A Modest Study of WSPR-2 Spectral Width

Barry Johnson, W4WB
Huntsville, Alabama, USA
and
Gene Marcus, W3PM
Madison, Alabama, USA

24 July 2024
(Revised 06 January 2025)

Table of Contents

Key Findings

- The spectral width of 40m, using a GPSDO transmitter and receiver, was not impacted over a 27 km path with obscuration compared to the direct 10.3 km clear line-of-sight path; both were 11.2 mHz.
- The spectral width for 40m using a directly connected GPSDO transmitter and receiver through a shielded precision attenuator system was also determined to be 11 mHz and can be considered as the baseline spectral width for 40m.
- The reference source stability is clearly important – TCXO vs. GPSDO – in establishing spectral width.
- The average spectral width for a 10 MHz GPSDO reference source is about 3.5 times better than for a 26 MHz GPSDO reference source and a 4 MHz GPSDO reference source is over 5 times better!
- The average spectral width for typical frequency hopping is about 30% greater than when the transmit frequency for each band is fixed.
- SNR appears to be essentially uncorrelated to the spectral width.
- Tests comparing the receiver and the transmitter using TCXO's and GPSDO's revealed that the average spectral width for a TCXO receiver is about 50% greater than for a GPSDO receiver when the GPSDO transmitter is used. This takes into account TCXO accuracy and stability specifications for both transmitter and receiver systems.
- The microprocessor word length did not impact the values computed to input to the Si5351. Specifically, the input parameters for the Si5351 were identical when computed using either a 16-bit ATmega328P MCU or a 32-bit ESP8266.

Overview

The question posed by Gwyn G3ZIL was, "What is the minimum obtainable spectral width of WSPR-2 signals?" To answer this seemingly simple question was anything but simple as will become evident in the several reports comprising this document.

A simple answer could be thought to be to transmit a WSPR-2 signal to a nearby receiving station with both transmitter and receiver each having a GPSDO reference source. We first made measurements between the QTHs of W4WB and W3PM which have a line-of-sight (LOS) distance of about 27 km with two small mountains blocking an unobscured view. The results were encouraging, but the impact of the mountains obscuring the path was unknown. We next decided to find an unobscured line-of-sight (LOS) receiver location. It was determined that a clear 10.3 km LOS existed from the W4WB QTH to the National Space Science & Technology Center building located on the campus of the University of Alabama in Huntsville (UAH). A RX888 MKII GPSDO receiver was located at UAH, and two transmitters were located at the W4WB QTH. One transmitter was a ZachTek Desktop Transmitter with an Abracon ASTX-H11 TCXO oscillator on 25 MHz TCXO (2.5 ppm) reference source, and the other transmitter was a new version of the ZachTek Transmitter, WSPR-TX XP Plus with a 25 MHz TCXO (2.5 ppm) reference source and that also allows the use of an external 10 MHz GPSDO reference source. Tests were also performed with the GSPDO receiver located at the W3PM QTH.

Harry Zachrisson (ZachTek.com) modified his software to allow the transmit frequency to remain fixed rather than hopping over the spectrum of each band as is common. This was to remove the "hopping" as a variable in the spectral width measurements. It was found that the presence of the obscuring mountains had negligible influence on the spectral width, which was found to be 11.2 mHz on 40m. Further, the 40m spectral width was found to be 36 mHz with the ZachTek Desktop Transmitter with its internal 25 MHz TCXO reference source.

We observed that when a band was open, the spectral width of our WSPR-2 signals was often highly disturbed and random-like. The WsprDaemon Co-channel SNR assessment panel by Gwyn G3ZIL indicated other stations were interfering at times with our signals. After some study, it was decided to abandon using over-the-air (OTA) methods to determine minimum spectral widths.

The test arrangement involved directly connecting a ZachTek WSPR-TX Desktop transmitter, which includes an internal TCXO and a port for selecting an external reference source, with a Bodnar 1420 external reference source through a shielded precision attenuator system to an RX888 MKII receiver using a 27 MHz Bodnar external reference source. The importance of using GPSDO reference sources, rather than TCXO reference sources, was demonstrated during the OTA testing. Using the test arrangement, the spectral width of the transmitter was measured from 80m to 10m with the Bodnar reference source set at each 10 MHz and 25 MHz. We used 25 MHz since the Si5351 specifies the reference source frequency should be in the 25 to 27 MHz range. We observed that the spectral width was smaller for the 10 MHz reference source. As a consequence, we decided to measure the spectral width for a range of reference source frequencies covering from 4 MHz to 27 MHz. Surprisingly, it was observed that a 4 MHz reference source frequency was superior to other choices.

Using a 4 MHz reference source frequency, the transmitter was changed from a fixed output frequency on each band to in-band frequency hopping. The average spectral width over the bands is 17.8 mHz using in-band frequency hopping and 13.3 mHz for a fixed output frequency on each band.

We also considered the impact of the transmitter's and receiver's reference source stability on the observed average spectral width. Our preliminary conclusion is that the impact of the reference source type on the spectral width is significantly less for the receiver than for the transmitter. Consequently, it is far more important to know if the transmitter utilizes GPSDO than the receiver for studies involving spectral width.

Another question considered was the relationship between SNR and spectral width. A review of the 10 MHz reference source data on July 6-7 indicated that, on 40m and 80m, a SNR difference of about 20 dB made no difference in the spectral width. On 10m, the SNR difference was 7 dB, and again, no spectral width difference was observed. It is noted, as expected, that the spectral width on 10m was 36 mHz, and on 40m and 80m it was 11 mHz. For the 4 MHz reference source data, the spectral width for 40m and 80m was 14.8 mHz and 12 mHz on 10m. A reasonable inference is that SNR and spectral width, for any reference source frequency, are essentially uncorrelated.

The final question investigated was whether the microprocessor word length impacted the values computed to input to the Si5351. The microprocessors used were an ATmega328P MCU (16-bit) and an ESP8266 (32-bit). The data for Si5351 registers 26-33 (PLL) and 42-50 (MultiSynth division) for a frequency of 1409713347 cHz using a 26 MHz reference (clock) frequency was compared. Both microprocessors computed the same data.

There are numerous other possible causes for the variation in spectral width such as the numerical methods employed to compute the values to input into the Si5351 registers. The process is multitiered and complex. What is the optimum reference source frequency for a given computational process to generate Si5351 register values to achieve the minimum average spectral width over the various bands? What is the maximum reference source stability to not impact spectral width? But perhaps the most important question to answer is "What is the maximum spectral width allowable for scientific investigations?"

Caveats:

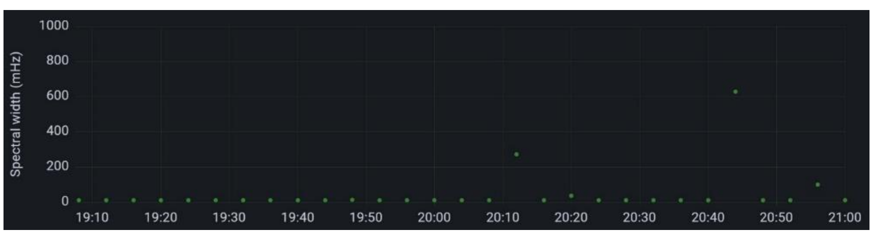
1. Creating a comprehensive system analysis that encapsulates and consolidates all possible sources of error to calculate spectral width definitively is outside the scope of this investigation.
2. This investigation's findings were made using the ZachTek transmit frequency algorithm. Other transmit frequency algorithms could potentially yield different results.

Acknowledgments: The authors appreciated the support of Harry Zachrisson (SM7PNV) of ZachTek by providing the WSPR-TX XP Plus transmitter and modifications of his software for our investigation, to Paul Elliott (WB6CXC) for his insights, and to Gwyn Griffiths (G3ZIL) for beneficial discussions and helpful WsprDaemon panels.

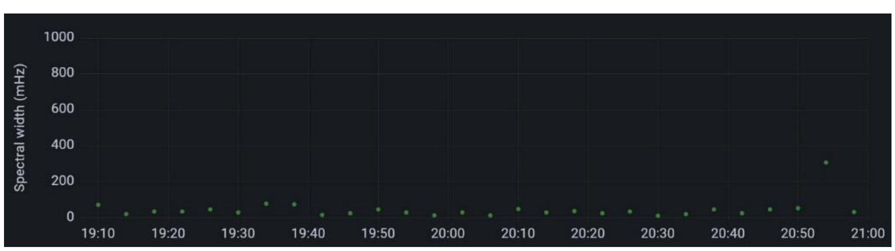
GPSDO Spectral Width Study on 40 m at a Fixed Transmit Frequency

by
Gene Marcus, W3PM
and
Barry Johnson, W4WB
20 June 2024

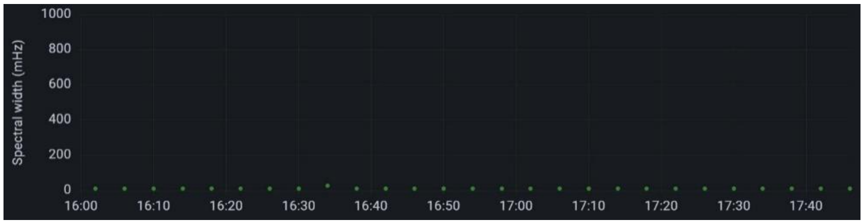
The figure below shows the spectral width on 40m for the custom ZachTek WSPR-2 transmitter that includes an internal TCXO and a port for the selection of an external reference source. In this case, the external reference source was a Bodnar 1420 set at 10 MHz. The GPSDO transmitter was located at the home of W4WB, which is on a mountain in Huntsville, Alabama, USA. The antenna used was a Ciro Mazzoni BABY loop antenna. The GPSDO receiver was provided by W3PM and was an RX888 MKII with a Bodnar reference source. The receiver was located in a laboratory at the National Space Science & Technology Center located on the campus of the University of Alabama in Huntsville, and utilized the K4UAH antenna (Hamstick for 20 m) located on the roof of the building. There was a clear line-of-sight (LOS) path between the antennas separated by 10.3 km. Rather than frequency hopping, the WSPR-2 transmitter operated on a fixed frequency as W4WB. The nominal spectral width was 11.2 mHz during the quiet time of the 40m band on June 16, 2024.



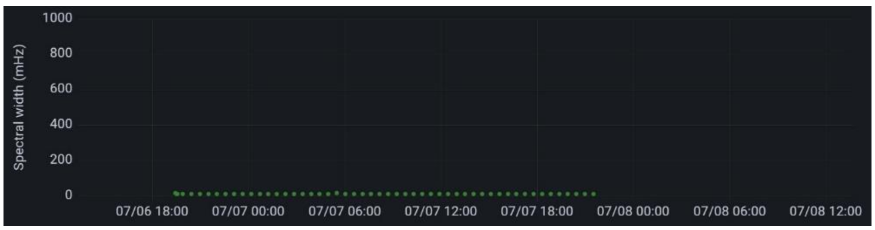
A second transmitter (ZachTek WSPR-TX Desktop) was also operated as W4RT from the home of W4WB and used its internal TCXO (2.5 ppm) and an AlexLoop for the antenna. The nominal time-coincident spectral width was 36 mHz as seen in the figure below.



On June 21, 2024, the ZachTek WSPR-TX XP Plus, with GPSDO, transmitter signals on 40m were received at W3PM's home using the same RX888 MKII with a Bodnar reference source used at the National Space Science & Technology Center. The distance between W4WB and W3PM homes is about 27 km and the LOS is blocked by two small mountains. The nominal spectral width was 11.8 mHz (removal of the two outlier values yields 11.2 mHz) during the quiet time of the 40 m band. The presence of the blocking terrain appears to have insignificantly affected the spectral width (11.2 vs. 11.2 mHz).



W3PM configured a test where the attenuated signal from the ZachTek transmitter (WSPR-TX XP Plus with GPSDO) was fed directly into the GPSDO RX888 MKII through a shielded precision attenuator system. The figure below shows that the spectral width of the WSPR-2 signal is 11 mHz. This is arguably the baseline value of the spectral width on 40 m for these GPSDO instruments.



Next, W3PM configured a test in which the attenuated signal from the aforementioned ZachTek WSPR-TX XP Plus transmitter was fed directly into the GPSDO RX888 MKII, but the transmitter reference source was its internal 25 MHz TCXO (2.5 ppm). The figure below shows that the spectral width of the WSPR-2 signal varies from 60 to 104 mHz, with an average value of 82 mHz for 9 samples. The reference source stability is clearly important.

See Report “Impact of the Transmitter’s and Receiver's Reference Source Stability on the Observed Spectral Width” on page 15 for additional information.

Variation of Spectral Width vs. GPSDO Reference Frequency vs. Band at Fixed Transmit Frequencies

by
Barry Johnson, W4WB
and
Gene Marcus, W3PM
10 July 2024

The test arrangement involves directly connecting a ZachTek WSPR-2 transmitter, which includes an internal TCXO and a port for selecting an external reference source, with a Bodnar 1420 external reference source through a shielded precision attenuator system to an RX888 MKII receiver using a 25 MHz Bodnar external reference source. The objective of these tests was to determine if the GPSDO reference frequency impacts the spectral width. Each band had a specific transmit frequency that was fixed during the tests. The reason for doing this was to effectively eliminate artifacts that may occur when typical transmit frequency hopping is used. This will be illustrated in the following report entitled "Spectral Width with 4 MHz Reference Source and In-Band Frequency Hopping". The Si5351 PLL data sheet specifies the reference frequency should be in the range of 25-27 MHz. Typically, ZachTek WSPR-TX XP Plus transmitters use an external 10 MHz reference frequency and have experienced good results. The use of 10 MHz was based on a publication by Harry Zachrisson entitled "Using the Si5351 directly with a 10MHz OCXO for increased stability."[1]

The spectral width was measured for 10 MHz and 25 MHz from 80m to 10m. The table below shows the spectral width for each band, and the table entries use the format [spectral width in mHz, (observed lowest and highest values)]. The last line presents a rough metric that is the average spectral width of the eight bands. The spectral width for the 10 MHz reference frequency is clearly superior to that of the 25 MHz reference frequency. We then conducted a thorough investigation into the behavior of 26 MHz and 27 MHz reference frequencies. Both of these reference frequencies yielded higher average spectral widths. Next, we investigated other reference frequencies, viz., 16 MHz, 7 MHz, 5 MHz, and 4 MHz. It is evident that the 4 MHz reference frequency produces superior spectral widths. What is the optimum reference frequency? It is yet to be determined, but there are further issues to consider.

BAND	4 MHz	5 MHz	7 MHz	10 MHz	16 MHz	25 MHz	26 MHz	27 MHz
80 m	14.8 (12-16)	10.3 (10-11)	11 (10-13)	15 (all 15s) mHz	11.2 (11-12)	11 (all 11s) mHz	12.1 (12-13) mHz	15 (all 15s) mHz
40 m	14.8 (14-15)	11.5 (10-12)	11 (all 11s)	11 (all 11s)	11.2 (11-12)	21 (11-25)	12.1 (12-13)	15.8 (12-24)
30 m	13.6 (12-15)	10.8 (10-11)	16.7 (16-17)	11.4 (11-12)	20.2 (17-23)	35.5 (35-36)	33.8 (30-37)	11.3 (11-12)
20 m	11.6 (11-14)	12 (11-14)	18.5 (18-19)	21.8 (20-23)	18.7 (15-22)	11 (all 11s)	45.3 (42-56)	80 (79-81)
17 m	14.6 (12-16)	13 (11-16)	11 (all 11s)	15.8 (14-17)	34.8 (33-37)	18 (all 18s)	14.1 (12-16)	68.8 (68-71)
15 m	14.0 (11-16)	21.5 (19-23)	28 (27-29)	31.6 (30-33)	31.8 (29-35)	63.3 (51-70)	83.6 (79-89)	138 (136-140)
12 m	11 (all 11s)	15.8 (12-23)	22 (21-23)	18.2 (18-19)	24.6 (21-29)	160 (154-164)	297 (280-320)	11.8 (11-14)
10 m	12 (11-15)	22.5 (17-28)	24 (all 24s)	36.2 (30-44)	28 (22-30)	13.7 (12-15)	75.9 (58-100)	187 (176-216)
Average [mHz]	13.3	14.7	17.8	20.1	22.6	41.7	71.7	67

[1] https://www.zachtek.com/post/2019/02/14/using-the-si5351-directly-with-a-10mhz-ocxo-for-increased-stability

Spectral Width with 4 MHz Reference Source and In-Band Frequency Hopping

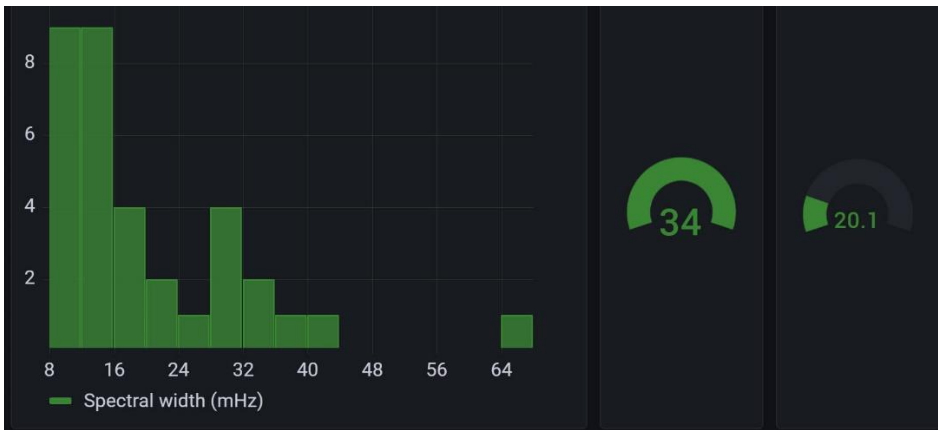
by
Barry Johnson, W4WB
and
Gene Marcus, W3PM
14 July 2024

The test arrangement involves directly connecting a ZachTek WSPR-TX XP Plus transmitter with a 4 MHz Bodnar 1420 external reference source through a shielded precision attenuator system to an RX888 MKII receiver using a 25 MHz Bodnar external reference source. The following plots show, by band, first the spectral width observed and the associated histogram with the number of samples and the average spectral width. These plots were generated using G3ZIL's worksheets. The average spectral width over the bands is 17.8 mHz. The table below shows the average spectral width by band.

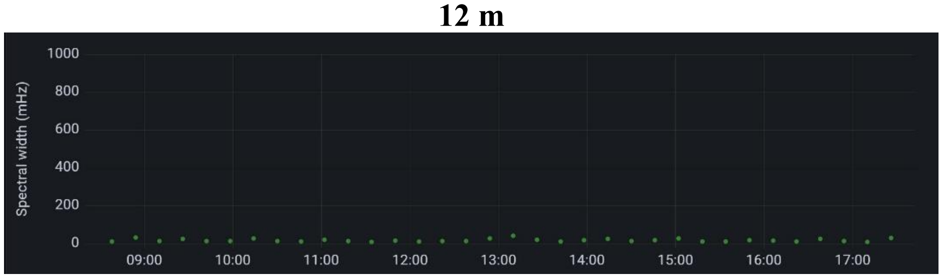
Band (meter)	Spectral Width (mHz)
10	20.1
12	18.3
15	19.4
17	19.0
20	20.3
30	15.2
40	14.9
80	18.5
160	14.6 (11.2 w/o outliers)

10 m

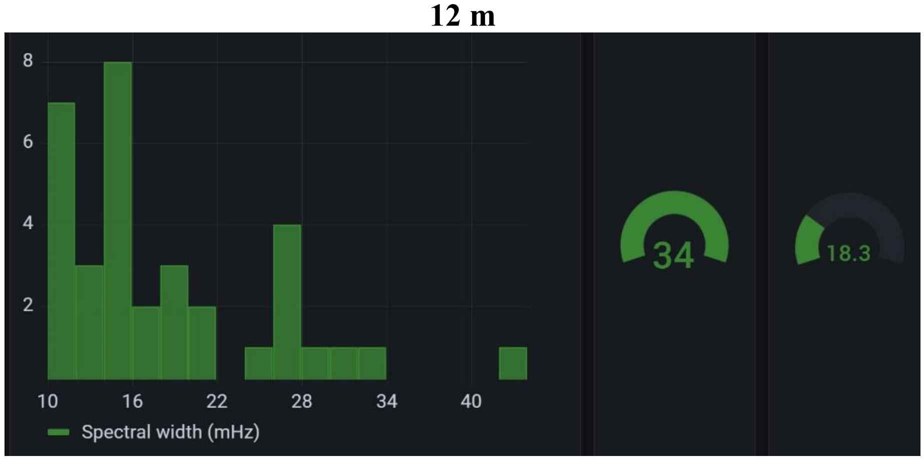
10 m



12 m

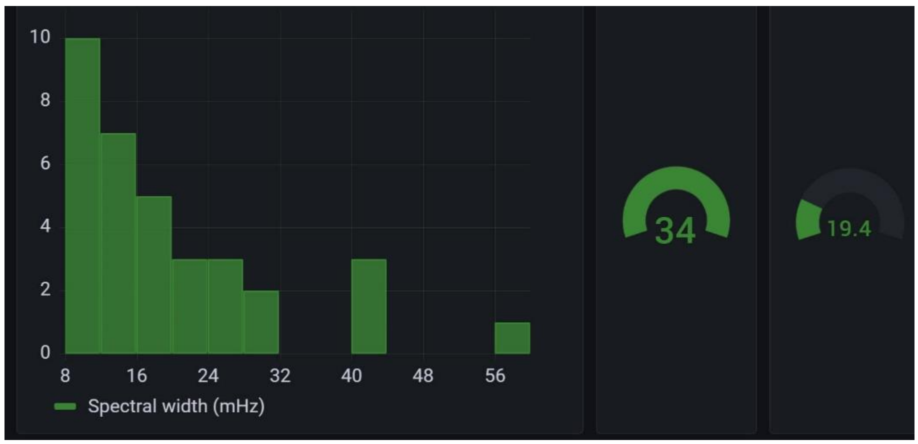


12 m

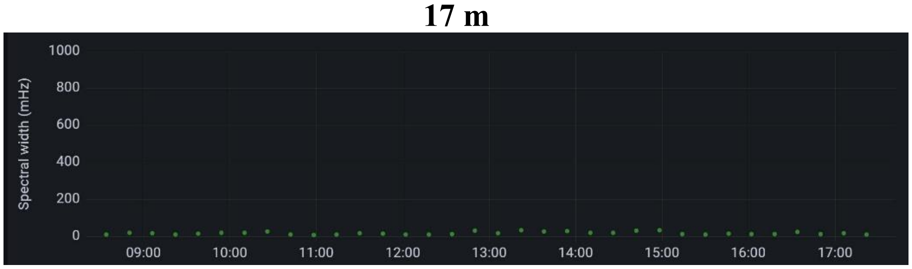


15 m

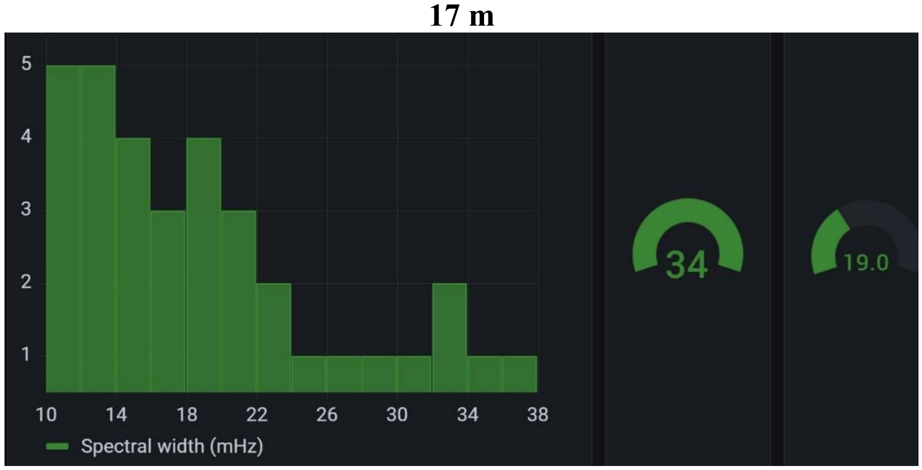
15 m



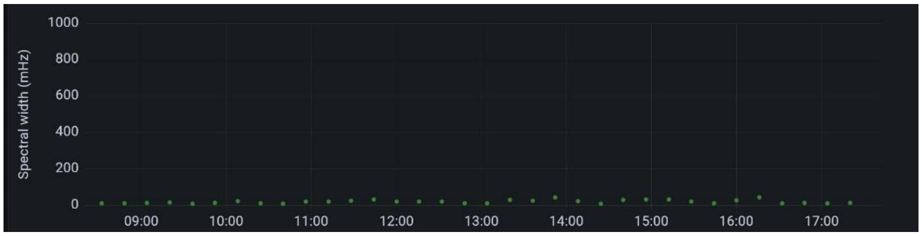
17 m



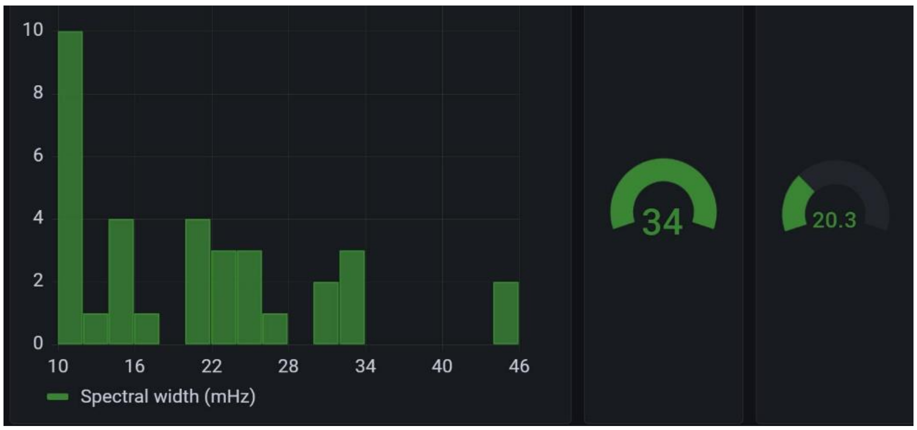
17 m



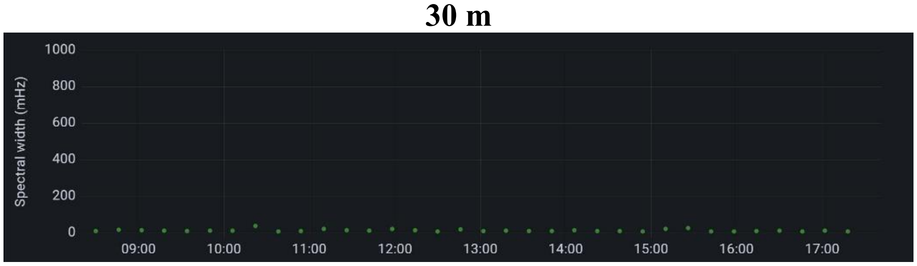
20 m



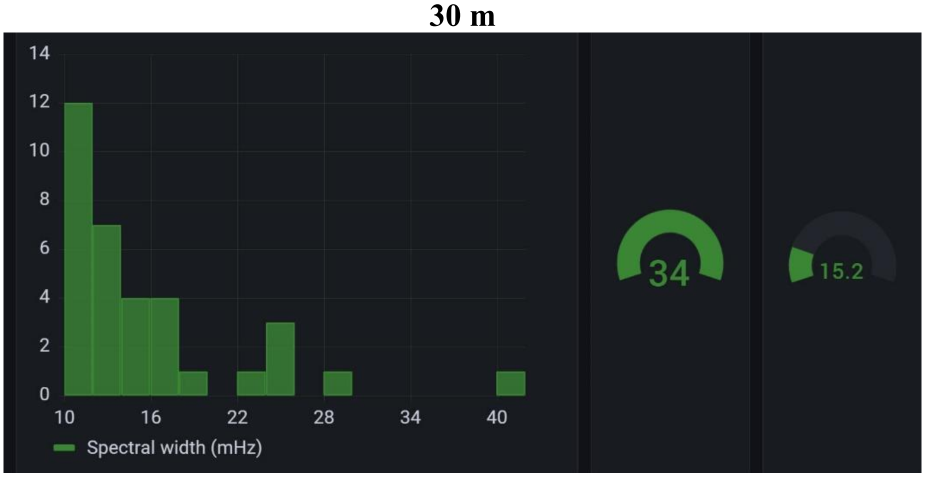
20 m



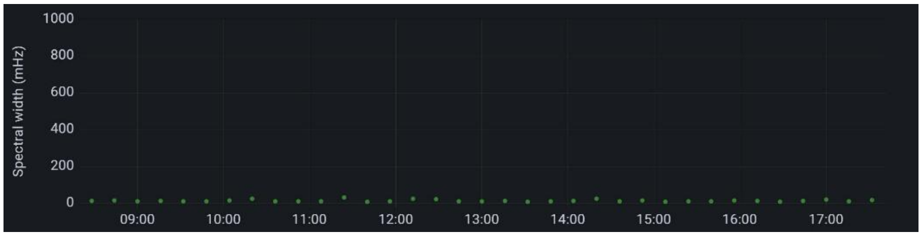
30 m



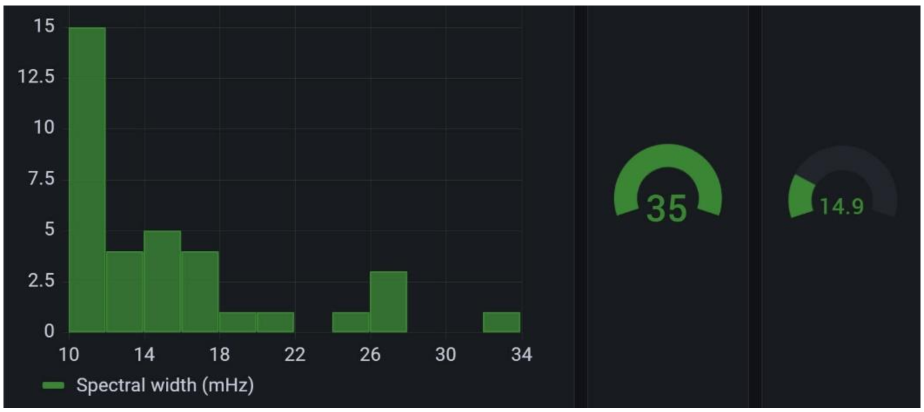
30 m



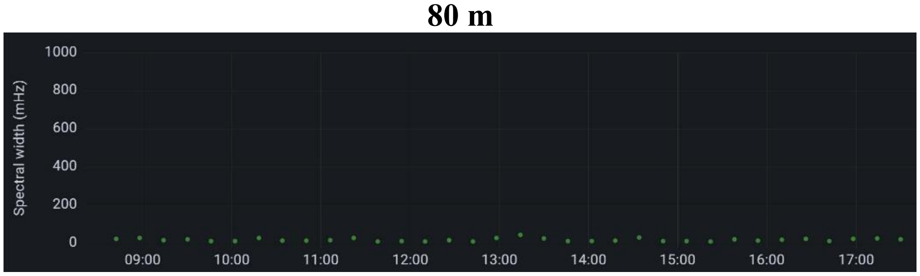
40 m



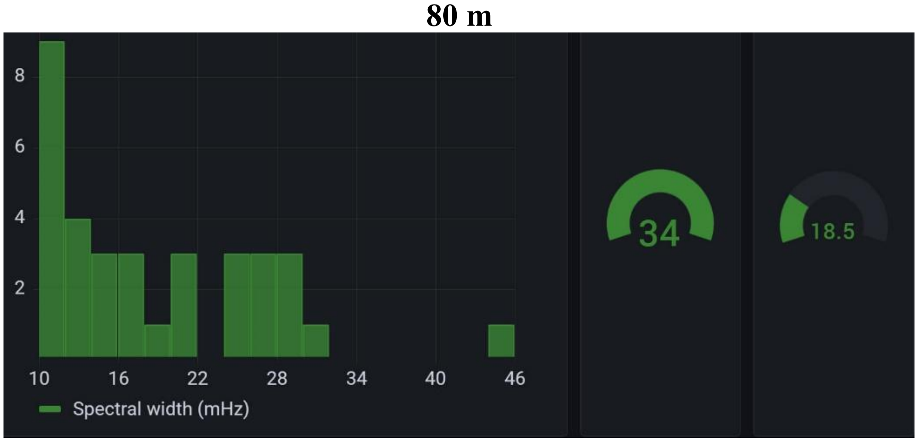
40 m



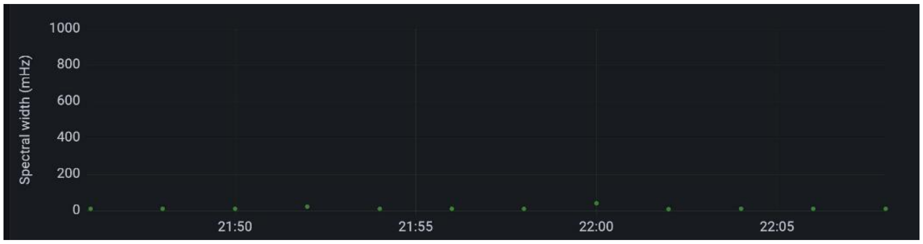
80 m



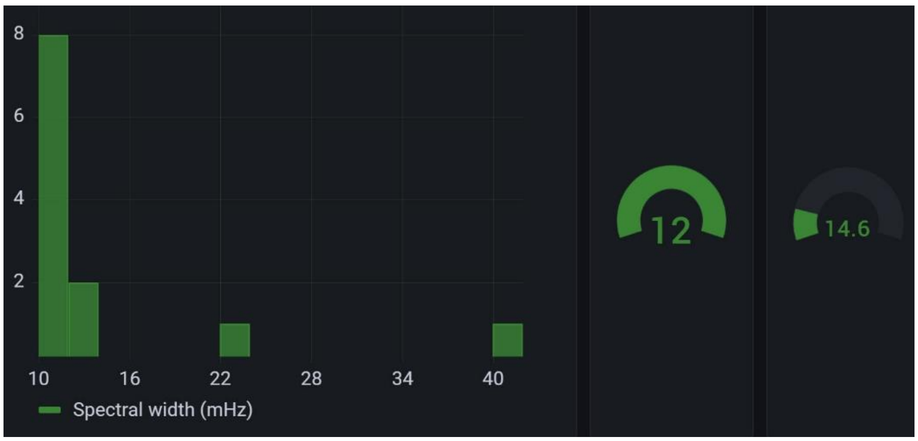
80 m



160 m


Spectral width (mHz)
1000
800
600
400
200
0
21:50
21:55
22:00
22:05

160 m


8
6
4
2
10
16
22
28
34
40
Spectral width (mHz)
12
14.6

Impact of the Transmitter’s and Receiver's Reference Source Stability on the Observed Spectral Width

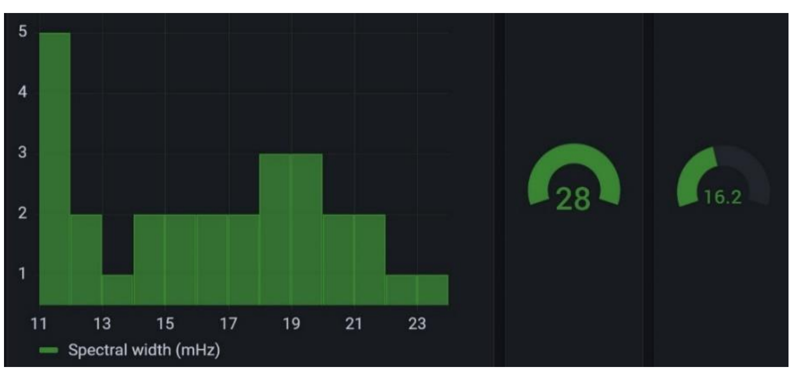
by
Barry Johnson, W4WB
and
Gene Marcus, W3PM
16 July 2024

We pondered the impact of the transmitter’s and receiver's reference source stability on the observed spectral width. Several tests were performed using W3PM’s direct connection of the transmitter to the receiver via a shielded precision attenuator system. The results are presented in the following images. The table below provides a summary of the observations. Using the transmitter and receiver TCXOs will clearly yield spectral widths greater than those shown in this table.

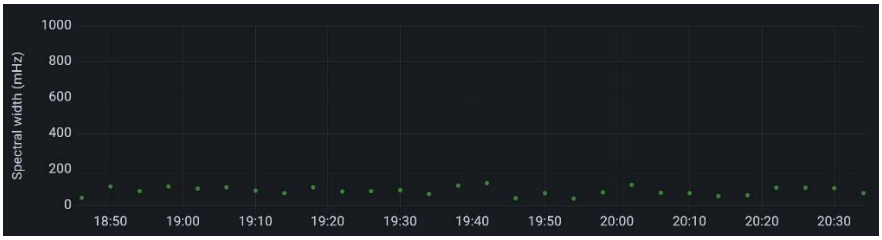
Transmitter	Receiver	Average Spectral Width
GPSDO	TCXO	16.2 mHz (28 samples)
TCXO	GPSDO	82.4 mHz (28 samples)
GPSDO	GPSDO	11 mHz (21 samples)

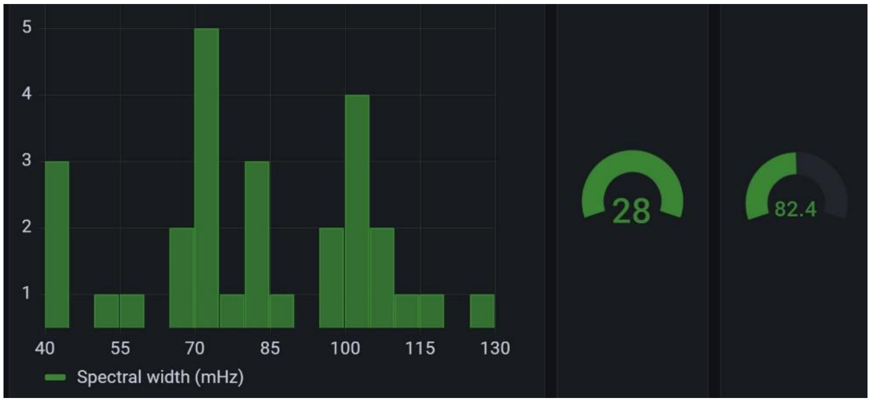
Our preliminary conclusion is that the impact of the reference source type on the spectral width is significantly less for the receiver than for the transmitter. Consequently, it is far more important to know if the transmitter utilizes GPSDO than the receiver for studies involving spectral width.

The next two figures show the spectral width for the direct connection of the ZachTek WSPR-TX XP Plus transmitter with a 10 MHz Bodnar external reference source and the RX888 MKII receiver using its internal 26 MHz TCXO reference source. The first figure shows the spectral width vs. time and the second figure shows a histogram of the spectral width samples.

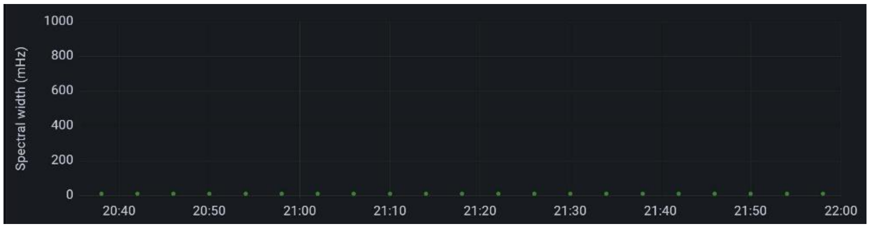


The following two figures show the spectral width for the direct connection of the ZachTek WSPR-TX XP Plus transmitter with its 25 MHz internal reference source and the RX888 MKII receiver using a 26 MHz external Bodnar reference source. This first figure shows the spectral width vs. time and the second figure shows a histogram of the spectral width samples.





The final figure shows the spectral width for the direct connection, via a shielded precision attenuator system, of the ZachTek WSPR-TX XP Plus transmitter with a 10 MHz Bodnar external reference source and the RX888 MKII receiver using a 26 MHz external Bodnar reference source. This figure shows the spectral width vs. time, and all of the values are 11 mHz.



Summary of Conversations Between
Barry Johnson (W4WB) and Gene Marcus (W3PM)
and
Gwyn Griffiths (G3ZIL) and Paul Elliott (WB6CXC)

In discussions with Paul Elliott (WB6CXC), the following bullet lists summarize these conversations.

- The Spread Spectrum feature in the Si5351 has not been utilized, and it is thought to be not beneficial.
- Paul created a Look Up Table (LUT) that contains parameters for the Si5351 that will produce sub-mHz spectral spreading.
- Paul noted that whether or not the algorithm uses integer math makes no difference as long as the precision is adequate. He has carefully used 32-bit integer math, 64-bit integer, and high-precision floating point calculations to generate exactly the same results. Both continuous fractions, or Farey-Sequence algorithms can generate excellent and accurate results as long as they are allowed to iterate to adequate depth. Paul is using a different numerical approach that is optimized for minimizing FSK error, but the ultimate results of any of these methods can arrive at the same answer. He mentioned these data sets usually provided an error of less than 1µHz of the desired FSK step.
- The ZachTek frequency-setting algorithm normally generates frequencies with a setting resolution of 10 mHz, which implies Harry is not attempting to eliminate FSK shift error. A 10mHz error will go unnoticed in normal WSPR usage; it's only when measuring spectral spreading that the effects will be observable.

Our thanks to Gwyn Griffiths (G3ZIL) for the interesting and beneficial conversations regarding such topics as how small a spectral width value is needed for ionospheric research; what is the co-channel interference for different spectral width values; for a given SNR, do smaller spectral widths allow close interfering stations to be shifted closer; what are the impacts of receiver frequency reference source stability drift upon decoding; what are the impacts of AFC for WSPR-2 and FST4W; and so on.