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Multi-Day WWVB Reception Phase Monitoring

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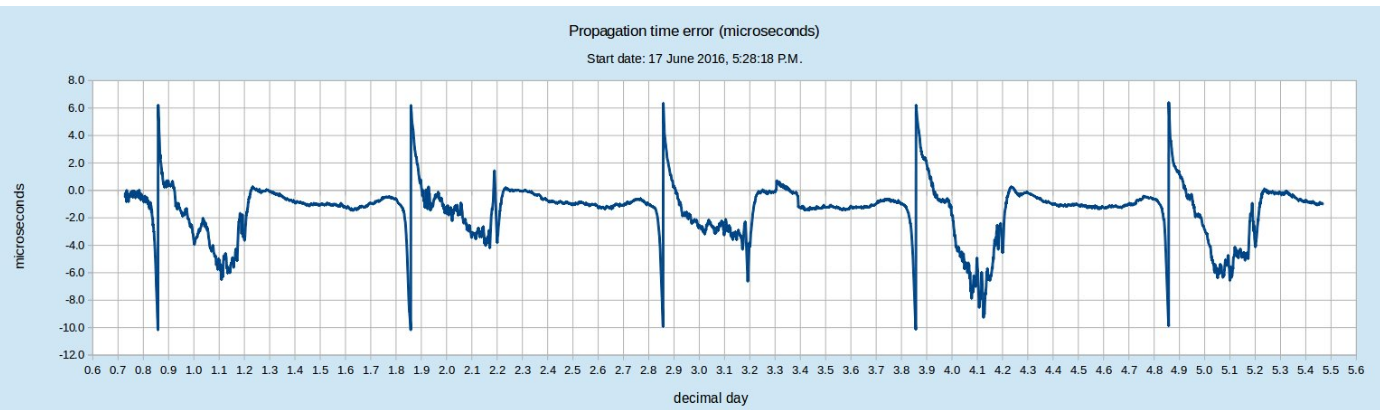
New (at W6BM) time-stamped logging hardware/software has allowed a rich data set to be gathered of the reception phase of WWVB at 60 kHz. By logging the time shift of the WWVB carrier over several days interesting artifacts become visible.

Equipment: Spectracom WWVB receiver (thanks John QX) operating as an RF front-end, feeding a homemade dephaser unit which removes the phase-shift modulation of the time code, which rendered obsolete older tracking receivers. The Fluke 207-5 VLF comparison receiver measures the phase of the WWVB carrier against a reference signal from a Thunderbolt GPS receiver and outputs an analog signal that is proportional to the time difference of the WWVB carrier to the GPS reference to an analog-to-digital converter based on the MCP3008 chip using the Raspberry Pi linux-based computer running a real-time stamped data logger.

The data log contains the time shift of the 60 kHz carrier, in microseconds, recorded over five days.



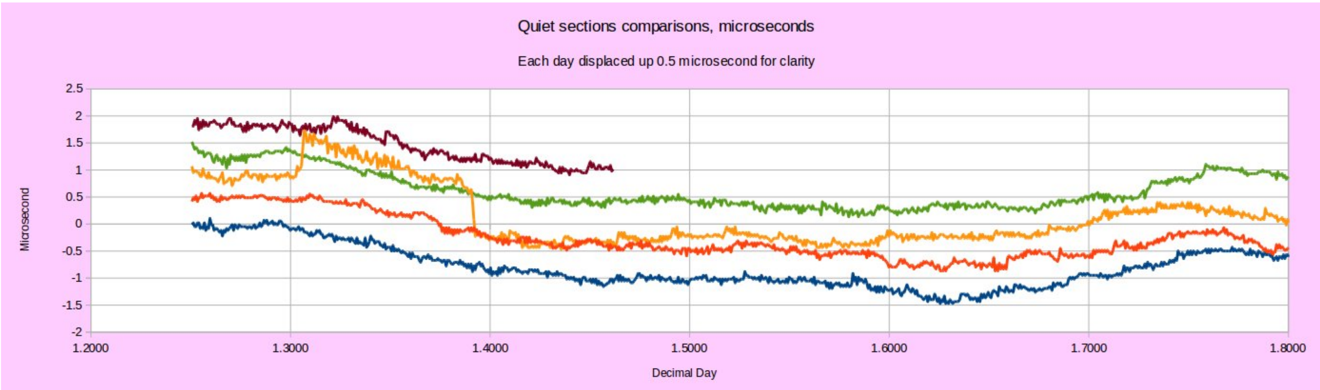
The abscissa is in units of days (N). The plot starts at day 0.7322 or 17 June 2016 05:28:18 P.M. (N = 0, 1, etc.) is midnight, (N+0.5) is noon. The ordinate is the time shift in microseconds of the WWVB carrier relative to the GPS reference. The ordinate of the plot is modulo 16.667 microseconds, so larger excursions are folded on the plot. (The plot looks almost like an electrocardiogram.)

At day (N+0.85) a phase slip of the received carrier by about 16 microseconds occurs, around 8:00 P.M. At around (N+0.19), about 6:00 A.M., the phase slip reverses. Between the two, the phase is erratic. Between (N+.25) to (N+0.8), 6 A.M to 8 P.M, the carrier phase is steady.

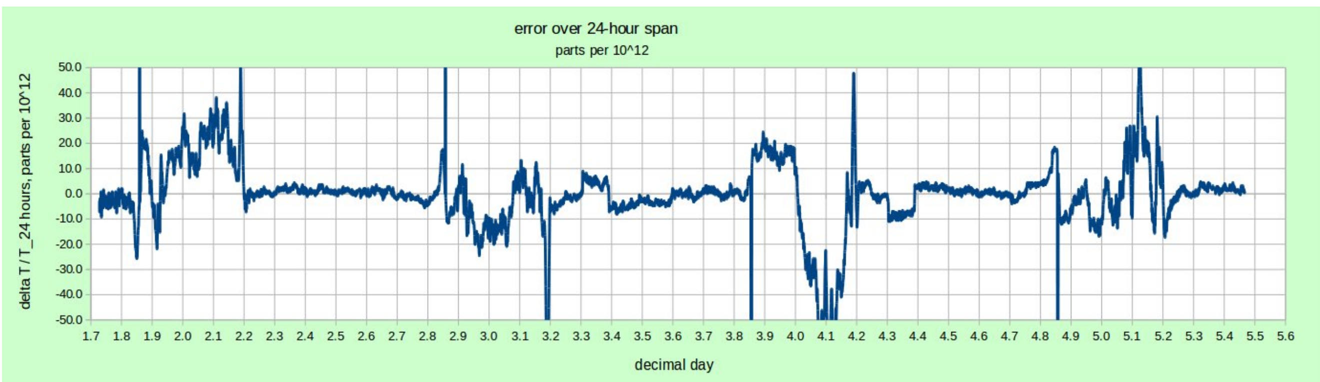
Although the time shift of the WWVB carrier is changing by several microseconds, starting at (N+0.25), the difference in time shift between two points separated by 24 hours is significantly less than one microsecond. It is this value that is valid when using WWVB to assess the drift of a local oscillator, so multiples of 24-hour data runs are necessary to achieve a high accuracy.

To establish a drift rate of a local source, or the time drift of WWVB signal itself, assuming a drift-free local source (GPS), the time difference between two points 24 hours apart is compared to the span between the two points, or 86,400 seconds.

The following plot shows a detail the time shift of the WWVB carrier phase from day (N+0.25) to (N+0.8), where the signal phase remains relatively steady over a 5-day period. (The time shift for each day is displaced upward by 0.5 microseconds for clarity. Day 3 (orange) clearly shows an anomaly).



The chart below shows the differential time difference between points 24 hours apart in units of one part in 10^{12} on the vertical axis. The plot starts at day 1.7322, one day after the start of the first plot. The differential error is the difference in absolute carrier time between two points 24 hours divided by 24 hours (86400 seconds). One microsecond carrier shift over 24 hours corresponds to a relative frequency offset error of 1.16 x 10^{-11} between WWVB and the local reference.



Between day 2.25 and 2.8, the differential time difference is less than 2 x 10^{-12}, with an rms spread of 1.3 x 10^{-12}.

Note that from day 3.31 to 3.39 there is a time shift anomaly of 0.8 microsecond, starting at 20 June 2016, 7:20:42 A.M. What is that? See below.

The relative error for day 4.25 to 4.8 shows the inverse error, as day 3 is used as a reference here, and day 5.25 to the end again shows very little shift relative to day 4 24 hours earlier.

Outside of the quiet signal conditions, the accuracy is much worse, as at this location, the signal is poor during the night hours.

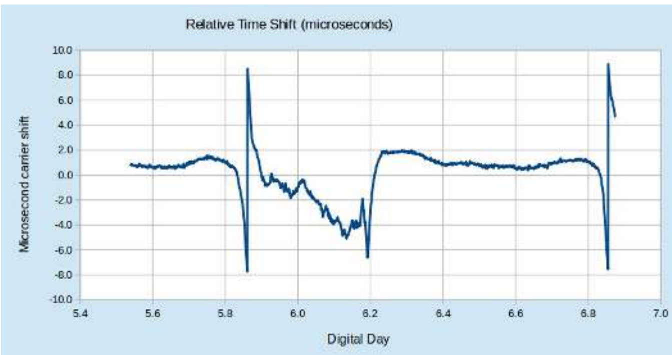
This indicates, that during quiet signal conditions that a comparison of the drift rate of a local oscillator, can be made with an accuracy of better than 1 part in 10^{11}, and possibly down to 2 parts in 10^{12}.

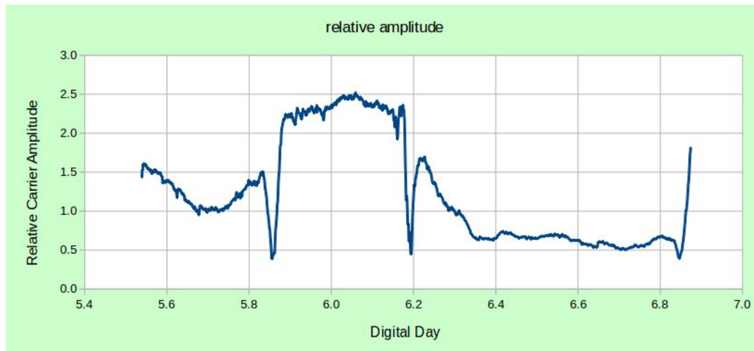
(*Warning! Wild speculation!*) The 0.8 microsecond offset from day 3.31 to 3.39 looks too constant or the wrong time scale to be caused by a meteor or CME, so is it from an event at WWVB itself? The station uses two top-loaded vertical antennas, 875 meters apart, each with its own transmitter, radiating a total of 50 kW ERP. The two antennas are sited on a bearing line of 145 degrees. The effective center of the signal phase is located midway between the two antennas.

If the south (farther) transmitter ceases transmission for a trip condition or for maintenance, the phase center of the origin of the signal moves 251 meters closer to Berkeley, as it is now radiating from the north (nearer) antenna. The motion of the effective transmitting location 251 meters closer to Berkeley would result in a time shift of 0.84 microseconds, close to the observed value of 0.8 microsecond. Is this what happened? Operation logs of WWVB are not available.

Amplitude measurement

On day 5.5 additional equipment was added to measure the signal strength of the WWVB carrier. The signal from a tuned loop antenna was amplified by tandem preamps and fed into the dual-conversion Collins-Tellestra tuned voltmeter. The 15 kHz IF signal was additionally amplified, rectified, filtered and fed into another analog input of the MCP3008 ADC.





The time variation of the carrier phase from day 5.5 is shown on the left, and the relative amplitude on the right. Since the WWVB signal is amplitude modulated with a 17 dB modulation depth, to measure the average carrier level, the signal strength was sampled 20 times a second, and then integrated over 60 seconds for each data point.

Note the carrier phase slip on day 5.85 and 6.19, and again at 6.85, as seen previously. The amplitude shows a pronounced dip at the same places, and, paradoxically, the strength is maximum during the night where the phase of the signal shows strong random variation. *The smooth and reproducible carrier phase occurs during the daylight period when the signal strength is weakest.*

The conditions were good over both day 5 and 6, and the time shift between the smooth parts of day 5 and 6 was -5.0×10^{-13}, with an rms deviation of 1.5×10^{-12}, showing good reproducibility.

The time variation and amplitude variation were measured through completely separate channels. The time variation used a whip antenna, the Spectracom, the dephaser and the Fluke comparator. The amplitude channel used a tuned loop, the Collins-Tellestra tuned voltmeter and signal detector. The signals came together only at two of the inputs of the ADC.

Lessons learned

The 60 kHz WWVB carrier can be used to calibrate the frequency offset of a local source under certain conditions. In the past at W6BM, single-points 24 hours apart of data from the Fluke 207-5 VLF comparator receiver were used to assess the frequency of local sources, including an HP 5061 cesium-beam primary frequency standard. It seems clear now that multiple points, 24 hours apart need be used, with data taken over several days to guard against anomalies in the received signal, which should appear when enough data is collected. Here, of course, the local signal is a GPS-disciplined 10 MHz crystal oscillator, whose time shift is measured in 10s of nanoseconds, so this test is then a measurement of the quality of signal from WWVB.

The equipment worked flawlessly over a period of six days, including the dephaser unit which removes the phase shift data information from the WWVB signal so that the Fluke 207-5 can lock onto the 60 kHz carrier. The data logger uses a driver written in C to control the MCP3008 ADC chip, which integrates with the Raspberry Pi 3 computer running Ubuntu-Mate 15.10 Linux without any additional hardware. The MCP3008 ADC chip provides 8 analog inputs to a 10-bit converter for $2.32.

Although WWVB provides a good frequency reference, long integration times and stable signals are required. Cheap GPS-disciplined oscillators provide a reliable frequency reference and additionally absolute time markers good to 10s of nanoseconds.