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A Low-Power, Real-Time, S-Band Radar Imaging System

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Motivation

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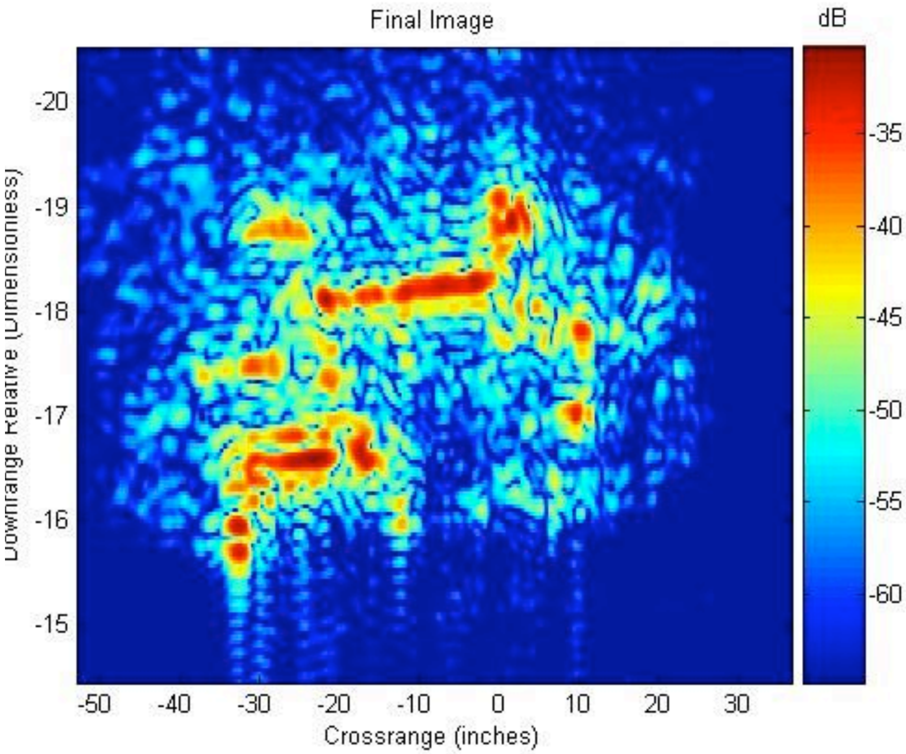
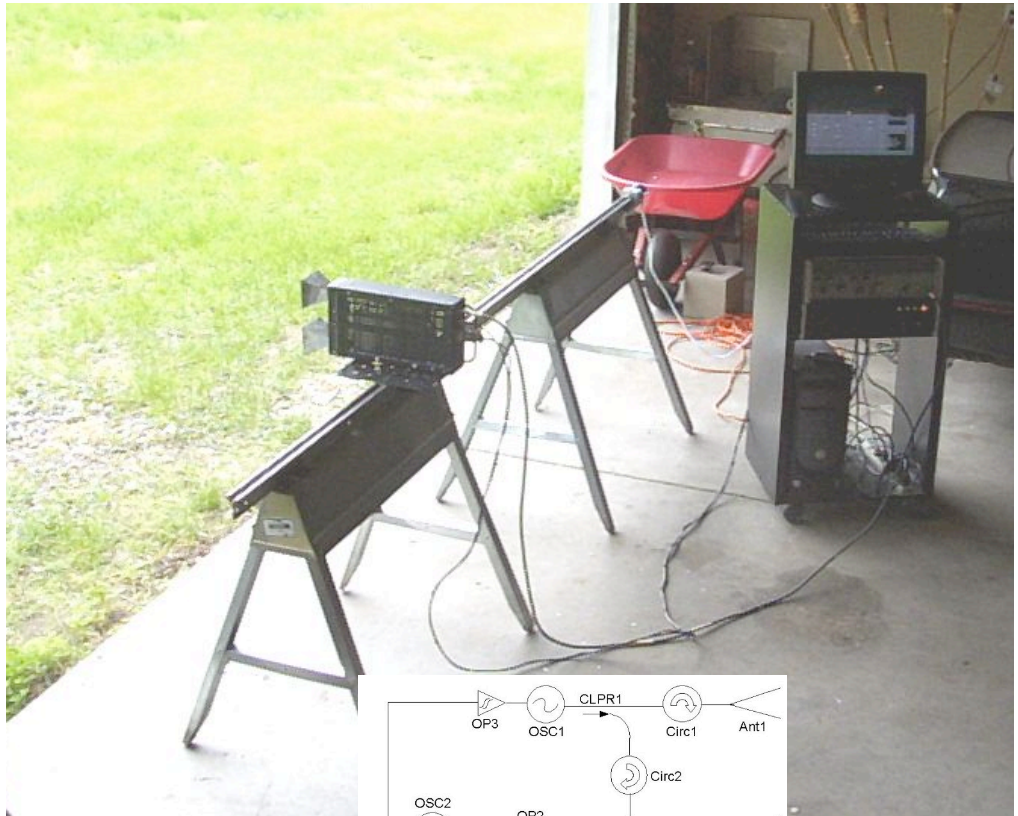
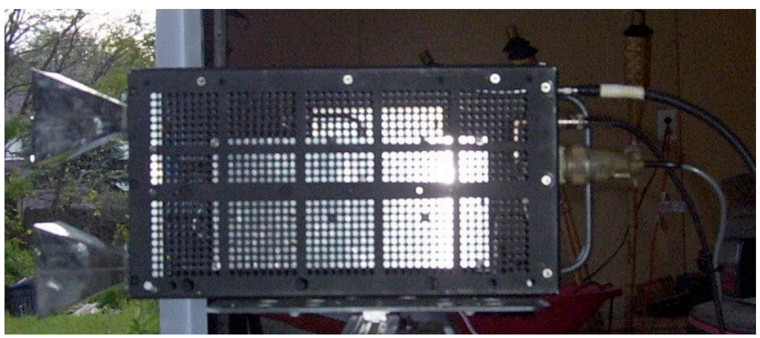
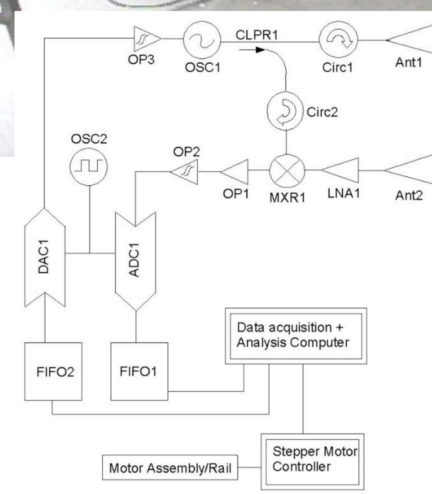
- **Objective:** **To locate unknown targets behind a lossy dielectric slab in a high clutter environment.**
- **Background**
  - **Leveraging existing infrastructure: the $240 rail SAR (AMTA 2006 [15]).**
- **Through-Slab model**
- **Radar system architecture**
- **S-band rail SAR**
- **X-band rail SAR**
- **Real-time S-Band Imaging System**

Leveraging Existing Infrastructure; The $240 rail SAR









Through-Slab Radar Model

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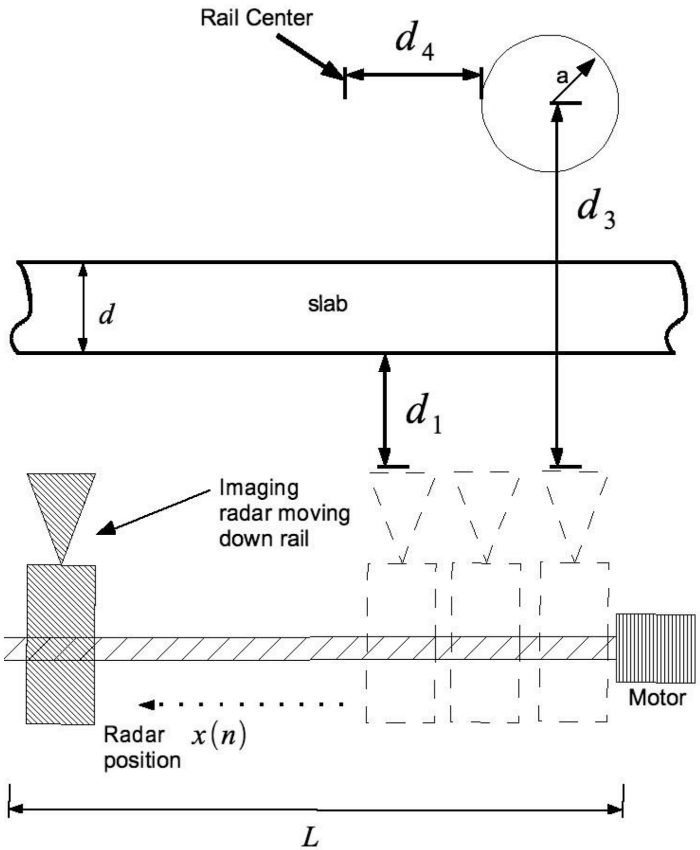
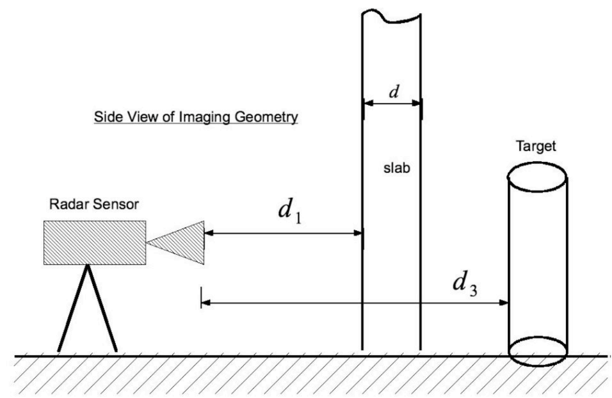
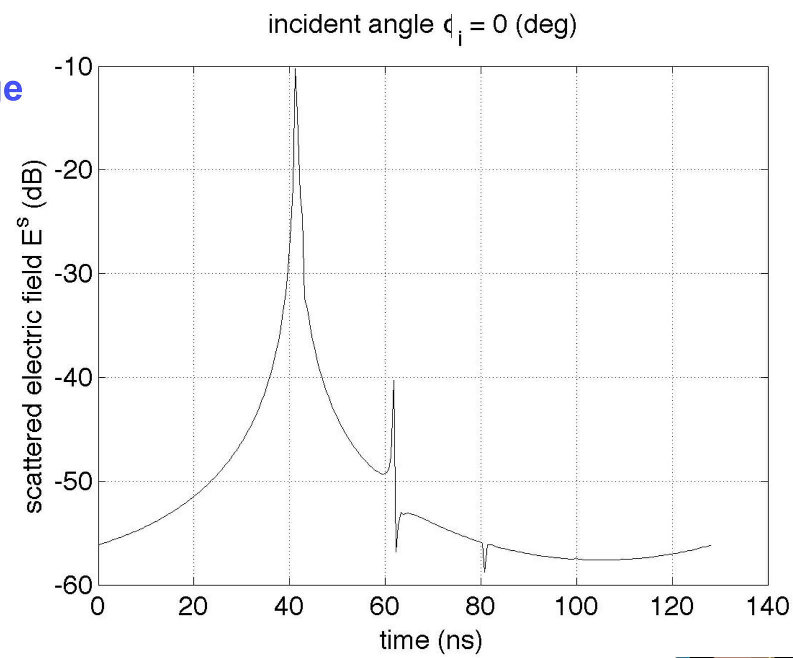


Top view

Side view:



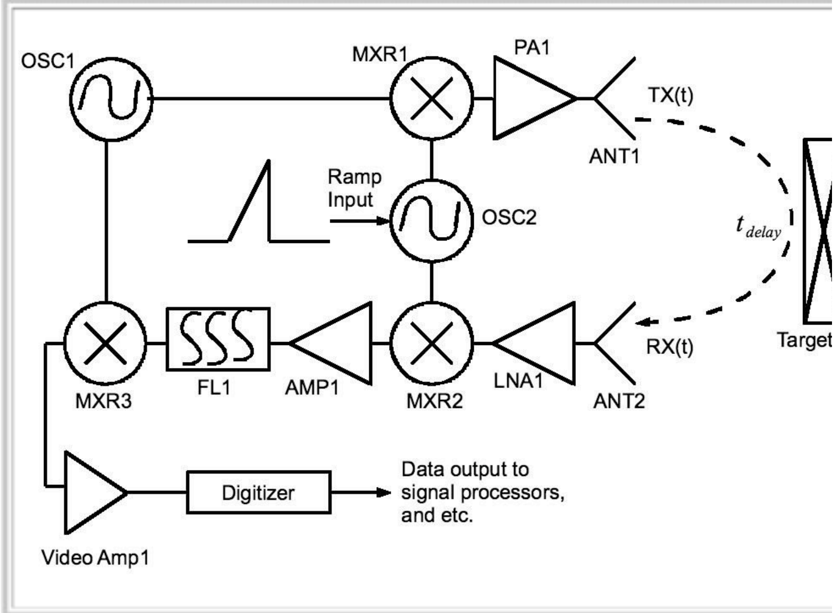
Simulated range profile:



The fundamental problem: Measurement dynamic range is limited by 'flash' off the slab.

Radar Architecture

A radar architecture was developed which allows for the use of a long time duration LFM pulse providing high sensitivity, while at the same time, eliminating the 'flash' due to the air-dielectric interface.



Assuming the chirped LO and fixed frequency BFO are represented by the equations:

$$BFO(t) = \cos\left(2\pi f_{BFO} t\right)$$
$$LO(t) = \cos\left(2\pi (2 \cdot 10^9 + c_r t) t\right)$$

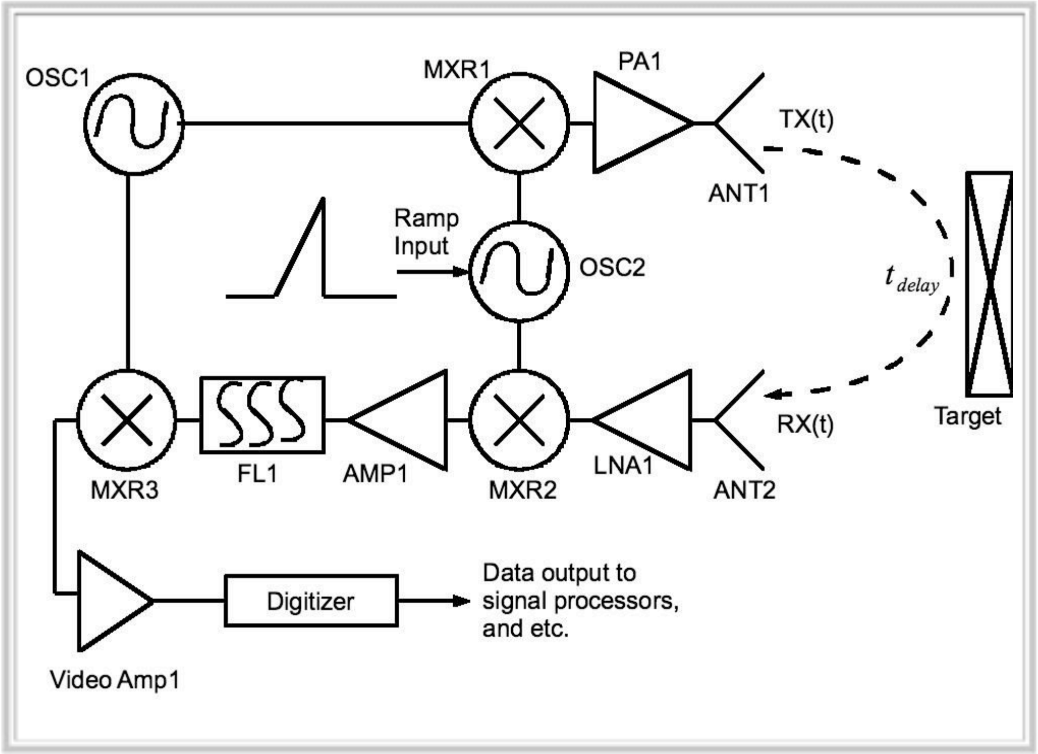
The transmitted waveform is the product of the above equations which results in two transmitted carriers that are LFM modulated:

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

And the received delayed waveform becomes:

$$RX(t) = \cos\left(2\pi (2 \cdot 10^9 + c_r t)(t - t_{delay}) + 2\pi f_{BFO}(t - t_{delay})\right)$$
$$+ \cos\left(2\pi (2 \cdot 10^9 + c_r t)(t - t_{delay}) - 2\pi f_{BFO}(t - t_{delay})\right)$$

Radar Architecture



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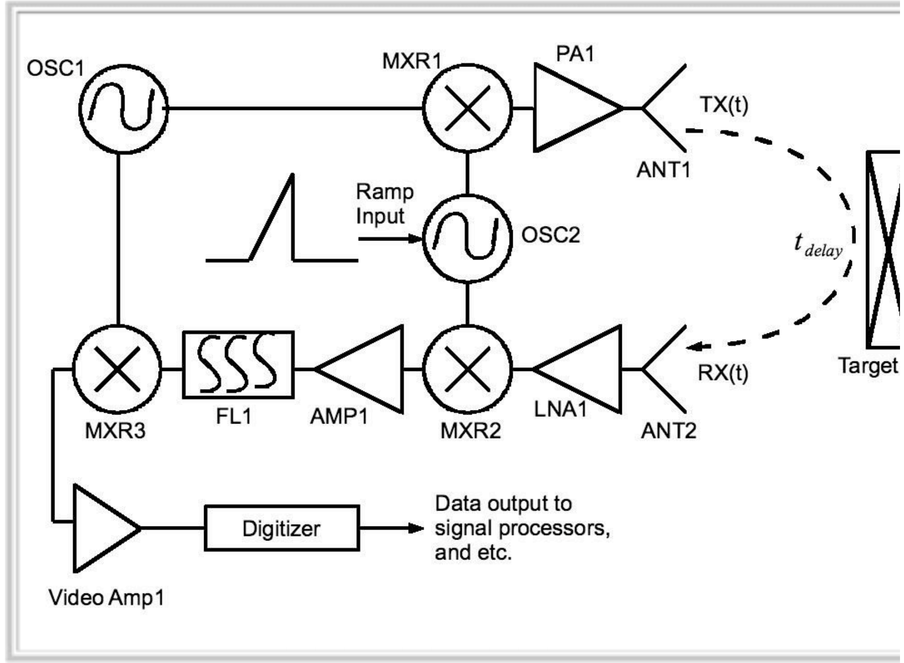
$$IF(t) = \cos\left(2\pi(f_{BFO} - c_r t_{delay})t\right) + \cos\left(2\pi(f_{BFO} + c_r t_{delay})t\right)$$

De-chirped IF bandwidth is spread spread above and below the BFO operational frequency.

Radar Architecture



THE IF IS FED THROUGH FL1, WHICH IS A HI-Q COMMUNICATIONS FILTER (SUCH AS A CRYSTAL FILTER). OSC1 IS SET TO A FREQUENCY SUCH THAT:

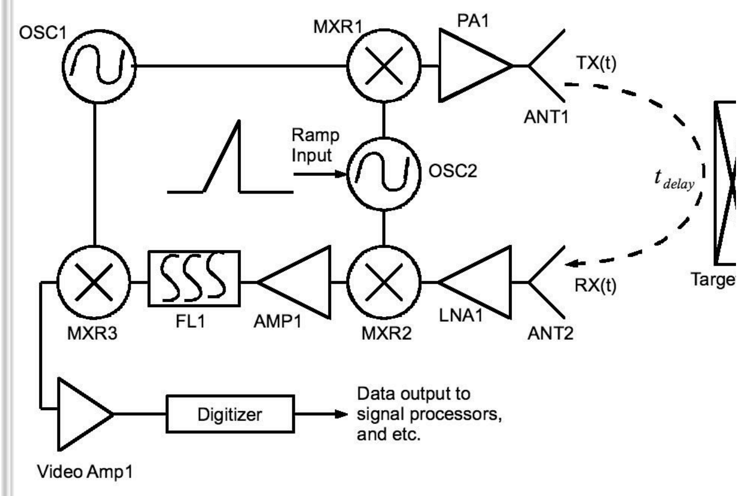
$$f_{BFO} \geq \frac{BW}{2} + f_c$$

FL1 passes one of the two de-chirped sidebands about BFO and limits the maximum/minimum detectable beat frequencies, resulting in an effective range gate:

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

SINCE THIS IS AN FMCW RADAR, AND RANGE TO TARGET IS IN THE FORM OF BEAT FREQUENCY TONES, FL1 EFFECTIVELY BECOMES A HARDWARE RANGE GATE

Radar Architecture



THE OUTPUT OF FL1 IS THEN CONVERTED DOWN TO BASE BAND VIA MXR3 AND OSC1:

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

VIDEO AMP1 IS AN ACTIVE LPF, SO THE HIGH FREQUENCY TERMS DROP OUT, LEAVING A HIGH-Q BAND LIMITED BASE-BAND VIDEO. BAND LIMITING IN FMCW RADAR RESULTS IN RANGE GATING (ONLY LETTING IN A CERTAIN BANDWIDTH OF BEAT TONES):

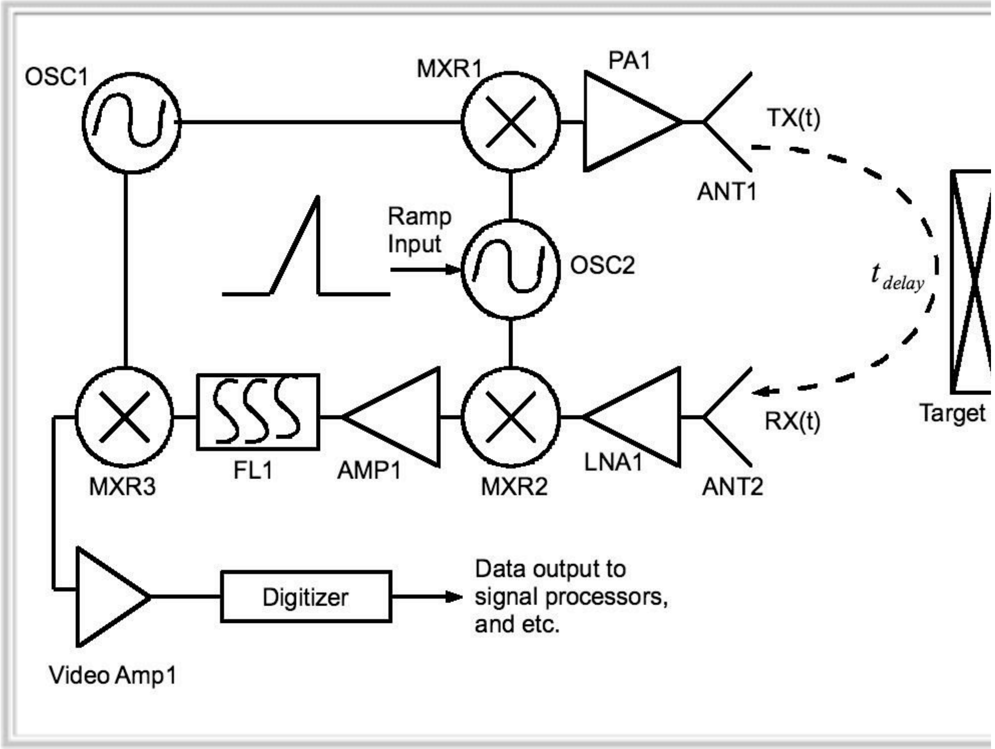
$$Video(t) = \begin{cases} \cos\left(2\pi c_r t_{delay} t\right) & \text{if } \frac{-BW}{2} + f_c - f_{BFO} < c_r t_{delay} < \frac{BW}{2} + f_c - f_{BFO} \\ 0 & \text{for all other values} \end{cases}$$

FRONT END IS FAIRLY ROBUST, LEAVING THE IF TO PREVENT DIGITIZER SATURATION. THIS IS A VERY EFFECTIVE RANGE GATE, AND WILL BE SHOWN IN THE RESULTING IMAGERY.

RANGE GATE IS ADJUSTABLE, SIMPLY INCREASE THE FREQUENCY OF OSC1 TO PUSH RANGE GATE FURTHER DOWN RANGE. CHANGING THE BANDWIDTH OF FL1 CHANGES THE LENGTH OF RANGE GATE

Radar Architecture

FURTHERMORE: THE NARROW BAND HI-Q IF FILTER FL1 REDUCES THE EFFECTIVE NOISE BANDWIDTH OF THE RECEIVER, GREATLY INCREASING SENSITIVITY.



A TYPICAL CRYSTAL FILTER HAS THE FOLLOWING SPECS:

$f_c = 10.7$ **MHz**

$BW = 7.5$ **KHz**

WHICH WOULD WOULD PROVIDE A THEORETICAL ANALOG RECEIVER SENSITIVITY (assuming NF=3.3 dB) OF **-131.9 dBm**

FOR A CHIRP RATE OF $c_r = 800 \cdot 10^9$ **Hz/Sec**

THIS WOULD PROVIDE AN EFFECTIVE RANGE GATE OF APPROXIMATELY **9.375 nS**

(plus additional gain due to pulse compression of a relatively long radar pulse.)

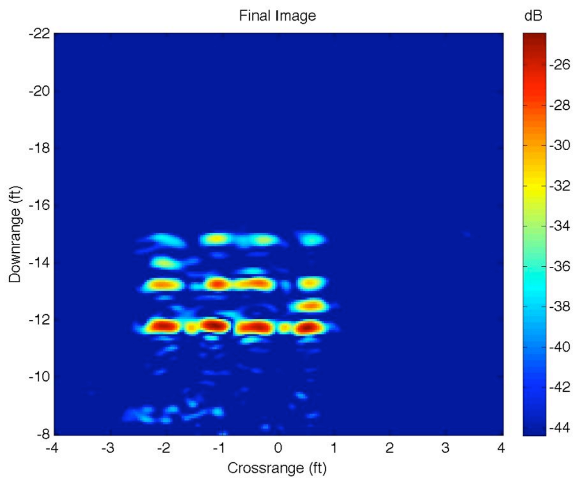
S-band rail SAR

Using this radar architecture an S-band rail SAR was developed:

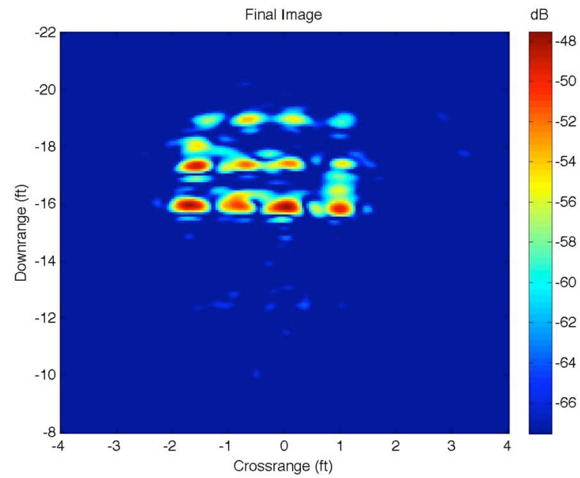
Free-space S-band rail SAR imagery of 6” tall metal rods

SAR imagery of 6” tall metallic rods using low transmit power was acquired using this radar system:

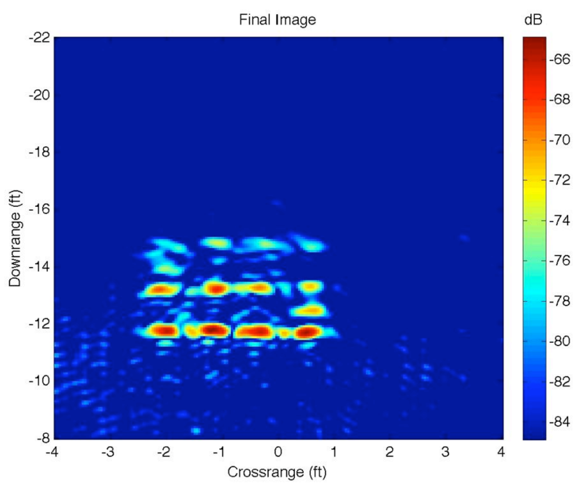
10 mW Tx



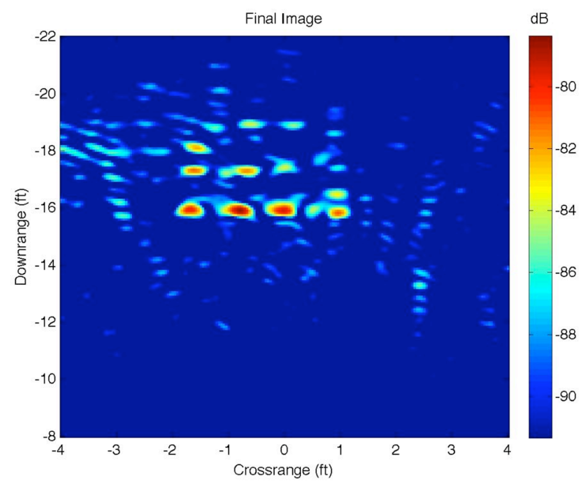
10 nW Tx



100 pW Tx

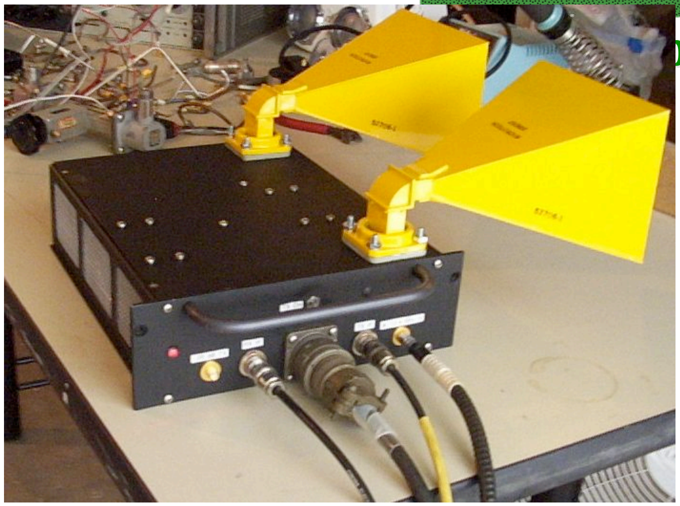


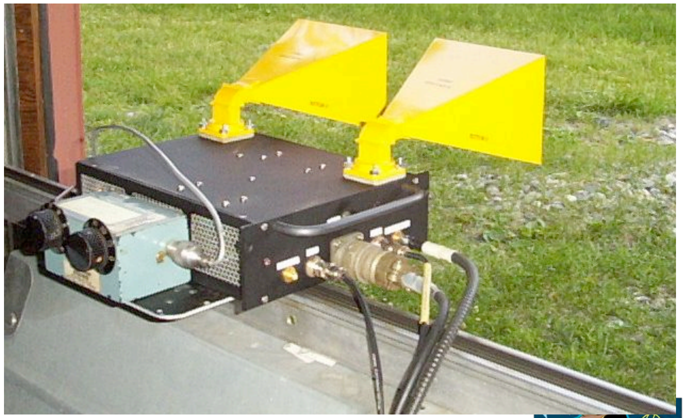
5 pW Tx



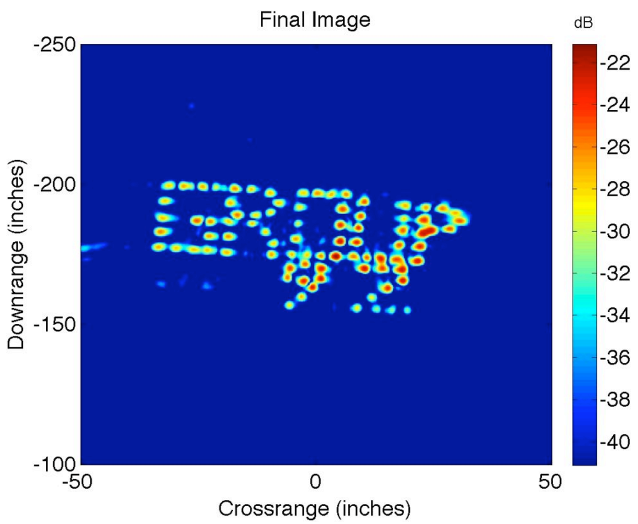
X-band front end

Using this radar architecture an X-band rail SAR was developed:

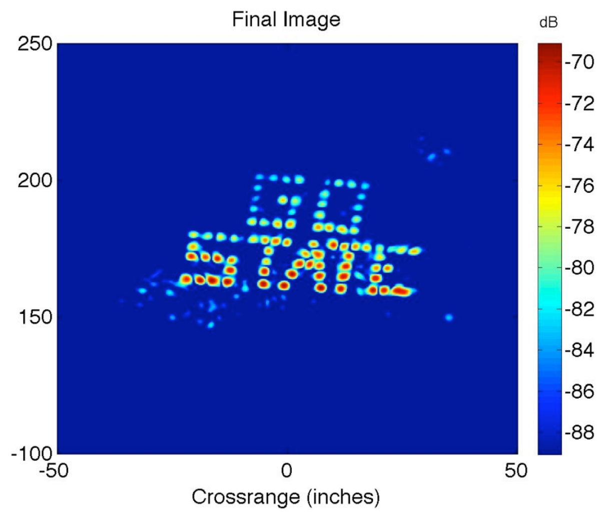




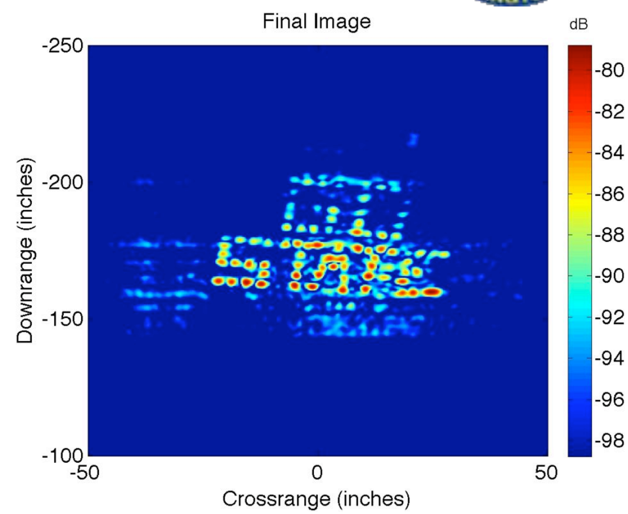
X-band Rail SAR imagery



10 mW Tx



100 nW Tx



10 nW Tx

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IEEE APS Magazine Measurements Corner, June 2008 [13]

S-Band Rail SAR Through-Slab

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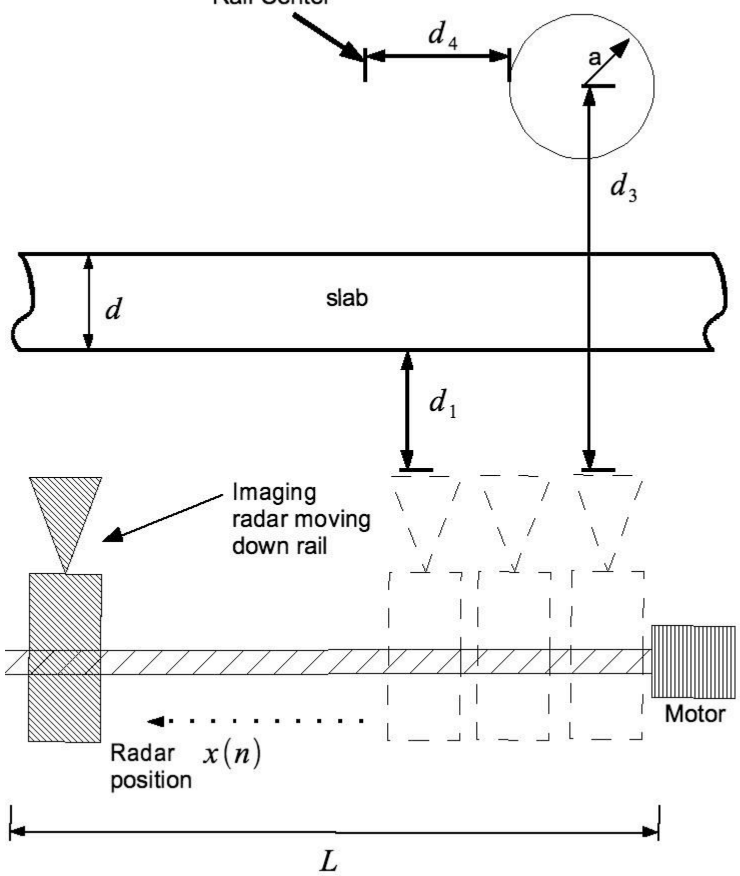
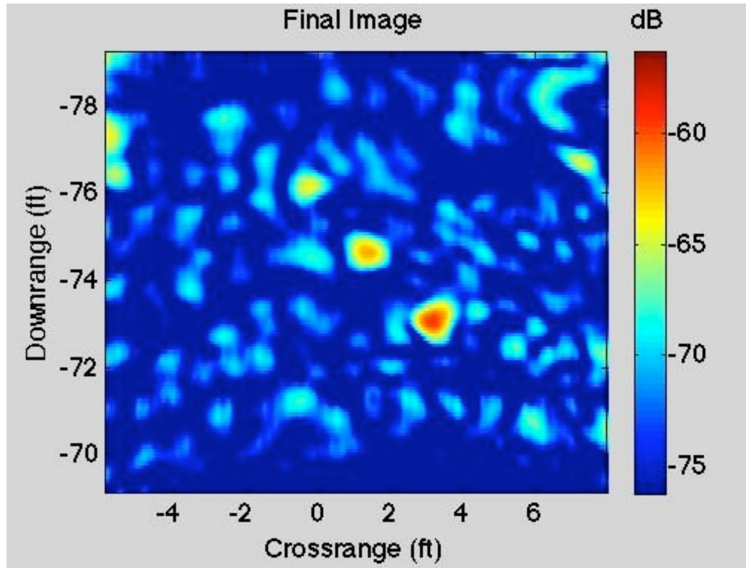
The S-band rail SAR tested in a through-slab imaging scenario.

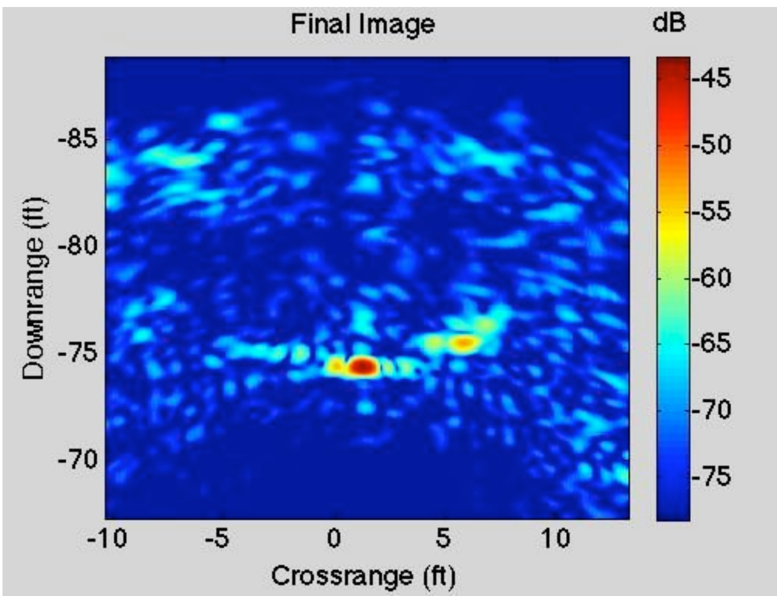


S-band Rail SAR Through-Slab Imagery

Row of 3 metal rods, 6" tall and 3/8" diameter



6" diameter cylinder



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Real-Time S-Band Radar Imaging Array

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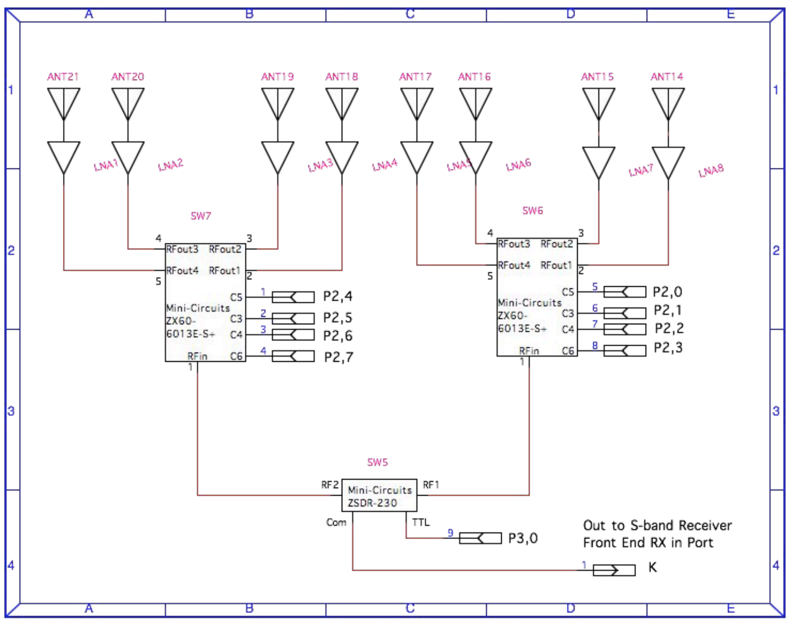
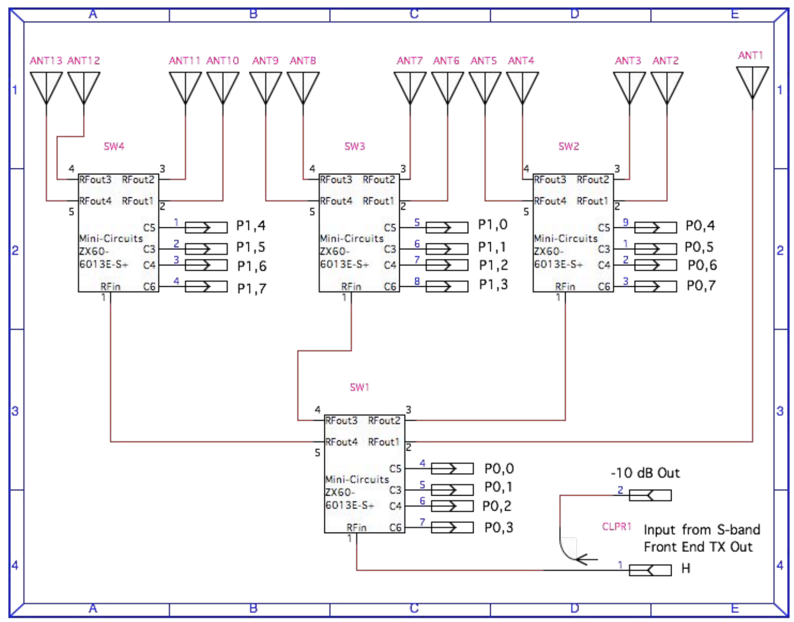
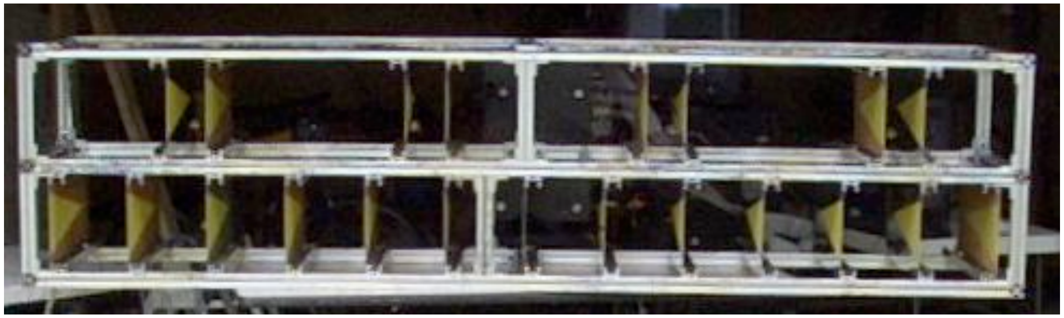
- A rail SAR is too slow for certain imaging applications. For this reason that a high speed array was developed which acquires an equivalent data set to a rail SAR.
- This data is processed in real time to display a continuously updated radar image at an approximate rate of one image every 1.9 seconds.
- Receiver and transmitter front ends are multiplexed across two separate sub arrays; a receive sub array and a transmit sub array.
- Combinations of transmit and receive elements create bi-static antenna pairs that allow the phase center to be guided down the length of the array.

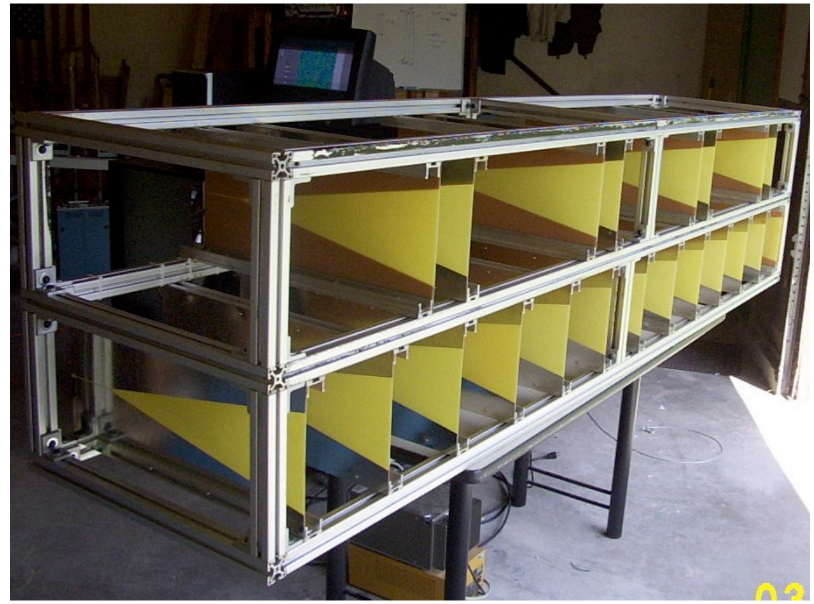




2008 BOSTON AMTA

Real-Time S-Band Radar Imaging System





Real-Time SAR Image of a Cylinder in Free Space

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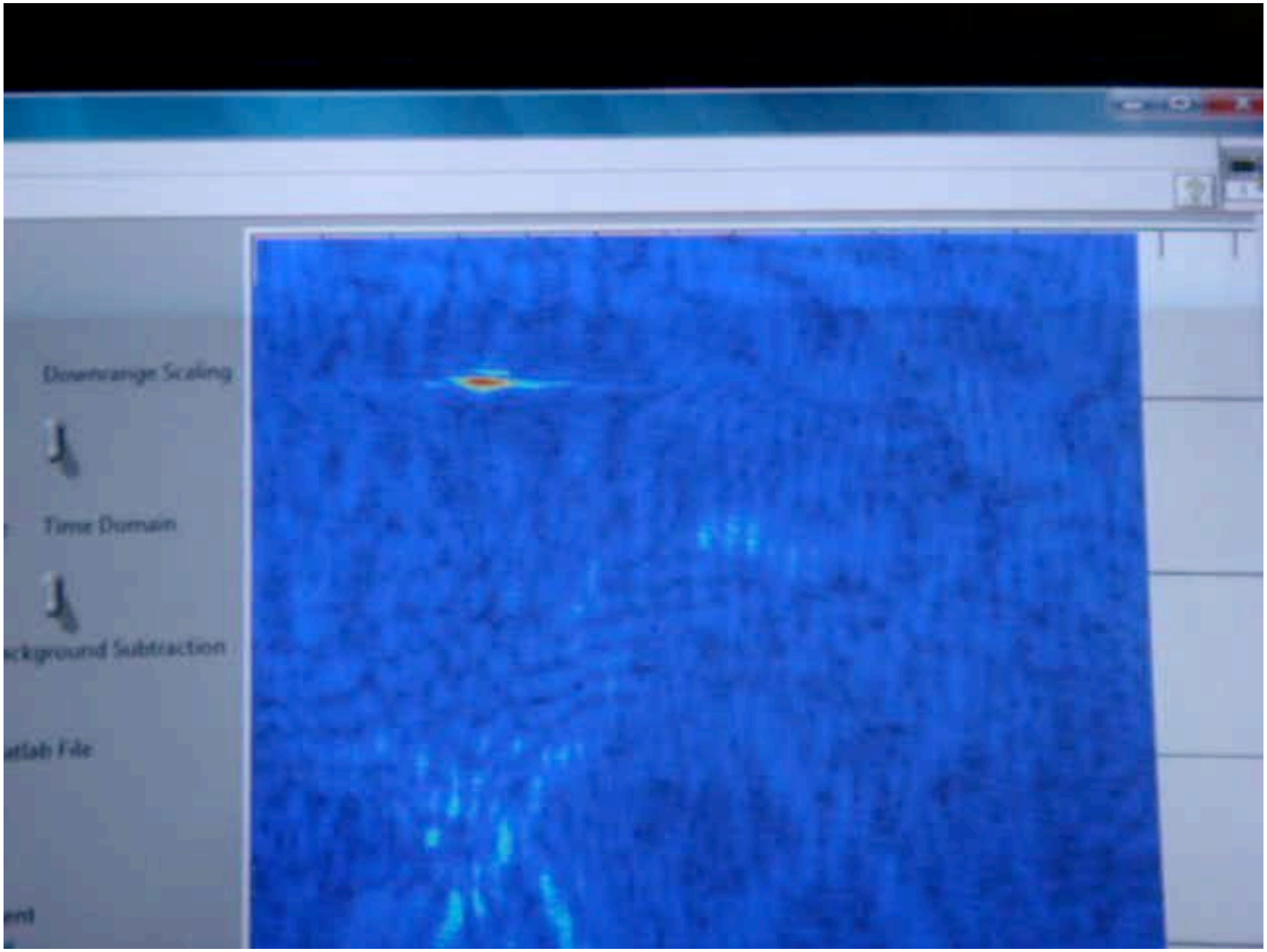
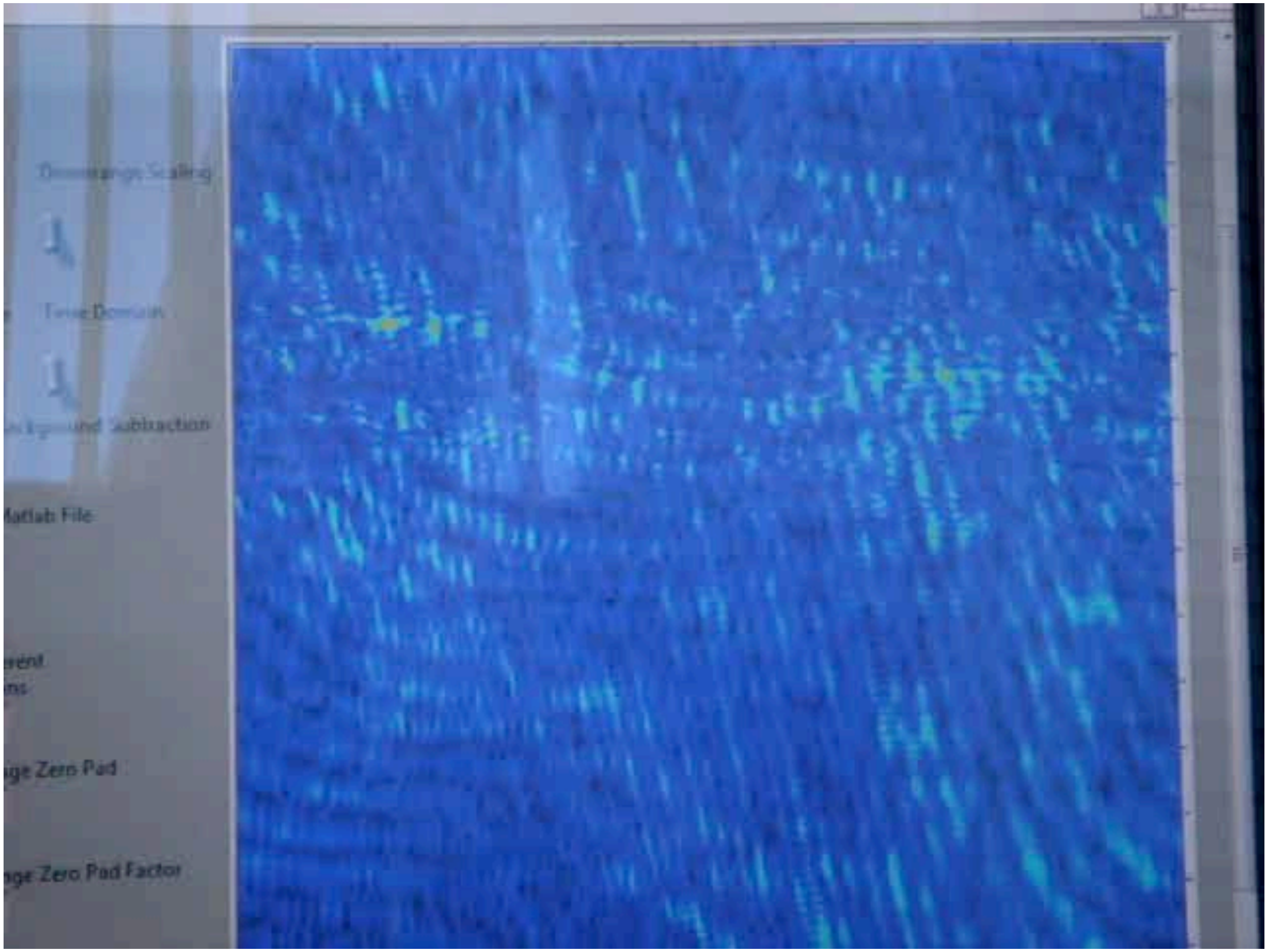


Real-time soda can through a 4” thick solid concrete wall



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Discussion and future work

- **Summary:**
  - **A modified FMCW radar architecture which implements a hardware range gate without the use of time domain electronic switches or pulsing**
  - **Large S-band array for through-slab imaging**
  - **System operates at stand-off range**
  - **Produces real-time SAR imagery of what is behind a concrete wall**
    - **Objects as small as coke cans detected**
- **Future work includes:**
  - **Using the modified FMCW design on other applications**
  - **Increasing array speed to 5-10 frames per second**
    - **this is done by upgrades:**
    - **data acquisition (more efficient software?)**
    - **Faster YIG oscillator, or possibly switch to DDS wave form generator**
- **For more information Google 'A Low Power Radar Imaging System' or go to: www.msu.edu/~charvatg**

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