# The Long-Term Timing Performance of Satellite Time and Location Receivers Utilizing Signals from Low Earth Orbit Satellites.

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**ABSTRACT**

We present the long-term timing accuracy and stability of STL receivers by validating their performance against UTC(NIST), the timing reference at the National Institute of Standards and Technology (NIST), for a duration of 100 days. STL is an existing timing and location service based on signals from Low Earth Orbit (LEO) satellites, available anywhere in the world.

The data show that an STL receiver with an oven-controlled crystal (OCXO) or a rubidium (Rb) oscillator provides a stable timing solution and maintains an average offset less than one nanosecond (ns) to UTC(NIST) after calibration. An STL receiver with a Rb oscillator was able to maintain a Maximum Time Interval Error (MTIE) [10] of less than 80 nanoseconds to UTC(NIST) over a period of 66 days, increasing to 90 ns at 100 days duration, meeting the ITU-T G.8272 PRTC-A mask limit of 100 ns. [9] Since the timing variation of these receivers is balanced around an average time offset close the zero, the maximum time offset from UTC(NIST) at any point for the 100 days will be about one half of the MTIE value or less than 50 ns for the STL receiver with a Rb oscillator.

The Time Stability (TDEV) of the STL receiver with a rubidium oscillator is less than 9 ns for all values of observation interval tau and the stability (ADEV) is below $2 \times 10^{-13}$ at one day continuing to average down, reaching below $3 \times 10^{-14}$ at eight days. All the timing measurements done with these four STL receivers at NIST and a remote lab location were done using Iridium-only antennas (no GPS band) for the duration of all the testing.

## 1. INTRODUCTION AND BACKGROUND

There are many critical infrastructure operations today that require time references with better than 1 µs accuracy [1] which typically depends on GPS-disciplined clocks. For example, timing synchronization is critical in 5G networks, and without it their data rates are severely compromised. 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]. All these factors clearly point to the need for an alternate timing solution that can provide an accurate time reference in areas where GPS signals are either not available or have been compromised.

*The work described here was performed under a memorandum of understanding (MOU) between Satelles and NIST. All commercial services and products mentioned in the paper are identified for technical completeness. Such identification is not intended to imply recommendation or endorsement of any product or service by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*

STL (Satellite Time and Location) is a Positioning, Navigation, and Timing (PNT) service using the Iridium constellation of Low Earth Orbit (LEO) satellites. 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 stronger than GPS, allowing them to penetrate GPS-challenged environments where signals are obstructed or degraded, including indoors and underground Commercial products that synchronize to STL signals have been available for several years and have consistently demonstrated sub-microsecond accuracy [4, 5].

This evaluation was launched to quantify the long-term accuracy and stability of the pulse per second (PPS) timing outputs produced by receivers utilizing STL technology. This was accomplished by installing two STL receivers at the NIST site in Boulder, Colorado and measuring the difference between their STL-generated PPS and the UTC(NIST) standard PPS reference. This evaluation used two STL Evaluation Kit (EVK2) receivers, one with an internal oven-controlled crystal oscillator (OCXO) that represents the typical commercially available STL receivers in use today, and a second EVK2 receiver with an external rubidium (Rb) oscillator that represents an STL receiver that would be used in a high-performance timing application. A similar evaluation was carried out in parallel on two equivalent STL receivers at a remote lab in Folsom, California, using setups that were as close as possible to those used at NIST. Additionally, the timing performance of an STL receiver with a miniature atomic clock was also evaluated at the remote lab.

Since one of the key measurements being presented from this evaluation is Maximum Time Interval Error (MTIE), we will offer some more details on this measurement. MTIE is defined by the International Telecommunication Union (ITU), Telecommunications Standardization Sector (ITU-T) G.810 as the maximum peak-to-peak delay variation of a given timing signal with respect to an ideal timing signal within an observation time ($\tau = n\tau_0$) for all observation durations of that length within the measurement period (T). It is estimated using the following formula: [10]

$$\mathrm{MTIE}(n\tau_0) \cong \max_{1\le k\le N-n}\left[\max_{k\le i\le k+n} x_i - \min_{k\le i\le k+n} x_i\right], \quad n = 1,2,\ldots,N-1$$

Where: $x_i$ are time error samples; N is the total number of samples; $\tau_0$ is the sample interval; $\tau$ is the observation time; n is the sample number within the observation time $\tau$.

## 2. MEASUREMENTS AT NIST

### 2.1 Configuration at NIST

In the beginning of 2023, two STL receivers that had been previously used for another evaluation at NIST in 2022 were set up for this long-term data collection effort. These STL receivers were initially calibrated at the remote lab in Folsom, California [8] prior to installation at NIST. STL receiver #1 (EVK2-191) with an internal OCXO oscillator and STL receiver #2 (EVK2-199) with an external rubidium oscillator were connected to a common active Iridium antenna on the roof at NIST. The rubidium oscillator used with EVK2-199 was free running for the duration of the evaluation. The rubidium oscillator was initially set up with PPS input to discipline its frequency, and disciplining was disconnected prior to the start of the evaluation. The PPS outputs from both STL receivers (EVK2-191 and EVK2-199) were connected to a datalogger/time interval counter (TIC) where their outputs were simultaneously compared to UTC(NIST). The datalogger measured several input channels compared to UTC(NIST) sequentially via a multiplexer, so that only one TIC is needed and the ten-minute averages of each of the 1 PPS measurements were stored. The setup for the two STL receivers and the measurement system described above is shown in Figure 1. The STL antenna delay and all cable delays associated with the receiver and measurement equipment setup were carefully measured, and the appropriate delay compensation was applied to all measurements.

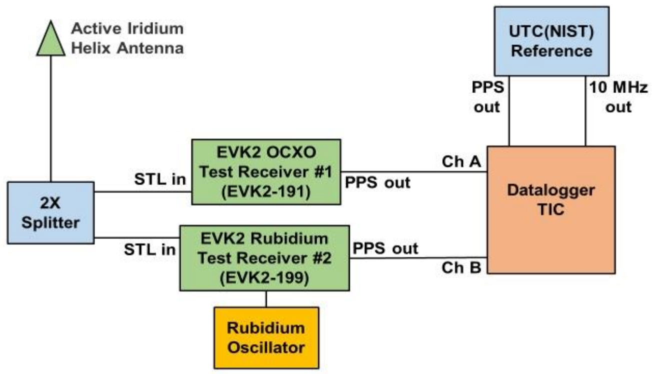


**Figure 1.** Configuration for comparing STL receiver timing to UTC(NIST).

### 2.2 Measurements at NIST

The measurements at NIST were conducted throughout 2023 on the two STL receivers. The data presented here for STL receiver #1 (EVK2-191), internal OCXO oscillator, and STL receiver #2 (EVK2-199), external rubidium oscillator, were not collected at the same time although there is some overlap of the data. STL receiver #1 was already in use at NIST from another evaluation the previous year, so there was minimal calibration work needed before starting this evaluation. STL receiver #2 (EVK2-199) was installed at NIST in 2023, so it required additional correlation effort to calibrate the offset before the measurements on that receiver could begin. Also, we changed the receivers' RF input Low Noise Amplifier (LNA) from Automatic Gain Control (AGC) mode to fixed gain to eliminate the delay variation through the LNA for different gain values. This change shifted the receivers' offset by more than 50 ns, so data needed to be collected for several weeks to recalibrate the receiver. A few equipment failures during the year prevented collecting continuous data on both receivers over the same time period or for the same duration. The long-term data collection for the 66-day test started in May 2023: from 05/21/23 to 07/26/23 for the OCXO receiver (EVK2-191) and from 07/09/23 to 09/13/23 for the rubidium receiver (EVK2-199). The average offset to UTC(NIST) was -3 ns and +4 ns for the OCXO and rubidium receivers, respectively. At 66 days the OCXO receiver (EVK2-191) had an MTIE of 330 ns which represents a maximum offset to UTC(NIST) of 178 ns and a 99% confidence interval range of 119 ns. The 66 days timing performance for the OCXO receiver is summarized in Figure 2 and Table 1.

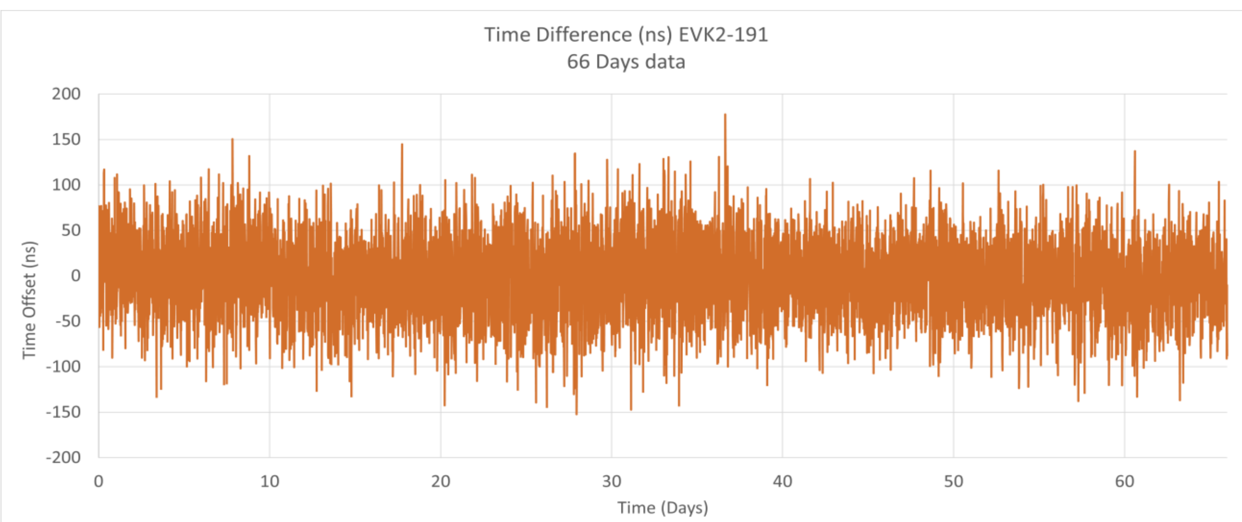


**Figure 2.** STL OCXO receiver timing performance relative to UTC(NIST) over a 66-day period.

| EVK2-191 (OCXO) NIST | May 21 to July 26 (66 days): | |
|---|---|---|
| Maximum | 177.67 | ns |
| Minimum | -152.14 | ns |
| Average | -2.97 | ns |
| Standard Deviation | 39.71 | ns |
| 99% confidence interval range | 119.14 | ns |
| MTIE | 329.81 | ns |

**Table 1.** STL OCXO receiver timing performance relative to UTC(NIST) for a 66-day period.

The rubidium receiver (EVK2-199) had much lower variation as expected due to its more stable clock, which requires fewer frequency adjustments with a longer control loop period. STL receiver firmware uses the clock model parameter to inform the Kalman filter of the estimated frequency stability of the local oscillator. 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.

At 66 days the rubidium receiver (EVK2-199) had an MTIE less than 80 ns, representing a maximum offset to UTC(NIST) of 42 ns with a 99% confidence interval range of 37 ns. We continued the measurements for a duration of 100 days and MTIE increased by 11 ns. The results at 100 days yielded an MTIE of 91 ns, which represents a maximum offset to UTC(NIST) of 49 ns with a 99% confidence interval range of 45 ns. The 66 and 100-days timing performance for the rubidium receiver is seen in Figure 3a/b and is summarized in Table 2. The raw data for the rubidium receiver (EVK2-199) had a 15 ns offset to UTC(NIST) that was calibrated out in the data that follows. If there had been more time to characterize the average measurements from the receiver before the start of the 100-day test, the additional 15 ns offset adjustment would have been integrated in the calibration value of the receiver and the raw data would be the same. Given the stability of these receivers and how the offset calibration is applied, the post processing doesn't skew the results.

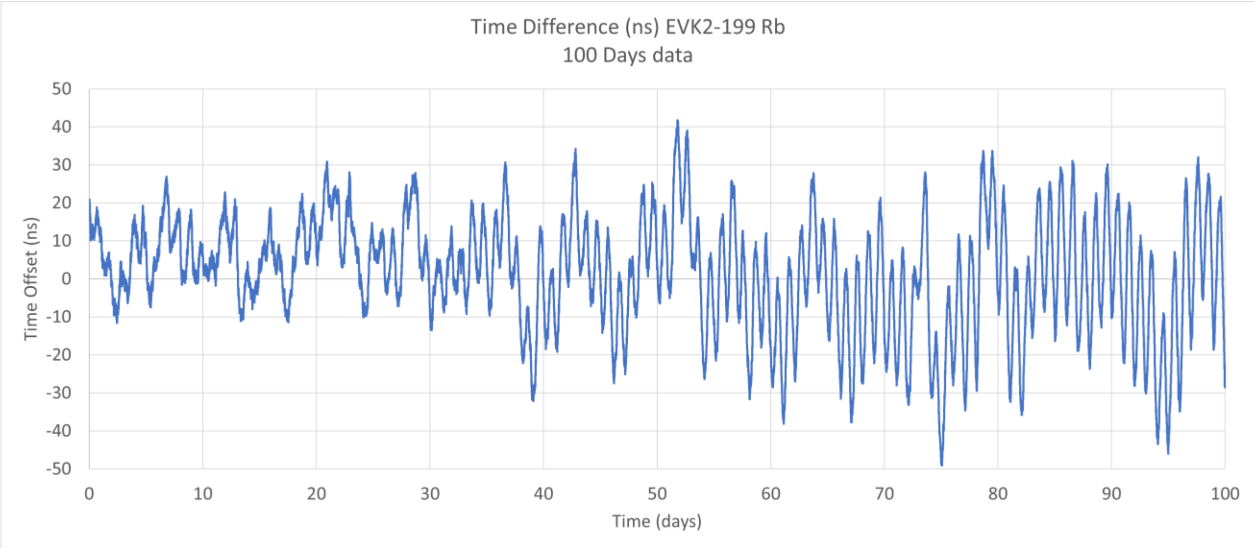


**Figure 3a.** STL rubidium receiver timing performance relative to UTC(NIST) for a 66/100-day period.


**Figure 3b.** STL rubidium receiver MTIE relative to UTC(NIST) for a 66-day period. The first data point is at 600 seconds because 10-minute average data is used.

| EVK2-199 (rubidium) NIST | 66 Days Zero Offset (July 9 to Sept. 13): | 100 Days Zero Offset (July 9 to Oct. 16): | |
|---|---|---|---|
| Maximum | 41.78 | 41.78 | ns |
| Minimum | -38.02 | -48.93 | ns |
| Average | 4.24 | 1.54 | ns |
| Standard Deviation | 12.46 | 15.09 | ns |
| 99% confidence interval range | 37.37 | 45.28 | ns |
| MTIE | 79.80 | 90.71 | ns |

**Table 2.** STL rubidium receiver timing performance relative to UTC(NIST) for a 66/100-day period.

Around halfway through the 100 days test, a slight increase in the peak-to-peak variation was noticed, which we attribute to the small increase in MTIE from 66 to 100 days. We identified that the clock model used for this test was not optimal for the stability of a rubidium oscillator, and a longer control loop period should have been used to avoid making frequency adjustments more often than needed. We believe this led to larger diurnal variation over the duration of the test than should have been seen with a rubidium oscillator. Subsequent measurements on the receiver using a clock model with a longer control loop period produced stable results with much less diurnal variation. Additional analysis is needed to identify the best clock model value to use with a rubidium oscillator for stable long-term operation. However, it's clear that the peak-to-peak variation seen in the 100-day data can be improved with better clock model selection.

## 3. MEASUREMENTS AT FOLSOM LAB SITE

### 3.1 Configuration at Folsom lab site

A second pair of STL receivers (OCXO and Rb) that had been set up and measured at NIST in Boulder were installed at a remote lab in Folsom, California: STL receiver #1 (EVK2-189) with an internal OCXO oscillator and STL receiver #2 (EVK2-119) with an external rubidium oscillator. The setup for these two STL receivers in Folsom attempted to follow the setup at NIST as closely as possible. Unfortunately, there were a few differences that could not be avoided during the time of this evaluation. The two STL receivers were connected to a common active Iridium antenna on the roof in Folsom with the same cable type and length as used at NIST. However, the Iridium antenna on the roof in Folsom is an older version from a different manufacturer, but still a helix type. It was expected to have similar group delay as the antenna used at NIST. The same type of external rubidium oscillator used at NIST was used with EVK2-199 in Folsom. Since it was also used as a clock reference for other equipment in the Folsom lab, it was not free running and was set up with PPS input disciplining its frequency during measurements at Folsom. However, EVK2-199 was configured with the same clock model as the Rb receiver used at NIST so it wouldn't take advantage of the improved stability from disciplining. The comparable performance of the two systems indicates that the disciplining wasn't a significant factor. The PPS output from both STL receivers (EVK2-189 and EVK2-119) were connected to Time Interval Counters (TIC) and compared to a L1/L2 GPS timing reference with measurements taken on each PPS edge. Ten-minute averages of the TIC data are used for consistency with the measurements at NIST. The setup for the two STL receivers and the measurement system described above is shown in Figure 4.

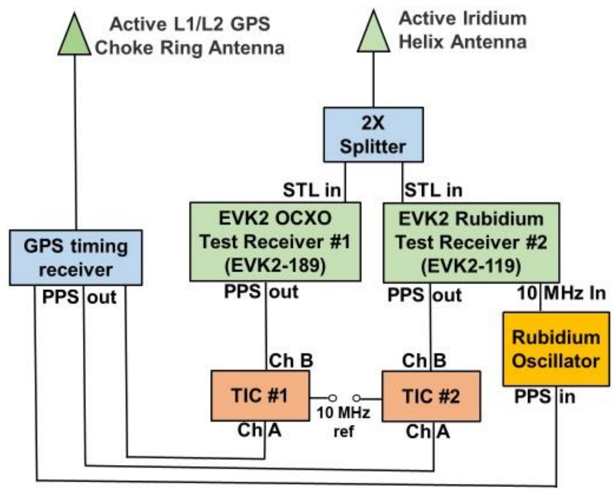


**Figure 4.** Configuration for measuring STL receiver timing error at Folsom lab.

### 3.2 Measurements in Folsom

Measurements at the Folsom timing lab were conducted in parallel throughout 2023 on the other two STL receivers that had been previously measured at NIST. These matched receivers at NIST and in Folsom were used to calibrate the measurement setup at the Folsom timing lab, enabling good correlation of the measurements between the two sites. Since the group delay of the L1/L2 GPS antenna at the Folsom lab could not be measured, there was always some uncertainty setting up the delay calibration for the GPS timing reference. The average offset measurements from the matched STL receivers were used to calibrate the timing reference at the Folsom timing lab. The resulting measurements on the STL receivers at the Folsom timing lab matched well with similar measurements at NIST, matching within a few nanoseconds with similar statistics.

Similar measurements to those conducted at NIST were repeated on the second pair of STL receivers at the Folsom timing lab. However, we were not able to complete continuous long-term measurements of the same duration as those done at NIST due to equipment problems. The data presented here for STL receiver #1 (EVK2-189), internal OCXO oscillator, and STL receiver #2 (EVK2-119), external rubidium oscillator was not collected at the same time as the measurements at NIST, but the strong correlation of the results suggests that was not a significant factor. The average offset to the Folsom GPS timing reference was -3 ns and +2 ns for the OCXO and rubidium receivers respectively. At 64 days the OCXO receiver (EVK2-189) had an MTIE of 263 ns or a maximum offset of 140 ns with a 99% confidence interval range of 107 ns. The 64 days timing performance for the OCXO receiver is seen in Figure 5 and summarized in Table 3.

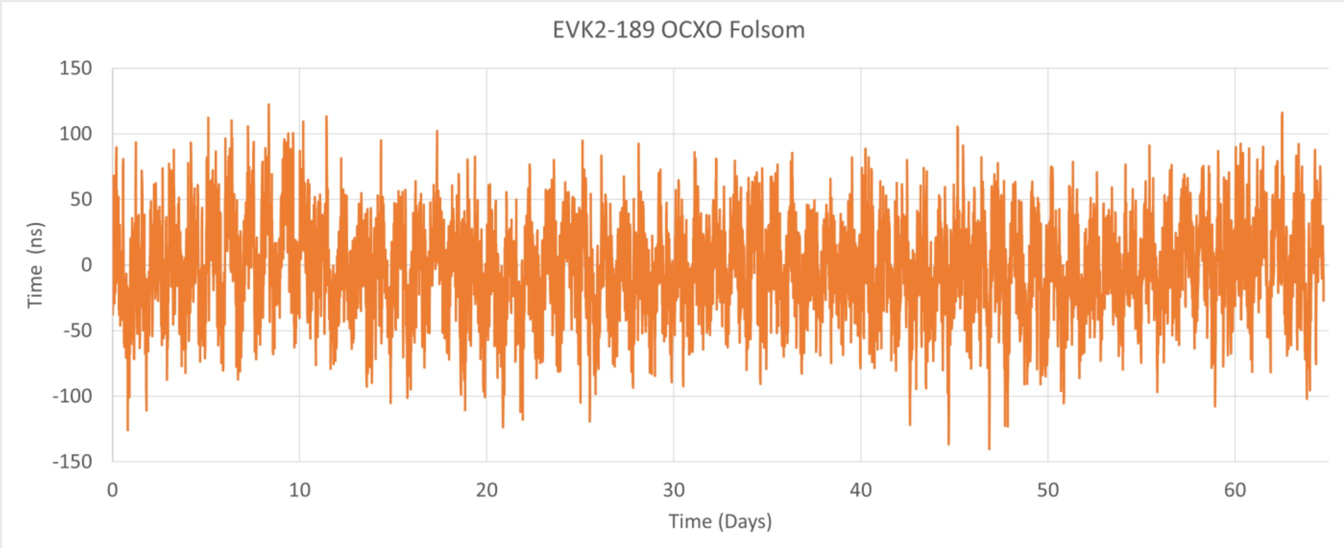


**Figure 5.** STL OCXO receiver timing performance relative to GPS at Folsom lab over 64 days.

| EVK2-189 (OCXO) Folsom | Nov. 8 to Jan 12 (64 days): | |
|---|---|---|
| Maximum | 122.54 | ns |
| Minimum | -140.32 | ns |
| Average | -2.98 | ns |
| Standard Deviation | 35.63 | ns |
| 99% confidence interval range | 106.88 | ns |
| MTIE | 262.86 | ns |

**Table 3.** STL OCXO receiver timing performance relative to GPS at Folsom lab over 64 days.

As was observed at NIST, the measurements at the Folsom lab for the rubidium receiver (EVK2-119) had much lower variation as expected. At 69 days its MTIE was less than 90 ns or a maximum offset of 47 ns with a 99% confidence interval range of 41 ns. These results are very close to the 66- and 100-days data collected on the rubidium STL receiver at NIST. The 69 day timing performance for the rubidium receiver at Folsom is seen in Figure 6a/b and summarized in Table 4.

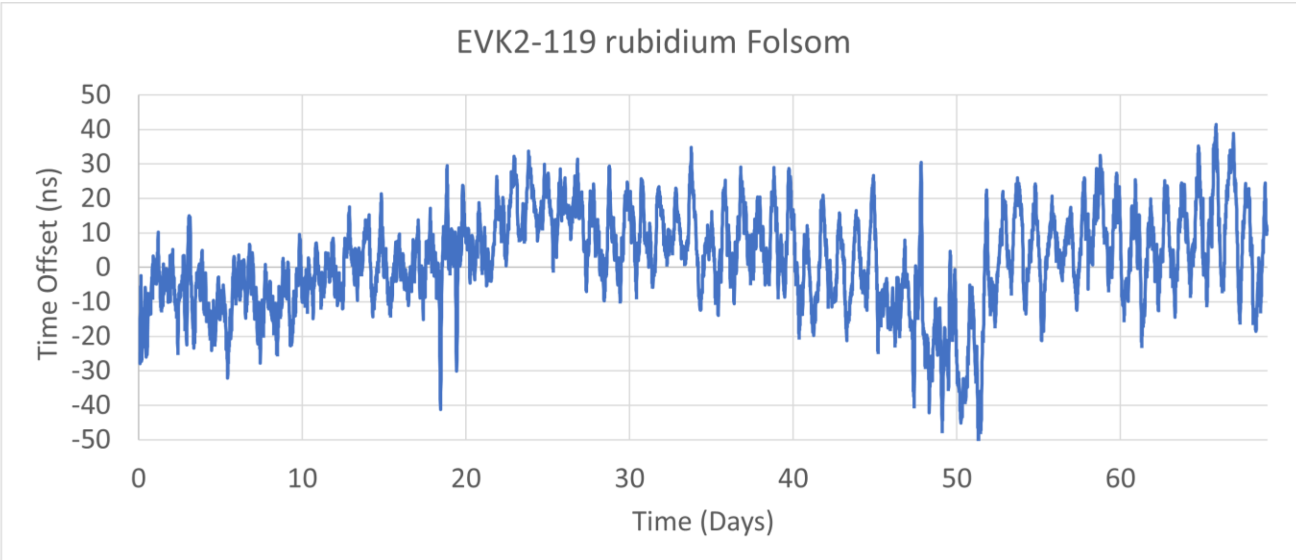


**Figure 6a.** STL rubidium receiver timing performance relative to GPS at Folsom lab over 69 days.

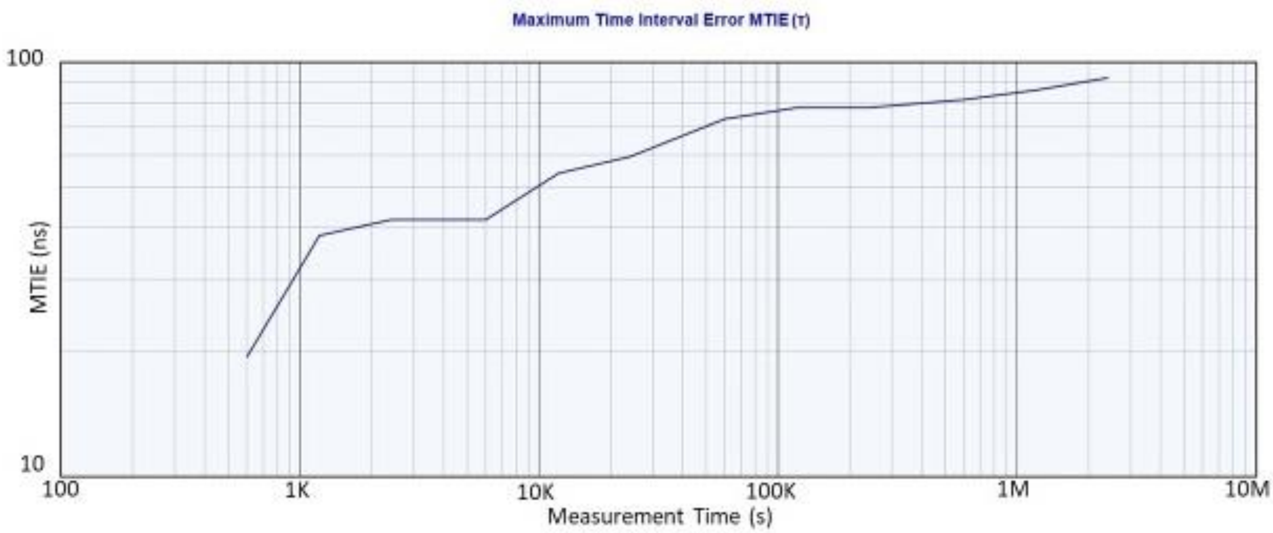


**Figure 6b.** STL rubidium receiver MTIE relative to GPS at Folsom lab over 69 days. The first data point is at 600 seconds because 10-minute average data is used.

| EVK2-119 (rubidium) Folsom | Aug. 4 to Oct. 12 (69 days): | |
|---|---|---|
| Maximum | 41.41 | ns |
| Minimum | -50.85 | ns |
| Average | 1.96 | ns |
| Standard Deviation | 13.84 | ns |
| 99% confidence interval range | 41.52 | ns |
| MTIE | 92.25 | ns |
| | | |

**Table 4.** STL rubidium receiver timing performance at Folsom lab over 69 days.

## 4. CORRELATION OF FOLSOM TIMING MEASURMENTS TO NIST

The matched setup and STL receivers in Folsom and NIST were used to null out the unknown delays for the Folsom GPS timing reference. [8] This enabled more accurate offset calibration of the Folsom lab's GPS timing reference than was possible with other means. After this calibration of the Folsom lab's timing reference, the average offset measurements for both OCXO and rubidium STL receivers between NIST and Folsom correlated within a nanosecond. The differences in the PPS error statistics between Folsom and NIST for the STL measurements are summarized in tables 5 and 6 for the OCXO and rubidium receivers, respectively. The comparison for the rubidium receivers used the NIST data for 100 days and the Folsom data for 69 days because there was a larger overlap of the test dates than there would be with the NIST 66-day data.

| | EVK2-191 NIST | EVK2-189 Folsom | Difference | |
|---|---|---|---|---|
| Maximum | 177.67 | 122.54 | 55.13 | ns |
| Minimum | -152.14 | -140.32 | -11.82 | ns |
| Average | -2.97 | -2.98 | 0.01 | ns |
| Standard Deviation | 39.71 | 35.63 | 4.08 | ns |
| 99% confidence interval range | 119.13 | 106.88 | 12.26 | ns |
| MTIE | 329.81 | 262.86 | 66.95 | ns |

**Table 5.** STL OCXO receiver timing measurement differences between Folsom and NIST

| | EVK2-199 NIST (100 day) | EVK2-119 Folsom (69 day) | Difference | |
|---|---|---|---|---|
| Maximum | 41.78 | 41.41 | 0.37 | ns |
| Minimum | -48.93 | -50.85 | 1.92 | ns |
| Average | 1.54 | 1.96 | -0.42 | ns |
| Standard Deviation | 15.09 | 13.84 | 1.25 | ns |
| 99% confidence interval range | 45.28 | 41.52 | 3.76 | ns |
| MTIE | 90.71 | 92.25 | -1.54 | ns |

**Table 6.** STL rubidium receiver timing measurement differences between Folsom and NIST

This correlation effort also identified small random variations on the order of 10 to 20 ns from the GPS timing reference at the Folsom lab. These small variations were initially seen on the measurements for a rubidium STL receiver but were later found to have originated from the primary GPS timing reference in Folsom. This was confirmed by continuous monitoring of several GPS timing references in the Folsom lab. The same small variations seen on the STL receiver measurements were also observed at the same times for measurements between the Folsom lab's primary GPS timing reference and other GPS references. This reinforces the need for multiple timing references for any critical timing measurements and the value of validating STL timing receiver performance directly at NIST. Figure 7 shows the alignment of the variations on the STL receiver measurements with those seen on the primary GPS timing reference against other GPS references in the Folsom lab. It's clear that the STL receivers' stability was better than what was seen in the initial measurements.

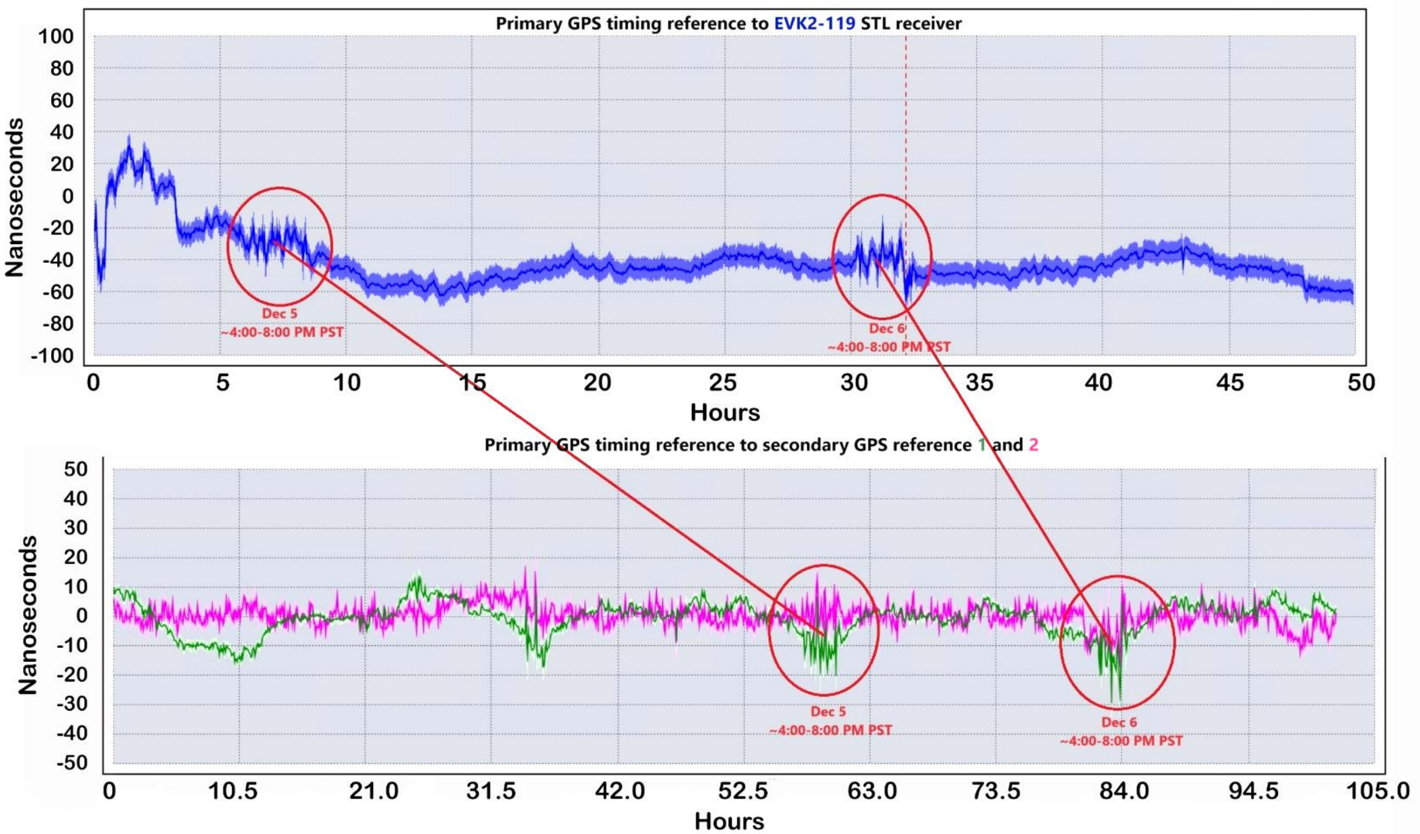


**Figure 7.** GPS timing reference variations at the Folsom lab

## 5. STABILITY ANALYSIS

The discussion thus far has focused on measuring the long-term timing accuracy of STL receivers with respect to UTC(NIST). It is also important to estimate the stability of the receivers' 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 $\tau$, or tau, denotes the averaging period [7]. The Time Stability (TDEV) of the STL receiver with a rubidium oscillator is less than 9 ns for all tau values, and the stability (ADEV) is below $2 \times 10^{-13}$ at one day continuing to average down, reaching below $3 \times 10^{-14}$ at eight days. Figure 8 shows a TDEV plot for the rubidium-based STL receiver to an OCXO-based GPS disciplined clock (GPSDC) at NIST (a) and the Folsom lab (b) We note the strong correlation for the TDEV measurements from NIST and Folsom. The Allan deviation (ADEV) for the rubidium-based STL receiver to an OCXO-based GPS disciplined clock (GPSDC) at the Folsom lab is shown in Figure 9.

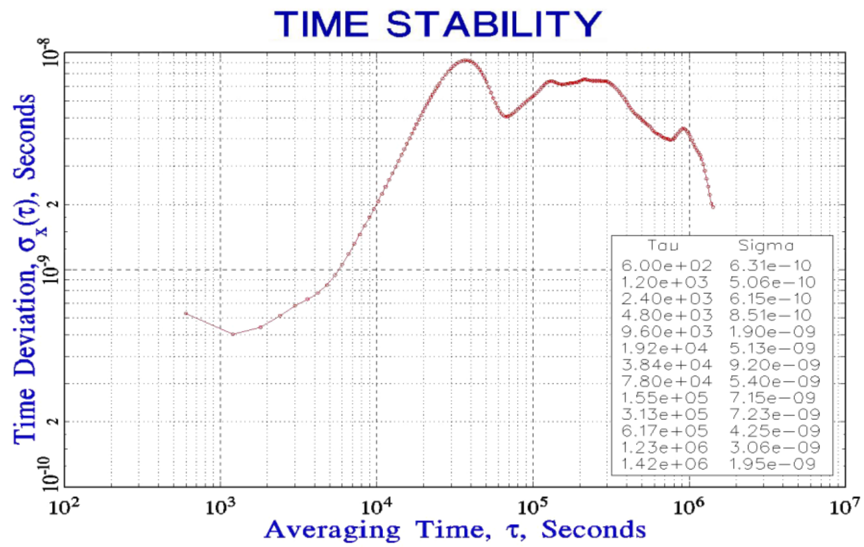


**Figure 8a.** Time stability (TDEV) of EVK2-199 Rb receiver with respect to UTC(NIST)

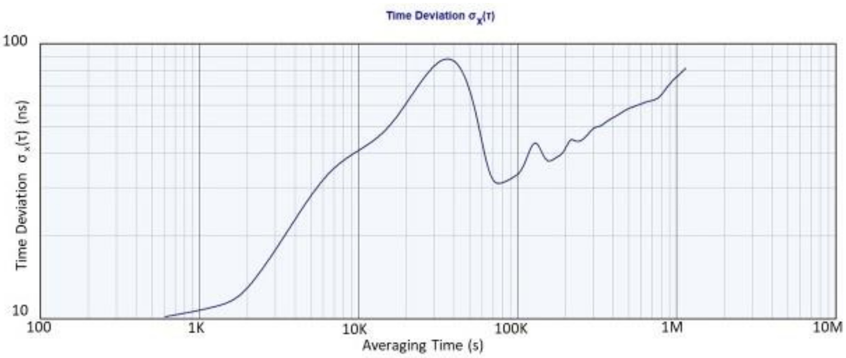


**Figure 8b.** Time stability of EVK2-119 receiver at Folsom lab with respect to GPS

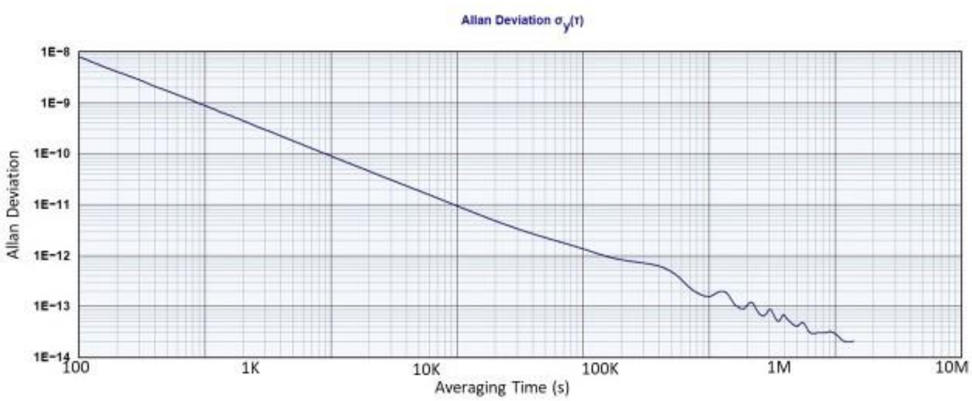


**Figure 9.** Stability (ADEV) of STL rubidium receiver with respect to GPS at Folsom lab

## 6. MINIATURE RUBIDIUM STL RECEIVER EVALUATION

A rubidium STL receiver like EVK2-199 used for the 100-day MTIE measurements at NIST relies on an external rubidium oscillator to supply its more stable clock. The rubidium oscillators used were large bench top units that require AC line power. We evaluated the timing performance of an STL receiver using a miniature atomic clock. This enables a much smaller form factor for the rubidium STL receiver that's close to the same size as the OCXO EVK2 receiver and operates on a single 5V power supply (Figure 10a/b). This evaluation was done using a ruggedized Mini-Rubidium-Oscillator (mRO) integrated into an EVK2 receiver with a custom lid to accommodate the height of the mRO (Figure 10). All the measurements were performed at the Folsom lab using the same L1/L2 GPS timing reference as was used for the other STL receiver measurements. Due to the strong correlation of other STL receiver measurements between Folsom and NIST, these results are expected to be within 20 to 30 ns of what they would be at NIST. A 20-day measurement on the STL mini-rubidium receiver realized timing performance close to a benchtop rubidium receiver with an MTIE of 134 ns. The STL mini-rubidium receiver timing performance is seen in Figure 11 and statistics are compared to a bench top Rb receiver (EVK2-119) in Table 6.



(a) 2" X 2" mini-Rb oscillator inside the receiver (b) Enclosed mini-Rb receiver, close to OCXO receiver size

**Figure 10.** STL mini-rubidium receiver form factor

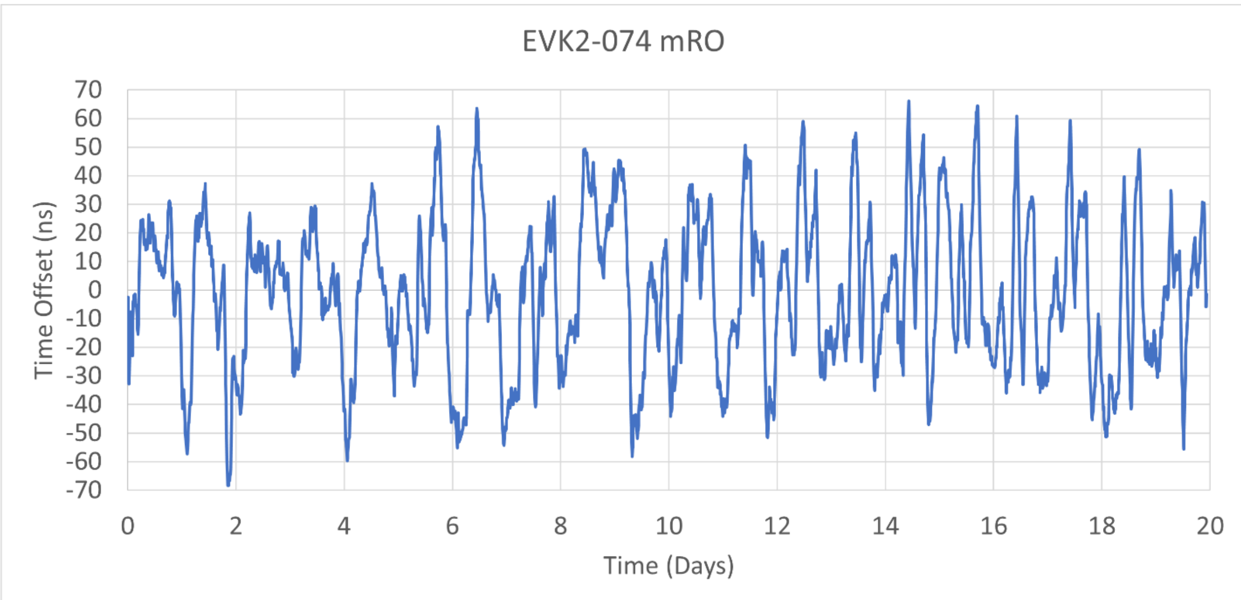


**Figure 11.** STL mini-rubidium receiver timing performance at Folsom lab over 20 days

| mini-rubidium | EVK2-074 mRO (20 days): | EVK2-119 Rb (69 day) | Difference | |
|---|---|---|---|---|
| Maximum | 66.10 | 41.41 | 24.69 | ns |
| Minimum | -68.29 | -50.85 | -17.44 | ns |
| Average | -0.80 | 1.96 | -2.76 | ns |
| Standard Deviation | 26.36 | 13.84 | 12.52 | ns |
| 99% confidence interval range | 79.07 | 41.52 | 37.55 | ns |
| MTIE | 134.39 | 92.25 | 42.14 | ns |

**Table 6.** STL mini-rubidium receiver timing performance

## 7. SUMMARY AND CONCLUSION

We have presented measurements verifying that typical STL timing receivers can provide a stable and accurate timing solution with an average offset within a few nanoseconds of UTC(NIST). Furthermore, STL timing receivers with a high-quality oscillator can maintain a Maximum Time Interval Error (MTIE) less than 100 ns for long durations, meeting the ITU-T G.8272 PRTC-A requirement for a primary reference clock. Due to the STL receivers' close-to-zero average time offset, the maximum time offset from UTC(NIST) at any point for any measurement duration is about one half the MTIE value or less than 50 ns for 100 days. The stability of the STL receivers enables them to provide accurate long-term timing as seen by the correlation between performance results at NIST and the Folsom lab. STL timing receivers using miniature rubidium oscillators can provide accurate timing with performance close to a benchtop rubidium receiver in a small and portable form factor.


## 8. ACKNOWLEDGEMENTS

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