Measurements of Propagation Delays Between WWV/WWVH and Anchorage, Alaska

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1. Introduction

The measurements described here show that the propagation delays between WWV or WWVH time service broadcast stations and a receiver in Anchorage, Alaska are discernible in an audio recording. The propagation delays are on the order of 13 to 15 ms. These measurements are an initial step toward determining the time resolution that might be attainable while analyzing audio recordings of Jupiter s-bursts and other high frequency radio phenomena. It is noted that measuring easily recognizable audio tones (as in this paper) are presumably much easier than measuring noise-like extraterrestrial radio emissions.

As described in detail below, post-processing measurements with sub-millisecond resolution can be achieved when the received signal voltage amplitudes are roughly > 6 dB above background noise. At lower voltage signal-to-noise ratios, the ability to recognize the start and end intervals of the WWV/WWVH tones is degraded but measurements with millisecond resolution are still possible.

Summary of measurement results:

Measurement	**Measured value**	**Remarks**
Soundcard timing accuracy	+10 ppm	measured over 0.2 to 3 minute intervals using PPS
Excess propagation delay	0 to +4 ms	Referred to calculated delay
PPS interval	1.000 010 s	Typical
PPS pulse width	100 ms	Measured between leading to trailing edges
Resolution	1 µs	Waveform displayed in Goldwave audio software
WWV or WWVH second tock width	5 to 8 ms	Transmitted width is 5 ms
WWV or WWVH minute tone width	800.3 to 800.4 ms	Transmitted width is 800 ms

2. WWV and WWVH

WWV is located near Boulder, Colorado (40° 40' 47.8" N; 105° 02' 25.1" W for 10 MHz antenna) and WWVH is near Kekaha, Kauai, Hawaii (21° 59′ 18.2" N; 159° 45′ 51.3" W for 10 MHz antenna). These stations transmit HF carrier frequencies modulated in specific ways at specific times {WWV} {WWVH}. The transmitters use the UTC time reference and may be compared to a local UTC time reference for propagation delay measurements at a receiver. Of particular interest are the second marker tick tones (called *tocks* here because of their sound) and minute marker tones.

The tocks are transmitted at 1-second intervals and consist of 5 cycles of 1000 Hz tone (total duration 5 ms). The minute tones are transmitted at 1-minute intervals and consist of 800 cycles of 1000 Hz tone for WWV and 960 cycles of 1200 Hz tone for WWVH (total duration of both tones is 800 ms) except tones on the hour (minute 60) are 1500 Hz. Although WWV and WWVH transmit other tones at specific times and cadences, I made no effort to identify or measure them.

3. Local UTC Time Reference

The time reference used in these measurements was the PPS signal derived by a local GNSS receiver. The rising edge of the PPS signal is aligned with the beginning of the UTC second. The PPS is coupled to one channel of a PC soundcard stereo Line In port and recorded at the same time as the WWV and WWVH signals on the other channel. The **Appendix** describes the modifications to a GpsNtp-Pi network time server to obtain the PPS signal.

4. Propagation Characteristics

The time station transmissions are received via multi-hop ionospheric propagation to Anchorage. The great circle distance from WWV to Anchorage is 3800 km and from WWVH to Anchorage is 4400 km. However, the propagation paths are longer because for each hop they must travel from the transmitter up to the ionosphere where they are refracted back down to the surface.

Predictions by the ACE-HF software indicate that the propagation mode at the time of measurements for both WWV and WWVH was 2-hop via the F2 region (table 1) but other modes are possible including modes with lateral refractive paths. For example, a 1-hop F2 circuit reduces the path distance by about 100 km compared to a 2-hop circuit (reduction in delay of about 0.3 ms) and a 3-hop F2 circuit adds around 140 km compared to a 2-hop circuit (increase in delay of about 0.5 ms).

Table 1 ~ Distances, propagation delays and modes from the time station to Anchorage, Alaska. Delays assume the speed of light in air is 299 700 km/s.

Time Station	Location USA	Great circle distance (km)	Path distance (km)	Propagation delay (ms)	Propagation Mode
WWV	Boulder, Colorado	3800	4000	13.3	2F2
WWVH	Kekaha, Kauai, Hawaii	4400	4590	15.3	2F2

5. Time Measurement Methods

All measurements were made with respect to the PPS time reference. The overall accuracy of the soundcard and wave recorder timing was determined by measuring the PPS pulse width and time interval between two or more PPS pulses. The durations and time intervals of the received WWV and WWVH one second marker tock and one minute marker tones also were measured for comparison. The propagation delay was measured by comparing the leading edges of the PPS reference pulses to the leading edges of received one second tocks and one minute tones.

The specific measurements discussed in the following sections are typical. Over 100 time measurements were made on the recorded waveforms, but no statistical analyses are provided. Generally, when received signals were strong, the measured intervals were closer to predicted values.

6. Instrumentation

The instrumentation consisted of much more than just a receiver and soundcard (figure 1). The WWV and WWVH time signals were received on an Icom R75 general coverage receiver connected to an HF log periodic antenna (antenna location 61° 11' 58.02" N; 149 °57' 22.88" W). The receiver was set to LSB and operated with AGC at all times. It was tuned to the frequency with the strongest signal at the time of the recording. Frequencies used were 5, 10, 15 and 20 MHz; the time signal transmission format is identical for all frequencies. The entire RF-to-AF chain was analog, and the conversion to digital was at the soundcard. The receiver audio was fed through an analog mixer to the soundcard.

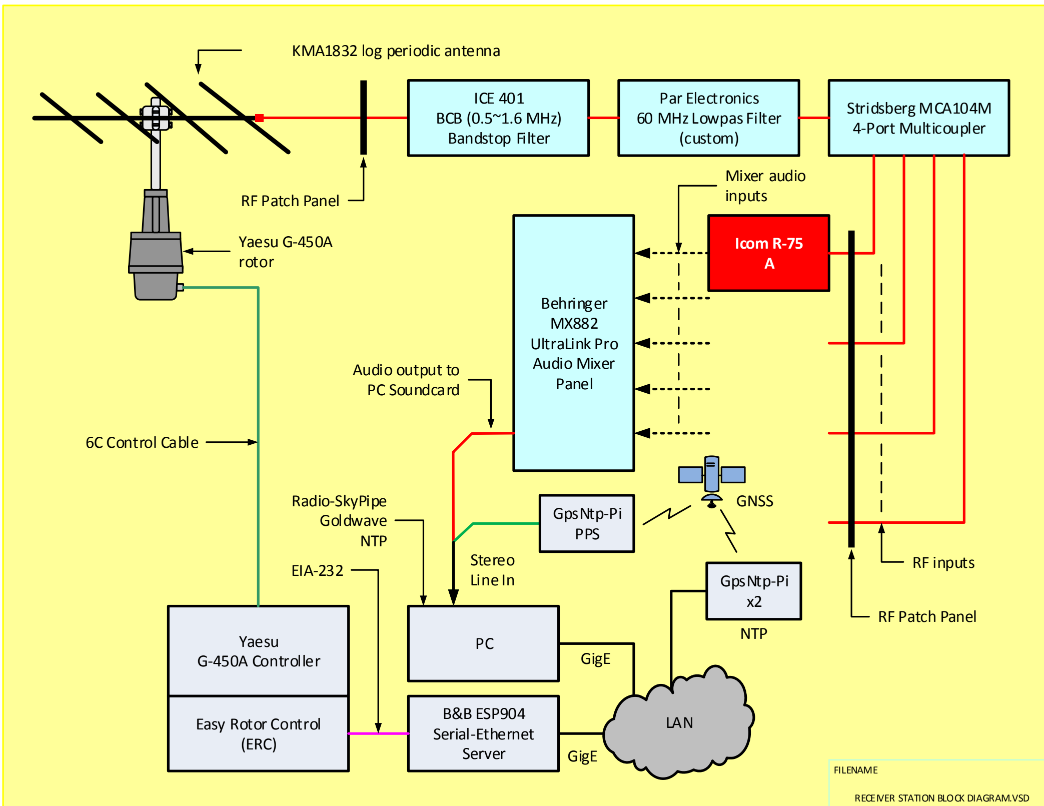


Figure 1 ~ Instrumentation setup. The overall system consists of several receivers and other components not related to the measurements and omitted for clarity. The RF-to-AF chain to the soundcard is analog.

A GpsNtp-Pi network time server was modified to include a PPS buffer amplifier, level control and PPS LED indicator. The GpsNtp-Pi uses the GlobalTop Technology FGPMMOPA6H GNSS receiver, which is not optimized for timing applications; however, its specified PPS jitter of 10 ns is insignificant compared to the delay measurements described here. The PPS output level was adjusted to 100 mV zero-peak for most measurements. The PPS is output by the GNSS receiver only when it has attained a fix and is tracking the GNSS satellites.

The PPS output and receiver were connected to the stereo Line In jack of the soundcard in a Lenovo A61e desktop PC running Windows 7 and Radio-SkyPipe (RSP) and Goldwave software. The soundcard is based on the

ADI 1982 HD (SoundMax) chipset. The PC runs the Network Time Protocol (NTP) and its real-time clock is synchronized within 10 ms of UTC by two local GpsNtp-Pi time servers.

7. Record and Playback

Both Radio-SkyPipe and Goldwave were used for audio recording. Only Goldwave was used for playback and analyses. A few other programs were collecting unrelated data during the recording sessions with the RSP wave recorder, and the PC CPU was running close to 100% load. The recordings with Goldwave were made while RSP was closed and the CPU was running about 50-75% load. Analyses of the various timing intervals discussed in the next section indicate that CPU load had no obvious effects on the recorded time intervals.

Thirteen 5 minute recordings were made with the RSP wave recorder on 22, 23 and 31 January and 1 and 2 February 2016. RSP was setup for 16-bit stereo with 12 000 Hz sampling rate, giving a total bit rate of 384 kb/s. RSP also was used to capture data files at 0.1 Hz sampling rate for plotting on a strip chart; however, the plots were not used in the timing analyses because of the low time resolution. See section 11 for representative RSP plots.

Seventeen 5 minutes recordings were made with Goldwave software on 2 and 3 February. The Goldwave default settings were used: 16-bit with 44 100 Hz sampling rate, giving a total bit rate of 1411 kb/s. The higher sampling rate of the Goldwave recordings did not provide any benefit or better measurements than the RSP audio recordings. Most of the measurement details in the following sections were from the RSP wave recorder files.

The wave files were loaded into Goldwave for playback and analysis. The Goldwave playback window allows unlimited zooming into the displayed waveform. Adjustable cursors are then used to determine the start and stop times and differential times, which are displayed on the status bar at the bottom of the main window along with other data (figure 2). The Goldwave cursors can be set with 1 µs resolution.

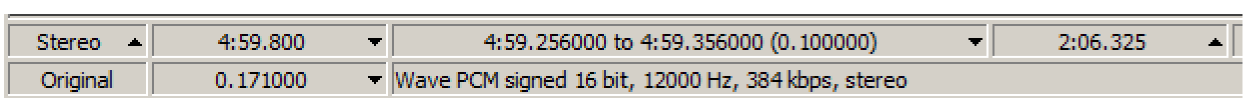


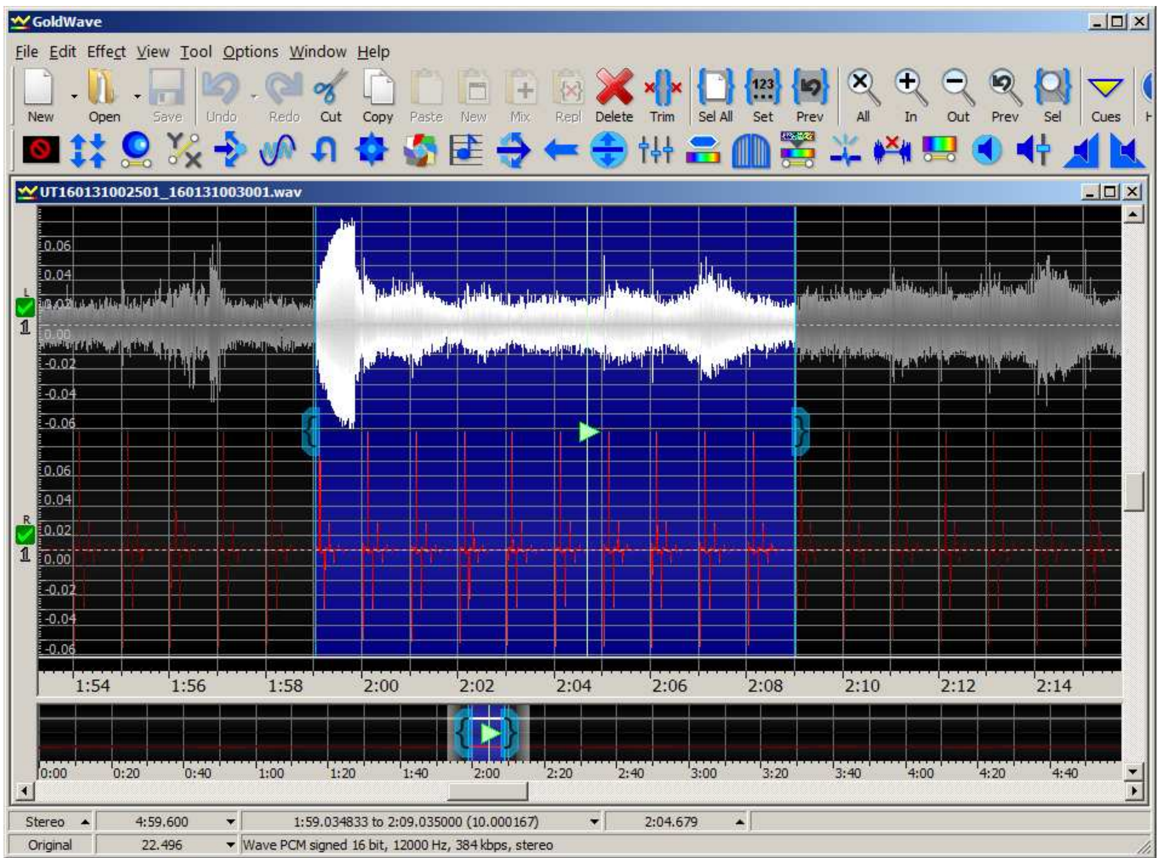
Figure 2 ~ Status bar on the Goldwave software main window from which all measured time data in this paper were derived. The upper and lower status fields on the far left indicate the displayed mode (Stereo) and file status (Original). The next two show the total time of the wave file (4:59:800 min) and the time interval displayed in the main window (0.171000 s). The main window is not shown in this image. The next shows the times displayed by the playback cursors and their difference (0.100000 s). Below the cursor interval are format metadata (Wave format using pulse code modulation, 16 bit ADC, 12000 Hz sampling rate, 384 kbps total data rate, stereo mode). Finally, at upper-right is the controlled playback cursor position (2:06:325 min). This cursor is unrelated to the measurements.

8. PPS Analysis

For all measurements I assumed the PPS signal was perfectly accurate, exactly 1.000 000 s pulse period, and that any measured variations were due to soundcard or software timing errors. This assumption is supported by measurements of the PPS in the GpsNtp-Pi network time servers (see documentation available here: {GpsNtp-PI}.

I made many measurements of the PPS intervals including the interval between two PPS pulses and the average of several intervals. Rather than develop statistics of the measurements, I spot-checked numerous intervals and looked for departures from the typical values noted here. Generally, there were no aberrations.

One set of measurements was the average PPS interval for ten and sixty pulses (figure 3). The ten PPS measurement showed an average interval of 1.000 017 µs, and the sixty PPS measurement showed 1.000 008 µs average. Also, three individual 60 s intervals were analyzed in one recording and up to 567 µs additional delay was observed (9.5 µs average). A 180 s interval showed 1474 µs additional delay (8.2 µs average). These measurements are typical and indicate the soundcard timing was slightly slow on the order of 10 ppm (it was always slow and never fast). The PPS pulse width always measured 100 ms throughout the recordings.



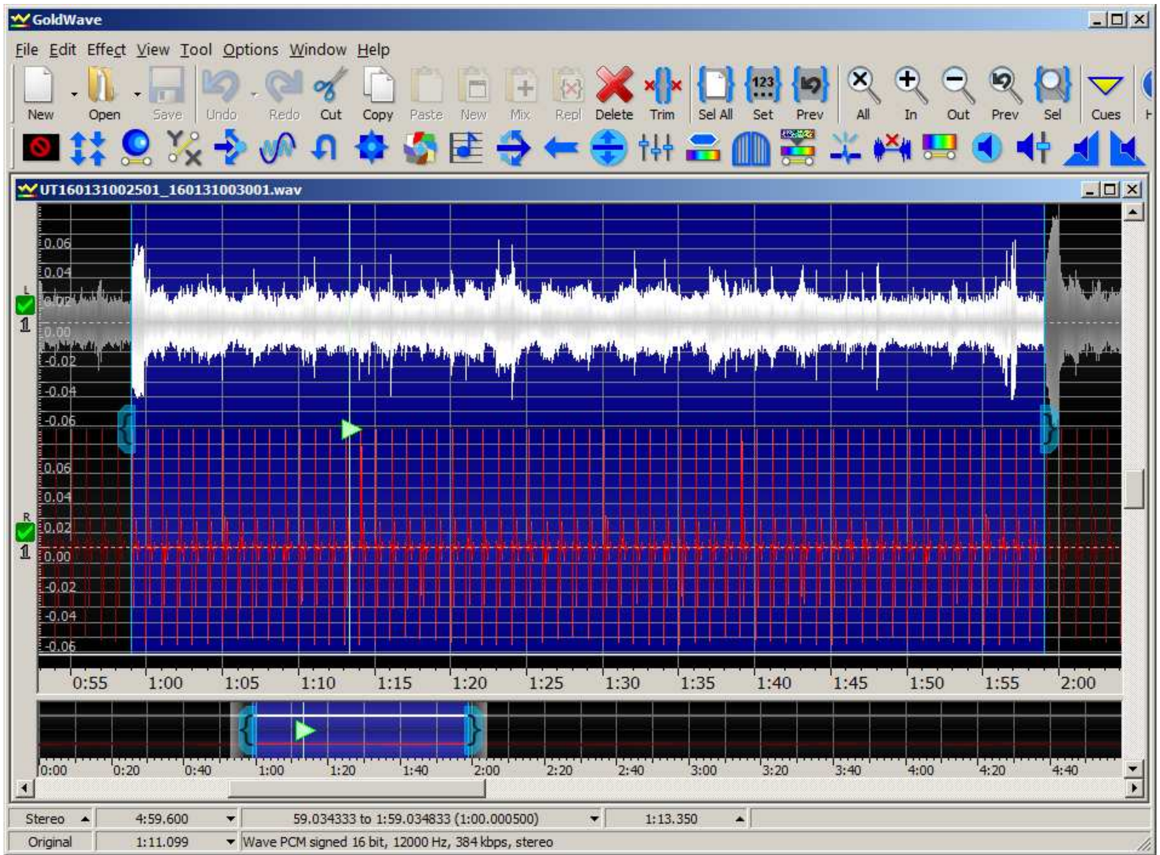


Figure 3 ~ Representative measurements of average PPS interval. The measured PPS intervals happened to coincide with the minute tone markers, seen as the pulse on the upper (white) traces. Upper: Measurement of ten PPS (10 s) showed a total interval of 10.000 167 s (see status bar at bottom of window), giving an average interval of 1.000 017 µs. Lower: Measurement of sixty PPS (60 s) showed 60.000 500 s, or 1.000 008 µs average.

9. Tock Analysis

A tock is transmitted at the beginning of each second and consists of 5 cycles of a 1000 Hz sinewave, giving a 5 ms pulse. The tock is preceded by 10 ms of silence and followed by 25 ms of silence. Receiver AGC characteristics may affect how the pulses are recognized in a recording display. The time signal recordings were much better on 31 January and on 1 and 2 February than on 22 and 23 January.

The tock is delayed with respect to the PPS due to propagation (figure 4). During some of the recordings, WWVH was stronger than WWV and during others WWV was stronger. The propagation delay always was easily discernible, and I could consistently measure a delay of 15 to 18 ms between the PPS and the WWV or WWVH second tock. The measured tock pulse width varied from 5 to about 8 ms but recordings of stronger received signals consistently showed pulse widths very close to 5 ms. Noisy tocks were more difficult to measure (figure 5). Additional waveform plots show wide and narrow views of a PPS leading edge and a following tock (figure 6).

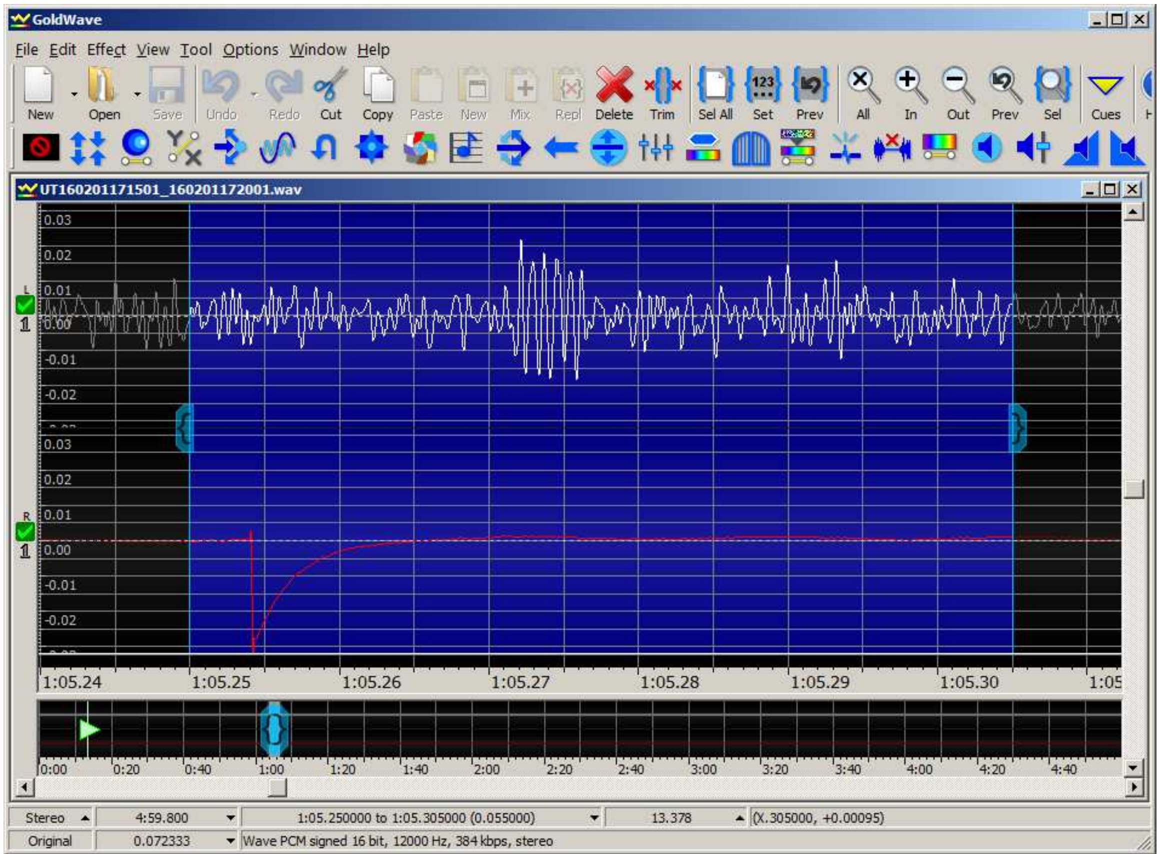


Figure 4 ~ A clearly visible tock transmitted by WWV, shown in the middle of the white trace, is 5 ms long and composed of 5 cycles of a 1000 Hz sinewave. When transmitted the tock is preceded by 10 ms of silence and followed by 25 ms of silence. When received, the silent intervals are filled with receiver and other background noise as shown here. The leading edge of the PPS is seen as a downward pulse on the red trace near the left cursor. The time between the PPS leading edge and tock is the propagation delay. The cursors in this screenshot were purposely moved out of the way so that PPS and tone features can be seen. The total display width of this example is 72 ms and the blue area is bound by start and finish cursors separated by 55 ms.

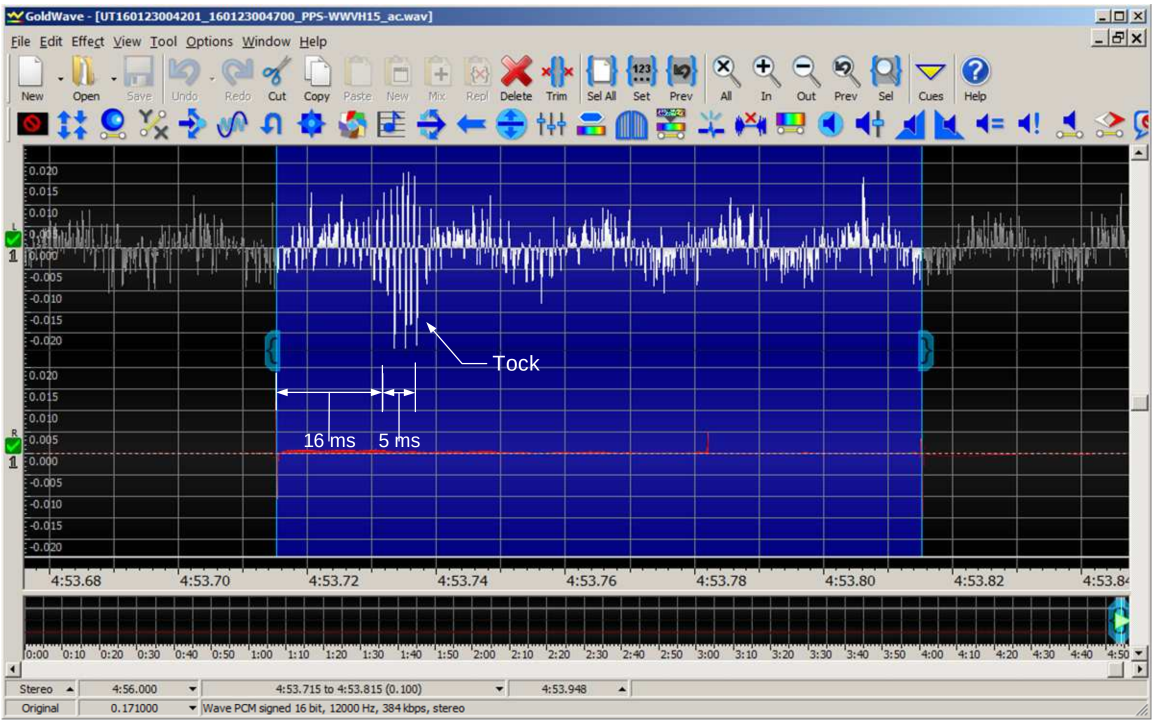
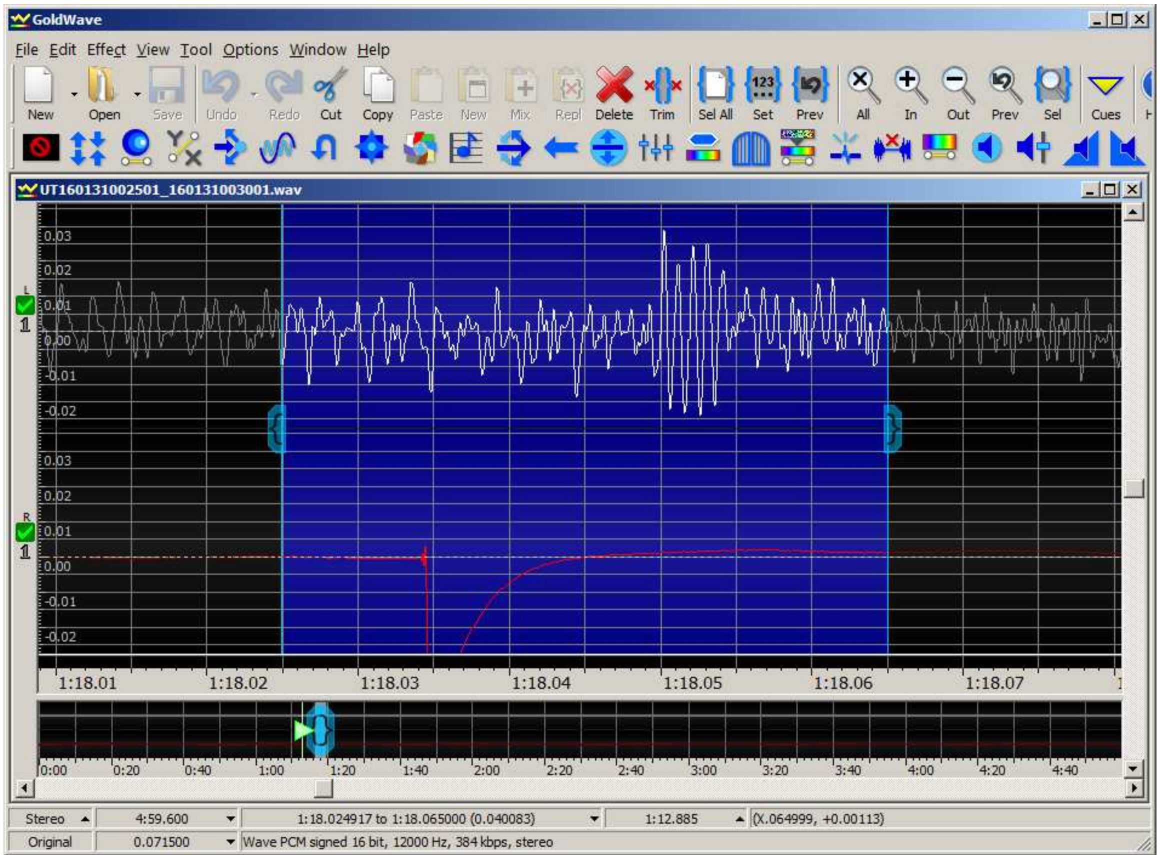


Figure 5 ~ Annotated tock display with fairly high level of background noise. A time slice of about 150 ms around the 100 ms PPS pulse is shown. The bottom trace (red) is the PPS and the upper trace (white) is WWVH. The 100 ms wide PPS pulse appears as a downward and then an upward spike at the beginning and end of the pulse due to its ac coupling to the soundcard. The blue area shows the PPS boundaries. If the blue boundary is moved away, the spikes are easy to see; however, the beginning of the tock has to be estimated. The tock is the enhanced periodic signal that follows about 16 ms after the left cursor. The tock amplitude is about twice the amplitude of periodic background noise in this image.

The measured delays between the PPS and tock exceeded the calculated values by 0 to +4 ms (4 ms delay is equivalent to about 1200 km extra path distance). The measured delays were never less than calculated. The source of the extra delay in the measurements is unknown but could be caused by soundcard timing drift, wave recorder characteristics, higher propagation mode or modes, or lateral or anomalous propagation paths. The details discussed in the PPS Analysis section above appear to indicate that soundcard timing errors would not account for the extra delay. Another measurement variable is the approximate 2 ms difference between the reception of WWV and WWVH due to the different path lengths. This potentially could cause some ambiguity in reading the Goldwave plots.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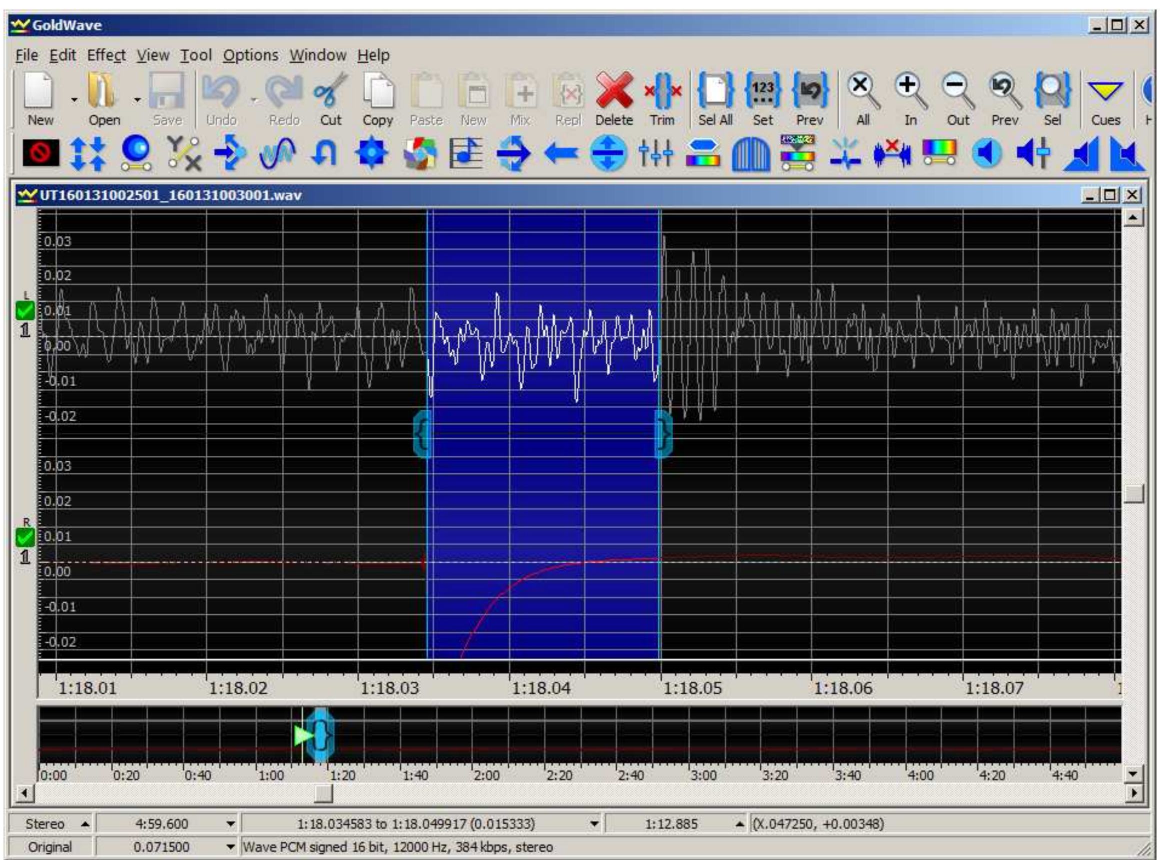
1:18.01
1:18.02
1:18.03
1:18.04
1:18.05
1:18.06
1:18.07
1:18.024917 to 1:18.065000 (0.040083)
1:12.885
(X.064999, +0.00113)
Wave PCM signed 16 bit, 12000 Hz, 384 kbps, stereo


GoldWave
UT160131002501_160131003001.wav
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1:18.02
1:18.03
1:18.04
1:18.05
1:18.06
1:18.07
1:18.034583 to 1:18.049917 (0.015333)
1:12.885
(X.047250, +0.00348)
Wave PCM signed 16 bit, 12000 Hz, 384 kbps, stereo

Figure 6 ~ Wide and narrow screenshots of the PPS and tock signals. Upper: The PPS leading edge and tock waveform are easily visible. The tock shown here consists of exactly 5 cycles. Lower: The cursors have been positioned at the PPS leading edge and tock tone leading edge.

10. Minute Tone Analysis

The WWVH minute tone is a 1000 Hz (WWV) or 1200 Hz (WWVH) sinewave lasting 800 ms. The tone is easy to hear but not always easy to see in the recording displays when the path signal-to-noise ratio is low. When the path is good and tones are clean, I could measure 15 to 18 ms delay between the PPS and the minute tone (same delays as measured with the second marker tocks); however, the start of the tone is often subjective because of its shape in the recording (figure 7). My measurements were based on the zero-crossing of the received sinewave. .

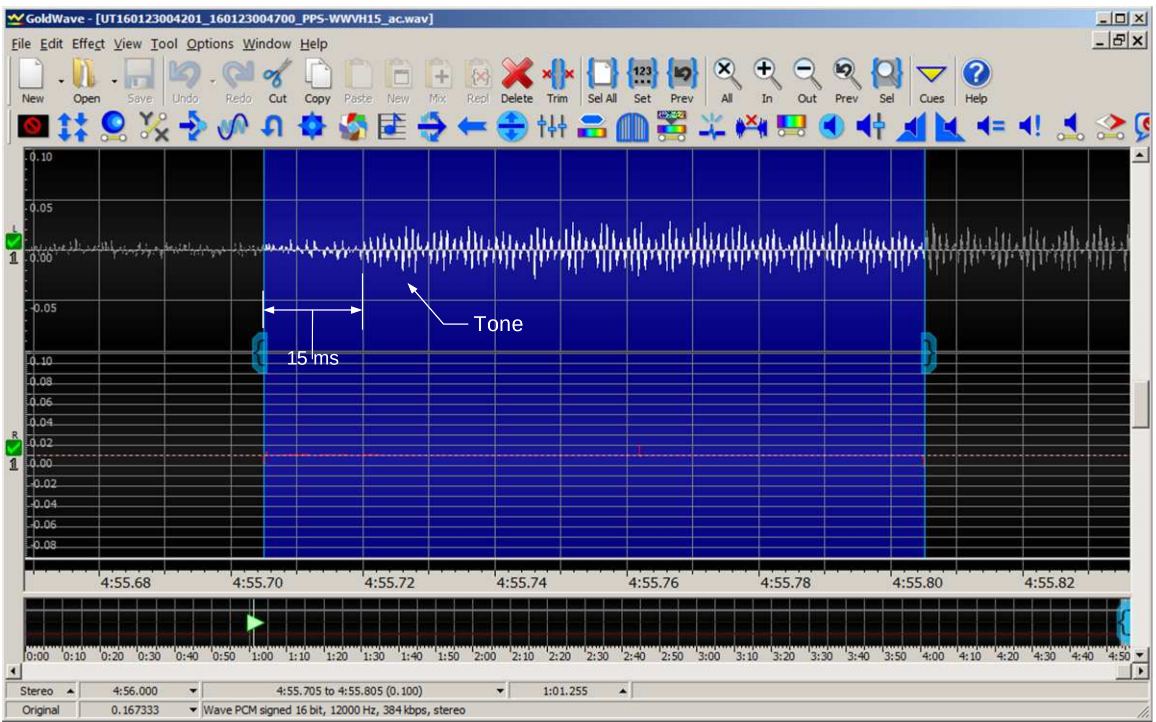
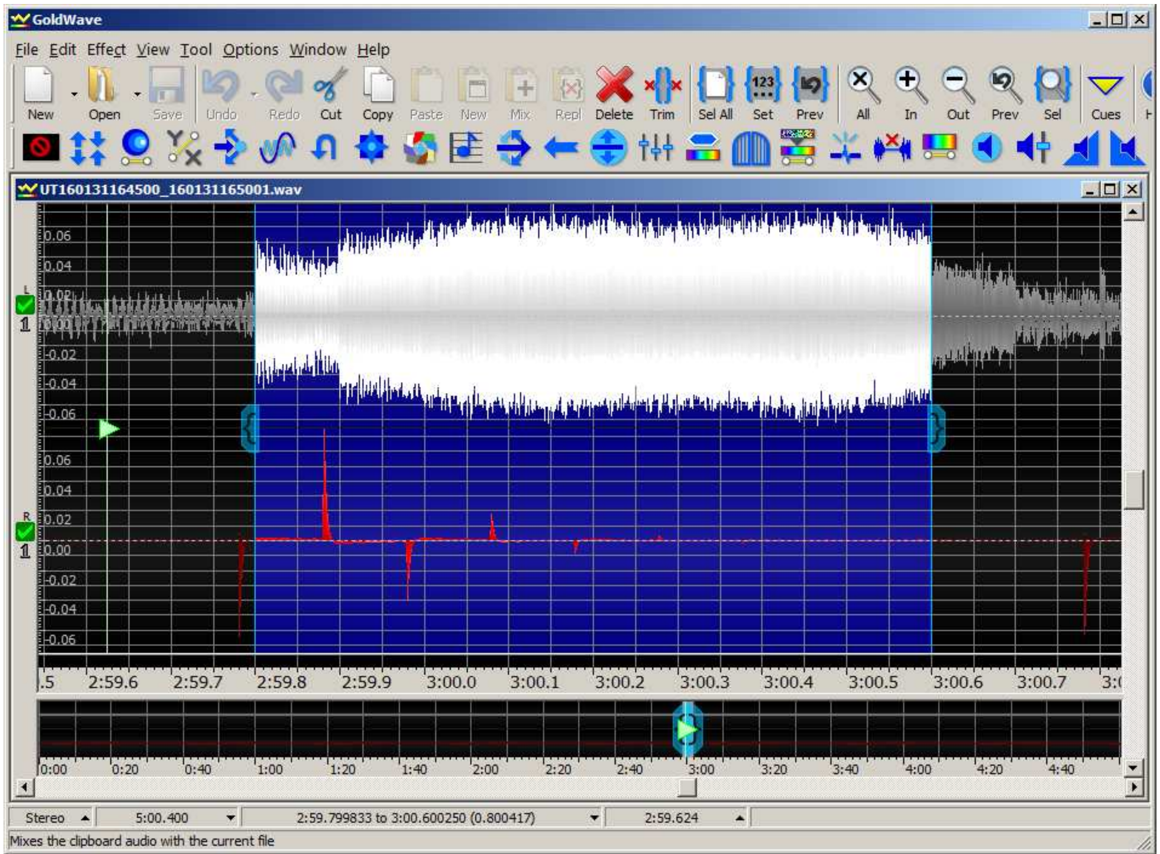


Figure 7 ~ Annotated minute tone display showing the PPS leading edge and beginning of the minute tone. As in other screenshots, the bottom trace (red) is the PPS (the edges are not visible because of the cursors) and upper trace (white) is the WWVH tone. The blue area shows the PPS leading and trailing edges (100 ms measured width).

A sequence of three images (figure 8) shows various views of a typical WWVH minute tone with respect to the PPS. For this sequence, the measured delay after the PPS was about 18.9 ms . Measurements of several individual tones showed a width in the range of 800.3 to 800.4 ms, 0.3 to 0.4 ms longer than the transmitted width of 800 ms.

The measured propagation delays within a particular recording were consistent within about 1 ms but some variations were noted across the different recording sessions. During a session on 31 January using WWV on 5 MHz, the measured delays were around 15.3 ms, compared to the predicted delay of 13.3 ms. Another set of wide and narrow views of a typical PPS-tone pair is shown for comparison, this one with 14.4 ms delay (figure 9).


GoldWave
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New Open Save Undo Redo Cut Copy Paste New Mix Repl Delete Trim Sel All Set Prev All In Out Prev Sel Cues
UT160131164500_160131165001.wav
2:59.6 2:59.7 2:59.8 2:59.9 3:00.0 3:00.1 3:00.2 3:00.3 3:00.4 3:00.5 3:00.6 3:00.7
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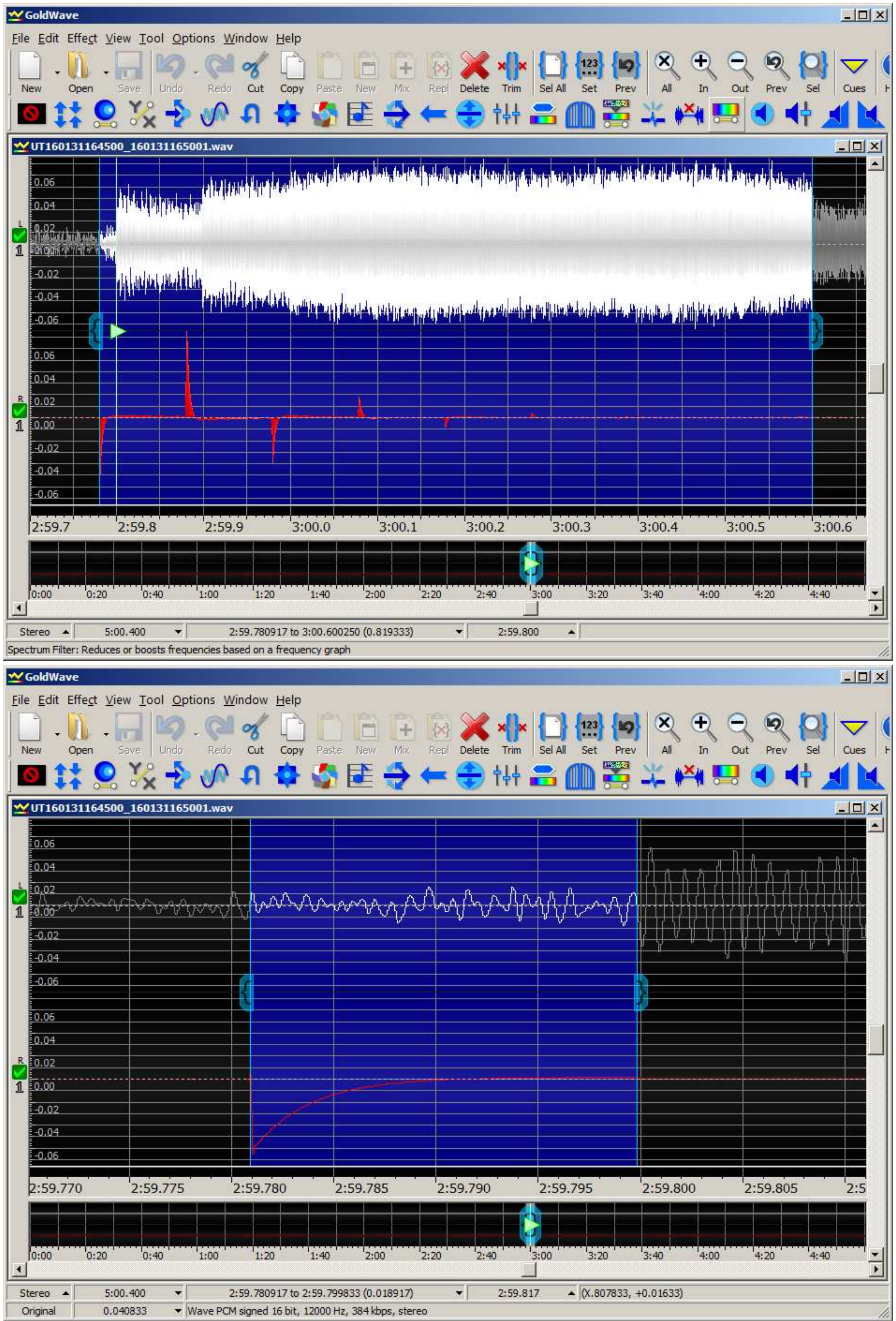
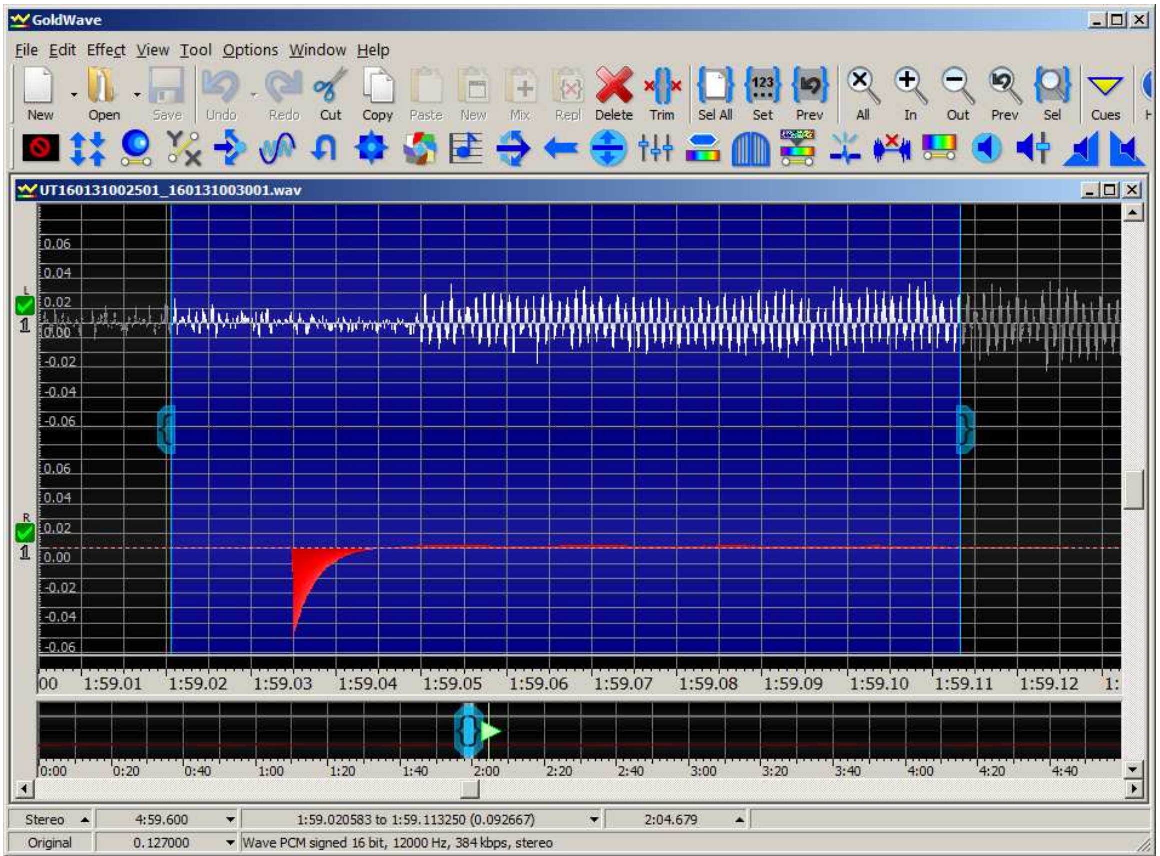


Figure 8 ~ Three displays of the minute tone measurements. For all measurements the display was zoomed in to accurately set the cursors.


GoldWave
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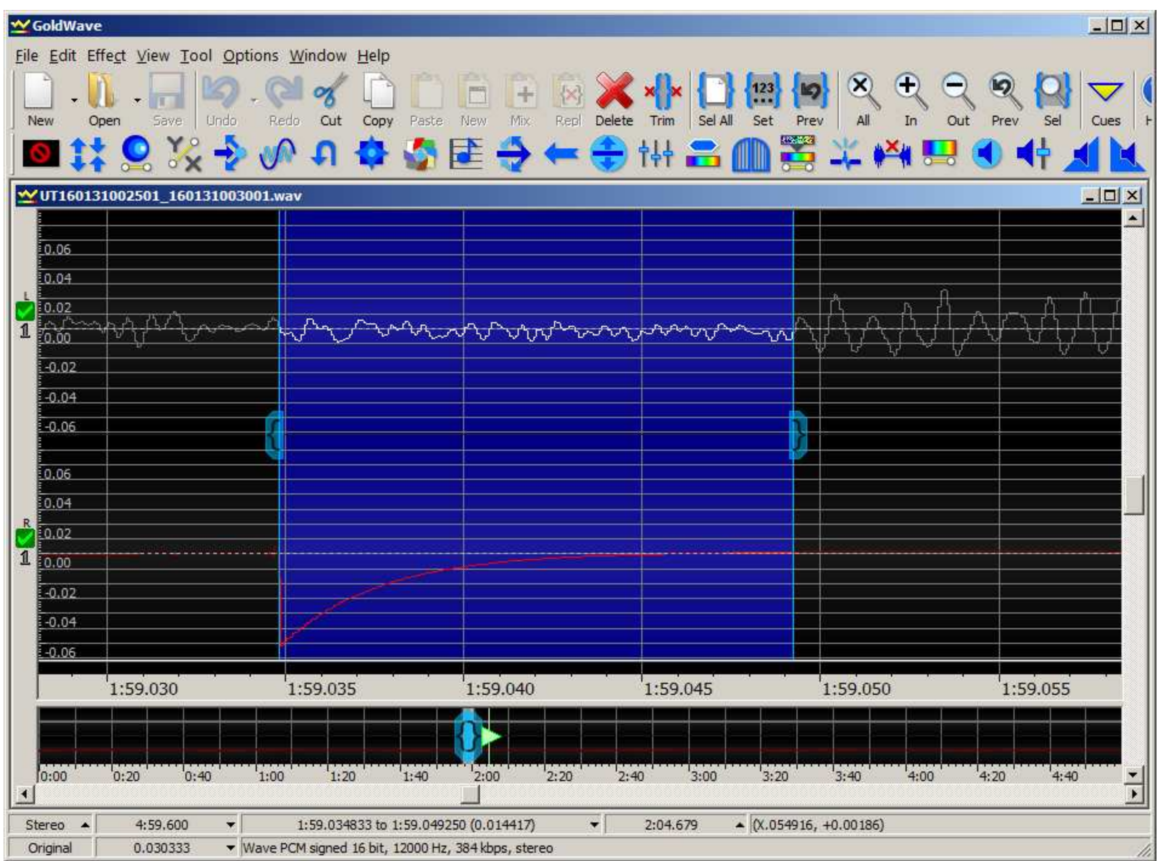
1:59.01 1:59.02 1:59.03 1:59.04 1:59.05 1:59.06 1:59.07 1:59.08 1:59.09 1:59.10 1:59.11 1:59.12
Stereo 4:59.600 1:59.020583 to 1:59.113250 (0.092667) 2:04.679
Original 0.127000 Wave PCM signed 16 bit, 12000 Hz, 384 kbps, stereo


GoldWave
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New Open Save Undo Redo Cut Copy Paste New Mix Repl Delete Trim Sel All Set Prev All In Out Prev Sel Cues
UT160131002501_160131003001.wav
1:59.030 1:59.035 1:59.040 1:59.045 1:59.050 1:59.055
Stereo 4:59.600 1:59.034833 to 1:59.049250 (0.014417) 2:04.679 (X.054916, +0.00186)
Original 0.030333 Wave PCM signed 16 bit, 12000 Hz, 384 kbps, stereo

Figure 9 ~ PPS and minute tone displays. Upper: The cursors have been moved aside so the PPS pulse and tone can be seen. Lower: The display has been zoomed in and cursors set to the PPS leading edge and beginning of minute tone. The delay indicated by the cursors is 14.4 ms.

11. Radio-SkyPipe Plots

The audio was viewed in real-time in the RSP strip-chart to verify recorded signal levels. The associated data were saved for later plotting (figure 10). The 0.1 Hz sampling rate used in the RSP data does not allow timing analysis with millisecond resolution; however, coarse alignment of the WWVH minute tone (near-vertical lines in the red trace) with the PPS pulse may be clearly seen in the plot.

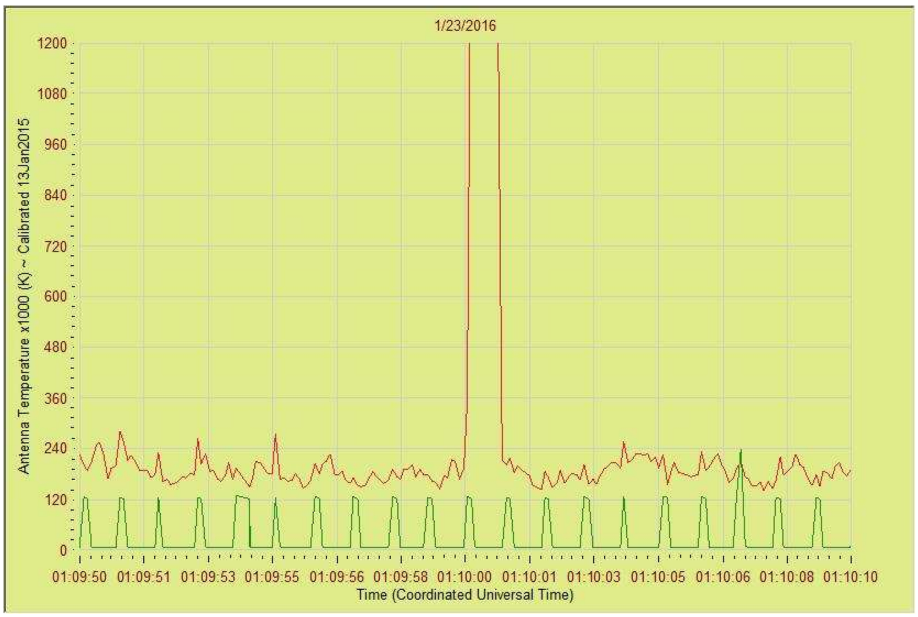


Figure 10 ~ Radio-SkyPipe plot of the soundcard input audio showing a minute tone received from WWVH (red trace) and the PPS (green trace). Visible in the red trace are the 1-second tocks. Plot duration is 20 s. Amplitudes were arbitrary and not calibrated (contrary to vertical scale label).

A 3 minute RSP plot shows three consecutive minute tones at 0116, 0117 and 0118 on 23 January along with the PPS pulses (figure 11). The receiver AGC was disabled during these measurements, and the received signal level is seen to vary as a consequence of multi-hop ionospheric radio propagation.

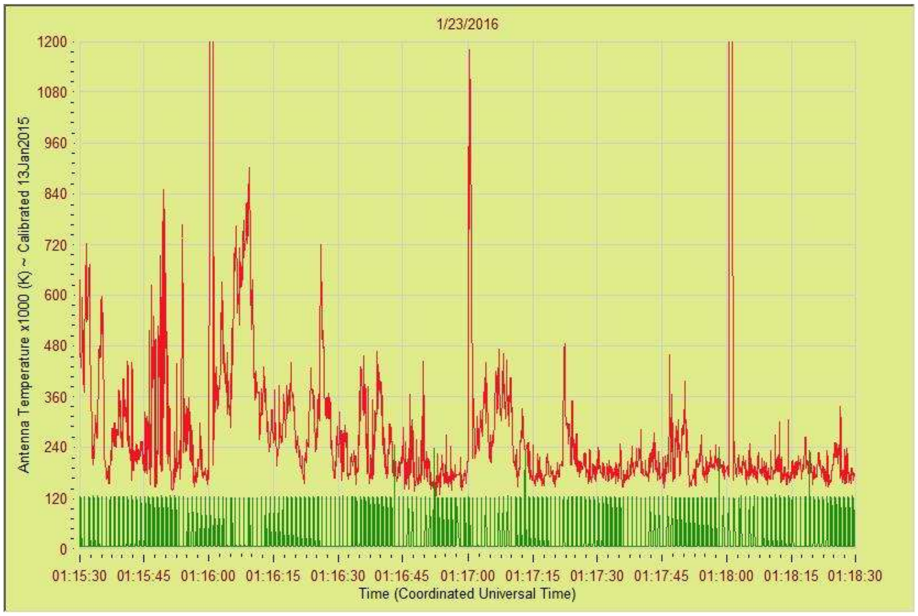


Figure 11 ~ Radio-SkyPipe plot of the soundcard input audio showing three minute tones from WWVH. Plot duration is 3 min. Amplitudes are arbitrary (not calibrated). Green trace: PPS output; Red trace: R75 receiver audio output. The R75 receiver output variations are due to varying propagation conditions.

12. Discussion

The measurements described above apply to signals that are visually and audibly easily recognizable, thus enabling measurements with microsecond resolution. At present it is unknown if this type of measurement can be applied to noise-like signals such as Jupiter s-bursts or solar radio bursts. Solar radio bursts usually have diffuse beginnings and endings, making their measurements very difficult. Jupiter s- bursts may be more amenable to measurements of this type but, in any case, such measurements will be subjective.

13. Conclusions

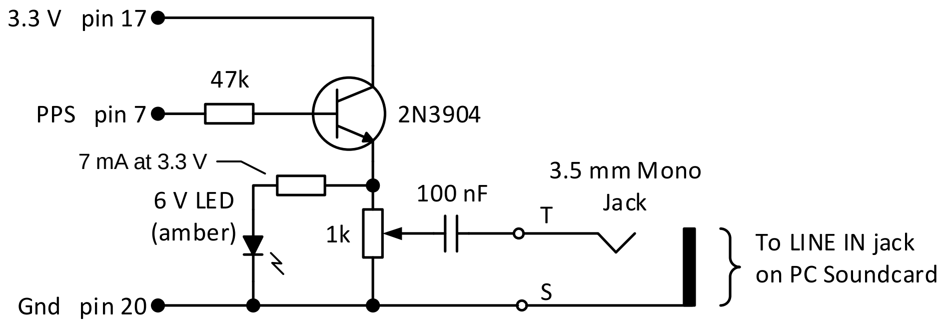
Measurement resolutions and accuracies of < 1 ms are attainable using wave recordings of WWV and WWVH signals when propagation is good.

14. References

{GpsNtp-PI} http://www.reeve.com/RadioScience/Raspberry%20Pi/GpsNtp-Pi.htm
{WWV} http://www.nist.gov/pml/div688/grp40/wwv.cfm
{WWVH} http://tf.nist.gov/stations/wwvh.htm

Appendix ~ Modifications to GpsNtp-Pi

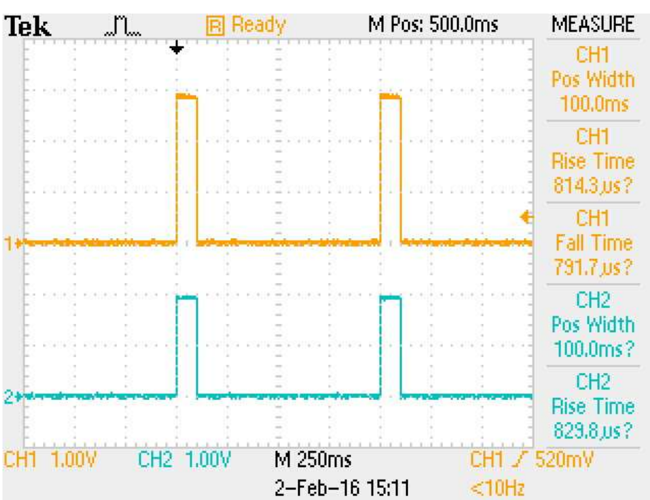
Schematic: The PPS output of the GNSS receiver in the GpsNtp-Pi network time server was buffered by an NPN emitter-follower. See schematic below. Power and PPS signal were taken from the GPIO connector on the GNSS receiver mezzanine board in the GpsNtp-Pi. The LED has a built-in current limiting resistor that provides 7 mA at 3.3 V. The total collector-emitter current is approximately 10 mA.

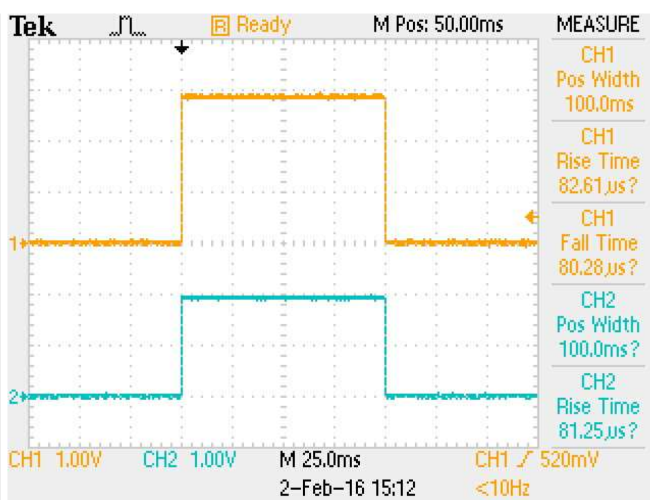


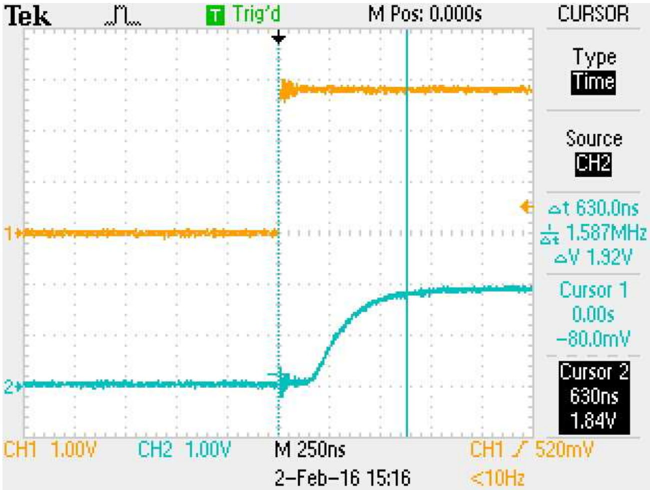
My initial modifications used flying leads and no shielding. I experimented with both dc and ac coupling of the signal to the soundcard and various PPS output voltages. After noting that the modification worked, I soldered the parts to the prototype area of the GNSS receiver mezzanine board and cleaned up the wiring.

While experimenting with different output voltage levels I noticed that the recorded PPS pulse intervals sometimes were lower than expected. For example, I noted occasional an pulse interval as low as 0.980 ms and high as 1.001 ms. I believe these variations were caused by overloading the soundcard input. Reducing the pulse level stabilized the measurements. Most measurements were made with 100 mV zero-peak input level.

Scope screenshots: Orange trace is the PPS input to buffer amplifier and cyan is the output across the emitter load potentiometer. Input-to-output delay is approximately 200 ns measured from the input pulse rising edge to the point where the output pulse starts to rise.



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Trig'd
M Pos: 0.000s
CURSOR
Type
Time
Source
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1.587MHz
△V 1.92V
Cursor 1
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Cursor 2
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CH1 520mV
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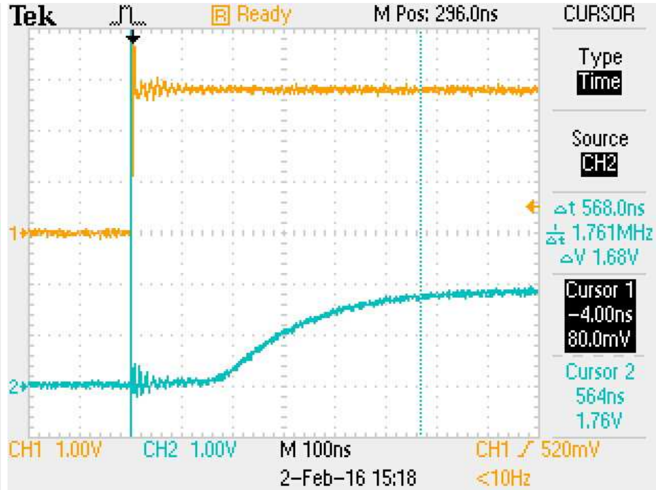
<10Hz

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Ready
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Type
Time
Source
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△V 1.68V
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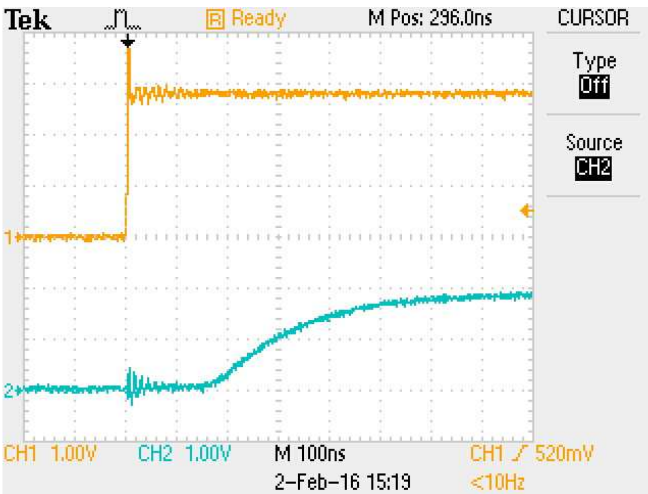
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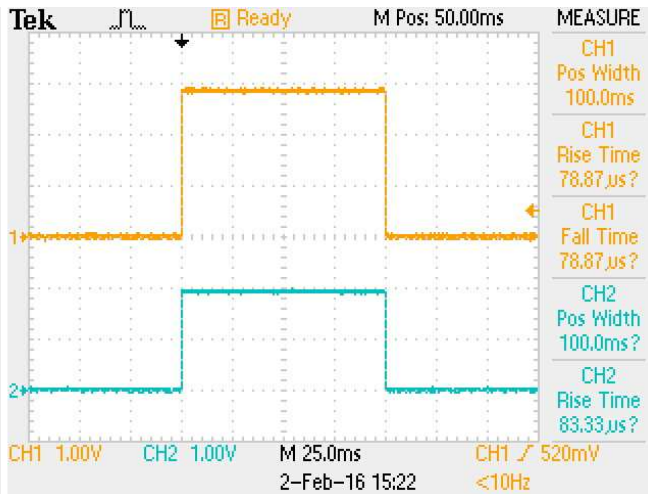
2−Feb−16 15:19
<10Hz

Tek
Ready
M Pos: 50.00ms
MEASURE
CH1
Pos Width
100.0ms
CH1
Rise Time
78.87µs?
CH1
Fall Time
78.87µs?
CH2
Pos Width
100.0ms?
CH2
Rise Time
83.33µs?
CH1 1.00V
CH2 1.00V
M 25.0ms
CH1 520mV
2−Feb−16 15:22
<10Hz

Document information

Author: Whitham D. Reeve

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