Development and Testing of a Low-Cost GPS RFI Emulation System

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BIOGRAPHY

Ken Johnston was the first military foreign national assigned to the US Joint Navigation Warfare Center (JNWC) in Albuquerque, New Mexico from 2009-2013 where he was involved in GPS Jamming Trials at White Sands Missile Range in New Mexico, at the Pacific Missile Range Facility in Hawaii, at the NATO Jamming Trial Unified Vision in Norway and at the Canadian Forces Base, Petawawa. He was recognized for his work as a GPS Analyst as recipient of the Commander US STRATCOM US Joint Service Commendation Medal. His life experience includes the Royal Canadian Air Force as an Air Combat Systems Officer (ACSO) retiring in 2014 after 36 years of military service. Previous presentations to CASI include GPS jamming and the DND Sapphire Space Surveillance project. Ken is a graduate of the US Air Force Institute of Technology, Wright-Patterson AFB, Ohio, USA and the Royal Military College of Canada. He has been the president of KTEQ GEOSPACE since 2015 and is based in Nova Scotia, Canada, specializing in GNSS Radio Frequency Interference (RFI).

ABSTRACT

This paper proposes a low-cost (less than $250 USD) emulation capability of low-power Global Positioning System (GPS) Radio Frequency Interference (RFI) that is representative of modernized GPS jammer waveforms and modulations. The proposed system is consistent with the policy and regulations for both Industry Canada Spectrum Management and US FCC while meeting the requirements of lab testing GPS RFI and assessing the impact on GPS receivers. During the past several years there has been a proliferation of GPS jammers also known as Personal Privacy Devices (PPDs) that have been well documented by NavCanada and in Institute of Navigation papers. In Canada, it is illegal to import, purchase, possess or operate a GPS jammer. These constraints present challenges for GPS RFI training and education, research and development, and for the GPS and satellite industry to develop and test detection and monitoring capabilities and to assess the impact of new RFI mitigation algorithms and techniques specifically designed to counter GPS RFI. During this research, GPS RFI signals were generated using a combination of low-cost wideband RF synthesizers, specifically RF evaluation boards and modules based on Analog Devices (AD) ADF4351 chip and a low-cost Direct Digital Synthesis FeelTech FY6300 Function/Arbitrary Waveform Generator. The equipment was configured to generate examples of GPS RFI including Continuous Wave (CW), multi-tone, stepped tone, chirp waveforms, pulsed, narrowband and wideband noise waveforms, and Pseudo Random Noise (PRN) waveforms that were tailored to closely match the relevant GPS RF spectrum but could be easily modified for other GNSS systems based on the needs of a user. The combination of the ADF4351 and the FY6300 effectively jammed a Ublox NEO-7N GNSS receiver using selected RFI waveforms.

KEYWORDS

GPS Radio Frequency Interference (RFI), GPS Jamming, Analog Devices ADF4351, FeelTech FY6300, DDS Arbitrary Waveform Generator (AWG), Software Defined Radio (SDR), AIRSPY R2, Signal Hound USB-SA44B, Signal Hound VSG25A, Ublox NEO-7N GNSS Receiver

INTRODUCTION

A presentation to the ICAO Regional Preparatory Group Workshop for the International Telecommunications Union World Radio Conference in February 2018 in Mexico City by Mitch Jevtovic with Nav Canada highlighted the results of ground and flight testing of Personal Privacy Devices (PPD). Over the period of six months of data gathering of PPDs in the vicinity of Toronto Pearson International Airport a total of 604 GPS Jammer events were recorded [1]. There were no significant consequences to airport operations during this period. As part of his research, several PPDs were tested against an airborne GPS receiver at the Canadian Forces Base (CFB) Petawawa. An example of a PPD previously tested at CFB Petawawa is shown in Figure 1.

Figure 1 - Example of Personal Privacy Device

In response to the growing proliferation of jammers over the past decade, the Canadian government and Industry Canada have updated regulations and policies on PPDs:

"The importation, manufacturing, distribution, offering for sale, sale, possession and use of radio communication jamming devices in Canada are prohibited under sections 4, 9 and 10 of the Radio Communication Act."

"A conviction under the Radio Communication Act carries a fine of up to $5,000 and/or imprisonment not exceeding one year (individual) or a fine of up to $25,000 (corporation), as well as forfeiture of the radio apparatus and possibly an injunction to refrain from activity related to the offence". [2, 3, 4].

Although there has been an increase in the use of PPDs in Canada, the testing of these devices and the development of countermeasures is somewhat difficult because government policies prevent the unauthorized purchase of PPDs. The legal restrictions which limit access to GPS jammers can present challenges to industry and academia for testing, detection, spectrum monitoring, recording and playback verification and validation, as well as algorithm mitigation development against real world GPS jamming threats.

In the United States, RF Signal Generators, fall under the definition of "*Exempted Devices*" specifically "*a digital device used exclusively as industrial, commercial, or medical test equipment*" under the Code of Federal Regulations (CFR), Title 47 Chapter 1 Sub-chapter A Part 15 Section 15.103 [5]. Consistent with US law, it is not against the law in Canada to import, manufacture, distribute, offer for sale, sell or possess RF signal generators or function/arbitrary waveform generators. To confirm this point, the Government of Canada actually sells used RF Signal Generators that cover the GPS L1/L2/L5 Frequency Spectrum on the Government of Canada GCSurplus, Buy and Sell website. Over the past few years, the Gov of Canada has sold more than 16 RF Signal Generators, several of which were capable of generating at least 10 dBm of RF signal output at GPS frequencies. In some examples the equipment sold may have required repairs prior to actually being functional. In one example, a Hewlett Packard 83640B model previously used by the Canadian Department of National Defence was sold by GCSurplus for $5K (CDN) in August 2020 [6]. This particular model operates from 10 MHz to 40 GHz and has up to 10 dBm of power output.

RF vector/signal generators and waveform generators are used by industry and academia to legally emulate actual GNSS jammer signals as an alternative to using actual PPDs for testing GNSS interference. During GPS RFI testing in 1998 at the US Air Force Institute of Technology at Wright Patterson AFB, Dayton, Ohio, a Hewlett Packard (HP) RF Signal Generator HP8643A was used to generate CW and Swept CW signals at GPS L1 band and the results were viewed on a HP Spectrum Analyzer (HP 8563A) while the effects were observed on a survey grade GPS receiver, as shown in Figure 2. The results were reported in technical papers at the Institute of Navigation in Nashville, TN in September 1999 and at the CASI conference in Ottawa in May 2000 [7,8]. The sponsor for this original research was the Canadian Department of National Defence.

Figure 2 - GPS RFI Equipment Lab Test Setup US Air Force Institute of Technology 1998

A brief review of manufacturers of modern RF test equipment highlights the frequency and power level outputs of RF signal generators available for purchase in the US and Canada that covers the GNSS Frequency spectrum. A few select examples include the Rohde and Schwarz R&S SMW200A Vector Signal Generator (18 dBm) [9], Tektronix TSG4102A RF Vector Signal Generator (16.5 dBm) [10], Keysight CXG RF Vector Signal Generator N5166B (18 dBm) [11], Rigol DSG821 RF Signal Generator (13 dBm) [12], and the Signal Hound VSG25A (10 dBm) [13]. These systems are representative of equipment capabilities that could be used for emulating GPS RFI by government, industry and universities. For this paper, a Signal Hound VSG25A was used for generating reference test signals for comparison to the ADF4351 outputs.

In this research, an alternative to GPS RFI Emulation using low-cost commercial-off-the-shelf (COTS) hardware and software is developed and discussed. GPS RFI signals were generated using a combination of a wideband RF synthesizer, specifically RF Evaluation Boards based on Analog Devices (AD), ADF4351 module [14, 15] along with Direct Digital Synthesis (DDS) Signal/Function/Arbitrary Waveform Generators (AWG) such as the FeelTech FY6300 [16], FeelElec FY6900 [17], Juntek PSG9080 and Juntek JDS2800. For this paper, the FeelTech FY6300 was the primary AWG used along with the associated software program for uploading specific user developed arbitrary waveforms.

The equipment was configured and optimized to generate examples of GPS RFI including Continuous Wave (CW), Multi-tone, Stepped Tone, Chirp, Pulsed, Narrowband and Wideband Noise Waveforms, and Pseudo Random Noise (PRN) waveforms that were tailored specifically to align with the associated GPS RF spectrum but could be easily modified for other GNSS RF Spectrum based on the needs of a user. The recording and evaluation of the generated RFI waveforms was limited to the use of low-cost spectrum analyzers, Software Defined Radios (SDR) and U-blox receivers.

AIM

The aim of this research was to develop a simple, user-friendly and low-cost (under $250 USD) system for generating effective and repeatable GPS RFI that could be used for testing, research and development, and training and education while at the same time complying with Canadian and US Government policies on GPS jammers. The paper will also highlight some precautions that should be followed to understand and avoid potential GNSS interference for real world GNSS users while conducting GNSS RFI lab testing.

GPS RFI THEORY REVIEW

Pulse Width, Bandwidth and RF Spectral Power

Many electronic and Radar text books describe the fundamental principles of the relationship between Pulse Width (PW) and Bandwidth (BW). An excellent explanation of the spectrum of a pulsed signal can be found in Chapters 16 and 17 by Stimson [18]. *A key relationship to recall is that the null-to-null bandwidth of the central lobe of a single pulse is equal to two divided by the pulse width. As an example, for a 1,000 nano-second PW, the null-to-null BW is 1 MHz and the spectral central lobe is 2 MHz wide. Additionally, the spectrum of a coherent pulsed signal consists of a series of lines that occur at intervals equal to the Pulse Repetition Frequency (PRF) on either side of the center frequency and fit with an envelope having a sin x/x shape with nulls at multiples of one divided by the pulse width above and below the center frequency.*

The GPS L1 C/A code signal spectrum of 1023 chips is transmitted at a rate of 1.023 MBps resulting in a single chip pulse width of 977.5 nanoseconds and the 1023 chips combine with a length of 1 millisecond. The corresponding spectral central lobe is +/- 1.023 MHz with each spectral side lobe having a spacing of 1.023 MHz and spectral lines spaced at 1 KHz apart [19, 20]. The Doppler shift of the center frequency of each GPS satellite varies by approximately +/- 5 KHz as satellites are moving towards and away from a static user.

As a starting point for emulating a GPS RFI signal by using an Arbitrary Waveform Generator (AWG), a pulsed signal with a PW of approximately 977.5 nanoseconds at a PRF of 1 KHz could potentially generate a similar power spectrum to the GPS L1 C/A code. A rectangular pulse with a fixed PW of 977.5 nanoseconds (ns) would set the null spacing of 1.023 MHz, and then a swept frequency could be used in an AWG to sweep the PRF spectral lines between 5 KHz and 20 KHz. In the FY6300 the nearest fixed ADJ-PULSE width setting is 980 ns. The spacing of the spectral lines for a coherent pulse train equals the PRF and as the PRF is increased the spectral lines move further apart.

The duty cycle of a single SQUARE waveform pulse at a frequency of 10 KHz can be adjusted on the FY6300 from the normal 50% to approximately 0.977% and 1.955% to create an equivalent rectangular PW of approximately 977 ns and 1955 ns respectively. The duty cycle of a 10 KHz rectangular pulse waveform can then be swept using the SWEEP mode between these two duty cycles which would be the equivalent of sweeping between these two pulse widths. Basically, the spectrum including nulls between approximately 511.5 KHz and 1.023 MHz are swept forward and back at a given sweep rate. An example of a square waveform Duty Cycle sweep using a Sweep Time of 1 second, with a Linear and Forward-Back Sweep, will be discussed in the results section of this paper.

Random Noise, Additive White Gaussian Noise (AWGN) and arbitrary Pseudo Random Noise (PRN) waveforms for creating a similar spectrum were also investigated as a source of GPS RFI. Because the noise waveforms are digitally synthesized, by selecting any of the FY6300 noise waveforms which consist of 8192 points and using the FY6300 at a fixed frequency of 124.87793 Hz, the user can optimize the pulse width of 977 ns and the corresponding spectrum null spacing of GPS L1 C/A code of 1.023 MHz. This was verified using an oscilloscope set to measure the actual PW of the individual pulses(chips) of Random Noise, AWGN, and a User Defined Custom PRN sequence of 8192 data points of the FY6300. See Figures 3A, 3B, and 3C for examples of the three noise waveforms (voltage vs time) and the associated pulse width as measured manually using both a Rigol 1202Z-E and a Hantek 6204BD oscilloscope (Note: 976 ns pulse width and the equivalent frequency/null spacing limitation of 1.024 MHz as measured manually on scope). Note the voltage differences of the Random Noise as compared to the AWGN. Examples of these three RFI waveforms are discussed further in the Results section of the paper.

Figure 3A – RANDOM NOISE (8192 data points x 124.877930 Hz) = Pulse Width of 977 ns = 1.023 MHz Nulls

Figure 3B – AWGN (8192 data points x 124.877930 Hz) = Pulse Width of 977 ns = 1.023 MHz Nulls

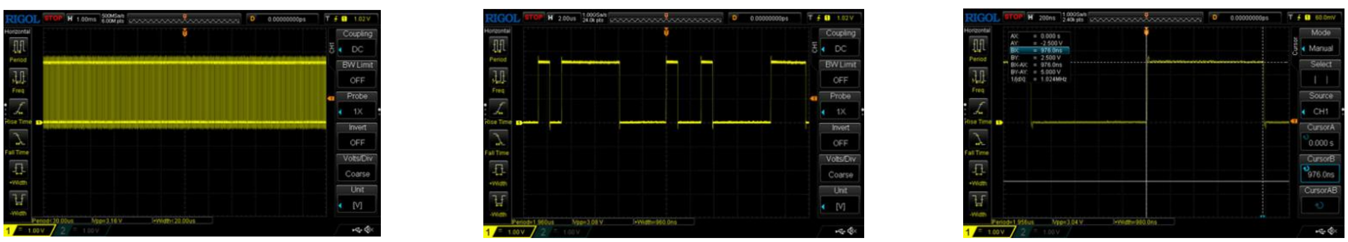

Figure 3C – User Defined PRN waveform (8192 “chips” x 124.877930 Hz) = PW of 977 ns = 1.023 MHz Nulls

Other GNSS specific RFI desired spectrum null spacings of 511.5 KHz, 2.5575 MHz, 5.115 MHz, and 10.23 MHz can be achieved by selecting a FY6300 Random Noise/AWGN waveform at the frequencies of 62.438965 Hz, 312.194824 Hz, 624.389648 Hz, and 1.248779297 KHz respectively. Channel Two of the FY6300 can be used to generate the required Binary Offset Carrier (BOC) square wave modulated with the noise waveform of the appropriate bandwidth from Channel One of the FY6300. The ADF4351 module is used to generate the center frequency for GPS L1, L2 and L5. An example of the GPS spectrum is shown in Figure 4. Examples of GNSS RFI regarding GPS L1 C/A, GPS L1C BOC (1,1), GPS L1 M Code BOC (10,5), GPS L2C, Galileo BOC (15,2.5), and GPS L5 are shown in the Results section of the paper.

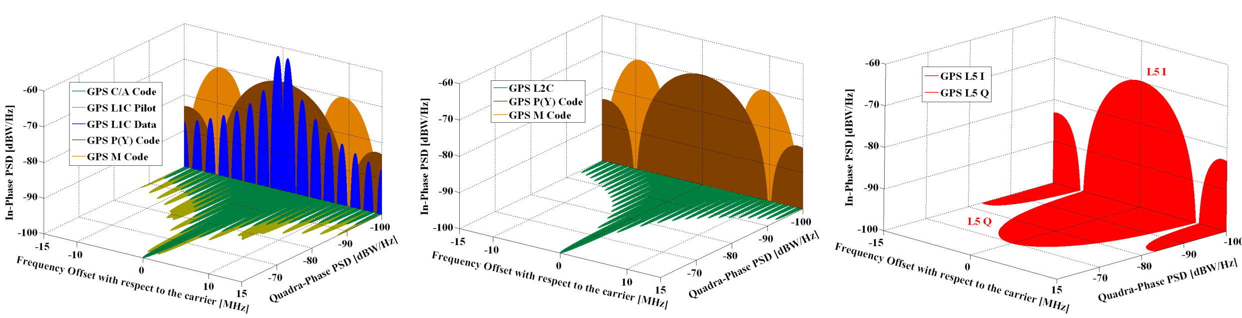

Figure 4 – GPS Signals Spectra [21]

RF Mixers

Mixers are typically used to change the frequency of an RF signal to an intermediate frequency (IF) using a local oscillator (LO). A key principle of using mixers is that when two sinusoidal signals are multiplied together, both the sum and difference of frequency components appear as shown in Figure 5. The system designer may choose to filter out unwanted signals and use either the upper or lower converted of the IF output signals. In the case of lower quality passive mixers, both harmonics and intermodulation products may appear in the output [22]. The reduced output signal levels, as a result of mixing of the RF signal and LO signal, could be a concern in a jammer design; however, in the case of lab testing, additional attenuation will still be required. In this research in generating a GPS RFI waveform, a mixer is used to combine a significantly lower frequency arbitrary waveform generated with a FY6300 AWG with a higher frequency RF signal generated in the GPS L1, L2, L5 or GLONASS L1 band using an ADF4351 module. A mixer board using the Mini-Circuits RMS-11X was used in this research, although it was operated outside the design specifications. The cost of this module was $12 USD.

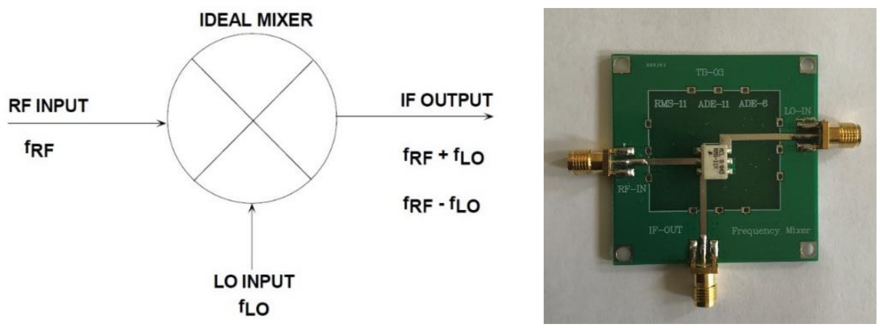

Figure 5 - Example of an Ideal Mixer and Actual Mixer [23]

Chirp Waveforms

As has been highlighted by J. Grabowski, R. Mitch and O. Towlson, et al [24, 25, 26], one of the design outputs of PPDs is the Chirp waveform. Chirp waveforms may be either linear or logarithmic and can have a variety of starting and stopping frequencies over a given time base. In a basic example a plot was generated using a starting frequency of 1 Hz and an ending frequency of 25 Hz over 1 second. From the Power Spectral Density (PSD) plot it can be seen that the energy is concentrated up to the ending frequency of 25 Hz as shown in Figure 6 [27]. Ideally an RFI signal would be designed to be centered on the GNSS band of interest.

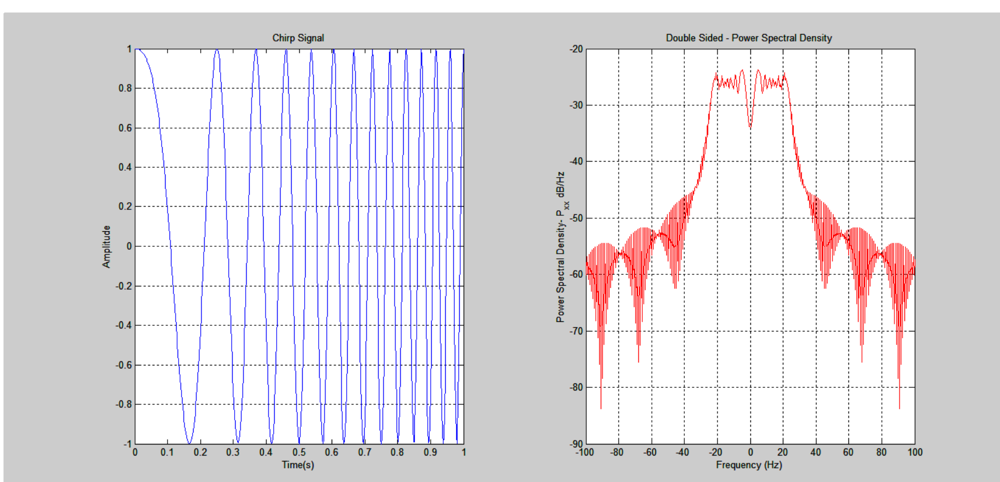

Figure 6 - Matlab Example of Chirp waveform from 1 Hz to 25 Hz

During this research, the built-in Chirp waveform in the FeelTech FY6300 was optimized for RFI for the civil GPS L1 and L2 signals using the AWG at a frequency of 10.7 and 5.35 KHz respectively. Customized User Defined Chirp waveforms can be generated using Mathworks Matlab or Microsoft Excel software and loaded and saved into the AWGs used in this research. Examples of the FY6300 Chirp waveform tailored to closely match with the spectrum of the GPS L1 C/A code and GPS L2 CM code are provided in the Results section of this paper.

RF Signal Generators and Power Levels

Modern RF Signal Generators can output at least 10 dBm. For RFI testing, a user should consider the output power levels of a signal generator at GPS L1 and typical Free Space Path Loss (FSPL) including other signal losses after the Signal Generator such as cable, connector and antenna losses, and antenna signal masking that might occur. Figure 7 was generated using the formula for a Free Space Path Loss (FSPL) of 20*log (4*π*D/λ) where λ is the wavelength of GPS L1 of 0.19042541 meters and D is the distance in meters between the RFI source and receive antenna [28]. The two plots are for an initial 10 dBm and a zero dBm signal. For a 10 dBm signal generated the power level at 100 meters would be approximately -66 dBm and for a 0 dBm signal -76 dBm respectively. Given that actual GPS signals received are on the order of -130 dBm, these levels of RFI signals may have an impact on GPS signal reception. RF attenuation is therefore required in order to lower this signal level for lab testing when injecting the RFI waveform into a GPS Receiver. This fact may not be apparent to users of RF Signal Generators. As a general rule, an antenna that operates in the GPS band should not be directly connected to an RF Signal Generator while generating signals in the GPS spectrum in the lab, unless the user is aware of the potential RFI that could be broadcast and takes the necessary precautions such as reducing the power output and the addition of mixers and attenuators.

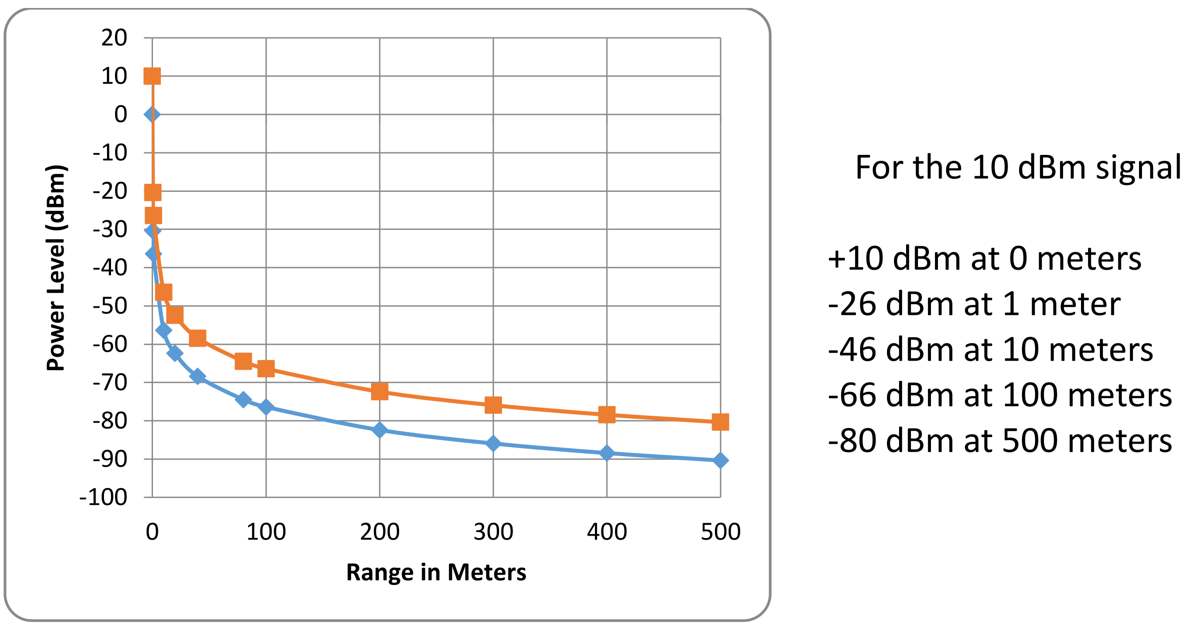

Figure 7 - RF Path Loss for GPS L1 Frequency for a 0 and 10 dBm signal over a range of 500 meters

COMMENT ON PERSONAL PRIVACY DEVICES (PPD) CHARACTERISTICS

The technical parameters of PPDs have been documented and discussed in many papers including J. Grabowski, R. Mitch and O. Towlson, et al [24, 25, 26]. These PPDs generate waveforms such as tones, Chirp, Pulsed, Narrowband or Wideband Noise and GPS L1 C/A code but many have capability deficiencies such as being well off of the center frequency and/or out of the GPS band, and mismatching of RFI with both actual GPS spectrum characteristics and power levels. It is expected that improvements in these deficiencies will be made in the coming years and moving forward will make use of improved low-cost RF signal synthesis and arbitrary waveforms that are more closely matched with the GPS signal spectrum.

ADF4351 WIDEBAND RF SYNTHESIZER

The ADF4351 is a wideband RF synthesizer with an integrated Voltage Controlled Oscillator chip made by Analog Devices (AD) and is capable of generating an RF signal between 35 MHz and 4.4 GHz up to 5 dBm. Further technical details may be found in the ADF4351 specification sheet [14]. Of note, the RF signal output between 2.2 and 4.4 GHz is a sine wave; however, between 35 MHz and 2.2 GHz the output is a square wave. An ADF4351 Evaluation Board produced by AD is available for purchase both in the US and Canada either directly from AD or via DigiKey for approximately $175 USD as shown in Figure 8. In addition to the evaluation board, AD also provides evaluation software that is compatible with the AD Original Equipment Manufacturer (OEM) module as shown in Figure 9 [15]. As an alternative, low-cost evaluation boards (under $50 USD) are available on EBay that include the ADF4351 chip including a modified clone of the original board that includes the Cypress FX2LP (CY7C68013) USB microcontroller chip. The AD software also works with the clone modules that include the Cypress chip or alternatively standalone ADF4351 evaluation boards connected to a standalone Cypress chip module. Some RF enthusiasts may find the AD evaluation software useful for determining the HEX code to program the six memory registers of the ADF4351 when programming their own custom microcontroller such as an Arduino UNO or Raspberry PI [29]. More recently, RF modules/boards are available with an ADF4351 chip that is already integrated with a microcontroller and input/display interface providing RF signal generation without the requirement for using a PC or the AD evaluation software. Several examples of EBay clones of the OEM evaluation board and standalone ADF4351 boards with separate input and display are highlighted in Table 1 and discussed in the Results section of this paper [30].

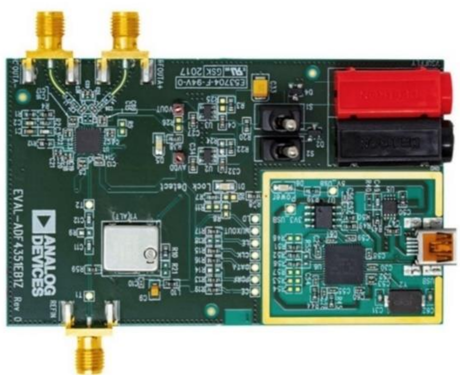

Figure 8 - Original Analog Devices ADF4351 Evaluation Board [31]

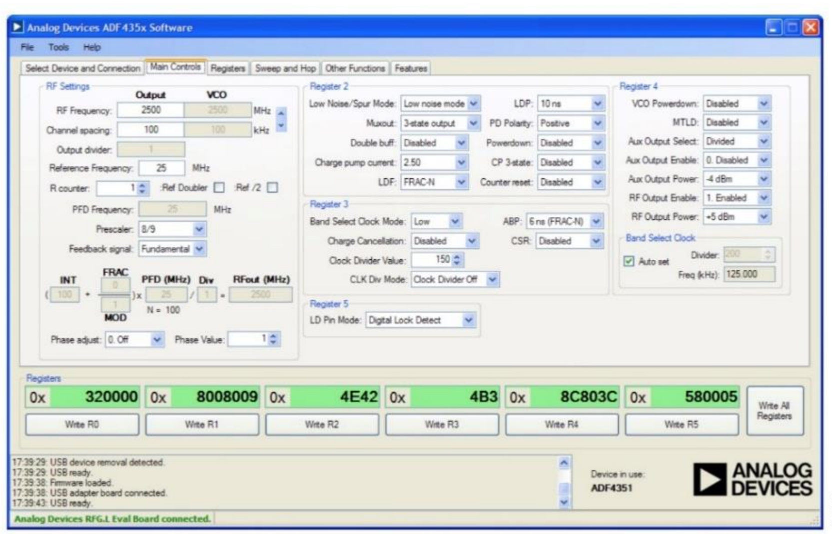

Figure 9 - ADF4351 Evaluation Software [32]

Table 1 - RF Wideband Synthesizer Evaluation Boards/Modules based on Analog Devices ADF4351 chip

						
MODULE NUMBER	AD ADF4351 Original Equipment Manufacturer (OEM)	ADF4351 (Module#1) Original Eval Board (clone)	ADF4351 (Module #2) standalone plus micro-controller plus input key panel and 1602 LCD	ADF4351 (Module #3) standalone plus micro-controller plus input Touch Screen	ADF4351 (Module #4) standalone plus micro-controller plus input key panel and OLED	ADF4351 (Module #5) standalone used with Arduino Uno and 1602 LCD shield
DESIGN	OEM (Available from AD or via Digikey)	EBay modified clone of original board includes Cypress FX2LP USB	EBay module with user input interface	EBay module with user input interface	EBay module with user input interface	EBay module with user specific designed / Arduino/ PC interface
AD ADF4351 PC EVALUATION SOFTWARE COMPATIBLE	YES Controlled via PC Software	YES Controlled via PC Software	NO Standalone Device	NO Standalone Device	NO Standalone Device	Standalone Device but user can add separate Cypress FX2LP
SINGLE TONE	YES	YES	YES	YES	YES	YES
FREQUENCY HOPPING	YES	YES	NO	NO	NO	YES
FREQUENCY STEPPING	YES	YES	User Control Manually	YES	YES	YES
POWER OUTPUT ADJUSTABLE	YES	YES	NO	YES	YES	YES
COST (USD)	$175	$45	$20	$40	$30	$25

FUNCTION/ARBITRARY WAVEFORM GENERATION

A summary of the capabilities of four low-cost Field Programmable Gate Array (FPGA) based Direct Digital Synthesis (DDS) Function/AWGs used initially in this research are included in Table 2. All of these models have a dual channel output. The results in this paper are focused on the use of the FeelTech FY6300. Further technical details can be found in the associated user manual for each of these AWGs [16, 17, 33, 34].

Table 2 – Function/Arbitrary Waveform Generator Features

	FeelTech FY6300(40M)	FeelElec FY6900(60M)	Juntek PSG9080(80M)	Juntek JDS 2800(60M)
				
SINE FREQ LIMIT	40 MHz	60 MHz	80 MHz	60 MHz
SQUARE WAVE LIMIT	25 MHz	25 MHz	30 MHz	25 MHz
ARB FREQ LIMIT	0-10 MHz	0-10 MHz	1-50 MHz	0-6 MHz
BITs	14 BITs	14 BITs	14 BITs	14 BITs
SAMPLE RATE	250 MSa/s	250 MSa/s	300 MSa/s	266 MSa/s
DATA POINTS	8192	8192	8192	2048
BUILT-IN WAVEFORMS	34	33	22	17
ARB WAVEFORMS	64	64	99	60
BUILT-IN CHIRP WAVEFORM	YES	YES	NO	NO
SWEEP DIRECTION	Forward/Back/ Both	Forward/Back/ Both	Forward/Back/ Both	Forward/Back/ Both
SWEEP TYPE	Linear/Log	Linear/Log	Linear/Log	Linear/Log
SWEEP TIME	0.01 to 999.99 secs	0.01 to 999.99 secs	0.01 to 640 secs	0.1 to 999.9 secs
MODULATION TYPES	FSK/ASK/PSK/ BURST/AM/FM/ PM	FSK/ASK/PSK/ BURST/AM/FM/ PM	FSK/ASK/PSK/ BURST/AM/FM/PM PWM	PULSE/ BURST
POWER SOURCE	DC(5V)/USB	AC/USB	AC/DC(5V)/USB	DC(5V)/USB
COST (USD)	$110	$114	$188	$82

GPS RFI EMULATION EQUIPMENT SETUP

Figure 10 outlines the set up for the GPS RFI Emulation and Testing. In some configurations the microcontroller and display are built into the ADF4351 module board negating the need for a PC interface. A laptop computer was required when using a USB based software defined radio as a spectrum analyzer along with the associated software.

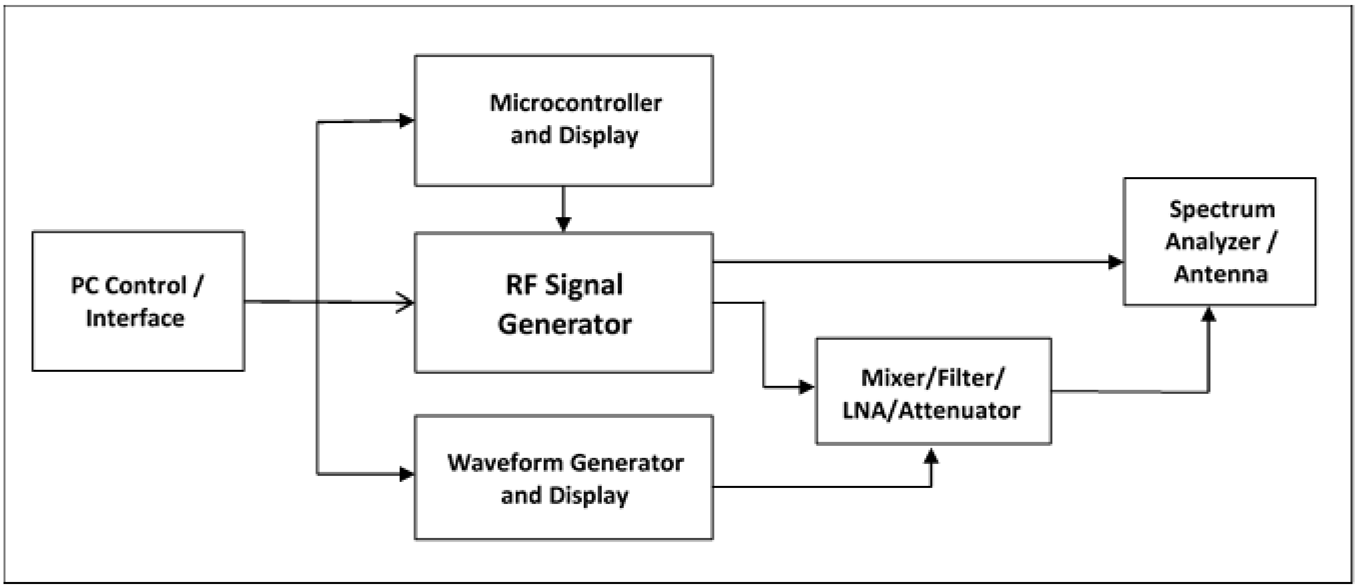

Figure 10 - GPS RFI Emulation Equipment Set Up

SOFTWARE DEFINED RADIOs (SDR)

Several low-cost SDR/spectrum analyzers used in this research are highlighted in Table 3. A Signal Hound USB-SA44B Spectrum Analyzer/Measuring Receiver along with the associated Spike Software Version 3.5.16 was used for measuring GPS RFI signal levels. The Signal Hound covers a frequency spectrum from 1 Hz to 4.4 GHz [35].

On the lower cost end several SDR based receivers were used in this research that are compatible with SDR# Software and Spectrum Spy Software. These included the AirSpy R2 (10 MHz), the AirSpy Mini (6 MHz), the RTL-SDR V2 (2.4 MHz) and an open-source clone of the original board by Great Scott Gadgets of a HackRF One (20 MHz) [36-39]. Note the HACKRF One was limited to receive only of 10 MHz when using the SDR# software. A wider spectrum span was captured in screen shots using the Spectrum Spy software program but it was noted that Airspy R2 RF spurs appeared at multiples of 20 MHz and these figures were not presented in the paper.

A gaming computer, an MSI GE75 Raider with an Intel Core i7 10th Gen 10750H, 16 GB RAM, a SSD, and nVidia GEFORCE RTX, was used for recording and playback of the Airspy R2 SDR# I&Q Wave files and the Signal Hound USB-SA44B Spike SHR files.

Table 3 - Software Defined Radios [35, 36, 37, 38, 39]

	RTL-SDR (V2)	AIRSPY MINI	AIRSPY R2	HACKRF ONE (Clone)	SIGNAL HOUND USB-SA44B
					
FREQ RANGE	24 MHz – 1.766 GHz	24 MHz – 1.8 GHz	24 MHz – 1.8 GHz	1 MHz - 6.0 GHz	1 Hz to 4.4 GHz
MAX BANDWIDTH	2.4 MHz	6 MHz	10 MHz	20 MHz	250 KHz / SPAN up to 4.4 GHz
ADC RESOLUTION	8 BITS	12 BITS	12 BITS	8 BITS	24 BIT ADC converted to 16 BIT I&Q
BIAS TEE / ACTIVE ANTENNA	Not used (but avbl on V3 units)	YES	YES	YES	NO
SOFTWARE	SDR# v1.0.0.1700	SDR# v1.0.0.1700	SDR# v1.0.0.1700	SDR# v1.0.0.1700	SPIKE v3.5.16
TX/RX	RX ONLY	RX ONLY	RX ONLY	HALF DUPLEX	RX ONLY
COST (USD)	$25	$99	$169	$120	$1020

UBLOX NEO-7N GNSS RECEIVER

Although capable of receiving multiple GNSS satellite constellations, the Ublox NEO-7N GNSS receiver was constrained to receiving only GPS and WAAS satellites. The U-Center software provided by Ublox, shown by the workspace setup in Figure 11, provides the user the capability to record and replay GNSS data in specific NMEA and UBX format. Ublox receivers including the LEA-6N, NEO-7N, and NEO-M8N provide the user the ability to log NMEA data of interest such as the number of satellites used in the navigation solution and satellite SV C/No as well as Ublox specific receiver data including RFI related tools such as Automatic Gain Control (AGC), Jamming Detection Indicator, and Noise Level (GPS) [40, 41, 42]. Selected GPS RFI signals from this research impacted the Ublox NEO-7N receiver and confirmed some of the capabilities of the Ublox receiver for detecting and flagging GPS RFI. Examples are provided in the Results section of the paper.

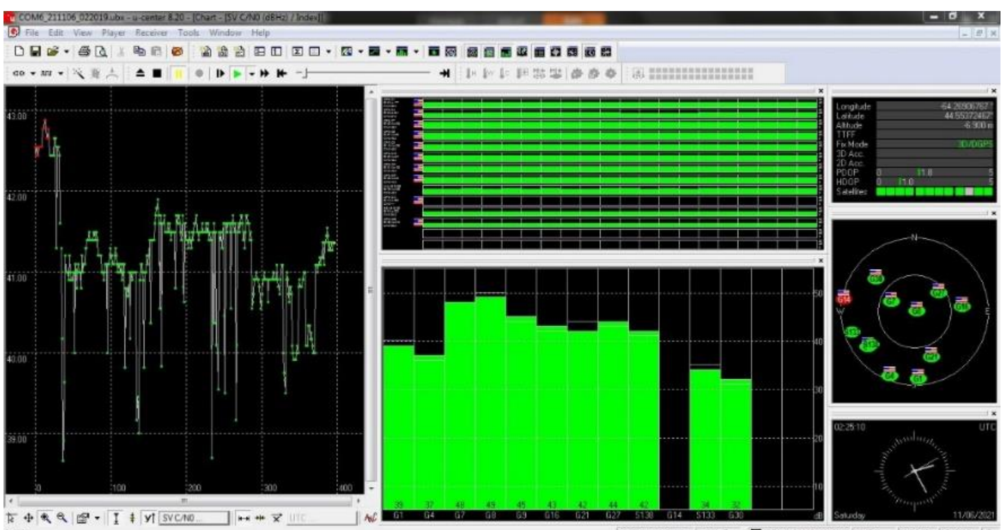

Figure 11 - Screen Shot of Ublox U-Center software

SIGNAL HOUND – REFERENCE SYSTEM TEST EQUIPMENT

The Signal Hound VSG25A shown in Figure 12 was used as the test reference system along with Signal Hound USB-SA44B Spectrum Analyzer show in Figure 13 and a Signal Hound BB60C Spectrum Analyzer and RF Recorder shown in Figure 14. The specifications for the VSG25A are highlighted in Table 4 [13].

Figure 12 – Signal Hound VSG25A

Table 4 – Signal Hound VSG25A Specifications

Freq Range	100 MHz to 2.5 GHz
Frequency Resolution	< 1 Hz
Signal Amplitude	-40 to +10 dBm +/- 1.5 dB
Pulse Width	6 ns to 25 ms
Multi-Tone Test Pattern	Tone Count, 2 to 1023 Tone spacing, 1 KHz to 10 MHz
Modulation Types	AM, FM, CW, FSK, GFSK, OOK, GMSK, BPSK, DBPSK, QPSK, etc.
Custom Modulation	Input I/Q Data: User Generated CSV file Pattern Length, 2 to 2048 samples
Cost	$ 545 USD

Figure 13 – Signal Hound USB-SA44B [35]

Figure 14 – Signal Hound BB60C Spectrum Analyzer [35]

TEST RESULTS - ADF4351 and FY6300

The results of GNSS RFI emulation are highlighted in the associated spectrum plots for given ADF4351 and FY6300 configurations. The ADF4351 Modules #2 and #3 required a frequency correction offset, approximately 10-20 KHz depending on the unit, applied to it to correctly align it to GPS L1/L2/L5 frequencies. Figures 15-30 highlight the frequency and waveform results with specific GNSS RFI targets in mind: GPS L1 C/A Code, GPS L1 C BOC (1,1), GPS L1 M Code BOC (10,5), GALILEO BOC (15, 2.5), GPS L2 CM, GPS L5, and GLONASS L1. The figures highlight the sixteen RFI waveforms that were generated for given combinations of the ADF4351 and the FY6300 AWG. Table 5 provides a summary of the examples of GNSS RFI generated.

Table 5 – 16 x GNSS RFI Example Waveforms

FIG #	FY6300 Waveform	ADF4351 Module #2 (Unless spec'd) & FREQ	CH 1 Initial / Freq OUT	CH 2 Internal Source	Sweep Start	Sweep Stop	Sweep Linear or Log	Sweep Time (secs)	Sweep Direction	Mod PSK
15	-	GPS L1	-	-	-	-	-	-	-	-
16	-	Module #1 GPS L1 +/- 1 MHz	-	-	-	-	-	-	-	-
17	-	Module #1 GPS L1 +/- 4 MHz in 200 KHz steps	-	-	-	-	-	-	-	-
18	Built-In Waveforms approximately 1 sec each	GPS L1	10 KHz	-	-	-	-	-	-	-
19	CHIRP	GPS L1	10 KHz	-	-	-	-	-	-	-
20	ARB37 PRN SEQUENCE USER DEFINED	GPS L1	125 Hz	-	-	-	-	-	-	-
21	RANDOM NOISE	GPS L1	125 Hz	1.023 MHz SQR	-	-	-	-	-	PSK Mod On
22	AWGN	GPS L1	625 Hz	10.23 MHz SQR	-	-	-	-	-	PSK Mod On
23	AWGN	GPS L1	312.5 Hz	15.345 MHz SQR	-	-	-	-	-	PSK Mod On
24	ADJ-PULSE (1960 ns)	GPS L2	20 KHz	-	-	-	-	-	-	-
25	CHIRP	GPS L2	4 KHz	-	-	-	-	-	-	-
26	RANDOM NOISE	GPS L5	1.2487793 KHz	-	-	-	-	-	-	-
27	ADJ-PULSE (1960 ns)	Module #1 GLONASS L1 14 steps of 562.5 KHz	10 KHZ	-	-	-	-	-	-	-
28	SQUARE WAVE	L1	10 KHz and Duty Cycle 0.977 %	-	DUTY CYCLE 0.977 %	DUTY CYCLE 1.955 %	LIN	1	Fwd and Back	-
29	ECG	L1	29 KHz	-	29 KHz	58 KHz	LIN	1	Fwd and Back	-
30	-	Module #3 GPS L1 Start 1572.4 MHz End 1578.4 MHz Sweep Step 1 KHz	-	-	-	-	-	-	-	-

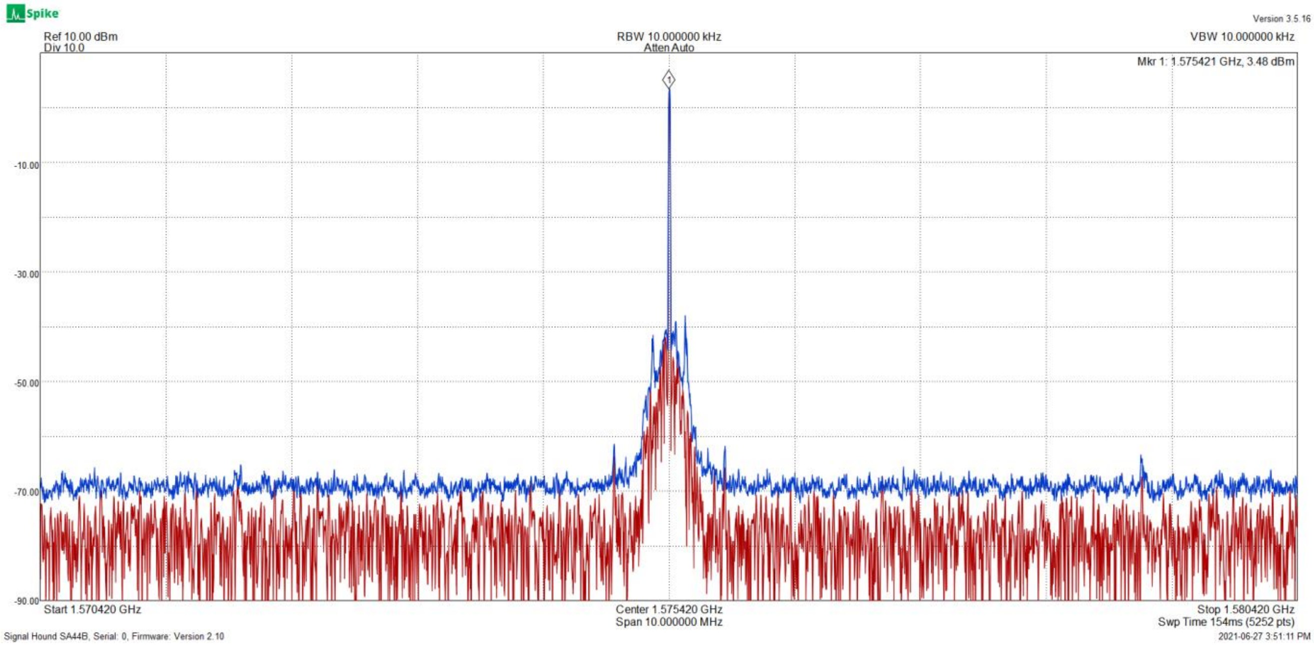

Figure 15 - ADF4351 MODULE #2 as a GPS L1 single tone source (no AWG)
Signal Hound SDR centered on GPS L1 with 10 MHz span (Peak of 3.48 dBm)

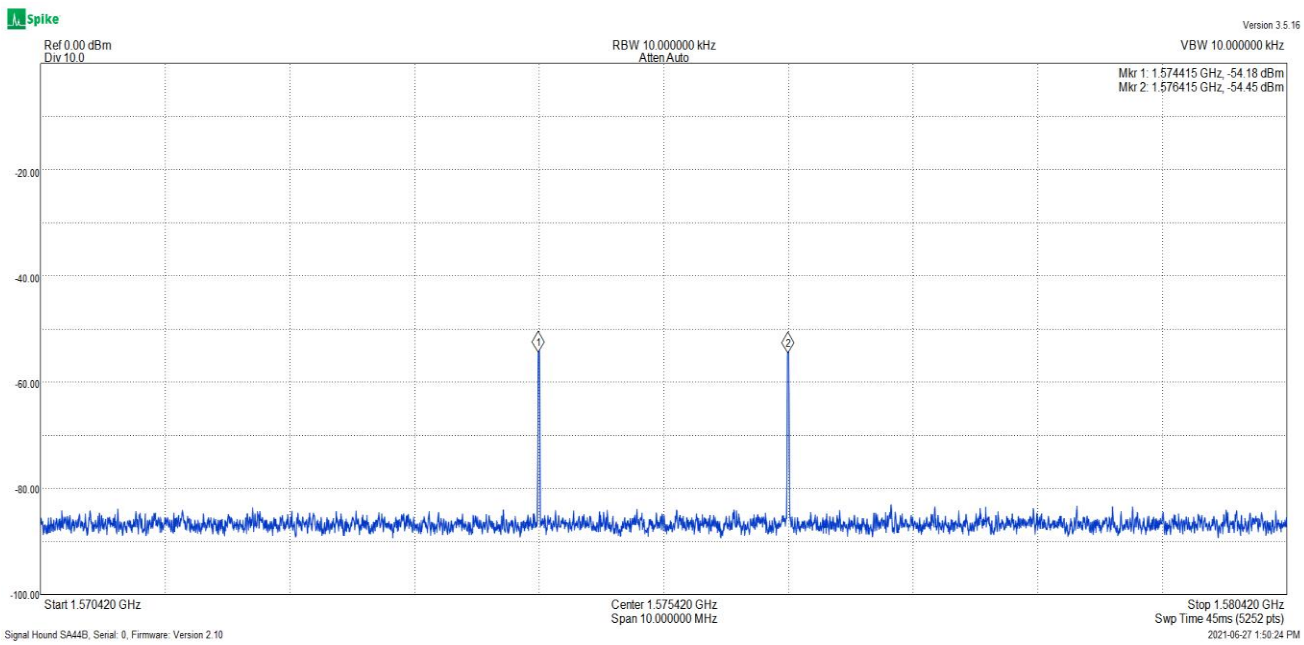

Figure 16 - ADF4351 MODULE #1 – Frequency Hop +/- 1 MHz from GPS L1 (no AWG)
Signal Hound SDR centered on GPS L1 with 10 MHz span (max hold in blue)

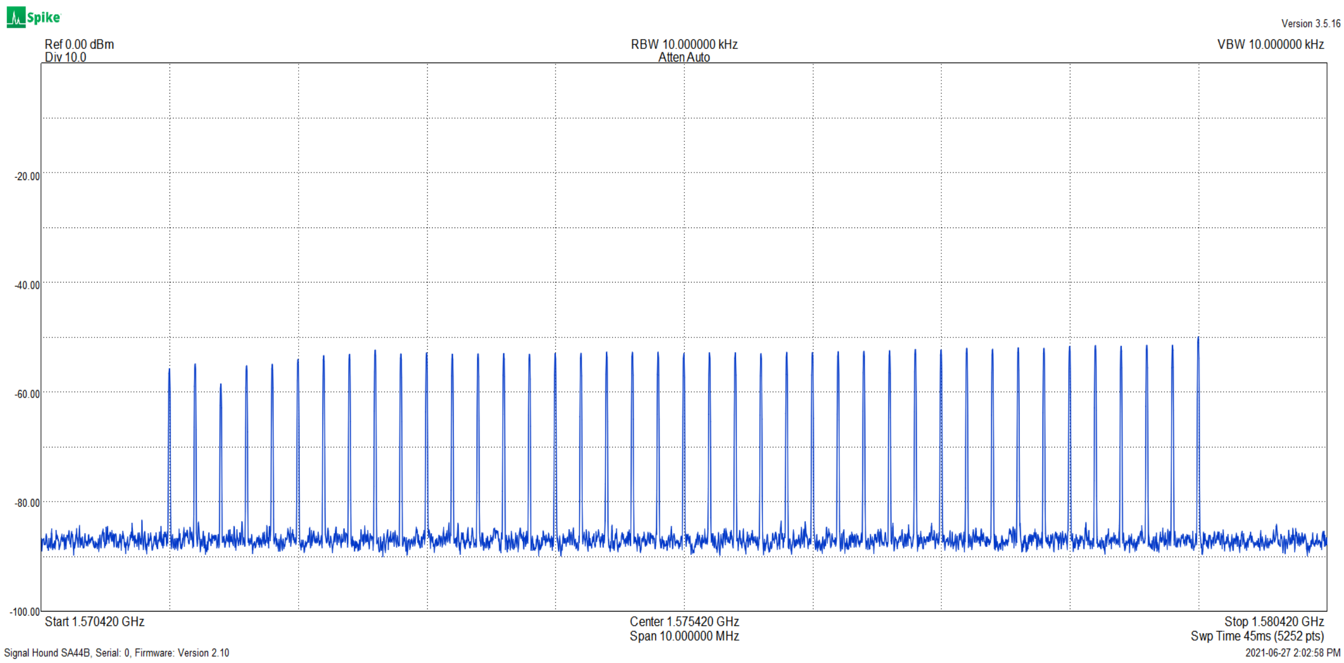

Figure 17 - ADF4351 MODULE #1 – GPS L1 +/- 4 MHz and frequency step of 200 KHz (no AWG)
Signal Hound SDR set to 10 MHz span centered on GPS L1 (max hold in blue)

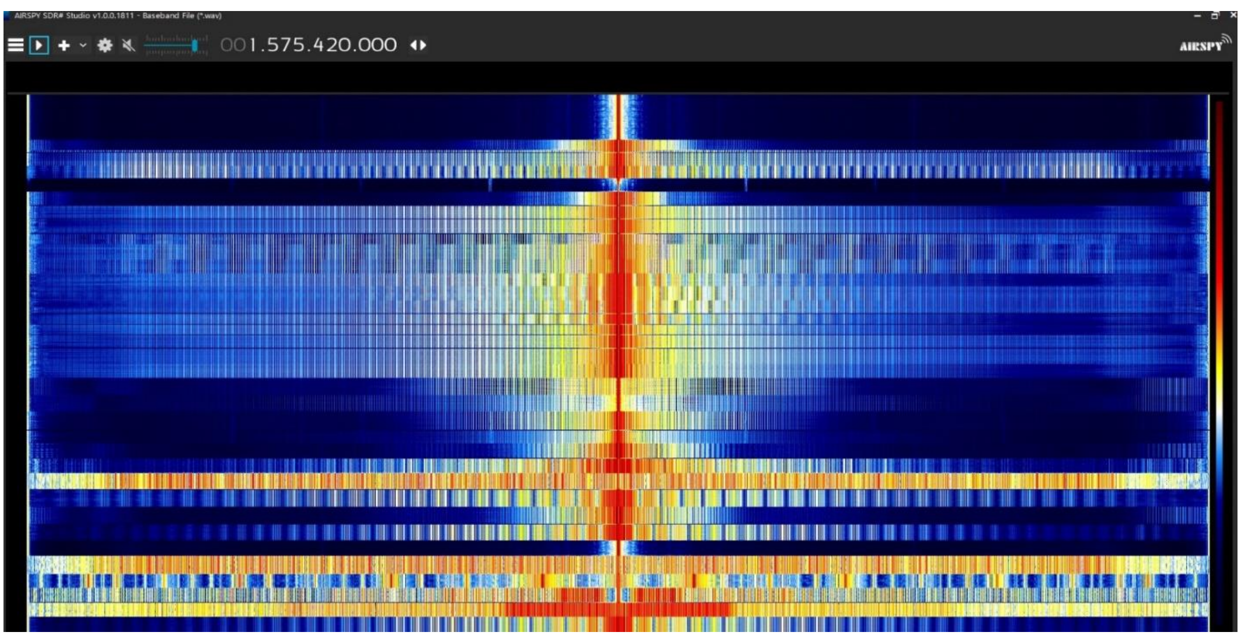

Figure 18 - ADF4351 Module #2 (Centered on GPS L1) + FEELTECH FY6300 AWG
(CH 1 various built-in waveforms at 10 KHz) Waterfall Display of Airspy R2 at 8 MHz span

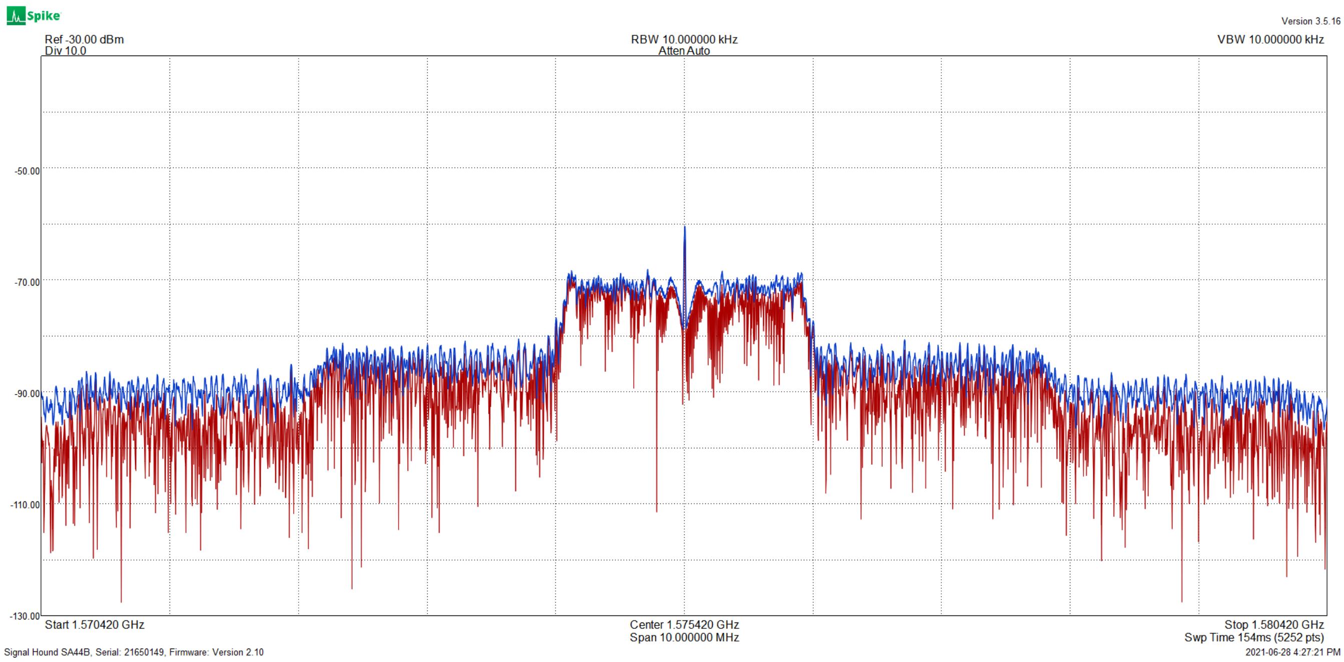

Figure 19 - ADF4351 Module #2 + FEELTECH FY6300 and CH 1 CHIRP at 10 KHz (Optimum 10.7 KHz)
Signal Hound SDR with 10 MHz Span centered on GPS L1 (max hold in blue)

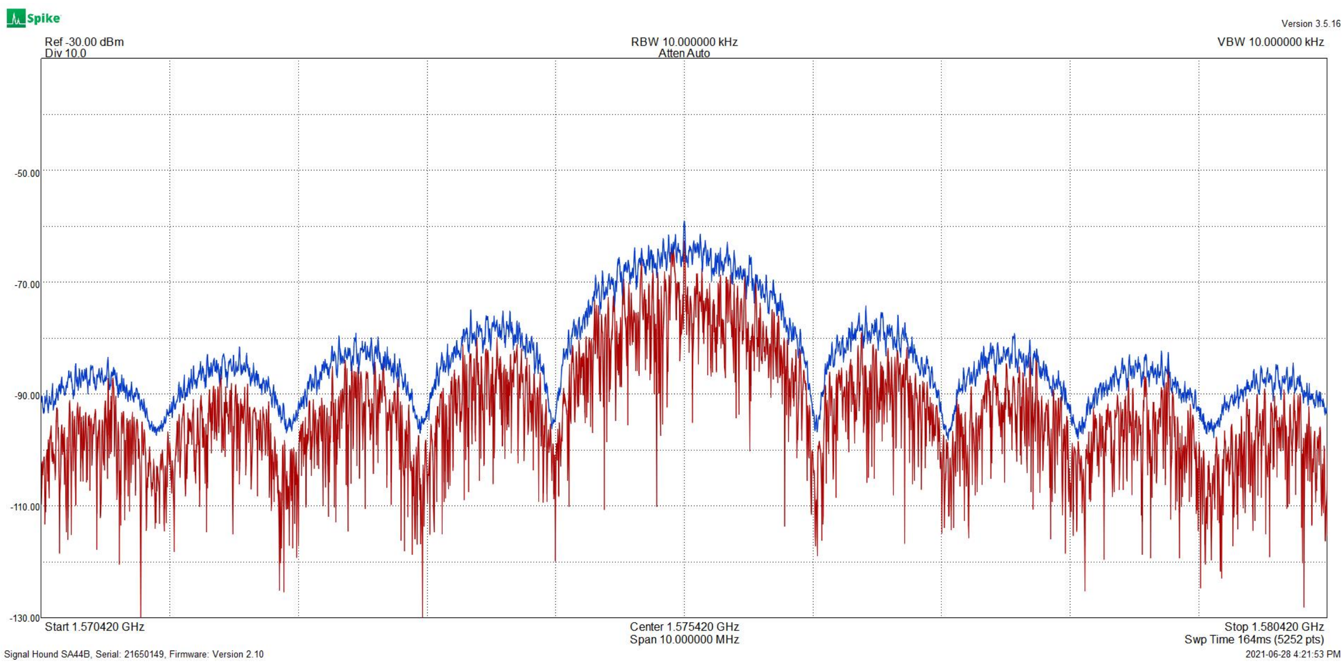

Figure 20 - ADF4351 Module #2 + FEELTECH FY6300 and CH 1 Custom ARB37 PRN at 125 Hz
Signal Hound SDR with 10 MHz Span centered on GPS L1 (max hold in blue)

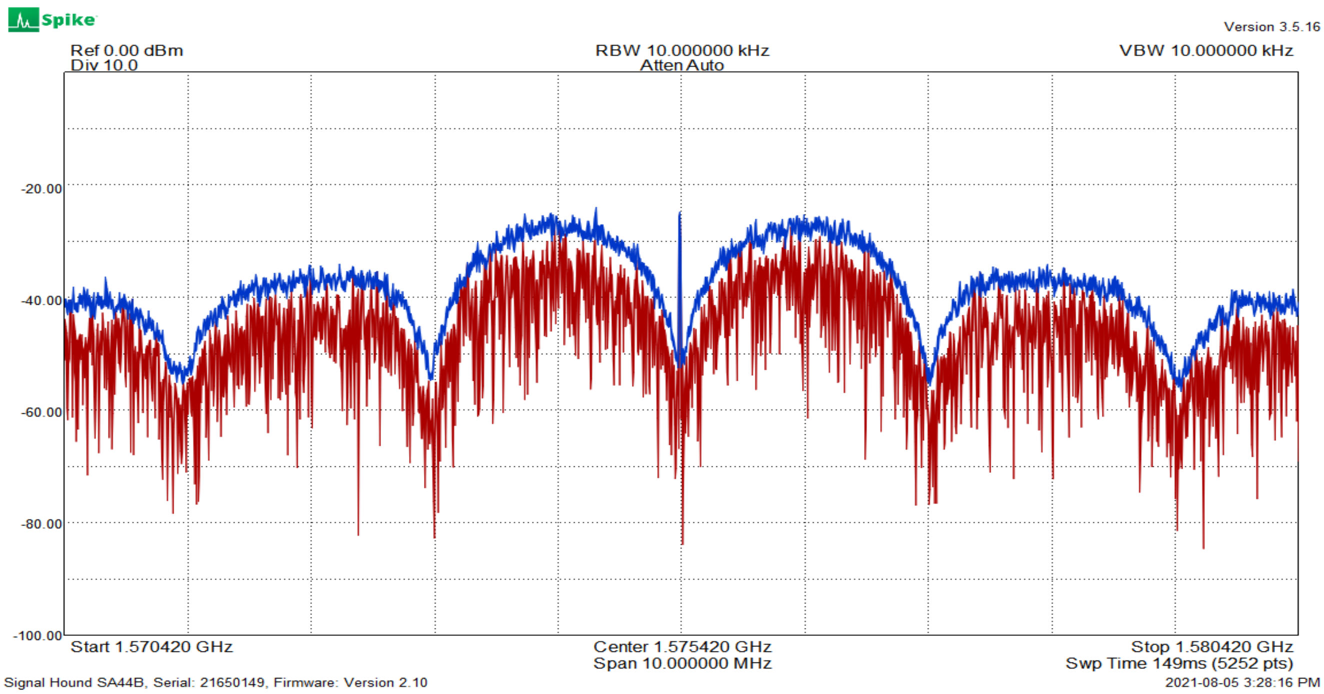

Figure 21 - ADF4351 Module #2 GPS L1 + FEELTECH FY6300 CH1 Random Noise Waveform at 125 Hz
CH2 Source set to 1.023 MHZ and PSK MODULATION ON (max hold in blue), SDR Span 10 MHz
Example of RFI for GPS L1 BOC (1, 1)

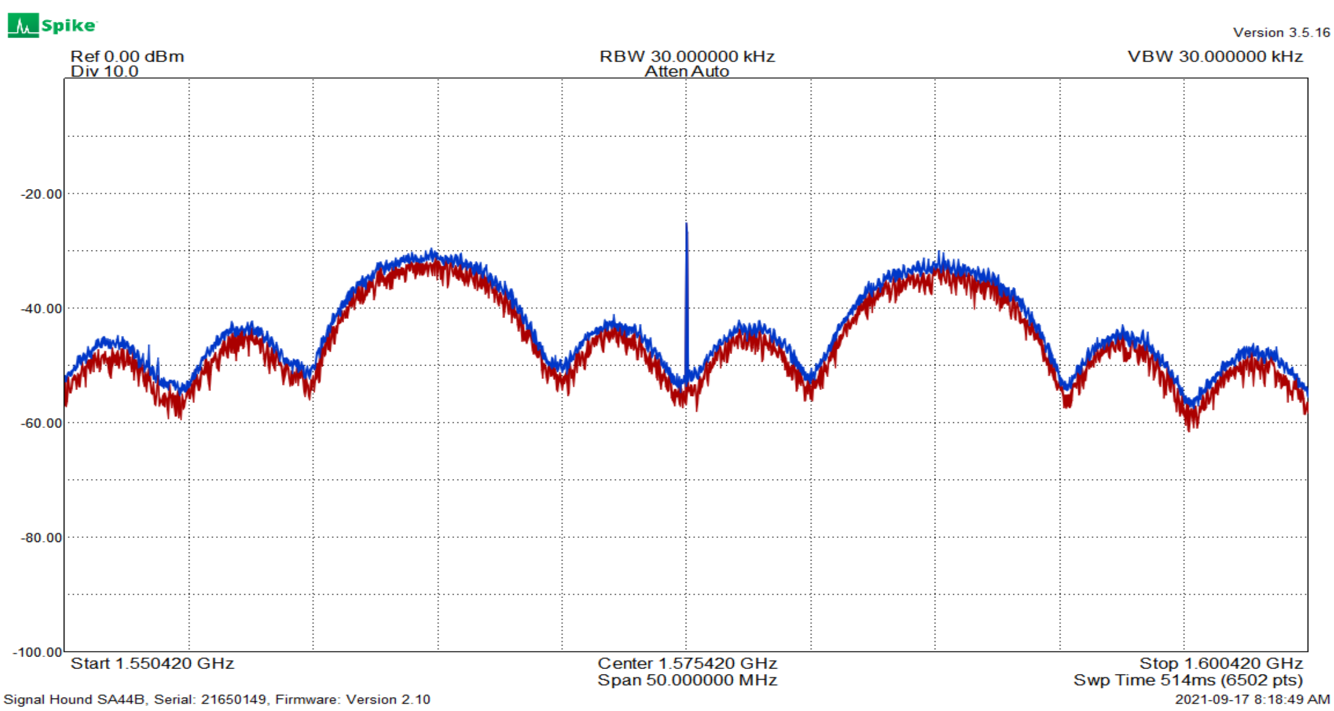

Figure 22 - ADF4351 Module #2 at L1 + FEELTECH FY6300 CH1 AWGN at 625 Hz
CH2 Source set to 10.23 MHZ and PSK MODULATION ON, SDR Span 50 MHz
Example of RFI for GPS L1 BOC (10, 5) (max hold in blue)

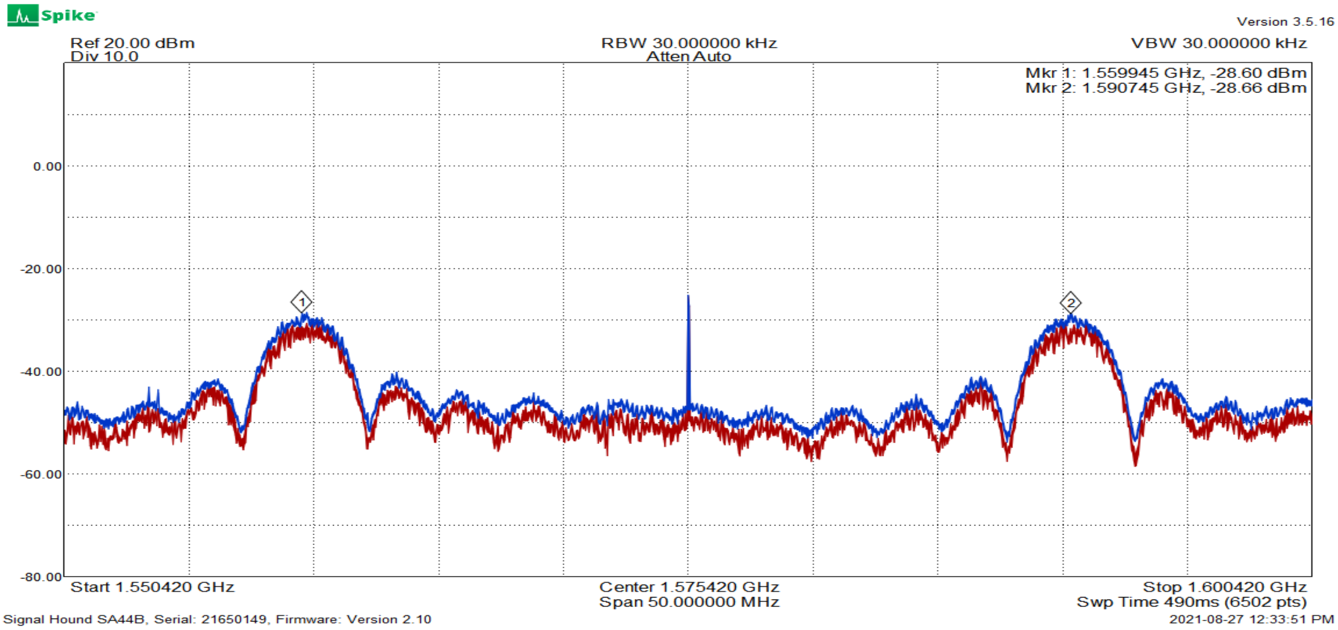

Figure 23 - ADF4351 Module #2 at L1 + FEELTECH FY6300 CH1 AWGN at 312.5 Hz
CH2 Source set to 15.345 MHZ and PSK MODULATION ON, SDR Span 50 MHz
Example of RFI for GALILEO BOC (15, 2.5) (max hold in blue)

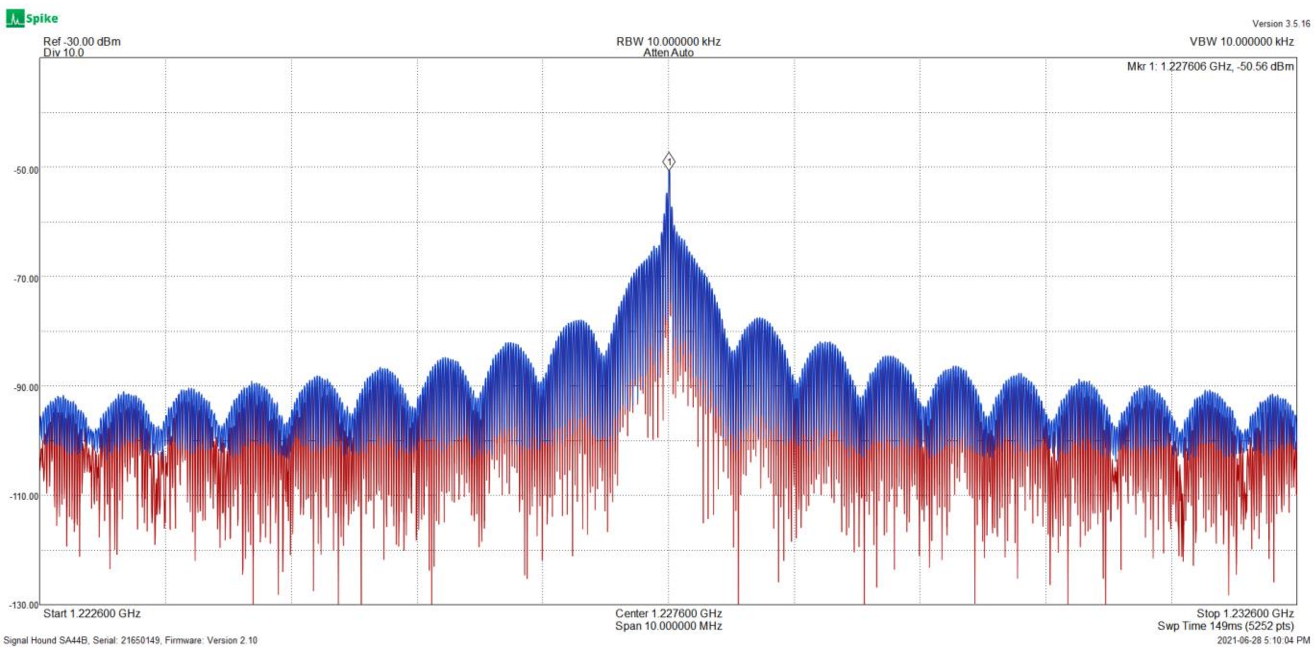

Figure 24 - ADF4351 Module #2 (GPS L2) + FEELTECH FY6300 and CH1 ADJ-PULSE (1960 ns) at 20 KHz
Signal Hound SDR with 10 MHz Span centered on GPS L2 (max hold in blue)

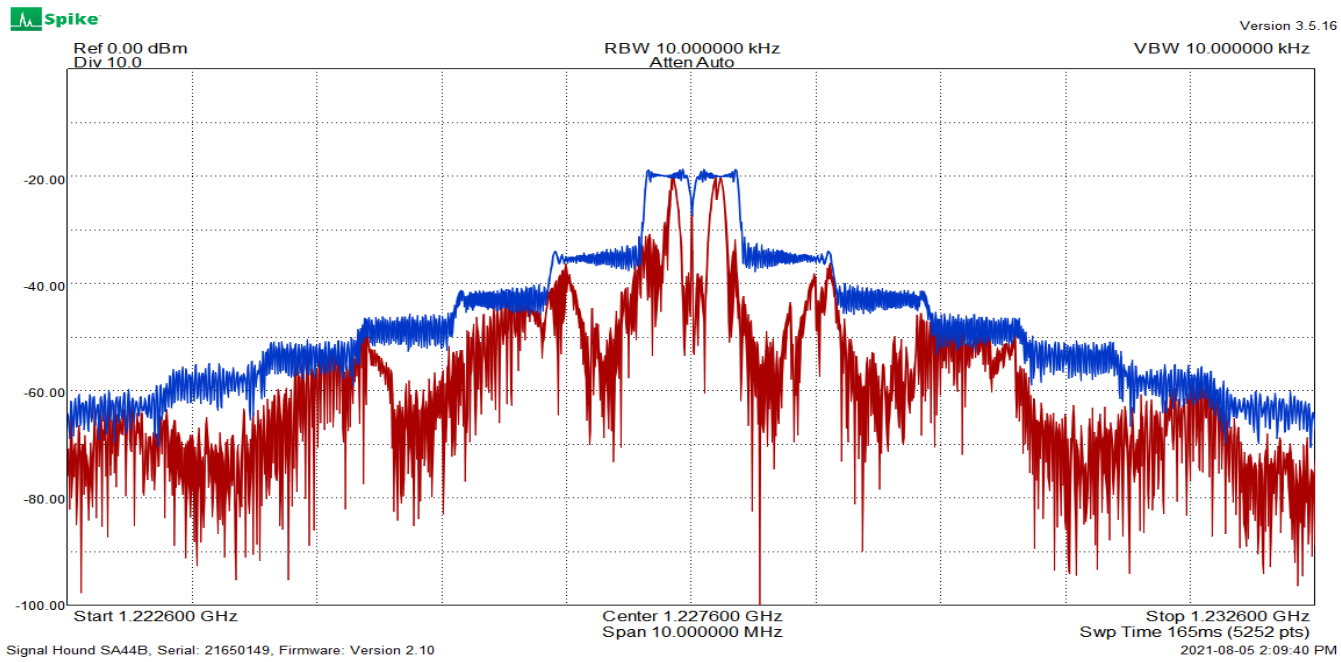

Figure 25 - ADF4351 Module #2 (GPS L2) + FY6300 and CH1 CHIRP at 4 KHz (Optimum 5.35 KHz)
Signal Hound SDR with 10 MHz Span centered on GPS L2 (max hold in blue)

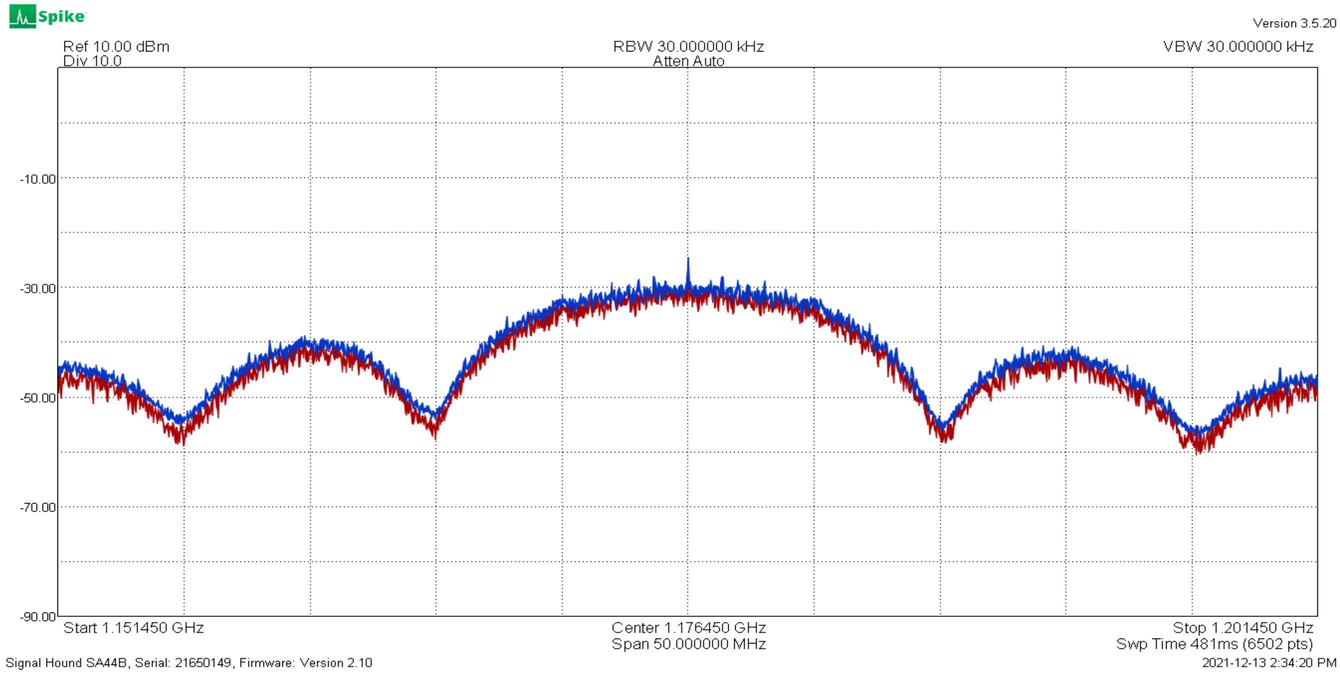

Figure 26 - ADF4351 Module #2 (GPS L5) + FEELTECH FY6300 and CH1 RANDOM NOISE 1.2487793 KHz
NOTE: Signal Hound SDR at 50 MHz Span for the L5 Waveform (max hold in blue)

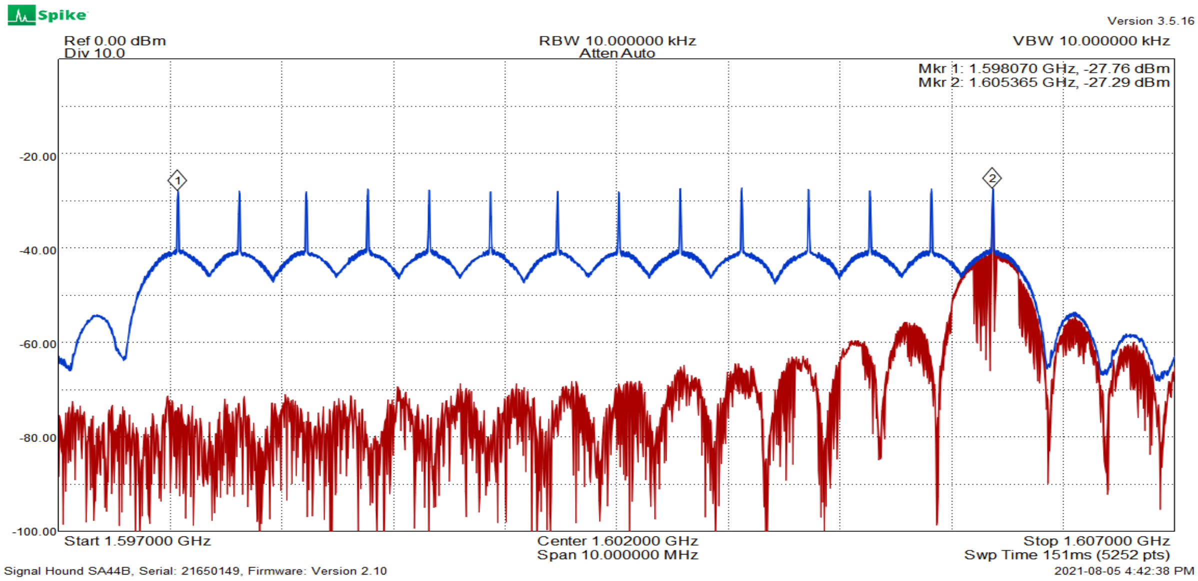

Figure 27 - ADF4351 Module #1 (GLONASS L1 and FREQ STEP OF APPROX 562.5 KHz)
+ FEELTECH FY6300 CH1 ADJ-PULSE (1960 ns) at 10 KHz
Signal Hound centered on GLONASS 1.602 GHz and 10 MHz span (max hold in blue)

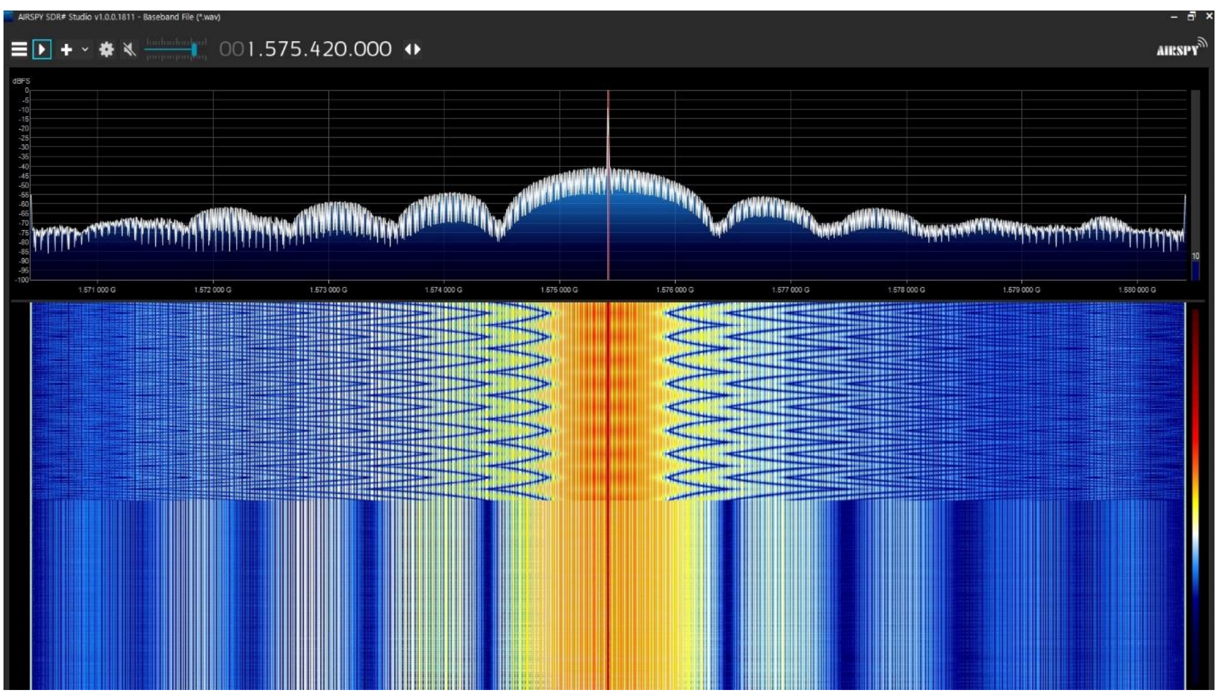

Figure 28 - ADF4351 Module #2 L1 + FY6300 CH1 Square Waveform at 10 KHz (0.977% Duty Cycle)
Sweep Mode Duty Cycle Start 0.977% (PW=977 ns) and End 1.955% (PW=1955 ns) in 1 sec Forward/Back
Airspy R2 and 8 MHz BW Display

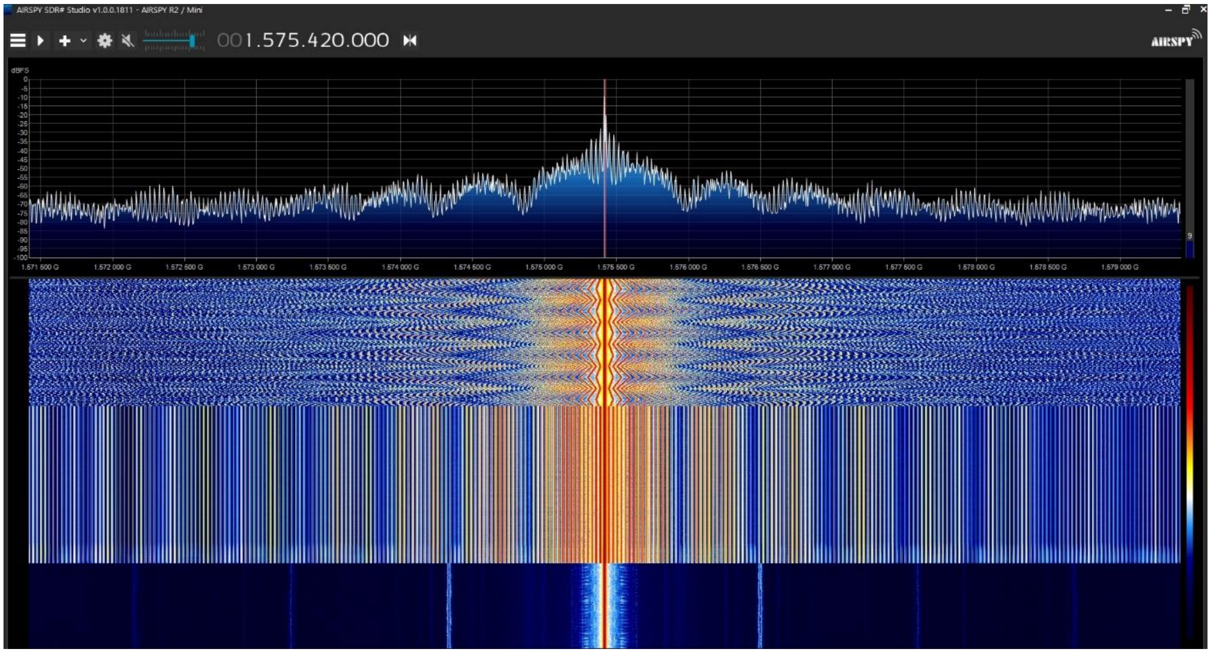

Figure 29 - ADF4351 Module #2 L1 + FY6300 CH1 ECG Waveform at 29 KHz then
Sweep Start Frequency 29 KHz and End 58 KHz at 1 second Forward/Back
Airspy R2 and 8 MHz BW Display

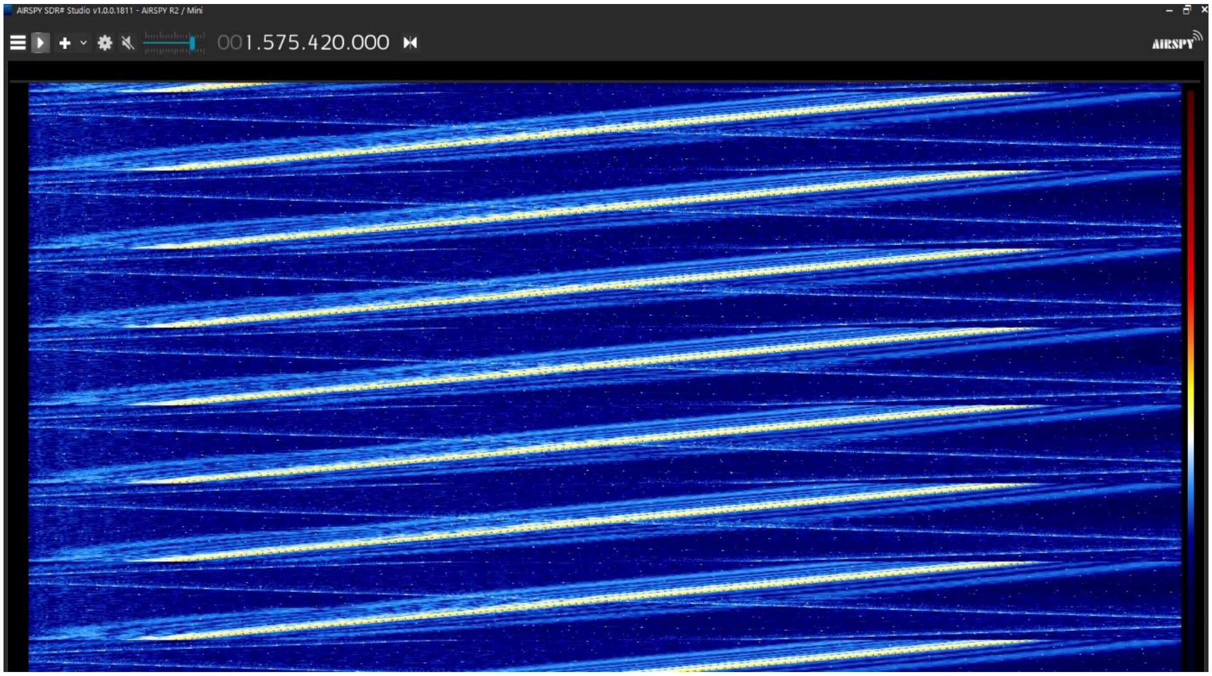

Figure 30 - ADF4351 Module #3 (Touchscreen Model) (No FY6300)
Sweep Start Frequency 1.57242 GHz and Sweep End Frequency1.57842 GHz
Sweep Step Size of 1 KHz (Default fixed Step Time on Module #3)
(ADF4351 Module #3 takes 6 seconds to sweep 6 MHz BW in 1 KHz step)
Airspy R2 and 8 MHz BW Waterfall Display

TEST RESULTS - UBLOX NEO-7N RECEIVER - GPS RFI

The Ublox NEO-7N receiver was configured to receive only GPS and WAAS signals for this testing. The receiver was subjected to eight different GPS RFI waveform events generated using the ADF4351 and the FY6300 AWG with the exception that the first RFI event was using just ADF4351 Module #3. The first event was followed by six built-in FY6300 waveforms mixed with ADF4351 Module #2 centered on GPS L1. The last of the eight RFI events was a customized PRN sequence arbitrary waveform created in Matlab/Excel [43,44] and uploaded into the ARB40 waveform memory location in the FY6300. The settings for the eight selected RFI waveforms are shown in Table 6. The test scenario set up was approximately10 minutes of no RFI followed by GPS RFI for five minutes followed by 10 minutes of no RFI in order to allow the Ublox receiver to recover to a 3D/DGPS status. The signal level of the RFI was set to a threshold above the noise floor that would present a challenge for the Ublox receiver to maintain lock [42]. For some events the receiver would lose the 3D/DGPS fix and revert to acquisition mode during the RFI which allowed for a comparison between the effects.

For the first RFI waveform the ADF4351 signal from Module #3 was sent through the mixer with the FY6300 turned off. All other tests were with ADF4351 Module #2 set to L1. Previous testing confirmed that the built-in Chirp waveform on the FY6300 set to 10.7 KHz generates a main RFI lobe BW of approximately 2.046 MHz. As expected from the RFI theory discussed earlier and preliminary testing, an ECG waveform set to 58.3 KHz on the FY6300 generated a PW of approximately 977 ns. The FY6300 Random Noise, AWGN, and User Defined PRN sequence waveforms generated a PW of approximately 977 ns and associated null-to-null spacing of 1.023 MHz when Channel 1 was set to a frequency of 124.877930 Hz. No PSK modulation was used during the Ublox testing. All eight GPS RFI waveforms jammed the Ublox NEO-7N receiver to varying degrees at the fixed attenuated power level. The Ublox RFI data parameters of Jamming Indicator, Noise (GPS), and AGC, combined with the normal NMEA outputs such as SV C/No confirmed the detection of GPS RFI as shown in Figure 31 and Figure 32.

Table 6 - ADF4351/FY6300 Test Waveforms and Sweep Settings tested with Ublox NEO-7N

FY6300 Waveform	PW Set	CH 1 Initial / Freq OUT	CH 2 EXT OUT	Sweep Source Start	Sweep Source Stop	Sweep Linear	Sweep Time (secs)	Sweep Direction	Modulation PSK
ADF4351 GPS L1 +/- 3 MHz 1 KHz steps	-	-	-	-	-	-	-	-	-
CHIRP	-	10.7 KHz	-	-	-	-	-	-	-
ECG	-	58.3 KHz	-	-	-	-	-	-	-
SQUARE WAVE	-	10 KHz and Duty Cycle 0.977 %	-	DUTY CYCLE 0.977 %	DUTY CYCLE 1.955 %	LINEAR	1	Forward and Back	No PSK Modulation
ADJ-PULSE	980 ns	5 KHz	-	FREQ 5 KHz	FREQ 20 KHz	LINEAR	1	Forward and Back	No PSK Modulation
RANDOM NOISE	-	124.87793 Hz	-	-	-	-	-	-	-
AWGN	-	124.87793 Hz	-	-	-	-	-	-	-
ARB40 PRN SEQUENCE	-	124.87793 Hz	-	-	-	-	-	-	-

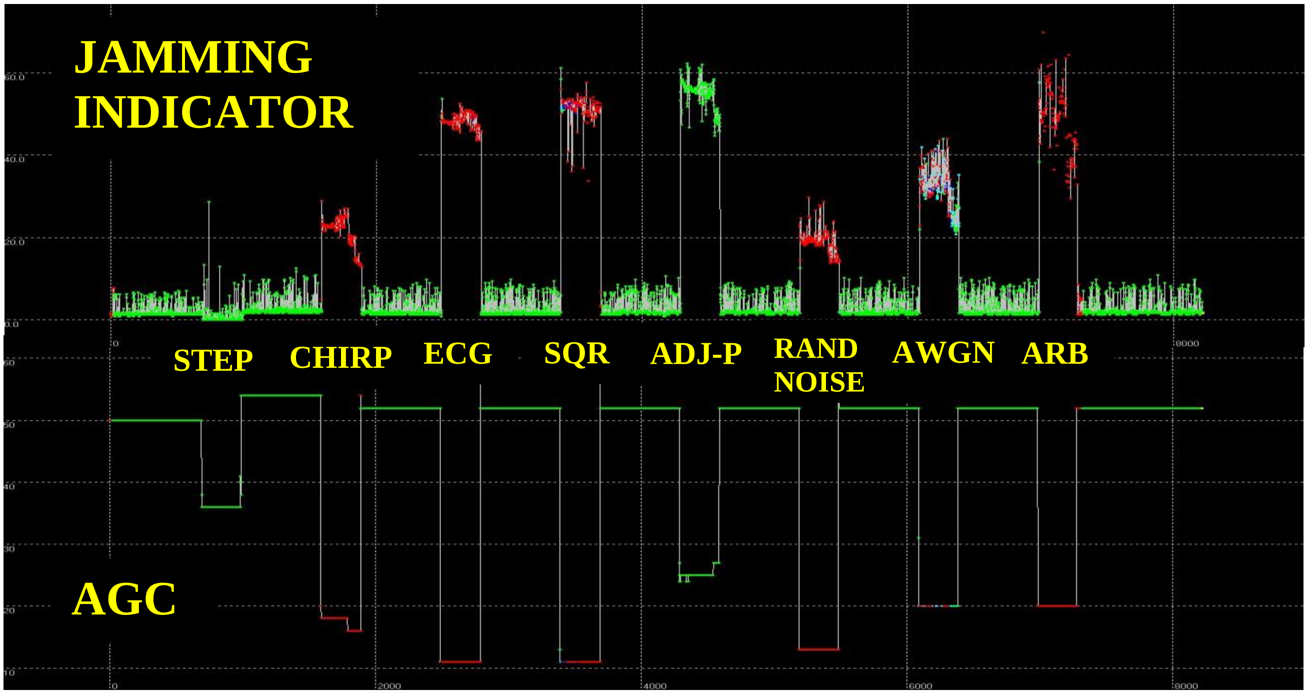

Figure 31 - Ublox NEO-7N Jamming Indicator and AGC
Bottom axis is Time in seconds, Vertical axis is 0-60 for JAMIND and 0-60 for AGC

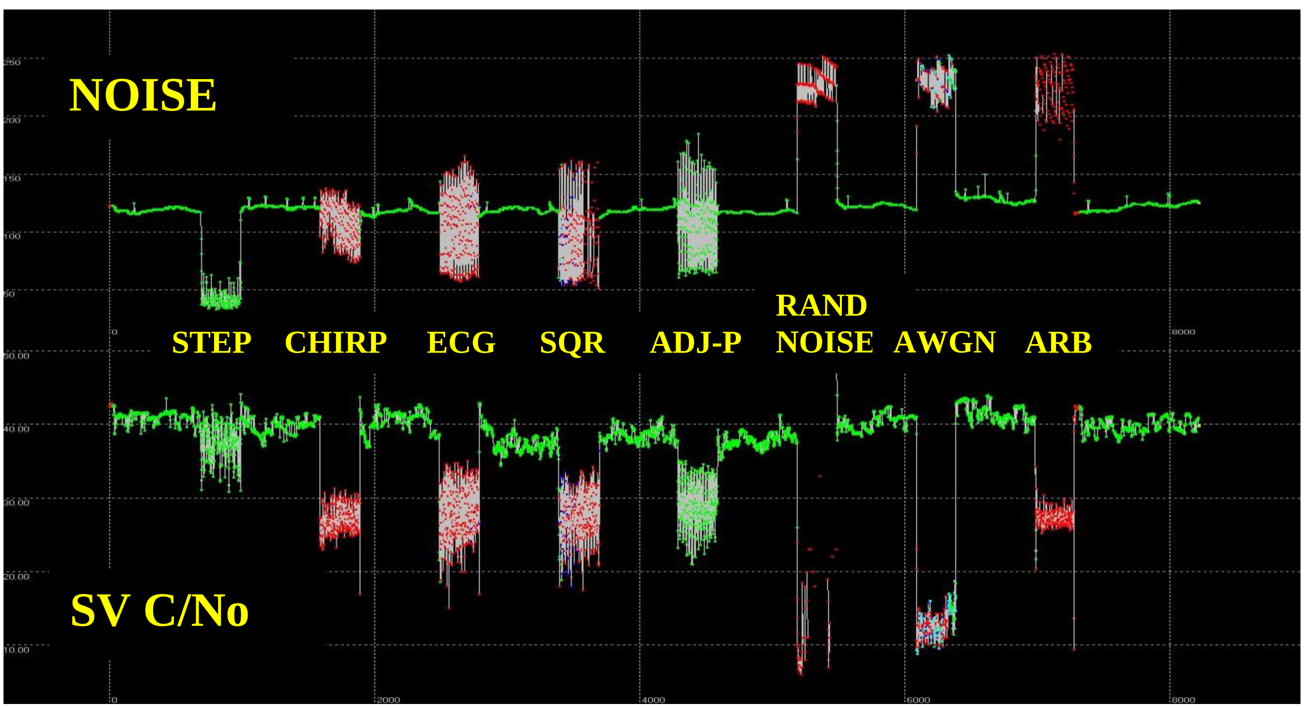

Figure 32 – Ublox NEO-7N Noise (GPS) and SV C/No
Bottom axis is Time in seconds, Vertical axis is 0-250 for NOISE and 0-50 dB-Hz for SV C/No

A few observations were made of the Ublox U-center plots of the four parameters (Jamming Indicator, AGC, NOISE, and SV C/No) for the eight RFI waveform events. Note, the color red is an indication of the loss of 3D/2D fix lock status. The first event using a stand-alone ADF4351 to generate the 1 KHz Step across +/- 3 MHz of GPS L1 frequency band had the least impact on the Ublox NEO-7N receiver. Of note, the JAMIND and NOISE parameter actually went down in value compared to the non-RFI windows except for a few spikes of the JAMIND during this event. The SV C/No was impacted the least. The second least effective RFI was the Fixed ADJ-Pulse of 980 ns with a swept frequency of 5 to 20 KHz as indicated in the four parameters in the green but it is worth noting that the JAMIND flagged this at a relatively high level. The CHIRP, ECG, and SQUARE (with swept Duty Cycle) all caused the receiver to lose lock (in red). As expected, the Noise parameter values were higher for the Random Noise, AWGN and ARB40 PRN sequence. The Random Noise waveform appeared to be more effective as compared to the AWGN; this may be on account that the Random Noise has higher average voltage levels as compared to the AWGN as observed on the oscilloscope in the Figures 3A and 3B. The combination of a relatively high Noise value for the ARB40 PRN sequence and a corresponding SV C/No level with a relatively narrow span of values compared to the other waveforms possibly suggests partial correlation with the user defined ARB40 PRN sequence waveform on all channels of the receiver.

During the Ublox NEO-7N RFI testing, only Channel 1 of the FY6300 was used; however, some analysts may wish to take advantage of using the Channel 2 output to generate other RFI waveforms and/or to duplicate the same RFI waveform (such as a PRN sequence) at an optimized phase offset from Channel 1. A limitation of the FY6300 is that only Channel 1 output can be configured for the Sweeping Mode.

SUMMARY AND CONCLUSIONS

The main focus of this paper was the low-cost emulation of effective GPS RFI signals using the combination of a FeelTech FY6300 Function/Arbitrary Waveform Generator with RF modules based on the Analog Devices ADF4351 wideband RF synthesizer chip. An RF mixer board using the RMS-11X chip by Mini-Circuits was used to mix waveforms from the FeelTech FY6300 with the ADF4351 RF signals. The impact of the RFI waveforms was verified using a Ublox NEO-7N receiver. The Signal Hound Vector Signal Generator (VSG25A) provided an accurate reference for generating RF test signals for comparison to the ADF4351.

The capabilities of the ADF4351 wideband RF synthesizer modules were examined using a PC and the ADF4351 Evaluation Software, followed by testing of the ADF4351 standalone modules. The ADF4351 units were used to generate RF test signals at GPS L1, GPS L2, GPS L5, GLONASS L1 Band and mixed with the waveform capabilities of FY6300. A Signal Hound VSG25A was used to generate a reference test signal in order to compare with the ADF4351 outputs. A Signal Hound USB-SA44B Spectrum Analyzer and Signal Hound BB60C Spectrum Analyzer and RF Recorder were used to verify the frequency and power level outputs of the ADF4351 modules and to determine any required frequency offset correction (up to 20 KHz). Most of the ADF4351 modules tested include a capability to sweep across a set bandwidth in user defined frequency steps.

In this research, GPS RFI signals were optimized to closely match the null spacings of the GPS RF spectrum. Spectrum matching of real-world GPS jamming signals has been noted by Todd Humphreys [45]. The RFI for GPS L1 C/A code was achieved by selecting waveforms with pulse widths (PW) of approximately 977.5 ns and/or the corresponding frequency of various built-in waveforms to achieve this same PW. A Rigol oscilloscope was used to measure the PW of the selected FY6300 waveforms. The FY6300 Random Noise, Additive White Gaussian Noise, and a Custom User Defined PRN sequence waveform when set to a frequency of 124.877930 Hz (with a waveform memory pattern of 8192 points) generated an RFI source with a chip length/PW of approximately 977.5 ns and a null-to-null spacing of 1.023 MHz.

To further demonstrate the concept of GPS RFI using a matching PW, the FY6300 ECG heart rate waveform was set to a frequency of 29 and 58 KHz which generated a PW on the Rigol oscilloscope of approximately 1955 ns and 977 ns and a corresponding null-to-null spacing of approximately 511.5 KHz and 1.023 MHz respectively. A Square waveform set to a frequency of 10 KHz with a duty cycle setting of 0.977% and 1.955% generated PWs of 977 ns and 1955 ns and the associated null spacings of 1.023 MHz and 511.5 KHz respectively. The built-in Chirp waveform set to a frequency of 5.35 KHz and 10.7 KHz generated a main spectral lobe RFI spacing of approximately 1.023 MHz (for L2C) and 2.046 MHz (for L1 C/A) respectively. Eight selected RFI waveforms generated with the ADF4351 and the FY6300 impacted the Ublox NEO-7N receiver to varying degrees and confirmed the usefulness of the built-in Ublox RFI features.

Based on this research, Table 7 provides a summary of the recommended initial Channel 1 settings for using the FY6300 to generate RFI centered at the GPS L1 C/A, L2C, and the L5 spectrum. A researcher may be interested in using the capabilities of the FY6300 to sweep a selected waveform between two frequencies or to sweep a square waveform at a given frequency between two duty cycles depending on the GNSS receiver under test.

Table 7 – Recommended FY6300 Initial Channel 1 Settings for GPS L1 C/A, L2C, and L5

WAVEFORM	**Target - GPS L1 C/A**	**Target - GPS L2C**	**Target - GPS L5**
CHIRP	10.7 KHz	5.35 KHz	-
ECG	58.3 KHz	29.1 KHz	-
SQUARE	10 KHz DUTY CYCLE 0.977 %	10 KHz DUTY CYCLE 1.955 %	-
RANDOM NOISE AWGN CUSTOM ARB PRN	124.877930 Hz	62.439 Hz	RANDOM NOISE 1.2487793 KHz

In some of the RFI examples in this paper, the second output channel of the FY6300 was used as the internal source for BOC frequency offset, for sweep frequency and for PSK modulation. Based on this research, Table 8 provides a summary of the recommended initial Channel 1 and Channel 2 settings for using the FY6300 to generate RFI using the ADF4351 centered at the GPS L1 for three BOC waveforms.

Table 8 – Recommended FY6300 Initial Channel 1 and 2 Settings for three BOC waveforms

WAVEFORM	**Target – BOC (1,1)**	**Target – BOC (10,5)**	**Target – BOC (15,2.5)**
CHANNEL 1 RANDOM NOISE	124.877930 Hz	624.38965 Hz	312.194825 Hz
PSK MOD ON	√	√	√
CHANNEL 2 SQUARE	1.023 MHz	10.23 MHz	15.345 MHz

ADF4351 Evaluation boards ranged in price between $20 and $50 USD for EBay versions or up to $175 USD for the original Analog Devices OEM Evaluation Board. The cost of the FeelTech FY6300 AWG was $110 USD. Other additional costs included the RMS-11X mixer board purchased on EBay for $12 USD, a signal combiner board for $10 USD, RF attenuators for $40 USD, and a Taoglas GPS-GLONASS (TG.08.0113) whip-tilt antenna from Digi-Key for $16 USD. In total, a GPS RFI emulation test equipment system, including hardware and software, was achieved for under $250 USD.

Supporting equipment for this research and testing included a Ublox NEO-7N receiver combined with a Taoglas Dominator GPS/GLONASS active antenna. An Airspy R2 Software Defined Radio (SDR) was used along with the SDR# software for measuring, recording and playback of approximately 10 MHz bandwidth (8 MHz displayed) of various GPS RFI signals. A Signal Hound USB-SA44B Spectrum Analyzer and a Signal Hound BB60C Spectrum Analyzer and RF Recorder were used for recording and playback of spectrum captures of 10 MHz and greater bandwidth spans and for precise measurement of the center frequency output of the ADF4351 modules. The PWs of selected FY6300 waveforms at various settings were verified using a Rigol 1202Z-E oscilloscope.

In summary, GPS RFI emulation using an ADF4351 mixed with waveforms from the FeelTech FY6300 shows potential to support low-cost GNSS RFI research, testing, training and education. In this research, the combination of the ADF4351 modules with the FY6300 allowed the flexibility of generating various RFI waveforms including CW, Multi-Tones, Stepped Tones, along with Chirp, Narrowband and Wideband Noise, Pulsed Waveforms including ADJ-PULSE, ECG, and SQUARE/Rectangular Wave (Duty Cycle) and Custom User Defined PRN sequences. The RFI waveforms were optimized to closely match the nulls and main lobes of the actual GPS spectrum and the impact was observed on a Ublox NEO-7N receiver.

ACKNOWLEDGMENTS

This paper was originally presented at the Institute of Navigation (ION) International Technical Meeting (ITM) in Los Angeles, California, USA in January 2022 [46]. The main differences between the two papers are the removal of the discussion on 315 MHz oscillators and low-power GPS RFI harmonics used to jam a Garmin Nuvi receiver and the addition in this paper of background information about the Signal Hound Vector Signal Generator (VSG25A). Although not directly referenced, the additional references [47-61] were beneficial as background to the development of this paper.

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