Frequency Calibration for SDRs - Without GPS

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Summary: I will describe a program that commands your Software Defined Radio to frequency precise TV signals. By looking at your local TV signals, calibration to less than 100 Hz at 600 MHz is easily attainable even with an inexpensive RTL-SDR Dongle.

Perceived AMSAT Need: To make a satellite/terrestrial ground station as inexpensive as possible it is probably necessary to use some parts that have significant frequency error for use with the 5 GHz and 10 GHz bands. This would include the transmitter frequency determining components, baseband frequency source and all the mixers used to up-convert the baseband to 5->6 GHz (C-Band). Similarly, on the receive side we need to down-convert the signal to baseband with the possibility of intermediate conversions in between. In the end to handle the modulation it is envisioned that a software defined radio will be needed to demodulate the received satellite data/audio/beacon etc.

Solutions: The easiest way and most expensive way to handle the frequency uncertainty is to have an atomic frequency source ($$$). The second best method is to have a GPS Disciplined Oscillator. With a moderate cost, this might be a solution for many hams. The third method is to have a crystal oscillator and a way to calibrate its frequency. This being the least expensive path provides the reasoning for an inexpensive calibration source. I put together a program (free) so that this uncertainty can be minimized. This tool can be easily modified under GNU Radio Companion for other SDRs or used as is.

Different Methods: At HF you could use WWV, WWVH, CHU or the Russian frequency and time broadcasts. If your source is low frequency you could compare it to them and get some measure of accuracy. Since we need a way to calibrate a signal at significantly larger frequencies than the ones at HF, this can be difficult. You could use the harmonics of your oscillator by making a comb generator. If your crystal oscillator is portable and fairly stable with frequency, a local club can provide someone with access to a stable source to compare it to. An additional method is to use a source that is broadcast on UHF. In the US it is the ATSC, high definition TV, signals. These signals use multiple frequency tones to broadcast the picture and audio via digital encoding. For their scheme to work, they need a reference frequency for the TV's AFC to lock onto. To prevent adjacent channel interference the frequency has to be common with its neighbor. This pilot tone frequency is what we exploit. The mandated FCC frequency specification for the TV stations is no longer required, but most stations have designs that predate that. Many have Atomic Clocks (Cesium or Rubidium). They also use a GPS Disciplined Oscillator if not an Atomic clock. Now what remains is to find the pilot tones and see where your receiver says they are. You can compare the two to determine the frequency error. By looking at several stations you can determine your frequency error versus frequency. Once you know that, you can correct the slope of that error with your Software Defined Radio ppm setting. There will then be some residual error because of the capability to set the ppm accurately is limited. We can measure the delta.

Why is UHF calibration good enough?: Using a Block Low Noise Down-Converter like an AVENGER, with its output at UHF makes it a good fit for this calibration technique. If you have a direct down conversion receiver, from 10GHz to baseband this program won't help very much. If your SDR has a wide band operating capability using the latest 70MHz to 6GHz chip sets, then you can also utilize this to calibrate your receiver also.

Pilot tone –Technical: For those interested in the basis for the pilot tone, here are a few quotes and references:

1) "Consequently, the pilot frequencies of all transmitters in a network shall be maintained within ±1/2 Hz of nominal frequency (i.e., ±1 Hz of one another)." *"ATSC Standard for Transmitter Synchronization, Doc. A/110:2011, 8 April 2011 page 74.

2) The formula for determining the location of the pilot with respect to the lower edge of the theoretical occupied bandwidth is:

$$\text{pilot frequency} = \left[6 - \frac{Tr \times \frac{208}{188} \times \frac{313}{312}}{4} \right] \div 2\ \text{MHz} \quad = 309440.55944056\ \text{Hz (I used 309441.Hz)}$$

Tr is the Transport bit rate, Tr (approximately 19.39 Mbps) in a 6 MHz channel

From; ATSC Digital Television Standard – Part 2: RF/Transmission System Characteristics, Doc. A/53 Part 2: 2011, 15 December 2011

3) A more precise Tr is:

$$T_r = 2 \times \left(\frac{188}{208}\right)\left(\frac{312}{313}\right)\left(\frac{684}{286}\right) \times 4.5 = 19.3926584597511\ \text{Mbps}$$

From: ATSC: "Digital Television Standard, Part 3 – Service Multiplex and Transport Subsystem Characteristics," Doc. A/53, Part 3:2009, Advanced Television Systems Committee, Washington, D.C., 7 August 2009.

This means that every 6 MHz, starting at 470,309440.55944056 Hz to 686.309… MHz you ***might*** have a constant CW tone to lock onto and calibrate your system, if you have TV reception in your area.

The Program: The goal was to provide a spectrum plot and a waterfall plot of the ATSC pilot carriers. GNU Radio provided an easy way to implement a calibration program. *Figure 1* shows the Block Diagram of the receiver. The SDR receiver that I targeted was a simple, inexpensive RTL-SDR Dongle. Its frequency error was initially high but can be corrected to be less than 100 Hertz at 600 MHz. GNU Radio is best run under the Linux operating system, but can also run under windows. Here is a link to the program.

https://github.com/WA1CYB/satellite_ground_emulator/tree/master/Ascent/Frequency%20Calibration

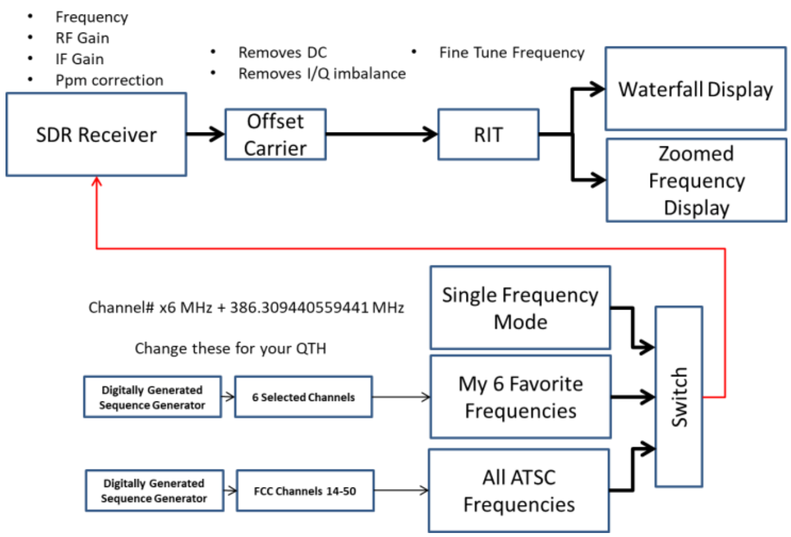

Figure 1 - Frequency Calibration Receiver Block Diagram

Figure 2 shows a screenshot of the program using a RTL-SDR taken from my QTH in the Boston Area. Ideally the waterfall would have one straight red line as the receiver jumps between the 6 selected frequencies, all centered on zero Hz in the display. Use the *Auto Scale* button and the sliders to optimize the display. You can also change the mode to scan all channels, or just look at one channel.

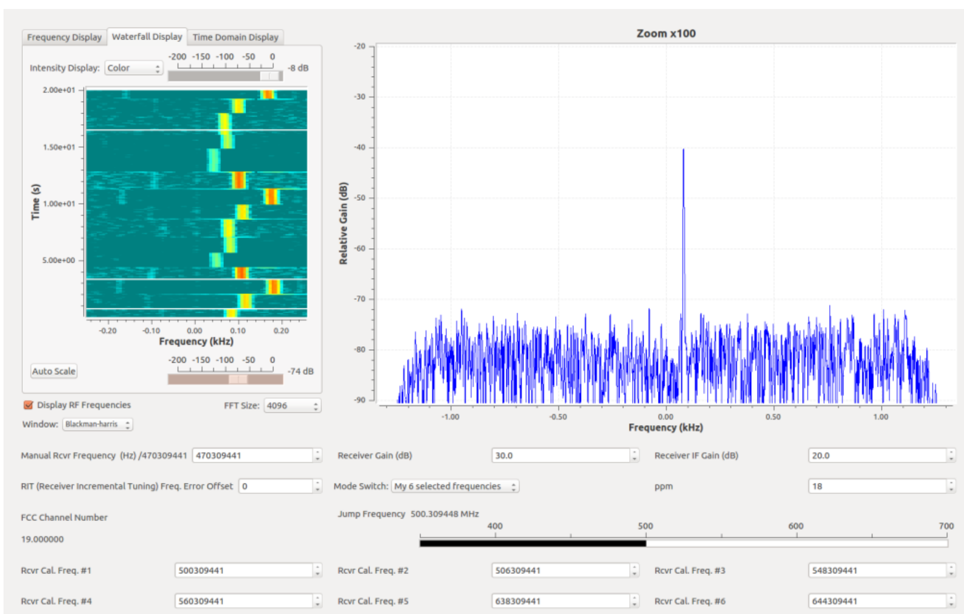

Figure 2 - RTL-SDR in 6 selected frequency mode, RIT = 0Hz

The part per million (ppm) setting is the major error source for this RTL-SDR. When the program is first run, use the frequency display tab on the left graph. This covers a wider bandwidth than the displayed frequency on the right. Change the ppm number to get the strongest channel as close as possible to zero Hz. After that, use the right hand display along with the waterfall tab to fine-tune and center the group of selected frequencies as close as possible to zero hertz. To finalize the calibration, use the Receiver Incremental Tuning (RIT) to fine tune the selected frequencies to the center of the waterfall. With the ppm and RIT values you can optimize your frequency readout in your favorite program.

Changing the selected frequencies is done by using up/down arrows next to the selected frequency box. Note the arrows will increment the value by the channel separation, 6 MHz. Alternatively, you can type in a frequency or copy and paste the frequency in any of your 6 selected values.

Figure 3 shows a screenshot of the program using an ETTUS N-210, with a GPS-DO with no calibration routines done before the program was run. A much better starting point compared to the RTL-SDR, but at a cost. In my experience other SDRs performance is between these two SDR types.

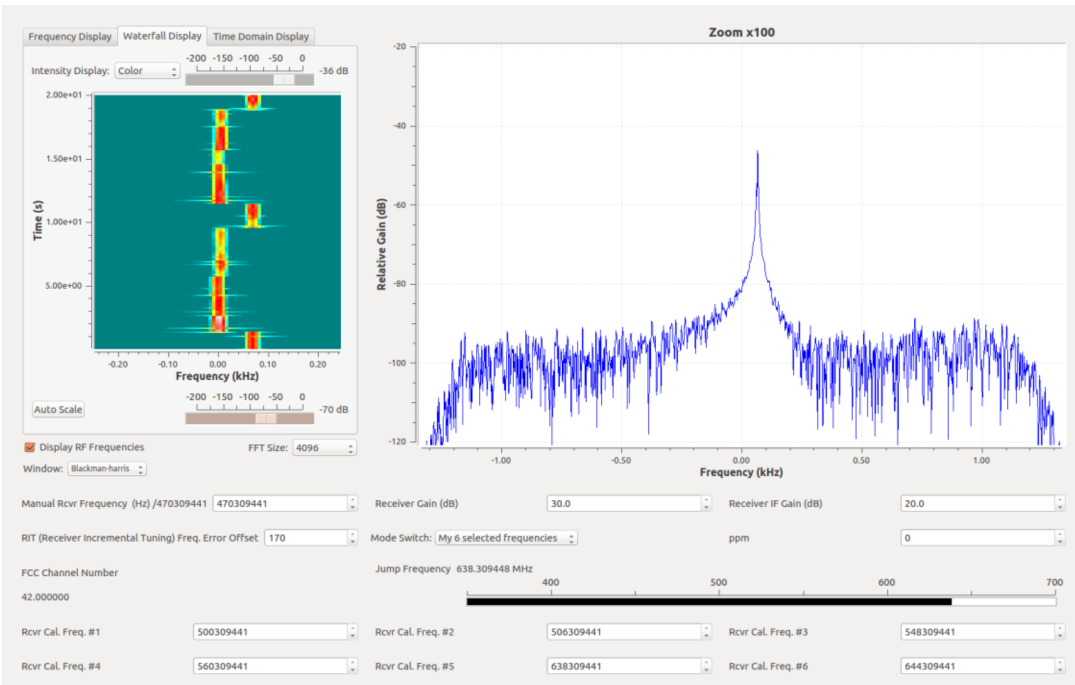

Figure 3 – ETTUS N-210 (un-calibrated) in 6 selected frequency mode

For the observant person, you will notice that the displayed jump frequency is not exactly the desired frequency (7 Hz off) even though the correct frequency (within 1 Hz) was sent to the SDR. The reason appears to be the limit of a 32 bit display/command. That's the best I could do with the standard GNU Radio flow graph. Another discovered oddity is the ppm value can only be an integer. The reason is the RTL-SDR driver can take a ppm value with more precision, but the RTL-SDR ignores all but the integer portion. You can also observe the frequency drift of the SDR from a cold start. After 10 to 15 minutes the RTL-SDR is remarkably stable.

Conclusion:

The ATSC TV signals in North America can be used to calibrate your SDR receiver with less than 100 Hz error up to the 23 cm band even with an inexpensive RTL-SDR. This tool provides a method to accomplish that. A calibrated SDR receiver makes operating you favorite satellite program easier to get on frequency.