1-2019

# VHF Transmitter Development For Wildlife Tracking

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# VHF TRANSMITTER DEVELOPMENT FOR WILDLIFE TRACKING

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A Thesis Submitted to the Graduate Faculty of

GRAND VALLEY STATE UNIVERSITY

In

Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE IN ENGINEERING

School of Engineering

December 2018

**Acknowledgments**

Thank you to my employer, EBW Electronics, for purchasing supplies for this project and supporting me throughout my masters studies.

## Abstract

Wildlife biologists often use collars with VHF transmitters to gather wildlife data. The purpose of this project is to determine the best approach to designing a wildlife tracking VHF transmitter on a Printed Circuit Board (PCB). A variety of frequency generation methods were considered for the transmitter, including transistor-based crystal oscillators and chip based solutions from the chip manufacturers Analog Devices and Silicon Labs. Prototypes of the feasible options were built and evaluated for cost, power consumption, efficiency, size, frequency range, signal bandwidth, and frequency stability. It was found that the Silicon Labs Si4010 chip was the best solution based on these criteria; the design allowed for flexibility in output frequency and power, a low BOM cost, and very low power consumption.

# Contents

**List of Tables**

## List of Figures

## Acronyms

| | |
|---|---|
| ATS | Advanced Telemetry Systems |
| dBm | Decibel Milliwatts |
| FCC | Federal Communications Commission |
| GPS | Global Positioning System |
| HFF | High Frequency Fundamental |
| LPF | Low Pass Filter |
| MSOP | Mini Small Outline Package |
| PCB | Printed Circuit Board |
| PCBA | Printed Circuit Board Assembly |
| PLL | Phase Lock Loop |
| PPM | Parts Per Million |
| UHF | Ultra High Frequency |
| VHF | Very High Frequency |

# Chapter 1
# Introduction

## 1.1 Background

Very High Frequency (VHF) transmitters are commonly used in wildlife research. These transmitters are battery-powered devices that send out low power, low duty cycle pulses at a specific frequencies in the 148 to 152 MHz range. The transmitters are integrated into animal collars and biologists then track the movements of these animals by regularly visiting the area with a VHF receiver and directional antenna. Different frequencies are used to differentiate between the animals.

There are other methods for wildlife tracking that are based on satellite communications and Global Position System (GPS). Satellite tracking involves a collar that transmits a signal, received by satellites that calculate the animal's location. GPS collars work in the opposite way; satellites are used to transmit signals, and the collar receives those signals and calculates its location based on the content and strength of each signal. These two satellite-based tracking methods can continuously log data, giving biologists much more data than VHF tracking can. However, these extra data come with a cost. Satellite-based systems are much more complex than VHF transmitters, and that makes them larger in size and weight, higher in power consumption, and much more expensive. The result of this is that fewer animals can be tracked due to their size and cost [1].

When GPS or satellite tracking is used, VHF transmitters are still useful to have on the collar. They can be used as a low cost backup to the primary tracking method. Even after a satellite-based collar depletes its battery, a very low power VHF transmitter can allow the user to still track the animal, recover the hardware, and recover any data that may remain in the collar. Since the collars are very expensive, it is more economical to replace the batteries and re-use the collar than to purchase a new one [1].

## 1.2 Purpose

The purpose of this project is to design a small, lightweight, efficient VHF transmitter that can be used for wildlife tracking. Grand Valley State University (GVSU) has developed several Ultra High Frequency (UHF) and Satcom based collars, however, they all have relied on a 3rd party VHF beacon for backup. The goal of this project is to develop an in-house option that can be incorporated in future collars, thus allowing customization of tracking collars for specific animals studied at GVSU.

## 1.3 Scope

The scope of this project is only to develop the VHF transmitter, with an emphasis on frequency generation. While the power consumption of this device is taken into consideration, the type, size, and lifespan of battery are not discussed. When the VHF transmitter is used as a supplement to a satellite based system, it is expected that both systems will be powered by the same battery. Similarly, output power is taken into consideration, but since the receiver is not part of the scope, transmission distance is not included in this project. Multiple frequency generation methods, including transistor-based crystal oscillators and Phase Lock Loops (PLLs), will be evaluated.

In order to be used legally, this design may require testing for compliance with the Federal Communication Commission (FCC). The scope of this project does not include FCC certification; however, the topic will briefly be discussed in Appendix D to help prepare the transmitter for legal use. All tests involving transmitting were done in the 2-meter amateur radio band via a licensed amateur radio operator. The typical band for wildlife tracking is 148 to 152 MHz, and the 2-meter amateur band is directly adjacent, at 144 to 148 MHz. Since these bands are so close, the applications can be developed in the amateur radio band, with only slight adjustments required to adapt the design to the wildlife tracking band.

### 1.4 Research Question

The research subject of this project is to find which frequency generation method is best suited for the VHF transmitter. A transistor-based crystal oscillator is the simplest approach to frequency generation, but it has its limits. A more complex system, such as a PLL has many more features and is more flexible, but those advantages came at a cost. These designs will be discussed in Chapter 3. In order to decide which design should be used, quantifiable criteria will be established and the designs will be evaluated according those criteria in Chapter 4.

### 1.5 Significance

Wildlife tracking is important to help biologists understand the environment and VHF transmitters are a vital part of wildlife tracking. With better tracking tools, biologists can get more data and ultimately learn more about the environment. Designing a low cost transmitter will allow the GVSU biology department to pursue more tracking options, whether that be tracking animals with VHF transmitters and directional antennas or using the transmitter as part of a larger GPS or satellite system.

# Chapter 2

## Literature Review: Frequency Generator Designs

Tracking wildlife with VHF transmitters and directional antennas is an established technology; biologists have been doing this for many years. A variety of products already exists in this market from companies like Advanced Telemetry Systems (ATS) and American Wildlife Enterprises. The product designs are intellectual property that is not publicly shared, so there is not currently publicly disseminated literature for state-of-art wildlife tracking VHF transmitters. From ATS specification documents, it is clear that the transmitters are a crystal-based systems and that the pulse width can be controlled by a microcontroller [2]. Since not much more can be determined about those designs, this literature review looks at the various other designs that generate signals and transmit in the VHF range.

### 2.1 Discrete Transistor-Based Oscillators

While wildlife tracking is commonly done around 150 MHz, it has not been exclusively done there. A US Forest Service book from 1968 gives some detail for a 27 MHz transmitter that was used for tracking animals. A simple Colpitts Oscillator was used for this system, however the frequency is much lower than what is commonly used today, and the design used large capacitors and coils that made the system heavy [3]. While the operating principles haven't changed, electronic technology has changed a lot since 1968, so it can be expected that this transmitter design can be improved.

Though they are not common, crystal oscillators have been designed all the way up into the UHF band. A paper from a 2003 IEEE symposium presented a circuit for a 622 MHz Colpitts oscillator based on a High Frequency Fundamental (HFF) crystal [4]. Crystals in the high VHF and low UHF range can be purchased, however, the crystals are typically custom manufactured at those high frequencies because they are uncommon and the crystal is very thin. In that paper, Matsuoka et al. proposed a modification to a Colpitts oscillator to decrease the crystal drive current. Matsuoka also demonstrated the ability to tune a crystal oscillator +/- 160 ppm; tuning a crystal oscillator enables the same circuit to create multiple transmitter frequencies [4]. Designing a system around custom HFF crystals is clearly an option for VHF wildlife tracking, though procuring the custom crystals may be challenging.

In his 1995 book, Randall Rhea outlines some alternate options for generating VHF signals with crystal oscillators. The first is an overtone oscillator, which is built around an overtone crystal instead of an HFF crystal. Overtone crystals in the 150 MHz range are also typically manufactured custom for the application, so this design option is similar to designing around an HFF crystal. Crystals tend to have stronger odd than even harmonics, and crystals can be custom manufactured to take advantage of the strong odd overtones [5]. Overtone crystals are discussed in more detail in Section 3.3.

The other option from Rhea's book is an oscillator with a frequency multiplier. Rhea has developed a crystal-based oscillator that operates at its fundamental frequency, but uses an LC network to "multiply" the frequency into the VHF range. This circuit can be used with off-the-shelf crystals [5]. The oscillator multiplier is explored further in Section 3.4.

A search of electronics component vendors shows that it is very hard to find crystals in the VHF range. A typical Pierce or Colpitts crystal oscillator is not as simple a solution at 150 MHz as it is at 10 MHz. While there are crystal-based solutions with custom crystals and frequency multipliers, there are some concerns. Custom crystals are expensive and frequency multipliers have potential to create many unwanted harmonics. Also, while crystal oscillators can be tuned at the ppm level, different crystals are required for frequencies farther out than that. Because of these potential issues, a more flexible design was also pursued in the form of chip-based solutions.

### 2.2 PLL-Based Solutions

The VHF range that is used for wildlife tracking is right next to the 2-meter amateur radio band. Many amateur radio circuits are open source, including some transmitters used for "fox hunts," an activity in which a transmitter is hidden, and the first person to find it wins the hunt. Many amateur radio designs use a PLL for generating signals. For example, in his 2 meter transmitter, Bob Simmons uses an Analog Devices ADF7012 as the base of his circuit [6]. Amateur radio applications typically do not have the size and power constraints that a VHF transmitter on a wildlife tracking collar has, however, their designs are a good place to start.

Designing a VHF transmitter around PLL chips is an alternative to the previously presented transistor based crystal oscillator designs. PLL chips typically use a 10 MHz frequency reference, and can generate signals all the way into the GHz range. A PLL is a much more complicated design than a transistor based oscillator. Since integrated circuits have been getting smaller, less expensive, and more efficient, a more complex design, while not necessary, could be an improvement over crystal-based VHF transmitters. PLLs are discussed in more detail in Section 3.5 and a design using the Analog Devices ADF4351 chip is presented.

In addition to PLLs, other RF transmitter chips that are sold today have potential to achieve similar results. For example, Silicon Labs has developed and patented a crystal-less transmitter chip design that operates in the VHF and UHF ranges. In addition to generating the frequency, their chips also include an onboard microcontroller to set up the frequency generator. The Si4010 chip with this technology is further discussed in Section 3.6 and a design using this chip is presented. This chip also has the capability of transmitting data instead of just a carrier signal, and it is typically used for key fob communications [7].

# Chapter 3

# Methodology: Design Evaluation

## 3.1 Criteria of Evaluation

In order to design a VHF transmitter that is useful for biologists, the first step is to establish quantifiable metrics to evaluate how good each design is. For this project, seven different metrics were used to determine which design was optimal: cost, power consumption, efficiency, size, frequency range, signal bandwidth, and frequency stability.

- **Cost:** The cost of the transmitter is very important. A low cost transmitter can allow more animals to be tracked, and more data to be collected. For the purpose of this project, material cost in US dollars was used to quantify cost. The transmitters that GVSU typically buys are around $200 apiece, so any design that is worth building must cost less than that.

- **Power Consumption:** The most useful transmitter consumes as little power as possible. All else being equal, a transmitter with lower power consumption will either extend the life of the battery or allow a smaller battery to be used. A longer battery life is clearly an advantage because it allows biologists to collect more data without having to recapture an animal. In the case that the VHF transmitter supplements a more expensive system, the longer battery life gives the user a better chance of recovering the collar. In a VHF transmitter, the battery typically takes up the most room, so battery size can be even more important than the size of the PCB, and the size of the battery is determined in large part by the amount of power that the transmitter takes. Since VHF transmitters are typically periodic, average power consumption in Milliwatts was used, with the duty cycle assumed to be 1%.

- **Efficiency:** Useful transmitters also must be efficient. A VHF transmitter consumes DC power, and turns it into RF power in the VHF band; some of that power will be lost due to quiescent draw, and some of the power will be converted to undesired harmonics. A more efficient transmitter has a greater output power, given the same input power. Higher output power correlates to further transmission distance, and further transmission distance is beneficial to the user because animals can be located from farther away. The logarithmic power units Decibel-milliwatts (dBm) were used to measure maximum output power. The efficiency was calculated as average output power divided by the average input power as shown in the following equation.

$$Efficiency = \frac{P_{out\,avg}}{P_{in\,avg}} \times 100\% = \frac{DC * 0.001 * 10^{\frac{P_{dBm}}{10}}}{P_{in\,avg}} \times 100\% \tag{3.1}$$

- **Size:** It is desirable to make VHF transmitters as small as possible, because that allows them to be attached to the widest variety of animals. Wildlife biologists want to get data with the least interference possible with the wildlife, and a smaller transmitter interferes less with the wildlife than a large one. Since all of the types of transmitters were built on Printed Circuit Boards (PCBs), the size was quantified as the area of the circuit board in square inches.

- **Frequency Range:** The most useful transmitter has the greatest frequency range. The frequency of the VHF signal is used to identify individual animals, so no two animals in the same area can have VHF transmitters at the same frequency. A greater frequency range allows for more channels and therefore allows more animals to be tracked in one location. The frequency range of each transmitter design was quantified in MHz, with the maximum of 4 MHz, the width of the entire 148 to 152 MHz band that is typically used for wildlife tracking.

- **Phase Noise:** The frequency range is only one of the factors that determines the number of frequency channels. The phase noise of the signal is also important. The most useful transmitter has the lowest phase noise. The lower the phase noise, the tighter the VHF channels can be made, so for the same frequency range, more channels

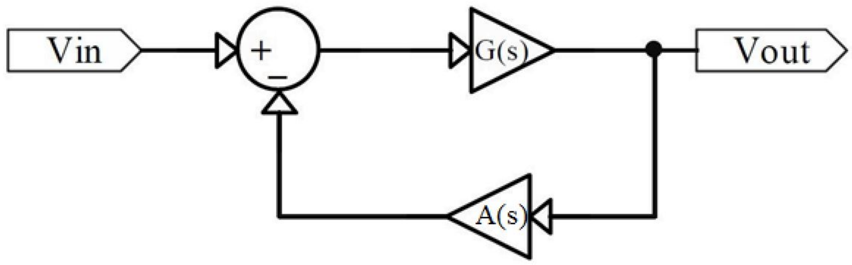


Fig. 3.1: Block diagram of a feedback loop

can be used. An ideal signal is a pure sine wave with frequency content only at one frequency; the desired fundamental. All signals have some variation due to minor instabilities in phase, and that variation spreads out the frequency spectrum. How much spread there is can be measured with phase noise, which is the power in a 1 Hz bandwidth at a given offset from the carrier as it relates to the carrier strength. For this project, the phase noise was measured with a spectrum analyzer at 1, 10, and 100 kHz offsets from the carrier.

- **Frequency Stability:** Frequency stability is also important for a transmitter because the VHF transmitters used in wildlife tracking are exposed to the outside temperatures. If temperature causes the frequency to drift, biologists might confuse the animal with another one, or miss it entirely. Frequency stability was measured as frequency variation in parts per million (ppm) over 0 to $100^o$ C, the range of temperatures that a transmitter in Michigan might see.

### 3.2 Oscillators

An oscillator is a closed loop system that generates a sinusoidal signal at a single frequency. The input of the oscillator is a DC voltage and the output is an AC signal. The oscillator can be thought of as a control system G(s) that feeds back on itself. A block diagram of this system is shown in Figure 3.1.

From control theory, it is known that the transfer function of this system is

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{G(s)}{1 + A(s) * G(s)} \tag{3.2}$$

Therefore the output can be described as

$$V_{out}(s) = V_{in}(s)\frac{G(s)}{1 + A(s) * G(s)} \tag{3.3}$$

From the open loop transfer function G(s), it can be determined if the system is stable. The open loop transfer function will typically take the form of one polynomial divided by another polynomial. Each $n^{th}$ order polynomial has $n$ values that make the result zero. When those zeros are in the numerator, they are called zeros, but when the zeros are in the denominator, they are called poles. There may be repeated or complex poles and zeroes, but all of them can be plotted on the S-plane.

If all of the poles are on the left hand side of the S-plane, it is known that the system is stable. If the system has a pole in the right hand side of the S-plane or repeated poles on the $j\omega$ axis, it is known that the system is unstable. When designing most control systems it is desirable to have an unconditionally stable system, but when designing an oscillator, it is desirable to have an unstable system [8].

The transfer function can be converted from the S-domain to the frequency domain by replacing $s$ with $j\omega$. Further investigation into Equation 3.3 shows that if $\frac{G(j\omega)}{1+A(s)*G(j\omega)} > 1$, small noises in $V_{in}$ will be amplified. The amplification occurs when $A(j\omega) * |G(j\omega)| > 1$ and $\angle A(j\omega) * G(j\omega) = -180^o$, which causes the denominator to become smaller than the numerator. Once the noise is amplified, the loop gain $A(j\omega) * G(j\omega) > 1$ will generate an oscillation. Often in oscillator designs all gain is associated with $G(j\omega)$ and $A$ just includes the crystal.

From control theory, it is also known that the stability of a system can be evaluated from the open loop Bode plot. The Bode plot has two parts, the magnitude $|G(j\omega)|$ and the phase $\angle G(j\omega)$. It is known that if $|G(j\omega)| < 0dB$ at $\angle G(j\omega) = -180^o$ the system will be stable, and if $|G(j\omega)| > 0dB$ at $G(j\omega) = -180^o$ the system will be unstable. When simulating circuits digitally or measuring circuits in the lab, this method often proves to be more practical for the designer than calculating the poles and zeros of the system [8].

For this project, Genesys simulation software was used to aid in the oscillator design. This software package allows the user to simulate the open loop response of the oscillator as well as optimize the design based on parameters such as oscillating frequency and gain margin. Since the system is an oscillator that must be unstable, the Bode plot is different than a control system that must be kept stable. A control system is typically analyzed as a negative feedback loop, while an oscillator is typically analyzed as a positive feedback loop, changing the output voltage equation to Equation 3.4. This difference introduces a $180^o$ phase shift into the analysis, and therefore the system must have a greater than unity gain at $0^o$ rather than at $-180^o$.

$$V_{out}(s) = V_{in}(s)\frac{G(s)}{1 - A(s) * G(s)} \tag{3.4}$$

To minimize the frequencies of instability, resonant reactive circuit elements are placed in the feedback loop. These resonant structures often take the form of inductors and capacitors. Their impedances, $j\omega L$ and $\frac{-j}{\omega C}$ respectively, can add together in series or parallel combinations to create a resonance. The impedance of an RLC network is typically complex, with the imaginary component coming from the inductor and capacitor. Since the inductor and capacitor impedances have opposite signs, they can cancel out, and that is called a resonance.

A major disadvantage of using inductors and capacitors for the resonant structure is that component values are prone to drifting as the ambient temperature changes and as the parts age, which results in an unstable output frequency. The tolerances on off-the-shelf capacitors and inductors are also far too large to generate a reliable frequency reference. In addition to that, discrete inductors and capacitors have parasitic resistances that make LC resonators dissipate a non-negligible amount of power, and therefore have a lower quality factor and greater phase noise than other types of resonators.

A much more reliable frequency reference can be designed using a piezoelectric crystal as the circuit's resonant structure. A crystal is an electromechanical component made of quartz. The resonant frequency of the crystal is determined by the geometry of the quartz. Its resonant frequency can be controlled much more tightly than capacitance and inductance values. A tight tolerance on a capacitor would be 5%, while a tight tolerance on the frequency of a crystal would be 10 ppm (or 0.001%), and the frequency of a crystal does not drift as much as a capacitor does.

The crystal can also be modeled as an RLC electronic circuit as shown in Figure 3.2. This model allows the crystal to be designed and simulated using standard electrical components. $L_m$, $C_m$, and $R_m$ are the motional parameters; they depend on the geometry of the crystal. $R_m$ represents the Ohmic loss at resonance, and $C_m$ and $L_m$ are the electrical representations of the kinetic energy modes within the crystals. $C_o$ is the value of the parasitic capacitance in the leads of the part.

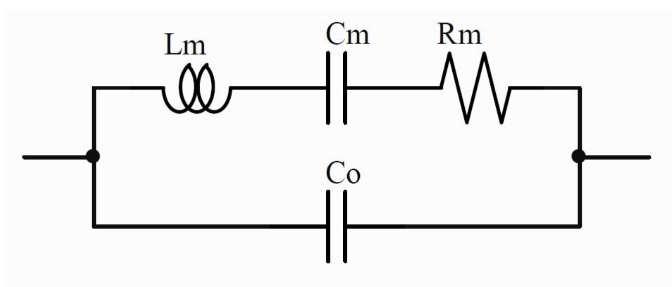


Fig. 3.2: RLC approximation of a quartz crystal

The main resonance is best represented by a series combination of $L_m$ and $C_m$. Like electrical resonances, if these two values are known, the resonant frequency can be calculated using the following equation:

$$f_{resonant} = \frac{1}{2\pi\sqrt{L_m C_m}} \tag{3.5}$$

From the electrical approximation in Figure 3.2, the impedance can be plotted over a range of frequencies to see the resonant point. The impedance can be described as

$$Z_{crystal} = (j\omega L_m + \frac{1}{j\omega C_m} + R_m)||\frac{1}{j\omega C_o} \tag{3.6}$$

This equation can be manipulated to produce the following result:

$$Z_{crystal} = \frac{(\frac{L_m}{C_o} - \frac{1}{\omega^2 C_m C_o}) - j(\frac{R_m}{\omega C_o})}{(R_m) + j(\omega L_m - \frac{1}{\omega C_m} - \frac{1}{\omega C_o})} \tag{3.7}$$

From that equation, the magnitude and phase of the crystal can be calculated. The equation for the magnitude is shown below. The phase can be calculated using the $arctan(imaginary/real)$ method, however, the signs of the coefficients need to be accounted for.

$$|Z_{crystal}| = \frac{\sqrt{(\frac{L_m}{C_o} - \frac{1}{\omega^2 C_m C_o})^2 + (\frac{R_m}{\omega C_o})^2}}{\sqrt{(R_m)^2 + (\omega L_m - \frac{1}{\omega C_m} - \frac{1}{\omega C_o})^2}} \tag{3.8}$$

As an example, a typical 10 MHz crystal might have the following parameters [5]:

$$R_m = 200\Omega, C_m = 8 \times 10^{-16}F, L_m = 0.317H, C_o = 5pF$$

The resulting impedance plot is shown in Figure 3.3. This plot has a very narrow valley with a minimum impedance at 10 MHz. Also at that resonant point, it can be seen that the phase is zero, which verifies that the point is indeed a resonance. At DC, the impedance is very high because of the capacitors in both branches of the model. At very high frequency, the motional branch of the model is effectively bypassed because of the high impedance in $L_m$, and the capacitance of the leads, $C_o$, is the dominant part of the circuit.

From the phase plot it can be seen that there are two resonant points. The phase in the plot starts at $-90^o$ since the motional capacitance is very high impedance. The circuit then transitions to be inductive after the resonance, which is a series resonance. Then there is another resonance, which is a parallel resonance between the motional parameters and the parasitic capacitance. Instead of a minimum, there is a peak at the parallel resonance, and then the parallel parasitic capacitance dominates the circuit.

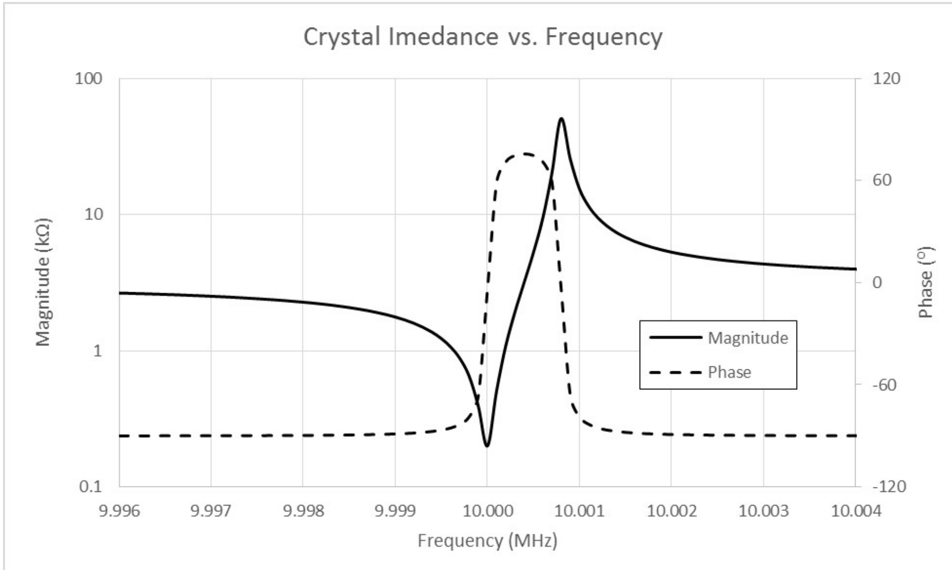


Fig. 3.3: 10 MHz crystal impedance around its resonant point

The series resonant frequency with the minimum impedance is the point that the oscillator will oscillate at. This low impedance point in the feedback loop, allows for a greater than unity gain at the resonant frequency, which is required for oscillation. The high feedback impedance at other frequencies results in a less than unity gain, therefore the system cannot oscillate at those frequencies. The previously discussed transfer function and Bode plot are dependent on the impedance described by Equation 3.7.

## 3.3 Overtone Oscillator

Quartz crystals are most widely available in the 0.6 MHz to 30 MHz range. Crystals at higher frequencies tend to be very thin, making them harder to manufacture and less rugged [5]. At 150 MHz, the typical frequency for wildlife tracking, HFF crystals are very thin, and a more reasonable solution is to design an oscillator using an overtone crystal.

The linear crystal model in Figure 3.2 is not a perfect model for the crystal. No crystal has just two resonant points; the non-linear effects within crystals also have resonant points that are especially strong at the odd harmonics. Crystals can be specially cut to accentuate one of those odd harmonics. A 150 MHz oscillator could be designed with a 150 MHz HFF crystal, but it could also be designed with a 50 MHz crystal operating on the 3rd harmonic, or a 30 MHz crystal operating at the 5th harmonic [5].

Genesys can be used as a tool to help design an overtone oscillator. The Butler emitter follower oscillator from Randall Rea's oscillator design book was used as the starting point for this oscillator. The schematic is shown in Figure 3.4 [5]. It is based on a 30 MHz crystal operating at the 5th harmonic. Open loop operation is used for the analysis; for closed loop operation, Port 2 is shorted to Port 1.

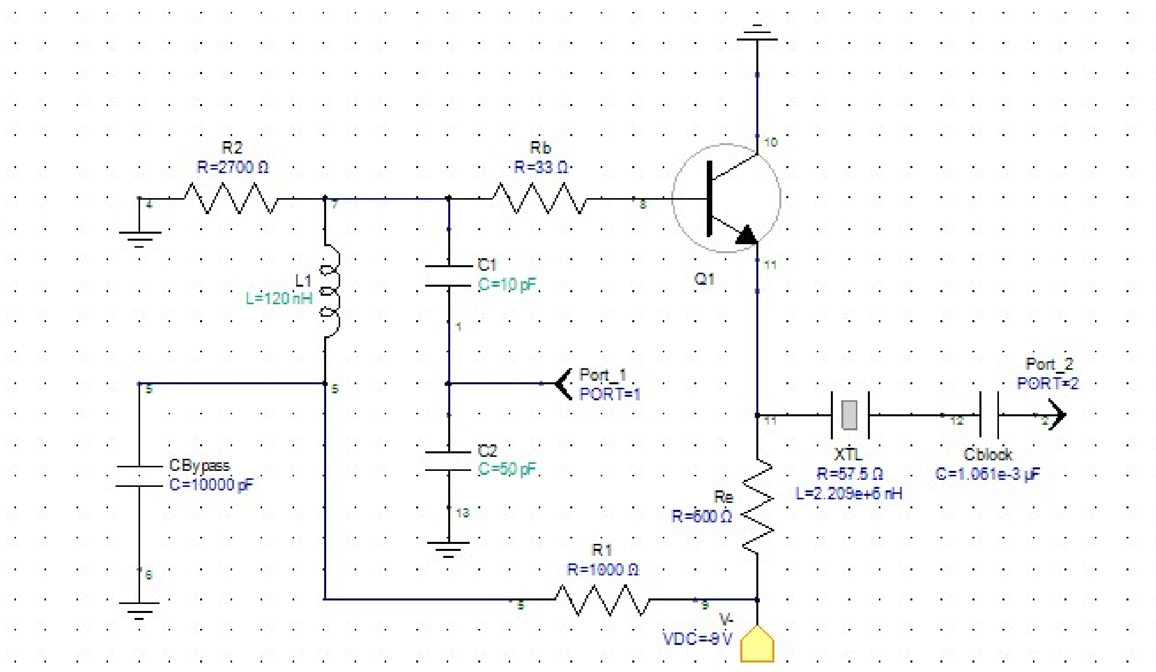


Fig. 3.4: Butler emitter follower schematic with overtone crystal

From this schematic, Genesys can generate a Bode plot based on the S21 magnitude and phase. That Bode plot, however, is only accurate if there is a good match between Port 2 and Port 1. If there are significant reflections, there will be additional power loss, and using S21 as the Bode plot is not accurate. A more accurate Bode plot can be generated, if all S Parameters are taken into consideration. In their paper on open-loop oscillator design, Mitch Randall and Terry Hock derived the gain to be [9]

$$G = \frac{S21 - S12}{1 - S11S22 + S12S21 - 2S12} \tag{3.9}$$

All four S-parameter values can be simulated in Genesys and the output of the above equation can be plotted as magnitude and phase. Then the system can be tuned to set G as required by Equation 3.9. The circuit can be optimized using the goal function in Genesys, where the circuit can be tuned to have the zero crossing and a greater than unity gain at the desired frequency, in this case 150 MHz. From Figure 3.5 , it can be seen that the phase crosses zero at 150.001 MHz and the gain is 9.945 dB at that point, therefore this system will oscillate at 150.001 MHz.

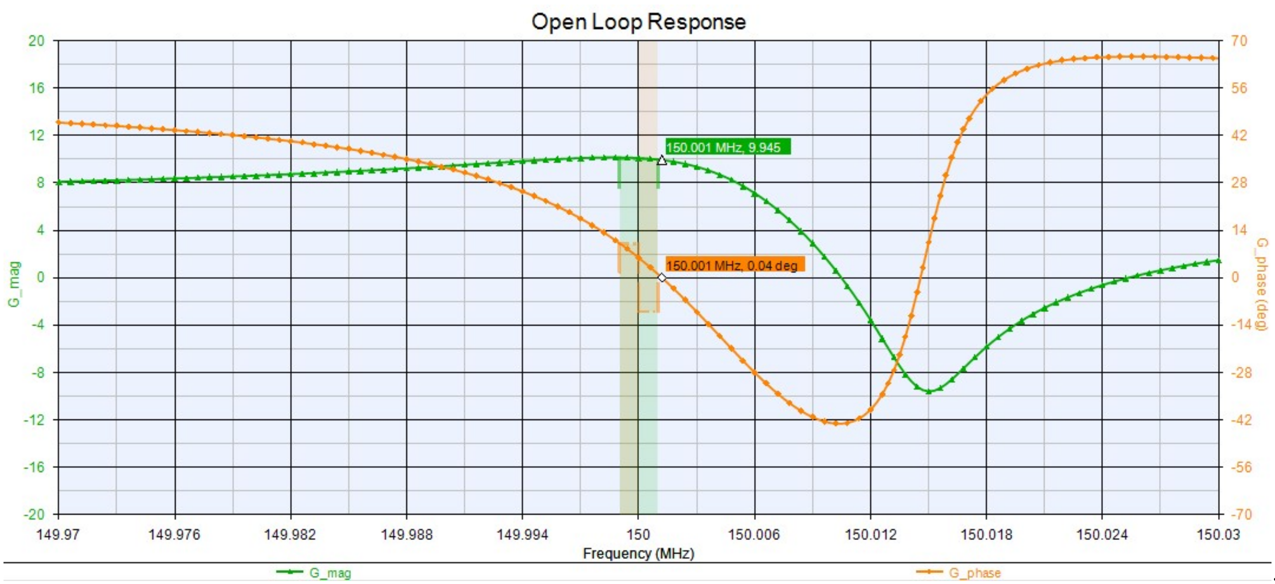


Fig. 3.5: Tuned Butler overtone oscillator Bode plot for 150 MHz

## 3.4 Oscillator with Frequency Multiplier

Instead of using custom overtone crystals, a frequency multiplier can be used with widely available fundamental mode crystals. The base oscillator is not any different from a typical crystal oscillator and typically a Butler or Colpitts is used as a base. However, connected to the collector of the BJT is an LC resonant circuit that resonates at the desired harmonic. Schematics of typical Colpitts and Butler oscillator multipliers are shown in Figure 3.6. The LC resonant circuit cannot generate the harmonic on its own, but since crystal oscillators do not generate perfect sine waves, the higher frequencies resonate with the LC tank [5].

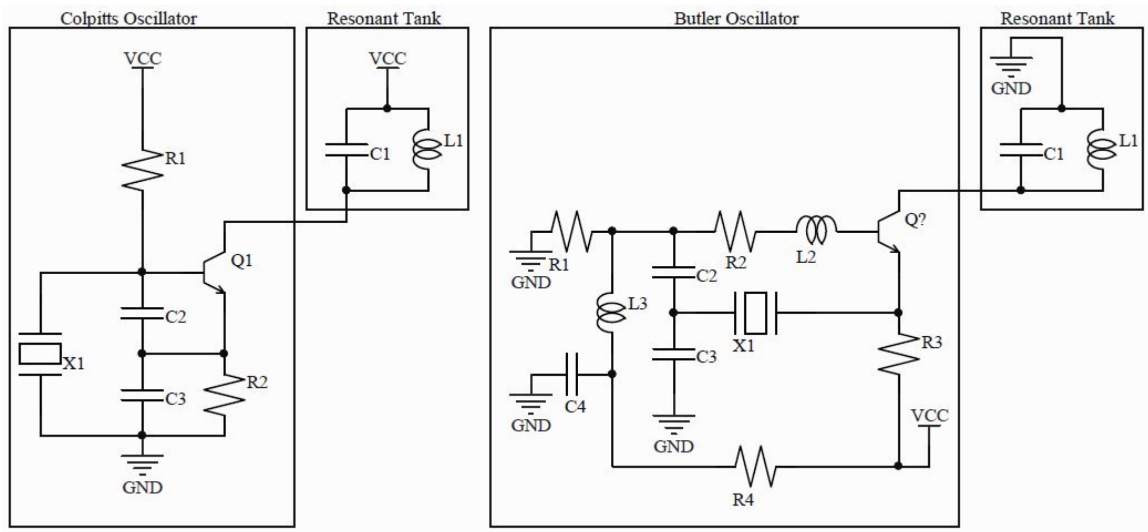


Fig. 3.6: Colpitts and Butler Oscillators with LC resonator multipliers

A Butler frequency multiplier oscillator was designed using Genesys in the same way that the overtone oscillator was designed. The schematic is shown in Figure 3.7 and the Bode plot is shown in Figure 3.8. The Bode plot shows greater than unity gain at the fundamental frequency, unlike the overtone oscillator, which has its crossover frequency at the harmonic. A prototype of this circuit was also built to evaluate.

## 3.5 Phase Lock Loop

Another way to generate a VHF signal is with a PLL. A PLL is a much more complicated system than an overtone or frequency multiplied oscillator. Because of the wide array of integrated circuits available now, it is a viable design option for a VHF transmitter, despite its complexity.

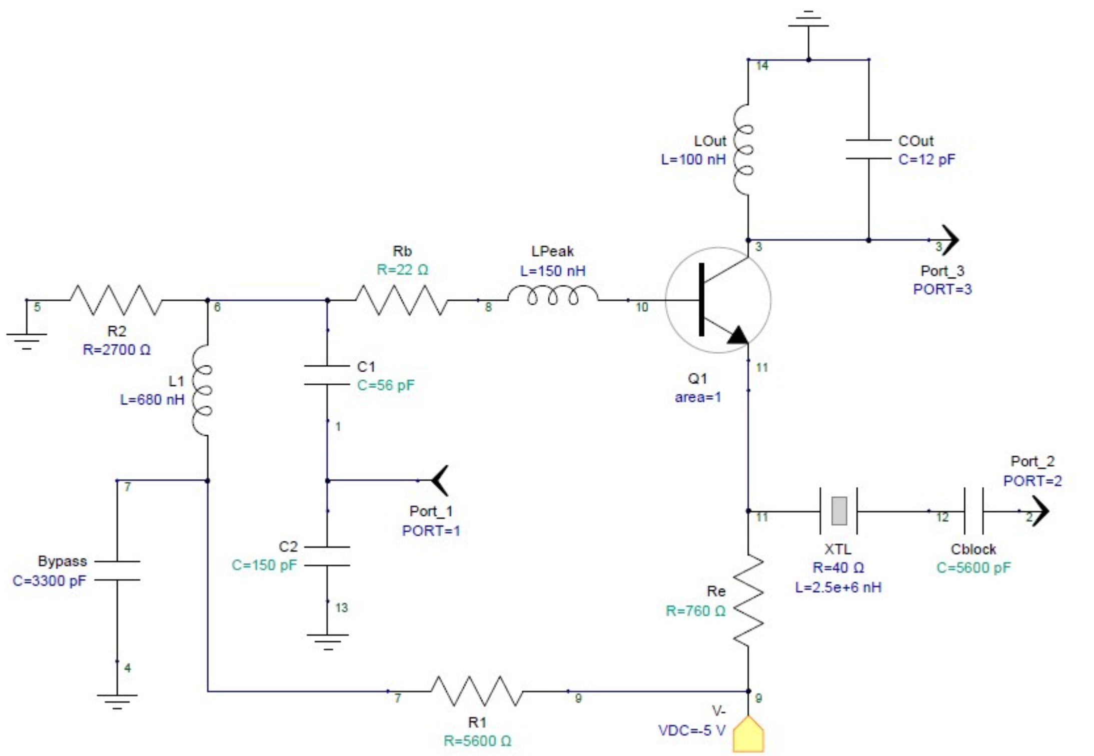


Fig. 3.7: Butler overtone oscillator schematic with values from Genesys

A PLL has two oscillators. One oscillator is a frequency reference. It is very important that this reference be very stable, so this is typically a crystal oscillator. The other oscillator is a Voltage-Controlled Oscillator (VCO), in which the output frequency can be tuned based on an input voltage signal.

The frequency generated by the VCO is the output of the system. That output feeds back to a phase detector to be compared with the reference. If the reference and the VCO output do not consistently match phase, it is known that the frequencies are not the same. The voltage going to the VCO can then be adjusted through a charge pump until the phases consistently match and the system locks. The PLL uses closed loop control to maintain the correct frequency out of the VCO.

If the VCO only maintained the same frequency as the reference, that would not be useful for a VHF transmitter, but by using prescalers and frequency dividers, PLLs can be

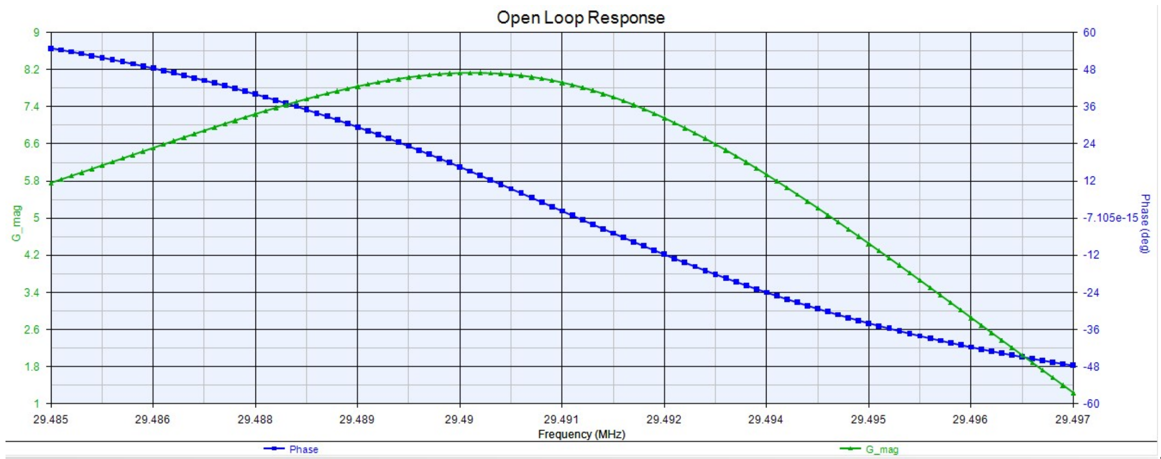


Fig. 3.8: Butler overtone oscillator Bode plot from Genesys simulation

programmed to have a large range of output frequencies. For example, if the output signal were fed back to the phase detector through a frequency divider that divided the frequency by 8, when the system locks, the output frequency would be 8 times the reference frequency. Since the VCOs are stabilized by the phase detector and charge pump, LC resonances can be used to generate much higher frequencies than crystal oscillators can. A high level block diagram of a PLL is shown in Figure 3.9.

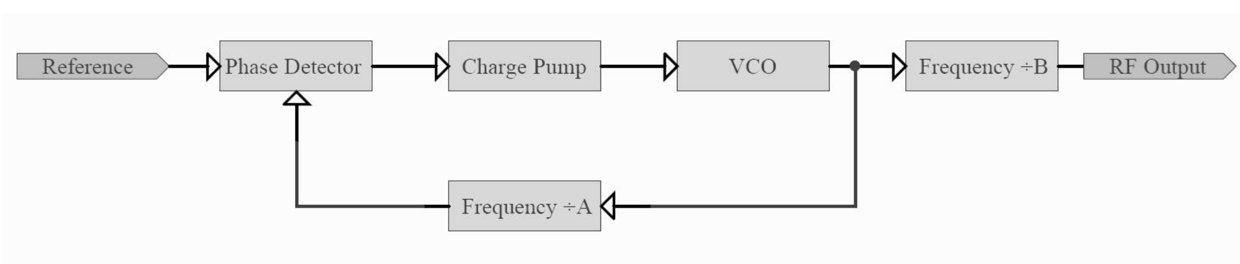


Fig. 3.9: Block diagram of a PLL

The block diagram in Figure 3.9 shows an Integer-N PLL, which has the following output frequency:

$$F_{outint} = F_{ref} * \frac{A}{B} \tag{3.10}$$

The alternative, a Fractional-N PLL, allows for finer frequency tuning. In a Fractional-N

PLL, the reference frequency is multiplied by an integer plus a fractional value, yielding the following equation [10]:

$$F_{outfrac} = F_{ref} * (\frac{A}{B} + C) \tag{3.11}$$

The Analog Devices ADF4351 was used as a base for the prototype system, and that chip uses a Fractional-N PLL.

A PCB was designed to help evaluate the ADF4351. A 10 MHz crystal oscillator was used as a reference, the chip was provided with a regulated 3.3 V, and a transformer balun was used to convert the single balanced output to an unbalanced output. The Serial Peripheral Interface SPI was programmed with an Arduino, and a resistive 5 V to 3.3 V level shifter as shown in Figure 3.10. The output of this level shifter decreases with loading, but since the ADF4351 input pins are high impedance, the output levels are adequate. The schematic of the ADF4351 board can be found in Appendix A Figure A.1 and the BOM is shown in Appendix B, Table B.1. A picture of the layout is shown in Figure 3.11, and the register values that were used are shown in Figure 3.12.

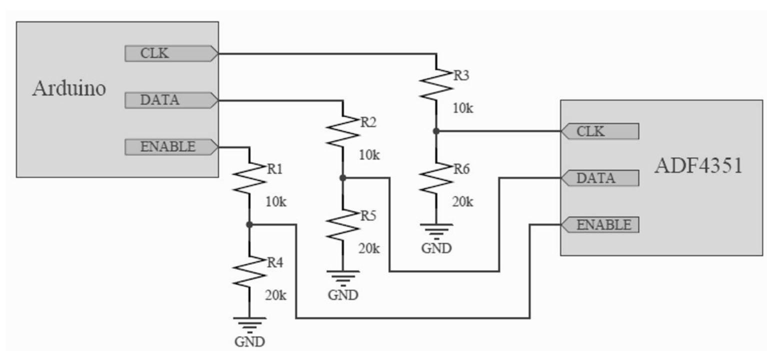


Fig. 3.10: Resistive 5 V to 3.3 V level shifter

## 3.6 Silicon Labs Si4010

The Silicon Labs Si4010 is a chip that achieves a similar output to a PLL, but it operates on different principles. The frequency generation comes from a finely tuned LC oscillator that operates at 3.9 GHz. The frequency can then be divided down to the desired frequency.

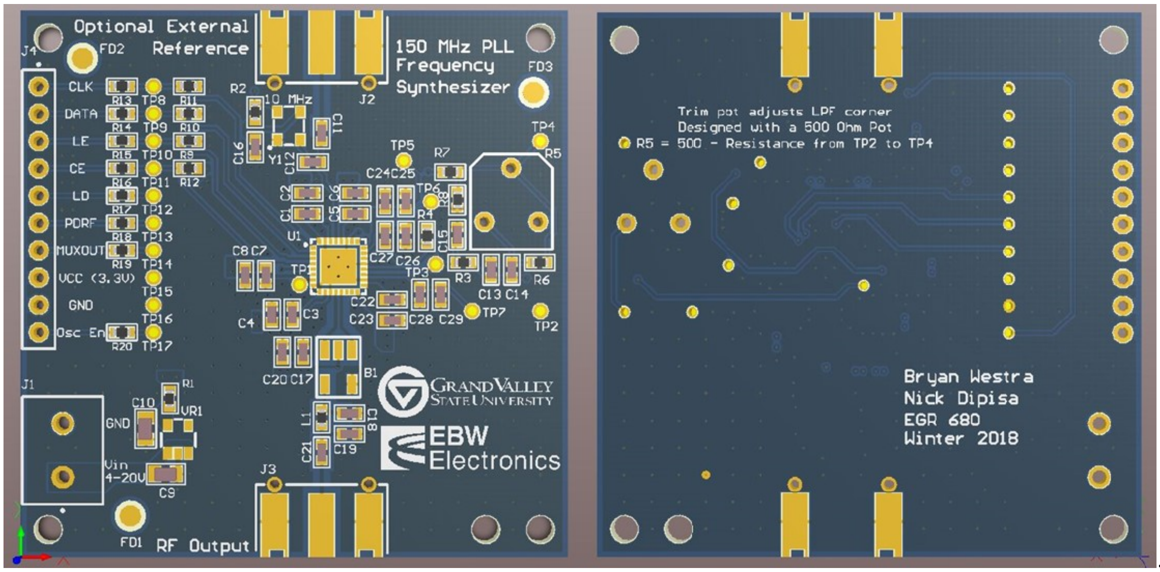


Fig. 3.11: Picture of the ADF4351 layout

The manufacturer rates this process at a +/-150 ppm tolerance for the output frequency, but that can be reduced to +/-10 ppm with a crystal oscillator reference, which is used to tune the output frequency before each transmission. Unlike a PLL, when this chip is transmitting, it is in open loop control, not closed loop control. Rather than an SPI or I2C bus to program the chip, there is a microcontroller embedded into the chip, and therefore the frequency can be set in Non-Volatile Memory, and run on its own [7].

A PCB was designed to evaluate this chip. Since the chip was intended to run straight off a battery, no voltage regulation was done, however a Hall effect sensor and low $R_{dson}$ transistor created a magnetic switch to turn the board on and off. In order to keep the PCB as small as possible, the Mini Small Outline Package (MSOP) version was used. Like the Analog chip, the Silicon Labs chip has a balanced output, and for this circuit an LC balun was used to convert to the unbalanced output required for a whip antenna. The balun that was used was the one recommended by the ADF4351 datasheet [10]. The PCB included a programming header to allow the firmware to be burned on the board, and an external 10 MHz crystal paired with the Si4010's internal Colpitts oscillator was used as a frequency reference. An optional gain block was also added to the layout to amplify the signal if

| 0 | R | INT | | | | | | | | | | | | | | | | FRAC | | | | | | | | | | | | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | N16 | N15 | N14 | N13 | N12 | N11 | N10 | N9 | N8 | N7 | N6 | N5 | N4 | N3 | N2 | N1 | F12 | F11 | F10 | F9 | F8 | F7 | F6 | F5 | F4 | F3 | F2 | F1 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 240 | | | | | | | | | | | | | | | | 0 | | | | | | | | | | | | | | |

| 1 | R | | | PA | PS | PHASE | | | | | | | | | | | | MOD | | | | | | | | | | | | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | PH1 | PR1 | P12 | P11 | P10 | P9 | P8 | P7 | P6 | P5 | P4 | P3 | P2 | P1 | M12 | M11 | M10 | M9 | M8 | M7 | M6 | M5 | M4 | M3 | M2 | M1 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| | | | | | | 1 | | | | | | | | | | | | 4095 | | | | | | | | | | | | | | |

| 2 | R | LN Mode | | MUXOUT | | | DBR | DBR | R-counter | | | | | | | | | | DB | Charge Pump I | | | | LDF | LDP | PD | PD | CP3 | CR | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | L2 | L1 | M3 | M2 | M1 | RD2 | RD1 | R10 | R9 | R8 | R7 | R6 | R5 | R4 | R3 | R2 | R1 | D1 | CP4 | CP3 | CP2 | CP1 | U6 | U5 | U4 | U3 | U2 | U1 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| | | | | | | | | | 1 | | | | | | | | | | | 5.00 mA | | | | | | | | | | | | |

| 3 | R | | | | | | | | BCM | ABP | CC | R | | CSR | R | CDM | | Clock Divider Value | | | | | | | | | | | | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | F4 | F3 | F2 | 0 | 0 | F1 | 0 | C2 | C1 | D12 | D11 | D10 | D9 | D8 | D7 | D6 | D5 | D4 | D3 | D2 | D1 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |

| 4 | R | | | | | | | | FB | RF Divider | | | Band Select Clock Div Value | | | | | | | | VCO | MTL | AUX | AUX | AUX | | RF | OUTPUT | | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | D13 | D12 | D11 | D10 | BS8 | BS7 | BS6 | BS5 | BS4 | BS3 | BS2 | BS1 | D9 | D8 | D7 | D6 | D5 | D4 | D3 | D2 | D1 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| | | | | | | | | | | 16 | | | | | | | | | | | | | | | | | | | | | | |

| 5 | R | | | | | | | | LD PIN | | R | | | | | | | | | | | | | | | | | | | Control Bits | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | D15 | D14 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | C3(0) | C2(0) | C1(0) |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |

Fig. 3.12: Register values for a 150 MHz signal on the ADF4351

needed, but that feature was not used for testing. The entire schematic can be found in Appendix A Figure A.2 and the BOM is shown in Appendix B, Table B.2. A picture of the layout is shown in Figure 3.13. The software that was loaded onto this board was written in Simplicity Studio, and the main.c file is shown in Appendix C.

## 3.7 Back End Design

Each of the different frequency generation methods requires similar output filtering and a whip antenna. The Low Pass Filter (LPF) used in the prototypes is a passive, third order, Butterworth filter. The filter was designed to have a corner frequency at 170 MHz and to have 25 dB of attenuation at 300 MHz, the closest harmonic. This filter could also be used for impedance matching to the whip antenna.

A whip antenna was used to transmit the signal. The whip antenna that was used was only 8 inches long in order to interfere with the animal wearing the collar as little as possible. It would be beneficial to have the antenna tuned to either a half or a quarter of a wavelength, but the wavelengths at 150 MHz are around 80 inches long. Even a quarter of a

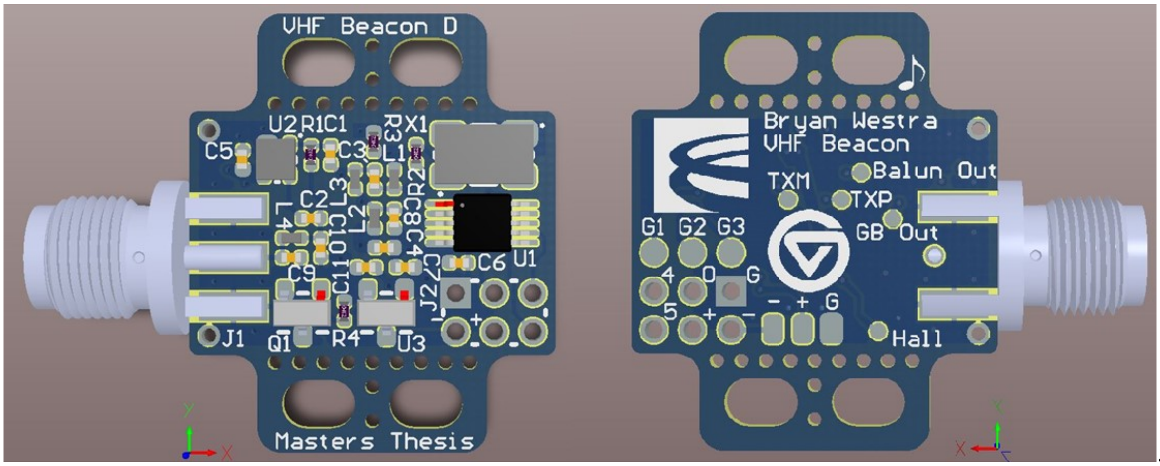

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Fig. 3.13: Picture of the Si4010 layout

wavelength would be very difficult to deal with on an animal. The whip antenna was simply made out of a piece of 22-gauge topcoat wire. Topcoat wire is stranded wire that has been tinned before the insulation was put on. This type of wire was used because it is rigid like solid wire, but does not crack as easily.

# Chapter 4

## Results and Discussion: Design Evaluation

In this section, the designs discussed in Chapter 3 are evaluated. Some of the evaluation comes in the form of lab testing, and some comes in the form of theoretical design evaluation. The evaluation is described in detail in the following sections, and a summary of the information is shown in Table 4.1. The intention of this evaluation is not to determine these values to high precision, but to measure and estimate values well enough to determine which design is best suited for wildlife tracking.

### 4.1 Cost

The approximate material cost of each VHF transmitter design was determined by creating a Bill of Materials (BOM) and finding the cost of the components in quantities of 100 from online distributers. The bare PCB cost was assumed to be $2.57 for all boards, which is the cost of a 4-layer board with 1 ounce copper from PCBWay when ordered in quantities of 100. There are other costs associated with building Printed Circuit Board Assemblies (PCBAs), such as shipping parts and buying stencils, assembly equipment, and supplies, but these costs were not taken into consideration since they are effectively the same for all the designs.

The main cost driver for the overtone oscillator is the cost of the crystal. This design requires a custom crystal. Correspondence with a representative from Transko Crystals reveals that crystals from them average $50 each with a minimum order cost of $100 [11]. Since different frequencies are used to differentiate between animals, these high crystal costs effectively eliminate the overtone design for this application. It may be more viable for a large company that supplies many different customers and buys crystals in higher quantities; however, a minimum of $100 for each frequency is not viable for small quantity builds. Because of this high cost, a prototype with an overtone crystal was not made.

The oscillator multiplier is much cheaper, with crystals available at low quantities for less than a dollar. The rest of the circuit also uses typical off-the-shelf parts. One of the challenges with this design is that the output needs to be filtered with a bandpass filter, because there are lower frequency signals, including the fundamental, that need to be attenuated. The higher the frequency multiplication (given the same output frequency), the closer the harmonics are, and therefore a higher Q bandpass filter is required to filter out harmonics. The other challenge with buying parts for the multiplier design is that different crystals are required to create a large number of channels, and each circuit may need to be individually tuned due to different parasitics. In addition, different crystal packages may need to be accommodated based on crystal availability at different frequencies. Only the frequency generation component of the oscillator multiplier system was built and tested, but the additional items that would be necessary were estimated in the BOM, see Appendix B Table B.3. The total estimated BOM cost came to $8.32, much lower than the price of a custom crystal.

The Analog Devices and Silicon labs circuits have the advantage that they can be built the exact same way every time, and then programmed for whatever output frequency is required. The Analog devices circuit is the more expensive one because of the cost of the ADF4351 PLL chip, and the additional microcontroller needed to configure the chip upon startup. The BOMs from the boards that were built for evaluation purposes were updated to reflect the needs of the final system, including taking off unnecessary connectors and adding modulating circuits where necessary. The BOMs for the PCBAs based on the Analog Devices and Silicon Labs chip are found in Appendix B, Table B.4 and Table B.5, respectively. The ADF4351 PCBA is estimated to cost around $20.29, while the Si4010 PCBA is estimated to cost around $7.52.

## 4.2 Power Consumption

Wildlife tracking transmitters operate at a low duty cycle pulse. That means that two different power levels need to be taken into account; the current during the on time, and the current during the off time. For the purposes of this project, a 20 ms pulse every 2 seconds (a duty cycle of 1%) was used. The overtone oscillator was not built due to the very high crystal costs, but the three other designs were built and tested in the lab. In order to make the measurements consistent, the power consumption of all of the designs were measured with a 50 Ω load on the output.

The oscillator multiplier was powered at 5 V and the current draw was measured at 4.43 mA, resulting in a total power consumption of 22.15 mW while on. A modulating circuit was not designed and built for this circuit, so the off-cycle current draw was estimated at 0.5 mA, yielding an average current draw of 0.539 mA at 5V.

The ADF4351 PCBA was powered with 3.3 V with the linear regulator bypassed. This is accurate for the scenario in which the system could be powered from another system that already has a regulated 3.3V. If it were used on its own, it would need the regulator and an input voltage above the regulator's dropout rating. This circuit took much more power than the oscillator; while idle, the chip drew 70 mA and while operating, it drew 127 mA. The off time current draw was measured with the chip disabled, and the draw was 2 mA. With the design operating at a 1% duty cycle, the average current draw was 3.25 mA, much higher than the oscillator.

The Si4010 PCBA was tested in the exact same way as the ADF4351. The Si4010 was a chip developed to run on coin cell batteries, so the power levels were much lower. While operating the chip drew 19.2 mA at 3.3V, and the low power sleep mode only drew 800 nA. With the same duty cycle the Si4010 drew only 0.193 mA on average.

### 4.3 Efficiency

The output powers of the circuits were measured using a spectrum analyzer, with a 50 Ω load. The main purpose of this project was signal generation, not amplification. Any of these designs can be amplified with off-the-shelf components; however, it is advantageous if the signal that is generated is stronger. As is typical for an RF signal, the outputs were measured with a logarithmic scale. In this case the units used were dBm.

The oscillator multiplier design had very low output power at -23 dBm. Both of the chip-based designs had programmable outputs. The ADF4351 had 4 options ranging from -4 dBm to 5 dBm. The power was measured at the 5 dBm setting, and the actual output was measured at 7.62 dBm. The Silicon Labs chip was programmable with a 7-bit number, and at its max output, it reached 3.34 dBm.

Based on the output power measured, the efficiency of the frequency generation was calculated. Some of the lost power is due to a quiescent draw, and some of it is due to other harmonics. The Si4010 system was the most efficient at 3.39%. The ADF4351 system was only 0.54% efficient, and the oscillator multiplier was by far the least efficient at 0.0070%.

### 4.4 Size

The size of the PCB required for each system is dependent on quite a few factors. Also, not every design was laid out on a PCB in a final configuration. Because of the importance of the size of the board, an estimate was made of how big the PCB would need to be based on the necessary components. It was assumed that component density would be the same on all of the boards, and components would only be placed on one side. The Si4010 board was designed on 0.375 $in^2$ footprint size, which was adequate to fit everything necessary for the system on it. The ADF4351 board was designed on a 4 $in^2$ footprint, but the board size could be made significantly smaller by leaving off the bulky connectors used for evaluation, using 0402 components instead of 0603 components, and decreasing component spacing. It is estimated that the ADF4351 system could be made as small as 1.00 $in^2$. A PCB layout was not done for the oscillator multiplier, but based on the components needed for the circuit it was estimated to require 0.500 $in^2$.

The weight of each system is also important, and since all of the circuit boards were assumed to have similar component densities, the weight of each system can be assumed to correlate to the size. From the Silicon Labs board, it was found that the typical mass for a

0.031" PCBA is approximately 4 grams per square inch. The Silicon Labs PCBA weighed around 1.5 grams, while the ADF4351 system would be expected to be the heaviest at around 4 grams.

### 4.5 Frequency Range

Systems solely based on a crystal oscillators have a much narrower frequency range than most chip-based solutions. Crystal oscillators can be tuned, or pulled, with different capacitance values, but the amount that the frequency can be pulled is a very small percentage of the fundamental frequency. A typical oscillator can be pulled around 0.2% of the fundamental frequency. An oscillator multiplier would be expected to have a similar pull range; however, overtone oscillators cannot be pulled nearly as far. Overtone oscillators are known to have a pull range that is inversely proportional to the square of the overtone, and because of that, each different channel would require a different crystal [5].

Both of the chip-based systems that were built have much more flexible output frequencies than the crystal based systems. Because the chips are very flexible, the limiting factor for frequency is the output filtering and the balun. A passive low pass filter on the output is tuned to attenuate the $2^{nd}$ and $3^{rd}$ harmonics without attenuating the fundamental. With 150 MHz separation between harmonics, it can be expected that the devices can operate over the entire 4 MHz range that is typically used for wildlife tracking.

### 4.6 Phase Noise

The phase noise of the PLL-based solutions were measured with a spectrum analyzer. The measurements were made using a 100 Hz resolution bandwidth on a Rigol DSA815. Phase noise measurements with a 1, 10, and 100 kHz offset were taken. The ADF4351 performed better with -65.1, -84.5, and -107.4 dBc/Hz respectively. The spectrum of the ADF4351 is shown in Figure 4.1. The Si4010 did not have as clean of a signal. The phase

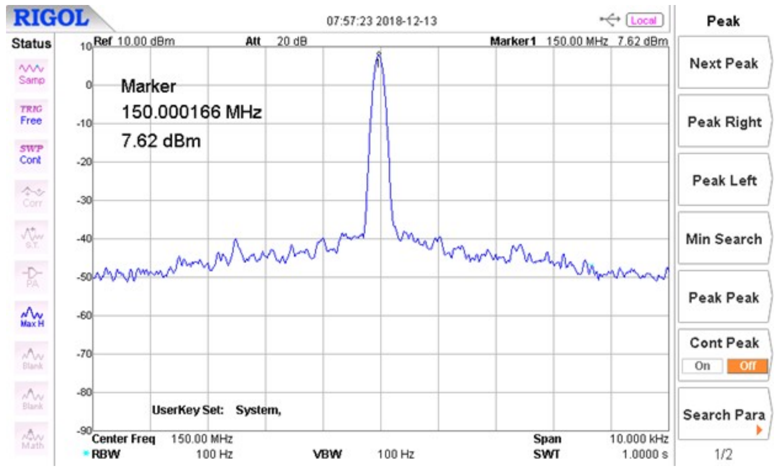


Fig. 4.1: ADF4351 spectrum at 150 MHz with a 100 Hz resolution bandwidth

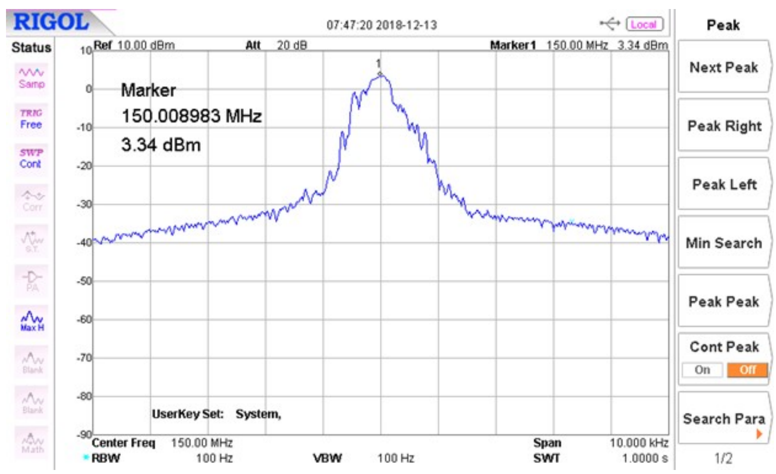


Fig. 4.2: Si4010 spectrum at 150 MHz with a 100 Hz resolution bandwidth

noise was -43.6, -72.7, and -95.5 dBc/Hz respectively, and the spectrum is shown in Figure 4.2.

### 4.7 Frequency Stability

The frequency stability of the RF outputs were measured over the temperature range of 0 to $100^{o}F$, which is the range of temperatures that are typically seen in Michigan. The circuits were placed in a thermal chamber, and the frequency was measured on a spectrum analyzer. By far, the best performance came from the ADF4351 circuit. Over the entire

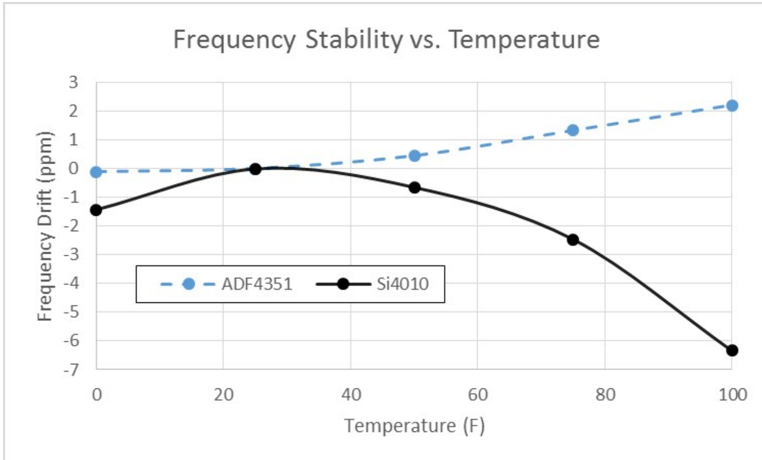


Fig. 4.3: Si4010 and ADF4351 frequency stability versus temperature

temperature range, the frequency only varied by 2.33 ppm. The Si4010 had significantly less consistent output with a frequency range of 6.34 ppm, and the oscillator multiplier had the greatest variation at 9.05 ppm. A plot of the frequency variation over temperature of the PLL-based systems is shown in Figure 4.3.

## 4.8 Discussion

Of all of the designs that were considered and built, the Si4010 based system is clearly the best option based on the data in Table 4.1. The Si4010 comes in a small MSOP that can be designed into a system with minimal extra circuitry. This makes the system inexpensive, and allows it to fit on a small circuit board. The chip is also optimized for battery use, having a very low power sleep mode, and a wide range of usable voltages.

The ADF4351 was not a good option for this application. The circuit worked very well; the output frequency was accurate and stable over a wide temperature range. However, the chip took too much power for a battery-powered application. In other applications, the extra power consumption and complexity of the circuit would be worth it for an accurate stable output over a very wide frequency range, but not all of these features are necessary for a simple VHF beacon.

Table 4.1: Design Evaluation Summary Table

| | Oscillator Multiplier | ADF4351 | Si4010 |
|---|---|---|---|
| BOM Cost ($) | $8.32 | $20.29 | $7.52 |
| On Current (mA) | 4.43 | 127 | 19.2 |
| Off Current (mA) | 0.5 | 2 | 0.0008 |
| Average Draw (mA) | 0.539 | 3.25 | 0.193 |
| Output Power (dBm) | -23 | 7.62 | 3.34 |
| Efficiency | 0.0070% | 0.54% | 3.39% |
| PCB Size ($in^2$) | 0.500 | 1.000 | 0.375 |
| Frequency Range (MHz) | 0.3 | 4 | 4 |
| Phase Noise (dBc/Hz) 1 kHz offset | (-) | -65.1 | -43.6 |
| Phase Noise (dBc/Hz) 10 kHz offset | (-) | -84.5 | -72.67 |
| Phase Noise (dBc/Hz) 100 kHz offset | (-) | -107.85 | -95.5 |
| Frequency Deviation over $0 - 100^oF$ (ppm) | 9.05 | 2.33 | 6.34 |

The Overtone Oscillator system was ruled out based on the cost of custom crystals and the fact that a different frequency crystal is required for each channel. The oscillator multiplier system was much more affordable. An oscillator multiplier could be used for frequency generation for a VHF transmitter, but it did not match the performance of the Si4010. The oscillator multiplier took more power than the Si4010 and the design was not nearly as configurable.

# Chapter 5

# Conclusion

## 5.1 Future Work

FCC Testing Integrated in GPS or satellite system Back end tuning Transmitting data

In order to be used for wildlife tracking, the transmitter must be tested in an FCC certified lab to verify that it conforms to Title 47. The transmitter may be integrated into GPS and satellite systems designed by the GVSU School of Engineering. The board design from this project can be integrated to the system as is, or the circuit can be added to another circuit board. When integrating with other systems, the Si4010 system could be further developed to transmit data. The Si4010 chip was designed to be able to transmit data through Frequency Shift Key encoding with a maximum frequency deviation of 275 ppm [7].

In addition to integration, more tuning work can be done to optimize the output power. The balun and output filter are both built with chip capacitors and inductors, and they could be tuned to match each other and the whip antenna better. For some larger animals, a loop antenna could also be developed. This antenna geometry could take advantage of the balanced output of the Si4010.

## 5.2 Summary

Based on the prototypes that were built, it was determined that the system based on the Silicon Labs Si4010 was the design best suited for use in a wildlife tracking collar. That system had the lowest power consumption, it was the least expensive, and the design was very flexible. The system based on the ADF4351 generated a more stable, tighter bandwidth signal, but its high power consumption and high cost made it less viable. The HFF and overtone crystal oscillator designs resulted in a simpler system, but the expensive custom crystals prevented them from being economically viable. Finally the oscillator multiplier design was economically viable, but the tight filtering and tuning required to make the system work made the system harder to produce, while still offering no cost or size advantage over the Si4010. The low cost of the Si4010-based system will allow more animals to be tracked and more data to be collected than is possible with the more expensive transmitters that are available now. This design can also supplement UHF and Satcom tracking collars that GVSU is currently developing.

# Appendices

# Appendix A

## Schematics

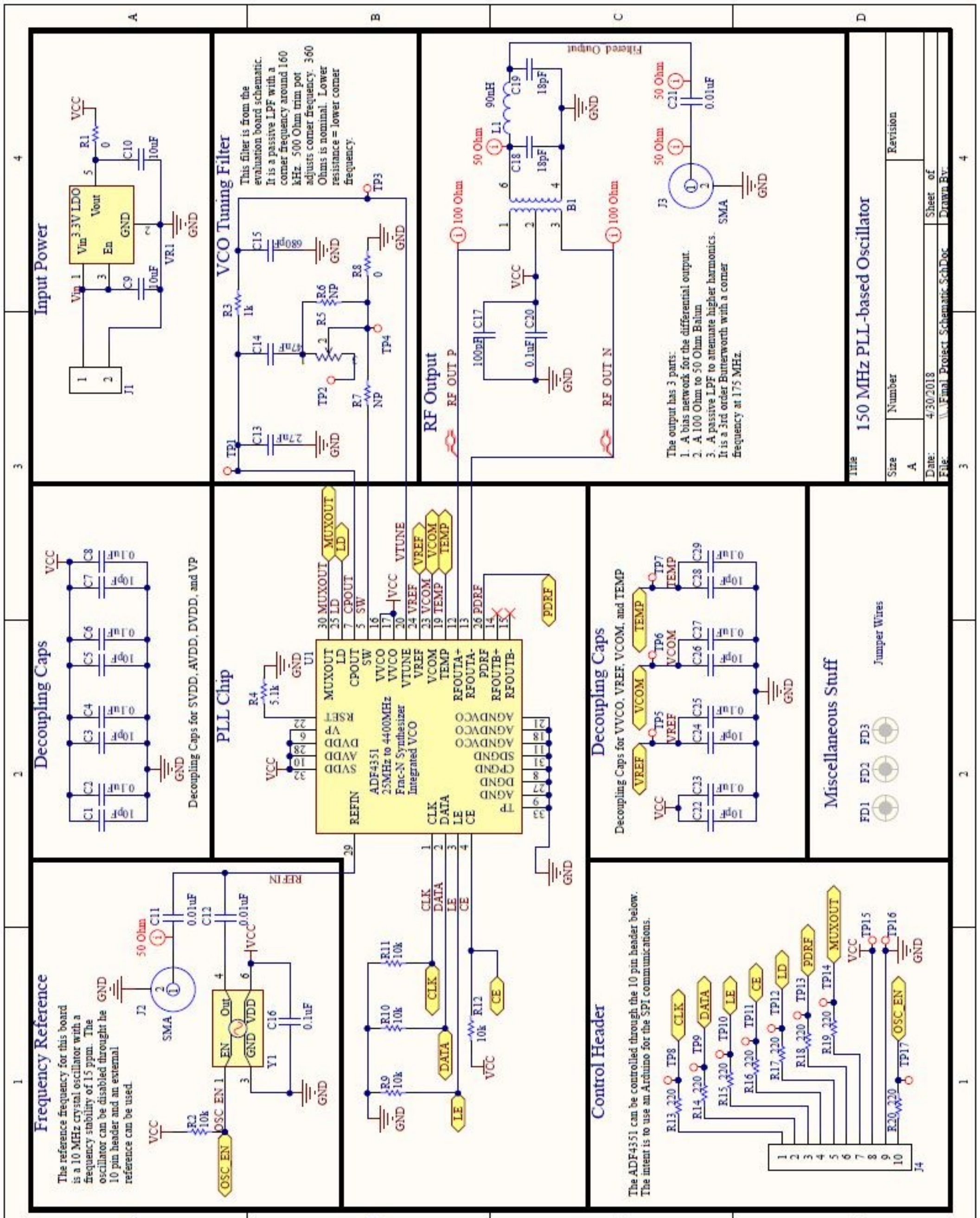


Fig. A.1: Schematic for ADF4351 evaluation PCB designed for this project

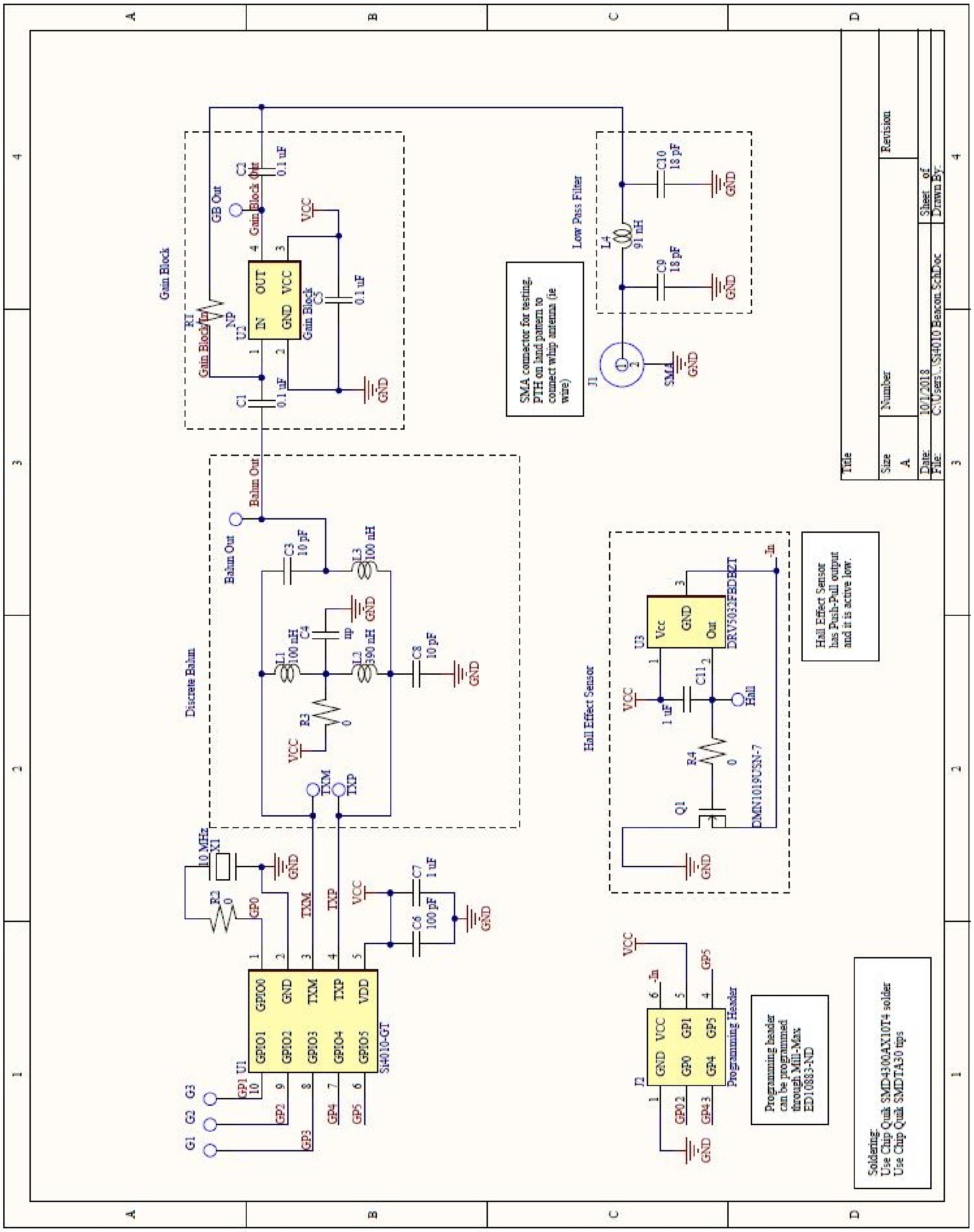


Fig. A.2: Schematic for Si4010 evaluation PCB designed for this project

# Appendix B

## Bills of Material

Table B.1: ADF4351 Test Board BOM

| Reference Designator | Description | Value | Mfg Part Number | Price Each | Qty | Total Price |
|---|---|---|---|---|---|---|
| J1 | Connector | | Wurth 691137710002 | $0.380 | 1 | $0.380 |
| VR1 | 3.3V LDO | | Diodes AP2204K-3.3TRG1 | $0.262 | 1 | $0.262 |
| J4 | Header | | Sullins PREC010SAAN-RC | $0.230 | 1 | $0.230 |
| R5 | Trim Pot | | Bourns 3306F-1-501 | $0.430 | 1 | $0.430 |
| U1 | ADF4351 | | Analog ADF4351BCPZ-RL7 | $10.448 | 1 | $10.448 |
| B1 | Balun | | Pulse CX2045LNL | $1.986 | 1 | $1.986 |
| C1, C3, C5, C7, C22, C24, C26, C28 | Chip Capacitor | 10pF | Kemet C0603C100J1GACTU | $0.010 | 8 | $0.080 |
| C11, C12, C21 | Chip Capacitor | 0.01uF | Kemet C0603C103K3RACTU | $0.010 | 3 | $0.030 |
| C13 | Chip Capacitor | 2.7nF | Kemet C0603C272K5RACTU | $0.110 | 1 | $0.110 |
| C14 | Chip Capacitor | 47nF | Kemet C0603C472J1HACTU | $0.170 | 1 | $0.170 |
| C15 | Chip Capacitor | 680pF | Kemet C0603C681K5RACTU | $0.010 | 1 | $0.010 |
| C17 | Chip Capacitor | 100pF | Kemet C0603C101J3GACTU | $0.010 | 1 | $0.010 |
| C18, C19 | Chip Capacitor | 18pF | Kemet CBR06C180FAGAC | $0.344 | 2 | $0.688 |
| C2, C4, C6, C8, C16, C20, C23, C25, C27, C29 | Chip Capacitor | 0.1uF | Kemet C0603C104K4PAC7867 | $0.010 | 10 | $0.100 |
| C9, C10 | Chip Capacitor | 10uF | Taiyo TMK212BBJ106KG-T | $0.064 | 2 | $0.128 |
| L1 | Chip Inductor | 90nH | Murata LQW18AN91NG8ZD | $0.190 | 1 | $0.190 |
| Y1 | Crystal Oscillator | 10 MHz | ECS ECS-3225S33-100-FN-TR | $0.954 | 1 | $0.954 |
| R1, R8 | Chip Resistor | 0 | Yageo AC0603FR-070RL | $0.010 | 2 | $0.020 |
| R13, R14, R15, R16, R17, R18, R19, R20 | Chip Resistor | 220 | Yageo RC0603JR-07220RL | $0.010 | 8 | $0.080 |
| R2, R9, R10, R11, R12 | Chip Resistor | 10k | Yageo RC0603JR-0710KL | $0.010 | 5 | $0.050 |
| R3 | Chip Resistor | 1k | Yageo AC0603FR-071KL | $0.010 | 1 | $0.010 |
| R4 | Chip Resistor | 5.1k | Yageo RC0603JR-074R7L | $0.010 | 1 | $0.010 |
| J2, J3 | SMA Connector | | Molex 732511150 | $3.330 | 2 | $6.660 |
| | Bare PCB | | PCBway | $2.570 | 1 | $2.570 |
| | | | | | | $25.606 |

Table B.2: Si4010 Test Board BOM

| Reference Designator | Description | Value | Mfg Part Number | Price Each | Qty | Total Price |
|---|---|---|---|---|---|---|
| C1 | Chip Capacitor | 0.1 uF | Samsung CL05B104KO5NNNC | $0.013 | 1 | $0.013 |
| C3, C8 | Chip Capacitor | 10 pF | Kemet C0402C100J3GACTU | $0.013 | 2 | $0.025 |
| C6 | Chip Capacitor | 10 pF | Kemet C0402C101K4GACTU | $0.013 | 1 | $0.013 |
| C7, C11 | Chip Capacitor | 1 uF | Samsung CL05A105KO5NNNC | $0.028 | 2 | $0.055 |
| C9, C10 | 18 pF | | Kemet CBR04C180F5GAC | $0.223 | 2 | $0.446 |
| J1 | SMA Connector | | Linx CONSMA003.031 | $3.670 | 1 | $3.670 |
| L1, L3 | Chip Inductor | 100 nH | TDK MLG1005SR10JT000 | $0.035 | 2 | $0.069 |
| L2 | Chip Inductor | 390 nH | TDK MHQ1005PR39HT000 | $0.253 | 1 | $0.253 |
| L4 | Chip Inductor | 91 nH | TDK MLG1005S91NJT000 | $0.035 | 1 | $0.035 |
| Q1 | N-channel FET | | Diodes DMN1019USN-7 | $0.442 | 1 | $0.442 |
| R1, R2, R3, R4 | Jumper Resistor | 0 | Yageo RC0402JR-070RL | $0.007 | 4 | $0.028 |
| U1 | Si4010 | | Silion Labs Si4010-C2-GT | $3.750 | 1 | $1.883 |
| U3 | Hall Effect Sensor | | TI DRV5032FBDBZT | $0.890 | 1 | $0.890 |
| X1 | Crystal | 10 MHz | ECS ECS-100-10-30B-CKL-TR | $0.607 | 1 | $0.607 |
| | Bare PCB | | PCBway | $2.570 | 1 | $2.570 |
| | | | | | | $10.986 |

Table B.3: Oscillator Multiplier BOM

| Description | Value | Mfg Part Number | Price Each | Qty | Total Price |
|---|---|---|---|---|---|
| Crystal | 30 MHz | | $0.750 | 1 | $0.750 |
| Chip Inductor | Multiple | | $0.250 | 6 | $1.500 |
| Chip Capacitor | Multiple | | $0.050 | 12 | $0.600 |
| Chip Resistor | Multiple | | $0.010 | 6 | $0.060 |
| NPN BJT | | Diodes MMBTH10 | $0.068 | 1 | $0.068 |
| Voltage regulator | | | $0.250 | 1 | $0.250 |
| N-channel FET | | Diodes DMN1019USN-7 | $0.442 | 2 | $0.884 |
| Hall Effect Sensor | | TI DRV5032FBDBZT | $0.890 | 1 | $0.890 |
| Bare PCB | | PCBway | $2.570 | 1 | $2.570 |
| Microcontroller | | | $0.750 | 1 | $0.750 |
| RF Gain Block | | | $0.750 | 1 | $0.750 |
| Whip Antenna | 8” | | $0.200 | 1 | $0.200 |
| | | | | | $8.322 |

Table B.4: ADF4351 Test Board BOM

| Reference Designator | Description | Value | Mfg Part Number | Price Each | Qty | Total Price |
|---|---|---|---|---|---|---|
| VR1 | 3.3V LDO | | Diodes AP2204K-3.3TRG1 | $0.262 | 1 | $0.262 |
| R5 | Chip Resistor | | | $0.010 | 1 | $0.010 |
| U1 | ADF4351 | | Analog ADF4351BCPZ-RL7 | $10.448 | 1 | $10.448 |
| B1 | Balun | | Pulse CX2045LNL | $1.986 | 1 | $1.986 |
| C1, C3, C5, C7, C22, C24, C26, C28 | Chip Capacitor | 10pF | Kemet C0603C100J1GACTU | $0.010 | 8 | $0.080 |
| C11, C12, C21 | Chip Capacitor | 0.01uF | Kemet C0603C103K3RACTU | $0.010 | 3 | $0.030 |
| C13 | Chip Capacitor | 2.7nF | Kemet C0603C272K5RACTU | $0.110 | 1 | $0.110 |
| C14 | Chip Capacitor | 47nF | Kemet C0603C472J1HACTU | $0.170 | 1 | $0.170 |
| C15 | Chip Capacitor | 680pF | Kemet C0603C681K5RACTU | $0.010 | 1 | $0.010 |
| C17 | Chip Capacitor | 100pF | Kemet C0603C101J3GACTU | $0.010 | 1 | $0.010 |
| C18, C19 | Chip Capacitor | 18pF | Kemet CBR06C180FAGAC | $0.344 | 2 | $0.688 |
| C2, C4, C6, C8, C16, C20, C23, C25, C27, C29 | Chip Capacitor | 0.1uF | Kemet C0603C104K4PAC7867 | $0.010 | 10 | $0.100 |
| C9, C10 | Chip Capacitor | 10uF | Taiyo TMK212BBJ106KG-T | $0.064 | 2 | $0.128 |
| L1 | Chip Inductor | 90nH | Murata LQW18AN91NG8ZD | $0.190 | 1 | $0.190 |
| Y1 | Crystal Oscillator | 10 MHz | ECS ECS-3225S33-100-FN-TR | $0.954 | 1 | $0.954 |
| R1, R8 | Chip Resistor | 0 | Yageo AC0603FR-070RL | $0.010 | 2 | $0.020 |
| R13, R14, R15, R16, R17, R18, R19, R20 | Chip Resistor | 220 | Yageo RC0603JR-07220RL | $0.010 | 8 | $0.080 |
| R2, R9, R10, R11, R12 | Chip Resistor | 10k | Yageo RC0603JR-0710KL | $0.010 | 5 | $0.050 |
| R3 | Chip Resistor | 1k | Yageo AC0603FR-071KL | $0.010 | 1 | $0.010 |
| R4 | Chip Resistor | 5.1k | Yageo RC0603JR-074R7L | $0.100 | 1 | $0.100 |
| J3 | Whip Antenna | 8” | | $0.200 | 1 | $0.200 |
| | Hall Effect Sensor | | TI DRV5032FBDBZT | $0.890 | 1 | $0.890 |
| | N-channel FET | | Diodes DMN1019USN-7 | $0.442 | 1 | $0.442 |
| | Microcontroller | | | $0.750 | 1 | $0.750 |
| | Bare PCB | | PCBway | $2.570 | 1 | $2.570 |
| | | | | | | $20.288 |

Table B.5: Si4010 Test Board BOM

| Reference Designator | Description | Value | Mfg Part Number | Price Each | Qty | Total Price |
|---|---|---|---|---|---|---|
| C1 | Chip Capacitor | 0.1 uF | Samsung CL05B104KO5NNNC | $0.013 | 1 | $0.013 |
| C3, C8 | Chip Capacitor | 10 pF | Kemet C0402C100J3GACTU | $0.013 | 2 | $0.025 |
| C6 | Chip Capacitor | 10 pF | Kemet C0402C101K4GACTU | $0.013 | 1 | $0.013 |
| C7, C11 | Chip Capacitor | 1 uF | Samsung CL05A105KO5NNNC | $0.028 | 2 | $0.055 |
| C9, C10 | 18 pF | | Kemet CBR04C180F5GAC | $0.223 | 2 | $0.446 |
| J1 | Whip Antenna | 8” | | $0.200 | 1 | $0.200 |
| L1, L3 | Chip Inductor | 100 nH | TDK MLG1005SR10JT000 | $0.035 | 2 | $0.069 |
| L2 | Chip Inductor | 390 nH | TDK MHQ1005PR39HT000 | $0.253 | 1 | $0.253 |
| L4 | Chip Inductor | 91 nH | TDK MLG1005S91NJT000 | $0.035 | 1 | $0.035 |
| Q1 | N-channel FET | | Diodes DMN1019USN-7 | $0.442 | 1 | $0.442 |
| R1, R2, R3, R4 | Jumper Resistor | 0 | Yageo RC0402JR-070RL | $0.007 | 4 | $0.028 |
| U1 | Si4010 | | Silion Labs Si4010-C2-GT | $3.750 | 1 | $1.883 |
| U3 | Hall Effect Sensor | | TI DRV5032FBDBZT | $0.890 | 1 | $0.890 |
| X1 | Crystal | 10 MHz | ECS ECS-100-10-30B-CKL-TR | $0.607 | 1 | $0.607 |
| | Bare PCB | | PCBway | $2.570 | 1 | $2.570 |
| | | | | | | $7.516 |

# Appendix C

## Software

```
/*******************************************************************************
Project:        VHF wildlife tracker
Written By:     Bryan Westra
Hardware:       Si4010 RH Transmitter
Date Written:   10/12/18
Description:    This program is based on the Silicon Labs "tone demo" example. It
                generates a VHF chirp calibrated to an external crystal and goes
                into low power sleep mode while the output is off.
*******************************************************************************/

#include <stdlib.h>
#include "si4010.h"
#include "si4010_api_rom.h"
#include "tone_demo.h"


// main function, which generates a low duty cycle vhf chirp

void    main(void)
{
    // turn on the oscillator
    bXO_CTRL |= M_XO_ENA;

  while ( 1 )
   {

    int Output_Power = 120;          // Range = 0 to 127
    float Frequency = 150000000;         // Units = Hz

    //Set DMD interrupt to high priority,
      // any other interrupts have to stay low priority
      PDMD=1;
      // Disable the Matrix and Roff modes
      PORT_CTRL &= ~(M_PORT_MATRIX | M_PORT_ROFF | M_PORT_STROBE);
      PORT_CTRL |=  M_PORT_STROBE;
      PORT_CTRL &= ~M_PORT_STROBE;

      // LED control bit off
      GPIO_LED = 0;

      // Call the system setup. This just for initialization.
      // Argument of 1 just configures the SYS module such that the
      // bandgap can be turned off if needed.
      vSys_Setup( 1 );

      // Setup the bandgap for working with the temperature sensor here.
      // bSys_FirstBatteryInsertWaitTime set to non zero value.
      vSys_BandGapLdo( 1 );

      // PA setup.
      // fAlpha and fBeta has to be set based on antenna configuration.
      // Chose a PA level and nominal cap. Both values come from
      // the calculation spreadsheet.
      rPaSetup.fAlpha      = 0.0;
      rPaSetup.fBeta       = 0.0;
      rPaSetup.bLevel      = Output_Power;
      rPaSetup.wNominalCap = 256;
      rPaSetup.bMaxDrv     = 1;

      // PA setup
      vPa_Setup( &rPaSetup );

      // ODS setup .. results from calculation spreadsheet.
      // Set to 1kbps OOK
      rOdsSetup.bModulationType = 0; // 1 .. FSK, 0 .. OOK
      rOdsSetup.bClkDiv         = 5;
      rOdsSetup.bEdgeRate       = 0;

      // Set group width to 7, which means 8 bits/encoded byte to be transmitted.
      // The value must match the output width of the data encoding function
      // set by the vStl_EncodeSetup() below.
      rOdsSetup.bGroupWidth     = 7;
      rOdsSetup.wBitRate        = 4000;  // 1kbps
```

```
      // Configure the warm up intervals LC: 8, DIV: 5, PA: 4
      rOdsSetup.bLcWarmInt  = 8;
      rOdsSetup.bDivWarmInt = 5;
      rOdsSetup.bPaWarmInt  = 4;

      // ODS setup
      vOds_Setup( &rOdsSetup );

      // Set STL encoding as none. No encode function, therefore use NULL pointer
      vStl_EncodeSetup( bEnc_NoneNrz_c, NULL );

      // Generate the frame to use. Example array is fixed in CODE
      // as constant for this example. Assign the beginning of the array
      // to the pbFrameHead pointer.
      pbFrameHead = (BYTE xdata *) abTone_FrameArray;

      // Setup frequency casting .. needed to be called once per boot
      rXoSetup.fXoFreq    = 10000000.0;    // Frequency of the external crystal [Hz]
      rXoSetup.bLowCap    = 1;             // Capacitance setup of crystal 0 = above 14p
f, 1 = below 14pf

      vFCast_XoSetup(&rXoSetup);

      // Wait until oscillator is stable
      while( (RBIT_DATA & (0x10)) == 0 );

      //  Set input to 150 MHz
      vFCast_Tune( Frequency );

      // Turn off crystal oscillator
      bXO_CTRL &= (~M_XO_ENA);

      //  Wait until there is a valid demodulated temperature sample
      while ( 0 == bDmdTs_GetSamplesTaken() ) {}

      //  Tune the PA with the current temperature as an argument
      vPa_Tune( iDmdTs_GetLatestTemp() );

      //  Setup the Run the Single Tx Loop
      vStl_PreLoop( );

      //  Encoding is none. First Tx byte will turn the PA on.
      //  Set ODS such that it transmits all 1's output if there
      //  is no data .. value 3 below. Any additional ODS_CTRL settings
      //  must be done after the vStl PreLoop() call.
      ODS_CTRL = (ODS_CTRL & (~M_ODS_SHIFT_CTRL)) | (3 << B_ODS_SHIFT_CTRL);

      // Transmit Command
      // I find that 3 1 byte transmissions is around 20 ms
      vStl SingleTxLoop( pbFrameHead,1 );  // Frame length in bytes
      vStl SingleTxLoop( pbFrameHead,1 );
      vStl_SingleTxLoop( pbFrameHead,1 );

      // Stop Transmitting
      vStl_PostLoop();

      // Go into Sleep Mode for 2 seconds
      vSleepTim SetCount((lSleepTim_GetOneHourValue()/1800)|0x01000000);
      vSys_Shutdown();

  }

// This will never happen.
  return;
}
```

# Appendix D

## FCC Compliance

While the issue of FCC Compliance was not central to this project, it is important to consider. This device is an intentional radiator, and therefore must comply with the FCC regulations in Title 47 Part 15. Much of the work done on this project was on frequency generation, and that work was done without an antenna attached. All of the testing done with radiated power was done in the 2-meter Amateur Radio band with the proper licensing. It is known from correspondence with wildlife tracking companies that Title 47, Part 15.231 on periodic operation of radiators applies to this type of device [12]; however, the author is not an expert on federal regulations. In order to verify that the device meets FCC requirements, it must be taken to an FCC certified lab.

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[4] J. Matsuoka, T. Sato, and T. Ohshima, "A circuit for high frequency crystal oscillators," in *Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003. Proceedings of the 2003 IEEE International*, pp. 569–574. IEEE, 2003.

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[10] Analog Devices, "ADF4351 Datasheet," [https://www.analog.com/media/en/technical-documentation/data-sheets/ADF4351.pdf], 2017.

[11] S. Jacobs, email, June 2018.

[12] P. Keenlance, email, October 2018.