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

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Abstract

USNO previously 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 mid-term stability evaluation. Two receivers showed poor performance during these tests. Newer versions of these receivers were released and have been reevaluated. 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. In 2007, the USNO GPS team evaluated several 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 incorporated the necessary prerequisites for a receiver to be defined as a carrier-phase GNSS timing receiver **[2]**. Several of the receivers tested were updated and retested to verify performance enhancement from the updated hardware. This paper reports the results of the tests for the following three receivers: Septentrio PolaRx3eTR, Javad Delta G3T, and the NovAtel ProPak-V3. Due to the availability and reliable Standard Positioning Service (SPS) timing, we chose to use a NovAtel ProPak-V3 as the benchmark for the 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 **[2]**:

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 **[3]**.

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 **[2]**.

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. Data were collected from a reference receiver which was operated in a thermally stable test chamber. 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, binary data were collected from each receiver and then converted to RINEX format for analysis. Custom processing tools that were previously used were updated to extract all code and carrier measurements from the RINEX files. 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-d display the bin averages of code and carrier delays versus temperature for each receiver.

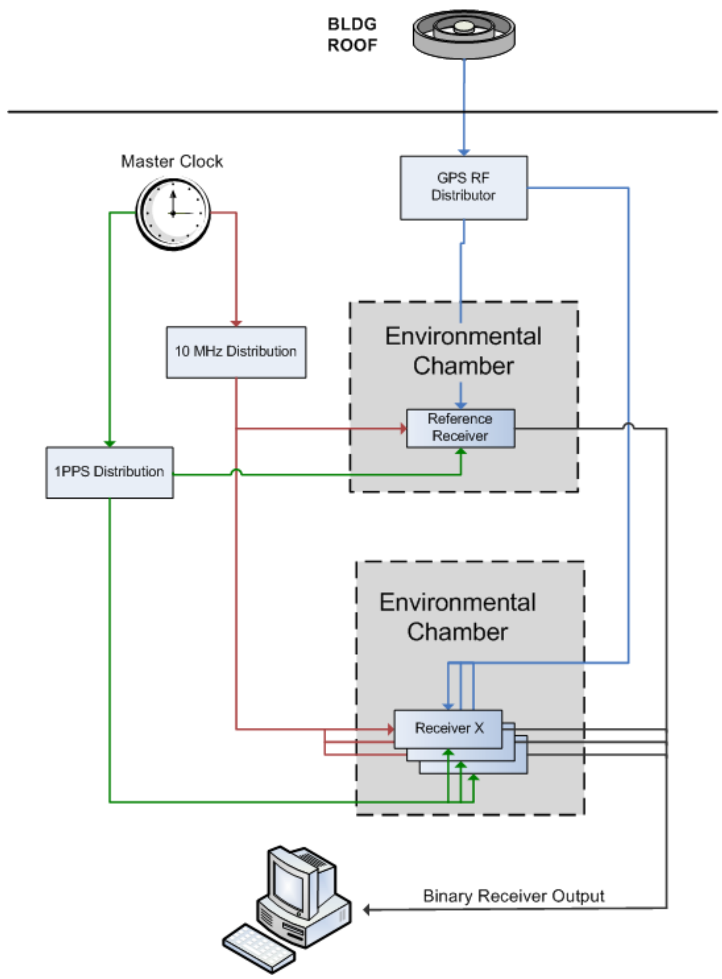


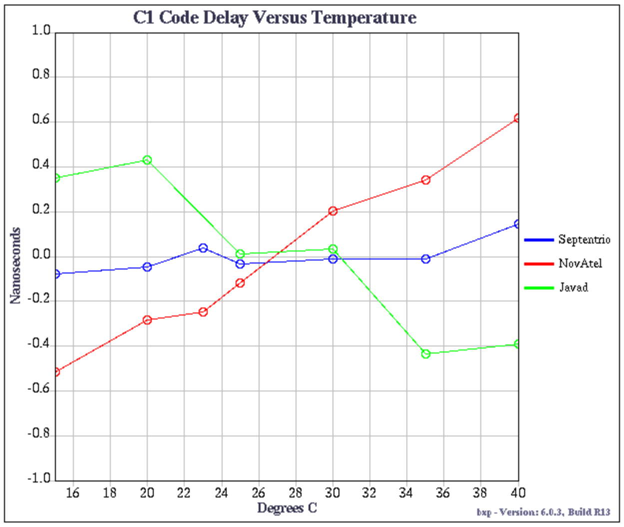
Figure 1. Hardware configuration for receiver thermal testing.

Figures 2a and b show a high level of temperature insensitivity in code measurements (C/A and P2) for the Septentrio PolaRx3eTR. While being much improved over the Javad Lexon-GGD that was previously tested, the Javad Delta G3T code measurements showed varying responses to temperature shifts. Most interesting is the change in direction of code delay at each temperature shift. The NovAtel ProPak-V3, while still being predictable, had slightly worse code performance compared to its previous version.

The carrier-phase measurements (L1 and L2), shown in Figures 2c and d, showed the Septentrio PolaRx3eTR with the best response, improving on its L2 carrier measurement. The Javad Delta G3T produced similar improvements in both bands. The NovAtel ProPak-V3 shows an identical, predictable trend across both bands. The temperature coefficients for all the receivers are provided in Table 1.

POWER-CYCLE RETRACE AND TICK-TO-PHASE REPEATABILITY

As stated, the goal of this evaluation was to identify GPS receivers that function properly as timing receivers. Tick-to-phase repeatability tests were carried out to validate that the internal time reference of the receiver would synchronize to an external time reference, thus making the phase of the timing receiver's internal time reference fully deterministic when given the tick-to-phase relationship of the receiver's externally supplied reference signals.



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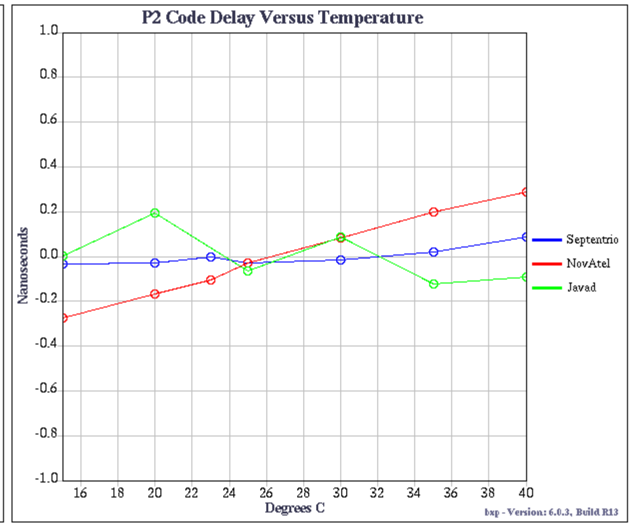

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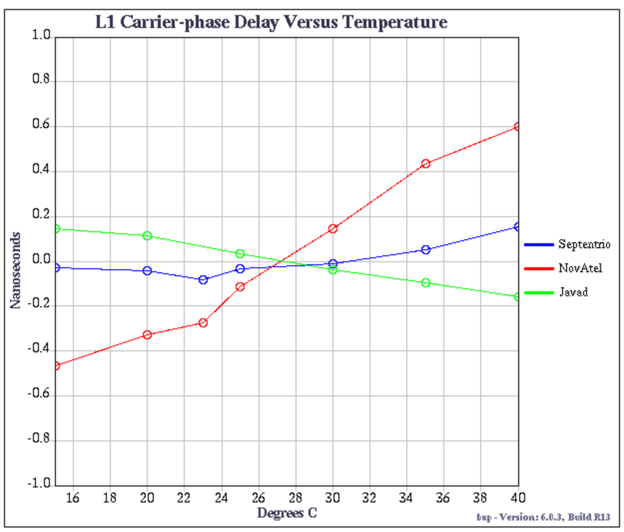

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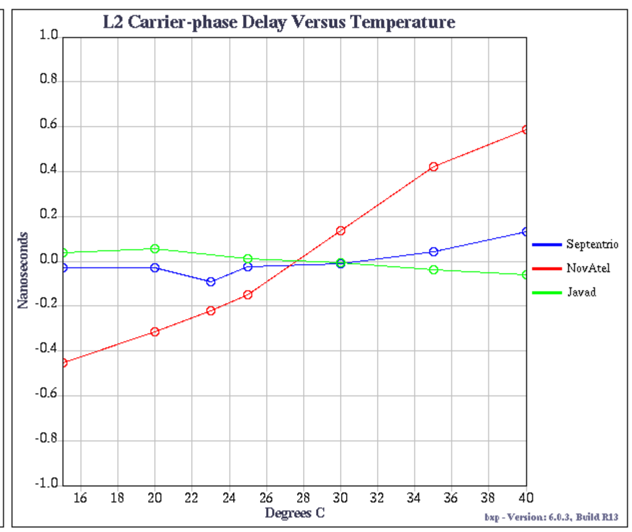


(d)

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

Table 1. Receiver temperature response coefficients.

Receiver	Picoseconds/Degree C (10 ps/C uncertainty)			
	C/A	P2	L1	L2
NovAtel ProPak-V3	48	24	44	43
Septentrio PolaRx3eTR	5	3	9	6
Javad Delta GTR	-44	40	-13	-3

Reliability of the timing receiver's internal tick-to-phase relationship was analyzed using identical live GPS signals and reference signals (10 MHz and 1PPS) from the USNO Master Clock in both the timing receiver and external time reference. The timing receiver's GPS signal measurements were monitored while calibrated phase differences between the supplied reference signals were imposed. The RF code and carrier signals received by the timing receiver are measured against the receiver's internal time reference, so its phase must, therefore, be traceable to the provided external 1 PPS signal. This allows all measurements to be projected back to the site's time reference, synchronizing the timing receiver to the external 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.

Simultaneously with tick-to-phase repeatability tests, power-cycle retrace was tested. Consistency between power cycles was verified to ensure that the NovAtel and Javad timing receivers repeatedly selected the appropriate cycle of the 10 MHz reference for use as its internal reference for all pseudorange measurements.

As shown in Figure 3, the experimental setup uses a frequency synthesizer to provide the ability to adjust the tick-to-phase relationship provided to each test receiver. The synthesizer is 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 measured by a Time-Interval Counter (TIC) and the receiver's measured output is expected to mimic the state of the tick-to-phase at the receiver's input. The test receiver's RINEX output is differenced with the reference receiver to see the tick-to-phase shifts, as shown in Figures 4-6. The frequency synthesizer that was used is very sensitive to temperature changes and causes each step imposed on the input frequency to be slightly uneven.

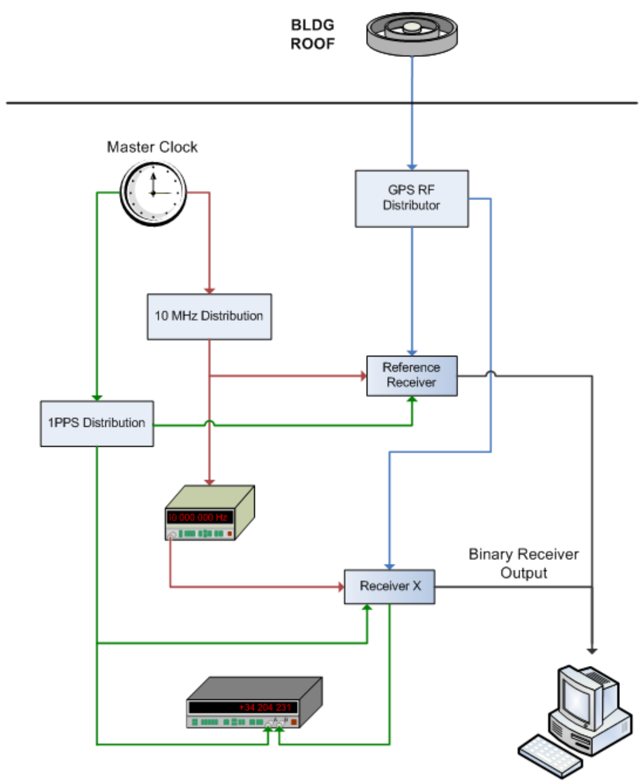


Figure 3. Test setup for power-cycle retrace and tick-to-phase repeatability.

Figure 4 illustrates the desired results, demonstrated by the NovAtel ProPak-V3 receiver. Each step represents a 5 ns shift in the phase of the frequency reference given to 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.

At one of the steps, a very large jump, far in excess of 5 ns, is observed; this is expected. There will be a jump every time the phase shifts far enough to cross the wavelength of either itself or the receiver's internal oscillator. This jump is due to the arrival of the input pulse crossing to the leading edge of the next wave from the trailing edge of the previous wave. If the previous step is increased 5 ns to correspond to the expected value, and then the new value is subtracted from this expected value, the resultant number is approximately 50 ns. This corresponds to an internal oscillator frequency of 20 MHz.

The Javad and Septentrio receivers both show this behavior. As seen in Figure 5, the Javad Delta G3T, when operated in timing mode, has an internal ADC sampling frequency of 80 MHz. Results of the previously tested Septentrio PolaRx2eTR **[2]** is displayed in Figure 6. Although untested, it is expected that the Septentrio PolaRx3eTR Pro would behave similarly, as, according to the manufacturer, the internal frequency and timing synchronization architecture remains unchanged.

The tick-to-phase value to a receiver represents a delay in the receiver timescale. Accordingly, determining the external tick-to-phase is important for proper receiver calibration. Users should be advised to avoid a setup where the tick-to-phase value lies close to a crossover point to prevent an ambiguity in wave selection and/or jumps in the data equal to the wavelength of the oscillator frequency due to a changing selection.

During the retrace and tick-to-phase tests, all receivers behaved as expected.

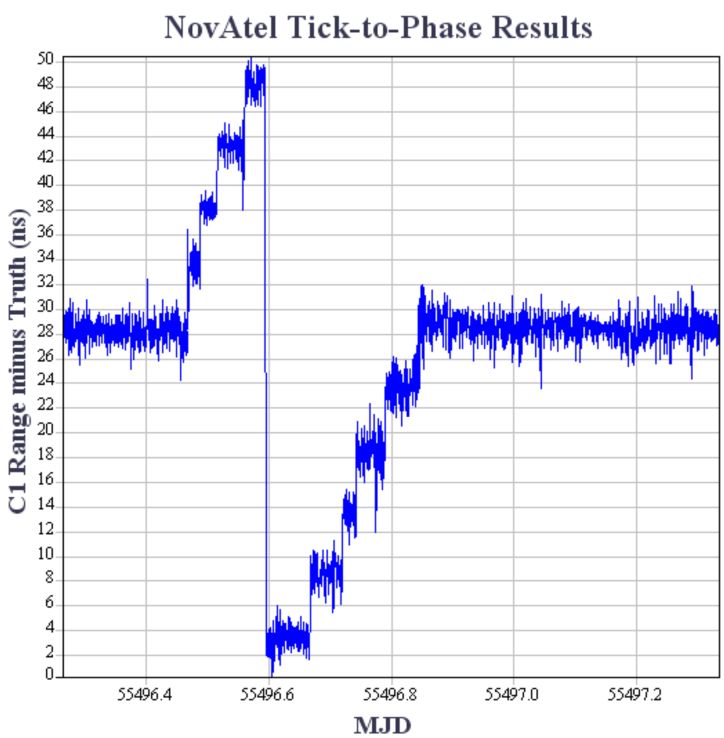


Figure 4. Power-cycle and tick-to-phase test results for the NovAtel ProPak-V3.

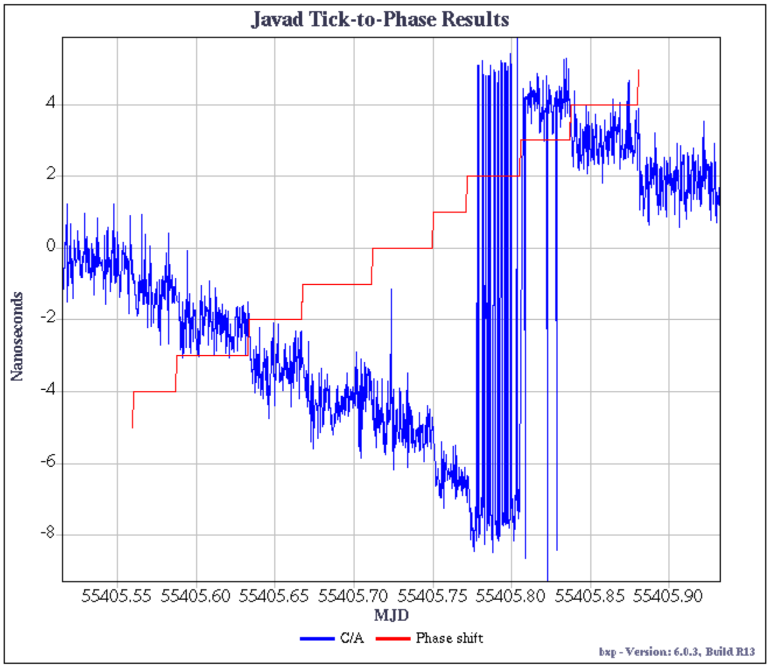


Figure 5. Power-cycle and tick-to-phase test results for the Javad Delta G3T.

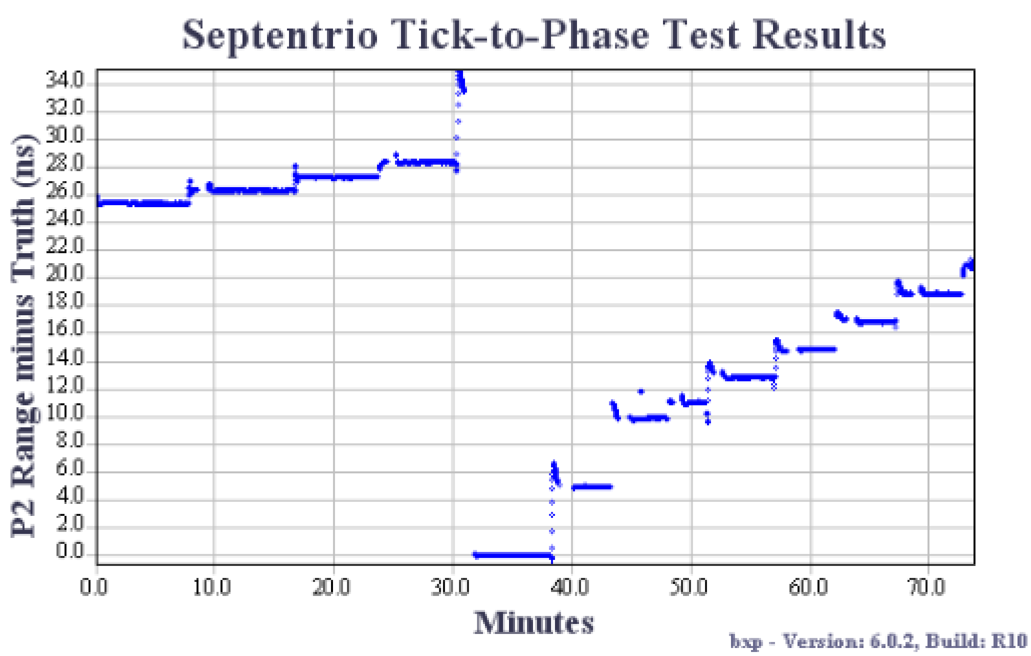


Figure 6. Power-cycle and tick-to-phase test results for the Septentrio PolaRx2eTR **[2]**.

RECEIVER STABILITY TESTING

Three GPS carrier-phase receivers were run side-by-side in a temperature-controlled room with a common clock and antenna feed for two weeks. We then differenced the raw pseudorange data.

Common mode error sources will tend to cancel, but if receivers are employing different correlator types, multipath errors may not completely cancel. The differenced RINEX data sets were compared using a three-cornered-hat analysis and methods developed by Torcaso *et al.* **[5]** to deduce individual stabilities. The Javad Delta G3T was unavailable for this analysis; an Ashtech ZXII3T was used in its place.

There are only results for L1 C/A and L2 P(Y) codeless, since the NovAtel ProPak-V3 receiver does not produce codeless measurements for L1 P(Y). The results of the three-cornered-hat are shown in Figures 7a-b below. The three-cornered-hat method requires that several assumptions and conditions be fulfilled to get pertinent results; from Audoin and Guinot **[4]**:

- The clocks have comparable quality
- Their fluctuations are not correlated
- Measurements are made simultaneously
- Uncertainty in the estimation of the stabilities is sufficiently small. The particular condition that breaks down has not been determined at the time of publication of this paper.

The Torcaso *et al.* analysis, shown in Figures 8a-b below, treats the uncertainties introduced by the assumptions of non-correlation in the three-cornered-hat method, which usually begins to fail at large tau. The small-tau slope of each signal is given in Table 2.

Table 2. Small-tau slopes.

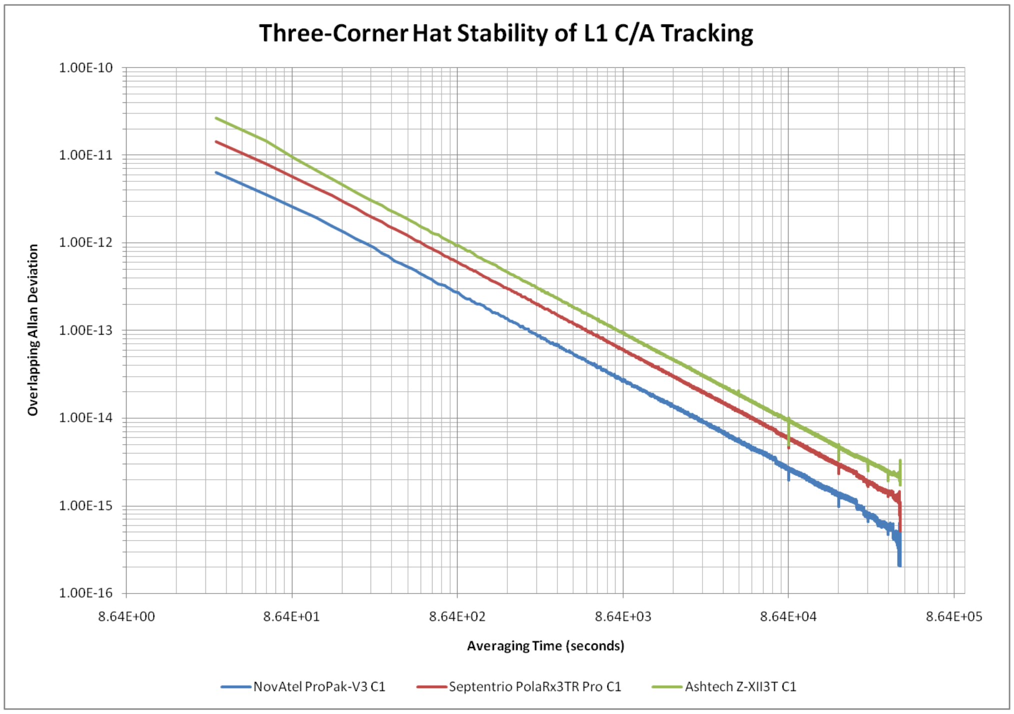
Receiver	tau = 1000	
	C/A	P2
NovAtel ProPak-V3	-0.94	-0.92
Septentrio PolaRx3eTR	-0.98	-0.98
Ashtech ZXII3T	-0.99	-0.98

The L1 C/A and L2 P(Y) code measurements show a mostly straight line with slope -1. This indicates that receiver delay variations are not evident in the code measurements.

CONCLUSION

The Septentrio PolaRx3eTR yielded the best temperature stability in each code and carrier-phase measurement, fixing the high L2 instability in the previous version. The Javad Delta G3T showed vast improvements in both code and carrier-phase groups. The NovAtel ProPak-V3 receiver demonstrated similar performance in carrier-phase measurements to those previously recorded, but worse code measurements. The change in code delays now coincides with the change in carrier-phase delays. For the power-cycle retrace and tick-to-phase tests, each receiver reacted as expected. Each shift to the input phase resulted in a corresponding jump in the 1 PPS output.

The Septentrio PolaRx3eTR and Javad Delta G3T receivers both improved over their previous versions and, along with the NovAtel ProPak-V3, perform well as timing receivers. It should be noted that the Javad Delta G3T was difficult to place in timing mode, but once in timing mode performed well. These issues could perhaps be attributed to inexperience with the receiver, though the procedure to set the receiver in timing mode is not trivial.



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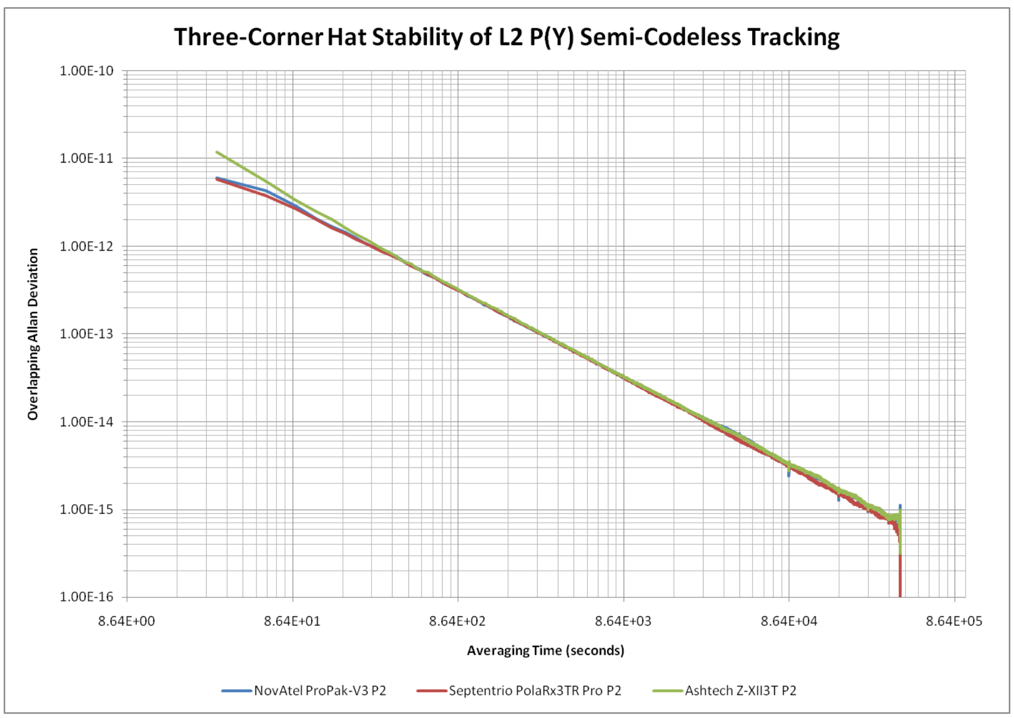
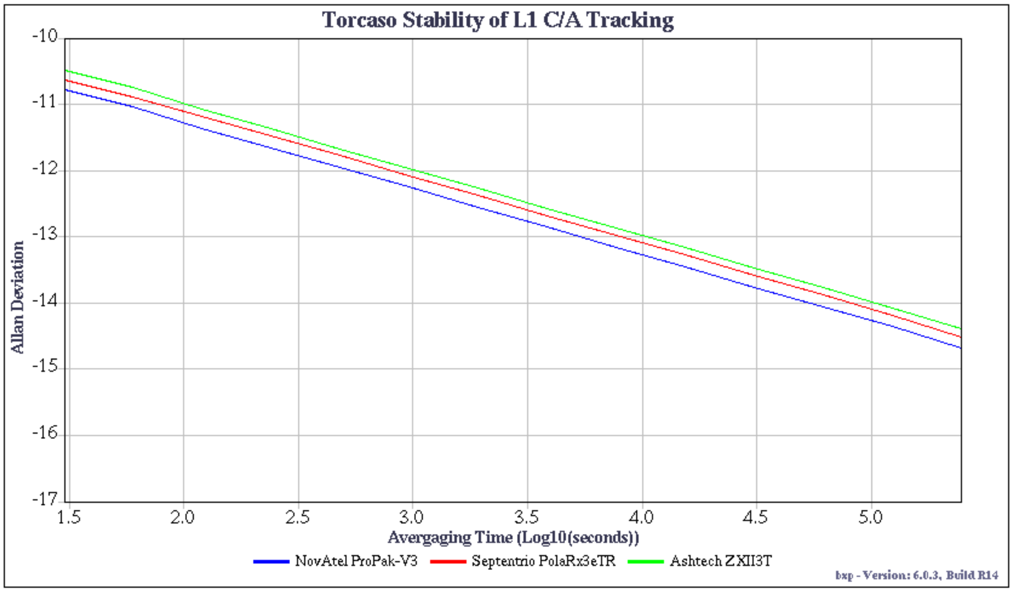


(b)

Figure 7. Three-cornered-hat code analysis.



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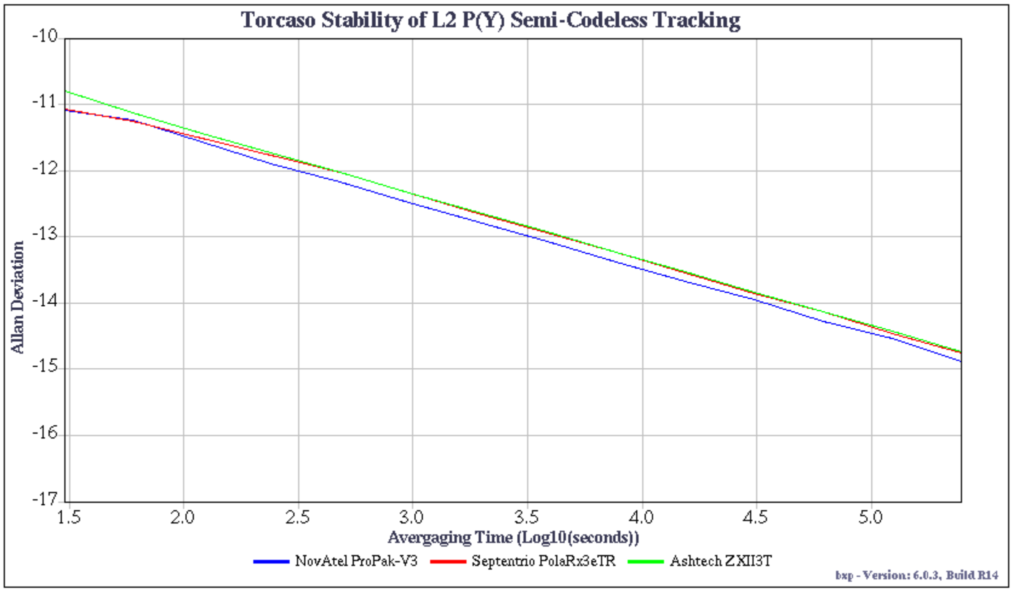

(b)

Figure 8. Torcaso *et al.* code analysis.

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