Measuring the Timing Accuracy of Satellite Time and Location (STL) Receivers

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ABSTRACT

We present measurements of the timing accuracy and stability of Satellite Time and Location (STL) receivers with respect to UTC(NIST), the coordinated universal time scale (UTC) operated by the National Institute of Standards and Technology (NIST). Operated by Satelles, STL is a timing and location service that utilizes the Iridium constellation of 66 low Earth orbit (LEO) satellites. The service is available globally and resilient to regional outages of the Global Positioning System (GPS). We demonstrate that a typical STL receiver with an oven-controlled crystal oscillator (OCXO) can provide a stable output pulse with an average time offset near 10 ns and a maximum time offset of less than 200 ns with respect to UTC(NIST). We also present measurements of an STL receiver with a local rubidium oscillator that demonstrates improved short-term stability and a maximum time offset of less than 75 ns.

1. INTRODUCTION AND BACKGROUND

Numerous critical infrastructure operations currently require time accurate to within 1 µs or better [1] and typically are dependent on GPS disciplined clocks to provide this accuracy. The vulnerabilities of GPS and other Global Navigation Satellite Systems (GNSS) are well documented [2] and the large economic losses that can result from extended GPS signal outages have been extensively studied [3]. These factors point to the obvious need for alternative timing solutions that can provide an accurate time reference in areas where GPS signals are either not available or have been compromised.

The Satellite Time and Location (STL) provides a positioning, navigation, and timing (PNT) service using the Iridium constellation of low Earth orbit (LEO) satellites. The Iridium satellite constellation consists of 66 active satellites in polar orbit at an altitude of approximately 780 km and an inclination of 86.4°. The orbital period (from pole to same pole) is roughly 100 minutes. The 66 active satellites are equally dispersed in six orbital planes, spaced 30° apart, with 11 satellites in each plane.

Due to the proximity of LEO satellites (25 times closer to the Earth than GNSS satellites) and a high-power satellite signal, STL signal strengths at ground level are 1,000 times (30 dB) stronger than GPS, allowing them to penetrate into GPS-challenged environments where signals are obstructed or degraded, including indoors and underground. The complex, overlapping beam patterns of the satellites combined with signal authentication techniques allow STL to deliver a trusted time and location capability that is highly secure. Commercial products that synchronize to STL signals have been available for several years and have consistently demonstrated sub-microsecond accuracy [4, 5].

The intent of this new evaluation was to better measure and quantify the accuracy and stability of the pulse per second (PPS) timing outputs produced by recently developed STL receivers by comparing them to UTC(NIST). This was accomplished by installing STL receivers at the NIST site in Boulder, Colorado and comparing STL time to UTC(NIST) for several months. The initial evaluation used two Evaluation Kit (EVK2) receivers with local oven-controlled crystal oscillators (OCXO), devices that represent the typical commercially available STL receivers in use today. Further evaluation was done using an EVK2 receiver to discipline an external rubidium (Rb) oscillator. Prior to beginning the measurements, all antenna and cable delays were measured, and delay compensation was applied.

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2. MEASUREMENT CONFIGURATION

2.1 Measurements at Satelles

Two STL receivers (EVK2-189 and EVK2-191) were prepared and tested at a Satelles laboratory in Folsom, California where their PPS offset delay was calibrated using a GPS timing reference. The delay calibration of both devices was then verified at a Satelles laboratory in Mountain View, California and the results correlated within a few nanoseconds. The two laboratories used two slightly different setups to make the timing measurements. At the Folsom laboratory the measurements were performed using separate GPS and STL antennas with equal length cables so that antenna and cable delays would mostly cancel (Figure 1a). At the Mountain View laboratory the measurements were performed with a common antenna and cable for the STL receivers and the GPS reference clock so that antenna and cable delays would not be a factor (Figure 1b).

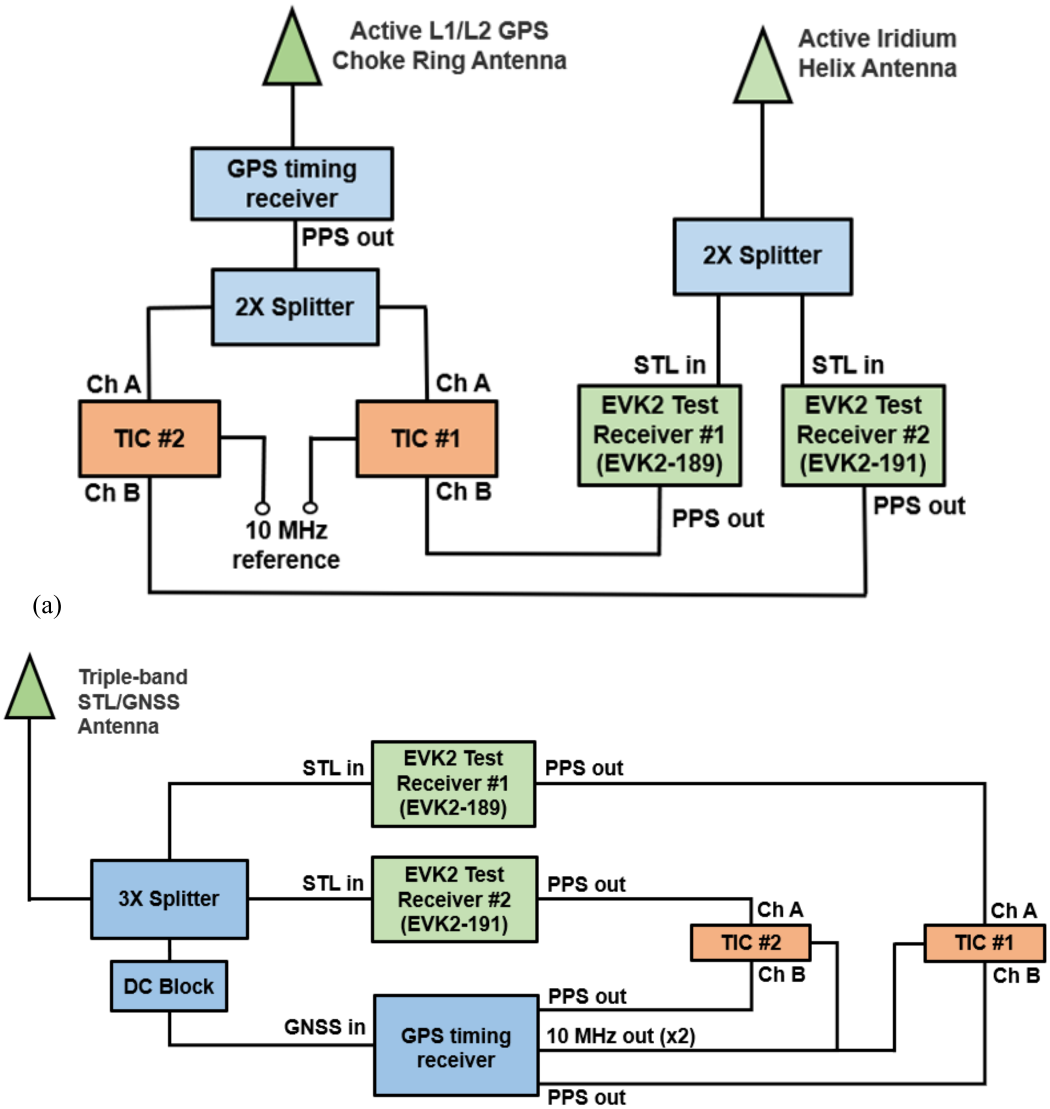
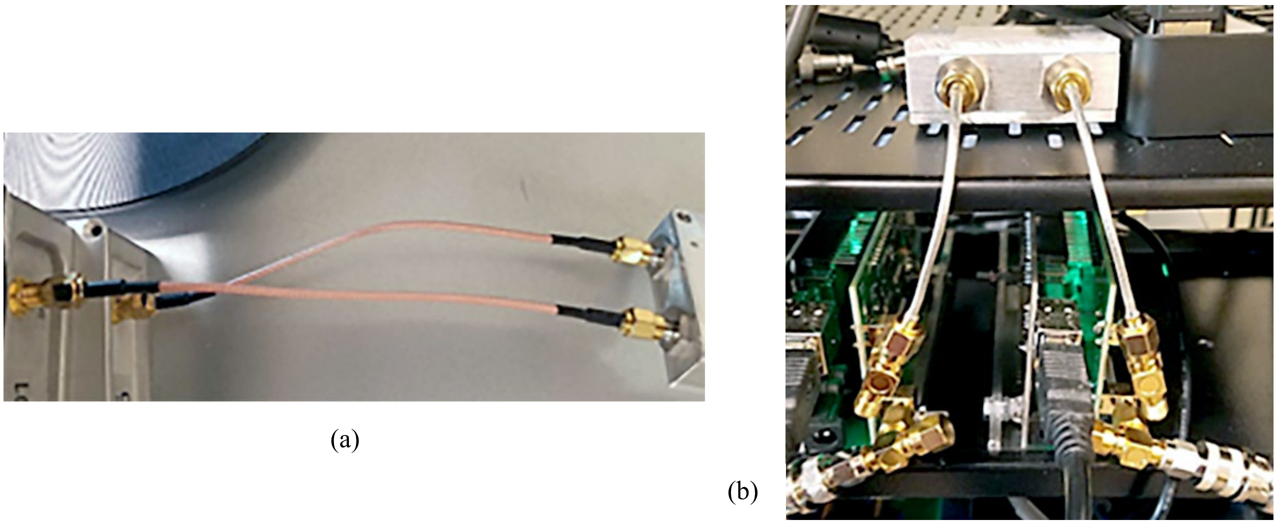


Figure 1. Measurement configurations at the Folsom (a) and Mountain View (b) laboratories.

The Folsom laboratory calibration relied on equal length cables to avoid the need to measure and compensate for cable delays. Examples of matched cables of equal length are shown in Figure 2. Equal length antenna cables were used for the GPS and STL antennas, as well as for the two cables connecting the PPS outputs of the EVK2 and GPS reference receivers to the time interval counter (TIC). The group delay for the Tallysman HC610 Iridium Helix antenna used for the STL receivers in the calibration was measured to be 34 ns with a network analyzer. It was not possible to measure the group delay for the Antcom L1/L2 GPS antenna used for the reference receiver, so it was assumed to be similar. However, it may have contributed to the uncertainty of the initial delay calibration values.



(a) (b)

Figure 2. Equal-length cables for antenna signals to both STL receivers (a) and PPS outputs (b).

A series of baseline measurements were conducted to determine the PPS time differences for the two EV2 receivers compared to the GPS reference at the Folsom laboratory. The final baseline measurements for the EVK2-189 and EVK2-191 are shown in Figures 3(a) and 3(b), respectively. These measurements took place over a 48-hour period on September 14-16, 2021 (MJD 59471 to 59473). The peak-to-peak variation was < 300 ns and the average time offsets were ~202 ns. Therefore, a calibration value of 202 ns was entered into each receiver to compensate for the delay.

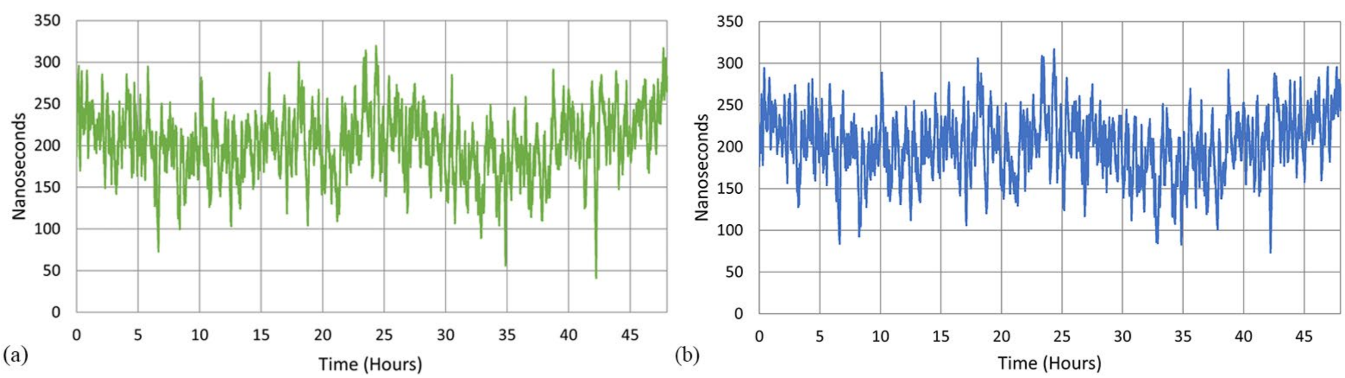


Figure 3. Time differences of two STL receivers compared to GPS at the Folsom laboratory for 48 hours.

After the calibration delay values were entered, additional 24/48-hour measurements were conducted (measurement periods that are even multiples of 24 hours reduce the effects of diurnal variations on the average time offset). The final 48-hour measurement (172,800 data points) was conducted on October 4-6, 2021 (MJD 59491 to 59493). The two receivers, each compensated for delay by 202 ns, produced an average time offset within 0.09 ns of each other, 1.22 ns for EVK-189 and 1.31 ns for EVK2-191, as shown in Figures 4(a) and 4(b).

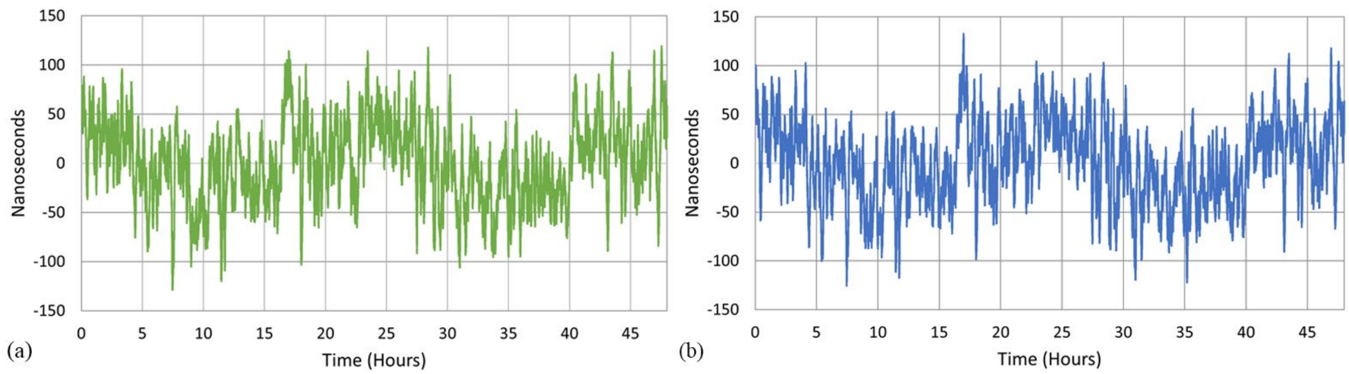


Figure 4. Time differences of two delay compensated STL receivers compared to GPS at the Folsom laboratory for 48 hours.

The Mountain View laboratory calibration setup involved a slightly different approach. A single combined GPS/STL antenna with a common cable run was used to cancel the cable delay instead of the two equal length cables used in the Folsom laboratory measurements. The group delay for this antenna was unknown but assumed to be the same for GPS and STL bands so that it would cancel out in the measurements. If this assumption is not true it would have introduced some error in the delay calibration. The Folsom and Mountain View measurements produced delay calibration values that were in close agreement, but the final offset measurements from Mountain View indicated that the delay compensation should be increased by 6 ns, to 208 ns. It was decided to use this larger delay value instead of the initial 202 ns due to lack of knowledge about the unit delay for the Antcom L1/L2 GPS antenna used by the reference receiver in Folsom. Therefore, a delay calibration value of 208 ns was stored in the configuration of the two receivers prior to shipment to NIST in Boulder, Colorado.

2.2 Measurements at NIST

In November of 2021, the previously calibrated STL receivers were installed at NIST, along with the same signal splitter, antenna cable, and antenna that were used in initial calibrations. The PPS output from both receivers was then simultaneously compared to UTC(NIST) using a datalogger/TIC (Figure 5). The measurements continued for 100 days, from 11/22/2021 to 03/01/2022, MJD 59540 to 59639. The datalogger measures several input channels compared to UTC(NIST) sequentially via a multiplexer, so that only one TIC is needed. Ten-minute averages of the 1 PPS measurements were stored. The average time difference between EVK2-189 and UTC(NIST) was -49.8 ns and -44.0 ns for EVK2-191, shown in Figure 6(a) and 6(b). The average time difference between the two receivers was 5.8 ns.

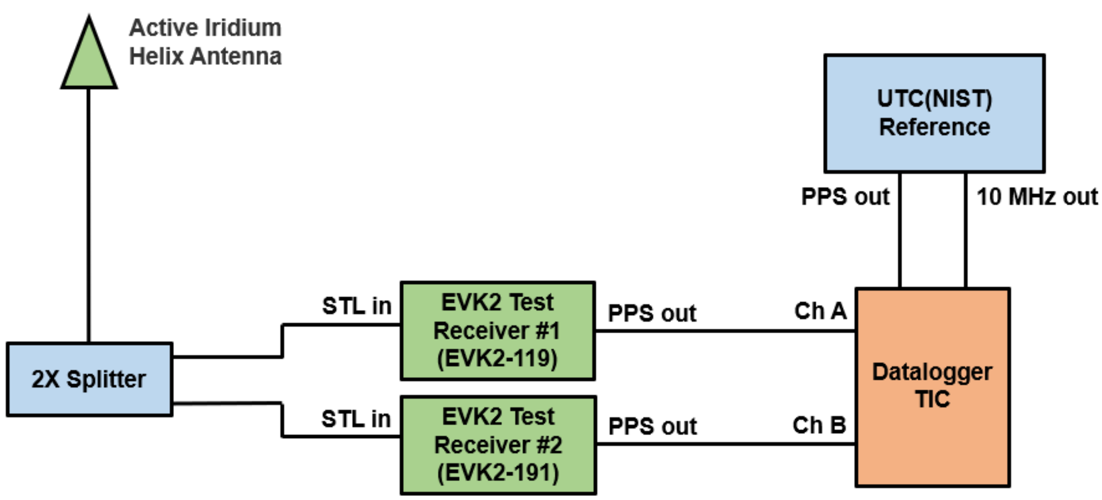


Figure 5. Measurement configuration for comparing two STL OCXO-based receivers to UTC(NIST).

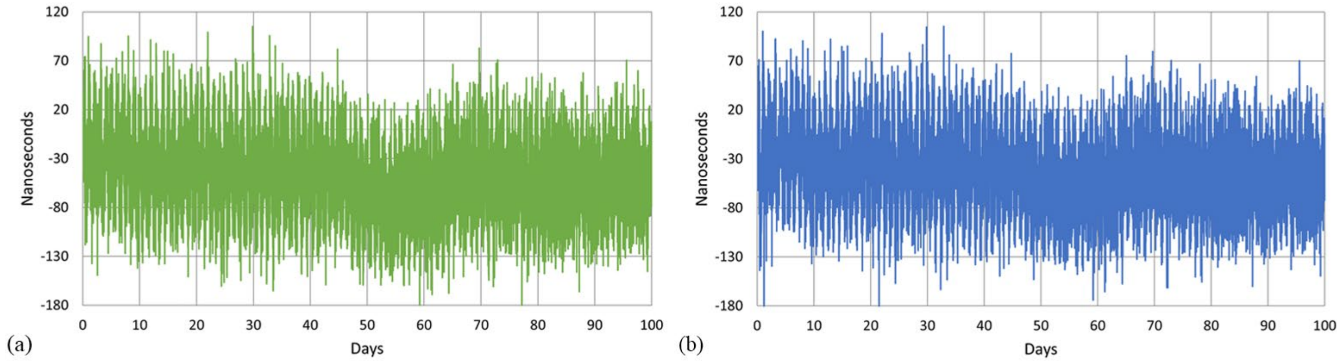


Figure 6. Time differences (ten-minute averages) of two STL receivers compared to UTC(NIST) for 100 days.

The average time offset of STL – UTC(NIST) recorded at NIST differed by more than 40 ns from the STL – GPS time difference previously recorded at Satelles. There are several factors that might explain this discrepancy. The first, and perhaps most obvious factor, is that there was likely some error in the delay calibration of the GPS reference clock at Satelles, as it is difficult to precisely calibrate the receiver and antenna group delays for a GPS clock without access to an independent UTC time scale, and the device had not been previously calibrated by NIST or another UTC(*k*) provider. Another possible factor, albeit a small one, is that the time offset between UTC(USNO, via GPS) and UTC(NIST) may have been different during the Satelles and NIST measurements. However, our investigation shows that this was a non-factor, because during the 48-hour Satelles measurement UTC(USNO, via GPS) – UTC(NIST) was 3.25 ns on average, and that during the 100-day NIST measurement it was 3.23 ns, or essentially the same [6]. Upon further investigation, we found another, less obvious factor that is likely the main reason for the > 40 ns discrepancy. Long-term measurements show that the received STL data has a small linear frequency offset of parts in 10^{15} that can continue for weeks or months, resulting in an accumulated time offset. Section 4 explores this long-term frequency offset in more detail.

After the 100-day measurement was completed at NIST, the delay calibration parameters in the STL receivers were adjusted by an additional 45 ns to bring their average offset with respect to UTC(NIST) closer to 0. Figure 7(a) and 7(b) shows the results for EVK2-189 and EVK2-191, respectively, when compared to UTC(NIST) for a nine-day period (March 15-23, 2021, MJD 59653 to 59661) after the additional delay adjustment. The average time offset during this period was -22.1 ns for EVK2-189 – UTC(NIST) and -14.6 ns for EVK2-191 – UTC(NIST).

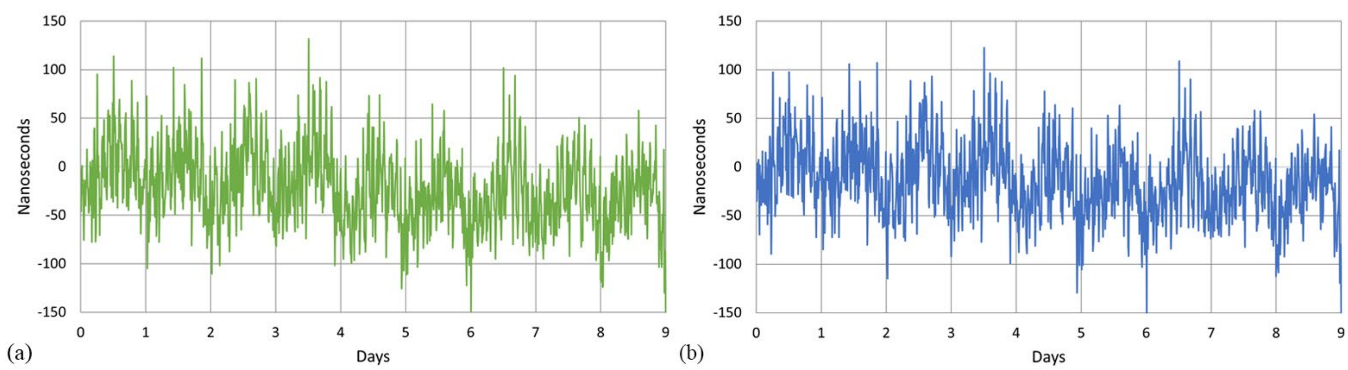


Figure 7. Time differences of two STL receiver after delay calibration, when compared to UTC (NIST) for nine days.

The EVK2-189 receiver was then returned to the laboratory in Folsom to further study the correlation between measurements made at Satelles and NIST. The EVK2-191 receiver remained at NIST for long term data collection. Subsequent timing measurements made at Folsom using EVK2-189 along with other EVK2 receivers (configured to use the same delay calibration value) yielded very similar results.

2.4 Further Measurements at NIST

An additional EVK2 receiver (EVK2-119) with an external rubidium oscillator was delivered to NIST and installed in October 2022 to compare to the OCXO based device (EVK-191). The configuration for this comparison is shown in Figure 8. In an STL receiver firmware the clock model parameter informs the Kalman filter of the estimated frequency stability of the local oscillator, with higher values corresponding to lower stability, and vice-versa. The clock model allows optimization of the tradeoff between relying on the satellite signals for long-term frequency stability, and relying on the local oscillator for short-term frequency stability. A local oscillator with superior stability (such as a rubidium oscillator) and a clock model that takes advantage of that stability, should outperform a less stable oscillator (such as an OCXO), even if an optimal clock model has been selected for the latter.

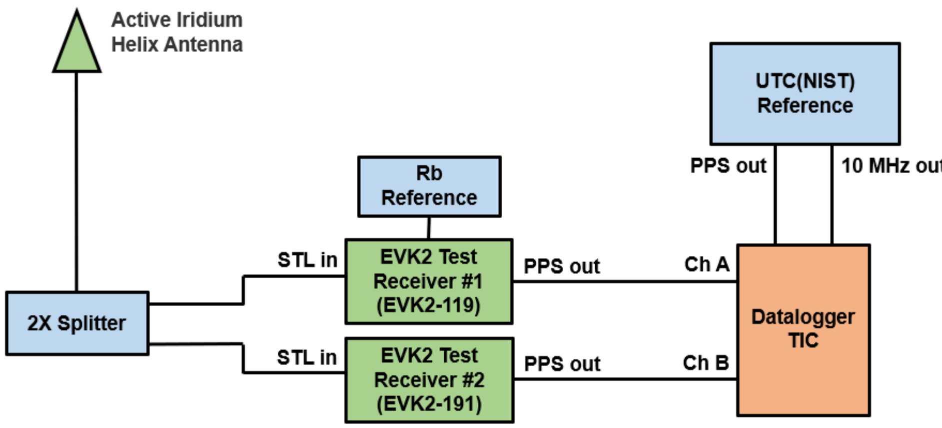


Figure 8. Measurement configuration for comparing OCXO-based and rubidium-based STL devices to UTC(NIST).

Measurements were conducted for 30 days (11/30/2022 to 12/29/2022, MJD 59913 to 59942) with results shown in Figure 9. As expected, the rubidium-based device showed a significant improvement in stability over the OCXO-based device. The rubidium device requires fewer frequency adjustments and so the period of the control loop could be increased. With respect to UTC(NIST), it had a peak-to-peak variation of < 80 ns and an average time offset of 17.6 ns. The OCXO device had a similar average time offset but the peak-to-peak variation was much larger, greater than 300 ns.

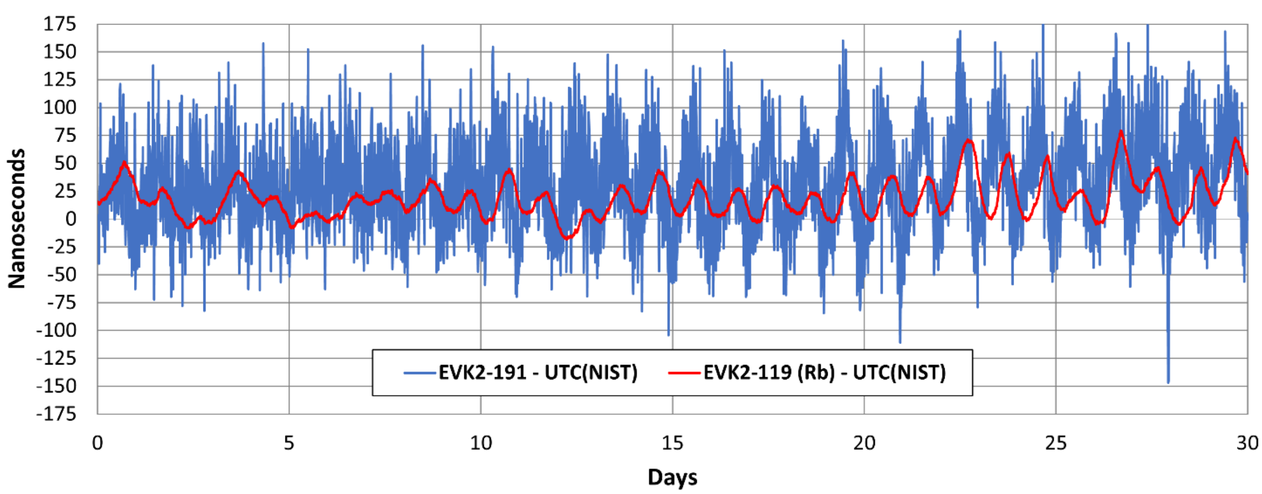


Figure 9. Comparison of STL receivers with rubidium and OCXO local oscillators to UTC(NIST) for a 30-day period.

3. STABILITY ANALYSIS

The previous discussion has focused on the delay calibration of receivers, which improves their time accuracy with respect to UTC(NIST). It is also useful to estimate the stability of their 1 PPS outputs, because their stability during a given period establishes the potential limit of their accuracy during that same period. A standard metric for estimating time stability over a given period is the time deviation (TDEV), $\sigma_x(\tau)$. The symbol τ, or tau, denotes the averaging period [7].

Figure 10 shows a TDEV plot comparing the OCXO and rubidium-based STL receivers to an OCXO-based GPS disciplined clock (GPSDC). The TDEV for the GPSDC is about 2 ns at τ = 1 day, compared to 5 to 10 ns for the two STL devices. These TDEV values establish the limits of each device's potential accuracy at τ = 1 day, assuming that all delays are perfectly calibrated. The EVK2-119 (Rb) is stable to < 1 ns for averaging periods out to about one hour, exhibiting better short-term stability than the GPSDC, but has worse stability than the GPSDC for periods of several hours out to several days. The instability of all three devices reaches a peak at an averaging period of about 12 hours, and the stability advantage that EVK2-119 has when compared to EVK2-191 is only for periods of less than about 18 hours.

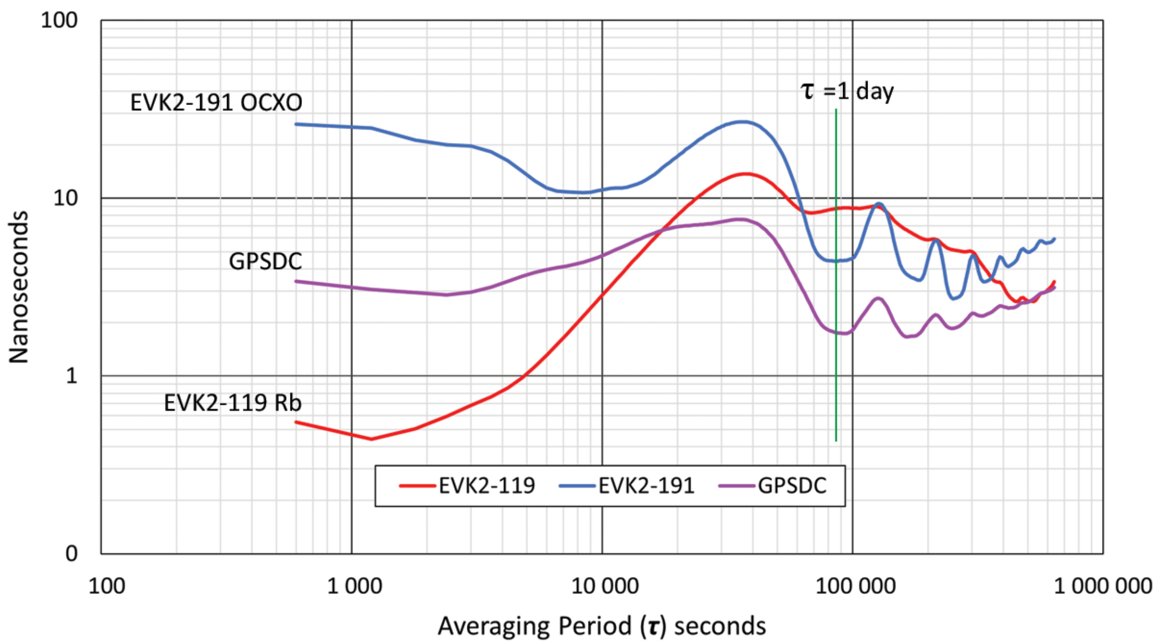


Figure 10. Time stability of two STL receivers and a GPSDC with respect to UTC(NIST).

4. LONG-TERM FREQUENCY AND TIME OFFSET OF STL SIGNALS

Previously (Section 2.2) we discussed a small frequency offset in received STL signals that is noticeable in long-term comparisons with both GPS and UTC(NIST). This frequency offset is negligible in GPS – UTC(NIST) comparisons made during the same intervals. To illustrate this, Figure 11 shows the results obtained from measuring STL – UTC(NIST), via EVK2-191, and GPS – UTC(NIST) for a 100-day period ending on March 1, 2022 (MJD 59540 to 59639). The STL data has a small frequency offset, computed from the slope of a linear fit applied to the phase data, of -2.7×10^{-15}, resulting in a time offset that accumulates at an average rate of about 0.23 ns per day. This results in a change in STL – UTC(NIST) time difference of more than 20 ns during the 100-day period. In contrast, the slope of the GPS data with respect to NIST is barely discernible, with a frequency offset of -0.4×10^{-15}. Therefore, the time offset of GPS changes by only a few nanoseconds in 100 days.

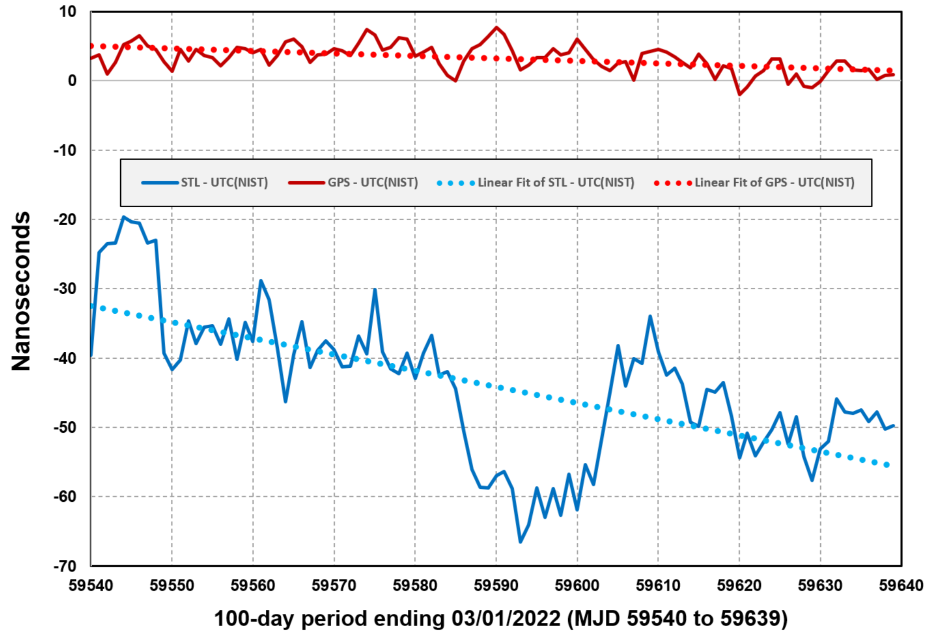


Figure 11. 100-day comparison of STL and GPS to UTC(NIST), showing a small negative frequency offset in the STL data.

Continuous STL data were not available for a longer period, so we were unable to see if the trend in the STL data continued with respect to UTC(NIST). However, a second 100-day STL – UTC(NIST) comparison involving EVK2-191, along with a GPS – UTC(NIST) comparison, was conducted some months later, for the 100-day period ending on January 12, 2023 (MJD 59857 to 59956). These results are shown in Figure 12. The STL data now had a positive slope with respect to UTC(NIST). The direction of the slope reverses in the last 10 days of the comparison, but prior to the reversal it was about $+6 \times 10^{-15}$, and the overall frequency offset for the 100-day period is still $+4.6 \times 10^{-15}$, resulting in a time offset that accumulated at an average rate of about 0.39 ns per day. This resulting change in the STL – UTC(NIST) time difference was about 50 ns for the first 90 days of the comparison. Again, the slope of the GPS data with respect to NIST is barely discernible, with a frequency offset of $+0.3 \times 10^{-15}$ and a change in the time offset of just a few nanoseconds during the 100 days.

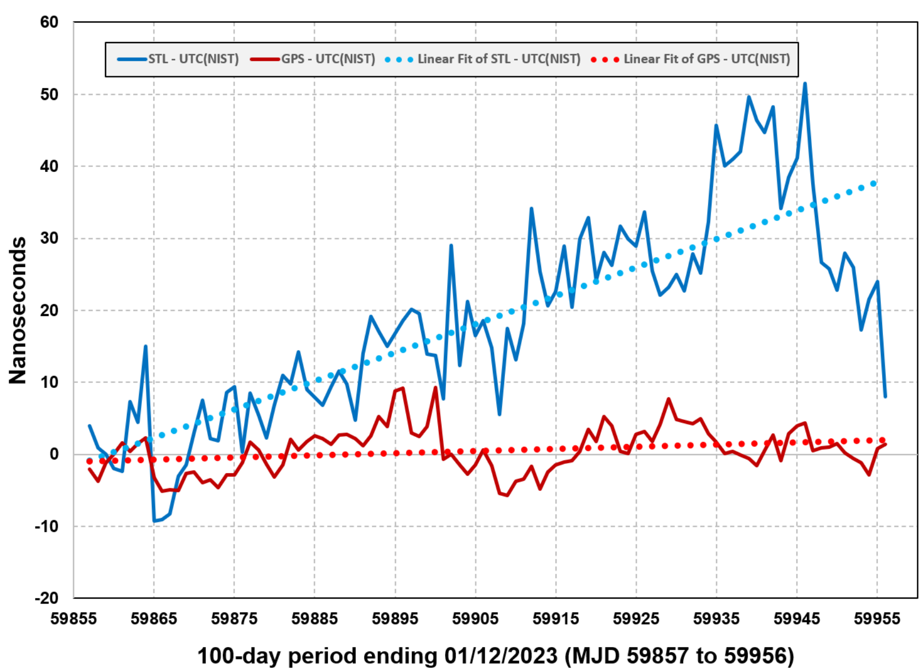


Figure 12. 100-day comparison of STL and GPS to UTC(NIST), showing a small positive frequency offset in the STL data.

The exact causes of the small frequency offset that appears in STL data for extended periods are unknown. We do know, however, that the slope of the frequency offset periodically reverses and that over a sufficiently long period, perhaps one year, it may not significantly affect the average time offset. For industrial timing applications that only require sub-microsecond accuracy, this small frequency offset is insignificant. However, it does affect the repeatability of delay calibrations of STL receivers, as was seen in Section 2.2 when the results of the two-day delay calibration conducted at Satelles differed significantly from the results of 100-day calibration conducted at NIST. Further investigation is needed, but it appears that the uncertainty of an STL receiver delay calibration is limited to tens of nanoseconds unless a very long averaging period is utilized.

5. SUMMARY AND CONCLUSION

Timing receivers, locked to signals originating from a LEO satellite constellation provide a globally available time reference that can serve as either a backup or alternative to signals from GPS. We have presented measurements that have verified the performance of STL receivers by comparing them to both GPS and UTC(NIST). Strong repeatability was achieved between several devices and measurement campaigns, demonstrating that even an uncalibrated STL receiver should provide sub-microsecond accuracy, and that accuracies of < 100 ns are achievable with delay calibration. Future improvement is possible through continued technological advances at Satelles, perhaps aided by further collaboration with NIST.

6. ACKNOWLEDGEMENTS

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The work described here was performed under as a result of a memorandum of understanding (MOU) between Satelles and NIST. The commercial services and products offered by Satelles are described and identified for technical completeness and this implies no endorsement by NIST. Products and services offered by other companies may be found to work equally well or better.

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