Measuring the Frequency Accuracy and Stability of WWV and WWVH

An examination of just how accurate these frequency standard stations are.

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Radio station WWV is known as a source of accurate time. However, since March 6, 1923, the original purpose of WWV has been to provide standard frequency signals, with signals broadcast in the LF and MF bands. As detailed in Hoy J. Walls' "The Standard-Frequency Set at WWV" in the October 1924 issue of *QST*, this was in the early days of broadcast radio, when having an accurate frequency reference was essential for keeping stations from interfering with each other. A century later, the standard frequency signals remain essential to radio broadcasters, calibration laboratories, space weather researchers, and radio amateurs.

WWVH joined WWV on the air in 1948. Both stations broadcast on 2.5, 5, 10, and 15 MHz, with WWV also available on 20 and 25 MHz (see Figure 1). This article examines the frequency accuracy and stability of the WWV and WWVH signals as transmitted and as received. We'll use the term WWV/H when referring to both stations.

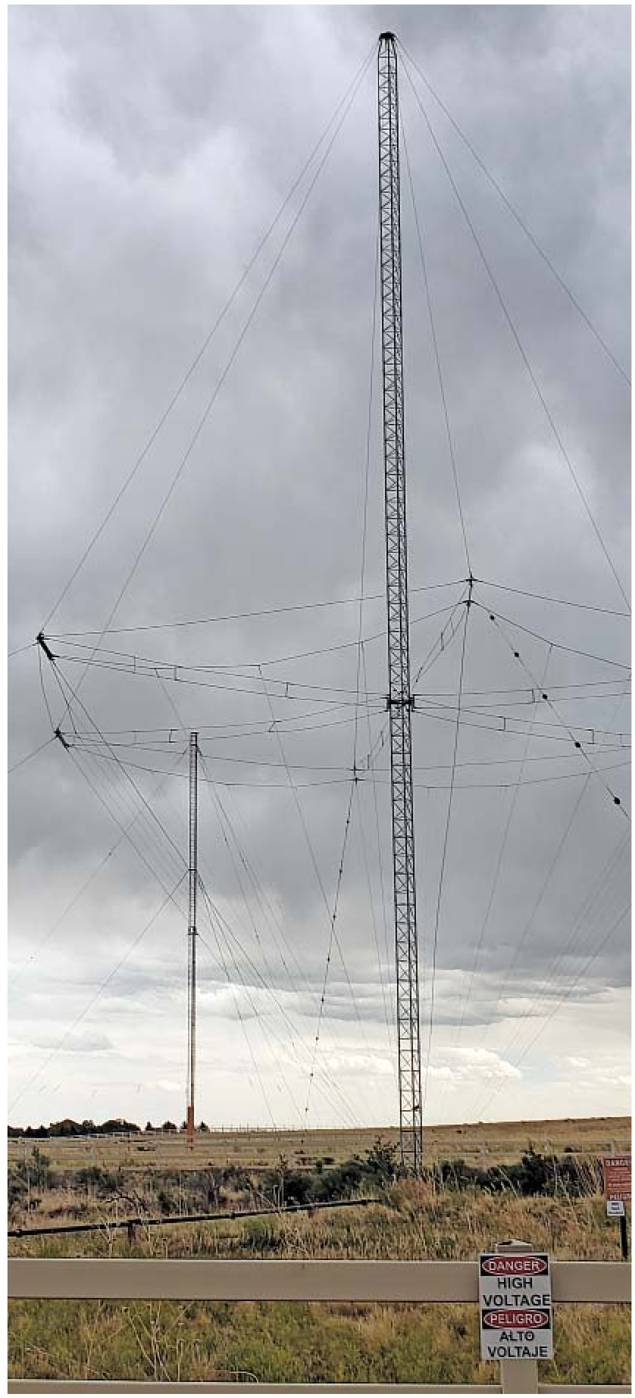

Figure 1 — The antenna in the foreground is a standby broadband antenna with an inverted cone design. It can operate at any of the WWV frequencies from 2.5 to 25 MHz. The primary 5 MHz antenna is in the background.

Basic Terminology

Frequency accuracy is the difference between the actual frequency of a signal and its *nominal frequency*. Nominal frequency examples include the 14.074 MHz displayed on a transceiver dial when working FT8, and the 10.000 MHz carrier frequency assigned to WWV/H. Measuring how much they differ requires comparing them to a reference frequency that is known to be more accurate. That comparison produces a quantity called Δf, where Δ indicates the difference between two frequencies.

Δf is often a tiny fraction of 1 Hz. It is common practice to divide Δf by the nominal frequency f and to express frequency accuracy as a unit-less value. For instance, if a nominal 10 MHz (10^7 Hz) signal is inaccurate by 1 Hz, we can say that its accuracy is one part per 10 million, or one part in 10^7. Table 1 shows accuracy values for three nominal WWV/H frequencies (2.5, 5, and 10 MHz) when Δf is equal to 1 Hz, 1 mHz, or 1 µHz.

Stability indicates how much a frequency changes over a given period, not how accurate the frequency is with respect to its nominal value. Stability is just as important as accuracy because the accuracy during a given period can never be better than the stability during that same period. Stability sets the limits for the possible accuracies we can obtain.

Consider a transceiver that produces a stable, yet inaccurate frequency. We can correct it by adjusting the local oscillator until the frequency is accurate. Next, consider a transceiver that is not stable, but that temporarily produces an accurate frequency after its local oscillator is adjusted. That oscillator won't stay accurate for long because its frequency is constantly changing. Hams often use the term "drift" instead of "instability." A transceiver with an unstable or drifting local oscillator can only be fixed with continuous adjustments.

The *Allan deviation* (ADEV) is a statistic used by engineers and scientists to estimate frequency stability. It is computed by taking the differences of successive pairs of frequency accuracy estimates, obtained as $\Delta f / f$, then applying a statistic similar to standard deviation to these differences. There are many references about ADEV, including *NIST Special Publication 1065*.[1] Free software tools for calculating ADEV are also available.[2, 3] In the following sections, we'll use stability data obtained with ADEV to establish accuracy limits for the WWV/H signals, both as transmitted and as received.

The Transmitted Accuracy of WWV and WWVH

Understanding WWV/H accuracy requires knowledge of atomic clocks, Coordinated Universal Time (UTC), and NIST's own version of UTC, UTC(NIST). Atomic clocks define the units of both time interval and frequency. The second is defined by counting energy transitions of the cesium-133 atom; by international agreement, the time interval required for 9,192,631,770 of these transitions defines 1 second. Frequency is measured by counting the cycles that occur during a 1-second interval, so cesium atomic clocks serve as primary measurement standards for time interval and frequency. The International Bureau of Weights and Measures in Paris, France, is responsible for computing UTC, which serves as the international standard for time interval and frequency.

Supporting real-world measurements in the US is a key responsibility of NIST. It involves maintaining primary standards for all physical quantities, including time and frequency. Like UTC, UTC(NIST) is based on a weighted average of atomic clocks — most of which are hydrogen masers — to ensure the best stability. UTC(NIST) differs from UTC because it produces physical signals. The physical signals closely agree with the UTC computations, producing time accurate to within a few nanoseconds and frequency stable to parts in 10^{15} when averaged for 1 day.

Because NIST operates WWV/H, it controls the radio station signals with UTC(NIST). The WWVH time scale consists of a single cesium clock, with other cesium clocks available on standby. The time scale at WWV includes five cesium clocks that are combined with a weighted average algorithm in a similar fashion as UTC and UTC(NIST). However, the absence of hydrogen masers makes the WWV time scale about a factor of 10 less stable than the primary time scale in Boulder.

Locking the WWV/H time scales to UTC(NIST) ensures continuous accuracy. The stations broadcast time accurate to within nanoseconds and frequency accurate to less than 1×10^{-13}, limited by their stability over a given measurement period. To demonstrate this, we made measurements comparing the WWV/H time scales to UTC(NIST) during June and July 2022. The results are shown in Figure 2, which graphs frequency stability versus the averaging period in hours. The WWV time scale, advantaged by more atomic clocks and fewer frequency corrections, is more stable than the WWVH time scale at short averaging periods. But, their stability is about equal when averaged for 72 hours, reaching parts in 10^{15}. After 24 hours of averaging, both stations are stable and accurate to well below 1×10^{-13}.

The Received Accuracy of WWV and WWVH

WWV/H often serve as calibration references, by which the device under test (DUT) is typically a quartz oscillator found in a test instrument, such as a frequency

Table 1 — Examples of Frequency Accuracy Numbers for Varying Quantities of Δf

Nominal Frequency (MHz)	Frequency Accuracy (when Δf = 1 Hz)	Frequency Accuracy (when Δf = 1 mHz)	Frequency Accuracy (when Δf = 1 μHz)
2.5	4×10^{-7}	4×10^{-10}	4×10^{-13}
5	2×10^{-7}	2×10^{-10}	2×10^{-13}
10	1×10^{-7}	1×10^{-10}	1×10^{-13}

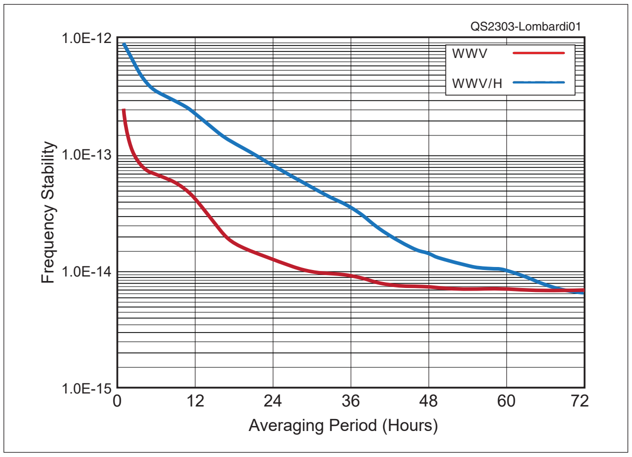

Figure 2 — The transmitted frequency stability of WWV and WWVH for averaging periods ranging from 1 to 72 hours.

counter, or in a radio receiver or transmitter. Historically, most of these calibrations have involved some variation of the zero-beat method, or methods where WWV/H signals are used to trigger an oscilloscope. Modern ham transceiver calibrations often involve computers. One method, described in Dave McCarter's, VE3GSO, "Measuring Frequencies at VE3GSO" in the April 2015 issue of *QST*, involves measuring Δ*f* at several WWV/H test points with software and a sound card, then using the results to calibrate a receiver dial. Software such as *fldigi* and *WSJT-X* include built-in frequency measurement tools that can utilize WWV/H. This is also detailed in Michael Foerster's, WØIH, "Using *WSJT-X* to Graph Radio Frequency Stability" in the August 2021 issue.

For calibrations with WWV/H as the reference, two tenets generally hold true. First, the calibration is a quick check of frequency, with little or no averaging. During an ARRL Frequency Measuring Test, the contestant has just 1 minute to determine the frequency of the incoming signal, which precludes extensive data collection. The second tenet is that the exact accuracy of the received WWV/H signal is unknown. All we know is that the received signal is the reference, and it is believed to be more accurate than the DUT. We can guess (and usually we're correct) that the received accuracy of WWV/H will be within 1 Hz, or within one part in 10^7 at 10 MHz (see Table 1). That's accurate enough to calibrate a transceiver because the tuning resolution of modern transceivers is usually no finer than 1 Hz, with older equipment having coarser resolution.

If our goal is to determine the true accuracy of received WWV/H signals without making guesses, we need to flip both tenets by averaging the data. We also need to make WWV/H the DUT, not the reference. Finally, we should know in advance that the received accuracy of WWV/H will be much worse than the transmitted accuracy, likely 1,000 to 1 million times worse! This means that signals accurate at the µHz level when broadcast will only be accurate at the mHz-to-Hz level when received.

To understand why so much accuracy is lost, consider how HF radio signals propagate. A huge advantage of HF signals is their ability to travel long distances via skywave propagation. However, this advantage becomes a disadvantage when measuring frequency. As shown on **www.arrl.org/qst-in-depth**, HF signals are refracted when they reach the ionosphere. The signals that propagate at a steep enough angle pass through the ionosphere into space, but the remaining signals are reflected to Earth. Therefore, the signal path between the transmitter and receiver is related to the change in the ionosphere's height at the point of reflection. When the height of the ionosphere is increasing at the point of reflection, the signal path gets longer and the received frequency decreases. Conversely, if the height of the ionosphere is decreasing, the signal path gets shorter and the received frequency increases. Groundwave signals that travel along Earth's surface are not affected by the motion of the ionosphere, but their coverage area is limited. The skip zone, or the area where the signals can't be received, begins just beyond the reach of the groundwave signals and ends where the first skywave signals return to Earth.

The difference between the received and transmitted frequencies is called the *Doppler shift* or *Doppler frequency*. It can be considered equivalent to the Δ*f* quantity discussed earlier, as it indicates the difference between the received frequency and the nominal frequency of the carrier. Therefore, if we can measure the Doppler shift, we can determine the received accuracy of WWV/H. This measurement capability is now available through the efforts of the Ham Radio Science Citizen Investigation (HamSCI; **www.hamsci.org**), which advances scientific research through amateur radio activities. Their goal is more ambitious than simply measuring WWV/H; they are building a space weather network to monitor how solar activity affects Earth's atmosphere, including its impact on telecommunication and electrical utilities. This project is also discussed in the August 2021 issue, in "Ham Radio Creates a Planet-Sized Space Weather Sensor Network" by Kristina Collins, KD8OXT; David Kazdan, AD8Y, and Nathaniel A. Frissell, W2NAF. WWV/H are ideal space weather beacons because they transmit signals of known accuracy on multiple frequencies in the HF spectrum. Measuring WWV/H from numerous locations allows HamSCI to collect vast amounts of ionospheric data, which is a feat that wouldn't be possible without radio amateur participation.

Even so, HamSCI's initial efforts to measure WWV/H via amateur stations had some shortcomings. One problem was that every station needed a frequency reference more accurate than the received WWV/H signals. Otherwise, the measurements would determine only the inaccuracy of the receiver's local oscillator.[4] Another problem was that amateurs who continuously measured WWV/H with their regular rig couldn't pursue other ham activities; a separate dedicated receiver was needed.

Both problems were solved by the development of the low-cost Grape 1 Personal Space Weather Station (PSWS). The Grape 1 PSWS can be viewed at **www.arrl.org/qst-in-depth**, and it consists of three main components: a WWV/H receiver and antenna, a GPS disciplined oscillator (GPSDO), and an instrument controller. The receiver, a simple heterodyne unit designed for this application, allows selection of either 2.5, 5, or 10 MHz. The GPSDO, a Leo Bodnar Mini Precision GPS Reference Clock, provides the local oscillator signal for the receiver and includes a phase-locked loop (PLL) that is set 1 kHz below the incoming carrier frequency. The PLL output is mixed with WWV/H, producing a 1 kHz frequency that is used to measure the Doppler shift. The GPSDO ensures that atomic clock accuracy is present at the receiving sites because its signals are referenced to the time scale of the US Naval Observatory, UTC(USNO), which is a national standard of time and frequency equivalent to UTC(NIST). The instrument controller is a Raspberry Pi 4 Model B that runs a modified version of *fldigi* in frequency analysis mode. The measurement data stored every second includes the time of day, the signal amplitude, and the Doppler frequency (with 1 mHz resolution).[5]

The HamSCI researchers are mainly interested in studying events such as traveling ionospheric disturbances (TIDs). These are caused by variations in the electron density of the ionosphere, so skywave reception is of primary interest. Figure 3 graphs the Doppler frequency of the 10 MHz WWV signal, as measured for 72 hours at W2NAF in Pennsylvania, located 2,466 kilometers from the transmitter. At this distance, the 10 MHz signals were not always receivable, and readings where the signal amplitude was less than 5 mV were discarded. The Doppler frequency peaks and changes direction around sunrise and sunset. The peak-to-peak variation is about ±1.5 Hz, but the

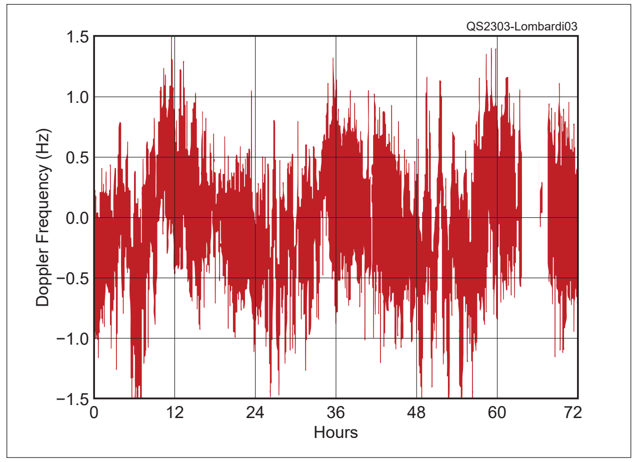

Figure 3 — The Doppler frequency shift of 10 MHz WWV skywave signals, as measured for 72 hours from Pennsylvania, at a distance of 2,466 kilometers from the transmitter.

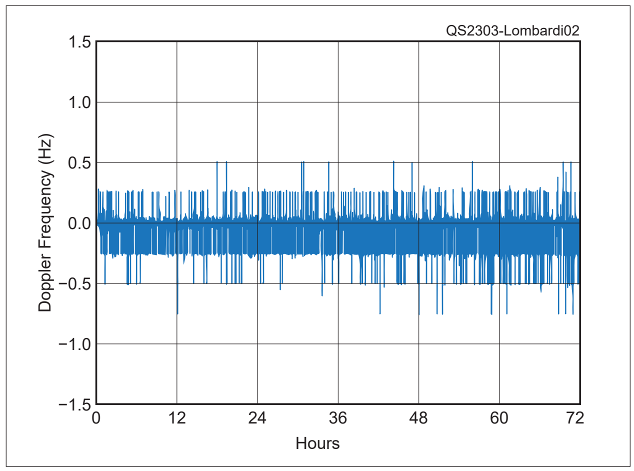

Figure 4 — The Doppler frequency shift of 5 MHz WWV groundwave signals, as measured for 72 hours from Colorado, at a distance of 14 kilometers from the transmitter.

Doppler frequency is usually less than 1 Hz, with the average close to 0 Hz.

The accuracy of the skywave data in Figure 3 is more than adequate for ham radio applications, but better accuracy can be obtained via groundwave reception. This was demonstrated by measuring the 5 MHz signal for 72 hours from station WØDAS in Colorado, located just 14 kilometers from the transmitter (see Figure 4).[6] For comparison, the groundwave data were graphed with the same ±1.5 Hz scale used for the skywave data. But here, the Doppler frequency rarely exceeds 0.5 Hz, with no discernible variation at sunrise or sunset because the ionosphere was not involved.

To determine the accuracy limits, the frequency stability of 10 amateur stations was computed using 72 hours of

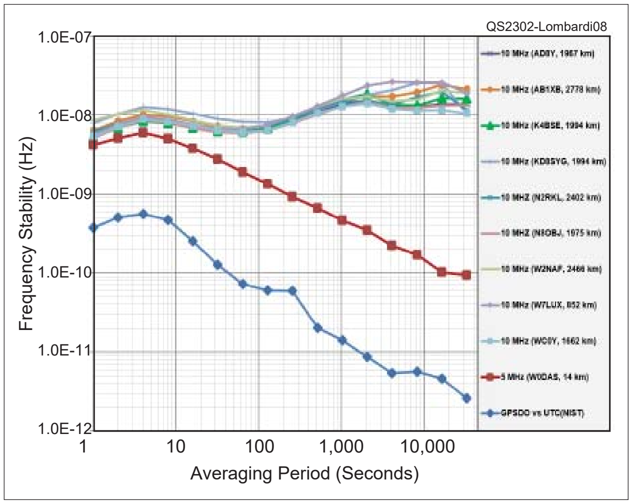

Figure 5 — The received frequency stability of WWV, measured at nine sites receiving sky wave and at one site receiving ground wave. The frequency stability of the reference GPSDO is also shown.

data and by measuring the Doppler frequency every second. The 10 stations include the two shown in Figures 3 and 4, plus eight additional stations that received 10 MHz skywave signals.[7] The results are featured in Figure 5, with stability estimates provided out to periods of 32,768 seconds (about 9.1 hours). The nine stations receiving the 10 MHz sky wave produced remarkably similar results, with stabilities ranging from about five to eight parts in 10^9 for 1-second periods. Averaging for periods of 1 hour or longer made the stability worse, increasing to a few parts in 10^8. Averaging for 24 hours would partially cancel the sunrise/sunset effect and likely improve those results. In contrast, the stability of the groundwave data continuously averaged down, reaching about 1×10^{-10} after a few hours for an accuracy limit of less than 1 mHz. To prove that the reference oscillator was not the limiting measurement factor, we measured the stability of a Leo Bodnar GPSDO via direct comparison to UTC(NIST) in Boulder. Those results show that the GPSDO was at least a factor of 10 more stable at all averaging periods than the groundwave measurements, thus contributing no significant measurement uncertainty.

Summary

The standard frequency broadcasts of WWV/H began a century ago and remain essential today, serving both as calibration references and space weather beacons. The frequency accuracy of the transmitted WWV/H signals is less than one part in 10^{13}. The frequency accuracy of the received signals, limited by their stability over the measurement interval, ranges from a few parts in 10^8 for sky wave to about one part in 10^{10} for ground wave.

Acknowledgments

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Notes

[1]W. J. Riley, K2HRT, "Handbook of Frequency Stability Analysis," *NIST Special Publication 1065*, Jul. 2008, pp. 136.

[2]W. J. Riley, K2HRT, wrote the *Stable32* software for Windows, which calculates ADEV and many similar statistics. *Stable32* is available on GitHub via IEEE (**www.github.com/IEEE-UFFC/stable32**) and from **www.stable32.com**.

[3]Open-source Python libraries for ADEV are available from **www.pypi.org/project/AllanTools**.

[4]K. Collins, KD8OXT; A. Montare, KB3UMD; N. Frissell, W2NAF, and D. Kazdan, AD8Y, "Citizen Scientists Conduct Distributed Doppler Measurements for Ionospheric Remote Sensing," *IEEE Geoscience and Remote Sensing Letters*, Mar. 2021, vol. 19, article no. 3504605, pp. 1-5.

[5]J. Gibbons, N8OBJ; K. Collins, KD8OXT; D. Kazdan, AD8Y; and N. Frissell, W2NAF, "Grape Version 1: First prototype of the low-cost personal space weather station receiver," *HardwareX*, Apr. 2022, vol. 11, article no. E00289, pp. 1-13.

[6]David Swartz, WØDAS, is the president of the WWV Amateur Radio Club. For more information about the club, visit **https://wwvarc.org**.

[7]The eight stations, listed alphabetically with their state and distance from the transmitter in parentheses, are: AD8Y (Ohio, 1,967 kilometers), AB1XB (Massachusetts, 2,778 kilometers), K4BSE (Georgia, 1,994 kilometers), KD8SYG (Ohio, 1,994 kilometers), N2RKL (New York, 2,402 kilometers), N8OBJ (Ohio, 1,975 kilometers), W7LUX (Arizona, 852 kilometers), and WCØY (Indiana, 1,662 kilometers). The skywave data shown in Figure 5 were collected on May 29 – 31, 2022.

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