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E157 RF Design
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Design Project 2
December 13, 2024

1 Summary Information

The secret message is “HMC”. The maximum range that we predicted our receiver would work at was 250 m. The maximum range we were able to test was 72.3 m due to running out of cable length in the hallway. The analytical system temperature was 8.22E+10 K and the measured temperature was 7.13E+07 K. The analytical receiver IIP3 was -26.77 dBm and the measured one was -62.5 dBm.

2 Pictures of Received Data

Figure 1: Picture of setup at 3 m range

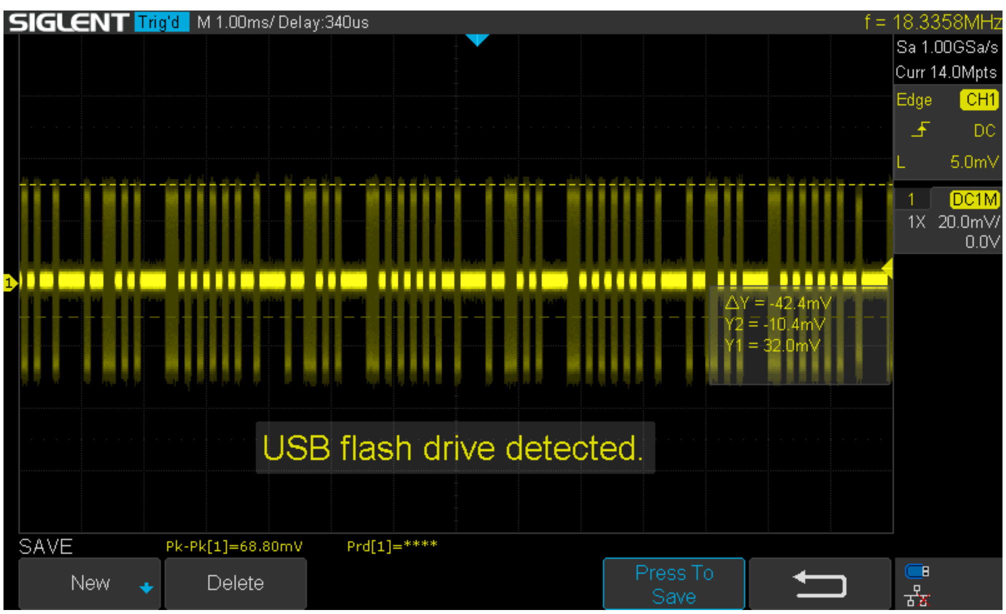


Figure 2: Oscilloscope trace at 3 m range

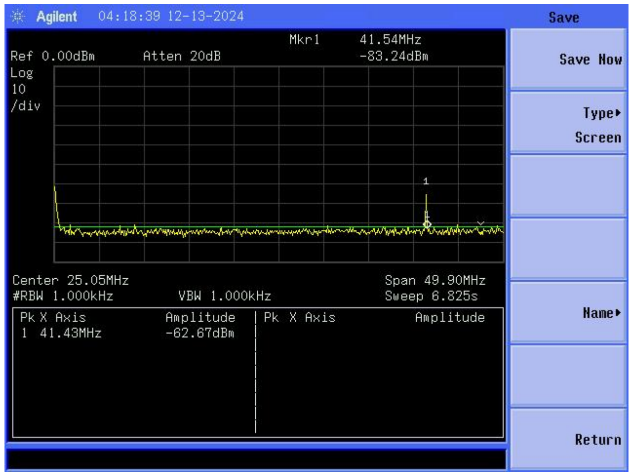


Figure 3: Spectrum at 3 m range


Figure 4: Picture of setup at max range

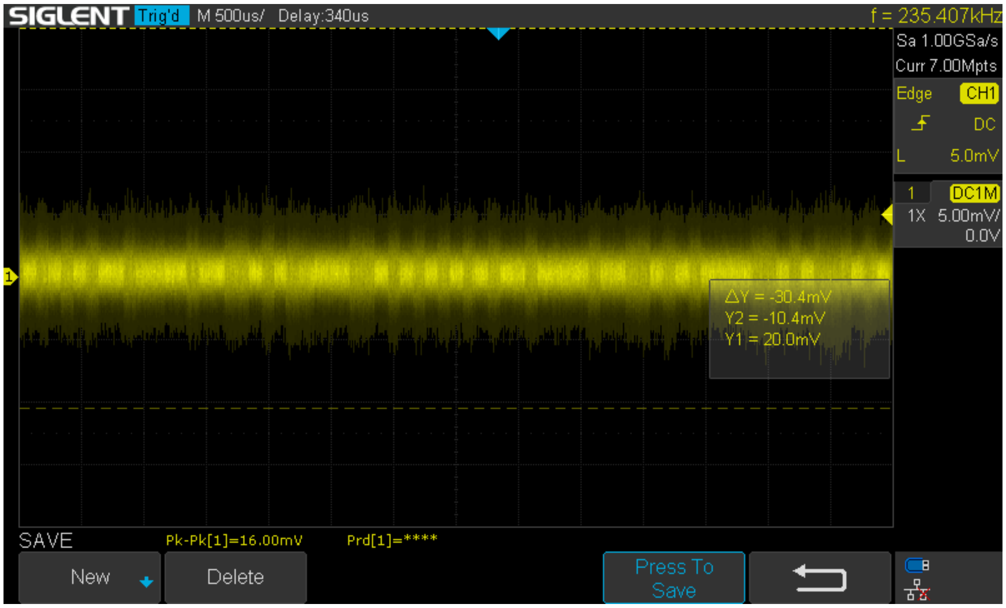


Figure 5: Oscilloscope trace at max range

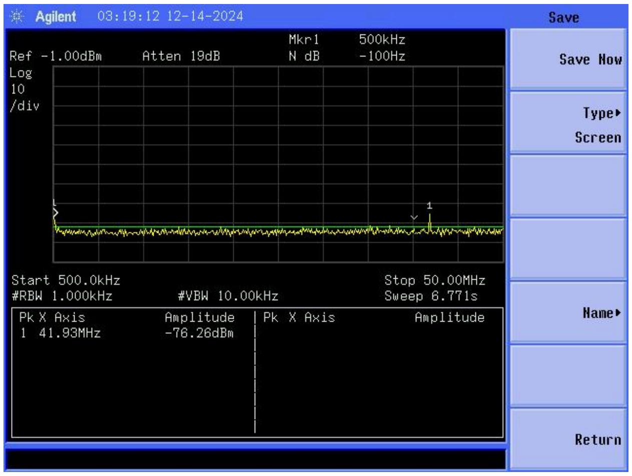


Figure 6: Spectrum at max range

3 Oscilloscope Trace Decoding

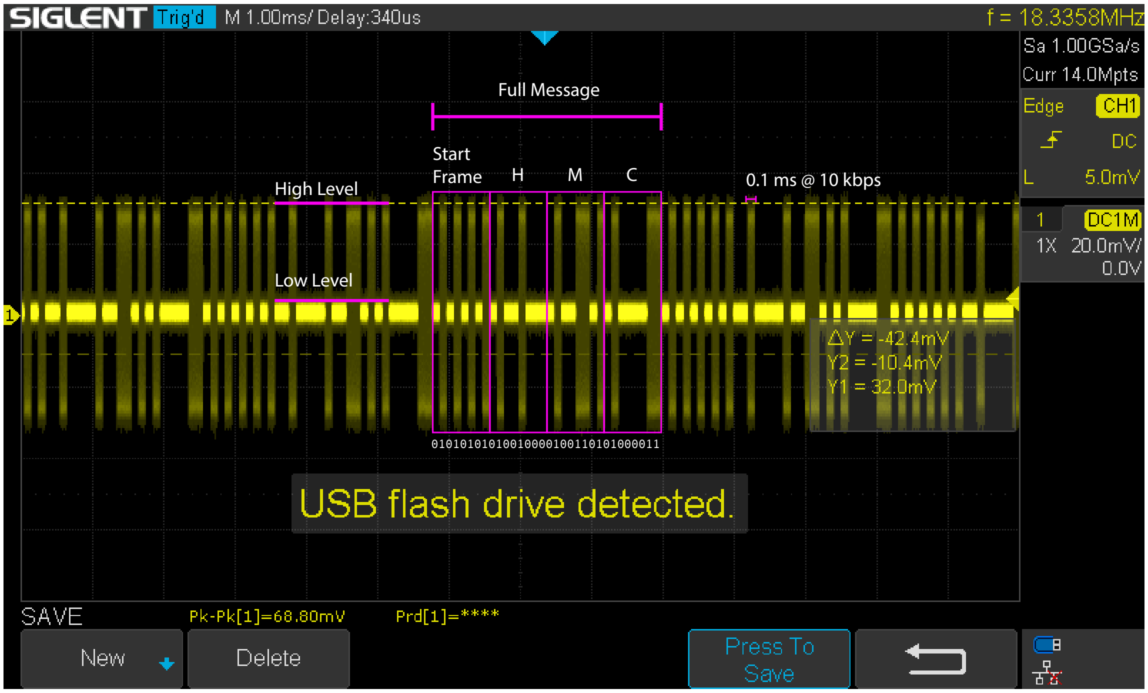


Figure 7: Annotated oscilloscope trace for decoding

The oscilloscope trace can be decoded by treating it as a 10 kbps signal where the high and low levels indicated above represents 1s and 0s respectively (the exact high level voltage depends on distance). The component representing the 0 frequency is attenuated by the mixer, so it is not visible and only the component representing the 1 frequency is left. The data is transmitted at 10 kbps so the duration of each bit is 0.1 ms.

Each message starts with a `01010101` frame which can be ignored, followed by 24 bits encoded as described above. The 24 bits should be split up into groups of 8 and decoded as ASCII characters, resulting in the message "HMC".

4 Antenna Information

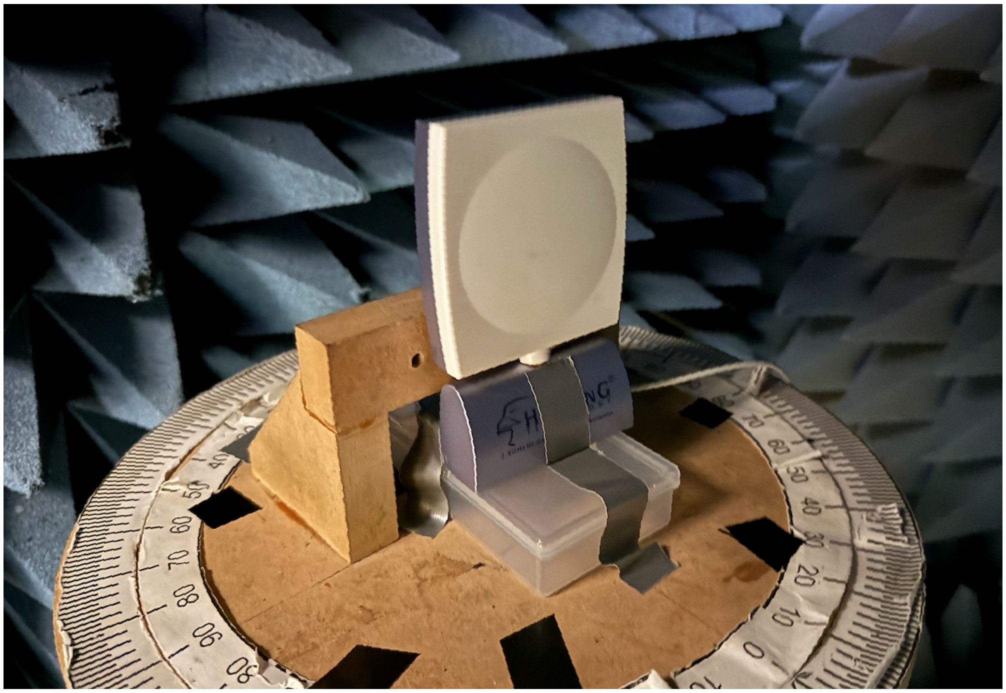


Figure 8: Hawking H-A16SD Antenna in anechoic chamber

As this is not an antenna we measured in lab 5, we extracted the radiation pattern and S11. The radiation pattern was measured in the RF lab anechoic chamber with the Keysight 8753D VNA on a turn table as pictured above. S21 was measured at incremental angles and the antenna gain was calculated using the following equation:

$$G_{TX} = S21 - G_{cal} - 20\log\left(\frac{\lambda}{4\pi r}\right)$$

Producing the following plot:

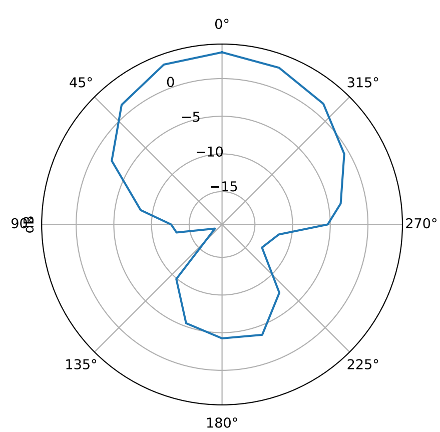


Figure 9: H-A16SD radiation pattern

The directivity of this antenna is 3.49 dB. At 0 deg we also measured S11 and other S parameters:

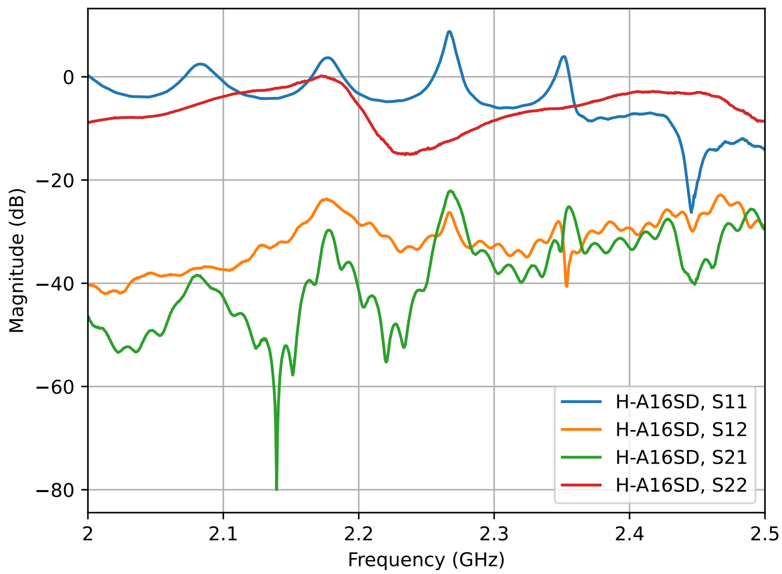


Figure 10: H-A16SD S parameters

At the frequency we are working at (around 2276 MHz) we measured an S11 of 0.39 dB which should be impossible for a passive component like an antenna. We hypothesize that this is due to our reference plane being too far away from the antenna and that the homemade RP-SMA to SMA adapter could be causing issues, but did not have time to test this.

5 Receiver Schematic

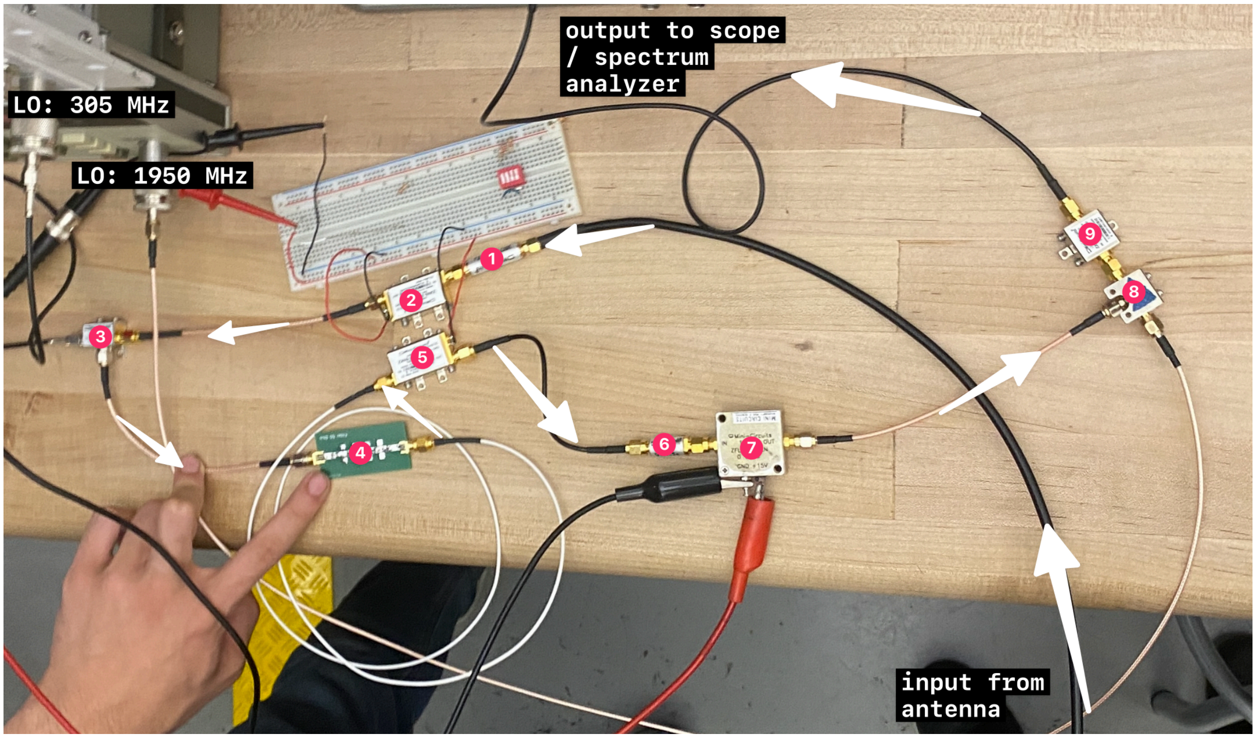


Figure 11: Picture of Receiver

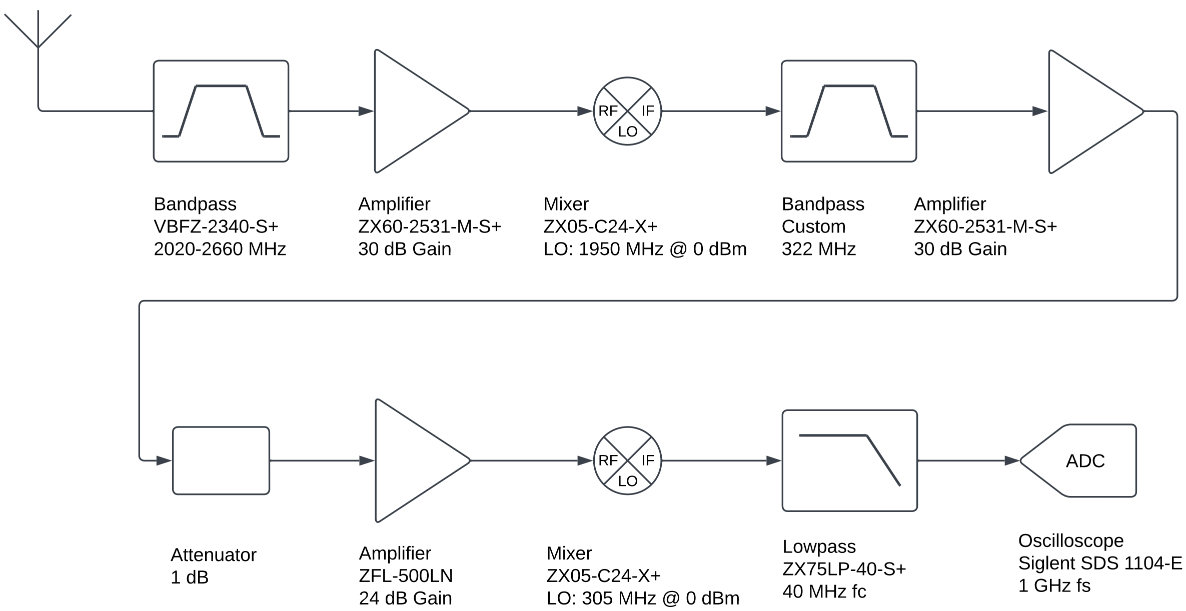


Figure 12: Receiver Schematic

The custom bandpass filter was built as a 2nd order chebyshev filter designed using Marki LC Filter Design Tool. The S21 log magnitude is provided below for reference

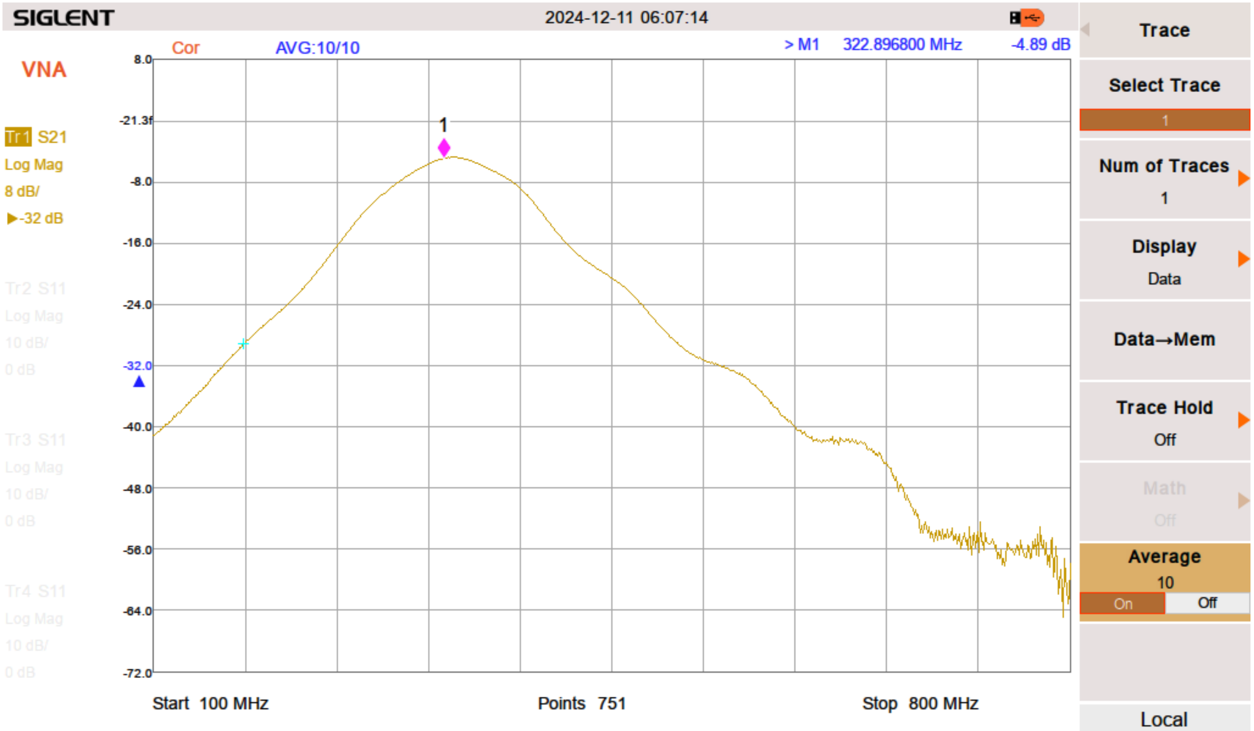


Figure 13: Custom Bandpass filter S21

6 Receiver Spectra

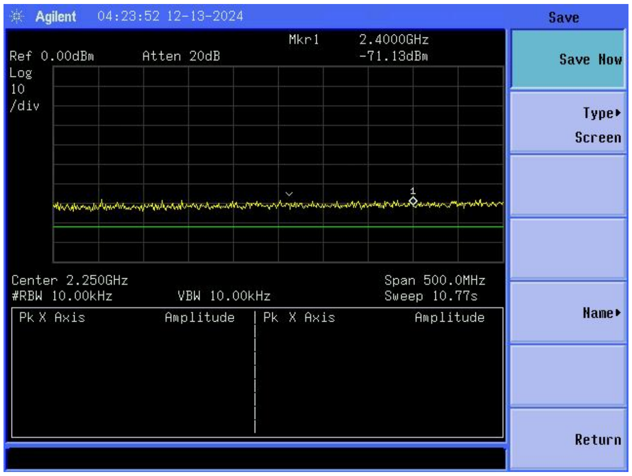


Figure 14: Stage 0: Raw antenna spectra

Due to the high noise floor, it is not possible to see any peaks in this data.

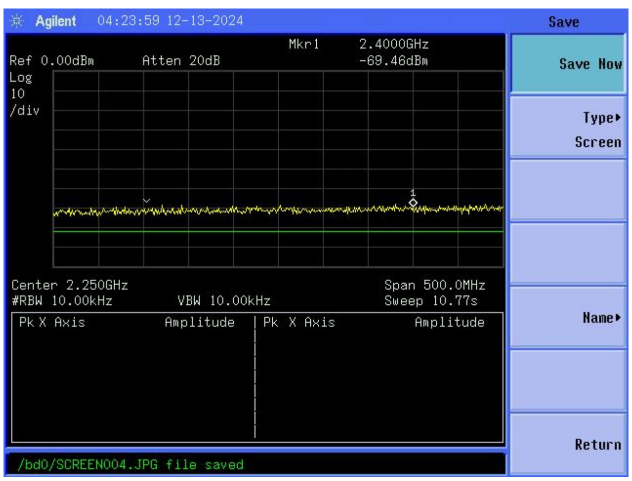


Figure 15: Stage 1: After wide bandpass filter

Due to the high noise floor, it is not possible to see any peaks in this data.

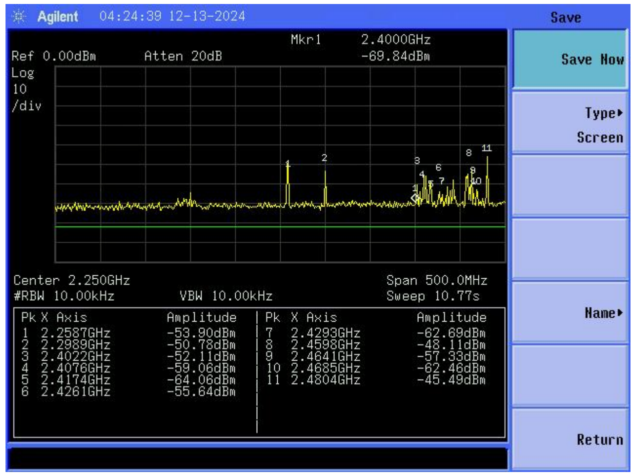


Figure 16: Stage 2: After amplifier

The two peaks at 2.258 and 2.298 GHz are the two tones of our signal. The peaks between 2.4 and 2.5 GHz are from WiFi, the small bump around 2.15 GHz is likely a cellular band using OFDM modulation.

(a) IF Spectra (b) RF Spectra

Figure 17: Stage 3: After mixer (LO = 1950 MHz)

In the IF spectra the peaks at 311.3 and 347.1 MHz are the two tones of our signal. The peaks from 450 Mhz to 485 MHz are from WiFi as before, and the bump around 100 MHz is cellular signal. There are no peaks in the RF spectra because the low input power to the mixer was not enough to cause leakage above the noise floor.

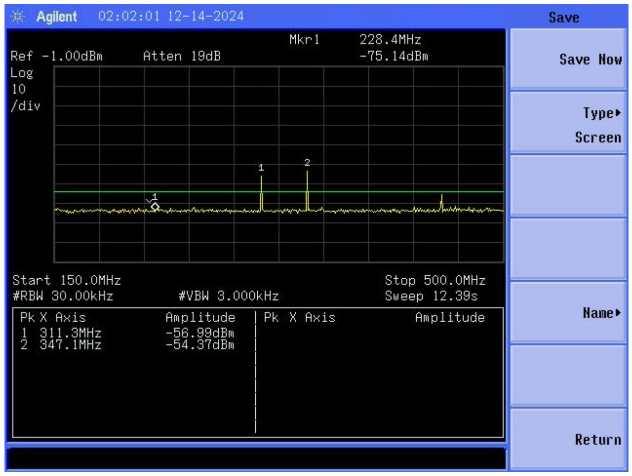


Figure 18: Stage 4: After bandpass filter

The peaks at 311.3 and 347.1 MHz are the two tones of our signal. A small peak from WiFi that was not fully filtered out is visible around 460 MHz.

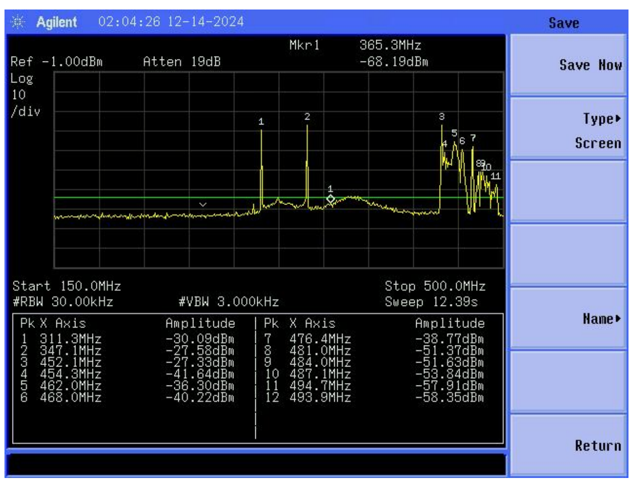


Figure 19: Stage 5: After amplifier

In the IF spectra the peaks at 311.3 and 347.1 MHz are the two tones of our signal. The peaks from 450 to 500 MHz are from WiFi. The shape of the noise floor has changed due to the bandpass filter.

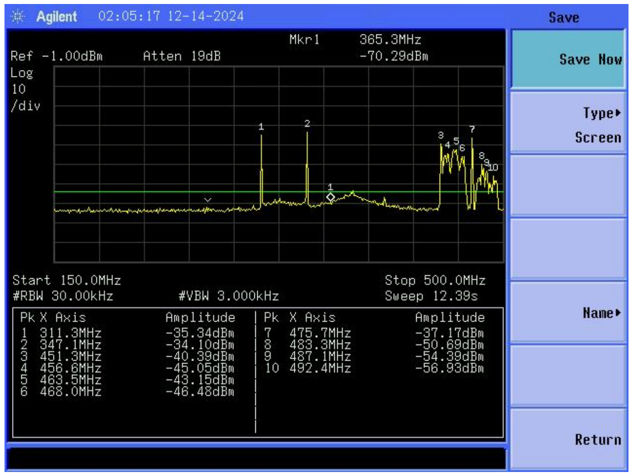


Figure 20: Stage 6: After attenuator

The peaks visible after the attenuator are the same as before the attenuator, just decreased by 3 dB.

Figure 21: Stage 7: After amplifier

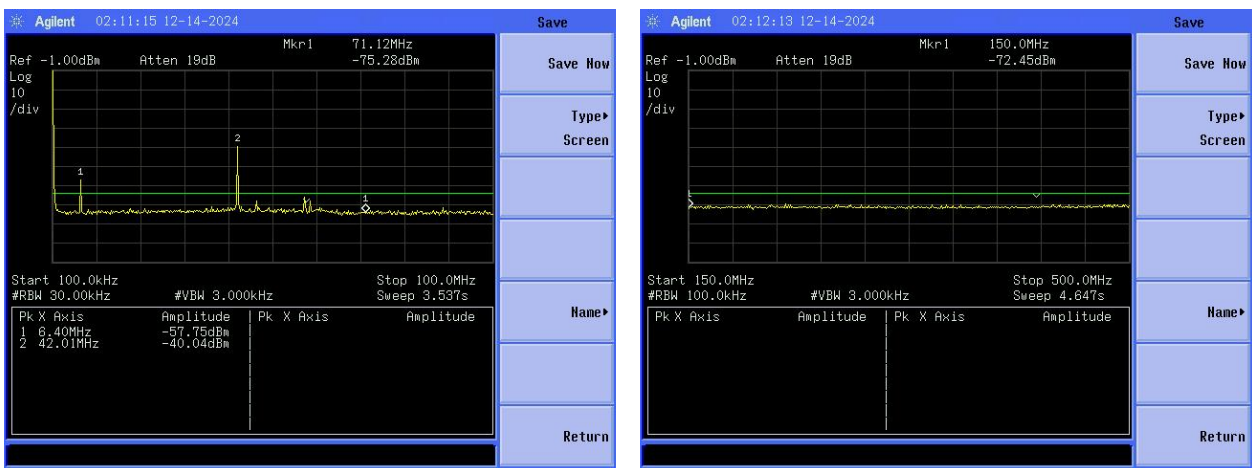
The peaks at 311.3 and 347.1 MHz are the two tones of our signal. The bump at 380 MHz is due to the shape of the bandpass filter. The peaks between 450 and 500 MHZ are from WiFi. Note that the amplifier added additional noise around 100 MHz.

(a) IF Spectra

(b) RF Spectra

Figure 22: Stage 8: After mixer

In the IF spectra the peaks at 6.4 and 42 MHz are the two tones of our signal. The bump around 80 MHz is due to the shape of the bandpass filter. The peaks in the RF spectra are leakage through the mixer due to the higher power. They appear at similar frequencies as to before the mixer.



(a) IF Spectra

(b) RF Spectra

Figure 23: Stage 9: After lowpass filter

In the IF spectra the peaks at 6.4 and 42 MHz are the two tones of our signal. There are no peaks in the RF spectra as the lowpass filter has filtered them out.

7 Theoretical Signal and Noise Levels

The link and noise budget excel spreadsheet with all calculations is here `github.com/kavidey/e157/raw/refs/heads/main/dp_02/receiver/link_budget.xlsx`

7.1 Signal Level Theory

Signal levels were calculated at each component in the receiver chain using their corresponding equations. Passive components including mixers, filters, and attenuators reduce signal strength via insertion loss. Amplifiers increase signal strength via gain, and generate distortion and intermodulation harmonics. For this report, we only focused on the IM3 harmonics those are in the baseband and we are not doing direct downconversion. IM3 harmonic size was calculated from OIP3 and IIP3 using the following formula:

$$IM3 = OIP3 - 3 \cdot (IIP3 - Pin)$$

OIP3 was read off of amplifier datasheets directly (ZX60-2531MA+ and ZFL-1000LN). IIP3 was calculated from datasheet "Output power at P-1dB" as $IIP3 = P_{-1dB,out} - (G_{ain} - 1) + 9.6$. Propagating power through each step of the receiver chain. A full list of important component properties in section 9.

		TX source	TX antenna	RX antenna	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9
	Stage Name				Wide BPF	Amplifier	Mixer	Narrow BPF	Amplifier	Attenuator	Amplifier	Mixer	LPF
Receiver characterization theory	Tone 1 power	NA	NA	-40	-41.4	-4.4	-10.4	-15.9	19.1	16.1	39.1	33.1	32.1
	Tone 1 frequency	NA	NA	2256	2256	2256	306	306	306	306	306	1	1
	Tone 2 power	NA	NA	-40	-41.4	-4.4	-10.4	-15.9	19.1	16.1	39.1	33.1	32.1
	Tone 2 frequency	NA	NA	2296	2296	2296	346	346	346	346	346	41	41
	IM3 power	NA	NA	NA	NA	-90	-96	-101.5	-13.5	-16.5	80.3	74.3	73.3
	IM3 lower frequency	NA	NA	NA	NA	2216	266	266	266	266	266	39	39
	IM3 upper frequency	NA	NA	NA	NA	2336	386	386	386	386	386	81	81
	DANL	NA	NA	NA	-159.15	-111.33	-109.55	-115.73	-82.81	-85.81	-63.01	-61.04	-72.65
Receiver characterization measurement	Tone 1 power	NA	NA	NA									<DANL
	Tone 1 frequency	NA	NA	NA									1
	Tone 2 power	NA	NA	NA									-61.4
	Tone 2 frequency	NA	NA	NA									41
	IM3 power	NA	NA	NA									-75.3
	IM3 lower frequency	NA	NA	NA									39
	IM3 upper frequency	NA	NA	NA									81
	DANL	NA	NA	NA									-71

Figure 24: Theoretical and measured signal power levels

These calculations were repeated for 3 m and max range test which are available in the spreadsheet linked above. In all cases the predicted noise power is quite a bit higher than the measured one. In the example above, the predicted baseband power is much larger than the expected, resulting in massively larger IM3 components.

7.2 Noise Level Theory

Noise levels were calculated in a few steps. First, the noise temperature of each component was calculated from theory: $T_p = \left(\frac{1}{L} - 1\right) T$ for passives and $T_a = (nf - 1)T$ for amplifiers. Next, the system temperature at each point in the receive chain was calculated as $T_{out} = \{G \text{ or } L\} \cdot (T_{in} + T_d)$ where T_d is the component temperature. Notably the system temperature was multiplied by two for mixers as the produce two copies of the noise. This temperature was also converted to dBm for easier comparison to measured noise level. Note that the assumed antenna noise as 290K from pointing at earth.

		TX Noise	RX Noise	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9
				Wide BPF	Amplifier	Mixer	Narrow BPF	Amplifier	Attenuator	Amplifier	Mixer	LPF
Theory without antenna	Stage Noise Contribution Theory [K]	0.00E+00	0.00E+00	1.10E+02	2.89E+02	8.65E+02	7.39E+02	2.89E+02	2.89E+02	2.75E+02	8.65E+02	7.51E+01
	System Noise Temperature Theory [K]	0.00E+00	0.00E+00	7.99E+01	1.85E+06	9.28E+05	2.62E+05	1.31E+09	6.58E+08	1.31E+11	6.60E+10	5.24E+10
	System Noise Temperature Theory [dB]			-139.57	-95.93	-88.92	-99.65	-62.64	-65.64	-42.64	-50.40	-46.63
Theory with antenna	Stage Noise Contribution Theory [K]	0.00E+00	2.90E+02	1.10E+02	2.89E+02	8.65E+02	7.39E+02	2.89E+02	2.89E+02	2.75E+02	8.65E+02	7.51E+01
	System Noise Temperature Theory [K]	0.00E+00	2.90E+02	2.90E+02	2.90E+06	1.46E+06	4.11E+05	2.06E+09	1.03E+09	2.06E+11	1.04E+11	8.22E+10
	System Noise Temperature Theory [dB]		-133.98	-133.98	-93.98	-86.96	-97.69	-60.69	-63.69	-40.69	-48.45	-44.68
Measured with antenna	Spectrum Analyzer RBW [Hz]		1.00E+04	1.00E+04	1.00E+04	1.00E+05	3.00E+04	3.00E+04	3.00E+04	3.00E+04	1.00E+04	3.00E+04
	Spectrum Analyzer Measurement DANL [dB]		-70.00	-70.00	-70.00	-60.00	-65.23	-65.23	-65.23	-65.23	-70.00	-65.23
	Receiver Noise Measurement [dB]		-71.1	-69.5	-69.8	-61.9	-75.1	-68.2	-70.3	-51.5	-74.8	-75.3
	Receiver Noise Measurement [K]		5.62E+08	8.13E+08	7.58E+08	4.68E+08	7.46E+07	3.65E+08	2.25E+08	1.71E+10	2.40E+08	7.13E+07

Figure 25: Theoretical and measured signal noise levels

Similar to the signal power, the analytical noise temperature much larger (three orders of magnitude higher) than the measured noise temperature. Both of these is likely due to over estimating the gain of the amplifiers.

The theoretical maximum range was calculated by testing different distances in the spreadsheet until the signal power was equal to the noise power.

8 IP3 Distortion Characterization

To measure the IIP3 of our amplifier we replaced the antenna with a two tone signal generator. We tested a range of input powers and measured the output power of the fundamental and the IM3 terms to make the following plot.

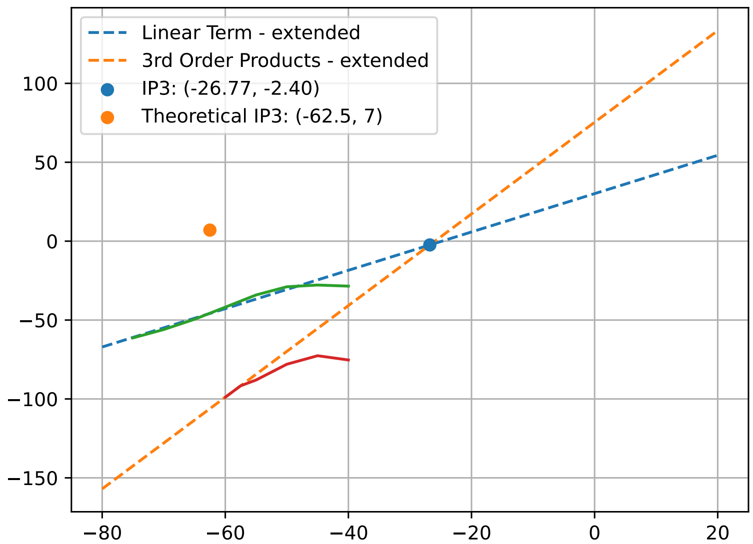


Figure 26: Analytical and measured IIP3

Running a linear regression we get:

Term	Slope	Intercept
Linear	1.21	30.12
3rd Order	2.9	75.34

To calculate the analytical IP3 point we used the following logic. We only need to consider the IM3 components generated by the last amplifier because they are orders of magnitude larger than the earlier ones. This allows us to simplify the receiver chain into gain → amplifier → attenuation.

Adding additional (assumed perfectly linear) gain G before the final amplifier reduces the input power needed to achieve the same output power. In other words reduces $IIP3$ to $IIP3_{combined} = IIP3_{amplifier} - G$ while keeping the same $OIP3$. Adding additional attenuation L after the final amplifier reduces the total output, keeping $IIP3$ the same and reducing $OIP3$ to $OIP3_{combined} = OIP3_{amplifier} - L$.

Our final amplifier (stage 7) is the ZFL-1000LN which has an $IIP3$ of -6.4 dBm and $OIP3$ of 14 dBm (from the device datasheet). Adding up all the amplification and attenuation from stages 1-6, we get G = 56.1 dBm and addding up the attenuation from stages 8-9 we get L = -7 dBm. This results in analytical $IIP3$ = -62.5 and $OIP3$ = 7 dBm.

To verify this calculation, we tested different power values in the signal and noise level excel spreadsheet we made for section 7 until the IM3 components were equal to the signal power. This yielded an $IIP3$ = -61 dBm and $OIP3$ = 10 dBm, fairly close to the other analytical method.

Note that both analytical methods are fairly far away from the measured value. This is likely due to a combination of noisy measurements (neither line in the measured plot has the correct slope) and incorrect gain/IIP3/OIP3 values as discussed in section 7. The data here implies that IIP3 and gain before stage 7 are less accurate the OIP3 and the attenuation after stage 7.

9 Additional Notes

All of the data, code, and figures are available in this github repo: github.com/kavidey/e157/tree/main/dp_02.

Useful Information									
Mixer LO		**Transmit Antenna**		**ZX60-2531MA+ Amplifier**		**Custom BPF**		**ZX75LP-40-S+ LPF**	
LO1	1950	Antenna Return Loss [dB]	-10	Gain @ 2200 MHz [dB]	37	Insertion Loss [dB]	5.5	Insertion Loss [dB]	1
LO2	305	Antenna Directionality [dBi	4	Gain @ 300 MHz [dB]	35	226 MHz Attenuation [dB	20	75 MHz Attenuation [dB]	44
				IIP3 [dB]	-2.4	386 MHz Attenuation [dB	10	100 MHz Attenuation [dB	60
Physical Parameters		**Receive Antenna**		OIP3 [dB]	27	200 MHz Attenuation [dB	24	150 MHz Attenuation [dB	57
Distance [m]	3	Antenna Return Loss [dB]	-10	NF [dB]	3	450 MHz Attenuation [dB	20		
Physical Temperature [K]	290	Antenna Directionality [dBi	4						
Boltzmann's Constant	1.3806E-23			**ZX05-C24+ Mixer**		**ZFL-1000LN Amplifier**			
		VBFZ-2340-S+ BPF		Conversion Loss [dB]	6	Gain [dB]	23		
Spectrum Analyzer		Insertion Loss [dB]	1.4			IIP3 [dB]	-6		
Noise Temperature [K]	724000000	Band Start [MHz]	2020			OIP3 [dB]	14		
		Band Stop [MHz]	2660			NF [dB]	2.9		

Figure 27: Receiver component parameters (from datasheets and calculated)