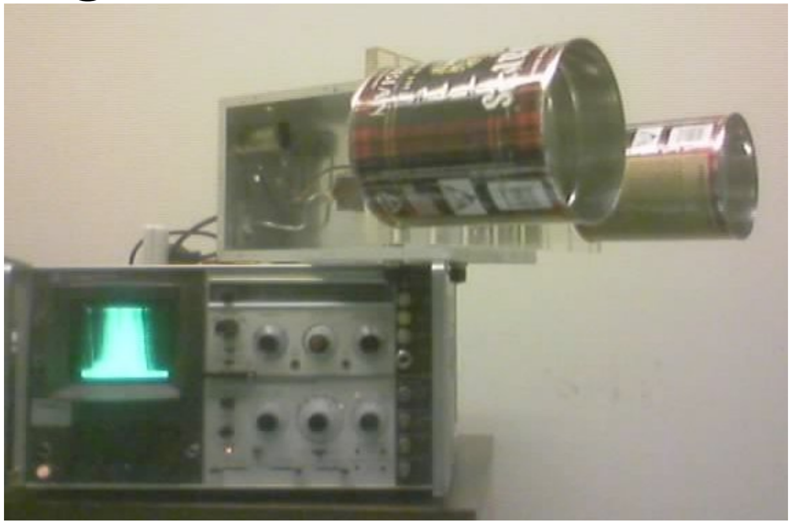
A Low-Cost Approach to FMCW Radar: Through-Wall Microwatt Radar



Michigan State University:
Michael Hirsch (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 (simpler hardware, soundcard-like ADC sampling rates)

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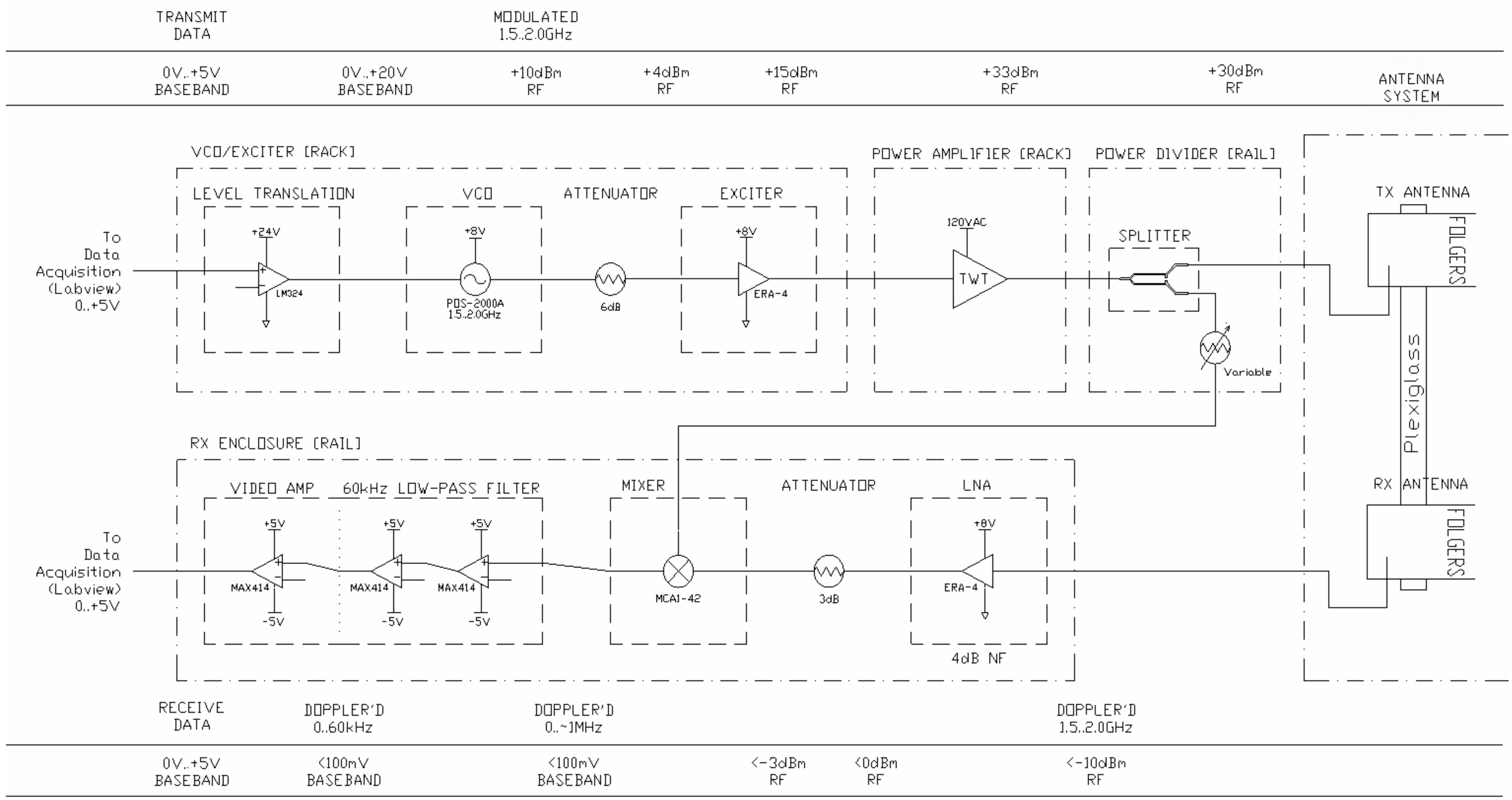
Radar Block Diagram

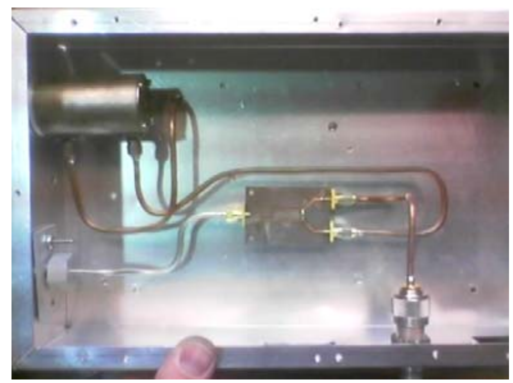


Radar Hardware

Rack unit: LEDs show power supply status

Rack unit: TX modules and power supply

Front-end unit: RX modules



Front-end unit: power divider

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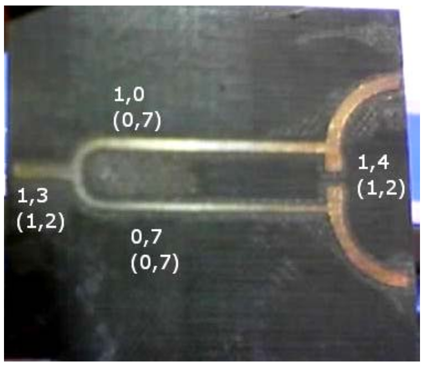
Radar Hardware



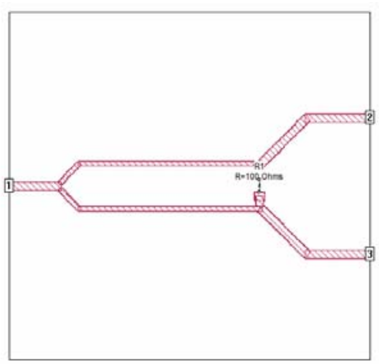
Machining issues:

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

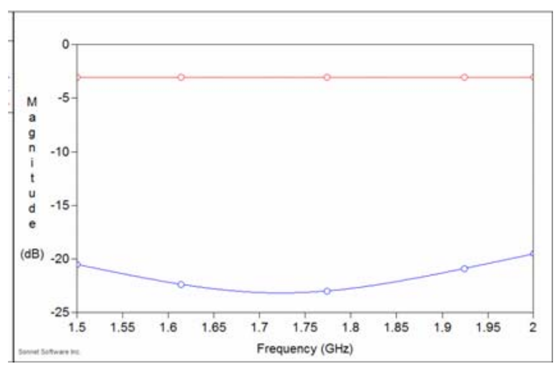
$$\varepsilon_{r,eff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2} \times \frac{\ln\left(\frac{\pi}{2}\right) + \left(\frac{1}{\varepsilon_r} \times \ln\left(\frac{4}{\pi}\right)\right)}{\ln\left(\frac{8h}{w}\right)} \right) \quad \text{(following [6])}$$

along with :

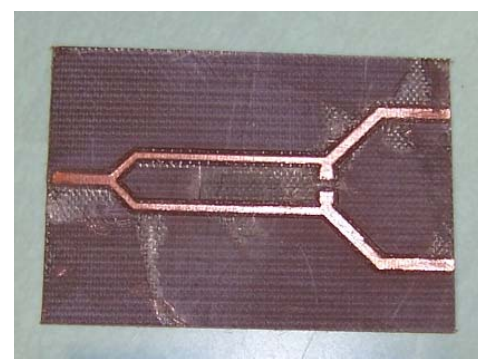
$$Z_0 = \frac{377}{2\pi\sqrt{\frac{\varepsilon_r + 1}{2}}} \times \left(\ln\left(\frac{8h}{w}\right) + \frac{1}{8}\left(\frac{w}{2h}\right)^2 - \frac{1}{2} \times \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(\ln\left(\frac{\pi}{2}\right) + \frac{1}{\varepsilon_r}\ln\left(\frac{4}{\pi}\right) \right)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



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:

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

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Antennas

Measured VSWR of open-ended waveguide antenna

Thin cylindrical probe

The antennas were deemed adequate for initial experimentation

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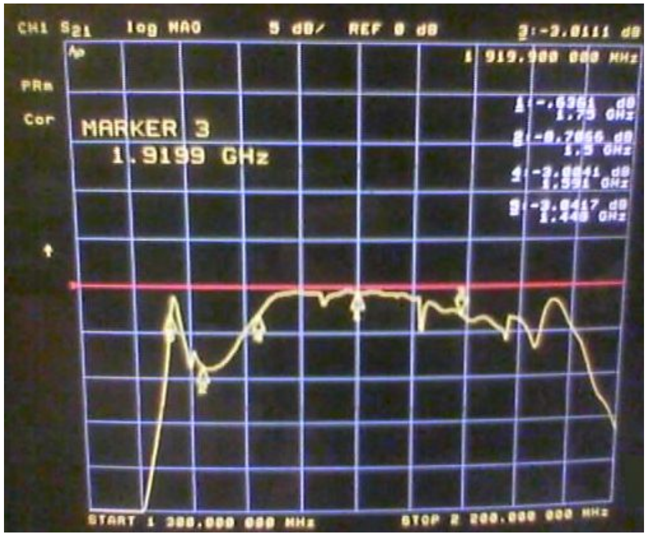
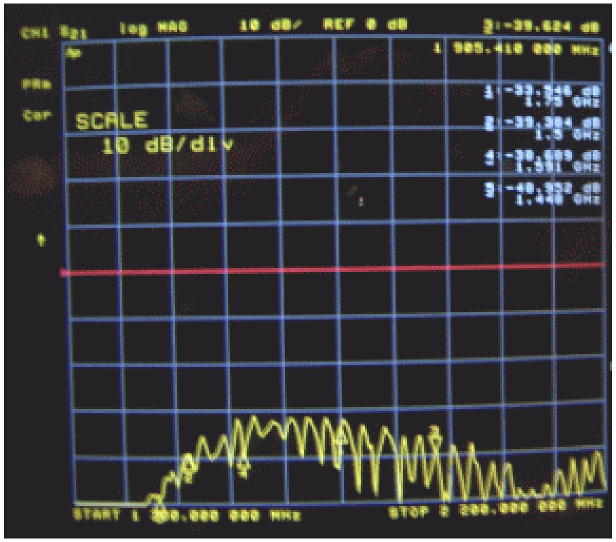
Antennas

- 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

Corner reflectors were constructed to test the radar

17dBsm corner reflector

0.45m per side:

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

0dBsm and 7.8dBsm

0.17m per side:

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

0.26m per side:

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

Square corner reflector [2]:

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

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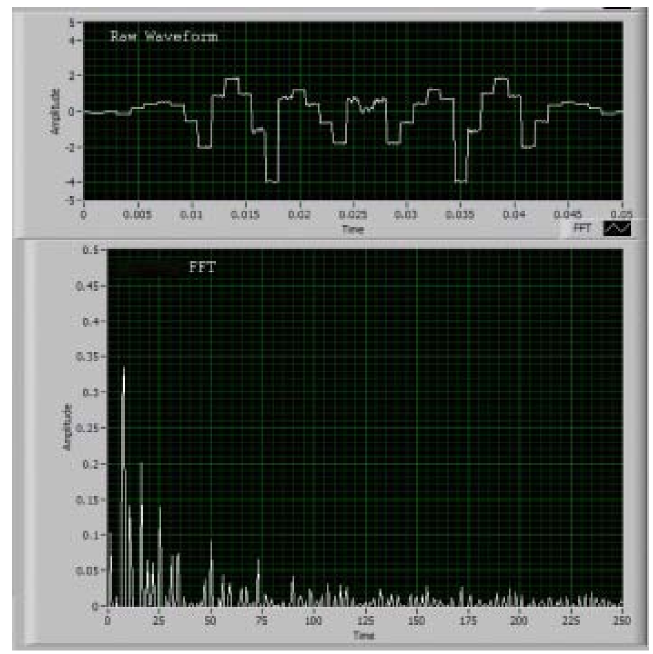
Digitizer

6024E 100Hz triangle wave output

- 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



Video amp output and FFT with 6024E

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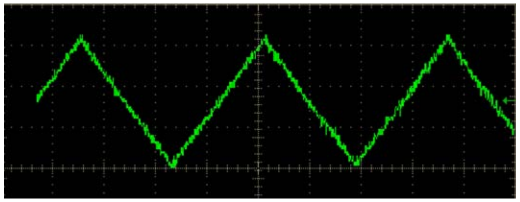
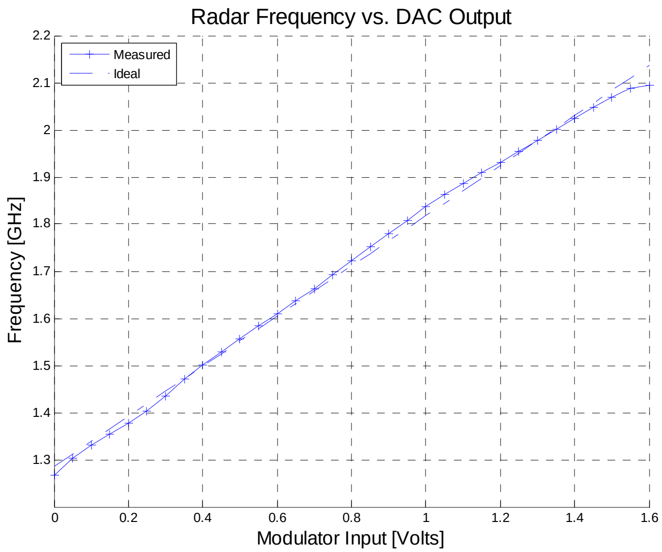
Digitizer

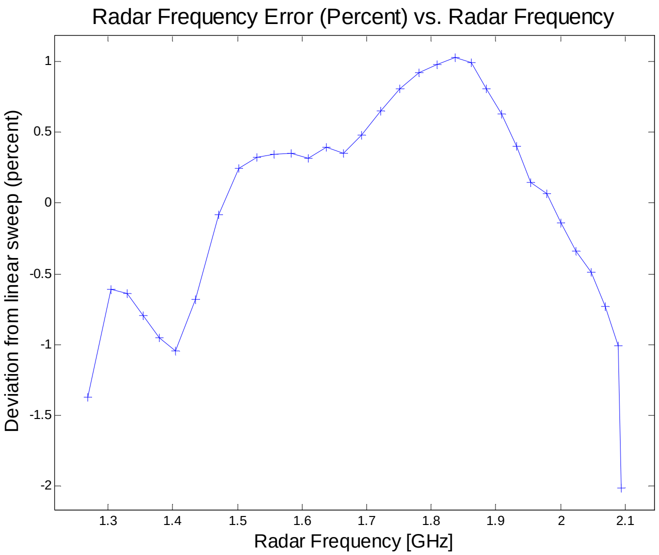


700Hz output to modulator

Function Generator: 12 bit DAC

Digitizer: 8 bit, 250ks/s





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:

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

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

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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 = beat frequency of scatterer

t_R = roundtrip time of radar energy

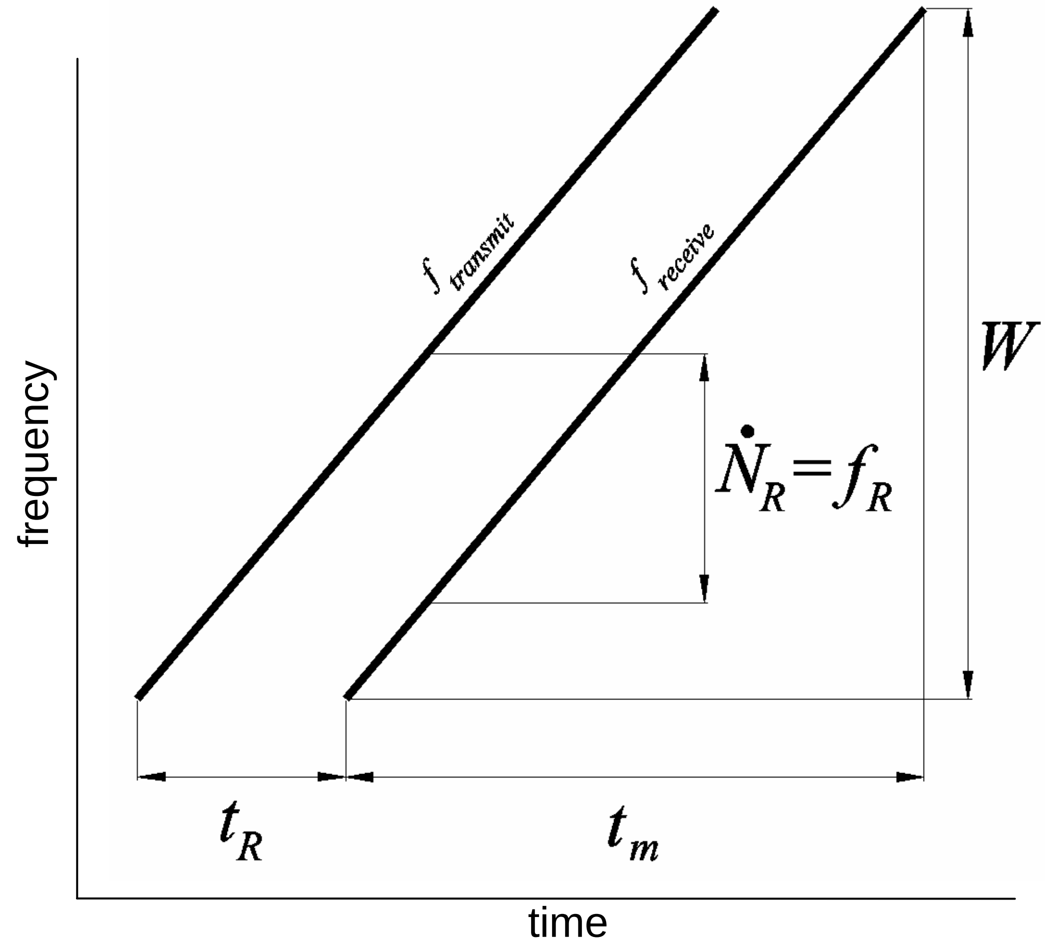
R = physical range to scatterer

$\dot{f}_r = \frac{df_r}{dt} = Wf_m = \frac{W}{t_m}$, 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:



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FMCW Ranging

FMCW Range$: R = \dfrac{cf_R}{2\dot{f}_r},\ f_R = \dot{f}_r t_R = \dfrac{dN_R}{dt} = \dot{N}_R$

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 *beat 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].

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FMCW Ranging

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

We determine range with FMCW through the range frequencies.

It is generally understood that FMCW radar has lower 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 sweep time. The difference in beat 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.

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

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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.

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FMCW Ranging

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

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

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

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

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

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FMCW Ranging

We may note the following:

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

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

- 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

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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 ADC sampling rates with FMCW vs. pulsed radar.

$$R_i = \frac{c t_{R,i}}{2}$$

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]:

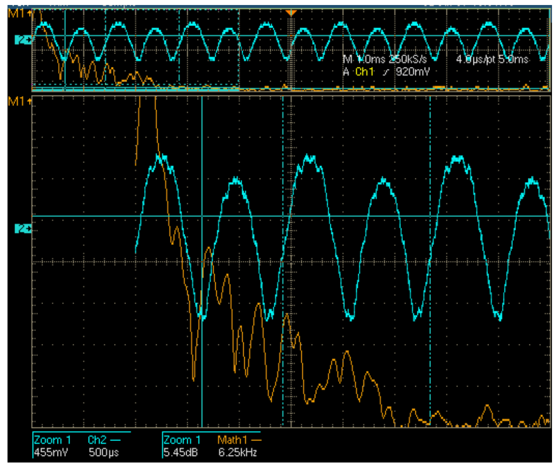
$$\Delta R \propto \Delta t_R,\ \delta R \propto \tau_r, W_\tau \propto \frac{1}{\tau_r}, \delta R \propto \frac{1}{W_\tau}, \text{where } \tau_r \text{ is radar pulse duration}$$

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

Direct feed-through TX to RX

amplitude

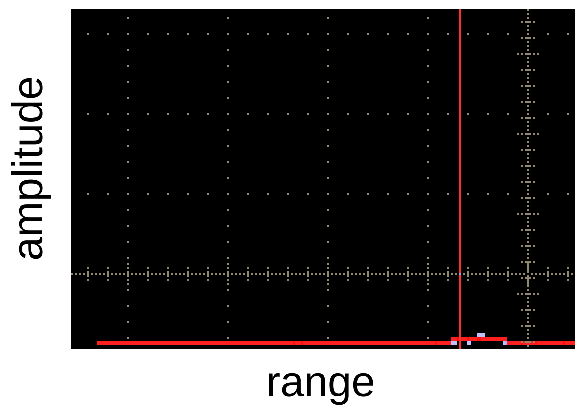


time

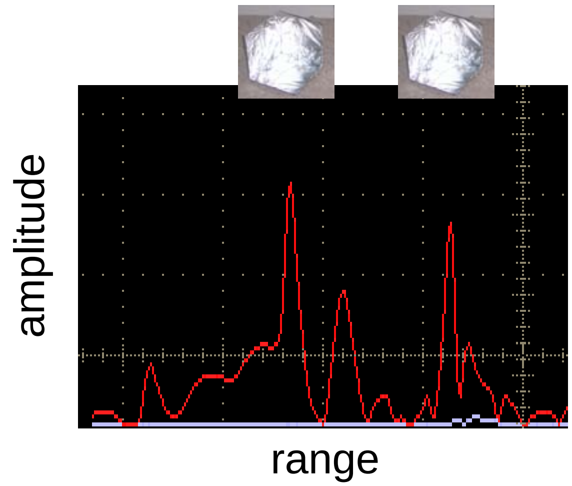
While improved processing is in work, an improvised method is used to detect scatterers in the high clutter environment:

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

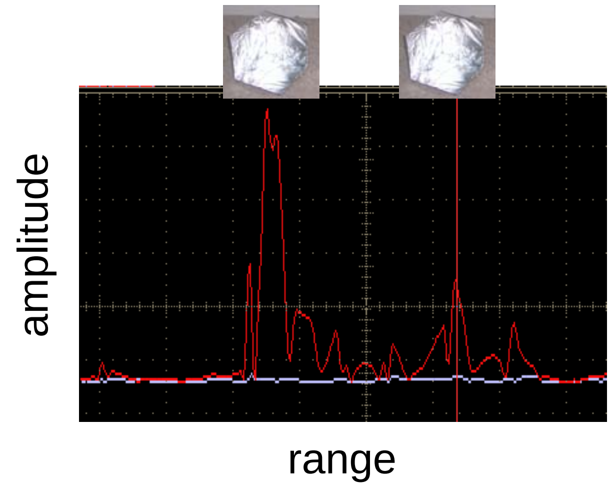
Digitizer



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

Thanks to R. Duncan and G. Linde of the Naval Research Laboratory for discussion

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