A Low-Power, High Sensitivity, X-Band Rail SAR Imaging System

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Abstract

Wide-band radar imaging with range gating and high sensitivity can be achieved with the use of low-cost commercially available narrow-band IF filters. Such filters reduce the effective receiver noise bandwidth of the radar system allowing for high sensitivity comparable to that of single-side-band radio receivers, while at the same time acquiring de-chirped wide-band received waveforms. A carefully developed radar architecture based on the use of these IF filters is shown in this paper. This radar architecture is then implemented in an X-band linear rail synthetic aperture radar (SAR) imaging system. The X-band rail SAR is a linear FM chirped radar which chirps from approximately 7.5 GHz to 12.5 GHz. The radar front end is mounted on to an 8 foot long linear rail. Transmit power is adjustable to 10 dBm or less. It will be shown that objects as small as groups of pushpins in free-space could be imaged using transmit power as low as 10 nano-watts. These results are compared to previous direct conversion X-band FMCW rail SAR work. A high sensitivity X-band rail SAR such as this could be useful for measuring low radar cross section (RCS) targets. This radar could be used in high clutter environments that require a range gate. This low-power X-band rail SAR could be useful for operation in restricted transmit areas where maximum radiated power is severely limited. Other applications include any that require low transmit power such as automotive radar.

Index Terms – Synthetic aperture radar, Rail SAR, Chirp modulation, FMCW, X-band, Radar imaging, low-power, nano-watt radar, Radar cross sections, Radar equipment, Radar applications, Radar receivers, Radar transmitters

1 Introduction

It will be shown in this paper that a low-power, high sensitivity, X-band rail SAR imaging system based on the use of commercially available narrow band IF filters is capable of imaging target scenes made up of small radar cross section (RCS) targets using only 10 nano-watts of transmit power. This is achieved by using narrow IF filters to reduce the effective receiver noise bandwidth of the radar system allowing for high sensitivity comparable to that of single-side-band radio receivers, while at the same time acquiring de-chirped wide-band received waveforms. A carefully developed radar architecture based on the use of these IF filters will be shown in this paper. This radar architecture has many desirable features including; a wide-bandwidth chirp, short duration range gating, high dynamic range, high sensitivity, and low transmit power. The radar architecture will be described in Section 2. The hardware implementation of this system will be described in Section 3. Imaging results using full power, 10 milli-watts, will be shown in Section 4.1. Imaging results using low power, down to 10 nano-watts, will be shown in Section 4.2. Imaging results compared to a direct conversion FMCW radar system from [1] will be provided in Section 4.3. It will be shown that the high sensitivity range-gated FMCW radar architecture is highly effective at the X-band frequency range for applications such as RCS measurement where range gating and transmit power power limits are necessary but high sensitivity is required.

2 Radar Architecture

When operating a typical linear FM or FMCW radar system, such as those from [1] through [6], the resulting range to target information from a de-correlated linear FM radar chirp is in the form of low frequency beat tones. The more distant the target the higher the resulting frequency of the de-correlated beat tone. For this reason it is possible to implement a short duration range gate in a linear FM radar system by simply placing a band pass filter (BPF) on the output of the Video Amp in a traditional design FMCW radar system such as that shown in [1] through [6]. However, this is challenging to implement in practice because it is difficult to design effective high Q bandpass filters at base-band with comparable performance to communications IF filters. Much higher performance BPF's are available in the form of widely used IF communications filters which operate at high frequencies. These filters are found in two-way radios, various types of communication, and television receivers. Examples of these IF filters include; crystal filters, ceramic filters, SAW filters, and mechanical filters.

These communications IF filters typically operate at standard IF frequencies of 10.7 MHz, 21.4 MHz, 455 KHz, 49 MHz and etc. These communications filters are high Q, where Q is defined as [7]:

$$Q = \frac{f_c}{B},$$

where f_c = center frequency of the BPF and $B = -3$ dB bandwidth of the filter.

A typical operating frequency of a crystal filter is $f_c = 10.7$ MHz with a bandwidth of $B = 7.5$ KHz. The resulting Q of this filter is 1426.7. High Q's such as this are difficult to achieve with BPF designs at base-band audio frequencies. The radar architecture shown in this paper uses high Q IF filters to create a short duration range gate, while at the same time, reduces receiver noise bandwidth B_n causing a dramatic increase in receiver sensitivity. With this design; the shorter duration the range gate, the more sensitive the radar receiver.

A simplified block diagram of the radar system is shown in Figure 1. In the following explanation amplitude coefficients will be ignored. OSC1 is a high frequency tunable oscillator. The frequency output of OSC1 is f_{BFO} which can be represented by the equation:

$$BFO(t) = \cos\big(2\pi f_{BFO} t\big).$$

The output of OSC1 is fed into the IF port of MXR1. The LO port of MXR1 is driven by

OSC2. OSC2 is a 7.5 GHz to 12.5 GHz voltage tuned YIG oscillator. OSC2 is linear FM modulated by a ramp input, where the output of OSC2 can be represented by the equation:

$$LO(t) = \cos\big(2\pi(2\cdot 10^9 + c_r t)t\big).$$

OSC1 and OSC2 are mixed together in MXR1 to produce the transmit signal which is then amplified by power amplifier PA1. The output of PA1 is fed into the transmit antenna ANT1 and propagated out towards the target scene. The transmitted signal out of ANT1 is $TX(t)$, where:

$$TX(t) = LO(t)\cdot BFO(t),$$

$$TX(t) = \cos\big(2\pi(2\cdot 10^9 + c_r t)t\big)\cdot\cos\big(2\pi f_{BFO} t\big).$$

After some simplification this becomes

$$TX(t) = \cos\big(2\pi(2\cdot 10^9 + c_r t)t + 2\pi f_{BFO} t\big) + \cos\big(2\pi(2\cdot 10^9 + c_r t)t - 2\pi f_{BFO} t\big).$$

The transmitted signal is made up of two carrier frequencies. The LO plus the BFO, and the LO minus the BFO. Both tones are linear FM modulated, amplified, then radiated out towards the target scene. When the transmitted waveform $TX(t)$ is radiated out to the target scene it is then reflected off of a target, delayed by some round trip time t_{delay} and propagated back to the receiver antenna ANT2. The received signal at ANT2 is represented by the equation:

$$\begin{aligned} RX(t) = {} & \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay})\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay})\big). \end{aligned}$$

The output of ANT2 is amplified by LNA1 and fed into MXR2. The LO port of MXR2 is fed by OSC2. The IF output of MXR2 is the product

$$IF(t) = LO(t)\cdot RX(t).$$

Evaluating this product results in

$$\begin{aligned} IF(t) = {} & \cos\big(2\pi(2\cdot 10^9 + c_r t)t\big)\cdot\cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay})\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)t\big)\cdot\cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay})\big). \end{aligned}$$

Multiplying out the terms in the above equation results in

$$\begin{aligned} IF(t) = {} & \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay}) + 2\pi(2\cdot 10^9 + c_r t)t\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay}) + 2\pi(2\cdot 10^9 + c_r t)t\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\big). \end{aligned}$$

As a practical consideration the IF port of MXR2 can not output microwave frequencies so the high frequency terms can be dropped resulting in:

$$\begin{aligned} IF(t) = {} & \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\big) \\ & + \cos\big(2\pi(2\cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\big). \end{aligned}$$

Expanding out the terms inside of the cosine argument results in:

$$\begin{aligned} IF(t) = \cos\Big[& 2\pi(2\cdot 10^9 + c_r t)t - 2\pi(2\cdot 10^9 + c_r t)t_{delay} \\ & + 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\Big] \\ + \cos\Big[& (2\pi(2\cdot 10^9 + c_r t)t - 2\pi(2\cdot 10^9 + c_r t)t_{delay} \\ & - 2\pi f_{BFO}(t - t_{delay}) - 2\pi(2\cdot 10^9 + c_r t)t\Big]. \end{aligned}$$

Letting the high frequency terms cancel out:

$$\begin{aligned} IF(t) = {} & \cos\Big[- 2\pi(2\cdot 10^9 + c_r t)t_{delay} + 2\pi f_{BFO}(t - t_{delay})\Big] \\ & + \cos\Big[- 2\pi(2\cdot 10^9 + c_r t)t_{delay} - 2\pi f_{BFO}(t - t_{delay})\Big]. \end{aligned}$$

As another practical consideration the DC blocking capacitors in the IF amplifier AMP1 will reject the DC phase terms, resulting in:

$$IF(t) = \cos\big(- 2\pi c_r t t_{delay} + 2\pi f_{BFO} t\big) + \cos\big(- 2\pi c_r t t_{delay} - 2\pi f_{BFO} t\big).$$

Simplifying the arguments in the cosine terms:

$$IF(t) = \cos\big(2\pi(f_{BFO} - c_r t_{delay})t\big) + \cos\big(2\pi(f_{BFO} + c_r t_{delay})t\big).$$

$IF(t)$ is fed into the high Q IF filter FL1. FL1 has a center frequency of f_c and a bandwidth of BW. OSC1 is set to a frequency such that $f_{BFO} \geq \frac{BW}{2} + f_c$ causing FL1 to pass only the lower sideband of $IF(t)$, thus causing the output of FL1 to be:

$$FIL(t) = \begin{cases} \cos\left(2\pi(f_{BFO} - c_r t_{delay})t\right) & \text{if } \frac{-BW}{2} + f_c < f_{BFO} - c_r t_{delay} < \frac{BW}{2} + f_c \\ 0 & \text{for all other values} \end{cases} \quad (1).$$

Only beat frequencies in the range of $\frac{-BW}{2} + f_c < f_{BFO} - c_r t_{delay} < \frac{BW}{2} + f_c$ are passed through IF filter FL1. FL1 is a high Q crystal filter with a steep pass-band frequency response. Since in an FMCW radar system the range to target is directly proportional to the beat frequency $c_r t_{delay}$, then the band limited IF signal (which is is proportional to downrange target location) is effectively a hardware range-gate.

Increasing the bandwidth of FL1 increases the range-gate duration. Decreasing the bandwidth of FL1 decreases the range-gate duration. It is for this reason that the range-gate is adjustable if a number of different bandwidth filters were used, switched in and out of the IF signal chain.

If f_{BFO} were increased then the filter FL1 passes only signals that fit the equality in Equation 1. Since the $c_r t$ term is subtracted from f_{BFO} then the $c_r t$ term would have to be greater in size to compensate for a higher f_{BFO} frequency in order to let the IF signals pass through FL1. Thus, the filter FL1 would only pass beat tones further down range but at the same range duration in length if the frequency f_{BFO} were increased. So the range-gate is adjustable in physical downrange location (physical down range time delay).

In addition to these desirable properties the narrow bandwidth of FL1 greatly increases the receiver sensitivity because it is well known in communication receiver theory that the narrower the IF bandwidth the better the sensitivity. According to [8] for an ideal receiver the sensitivity of a SSB or CW receiver can be approximated by calculating the minimum detectable signal (MDS) which is related directly to the IF bandwidth:

$$MDS_{dBm} = -174 + 10\log_{10} B_n + NF \qquad (2),$$

where:

B_n = noise bandwidth of the receiver (Hz), which is the IF bandwidth for an ideal receiver:

-174 dBm is the available thermal noise power per Hz at room temperature of 290°K:

$NF = 3.3$dB front end noise figure for a typical broad band amplifier (this NF is chosen arbitrarily for example).

In the case of the radar system developed for this research, FL1 has an $f_c = 10.7$ MHz and $BW = 7.5$ KHz. According to Equation 2 the receiver sensitivity would be -131.9 dBm without signal processing gain. In addition to high sensitivity the bandwidth would provide a short duration range-gate of 9.375 nS for a chirp rate of $c_r = 800$ GHz/second. This sensitivity performance is significantly greater than a short pulsed radar system with a 9.375 nS range-gate, requiring an IF bandwidth of approximately 100 MHz to capture a single pulse, which according to Equation 2 would provide a sensitivity of approximately -90.4 dBm. Additional gain for both types of systems, short pulse and high sensitivity linear FM, can be achieved through signal processing coherent integration and other methods.

One last step occurs in the signal chain shown in Figure 1 where the output of FL1 is downconverted to base band through MXR3. The LO port of MXR3 is driven by OSC1. The output of MXR3 is fed through Video Amp1 and can be represented by the equation:

$$Video(t) = BFO(t) \cdot FIL(t).$$

Video Amp1 is an active low pass filter, rejecting the higher frequency component of the cosine multiplication, resulting in the video output signal:

$$Video(t) = \begin{cases} \cos\left(2\pi c_r t_{delay} t\right) & \text{if } \frac{-BW}{2} + f_c - f_{BFO} < c_r t_{delay} < \frac{BW}{2} + f_c - f_{BFO} \\ 0 & \text{for all other values} \end{cases}.$$

The result is a range gated base-band video signal. This result is similar to a traditional FMCW radar system except that this signal is band limited by a high Q bandpass filter with an adjustable center frequency which effectively range-gates the video signal that is fed into the digitizer and reduces the noise bandwidth of the radar receiver allowing for high sensitivity.

3 Hardware Implementation

The hardware implementation of this radar system is a linear rail SAR much like [1] where the radar sensor is mounted on a linear rail and moved automatically down the rail acquiring range profiles of the target scene at evenly spaced increments across the rail. Using this data a SAR imaging algorithm from [9] produces a radar image of the target scene. A picture of the radar system is shown in Figure 3. The radar front end is shown in Figure 2. The radar is chirped from approximately 7.5 GHz to 12.5 GHz resulting in 5 GHz of chirp bandwidth. The chirp time is 10 milli-seconds. The IF filter center frequency is 10.7 MHz with a bandwidth of 7.5 KHz. The IF bandwidth is set by two ECS-10.7-7.5B crystal filters in series with a number of IF amplifiers and adjustable attenuators in between so as to maximize the usable dynamic range of the digitizer. The radar video output is digitized by a 16 bit 200 KSPS ADC. The transmit power is approximately 10 milli-watts and adjustable down to pico-watts by placing a step attenuator in series with the transmit antenna. The transmit and receive antennas are standard gain horns. The aperture spacing across the linear rail is approximately 1 inch spanning 90 inches of rail. Complete design details of this system are presented in [10].

4 Measured Results

The rail SAR was tested by imaging targets in free space which were placed on a styrofoam table in an outdoor installation. Calibration and coherent background subtraction were used in all imagery shown. A picture of the measurement setup is shown in Figure 3.

4.1 Radar imagery using full power

Approximately 10 milliwatts of transmit power was used for the measurements shown in this section.

A rail SAR image of a 1:32 scale model F14 aircraft coated in aluminum foil was measured and the resulting image is shown in Figure 4. This image clearly shows an aircraft slightly off-axis. Many details are noticeable including the nose and wings. Much of the metal surface was illuminated in this radar image.

A rail SAR image of a group of pushpins was acquired. Pushpins are the small plastic and metal thumbtacks that are used to hold up papers and posters. Pushpins are low RCS targets at X-band and are often used for demonstrating the capability of RCS measurement systems. A picture of a pushpin is shown in Figure 5a. A picture of a target group made up of pushpins is shown in Figure 5b. A radar image of a group of pushpins was acquired and is shown in Figure 6. The location of all pushpins is clearly shown. Looking at this radar image it is possible to count each of the individual pushpins. Some cross range blurring of the pushpins making up the 'G' is noticeable. This was likely due to wind gusts on the day this image was acquired. Fading out is noticeable at the bottom of the '92.' This is due to the -3 dB cutoff of the IF filter functioning as a range-gate which happened to be set too close to the bottom of the target scene.

A zoomed out radar image of the group of pushpins is shown in Figure 7. No additional downrange clutter and very little crossrange clutter is present in this image. This image demonstrates the effectiveness of the range-gate.

4.2 Low power free-space X-band imaging

In the measurements shown in this section transmit power was reduced by placing a step attenuator before the transmit antenna.

A rail SAR image was acquired of a group of pushpins using only 100 nano-watts of transmit power. This result is shown in Figure 8. This image is nearly identical to the full power image of a group of pushpins shown in Figure 6 (except for the text in the image). Clutter and signal-to-noise are nearly identical in both images.

An X-band rail SAR image was acquired of a group of pushpins using only 10 nano-watts of transmit power. This result is shown in Figure 9. The pushpins further down range in this image have faded into the noise compared to the full power image shown in Figure 6. All pushpins in this image are clearly visible.

An X-band rail SAR image was acquired of a group of pushpins using only 1 nano-watt of transmit power. This result is shown in Figure 10. Only a few pushpins on the bottom row of letters are visible. This transmit power level is too low for use in imaging low RCS targets such as pushpins.

A low power radar system such as this one could be used for RCS measurements and detection applications such as automotive radar. Based on the low-power results presented in this section a radar system using this architecture could be developed to meet various regulations for transmit power allowing for the widespread use of high performance radar sensors.

4.3 Comparison to a typical FMCW radar imaging system

A low cost X-band rail SAR imaging system was developed in [1] capable of imaging small objects such as scale model aircraft and pushpins. The radar system developed for [1] was a simple direct conversion FMCW system with a transmit power of approximately 31 milliwatts and a chirp bandwidth of 5 GHz, from 7.5 GHz to 12.5 GHz. The transmit and receive antennas used in this system are standard gain horns. In this section imagery from the radar system developed in [1] will be compared to radar imagery produced by the rail SAR in this paper.

Figure 11 shows a radar image of a 1:32 scale model F14 aircraft from [1]. Figure 4 shows a radar image of the same model acquired using the X-band rail SAR from this paper. Both images are in agreement.

Figure 12 shows a radar image of a pushpin target scene from [1]. Figure 6 shows a radar image of a pushpin target scene measured using the X-band rail SAR from this paper. The image from [1] in Figure 12 shows more clutter and the amplitude return of the pushpins in the last few rows is shown fading into the noise.

A zoomed-out pushpin image from [1] is shown in Figure 13. Much clutter is present down range and some cross range. By contrast, the zoomed out image acquired by the X-band rail SAR from this paper shown in Figure 7 does not contain noticeable downrange clutter due to the range gate and much less cross range clutter.

In this section it was shown that the radar architecture presented in this paper is more effective compared to direct conversion FMCW for small rail SAR applications where down range clutter must be eliminated. It was also shown that the radar architecture presented in this paper has comparable imaging performance to a direct conversion FMCW rail SAR while at the same time transmitting a small fraction of the output power.

5 Conclusions

High resolution imagery of model aircraft and groups of pushpins were acquired using the radar architecture presented in this paper. Imagery of low RCS pushpin target scenes were acquired using extremely low transmit power. It was shown that this X-band rail SAR imaging system is more effective in reducing clutter and using less transmit power than previous direct conversion FMCW radar systems. With its simplicity of design this radar architecture could be used for RCS measurements, automotive radar, or other radar sensor applications where low transmit power, high sensitivity, and range gating are required.

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