Field Test of ATSC 3.0/BPS Precise Time Distribution

Jeff A. Sherman, David A. Howe
Time and Frequency Division, National Institute of Standards and Technology (NIST)
Boulder, Colorado, United States
jeff.sherman@nist.gov, david.howe@nist.gov

Abstract – The Broadcast Positioning System (BPS™) is a protocol for high-resolution time transfer between a reference clock at a ATSC 3.0 transmitter and a BPS receiver's disciplined-clock output. Time transfer is a prerequisite for (and useful by-product of) positioning/navigation systems such as Global Navigation Satellite Systems (GNSS); for example, the Global Positioning System (GPS). In principle, BPS may address potential vulnerabilities in critical applications with GNSS dependence, mostly due to relatively weak GNSS signal levels at Earth's surface. In 2024, BPS was added to the ATSC 3.0 transmission of the station KWGN in the Denver, Colorado metropolitan area. To measure BPS time transfer stability, BPS receivers were installed at two NIST campuses (the furthest: 106 km away) and compared against independent local atomic clock timescales. As an example, over one 50-day period and a non-line-of-sight (NLOS) transmission path of 30 km that includes terrain obstruction, we observed peak-to-peak time deviations on the order of tens of nanoseconds (including all variation of the reference time scales), a stability roughly comparable with ubiquitously deployed, single-band GPS receivers.

Overview and Motivation

GNSS, as a Positioning, Navigation, and Timing (PNT) utility, supports billions of dollars daily in economic activity [1]. Time synchronization (approximately at the level of one microsecond or better) by GNSS supports critical infrastructure sectors such as telecommunications, transportation, financial markets, and electric power transmission. However, GNSS signals are relatively weak at Earth's surface, making receivers vulnerable to accidental or purposeful interference. GNSS constellations are vulnerable to space weather phenomena or other disruptions. Therefore, we recognize motivation for other PNT or nation-scale time synchronization approaches as alternatives to (or augmentation of) GNSS usage: for example, terrestrial beacon sources, Low Earth Orbit (LEO) constellations (which share only some of the same risks as GNSS), or point-to-point one-way or two-way time transfer links.

The Broadcast Positioning System (BPS) protocol, compatible within ATSC 3.0, is described elsewhere [2–5]. Briefly, the time of transmission of each ATSC 3.0 frame's Bootstrap word is encoded within the Preamble portion of the ATSC 3.0 data frame. A BPS synchronizer device, connected to a local reference clock, observes the ATSC 3.0 transmission close to the transmitter and encodes additional data for a distinct Physical Layer Pipe (PLP) within the frame relating the transmitted timestamps accurately to the reference clock, the transmitter's spatial coordinates, and other metadata describing a local timing network. The design of BPS allows it to augment an existing ATSC 3.0 transmission chain with minimal modification. TV transmitters operate with up to 1 MW equivalent radiated power (ERP) over a wide range of allocated frequency bands. Collectively, TV transmitters constitute pre-existing infrastructure with nearly-universal national coverage of the United States, including borders and coastal regions. Finally, BPS takes advantage of a feature in ATSC 3.0 which allows portions of the transmission to be more robustly detected than the encapsulated TV data. Typically, the TV PLP service is configured to require 15 dB signal-to-noise ratio (SNR) for decoding; the BPS PLP requires only -5 dB SNR.

Experimental Setup and Prior Results

Initial observations of BPS time transfer measured against NIST atomic clock time scales were presented recently [6]. For context, we re-summarize the experimental setup and prior findings.

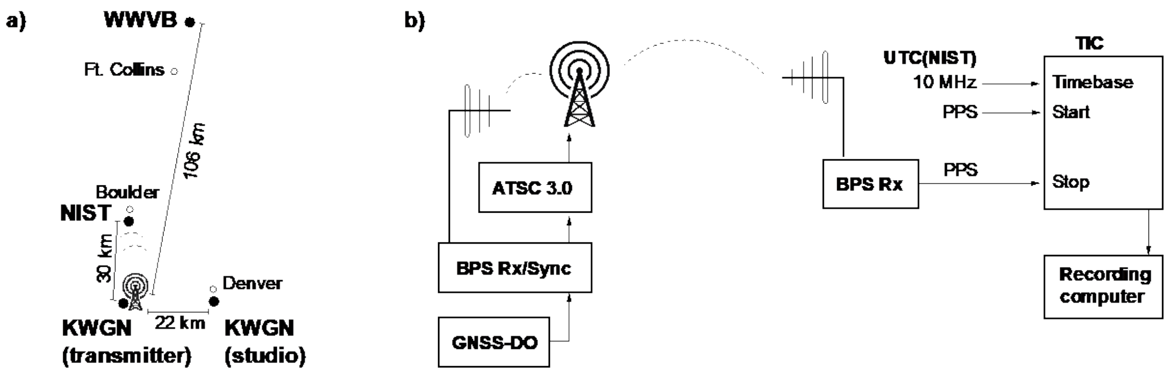

FIGURE 1: EXPERIMENTAL SETUP. A) GEOGRAPHIC LOCATIONS OF THE KWGN TRANSMITTER AND THREE BPS RECEIVER SITES (SEE TEXT). B) A BPS RECEIVER OUTPUTS A PULSE-PER-SECOND (PPS) SIGNAL, DERIVED FROM A QUARTZ OSCILLATOR DISCIPLINED BY BPS WHENEVER THE BPS SIGNAL CAN BE TRACKED. A TIME INTERVAL COUNTER (TIC) MEASURES THE TIME DELAY BETWEEN EACH PPS FROM THE LOCAL ATOMIC TIMESCALE AND BPS. AT THE NI+ST BOULDER FACILITY, THE LOCAL ATOMIC TIME SCALE IS UTC(NIST), NIST'S REALIZATION OF COORDINATED UNIVERSAL TIME. THE TIC ACCURACY AND LINEARITY ARE SUPPORTED BY A 10 MHZ REFERENCE SIGNAL COHERENT WITH UTC(NIST); THE TIC INSTABILITY IS APPROXIMATELY 50 PS PER SINGLE-SHOT MEASUREMENT, DECREASING TO 1 PS OVER AVERAGING INTERVALS LONGER THAN 1 HOUR.

Figure 1 illustrates the deployment and test of BPS in the Denver metropolitan area. Television station KWGN (Nexstar Media Group, Inc.) transmits ATSC 3.0 / BPS (channel 34, UHF 593 MHz) from a mountain-top tower west of Denver, Colorado. For convenience, the transmitter's reference clock is a GNSS-disciplined oscillator (GNSS-DO; Microchip TP4500) but independent atomic clocks have referenced BPS transmissions in separate studies. BPS receivers were installed at three locations, the KWGN studio (22 km east; clear line of sight [LOS]), the NIST campus in Boulder (30 km north; terrain obstructed non-line-of-sight [NLOS]), and the NIST WWVB radio station near Ft. Collins (106 km north; clear LOS). Each receiver (Avateq 1050) is paired with a roof-mounted, commercial-off-the-shelf (COTS) UHF TV directional antenna with no additional filters or amplifiers.

In the prior study [6], spanning 22 days from September 3, 2024, BPS was continuously observed and measured against atomic time scales at the NIST Boulder and WWVB facilities. Peak-to-peak variation (of about 55 ns) in these observations was highly correlated. We subtracted the NIST and WWVB observation records to remove variation due to the BPS transmitter's reference clock (a GNSS-DO, at the time configured to use L1 and E1 GPS and Galileo signals only). The remaining variation, about 30 ns peak-to-peak with a random-walk character, was highly correlated with an independent measurement of the difference between the atomic time scales, UTC(NIST) – UTC(NIST@WWVB), afforded by NIST measurements of GPS (L1 and L2 bands) in "common view" at both campuses. By subtracting this measurement of UTC(NIST) – UTC(NIST@WWVB), we obtained a residual series representing several irreducible elements related to BPS propagation and reception in typical deployments: two non-common paths (106 nm LOS and 30 km NLOS), two uncorrelated BPS receivers, noise in two time interval counters (TICs), and intra-facility signal distribution. Noise (of order 1 ns) due to the GPS common-view technique is also present in this "double-difference" signal, so analysis that follows overestimates the noise in BPS time transfer somewhat.

The peak-to-peak residual variation was approximately 22 ns, but over all possible averaging intervals the time deviation (TDEV) statistic remained below 2 ns. For context, over the same test period, the TDEV of UTC(NIST) – GPS(L1 only) remained below 4 ns. TDEV of UTC(NIST) – GPS(L1 and L2) remained below 0.8 ns. While the TDEV statistic does not fully characterize time transfer accuracy, it remains a useful measure when high-quality local clocks can be leveraged as holdover oscillators at both ends of a time transfer link, enabling optimal averaging of time-difference measurements to discern the state of clock rate and time offsets.

A separate finding in the prior stability study involved measurement of BPS at the KWGN studio, which employed an identically-configured GNSS-DO as a reference clock. These measurements, though not continuous, exhibited a maximum TDEV below 600 ps and TDEV below 300 ps for averaging intervals of several hours suggesting excellent time-transfer performance over a LOS propagation path.

New Results with an Additional 50 Days of Observation

In November, 2024, the KWGN BPS transmitter's GNSS-DO reference clock was reconfigured to use dual-band GNSS signals (L1/L2 GPS and the corresponding E1/E6 for Galileo) as originally intended. Thereafter, the direct observation of UTC(NIST) - BPS improved in stability significantly, reducing the need for "common-view" observations involving both UTC(NIST) and UTC(NIST@WWVB) atomic timescales to tease out performance limits.

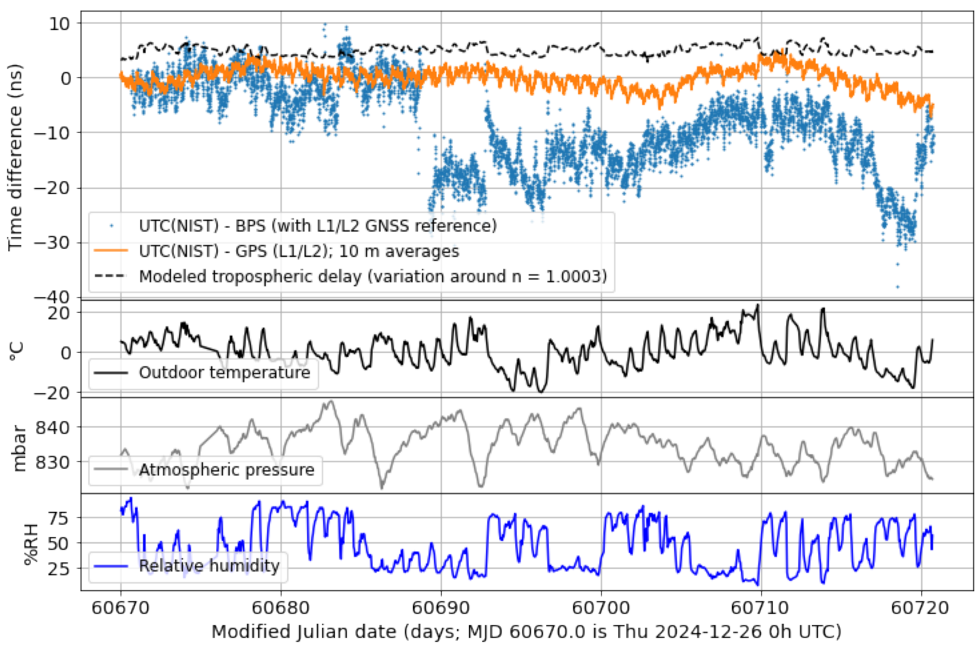

FIGURE 2: FROM 50 DAYS OF MEASUREMENT, WE PLOT TEN-MINUTE AVERAGES OF UTC(NIST) – BPS (BLUE) AND UTC(NIST) – GPS (ORANGE). INITIAL OFFSETS ARE SUBTRACTED FROM EACH SERIES SINCE SEVERAL FIXED OFFSETS (SUCH AS CABLE DELAYS) ARE NOT OTHERWISE COMPENSATED. OUTLIER POINTS ARE VERY RARE; THEY ARE DETERMINED AND REMOVED WHEN > 300 NS FROM THE MEDIAN. THE LOWER INSET PLOTS SHOW OUTDOOR MEASUREMENTS OF TEMPERATURE, ATMOSPHERIC PRESSURE, AND RELATIVE HUMIDITY AT THE NIST BOULDER FACILITY. WE NOTE POSITIVE CORRELATION WITH TEMPERATURE. SEE TEXT FOR DISCUSSION.

Figure 2 shows the measurement of UTC(NIST) - BPS compared with a NIST measurement of UTC(NIST) – GPS(L1 and L2). Strong positive correlation is observed between UTC(NIST) – BPS and the measured outdoor temperature at NIST Boulder; correlation is especially visible with fast temperature changes. The black dashed line in the top plot of Figure 2 is a computation of the expected BPS delay variation due changes in index of refraction according to temperature, pressure, and humidity variation [7]. The estimate is based on sensor data recorded on the NIST Boulder rooftop, includes no account of refractive effects or variation with elevation along the path and does not explain a significant amount of the variation in UTC(NIST) – BPS. Further study is merited, especially comparing NLOS and LOS propagation.

A sudden step of about -25 ns observed in the BPS data near Modified Julian Date (MJD) 60689 (2025-Jan-14) is likely related to known operator maintenance activity that involved lower transmitter power and/or a possible change to undetermined interference in the NLOS propagation of KWGN to NIST Boulder. Figure 3, below, examines this interval closely with BPS observations from both NIST Boulder and NIST WWVB facilities. Besides the apparent time step, the NLOS BPS receiver in Boulder lost lock for approximately 10 hours (during which no data are plotted). However, the LOS BPS measurement near Ft. Collins of UTC(NIST@WWVB) – BPS was uninterrupted and continuous throughout. From this we gather a single inconclusive anecdote about the sensitivity of BPS time transfer to NLOS path or other interference and its fluctuations.

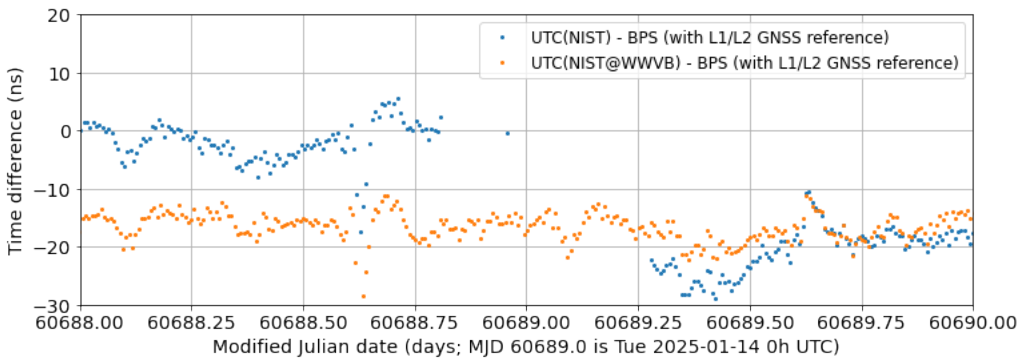

FIGURE 3: DURING A PERIOD WHERE KWGN TRANSMITTER POWER WAS ADJUSTED LOWER, THE BOULDER BPS RECEIVER LOST LOCK FOR ABOUT 10 HOURS (GAP IN BLUE SERIES) AND EXHIBITED AN APPARENT TIME STEP OF ABOUT -25 NS. OBSERVATION OF THE KWGN BPS SIGNAL AT THE NIST WWVB FACILITY SHOWS NO INTERRUPTION OR CHANGE.

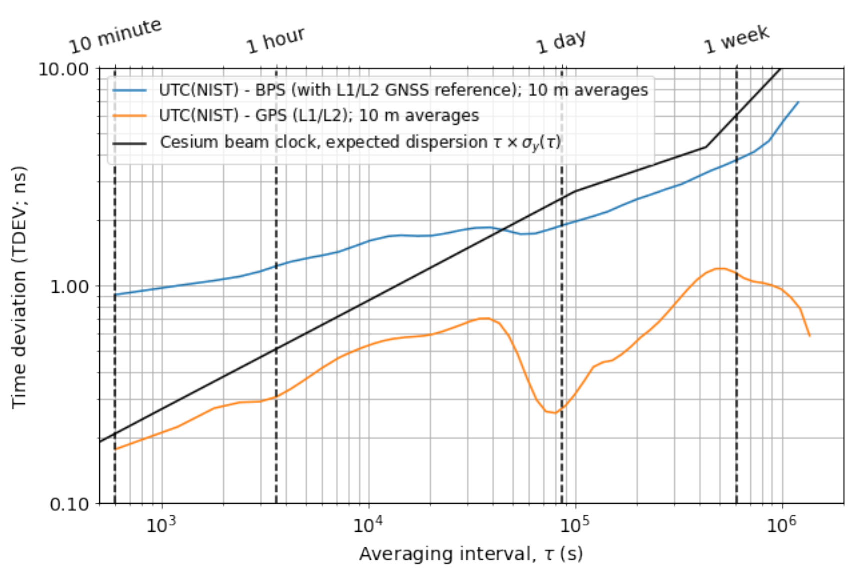

FIGURE 4: THE TIME DEVIATION (TDEV) TIME-DOMAIN NOISE STATISTIC IS A MEASURE OF AVERAGED TIME-DIFFERENCE FLUCTUATION AS A FUNCTION OF AVERAGING INTERVAL. TDEV IS INSENSITIVE TO TIME AND RATE OFFSETS. TDEV IS PLOTTED FOR THE DATA IN FIGURE 2 (BLUE AND ORANGE). FOR CONTEXT, WE ALSO PLOT THE EXPECTED TIME DISPERSION OF A COMMERCIAL CESIUM BEAM ATOMIC CLOCK (BLACK) BASED ON ITS SPECIFIED ALLAN DEVIATION $\sigma_y(\tau)$.

Figure 4 summarizes the variations observed in Figure 2 using the common Time Deviation (TDEV) statistic: a measure of expected fluctuations after averaging as a function of averaging interval. The fluctuations of UTC(NIST) – BPS are approximately within a factor of three or four from measured UTC(NIST) – GPS (L1 and L2); despite the impairments from NLOS propagation and no compensation of tropospheric index-of-refraction variations. For context, the expected time deviation of a rate-corrected COTS cesium beam atomic clock is also shown.

Outlook

Results presented here and in [6] suggest that in its tested state, BPS appears promising for high-resolution, GNSS-independent time transfer between fixed stations where initial offsets can be calibrated externally (e.g., by a one-time use of GNSS, traveling clock, etc.). Impairments due to reduced transmitter power, NLOS propagation, or tropospheric variation are observed on the order of ten nanoseconds over 30 km (and one instance of loss of lock); such effects are expected to depend on geographic details unique to each deployment. In general deployment, BPS receivers must compute (and remove) the signaling delay from transmitter to receiver accurately, either by using known or derived spatial coordinates.

Disclaimer

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. This paper is intended to accompany a presentation of the most-recent BPS time transfer observations and has not been subject to independent peer-review.

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