A?

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Engineering

# E4230
# Microwave EO Instrumetation

*(5 cr)*

*Jaan Praks*
*Aalto University*

# Q?

Lossless media is conducting or nonconducting?
What is blackbody?
If Sun would be hotter, would there be less visible light?
What abot microwaves?

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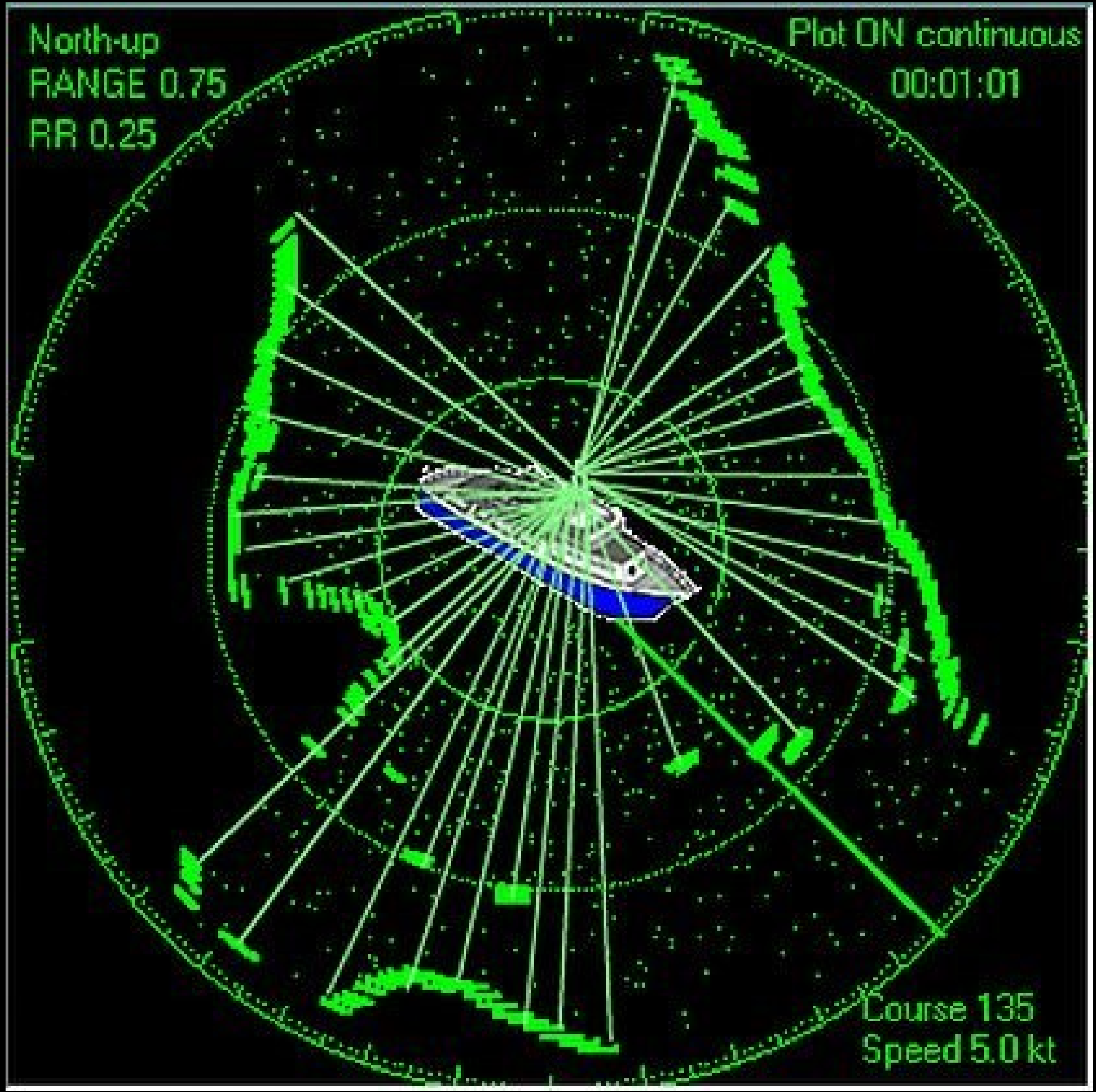
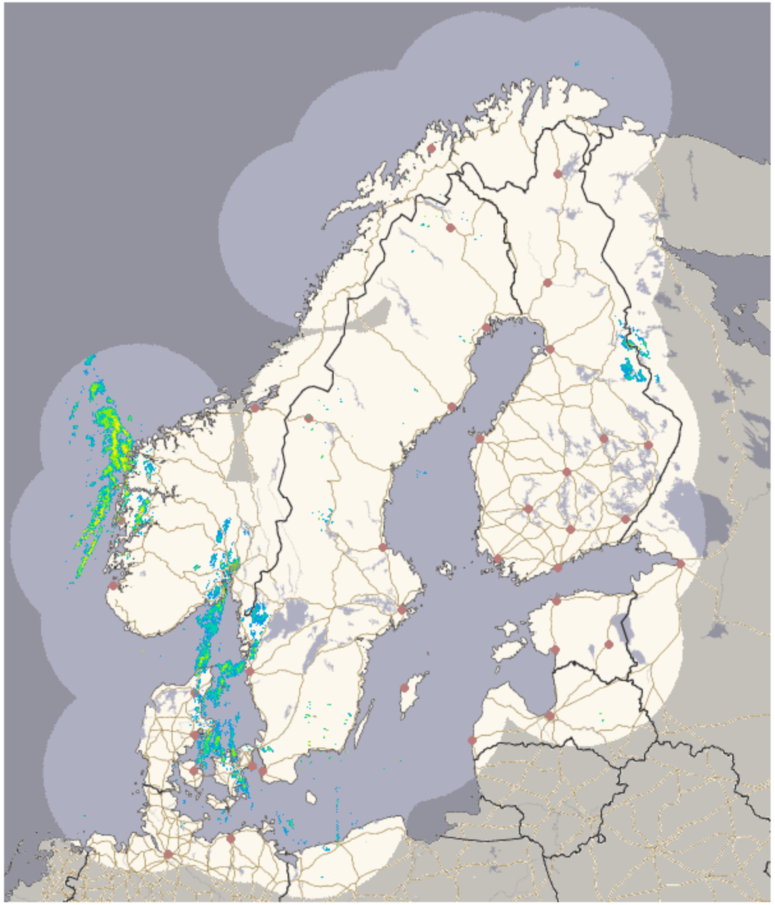
# What is common for next images?


North-up
RANGE 0.75
RR 0.25
Plot ON continuous
00:01:01
Course 135
Speed 5.0 kt


SPEED
LIMIT
25
YOUR
SPEED
27

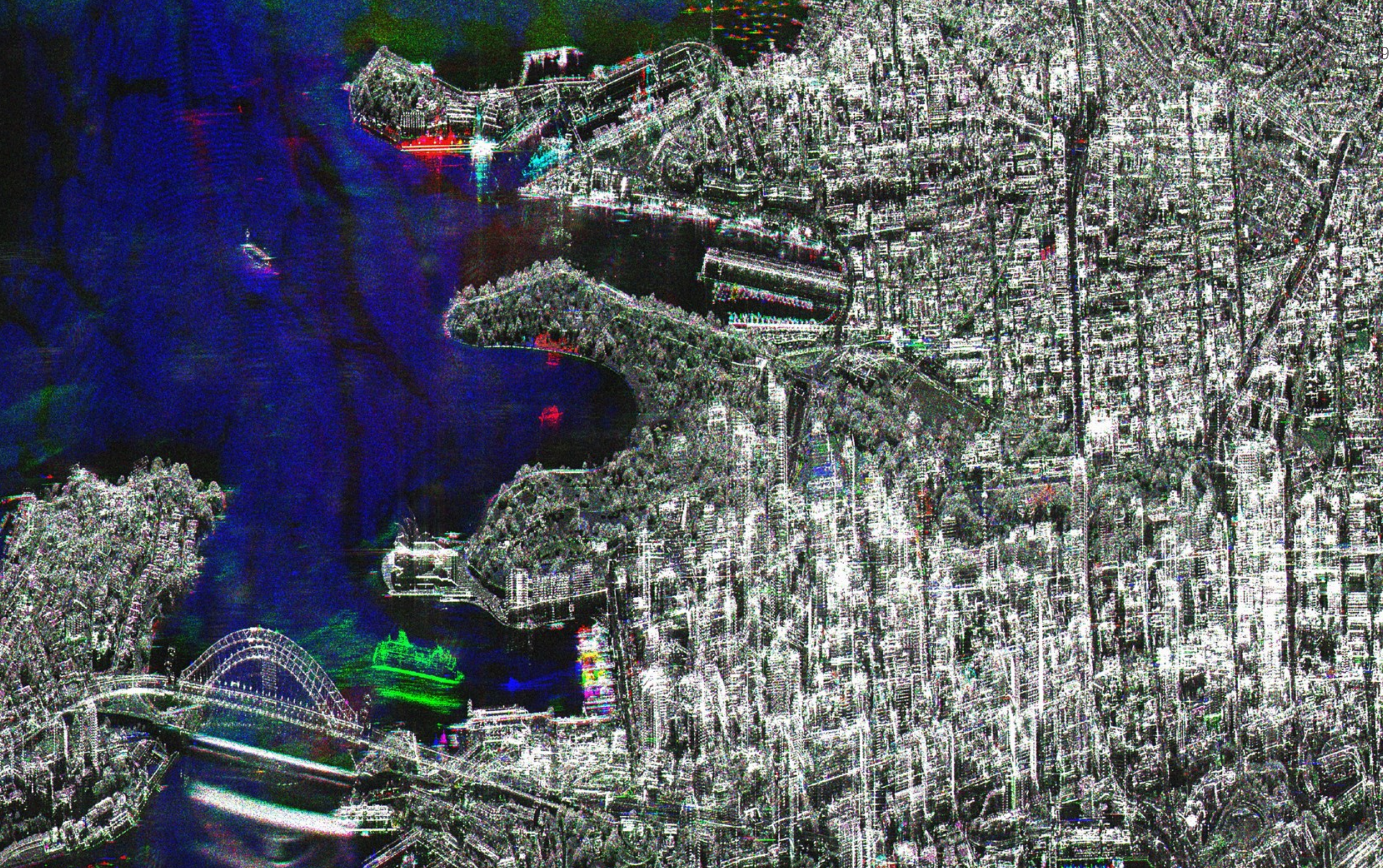
# Precipitation Nordic countries



5/3 04:15AM
5/3 04:30AM
5/3 04:45AM
5/3 05:00AM
5/3 05:15AM
5/3 05:30AM
5/3 05:45AM
5/3 06:00AM
5/3 06:15AM
5/3 06:30AM
5/3 06:45AM
5/3 07:00AM
5/3 07:15AM
5/3 07:30AM
5/3 07:45AM
5/3 08:00AM
5/3 08:15AM
5/3 08:30AM

Play

heavy
moderate
light



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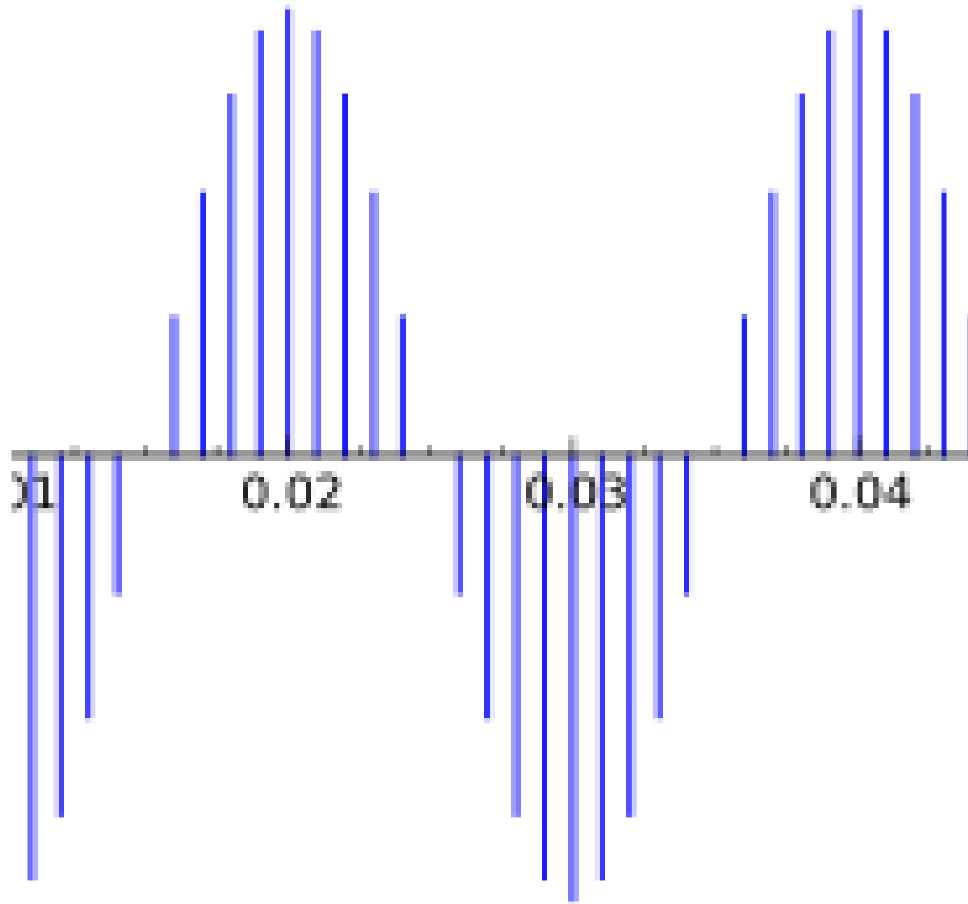
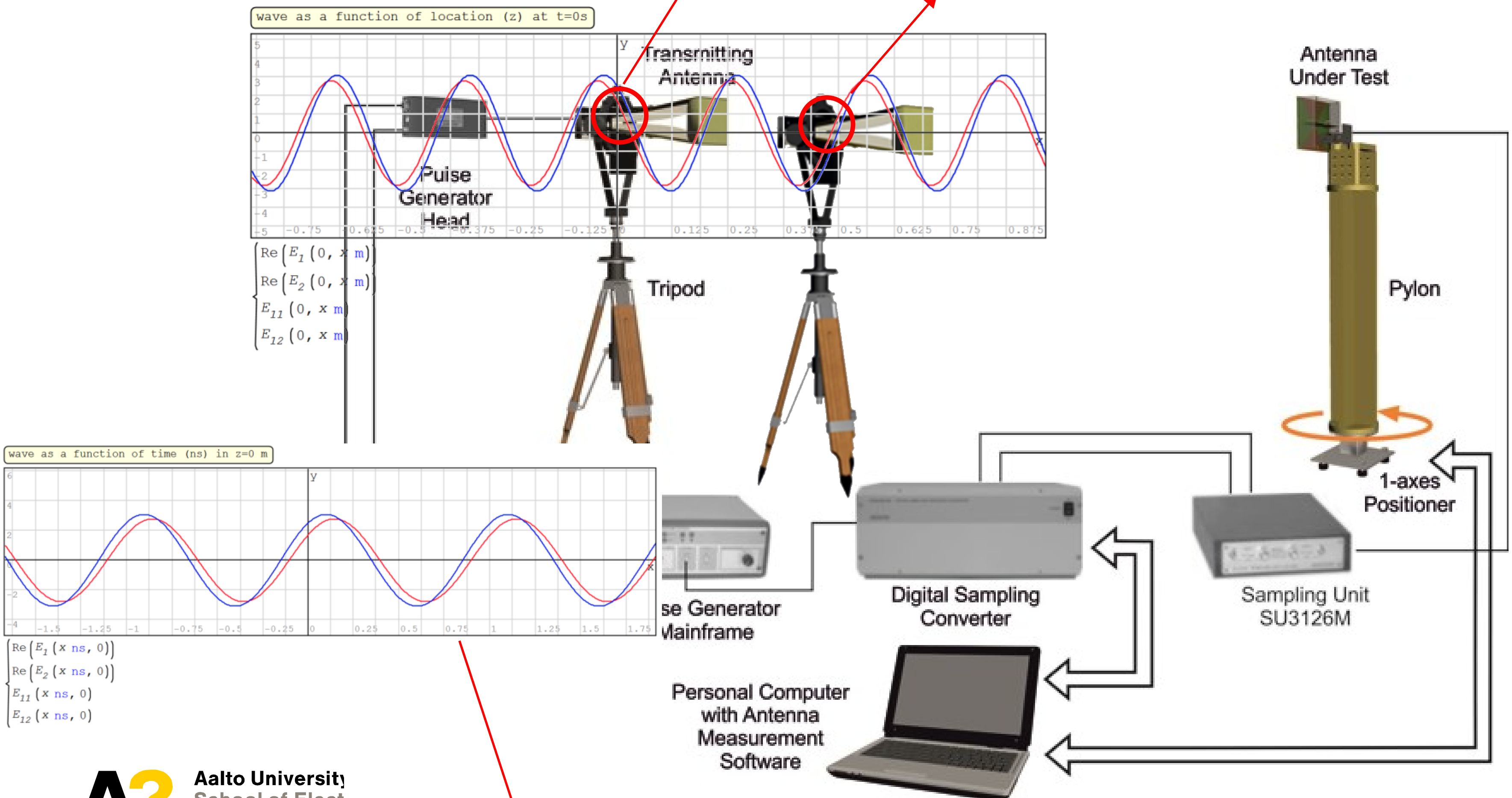
# Signals and digital signals



Measurements at x=0 and t=0

Measurements at x=32 cm and t=0




Measurements at x=0 and t= -2 .. 2 ns

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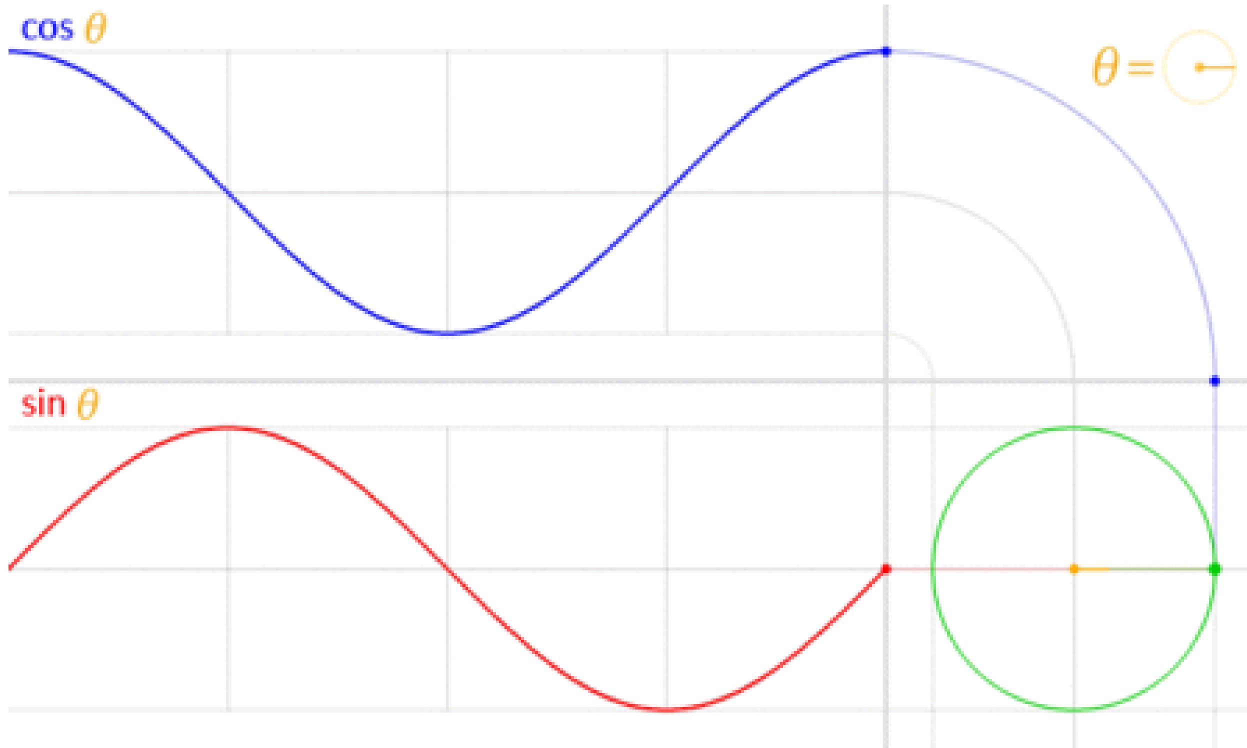
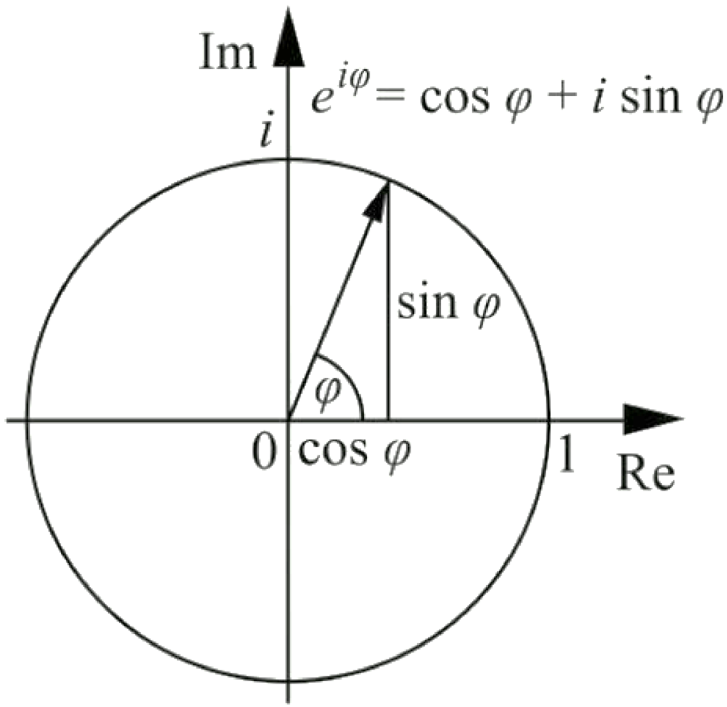
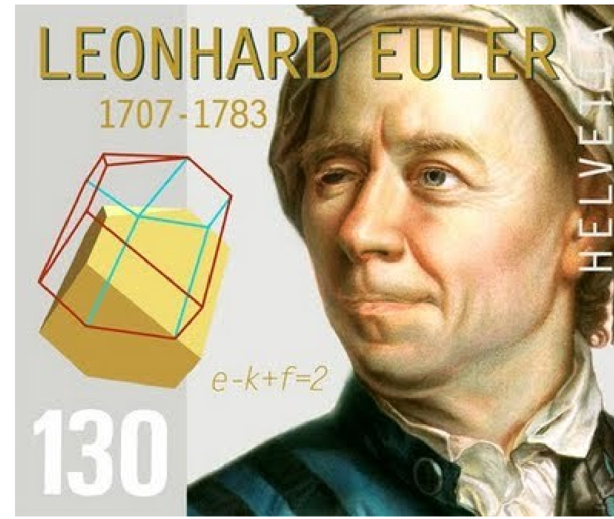
# Circle and coherent wave



# Euler’s identity




$$\mathbf{e}^{\mathbf{i}\pi} - 1 = 0$$

# Wave equation

## Wave solution for

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0.$$

Equivalent presentations either with exponent or cosine

$$E_1(z,t) := A_1 \cdot \mathbf{e}^{-i\cdot(k\cdot z)} \cdot \mathbf{e}^{-i\cdot(t\cdot\omega)}$$

$$E_2(z,t) := |A_1| \cdot \mathbf{e}^{-i\cdot(k\cdot z + t\cdot\omega + \varphi)}$$

$$E_3(z,t) := |A_1| \cdot \cos(k\cdot z + t\cdot\omega + \varphi)$$

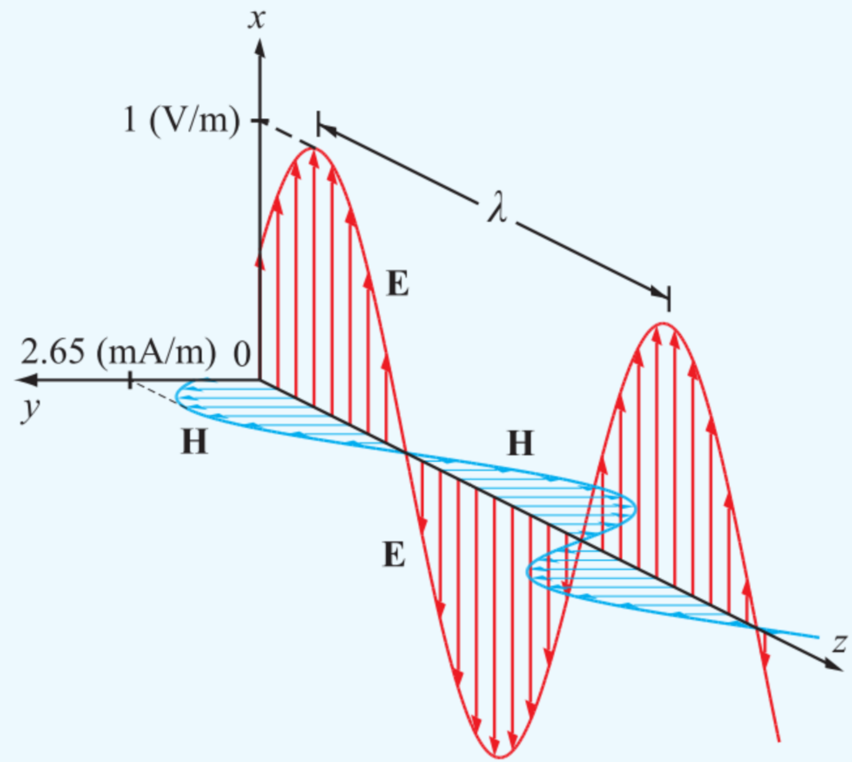
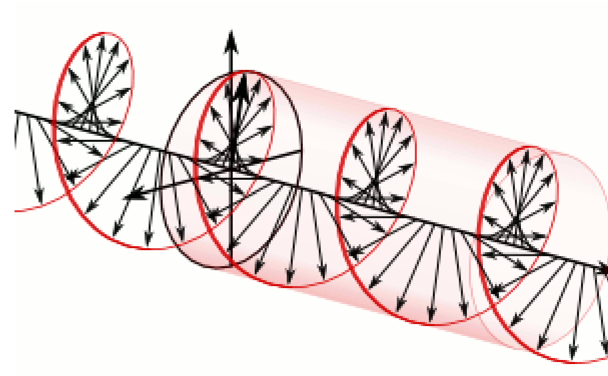
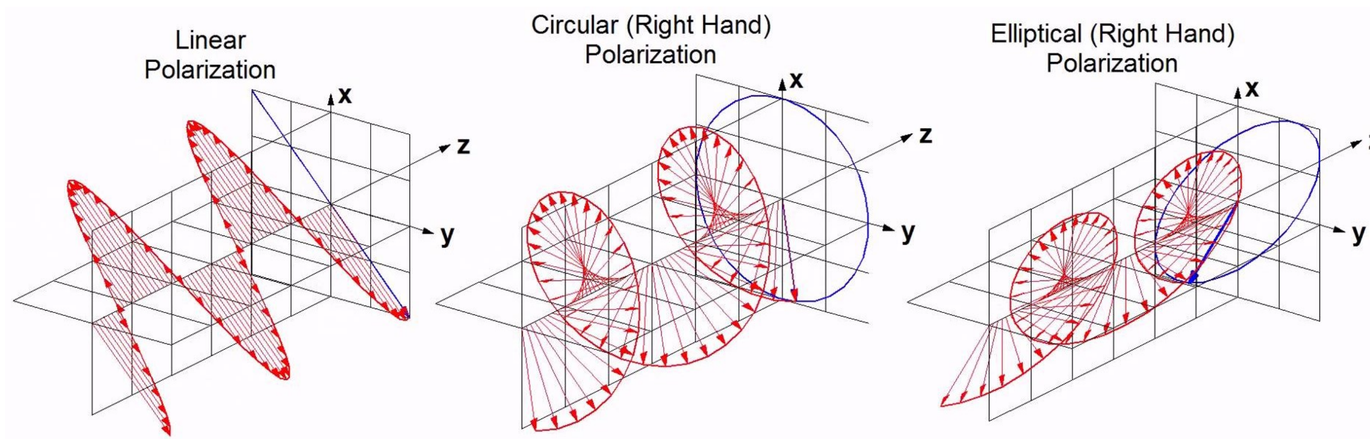



**Figure 2-3:** Spatial variations of **E** and **H** at $t = 0$ for the plane wave defined by Eq. (2.33).

# Polarization

The polarization of a uniform plane wave describes the locus traced by the tip of the E vector (in the plane orthogonal to the direction of propagation) at a given point in space as a function of time.





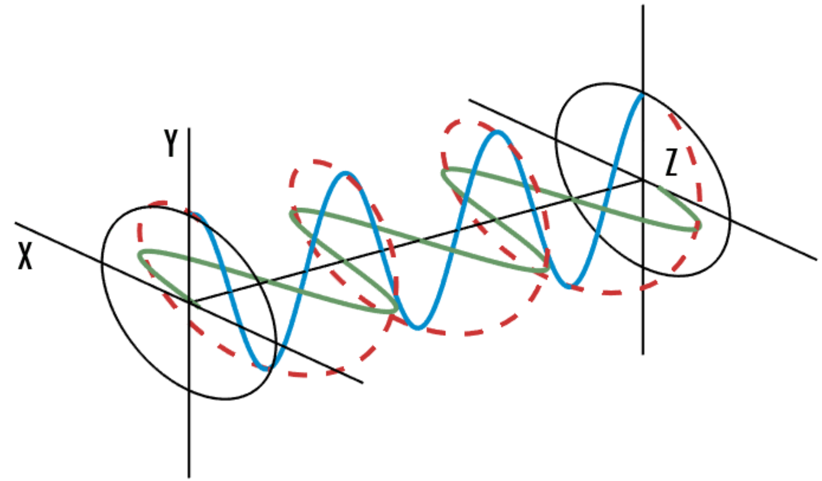
# Electric field

Usually, we inspect only electric field, and it can have both, x and y components.

$$E_x(z,t) := |A_x| \cdot \cos(k \cdot z + t \cdot \omega + \varphi_x)$$

$$E_y(z,t) := |A_y| \cdot \cos(k \cdot z + t \cdot \omega + \varphi_y)$$

Therefore, a single EM wave measurement is actually TWO complex numbers, one for H, one for V polarization.



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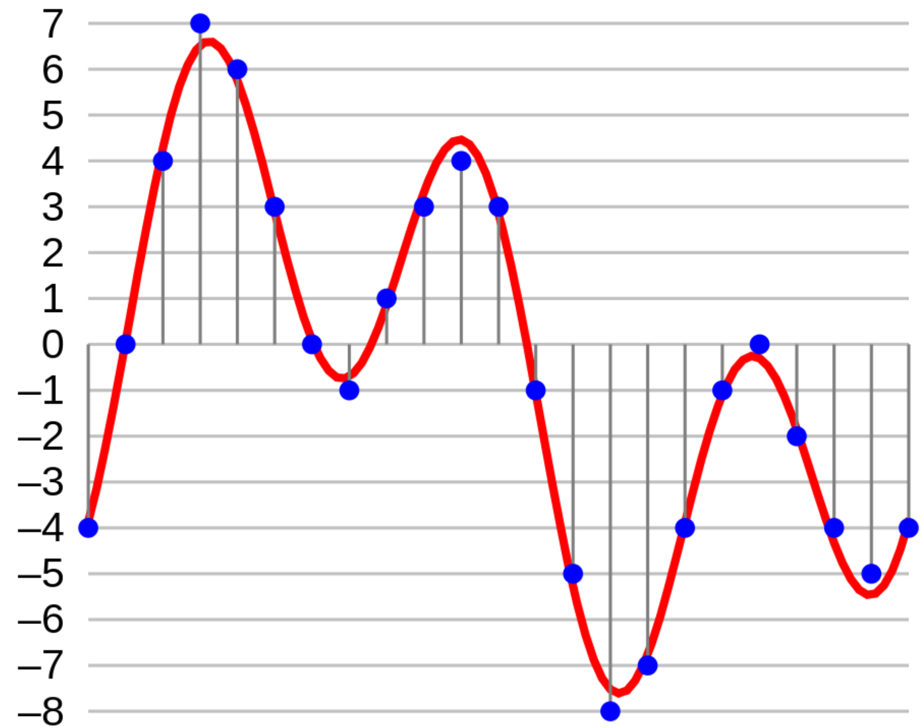
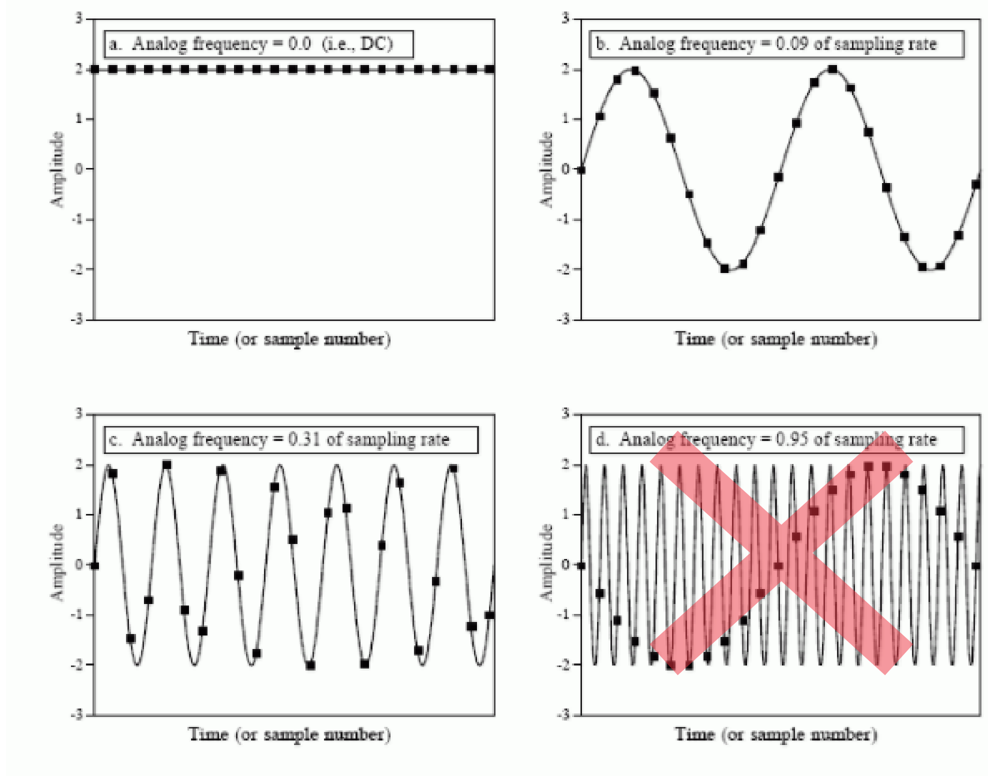
# Measuring RF signal with digital radio



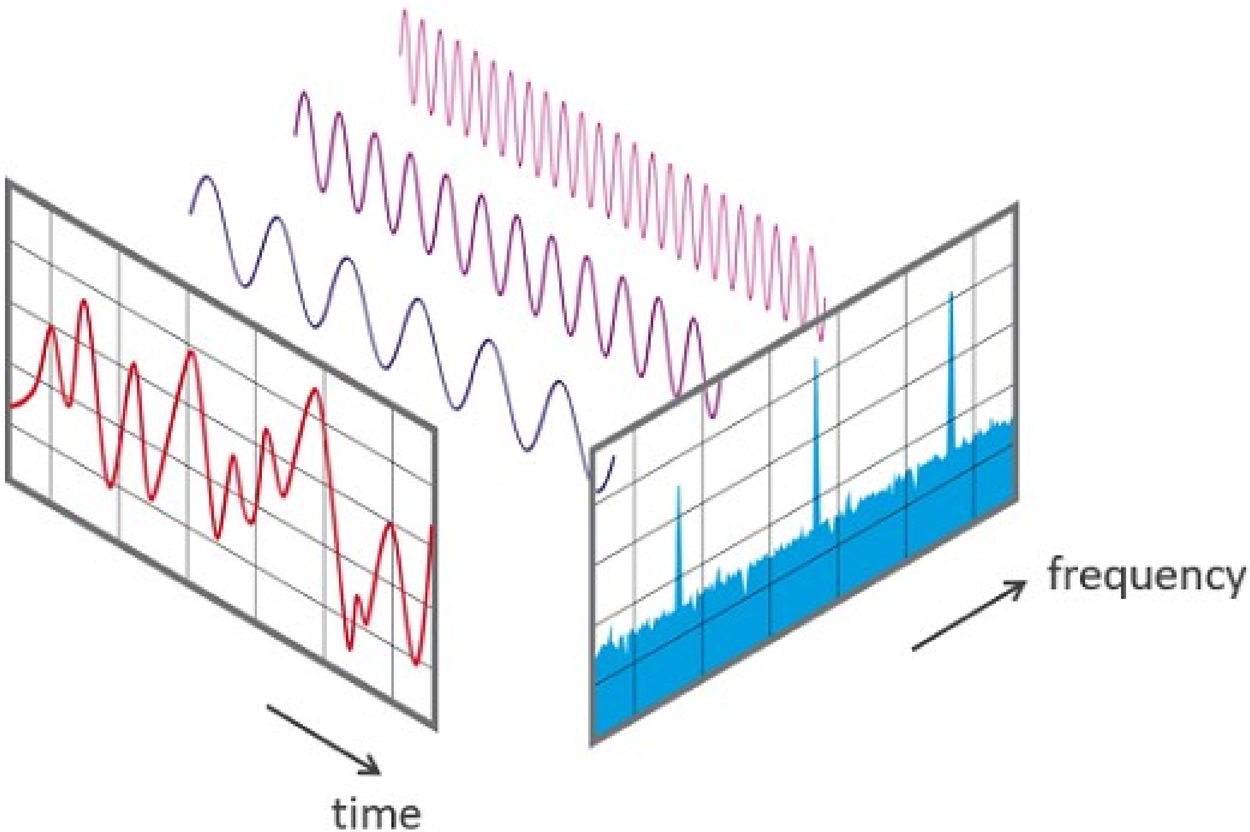
# Nyquist–Shannon sampling theorem

If a function x(t) contains no frequencies higher than B hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(**2**B) seconds apart.

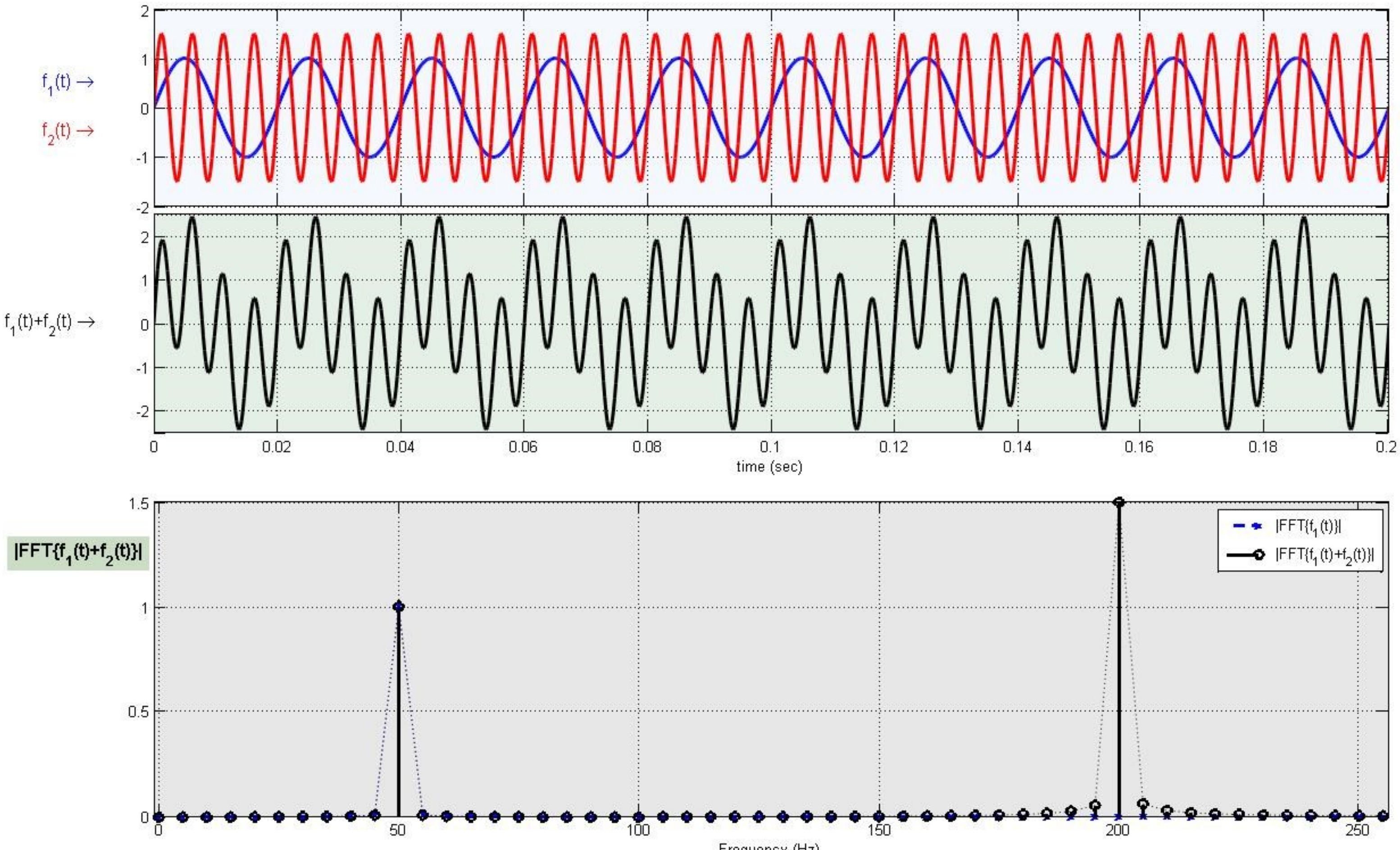
*Sampling frequency should be twice as high as highest frequency component in the signal.*

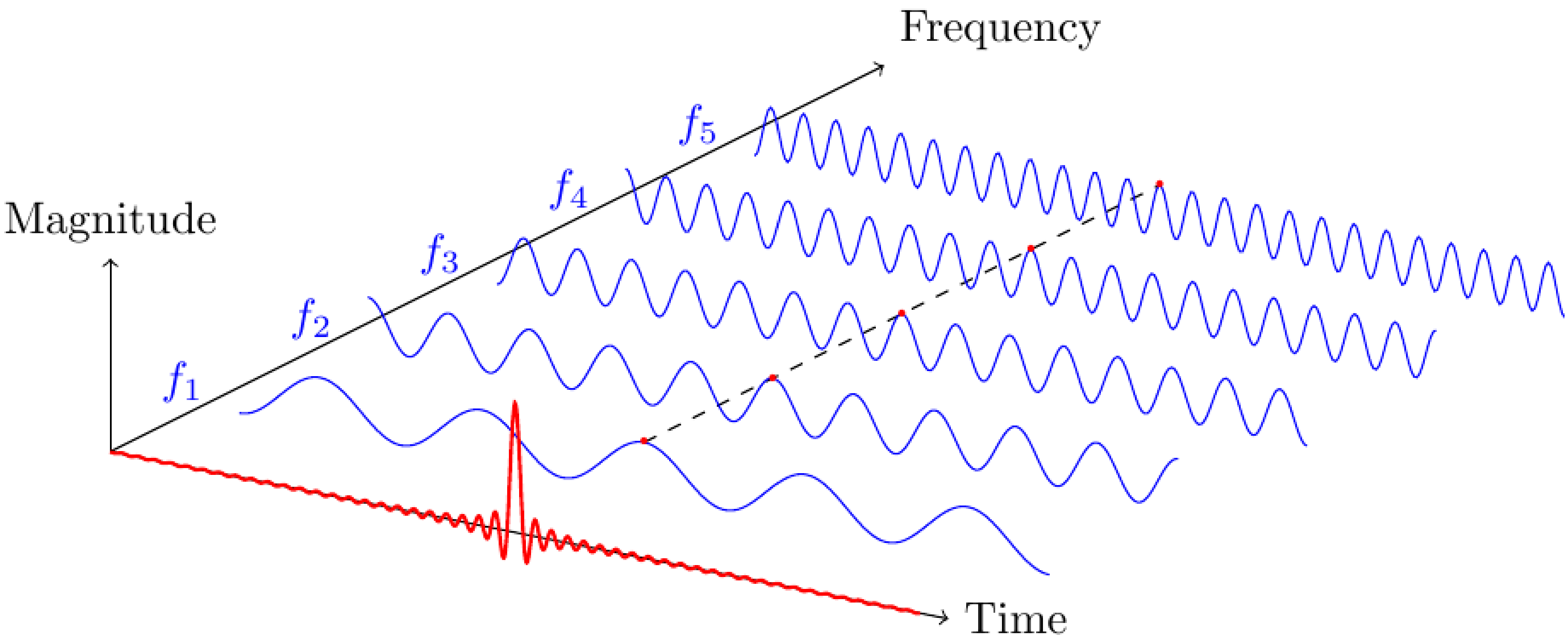


# Time domain / frequency domain



# Fast Fourier Transform (FFT)



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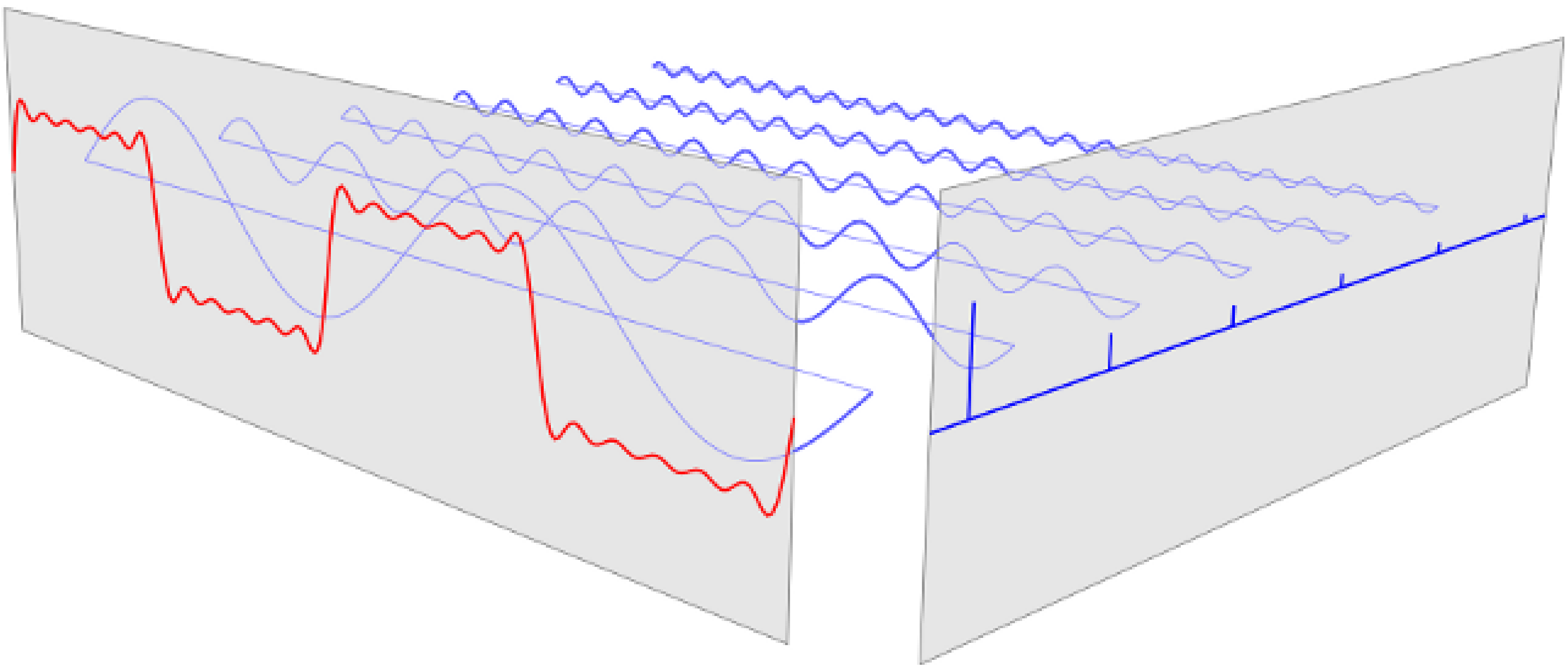

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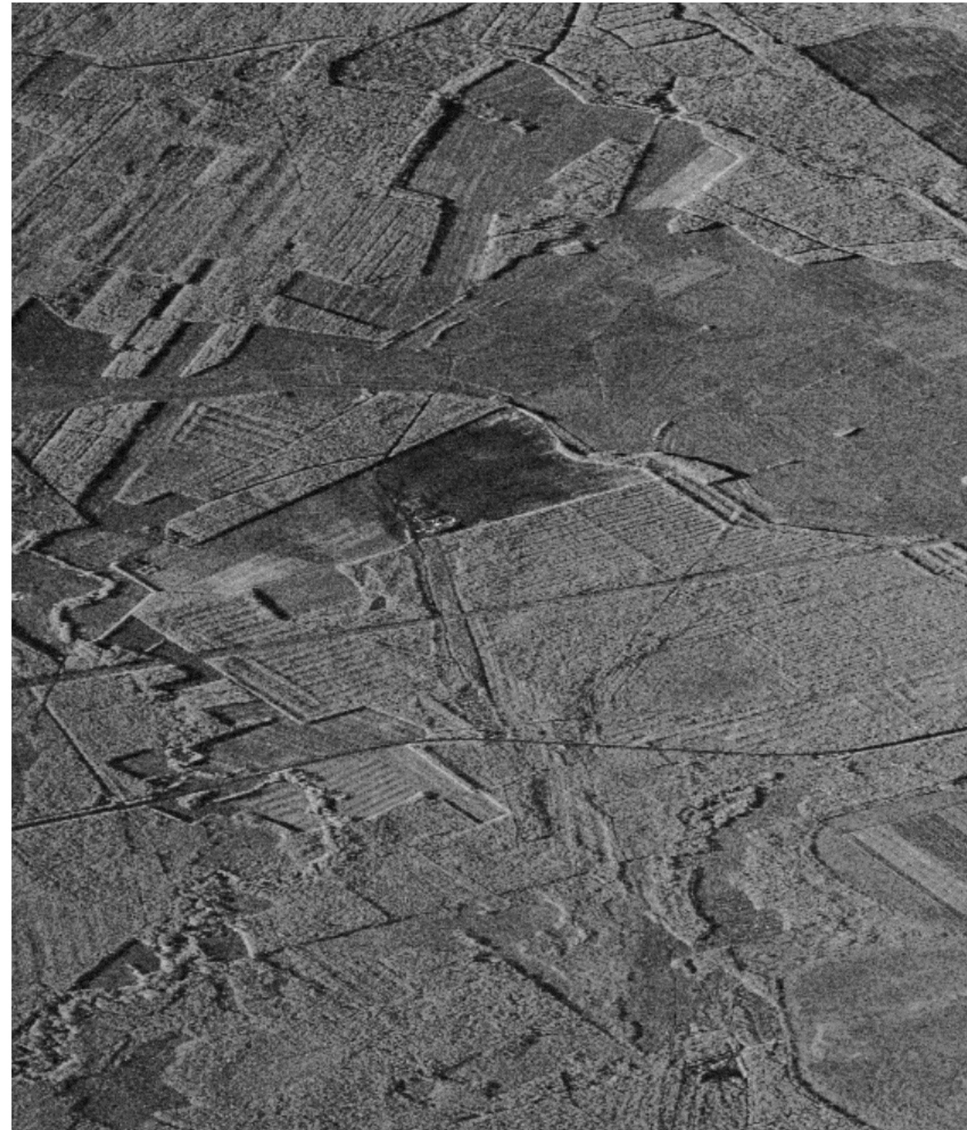
# Radar Scattering

## Chapter 5 in the course book

*Image by ICEYE radar*



# RADAR: Radio Detection and Ranging

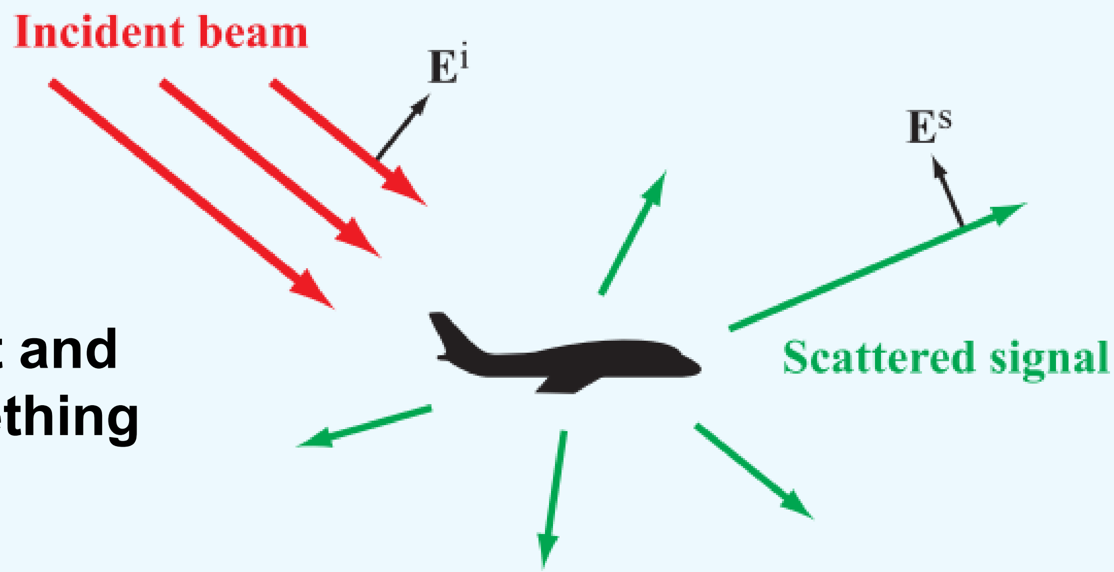
**Radar is a system that uses electromagnetic waves to identify the range, altitude, direction, or speed of both moving and fixed objects such as aircraft, ships, motor vehicles, weather formations, and terrain.**

**A radar system has a transmitter that emits either microwaves or radio waves that are reflected by the target and detected by a receiver, typically in the same location as the transmitter. Although the signal returned is usually very weak, the signal can be amplified.**

# Incident and scattering wave

**Incident beam**
**Incident angle**
**Scattered signal**

**Relation between incident and scattered wave tells something about the target!**

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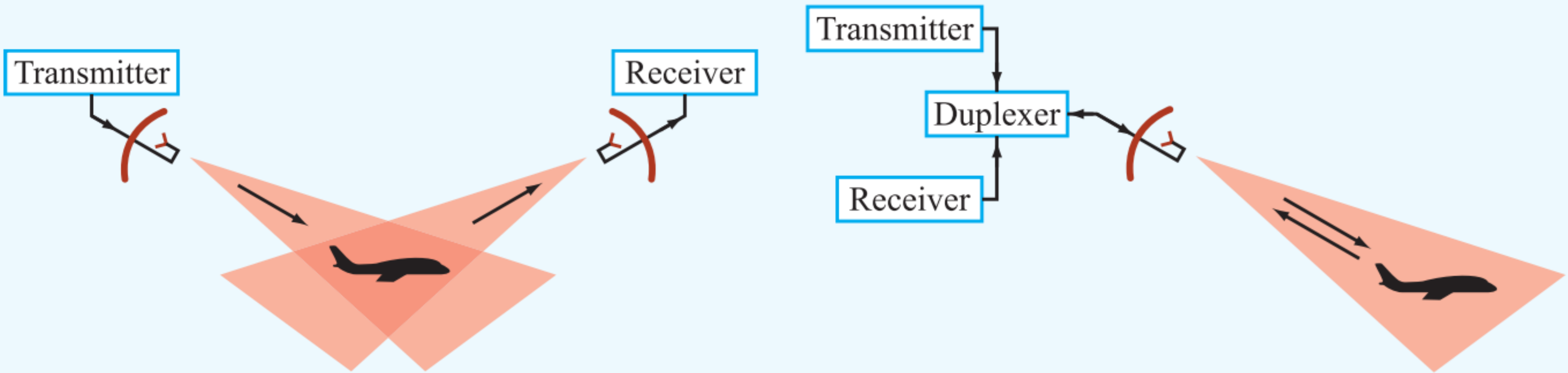
# Bistatic Radar vs Monostatic Radar




(a) Bistatic radar (b) Monostatic radar

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# Q?

**Which is more common, bistatic or monostatic radar?**

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# Coordinates

# EM wave in Spherical Coordinate System

$$\mathbf{E} = (\hat{\mathbf{v}} E_{\mathrm{v}} + \hat{\mathbf{h}} E_{\mathrm{h}}) e^{-jk\hat{\mathbf{k}}\cdot\hat{\mathbf{R}}}$$

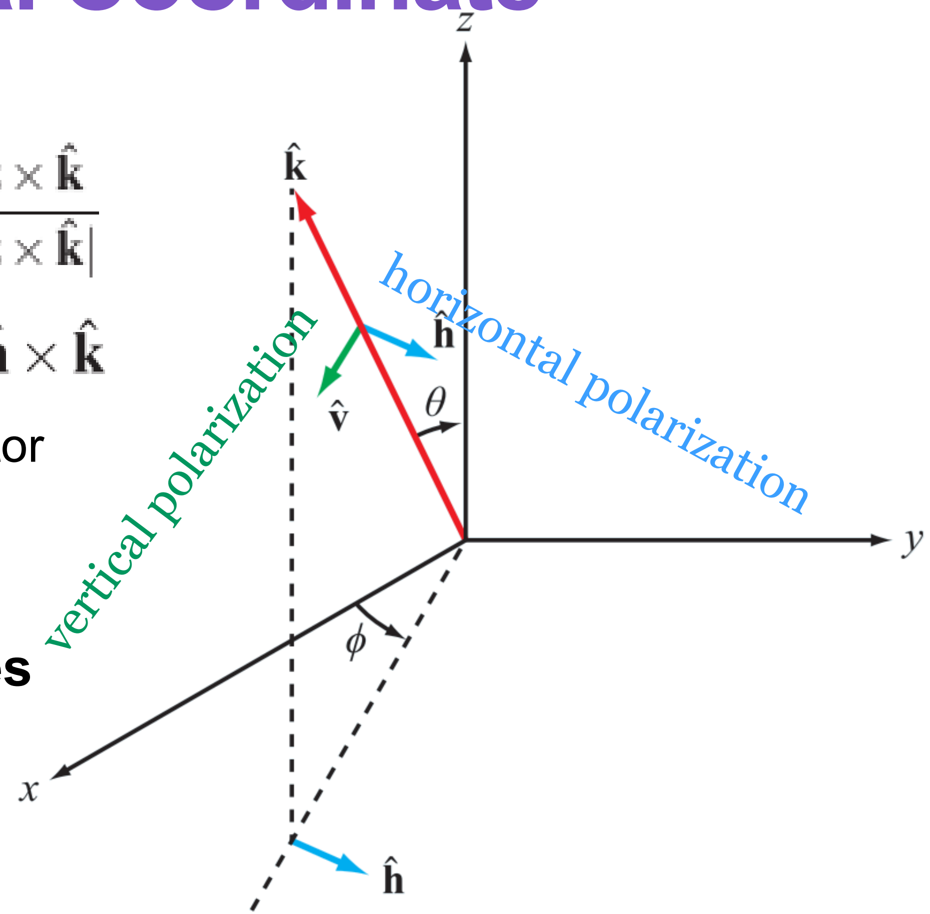
propagation phase factor

$$\hat{\mathbf{h}} = \frac{\hat{\mathbf{z}} \times \hat{\mathbf{k}}}{|\hat{\mathbf{z}} \times \hat{\mathbf{k}}|}$$

$$\hat{\mathbf{v}} = \hat{\mathbf{h}} \times \hat{\mathbf{k}}$$

$$\mathbf{E} = \begin{bmatrix} E_{\mathrm{v}} \\ E_{\mathrm{h}} \end{bmatrix}$$

**Complex amplitudes**



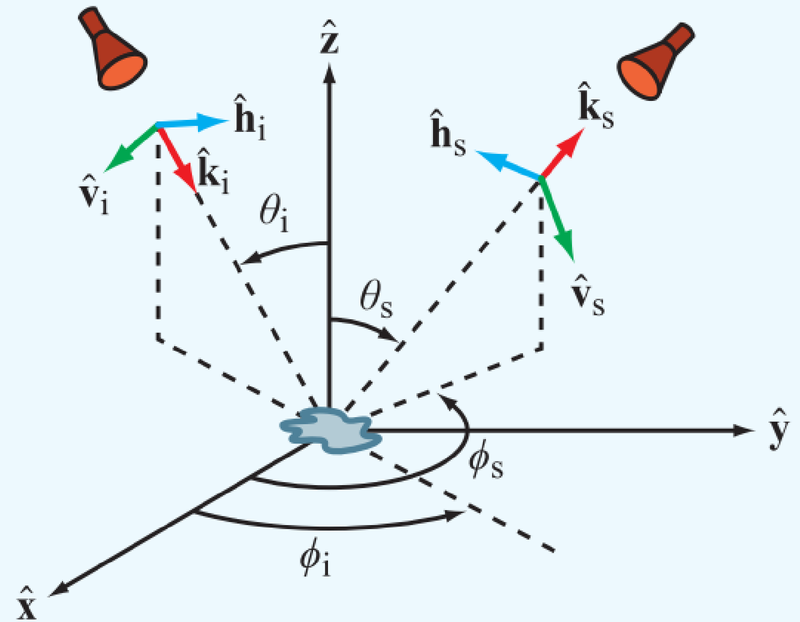
## Q?

## Where H V are not defined?

# Forward scattering alignment

FSA is a "wave-oriented" convention in that the directions of the vertical and horizontal unit vectors, **v** and **h**, are always defined with respect to the direction of propagation of the wave, **k**.

FSA is common in physics!




(a) FSA convention

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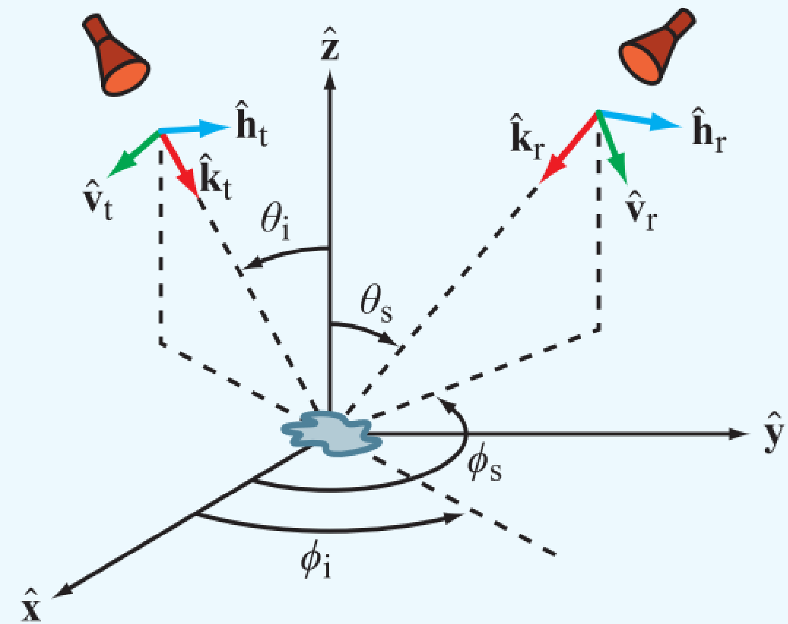
# Backscattering alignment

In the BSA convention the polarization unit vectors are defined with respect to the radar antennas.

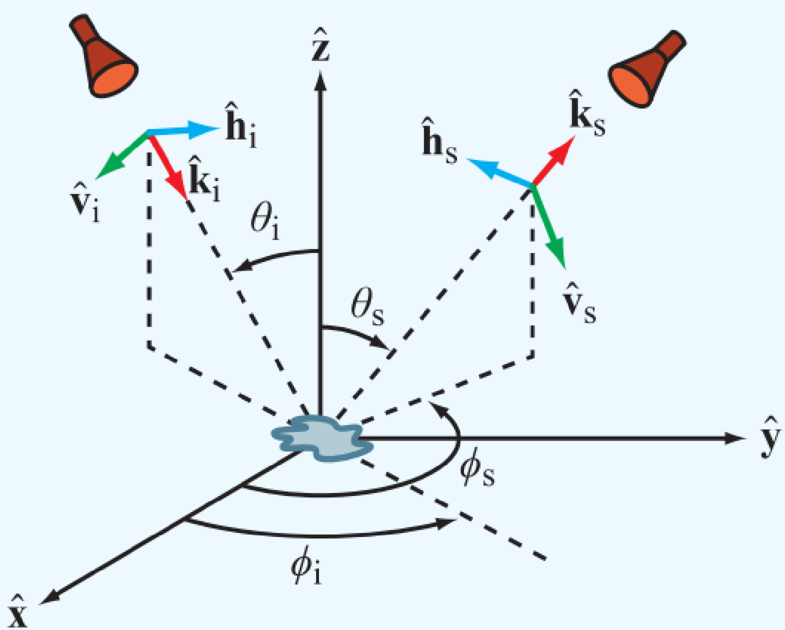
BSA convention, the vertical and horizontal unit polarization vectors of the scattered wave are **identical** with their counterparts of the incident wave.

BSA is common in engineering!

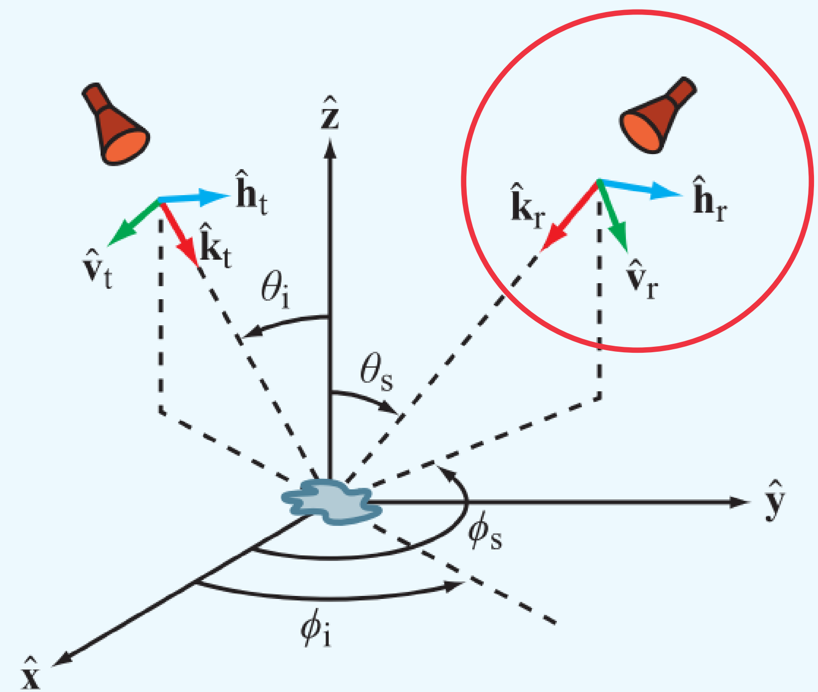



(b) BSA convention

# Scattering in FSA vs BSA




(a) FSA convention




(b) BSA convention

**Forward scatter alignment** **Backscatter alignment**

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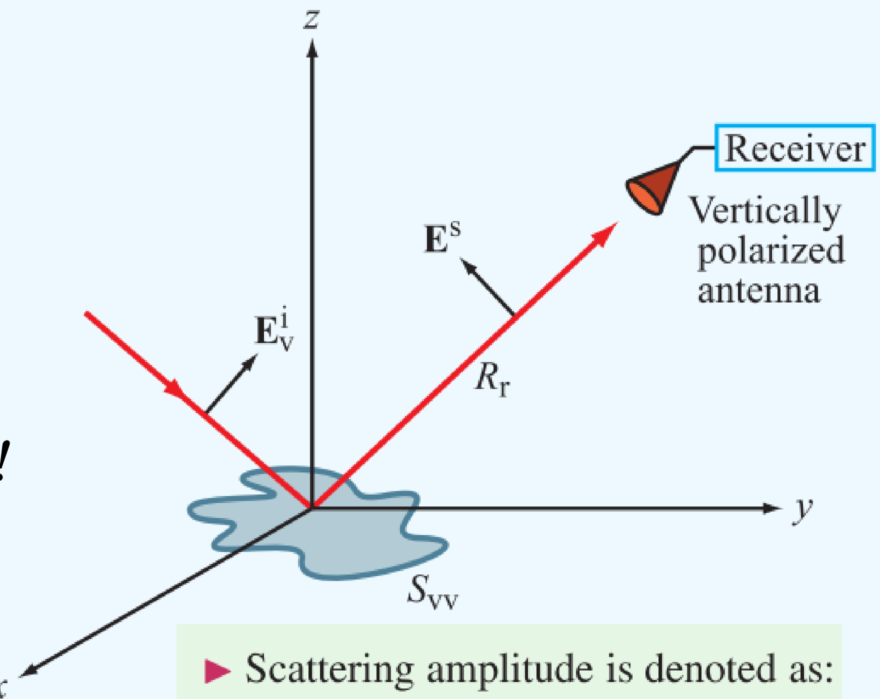
# Relation between $E^i$ and $E^s$

Single polarization case

$$E_h^s = \left(\frac{e^{-jkR_r}}{R_r}\right) \widetilde{S}_{hv}\, E_v^i$$

Where $\widetilde{S}_{hv}$ is *scattering amplitude defined at the location of the object!*

► Note that the first subscript of the scattering amplitude $\widetilde{S}_{pq}$ (where $p$ and $q$ may each be either v or h) refers to the polarization component of the scattered wave intercepted by the receive antenna and the second subscript refers to the polarization of the incident wave. ◄




► Scattering amplitude is denoted as:

$\widetilde{S}$ in FSA convention,
$S$ in BSA convention. ◄

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# Relation between $E^i$ and $E^s$

In the case of all E components

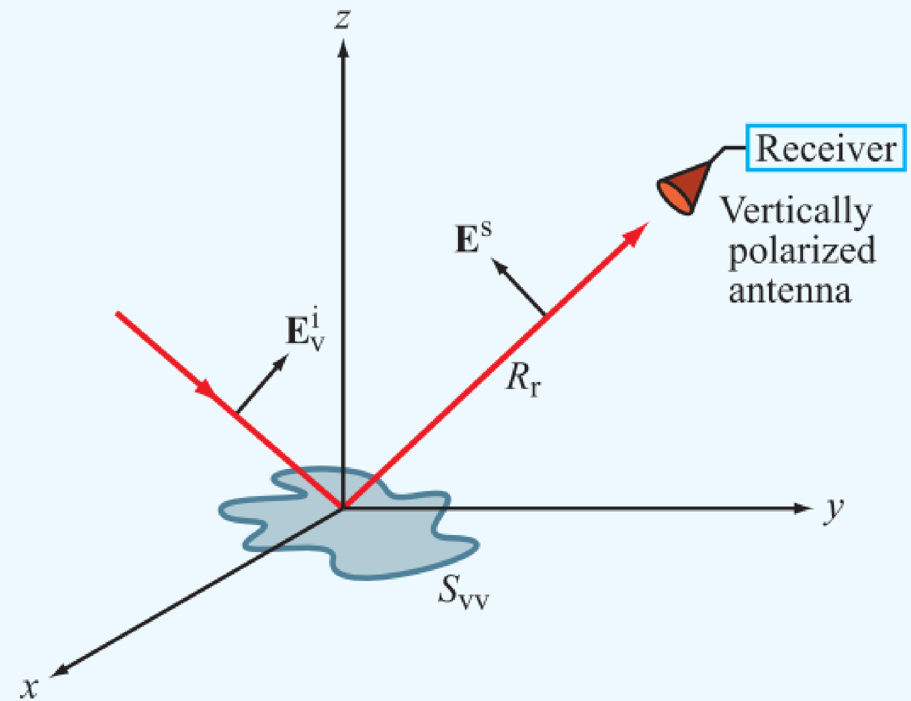
$$\mathbf{E}^{\mathrm{i}} = \hat{\mathbf{v}}_{\mathrm{i}} E^{\mathrm{i}}_{\mathrm{v}} + \hat{\mathbf{h}}_{\mathrm{i}} E^{\mathrm{i}}_{\mathrm{h}},$$

$$\mathbf{E}^{\mathrm{s}} = \hat{\mathbf{v}}_{\mathrm{s}} E^{\mathrm{s}}_{\mathrm{v}} + \hat{\mathbf{h}}_{\mathrm{s}} E^{\mathrm{s}}_{\mathrm{h}},$$

$$\begin{bmatrix} E^{\mathrm{s}}_{\mathrm{v}} \\ E^{\mathrm{s}}_{\mathrm{h}} \end{bmatrix} = \left( \frac{e^{-jkR_{\mathrm{r}}}}{R_{\mathrm{r}}} \right) \begin{bmatrix} \widetilde{S}_{\mathrm{vv}} & \widetilde{S}_{\mathrm{vh}} \\ \widetilde{S}_{\mathrm{hv}} & \widetilde{S}_{\mathrm{hh}} \end{bmatrix} \begin{bmatrix} E^{\mathrm{i}}_{\mathrm{v}} \\ E^{\mathrm{i}}_{\mathrm{h}} \end{bmatrix}$$

⇩

$$\mathbf{E}^{\mathrm{s}} = \left( \frac{e^{-jkR_{\mathrm{r}}}}{R_{\mathrm{r}}} \right) \widetilde{\mathbf{S}}\, \mathbf{E}^{\mathrm{i}}$$




$\widetilde{S}$ is the **scattering matrix**

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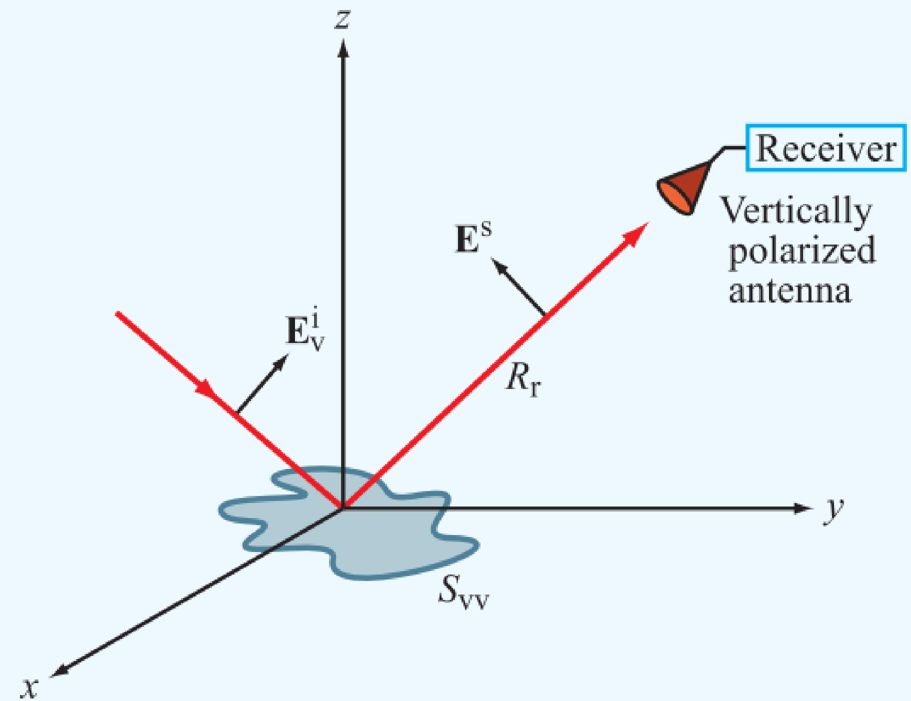
# Scattering matrix in BSA

$$\mathbf{S} = \begin{pmatrix} S_{\mathrm{vv}} & S_{\mathrm{vh}} \\ S_{\mathrm{hv}} & S_{\mathrm{hh}} \end{pmatrix} \qquad \textbf{(BSA)}$$

$$S_{\mathrm{vh}} = S_{\mathrm{hv}} \qquad \textbf{(backscatter)}.$$

Because of **reciprocity theorem**

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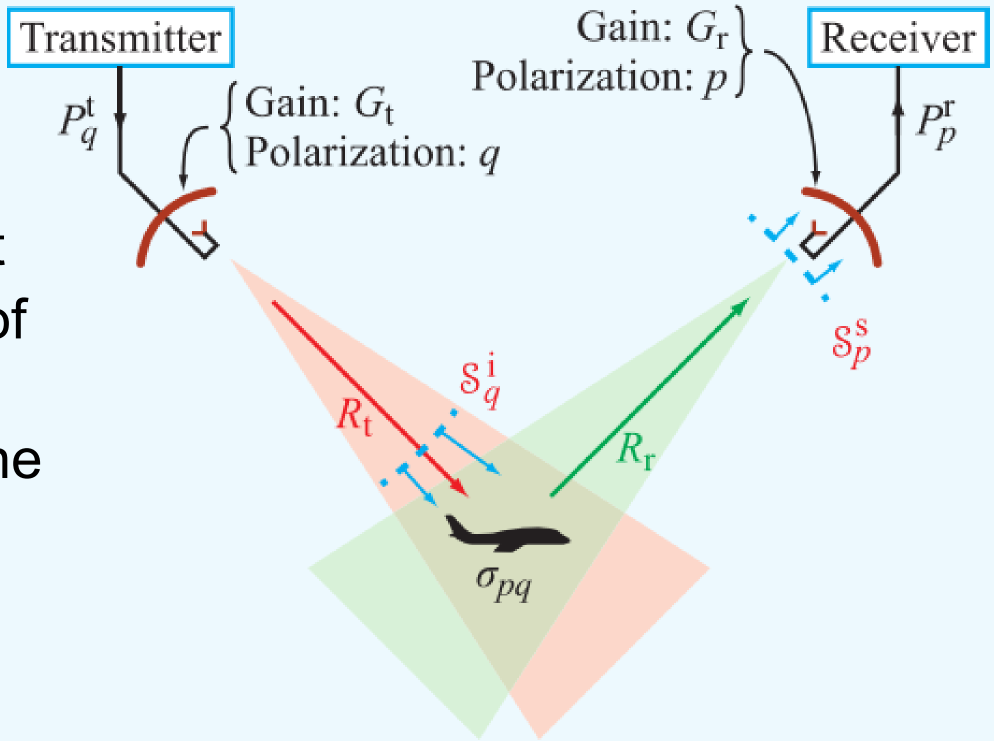
# Radar equation

Power density $\mathcal{S}_q^i$ of the incident wave is defined at the location of the target, whereas $\mathcal{S}_p^s$ of the scattered energy is defined at the location of the receive antenna.



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# Radar equation

Power density in target location

$$\delta_i = \frac{P^t G_t}{4\pi R_t^2}$$

Power received by target

$$P_{rs} = \delta_s A_{rs}$$

Power scattered by target

$$P_{ts} = P_{rs}(1 - f_a)$$

Power density in receiving antenna

$$\delta_r = \frac{P_{ts} G_{ts}}{4\pi R_t^2}$$

Power received by receiver antenna

$$P^r = \delta_r A_r$$

where

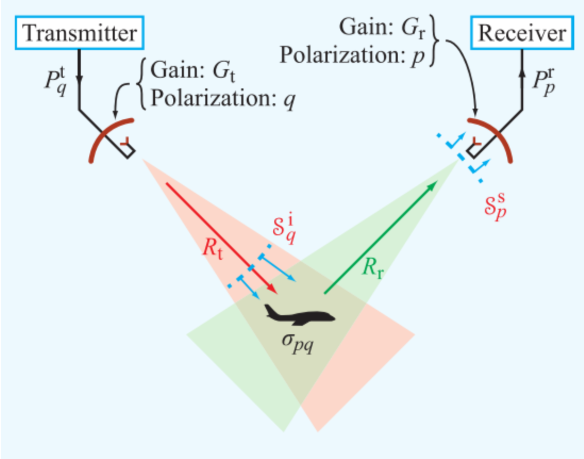
- $P^t$ = transmitter power
- $G_t$ = gain of the transmitting antenna
- $R_t$ = distance from the transmitter to the target
- $A_{rs}$ = effective aperture (area) of the target
- $\sigma$ = radar cross section, or scattering coefficient, of the target
- $f$ = target absorbtion
- $G_{ts}$ = target amplification to antenna direction
- $R_r$ = distance from the target to the receiver
- $A_r$ = effective aperture (area) of the receiving antenna

$\sigma$ Radar scattering cross section

$$P^r = \frac{P^t G_t A_r}{(4\pi)^2 R_t^2 R_r^2}\left[A_{rs}(1 - f_a)G_{ts}\right]$$

# Point target radar equation

$$\frac{P_p^{\mathrm{r}}}{P_q^{\mathrm{t}}} = \frac{G_{\mathrm{t}} G_{\mathrm{r}} \lambda^2}{(4\pi)^3 R_{\mathrm{t}}^2 R_{\mathrm{r}}^2} \sigma_{pq} \quad \text{(point-target bistatic radar equation).} \tag{5.29a}$$




When transmitting and receiving antenna are at the same spot

$$R_{\mathrm{t}} = R_{\mathrm{r}} = R \qquad G = G_{\mathrm{t}} = G_{\mathrm{r}}.$$

$$\frac{P_p^{\mathrm{r}}}{P_q^{\mathrm{t}}} = \frac{G^2 \lambda^2}{(4\pi)^3 R^4} \sigma_{pq} \quad \text{(point-target monostatic radar equation),} \tag{5.29b}$$

**Radar cross section unit is area**

# Radar cross section

Radar cross section describes detectability of an object by the radar. Typically radar aperture is big and the terget is small, (often assumed a point target).

Radar cross section unit is area unit ($m^2$)

Radar cross section (RCS) and radar backscattering are the same thing

# Connection between $\sigma$ and $S$

$p, q = \text{v or h}$

**For simple point target the relation is:**

$$\sigma_{pq} = \lim_{R_r \to \infty} \left( 4\pi R_r^2 \frac{\mathcal{S}_p^s}{\mathcal{S}_q^i} \right)$$

$$\sigma_{pq} = 4\pi |\widetilde{S}_{pq}|^2.$$

$$\mathcal{S}_p^s = |E_p^s|^2 / 2\eta_0$$

$$\mathcal{S}_q^i = |E_q^s|^2 / 2\eta_0$$

$$\widetilde{S}_{pq} = \widetilde{S}_{pq}(\theta_i, \phi_i;\ \theta_s, \phi_s; \theta_j, \phi_j) = \lim_{R_r \to \infty} \left[ R_r e^{-jkR_r} \left( \frac{E_p^s}{E_q^i} \right) \right]$$

# dB
# Decibel scale

$$G = \frac{P_1}{P_2}$$

$$G\ [\text{dB}] = 10\log G = 10\log\left(\frac{P_1}{P_2}\right) \qquad \text{(dB)}$$

$$\begin{aligned} A &= 10\log\left[\frac{\mathcal{S}(z)}{\mathcal{S}(0)}\right] \\ &= 10\log(e^{-2\alpha z}) \\ &= -20\alpha z \log e \\ &= -8.68\alpha z = -\alpha\ [\text{dB/m}]\ z \qquad \text{(dB)} \end{aligned}$$

$$\alpha\ [\text{dB/m}] = 8.68\alpha\ [\text{Np/m}]$$

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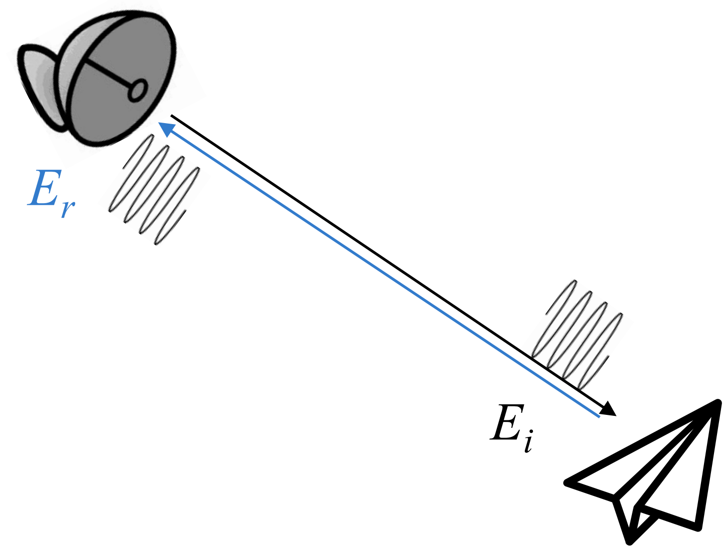
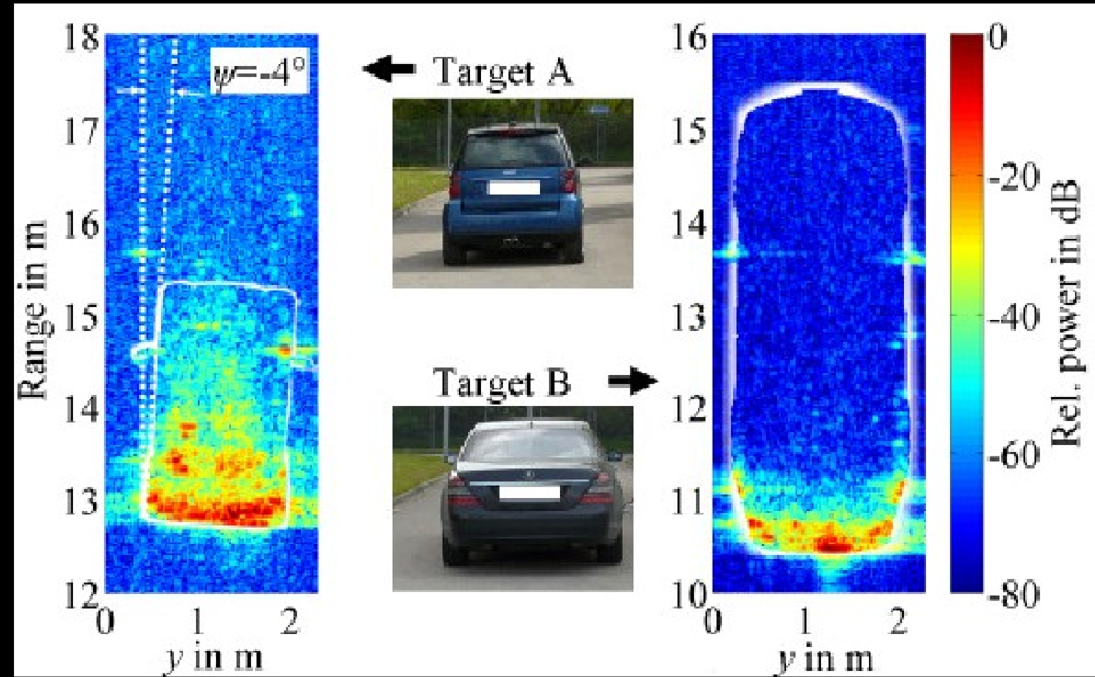
**Table 2-2: Power ratios in natural numbers and in decibels.**

| $G$ | $G$ [dB] |
|---|---|
| $10^x$ | $10x$ dB |
| 4 | 6 dB |
| 2 | 3 dB |
| 1 | 0 dB |
| 0.5 | −3 dB |
| 0.25 | −6 dB |
| 0.1 | −10 dB |
| $10^{-3}$ | −30 dB |

# Radar measurement value



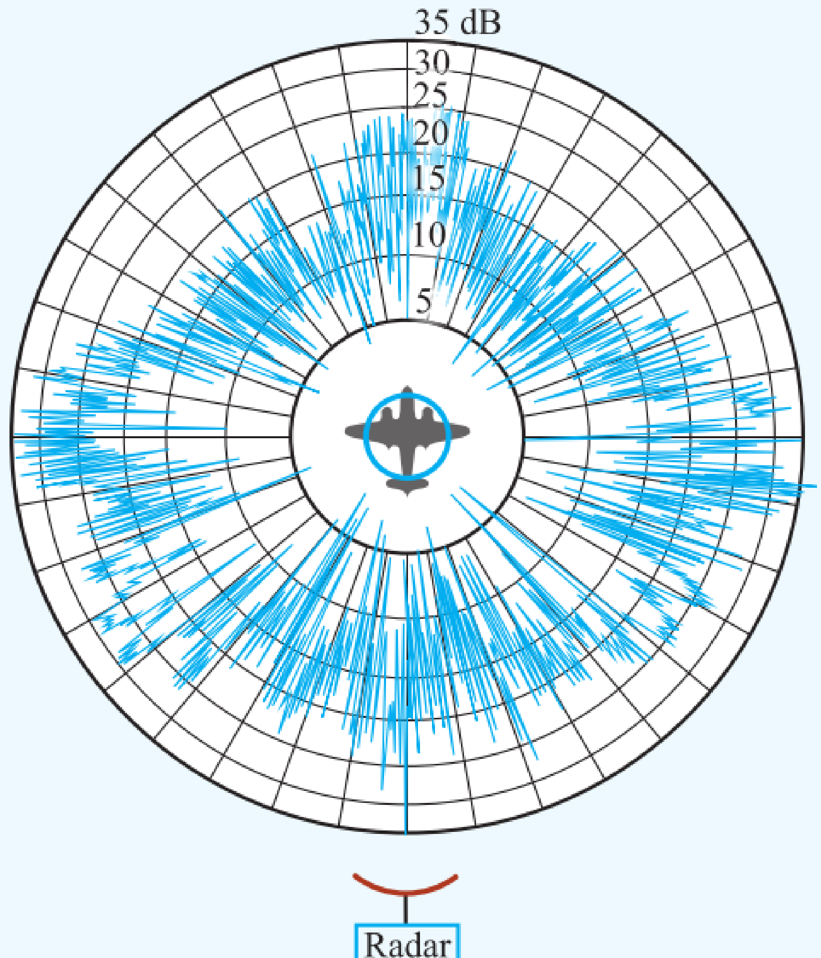

$$\rho = \frac{E_r}{E_i} = a + jb = Ae^{j\phi}$$



Range in m
y in m
ψ=-4°
Target A
Target B
Rel. power in dB


SILENT EAGLE

# Dependence on geometry

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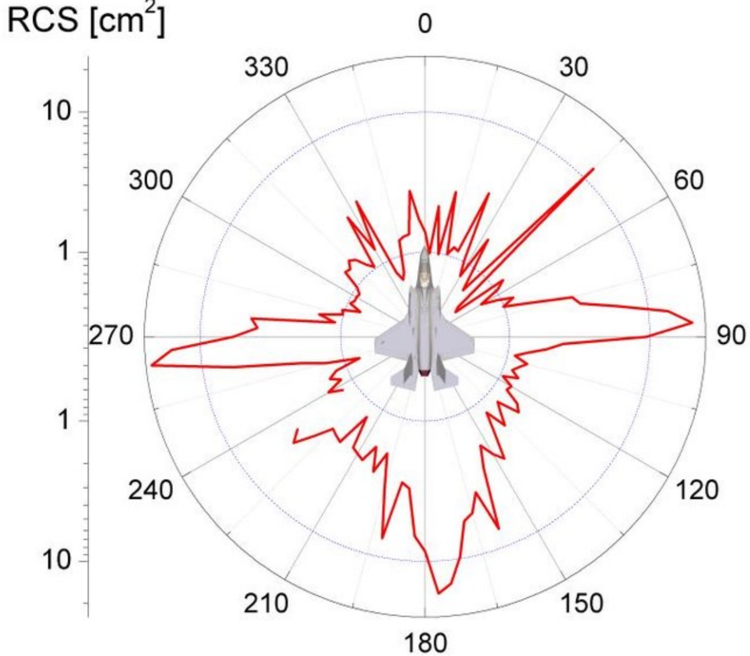
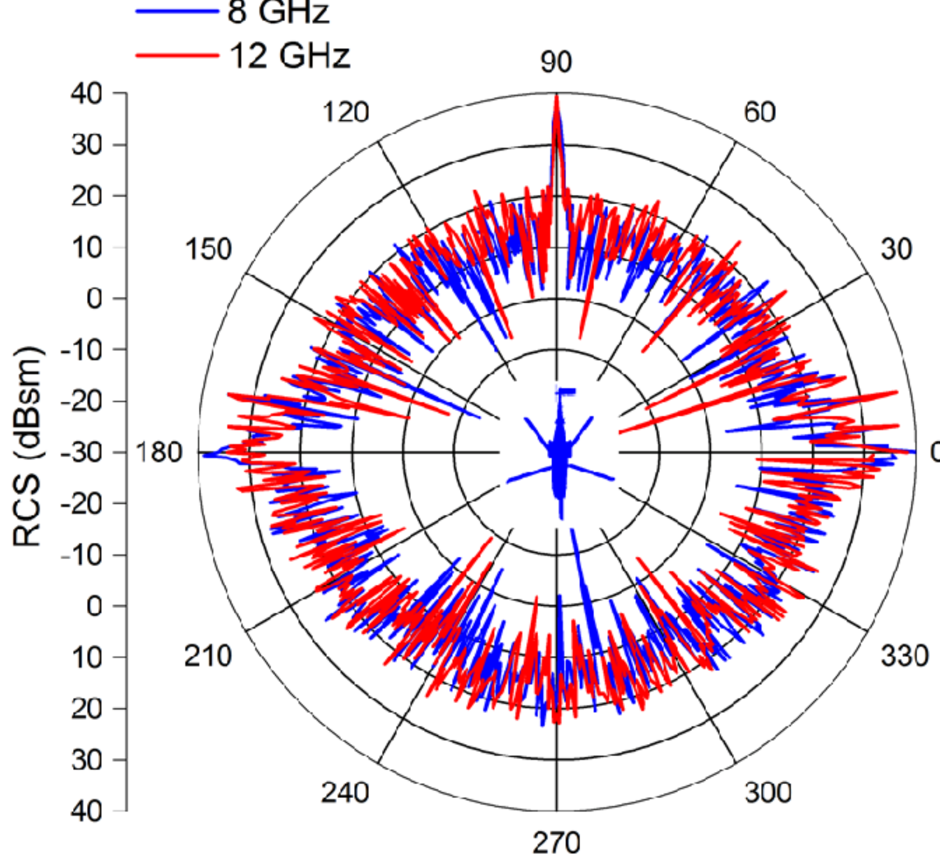
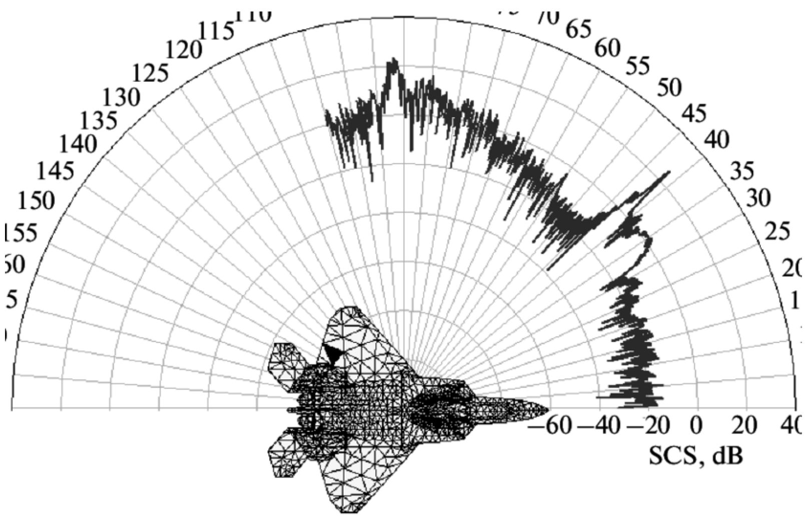
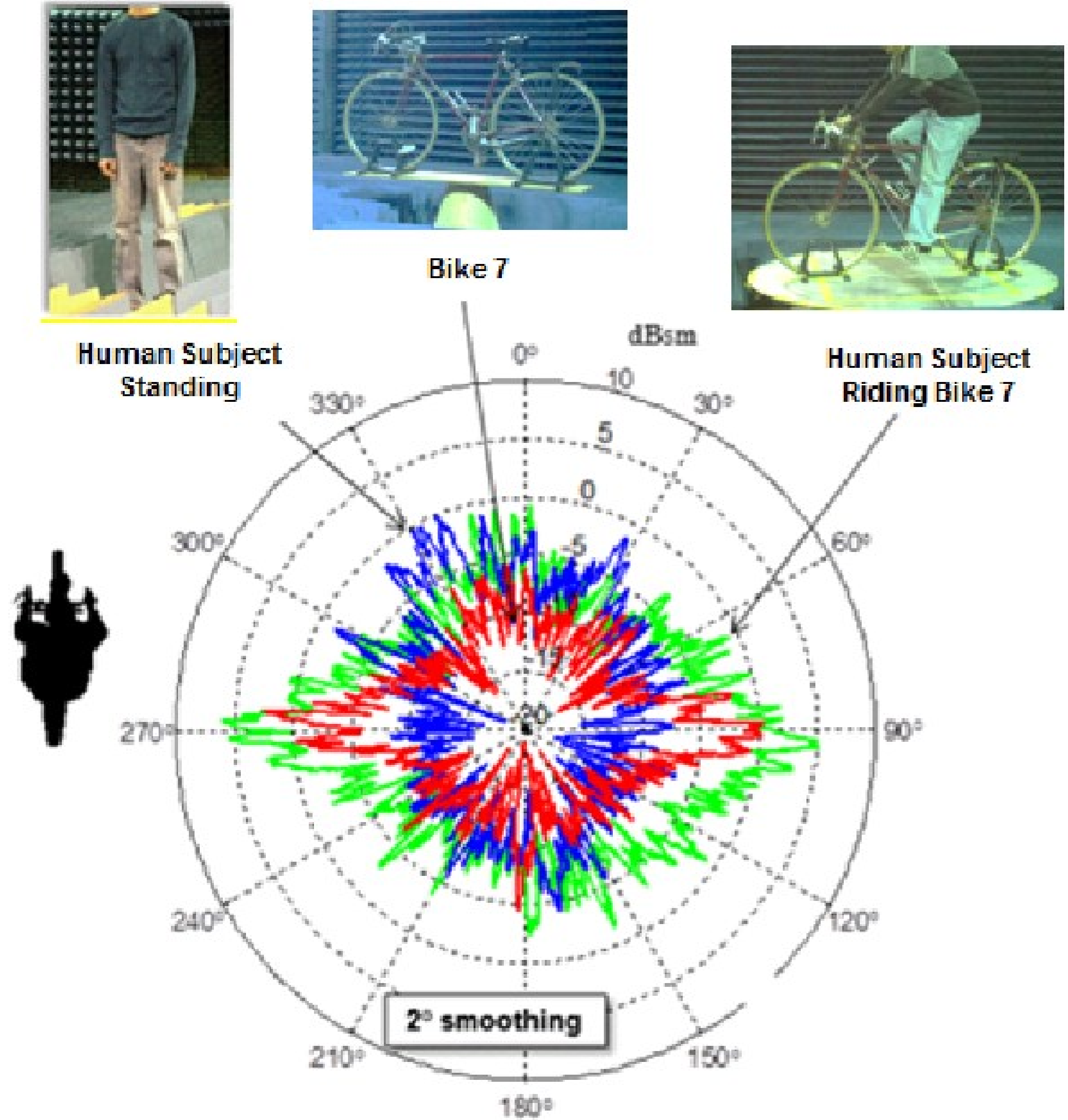
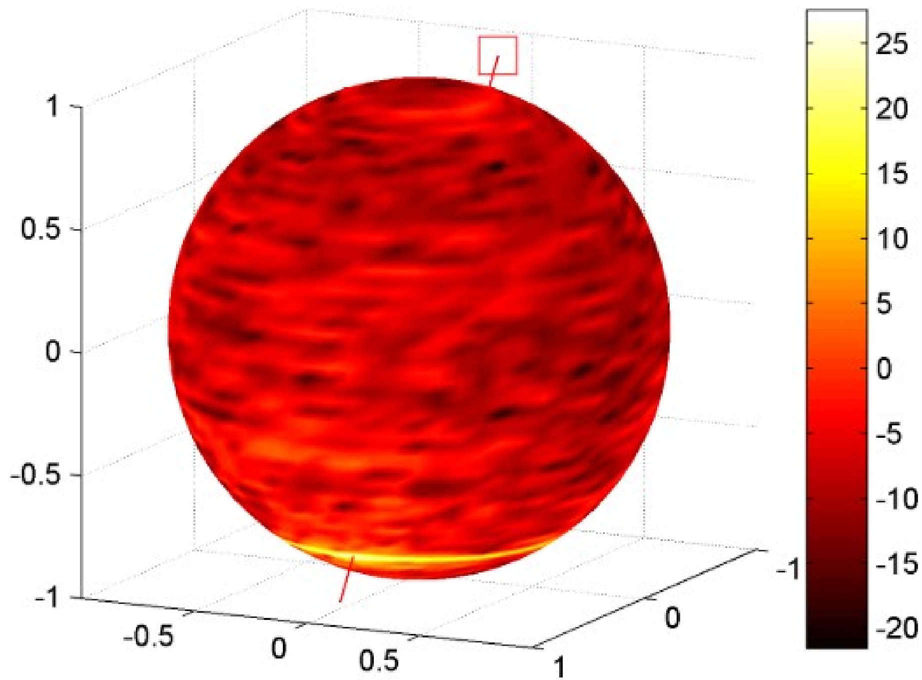

RCS [cm²]
0
30
60
90
120
150
180
210
240
270
300
330
10
1
1
10


8 GHz
12 GHz
RCS (dBsm)
90
120
60
150
30
180
210
330
240
300
270
40
30
20
10
0
-10
-20
-30
-20
-10
0
10
20
30
40

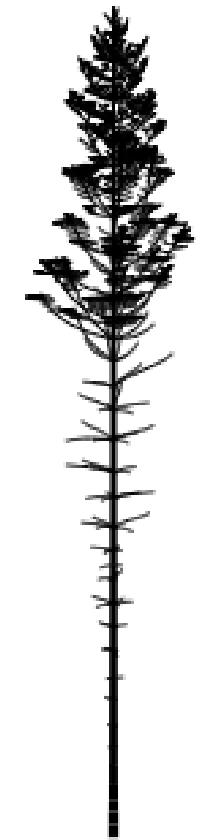

SCS, dB
−60 −40 −20 0 20
115
120
125
130
135
140
145
150
65
60
55
50
45
40
35
30
25

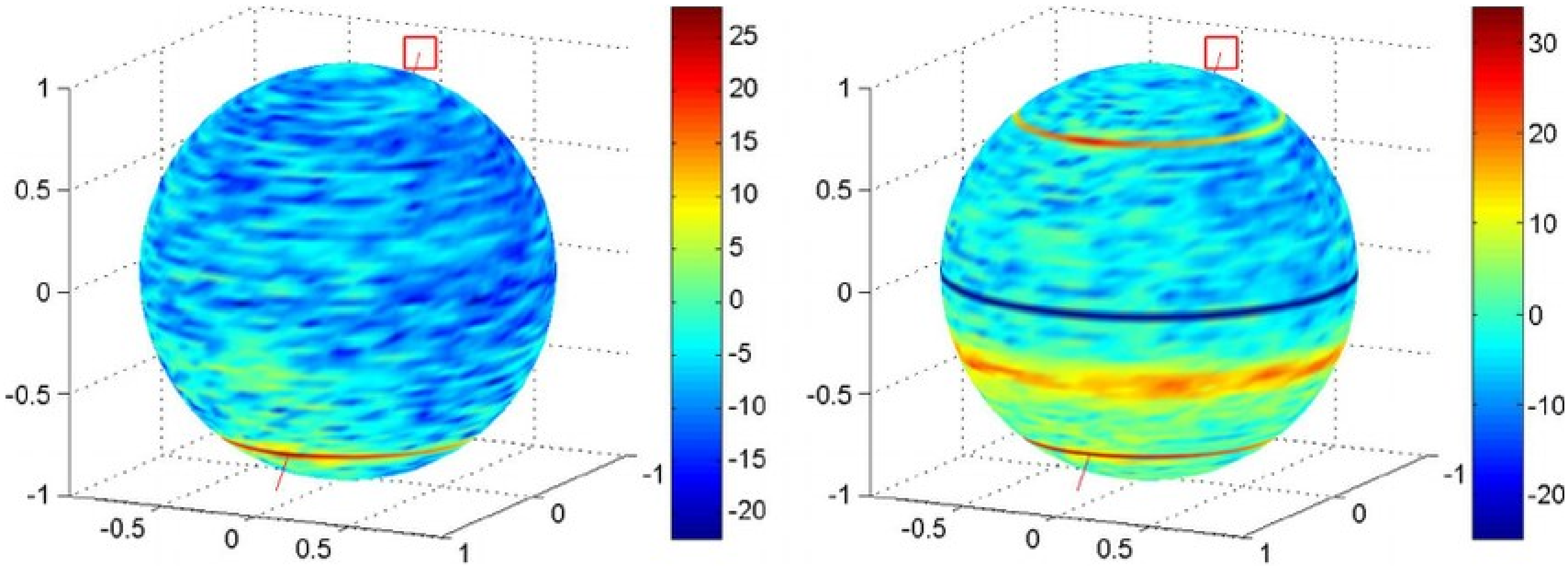

Bike 7
Human Subject Standing
Human Subject Riding Bike 7
dBsm
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
10
5
0
-5
-15
-20
2° smoothing

# Scattering pattern from a tree



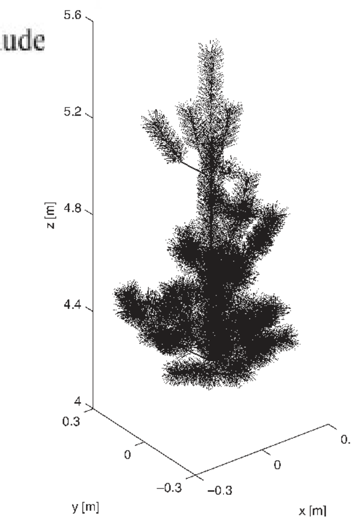

(a) Scattering from the pine tree without ground contribution.






(a) Without ground reflection

(b) Ground reflection include

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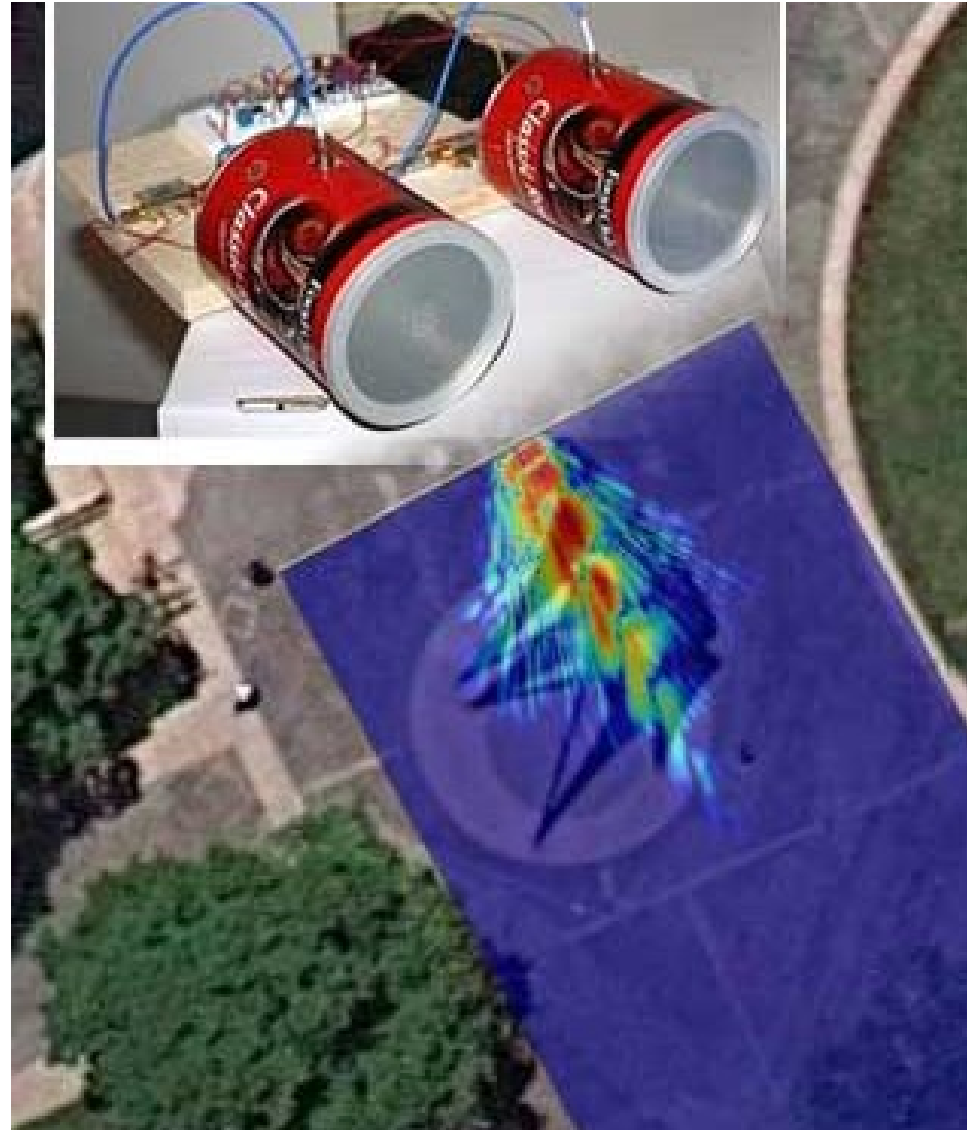
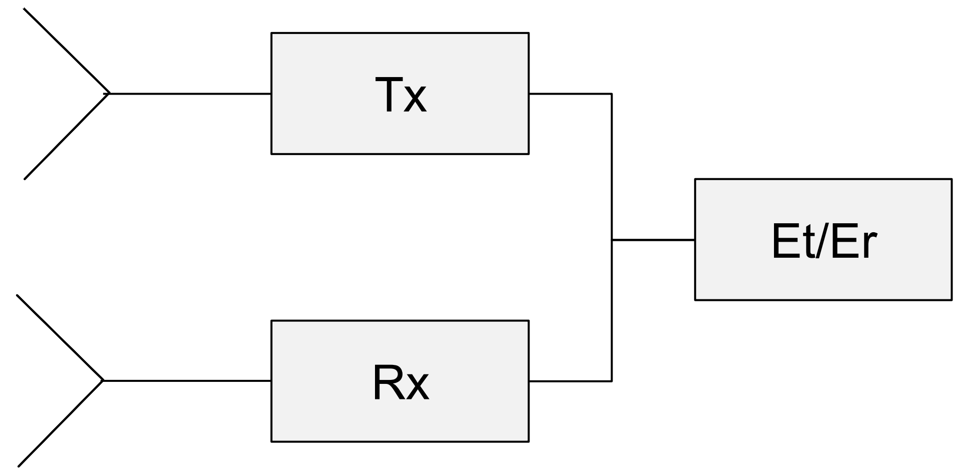
# simple RADAR

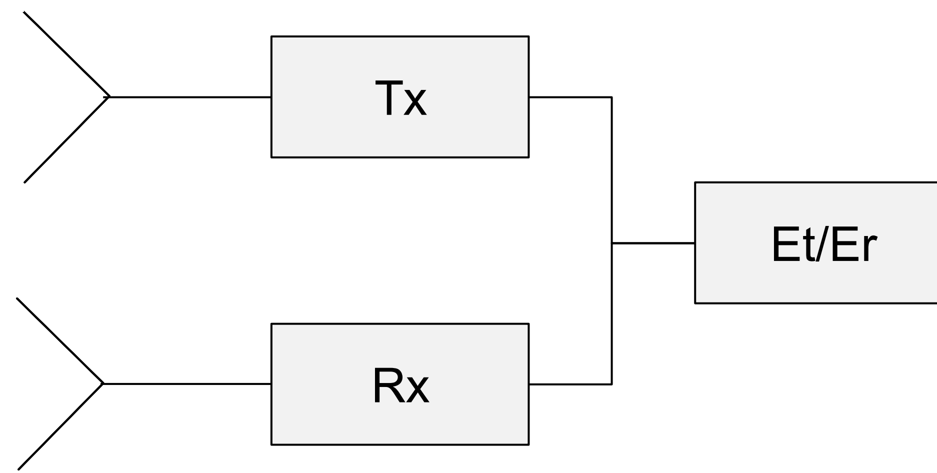


# Radar, how to separate transmission and reception

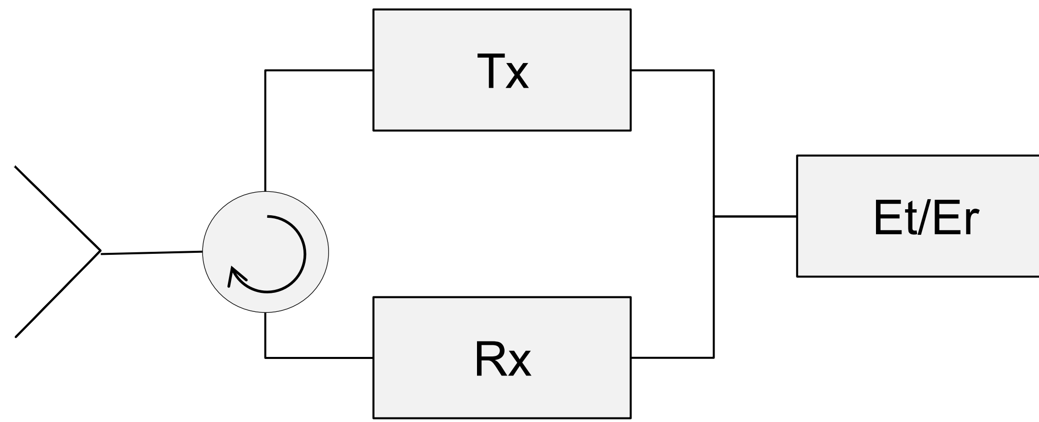
?



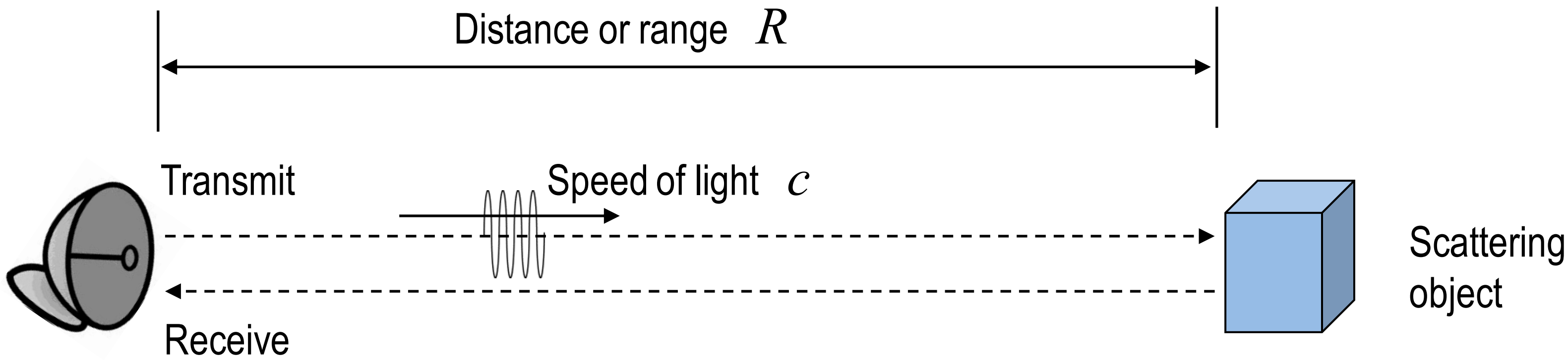
# Two strategies to make a radar
# Two antennas, separation in frequency



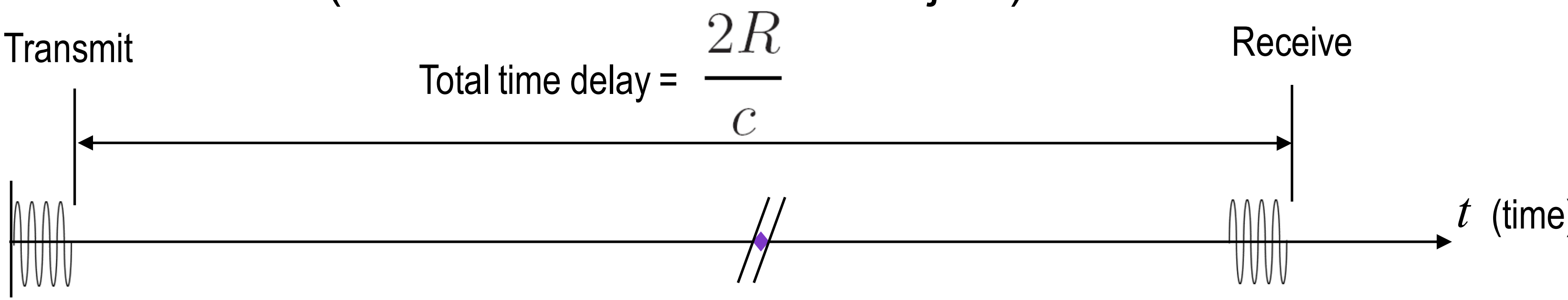
# Two strategies to make a radar one antenna, separation in time



# Radar measurement: temporal dimension




Received echo (backscattered from the object)

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# Time measurement problem

**Radar seems simple. Send the pulses and detect the time pulse traveled…**

Speed of light: 299 792 458 m/s

1 m in 0.0000000033 s

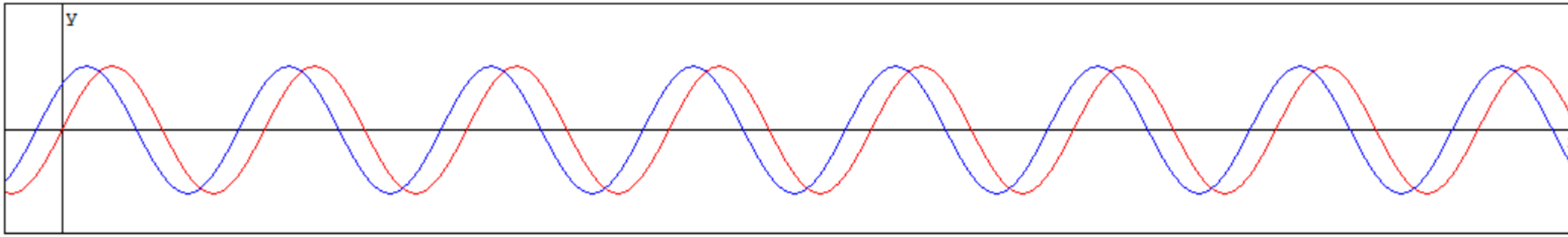
Sampling 100 x frequency..

100*c Hz=30 GHz

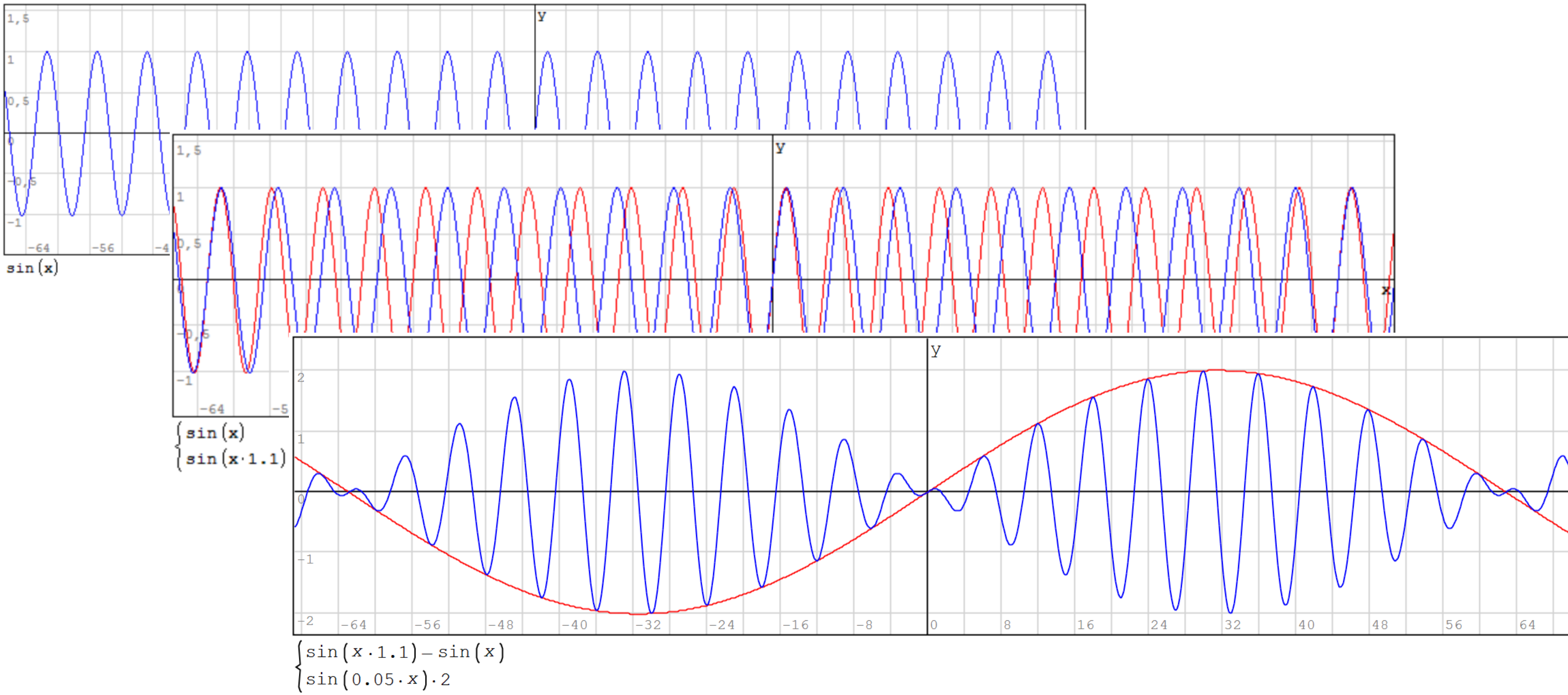
# Frequency differences

**It is easier to measure differences between frequencies than frequencies itself.**

# Two-way phase delay



# Mixing(Heterodyning)

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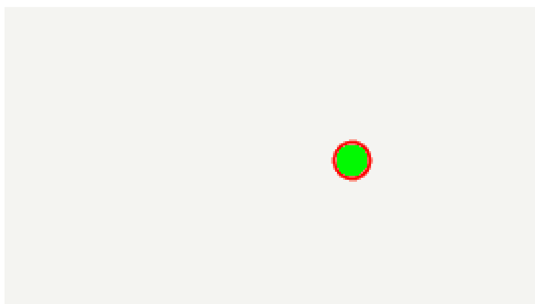
# Doppler frequency is easy to measure as frequency difference!



Example

2.4 GHz radar

Walking person 3 m/s

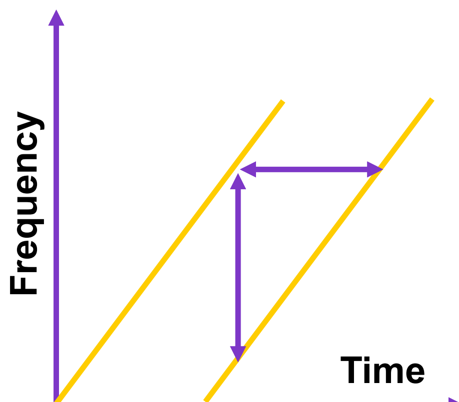
Frequency shift

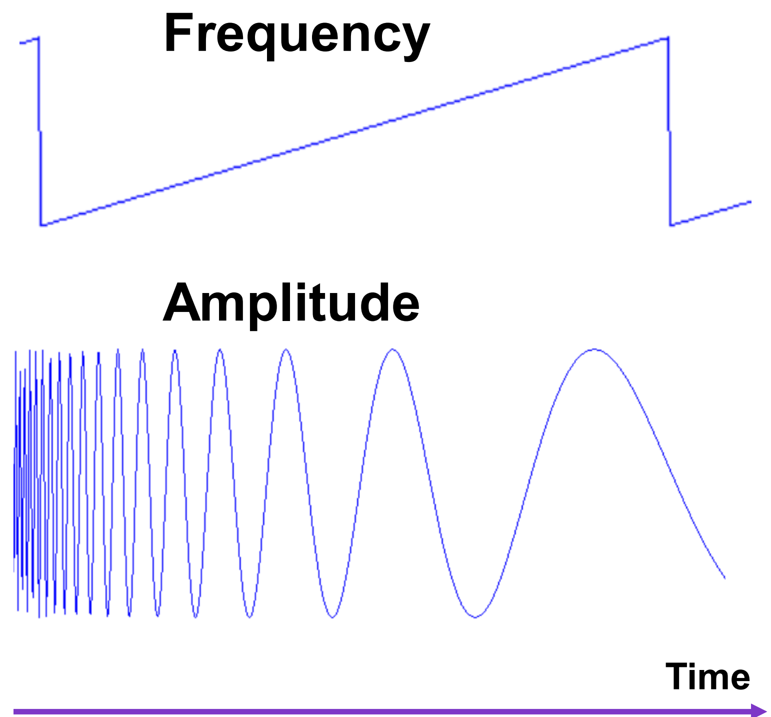
$$\Delta f = f\frac{v}{c}$$

24 Hz

# Also the distance can be measured as frequency difference

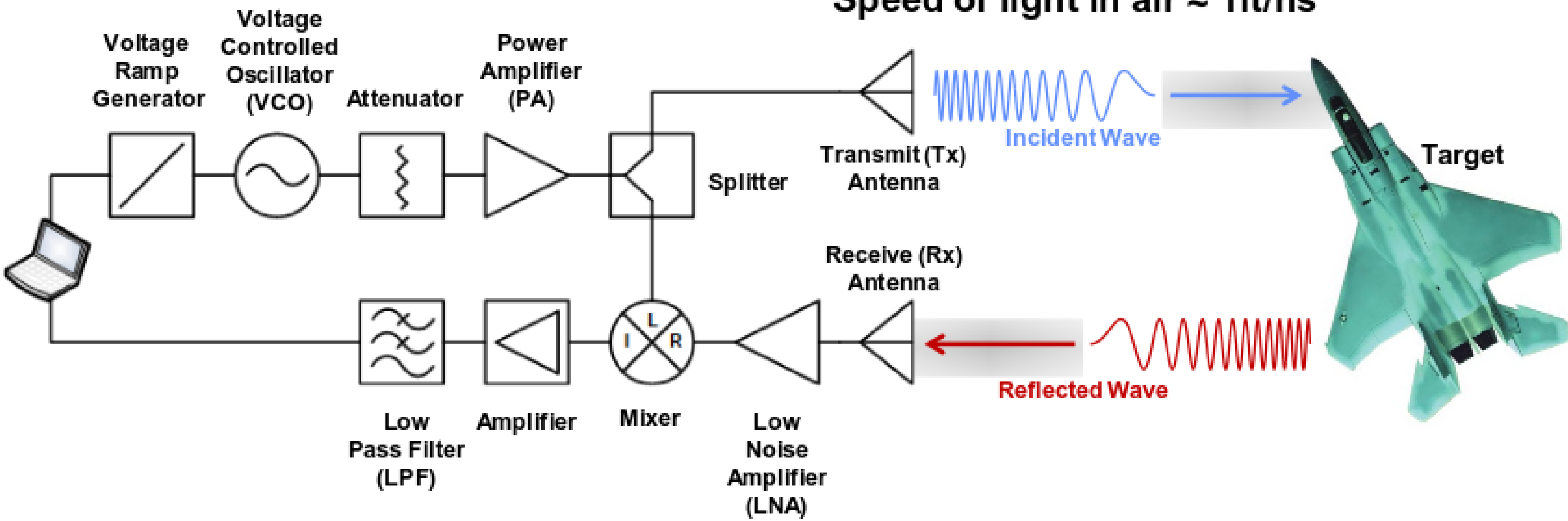
**If the transmitted frequency is changed over time, we can measure the distance as frequency difference as well.**



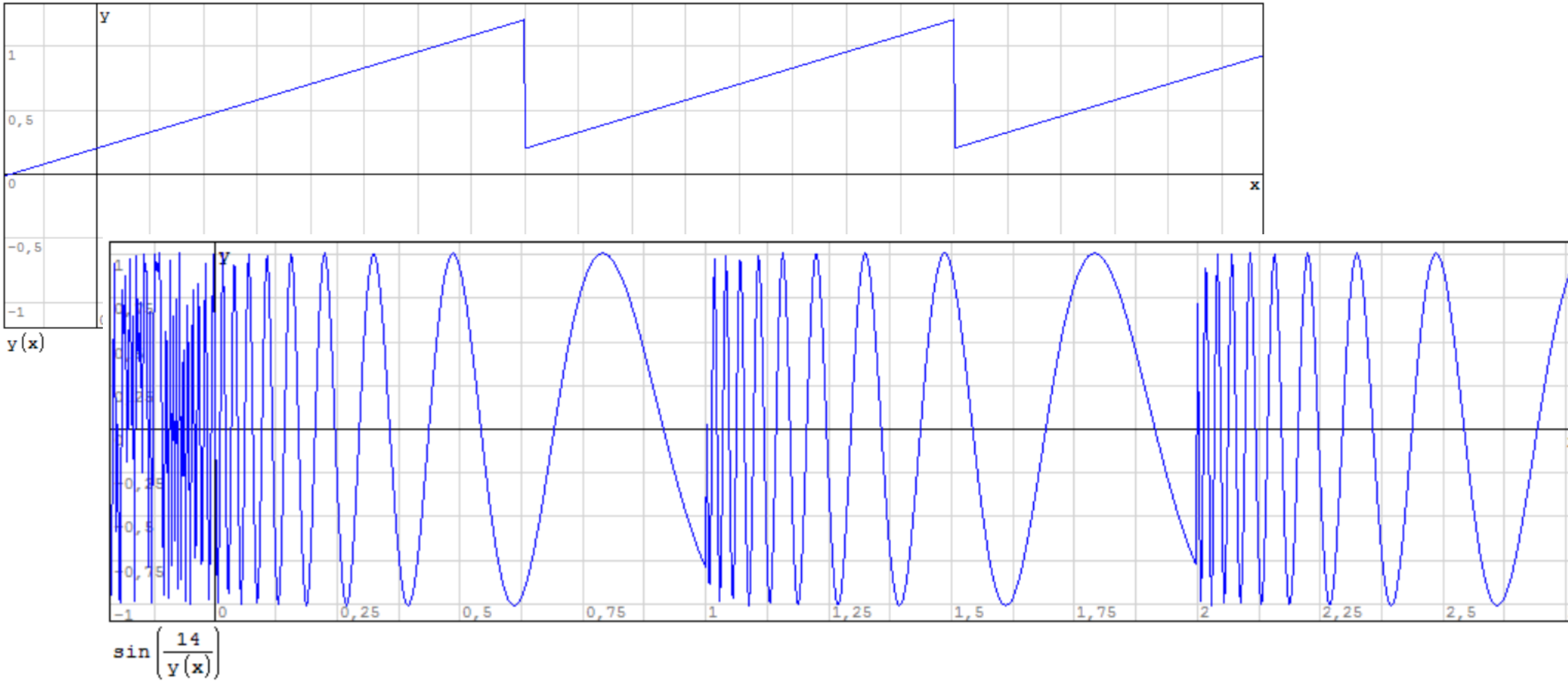



# Simple continuous wave radar

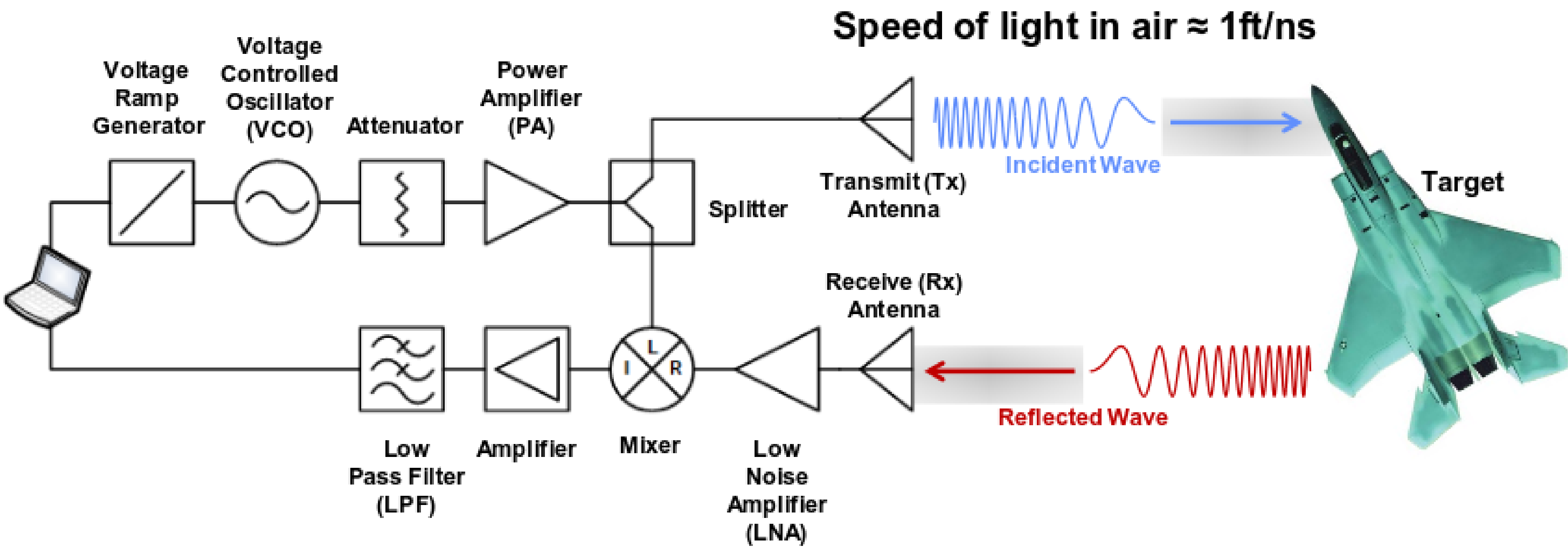
Speed of light in air ≈ 1ft/ns

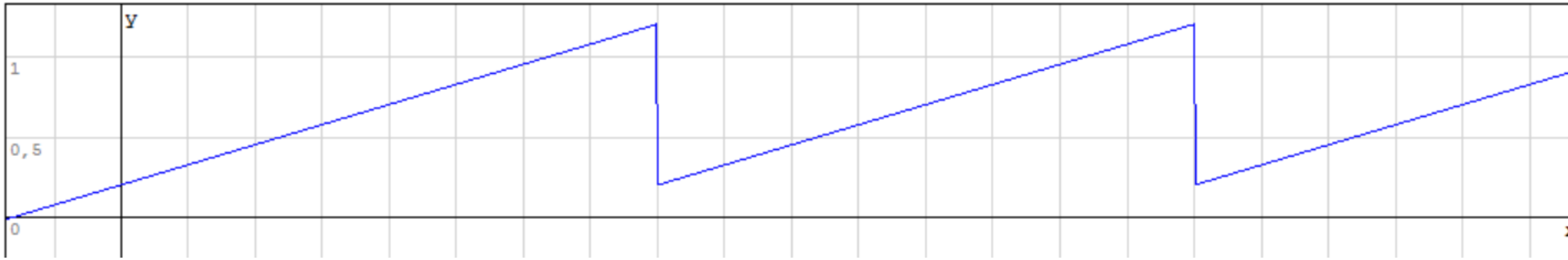


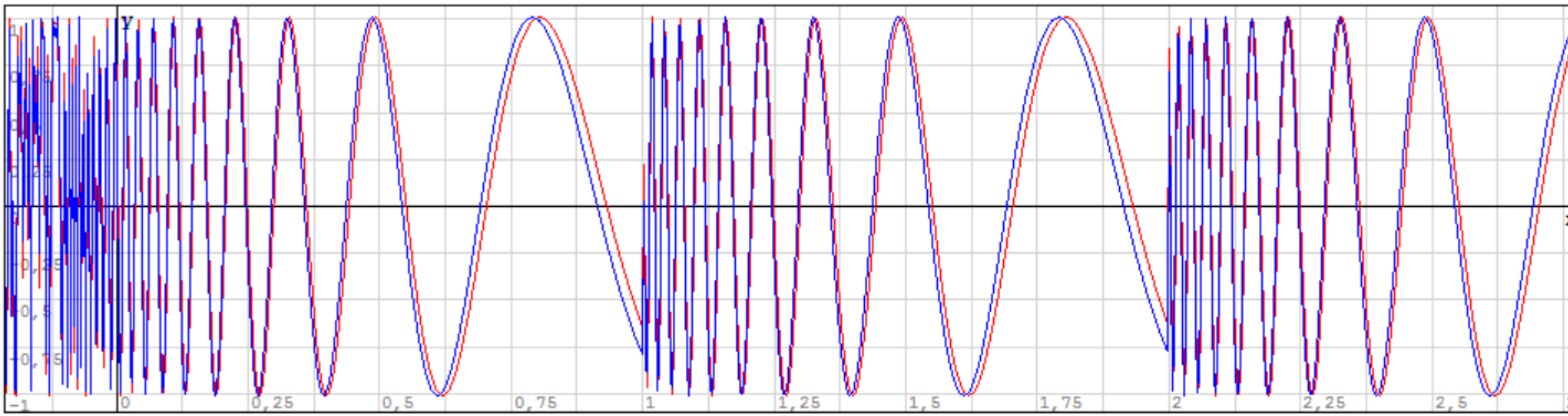
# Modulating



# Simple continuous wave radar






$$\sin\left(\frac{14}{y(x)}\right)$$

$$\sin\left(\frac{14}{y(x)}+0.2\right)$$

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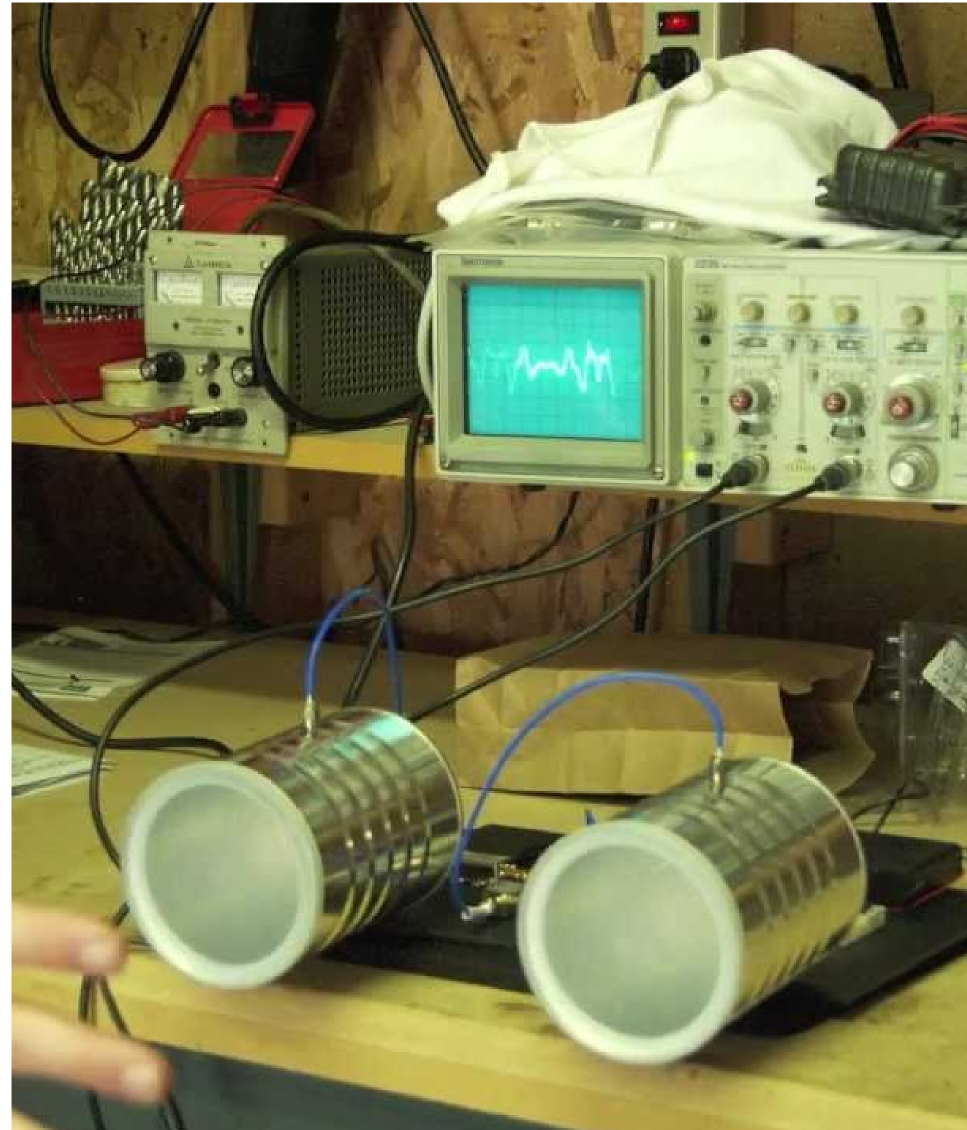
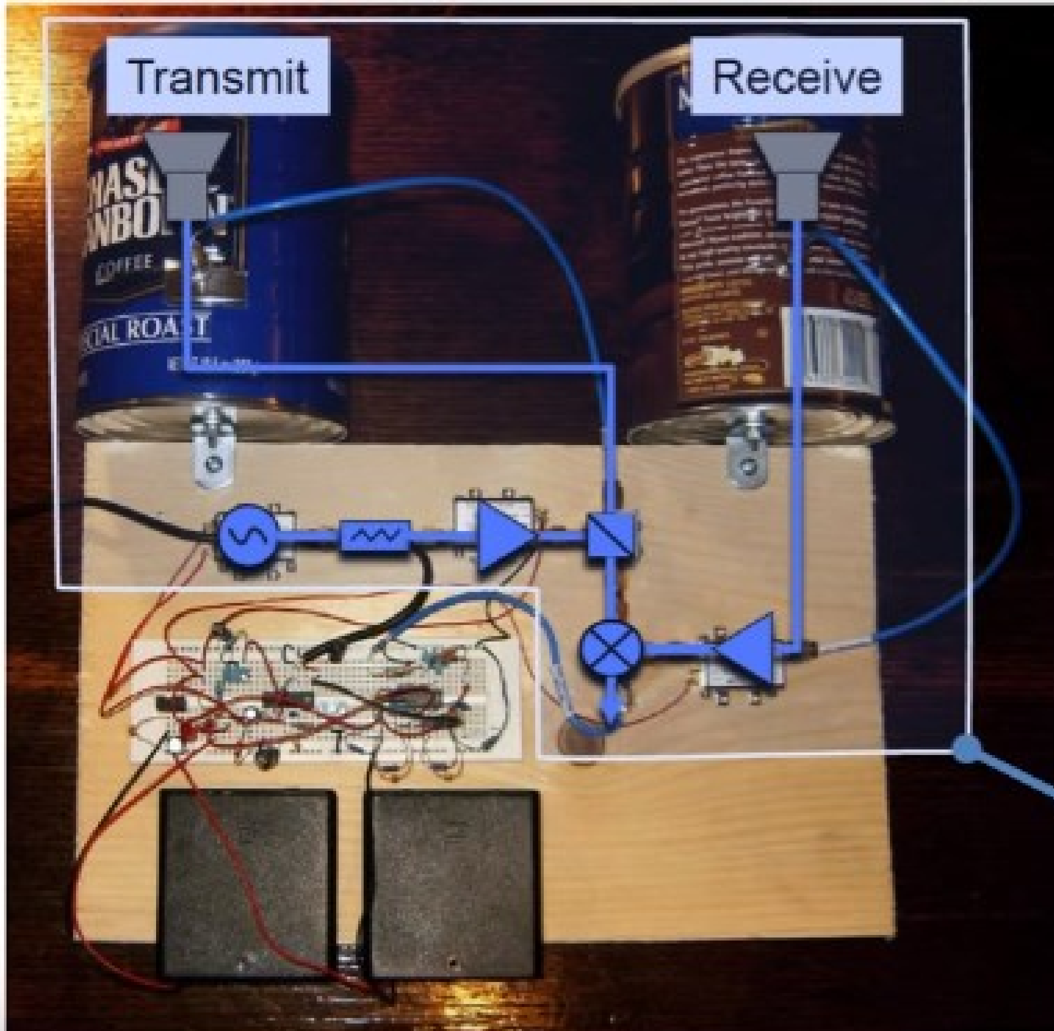
# Coffe-Can Radar






**Coffee-Can Radar***

Total BOM Cost : $360

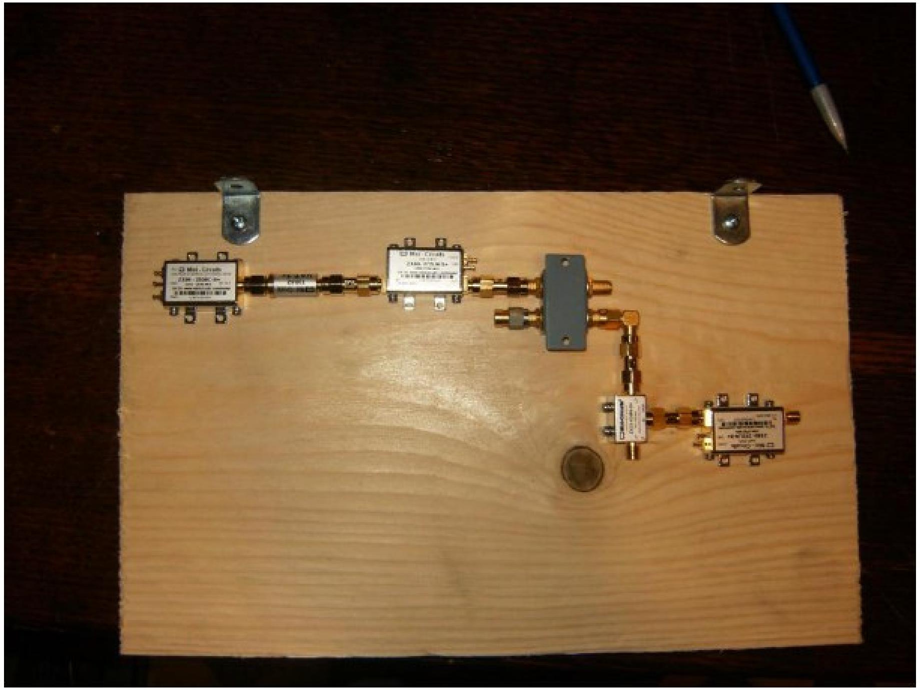
- RF BOM: $236
- Cantenna BOM: $54

Size ~ 15x12"

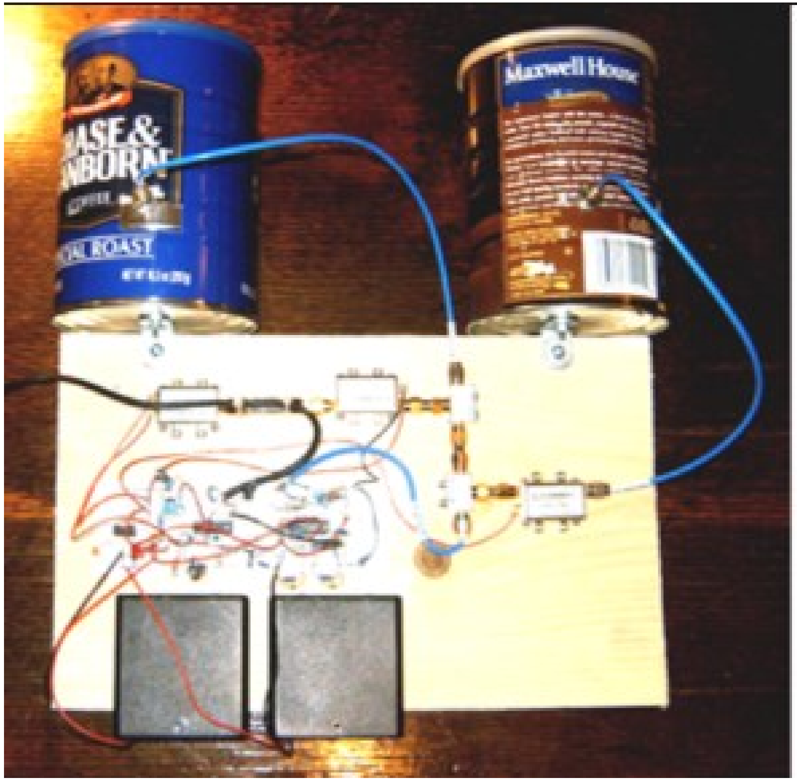
*Redesign this RF radar core*

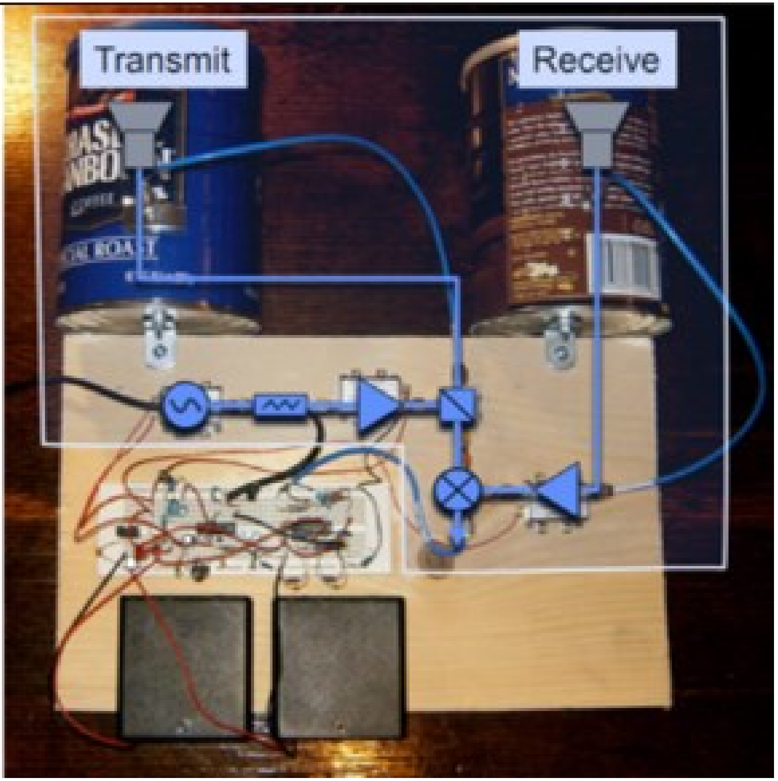
http://ocw.mit.edu/resources/res-ll-003-build-a-small-radar-system-capable-of-sensing-range-doppler-and-synthetic-aperture-radar-imaging-january-iap-2011/projects/MITRES_LL_003IAP11_proj_in.pdf

## MIT course how to build a simple FMCW radar



# Coffe can Radar

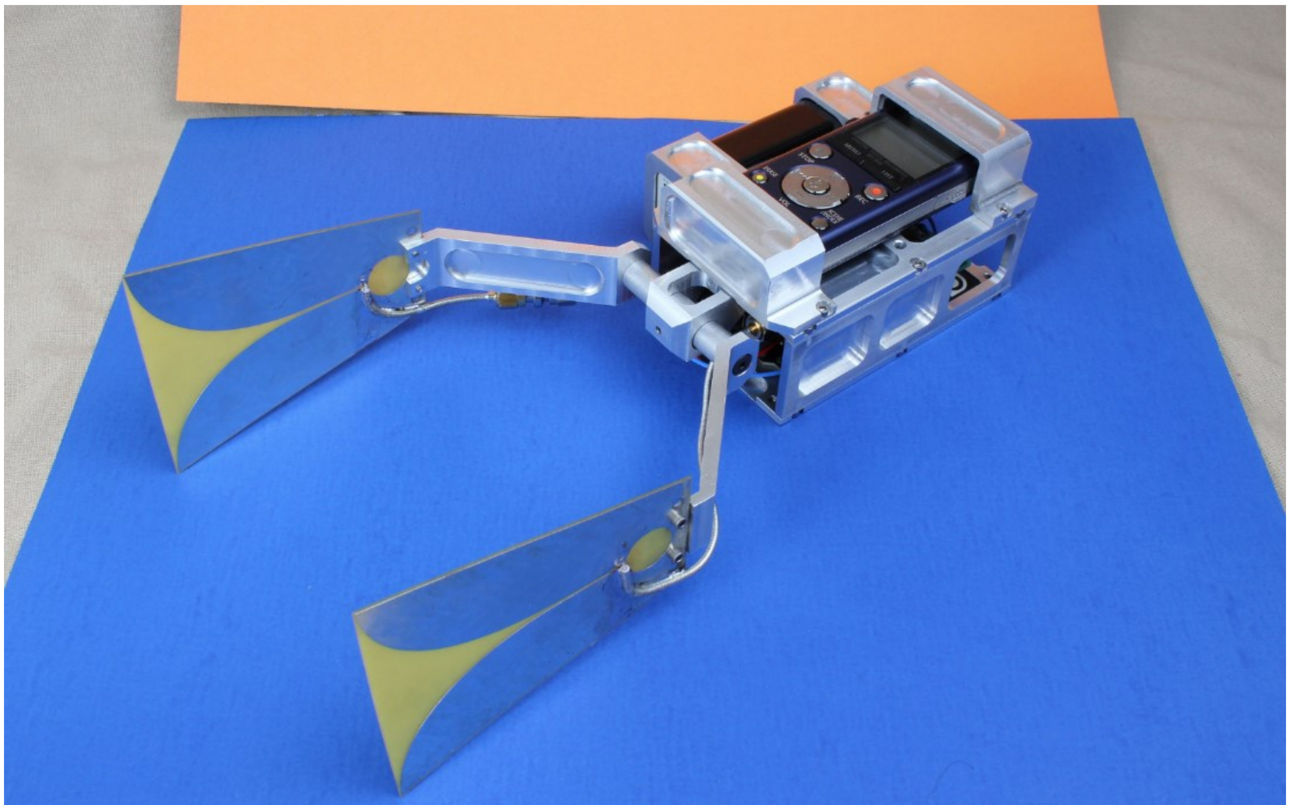



RDK Cantenna

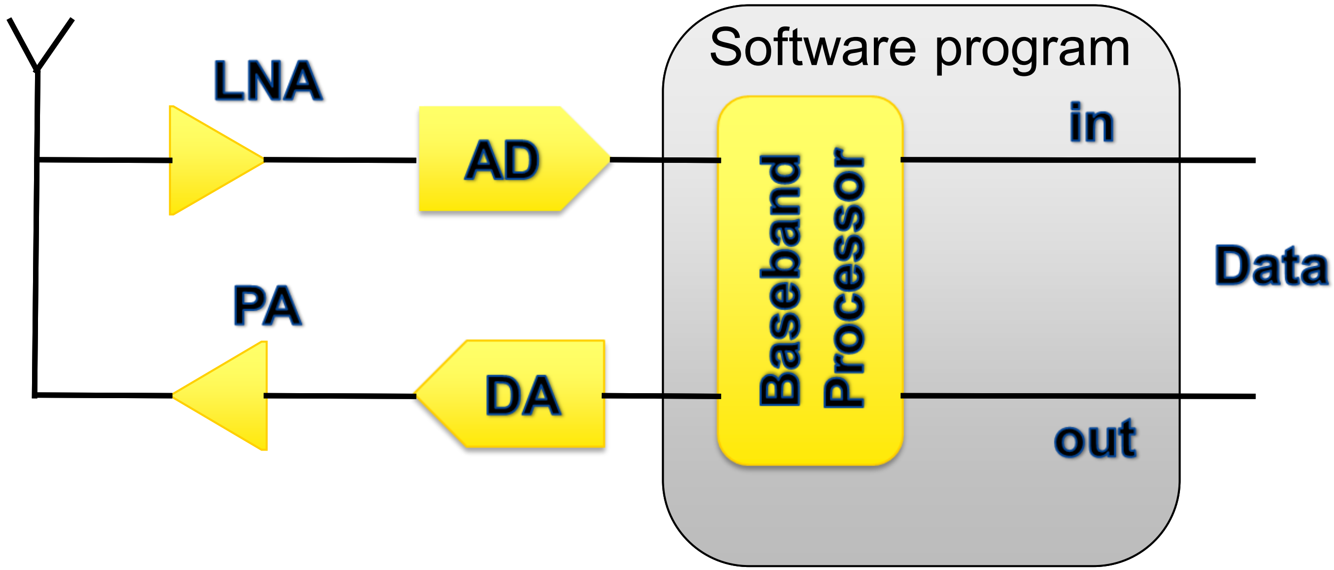

5–18 GHz
WA5VJB

# Small SAR



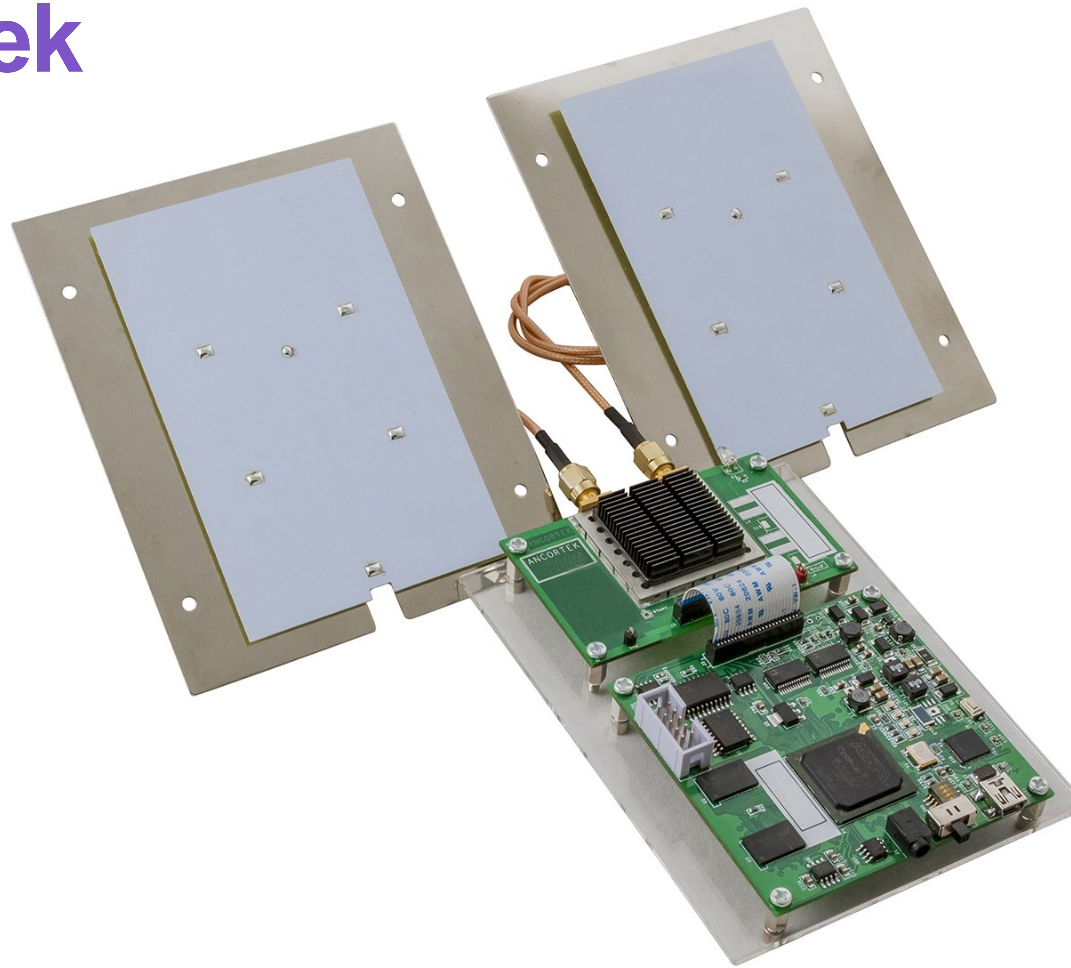
# Doppled demo audio (cars passing by)

# Software defined radio




- What is software?
  - Machine readable instructions that direct processor to do specific operations
  - Used when some operations will be changing or when all the required operations are not known beforehand
  - System functionality can evolve, software is easier to change than HW

# Simple SDR based FM radar by Ancortek

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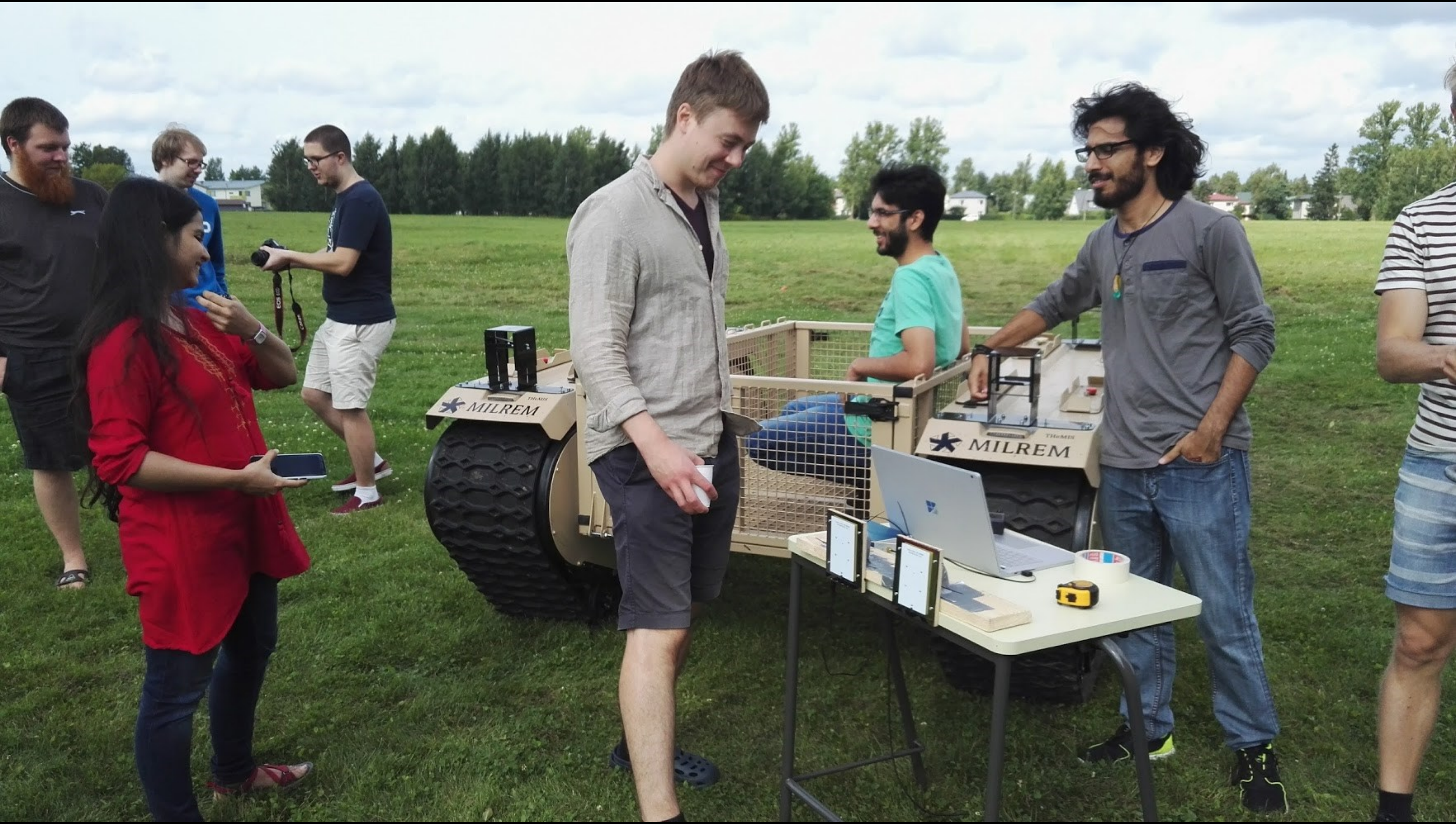
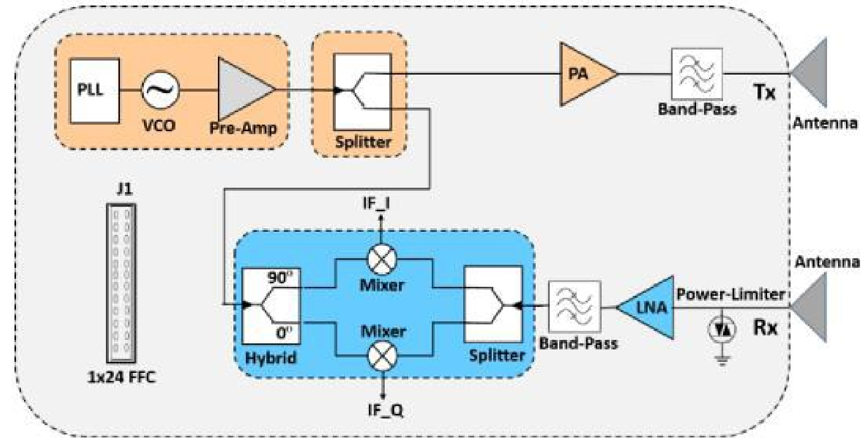
CROPP
MILREM
MILREM
MILREM
Aalto-1


MILREM
THeMIS
MILREM
THeMIS

# SDR radar: Ancortek SDR-KIT 580AD

- **TxRX signal mixing implemented in HW**
- **RF bandwidth**
  - 100 to 400 Mhz
- **Output Baseband Beat signal**
  - Digitalization of the beat signal
- **Connects to PC for postprocessing**



# Simple doppler radar

**No modulation**

**Continuous wave Doppler radar**

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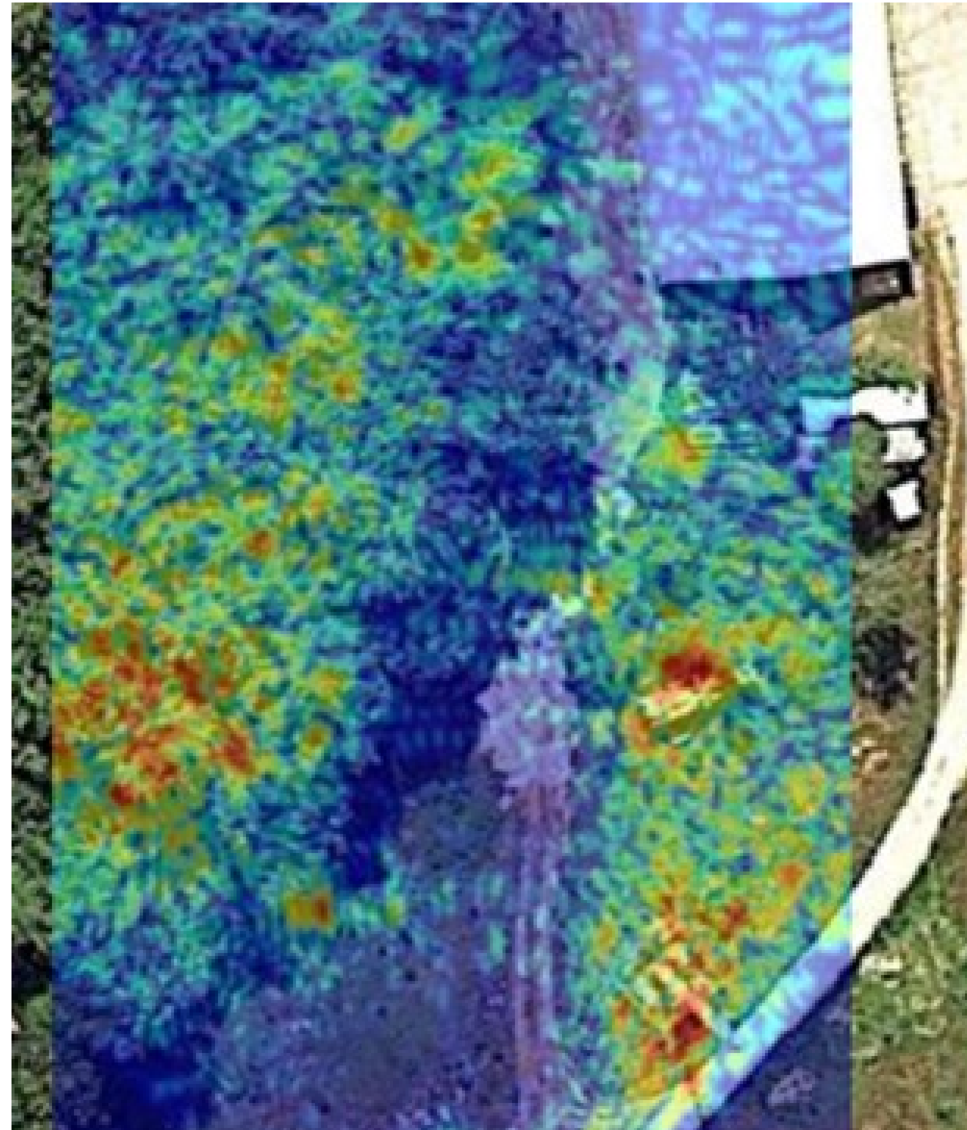
# Imaging with CWFM radar



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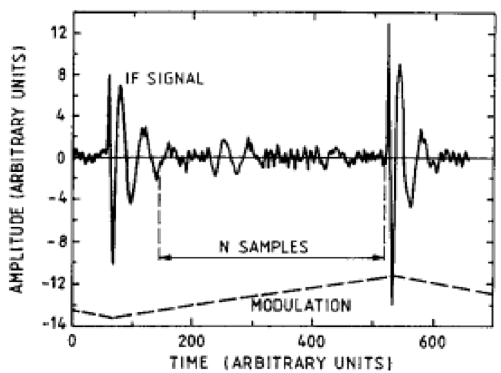
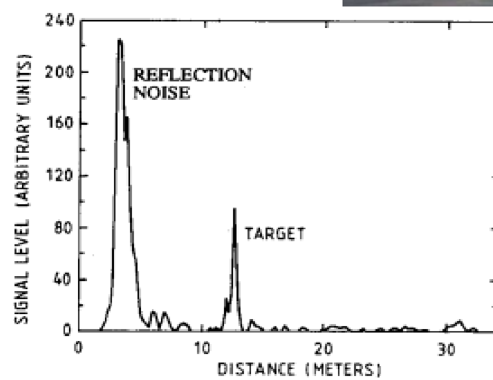
# Scattero meter

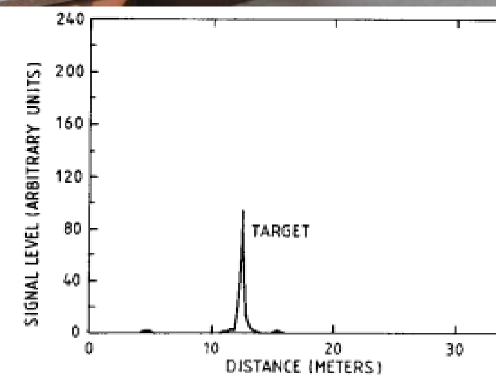
*Installing HUTSCAT*

# HUTSCAT, FM-CW radar

**HUTSCAT operates in C- and X-band and measures radar echo magnitude as a function of distance**

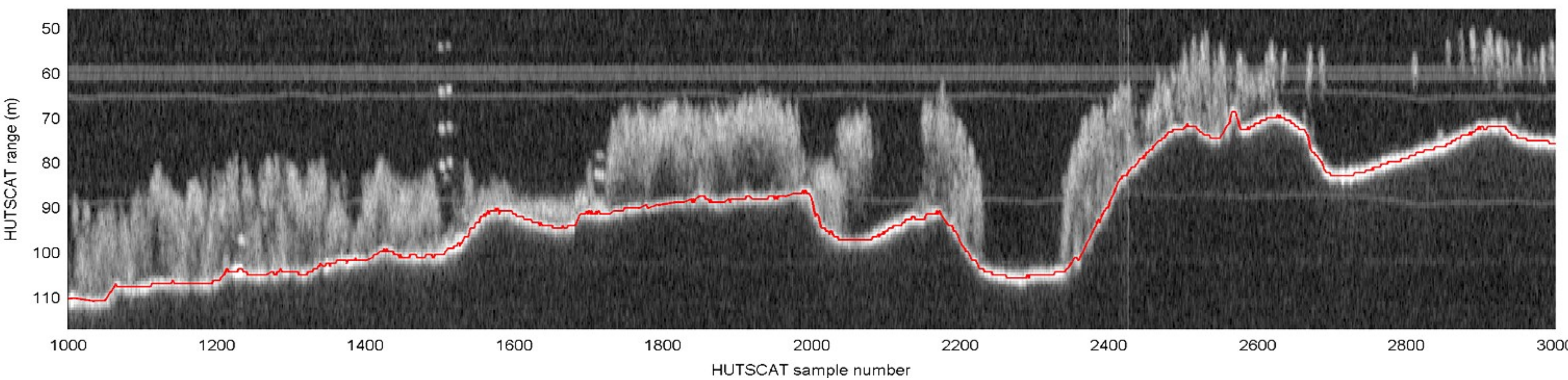


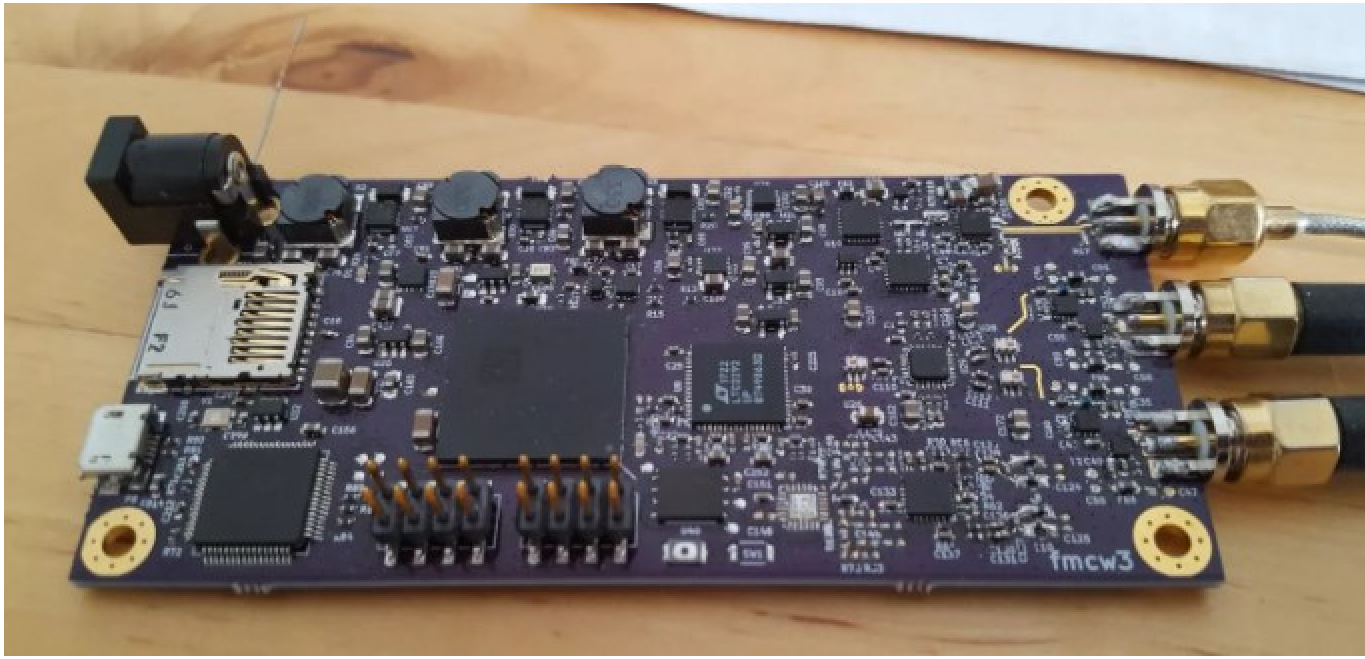
# HUTSCAT

- Scatterometer, one type of radar, measures the scattering profile
- X-band multipol (HH HV VH VV)
- C-band multipol (HH HV VH VV)
- Range resolution 0.65 m
- Vertical resolution is achieved by measuring the delay of the received pulse
- Horisontal resolution is achieved by platform movement

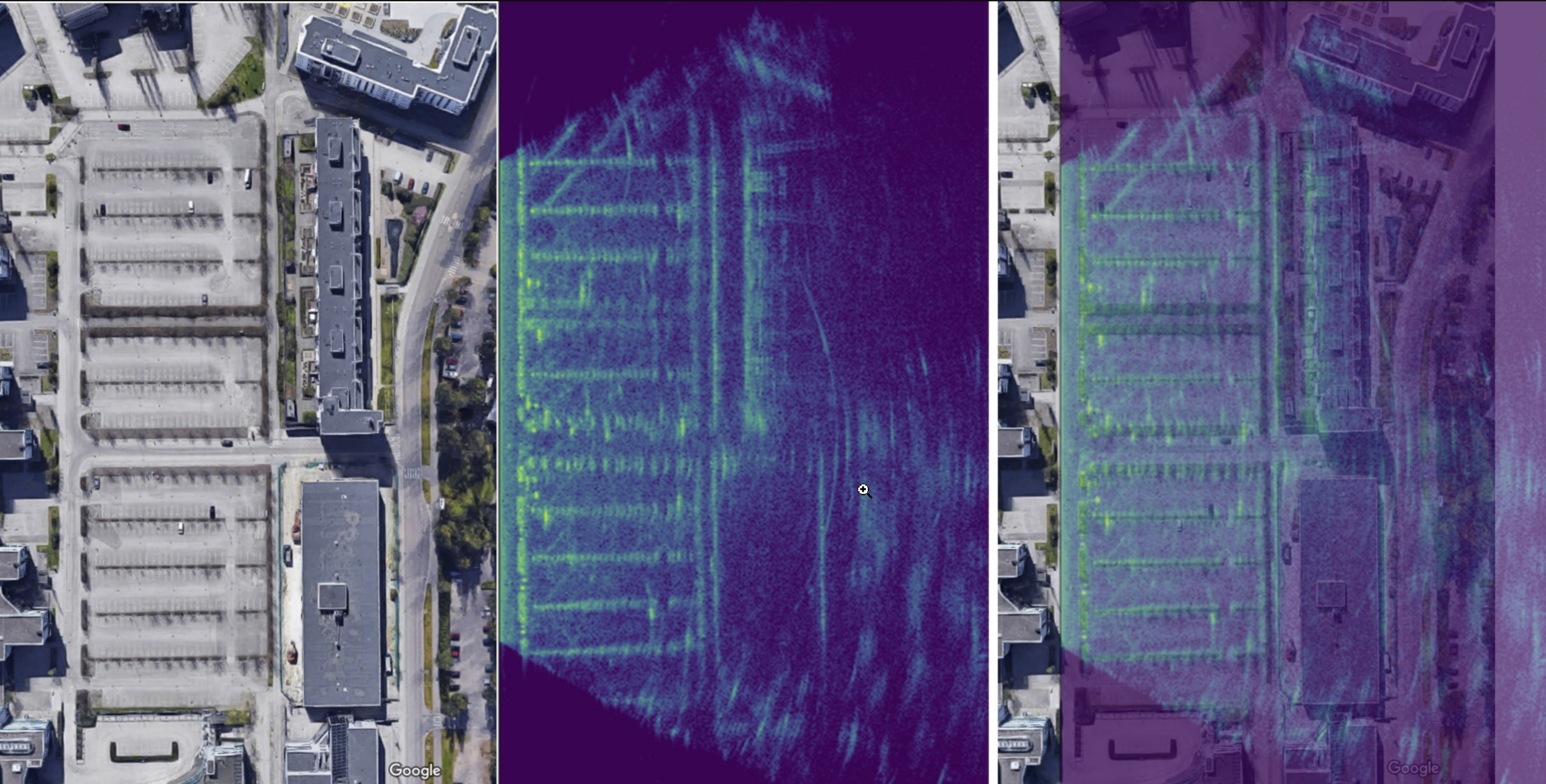


# Radar projects by Henrik

http://hforsten.com/third-version-of-homemade-6-ghz-fmcw-radar.html

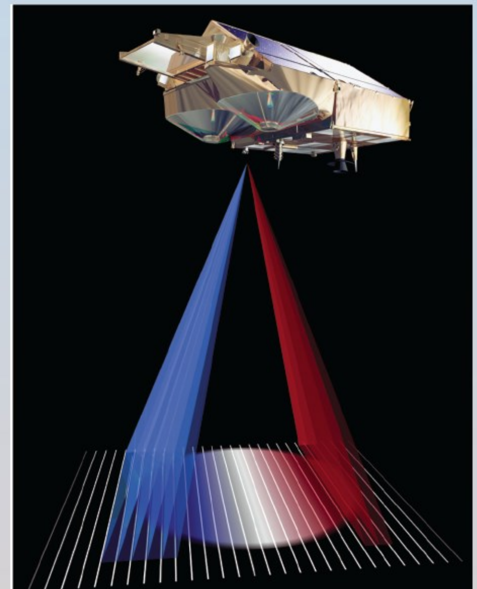



http://hforsten.com/6-ghz-frequency-modulated-radar.html


Google

- Ulaby
- Long
- Blackwell
- Elachi
- Fung
- Ruf
- Sarabandi
- Zebker
- Van Zyl

# Microwave Radar and Radiometric Remote Sensing



# END

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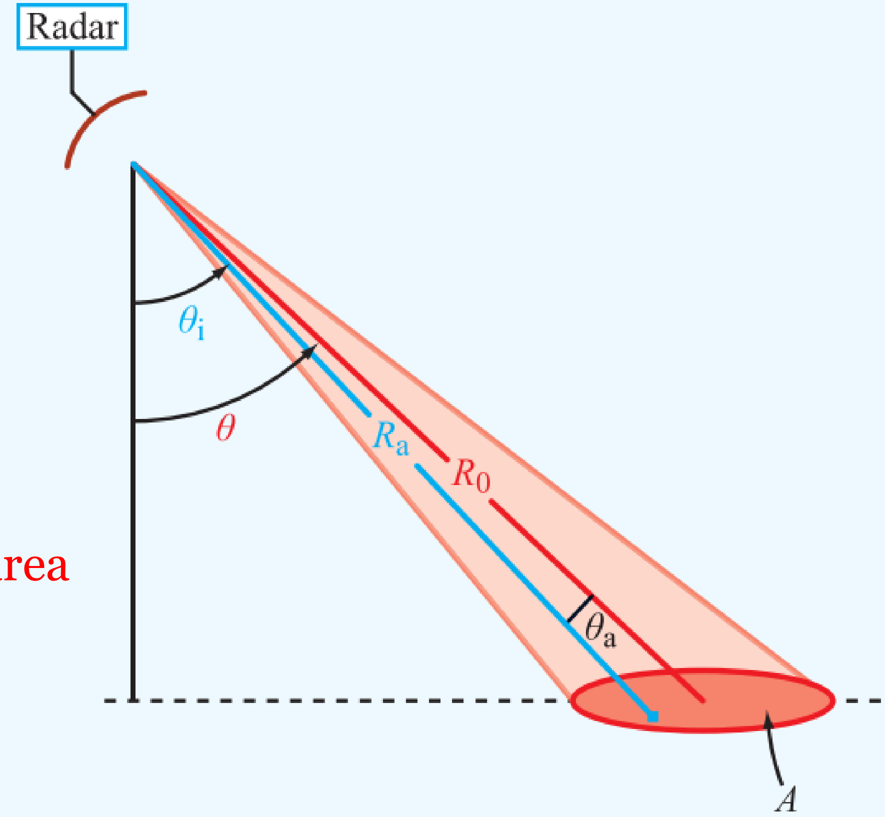
# Distributed targets and $\sigma_o$

*Installing radar reflector*

# When imaging land, the target is not point target!

$$P_p^{\mathrm{r}}(\theta) = \iint_A \frac{P_q^{\mathrm{t}}\, G^2(\theta_{\mathrm{a}}, \phi_{\mathrm{a}})\, \lambda^2}{(4\pi)^3 R_{\mathrm{a}}^4} \cdot \sigma_{pq}^0 \, dA$$

$$\sigma_{pq}^0 = \sigma_{pq}/A$$




- backscattering cross section per unit area
- backscattering coefficient
- radar reflectivity

are the same parameter

From: Microwave Radar and Radiometric Remote Sensing, by Ulaby and Long, 2014, with permission.

# Radar reflectivity measures
## (normalized to different area projections)

***Beta_o, $\beta_o$***

Slant range backscattering coefficient (measured)

***Sigma_o, $\sigma_o$***

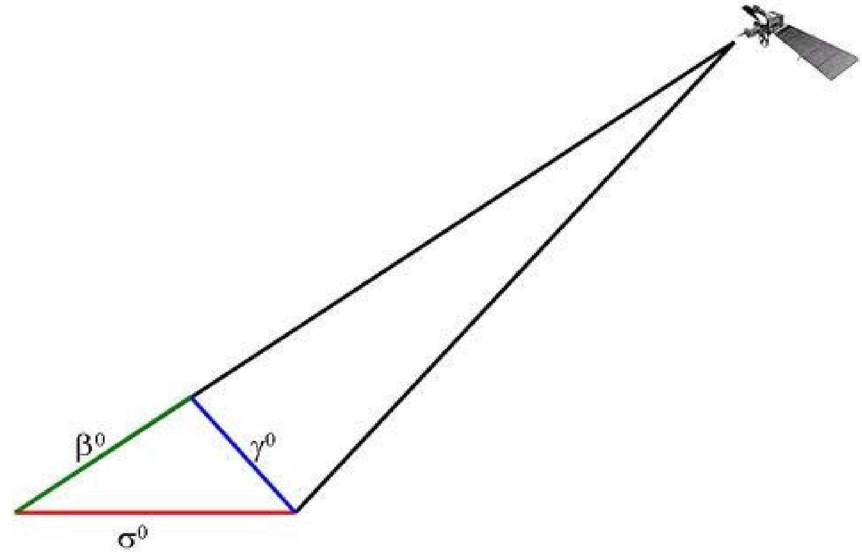
Ground area normalized backscattering coefficient (normalized by ground)

$$\sigma_0 = \beta_0 \sin(\theta)$$

***Gamma_o, $\gamma_o$***

used sometimes in calibration (normalized by antenna cone)

$$\gamma_0 = \beta_0 \tan(\theta)$$

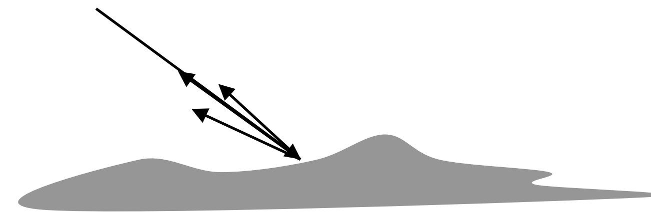


# Radar cross section, interpretation of $\sigma_0$

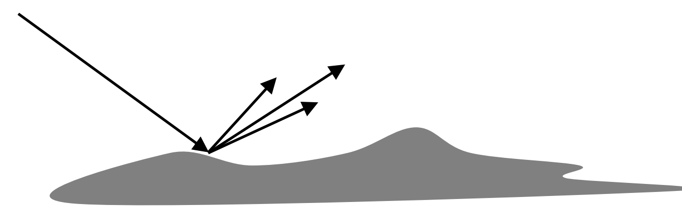
Normalized radar cross-section (backscattering coefficient) is given by:

$$\sigma_0(dB) = 10\log_{10}\left(\frac{received\,energy\,by\,the\,sensor}{energy\,if\,reflected\,isotropically}\right)$$

The backscattered coefficient can be a positive number if there is a focusing of backscattered energy towards the radar



The backscattered coefficient can be a negative number if there is a focusing of backscattered energy way from the radar (e.g. smooth surface)



# Measured values

- "Typical" values of backscattering coefficient:

| Values | Scenes |
|---|---|
| $\sigma_0 > 0$ dB | Man-made objects, urban areas<br>Slopes facing the radar |
| $-10$ dB $< \sigma_0 < 0$ dB | Very rough surfaces<br>Forests (dense vegetation) |
| $-20$ dB $< \sigma_0 < -10$ dB | Rough surfaces (sea with wind)<br>Agricultural crops |
| $\sigma_0 < -20$ dB | Calm water<br>Smooth surfaces (roads)<br>Very dry ground (sand) |

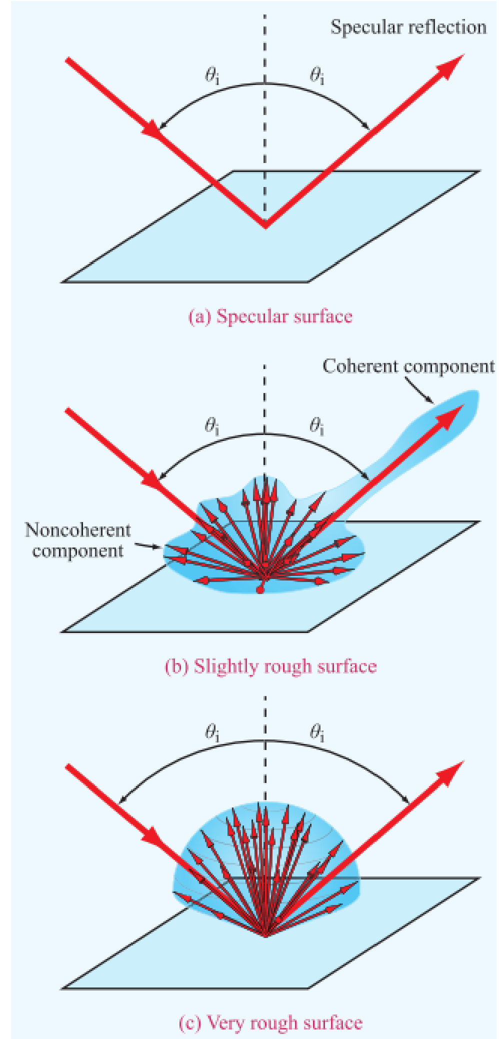
CAUTION: They are very dependent on frequency band and incidence angle

# Q?

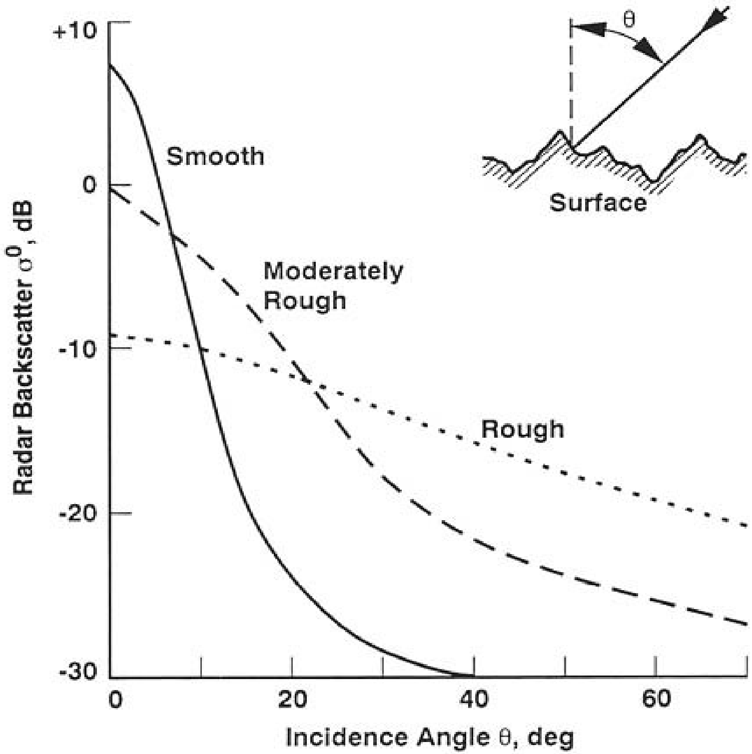
**Backscattering coefficient of the target is 2 dB, what kind of target can be in question?**

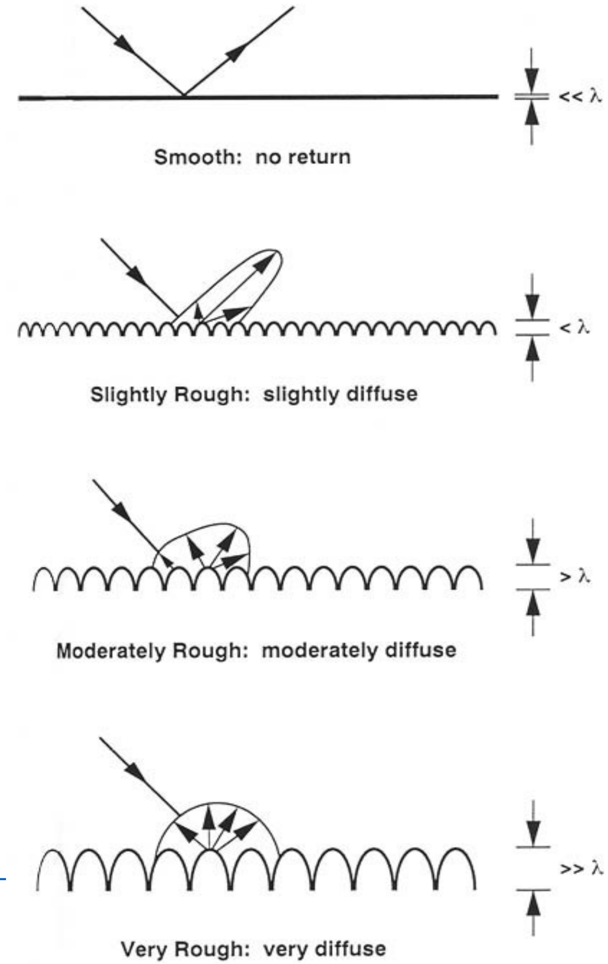
**Backscattering coefficient of the target is 0 dB, what kind of target can be in question?**

# Incidence angle and surface roughness



# Incidence angle and surface roughness

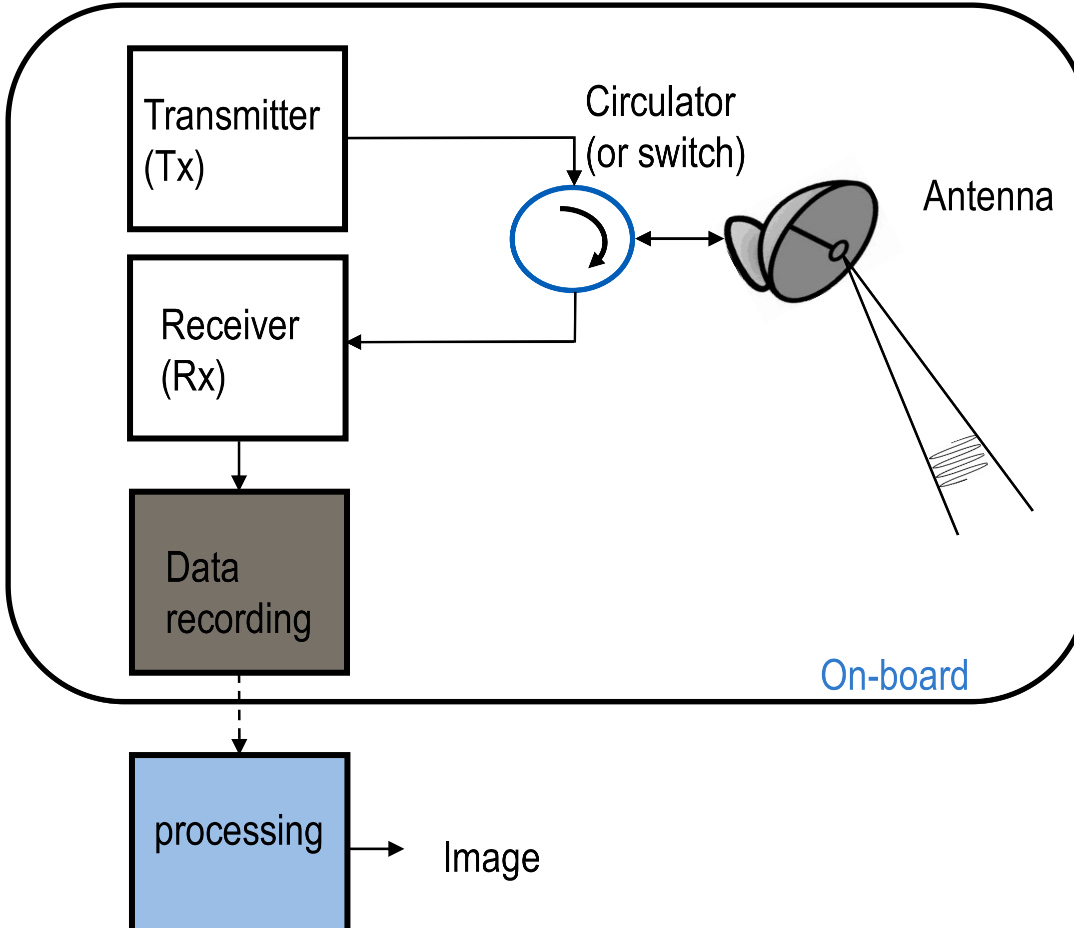





http://history.nasa.gov/JPL-93-24/ch5.htm
NASA: Guide to Magellan Image Interpretation
Chapter 5. Radar Interactions With Geologic Surfaces
Tom G. Farr

# Basic generic radar



# Q?

**Why point target and distributed target are handled seperately?**