Timing Calibration of a GPS/Galileo Combined Receiver

Blair Fonville[1], Edward Powers [1], Rigas Ioannides [2], Jörg Hahn [2], and Alexander Mudrak [2]

[1]US Naval Observatory, Washington, DC, USA
[2]European Space Agency - ESTEC, Noordwijk, The Netherlands
blair.fonville@usno.navy.mil

Abstract—Navigation users will soon benefit from multiple GNSS satellite constellations, potentially doubling or tripling the number of usable GNSS satellites. The improved satellite visibility, and reduced dilution of precision (DOP), will be particularly useful in urban canyon environments where sky visibility is challenged. The independent GNSS navigation time scales are typically traceable to UTC (module whole seconds) to better than 50 nanoseconds. To be useful for precision navigation solutions, this error needs to be reduced to below 5 nanoseconds. Therefore in 2004, GPS and Galileo agreed to develop and jointly broadcast a GPS-to-Galileo Time Offset (GGTO) message, which user receivers may use for system-to-system navigation timing traceability.

Working in cooperation, USNO (representing GPS) and ESA (Galileo Project) have agreed upon several methods to compute and coordinate the GGTO values. During the initial stages of the coordination, and throughout Galileo's In-Orbit Validation (IOV) campaign, the different methods will provide validation to the GGTO computations, ensuring the most accurate results.

One of the techniques to be employed by USNO will utilize a GPS/Galileo combined receiver. For its proper application, the special GGTO monitoring receiver must be precisely calibrated to account for its internal time delays among all of the GPS and Galileo channels. In September of 2012, USNO and ESA teamed up to perform calibrations of the USNO and ESA GGTO receivers using a combined GPS/Galileo multi-constellation simulator (Spirent), located at the European Space Research and Technology Centre (ESTEC) in Noordwijk, Netherlands. This paper details the procedures and the results of the experiment.

I. INTRODUCTION

With Galileo's In-Orbit Validation (IOV) phase coming to a close (the first two operational satellites were launched on 21 October 2011, and the second two were launched on 12 October 2012), and the Full Operational Capability (FOC) phase just around the corner, preparations by the U.S. Naval Observatory (USNO) and the European Space Agency (ESA) are underway for the monitoring and estimation of the coordinated GPS-to-Galileo Time Offset (GGTO). Galileo will begin broadcasting GGTO predictions as early as mid-2013. The GGTO predictions will be transmitted by GPS to users as a new set of parameters in the modernized navigation messages. These GGTO messages are designed to enhance GPS/Galileo interoperability by providing user receivers with a convenient way to combine the pseudorange measurements across the two navigation system constellations.

One of the four methods proposed in [1] for GGTO determination involves monitoring the constellation system time offset through the use of GPS/Galileo combined monitoring station receivers. In this technique, each agency will utilize a precisely calibrated timing receiver to simultaneously derive estimations of GGTO. Each monitoring receiver will produce differences of each system time with respect

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to the receiver's local clock; a double-difference estimates GGTO at each site, and the GGTO estimates will then be compared daily between USNO and ESA.

$$\Delta_{GPS} = GPS_t - CLK \tag{1}$$

$$\Delta_{GAL} = GAL_t - CLK \tag{2}$$

$$GGTO = \Delta_{GPS} - \Delta_{GAL} \tag{3}$$

Equation (1) describes the receiver's estimation of GPS system time with respect to (w.r.t.) the receiver's local clock. Equation (2) shows the receiver's estimation of Galileo system time w.r.t. the receiver's clock. And equation (3) shows the estimation of GGTO, where the double-difference removes the local clock. It is anticipated that daily comparisons of the GGTO estimations computed at each site will yield agreements of 5 nanoseconds (ns) 2 sigma.

$$|GGTO_{USNO} - GGTO_{ESA}| < 5\ ns\ (2\sigma) \tag{4}$$

Of course in order meet such demanding requirements, careful calibration of the inter-code, and inter-system, biases must first be conducted. In September of 2012, USNO and ESA teamed up to perform initial calibrations of two candidate GGTO monitoring receivers. This paper details the calibration procedures and takes a first look at the results obtained.

II. OBJECTIVES

A commonly used technique for achieving highly accurate and repeatable results for GNSS receiver calibration uses GNSS hardware simulators [2]. Today's technology facilitates GNSS simulators which are able to generate multi-constellation signals, comprising code families from each of the constellations and their respective frequency bands. The simulator generates two signals pertinent to receiver calibration: the GNSS signal in space (SIS), and a one pulse-per-second (1PPS) timing reference. These signals are applied to the receiver and tracked to produce pseudoranges for post-processing comparison to the true simulated ranges. The first step in the process is to calibrate the simulator itself. This ensures that timing biases introduced by the simulator, between each code family and with respect to the 1PPS timing reference, are known and can be removed from the true range data set.

For the GGTO receiver calibrations, we used a Spirent Communications GNSS simulator. Our first objective was to evaluate the simulator's suitability to serve as a calibration tool for GGTO time monitoring receivers. We analyzed and calibrated the simulator using a high-speed 20 GSa/s digital oscilloscope, and then performed an initial calibration of our GPS/Galileo combined receivers: a Septentrio PolaRx3eTR PRO and a Septentrio PolaRx4eTR PRO. The details of this process are provided in subsequent sections of this paper.

For this first iteration of testing we focused on the following GNSS signals:

- L1 Band (1575.42 MHz)
    - Galileo E1B/C
    - GPS C/A
- L5 Band (1176.45 MHz)
    - Galileo E5A
    - GPS Civil L5

Future tests will include GPS L2 P-Code and Galileo E5A+B as a composite signal.

Our primary objectives are then:

1. Evaluate the suitability of the multi-constellation simulator;
2. Produce preliminary GGTO receiver calibration;
3. Confirm the results using independent methods;
4. Establish a repeatable GGTO calibration methodology.

III. GNSS HARDWARE SIMULATOR CALIBRATION

The L1/E1 and L5/E5 signals used for this test were produced from an RF-combined output of physically separated simulator units, as shown in Figure 1. The GPS L1 signals were synthesized from one unit, GPS L5 from another, and the Galileo E1 and E5 signals from a third. Although the Spirent simulator's signals are expected to be largely factory-calibrated at its front RF transmission port, the signal powers at this main output are representative of GNSS SiS levels observed by a user on the surface of the earth, and are not directly viewable on an oscilloscope. We therefore manually combined the RF outputs of the three units from the rear panels' Mon/Cal ports, which provide signal levels 50 dB higher, and then amplified the sum using a low-noise 40 dB amplifier. The conditioned composite signal was then supplied to the oscilloscope for calibration, using the reference 1PPS as the trigger.

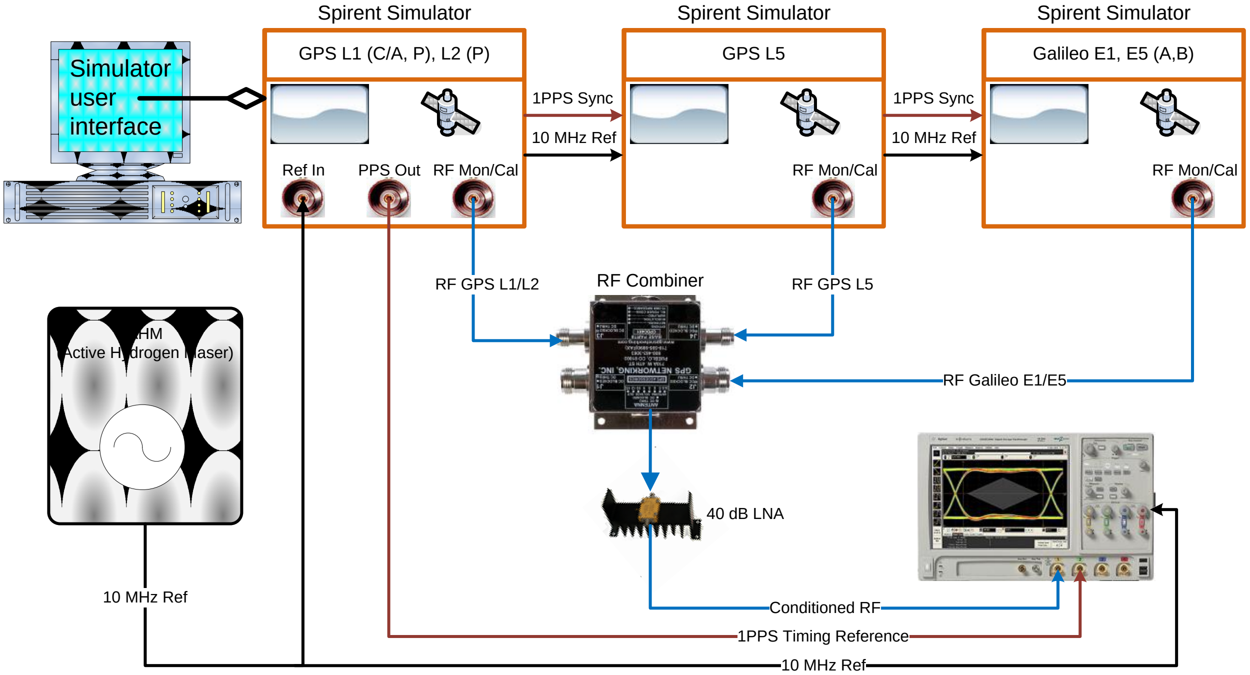
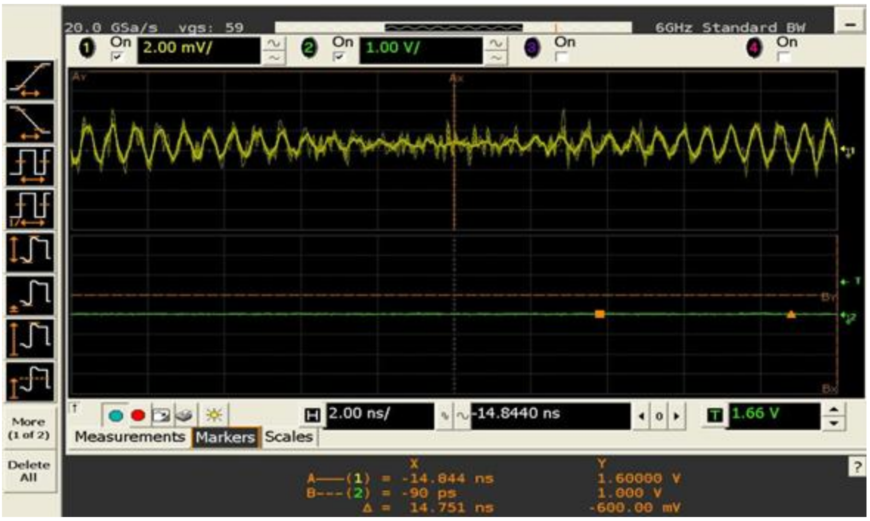


Figure 1. Simulator calibration, hardware setup.

Measuring code-offsets w.r.t. the 1PPS reference provides the data necessary to perform absolute calibrations of the receivers. While we only require relative differences between the GPS and Galileo codes for GGTO monitoring, obtaining absolute measurements yields more comprehensive troubleshooting figures, should we experience changes in receiver delays during future operation.

To perform the calibration we configured the simulator to operate in a unique mode where a single satellite was enabled for broadcast and the simulated receiver position was set equal to the position of the satellite, thus producing a zero-range, zero-Doppler scenario. The RF signal displayed on the oscilloscope was therefore stationary w.r.t. the 1PPS trigger. Any phase delay between the 1PPS trigger and the code's first chip transition represents the calibration correction for that individual code. This was performed for each code in each applicable band, for both GPS and Galileo. An example C/A chip transition is shown below in Fig. 2.

Prior to viewing the signals, we configured all simulated vehicles to operate with atmospheric effects disabled, clock correction terms set to zero, orbital perturbation models unused, and we disabled all other effects which would otherwise cause varying delays between the GPS and Galileo code families.



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                 X                 Y
A——(1) = -14.844 ns       1.60000 V
B---(2) = -90 ps           1.000 V
     Δ =  14.751 ns     -600.00 mV
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Figure 2. C/A chip transition located at -14.75 ns offset from reference 1PPS.

IV. GNSS RECEIVER CALIBRATION

With a full set of measurements collected from the oscilloscope for the simulator calibration, we were able to replace the oscilloscope with the GNSS receivers to collect pseudoranges. We note that it is important to remove any delays associated with equipment which is introduced solely for viewing the signals on the oscilloscope. In particular, delays in the LNA and its cabling were measured on a network analyzer. As shown in Fig. 3, the setup for receiver operation was otherwise unchanged from that of the simulator calibration.

For receiver tracking, we operated full GPS + Galileo scenarios. In each scenario we chose a GPS satellite and replicated all of its orbital parameters to a Galileo satellite. This provided us two space vehicles, one from each constellation, which behave as a single unit – overlapping each other in position, time, and motion. A calibrated difference of the receiver's pseudorange measurements for that satellite, therefore, provides us immediate code-bias results.

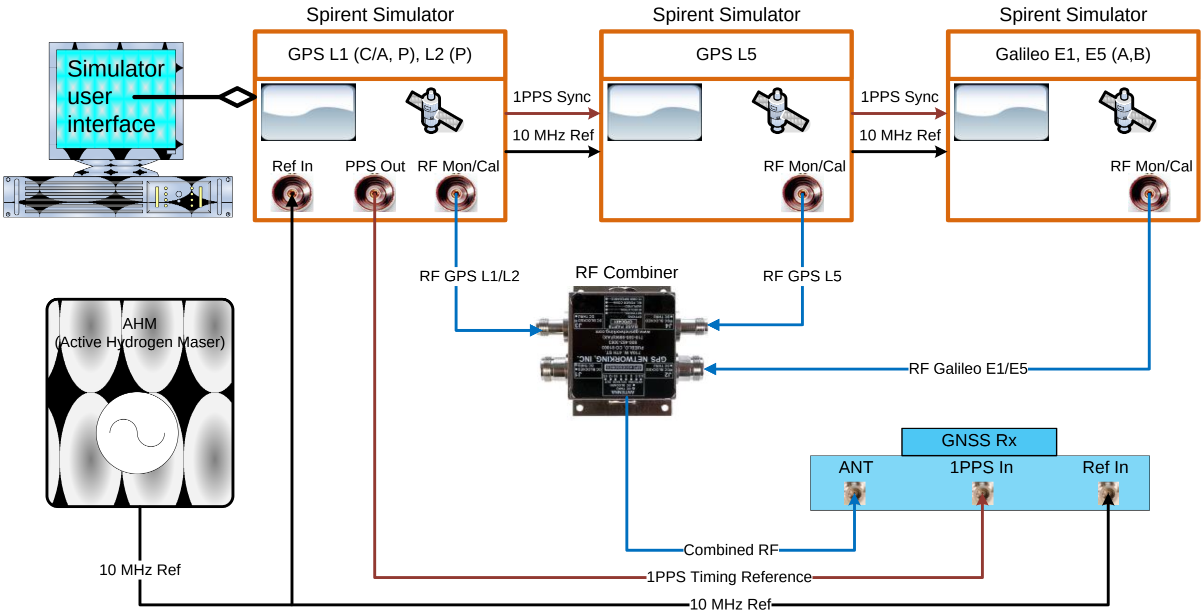


Figure 3. Receiver calibration, hardware setup.

V. CALIBRATION RESULTS

Relative calibration results for the Septentrio PolaRx4eTR are shown in Figures 4 and 5. Figure 4 shows that the receiver tracked the L5/E5 bands with solutions that settled nearly 8 ns ahead of the L1/E1 results. Such delays are not unexpected in receiver tracking as band-limiting filters, receiver correlator spacing, and internal channel delays all contribute to overall receiver pseudorange estimations [3].

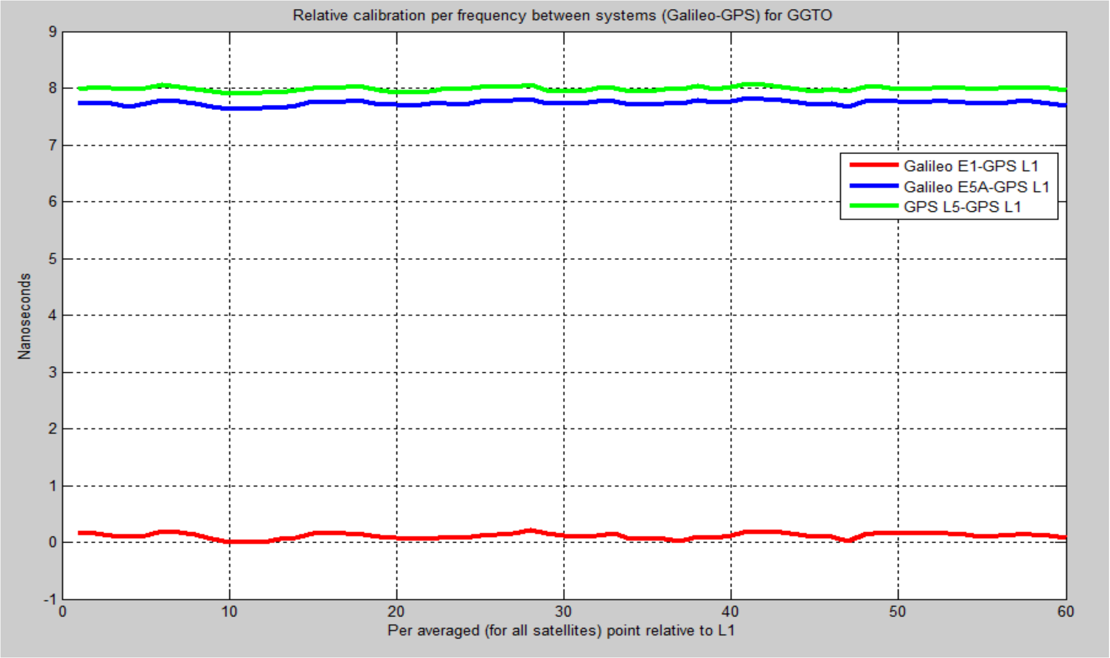


Figure 4. Relative receiver calibration results for PolaRx4eTR w.r.t. GPS L1 (C/A).

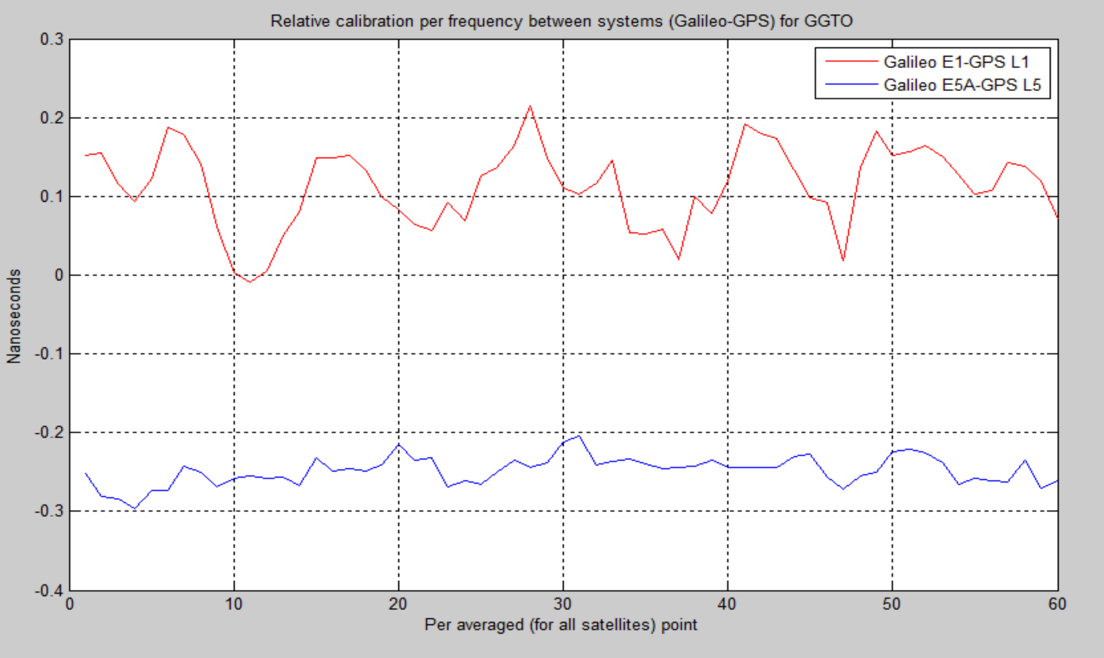


Figure 5. Relative receiver calibration results for PolaRx4eTR differenced by frequency band.

The PolaRx3eTR produced slightly different results, as shown in Fig. 6. Both receivers exhibited tightly grouped L1-E1 pseudoranges (approx. 100 ps separation for the PolaRx4eTR and 700 ps for the PolaRx3eTR) but, whereas the PolaRx4 produced small differences between E5 and L5, the PolaRx3 introduced a bias between the two codes of approx. 3 ns. Again, this can be explained if the older model receiver tracked the two codes using unique correlator spacing configurations, but this 3 ns bias is otherwise not yet fully investigated. It is also interesting to note that the 8 ns (L5/E5)-(L1/E1) difference seen in the PolaRx4 did not appear in the PolaRx3. The L5 minus L1 (C/A) average was only 1.1 ns.

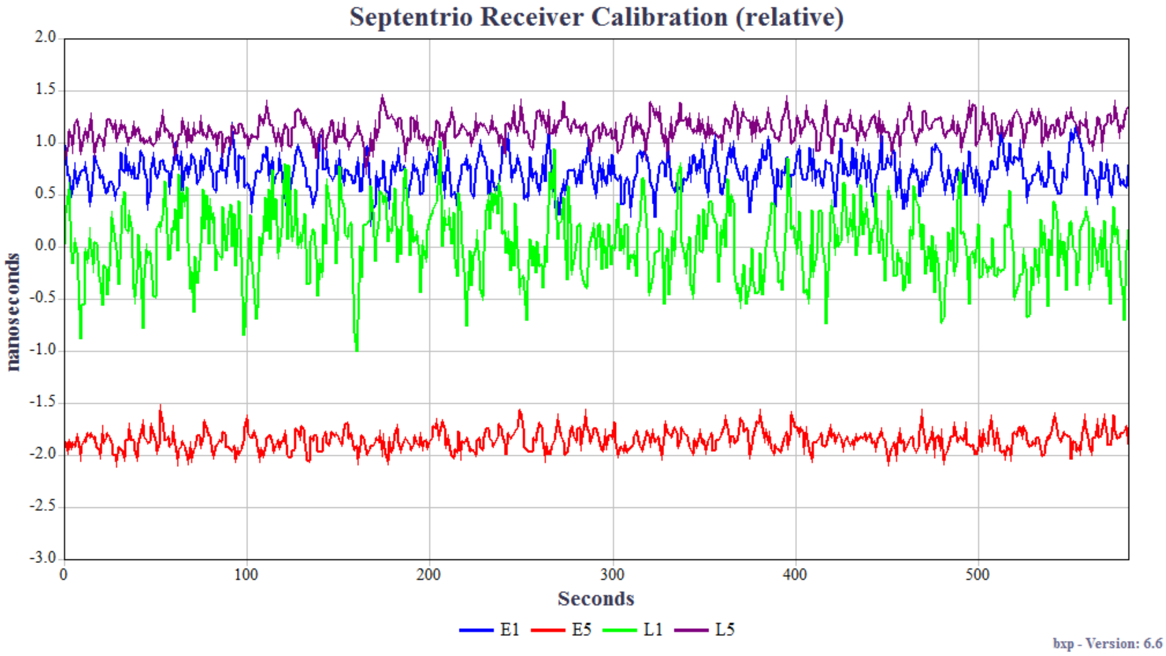


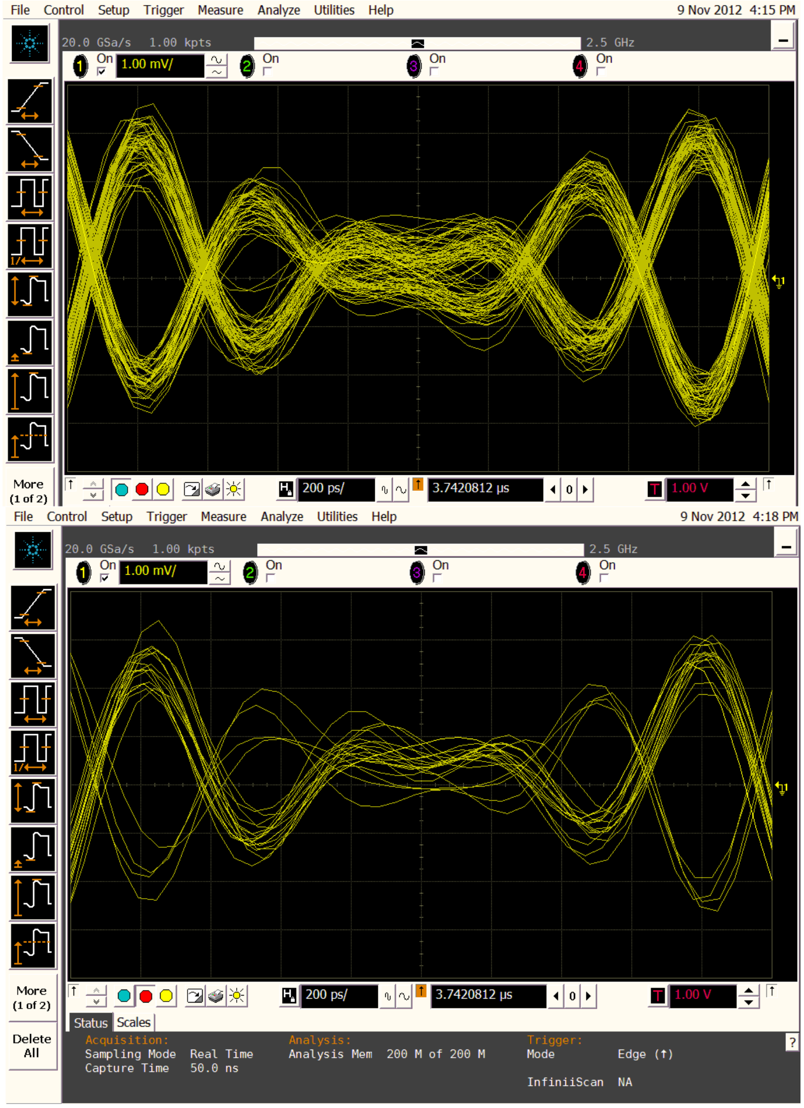
Figure 6. Relative receiver calibration results for PolaRx3eTR.

VI. CONFIRMATION OF RESULTS

In an effort to validate the data collected in the initial calibration, we later repeated the exercise described in the preceding sections using two independent GNSS simulators: a Rohde and Schwarz SMBV100A, which the manufacturer provided us for evaluation; and a simulator denoted AGNS, developed by the U.S. Space and Naval Warfare Systems Command (SPAWAR).

A. Confirmation via Rohde and Schwarz SMBV100A

The SMBV100A, which is a Vector Signal Generator (VSG), was loaned to us with L1/E1 signal generation options enabled. We operated the unit in a predefined “Static” satellite simulation mode, which produces C/A and E1 modulated signals with zero Doppler shift. Viewing the signals on an oscilloscope, we learned that the codes are digitally filtered with reasonably wide bandwidth, with no signal distortion (which can result from intermediate-frequency mixing), leading to highly calibratable signals. The chip transitions for C/A (top) and E1 (bottom) are shown in Fig. 7. No discernible code biases were witnessed.



Acquisition:
Sampling Mode Real Time
Capture Time 50.0 ns
Analysis:
Analysis Mem 200 M of 200 M
Trigger:
Mode Edge (↑)
InfiniiScan NA

Figure 7. Rohde and Schwarz SMBV100A code transitions. Top – C/A, Bottom – E1.

While the static mode configuration proved to be an excellent tool to verify the simulator's code generation integrity, the unit was not in our possession long enough to learn the necessary steps to build the custom dynamic scenarios necessary for full GGTO receiver calibration. The current state of the device does not offer a method to retrieve records of simulated truth ranges, so, using the PolaRx3 we settled on tracking the 2-SV static-mode configuration. Figure 8 shows the results. Whereas the previous calibration (using the ESTEC Spirent) produced a negative 700 ps L1-E1 offset, the SMBV100A resulted in a positive 700 ps, leading to a 1.4 ns discrepancy.

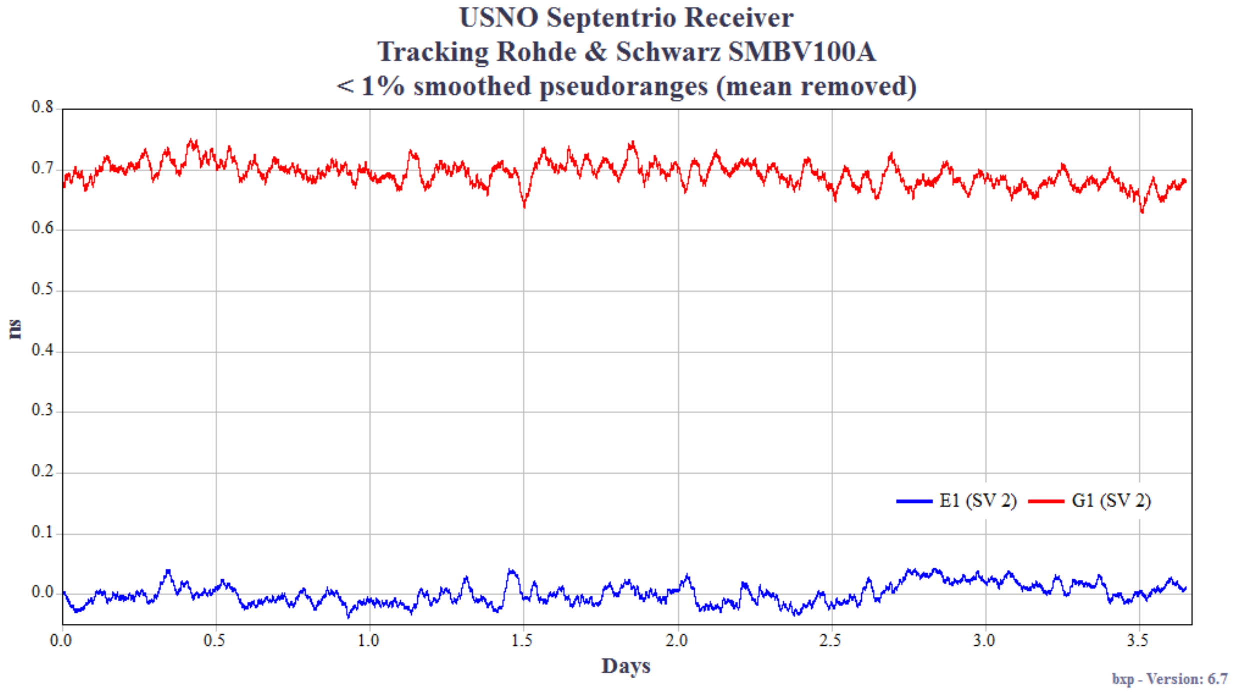


Figure 8. PolaRx3 relative calibration using SMBV100A.

B. Confirmation via AGNS

USNO's SPAWAR AGNS simulator was recently upgraded to include the L5 band for GPS. AGNS is a highly-configured FPGA-based GPS hardware simulator. As it has been part of USNO's test bench for many years, its operation is well-understood. While it does not facilitate simulation of Galileo signals, we were able to precisely repeat our original procedures to confirm the Spirent calibration results between L1 and L5.

Initiating the zero-range, zero-Doppler mode, we applied the signals to the oscilloscope and recorded the simulator calibration values for the L1 C/A and L5 codes. As before, we then generated a full-motion simulation and provided the RF signal to the receiver. In this case, we did not need to replicate orbital parameters, as we were only simulating GPS signals. As shown in Fig. 9, the calibrated C/A-L5 pseudorange differences averaged to -1.2 ns, a difference of only 100 ps from the previous calibration done with the Spirent simulator at ESTEC.

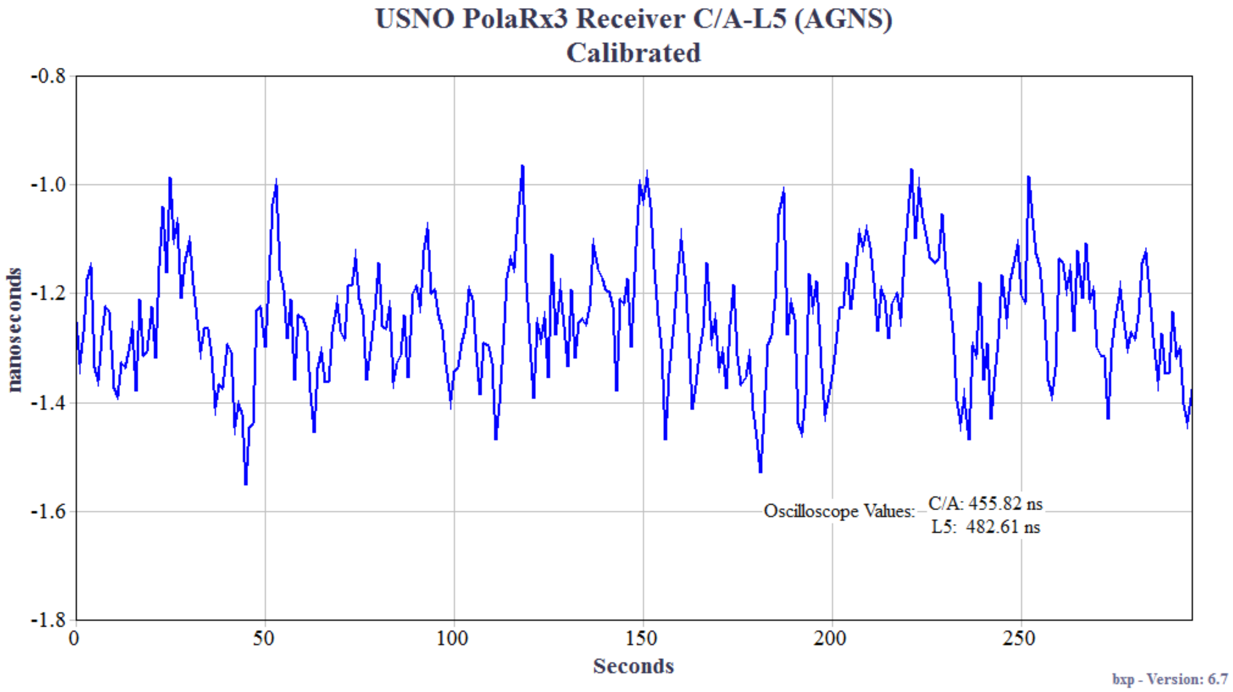


Figure 9. PolaRx3 relative calibration using AGNS. Average bias: -1.2 ns.

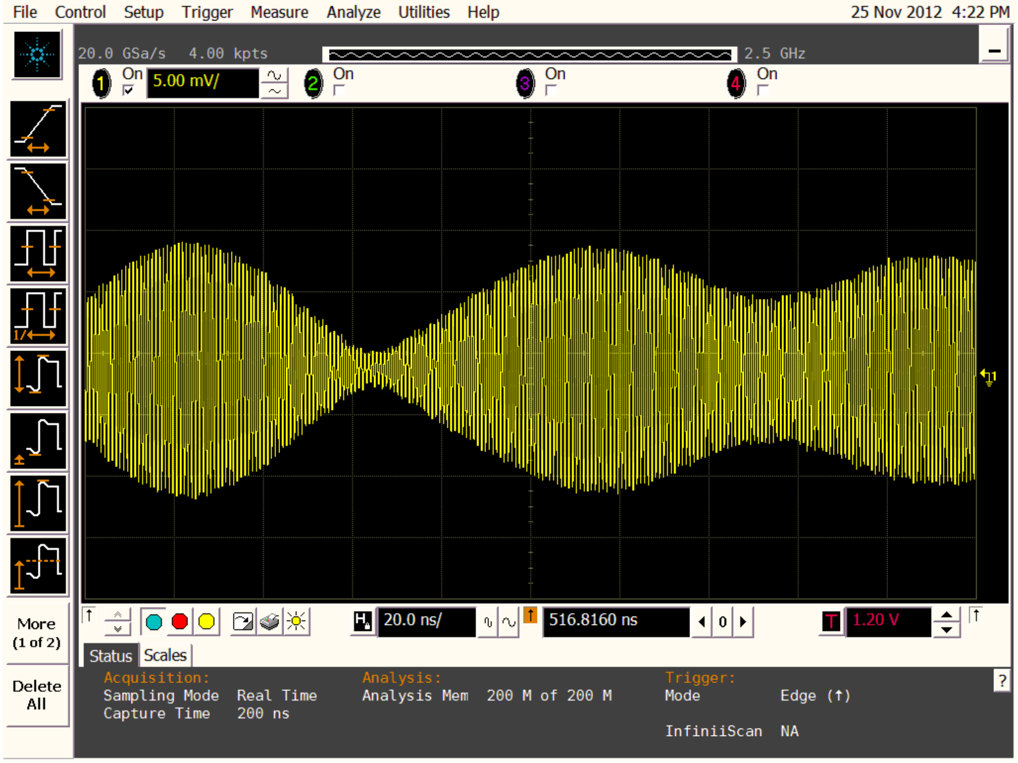
VII. CONCLUSIONS

With components of our initial calibration confirmed to within 1.5 ns by two independent GNSS signal sources, we were able to establish confidence in our procedures. However, as the specified performance of GGTO is defined to have an accuracy of 5 ns (2-sigma) [1], we will be required to maintain calibration repeatability < 1 ns. A good understanding of the error sources involved in the calibration discrepancies will help us achieve this goal.

Familiarity of the RF filtering processes implemented in each simulator, along with knowledge of the correlator spacings used by the GGTO monitoring receivers, will allow us to model and remove pseudorange biases due to associated tracking misalignments [3].

Additional calibration errors arise due to human error when attempting to determine the location of chip transitions on the oscilloscopes. Non-BPSK codes can be difficult to manually calibrate using this technique due to their code complexities. Furthermore, depending on the simulator’s frequency architecture, intermediate-frequency up-conversion processes can lead to harmonic mixing distortions, resulting in poorly defined chip transitions, as shown in Figure 10. We are currently working on measures to reduce the errors associated with manually determining the chip transition timings. Figure 11 demonstrates a tool we are developing which operates in real-time within the oscilloscope to automatically locate the precise timing of the chip transitions. This tool is especially useful for the GPS P-code, where the chip transitions come in and out of view with each successive trigger, as the P-code is longer than the 1-second trigger time. In this case, the custom tool only includes calculations in its running average when a transition is actually present.

As we work closer to reaching our final objectives, we are continually refining our methods. While our initial calibration is promising, we anticipate much iteration will be necessary before achieving consistent repeatability under 1 ns.



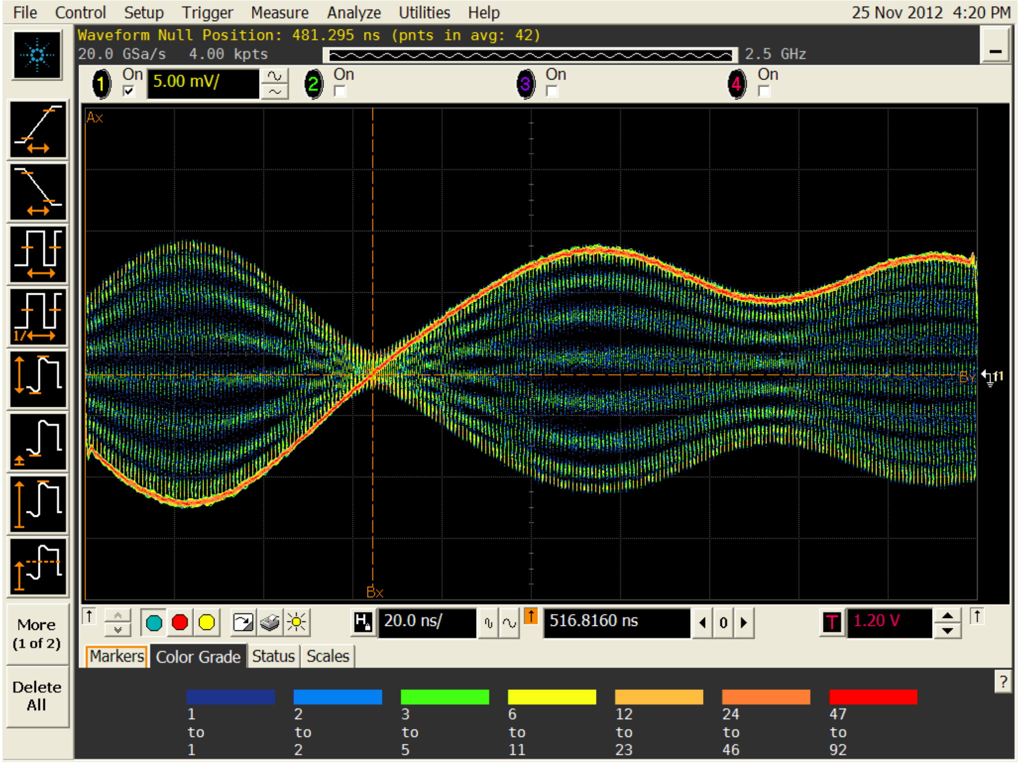
Acquisition:
Sampling Mode Real Time
Capture Time 200 ns

Analysis:
Analysis Mem 200 M of 200 M

Trigger:
Mode Edge (↑)

InfiniiScan NA

Figure 10. Example of an ill-defined chip transition.



Waveform Null Position: 481.295 ns (pnts in avg: 42)

Figure 11. Custom tool to automatically locate precise timing of chip transition.

DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, neither USNO nor ESA endorses any commercial product, nor do we permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

REFERENCES

[1] J. Hahn and E. Powers, 2005, "Implementation of the GPS to Galileo Time Offset (GGTO)," in Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada (IEEE 05CH37664C), pp. 33-212.

[2] J. Plumb, K. M. Larson, J. White, and E. Powers, 2005, "Absolute calibration of a geodetic time transfer system," IEEE Trans UFFC 52(11), pp. 1904–1911

[3] C. J. Hegarty, E. D. Powers, and B. Fonville, "Accounting for Timing Biases between GPS, Modernized GPS, and GALILEO Signals," Proceedings of the 18th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2005), Long Beach, CA, September 2005, pp. 2401-2407.