Time Transfer using High-Definition Television (HDTV) Broadcast Transmitters in Common View

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ABSTRACT

We have developed and demonstrated a time transfer system using high-definition television (HDTV) broadcast signals in common view. The system is comprised of a software defined radio (SDR), a TV antenna, a digitally programmed crystal oscillator (DOCXO) in remote systems that is disciplined to the master system reference clock, and standard servers connected to a network. Data are transferred via a low-bandwidth backchannel and the system is compatible with any HDTV waveform type that has an underlying framing structure. Using the time deviation (TDEV) as a standard metric for charactering stability, the residual noise floor of the master and remote nodes, co-located with a common antenna and receiving a HDTV signal in the ultra-high frequency (UHF) band, is less than 10 ps at all averaging periods of more than 100 s. We also report the results of field demonstrations where the master and remote systems each have their own antenna and are separated by a baseline of 210 m on the National Institute of Standards and Technology (NIST) campus in Boulder, Colorado. Future work is expected to utilize the system to compare the primary UTC(NIST) time scale in Boulder to the secondary UTC(NIST) time scale in Ft. Collins, Colorado, over a 78-km baseline.

1. INTRODUCTION

The common-view time transfer method is an established way to compare, synchronize, or discipline geographically separated clocks. It requires a common-view signal (CVS) to be continuously broadcast by a transmitter to clock sites that are within its coverage area. The clock sites receive the CVS and simultaneously compare it to their local clock. The accuracy of the CVS is not important, because it is not utilized as a time reference. Instead, it is only a vehicle used to relay or transfer time from one site to another.

A generic common-view system involving two sites is shown in Figure 1. Each site has a local clock and a CVS receiver, and both the clock and the receiver produce an output signal. The phase or time difference of the output signals are compared, typically with a time interval counter (TIC). At site A, the CVS received over the path d_{SA} is compared to Clock A, producing the phase or time difference of *Clock A – CVS*. At site B, the CVS received over the path d_{SB} is compared to Clock B, producing the phase or time difference of *Clock B – CVS*. Once both measurements are completed, some type of data transfer is required to allow the two measurements to be subtracted from each other. Subtracting the two measurements removes the contribution of the CVS. In addition, it removes the contribution of any delays common to both d_{SA} and d_{SB} (even if the magnitude of the delays are unknown), as well as any delays common to the system hardware at both sites, such as cable delays. However, any delays not common to both sites contribute measurement uncertainty, resulting in an uncertainty term of $d_{SA} - d_{SB}$ that represents the differential delay between the two common-view measurement systems. Thus, the basic common-view time transfer equation is $Clock\ A - Clock\ B = (Clock\ A - CVS) - (Clock\ B - CVS) + (d_{SA} - d_{SB})$. Ideally, the delays included in the $d_{SA} - d_{SB}$ term are calibrated and corrections are applied to the measurements to make the uncertainty of the clock comparisons as small as possible. The calibrated corrections for the experiment here require positions be known to cm-level.

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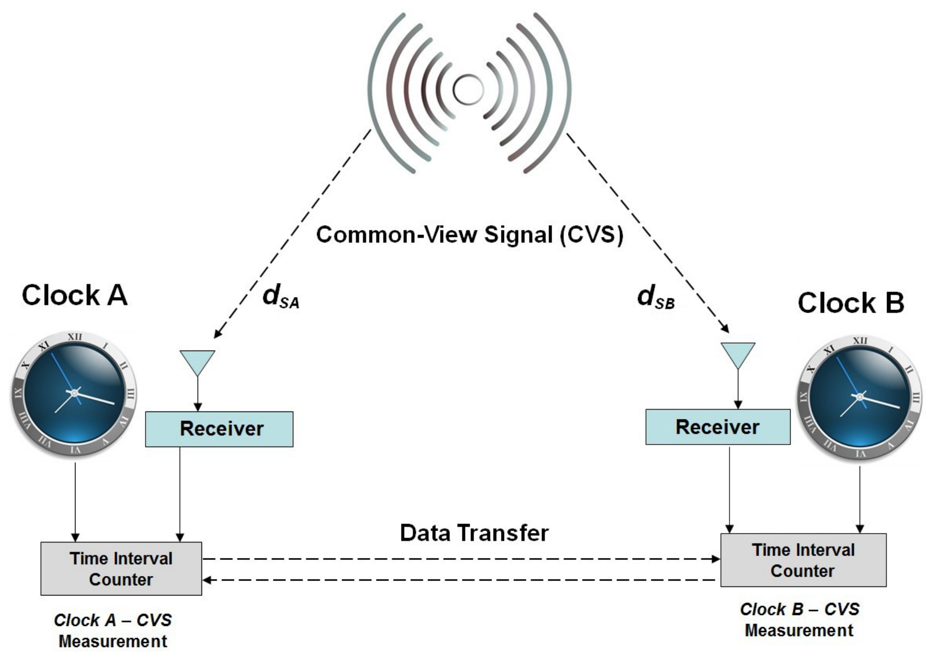

Figure 1. Diagram of generic common-view time transfer system.

For more than four decades, common-view time transfer has been nearly synonymous with global navigation satellite systems (GNSS), in particular with the Global Positioning System (GPS) [1]. Common-view time transfer via GNSS has an inherent advantage because the receiver's position is determined by the GNSS, which automatically performs ranging measurements to determine receiver position and to compensate for propagation delays. However, if the CVS originates from a non-GNSS source such as a terrestrial-based transmitter, and if the positions of the transmitter and the receivers are previously known, then d_{SA} and d_{SB} can still be measured and compensation for the delay differences can still be applied. Therefore, common-view time transfer via analog television signals was practiced more than a decade prior to the launch of the first GPS satellite [2]. From approximately 1968 to 1984 the technique was used to synchronize radio stations WWV and WWVB in Ft. Collins, Colorado to the NIST (then known as the National Bureau of Standards or NBS) time scale in Boulder, Colorado [3]. Much more recently, the United States Naval Observatory (USNO) and Naval Research Laboratory (NRL) have demonstrated common-view via digital television over an 11 km baseline in Washington, DC with a stability of about 1 ns when averaged for 1 d [4].

We have refreshed the technique using Advanced Television Systems Committee (ATSC) signals from high-definition television (HDTV) broadcast transmitters as the CVS. The new ATSC TV modulation has a substantial timing advantage when compared to older National Television System Committee (NTSC) modulation. Currently, HDTV ATSC 1.0 and 2.0 waveforms implement a 6 MHz, 8-Vestigial Sideband (VSB) modulation scheme which with adequate digital signal processing can produce picosecond precision in current software defined radios (SDR).

2. MOTIVATION FOR DEVELOPMENT OF HDTV COMMON VIEW SYSTEM

Time transfer systems based on GPS, utilizing either one-way or common-view time transfer, can achieve accuracies of less than 10 ns with respect to Coordinated Universal Time (UTC) if all system delays have been carefully calibrated. This outstanding performance has made GPS clocks ubiquitous in critical infrastructure timing systems, most of which require accuracy of near 1 μs [5]. However, the vulnerability of GPS clocks to both RF interference (jamming) and broadcasting of false signals (spoofing) [6] and the associated risk of huge economic losses [7], has made developing alternative timing signals that can substitute for GPS a major concern and priority for both government and industrial sectors.

Addressing these concerns and priorities is the primary motivation for our work. The common-view HDTV system described here has considerable potential for use as a substitute for GNSS in critical infrastructure timing systems, due to advantages that differentiate it from other time transfer techniques. These advantages include:

- High signal-to-noise ratios (SNR) for jammer resistance
- Potentially zero-dependence on GPS or GNSS receivers
- Nearly impossible to spoof
- Relatively simple and low-cost hardware and software
- The potential to install systems in any area with HDTV coverage

3. DESCRIPTION OF HDTV COMMON VIEW SYSTEM

It is customary for a common-view time transfer system to designate one clock as the reference clock. The other clock(s) can either simply be measured by recording their frequency and time differences with respect to the reference clock, or the measured differences can be converted to time or frequency corrections applied to the other clock(s) so that they are synchronized or disciplined to agree with the reference clock. Our system implements the latter method, consisting of a *Master* site and a *Minion* site (Figure 2). The clock at the *Master* site serves as the reference clock, and the clock at the *Minion* site is continuously disciplined to agree with the reference.

Each site receives HDTV signals and exchanges information via an Internet Protocol (IP) backchannel. The HDTV signals are well suited for use as a CVS due to their ubiquitous nature, high power levels, and necessary synchronization properties (framed structure). The HDTV signal frames are separated by a header, which consists of 512 complex symbols. We use this header to generate a synchronization pulse. By correlating the known header with the incoming HDTV signal, we obtain regularly spaced pulses at both the *Master* and *Minion* sites, and so the HDTV signal gives rise to a timing beacon that allows us to pinpoint a common time reference for the *Master* and *Minion* sites and once this point is marked, we can make the phase measurements necessary to align the *Minion* to the *Master*. Phase alignment is performed on the *Minion* side by adjusting its high-fidelity digital oven-controlled oscillator (DOCXO). Phase measurement data is exchanged using an IP backchannel. All processing is done in software using GNU Radio platform, and the *Master* and *Minion* computers are each connected via ethernet cable to a digitizer with a front end; in our case, the Universal Software Radio Peripheral (USRP). In addition to the network connection the *Minion* site also has a serial interface to control the DOCXO.

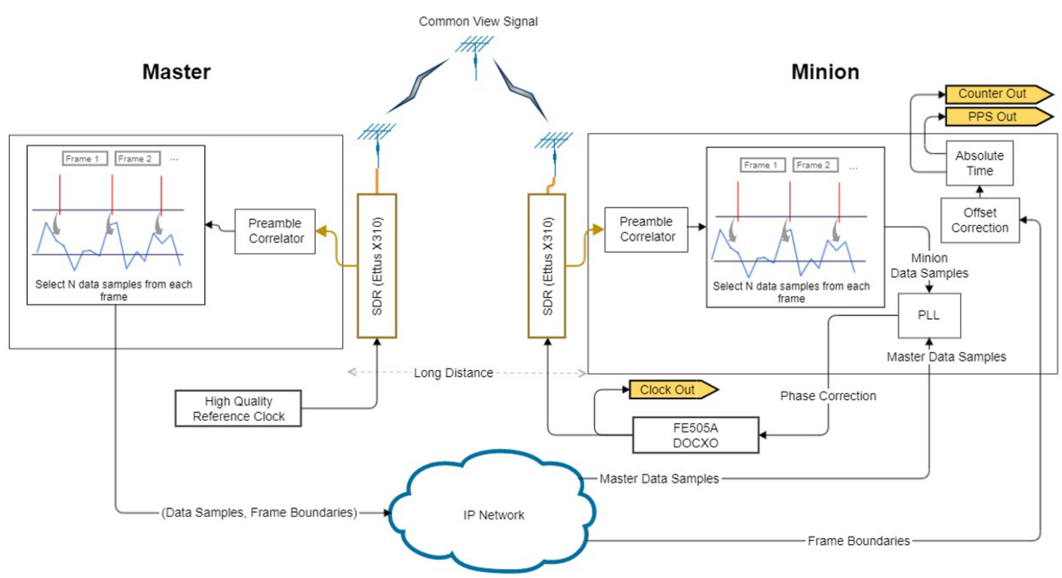

Figure 2. Diagram of HDTV Common View Time Transfer System.

3.1 System Software

Most of the processing is implemented in the software using a GNU Radio based framework. The GNU Radio platform is a very popular Digital Signal Processing (DSP) framework for Software Defined Radio (SDR) applications. GNU Radio is also an open-source development environment with extensive DSP libraries that allow rapid design and prototyping.

3.2 Master Site

The *Master* site receives Advanced Television Systems Committee (ATSC) HDTV signal and correlates received signal samples against known frame preamble samples to determine frame boundaries. This is done using an FFT-based complex Finite Impulse Response (FIR) filter with taps preloaded with 512 preamble complex samples. After passing through a FIR filter, strong correlation peaks allow the frame boundaries to be determined (Figure 3).

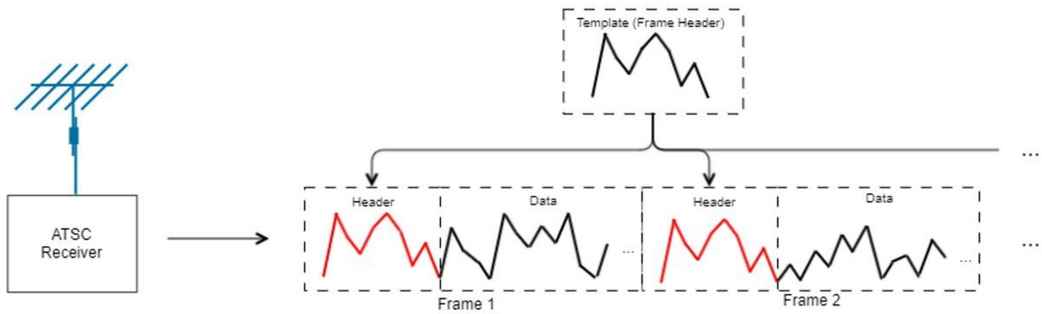

Figure 3. HDTV Frame Boundary Determination.

Once the frame boundaries are determined, the *Master* grabs 400 samples in the data portion of each frame and forwards that to *Minion* (Figure 4). The concept is to use data samples to uniquely identify a specific frame out of many. New frames are generated every 24.5 ms. This step must be completed in order to synchronize *Master* and *Minion* processing. This is a very common SDR problem, where most of the processing is offloaded into a nondeterministic environment such as Linux. While the sequence and integrity of the samples is guaranteed, their absolute time with respect to an external time reference is not known. What is known is that both the *Master* and *Minion* sites receive frames that can be uniquely identified by their nearly random and thus unique payloads.

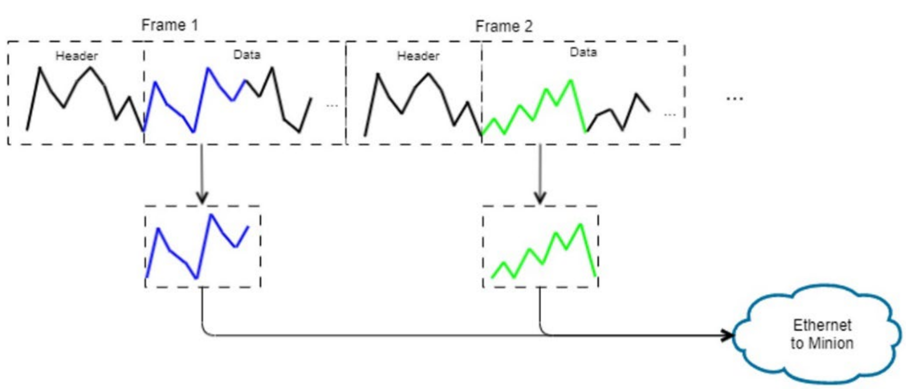

Figure 4. Frame Forwarding from *Master* to *Minion*.

3.3 Minion Site

The *Minion* uses the same technique as *Master* to obtain the same data samples for each received ATSC frame. Using correlation, it determines which set of data samples on *Minion* side correspond to data samples sent over from *Master*. Whichever set of samples from *Master* most strongly correlates with a set of samples on *Minion* are the samples from the same absolute frame of data of the incoming HDTV signal. In other words, we now know which frame our phase measurement belongs to. This is important because we must use phase measurements that happened at the same time on *Master* and *Minion*, otherwise the system will become unstable. This cross-correlation frame alignment process is shown in Figure 5.

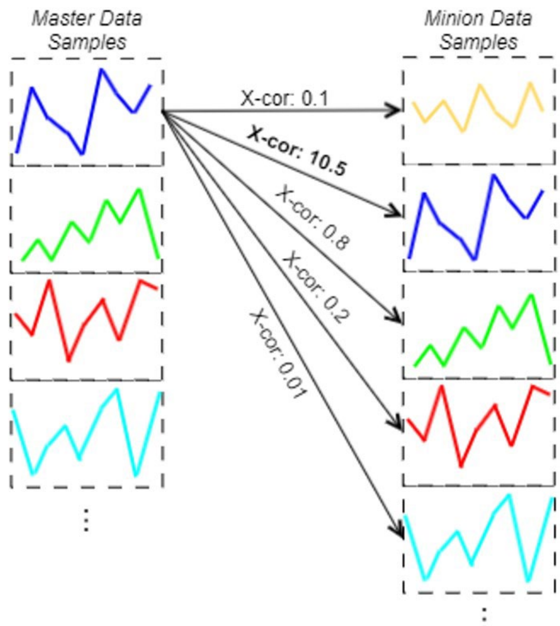

Figure 5. *Minion* Cross-Correlation Frame Alignment.

After the data samples from *Master* and *Minion* are aligned, the *Minion* correlates each set of matching samples against each other. As shown in Figure 6, the centroid of the resulting correlation peak, and its deviation from ideal (i.e., if *Master* and *Minion* sampling clocks were the same) represents the phase difference of the *Master* and *Minion* clocks. This phase difference - or error - is fed into a phase locked loop (PLL) on the *Minion* side in order to steer the *Minion*'s DOCXO local clock, described in the next section, to match the *Master's* reference clock. The process is continuously repeated to keep the *Minion* locked to the reference clock.

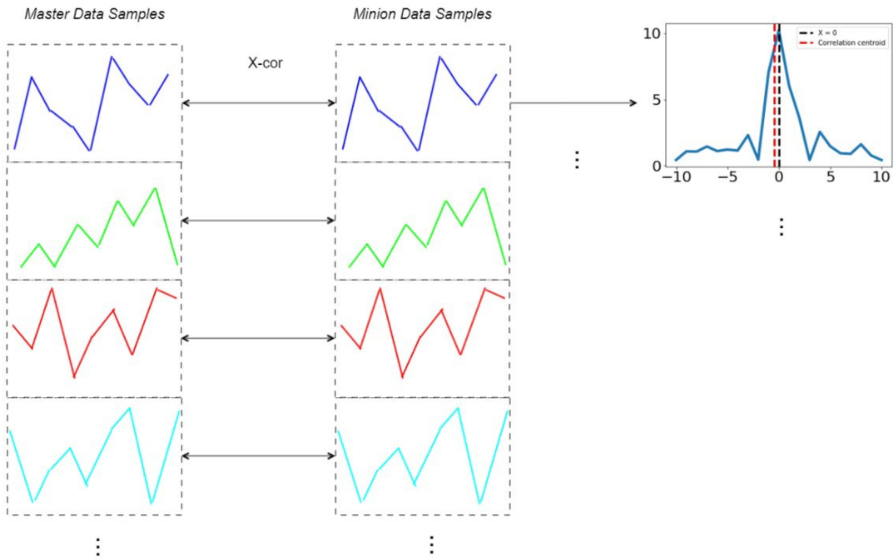

Figure 6. Phase Error Computation.

3.4 System Hardware

The *Master* and *Minion* sites have approximately the same hardware. Each site has a television antenna to receive the Common View signal, an Ettus USRP X310 SDR* to digitize the signal, and a General-Purpose Processor (GPP) to perform the necessary digital signal processing. Each radio is provided with a 10 MHz reference clock. The *Minion* clock, which is disciplined to the *Master*'s reference clock, is a high-fidelity voltage-controlled oscillator (FE505A*, DOCXO). The *Master* clock is a hydrogen maser atomic standard that is referenced to UTC(NIST). The *Minion*'s DOCXO is able to tune ±26 Hz around the nominal 10 MHz frequency with 14-bit precision. It is worth noting that the oscillator can only change frequency and locks to the correlation peak by a 2nd-order PLL. To control phase, one integration is implemented in software. The accuracy of lock of the *Minion* is directly proportional to the attainable accuracy of the DOCXO. In our case the device provides quantized resolution of 3.52×10^{-7} (Hz/step) = 0.175 ps/step of phase shift at 10 MHz. The integration time was chosen to be 1 s.

4. MEASUREMENT CONFIGURATIONS AND RESULTS

Measurements were performed in two configurations, a common location and common antenna test, and a test where the *Master* and *Minion* sites were separated by a short baseline (~210 m), with each site having its own antenna. The two configurations are shown in Figures 7(a) and 7(b) and measurement results are provided in the following sections.

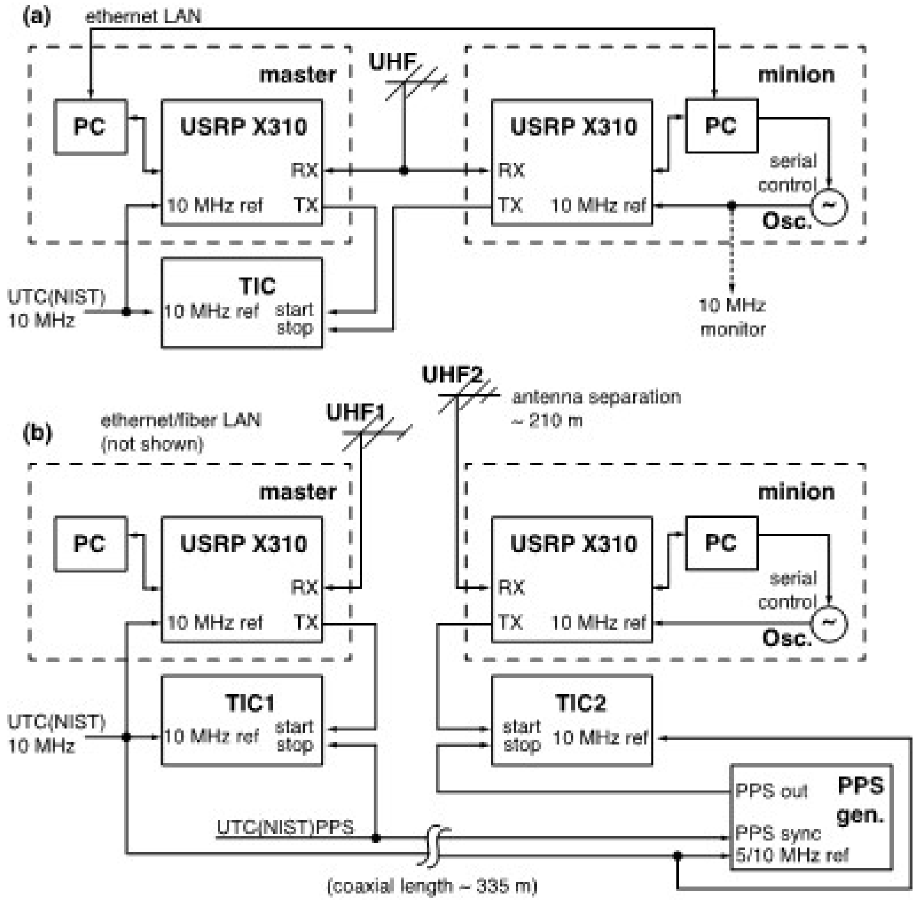

Figure 7. The upper portion (a) shows the configuration for common location, common antenna measurements and the lower portion (b) shows the configuration for separate location, separate antenna measurements. Ethernet/fiber LAN is in (b) but not shown in order to simplify the chart.

4.1. Common Location and Common Antenna Measurements

These zero-baseline measurements were made with co-located *Minion* and *Master* systems sharing the same antenna feed in Building 1 (B1) on the NIST campus. A UTC(NIST) reference signal at 10 MHz is distributed to each device via independent distribution amplifier channels. The HDTV antenna signal is shared with a passive RF splitter. A TIC measures the time difference of rising edges of pulse-per-second signals synthesized by the *Minion* and *Master* USRP X310* software-defined radio devices as shown in Figure 7(a).

As shown in Figure 8, the time-deviation (TDEV) of the TIC measurements was as low as 8 ps over an averaging interval of 700 s, less than 20 ps over an averaging interval of two days. TDEV is a standard statistic that can be interpreted as the time-transfer uncertainty. No data filtering was applied except a recursive median filter rejecting 5-sigma outlier measurements. Gaps caused by such outliers are rare (tens per million) and ignored in the time-domain analysis.

Optionally, a passive RF splitter was inserted between the *Minion* oscillator and the X310* device to allow phase noise analysis of the oscillator's 10 MHz signal. At long averaging intervals, no significant difference was observed in the stability of the oscillator's 10 MHz signal and the synthesized pulse per second (PPS) signal.

4.2. Separate Location and Separate Antenna Measurements

For these measurements, the *Minion* was relocated to an adjacent building (B81) on the NIST campus roughly 210 m from the *Master* and connected to a separate antenna of identical construction (Figure 7b). The TIC at the *Minion* site (TIC2) yields the most important data but contains an arbitrary offset with respect to UTC(NIST), as the time transfer scheme only guarantees a low offset between the *Master* and *Minion* pulse outputs. Therefore, TIC1 was occasionally recorded to verify stable operation of the *Master* as compared to UTC(NIST). Reference frequency (5 MHz or 10 MHz) and time (PPS) signals are passed between B1 and B81 over low-loss coaxial cabling. The frequency signals suffer an attenuation of about 8 dB over the approximate cable length of 335 m; this is compensated by low-noise, low-distortion amplifiers at the receiving end. The PPS signals experience significant stretching due to dispersion, negatively affecting the edge's slew rate. Therefore, NIST employs a "pulse-per-second regenerator" scheme (labeled "PPS gen." in Figure 7b), whereby an RF-to-pulse divider is made to count and divide the coaxial RF signal periods to reproduce the PPS signal. The nominally correct delay of the PPS reference is re-established (to within one cycle of the frequency reference), by a "one time" use of the stretched PPS coaxial signal to reset the counter/divider circuit ("PPS sync" in Figure 7b, a feature that is manually triggered on instrument startup). Operation of other distribution methods (e.g., White Rabbit, observations of GNSS signals) and regular calibrations verify that the delay variation between B1 and B81 has been stable to within 100 ps over many months of continuous operation.

Figure 8 shows a typical stretch of raw data (no averaging) collected between *Master* and *Minion* when separated by 210 m and connected to separate antennas. This particular measurement lasted nearly three days with a mean time offset near 0 and a peak-to-peak variation of about 5 ns.

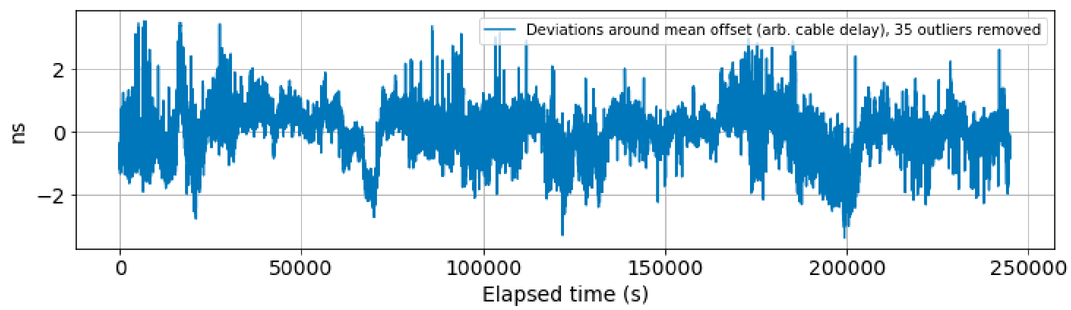

Figure 8. Time series data for a *Master* vs *Minion* comparison when the devices were separated by 210 m. The measurement rate is 1 s and all data are plotted except for 35 median-filtered outliers.

Figure 9 compares the time stability of the separate-antenna raw phase data shown in Figure 8 to raw phase data collected via the common-antenna experiment. While TDEV discounts any fixed frequency offset, separate analysis of both experiments' time-series data is consistent with < 10^{-15} frequency offset. After averaging intervals of roughly 1000 s, the residual noise in both experiments is roughly consistent with flicker phase-modulation. At intervals less than at 20 s the results are nearly equivalent due to the phase-locked control of the *Minion* oscillator, with radio propagation noise causing the separate-antenna results to become noisier at for periods longer than 20s. However, TDEV is still bounded below 400 ps at all averaging intervals for the separate antenna test. This stability represents the potential time accuracy limit for the system, obtainable if all differential system delays can be measured and compensated.

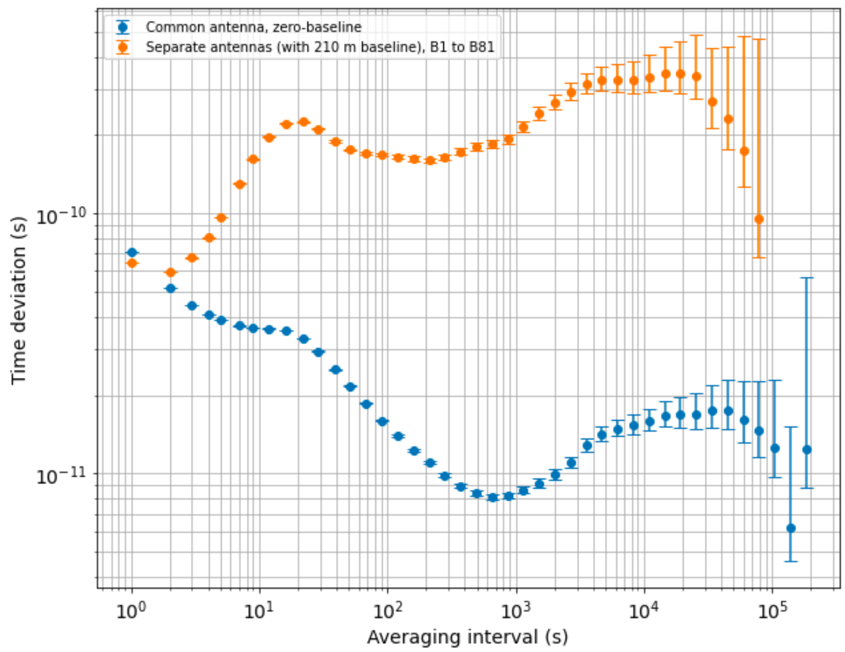

Figure 9. Time deviation (TDEV) statistic for zero-baseline, common antenna test (blue), and time transfer between adjacent NIST buildings (orange), where UTC(NIST) signals are separately distributed (see text). Error bars represent standard error (k = 1 or 68%) confidence intervals.

5. SUMMARY

We report common-view time transfer stability of ~200 ps from a fixed ground receiver (*Master*) to a remote receiver (*Minion*) over a 210 m baseline on the NIST campus in Boulder, Colorado. A HDTV broadcast at 521 MHz supplies the common-view signals. A low data rate IP communication channel between the *Master* and *Minion* is used for the exchange of meta data in which *N* symbols in the data portion of each receiver frame are forwarded to the *Minion* to serve as a unique identifier for each frame occurring every 24.5 ms. The model of residual timing noise of *Master* vs *Minion* is flat flicker-PM starting at 100 s using the time-stability statistic TDEV. This result is likely due to fluctuations in radio propagation since previous measurements showed the inherent noise between *Master* and *Minion* to be ~20 ps when connected to a common antenna. Our future work is expected to include measurements over a much longer baseline, the 78-km baseline between the Boulder campus and the NIST radio station site in Ft. Collins, Colorado.

6. ACKNOWLEDGEMENTS

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** Commercial products and companies are identified for technical completeness only and implies no endorsement by NIST. Other products might work equally well or better.*

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