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Introduction to Imaging Radar
INF-GEO 4310

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Literature

- Contact: yoann.paichard@ffi.no
- Suggested readings:
  - **Fundamentals of Radar Signal Processing**, M.A. Richards, McGraw-Hill, 2005
  - **High Resolution Radar**, D.R. Wehner, Artech House, 2nd Edition, 1995
  - **High Resolution Radar Cross-Section Imaging,** Mensa, D.L.,, Boston: Artech House, 1991.
  - **Digital Processing of Synthetic Aperture Radar Data,** I.G. Cumming and F.H. Won, Artech House, 2005
  - **Spotlight Synthetic Aperture Radar, W.S Carrara,** R.M. Majewski, R.S. Goodman, Artech House, 1995

Outline

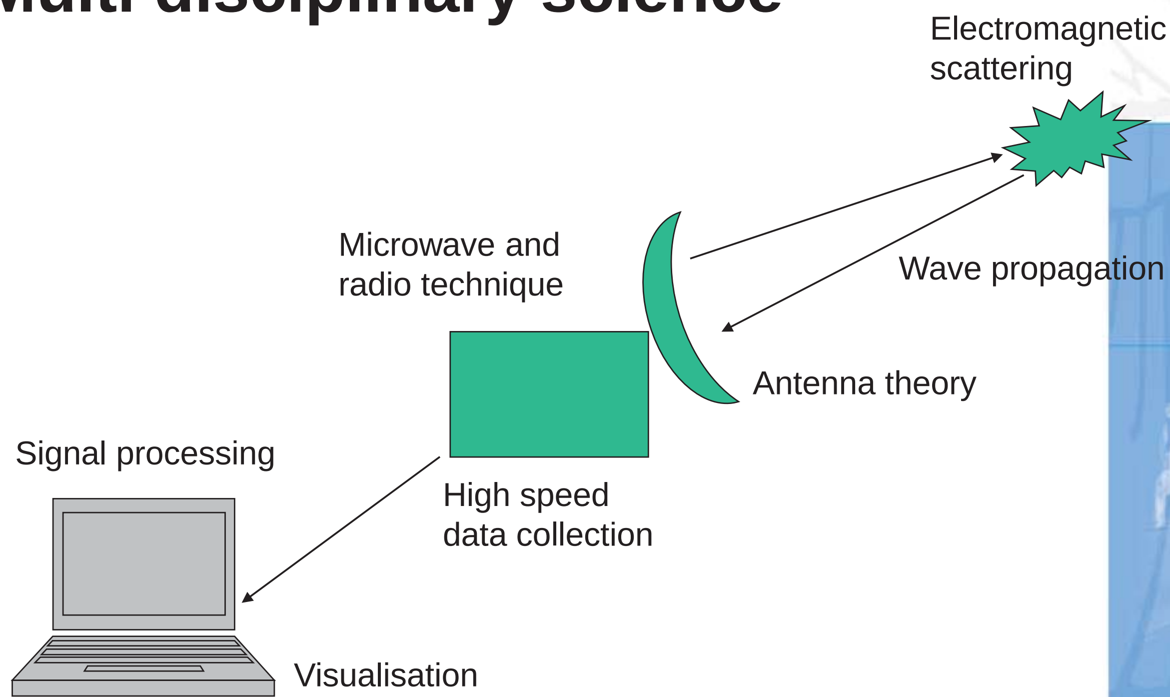
- Introduction
- Radar overview
- ISAR – Inverse Synthetic Aperture Radar
- SAR – Synthetic Aperture Radar
- GPR – Ground Penetration Radar

Introduction

RADAR = RAdio Detection And Ranging

1886	Heinrich Hertz confirmed radio wave propagation
1904	Hülsmeyer patented ship collision-avoidance system
1922	Ship detection methods at NRL (Taylor & Young, 700MHz)
1930s	England and Germany radar programs developed:
	Chain Home early warning system (22-50 MHz)
	fire control systems
	aircraft navigation systems
	cavity magnetron to transmit high-power microwaves
1940s	Establishment of MIT Rad Lab (British + American) radar for tracking, U-boat detection

Multi disciplinary science

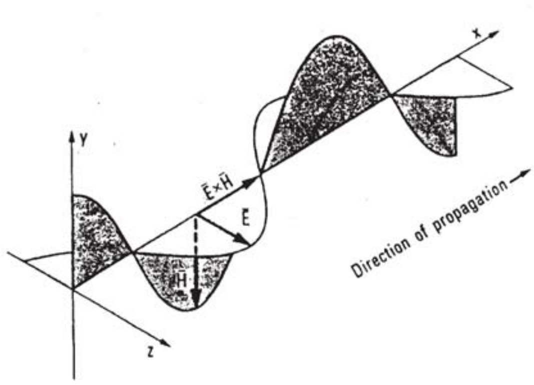


Why Radar

- Works day or night (unlike optical imaging)
- Works in all weather
- Penetrates clouds and rain
- Some radars can penetrate foliage, buildings, soil, human tissue
- Can provide very accurate distance measurements
- Sensitive to objects whose length scales are cm to m
- Can measure velocities (Moving targets)

Electromagnetic Waves

- An electromagnetic wave comprises two orthogonal vector components:
  - Electric field intensity E
  - Magnetic field intensity H
- Sinusoidal EM wave:



- Electric field oscillates back and forth.
- EM wave propagation is in the direction orthogonal to oscillation of both electric and magnetic fields.

Radiation of EM waves

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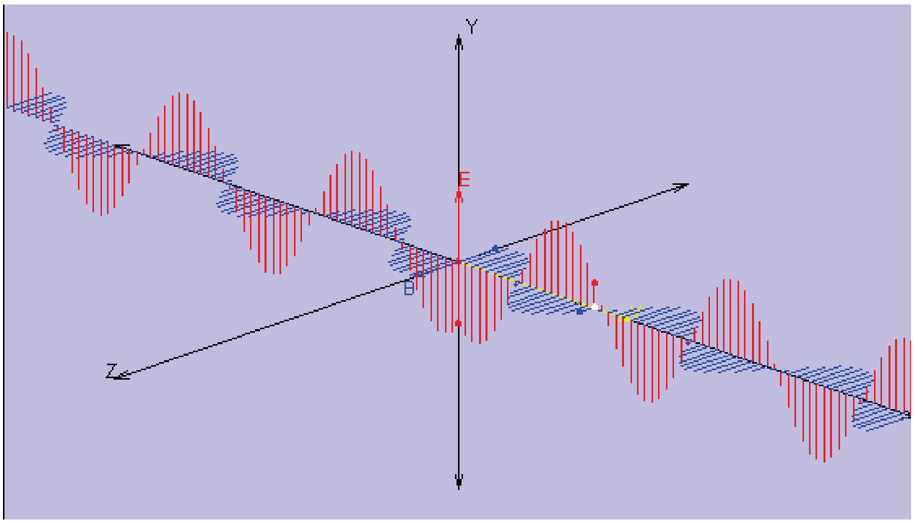

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The RF/Radar Spectrum

Band	Frequencies	Wavelengths
HF	3–30 MHz	100–10 m
VHF	30–300 MHz	10–1 m
UHF	300 MHz–1 GHz	1–30 cm
L	1–2 GHz	30–15 cm
S	2–4 GHz	15–7.5 cm
C	4–8 GHz	7.5–3.75 cm
X	8–12 GHz	3.75–2.5 cm
K_u	12–18 GHz	2.5–1.67 cm
K	18–27 GHz	1.67–1.11 cm
K_a	27–40 GHz	1.11 cm–7.5 mm
mm	40–300 GHz	7.5–1 mm

Maxwell's equations

$$\mu \frac{\partial H}{\partial t} + \nabla \times E = 0$$

$$\varepsilon \frac{\partial E}{\partial t} + \nabla \times H = \sigma E$$

$$\nabla \cdot \varepsilon E = \rho_f$$

$$\nabla \cdot \mu H = 0$$

Wave equations

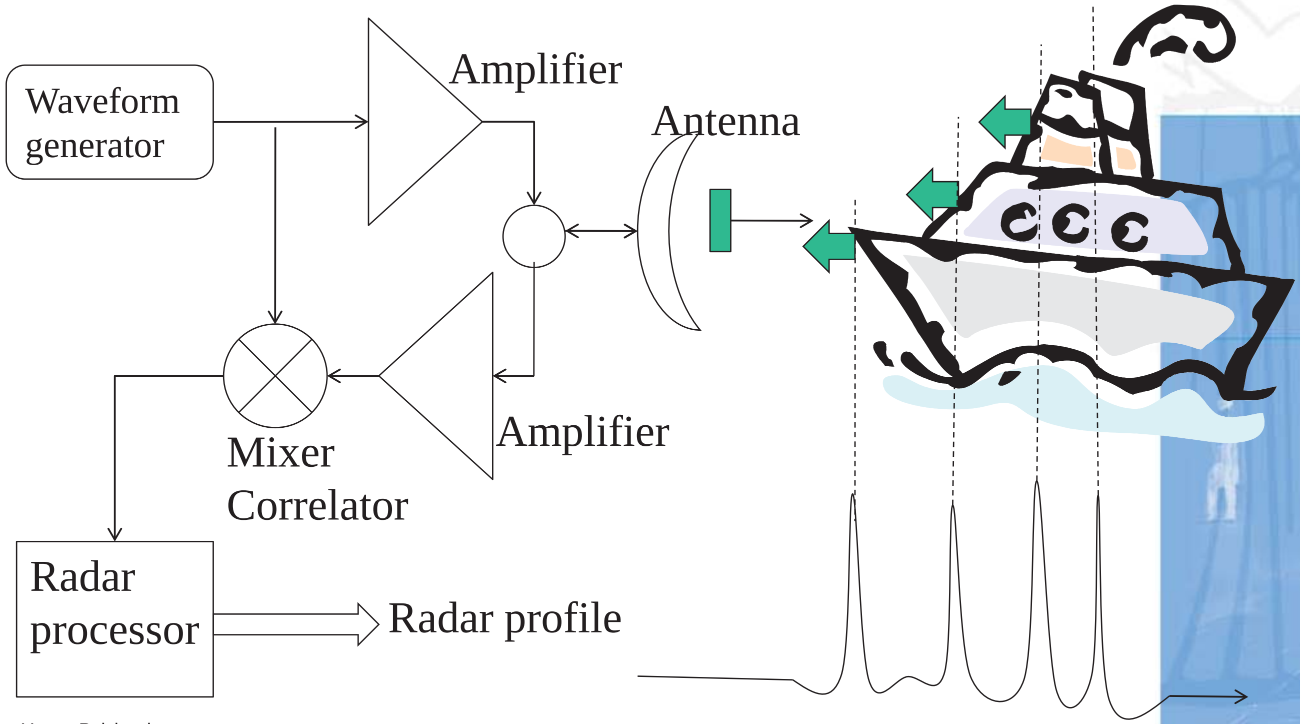
$$\nabla^2 E - \varepsilon\mu \frac{\partial^2 E}{\partial t^2} = 0$$

$$\nabla^2 B - \varepsilon\mu \frac{\partial^2 B}{\partial t^2} = 0$$

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r}} = \frac{c}{\sqrt{\varepsilon_r}}$$

Radar Overview

Radar principle



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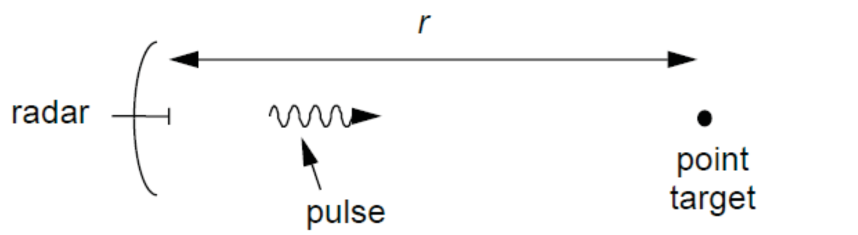
Radar principle

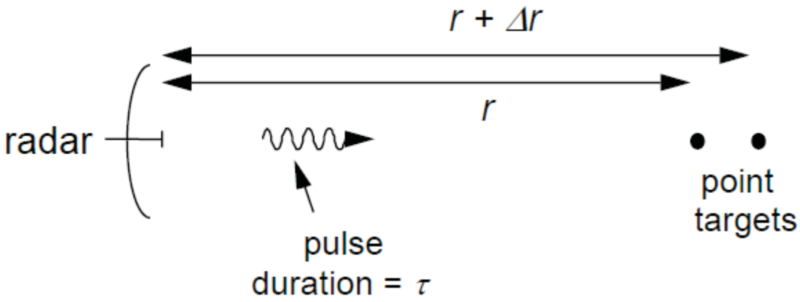


Two-ways propagation delay

Range of target: $r = \frac{ct}{2}$

- Radar range is sometimes quoted in nautical miles (1 nmi = 1.85 km), and velocity in knots (1 kt = 1 nmi/hr)

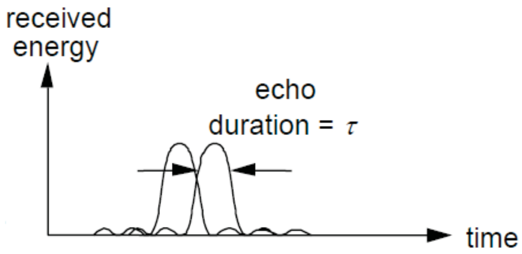
Range resolution



- Range resolution: defines the radar ability to separate 2 close targets
- Echoes can be separated in range if the width of the transmitted pulse is short enough:

$$\frac{2(r+\Delta r)}{c} - \frac{2r}{c} = \frac{2\Delta r}{c}$$

Set this = τ, then $\Delta r = \frac{c\tau}{2}$



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Range resolution

The spectrum of a rectangular pulse of length τ

$$f(t) = A\cos\omega_0 t \qquad -\frac{\tau}{2} \le t \le \frac{\tau}{2}$$

is a sinc function centred on ω_0

$$F(\omega) = \frac{\tau}{2}\left(\frac{\sin(\omega+\omega_0)\tau/2}{(\omega+\omega_0)\tau/2}\right)$$

whose bandwidth (at –3.9 dB) is $B = 1/\tau$

So we can write the range resolution as $\Delta r = \frac{c}{2B}$

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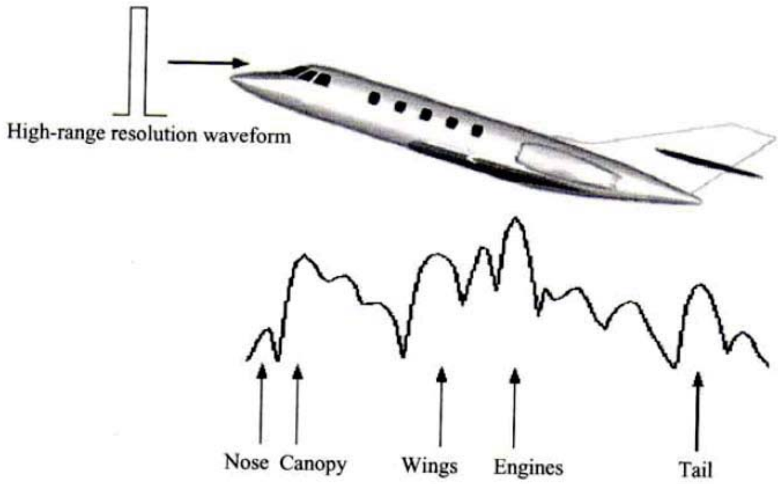
High range resolution



- For radar imaging, High Range Resolution (HRR) is required
- The range resolution must be smaller than the area or object of interest
- A bandwidth of (at least) 150 MHz is required to achieve 1m resolution

Radar waveforms

- Impulse Radar
- Step-frequency
- LFM-Chirp

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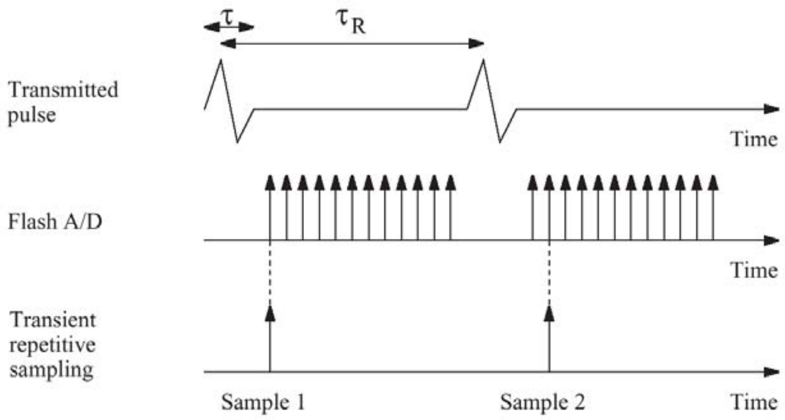
Impulse Radar



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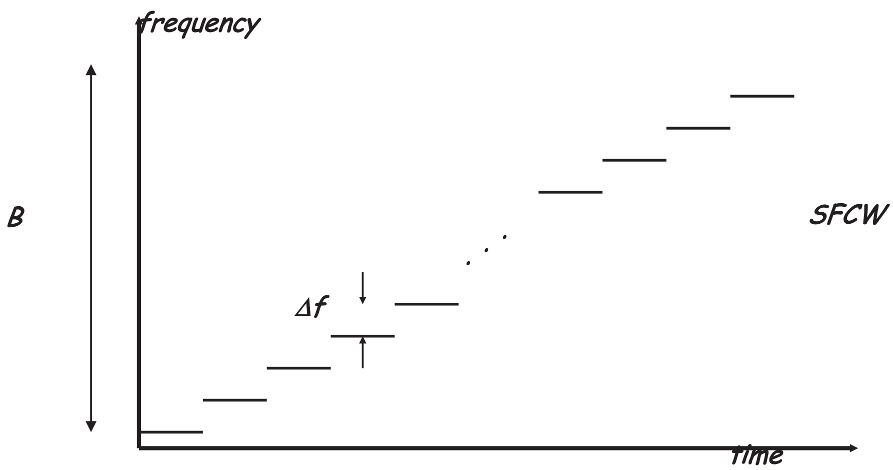
Step-frequency



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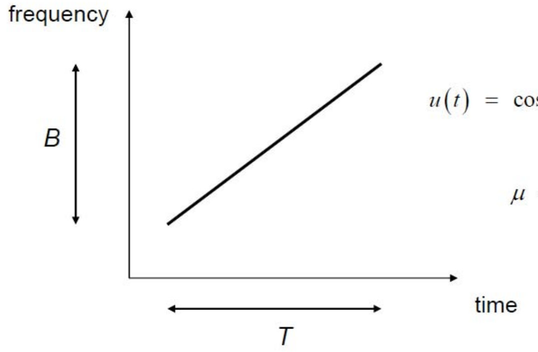
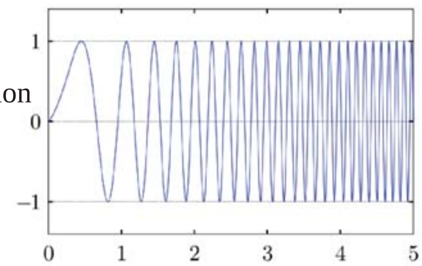
Linear Frequency Modulated Signal (Chirp)



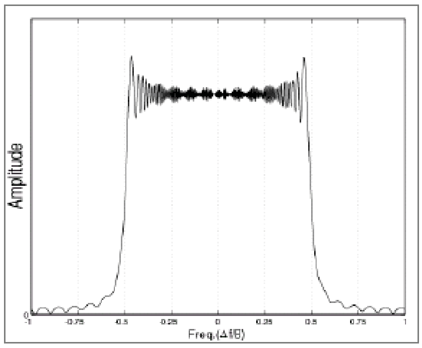
$$u(t) = \cos\left(\omega_0 t + \frac{\mu t^2}{2}\right), \quad -\frac{T}{2} \le t \le \frac{T}{2}$$

$$\mu = \frac{2\pi B}{T}$$

Time representation



Spectrum
(BT = 500)



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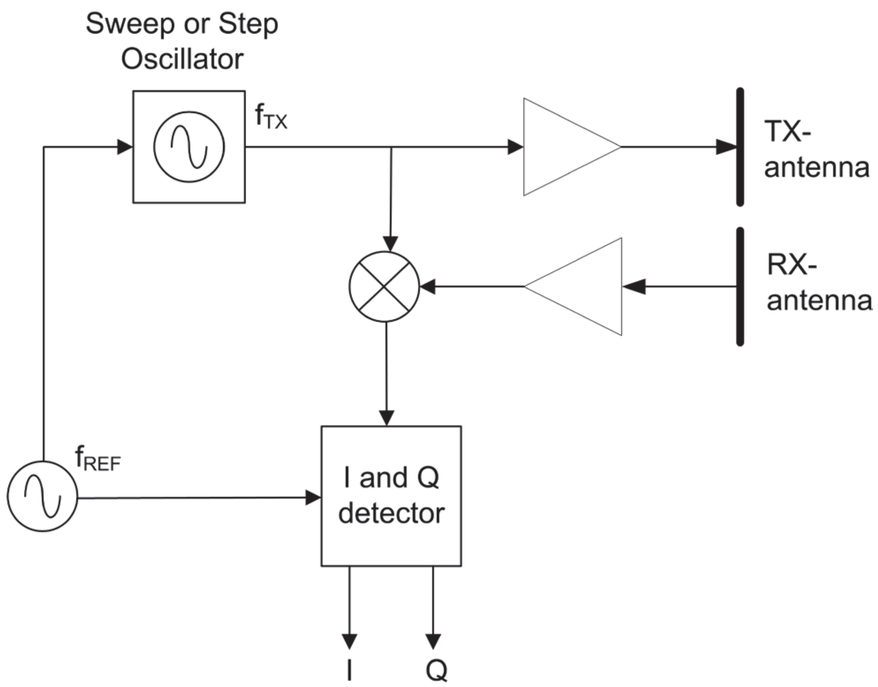
Basic Radar Circuit



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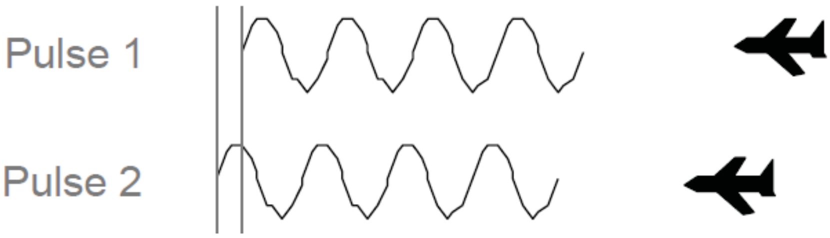
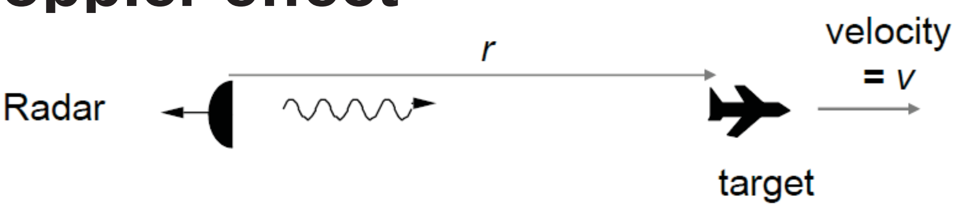
Doppler effect



- Doppler effect is the change in phase when an object is approaching or moving away from the radar
- Also true when the radar is on a moving platform (airborne radar) and looking at the ground
- We see a shift between the transmitted frequency and the received frequency since the rate of phase change is frequency change

Doppler effect



The phase represented by the two-way path from radar to target is

$$\phi = 2\pi \frac{2r}{\lambda}$$

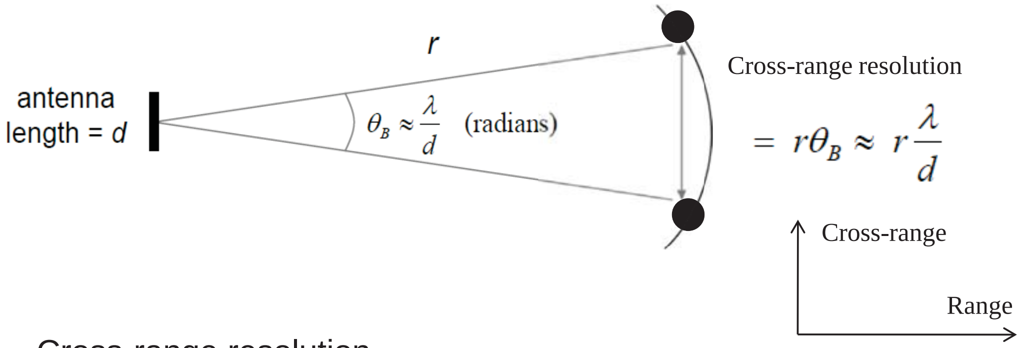
The Doppler shift is

$$f_D = -\frac{1}{2\pi}\frac{d\phi}{dt}$$

(– sign because an increase in path length represents a phase lag)

$$= -\frac{1}{2\pi}\frac{d}{dt}\left(\frac{4\pi r}{\lambda}\right) = -\frac{2}{\lambda}\frac{dr}{dt} = -\frac{2vf_0}{c}$$

Cross-range (angular) resolution



- Cross-range resolution
  - degrades in proportion to range
  - is too coarse for useful images: airborne radar with 1m antenna at 10GHz (X-band) give a resolution of 300m at 10km range
  - No possibility to increase physical antenna size, esp. on airborne radars

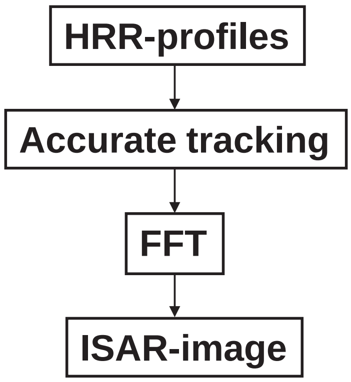
Synthetic Aperture Concept

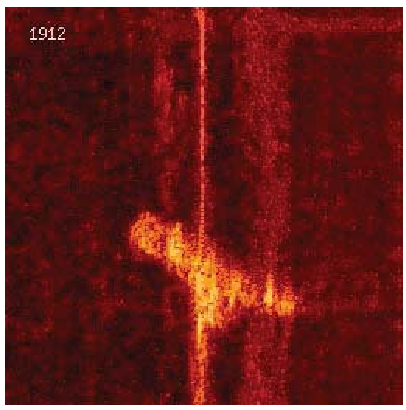
- We can use the motion of the radar or the object to improve the cross-range resolution
- SAR: Synthetic Aperture Radar: The motion of the platform is used to synthesize a larger antenna
- ISAR: Inverse Synthetic Aperture Radar. The motion of the object is used to synthesize a larger antenna

Inverse Synthetic Aperture Radar (ISAR)

ISAR

- Relative motion of the object makes a change in aspect angle
- Starts with High Range Resolution Profiles
- Main difficulty is accurate tracks





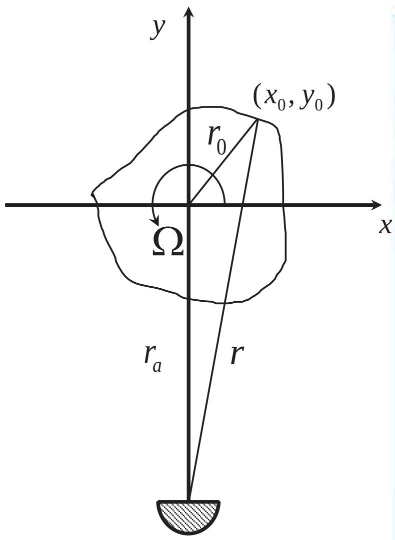
Range-Doppler Imaging

- **The object rotation gives cross range resolution**
- **Range**

$$r = r_a + x_0 \sin \Omega t + y_0 \cos \Omega t$$
$$\approx r_a + y_0$$

- **Doppler:**

$$f_d = \frac{2}{\lambda}\frac{dr}{dt} = \frac{2x_0\Omega}{\lambda}\cos \Omega t - \frac{2y_0\Omega}{\lambda}\sin \Omega t$$
$$\approx \frac{2x_0\Omega}{\lambda}$$



Resolution

Distance (range) $\Delta y = \dfrac{c}{2B}$

Azimut (Doppler) $\Delta f = \dfrac{1}{T}$

$$\Delta x = \frac{\lambda}{2\Omega}\Delta f = \frac{\lambda}{2\Omega T} = \frac{\lambda}{2\theta_p}$$

Example: $B = 800\,\text{MHz}$ $\Delta y = 18.75\,\text{cm}$

$\lambda = 1.8\,\text{cm},\ \Omega = 0.5°/\text{s}$

$T = 5\,\text{s}$

$\theta_p = 2.5°$ $\Delta x = 20.6\,\text{cm}$

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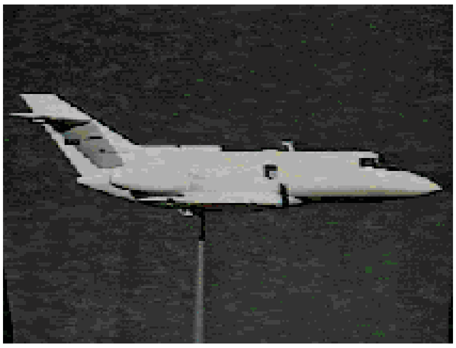
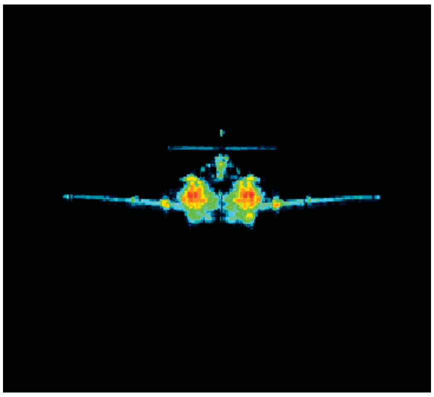
ISAR example





Courtesy from CompuQuest, inc.

	Total	Start	Stop	Step Size	Total Steps
Frequency (GHz)	4.0	8.0	12.0	0.01	401
Azimuth (deg)	25.0	167.5	192.5	0.1	251
Elevation (deg)	18.0	67.0	85.0	0.2	91

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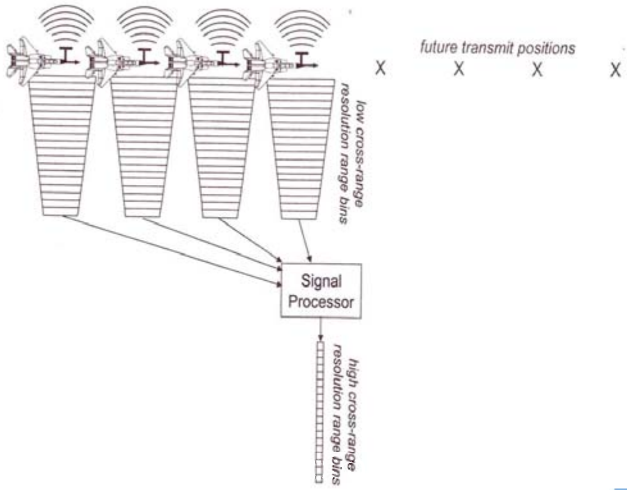
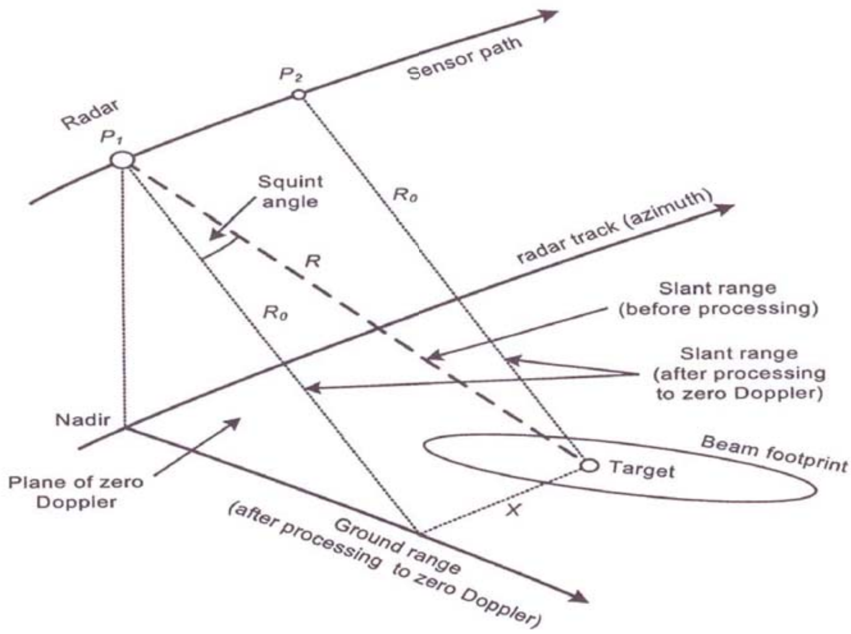
Synthetic Aperture Radar (SAR)

SAR overview



- 2 modes
  - Stripmap SAR: The constant as the platform moves. Used for continous mapping with average reolution.
  - Spotlight SAR: The antenna is steered over an area of interest: it improves the resolution on a particular region

SAR geometry



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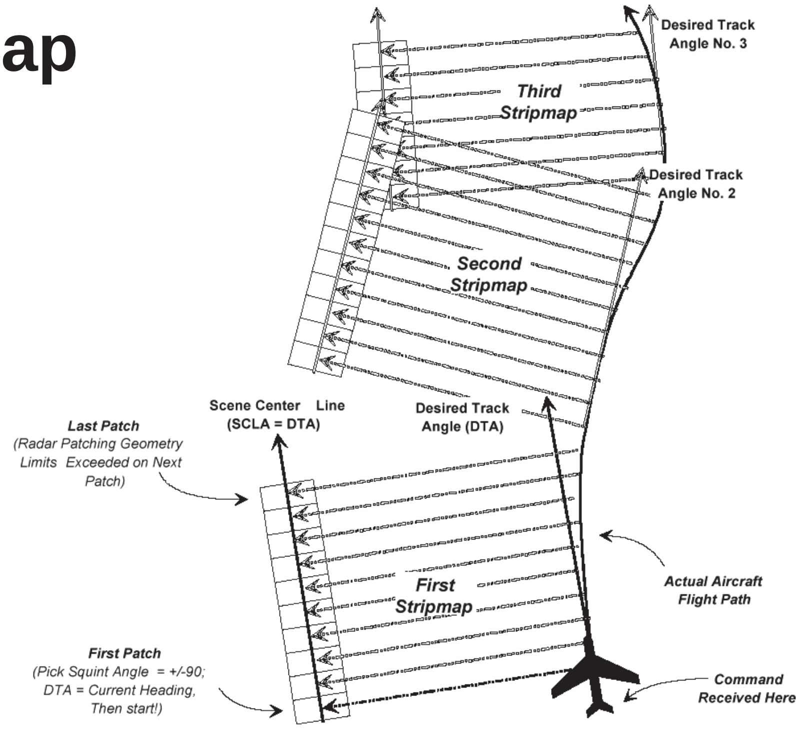
Stripmap



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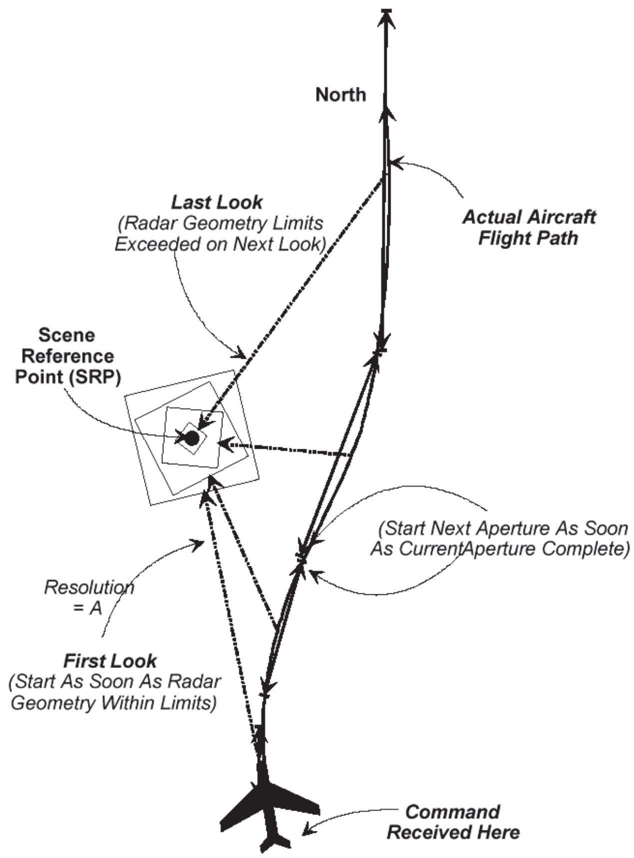
Spotlight



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Cross-Range Resolution

• Cross-range resolution is limited by Doppler resolution:

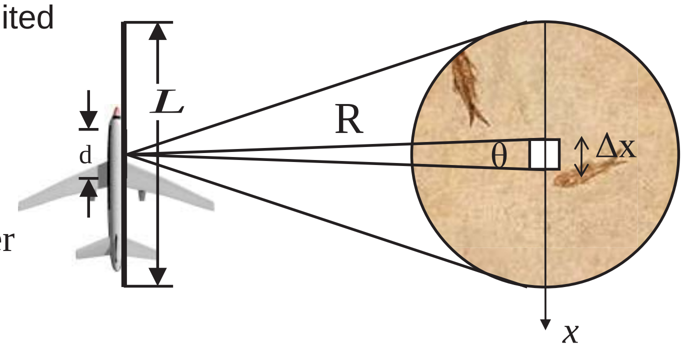
$$\Delta f_d = \frac{2v}{\lambda}\theta = \frac{2v}{\lambda}\frac{\Delta x}{R}$$

• Minimum resolvable Δx over time T is therefore:

$$\frac{1}{T} = \frac{2v}{\lambda}\frac{\Delta x}{R} \Rightarrow \Delta x = \frac{\lambda R}{2vT}$$

• Maximum time is limited by the size of the antenna (point must remain on the antenna beam during flight path)

$$vT = \frac{R\lambda}{d}$$



Minimum resolution

$$\Delta x = \frac{d}{2}$$ stripmap

$$\Delta x = \frac{\lambda}{2\gamma}$$ spotlight

Rotation angle of the antenna

Comparison of resolution

Real aperture

Distance:	**10 km**
Antenna:	**1 m**
Wavelenght:	**X-band**
Resolution:	**300 m**
Distance:	**100 km**
Resolution:	**3 km**
Distance:	**1000 km**
Resolution:	**30 km**

Synthetic aperture

SAR (Stripmap)

Antenna:	**1 m**
Wavelenght:	**X-band**
Resolution:	**0.5 m**

SAR (Spotlight)

Theoretical Resolution: 7.5 mm

Independent of distance!

Resolution effect

Resolution effect

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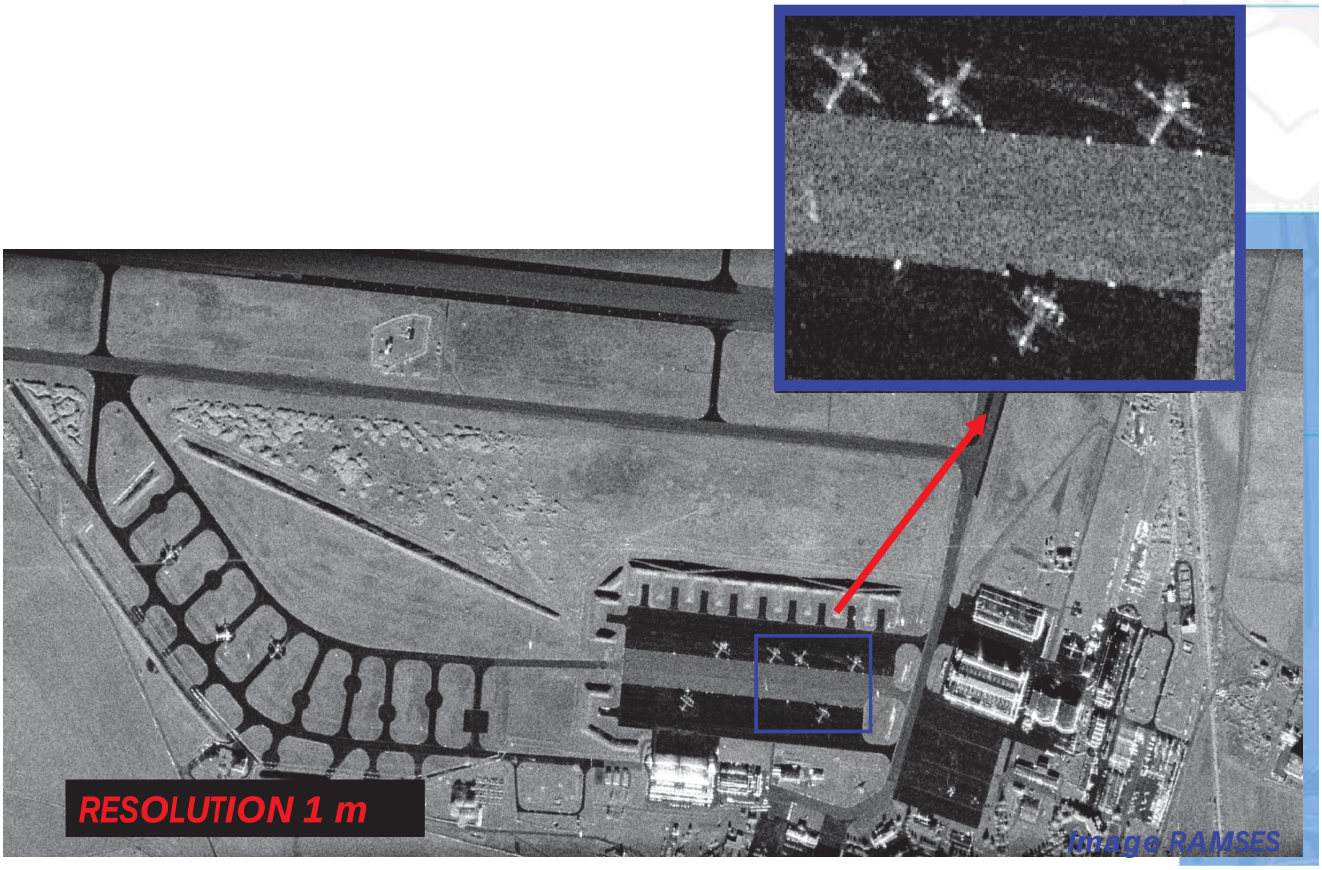

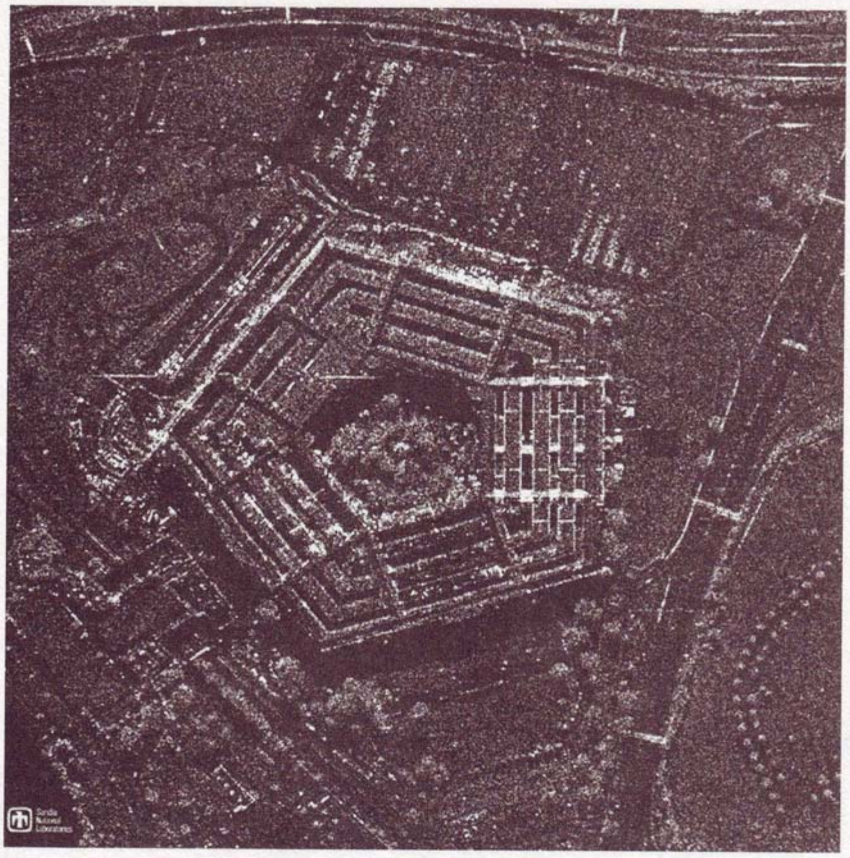

Figure 8.12 One meter resolution spotlight SAR image of the Pentagon. (Courtesy of Sandia National Laboratories.)

SAR images interpretation

- SAR images are coded in **grey levels** which are related to the microwave **backscattering properties of the surface**.
- The intensity of the backscattered signal varies according to roughness, dielectric properties and local slope. Thus the radar signal refers mainly to geometrical properties of the target.
- The following parameters are used during radar imagery interpretation:
  -tone : high intensity returns appear as light tones on a positive image, while low signal returns appear as dark tones on the imagery.
  -shape: some features (streets, bridges, airports...) can be distinguished by their shape. Note that shape is as seen by the oblique illumination.
  -size. The size of an object may be used as a qualitative recognition element on radar imagery. The size of known features on the imagery provides a relative evaluation of scale and dimensions of other terrain features.
  - **texture**: presence of speckles
  - **structure**: presence of recurrent structures on image (fields, building,…)

Special effects in SAR-images

- Geometrical distortion – 3 types:
  - Foreshortening
  - Layover
  - Shadow
- All related to that the ground is not flat.
- Can have a large influence for interpretation in areas where the topography is large.
- Speckle

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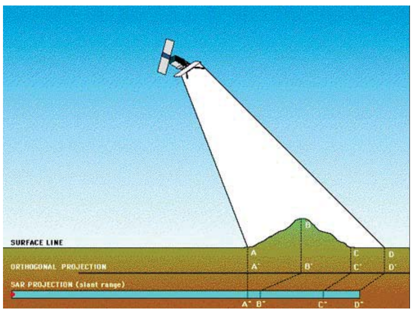
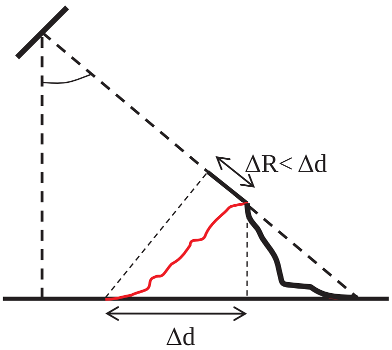
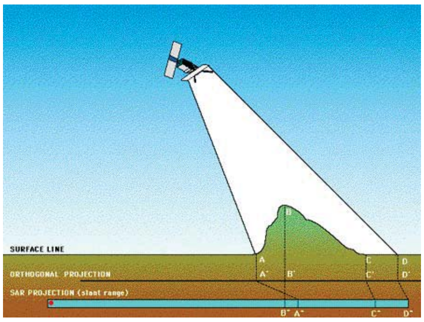
Foreshortening

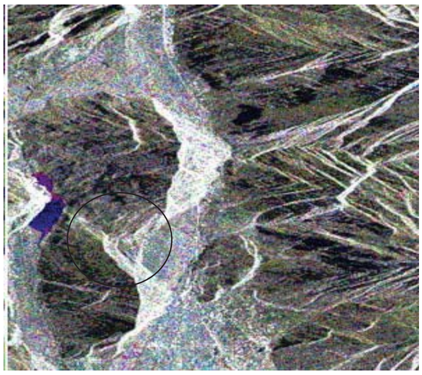


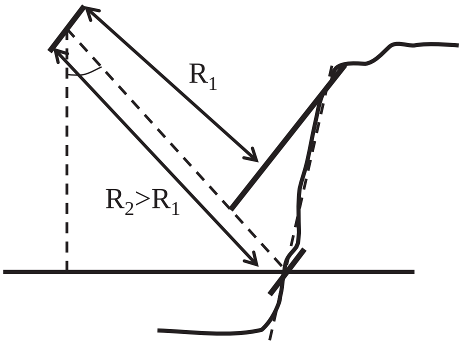


- For steep slopes, when projected on radar range axis, range differences between two points located on foreslopes of mountains are smaller than they would be at the ground
- As a result the mountains seem to "lean" towards the sensor.

Layover

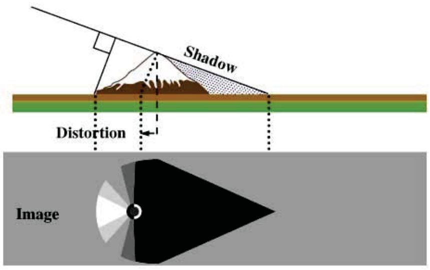


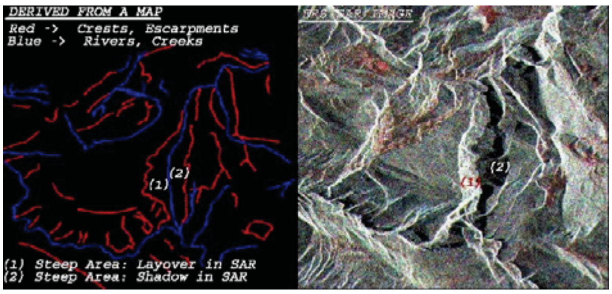


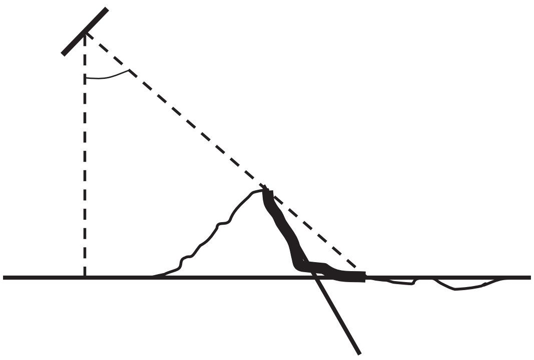


- Extreme case of foreshortening
- For a very steep slope, the foreslope is "reversed" in the range dimension
- Generally, these layover zones, appear as bright features on the image due to the low incidence angle.

Shadow







- A slope away from the radar illumination with an angle that is steeper than the sensor depression angle provokes radar shadows
- Radar shadows are longer in the far range than in the near range

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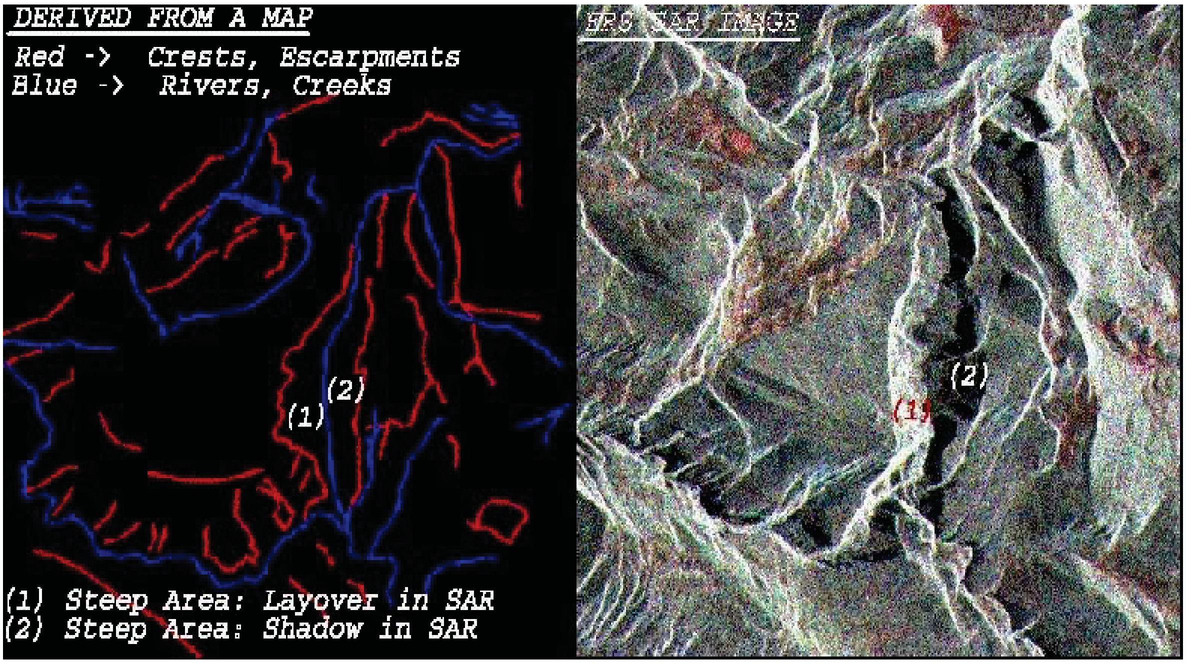

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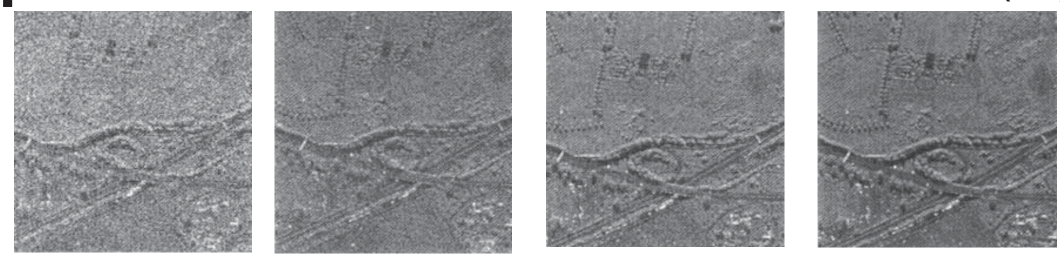
Speckle

Jakowatz & Co (1996)



1 look 2 looks 3 looks 9 looks

- SAR images exhibit grainy texture. This effect is caused by the coherent radiation used by radar systems. Each resolution cell contains several scattering centers whose elementary returns, by positive or negative interference, originate light or dark image brightness.
- Speckles create a "salt and pepper" appearance that can be reduced by averaging results from different frequency bands

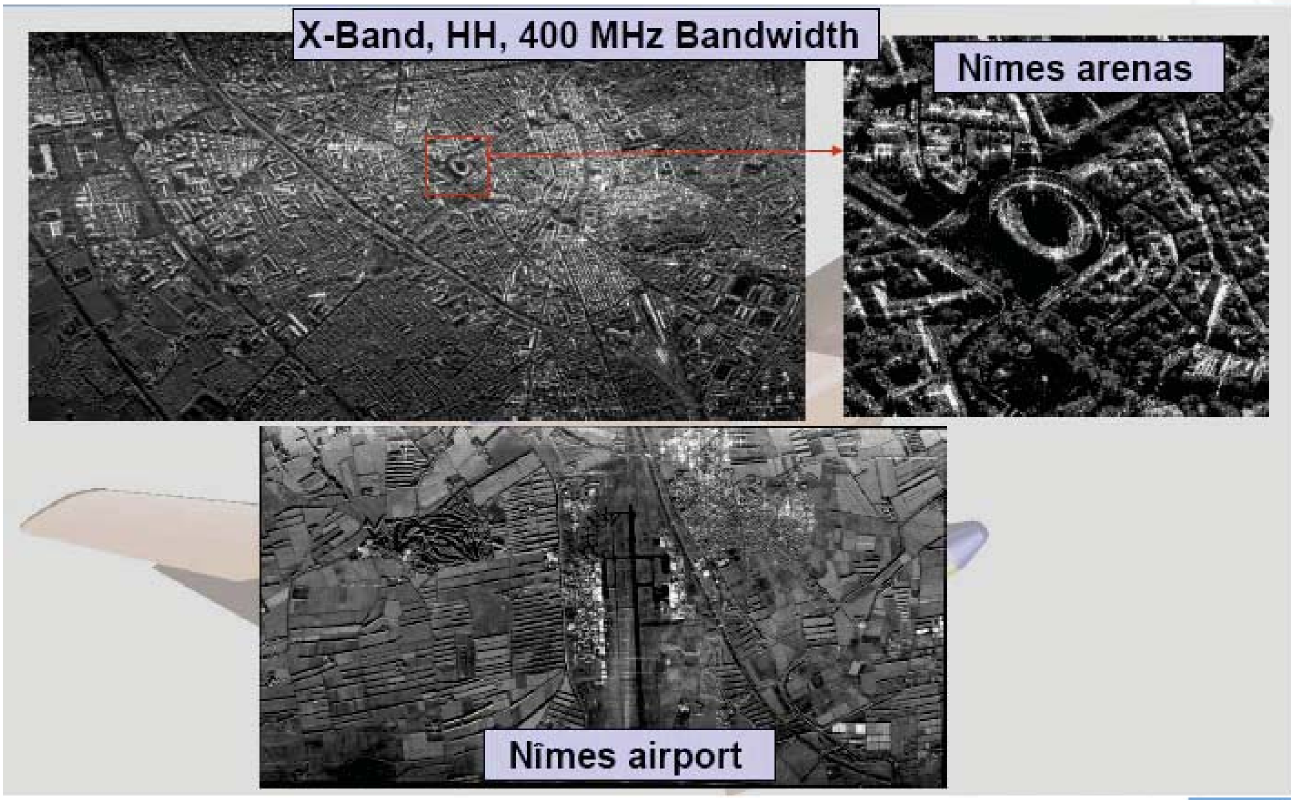
SAR systems

- Spaceborne Radars
  - Europe: ERS1, ERS2, ENVISAT
  - Canada: Radarsat , Radarsat2
  - Japon: JERS-1, PALSAR
  - USA: Seasat, SIR-C, SRTM
  - Germany: TerraSAR-X
  - …

Resolution ~ 15m

- Airborne Radars
- USA (NASA JPL): AIRSAR, UAVSAR
- France: RAMSES, Sethi, RAMSES-NG
- Germany: E-SAR, F-SAR
- Sweden: Carabas, Loram
- ...

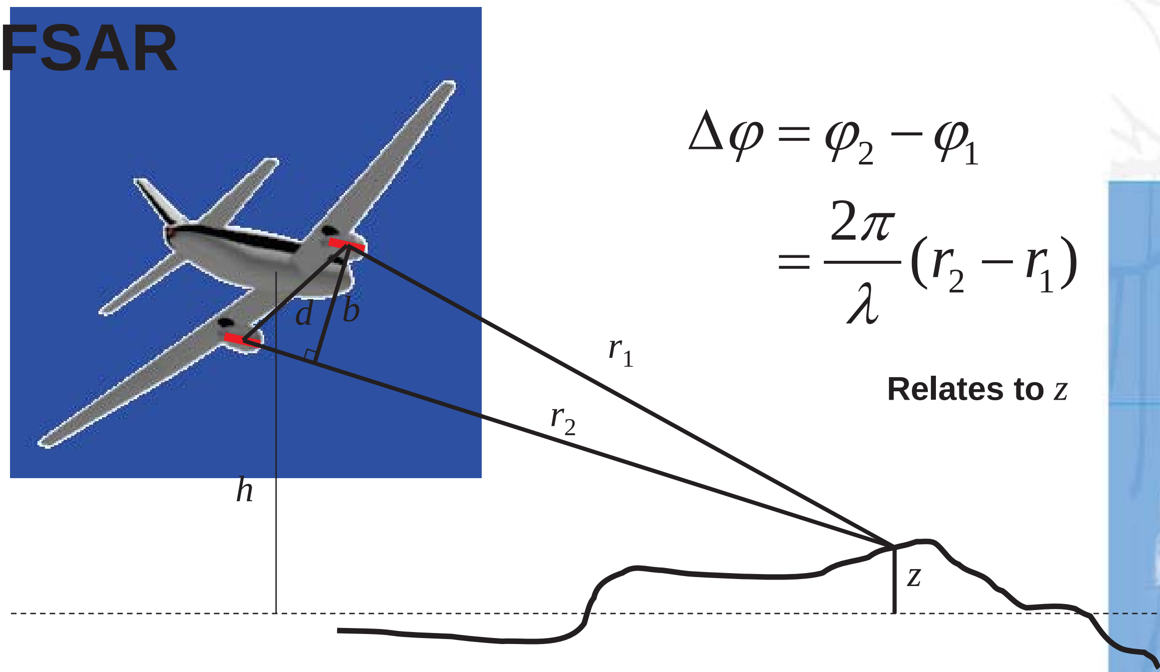
Resolution < 3m



Interferometry

- Interferometry is a method that use the phase difference resulting from two measurements taken at different observation points
  - General radar method not only usable for SAR
  - Very much used in SAR
- SAR-interferometry makes it possibly to resolve the altitude coordinate and thereby measure height.
  - Very sensitive since using the radar phase
  - The radar system needs to be accurate and stable
- Makes GEOCODING possible, that is reference image pixels to geographical reference system.

IFSAR

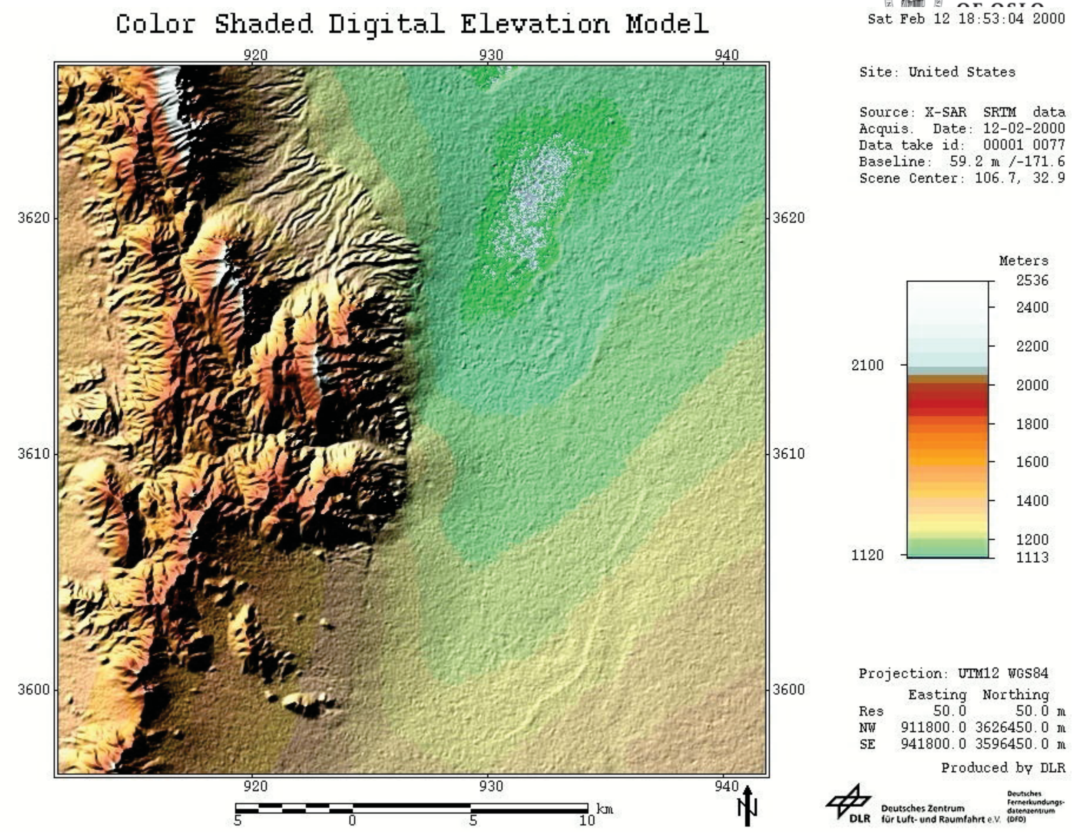


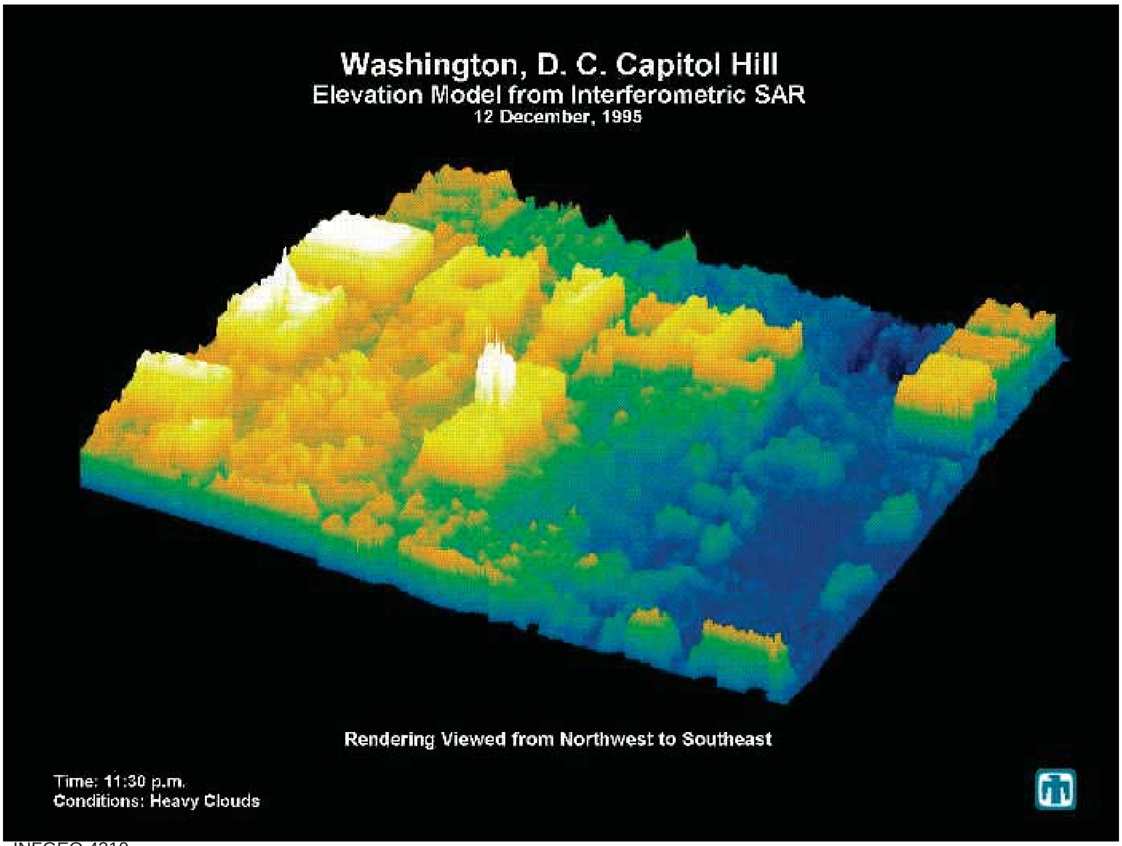
$$\Delta\varphi = \varphi_2 - \varphi_1$$
$$= \frac{2\pi}{\lambda}(r_2 - r_1)$$

Relates to z

Cross-track interferometry (CTI)

Two or Single pass interferometry


Color Shaded Digital Elevation Model
920
930
940
3620
3610
3600
Sat Feb 12 18:53:04 2000
Site: United States
Source: X-SAR SRTM data
Acquis. Date: 12-02-2000
Data take id: 00001 0077
Baseline: 59.2 m /-171.6
Scene Center: 106.7, 32.9
Meters
2536
2400
2200
2100
2000
1800
1600
1400
1200
1120
1113
Projection: UTM12 WGS84
Easting Northing
Res 50.0 50.0 m
NW 911800.0 3626450.0 m
SE 941800.0 3596450.0 m
Produced by DLR
5 0 5 10 km
N
DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.
Deutsches Fernerkundungs-datenzentrum (DFD)


Washington, D. C. Capitol Hill
Elevation Model from Interferometric SAR
12 December, 1995
Rendering Viewed from Northwest to Southeast
Time: 11:30 p.m.
Conditions: Heavy Clouds

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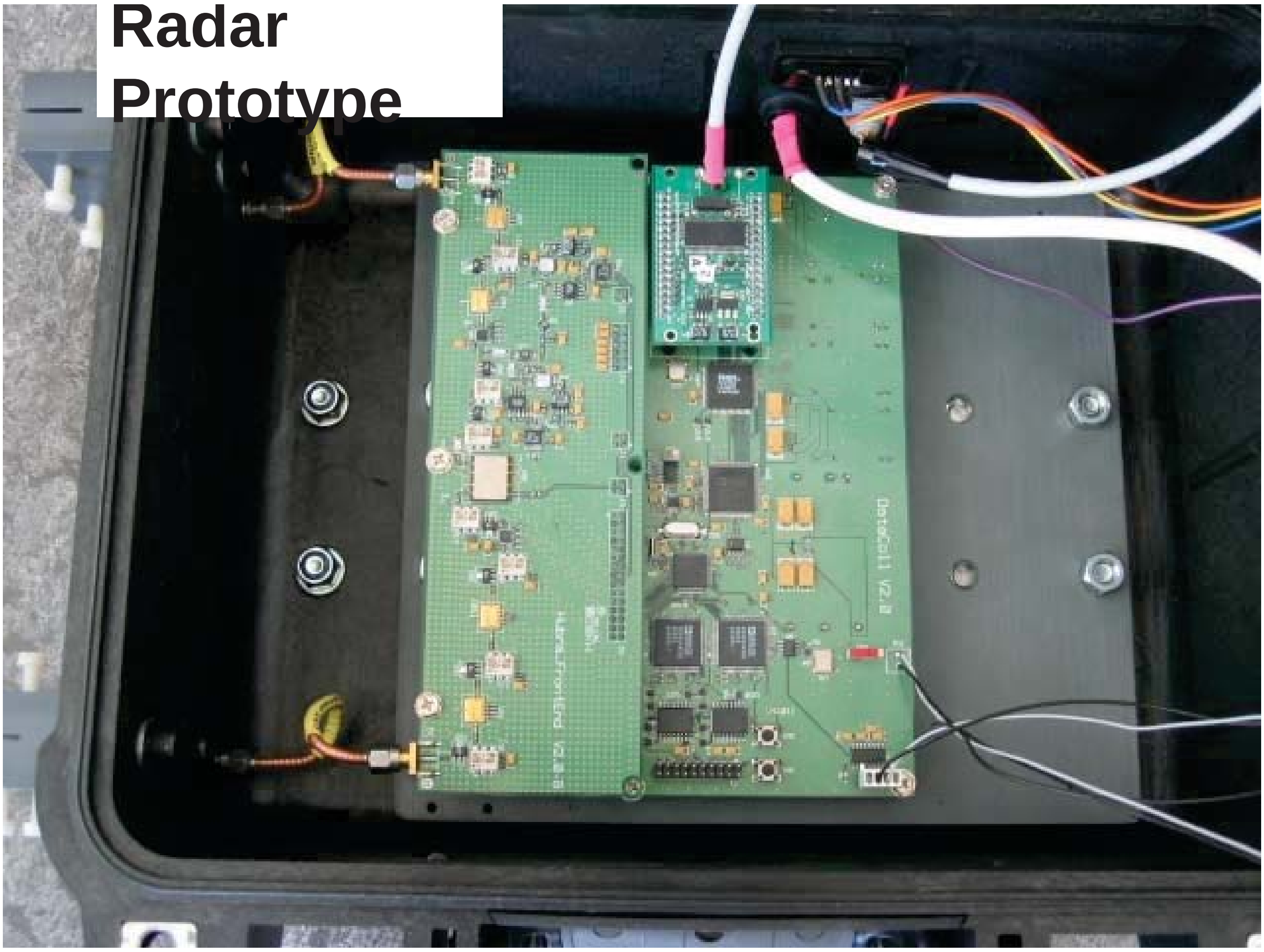
Ground Penetrating Radar (GPR)

Yoann Paichard
INFGEO 4310

Radar Prototype



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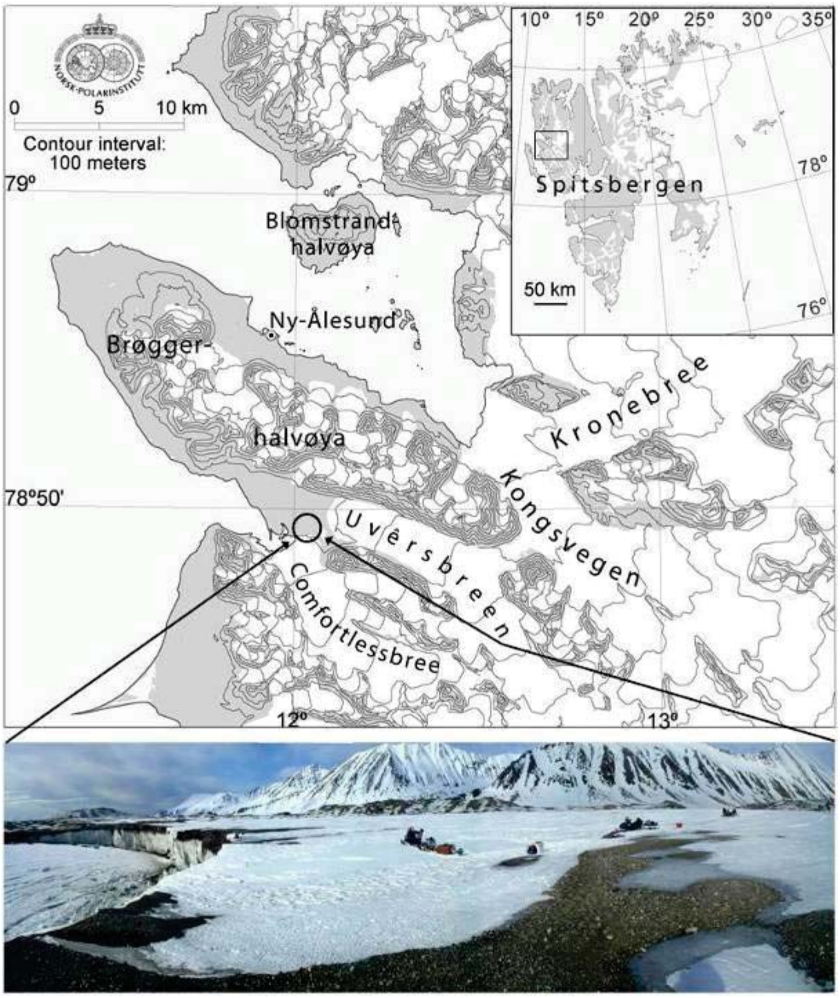

- Mean annual air temperature in NÅ is -6.3°C.
- Permafrost depth is ~100 m in costal areas and >500 m in mountainous areas.
- Active layer depth at the field site is believed to be ~2 m.
- This layer experiences thawing in the summer/autumn.

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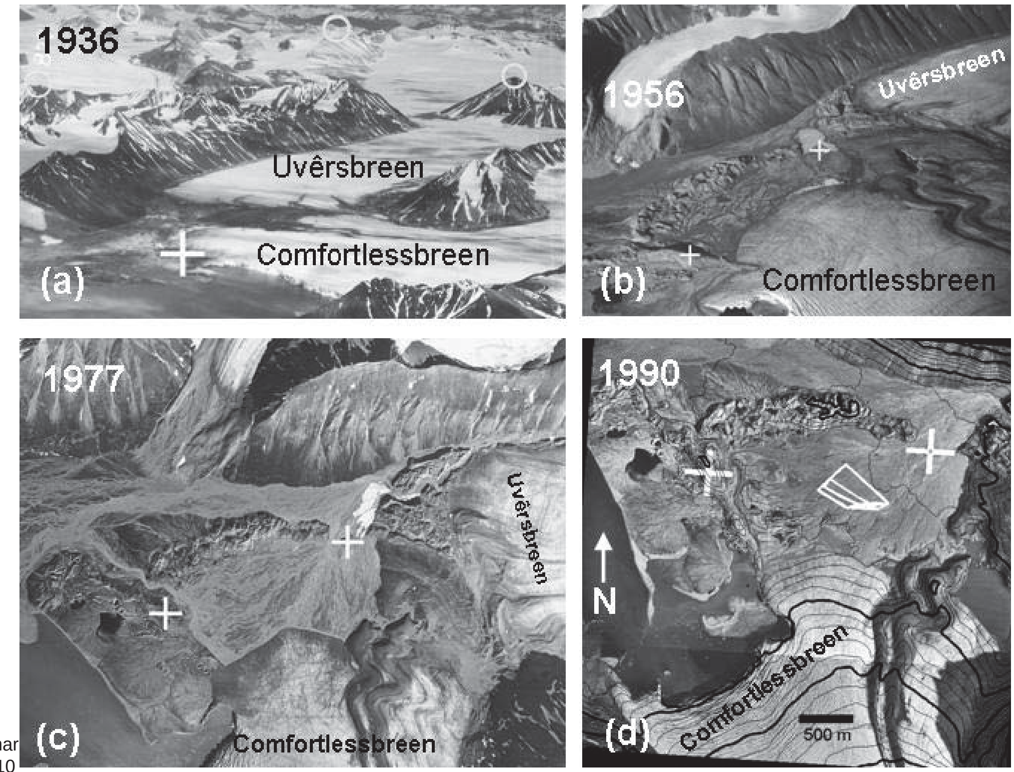
Aerial photographs



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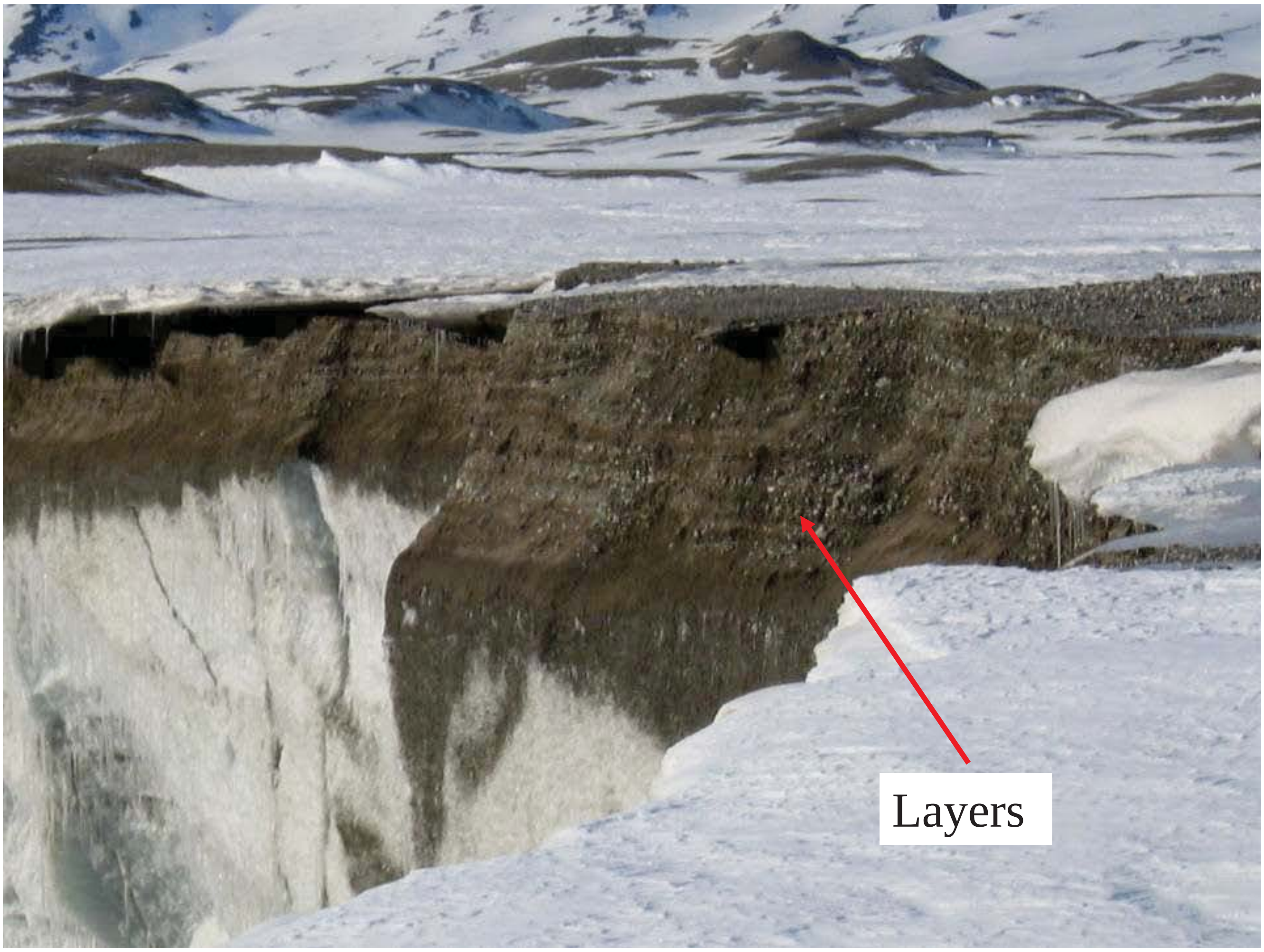
Uversøyra Field Test Area

Sediment Layer on Top of Ice



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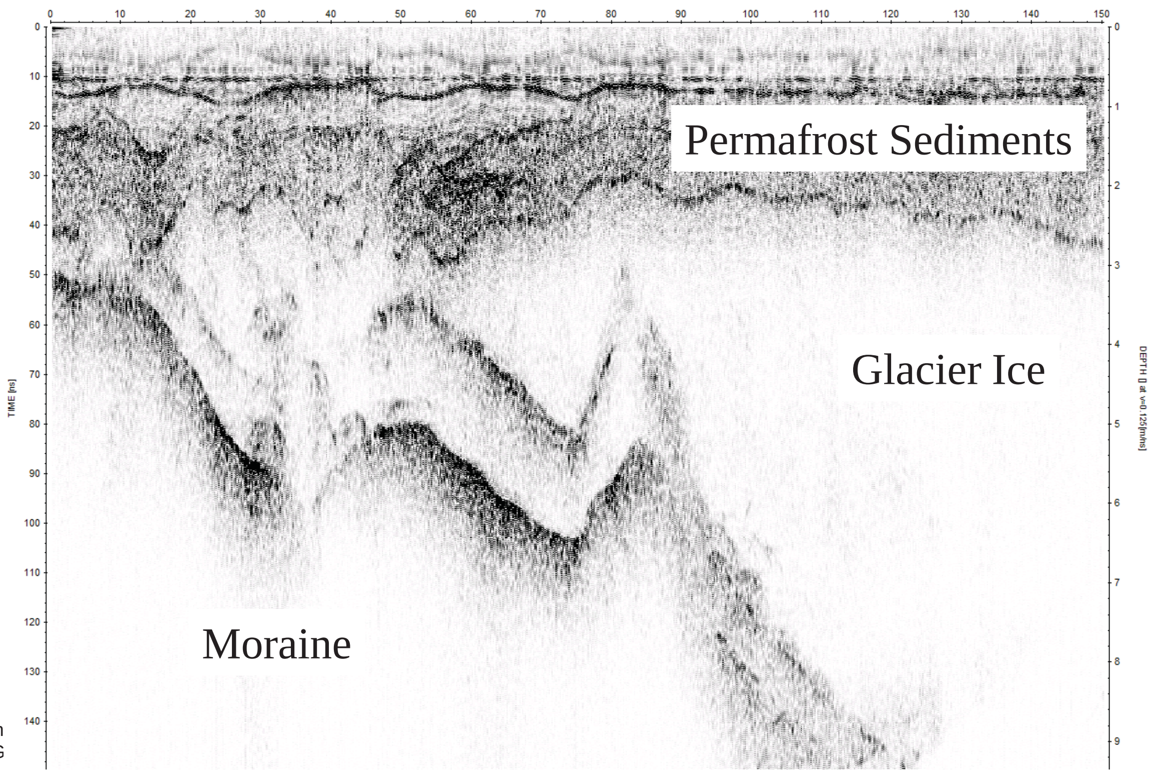
Interpretation



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INFG

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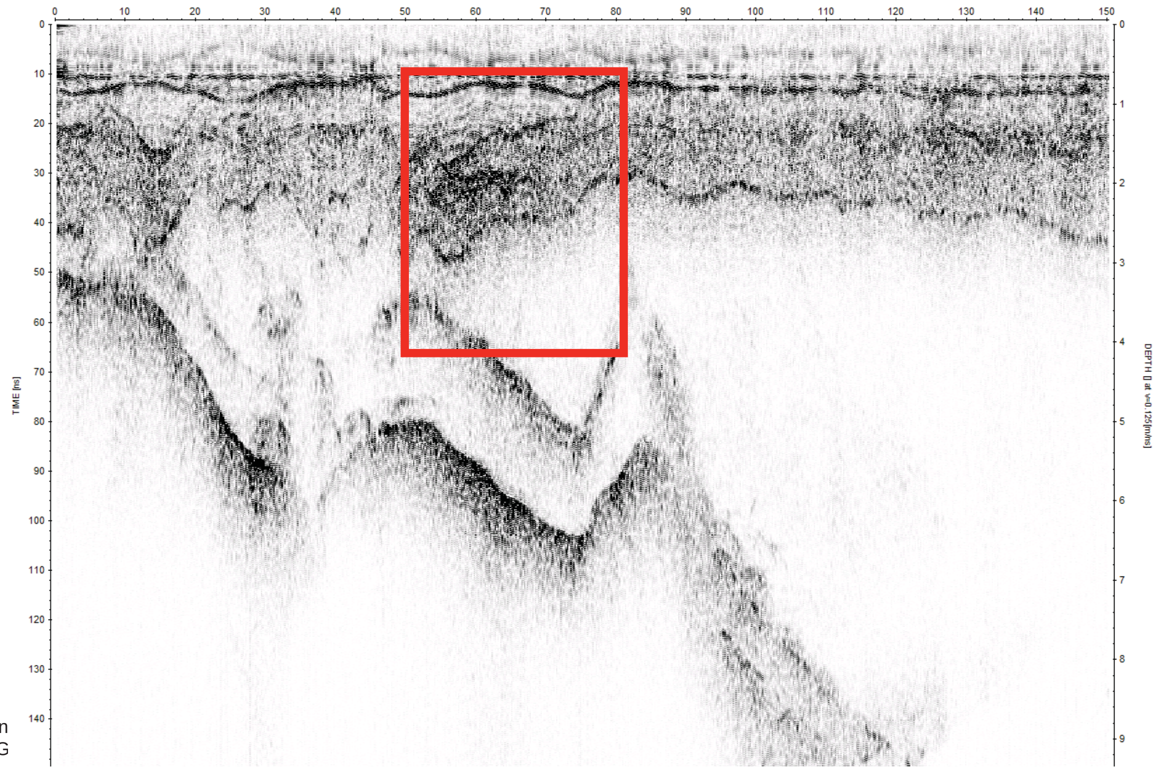
50 to 80 meter along profile



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