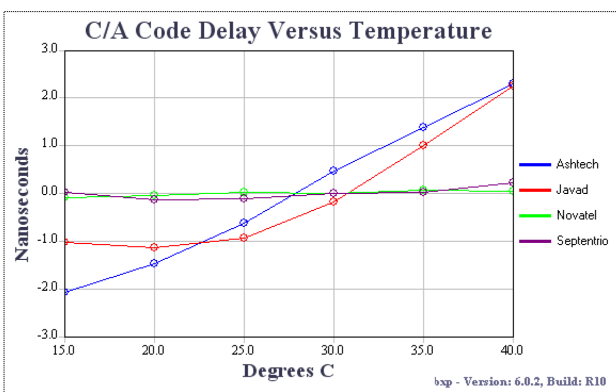

(e)

Figures 2a-2e. Receiver code and carrier-phase delays versus temperature.

Table 1. Receiver temperature response coefficients.

	Picoseconds/Degree C (20 ps/C uncertainty)				
	C/A	*P1*	*P2*	*L1*	*L2*
Ashtech Z12T	180	195	146	-3	0
Javad Lexon-GGD	135	160	217	293	294
NovAtel PROPAK-V3	5	NA	22	39	33
Septentrio PolaRx2eTR	9	6	5	-17	153

These tests are necessary when verifying that a receiver will operate properly as a timing receiver. For the calibration of timing receivers, the phase of a timing receiver's internal time reference must be fully deterministic when given the tick-to-phase relationship of the receiver's externally supplied reference signals. When RF code and carrier signals are received by a timing receiver, they are measured against the receiver's internal time reference. The phase of the internal time reference, therefore, must be traceable to the provided external 1 PPS so that all measurements may be projected back to the site's time reference. In practice, the receiver creates an internal frequency source (e.g., by directly passing the externally supplied frequency source, or by locking it to a PLL) which it uses to generate its internal time reference. The receiver uses the externally supplied 1 PPS reference signal to resolve the cycle of the internal frequency source that marks the start of a time epoch. The internal time reference is, therefore, synchronized to the external time reference, modulo one period of the internal frequency source.

The experimental setup to test for these conditions is shown in Figure 3.

As shown in Figure 3, a frequency synthesizer provides the ability to adjust the tick-to-phase relationship provided to each test receiver. The synthesizer and GPS simulator are locked to an unmodified copy of the Master Clock 10 MHz signal. With the phase of the 1 PPS fixed at the receiver, the tick-to-phase is stepped by making adjustments in the synthesizer. The adjustments are monitored by an oscilloscope to shield against human error, and each receiver's measured output is expected to mimic the state of the tick-to-phase at the receiver's input. A sample of the results collected is shown in Figure 4.

Figure 4 illustrates the desired results, demonstrated by the Septentrio PolaRx2eTR receiver. In the first four steps (at the left side of the plot), the phase of the external frequency reference is stepped in 1 nanosecond increments (w.r.t. the 1 PPS timing signal); the steps are correctly mimicked in the output of the receiver. The small gaps of data near the start of each new step show the results of receiver power-cycles. Note that the receiver's output phase does not resume at some arbitrary position, but instead retraces correctly. This verifies that when the receiver generates its internal timing reference, it properly utilizes the externally supplied 1 PPS signal when choosing a rising (or falling) edge of the frequency source for time synchronization. For the fifth step, a slew of 5 nanoseconds is applied and, as shown, when the receiver is power-cycled, the resulting phase jumps 33 nanoseconds. This is explainable because the receiver's internal oscillator has a frequency of 30 MHz (frequency-locked to the external 10 MHz) and, therefore, has a synchronization granularity of 33.3 nanoseconds. This marks the point where the internal phase of the 30 MHz signal crosses the 1 PPS edge. Accordingly, determining the external tick-to-phase which causes this condition is important for proper receiver calibration.

During the retrace and tick-to-phase tests, all receivers but one behaved as expected, where one receiver did not properly and/or consistently utilize the external 1 PPS timing signal.

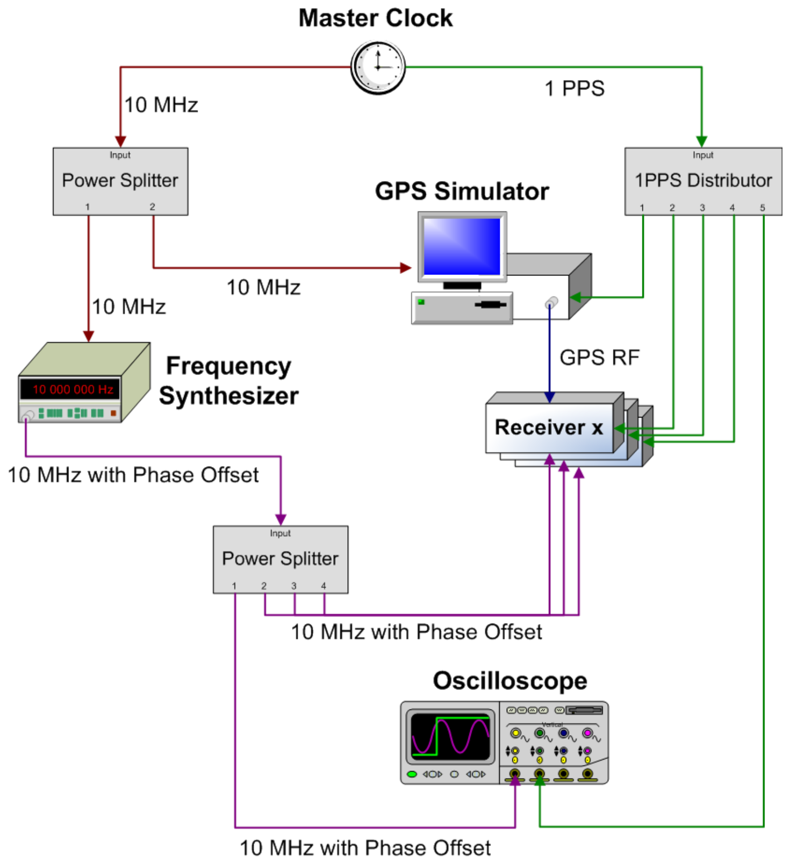

Figure 3. Test setup for power-cycle retrace and tick-to-phase repeatability.

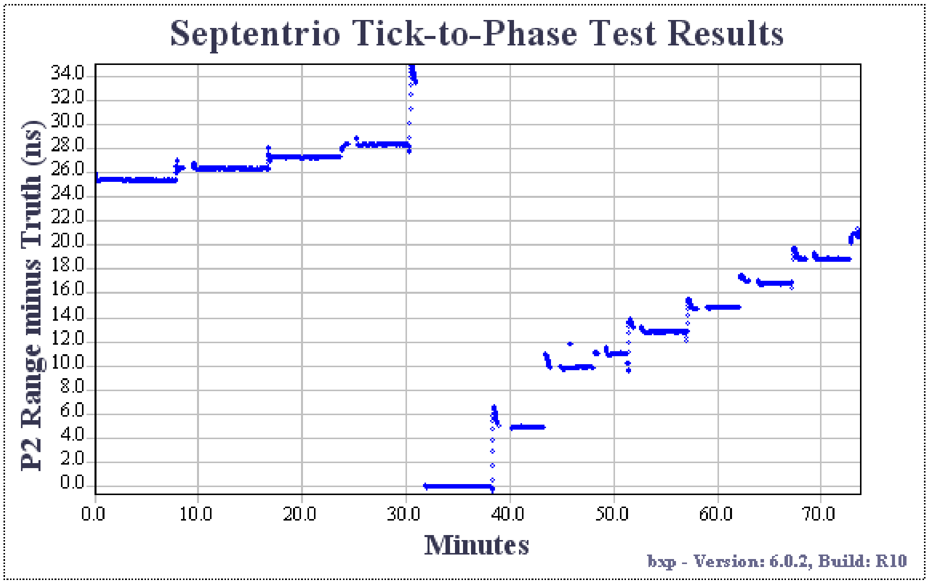

Figure 4. Power-cycle and tick-to-phase test results for the Septentrio PolaRx2eTR.

CONCLUSION

Although the Ashtech Z12T yielded the best temperature stability in the carrier-phase measurements, both the Septentrio PolaRx2eTR and the NovAtel PROPAK-V3 showed vast improvements in all three code-phase groups. Of these two, the NovAtel PROPAK-V3 receiver demonstrated better consistency across the carrier-phase bands. For the power-cycle retrace and tick-to-phase tests, one of the receivers under test exhibited trouble with proper time synchronization. The output phase of the receiver did follow the input phase correctly, which indicates a successful phase-lock to the external frequency source, but the receiver failed to retrace upon power cycles.

With the initial tests complete, a second stage of tests will be conducted to characterize such attributes as long-term hardware reliability, tolerance of RF power fluctuations, and long-term solution stability.

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ACKNOWLEDGMENTS

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REFERENCES

[1] E. Powers, P. Wheeler, D. Judge, and D. Matsakis, 1999, *"Hardware Delay Measurements and Sensitivities in Carrier Phase Time Transfer,"* in Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Appliations Meeting, 1-3 December 1998, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 293-305.

[2] G. Petit, Z. Jiang, J. White, R. Beard, and E. Powers, 2001, *"Absolute Calibration of an Ashtech Z12-T GPS Receiver,"* **GPS Solutions, Vol. 4,** no. 4, pp. 41-46.