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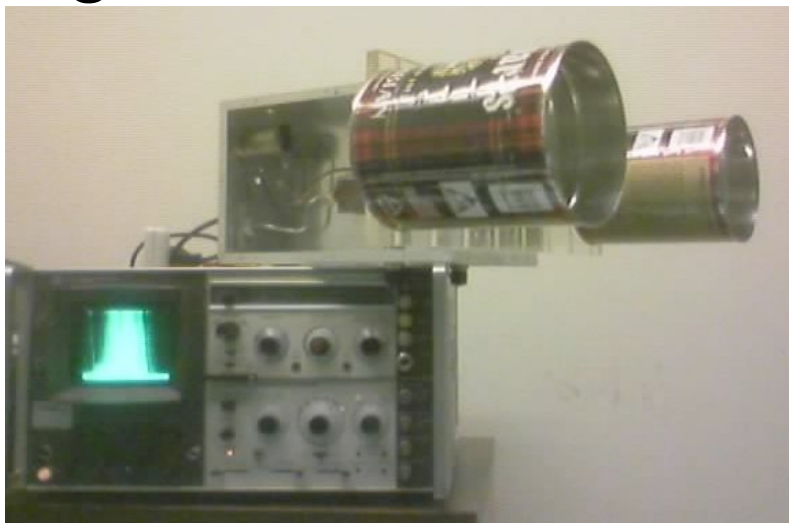
A Low-Cost Approach to FMCW Radar: Through-Wall Microwatt Radar



Michigan State University:
Michael A. Volz (presenting)
Gregory L. Charvat, Leo C. Kempel, Edward J. Rothwell

Motivation

- Sophomore-year Summer Research Internship
- Ten weeks allotted project time
- High-resolution imagery at close distances with FMCW radar has been shown to be achievable for a modest investment[4]
- This L-band radar system was intended for use with the SAR rail and associated data acquisition equipment used by G. Charvat for his thesis work.

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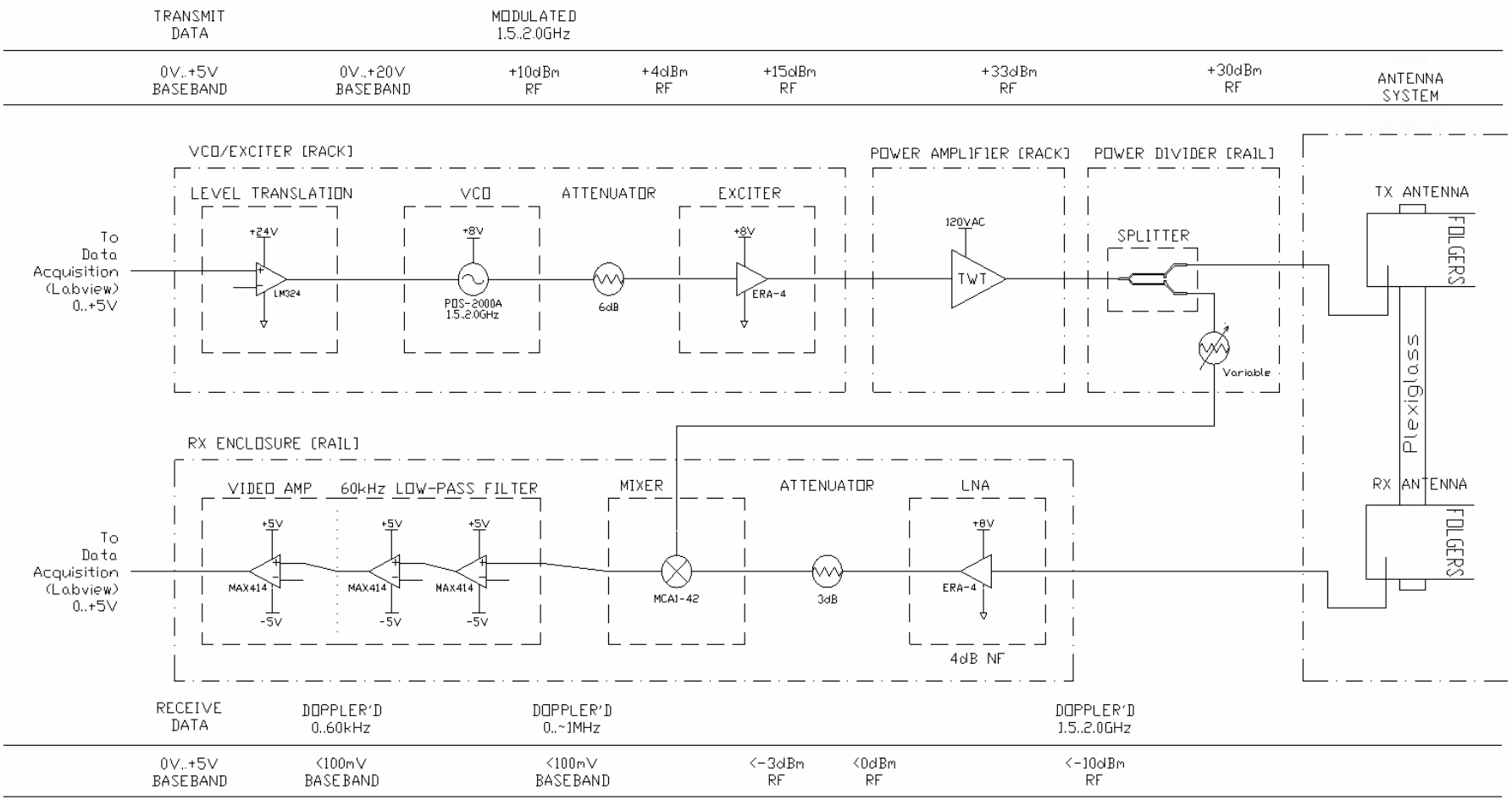
Discussion

- Digitizer and hardware construction issues will be discussed
- A brief synopsis of FMCW radar relevance and utility for high-resolution imaging will be presented
  (hint: simpler hardware, much lower digitizer sampling rates)
- This project led the author to work for the Naval Research Laboratory this summer in phased array angular accuracy analysis, as well as contributing to a senior-level EM lab course.

Radar Block Diagram



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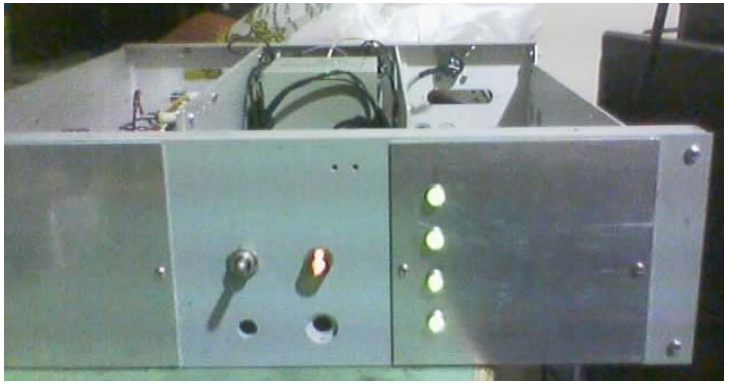
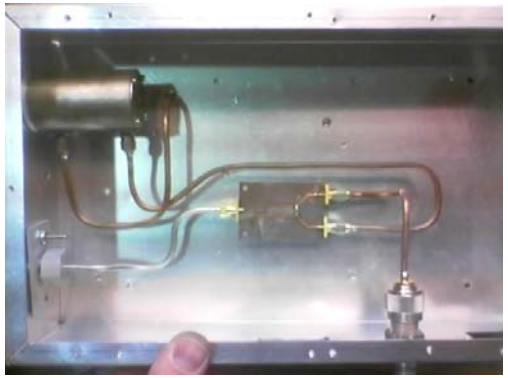
Radar Hardware



Rack unit: LEDs show power supply status

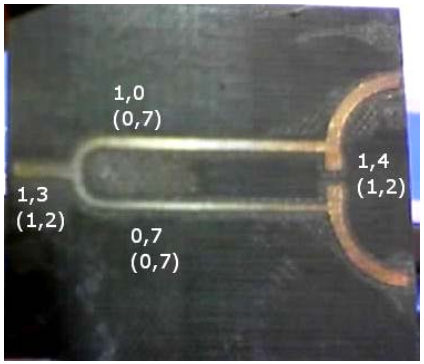
Rack unit: TX modules and power supply

Front-end unit: RX modules



Front-end unit: power divider

Radar Hardware



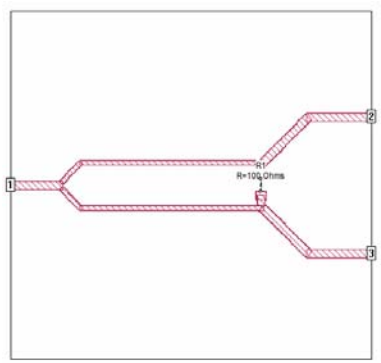
Machining issues:

- Designed dimensions[11]: in parentheses
  actual dimensions: top
- Had to design non-curved traces

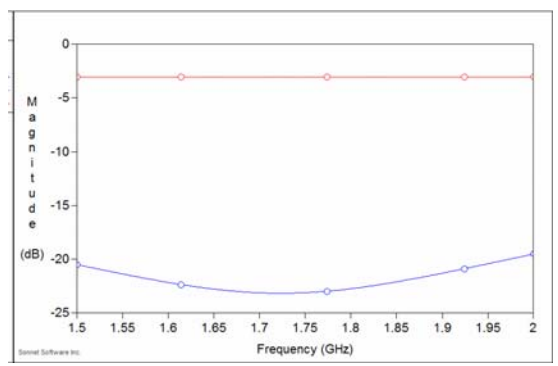
$$\varepsilon_{r,eff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2} \times \frac{\ln\left(\frac{\pi}{2}\right) + \left(\frac{1}{\varepsilon_r} \times \ln\left(\frac{4}{\pi}\right)\right)}{\ln\left(\frac{8h}{w}\right)} \right) \quad \text{(following [6])}$$

along with :

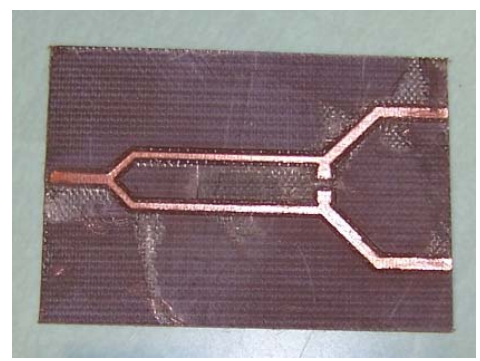
$$Z_0 = \frac{377}{2\pi\sqrt{\frac{\varepsilon_r + 1}{2}}} \times \left(\ln\left(\frac{8h}{w}\right) + \frac{1}{8}\left(\frac{w}{2h}\right)^2 - \frac{1}{2} \times \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(\ln\left(\frac{\pi}{2}\right) + \frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right)\right)\right)$$



Sonnet geometry



S11(blue), S12 & S13(red)

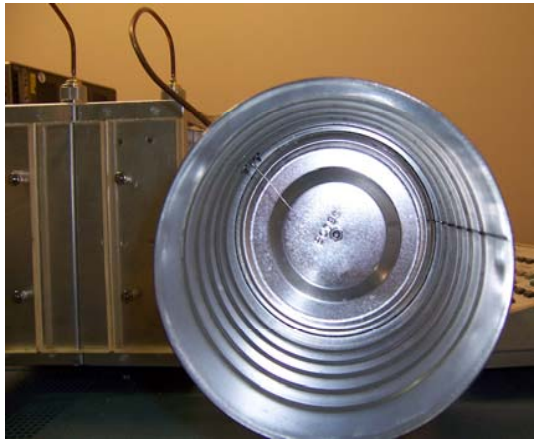


Actual construction

Antennas

- Open-ended circular waveguide are an experimental option for low-cost antennas where performance is not critical
- The thin cylindrical probe limited 2:1 VSWR bandwidth to approximately 300MHz

- Southworth's[13] data suggests maximum gain of 7dBi at 1.75GHz for 0.127m diameter open-ended waveguide
- Southworth presents measured data from which we reason this antenna's 3dB beamwidth may be less than 50 degrees



Antenna in final configuration

Antennas

•The zeros[1] of the relevant Bessel functions[13] determine cutoff frequencies for modes supported by a given waveguide diameter. Multiple families of modes exist[13], with cutoff frequencies:

$$\mathrm{TE}_{mn} : \text{where } J'_m(r_n) = 0 \qquad \mathrm{TM}_{mn} : \text{where } J_m(r_n) = 0$$

$$\frac{2\pi a}{\lambda} \geq r_n \Leftrightarrow f_{cutoff} = \frac{r_n c}{2\pi a}$$

The relevant cutoff frequencies for a = radius = 0.0635m are shown on the right:

$\mathrm{TE}_{11}: \; J'_1(r_n) = 0 \text{ for } r_n = 1.84118,$ $f_{cutoff,\mathrm{TE}_{11}} = \frac{1.84118c}{2\pi \times 0.0635} = 1.38\mathrm{GHz}$
$\mathrm{TM}_{01}: \; J_0(r_n) = 0 \text{ for } r_n = 2.40482,$ $f_{cutoff,\mathrm{TM}_{01}} = \frac{2.40482c}{2\pi \times 0.0635} = 1.81\mathrm{GHz}$
$\mathrm{TE}_{21}: \; J'_2(r_n) = 0 \text{ for } r_n = 3.05424,$ $f_{cutoff,\mathrm{TE}_{21}} = \frac{3.05424c}{2\pi \times 0.0635} = 2.30\mathrm{GHz}$

Antennas

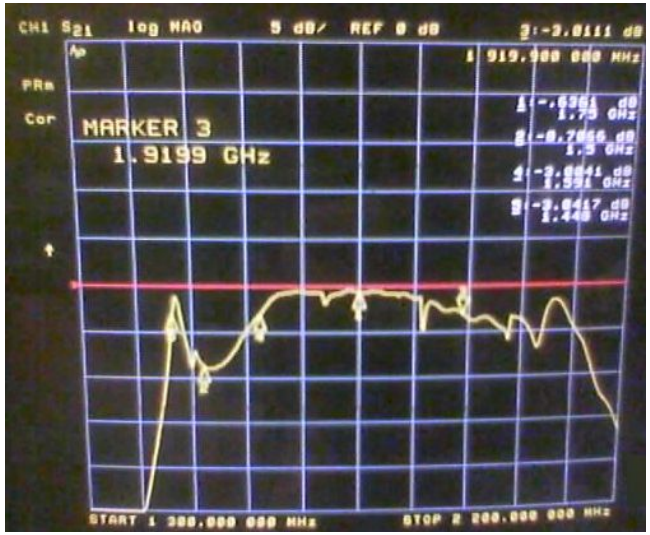
Measured VSWR of open-ended waveguide antenna

Thin cylindrical probe

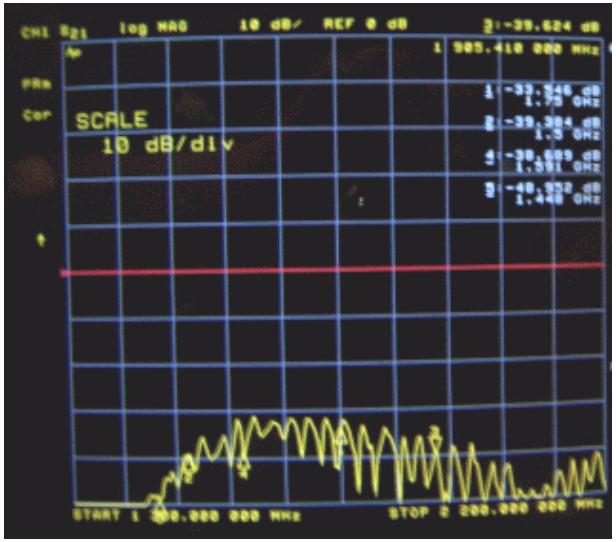
The antennas were deemed adequate for initial experimentation

Antennas

- The S12 was tested as an informal check to show that energy was being coupled, by holding the cans face-to-face
- Another S12 test measured the isolation of the antennas when mounted on the Plexiglas



Coupling: antennas held face-to-face



Coupling: antennas on Plexiglas

Corner Reflectors

17dBsm corner reflector

0dBsm and 7.8dBsm

Corner reflectors were constructed to test the radar

Square corner reflector [2]:

$$\sigma_{\max} = 10 \times \log_{10}\left(\frac{12\pi a^4}{\lambda^2}\right) \text{ [dBsm]}$$

0.45m per side:

$$\sigma_{\max} = 17\text{dBsm}$$

0.17m per side:

$$\sigma_{\max} = 0\text{dBsm}$$

0.26m per side:

$$\sigma_{\max} = 7.8\text{dBsm}$$

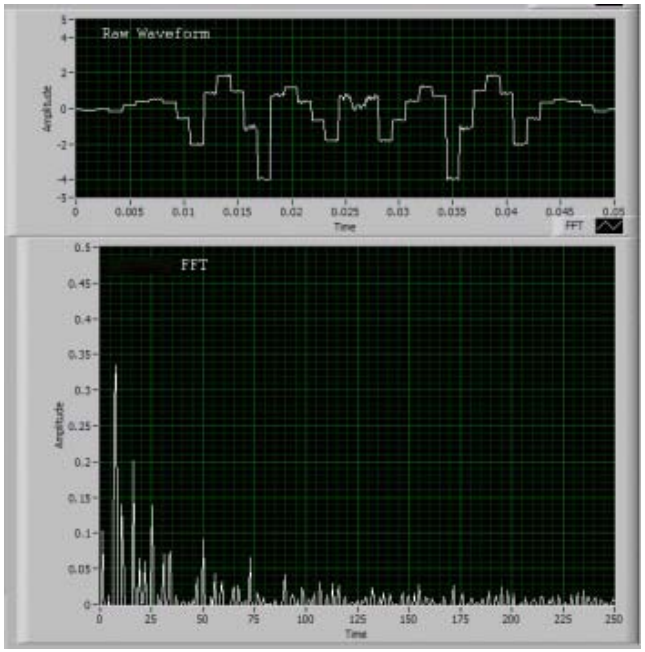
Digitizer

- The author relocated to Washington, DC for work at the Naval Research Laboratory Radar Division: AEGIS Coordinator

- A fourth-order Sallen-Key Butterworth[9] low-pass filter with f_c=60kHz was designed for use with a DAQCard-6024E digitizer (200ks/s)

- The 6024E has caused difficulties
  - –Insufficient output sampling rate
  - –Insufficient data processing capability

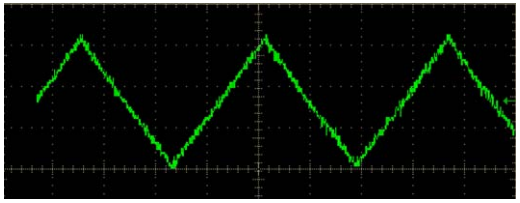
6024E 100Hz triangle wave output



Video amp output and FFT with 6024E

Digitizer

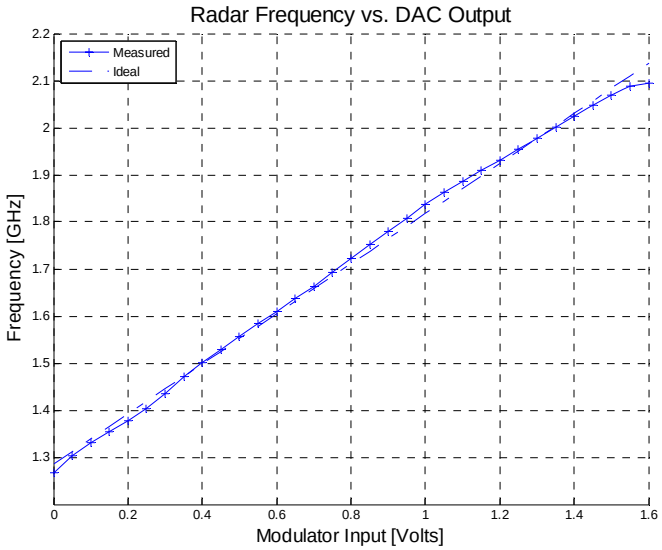
Digitization with NRL equipment

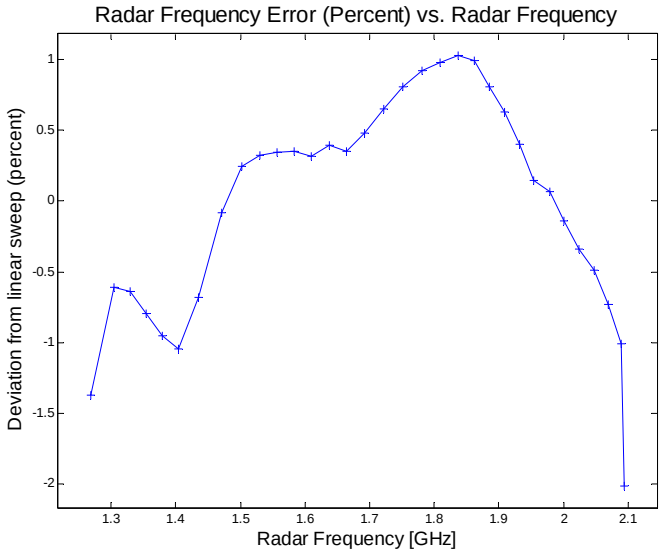


700Hz output to modulator

Function Generator: 12 bit DAC

Digitizer: 8 bit, 250ks/s





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Radar Sensitivity

The power at the receive antenna terminals from a scatterer in free space may be expressed as [2] [3]:

$$S_R = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \text{ [Watts]}$$ where the terms are as commonly defined.

We recognize $S_R \propto \frac{1}{R^4}$ as a significant relationship.

Of course, coupling and other noise sources also contribute.

Here, for a 0dBsm scatterer at 5m and 10m with 500μW TX power and 7dB antenna gain:

$$S_R = \frac{5\text{E-}4 \times 10^{\frac{7}{10}} \times 10^{\frac{7}{10}} \times \left(\frac{300}{1800}\right)^2 \times 1}{(4\pi)^3 \times 5^4} = -65.5\text{dBm}$$

$$S_R = \frac{5\text{E-}4 \times 10^{\frac{7}{10}} \times 10^{\frac{7}{10}} \times \left(\frac{300}{1800}\right)^2 \times 1}{(4\pi)^3 \times 10^4} = -77.6\text{dBm}$$

FMCW Radar Fundamentals

It may be observed[8] that:

$$R = \frac{ct_R}{2}; \quad t_R = \frac{f_R t_m}{W} = \frac{f_R}{\dot{f}_r} \longrightarrow R = \frac{c}{2} t_R = \frac{c}{2} \frac{f_R}{\dot{f}_r}$$

where: t_m = up or down ramp time of W

W = radar transmitter's swept frequency bandwidth

f_R = range frequency of scatterer

t_R = roundtrip time of radar energy

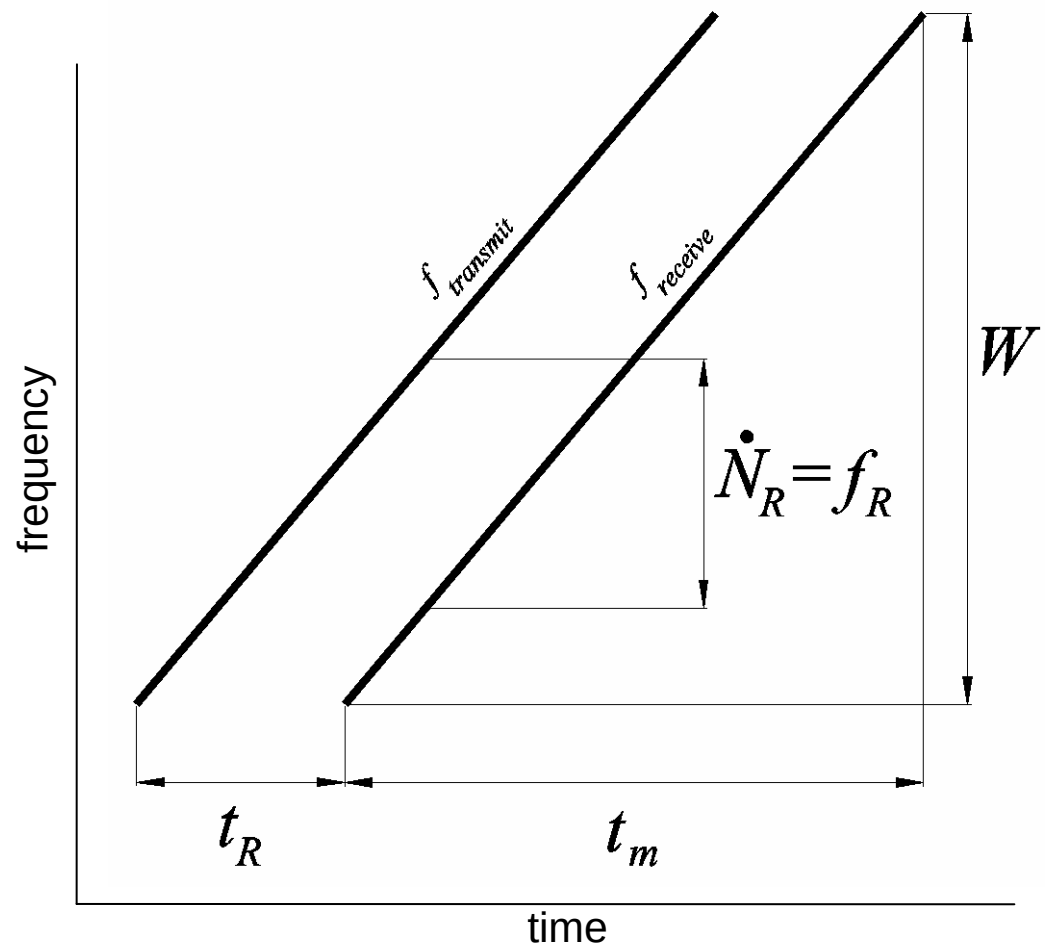
R = physical range to scatterer

$\dot{f}_r = \frac{df_r}{dt} = Wf_m = \frac{W}{t_m}$, the frequency sweep rate of the radar

Note: for FMCW radar, we derive t_R in a different manner than pulse radar, but apply t_R similarly.

FMCW Radar Fundamentals

FMCW f_R are due to:



FMCW Ranging

$$\textbf{FMCW Range}: R = \frac{c f_R}{2\dot{f}_r}, \quad f_R = \dot{f}_r t_R = \frac{dN_R}{dt} = \dot{N}_R$$

The f_R term is the result of the change with time in N standing waves[8] between radar and scatterer caused by the frequency change of the radar transmitter along with the roundtrip time delay.

$\dot{N}_R$ presents an ensemble of *range frequencies* f_R at the homodyne receiver's mixer output due to the scatterers' ranges.

Coupling from the transmitter to receiver will appear with largest amplitude as the lowest range frequencies observed.

Finally, $N_0 = \dfrac{2R}{\lambda_0}$ gives the number of standing waves[8].

FMCW Ranging

$$\textbf{FMCW Range}: R = \frac{c f_R}{2\dot{f}_r}, \quad f_R = \dot{f}_r t_R = \frac{dN_R}{dt} = \dot{N}_R$$

We determine range with FMCW through the range frequencies.

It is generally understood that FMCW radar has less hardware demands than a pulse radar of similar range resolution.

However, difficulties[12] ensue with high power monostatic FMCW radar.

Thus, FMCW radar is useful for short-range imaging systems, but pulsed radar may be more useful for long-range use.

(due to $S_R \propto \frac{P_t}{R^4}$)

FMCW Ranging

Scatterers with spacing ΔR will have range frequency difference:

$$\Delta f_R = \frac{2\Delta R \dot{f}_r}{c}$$

Example: a Hamming filter was used with frequency bin size 650Hz and $\frac{1}{1400}$ seconds up or down slope time. The difference in range frequencies between two scatterers with 0.5 meter spacing for the given parameters is shown to be:

$$\Delta f_R = \frac{2 \times 0.5 \times 4.2\text{E}11}{c} = 1400\text{Hz, a difference we can detect.}$$

Note: the minimum scatterer spacing is limited as described on the following page.

$$(\dot{f}_r = W f_m = 300\text{E}6 \times 1400 = 4.2\text{E}11\ [\text{s}^{-2}])$$

FMCW Ranging

Range resolution is determined in part by the minimum resolvable frequency difference:

$$\delta R = \frac{c\delta(\Delta N)}{2W}, \text{ where } \delta(\Delta N) = \text{unity, for a typical case[8]}$$

(N is the number of standing waves between radar and scatterer).

Here, we use 300MHz bandwidth, yielding:

$$\delta R = \frac{c \times 1}{2 \times 300\text{E}6} = 0.5\text{m}$$

0.5m is shown to be a lower bound for resolvable range difference with the given bandwidth.

FMCW Ranging

Maximum range frequency is another limit, since the radar's digitizer does not properly process range frequencies above this limit.

$$R_{\max,filter} = \frac{c f_{R,\max}}{2\dot{f}_r}$$

Here, maximum range frequency is assumed to be about 60kHz, based on the four-pole Sallen-Key Butterworth filter currently used.

$$R_{\max,filter} = \frac{c \times 60000}{2 \times 4.2\mathrm{E}11} = 21.4\mathrm{m}$$

This concern may be addressed by use of a higher-bitrate digitizer.

FMCW Ranging

We may note the following:

$$R \propto f_R, \qquad \text{so:} \qquad R_{\max} \propto f_{R,\max}$$

$$\boxed{\delta R \propto \frac{1}{W}} \qquad f_R \propto \frac{W}{t_m} = \dot{f}_r$$

- Increasing sweep time t_m decreases $f_{R,i}$, approaching the digitizer's frequency bin size (while increasing maximum range within $R_{\max,\, filter}$)
- Increasing radar bandwidth W increases f_R, approaching the low-pass video filter cutoff (useful for higher resolution within $f_{R,\max}$)

Thus, for a given digitizer and video filter bandwidth, we find tension between maximum range and range resolution

FMCW Ranging

$$\delta R \propto \frac{1}{W}$$

This relationship between range resolution and radar bandwidth reveals the utility of the FMCW method. High resolution is achievable at lower digitizer sampling rates with FMCW vs. pulsed radar.

$$R_i = \frac{ct_{R,i}}{2}$$

The range to a scatterer is related to the radar energy's round trip time[12].

For a simple pulse radar, the following relationships exist[3]:

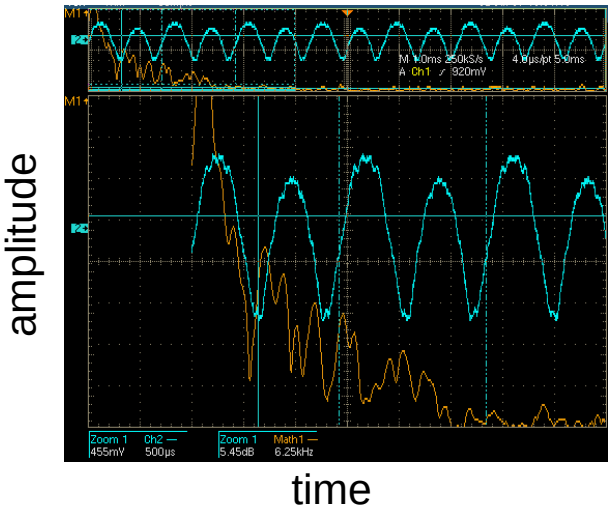
$$\Delta R \propto \Delta t_R,\ \delta R \propto \tau_r, W_\tau \propto \frac{1}{\tau_r}, \delta R \propto \frac{1}{W_\tau}, \text{where } \tau_r \text{ is radar pulse duration}$$

This implies that if a simple rectangular pulse is used, a much higher sampling rate (small τ_r is desired) will be needed for a given range resolution for pulse vs. FMCW

Digitizer

•Digitization and measurements were made using NRL equipment

Direct feed-through TX to RX

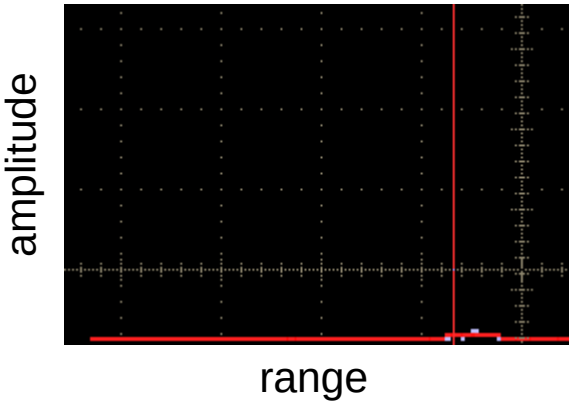


While improved processing is in work, an improvised method is used to detect scatterers in the high clutter environment:

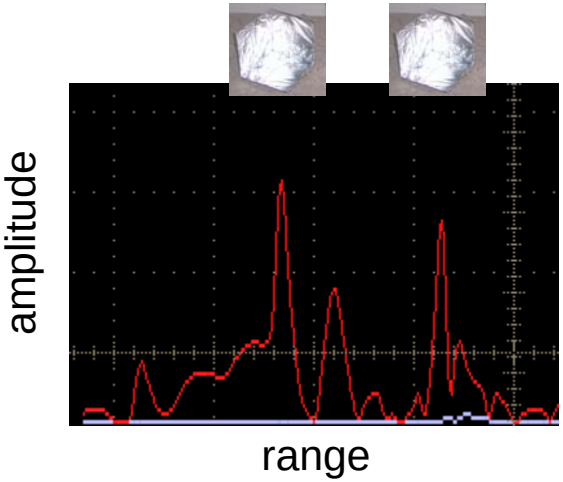
1. Capture background with no scatterers and store as reference
2. Create another trace as: $\mathrm{abs}(\mathrm{FFT}_{\mathrm{BackgroundRef}} - \mathrm{FFT}_{\mathrm{Realtime}})$
3. This allows a basic test of radar functionality

Digitizer

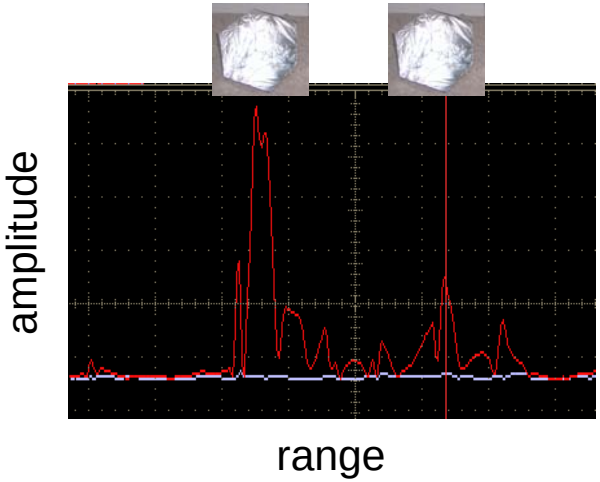
•Digitization and measurements were made using NRL equipment



Through-wall: -2.5dBm (560 microwatts)
No scatterers
6dB per division



Through-wall: -2.5dBm (560 microwatts)
0dBsm scatterers at 0.56m and 1.8m
6dB per division



NOT through-wall: 4.2dBm (3 milliwatts)
0dBsm scatterers at 2m and 4m
5dB per division

Through-wall detection of 0dBsm scatterers at microwatt power output levels is easily achieved.

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Future Extensions

- With sponsorship of a suitable digitizer, further hardware/software development would be worthwhile

- Hardware improvements
  - Shielded modules to reduce internal coupling

- Imaging algorithms

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Conclusion

- A useful L-band FMCW radar can be built at modest cost with off-the-shelf parts
  - An adequate digitizer is a must

- The understanding of radar systems and microstrip circuit design obtained through this project led to further work including:
  - Harmonic radar system hardware
  - Multi-band planar antenna miniaturization
  - Phased array angle accuracy analysis (NRL)

Special thanks to R. Duncan and G. Linde of the Naval Research Laboratory for their insights

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