Improving the Uncertainty of NIST Remote Time and Frequency Calibration Services

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The National Institute of Standards and Technology (NIST) has offered remote time and frequency calibration services since the late 1980s. At that time, the Services Group calibrated frequency references at a customer's site using terrestrial radio signals, and the service was later upgraded to using signals from the global positioning system (GPS) satellites. The original Time Measurement and Analysis Service (TMAS) was introduced in 2006, which used the GPS common-view method to make ongoing time comparisons between UTC(NIST) and a remote clock or oscillator, and the results were available in near real-time online. A major benefit of a remote calibration service is that the device under test (DUT) can be measured continually, while it is in operation, instead of being sent to a laboratory periodically. Constant legal traceability to the International System of Units (SI) warrants several advantages, including more robust traceability when using the calibrated device as a reference for local measurements and very early indication if the DUT is not working correctly.

Several improvements have been implemented since the service began. Originally, the system utilized a single-frequency eight-channel GPS timing receiver for the common-view measurements and relied on the self-survey for the position determination, which could be incorrect by several meters in height determination. The current TMAS uses a single-frequency 12-channel GPS timing receiver and the option to survey the antenna location with a geodetic receiver to augment the position accuracy. The combined measurement uncertainties are 11.8 ns for time measurements and 1×10^{-14} after one day of averaging for frequency measurements.

In this paper, we introduce substantial improvements to the service. The upgraded TMAS (named TMAS2) implements a dual-frequency Global Navigation Satellite System (GNSS) receiver capable of using satellite data from multiple constellations. The use of two frequencies broadcast from each of the GNSS satellites (designated as L1 and L2) affords improvements by minimizing ionospheric effects on the signals by applying measured differential corrections instead of using modeled corrections. The timing diurnals seen in the prior single-frequency GPS data due to propagation through the ionosphere are greatly reduced, resulting in better position determination and lower noise common-view comparisons. With significant reduction of Type A and Type B uncertainties, we expect the combined time uncertainty of the new service to be less than 5 ns and a frequency uncertainty towards 5×10^{-15} after one day of averaging.

Improvements to the TMAS are beneficial to current users of the calibration service, confers the ability to measure better clocks, and allows reporting data even closer to real-time. Also, there will be increased stability for the NIST disciplined clock (NISTDC) option of the service, where the common-view results are used to steer a rubidium oscillator contained within the measurement system. A highly portable version of the TMAS2 will sharpen calibrations of GNSS-independent NIST time and frequency services, such as Time over Fiber and Time over Satellite, and support the re-calibration of existing systems.

Keywords—Time metrology, GNSS, PNT, common-view GPS, uncertainty, calibration

I. Introduction

Estimating and measuring uncertainty for a remote time measurement introduces additional steps, compared to a local measurement. A time comparison in a lab comprises a reference pulse-per-second (PPS) signal traceable to the International System of Units (SI) and a PPS signal from a device under test such as an atomic oscillator, a National Metrology Institute (NMI) time scale/clock ensemble or a Global Navigation Satellite System (GNSS) receiver, compared with a time-interval counter (TIC). Uncertainties in the laboratory measurement are inherited from the reference, the cable delays, the environment, and the TIC. The combined uncertainty of a local measurement can be less than one nanosecond. However, remote measurements with common-view GNSS add several factors, such as time-transfer noise, calibration of the complete path, survey of the position (coordinates), effects from reflected signals (multipath) and the signal propagation through layers of the ionosphere.

II. Common-view GNSS

The common-view technique has been used to compare clocks and oscillators at two different locations for several decades [1,2]. For time comparisons, a local clock PPS output is compared to the PPS output of a Global Positioning System (GPS) or other GNSS receiver. This is done at a remote location as well, with the local clock at that site compared to the output of a GPS receiver. When the results of each measurement are subtracted, the contribution of GPS (common to both sides) is removed, and the remaining value reveals the difference between the two remote clocks. If the single (composite) output of the receiver is used, this is referred to as "all-in-view" common-view. However, the composite timing output of a GPS receiver is created with data from selected satellites "in-view" at the location of the outdoor antenna. This may be a simple- or weighted mean, where, for example, the satellites highest in observed elevation carry more weight in the average. With a receiver that can distinguish the contributions of individual satellite clocks to the composite solution, this technique becomes even more powerful for remote clock comparisons. The differences between the local clock and a particular satellite can be compared to the remote local clock to the same satellite at the same time. Using data from each of the satellites in common-view, it can produce results with uncertainties smaller than 12 ns with single-frequency (L1) receivers. With each site uploading the data to a cloud internet server, clock-difference results can be generated in near real-time, delayed only by the averaging period. This technique using the individual satellite comparisons is referred to as multi-channel common-view, and it is the more prevalent technique. The all-in-view technique is primarily used to compare remote clocks separated by very long distance, with only a few or no satellites in common-view at any given time [3].

If the clock or ensemble of clocks at one of the two sites is a national laboratory that has traceable measurements to the SI second and Coordinated Universal Time (UTC), then the other site can attain traceability to the SI and UTC through these comparisons. This is highly useful for national labs not currently comparing directly to the Bureau of International Measurements (*Bureau International des Poids et Measures* - BIPM), or as a near real-time estimate of their upcoming contributions and comparisons directly with the BIPM. Also, commercial manufacturers, research agencies and institutions, government entities, financial institutions, etc., can subscribe to this calibration service through NIST or possibly another agency to achieve these real-time comparisons and traceability.

III. SINGLE VS. DUAL-FREQUENCY RECEIVERS

GNSS satellites broadcast data over several different frequencies but, until recently, the dual frequency receivers were cost-prohibitive for a low-cost calibration service. A recent publication from NIST showed several advantages of dual-frequency receivers, including position determination and time transfer [4]. Dual frequency receivers are able to measure the effects of the ionosphere on the propagation delay of the signal instead of using modeled or post-processed solutions. For position determination, in particular, the survey of the height of the antenna, single frequency receivers may have a bias of greater than 10 m after a 24-hour survey, where dual frequency receivers achieve sub-meter accuracy. With common-view, on short baselines, with a common clock reference, the diurnal variations of the ionosphere mostly cancel out, so very "local" common view has shown peak-to-peak daily variations of 3-4 ns, where dual-frequency receivers show 2-3 ns, but over a period of 25 days, the single frequency range can be more than double the range of the more consistent data from the dual frequency receiver. A common metric for time transfer noise is time deviation (TDEV) at one day of averaging. In Section 4 of [4] the TDEV at one day is ~220 ps for dual-frequency common-view, which is less than half of the TDEV of ~500 ps for the single-frequency receiver measured simultaneously with a common clock and common antenna. The dual-frequency receiver supports a lower TDEV at one day for all baselines tested, the largest was 5314 km from Boulder, Colorado to Kauai, Hawai'i. With marked improvements in all of the metrics of uncertainty for common-view time transfer, Section IV shows a complete uncertainty analysis for the dual-frequency receiver that will be used in the next generation Time Measurement and Analysis Service (TMAS2) at NIST.

IV. MEASUREMENT UNCERTAINTIES

Estimating the uncertainty of TMAS2 includes both the Type A and Type B uncertainties as described in the ISO Guide to Uncertainty Measurement [5]. All contributing effects to previous NIST common-view uncertainty analyses [2,6] are included here.

A. U_A, Time Uncertainty

As previously mentioned, to evaluate Type A (statistical) uncertainty for time measurements we use the time deviation TDEV at an averaging time of one day. At several locations, common-view to Boulder Colorado, TDEV at 1 day are shown for several locations. To cover the continental United States, a value of 0.5 ns is estimated for the time uncertainty. It should be noted that TDEV is a measure of time stability, so frequency offset should be studied separately.

TABLE 1 BASELINE OF TESTS AND ASSOCIATED TDEV

Location	Baseline	TDEV @ 1 day
Boulder, CO	0 km	0.24 ns
Ft. Collins, CO	78 km	0.30 ns
Beverly MA	2963 km	0.41 ns
Kauai, HI	5314 km	1.47 ns

B. U_B, Calibration

We compare measurement systems for intervals of 10 days to determine the accuracy of time/frequency transfer, and the effectiveness of the 10 day interval for calibration [6]. Using 18 overlapping 10-day common-clock calibrations of systems, we can determine the uncertainty of the calibration value from day to day differences. The peak to peak range of calibrations is 0.26 ns, so we will assign a value of 0.35 ns to the calibration.

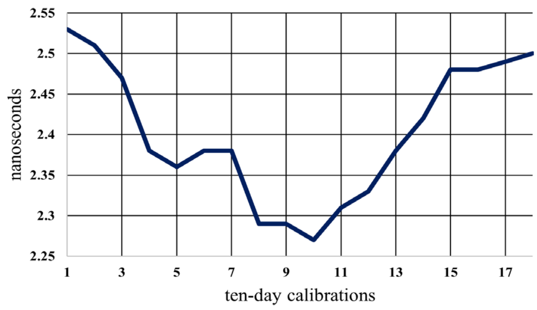

Fig. 1 Overlapping 10-day calibrations with a range of 0.26 ns.

This is considerably more stable than the single frequency receiver calibrations in previous analyses. It should be noted that, at NIST, the complete customer system (including the antenna, cable, hardware and any splitters or in-line amplifiers) is calibrated. This assures that everything that contributes to the delay is considered in the assigned delay value.

C. U_B, Coordinates

Dual-frequency GNSS receivers use ionospheric measurements from the two broadcast frequencies to remove the first order (99.9 %) of the delay of the ionosphere on the signal propagation [7]. This can result in more than an order of magnitude better height determination than when surveying with single-frequency receivers. Repeated 24-hour self-surveys showed better than 1 m accuracy in height determination, with a dispersion of 0.5 m and a standard deviation of around 0.25 m. However, this could still add up to 3 ns of time transfer bias due to coordinate uncertainty. Instead, we choose to submit the Receiver Independent Exchange (RINEX) observation files created by the receiver for post-processed results of the position. Through the Canadian Spatial Reference System Precise Point Positioning (CSRC-PPP) online application [8], height determination of < 10 cm can be achieved. Precise Point Positioning uses code and carrier phase measurements in the ionosphere-free combination to remove the ionospheric refraction, modeling of troposphere delays, and improved satellite orbit determination. With this extremely high position accuracy, we will assign 0.15 ns as the position uncertainty.

D. U_B, Environment

Previous receivers and TICs used for single frequency common-view were sensitive to temperature [6]. A room temperature change of a few degrees Celsius could change the time difference results by several nanoseconds. This also caused an issue with the calibration because if the system is calibrated at a different temperature than it is operated at the field location, there will be a bias in the results. In a common-clock test with the dual-frequency receivers, one receiver was put into a thermal chamber and subjected to some fast temperature variations of 5 °C above or below a "room temperature" setting ~ 23 °C and also left for 24 hours at extreme set temperatures > 31 °C and < 15 °C as well. The common-view timing data from the receiver show variations less than 0.37 ns during the entire test and show variations of 0.30 ns for the six days before the test, in an ordinary laboratory environment varying by +/- 0.5 °C.

Fig. 2 shows the common-view data during the time of the temperature swings. The relative humidity range in the chamber for this period varied from 22 % to 46 %, with no noticeable effects on the common-view data. We will assign 0.25 ns for uncertainty due to environment in order to account for any unknowns.

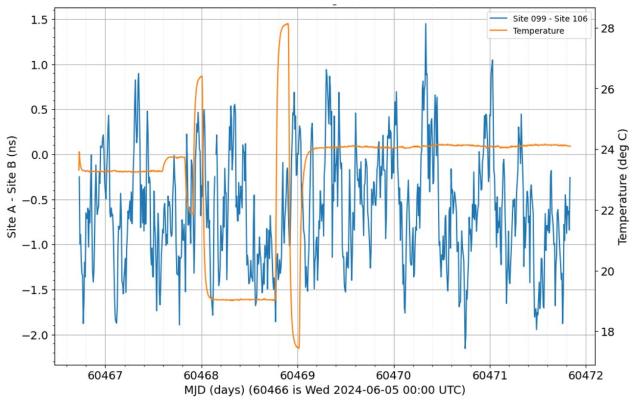

Fig. 2 Common-view data of dual-frequency receivers during large temperature swings shows no noticeable perturbations.

E. U_B, Multipath

Uncertainty due to_multipath comes from GNSS signals which are reflected off of a surface towards the antenna. This can add delay or noise. However, the antenna used for the remote calibration service has been optimized for multipath rejection, with circularly-polarized, symmetric radiation patterns, it rejects reflected signals because the polarity will be opposite to the non-reflected signal. We placed the antenna into a bad multipath environment and recorded the results: it was stuck to metal railings laying on surface of the roof, a few meters away from a building wall, and near several metal objects. For a 12-day period, the measured range of the common-view timing data was very small: 3.03 ns, and the TDEV at one day was 0.12 ns; slightly smaller than recent values with a normal sky view.

Fig. 3 shows a single-satellite common-view difference between a receiver with an antenna having a normal sky view and another antenna before and after it was placed in the bad multipath area. There are definitely some "noisy tails" on the edges of some of the tracks, where the satellite was low in the sky. Only data from two of the satellites during this time showed this effect. With the 10-minute averages, there is not enough bad data to make a noticeable change in the overall common-view performance. A value of 0.5 ns will be assigned for Type B multipath uncertainty.

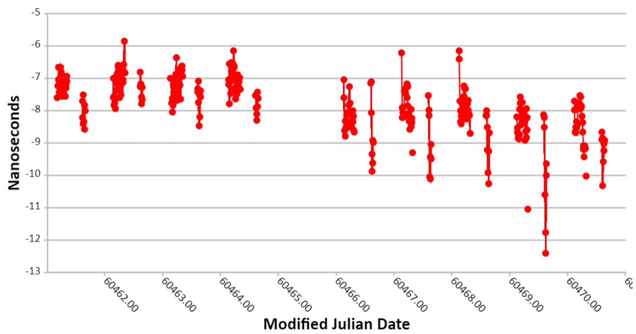

Fig. 3 Single satellite subtraction between multipath and rooftop mount with normal sky view before and after antenna placed in bad multipath area. The delay offset changed because the multipath location was not geodetically surveyed.

F. U_B, Ionosphere

The uncertainty due to ionosphere with single-frequency receivers is caused by imperfections in the modeled ionospheric (MDIO) corrections that are part of the GPS broadcast message. The dual-frequency receiver measures the ionosphere and mitigates most (99.9 %) of its effects [8]. Tropospheric effects in varied weather conditions and terrain can add several cm to the height uncertainty [9] so we assign 0.25 ns for these Type B effects. A recent solar storm caused single-frequency common-view timing data to change rapidly by +/- 30 ns, temporarily, yet it had little effect on the dual-frequency data. Fig. 4 shows a comparison of single-frequency and dual-frequency one-way GPS data compared to UTC(NIST) around the solar activity.

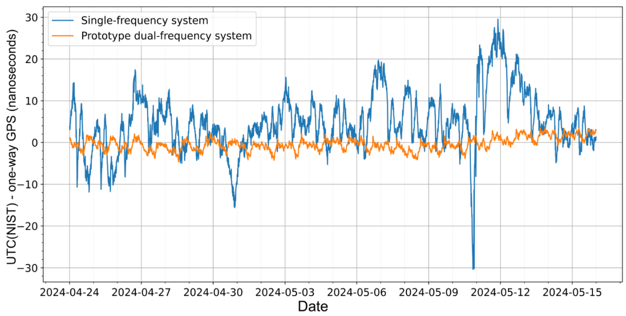

Fig. 4 Single-frequency and dual-frequency one-way GPS data comepared to UTC(NIST) before and during the solar storm on May 10, 2024.

G. U_B, Reference Delay

The reference delay is the delay of the cable (and any connectors) from the physical point of time reference to the measurement system. In the past, it was left to the lab at the remote site to make the cable delay measurement. However, at NIST the cables are measured with a high precision (50 ps resolution) time interval counter using the output from a cesium oscillator as its external timebase. The BIPM-recommended cable calibration method is followed, where two PPS signals are measured (and averaged for 100 s), and then the cable under test is inserted in-line with each of the PPS cables at separate times and the resulting delay changes should be equal and opposite. A value of 0.1 ns is used for the uncertainty of the reference delay measurement if it is done at NIST.

H. U_B, Resolution

The resolution of the software where the cable delay is entered is 0.1 ns. There may be a rounding error that would add 0.05 ns to the uncertainty.

I. U_B, Combined Uncertainty

Table 2 shows the Type A uncertainty and all of the Type B uncertainties discussed up to this point. These can be combined by adding in quadrature (the root sum of squares method), where *k* is the coverage factor:

$$U_c = k\sqrt{U_A^2 + U_B^2}\ . \qquad (1)$$

The coverage factor *k*=2, for 95.4 % confidence that the data lie within two standard deviations of the mean. The combined uncertainty, $U_{C,}$ is the final result of the analysis, which is calculated as 2.03 ns.

TABLE 2 MEASUREMENT UNCERTAINTIES

Uncertainty Component	**Assigned Value**
$U_{A,}$ Time Uncertainty	*0.5 ns*
$U_{B,}$ Calibration	*0.35 ns*
$U_{B,}$ Coordinates	*0.15 ns*
$U_{B,}$ Environment	*0.25 ns*
$U_{B,}$ Multipath	*0.5 ns*
$U_{B,}$ Ionosphere	*0.25 ns*
$U_{B,}$ Reference Delay	*0.1 ns*
$U_{B,}$ Resolution	*0.05 ns*
$U_{C,}$ k= 2	*1.77 ns*

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