HIGH PERFORMANCE HF/VHF SIGNAL GENERATOR

Replace that aging HP 8640 with an improved model

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How many times have you needed a piece of test equipment and thought about home-brewing as opposed to purchasing a commercial unit? Ultimately, you may have decided that the project would be too difficult and/or the resulting performance of a home-brew unit would be sub-standard. Here is your chance to home-brew a frequently used piece of test equipment – a HF/VHF signal generator. The unit described in this project has five notable characteristics that distinguish it from typical commercial units:

It has a small physical size

It has low phase noise

It has low amplitude for even and odd order harmonics

It has minimal output level variation over a wide frequency range

It has a low warm-up drift from a cold start

Signal generators come in all shapes, sizes, and prices. Over the past 40+ years, the gold standard for a used unit has been the HP 8640B. This model is known for its extremely low phase noise and output level accuracy. Good working units are still available for $400 to $800, however most of the units available on eBay are being sold as "Parts Only". Many parts in the units are proprietary, are hard to find, and the nylon gears become brittle and often crack or disintegrate[1]. The units are also large and heavy.

Later model Marconi, IFR, and HP units are also very popular. They cost a little more than the HP 8640s, are small in size, and are light in weight. The HP 8648[2] series is a good replacement for the 8640. They are more functional than the 8640, are smaller in size and can be picked up on eBay for $500 to $1000. However, their phase noise is much higher than the 8640/Marconi/IFR units.

The Marconi/IFR 2023A/2025s[3] have very low phase noise, are small in size, and can be picked up on eBay for $500 to $1000. Modern signal generators include the Keysight E4400 series[4]. They sell for $1000 to $3000. Their phase noise is extremely low. Refurbished units are often available on the Keysight web site. In today's economy, shipping costs for heavy units can reach $100+.

I did not want to spend $2000+ for a Keysight E44xx unit. My desired unit would supplement my IFR 2025 so that I could perform 3rd order Dynamic Range tests on receivers, as described in the ARRL Test Procedures Manual[5]. I wanted a frequency range of 500 KHz to 50 MHz and an output level with a 130 db adjustment range. An upper limit of 150 MHz would have been nice, but was not mandatory.

There are a large number of different digital chips that can be used to build a home-brew signal generator. They include the AD9951, AD9957, Si570, and the Si5351. There are even a larger number of web sites that sell various digital VFO/signal generator kits. I had previously used the Si570 chip as a VFO in my Atlas 210X LE transceiver, via the VFO kit from SDR-Kits[6]. The Si570 has very low phase noise[7], is very stable, and the VFO kit is inexpensive. I used the kit with the CMOS version of the Si570. This unit worked well from 3.5 MHz to 280 MHz.

I was ready to submit this article to QEX in early 2022, but things did not turn out as expected. The Si570 chip was no longer readily available and the price had increased to $50+ each. About the same time, SDR-Kits discontinued the Si570 VFO kit. Thus, it would be very difficult for someone to duplicate my Si570 signal generator.

In the fall of 2022, John Satterfield[8] created a VFO design for an Atlas 210X/215X transceiver, using the Si5351 chip. John's work looked very promising. John and I partnered together to create a Si5351 signal generator that would replace my original Si570 design. John wrote the needed code for the signal generator and made updates to support the features that I needed. Where-ever possible, I migrated my existing Si570 subcomponents to the new box. I completed the hardware build-out, packaging, and testing. These efforts produced a signal generator that mostly exceeded the performance of the original Si570 design.

The article in this link provides a good comparison between the Si570 and Si5351 chips:
http://nic.vajn.icu/PDF/SiliconLabs/Si5351_facts.txt

I found the following differences between the Si5351 and the Si570:

Si5351 has a much lower warmup frequency drift (see Figure 14 in the Appendix)
It is much easier to program the Si5351 (per articles on the Internet)
The Si5351 has a much flatter signal gain curve, flat out to at least 100 MHz
The Si5351 has a lower frequency limit of 100 KHz compared with 3.5 MHz on the Si570
The Si5351 is significantly lower in cost
The code for the Si5351 is open source
The Si5351 can be programmed via a USB interface on a Windows PC
The Si570 has about 6 db lower phase noise (see Figure 21 in the Appendix)
The Si570 has less spurs (see Figures 15 & 16 in the Appendix)
Improper loading on the output of the Si5351 can have significant impact on phase noise

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Audience

This document is written for ham radio operators that want to build a low cost signal generator that has similar performance as commercial units. A minimal amount of technical skills are needed to build the system. The author is in his mid-70s, has not so good close-in vision, etc. but was able to build the system without any problems. There are a minimal number of SMD parts that need to be soldered on the interface circuit board. One also needs to be able to accurately drill holes on the various aluminum enclosures and front panel. If one approaches the project in small discrete steps, then one should be successful in ending up with a fully functioning signal generator.

Objectives

This document provides a high level overview of the resulting signal generator that was built. Parts are readily available, thus one can assemble a signal generator that rivals the performance of commercial units. The following info and parts are available from the author: [9]

Detailed step-by-step engineering document with pictures, on how to build the signal generator
Parts list for major components
Microprocessor code for the ESP-32 microprocessor board
Printed circuit board for signal generator
Front panel for equipment enclosure

Options

Since the project goes together in modules, one can delete/add modules according to one's needs. Typical changes that might be considered include:

Use external DC power source - i.e. leave out the Mean Well power supply
Use an external step attenuator
Leave out the low pass filter board and use external low pass filters for all frequencies
Use Chinese Si5351 oscillator module as opposed to the QRP Labs Si5351board[10]

A low pass filter board is needed in order to cover the frequency range of 500 KHz to 34 MHz. The power switch has a bypass position so that an external low pass filter can be attached to the output jack. With appropriate external low pass filters, an extended frequency range of 500 KHz to 200 MHz can be covered.

Specifications

The main building block for the Si5351 Signal Generator is the interface circuit board. This board supports the ESP-32 microprocessor board, the Si5351 oscillator board, and 9 volt, 5 volt, and 3.3 volt voltage regulators. Interfaces are provided on the board for a 12 volt Mean Well power supply, a color TFT display, and the operation switches and controls.

Here is a summary of the specs for the signal generator described in this project:

Built-in DC power supply powered from 120 VAC
Low warmup frequency drift – less than 0.1 ppm drift over a 24 hour period
Operation range from 100 KHz to over 200 MHz
Symmetrical sine wave output from 1.2 MHz to 34 MHz, using internal low pass filters
Symmetrical sine wave output from 34 MHz to 200+ MHz using external low pass filters
Even/odd order harmonics are down >40 dB on all bands, using internal/external low pass filters
Typical spurs are more than 90 dB down from fundamental
Worst case spurs are down 50 dB from fundamental (31.236 MHz)
Signal Level Out:
    +/- 0.25 dB 500 KHz to 34 MHz
    +/- 0.5 dB 500 KHz to 149 MHz
Five frequency bands with 6 memories in each band
One customized band with IF Offset, for use as a VFO for a HF transceiver i.e. Atlas 210X
Frequency steps of 1 Hz, 10 Hz, 100 Hz, 1 KHz, 10 KHz, 100 KHz, 1 MHz, and 10 MHz
Frequency Lock
USB interface for programming from a Windows PC
Output signal level adjustable in 1 dB steps from 0 to -110 dB
Optical encoder
Source code that is easily customized, with minimal knowledge of programming
Bypass position allows one to use an external low pass or band pass filters
Compact size – See Figure 1 in the Appendix

Project Tasks

The project can be divided into the following mini-projects:
Procure parts
Assemble parts on Interface circuit board
Mount modules inside the two enclosures
Install front panel label circuit board
Install front panel controls and interface cables
Test unit

Theory of Operation

Please refer to Figure 4 – System Block diagram in the Appendix, for a better understanding of system operation.

Power

The signal generator does not need any external DC power for operation. AC power (120 VAC) is provided to the AC power socket on the rear of the unit. The AC voltage goes through the Corcom EMI filter and then to the front panel power switch. With the power switch in the ON position, AC voltage is provided to the Mean Well DC power supply. The DC power supply outputs 12.0 VDC to the Si5351 module. The Si5351 module outputs 5.0 VDC to the Low Pass Filter board.

When the power switch is in the BYPASS position, ground is applied to pin 19 of the ESP-32 microprocessor board. The code is setup to output 1001 on the four BCD lines going to the Low Pass Filter. That code enables the bypass relays on the board (originally was 6 meter band). BCD code 1001 is also outputted to the Low Pass Filter board if the generated frequency is greater than 34 MHz.

Si5351 Circuit Board

Please refer to Figure 5 – Si5351 Interconnect drawing in the Appendix. The Si5351 oscillator module outputs a +10 dB square wave signal to a Gali 6 MMIC amplifier[11] . The level of the output signal decreases as the frequency increases. When the Si5351 module is first energized, it initializes at 10.000.000 MHz. The output signal from the Si5351 module passes goes to the input of the low pass filter board. The various bands on the board is controlled by BCD signals from Si5351 module.

Low Pass Filter Board

The low pass filter board (See Figure 7 in the Appendix) greatly attenuates the odd and even order harmonics out of the Si5351 module. Without the low pass filter, the signal is an ugly square wave. See Figure 9 – Signal with no Low Pass Filter in the Appendix. Using the low pass filter results in a clean sine wave. See Figure 10 – Signal with Low Pass Filter in the Appendix.

The harmonics from the fundamental signal are very strong. See Figure 11 – Harmonics with no Low Pass Filter. With the low pass filter, the harmonics are greatly attenuated. See Figure 12 – Harmonics with Low Pass Filter in the Appendix. There are seven different low pass filters on the board, covering these bands: 160M, 80M, 40M, 20M, 15M, 10M, and 6M

Figure 13 – Low Pass Filter Sweeps in the Appendix is an example Elsie simulated sweeps. The real world sweeps are very close to the simulation.

The LC components for the 6M band have been removed. A short jumper coax cable has been installed from the input to the output of the filter. The 6M filter slot is selected when the BCD code of “1001” is received by the low pass filter board. The code of “1001” is received when one of the following two conditions are met:

Either the output frequency from the VFO is greater than 34 MHz
Or
The front panel Power switch is in the BYPASS position.

Attenuators

Three different types of attenuators are used
~ 5 dB equalizer pad (home-brew) on the Si5351 Interface board
1.5 dB pad (commercial or home-brew)
Variable 1 dB step attenuator (commercial unit) with 110 dB range

The equalizer on the Si5351 module circuit board normalizes the signal level between 500 KHz and 200 MHz. The output of the equalizer is fed into the input of the low pass filter. The output of the low pass filter board is fed to a 1.5 dB attenuator pad and then to the input of the lab quality step attenuator – a JFW50DR-001. The 1.5 dB pad provides a constant load on the output of the low pass filter when the step attenuator is set to no attenuation. The value of this pad is adjusted so that 0 dB is fed to the front panel SMA jack, with the step attenuator set for 0 dB.

The step attenuator has two controls. The large outer knob adjusts the output from 0 to -100 dB in 10 dB steps. The inner knob adjusts the output signal in one dB steps from 0 dB to 10 db. The combination of the two controls allow the output signal to be adjusted from 0 dB to -110 dB. The output of the step attenuator goes to the front panel SMA jack. If the output level needs to go below -110 dB, then an external pad can be inserted.

An external pad would be needed when measuring the MDS on a receiver. If an output level greater than 0 dB is needed, then an external amplifier can be attached to the front panel SMA jack.

Front Panel Controls

There are five controls on the front panel of the signal generator, in addition to the step attenuator knobs.

Power Switch

The Power Switch is a DPDT ON-OFF-ON toggle switch. This toggle switch has three positions – ON, OFF, and BYPASS. In the ON position, AC power is provided to the Mean Well DC power supply. There is a green LED inside the Mean Well power supply. This LED is lighted when AC power is supplied to the power supply module. When this power supply is energized, 12 volts DC power is provided to the Si5351 module. Inside the module, there are 9 volt, 5 volt, and 3.3 volt voltage regulators. The 5 volt line also provides power to the low pass filter board. The case of the Si5351 runs warm. This acts a TCXO oven to minimize frequency drift.

In the BYPASS position, power is supplied normally to all of the previously described modules. The Bypass switch also provides a ground to pin 19 of the ESP-32 module. This outputs a BCD code of 1001 to the low pass filter, resulting in the selection of the 6M filter slot. The filter components have been removed and a bypass coax cable installed from input to output.

In BYPASS, a square ware is outputted on the front panel SMA jack, regardless of the dialed in frequency. The output signal will have the fundamental frequency, even order harmonics, and odd order harmonics. The odd order harmonics will be very strong in level – i.e. the 3rd order harmonic will be about 10 dB down from the fundamental. An external low pass filter is attached to the front panel SMA jack in order to get the desired sine wave signal. The MCL SLP series of low pass filters work very well. See Table 1 in the Appendix. These filters can often be found on eBay at very low prices.

BAND/MEM Toggle Switch

This switch is spring loaded to the center off position. Momentary pushes to the BAND position will cycle the signal generator through six available bands. The frequency range of each band can be customized by changing the ESP-32 code. Momentary pushes to the MEM position will cycle a given band through six different memory channels. The frequency of each memory channel can be customized by changing the ESP-32 code.

STEP

This switch is a spring loaded push button switch. Momentary pushes of the switch will cycle the Si5351 through the various frequency step settings.

LOCK

This is a two position toggle switch. In the ON position, the front panel display frequency is locked – i.e. turning the Frequency Tuning Knob will not change the frequency.

FREQUENCY

The optical encoder is used to change the displayed frequency. One rotation of the knob will change the frequency about 25 KHz, when the Frequency Step is set for 1 KHz.

Final Testing

After the signal generator build was completed, I ran a set of test measurements to see if the box met my expectations. I was very pleased with the results.

Oscillator Stability

See Figure 14 – Warmup Drift in the Appendix. When the signal generator is powered on, it comes up on a frequency of 10.000.000 MHz. I measured the frequency with a HP 5385A frequency counter that was synchronized with a satellite frequency lock. I recorded the initial frequency and subsequent frequencies in one minute increments, with the frequency set to 100 MHz. The frequency started out at 6 Hz high. Within 2 minutes, the frequency was only 2 Hz high. During the next 10 minutes, the frequency rose to 12 Hz high. During the next 4 hours, the frequency gradually decreased to 4 Hz high. During any 24 hour period, the frequency did not deviate more than 10 Hz, depending upon the temperature of the room.

Output Level Accuracy

The output level of the signal generator was measured with a Boonton 4220A power meter and a 51101 power sensor. Internal low pass filters were used for frequencies of 400 KHz to 34 MHz. External Mini Circuit SLP low pass filters were used for frequencies greater than 34 MHz. For those frequencies, the front panel switch was placed in the LPF Bypass position. No Mini Circuits Low Pass Filter was available for a cutoff frequency greater than 150 MHz, so the level accuracy could not be measured for frequencies greater than 149 MHz.

Spurs

There were more spurs on the Si5351A, compared with the Si570 and IFR 2025. The number and signal level of the spurs depends upon the frequency being generated. Figure 15 and 16 in the Appendix shows typical worst case spurs in the VHF band and typical best case spurs in the HF band, when compared with the Si570 and the IFR 2025.

The spur generation depends upon the type of division being used inside the Si5351 chip. Even integer division results in the lowest number of spurs and fractional division results in the most number of spurs[12]. Figure 17 shows the result of fractional division on a Si5351 set to 10.000006 MHz. Figure 18 shows the signal from a Si570 set for the same frequency. Generally, the signal level of the spurs on a Si5351 is less than -90 dB, when the fundamental frequency is at a signal level of -30 dB.

I set the signal generator to a -30 dB output level and configured my Perseus receiver similar to what is shown in Figure 17. I then tuned the signal generator in 1 KHz increments from 500 KHz to 34 MHz and watched the spectrum display. I found that typical best case and worst case spur displays are shown in figures 19 and 20.

I observed these spurs with a sweep of each ham band:

160M	spurs greater than 90 down
80M	spurs greater than 80 dB down
40M	spurs greater than 73 dB down
30M	spurs greater than 77 dB down
20M	spurs greater than 70 dB down
17M	spurs greater than 70 dB down
15M	spurs greater than 65 dB down
12M	spurs greater than 53 dB down
10M	spurs greater than 57 dB down

Phase Noise

In my opinion, the magnitude of the phase noise in a signal generator is what separates the men from the boys. See Figure 21 – Phase Noise Comparison in the Appendix. This spectrum analyzer sweep shows the phase noise differences between a Si570 signal generator, an IFR 2025 signal generator, and the Si5351A signal generator. The phase noise was measured using the process described by Wes Hayward in the July/August issue of QEX – Oscillator Noise Evaluation with a Crystal Notch Filter[13]. I used a home brew 14.311 MHz crystal notch filter. The phase noise from the Si570 signal generator was about 6 dB less than what I measured on the Si5351A signal generator. That figure seems to match with what other hams have measured[14].

I initially confirmed that my Siglent SSA3021X spectrum analyzer met factory specs for internal phase noise. These two videos provide excellent info on how to make that measurement:

https://www.youtube.com/watch?v=MCBrhxPQotU

https://qrp-labs.com/images/qcx/phasenoise/PhaseNoiseDocForHans.pdf

The phase noise spec for the 3021, with a 10 KHz offset, is 98 dB/Hz. I measured -100.1 dB/Hz.

Using the notch filter method for measuring phase noise, my 14.311 MHz notch filter had an insertion loss of 2.5 db. With a 10 KHz offset, I the measured phase noise on the following devices (see Figure 21 in the Appendix).

IFR 2025 = -136 dB/Hz (factory spec = -140 dB/Hz)
Si570 = -138 dB/Hz
Si5351 = -133 dB/Hz

SUMMARY

There are no free lunches in the ham world, but one can come close. Considering that a Si5351 chip only costs a couple of dollars, the resulting performance is huge. The cost to build the signal generator described in this article will be $200+.

If one is patient, a high quality commercial signal generator can be obtained on eBay for less than $400. I picked up a couple of nice IFR 2023 units for less than $300 each. However, the pleasure received in home-brewing the Si5351 unit is immense. The Si5351 box is 1/10 the size of the IFR 2023. The Si5351 box is easily repairable. Some failures in the IFR 2023 can be extremely difficult to trouble-shoot, and in many cases, replacement parts are not available.

ARRL member Clint Chron W7KEC, holds an Amateur Extra Class license and has been continuously licensed since he received his Novice license (WL7DQP) in 1960. Several months later, his family moved to Texas and he became KN5HGF. He obtained his Conditional class license in 1961 as K5HGF. He got his Advanced class license in 1967 while in the Navy stationed at Treasure Island. He has over 50 years of technology experience, including several years in the cold war as a Nuclear Reactor Instructor at the US Navy Prototype testing site in Idaho and as a Reactor Operator on a fast attack nuclear submarine out of Pearl Harbor, Hawaii. After completing his Navy tour, he spent a number of years as a radio/microwave technician for the US Bureau of Land Management and US Forest Service in Alaska, Utah, Idaho, and Arizona. Clint retired as a Principal IT Hardware Engineer for the Charles Schwab Corp in 2013. Clint is passionate about designing and building ham radio equipment. His amateur station includes a Yaesu FTDX10, an Elad FMD Duo with TenTec 418 amplifier, and an Icom IC-7100 at his cabin in the Arizona White Mountains, plus a number of home-brew test equipment units.

References

[1] HP-8640 Service: Hints & Kinks
https://www.ve7ca.net/TstH86.htm

[2] HP8648 Signal Generator:
https://www.valuetronics.com/pub/media/vti/datasheets/Agilent%208648A,%208648B,%208648C,%208648D.pdf

[3] IFR 2023/2025:
https://www.valuetronics.com/pub/media/vti/datasheets/IFR%202023A,%202023B,%202025.pdf

[4] HP E4400 Signal Generator:
https://www.keysight.com/us/en/product/E4400B/esga-series-analog-rf-signal-generator-1-ghz.html

[5] ARRL Test Procedures Manual:
http://www.arrl.org/files/file/Technology/Procedure%20Manual%202011%20with%20page%20breaks.pdf

[6] The PA0KLT Low Noise VFO Synthesized Kit:
https://www.sdr-kits.net/PA0KLT-Kits

[7] Inside the Silicon Labs Si570 Programmable XO:
https://hifiduino.wordpress.com/2012/10/17/inside-the-silicon-labs-si570-programmable-xo/

[8] John Satterfield, KI5IDZ, john.satterfield@mindspring.com, 11900 Shoal Creek Dr
Frisco, TX 75035

[9] Clint Chron, W7KEC, kiheiman-spam@q.com, 1541 West Post Road, Chandler, AZ 85224

[10] QRP Labs Si5351 Oscillator with TCXO option
https://www.qrp-labs.com/images/synth/synth_assembly5.pdf

[11] Mini-Circuits Gali 6+ MMIC Amplifier
https://www.minicircuits.com/pdfs/GALI-6+.pdf

[12] Si5351A operation
https://rfzero.net/tutorials/si5351a/

[13] Hayward, "Oscillator Noise Evaluation with a Crystal Notch Filter" QEX, July/August 2008

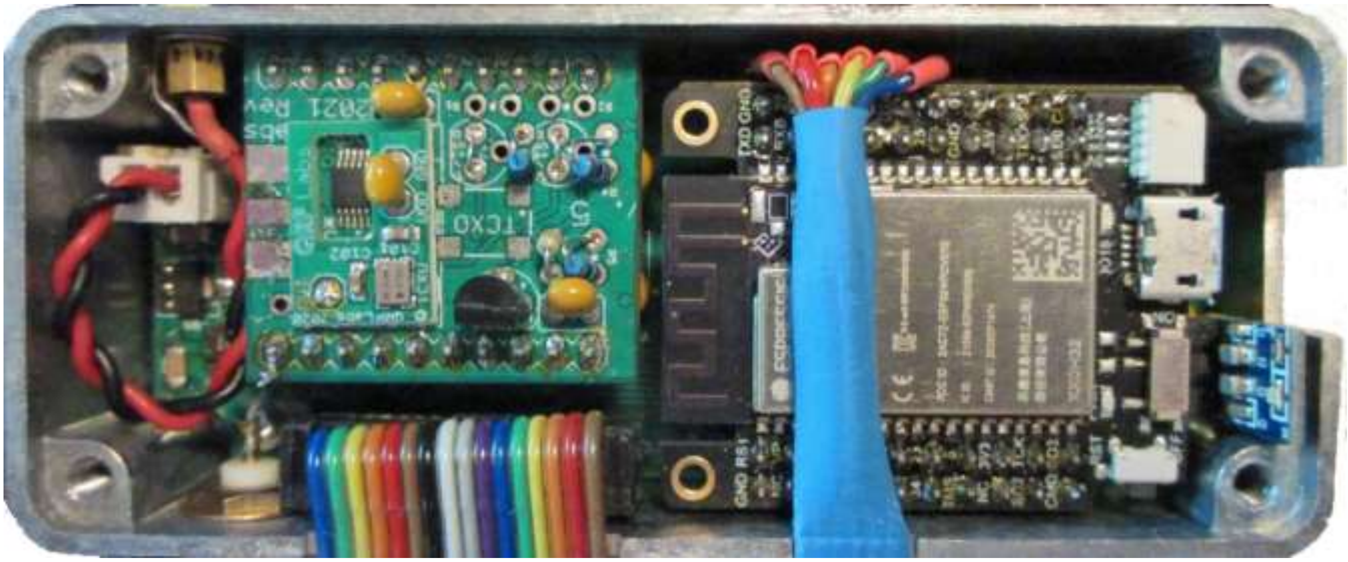
[14] Si5351A Phase Noise
https://qrp-labs.com/synth/phasenoise.html

APPENDIX

Figure 1 – Inside View

Figure 2 – Si5351 Module

+12 VDC IN



RF Out **To TFT Display & Front Panel Controls** **To Low Pass Filter**

Figure 3 – USB Programming Port

Figure 4 – System Block Diagram

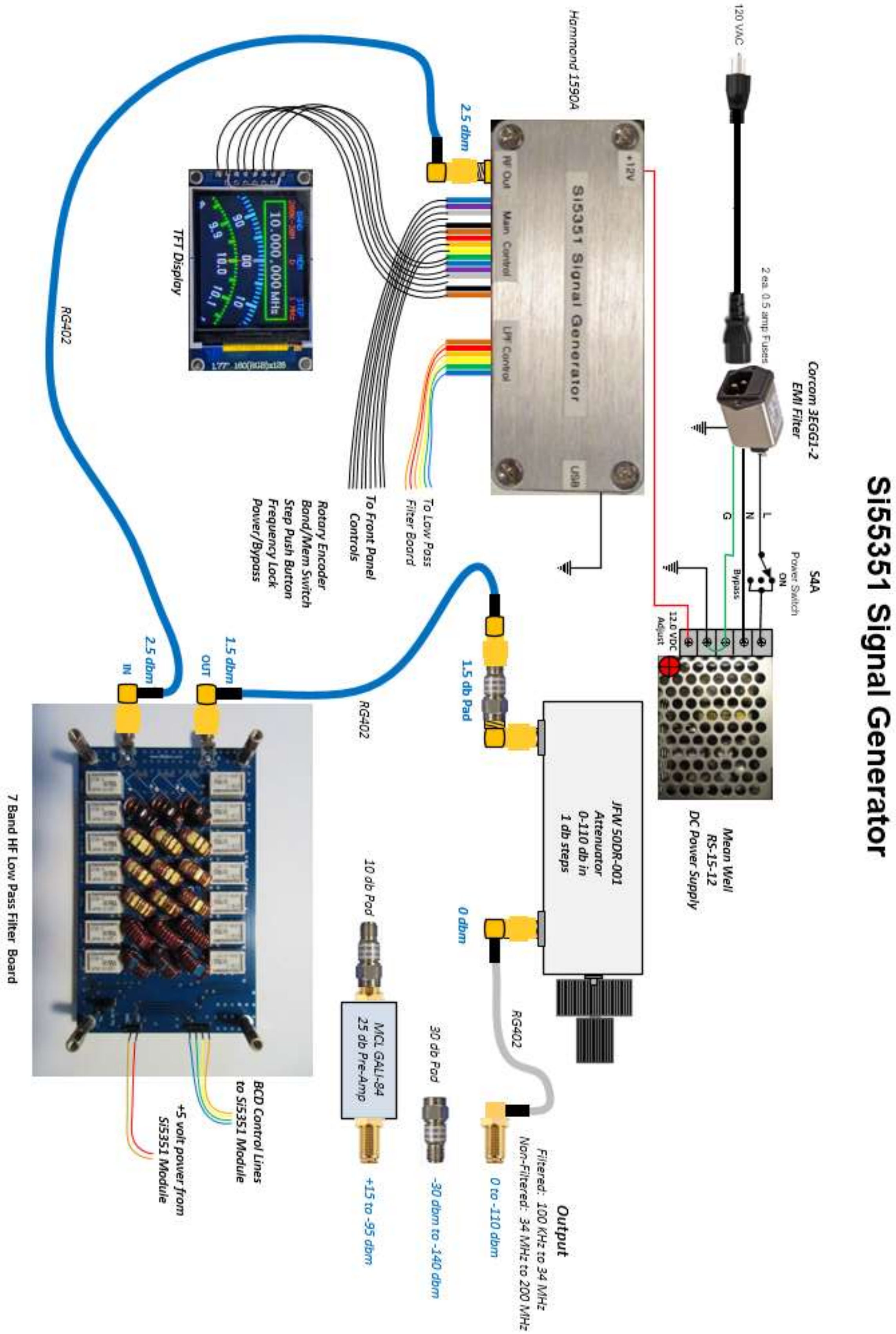


Figure 5 – Si5351 Interconnections

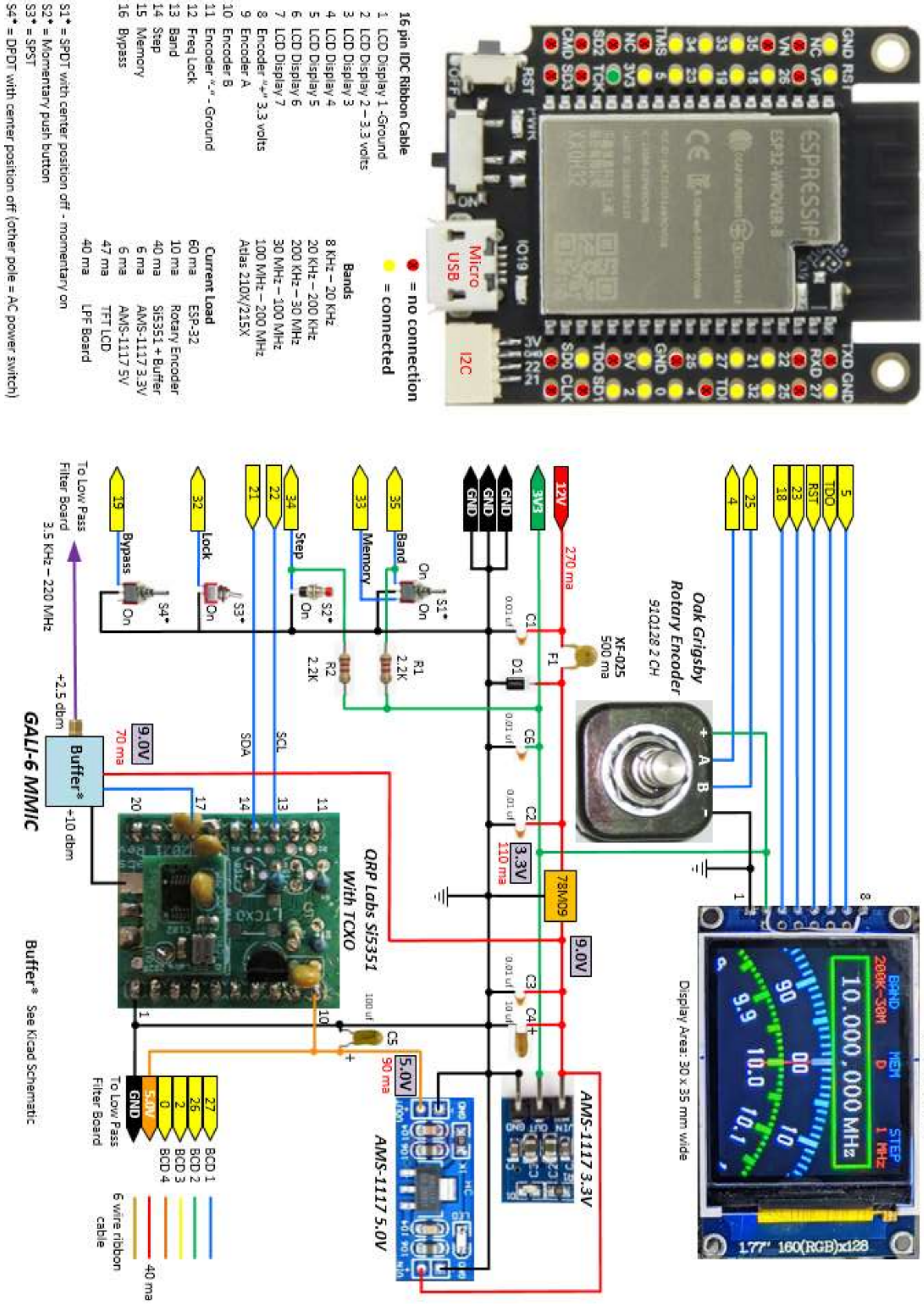


Figure 6 – Si5351 Schematic

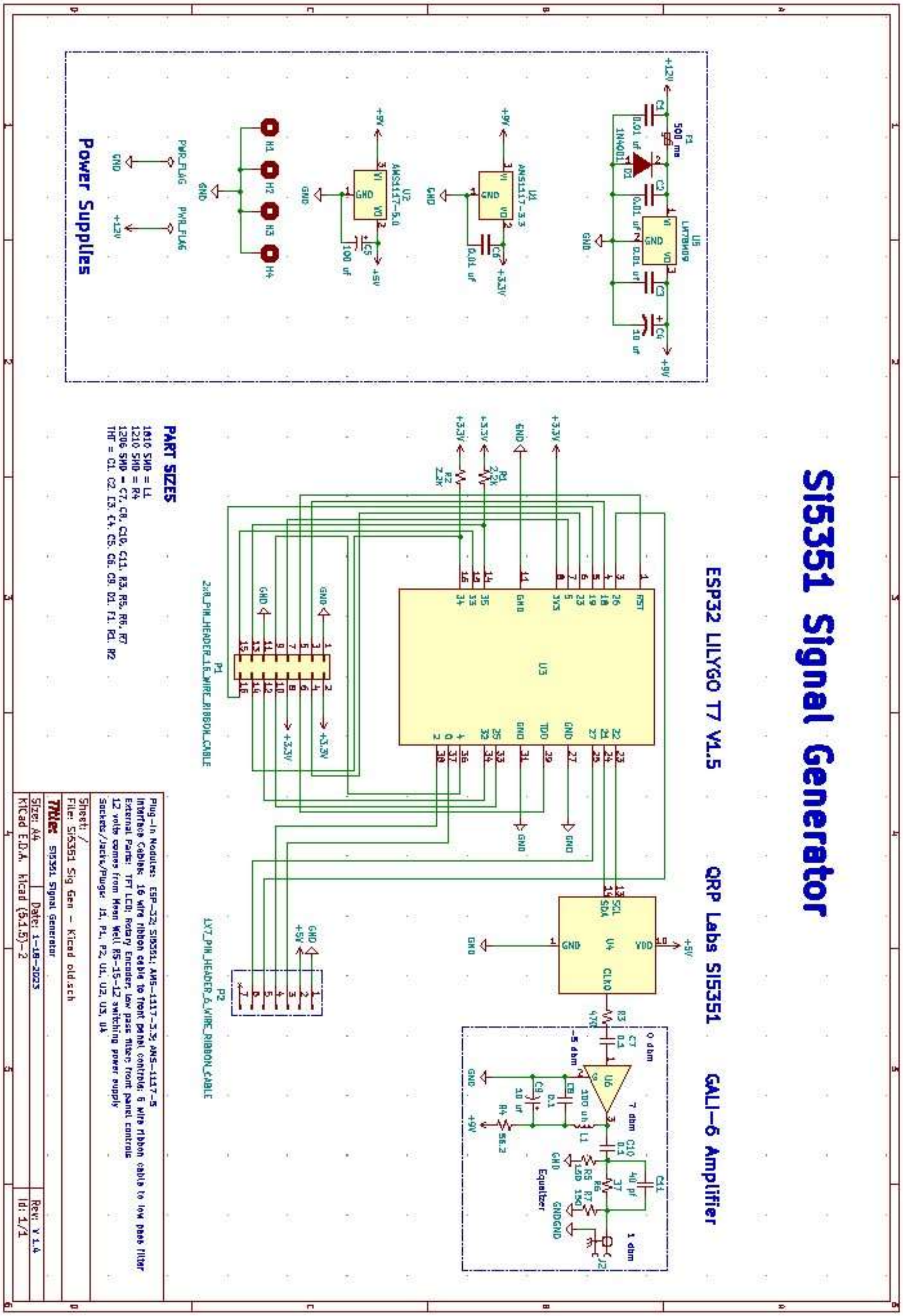


Figure 7 – Low Pass Filter Board – Top View

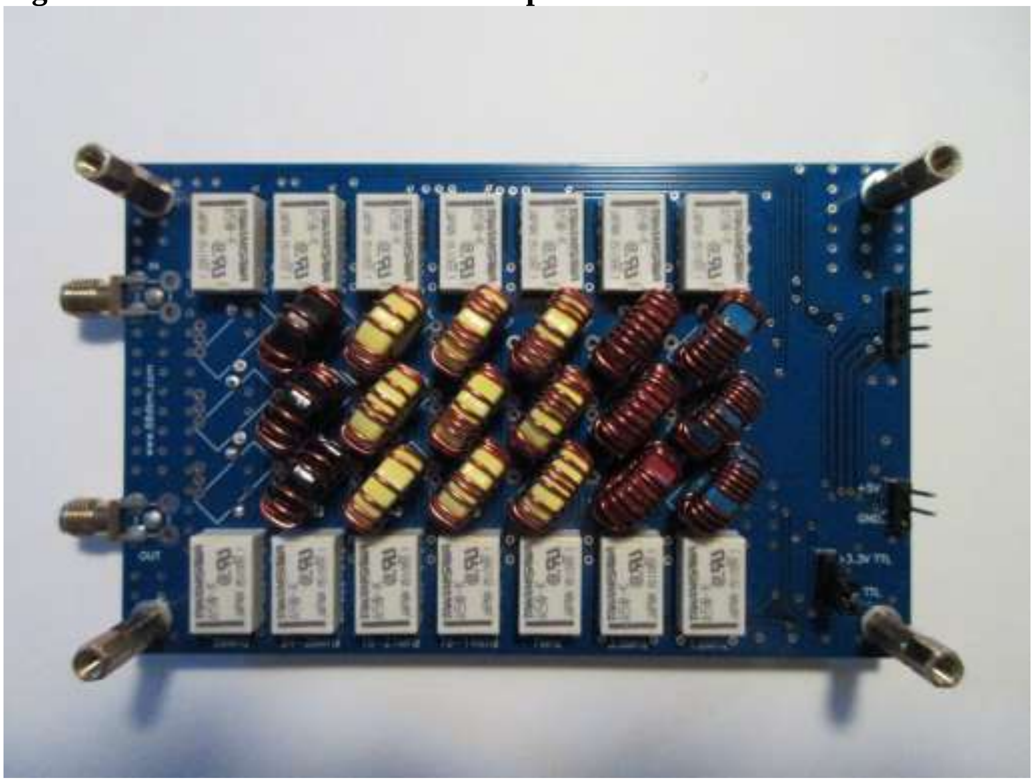


Figure 8– Low Pass Filter Board – Bottom View

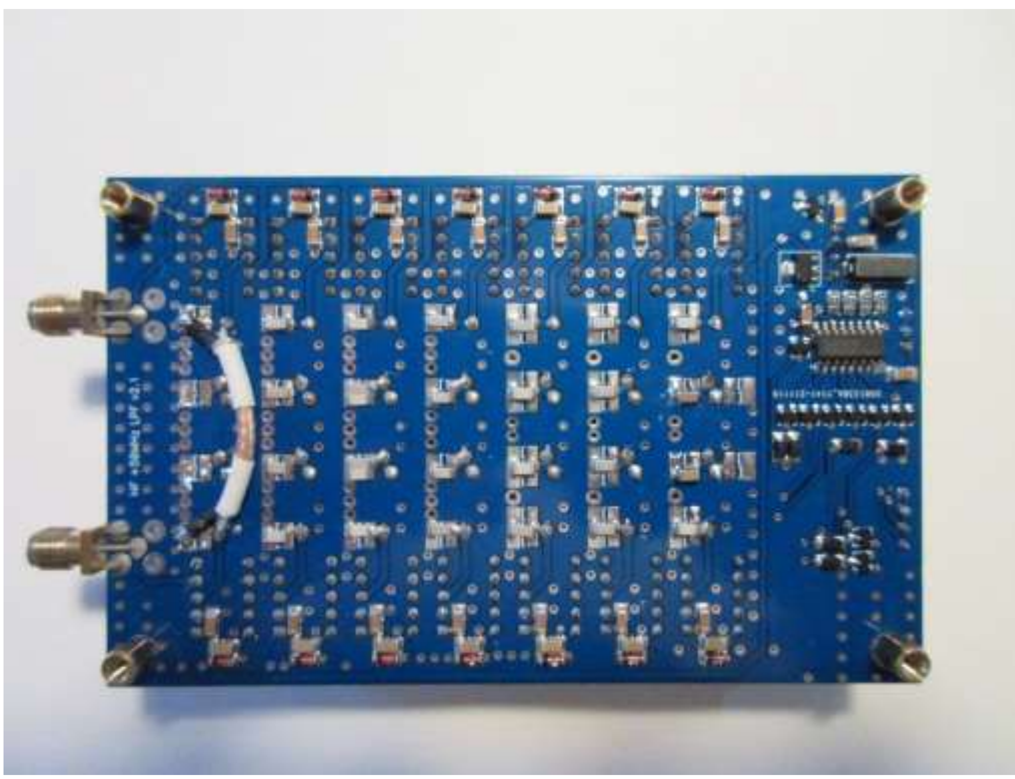


Figure 9 – Signal with no Low Pass Filter

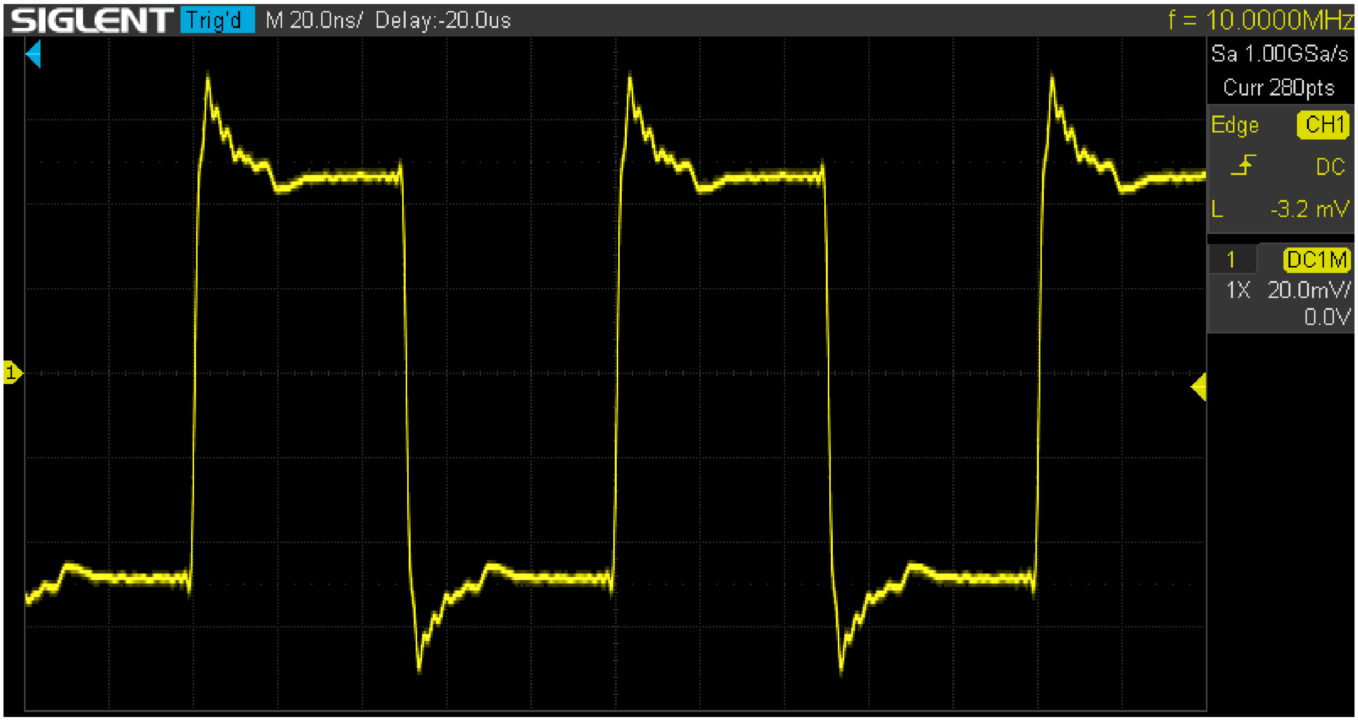


Figure 10 – Signal with Low Pass Filter

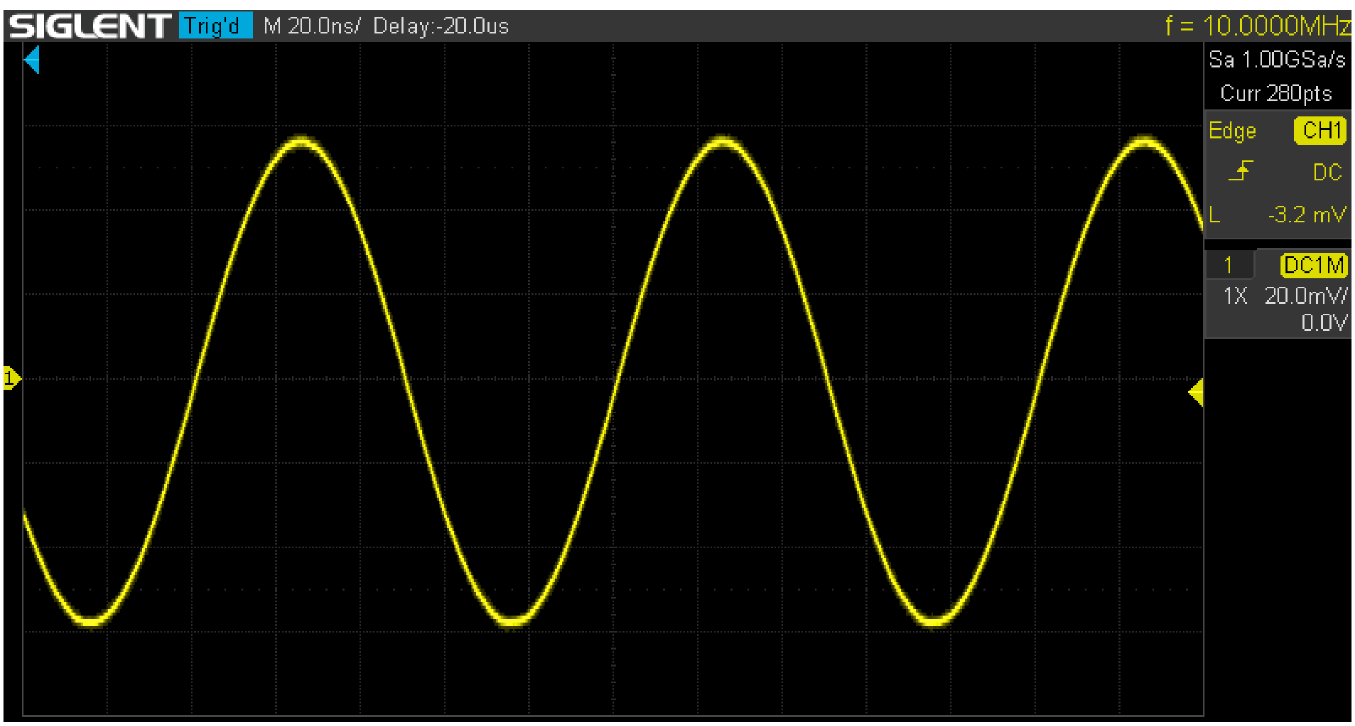


Figure 11 – Harmonics with no Low Pass Filter

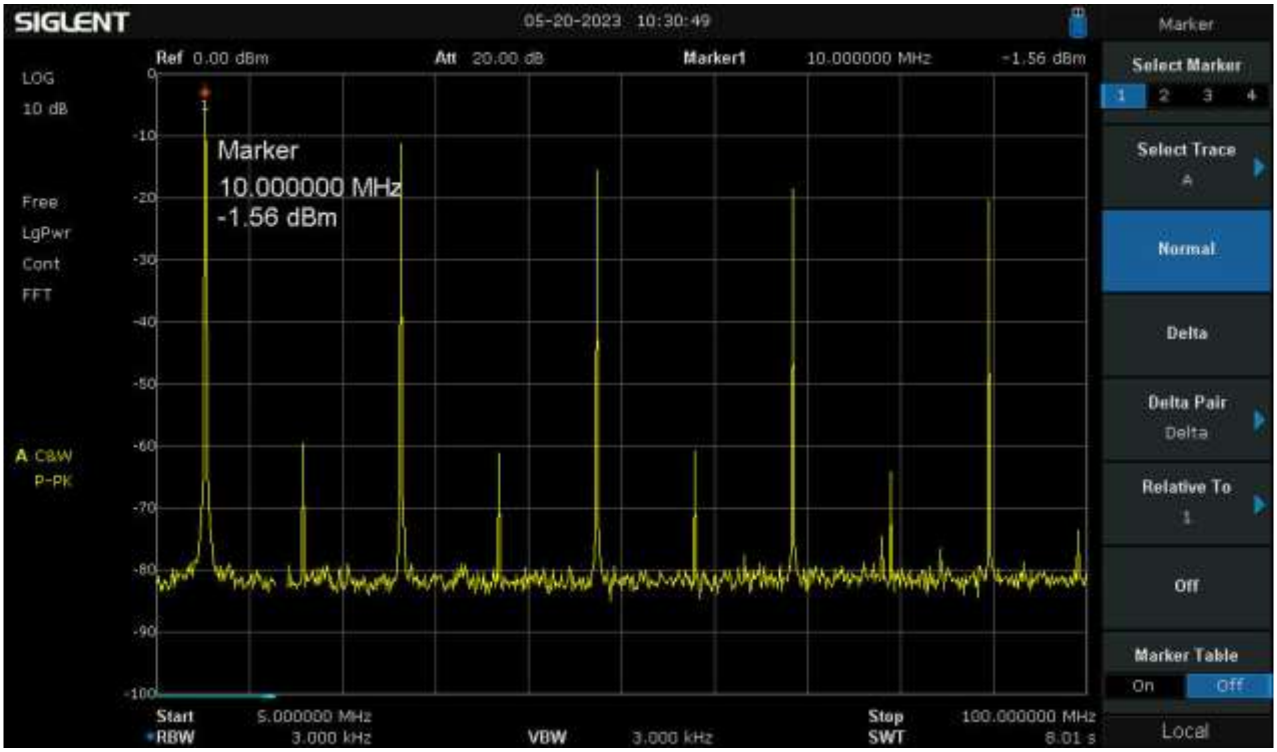


Figure 12 – Harmonics with Low Pass Filter

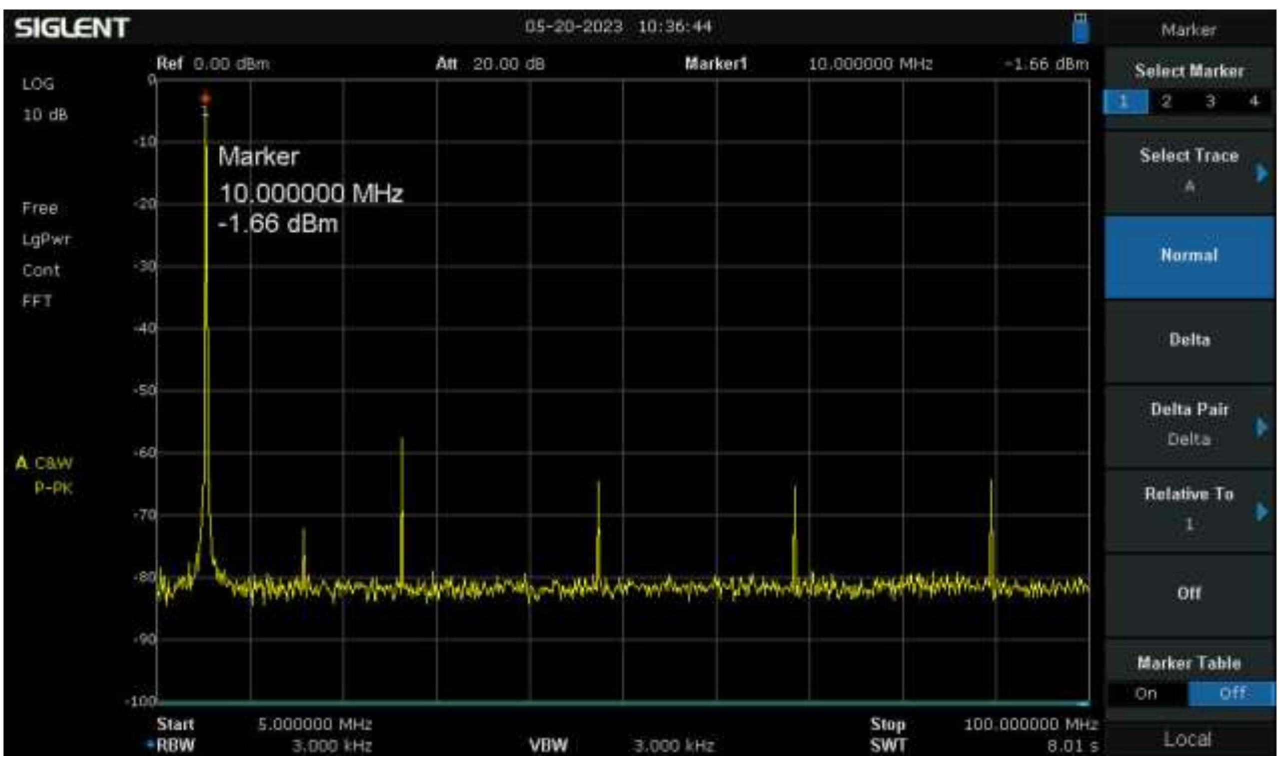


Figure 13 – Low Pass Filter Sweeps – Elsie Simulation

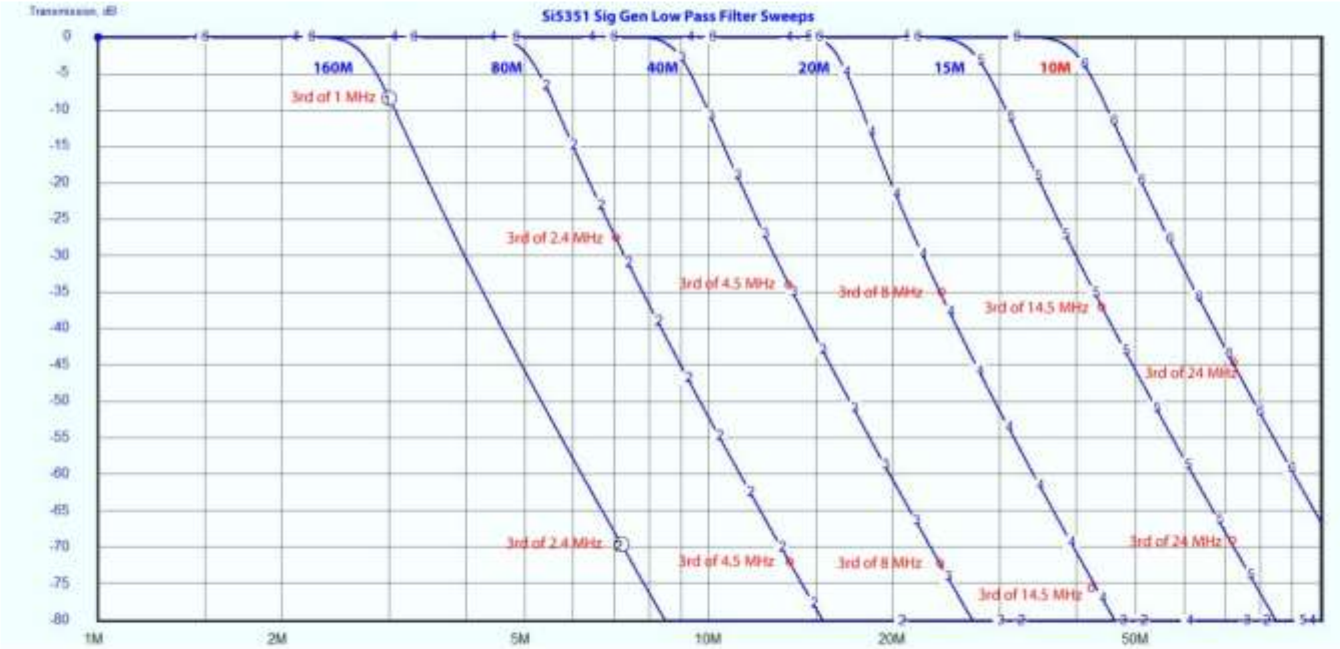


Figure 14 – Si5351 Warmup Frequency Drift

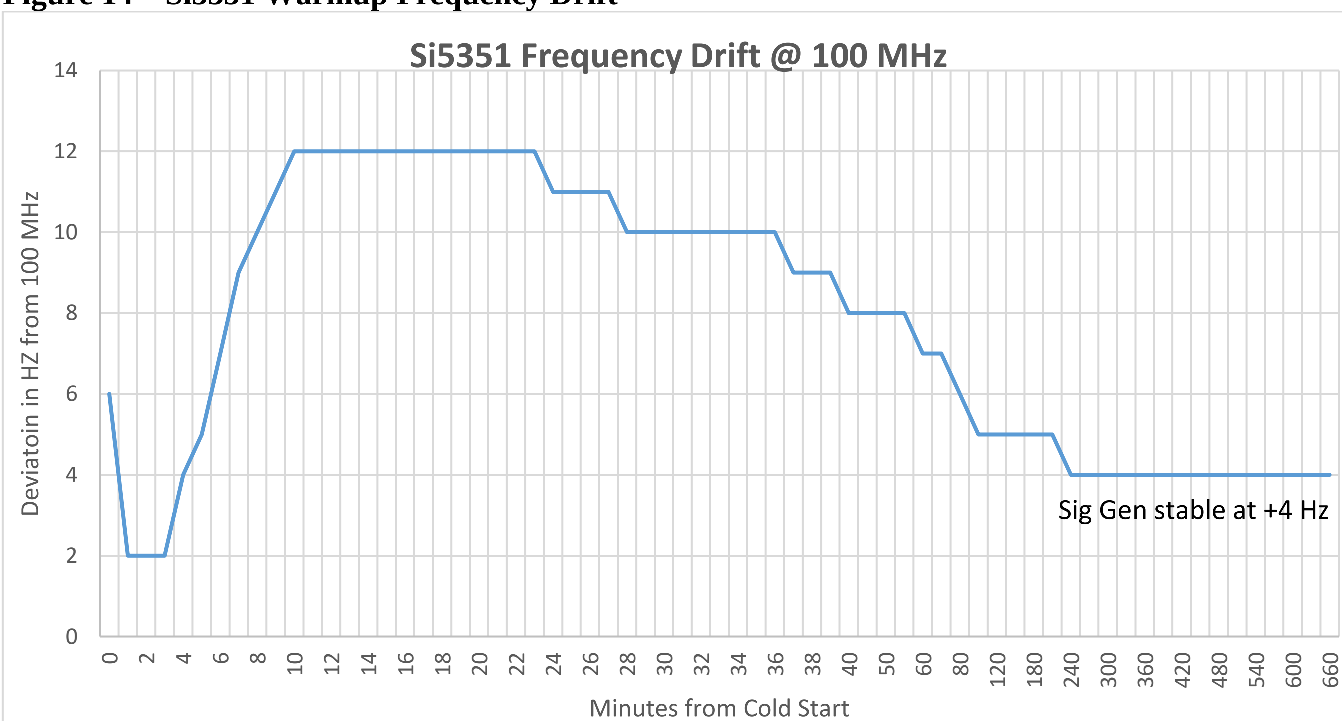
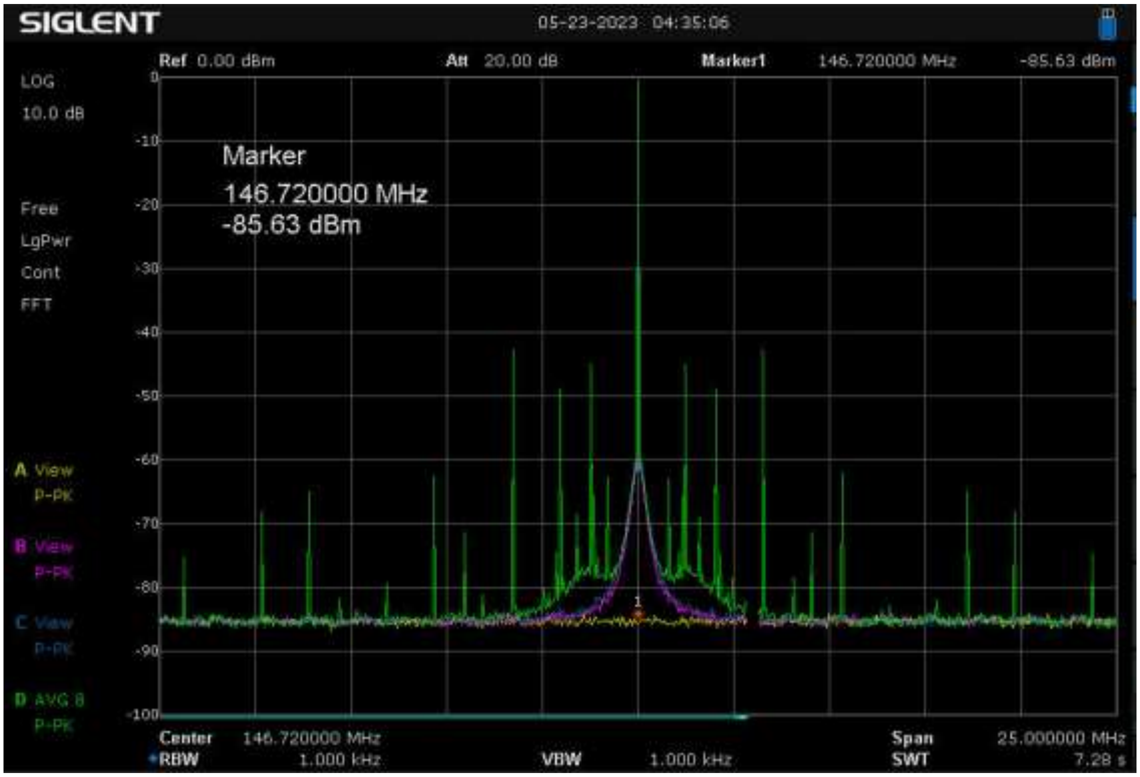
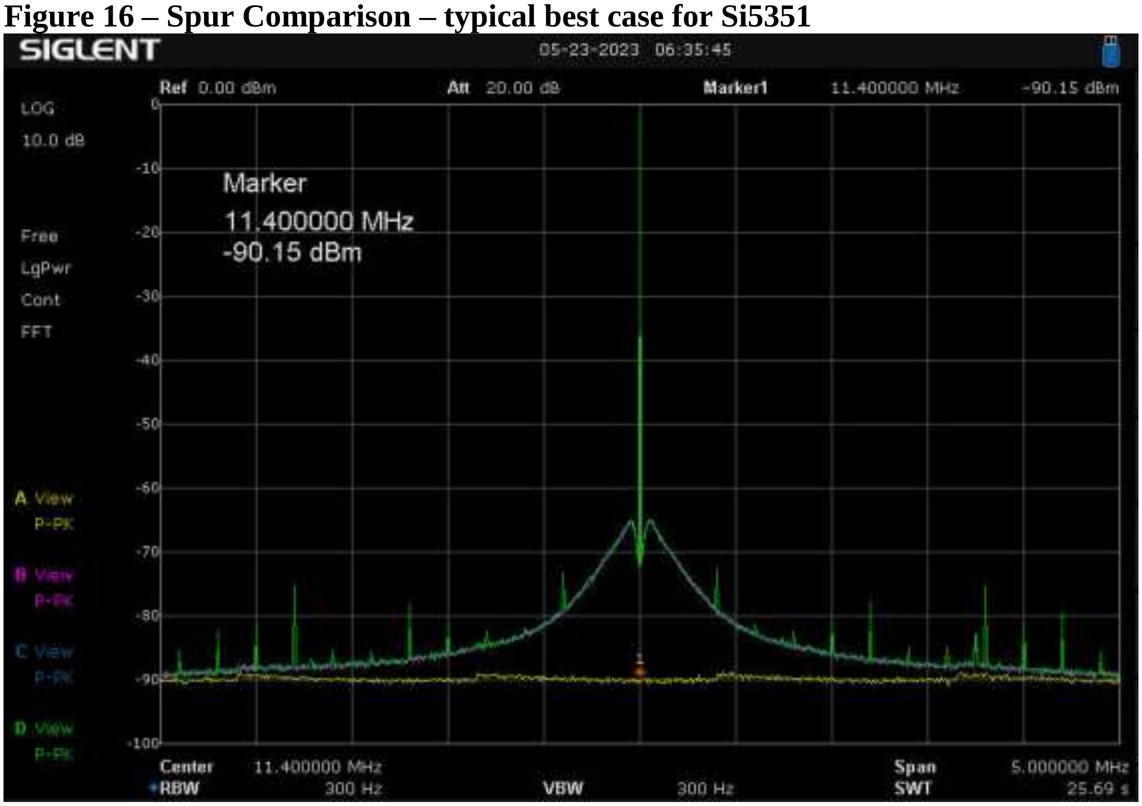


Figure 15 – Spur Comparison –typical worse case for Si5351 in VHF band



Yellow = SSA 3021X baseline Violet = IFR 2025 Blue = Si570 Green = Si5351

Figure 16 – Spur Comparison – typical best case for Si5351



Yellow = SSA 3021X baseline Violet = IFR 2025 Blue = Si570 Green = Si5351

Figure 17 – Si5351 Fractional Division

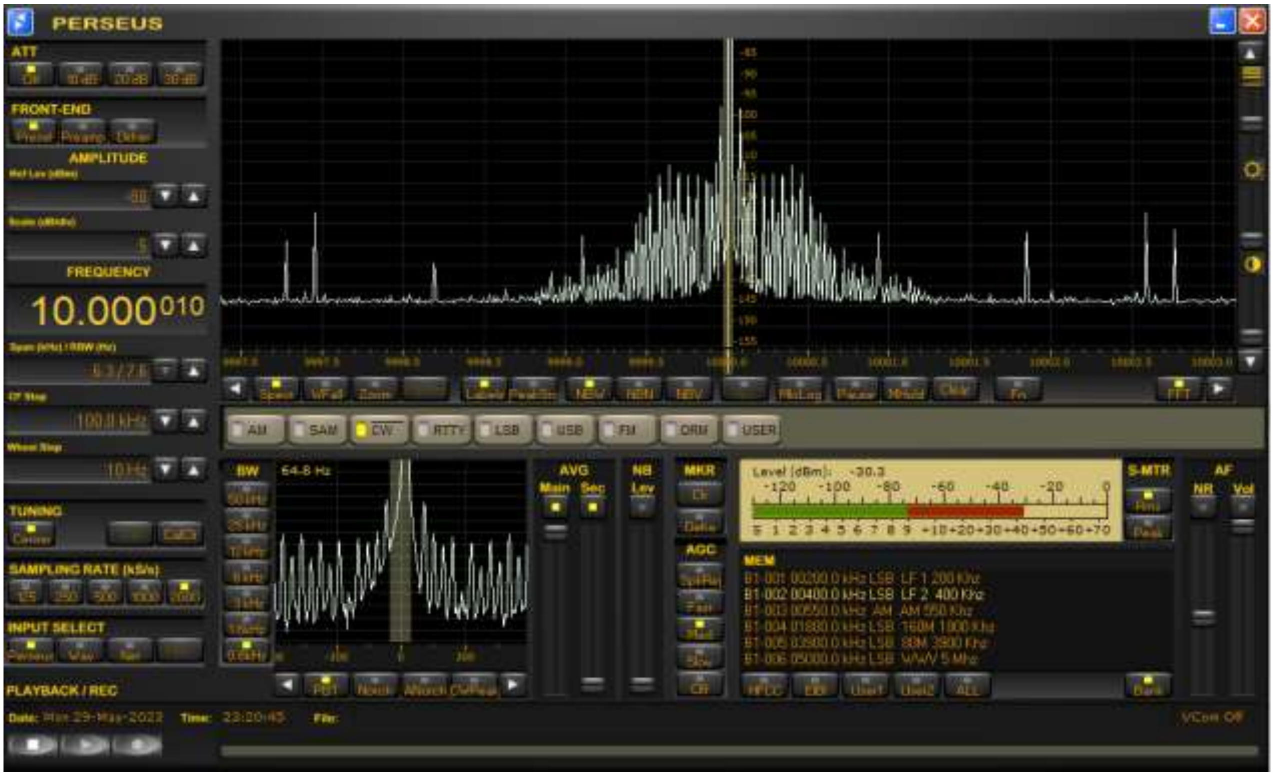


Figure 18 – Si570 No Fractional Division

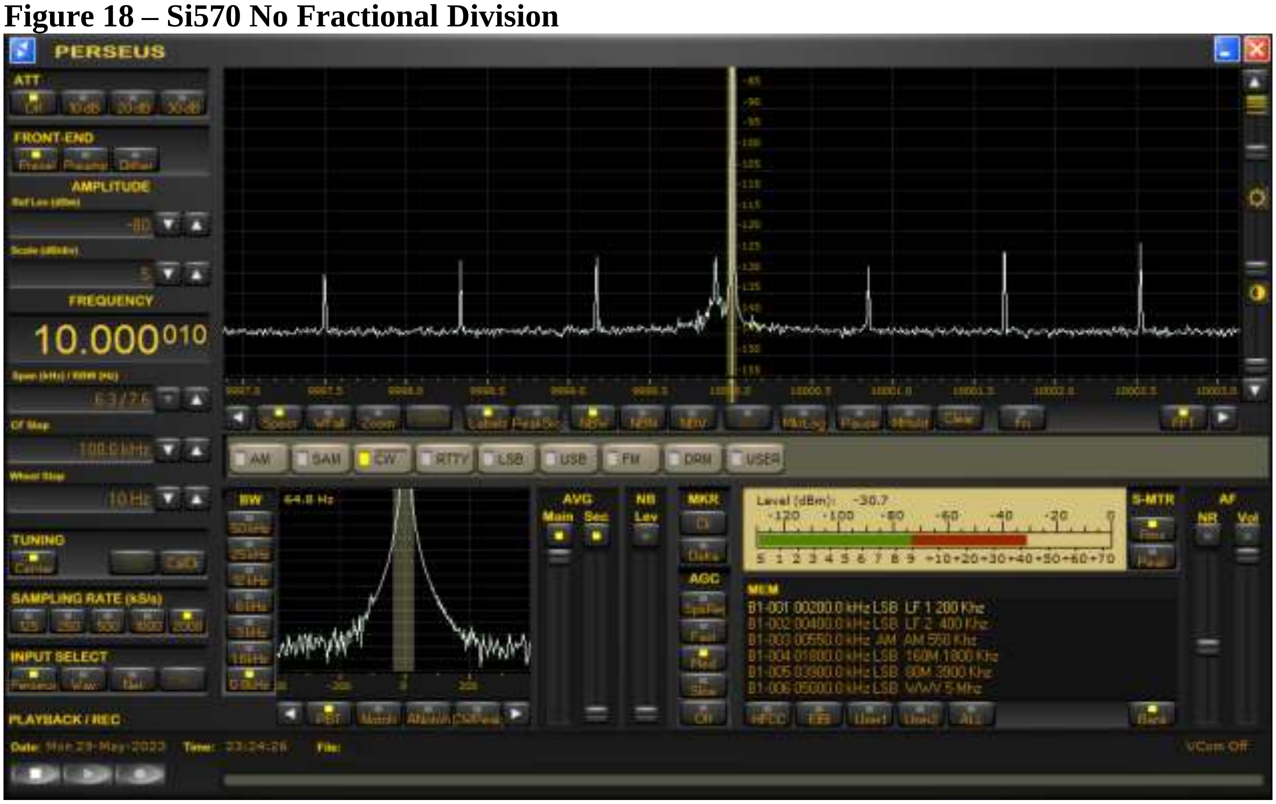


Figure 19 – Spurs Typical Best Case – Spurs Greater than 80 dB down

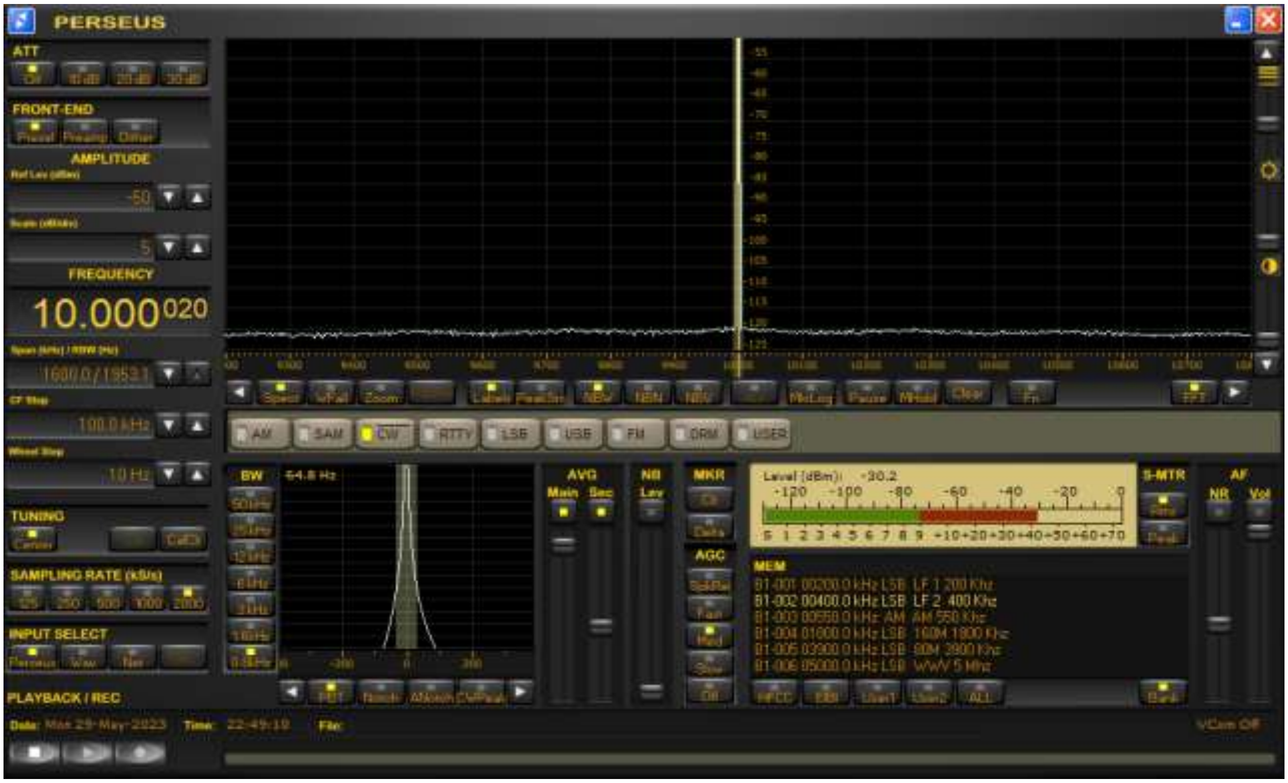


Figure 20 – Spurs Worst Case – Spurs Greater than 50 dB down

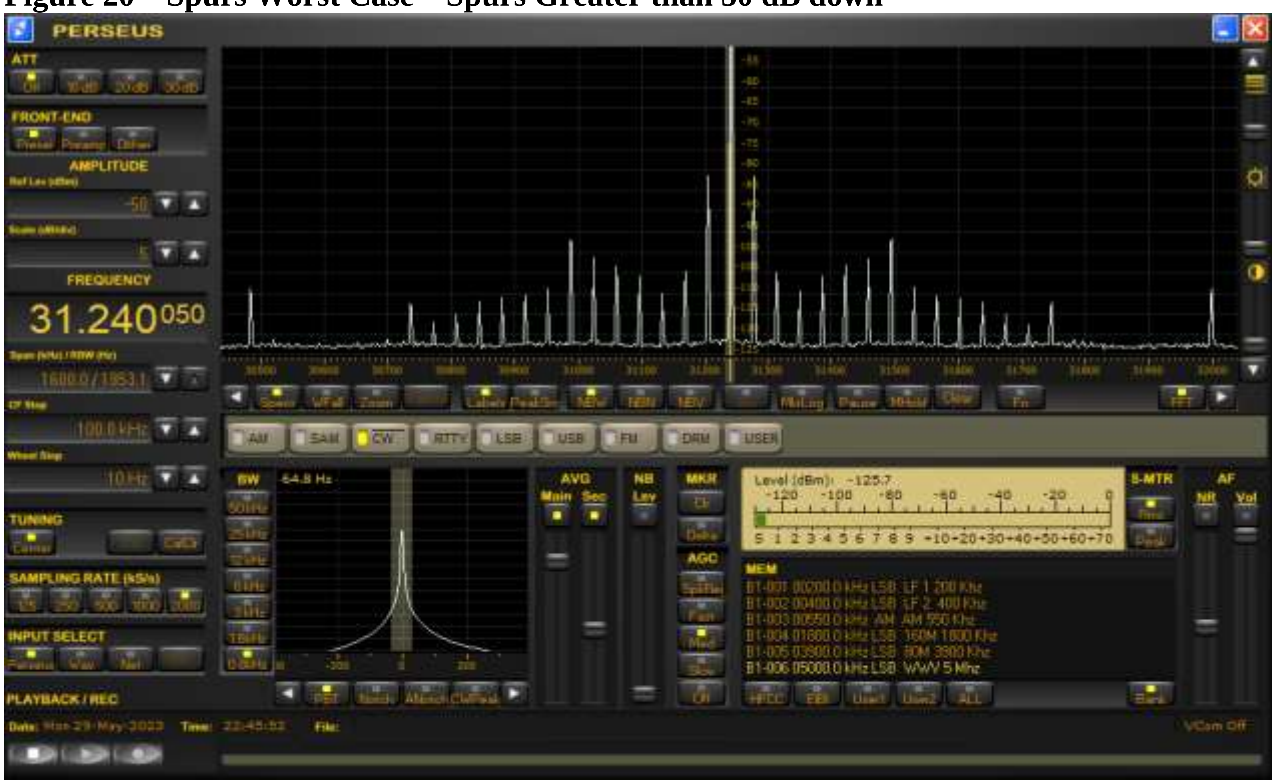
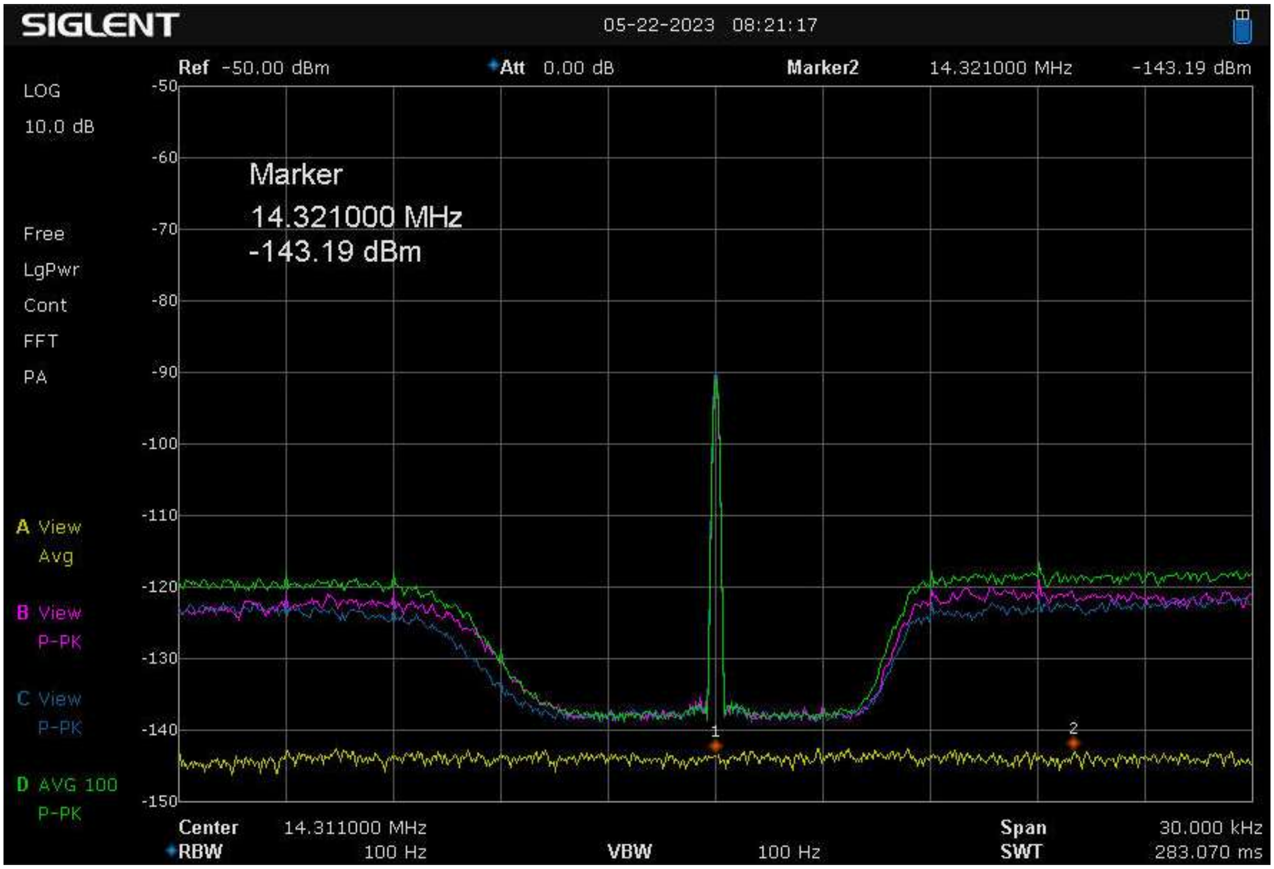


Figure 21 – Phase Noise Comparison



Yellow = SSA 3021X baseline   Violet = IFR 2025   Blue = Si570   Green = Si5351

Table 1 – Mini-Circuits SLP Low Pass Filters

MODEL	-1db PASSBAND	-3db CUTOFF
SLP-1.9	1.9 MHz	2.5 MHz
SLP-2.5	2.5	2.75
SLP-5	5	6
SLP-10.7	11	14
SLP-15	15	17
SLP-21.4	22	24.5
SLP-23	23	25
SLP-25	25	28
SLP-27	27	30
SLP-30	32	35
SLP-36	36	40
SLP-44	44	48.5
SLP-50	48	55
SLP-70	60	67
SLP-90	81	90
SLP-100	98	108
SLP-150	140	155
SLP-200	190	210
SLP-250	225	250