Echo Mode in *WSJT-X 2.6.0*

Bob Atkins, KA1GT, Charlie Suckling, DL3WDG, and Joe Taylor, K1JT

Most amateur Earth-Moon-Earth (EME) enthusiasts use echo testing as a tool for optimizing station performance. For the past twenty years the software package *WSJT-X* and its predecessor, *WSJT*, have included a basic Echo mode to facilitate such tests. This capability was developed and tested mainly on the VHF and lower UHF bands; it yielded uncalibrated estimates of relative signal-to-noise ratio (SNR) based on the peak value of the computed spectrum of echo signals recovered in a single polarization. For reliable evaluation of station performance these estimates were compromised by lack of any facility to match the actual linear polarization angle of return signals, and by making no quantitative allowance for Doppler spread. For these reasons, reported values of SNR could provide only rough limits on station performance.

Doppler shifts of EME signals are caused by changes in the total line-of-sight distance between a transmitting antenna, reflecting or scattering areas on the lunar surface, and a receiving antenna. The relevant rate of change is usually dominated by Earth rotation, which at the equator amounts to about 460 m/s. As a consequence, two-way Doppler shifts can be as large as ± 440 Hz at 144 MHz, ± 4 kHz at 1296 MHz, and ± 70 kHz at 24 GHz. Different reflection points on the lunar surface produce slightly different Doppler shifts, so the echo of a single-tone signal is spread out over a small and predictable frequency range. The full range of spread can be as large as 4 Hz at 144 MHz and 700 Hz at 24 GHz. Especially at lower frequencies, a majority of reflected power is returned from a region near the center of the lunar disk. Thus, the observed half-power Doppler spread is always considerably less than the full edge-to-edge range across the lunar disk. Further details on the characteristics of EME signals can be found in references [1] and [2].

Reference [2] describes a software program *EMEcho*, which was written explicitly to do lunar echo measurements with dual-polarization antennas and receiving equipment at K1JT (144 MHz) and W2PU (432 MHz, see [3]). As done in program *MAP65* for signals in the Q65 and JT65 modes, *EMEcho* automatically measures and matches the polarization angle of each received echo, thereby eliminating any signal loss from misaligned polarization. *EMEcho* includes a state-of-the-art planetary ephemeris and the associated software necessary for high-accuracy predictions of Doppler shift and frequency spread, so these quantities can be known in advance, at the time of any echo testing. *WSJT-X* provides only a single receiving channel, so it can't do adaptive polarization, but other features of the non-public *EMEcho* are now fully supported in *WSJT-X 2.6.0* [4]. In addition, the new Echo mode enables reliable, calibrated measurements of SNR even in circumstances with large Doppler spread, and thus especially on the higher microwave bands. Such measurements are possible not only for self-echoes but also for reception of a constant, unmodulated, key-down signal transmitted by another station, even if its strength is many dB below that required for normal communication. New Echo-mode features also facilitate measurements of Sun, Moon, and ground noise, all of which can be helpful aids for optimizing station performance.

Basic Operation

In normal use, Echo mode repeatedly cycles through the following steps every 6 seconds:

1. Transmit a fixed-frequency 1500 Hz tone for 2.3 s
2. Offset receiver frequency by the computed EME Doppler shift
3. Wait approximately 0.2 s for start time of received echo
4. Record the received signal for 2.3 s
5. Compute spectrum of received signal, accumulate average, and display results
6. Reset dial frequency to transmit value
7. Repeat from Step 1

WSJT-X includes rig control for nearly all modern SSB transceivers and can automatically adjust frequency settings (Steps 2 and 6) to compensate for changing Doppler shifts. Because some computer-controllable (CAT) radios allow frequency setting only to integer multiples of 10, 20, or 100 Hz, *WSJT-X* determines the frequency step size for a connected radio automatically. In Echo mode the program compensates for any remaining portion of Doppler shift by shifting the audio-frequency spectrum as part of step 5, before averaging takes place. If the Doppler shift is less than 750 Hz, as will always be true on 144 MHz and lower frequency bands, you can dispense with CAT control entirely and use only audio-frequency shifts for Doppler tracking.

Many of the new features are found in Step 5, the data analysis stage. In each cycle the program computes the total received noise power and its spectral distribution over the range 0 – 3000 Hz. Doppler tracking ensures that return echoes should always be centered at 1500 Hz, and the spectral peak should have width consistent with the precomputed Doppler spread. As an example, Figure 1 illustrates a short 1296 MHz echo-testing session conducted at KA1GT, reconstructed here by opening and processing ten saved *.wav files. Bob's station includes a 3 m prime-focus dish and transmitted power 240 W at the feed. The center-of-disk Doppler shift at the time of these tests was 2219 Hz, and the full-width Doppler spread 18 Hz. Horizontal lines in the waterfall display (top of Figure 1) separate the repeated 6 s cycles. Echo signals are clearly visible in each cycle, and as expected after Doppler correction they are centered at 1500 Hz. The strongest part of each echo appears to be about 5 Hz wide, but the waterfall also shows weak spectral wings out to the expected full width.

At the end of each echo cycle a line of data in the main text window displays the following information:

UTC	Time in `hhmmss` format
Hour	UTC in hours and decimal fraction
Level	Relative received noise power (dB)
Doppler	EME Doppler shift at center of lunar disk
Width	EME Doppler spread over full lunar disk
N	Number of accumulated echo or monitor cycles
Q	Estimated quality of averaged data on a 0 – 10 scale
DF	Offset of spectral peak from 1500 Hz
SNR	Average signal-to-noise ratio (dB/2500 Hz)
dBerr	Estimated uncertainty of SNR

SNR is measured on the same scale used in *WSJT-X* for signal reports, expressing the ratio of signal power to noise power in a 2500 Hz reference bandwidth. Signal power is integrated over the full-width Doppler spread. In the example shown in Figure 1, SNR was well determined at -10 dB almost from the start. With weaker signals you can improve accuracy by averaging over many echo cycles. The spinner control next to the **Clear Avg** button sets the maximum number of cycles to be included in the displayed average.

A window titled "Echo Graph" displays the average spectrum of received echoes, centered on the expected return frequency. Figure 2 shows examples of echo spectra obtained on three different bands: 144 MHz at station K8DIO, 1296 MHz at KA1GT, and 10 GHz at DL3WDG. The spectral peak in such plots should always appear close to 0 Hz, since full Doppler compensation is done by the software. If SNR is adequate, spectral width at the base of the peak will be close to the predicted values for Doppler spread or "width." For the three spectra shown in Figure 2 the predicted widths were 3.4, 18, and 228 Hz.

Echo-Mode Setup and Operational Details

Most program settings for echo testing can be the same as those you normally use for digital-mode EME. Optimum choices for a few parameters will depend on operating frequency, capabilities of your radio, and whether you use CAT control of its frequency settings. With most modern transceivers, and especially on 432 MHz and higher bands, CAT control is highly desirable because the software can then handle all details of changing EME Doppler shifts. To enable this capability go to **File | Settings | Radio** and set **Split Operation** to either **Rig** or **Fake It**.

As shown in Figure 3, the **Astronomical Data** window offers a number of Doppler tracking methods. For echo testing you should choose one of the following possibilities:

1. Use CAT control and set **Doppler tracking** to **Own Echo**. While receiving, the radio's dial frequency will be offset so that received echoes are centered at 1500 Hz. As noted above, any residual Doppler shift arising from frequency step sizes greater than 1 Hz will be compensated by shifting the audio spectrum.
2. If Doppler shift is less than 750 Hz you may set **Doppler tracking** to **None** and not use any CAT control for frequency settings. In this case, all necessary Doppler tracking will be done by shifting the audio spectra.
3. If you do not use CAT control but your radio has a calibrated Receiver Incremental Tuning (RIT) control, you may set **Doppler tracking** to **None** and compensate for most of the computed Doppler shift by manually setting RIT close to the current shift. Enter this setting in the **RIT** control on the **Astronomical Data** window. Any remaining portion of total Doppler shift will again be done by the software at audio frequencies.

With *WSJT-X* configured in one of these ways, a sequence of echo cycles can be started by toggling **Enable Tx** on the main window.

Measuring SNR of Another Station's Signal

The tools used to measure self-echoes can also be used to measure the strength of another station's weak signal, whether on the EME path or not. Arrange with the other station to transmit an unmodulated carrier and tune your SSB receiver to place the signal close to 1500 Hz. For signals too weak to see on the waterfall, this might require accurate frequency calibration at both stations. *WSJT-X* provides a FreqCal mode and procedure for calibrating a transceiver; you might also need to calibrate any transverter offsets. The transmitting station should set **Doppler tracking** to **None**, or leave the **Doppler tracking** box unchecked. You can transmit a fixed-frequency 1500 Hz tone by activating the **Tune** button on the main window when set to Echo mode.

On the EME path, Doppler correction should be done at the receiving end. As receiving operator you should ensure that **File | Settings | General | My Grid** is entered with full 6-character accuracy and that the transmitting station's 6-character locator is entered as **DX Grid**. Set the **Doppler tracking** method to **On DX Echo**. Toggling **Monitor** to its active state will then initiate a series of measurements analogous to the receiving and analysis portions (Steps 4 and 5) of the Echo-mode cycle. Figure 4 shows the Echo Graph and small portions of the waterfall and main window for one such series of measurements in which DL3WDG monitored a low-power transmission from a recently implemented 1296 MHz EME setup at club station W2ZQ. The reported average SNR for these measurements is -23 dB, the same as the signal report these two stations exchanged in a Q65-60C EME QSO a few minutes later. The small observed offset (DF = 4 Hz) of the peak frequency is consistent with plausible dial calibration errors.

Quantifying EME System Performance

Toggling **Monitor** on the main window initiates a series of measurements of total received noise power. Results are displayed as **Level** (in dB) in the main text window, and also sent to a file all_echo.txt in the program's log directory. The effective integration time for these measurements is 2.3 s, the duration of Step 4 of the echo cycle, and new results are displayed every 3 s. Be sure to turn the receiver AGC off for such measurements, and select **Total Power (dB)** in the drop-down control at bottom center of the Wide Graph window. While monitoring, this produces a slowly scrolling graphical representation of the measured noise levels. Figure 5 shows an example of this graphical feature during a sequence of on-off measurements peaking up on the Sun, to test antenna pointing at W2ZQ. Similar approaches can be used to measure "ground noise" by comparing the noise level pointed at cold sky to that pointed near the horizon. On the higher microwave bands you can measure moon noise, as well. These types of broadband noise measurements can be extremely helpful in evaluating your station's receiving performance.

Full two-way EME performance can be evaluated from SNR measurements of your self-echoes. By providing a link budget calculator such as *EMECalc* [5] with your antenna type and size, LNA noise figure, transmitter power, feedline losses, and other relevant details, you can estimate the amount of Sun noise you should see and the expected SNR of your echoes from the Moon. As one example, the 1296 MHz setup at W2ZQ has a 3 m dish, 200 W at the septum feed, and estimated system noise temperature 85 K. *EMECalc* predicts that such a system should measure

Sun noise of about 12.0 dB and self-echo SNRs ranging from -14.6 dB with the Moon at apogee to -12.3 dB at perigee. We are currently measuring values close to these ideals.

Conclusion

WSJT-X 2.6.0 provides a number of new tools that facilitate quantitative measurements of weak signals and accurate evaluation of an EME station's performance. In this paper we have described on how they work and provided a few relevant examples. Further details on how to use the features are provided in the *WSJT-X User's Guide* and the *Quick-Start Guide to Echo Mode*, both of which are available directly from the program's **Help** menu.

We thank Lloyd Korb, K8DIO, for sharing his 144 MHz echo measurements.

References:

1. Joe Taylor, K1JT, "Frequency Dependent Characteristics of the EME Path," Proceedings of 14th International EME Conference, Dallas, August 2010; https://physics.princeton.edu//pulsar/K1JT/EME2010_K1JT.pdf.

2. Joseph H. Taylor, K1JT, "High-Accuracy Prediction and Measurement of Lunar Echoes," *QEX*, November-December 2016, pp. 36-40; https://physics.princeton.edu/pulsar/K1JT/LunarEchoes_QEX.pdf.

3. Joe Taylor, K1JT, and Justin Johnson, G0KSC, "EME with Adaptive Polarization at 432 MHz," *Dubus*, 4/2014, pp. 53-61; https://physics.princeton.edu//pulsar/K1JT/EME_xpol_432.pdf.

4. *WSJT-X 2.6.0* is available for free download from the WSJT Home Page, https://physics.princeton.edu//pulsar/k1jt/.

5. Doug McArthur, VK3UM, *EMECalc 11.11*, downloadable from https://www.vk5dj.com/doug.html.

Figures:

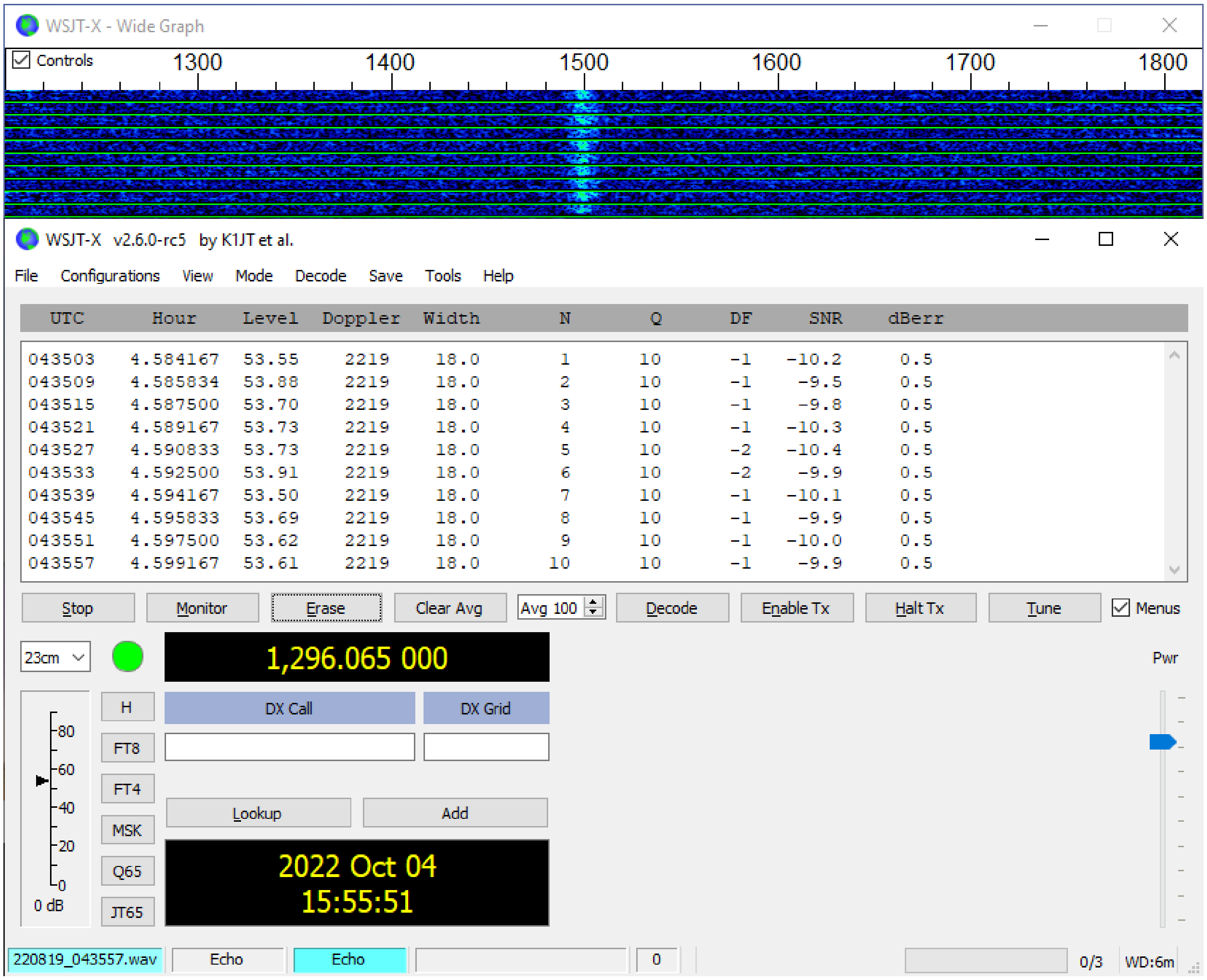

Figure 1. – Main screen and Wide Graph display for a sequence of ten lunar echoes at 1296 MHz, obtained at station KA1GT.

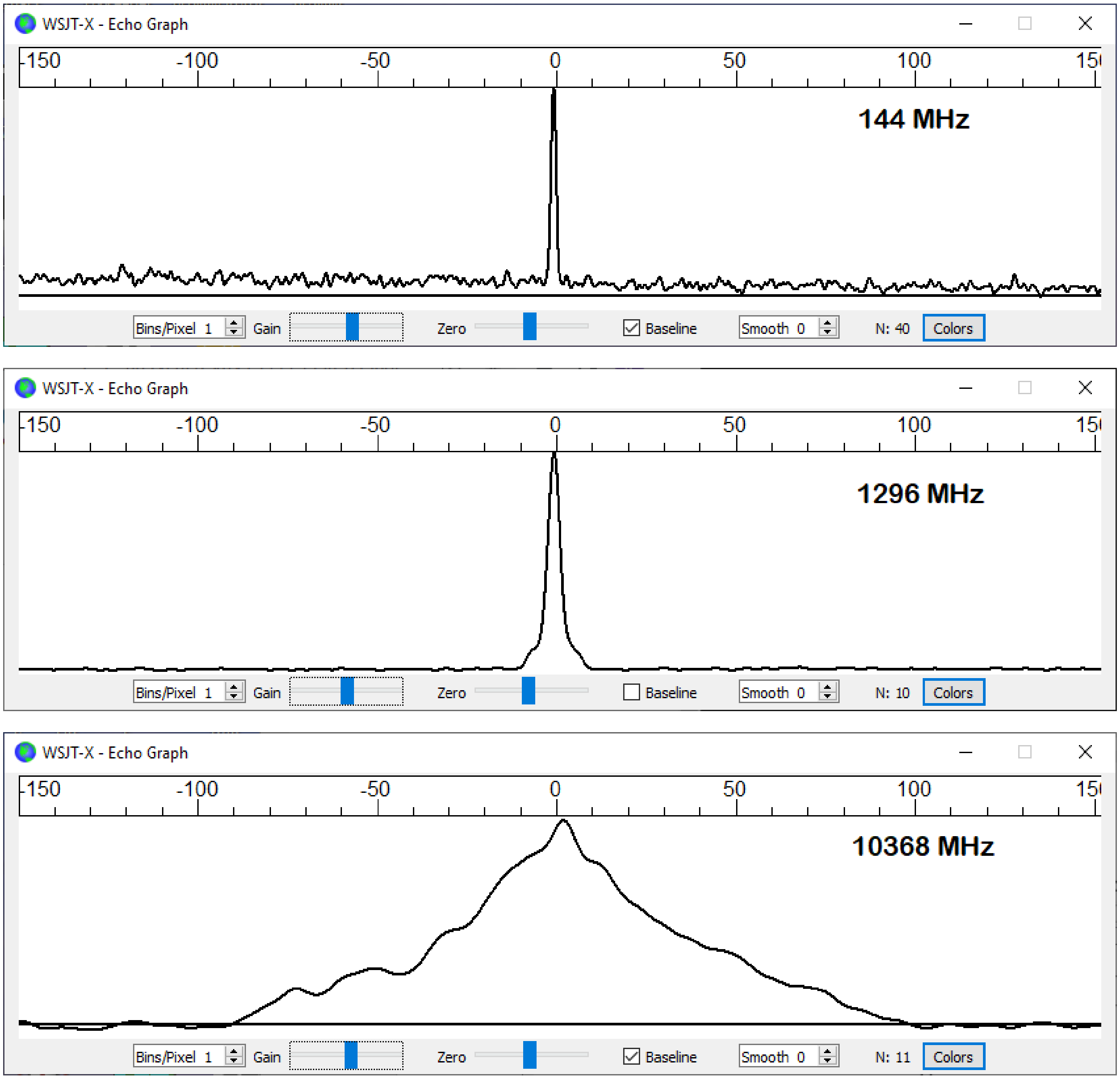

Figure 2. – Average spectra of lunar echoes at 144, 1296, and 10368 MHz observed respectively by K8DIO, KA1GT, and DL3WDG. The 1296 MHz plot is for the same ten echoes as shown in Figure 1. Reported SNRs for these measurements were -24.5, -9.9, and -9.6 dB.

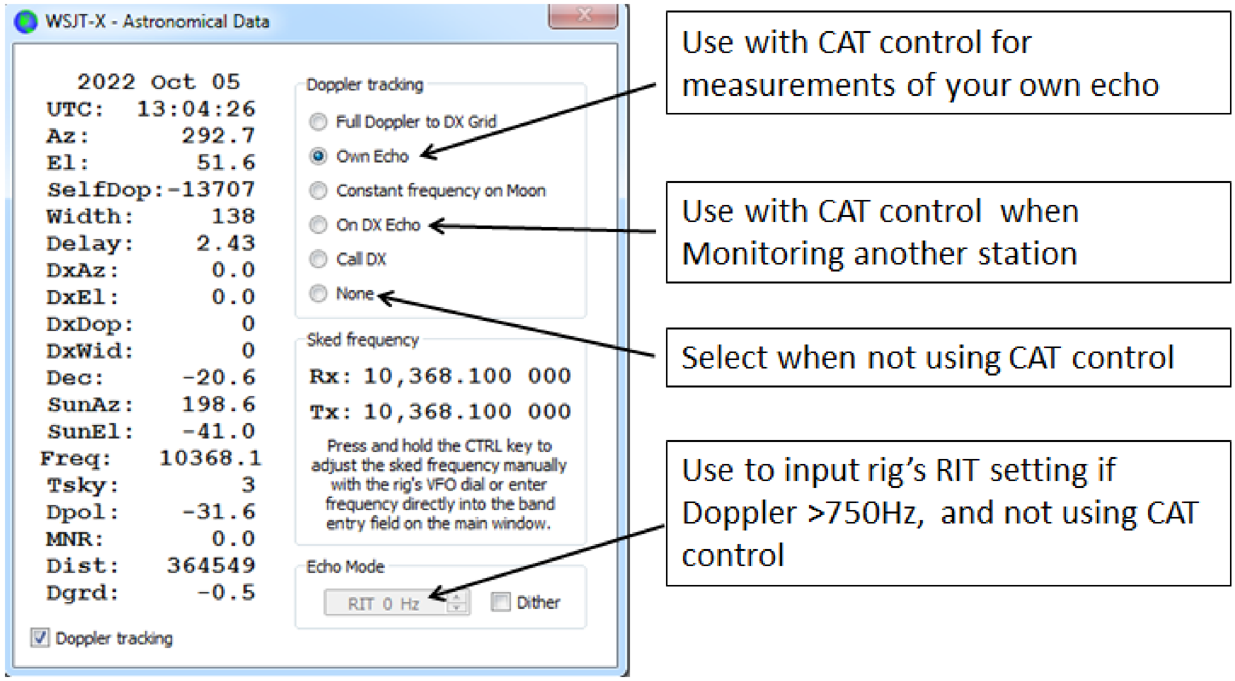

Figure 3. – The **Astronomical Data** window offers five different methods of Doppler tracking.

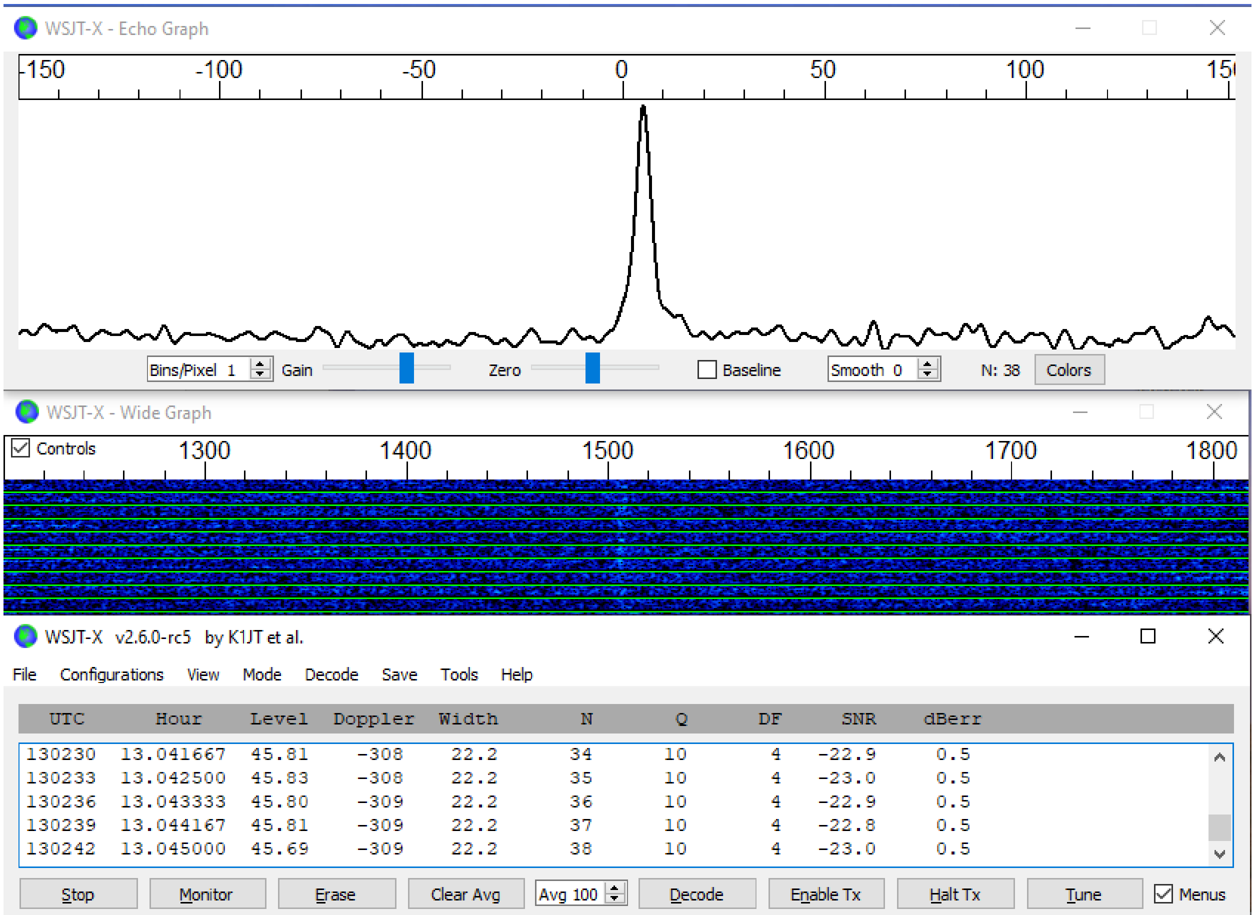

Figure 4. – Results of monitoring a low-power 1296 MHz unmodulated carrier transmitted by W2ZQ and received at DL3WDG.

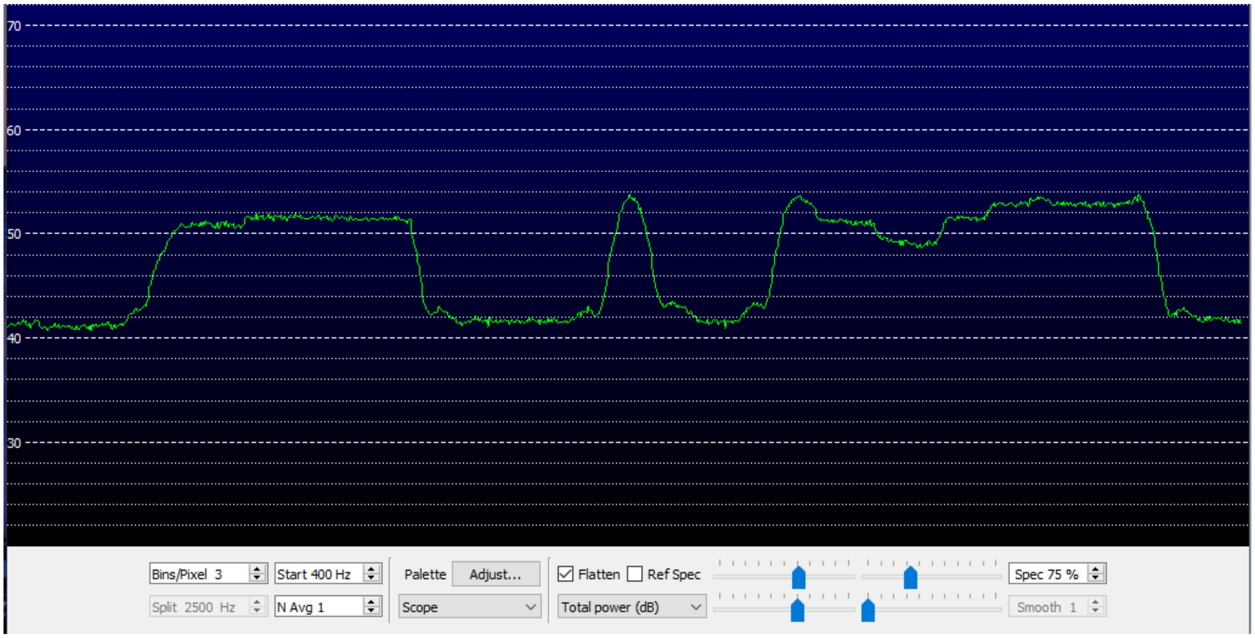

Figure 5. – Lower portion of the Wide Graph display during a series of pointing adjustments, peaking up on the Sun at W2ZQ. At this time we were observing about 11.5 dB of Sun noise.