Common-view comparison using two Iridium STL (Satellite Time and Location) receivers at national laboratories with a very long baseline

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Abstract

We compare the outputs of two Satellite Time and Location (STL) low Earth orbit (LEO) receivers in common-view with a very long baseline. By comparing the STL pulse per second (PPS) output to national laboratory timescales at distant locations, we can determine how well clocks or timescales can be compared. Values of Coordinated Universal Time (UTC) from the Bureau International des Poids et Mesures (BIPM) Circular-T data are used as the reference comparison of the timescales of the two laboratories.

The baseline between Boulder, Colorado in the United States and Taoyuan City in Taiwan is greater than 11,000 km. Also, the Iridium satellites are at a low altitude of 780 km, which largely limits the possibility of making common-view comparisons using LEO satellites. We are constrained to using the all-in-view technique (Johnson et al., 2023), where the composite output of a receiver is used for the comparisons and not individual satellites, as in traditional common-view techniques.

Comparisons of a commercially-available STL receiver compared to UTC(NIST) show one-day averages within a range of < 6 ns over several days, an Allan Deviation (ADEV) of 7.75×10^{-14} at one day of averaging and Time Deviation (TDEV) of < 4 ns at one day of averaging. These results show that it could be possible to compare time scales at long baselines, as well as clocks at commercial institutions, when global navigation satellite system (GNSS) signals may not be available.

INTRODUCTION

The National Institute of Standards and Technology (NIST) in the United States and National Standard Time and Frequency Laboratory (TL) in Taiwan have collaborated for many years, and both laboratories have been measuring STL receivers compared to each of their nation's timescales. The idea to work together for a long baseline comparison developed in 2025. The LEO satellites are 780 km from Earth, which is 25 times closer than Global Positioning System (GPS) satellites, and they offer a much greater (1000x) power of the broadcast signals. This allows for reception indoors and in GPS-challenged environments and, in some cases, the signals can be received underground. The satellite constellation comprises 66 active satellites, each with an orbital period of 100.4 minutes. The continued study of STL as a backup or alternative to GNSS is useful for the timing community.

LOW EARTH ORBIT RECEIVER TIMING PERFORMANCE

The STL devices utilize the LEO timing signals to discipline a local oscillator inside the receiver. There are clock model parameters that can be varied for the different kinds of oscillators utilized. Previous measurements of STL evaluation kits (not commercial products) show a peak-to-peak variation ~300 ns with an oven-controlled quartz crystal (OCXO)-based receiver and < 80 ns with a rubidium (Rb)-based receiver (Johnson et al., 2023). These are identified as EVK2-191 (OCXO) and EVK2-119 (Rb). Figure 1a shows ten-minute time averages of each receiver compared to the NIST timescale, UTC(NIST). The Rb-based receiver shows a smoother result and a smaller range.

Disclaimer: *The work described here was performed under collaboration for research. All commercial services and products mentioned are identified for technical completeness. Such identification is not intended to imply recommendation or endorsement of any product or service by NIST or TL, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*

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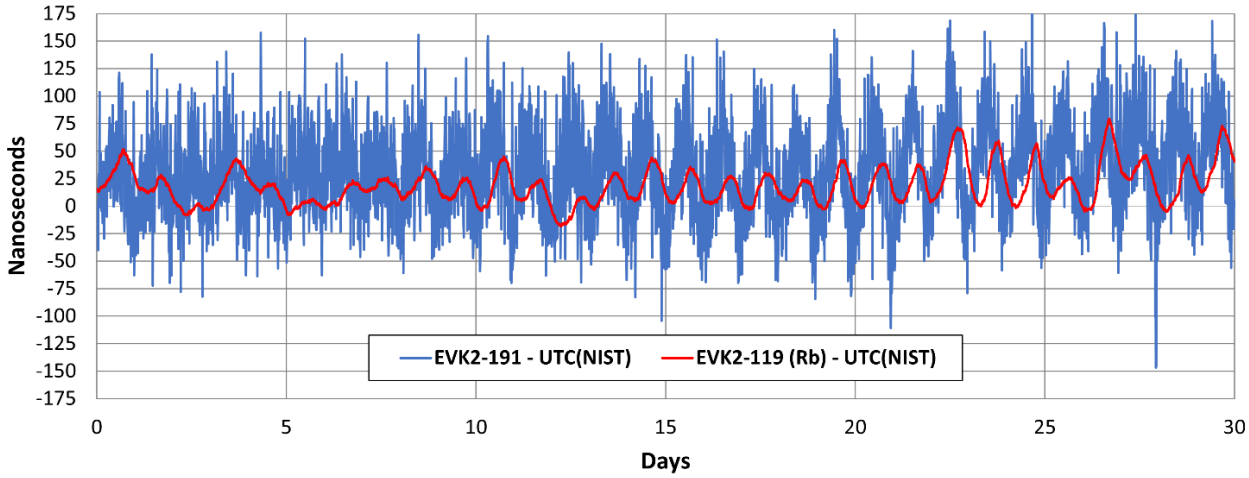
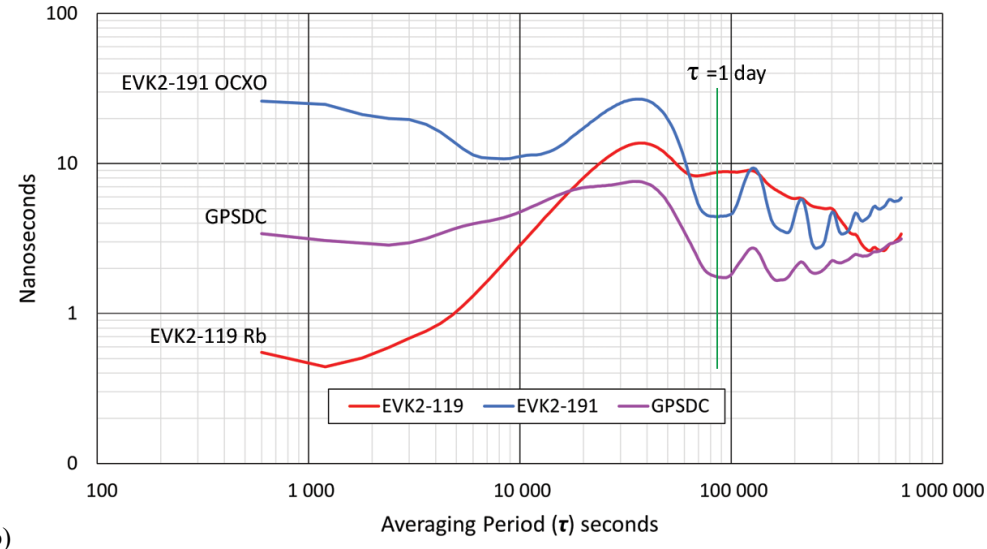
Figure 1b shows a TDEV stability comparison of these two receivers, with an OCXO-based GPS-disciplined clock (GPSDC) for reference. The Rb-STL receiver performs very well in the short-term (<10,000 s). The stability of each of the receivers is better than 10 ns at one day of averaging, with the GPSDC having the best stability. The Rb-STL receiver matches GPSDC stability after around five days of averaging.



a)



b)

FIGURE 1 Timing (a) and stability (b) performance of STL receivers and a GPSDC receiver compared to UTC(NIST).

COMMON-VIEW COMPARISONS

Comparing two clocks at separate locations to a common reference (e.g., a clock on-board a satellite) can reveal the difference between the two clocks. Figure 2a shows a satellite which is in view from two different locations at the same time. The time difference between Clock B and Clock C (at the time the Clock C signal is received at the location of Clock B) is subtracted from the time difference between Clock A and Clock C, resulting in the time offset between Clock A and Clock B. If this is done for all the satellites that are *in-common* (received by both locations at the same time), a result with very low uncertainty (< 10 ns) can be achieved (Novick, 2024).

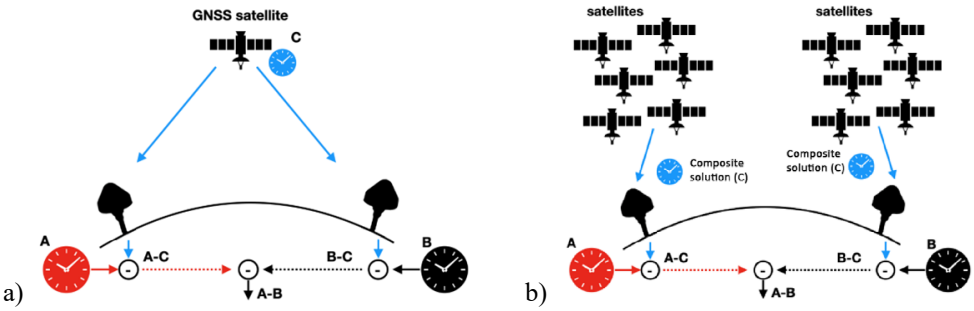


FIGURE 2 Differencing each of two clocks with a common reference can show time offset between the two clocks. Common-view (a) shows both sites looking at the same satellite at the same time and comparing the satellite clock to their local clocks. All-in-view (b) is both sites looking at different satellites at the same time and comparing the composite solution from the satellites to their local clocks.

However, if the two locations are too far apart to receive a signal from the same satellite broadcast at the same time, then the time of the satellite constellation (composite time of all the satellites in view) from each location must be compared. This *all-in-view* method (Fig. 2b) is an indirect comparison because the individual clocks on the satellites do not cancel, only the composite output of each receiver can be compared, which is derived from a different set of satellites. Because the LEO satellites are very low in altitude, their broadcast footprint is much smaller than GNSS satellites, and only a few satellites are in view at any time, the *all-in-view* method is the preferred method to use.

RESEARCH GOALS

Using the *all-in-view* remote comparison method to compare two clocks at remote locations, we attempt to determine if the method with LEO data is applicable for 1) calibrating a remote clock to a reference clock, if the receivers have been calibrated in relation to each other and/or 2) calibrating a remote receiver, if the difference between the remote clocks is known. We should be able to determine if either of these two outcomes are possible by using two remote locations where the difference in the clocks is known, and the receivers are calibrated. Both UTC(NIST) and UTC(TL) contribute to the generation of UTC, so the difference in the timescales can be derived from the Circular-T report published by the BIPM (*BIPM.org*). For the duration of the experiment, the difference between the timescales of the two laboratories was not greater than 3.2 ns.

EXPERIMENTAL SETUP FOR CALIBRATION

Two STL receivers of the same manufacturer/model were acquired on loan and set up at NIST. Each receiver used its own antenna, and the outputs were compared to UTC(NIST) with a multi-channel time interval counter (TIC) for ten days, as shown in Figure 3. The baseline between the antenna locations was less than one meter. One receiver, designated as STL-A was, on average, *greater* than UTC(NIST) by 17.3 ns and STL-B was *less* than UTC(NIST) by 16.3 ns. The outputs of the two receivers differed by a total of 33.7 ns. Calibration values were entered to match the time outputs of the two receivers to each other.

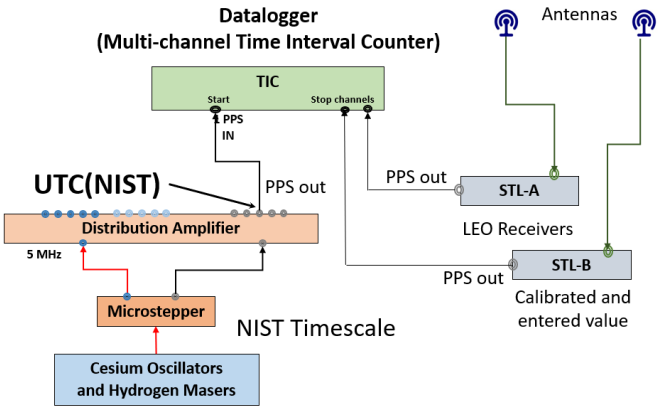
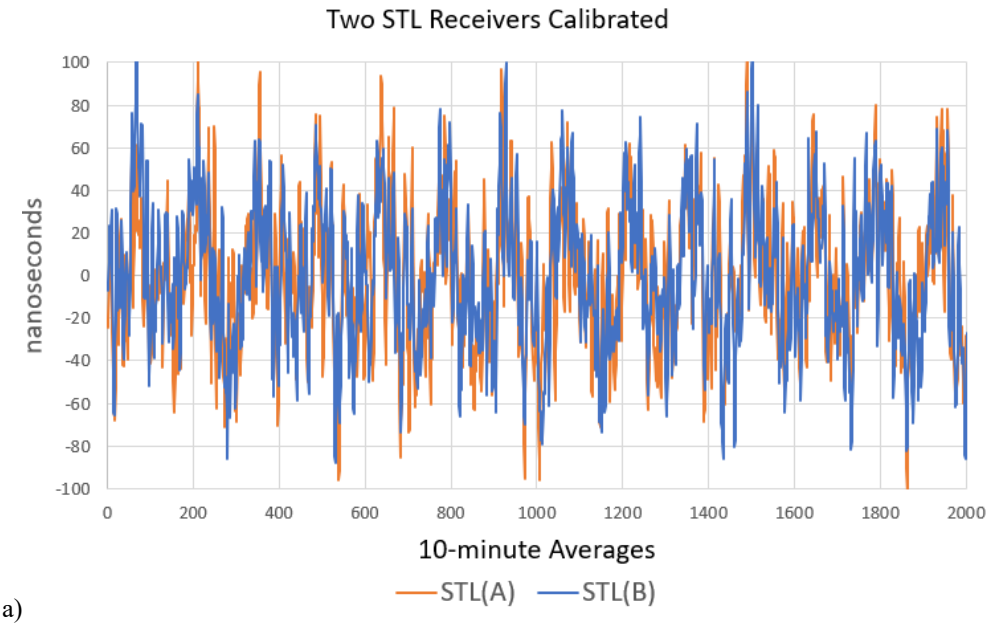
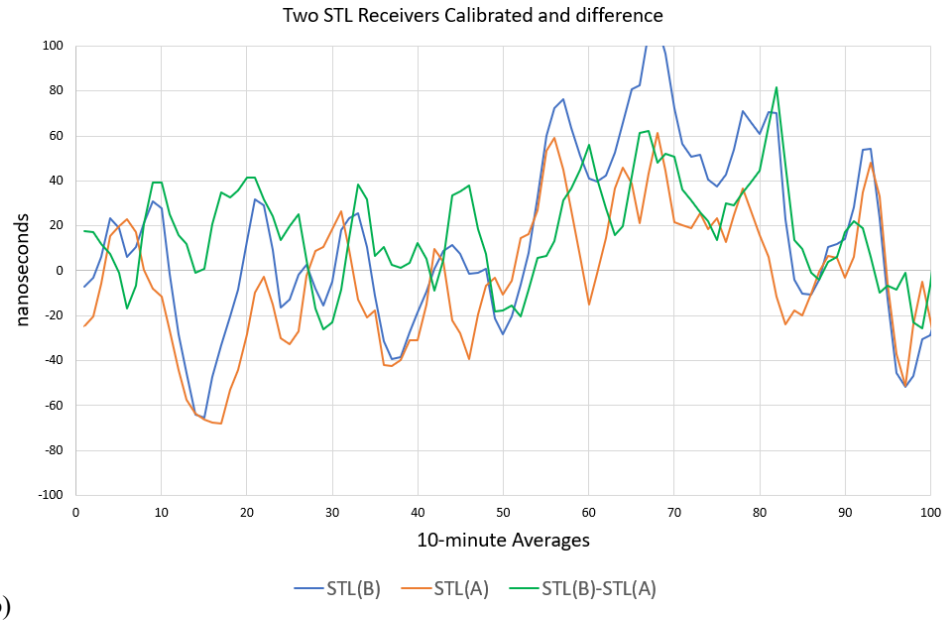


FIGURE 3 Experimental setup for initial measurements and receiver calibration at NIST.

For this short baseline test, Figure 4 shows that there is a diurnal trend which is similar for both receivers, but they don't overlap exactly. Figure 4b is a subset of 4a, showing a much shorter timeline, so that more details of the differences are apparent, and a third (green) line is added, showing the difference between the outputs of the two receivers over time. There is some cancellation. However, there are many points where the two outputs diverge from each other. The overall range of STL-A (for the whole dataset) is 209 ns, and the range of STL-B is 211 ns. The range of the difference between the outputs is 149 ns, so it shows that there is some cancellation/correlation between the two, but it is not as prominent as was expected.



a)



b)

FIGURE 4 Differences between two STL receivers with a very short baseline compared to UTC(NIST) at the same time.

The oscillators integrated within the two receivers are temperature-compensated quartz crystal oscillators (TCXO), which are among the least stable types. So, they each heavily depend on the clock model/algorithm steering from the satellite data. With that, there are differences in how the reactionary tuning of any two oscillators can differ, including one leading or lagging the other. Higher-stability oscillators would warrant better results (Johnson et al., 2024).

LONG BASELINE COMPARISONS

The receiver STL-B and its antenna and cable were sent to the TL laboratory in Taiwan and set up in a similar manner to NIST. The observed data was more stable when the TL antenna was placed outdoors on the roof, so the antenna at NIST was moved outdoors as well. The baseline between the two laboratories is greater than 11,000 km. Figure 5 shows the experimental setup at the TL lab.

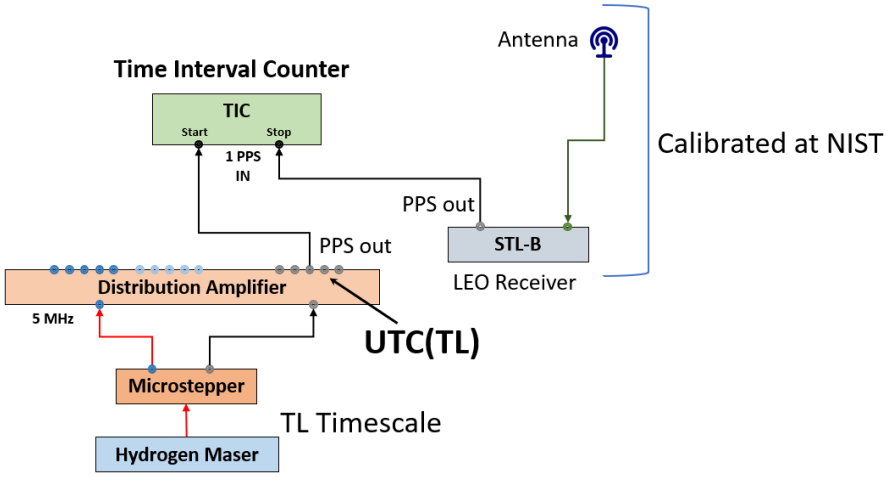
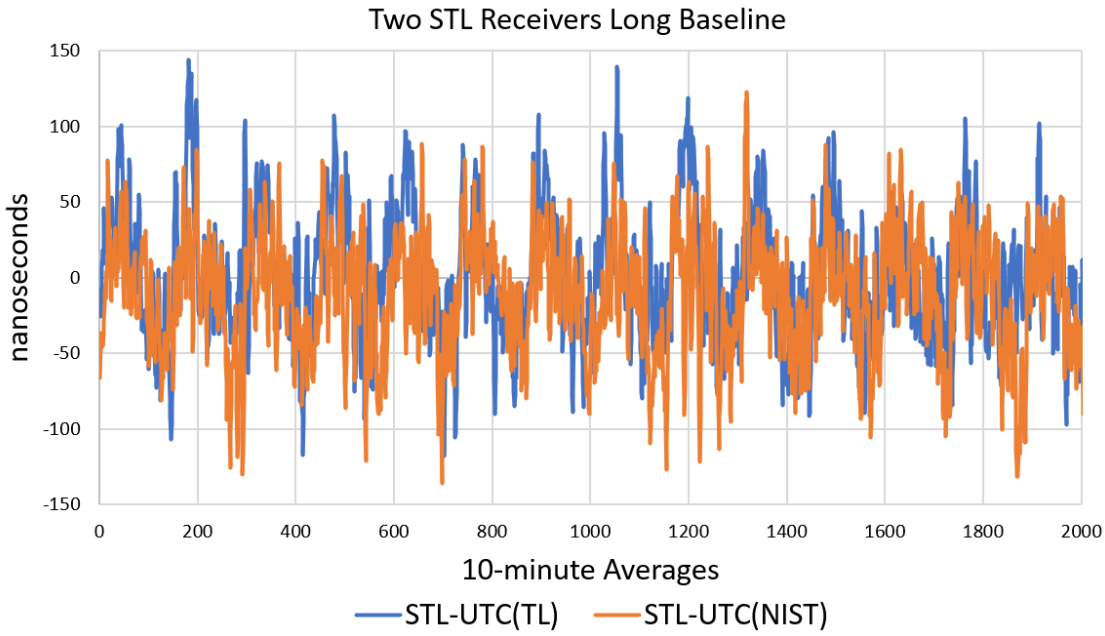


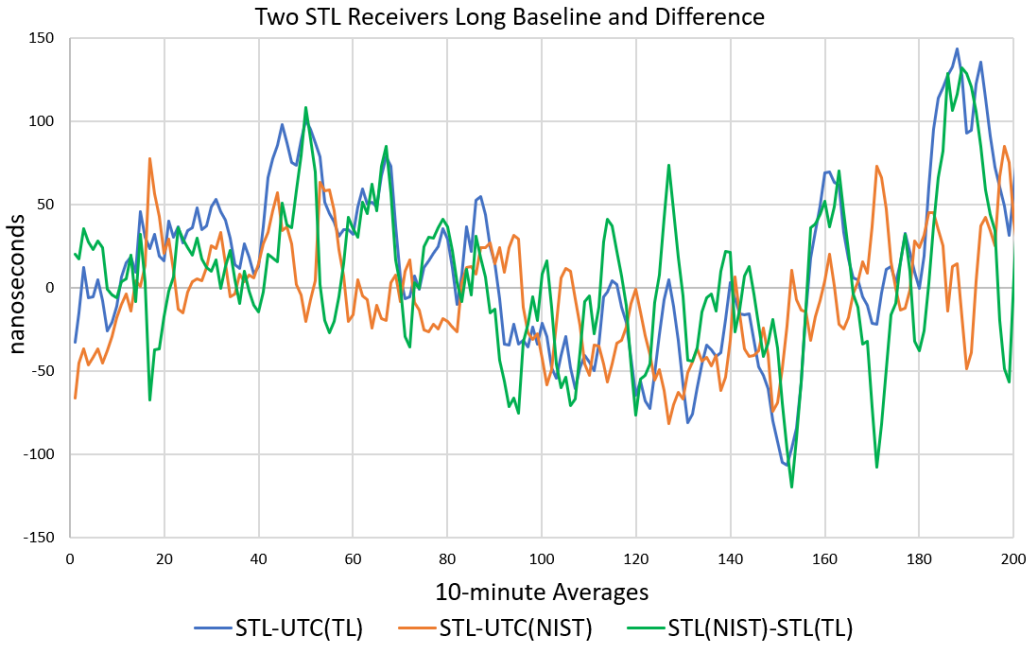
FIGURE 5 Experimental setup for initial measurements and receiver calibration at TL.

Comparing the results from each location at the same time, a similar diurnal pattern is seen. However, there are times when the signals diverge significantly (Figure 6a). Also, it should be noted that the signals are adjusted to be centered around zero, but the average output of STL-B compared to UTC(TL) was 57.8 ns. It is unclear if the calibration value remained in the receiver settings, and if there were other biases contributing to this result. Figure 6b shows a much shorter timeline, and a third (green) line is added, showing the difference between the outputs of the two receivers over time. There is cancellation at times. However, there are many points where the two outputs diverge from each other. The overall ranges of STL-A, STL-B and the differences (for the whole dataset) is about the same, so it shows that there is not enough cancellation to be useful.



a)

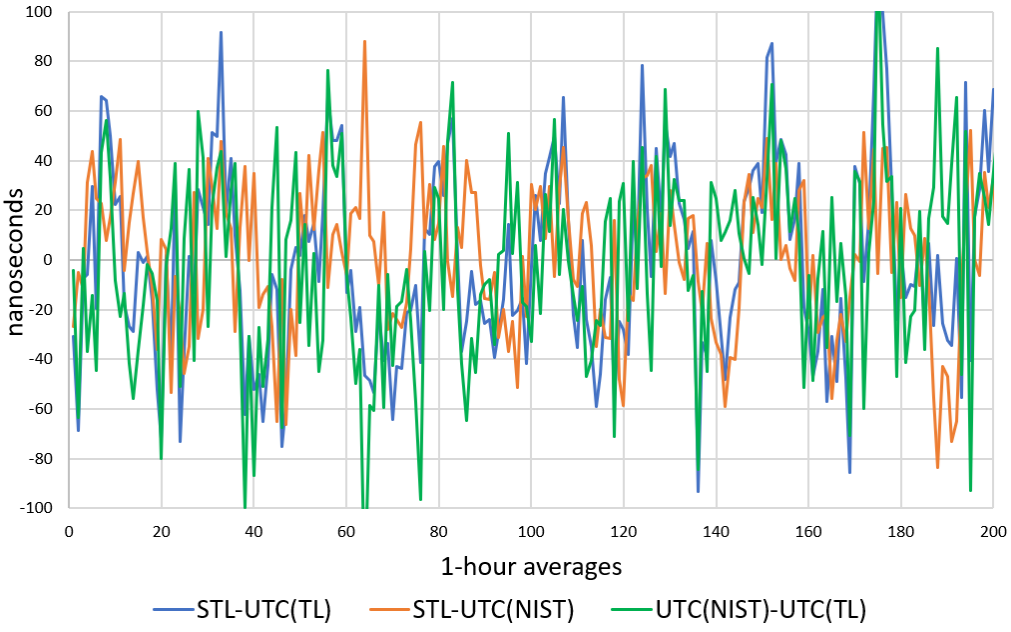
FIGURE 6a Differences between two STL receivers with a very long baseline (> 11,000 km) compared to UTC(NIST) and UTC(TL) at the same time (each point is a ten-minute average).



b)

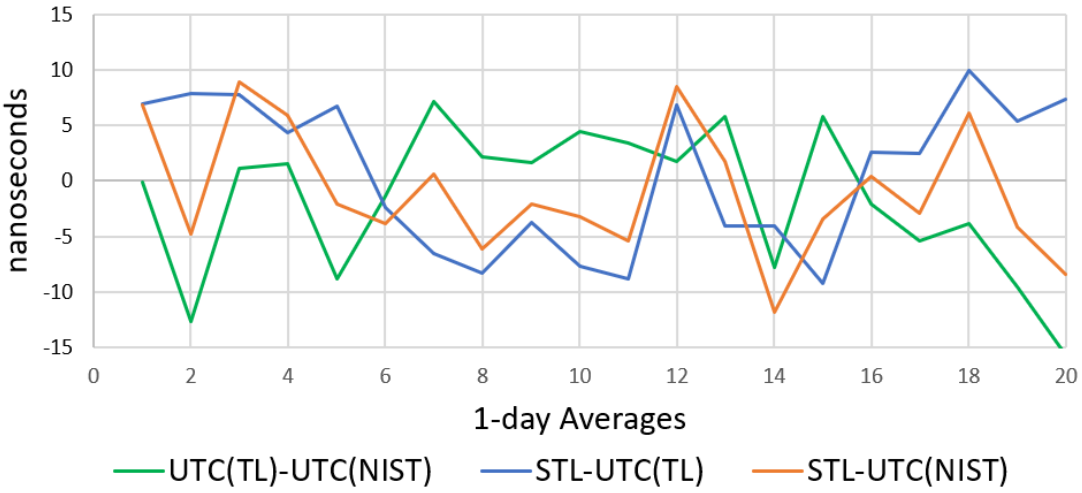
FIGURE 6b Detail plot from Fig. 6a of differences between two STL receivers with a very long baseline (> 11,000 km) compared to UTC(NIST) and UTC(TL) at the same time (each point is a ten-minute average).

Since the short-term variations do not cancel well with ten-minute averages for the very long baseline, it was supposed that more averaging was necessary. Figures 7a and 7b show the differences for one-hour averages and one-day averages, respectively. For the one-hour averages, the differences are worse than the time offsets of the individual receivers, showing very poor correlation. However, the one-day averages remove the diurnal variations and the shorter-term variations. The differences are around 5 ns or less for many of the points. There are still several differences in the one-day averages which are around 10 ns or greater.



a)

FIGURE 7a Differences between two STL receivers with a very long baseline (> 11,000 km) compared to UTC(NIST) and UTC(TL) at the same time with one-hour averages.



b)

FIGURE 7b Differences between two STL receivers with a very long baseline (> 11,000 km) compared to UTC(NIST) and UTC(TL) at the same time with and one-day averages.

CONCLUSIONS

Unfortunately, the short baseline test did not indicate strong correlation between receiver outputs, likely due to the dependence on the clock model controlling the output of each receiver. These issues persist for the very long baseline test, with the added disadvantage of very different ionospheric conditions at each site, resulting in very poor cancellation. Over long time scales (one day averages or longer), it would be possible to calibrate a receiver remotely, but with a relatively large uncertainty. Long averaging times can limit the benefits of common-view, but Johnson et al., (2026) shows promise in making near real-time corrections to the effects from the ionosphere. This could greatly improve common-view comparisons, along with the use of STL receivers with more stable oscillators.

ACKNOWLEDGMENTS

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REFERENCES

Johnson, P. & Novick, A. (2023). Measuring the Timing Accuracy of Satellite Time and Location (STL) Receivers. *ION Precise Time and Time Interval Systems and Applications Meeting Proceedings*, Long Beach, CA, USA.

Novick, A. & Montare, A. (2024). Improving the Uncertainty of NIST Remote Time and Frequency Calibration Services. *Proceedings of the 37th European Time and Frequency Forum (EFTF)*, pp 270-273, Neuchatel, Switzerland.

Johnson, P. & Novick, A. (2024). The Long-Term Timing Performance of Satellite Time and Location Receivers Utilizing Signals from Low Earth Orbit Satellites. *ION Precise Time and Time Interval Systems and Applications Meeting Proceedings*, Long Beach, CA, USA.

Johnson, P. & Novick, A. (2026). Validating the Timing Performance Improvement from Ionospheric Corrections on Iridium PNT Receivers with STL - Time Service that Utilizes only Signals from Low Earth Orbit (LEO) Satellites. *ION Precise Time and Time Interval Systems and Applications Meeting Proceedings*, Anaheim, CA, USA.