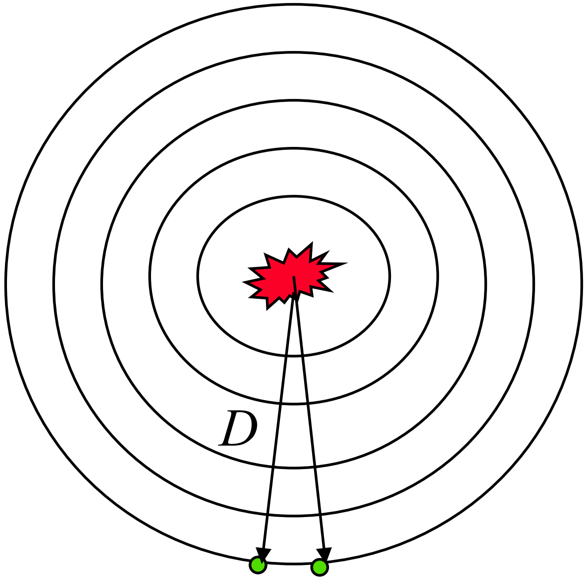
MAS836 – Sensor Technologies for Interactive Environments

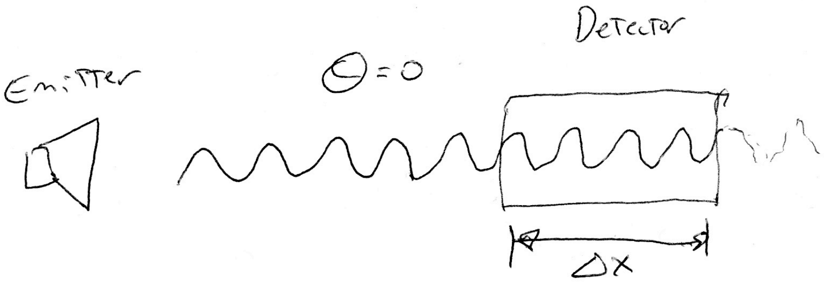
Lecture 12 – Radar and Coherent Sensor Processing

Acoustic (RF) Far Field

- Impinging Wave is a plane wave implies
- D >> λ (sound or RF propagation is radiative)
  - Otherwise…
  - Impinging wave not planar
  - If D<~ λ, antenna "feels" effects of target object
  - RF couples inductively or capacitively (analogous for sound)
  - Near Field!

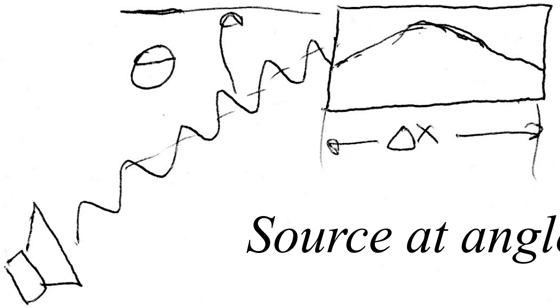


Where Beamwidth Comes From



$$\int_{\Delta X} V_{T_N}\,dx = V(T)\big|_N \Rightarrow 0$$

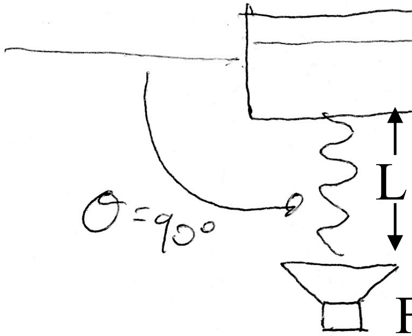
Source on edge



$$\int_{\Delta X} V_{T_N}\,dx = \alpha V(T)_N \Rightarrow \alpha V(T)_N$$

$(\alpha < 1)$

Source at angle



$$\int_{\Delta X} V_{T_N}\,dx = V(T)_N$$

(In far field, waveform at T_N is constant across aperture ΔX)

Source broadside

Far-field (L >> ΔX)

Beamwidth as Fourier Transform

$$V(T) = G\int_{X=-\infty}^{X=+\infty} A(X)\cdot \sin(\omega T + KX)\, dX$$

Gain

Aperture Shading Function (Shape)

"Wavenumber"

"

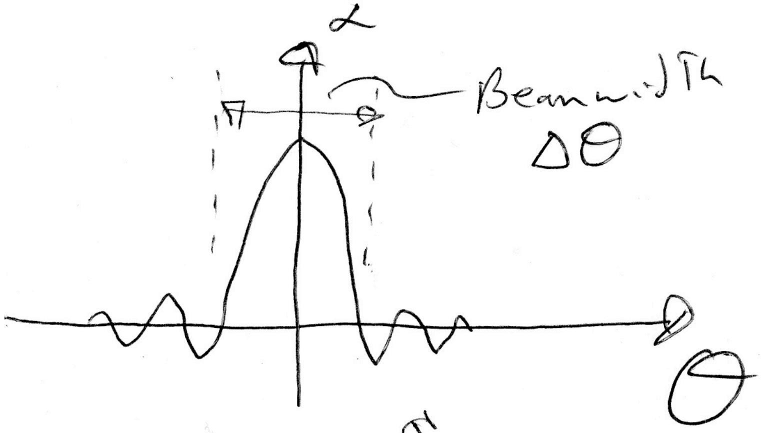
$\cos(\Theta)\, 2\pi/\lambda$

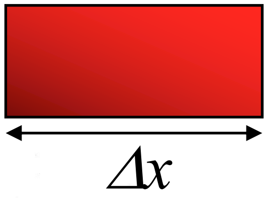
$$V(T) = G e^{i\omega T}\int_{\Delta X} A(x)\, e^{i\frac{2\pi\cos\theta}{\lambda}x}\, dx$$

$$|V(x)| \Longleftrightarrow |V(\cos\theta)|$$

Fourier Xform

Beamwidth of Rectangular Aperture





∝ Sinc Function $\left(\frac{\sin(x)}{x}\right)$

For Rectangular Aperture

$$\Delta\theta 3_{\mathrm{dB}} = 50^\circ \, \lambda/\Delta x$$

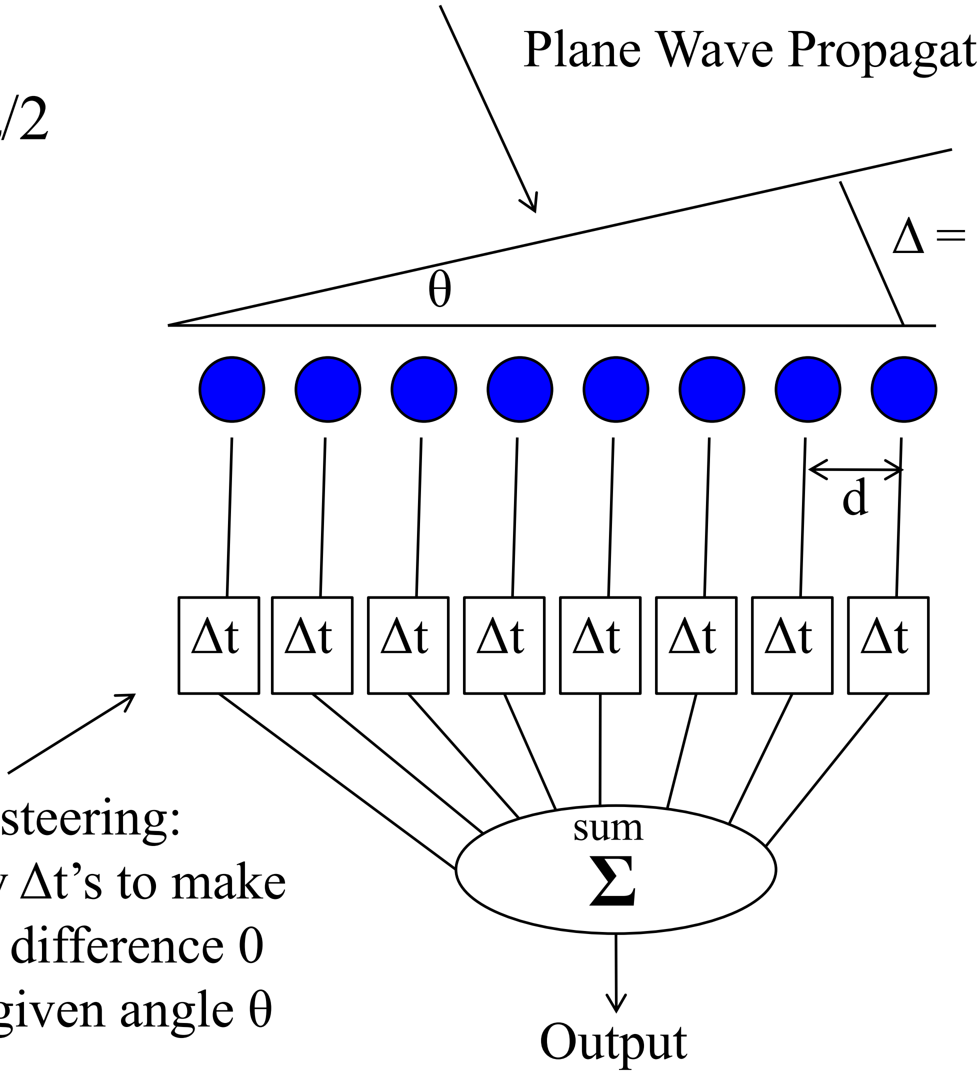
$$\lambda \ll \Delta x$$

Beamwidth and aperture width are conjugate variables!

Beamformers

$d \leq \lambda/2$

Plane Wave Propagation (speed = c)



Transducers (1 to n)

Waveform at element 0:

$\Psi = \sin(\omega t)$

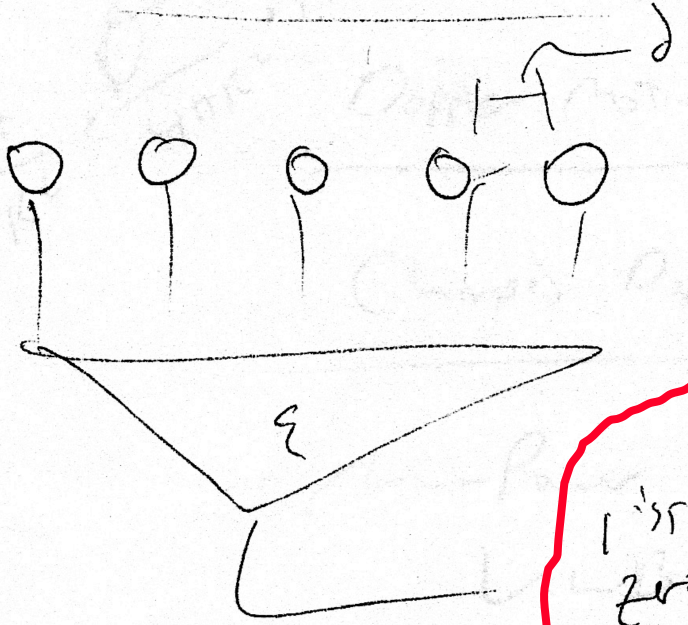
Waveform at element n:

$\Psi = \sin(\omega t + nd \bullet \sin(\theta)/c)$

Beamsteering:
Apply Δt's to make
phase difference 0
for a given angle θ

Works for Xmit and Receive – sonar and radar (any wave propagation)

Beamformers (spatial sampling)



$d \leq \lambda/2$

$\varphi_B = \sin^{-1}\left(\frac{\lambda}{N d}\right)$

1st zero crossing

→ Grating lobes (λ-spacing

Shading for side lobes '' + lobes)

(Hamming, Gaussian, Taylor weighting)

Beam Steering Xmit + Receive

→ work both ways

The Radar Equation

Antenna Gain

Power density @ R

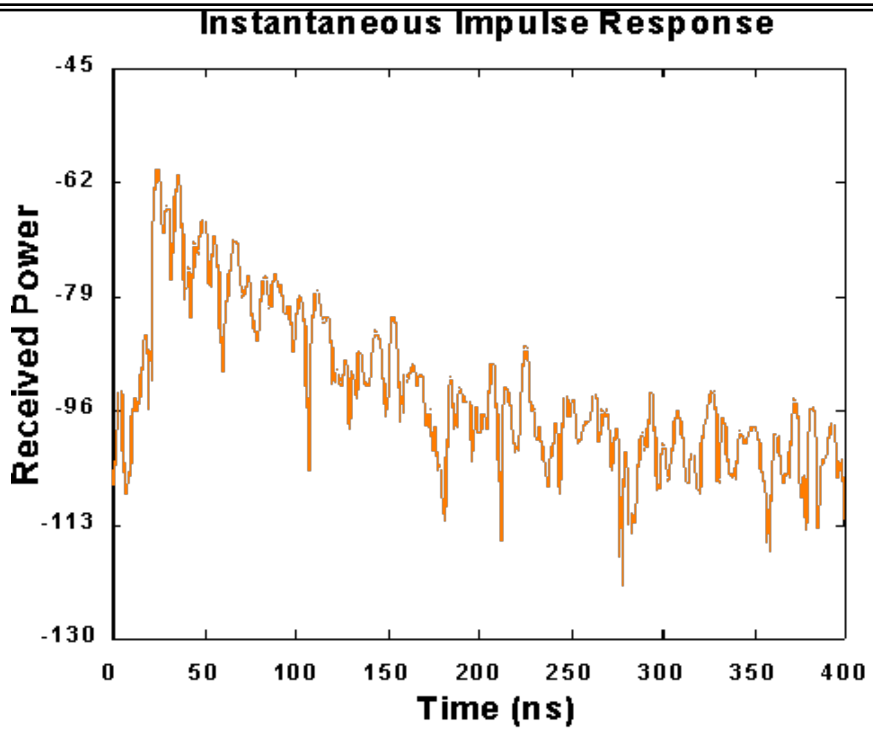
Target cross-section

Receiver efficiency

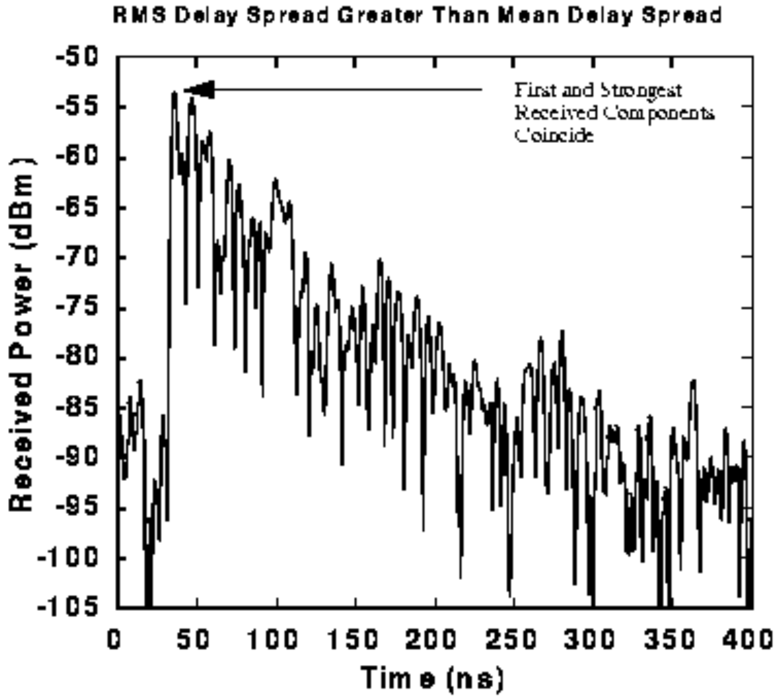
$$P_r = \frac{P_T G_T}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} \cdot A_e$$

This is just from spherical divergence – signal can go down as higher power of R, especially indoors (e.g., because of multipath, the indoors attenuation per factor above averages between R^{-3} and R^{-4}).

Wireless Signal Strength Indoors



Instantaneous Impulse Response



RMS Delay Spread Greater Than Mean Delay Spread

http://www.wirelesscommunication.nl/reference/chaptr03/2_4ghz.htm

http://www.slideshare.net/lbruno236/on-line-training-of-the-pathloss-model-in-bayesian

Etc..

Range from Received Amplitude

See our class on indoor location: *http://resenv.media.mit.edu/classarchive/S61.2011/*

- Many applications use this (RSSI), but it can vary widely with conditions, people, transmitter/receiver angles, etc.

- If you constrain the system to use state (e.g., where you were before), employ constraints (e.g., you can only go down this corridor from here, and it only goes right, etc.), and use other pieces of information (e.g., multiple RF sources), it can work better (Microsoft RADAR project).

- It's still not great – you want to use timing (UWB or SS)!

10 meters (coarse zoning), 3 meters (fingerprinting), 1 meter (xmit power step)

Yearly IPSN Contest on Indoor Location

Indoor Localization Competition

Co-located with IPSN 2015, April 13-17 2015, Seattle, WA, USA

http://research.microsoft.com/en-us/events/indoorloccompetition2015/

See the latest techniques and how well they work!

Vanderbilt Beat Phase Measurement

Xmit from 2 nodes at the same time for bursts of circa 100 ms

“Beats” in the carrier are low frequency (e.g., kHz)

Phase of beat frequency varies with position

Repeat with different pairs of nodes, and put localization map together

Get a few cm resolution across a football field w. multihop

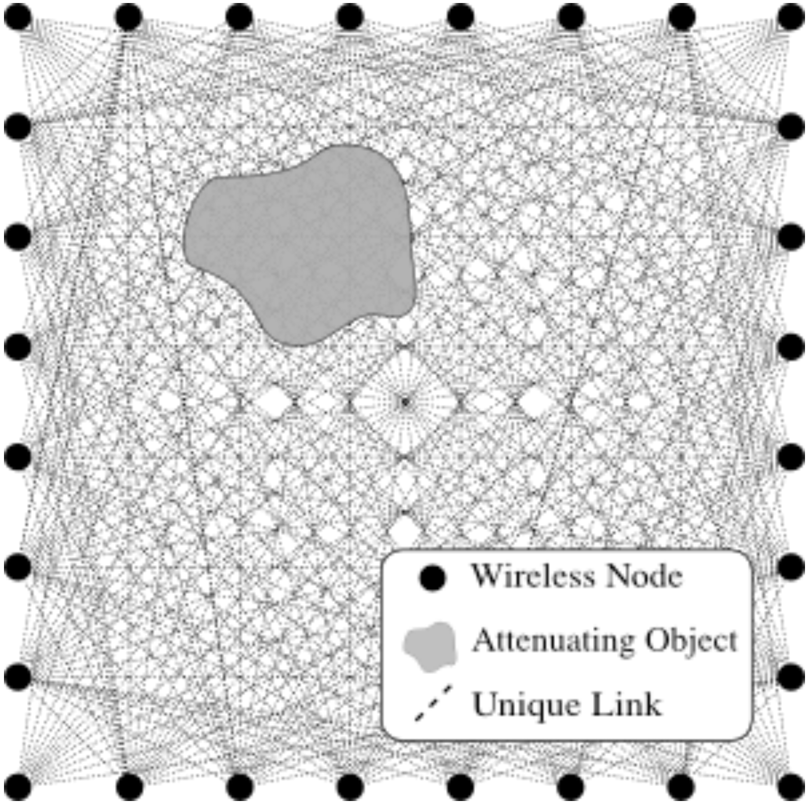
Multipath problems (they claim xmitting at different freqs helps and
Dynamic multipath tends to vary slowly)

http://www.isis.vanderbilt.edu/projects/rips

University of Utah Location from RF obscuration (tomography):

http://span.ece.utah.edu/

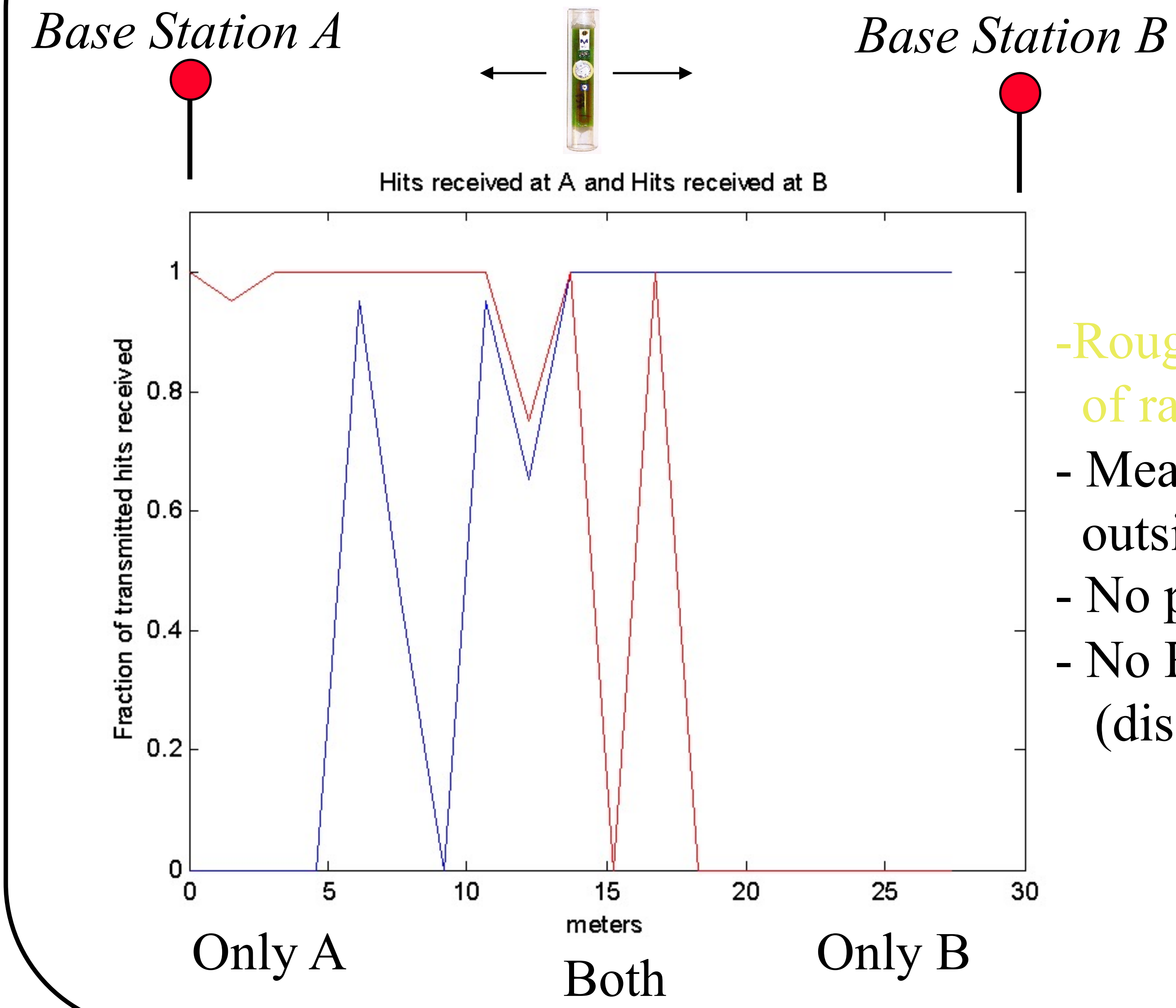
Tomographic RF Imaging at U. Utah



- Wilson & Patwari at U. Utah
- Nadav & Siegel at ML

http://span.ece.utah.edu/radio-tomographic-imaging

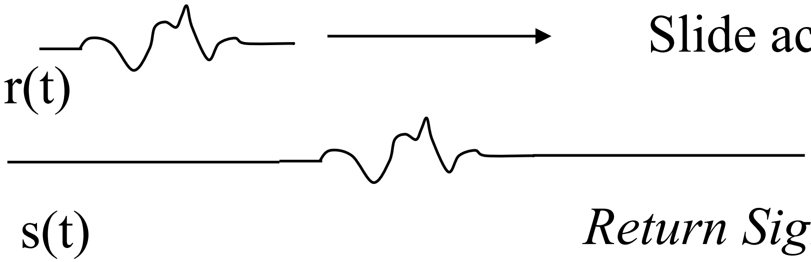
RF Zoning



- -Roughly 15 meters of range
- Measurements taken outside
- No people(!)
- No RSSI (discriminated signal)

Cross Correlation and Matched Filters

Stored “Transmitted” Reference Signal

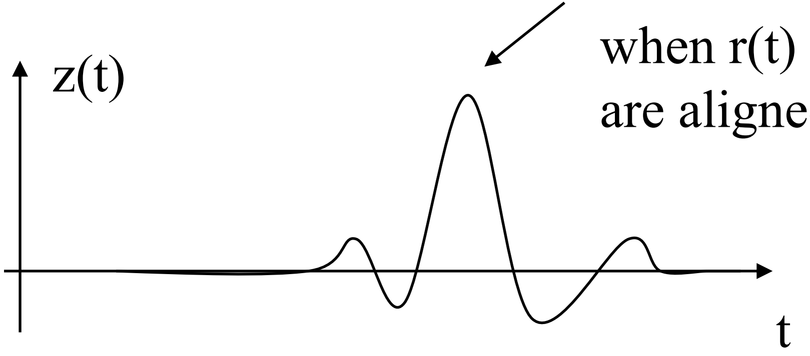


Slide across and integrate

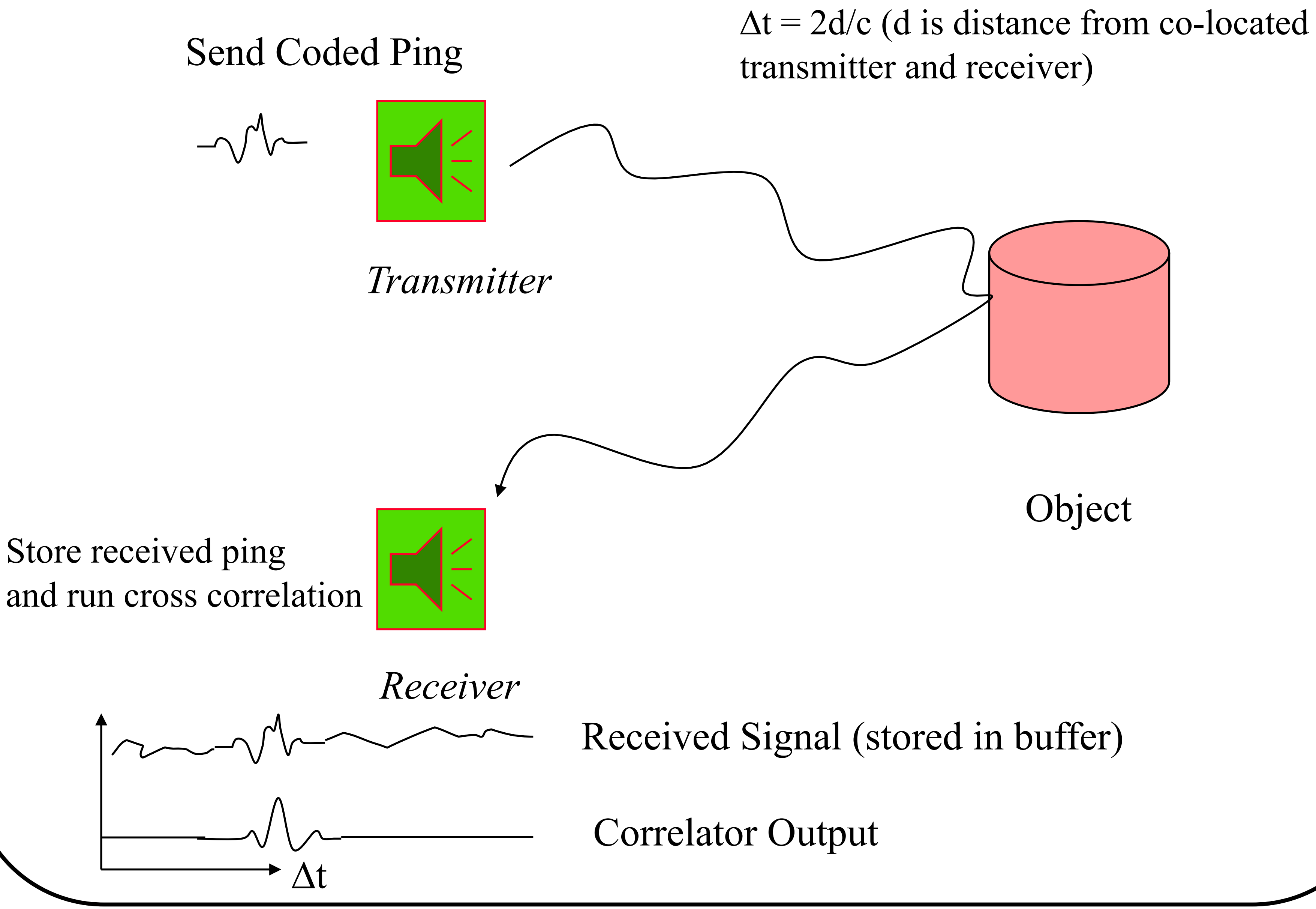
Return Signal

$$z(t) = \int_{-\infty}^{+\infty} s(\delta\text{-}t)\cdot r(\delta)\, d\delta$$

Correlation peaks when r(t) and s(t) are aligned.



Implementation in sonar or radar



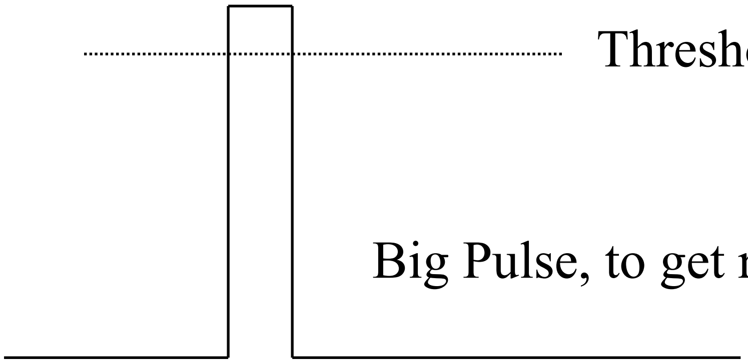
Δt = 2d/c (d is distance from co-located transmitter and receiver)

Received Signal (stored in buffer)

Correlator Output

Pulse Compression

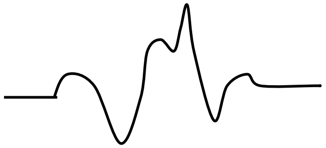
One Pulse



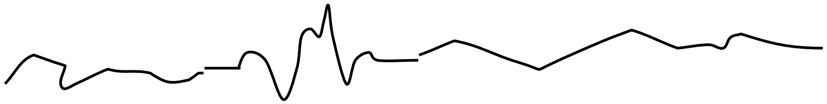
Threshold

Big Pulse, to get rising edge above threshold

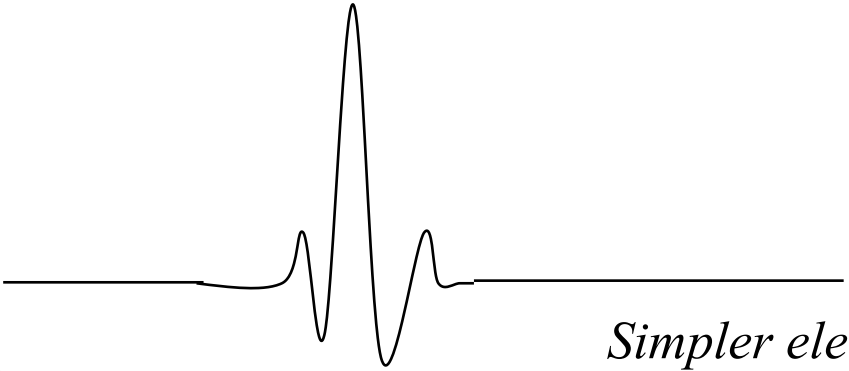
Need massive power, amplifiers…



Pulse spectrally spread out over longer time and wider frequency



Received Signal



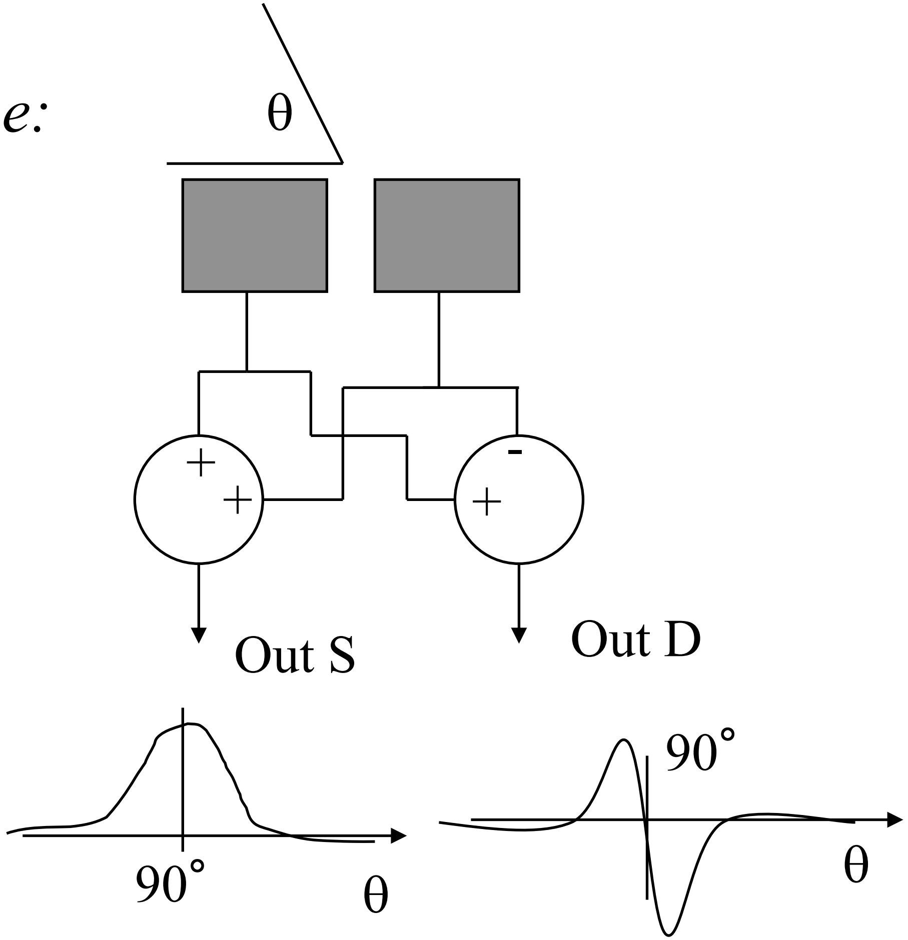
(forms big peak by integrating)

Reconstructed pulse from correlator

Simpler electronics, but need buffer, correlator

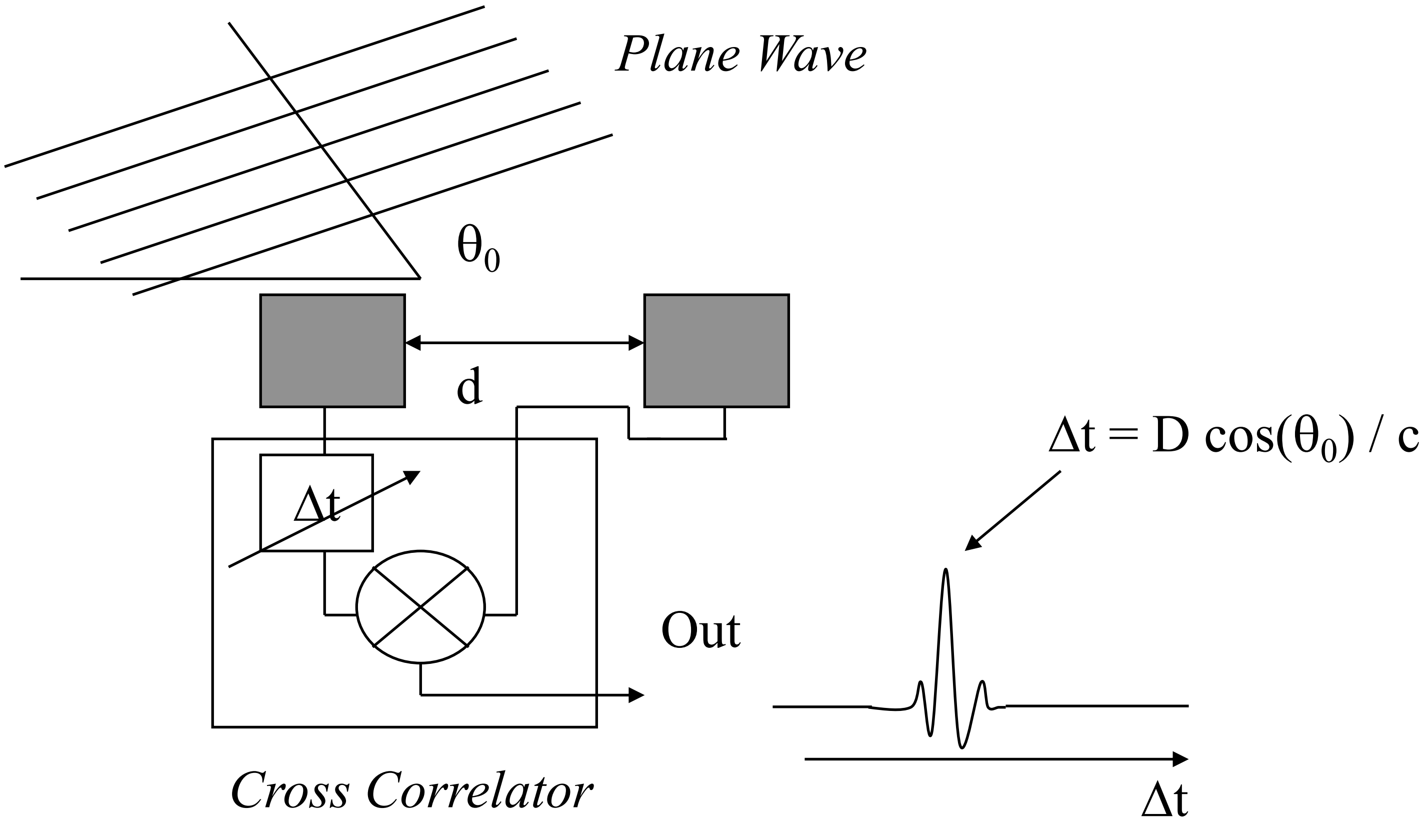
Direction of Arrival - Monopulse

Split-Aperture Monopulse:



D/S is proportional to the direction cosine (within beam)

Time-Difference-of-Arrival (TDOA)



Plane Wave

θ_0

d

Δt

Out

Cross Correlator

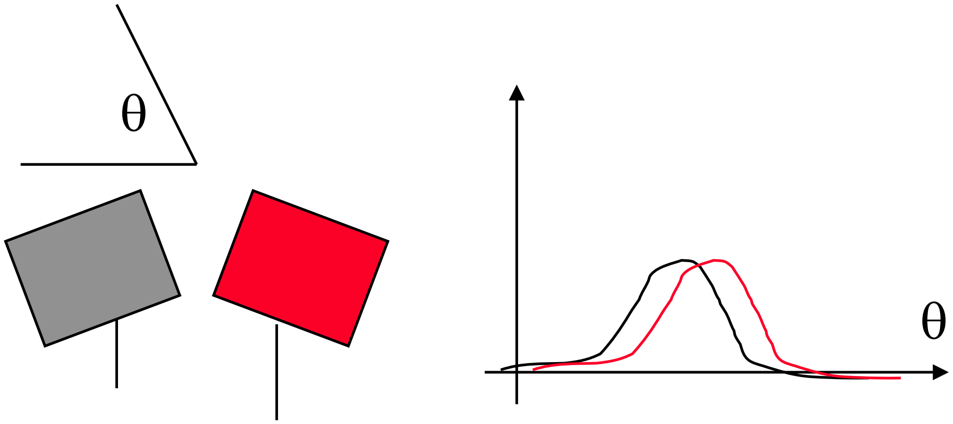
$\Delta t = D \cos(\theta_0) / c$

Δt

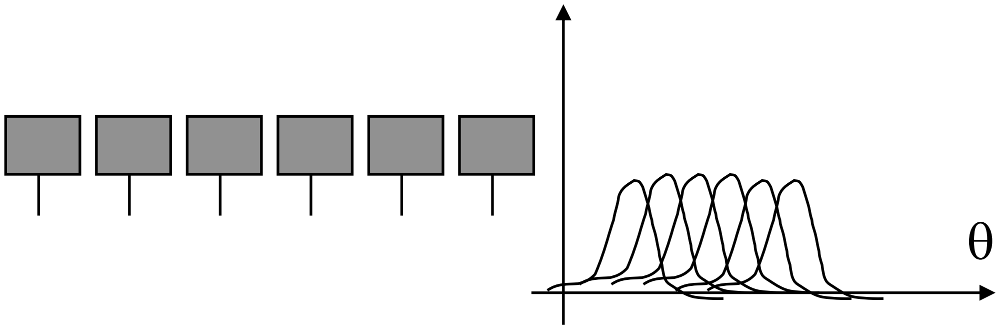
Direction of Arrival – other ways

- Point two transducers in different directions, with some overlap

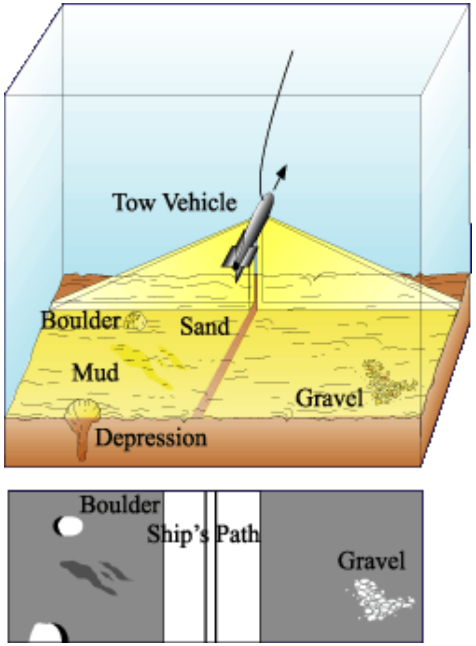
- Take amplitude of signals, and compare

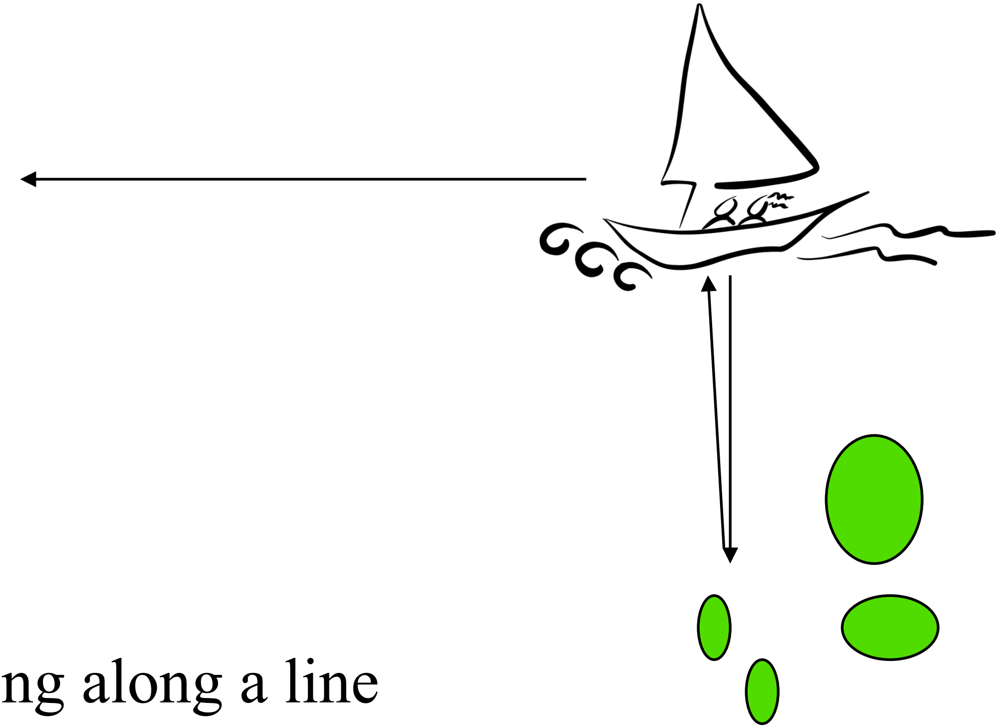


Form multiple beams, and compare amplitudes



Sidescan Sonar





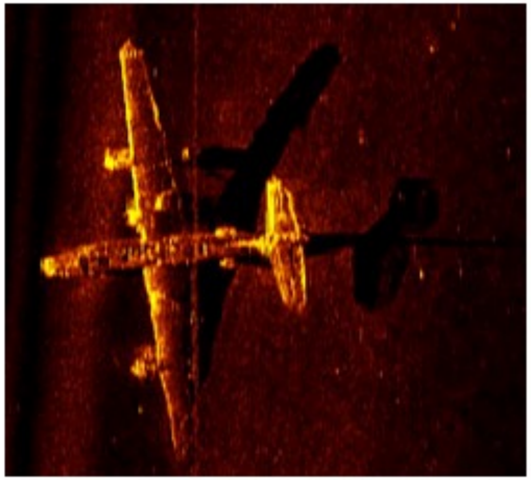
- Send chirp as boat is moving along a line
- Use narrow "fan beam" to illuminate a line on the bottom
- Use correlator so each scatterer produces a point
- Plot on strip chart intensity of return vs. time of return for each ping
- A better sidescan will also measure angle of the return, to sharpen plot (bathymetry)
- Invented in Boston Harbor by Doc Edgerton
- First marketed as "towfish" by EG&G

Draper Lab Sensors Group

- MIT Sea Grant Shed, Boston Harbor, summer 1993
- EG&G towfish with our Backgammon

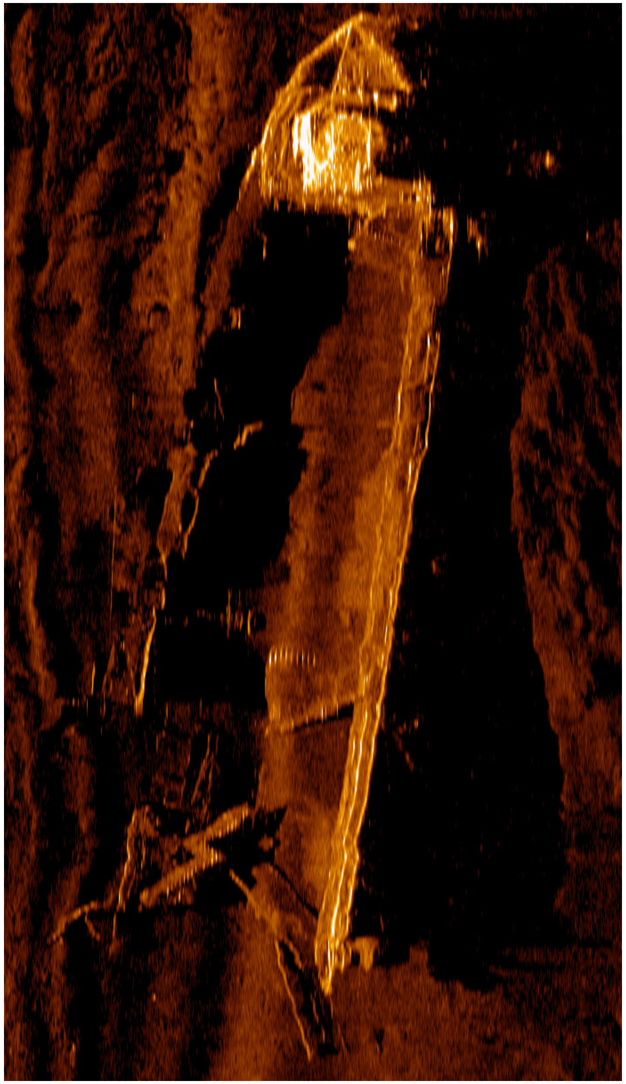
Sidescan Images

Sonar Image of A Navy PB4Y-2 Privateer



Navy PB4Y-2 Privateer. One of 736 built from May 1943 to the end of the war. The aircraft sits in 164 ft. of water in Lake Washington, WA and was imaged with a MSTL 600 kHz towfish. Images and sonar data courtesy of Crayton Fenn of Innerspace Exploration Team.

Note the boat trailer

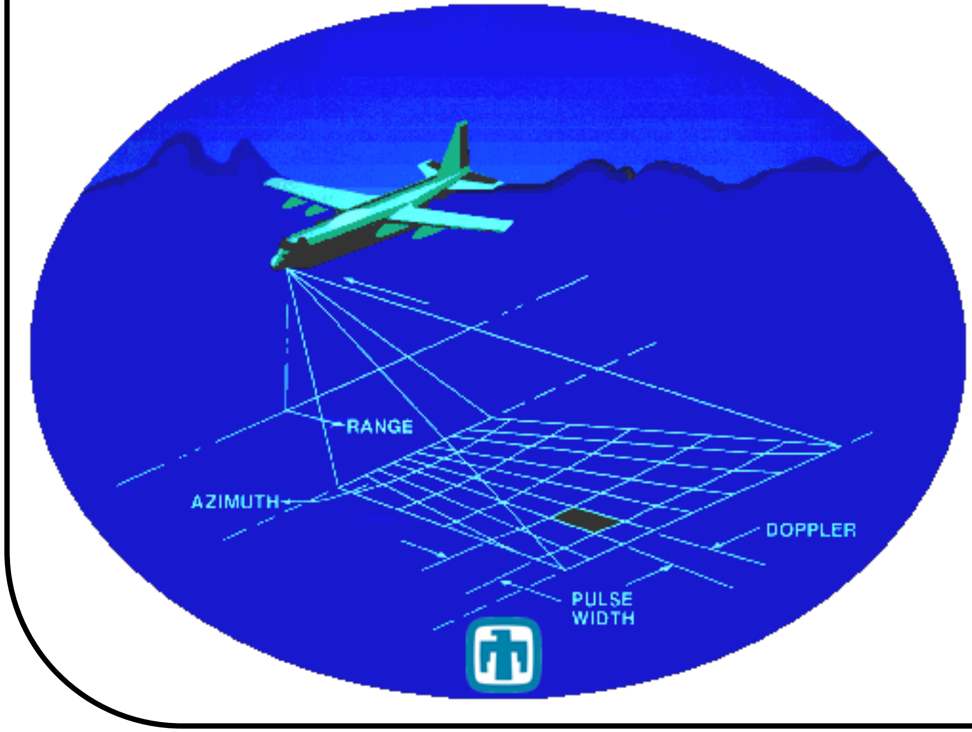


S.S. Edmund Fitzgerald

Other Techniques

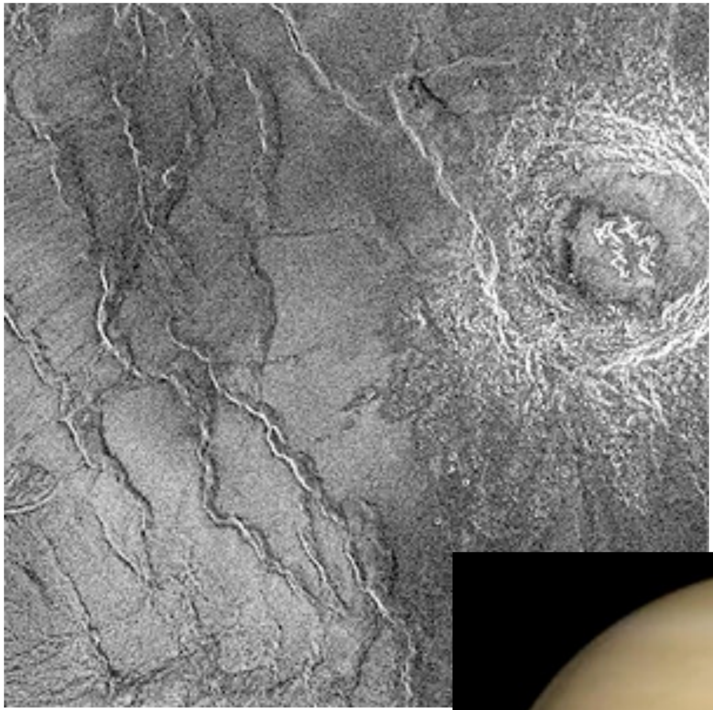
-CVL Sonar (correlators see bottom moving by for velocity)
- Works like Optical Mouse!

-Synthetic Aperture
-Maintain Phase Coherence and measure phase of return as vehicle moves
-Vehicle "traces out" antenna size (λ/D)



-Doppler shift for each return yields azimuth resolution
-Pulse timing yields range resolution
-Coded waveforms and correlation used!
-Problem with sonar (speed of sound too slow – vehicle motion between pings is significant), technique mainly for radar ($d < \lambda/4$)
-Focusing algorithms…

Synthetic Aperture Radar Images

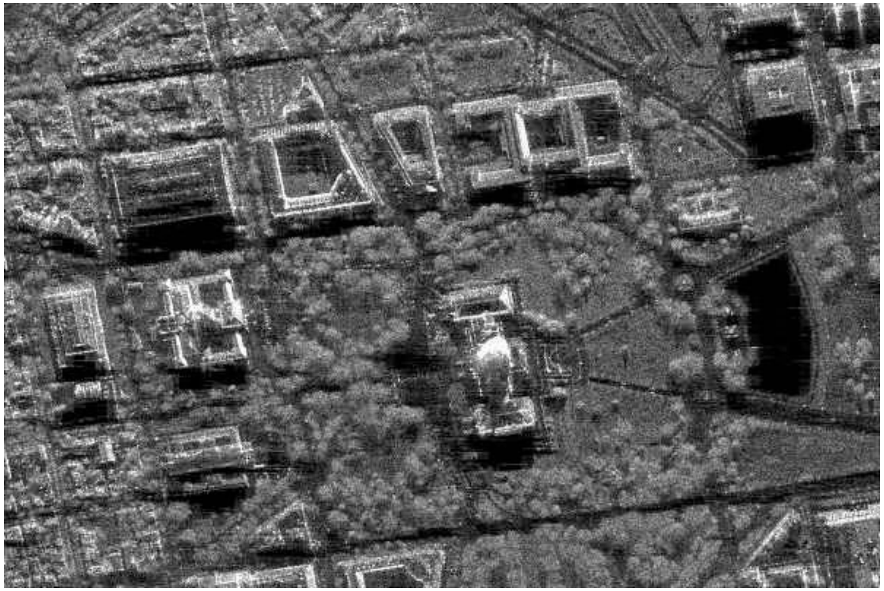


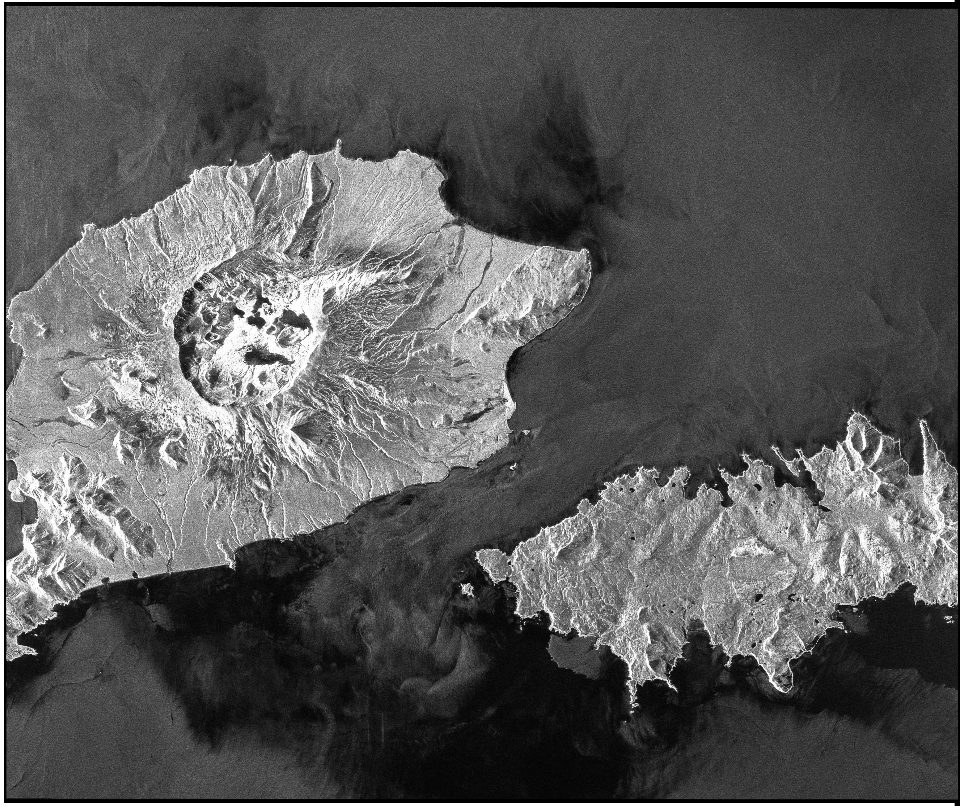
http://nssdc.gsfc.nasa.gov/imgcat

Magellan Spacecraft

SAR sees through the thick cloud layer

Terrestrial SAR Images





High Resolution!

Doppler

$$f_o = \left[\frac{1-(v/c)}{1+(v/c)}\right]^{1/2} f_s$$

When the source recedes from the observer, the observed frequency is

$$f_o = \left[\frac{1+(v/c)}{1-(v/c)}\right]^{1/2} f_s$$

When the source approaches the observer, the observed frequency is

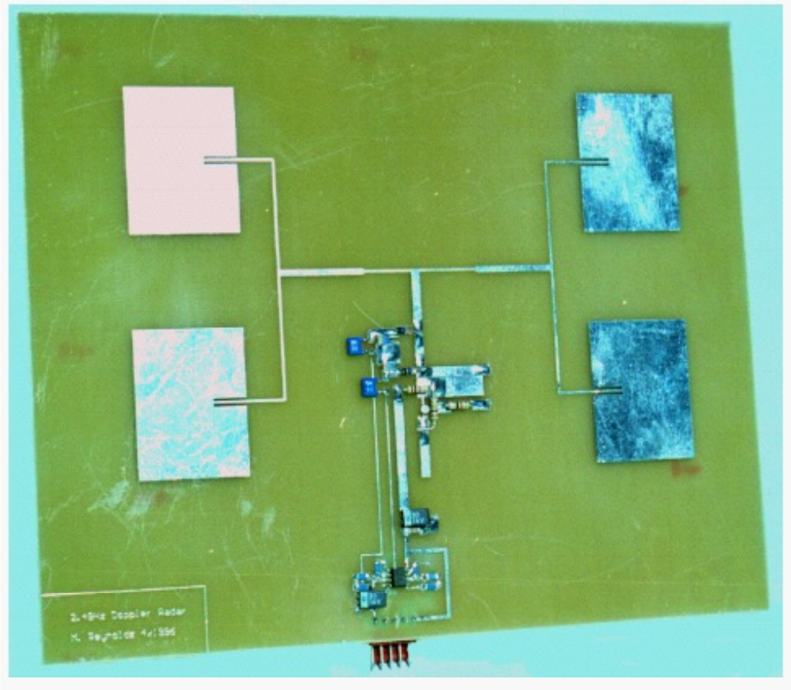
Doppler

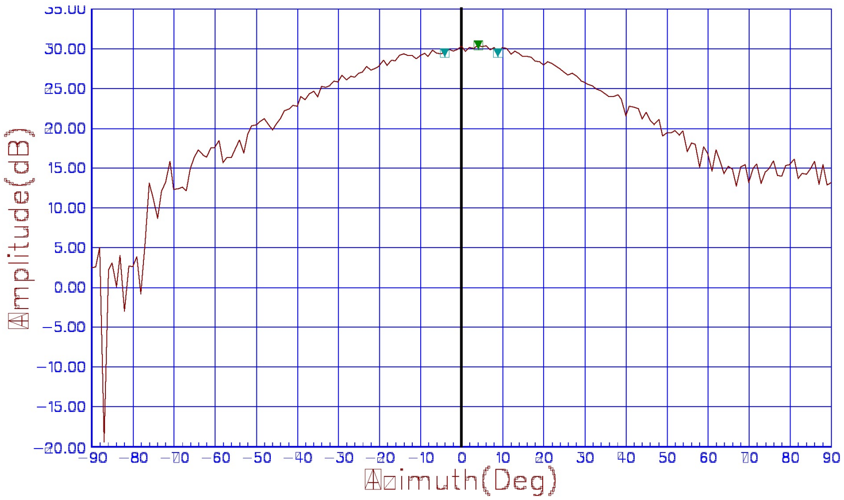
$$f_d = f_R - f_T = -\frac{2v_{\parallel}}{\lambda_0}\left(1+v_{\parallel}/c\right)$$

$$\simeq -2v_{\parallel}/\lambda_0$$

$$= \pm \frac{2vf\cos\theta}{c}$$

Quadrature Doppler Radar Head

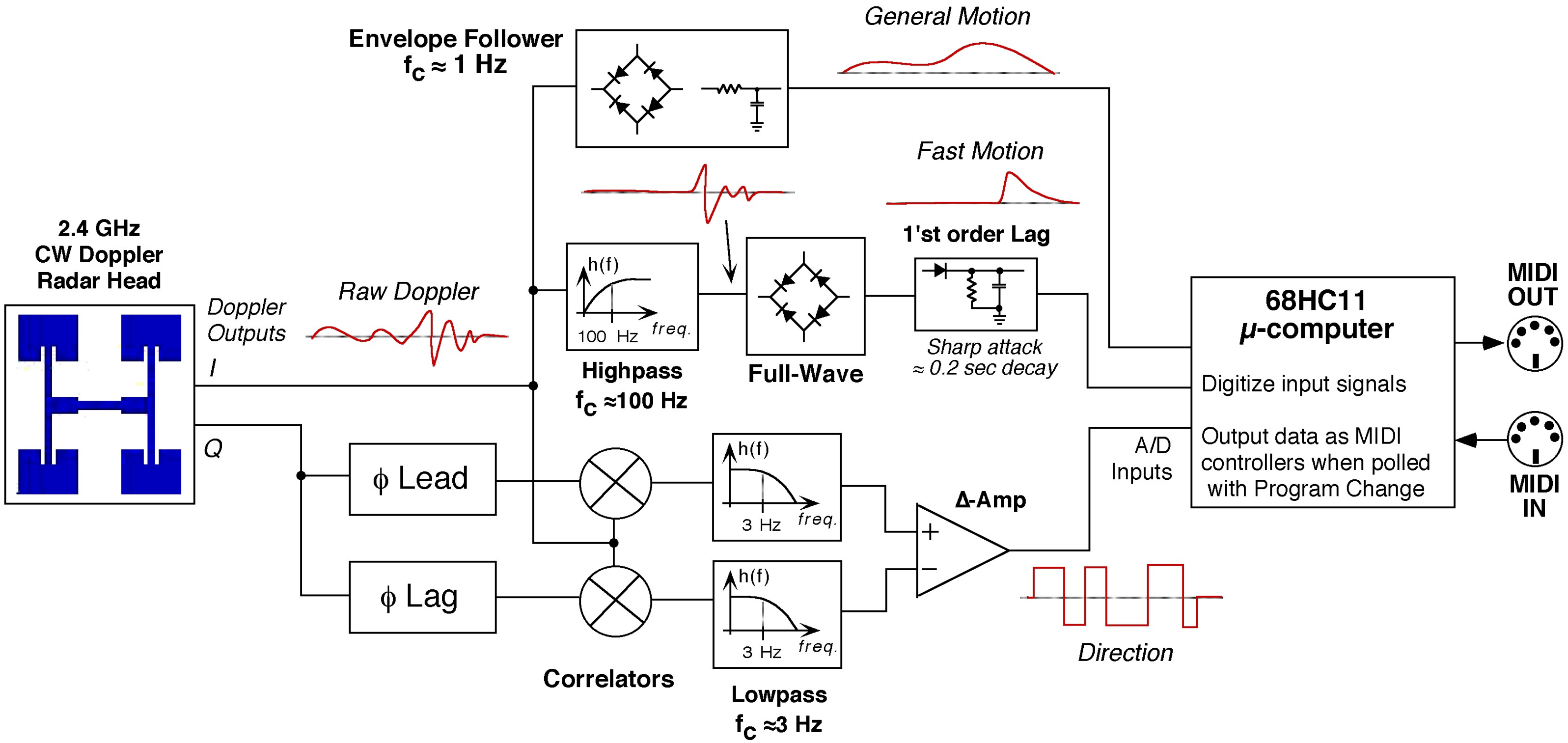




Horizontal Beam Profile

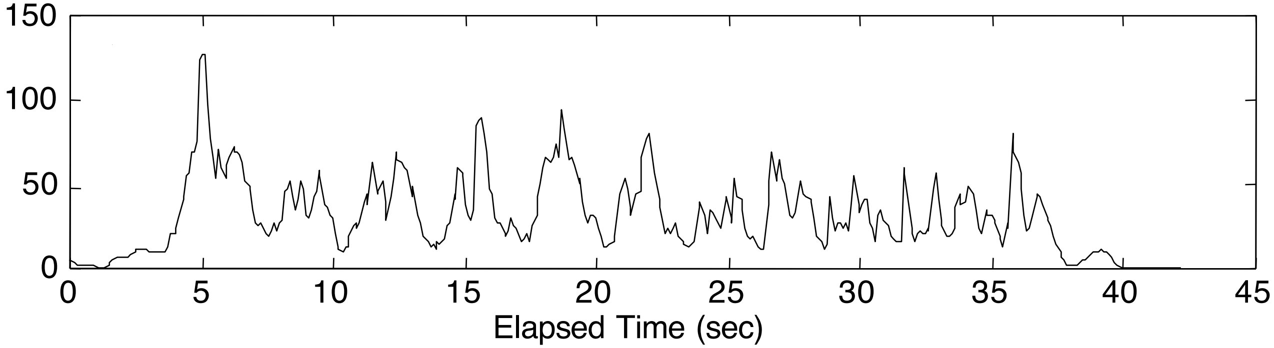
- 2.4 GHz CW Doppler microwave motion sensor
  - Close relative of microwave intruder detectors
- Low Power (<10 mW)
  - Flat micropatch antenna forms broad beam
  - Sensitive beyond 15 feet
  - Can sense through nonconductive material (walls, etc.)
- *Extremely* inexpensive
  - 1 microwave transistor, 2 hot carrier diodes, etc.

Radar Signal Conditioning

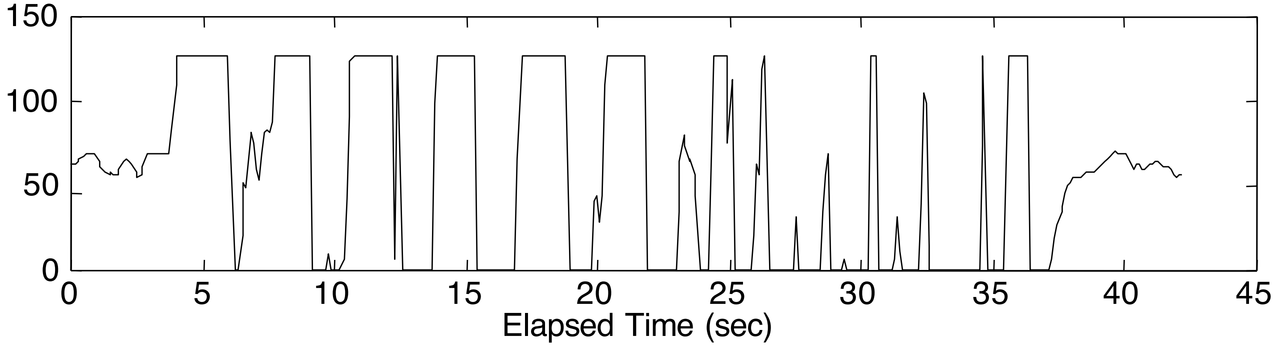


- Simple analog circuit provides 3 signals
  - General motion
  - Fast (velocity-weighted) motion
  - Direction
- Signals digitized at 50 Hz; processing needs minimal
  - As $f_{doppler}$ < 100 Hz, simple DSP possible

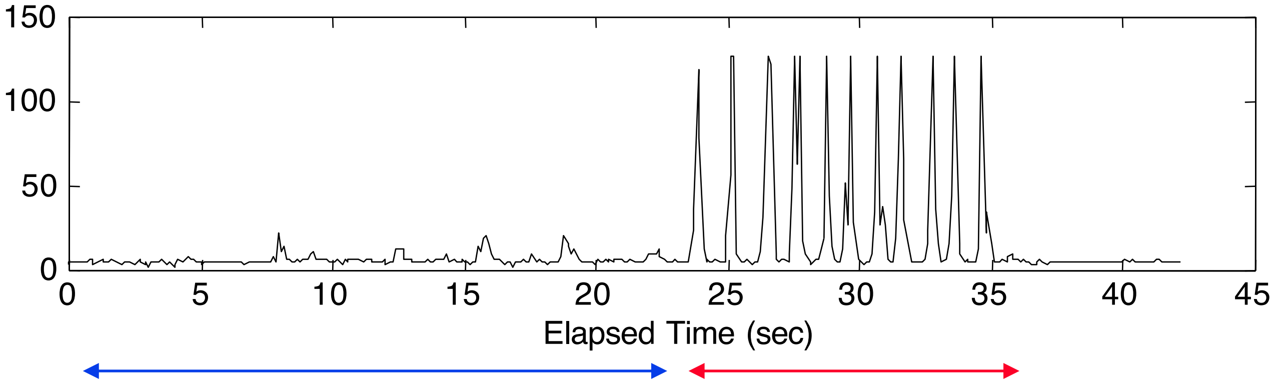
Radar Signals



Amount of general movement



Direction of axial motion

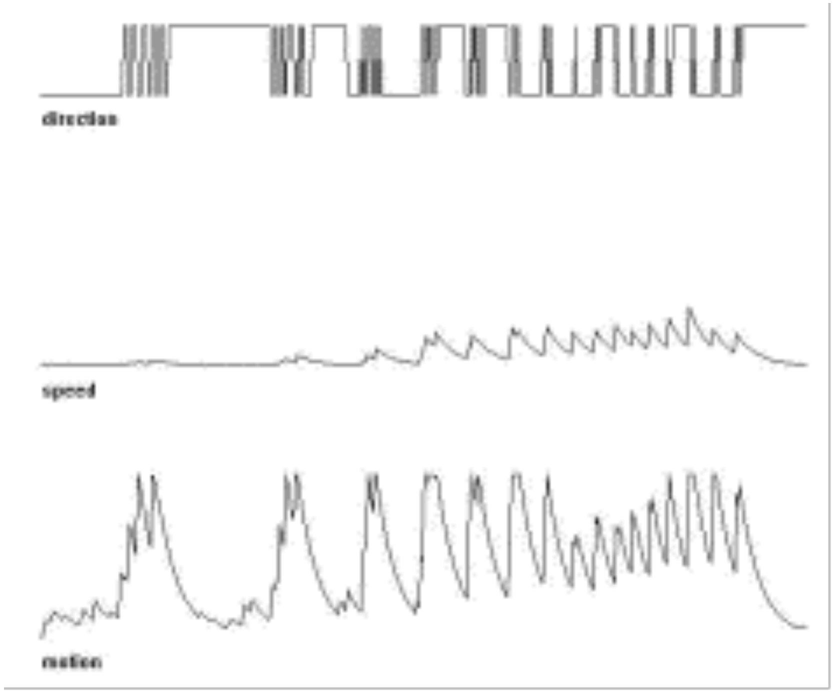


Fast movement signal

Slow cyclic motion along boresight

Fast hand motion

Quadrature Doppler Radar Head



Spiwak, M. (1995). Build a Radar Speed Gun. Popular Electronics., 12(6), 37-42,90.

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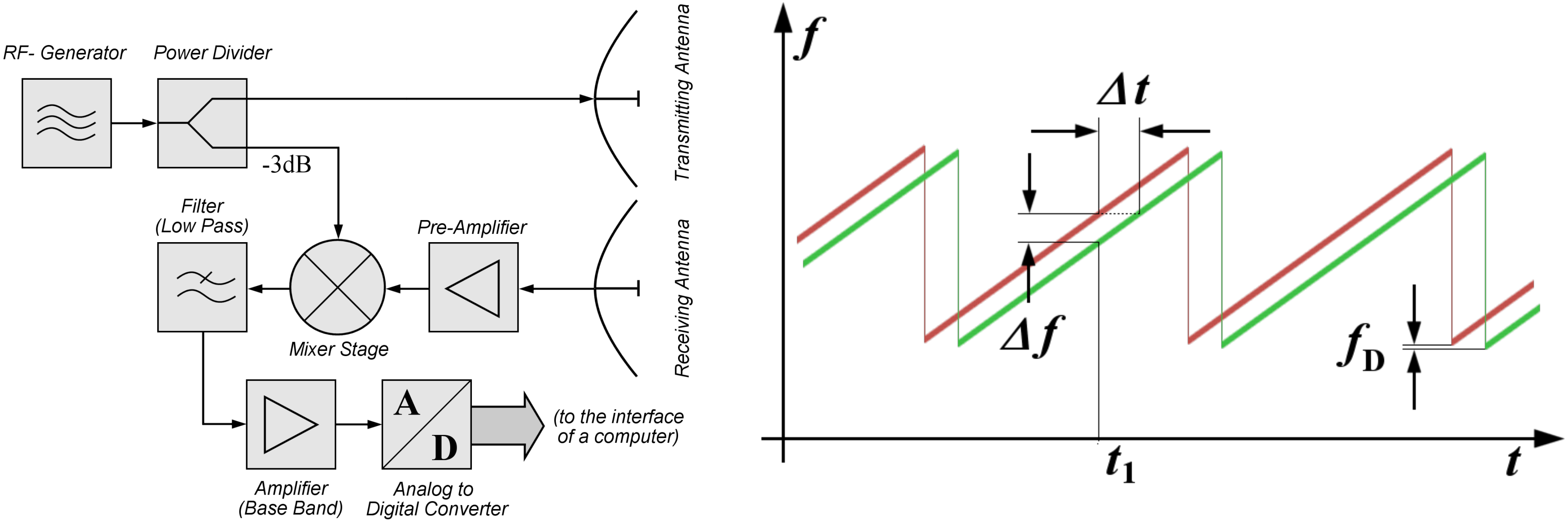
Rangefinding Radars

- Most tend to be swept-Doppler (backup radars)
  - Ohio State Radar
- Micropower Impulse Radars getting more common…

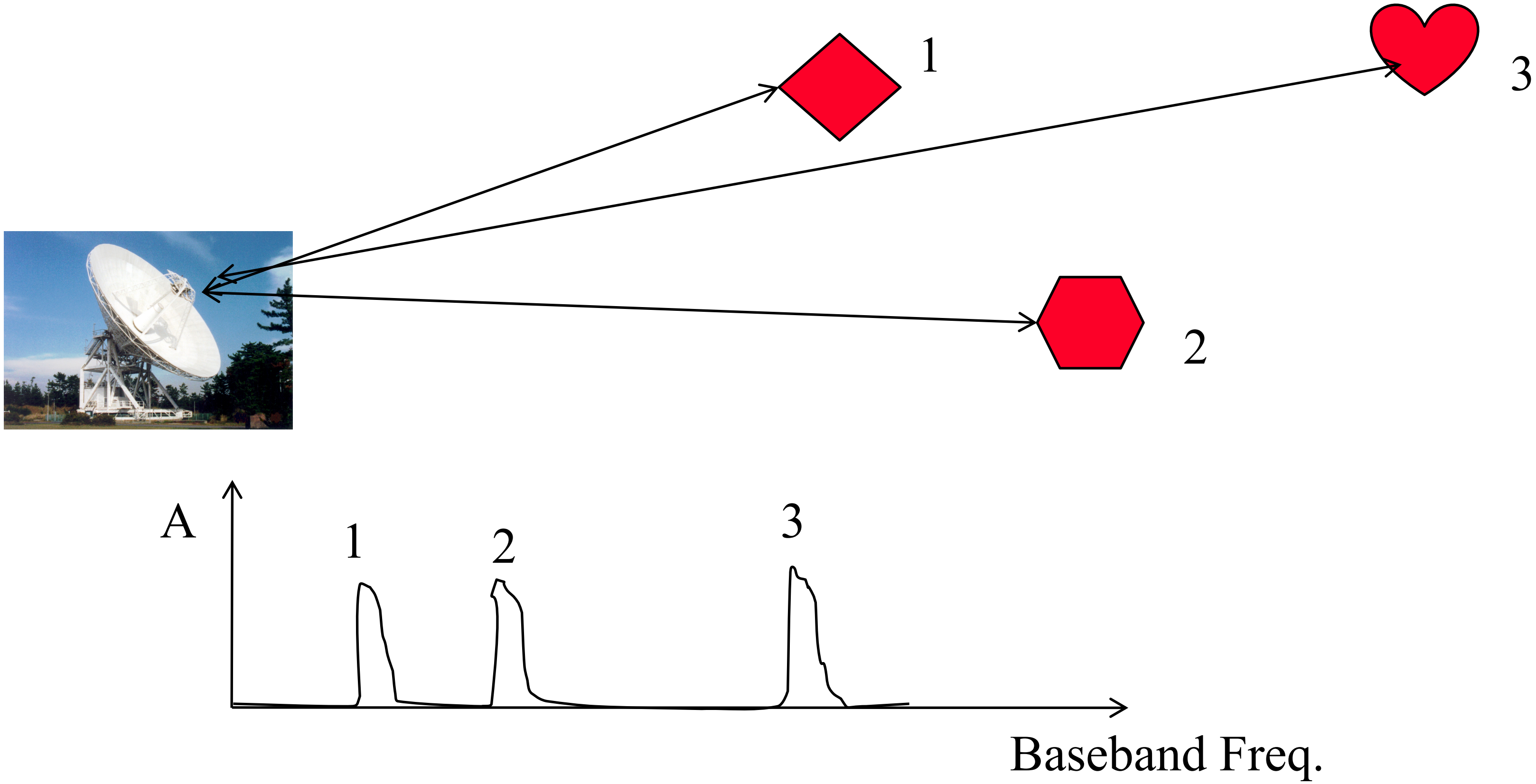
Swept Doppler Rangefinder



Wikipedia (Charly Whisky)

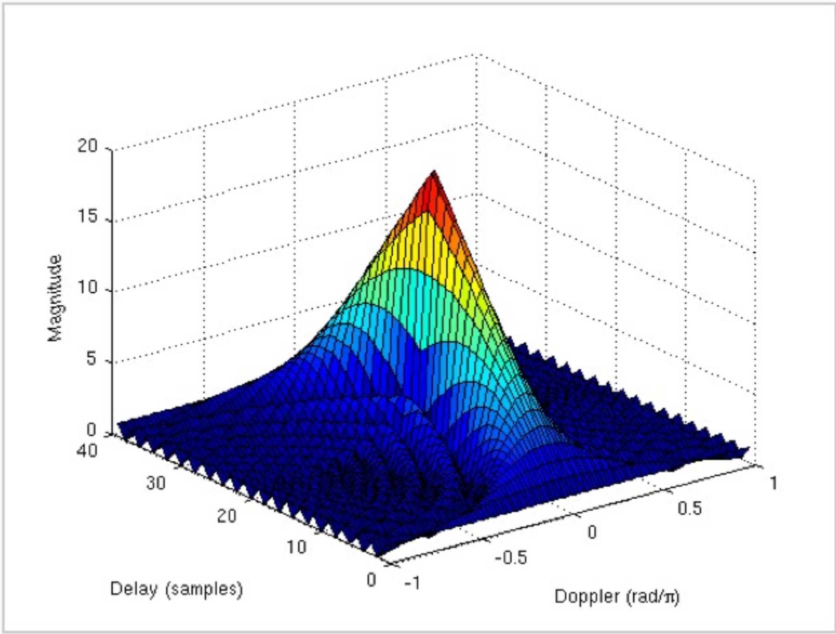
- Linearly ramp xmit frequency with time
  - – (LFM ‘chirp’)
  - – $f = f_0 + f_r \cdot t$
- Reflected signal is delayed by $2\Delta x/c$
  - – Hence shifted in frequency by $f_r \cdot 2\Delta x/c$

Swept-Doppler Radar

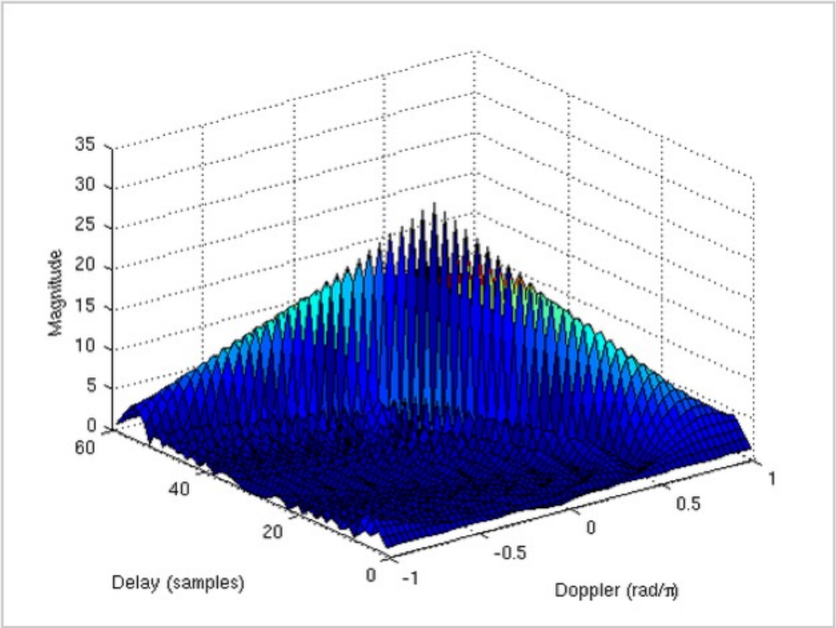


- Different demodulated frequency for each scatterer
- Can resolve with FFT

Ambiguity Functions



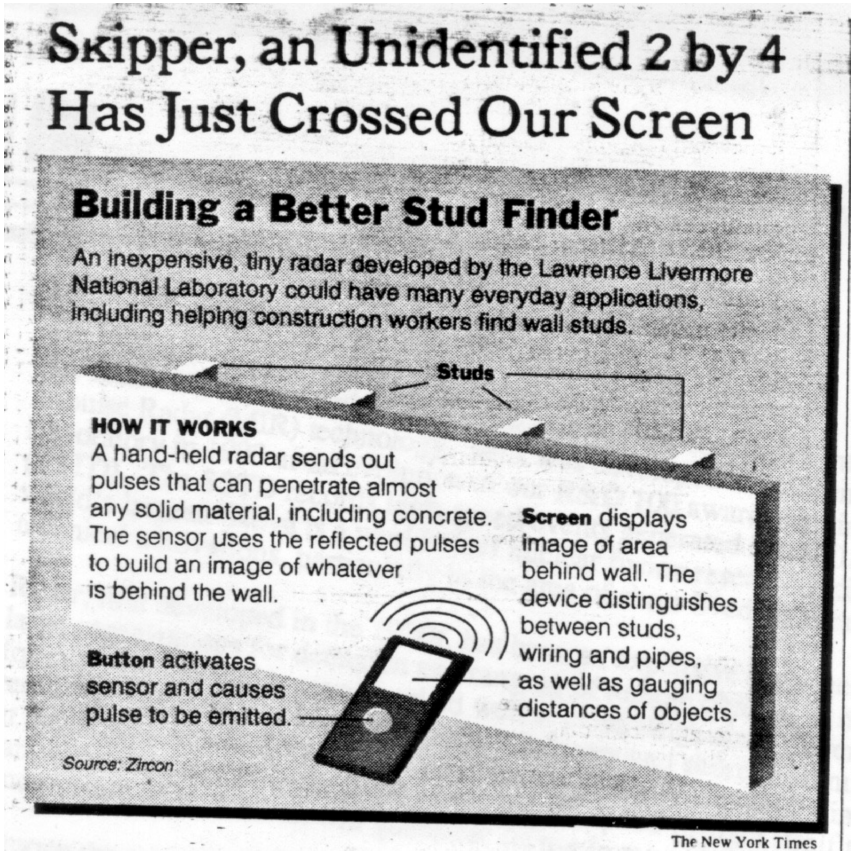
Ambiguity function for a square pulse



Ambiguity function for an LFM pulse

- Confounding of range and Doppler depending on transmit function and matched filter design

Micropower Impulse (UWB) Radar



Skipper, an Unidentified 2 by 4 Has Just Crossed Our Screen

Building a Better Stud Finder

An inexpensive, tiny radar developed by the Lawrence Livermore National Laboratory could have many everyday applications, including helping construction workers find wall studs.

Studs

HOW IT WORKS
A hand-held radar sends out pulses that can penetrate almost any solid material, including concrete. The sensor uses the reflected pulses to build an image of whatever is behind the wall.

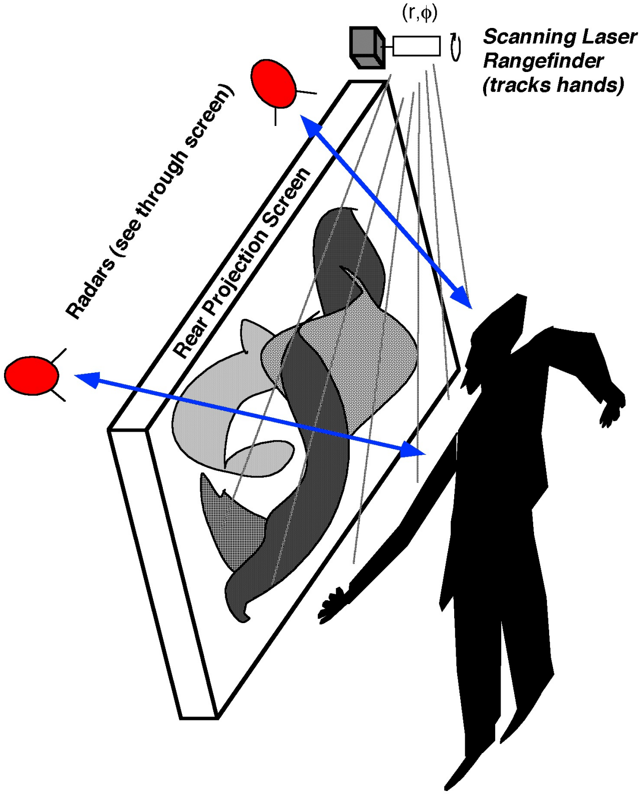
Screen displays image of area behind wall. The device distinguishes between studs, wiring and pipes, as well as gauging distances of objects.

Button activates sensor and causes pulse to be emitted.

Source: Zircon

The New York Times

New York Times, 1994



Typical Media Lab Example

- Work of Tom McEwan, LLNL
  - Originally developed as fast digitizer for NOVA laser

MIR Radar Block Diagram

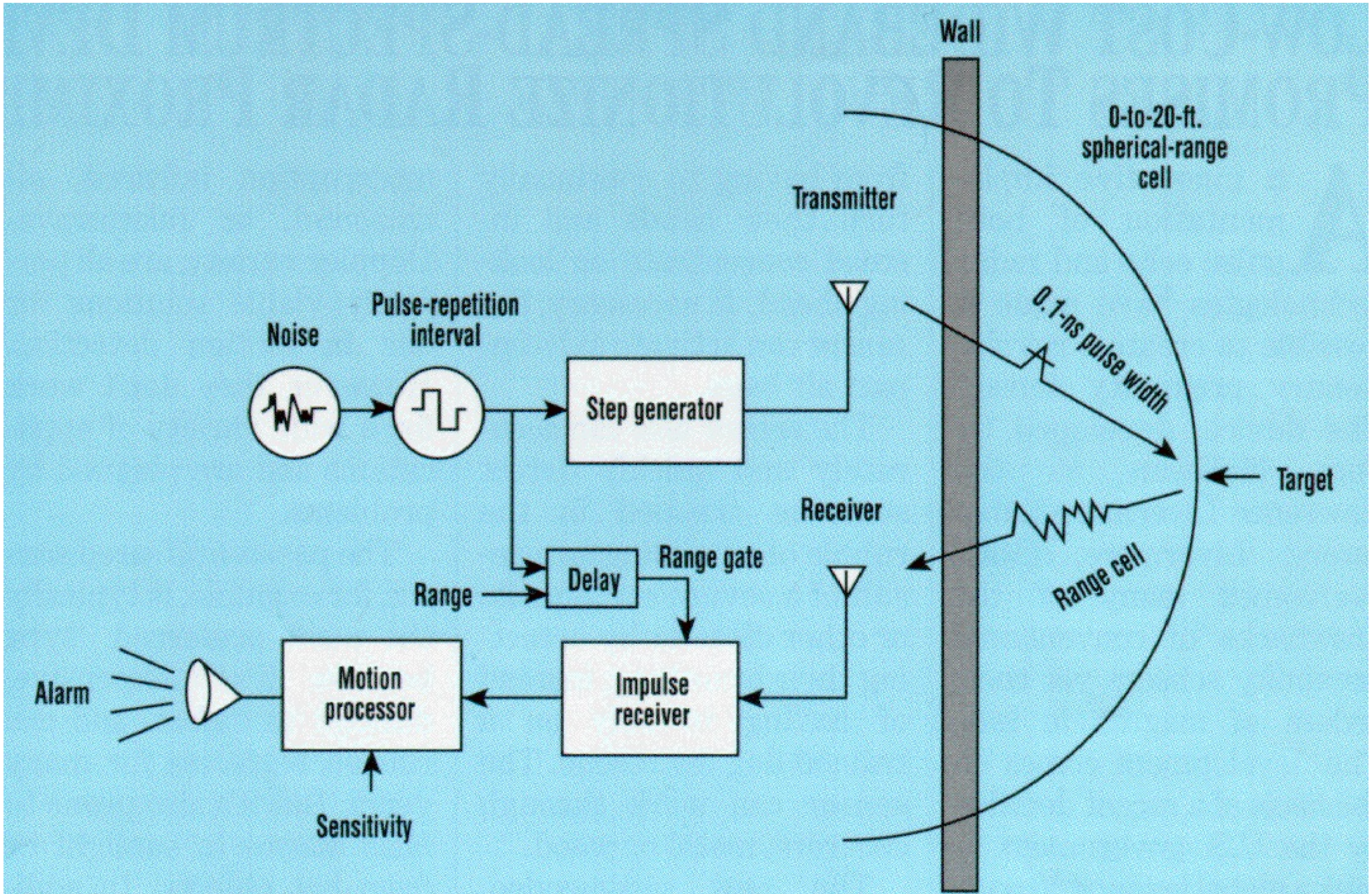
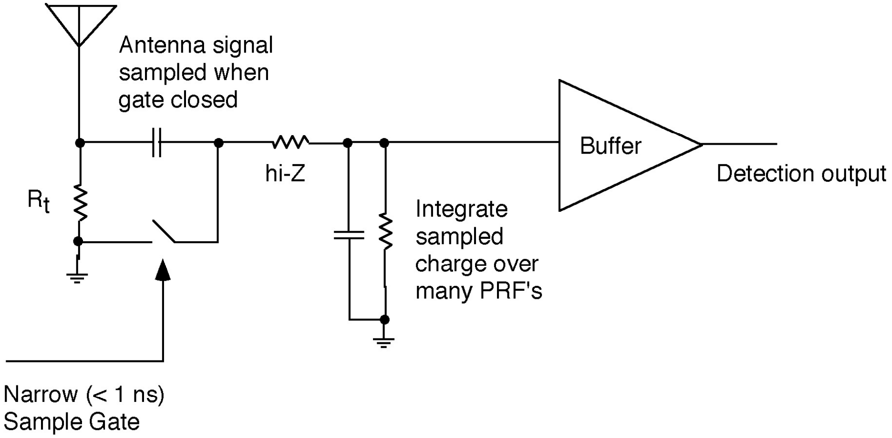


Fig. 2. Basic radar sensor schematic

Two ASIC's planned

One for fast UHF sampling, another for slow integration, PRF control, etc.

Sampling Circuitry

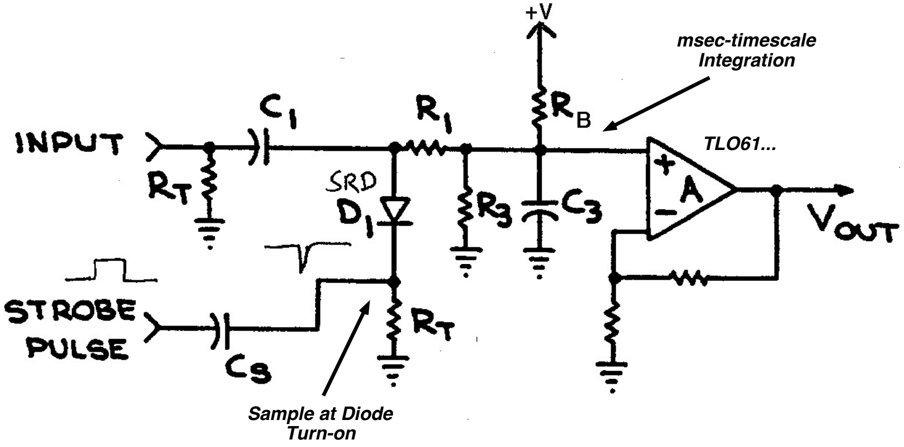


Antenna signal sampled when gate closed

Integrate sampled charge over many PRF's

Narrow (< 1 ns) Sample Gate

Functional Block



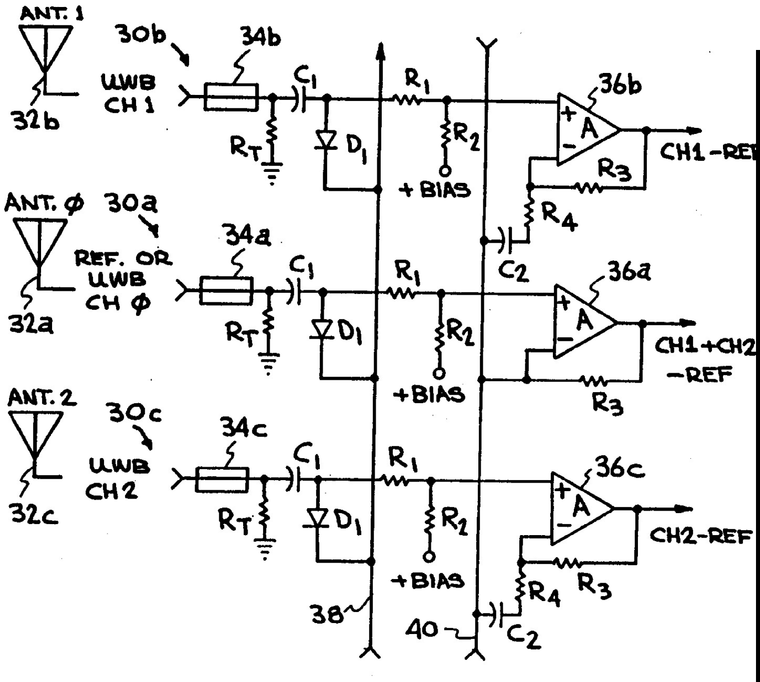
msec-timescale Integration

Sample at Diode Turn-on

US Patent 5,345,471

- Uses Simple diode switch for sampler
  - Use in sampling scopes over many decades...
  - Sampling correlates receiver w. range pulse

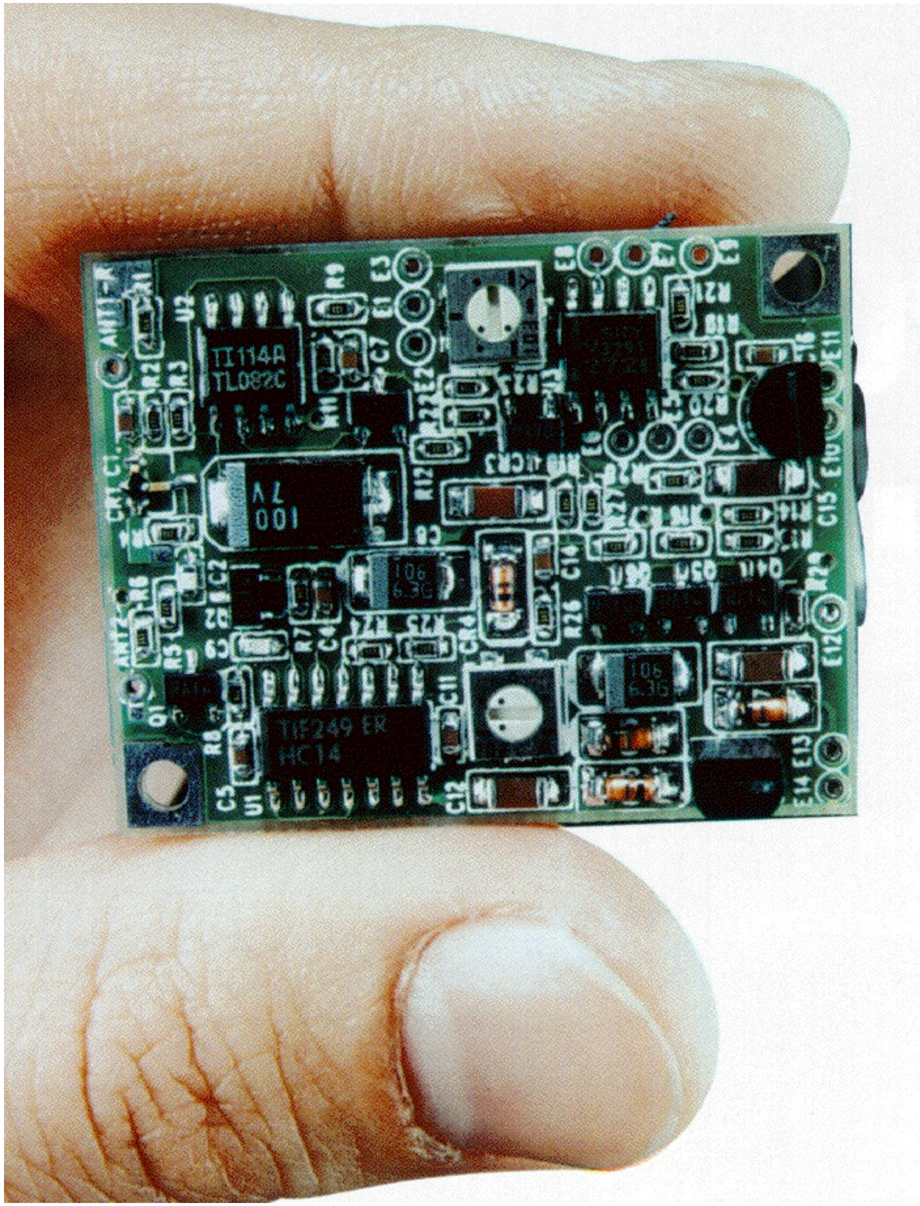
Receive Arrays, Sensitive Shells...



[redacted]

Application on market now:
Range-gate PIR motion sensors

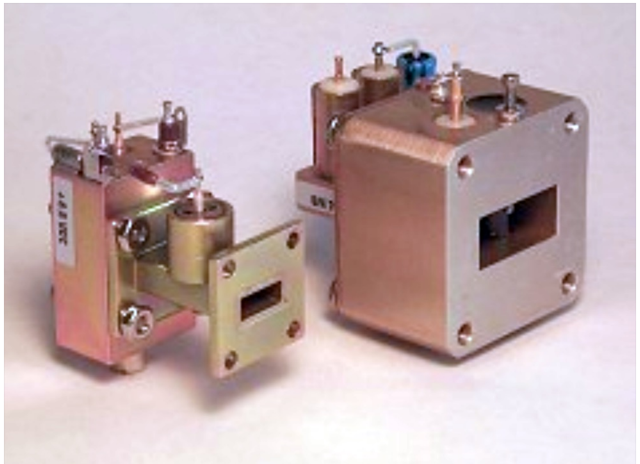
LLNL Circuit Card, 1995...



Not in studfinders yet,
But in motion detectors
(Sentrol) for range gating.

McEwan Systems makes them

Commercial Doppler & Ranging Radars



Doppler Motion Radars

http://www.samraksh.info/products.htm

From Bill Yerazunis at MERL:

Do you mean the microwave Gunnplexers? Little thing with about an inch of waveguide and then a pyramid-shaped horn with an open bottom?

I usually pick 'em up surplus, but here are good ones:

http://www.advancedreceiver.com/page31.html

They start out at about $250 and work up from there.

Note: keep your eyes open on the surplus / ham radio markets, as I have bought them for as little as ten dollars, including the horn antenna.

Here are some sources (google for "gunnplexer surplus") for Gunnplexers on the cheap:

http://www.hamtv.com/specials.html
http://www.shfmicro.com/gunn.htm (gunnplexers for under $100)

You can also salvage them out of burglar alarms or the gizmos used in supermarkets to automatically open the doors (not the rubber-mat style ones, the ones with a box above the door)

UWB Impulse Radars

From Prabal Dutta at UC Berkeley

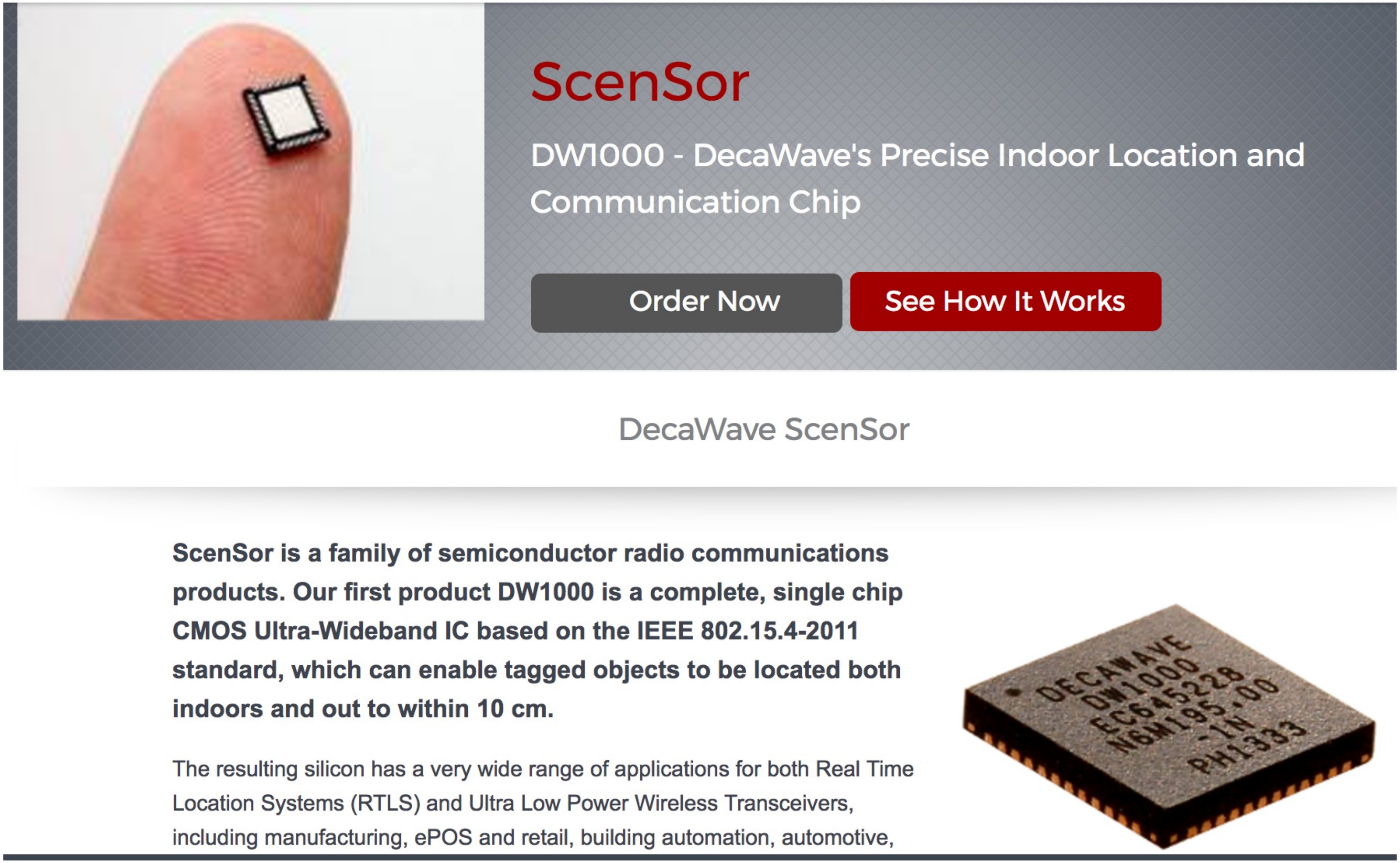
We used the TWR-ISM-002 unit from Advantaca (http://www.advantaca.com/).

McEwan Technologies makes UWB/TDR hardware as well:
http://www.getradar.com

Multispectral Solutions makes UWB for localization:
http://www.multispectral.com/

Impulse UWB chips become commodity

- Decawave devices



ScenSor

DW1000 - DecaWave's Precise Indoor Location and Communication Chip

DecaWave ScenSor

ScenSor is a family of semiconductor radio communications products. Our first product DW1000 is a complete, single chip CMOS Ultra-Wideband IC based on the IEEE 802.15.4-2011 standard, which can enable tagged objects to be located both indoors and out to within 10 cm.

The resulting silicon has a very wide range of applications for both Real Time Location Systems (RTLS) and Ultra Low Power Wireless Transceivers, including manufacturing, ePOS and retail, building automation, automotive,