# A UNIQUE APPROACH TO FREQEUCNY-MODULATED CONTINUOUS-WAVE RADAR DESIGN

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## ABSTRACT

Frequency-Modulated Continuous-Wave (FMCW) Radar has traditionally been used in short range applications. Conventional FMCW radar requires the use of expensive microwave mixers and low noise amplifiers. A uniquely inexpensive solution was created, using inexpensive Gunn oscillator based microwave transceiver modules that consist of 3 diodes inside of a resonant cavity. However these transceiver modules have stability problems which cause them to be unsuitable for use in precise FMCW radar applications, when just one module is used. In order to overcome this problem, a unique radar solution was developed which uses a combination of 2 transceiver modules to create a precise FMCW radar system. This unique solution to FMCW radar is proven to be capable of determining range to target, and creating Synthetic Aperture Radar images.

**Keywords:** FMCW, Gunn Oscillator, SAR, Linear SAR, Radar Imaging, Measurement Systems

## 1. Introduction

FMCW radar has been around for ages. In this paper, a novel method to FMCW radar design is explored. In section 2, a brief explanation of FMCW will be presented. The unique approach to FMCW radar design will then be presented in section 3. Finally, in section 4, the experimental results will be shown. These results include range profile data and SAR images created using the unique approach to FMCW radar design.

FMCW radar was first widely used in radio altimeters, starting in the mid 1930's (1). FMCW has a number of design advantages, including a high average power and short range capabilities. FMCW is unique in its ability to range targets extremely close to the radar transmit and receive antennas. The major disadvantage of FMCW radar (or any CW radar system) is antenna coupling. The transmit to receive antenna coupling limits dynamic range in a FMCW radar system.

The unique approach to FMCW radar takes advantage of transmitter to receiver coupling, utilizing the otherwise parasitic coupling to phase reference a pair of inexpensive transceiver modules into a coherent radar system. These inexpensive transceiver modules are based around a Gunn diode oscillator, and are more widely known as 'Gunnplexers.' These transceiver modules are primarily used in the consumer market, and are typically found in Doppler radar motion sensors, police radar guns, and automobile radar detectors.

The motivation behind this research was to create a very inexpensive FMCW radar system using readily available and inexpensive hardware. Results from this research have proven the ability for this inexpensive FMCW radar system for use as a general purpose range to target device, providing accurate range profile information. This system has also proven itself to be useful in a Synthetic Aperture Radar (SAR) system.

## 2. General Theory of Operation

A quick review of FMCW radar theory is necessary in order to fully explain the unique approach to FMCW radar design.

When a CW radar system is FM modulated, the range to target information provided is in the form of beat frequencies. This is known as FMCW radar. The beat frequencies on the video output of an FMCW radar system correspond to multiple targets and their corresponding ranges. FMCW radar systems are also capable of measuring the Doppler shift of a moving target. The block diagram of a basic FMCW radar system is shown in figure 1.

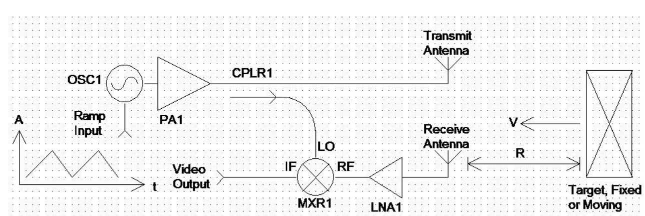


***Figure 1: Block diagram of a basic FMCW radar system.***

Looking at figure 1, OSC1 is FM modulated with a triangular ramp input with a period of 2 ms. The triangular ramp is an alternating linear ramp with both positive and negative slopes as shown in figure 2.

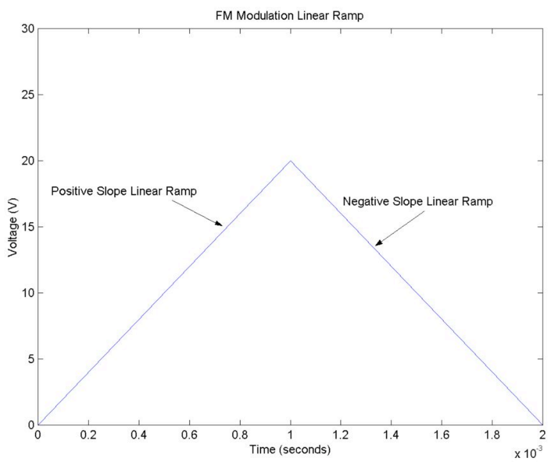


***Figure 2: Linear ramp used to FM modulate the FMCW radar system.***

The FM output of OSC1 is fed into PA1. PA1 amplifies OSC1 to an appropriate transmit level. The output of OSC1 is radiated out of the transmit antenna. The FM modulated carrier is reflected off of the target at a range of R meters. The reflected signal is delayed in time on its way to and from the target. The reflected signal is received by the receive antenna, and amplified by LNA1. The output of LNA1 is fed into the RF port of MXR1. Some power from PA1 is coupled into the LO port of MXR1. When the LO and the RF are multiplied together in MXR1, the IF output of MXR1 is the range to target in frequency. This range to target in terms of frequency is known as the beat frequency. The greater the beat frequency on the IF output port of MXR1, the greater the range to target. If the target is moving, then the Doppler shift of the moving target is added onto the beat frequency present on the IF port of MXR1. The relationship between frequency, FM chirp bandwidth, range to target, and Doppler frequency shift can be found using the equations for both a positive and a negative linear ramp modulation waveform [2]. When a positively sloped linear ramp FM modulates OSC1, the beat frequency at the IF port of MXR1 is represented by:

$$f_b = f_b^+ = \frac{8\Delta f f_m R}{c} - f_d \tag{1}$$

Where: $f_b =$ the beat frequency at the IF port of MXR1

$f_b^+ =$ the beat frequency at the IF port of MXR1 when OSC1 is modulated with a positive linear ramp.

$\Delta f =$ chirp frequency deviation

$f_m =$ FM modulation rate

$R =$ range to target

When a negatively sloped linear ramp FM modulates OSC1, the beat frequency at the IF port of MXR1 is represented by:

$$f_b = f_b^- = \frac{8\Delta f f_m R}{c} + f_d \tag{2}$$

Where: $f_b^- =$ the beat frequency at the IF port of MXR1 when OSC1 is modulated with a negative linear ramp

From the equations above, the range to target is found using:

$$R = \frac{c}{8\Delta f f_m}\left\langle f_b \right\rangle \tag{3}$$

Where: $\left\langle f_b \right\rangle =$ the average frequency difference

If the target is moving, the velocity of the target can be found using:

$$v = \frac{\lambda}{4}\left(f_b^- - f_b^+\right) \tag{4}$$

The amplitude of the return signals can be approximated using the radar range equation [2].

The most important concept explained here is that a shift in time corresponds to a shift in frequency. This is because the radar is frequency modulated in time. The current value of the transmitted frequency is different than what was transmitted 2 ns ago. These small and subtle frequency differences make up the beat frequencies on the IF output of MXR1, and hence the range to target information in the form of low frequency beats.

## 3. The Unique Approach to FMCW

The unique approach to FMCW radar design is based entirely around the use of two inexpensive microwave transceiver modules. These modules are Gunn diode based, and are more commonly known as 'Gunnplexers.' The microwave transceiver module in use for this system is the M/A-Com model MA87127-1 X-band microwave transceiver module.

The MA87127-1 is composed of three major components, VCO, mixer, and circulator as shown in figure 3. The VCO is fed into port 1 of the circulator. Port 2 of the circulator is connected to the WR-90 waveguide flange input/output port of the transceiver. Port 3 of the circulator is connected to the RF input of the mixer. Some power is coupled off the VCO and fed into the LO port of the mixer. The IF output of the mixer is connected to a small solder terminal on the outer case of the transceiver.

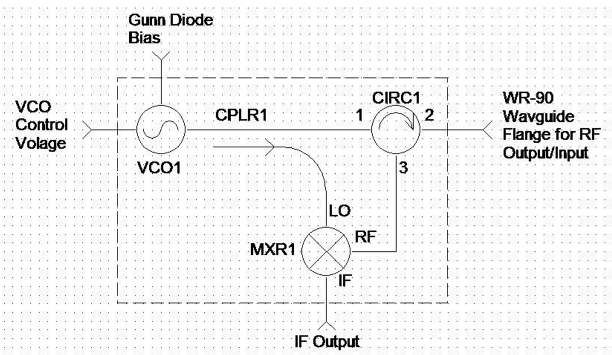


***Figure 3: MA87127-1 block diagram.***

VCO1 is a varactor controlled Gunn diode oscillator. A varactor diode is placed inside of a cavity Gunn oscillator as shown in figure 4. A bias voltage on the varactor diode between, roughly, 0 and 20 V controls the frequency of the Gunn oscillator. A second bias voltage of approximately 10 V is needed to cause the Gunn diode to oscillate at the frequency of the cavity that it is placed in.

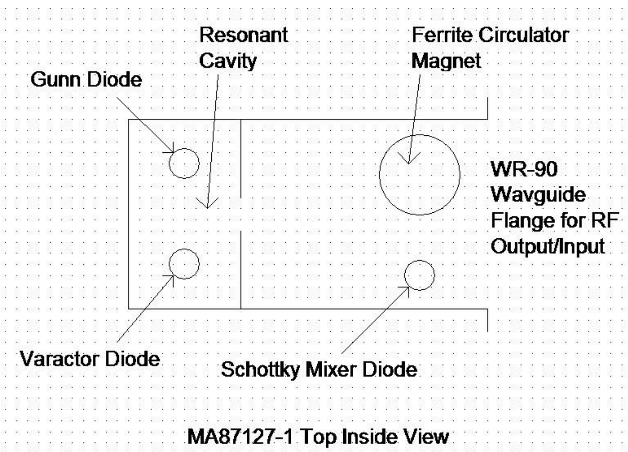


***Figure 4: MA87127-1 Physical Layout.***

CPLR1 is a symbolic representation of the coupling action that occurs between the Gunn oscillator diode and the Schottky mixer diode placed within close proximity (see figure 4).

MXR1 is created by the coupled power from the Gunn diode oscillator. This coupled power causes the Schottky mixer diode to switch on and off. This switching action causes the Schottky mixer diode to operate as a single balanced mixer.

CIRC1 is a ferrite circulator place inside of the resonant waveguide cavity that contains VCO1 and MXR1. CIRC1 is basically a large magnet precisely placed inside of the resonant cavity. CIRC1 causes RF power from VCO1 to exit the input/output port, and causes RF power coming into the input/output port to be transferred into MXR1.

When looking at figure 3, it appears as though one transceiver module alone can be utilized as an FMCW radar system. However, it was found in lab tests that the pass band of the IF port on MXR1 starts to roll off around 1 MHz, causing little to no response at audio frequency, which is were most beats from a short range FMCW radar system will be located. The transceiver module's receiver worked most efficiently at IF frequencies above 30 MHz, where the loss due to the mixer was found to be the least. The lack of an acceptable low frequency to near DC response from MXR1 renders one individual transceiver module useless for most short range FMCW radar applications. This problem is common for most microwave transceiver modules of this type.

Regardless of its shortcomings, when two MA87127-1 (or similar) transceiver modules are used, the unique FMCW radar design solution can be obtained.

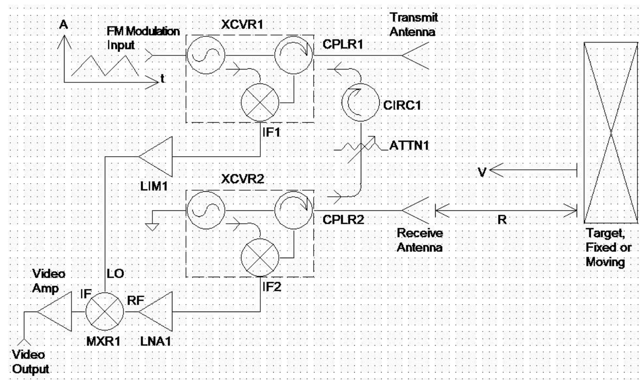


***Figure 5: Simplified block diagram of the unique FMCW radar solution.***

A simplified block diagram of the unique FMCW radar solution is shown in figure 5. XCVR1 is centered at frequency $f_1$ and FM modulated with a linear chirp, $kf_d$, where $k = \frac{volts}{second}$. The output of XCVR1 is represented with the equation:

$$TX_1(t) = A_c \cos[2\pi f_1 t + 2\pi k f_d] \qquad (5)$$

The output of XCVR1 is fed into the transmit antenna. The transmitted signal is reflected off of the target. The target is situated at a range R and moving at a velocity v (if it is moving). The range R and velocity v correspond to a time difference and Doppler shift between the original transmit signal and that which was picked up by the receive antenna and fed into XCVR2. This time difference corresponds to a beat frequency difference $f_b$

as was proven in section 2. Thus, the reflected signal from the target is represented by the equation:

$$TX_{1b}(t) = A_c \cos\left[2\pi f_1 t + 2\pi k f_d + 2\pi f_b t\right] \tag{6}$$

XCVR2 is set to a fixed frequency of $f_2$. XCVR2 is radiating a fixed frequency carrier at that frequency which can be represented by the equation:

$$TX_2(t) = A_c \cos\left[2\pi f_2 t\right] \tag{7}$$

As explained earlier, the IF output of each transceiver module is a product of its VCO frequency and any RF power that is coming into the input/output port of the module. Because of this, the IF output of XCVR2 can be calculated:

$$\begin{aligned} IF_2(t) &= TX_{1b}(t) TX_2(t) \\ &= \frac{A_c^2}{2}\cos\left[2\pi f_1 t + 2\pi k f_d t + 2\pi f_b t + 2\pi f_2 t\right] + \\ &+ \frac{A_c^2}{2}\cos\left[2\pi f_1 t + 2\pi k f_d t + 2\pi f_b t - 2\pi f_2 t\right] \end{aligned} \tag{8}$$

The higher frequency term can be dropped. This is a practical consideration since the IF output port of the transceiver modules is not capable of producing X-band microwave signals. Thus, the IF output of XCVR2 can be simplified as:

$$IF_2(t) = \frac{A_c^2}{2}\cos\left[2\pi f_1 t + 2\pi k f_d t + 2\pi f_b t - 2\pi f_2 t\right] \tag{9}$$

Simultaneously, some power from XCVR2 is coupled into XCVR1, taking advantage of a coupling problem that would otherwise limit a typical FMCW radar system. Power from XCVR2 is deliberately coupled out using CPLR2 and output through ATT1, CIRC1, and into CPLR1. The coupled power injected into CPLR1 is fed into XCVR1. The resulting frequency response at the IF port of XCVR1 is calculated using the equation:

$$\begin{aligned} IF_1(t) &= TX_2(t) TX_1(t) \\ &= \frac{A_c^2}{2}\cos\left[2\pi f_2 t + 2\pi f_1 t + 2\pi k f_d t\right] + \\ &+ \frac{A_c^2}{2}\cos\left[2\pi f_2 t - 2\pi f_1 t - 2\pi k f_d t\right] \end{aligned} \tag{10}$$

Like XCVR2, the higher frequency term can be dropped. Thus, the IF output of XCVR1 can be simplified as:

$$IF_1(t) = \frac{A_c^2}{2}\cos\left[2\pi f_2 t - 2\pi f_1 t - 2\pi k f_d t\right] \tag{11}$$

$IF_1(t)$ is fed into the input port of a limiting amplifier, LIM1. The output of LIM1 is used as the LO drive of MXR1. $IF_2(t)$ is fed into the input port of an LNA, which is represented by LNA1. The output of LNA1 is fed into the RF input port of MXR1. $IF_1(t)$ and $IF_2(t)$ are multiplied together in MXR1. The IF output of MXR1 is amplified by a video amplifier. The resulting product from MXR1 can be represented by the equation:

$$\text{Video Output} = IF_1(t) IF_2(t) \tag{12}$$

The IF port of MXR1 is not capable of reproducing the high frequency terms resulting from the multiplication of two sinusoidal signals. Therefore the video output of the radar system can be expressed as:

$$\text{Video Output} = \frac{A_c^4}{4}\cos\left[2\pi f_b t\right] \tag{13}$$

It is clear from the equation above, that the video output is the beat frequency difference $f_b$ due to distance from target R and velocity of target v. Thus, we have an FMCW radar system using two inexpensive microwave transceiver modules.

## 4. Experimental Results

Experimental results were found using the radar centered at an approximate frequency of 10.25 GHz. The radar system used in these experiments is shown in figure 6. In this configuration, both the transmit and receive antennas are mounted directly on top of each other on a metal front end assembly. The front end assembly is then slid down the length of a 12 ft long rectangular metal track, where linear SAR data is taken at regular intervals along the length of the track.

***Figure 6: The unique solution to FMCW radar.***

The first series of experiments were conducted in order to test the range linearity of the system. A single 30 dBsm standard radar target was placed directly in front of the front end assembly various ranges. Shown in this paper, are experiments where the standard target is placed at 25 ft (see figure 7) and 40 ft (see figure 8) from the front end assembly.

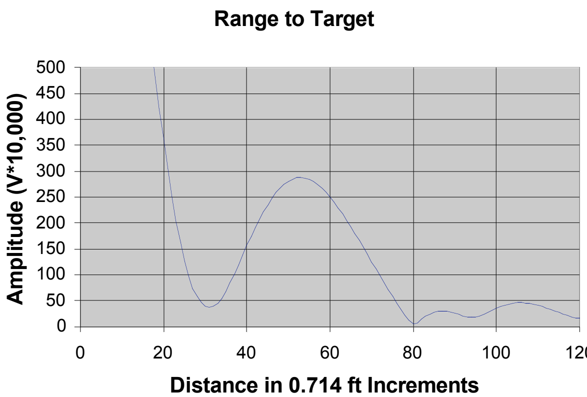


***Figure 7: 30 dBsm target placed at 25 ft in front of radar antenna fixture.***

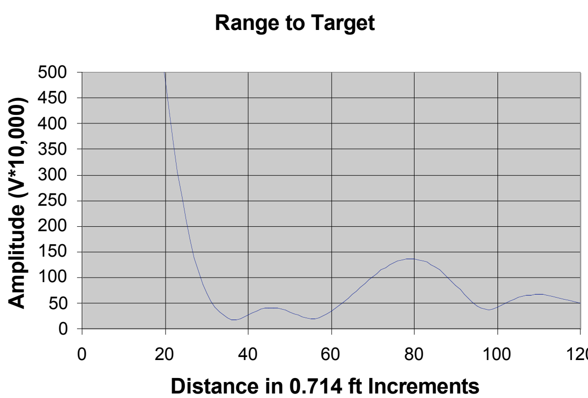


***Figure 8: 30 dBsm target placed at 40 ft in front of the radar antenna fixture.***

In figure 7, there is a small range offset of 13.2 ft. In figure 8, there is a small range offset of 15.96 ft. The range offset was found to be due to the length of the IF cables between the front end assembly and the IF chassis. It was also found that the further the target was located from the front end assembly, the greater the range offset. This is possibly due to the diminishing tuning linearity of the transmitter as it nears the maximum output frequency during a transmit chirp cycle. So, in effect, there are two range offsets affecting range accuracy.

In order to overcome the range offset problem, a constant mean range offset was introduced into the focused SAR algorithm.

The next series of experiments were conducted to test the ability of the radar for use in a SAR system. A focused SAR algorithm was implemented [4], where the unique approach to FMCW radar unit was used to provide the range profile data. In this experiment, the radar front end assembly was moved down a 12 ft linear track, where range profile data was taken every 1 inch. Shown in this paper, are two experiments. In the first experiment, a 30 dBsm target was placed at 25 ft from the linear SAR track (figure 9). In the second experiment, a 20 dBsm target was placed 25 ft from the linear SAR track, and a 30 dBsm target was placed 40 ft from the track (figure 10). In both experiments, the cross range data is shown in 1 inch increments, and the down range data in 0.714 ft increments. The Z axis data is shown in 1/10,000 fractions of a volt at 50 ohms.

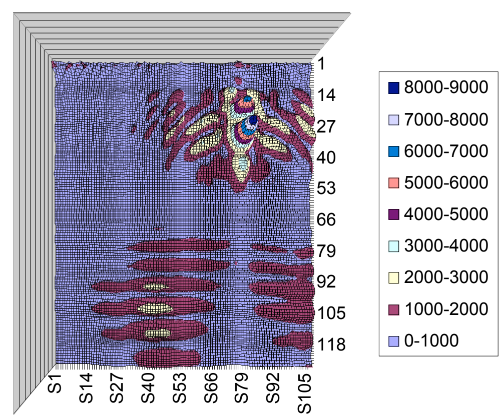


***Figure 9: 30 dBsm target located at a distance of 25 ft from the linear SAR track.***

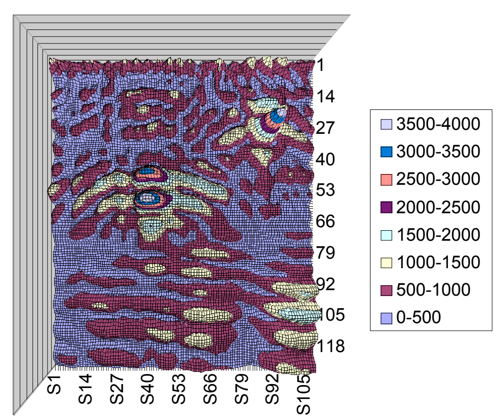


***Figure 10: 20 dBsm target located at a distance of 25 ft, and a 30 dBsm target located at 30 ft from the linear SAR track.***

From the SAR images shown in figures 9 and 10, it was determined that the unique solution to FMCW radar produced sufficient consistent range profile results to produce SAR images at a close range. Looking at figure 9, it is clear that the amplitude of the 30 dBsm target is substantially greater than the single range profile data in figure 7. Looking at figure 10, it is clear that the radar system is capable of resolving two different standard targets at different ranges, both in cross range, and in down range.

## 7. Summary

A unique approach to FMCW radar design was presented. This radar system was designed around readily available inexpensive microwave parts. It proved itself in its ability to range a target, with the exception of some range offset problems. These range offset problems were overcome by introducing a range offset into the range profile data. The unique solution to FMCW radar was then utilized as a focused SAR imaging system, capable of imaging standard radar targets at various ranges.

Future work will be conducted in developing a more linear transmit chirp at a low cost. The increased chirp linearity will reduce the range offset problems. A greater transmit bandwidth is always desirable in short range radar systems, and this too will be researched.

This system has the unique advantage of low cost. It has great potential for use in low-cost radar sensor and measurement applications.

## 8. REFERENCES

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