COMPARISON OF THE ONE-WAY AND COMMON-VIEW GPS MEASUREMENT TECHNIQUES USING A KNOWN FREQUENCY OFFSET*

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Abstract

Calibration and testing laboratories are seldom required to measure or certify signals with frequency offsets smaller than 1×10^{-12}. To compare the suitability of the one-way and common-view measurement techniques for calibration laboratories, we generate a 10 MHz test signal with a frequency offset of 10 µHz (1×10^{-12} offset) with respect to the UTC (NIST) time scale. We then compare the 10 MHz test signal directly to UTC (NIST) with a time interval counter, to the Global Positioning System (GPS) using the one-way measurement technique, and to UTC (NIST) using a multi-channel all-in-view common-view GPS measurement technique over a baseline of 6.2 m. The experiment is repeated using test signals with 4 µHz (4×10^{-13}) and 1 µHz (1×10^{-13}) frequency offsets, and the results are summarized and compared.

INTRODUCTION

In the world of international time and frequency transfer, oscillators with relative frequency offsets of parts in 10^{14} or 10^{15} are often compared to one another. To accurately measure a frequency offset this small, it is usually necessary to run the comparison for several weeks or months, so that the transfer noise averages down to a sufficiently low level. In contrast, the world of calibration and testing laboratories has more modest measurement requirements. Calibration laboratories are seldom required to measure or certify devices with frequency offsets smaller than 1×10^{-12}. However, they must usually limit the length of the calibration to 1 day, or several days, so that the device under test can be returned to the customer within a reasonable turnaround time.

Since GPS was declared fully operational in 1992, many calibration laboratories have decided to rely exclusively on GPS-disciplined oscillators (GPSDO) as their frequency reference. When Selective Availability (SA) was deactivated in May 2000, the performance of GPSDOs improved, and their use became even more widespread. Most calibration laboratories that formerly relied on low frequency (LF) radio broadcasts such as LORAN-C or WWVB as a frequency reference have now replaced their LF equipment with a GPSDO. Some laboratories that formerly operated a cesium standard have switched to a GPSDO, realizing that the acquisition cost of a GPSDO is often less than the repair cost of a cesium, and that a GPSDO never requires adjustment. When these labs calibrate another frequency device, they compare it directly to the GPSDO. This technique is known to the time and frequency community as a *one-way GPS comparison*.

While many calibration laboratories perform one-way GPS measurements, relatively few use the common-view GPS measurement technique, even though common-view services have been provided by NIST since 1983 **[1]** and for years by at least several other national metrology institutes **[2, 3, 4, 5]**. There are several reasons why the common-view method has not gained a foothold in the calibration world. Most common-view systems are designed to measure a 1 Hz timing signal, and most calibration laboratory customers are interested in having standard frequencies (and not time signals) calibrated. Although very simple conceptually **[6]**, a common-view GPS measurement is still more complex and takes longer to perform than a one-way measurement. It has the disadvantage of requiring data to be exchanged with a national laboratory. In some cases, the measurement results are not known until long after the actual measurement has been completed. The added complexity creates an additional burden for calibration laboratory personnel. And of course, the added processing time adds to the customer's turnaround time.

This paper does three things. First, it introduces a common-view system (being tested at NIST) that is capable of accepting any frequency up to 120 MHz as the test signal. This receiver connects to the Internet to allow the collected data to be processed in near real-time and eliminates most of the problems of postprocessing data. Second, it compares a one-way system to this new common-view system. It does so by having both systems simultaneously measure a 10 MHz test signal with a known frequency offset to see whether they can produce the correct answer in 1 day. This offset is originally set to 10 µHz. It is then reduced to 4 µHz, and finally to 1 µHz. This represents a thorough, real-world test of each system, since these frequency offsets are as small, or smaller, than a calibration laboratory is currently likely to be asked to certify. It then compares the measurements made with each system. To round out the comparison, the test signal is also directly compared to UTC (NIST) using a time interval counter. GPS is not involved at all in this direct measurement. Third, the paper briefly compares the one-way and common-view systems from a legal metrology and measurement traceability perspective.

MEASUREMENT CONFIGURATION

The following sections describe the instrumentation and measurement configurations used for each phase of this experiment.

TIME INTERVAL COUNTER AND FREQUENCY DIVIDERS

The time interval counter (TIC) used for the experiment is an Industry Standard Architecture (ISA) bus card designed at NIST for use in a standard PC **[7]**. The GPS receivers used in this experiment mount directly on this card. The TIC has a single shot resolution of < 30 ps, but differs from standard counters in at least two ways. First, it allows the connection of multiple start and stop inputs (software-selectable using a built-in multiplexer), but only one start and stop input are used for the measurements described here. Second, it has built-in programmable frequency dividers on most of the input channels. The dividers can be bypassed to allow the measurement of 1 pulse per second (pps) timing signals, or the divide ratio can be set to allow the measurement of frequency signals. Since the dividers are 24-bit devices, they can directly divide frequencies as high as 2^{24} Hz (16.77 MHz) to 1 pps. A divide-by-10 prescaler is software-activated if an input frequency higher than 16.77 MHz is used. This means that the TIC can theoretically measure input signals with frequencies as high as 167.77 MHz. However, to prevent crosstalk between adjacent counter channels, the software was written to limit the maximum input frequency to 120 MHz. A block diagram of the TIC is provided in Figure 1.
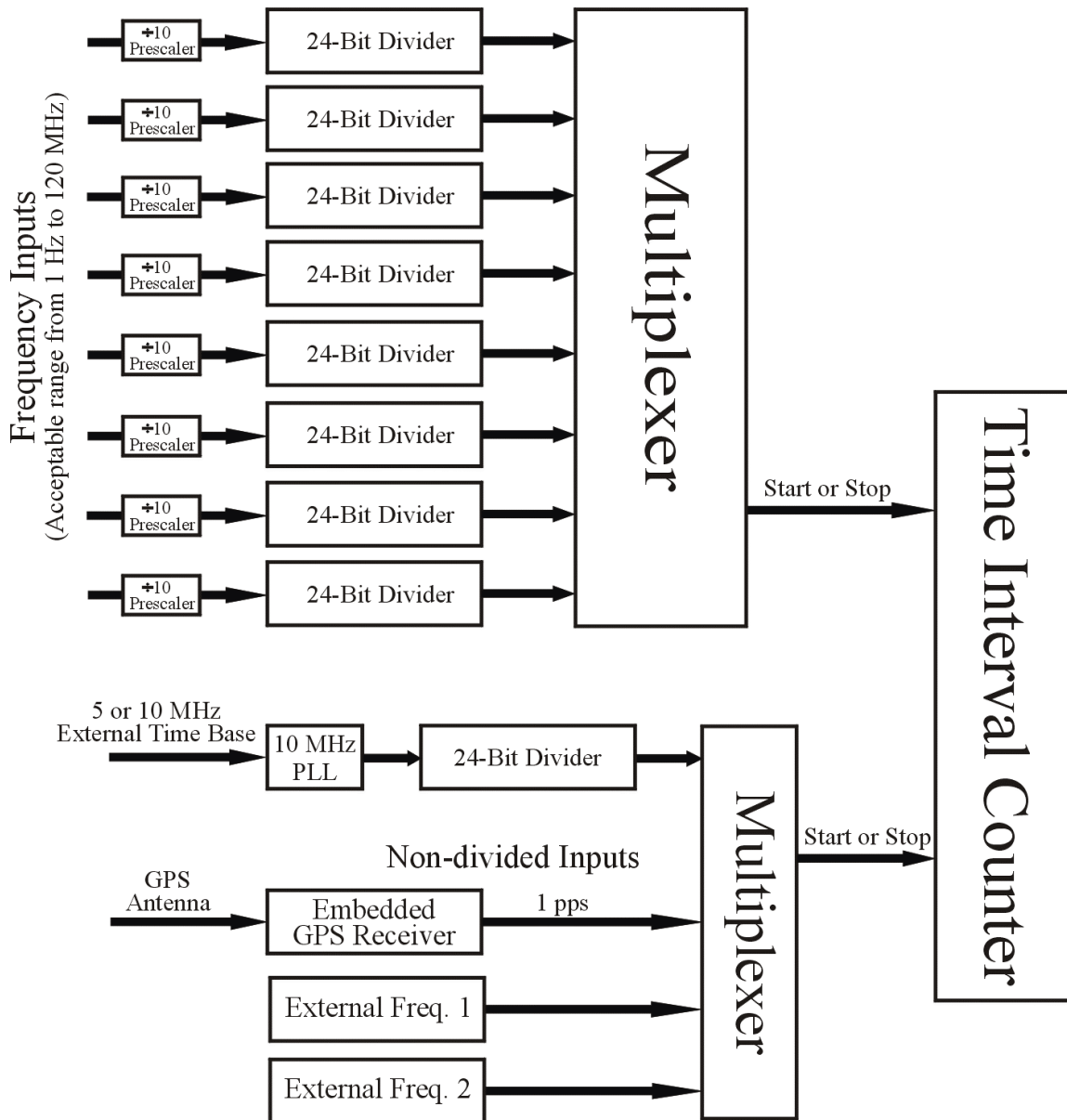
Figure 1. Block diagram of multi-channel time interval counter with embedded GPS receiver.

With the frequency dividers bypassed, the frequency stability of the counter $\sigma_y(\tau)$ has been previously measured at several parts in 10^{16} at τ = 1 day. When the dividers are turned on, as they are for the measurement of the 10 MHz test signal, additional measurement noise is introduced, and the instability increases to about 1×10^{-15} at τ = 1 day, but is still well below the noise floor of the transfer method.

DIRECT DIGITAL SYNTHESIZER

The direct digital synthesizer (DDS) used to generate the frequency offset can produce sine wave frequencies up to 12 MHz with 1 μHz resolution. The external time base for the DDS was generated using a 5 MHz signal derived from UTC (NIST) and an in-line low-noise frequency multiplier. The

frequency stability $\sigma_y(\tau)$ of the DDS was independently measured with a dual-mixer time-difference measurement system to be a few parts in 10^{15} at $\tau = 1$ day.

GPS RECEIVER AND ANTENNA

Two Motorola Oncore** UT+ receivers with version 3.2 timing firmware were used for this experiment. This receiver can simultaneously track up to eight satellites and provides an on-time 1 pps output. The receivers were connected to identical active 40 dB gain quadrifilar helix L1-band antennas (standard antennas with no choke ring) with approximately 25 m cables. The two antennas were separated by a baseline of 6.2 m.

The UT+ receiver was chosen because it is still available at this writing (November 2002), and because we have developed a library of software routines to work with this receiver. However, our tests show that it does not work as well as the now discontinued VP model in common-view mode. Figure 2 shows the results of a common-view common-clock measurement conducted at NIST between two VP receivers (10.0 firmware), and two UT+ receivers over the same interval (10 minute averages for approximately 30 days). The traces on the graph are separated for clarity. The peak-to-peak variation of the VP receiver is just 1.3 ns with an rms of about 300 ps. The peak-to-peak variation in the UT+ receiver is 6.4 ns with an rms of about 2.1 ns. The VP data are similar to results from previously published common-clock, common-view measurements **[8, 9]**, but the noise floor of the UT+ receiver is considerably higher. The bottom trace on the plot shows the results of a common-clock comparison using the VP and the UT+ over the same interval. This comparison shows the lack of short-term common-view cancellation between these two receivers. The peak-to-peak variation is about 40 ns, and the rms is about 7 ns.
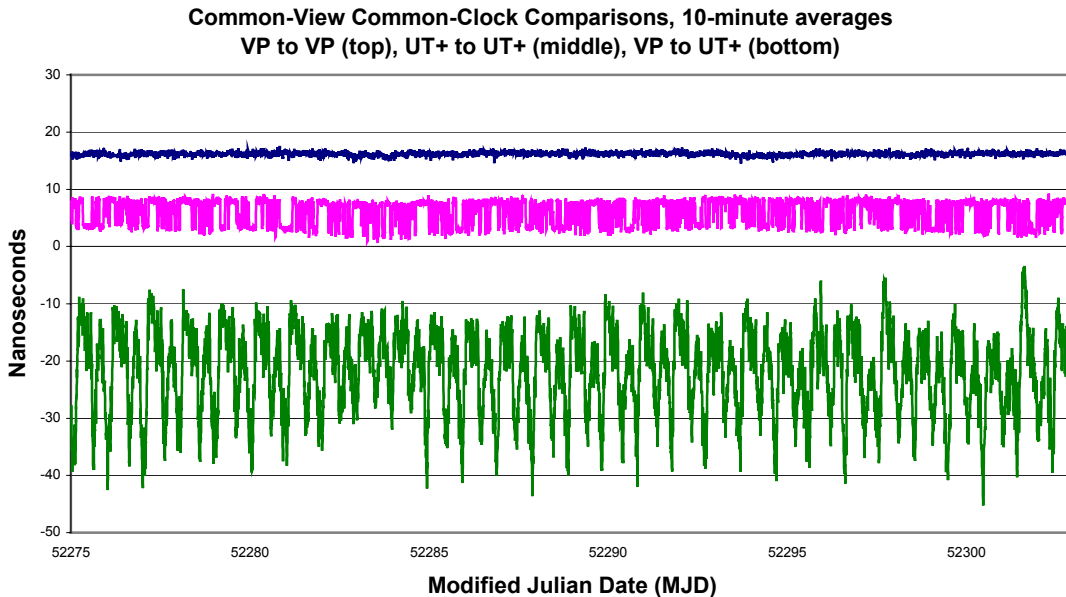

Figure 2. Results of VP to VP and UT+ to UT+ common-view common-clock comparisons.

** Identification of this commercial product is provided only to adequately describe the technical basis for this experiment. It neither implies nor constitutes endorsement by NIST.

The receivers were controlled using standard Windows computers with a software application written at NIST. The software that controls the receivers does not use a tracking schedule. It simply collects and stores data from up to eight visible satellites. Every satellite is measured for the entire period when it is visible above a 10° elevation angle. On average, about 400 minutes of data are collected from each satellite per day. This tells us that even though a given GPS satellite completes slightly more than two Earth orbits during a day, it is still visible from a fixed position on Earth more than 25% of the time. The UT+ receiver has the ability to apply both the broadcast ionospheric and tropospheric corrections, and this feature is enabled in software and used throughout the measurement.

The system makes a time interval measurement between the GPS pulse and the local clock every second. It uses information supplied by the receiver to produce a time offset reading for each individual satellite, and stores 10-minute averages for each satellite. If less than 600 readings are collected during a 10-minute segment, no data are stored. The data from a complete day is stored in a daily file as a 32 column $\times$ 144 row matrix. The 32 columns represent the possible number of GPS satellites (27 GPS satellites were usable throughout most of this experiment), with each satellite's data stored in the column whose number equals its pseudo-random noise (PRN) code. The 144 rows represent the number of 10-minute segments in 1 day. The collected data are uploaded to an Internet server using the file transfer protocol (FTP). During the remote calibration, this upload was performed every 24 hours, but the software can be modified to upload more frequently. All data graphing, reduction, and analysis are performed by Web-based applications developed at NIST that are hosted on the Internet server.
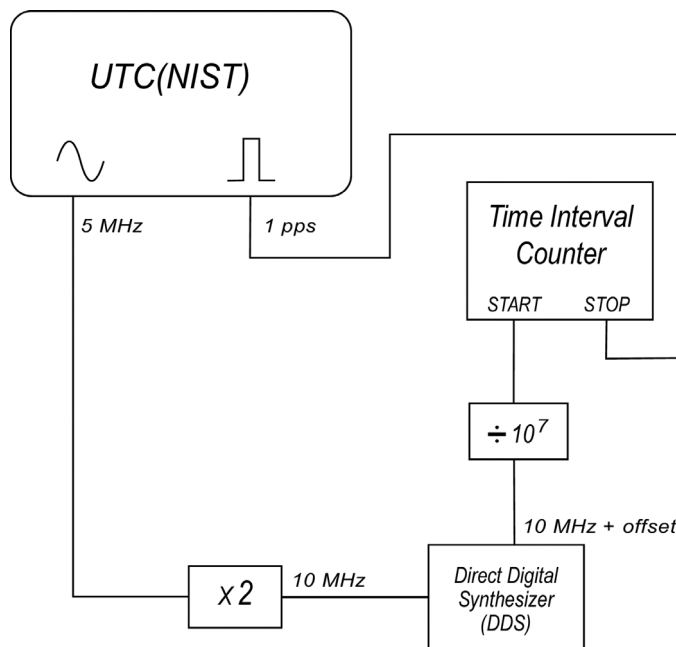
DIRECT COMPARISON SYSTEM

This system is illustrated in Figure 3. The test signal is divided by 10^7, and used to start the TIC. A 1 pps signal from UTC(NIST) stops the TIC. A 5 MHz signal from UTC(NIST) serves as the TIC's external time base reference.

ONE-WAY GPS SYSTEM

This system is illustrated in Figure 4. The test signal is divided by 10^7, and used to start the TIC. A 1 pps signal from the GPS receiver stops the TIC. A 5 MHz signal from UTC(NIST) serves as the TIC's external time base reference.

Figure 3. Direct comparison system without GPS.

MULTI-CHANNEL ALL-IN-VIEW COMMON-VIEW GPS SYSTEM

This system is illustrated in Figure 5. Two common-view systems are collocated in the same laboratory at NIST. One is compared to the test signal (divided by 10^7), and one is compared to a 1 pps signal from UTC (NIST). The TICs on both sides of the common-view comparison use a 5 MHz signal from UTC (NIST) as their external time base reference.
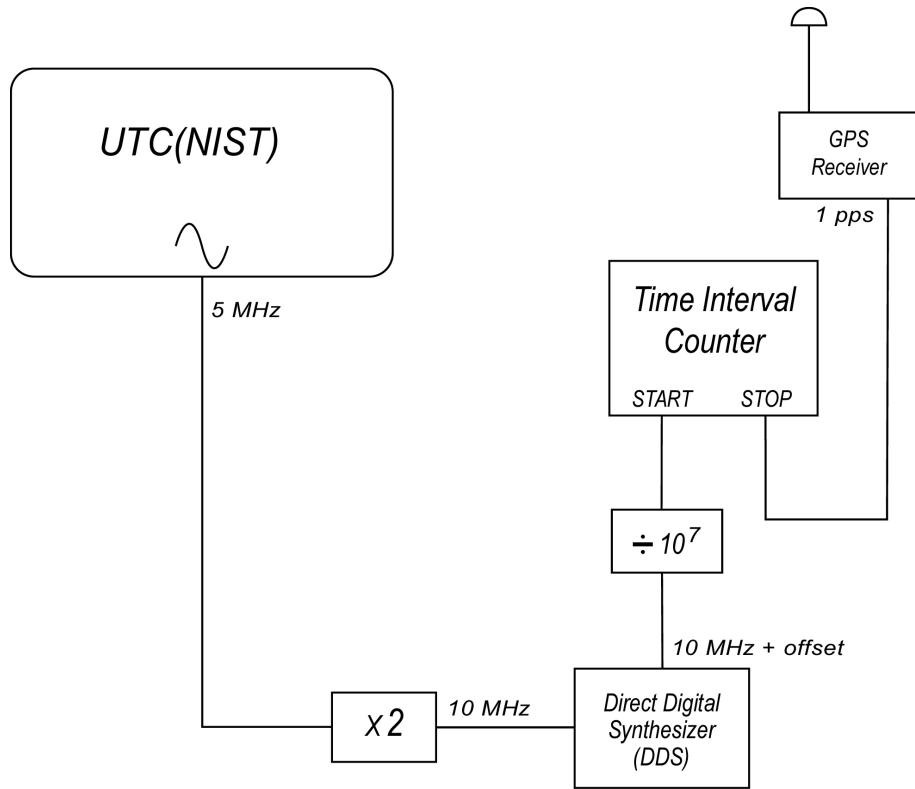
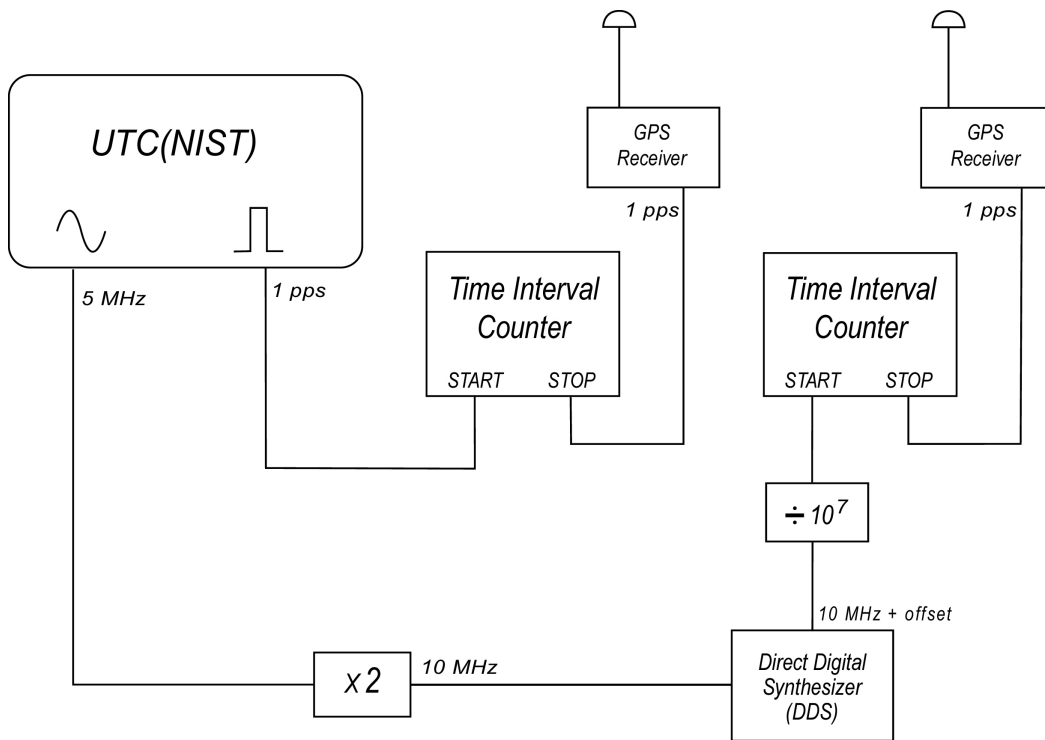Figure 4. One-way GPS measurement system.

Figure 5. Common-view GPS measurement system.

Data collected by each receiver are uploaded to an Internet server for processing. The data reduction and analysis software that runs on the server can be accessed using a standard Web browser. The Web software was developed as a common gateway interface (CGI) application for a Windows 2000 server. The CGI application was written using a combination of a compiled BASIC scripting language, and a Java graphics library. It can load up to 200 days of 10-minute averages (28800 data points) from two common-view receivers, align the data sets, perform the A minus B subtraction, graph the results, and calculate both the time deviation ($\sigma_x(\tau)$) and Allan deviation ($\sigma_y(\tau)$) of the data set. In addition, both sides of the common-view track recorded from any individual GPS satellite can be viewed, and tabular data can be copied from the Web page and pasted into a spreadsheet or other application for further analysis.

MEASUREMENT RESULTS

Three 7-day measurement runs were completed. The test signal was offset by 10, 4, and 1 µHz respectively for the three runs, and was simultaneously measured with the systems illustrated in Figures 3, 4, and 5. With a 10 µHz frequency offset (1×10^{-12}), the Δt for the 7-day interval is 604.8 ns. All three of the traces shown on the time difference plot in Figure 6 have a range very close to this value, and by looking at the 1-day plot segments, it is obvious that both the one-way and common-view techniques can be used to easily calibrate devices in 1 day with an offset this small.
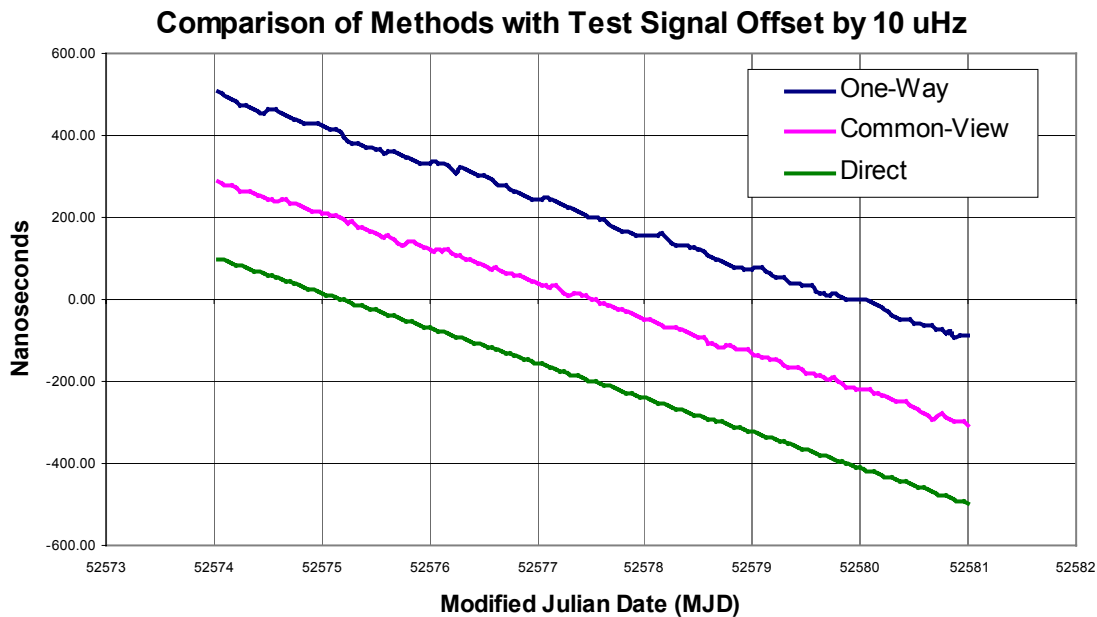

Figure 6. Comparison of three methods using a 1×10^{-12} frequency offset.

When the frequency offset is reduced to 4×10^{-13}, the Δt for the 7-day interval is correspondingly reduced by a factor of 2.5 to 241.9 ns (Figure 7). GPS diurnal variations are now clearly visible on the one-way trace, but a 1-day calibration using either the one-way or common-view would still yield the correct answer.

When the frequency offset is reduced to 1×10^{-13} (Figure 8), the Δt for the 7-day interval is reduced to 60.2 ns. Since the daily peak-to-peak variation of a GPS receiver is typically in the 20 to 40 ns range, it is

obvious that a 1×10^{-13} offset cannot be accurately measured in 1 day using one-way GPS. However, the slope of a linear least squares line fit to the 7-day one-way trace (not shown in the figure) indicates a frequency offset of 1.03×10^{-13}, or near the correct answer. The common-view trace is obviously less noisy. The 7-day frequency offset yields the correct answer of 1×10^{-13}, and the offset can be measured with reasonable confidence in a few days.

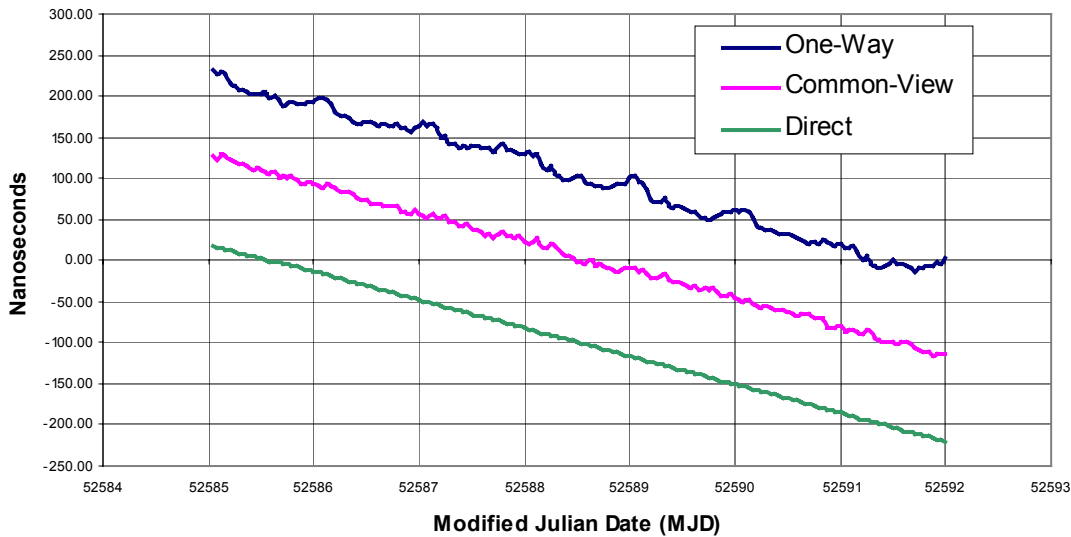**Comparison of Methods with Test Signal Offset by 4 uHz**

Figure 7. Comparison of three methods using a 4×10^{-13} frequency offset.

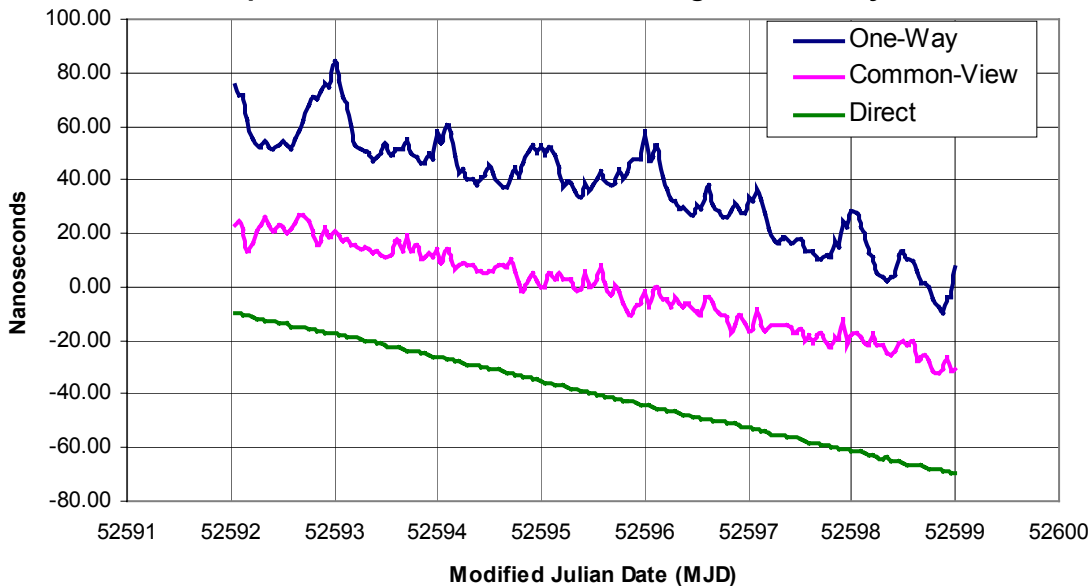**Comparison of Methods with Test Signal Offset by 1 uHz**

Figure 8. Comparison of three methods using a 1×10^{-13} frequency offset.

The Allan deviation of the 1 μHz frequency offset measurement is shown in Figure 9. At τ = 1 day, the stability of the comparison is slightly above 1×10^{-13} for the one-way method, and about 7×10^{-14} for the common-view method. The direct comparison method reaches a stability of about 6×10^{-15} at τ = 1 day. The stability of the direct comparison method is above the noise floor of the TIC, and is believed to be limited by the instability of the DDS.

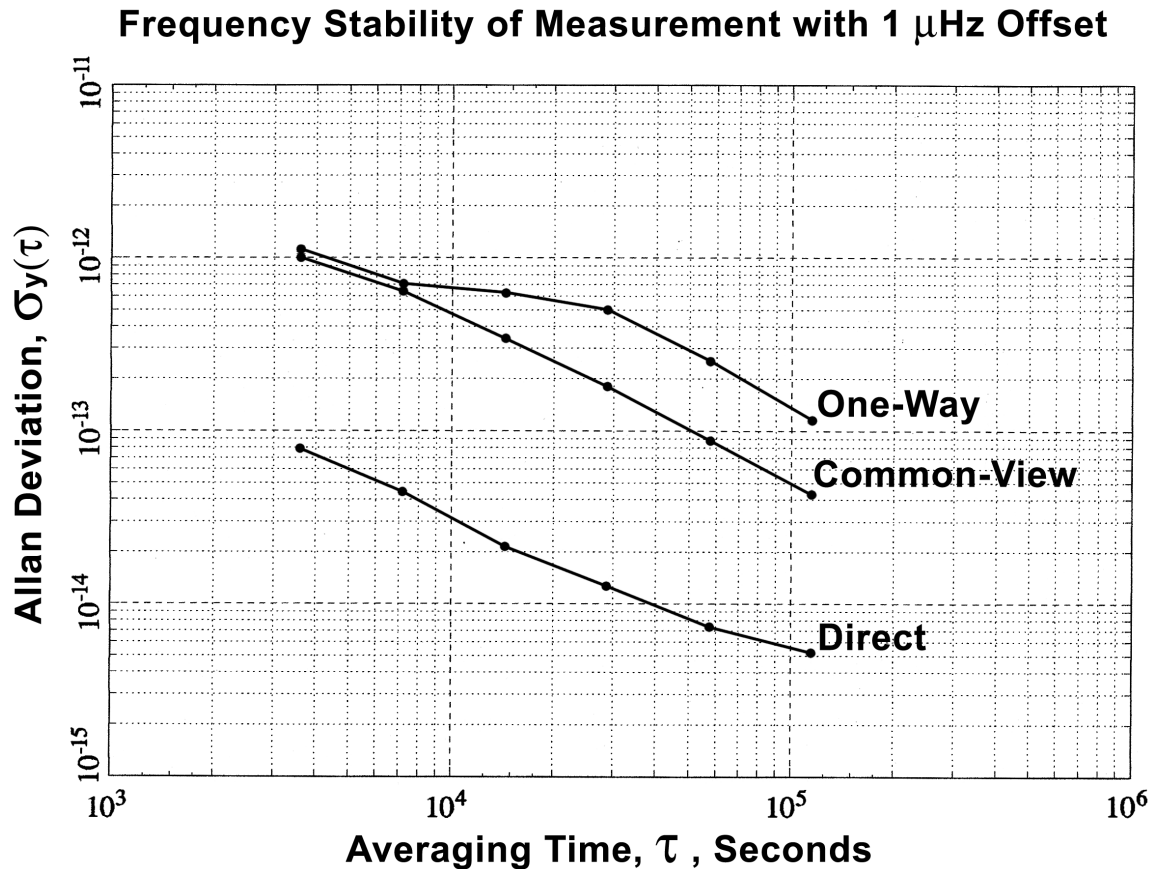**Frequency Stability of Measurement with 1 μHz Offset**

Figure 9. Comparison of Allan deviations of the three methods.

From a practical viewpoint, note that not much is gained by using the common-view method. The one-way method can meet all existing requirements of calibration and testing laboratories, although some GPSDOs might not be capable of producing the results shown here. We are aware that the noise floor for zero-baseline common-view could be lowered if a lower-noise GPS receiver were used for the measurement (Figure 2). We are also aware that the difference between one-way and near-zero-baseline common-view measurements is much larger than the difference between one-way and long-baseline common-view measurements, regardless of which receiver is used. Over a 1000 km baseline, for example, it might be difficult for a calibration laboratory to detect any difference at all between the two methods. Since the performance differences are probably not significant for calibration laboratories, a more important issue might be the difference in traceability chains, a topic discussed in the next section.

LEGAL METROLOGY AND TRACEABILITY ISSUES

For legal metrology reasons, calibration laboratories are required to show measurement traceability to national or international standards. Traceability is defined as:

> *The property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties* **[10]**.

When the one-way measurement technique is used to establish traceability to UTC (NIST), two comparisons are added to the traceability chain. The first compares the device under test to GPS. The uncertainty of this comparison is largely dependent upon the quality of the GPS receiver **[11, 12]**. The second compares GPS to UTC (NIST). Daily comparisons of GPS to UTC (NIST) are provided on the NIST Web site at *http://tf.nist.gov/service/gpstrace.htm*. Figure 10 shows a plot (obtained from the Web site) of GPS time received at NIST in Boulder, Colorado and compared to UTC (NIST) for the 100-day period ending 1 November 2002. Each data point represents a 1-hour average. The mean time offset for this period is 15.8 ns. The peak-to-peak variation in the time offset over this period is about 50 ns, and the frequency offset is near 1×10^{-15}.
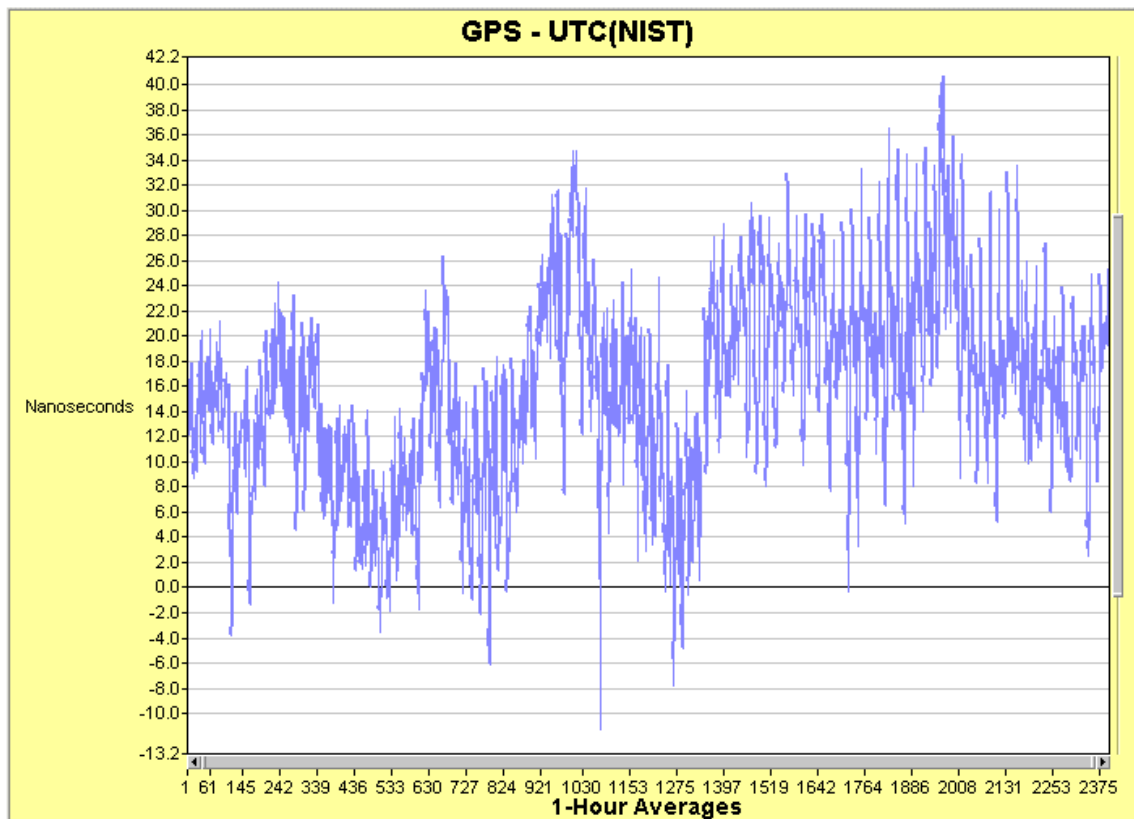

Figure 10. A GPS-to-UTC (NIST) comparison for the 100-day period ending 1 November 2002.

When the common-view measurement technique is used to establish traceability to UTC (NIST), the device under test is directly compared to UTC (NIST), and only one link is added to the traceability chain.

Thus, although the slightly smaller uncertainty of the common-view method might not be significant for most calibration laboratories, the common-view technique does have the advantage of providing a simpler, easier-to-understand traceability chain **[6]**.

SUMMARY AND CONCLUSION

This paper has described a comparison between one-way and common-view GPS measurement systems developed at NIST, by using both systems to measure a known frequency offset. The one-way method is shown to be capable of meeting all existing requirements of calibration and testing laboratories. The common-view method is shown to be capable of providing slightly smaller measurement uncertainties, and a simpler traceability chain to UTC (NIST).

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QUESTIONS AND ANSWERS

WILLIAM J. RILEY (Symmetricom): I wonder, Mike, is it possible to upload general data into this analysis routine on the Web? Or, does it depend on the use of your particular hardware along with it?

MIKE LOMBARDI: It is not possible the way it is now, but I have thought about that. It would be fairly easy to modify, to just allow any data to be entered from a form, or cut and pasted and copied over.

DEMETRIOS MATSAKIS (U.S. Naval Observatory): It seems like a very good service. I am curious to know how many companies or laboratories take advantage of it, or that you anticipate?

LOMBARDI: What I presented here is not in service at this point. NIST has an existing common-view time transfer service and an existing frequency measurement service. This is something that might become an improved version of the service we already have, but this is not in service yet. In terms of our existing frequency measurement service, it has about 50 calibration labs that subscribe.