Time Transfer Performance of the Broadcast Positioning System™ (BPS™)

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BIOGRAPHIES

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ABSTRACT

The Global Positioning System (GPS) is a widely used Global Navigation Satellite System (GNSS) that provides Positioning, Navigation, and Timing (PNT). GNSS vulnerability is well-known, and the search continues to find an independent system that can provide PNT services with comparable accuracy and precision, low user cost, and diverse coverage. NAB has developed and demonstrated a terrestrial PNT solution, known as the Broadcast Positioning System (BPS™), that uses existing NextGen TV (also known as ATSC 3.0 standard) transmission facilities to broadcast ns-level time. We investigate how accurately and reliably the ATSC 3.0 communications frames carrying BPS information function as time-reference beacons. This paper focuses on the BPS time transfer test results and stability using the KWGN TV station in Denver and NIST facilities in Boulder and Fort Collins, Colorado.

INTRODUCTION TO BPS™

BPS is a system and method of estimating time and position at a receiver using Advanced Television Systems Committee 3.0 (ATSC 3.0) broadcast signals. BPS is fully compliant with the ATSC 3.0 standard, which is deployed in the U.S. as NextGen TV. ATSC 3.0 is an ITU recognized digital broadcast standard that has been deployed or is being tested in Canada, Mexico, Republic of Korea, Brazil, India, and Caribbean nations. A BPS-enabled TV tower transmits signal emission time and the transmit antenna's location along with TV service. When the transmission facility uses a GNSS-independent reference clock, BPS delivers GNSS-independent timing data to a receiver. BPS user equipment (UE) at a known location computes time by receiving only BPS signals. Since BPS uses only television signals to transmit timing data, BPS works when GNSS, internet, and cellular connectivity are unavailable at the receiver. FIGURE 1 shows BPS transmission using ATSC 3.0 communication frames. The fundamentals of BPS technology are described in Mondal et al., 2021, Corl et al., 2023, Diamond et al., 2023, and Corl et al., 2024.

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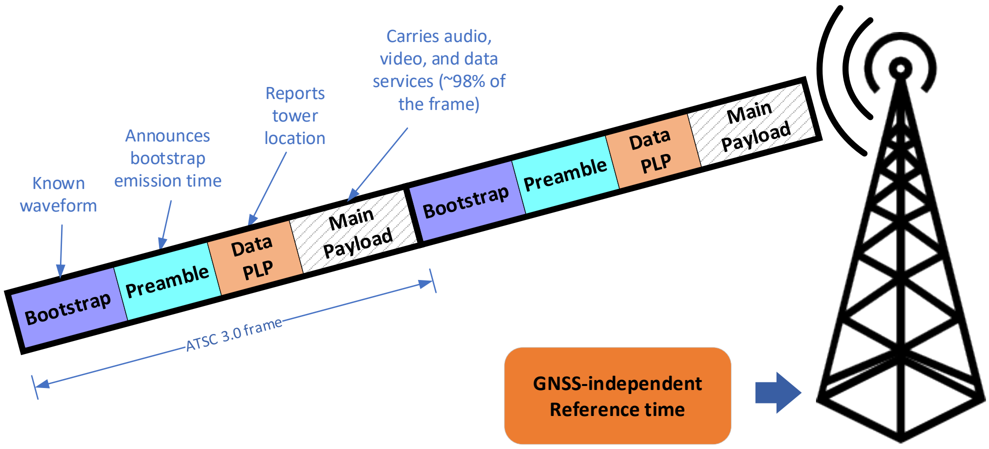

FIGURE 1: *BPS™ time delivery using ATSC 3.0 signal is shown. When BPS is enabled, an ATSC 3.0 frame carries a data Physical Layer Pipe (PLP) along with the information used for television service. BPS data service is overlayed on existing television service. This datacasting feature is supported by ATSC 3.0 and is fully compliant with the standard.*

NIST with Aerospace Corporation performed several field tests using HDTV and ATSC 1.0 signal protocol as common-view signals of opportunity (Tarasov et al., 2023). Results showed that the 6 MHz spread spectrum with commercial SDR hardware components readily support picosecond-level timing precision over short baselines. This further motivates the BPS and ATSC 3.0 framing.

The primary attribute of BPS is its independence of GNSS with infrastructure that can survive and continue to operate in emergency scenarios when GNSS satellites are accidentally or intentionally disabled. A BPS advantage over other alternate PNT methods is that it uses thirty-five 6 MHz television channels (54 MHz to 88 MHz, 174 MHz to 216 MHz, and 470 MHz to 608 MHz) with high-tower, high-power configurations, transmitting up to a million watts with 1000-foot high, surveyed antennas that make PNT resistant to jamming and spoofing. BPS in its simplest form can provide timing to national critical infrastructure that requires a time reference that is independent of GNSS. BPS is a free-to-use service that can complement GNSS service for the general public, when fully deployed. BPS supports an unlimited number of users.

The attributes of BPS are summarized below:

- TV station infrastructure that transmits BPS signals is already built out.
- ATSC 3.0 is an international standard deployed in multiple countries.
- BPS receivers are passive devices, meaning no uplink or internet connection is required.
- BPS operates in different frequencies than those of L-band GNSS and other satellite-based services.
- Diversity of BPS operating frequencies makes BPS resistant to jamming and spoofing.
- BPS transmitters use antennas hundreds of feet high and radiate power up to 1 Megawatt ERP, covering large areas.
- Nominal BPS SNR is thousands of times greater than GNSS SNR.
- A BPS network operations center (NOC) is capable of detecting system anomalies, including jamming and interference of TV signals.
- BPS can be offered as a free-to-use service to the public.
- Full-power TV stations carrying BPS have backup generators and are designed to continue to operate in the event of natural disasters and emergencies.
- BPS is capable of providing timing to mobile users.
- BPS signal and ground infrastructure can potentially be used for space PNT.

BPS™ DEPLOYMENT AND COVERAGE

BPS can be deployed on all ATSC 3.0 stations that are on air. At a minimum, BPS deployment requires a reference timing source and a broadcast time synchronization device known as BPS synchronizer. Refer to Mondal et al., 2021 and Corl et al., 2024 for block diagrams of BPS modules that are added to an existing ATSC 3.0 transmission chain to enable BPS service. FIGURE 2 shows how BPS was installed at WHUT, the first TV station in the nation to carry BPS. Operators also installed new software and firmware for a few pieces of existing hardware and measured signal delay through the entire transmission chain.

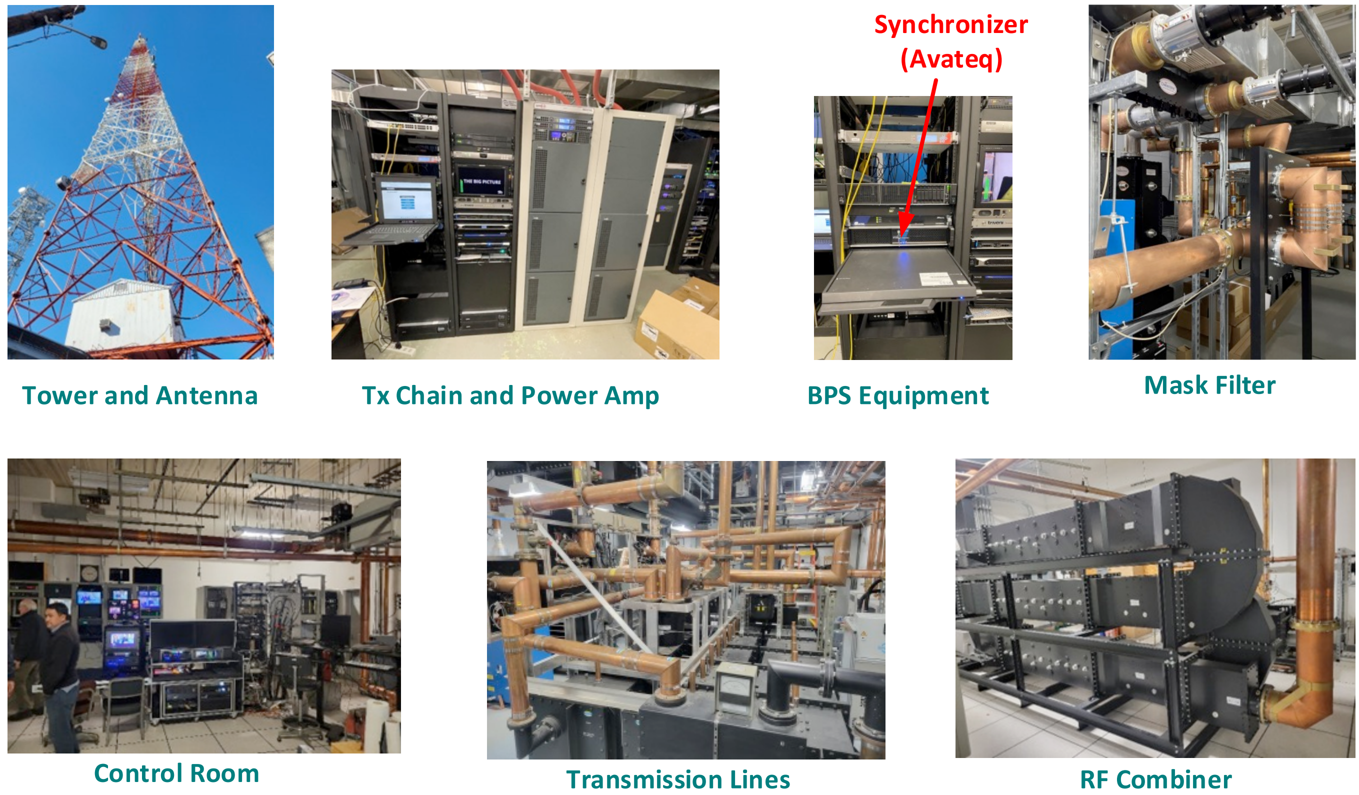

FIGURE 2: *BPS deployment at the WHUT TV station. Almost all the equipment and infrastructure already existed; only a synchronizer, shown with a red arrow, was added to enable BPS.*

ATSC 3.0 is being deployed in the US. The Nielsen designated television markets where ATSC 3.0 is currently deployed is shown in FIGURE 3. Broadcasters have deployed ATSC 3.0 on only one or two towers per market that have many more TV towers. The broadcasters' goal is to cover all the TV markets with ATSC 3.0 signal before diversifying into multiple ATSC 3.0 transmission facilities per market.

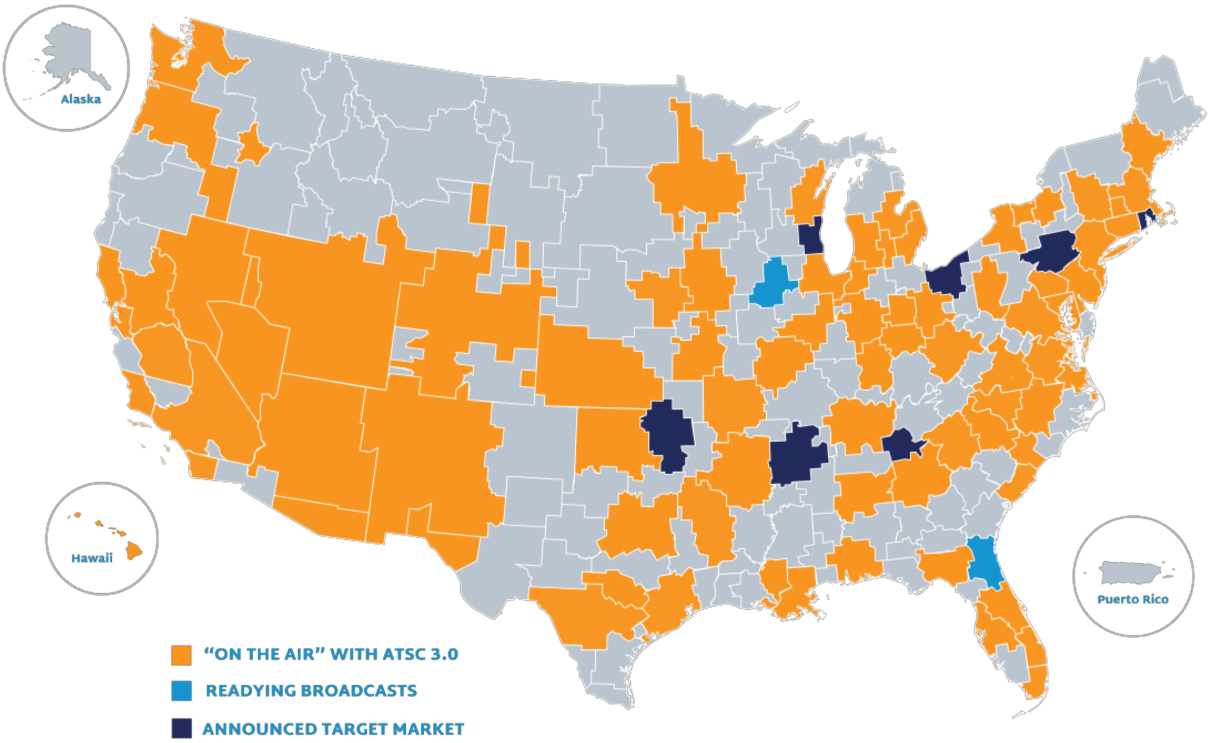

FIGURE 3: *ATSC 3.0 deployment in the US as of November 2024 (source https://www.atsc.org/nextgen-tv/deployments/). BPS can be deployed in these TV markets now. More TV markets are being prepared for ATSC 3.0 transmission.*

At full deployment on all 1600 full-power TV stations, BPS signals will cover the continental US, border areas, and coastal regions (FIGURE 4). The BPS signal is more robust than the TV service. The ATSC 3.0 standard enables transmission of multiple physical layer pipes (PLPs) with different quality of service (QoS) profiles within an RF channel. This is achieved primarily by choosing different signal constellations for modulation and different forward error correction rates for each PLP. The TV service PLP in the ATSC 3.0 frame is typically configured in such a way that 15 dB SNR is required to decode the signal at intended receivers. The BPS-carrying PLP, on the other hand, is configured in such a way that only -5 dB SNR is required to decode the signal at the receiver. Thus, BPS coverage is more robust than TV service coverage.

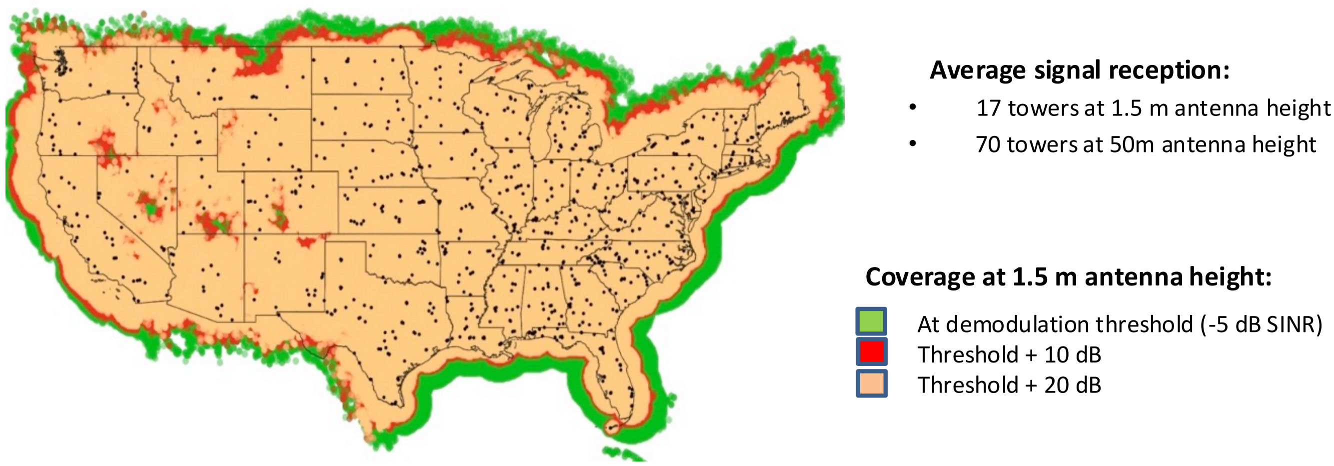

FIGURE 4: *BPS coverage at full deployment. Most of the continental US will be covered by at least one strong signal that is 20 dB above demodulation threshold. A typical point in the continental US will receive BPS signal from 17 towers on average.*

BPS has been deployed at the following TV stations: WHUT in Washington, DC; WNUV in Baltimore, Maryland; and KWGN in Denver, Colorado. WHUT is set up as a leader tower backed up by a cesium holdover clock. WNUV is configured as a follower of WHUT, meaning it derives its reference time from the WHUT signal. Both WHUT and WNUV can transmit BPS signals when GNSS is unavailable at either site; the cesium clock provides the reference. KWGN, however, is set up as a test site using GNSS timing as its reference. NAB is investigating GNSS-independent time sources such as UTC(NIST) over dark fiber or two-way satellite time and frequency transfer (TWSTFT) but has not yet installed those time delivery methods due to cost. Low Earth orbit (LEO) satellites and eLORAN have also been cited as GNSS independent timing sources. Although the above-mentioned sources would have made our system truly independent of GNSS, using GNSS as a reference still enabled us to characterize BPS time transfer capabilities using the KWGN signal. This paper shows the test results and analysis of BPS time transfer using the KWGN signal at NIST facilities in Boulder and Fort Collins, Colorado.

BPS™ TIME TRANSFER TEST

In this section we describe a BPS time transfer test conducted in the Denver metropolitan area in collaboration with NIST. Television station KWGN (Nexstar Media Group, Inc.) transmits ATSC 3.0/BPS (channel 34, UHF 593 MHz) from a transmitter located west of Denver, Colorado near Golden. As sketched in FIGURE 5a, signals were received at three locations: the KWGN studio (22 km east), NIST in Boulder, Colorado (30 km north), and the NIST WWVB radio station near Ft. Collins, Colorado (106 km north). The propagation mode is believed to be line-of-sight except to NIST in Boulder, where terrain marginally interferes.

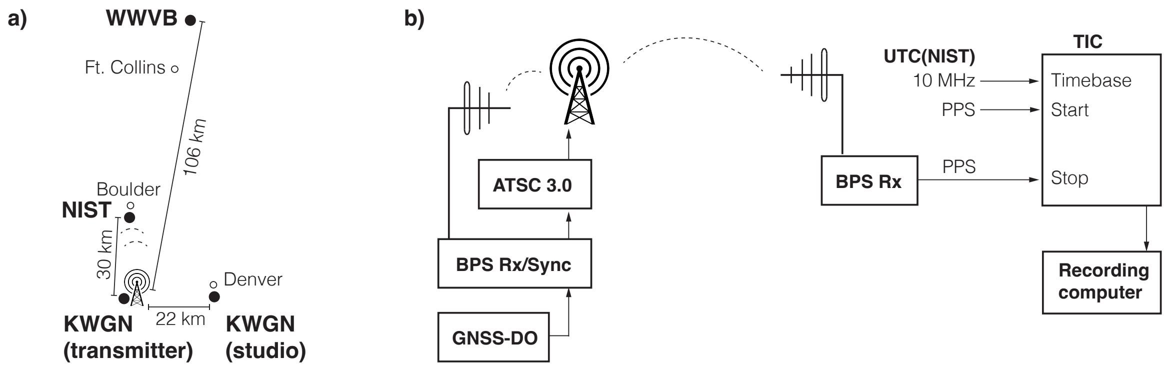

FIGURE 5: *Experiment schematic. a) Geographic locations of KWGN transmitter and three BPS receiver sites (filled circles), roughly to scale. Here, two dashed curves highlight the approximate location of terrain obscuring a line-of-sight transmission path to NIST in Boulder. b) Measurement arrangement at the transmitter and at NIST as an example receiver station: a time interval counter (TIC) records the time interval between pulse-per-second (PPS) signals from a BPS receiver (Rx) and local time reference. At the transmitter, a GNSS-disciplined oscillator (GNSS-DO) supplies the reference time signals. A BPS receiver/synchronizer (Rx/Sync) observes the ATSC 3.0/BPS on-air transmission and inserts timing correction data into BPS.*

At the BPS transmitter and the KWGN studio local time references are derived from a multi-constellation GNSS-disciplined oscillator (GNSS-DO; Microchip TP4500; configured for L1 GPS and E1 Galileo). At NIST, the time reference is the steered atomic clock ensemble UTC(NIST), NIST's realization of Coordinated Universal Time (UTC). At WWVB, the time reference is an independent steered cesium-beam clock ensemble loosely steered to follow UTC(NIST) and whose offset is independently and continuously measured by two GPS common-view techniques (Levine, 1999 and Montare et al., 2024). Though it isn't an official realization of UTC, we shall use the notation UTC(NIST@WWVB) to refer to the atomic time scale signal present at the station to distinguish it from the WWVB broadcast 60 kHz carrier or timecode, which are not involved. The UTC(NIST@WWVB) reference point exists in the campus's WWV building; signals are transported to the WWVB building by several hundred meters of coaxial cable because the WWVB building offered better vantage for the UHF receiver antenna.
The primary goal of this study is to demonstrate the potential stability of transmitted BPS, removing, if possible, variation due to the BPS transmitter's GNSS-based time reference. All BPS receivers were programmed with fixed signal delay estimates close to values given by the geometrical range and estimated index of refraction. In full operation, all delays in the transmission chain will require absolute measurement, calculation, or calibration. Receivers (especially mobile types) must accurately figure the signal delay given their estimated position (the BPS protocol includes the transmitter position). These issues are reserved for future study and are not critical for time transfer between fixed stations where a one-time calibration (e.g., using GNSS) is

tolerable. Time transfer accuracy can be no better than realized stability, but it is a necessary condition for correct functioning of a positioning/navigation BPS service.

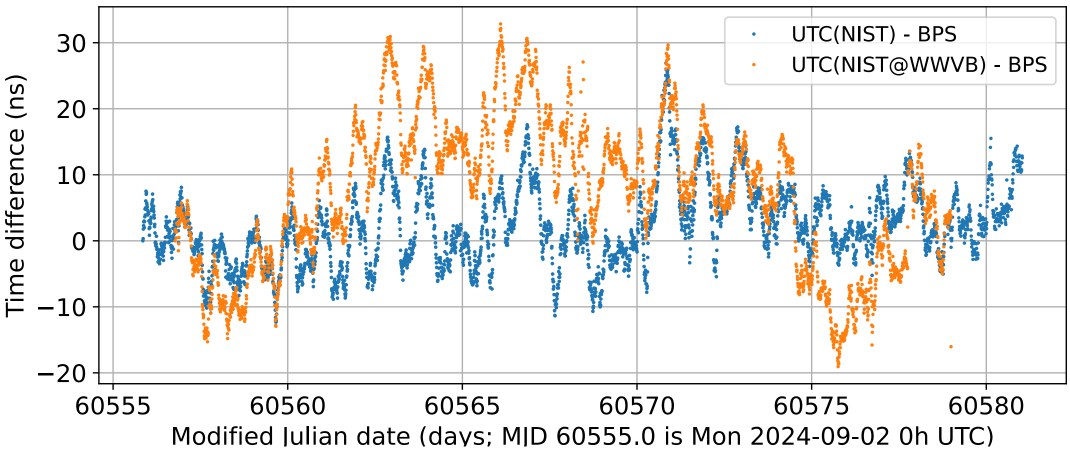

FIGURE 6: *Measurements of BPS vs. UTC(NIST) and the WWVB time scale, averaged into ten-minute intervals. A correlated diurnal modulation (amplitude ~ 10 ns) is visible. Because cable (with a delay of a few hundred ns) is inserted at each site to keep TIC measurements positively valued, and because our primary focus is establishing stability limits, initial offsets are subtracted from these measurement time series.*

At NIST and WWVB (see FIGURE 5b), time interval counters (TICs; BNC-1105 and Pendulum CNT-91, respectively) measured the time difference of pulse-per-second (PPS) signals from each local time reference and a BPS receiver (Avateq 1050) simultaneously for a period of 22 days beginning on September 3, 2024. FIGURE 6 shows these measurement records; plotted data are averaged over ten-minute intervals. The records are nearly continuous except for a period of about 30 minutes near the end of September 9, 2024 when BPS transmission was disabled for troubleshooting an unrelated issue with the television service. Prior to averaging, another 0.01% of PPS measurements at NIST were removed by a simple threshold (±300 ns from median) outlier filter. A correlated diurnal modulation is visible and explored further below.

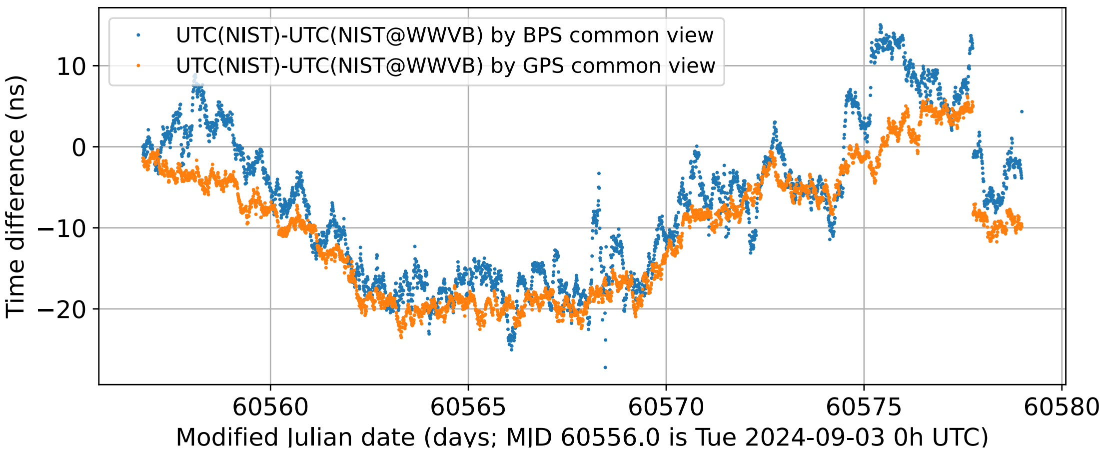

FIGURE 7: *Subtracting the two BPS measurements in FIGURE 5, we recover a BPS common-view measurement of UTC(NIST) – UTC(NIST@WWVB). This is compared with an existing dual-band GPS-common view measurement (no arbitrary offset subtracted; common-view link is calibrated).*

FIGURE 7 depicts the difference of the two measurements in FIGURE 6, UTC(NIST) – BPS and UTC(NIST@WWVB) – BPS. This subtraction is expected to remove timing variations that are commonly observed at NIST and WWVB: the BPS transmitter timing reference, the BPS synchronizer element (Avateq 1050), all other parts of the transmitter, and some portion of any variation in propagation delay. Also plotted is NIST's estimate of UTC(NIST)-UTC(NIST@WWVB) accomplished using a dual-band GPS common-view technique (Montare et al., 2024). We note that much of the observed diurnal modulation in FIGURE 6 is removed in the subtraction; the remaining variation is attributed mostly to the stability of the WWVB time scale.

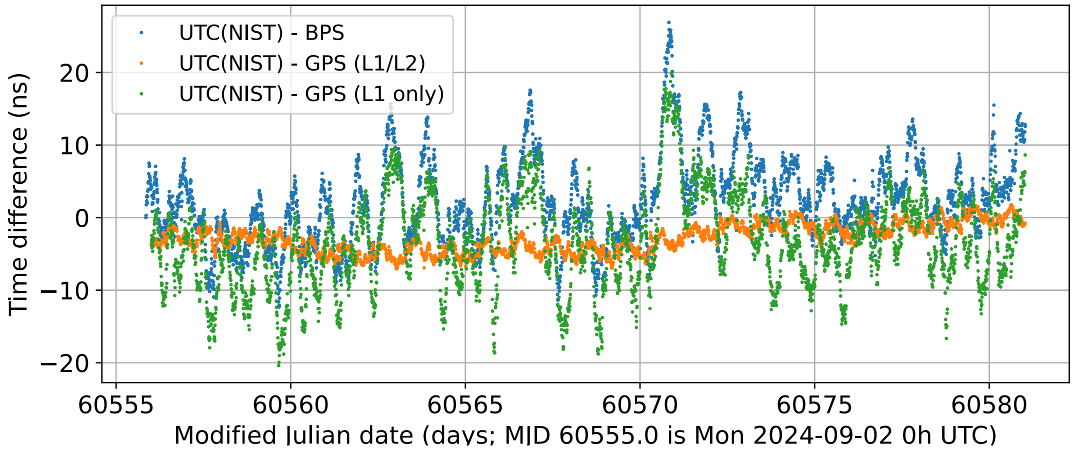

FIGURE 8: *We compare UTC(NIST) – BPS measurements with a single-band and dual-band measurement of UTC(NIST) - GPS.*

FIGURE 8 compares UTC(NIST) – BPS with two different measurements of UTC(NIST) – GPS; one is derived from a single-band receiver (L1, VP Oncore), the other from a dual-band receiver (L1/L2, ublox ZED-9FT) at NIST. The strong correlation of BPS with the single-band GPS measurements suggests that the BPS transmitter time reference is inheriting variation from single-band reception of GNSS. The correlation is imperfect in part because the BPS transmitter GNSS-DO made use of both GPS and Galileo constellations, whereas the NIST receiver was configured for GPS only.

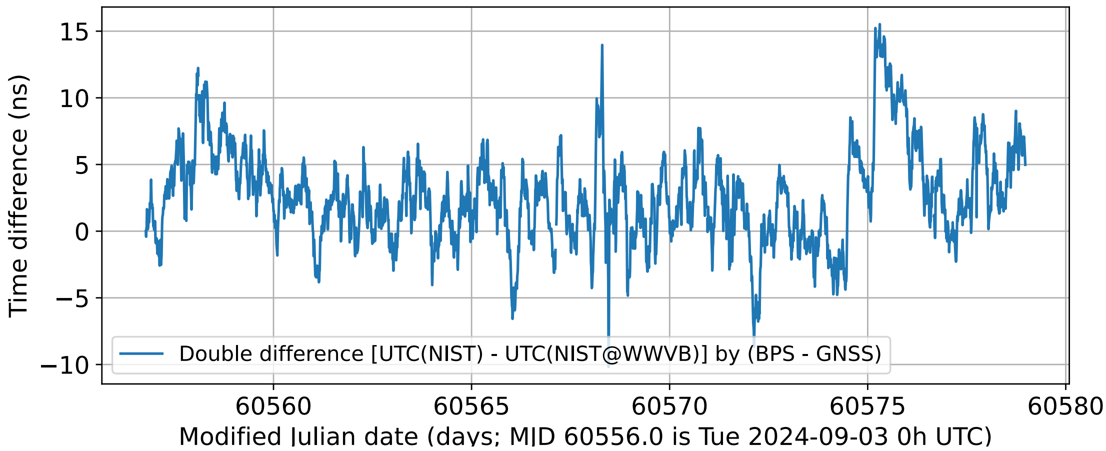

FIGURE 9: *We show the "double-difference" of two estimates of UTC(NIST) – UTC(NIST@WWVB): one using BPS as the transfer standard, and the other using dual-band GNSS. The remaining variation sets a bound on the noise performance of BPS time transfer as the variation between reference clocks is largely removed.*

FIGURE 9 depicts a subtraction of the two signals in FIGURE 7. In this "double-difference," we hope to remove long-term variation believed to represent the variation between the NIST and WWVB time scales. Potential noise sources that remain include: uncorrelated noise in the propagation modes to the two sites, uncorrelated noise in the BPS receivers, TICs, intra-facility signal distribution, and noise added by the GNSS common-view observation.

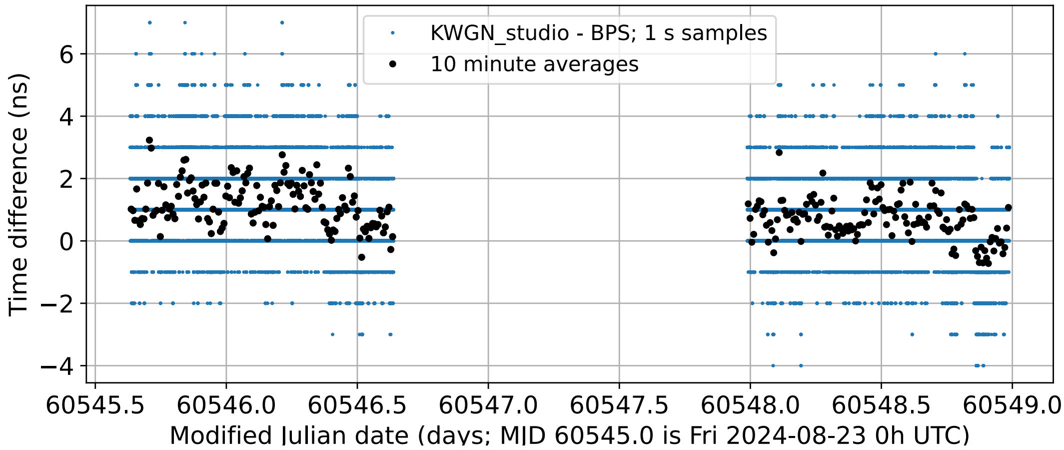

FIGURE 10: *Occasional day-long measurements were made at the KWGN studio of its local time reference against received BPS. No large diurnal modulation is seen as both the KWGN studio and transmitter use the same model and configuration of GNSS-DO as time reference; variation due to ionospheric noise is highly common over the short baseline.*

Independent and high-resolution evidence of BPS's time transfer stability bound is provided by occasional measurements at the KWGN studio of the received BPS timing signal against the local GNSS-disciplined oscillator, an identical model/configuration to that used at the BPS transmitter (see FIGURE 10). The studio measurement apparatus (also the Microchip TP4500) reports with a 1 ns quantization and was limited to recording for up to 1 day without intervention.

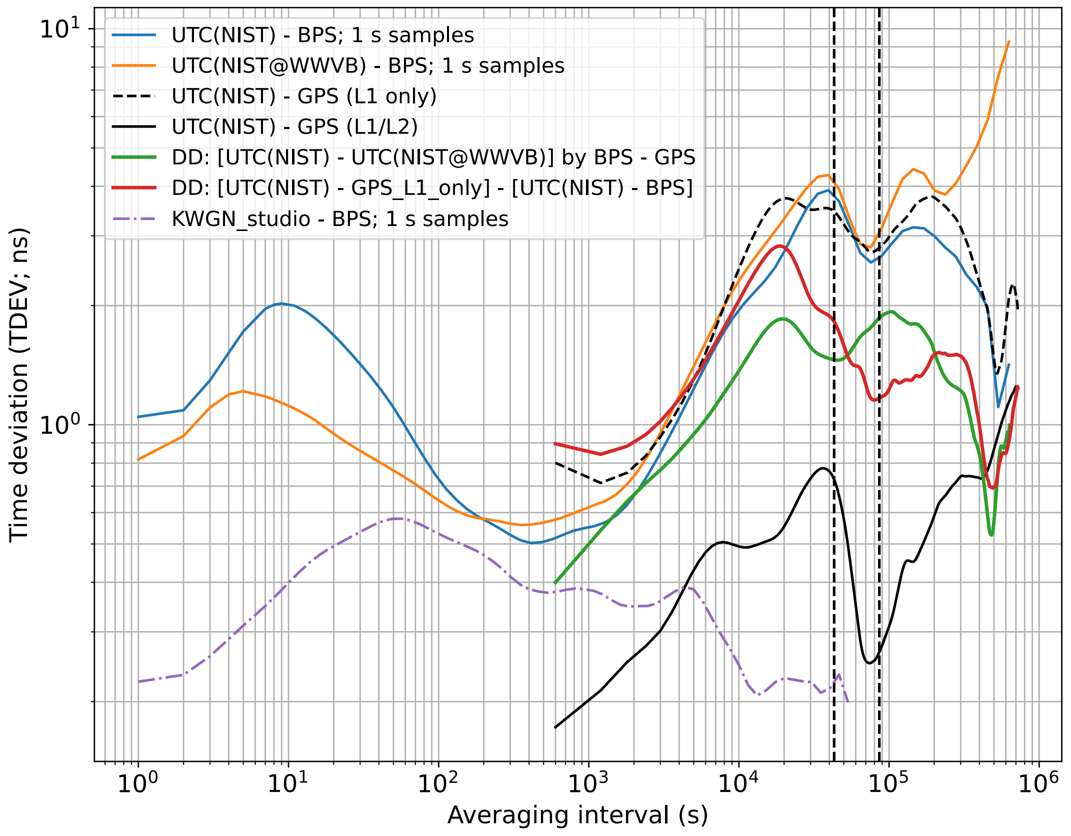

FIGURE 11: *Time deviation (TDEV) statistic for several measurements and derived products discussed in this work. Dashed vertical lines indicate where a TDEV peak and trough from a diurnal modulation is expected. For series representing time transfer measurements (i.e. where the station clocks are equal, variation is removed, or over intervals where the clock instability is negligible), the noise type is largely flicker-phase modulation with some periodic modulation. The tested BPS receivers exhibit some amount of stationary phase noise and servo quantization effects in the production of PPS outputs and benefit from about 200 s of measurement averaging.*

FIGURE 11 shows a time-domain noise analysis (time deviation statistic, TDEV) for several of the measurements and derived products above. The TDEV of double-difference (green curve) of UTC(NIST) – UTC(NIST@WWVB) by two common view methods (BPS – GPS) remains below 2 ns and is superior to the single-band GPS receiver. The noise in the double-difference includes the variation from the dual-band GPS common-view link, here shown to contribute about 800 ps at peak TDEV. We note that TDEV does not fully characterize time transfer uncertainty; like all similar time-domain functions TDEV discounts any constant time- and rate offsets. However, TDEV remains useful as a relative measure of stability and as an upper-bound on the stability performance of a steered-clock application based on time transfer that can make full use of continuous averaging and good free-running clock stability. Also, we note that FIGURE 9 constrains any rate error to a very low magnitude < 4e-15.

SUMMARY

BPS time transfer stability is studied using signal from a live TV station and two baselines, one exceeding 100km. We show that the ns-level timing of BPS can support PNT services comparable to GPS or other GNSS. This is done using a BPS signal observed in common view at two different locations. After adjusting for the common sources of errors, it is observed that the stability of BPS time transfer is comparable to or better than GNSS, making BPS a viable complementary PNT solution when GNSS is unavailable.

DISCLAIMER STATEMENT

Certain equipment, products, or proprietary methods are identified in this paper in order to specify the experimental procedure adequately. 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.

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REFERENCES

ATSC (2024). ATSC 3.0 Suite of Standards. https://www.atsc.org/atsc-documents/type/3-0-standards/

Corl, M., Anishchenko, V., & Mondal, T. (2023). BPS ATSC 3.0 Broadcast Emission Time Stabilization System Proof-of-concept. Proceedings of the 2023 NAB Broadcast Engineering and Information Technology (BEIT) Conference. https://nab.org/bps/BPS_ATSC_3_0_Broadcast_Emission.pdf

Corl, M., Anishchenko, V., Lopez F., & Mondal, T. (2024). ATSC 3.0 Broadcast Positioning System (BPS) Mesh Network. Proceedings of the 2024 NAB Broadcast Engineering and Information Technology (BEIT) Conference. https://nab.org/bps/ATSC_3_0_BPS_Mesh_Network.pdf

Diamond, P., Mondal, T., Weller, R., & Hansen, A. (2023). Delivering Traceable Reference Time for ATSC 3.0-based Broadcast Positioning System (BPS). Proceedings of the 2023 NAB Broadcast Engineering and Information Technology (BEIT) Conference. https://nab.org/bps/Delivering_Traceable_Reference.pdf

Levine, J. (1999). Time transfer using multi-channel GPS receivers. IEEE Trans. UFFC 46(2), p. 392–398, 1999. https://doi.org/10.1109/58.753028

Mondal, T., Weller, R., & Matheny, S. (2021). Broadcast Positioning System (BPS) Using ATSC 3.0. Proceedings of the 2021 NAB Broadcast Engineering and Information Technology (BEIT) Conference. https://nab.org/bps/Broadcast_Positioning_System_Using_ATSC30.pdf

Montare, A. A., Novick, A. N., & Sherman, J. A. (2024). Evaluating common-view time transfer using a low-cost dual-frequency GNSS receiver. Proceedings of the 55th Annual Precise Time and Time Interval Systems and Applications Meeting, Long Beach, California, January 2024, pp. 127-135. https://doi.org/10.33012/2024.19586

Tarasov K., Bauer B., Olsen S., Grayver E., Feil H., Sherman, J., Monture, A., Deutch, M., Nelson, G., Lombardi, M., Marczewski T., & D. Howe (2023). Time Transfer using High-Definition Television (HDTV) Broadcast Transmitters in Common View. Proc. 2023 PTTI Mtg., pp. 140-149. https://tf.nist.gov/general/pdf/3210.pdf