

Linearization of a voltage-controlled oscillator with Red Pitaya

Introduction

Hi, my name is Bryce, I'm a first year PhD candidate with the Terahertz Engineering Laboratory at the University of Adelaide in South Australia, where I'm researching high frequency LiDAR/RADAR systems among other things. The terahertz region of the electromagnetic spectrum is generally defined as being above 100 GHz and below 10 THz. There's a lot of interest in operating at these frequencies, especially for applications requiring a lot of bandwidth like ranging and telecommunications. However, working at these frequencies poses significant design challenges across generation, propagation, and detection.

The aim of this short report is to show how a Red Pitaya board was used to linearize a voltage-controlled oscillator (VCO) for the use in a Frequency Modulated Continuous Wave (FMCW) radar system.

Background

First, some brief background information. A FMCW radar system transmits a signal whose frequency is linearly modulated in time, and this can be sourced from a VCO by increasing and decreasing the tuning voltage. This signal is reflected off targets, and can be mixed with the original signal in a homodyne configuration, as shown in Fig 1. The RX signal experiences a time delay, so a frequency difference between the two signals is expected. The mixing process produces the intermediate frequency (IF), which is proportional to the target range and can be used to determine target velocity.

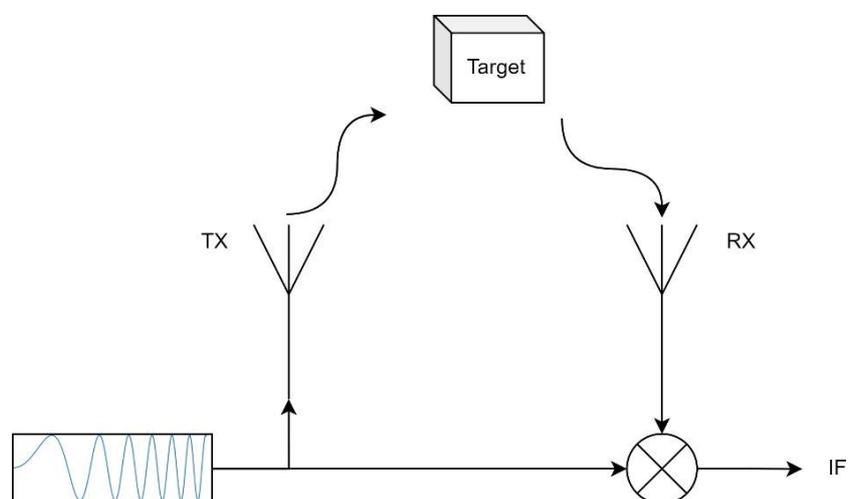


Figure 1: Simple overview of the working principle of the FMCW radar

The linearity of the frequency modulation is important to reduce measurement uncertainty and preserve distance resolution in the IF [1], [2]. Figure 2 shows an exaggerated example of a non-linear frequency ramp reflected off a stationary target. Since IF is proportional to the target distance, this is interpreted as the target moving away from the system. Unfortunately, the tuning voltage of the VCO is not linearly proportional to the output frequency (visible in Fig. 3), so steps must be taken to compensate for this.

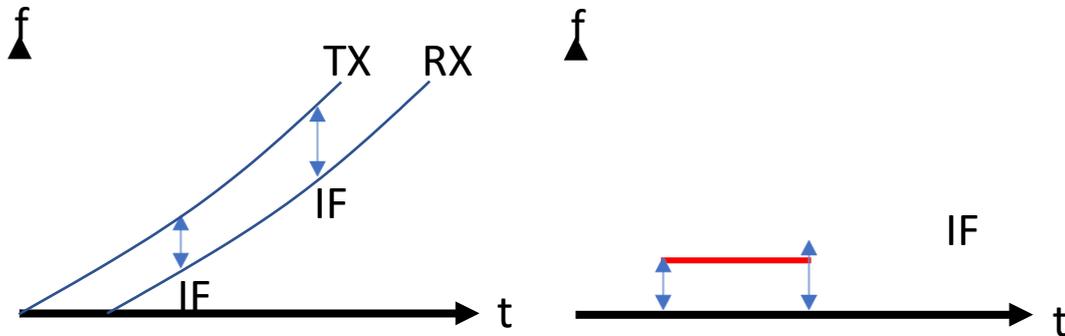


Figure 2: Effect of a non-linear frequency ramp on IF

Components/Equipment

VCO: Pasternack PE1V34002

Oscilloscope: Tektronix DPO 70604C

Signal Generator: Keysight N5173B

Spectrum Analyzer: N1996A Agilent CSA

Linearization

First, the VCO is characterized by applying a 0-1 VDC, 100 kHz triangle waveform to the VTUNE port with the Red Pitaya board. From the datasheet we can see the corresponding output frequency in Fig. 3 is expected to be roughly 7-8 GHz, exceeding the 6 GHz bandwidth of the oscilloscope. To work within this bandwidth, the output of the VCO is downmixed with a 3 GHz signal at -10 dBm, as shown in Fig.4.

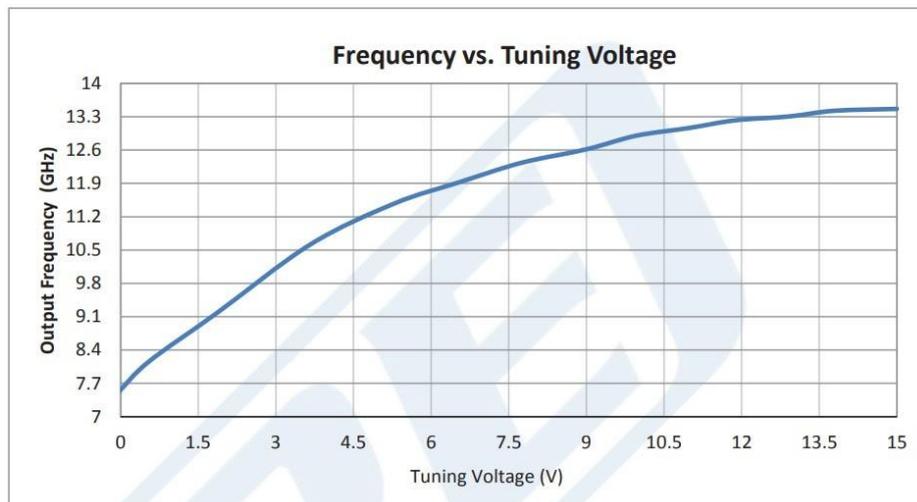


Figure 3: VCO output frequency vs Tuning voltage [1]

The VCO output and VTUNE voltage are acquired from the oscilloscope at 25 Gs/s using a Python script, with a related diagram and photo shown in Fig. 4. The results are then shown below in Fig. 5. A Fast Fourier Transformation is performed on windowed chunks of 512 samples (20.5 ns) of VCO output data, providing the spectrogram shown in Fig. 6. The frequency modulated signal is present, as well as the 3 GHz RF signal.

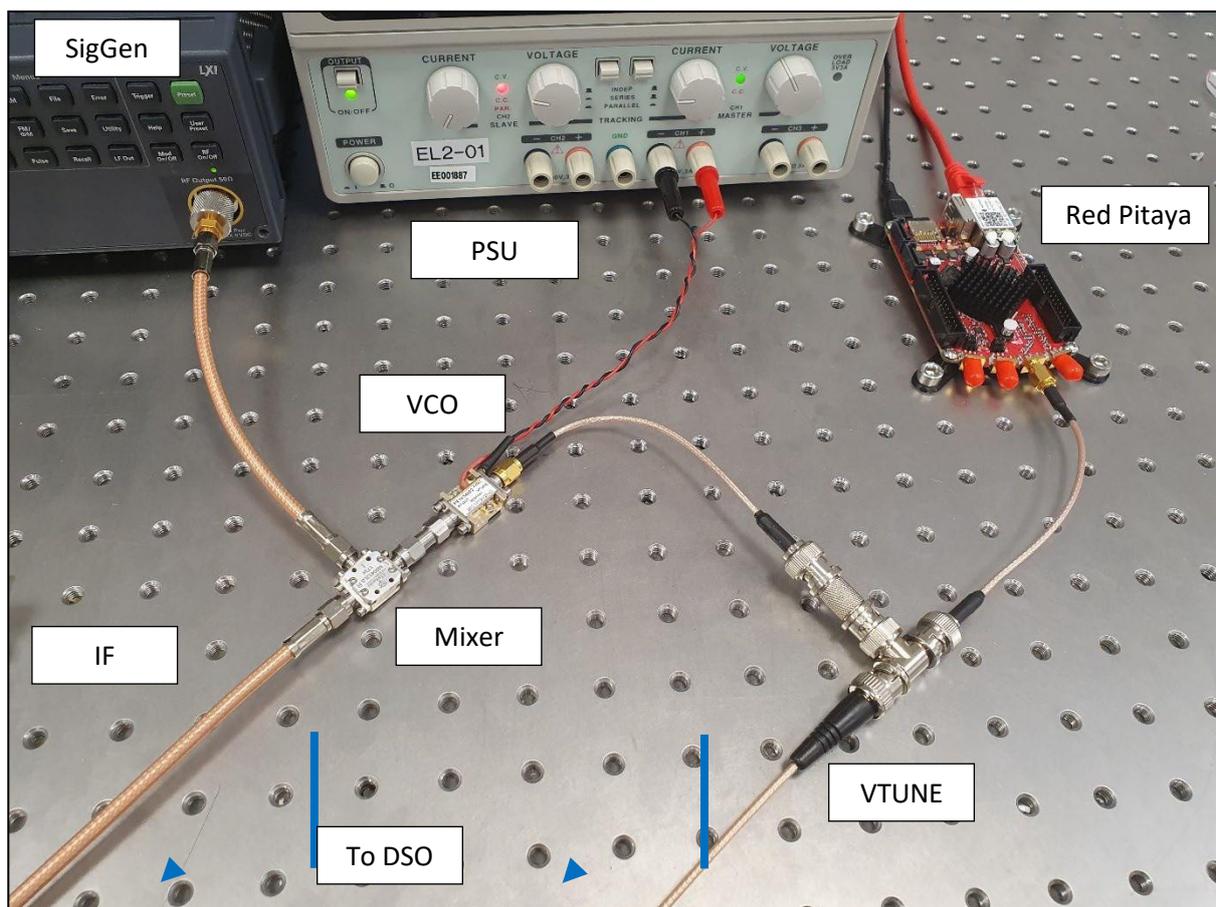
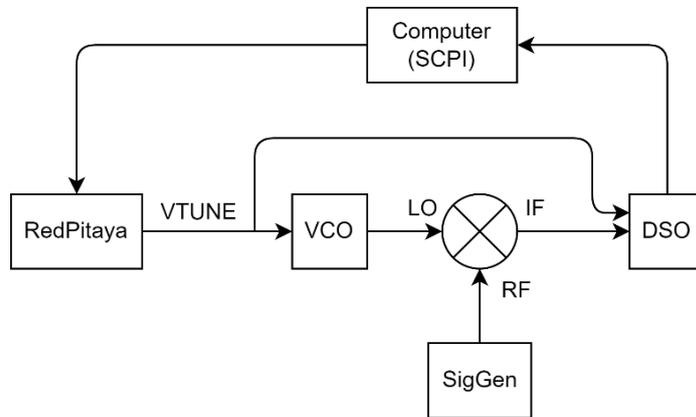


Figure 4: VCO characterization setup diagram and photo

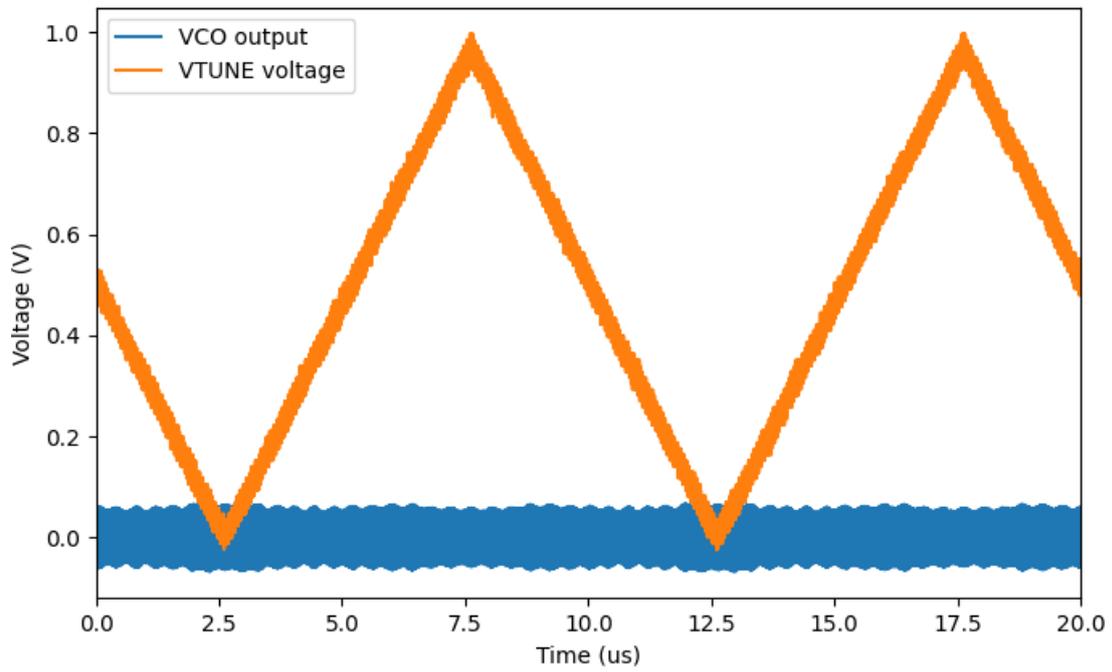


Figure 5: VCO output and VTUNE voltage data acquired from oscilloscope

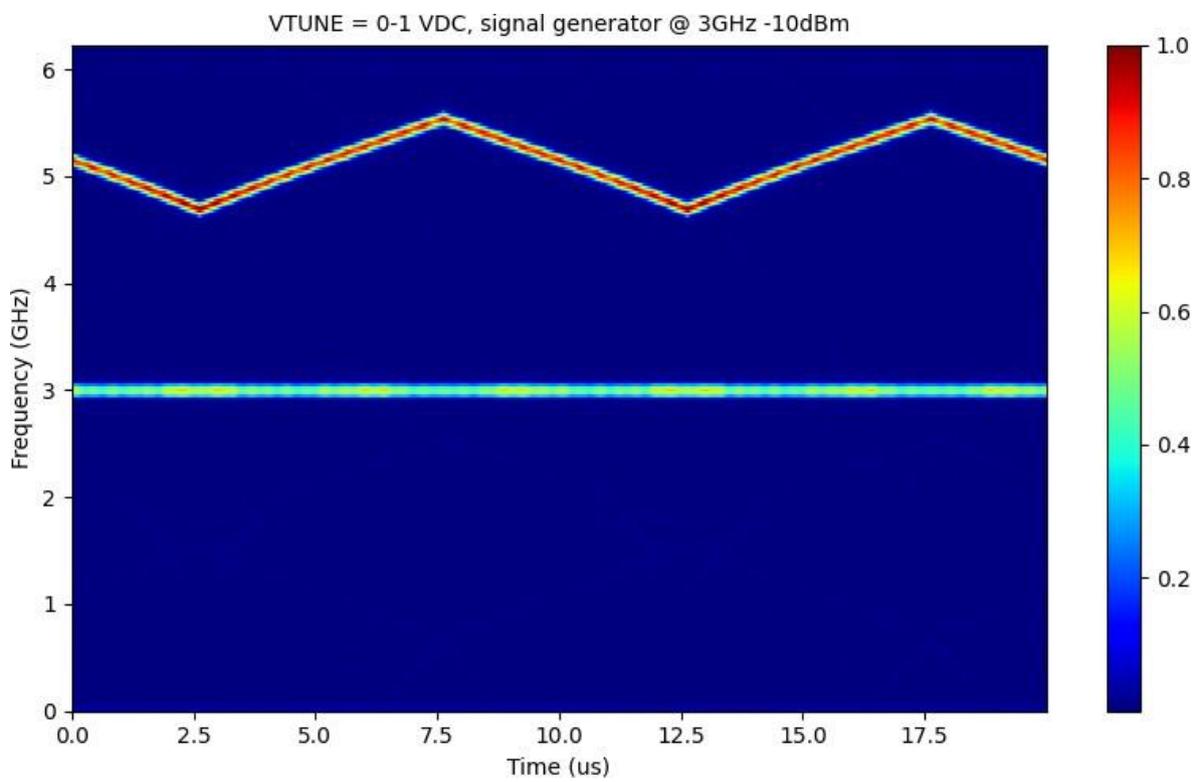


Figure 6: Spectrogram of VCO output

To extract the peak frequency in each FFT segment (vertical pixel column in Fig. 6), the region of interest shown in green in Fig. 7 is first defined to exclude the constant 3 GHz signal from being considered the peak frequency. A Lorentzian function is fitted to each FFT segment with the SciPy `curve_fit` function, as shown in Fig. 8. The peak frequency for each FFT segment is appended to a list and plotted against an ideal, linear triangle function fitted with the `curve_fit` function, as shown in Fig. 9. Taking the maximum frequency from the minimum, the bandwidth of the VCO output is 0.8482 GHz.

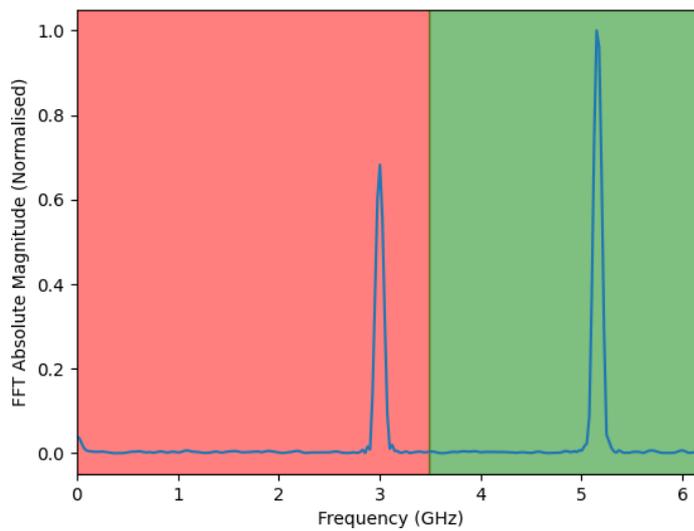


Figure 7: Lorentzian fitting region (green) and FFT segment

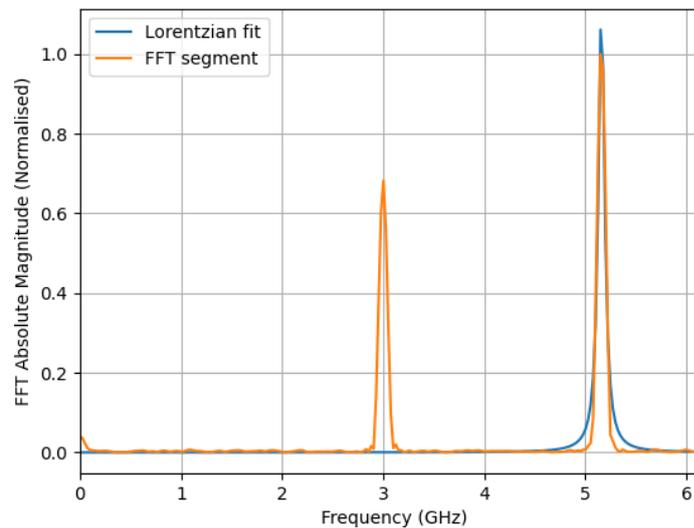


Figure 8: FFT segment with Lorentzian fit showing peak frequency of 5.16 GHz

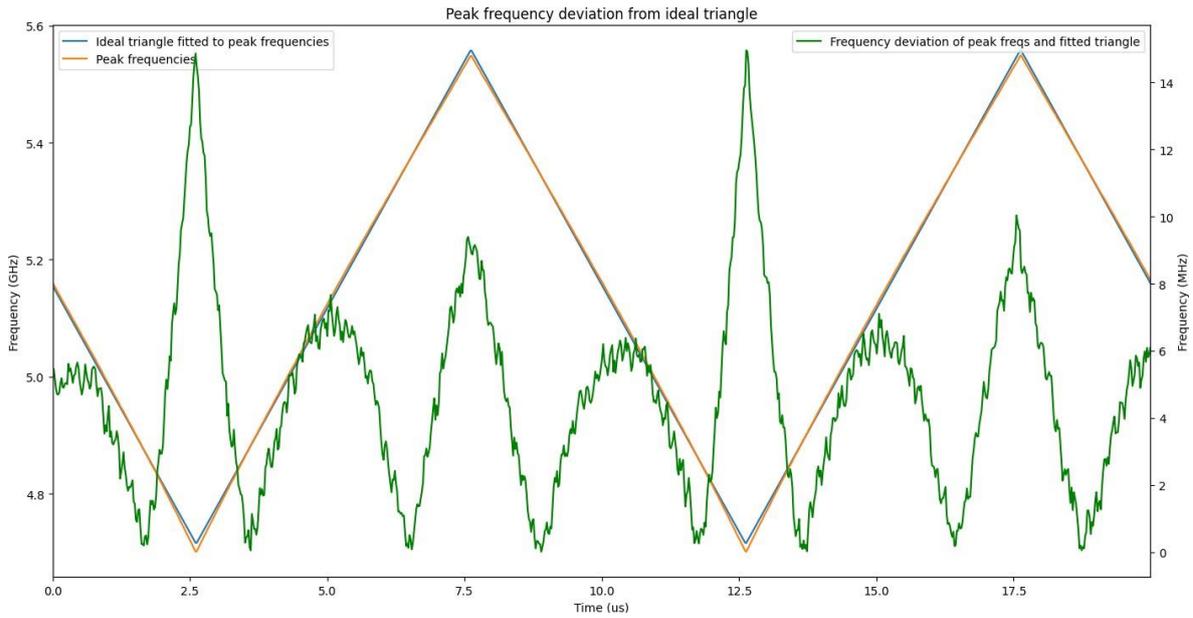


Figure 9: Peak frequency per FFT segment, an ideal fitted triangle, and the difference between the two

Figure 9 shows the non-linearity of the VCO in the deviation (green) from the linear triangle function. Taking the root mean square (RMS) of the frequency deviation results in 5.49 MHz, and this is a baseline for which we will measure the linearization process. Taking the mean of the positive frequency ramps in Fig. 9, a linear fit and compensation curve can be calculated and plotted, as shown in Fig. 10. The compensation curve is computed by taking the delta between the linear fit and the mean and adding it to the linear fit. This results in the series of delta values shown in Fig. 11, for later compensation. These are smoothed to reduce distortion over iterations of the linearization process.

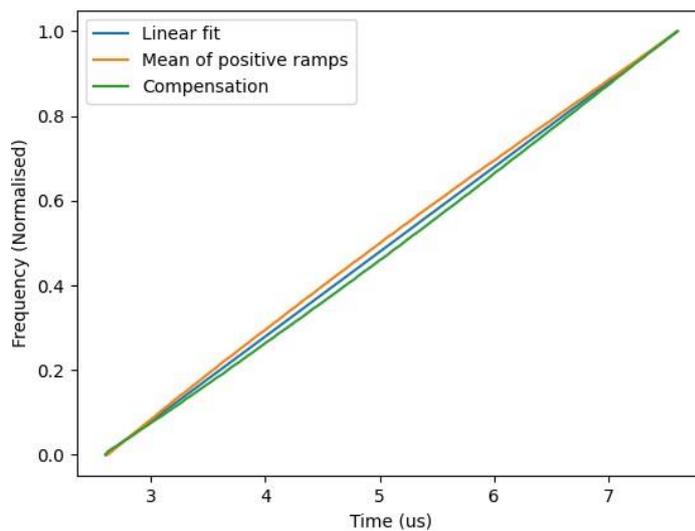


Figure 10: Mean of the positive frequency ramps plotted against a linear fit. The compensation curve is the mean mirrored about the linear fit.

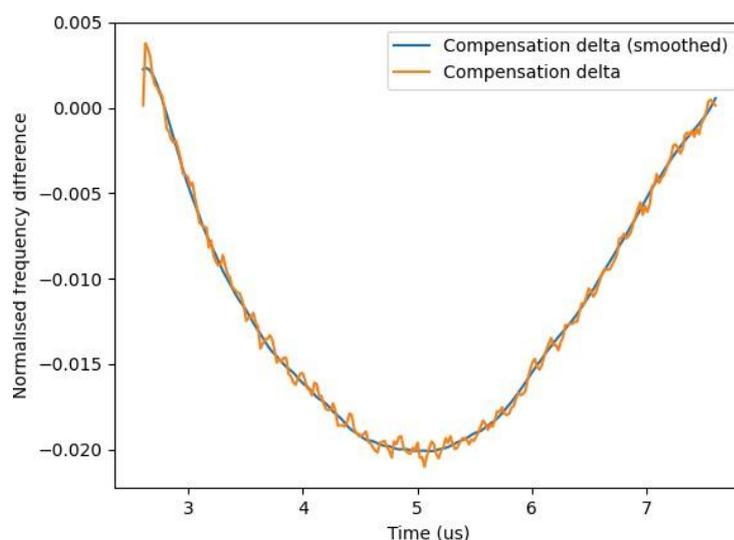


Figure 11: Original and smoothed compensation delta values

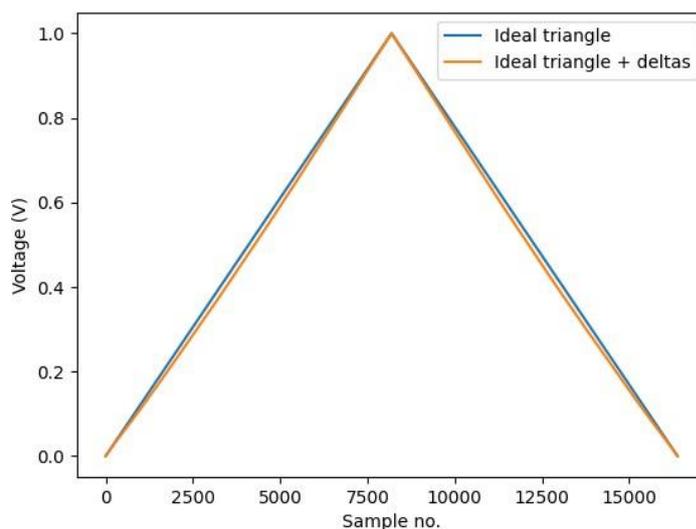


Figure 12: Ideal triangle uploaded to the Red Pitaya board for initial characterization, and the ideal triangle with compensation deltas added. The gain is set to 1 for illustration purposes.

Figure 12 shows the triangle initially uploaded to the Red Pitaya board, and one with the deltas added according to the following equation:

$$\text{new_comp} = \text{old_comp} + \text{comp_gain} * \text{deltas}$$

Note that the triangle is interpolated from the ≈ 245 FFT segment to 16,384 samples for the Red Pitaya board. The triangle is uploaded over the SCPI interface and set to 1 V at 100 kHz. This process is repeated iteratively to improve the linearity of the VCO output.

Figure 13 shows the testing of various gain levels. Most values trend towards a 0.6 MHz RMS deviation, except for gains closer to the upper range limits. This is a good improvement over the 5.5 MHz value recorded for the uncompensated VCO. It is worth noting that deviation tends to begin drifting back up. However, this is an issue that will likely be resolved in the future with the addition of some sort of gradient descent algorithm.

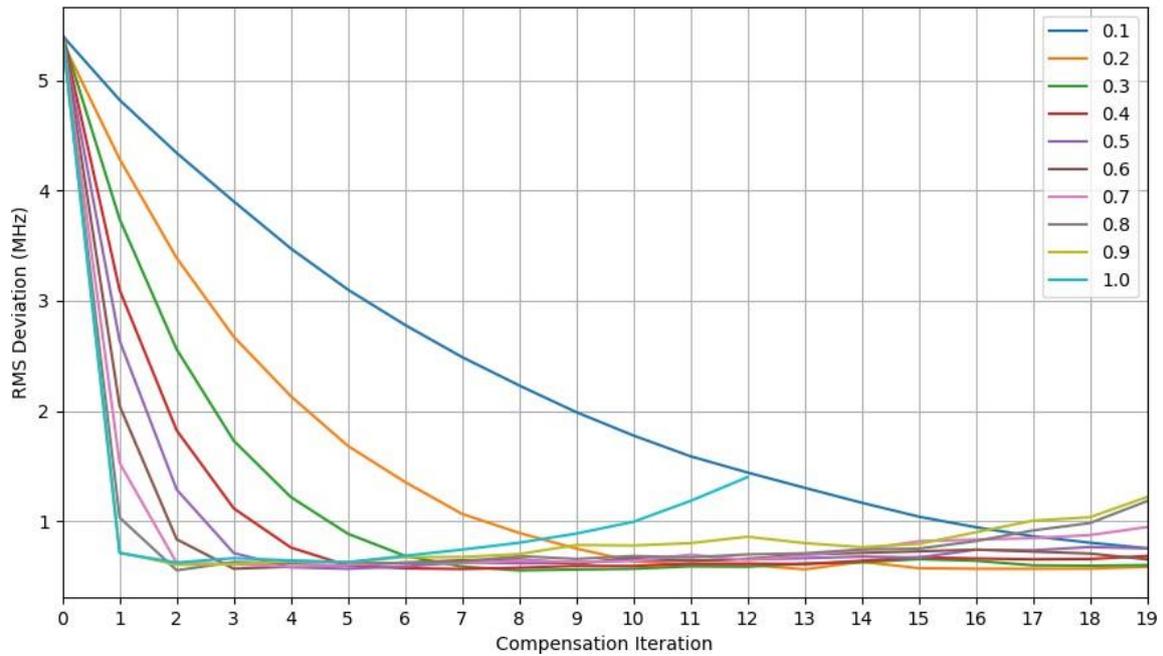


Figure 13: Testing different compensation gain levels over 20 iterations.

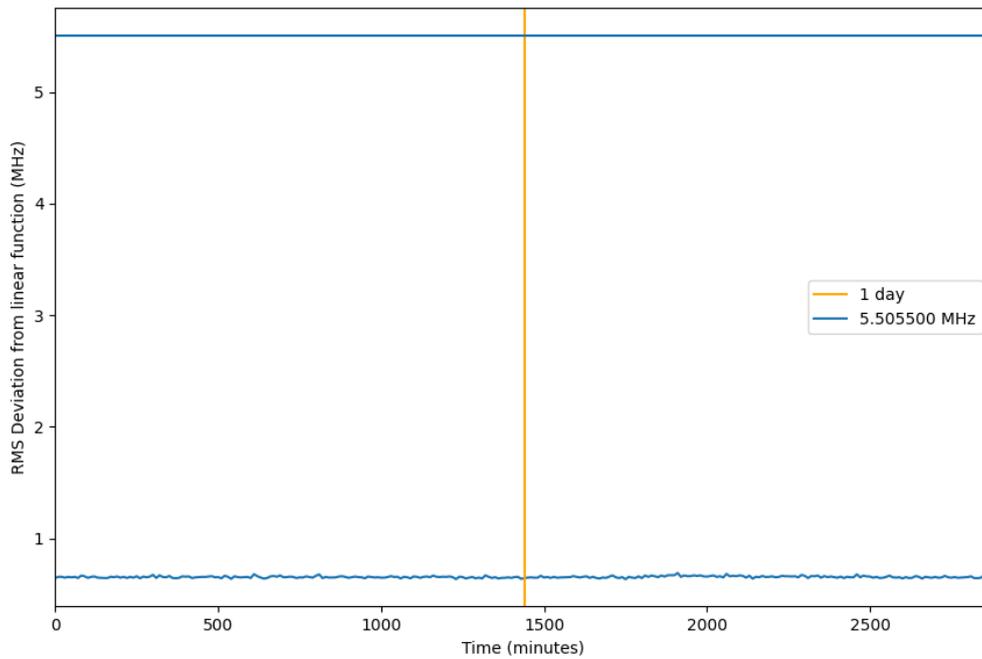


Figure 14: RMS deviation measured over 2 days. Compensation gain of 0.3, starting RMS of 5.51 MHz, mean of 0.65 MHz, Std Dev of 0.0083.

IF Testing

Now that the VCO has been linearized, a delay line setup similar to [3] is constructed according to the diagram and photo in Fig. 15 with a 10m RG316 coaxial cable. It is worth noting that RG316 supports a maximum of 3 GHz, and the intention here is to emulate poor conditions. The results are presented in Fig. 16, showing a reduction in main lobe width at an IF of 8 MHz.

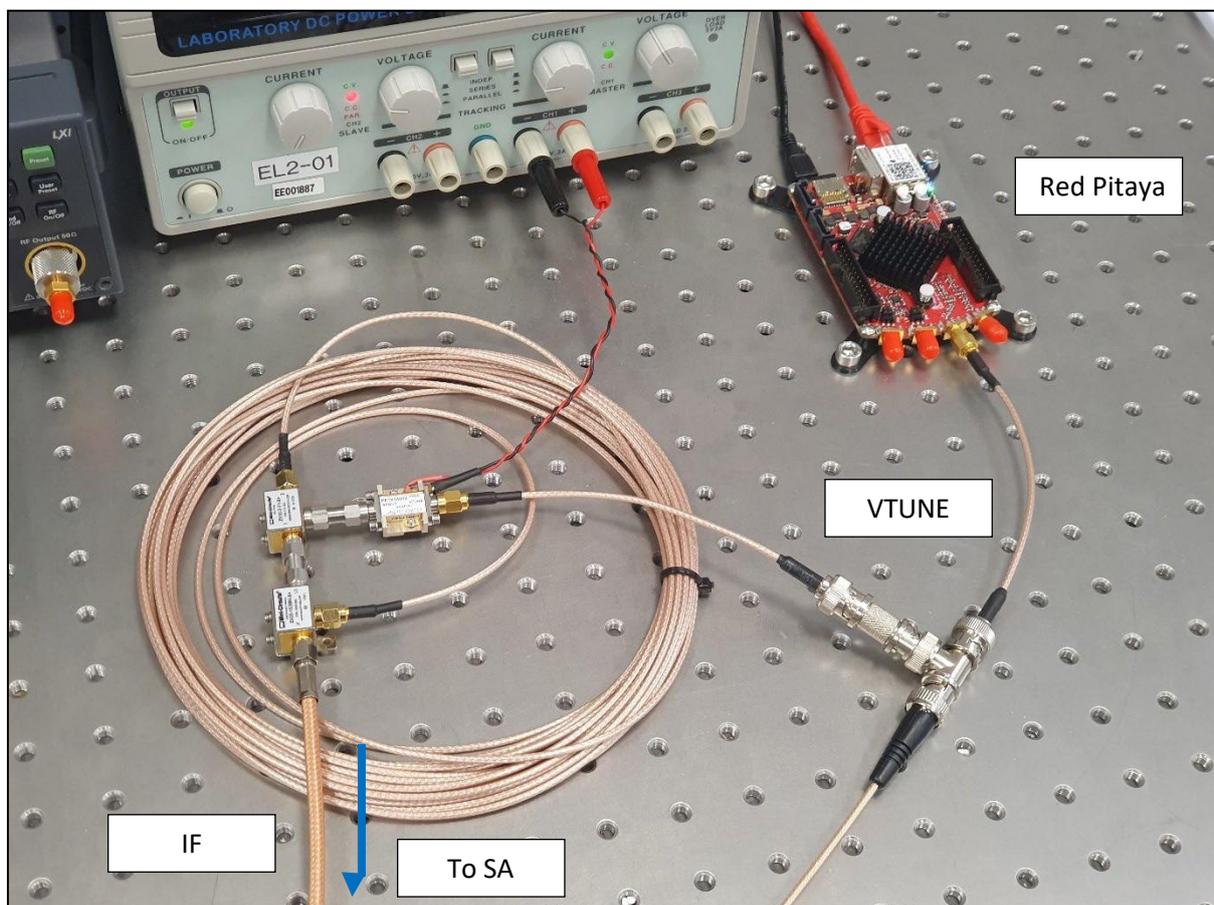
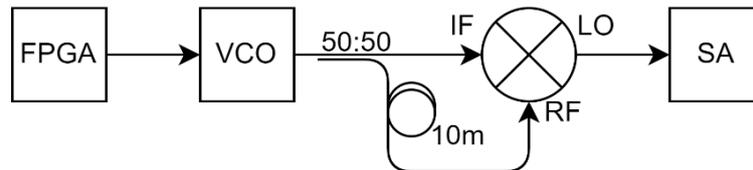


Figure 15: Delay line test setup. The VCO is fed the triangular waveform, the output is split, one arm runs through 10m of coaxial cable, both are downmixed and fed to the spectrum analyzer.

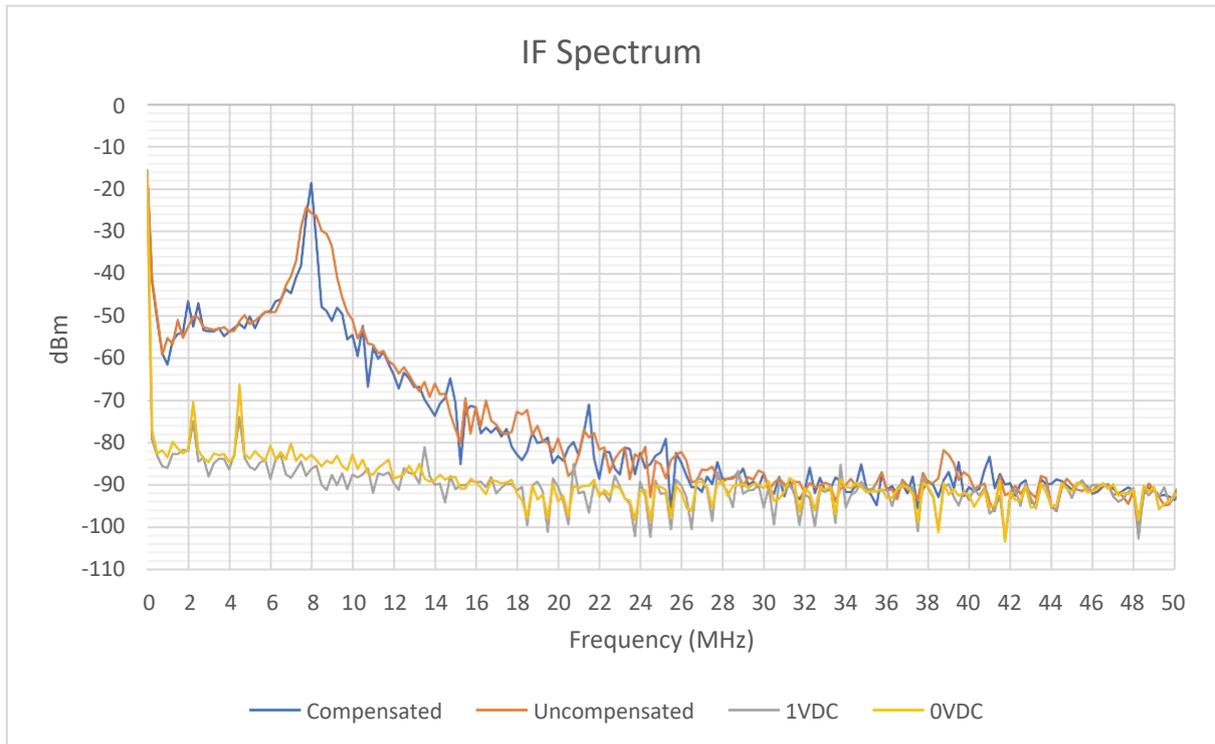


Figure 16: IF spectrum captured from spectrum analyzer for various VTUNE inputs

Discussion

The Red Pitaya board has been an incredibly useful tool in this project. Complete integration of Python across the whole project allows the linearization process itself to be fast and streamlined. The thorough SCPI documentation made integrating the device into the rest of the setup straightforward.

Future work on this project will likely involve making further small optimizations to the compensation algorithm. Additionally, amplifying the Red Pitaya's DAC in order to increase the maximum output voltage and hence output VCO frequency is something else on the to-do list. Integrating this work into a terahertz ranging system is also on the horizon.

Conclusion

This report has demonstrated how a Red Pitaya board was used in conjunction with custom Python scripts to apply a pre-distorted triangular tuning waveform to a VCO, in order to account for undesirable non-linear characteristics. The RMS frequency deviation from a fitted linear function was approximately 5.51 MHz before the linearization, and 0.65 MHz after.

References

- [1] S. Piper, "Homodyne FMCW radar range resolution effects with sinusoidal nonlinearities in the frequency sweep," in *Proceedings International Radar Conference*, 1995.
- [2] P.V. Brennan, Y. Huang, M. Ash and K. Chetty, "Determination of Sweep Linearity Requirements in FMCW Radar Systems Based on Simple Voltage-Controlled Oscillator Sources," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 47, no. 3, pp. 1594 - 1604, 2011.
- [3] J.R. Tedeschi, D.M. Sheen and S.L. McDaid, "Ultra-broadband voltage-controlled oscillator linearization for frequency modulated continuous wave MMW imaging systems," in *Radar Sensor Technology XXV*, 2021.
- [4] Pasternack, "Voltage Controlled Oscillator (VCO) 8 GHz to 12.5 GHz, Phase Noise of -83 dBc/Hz, Hi-REL Hermetic and SMA," n.d. [Online]. Available: <https://www.pasternack.com/voltage-controlled-oscillator-vco-12.5-ghz-pe1v34002-p.aspx>. [Accessed 04 July 2022].