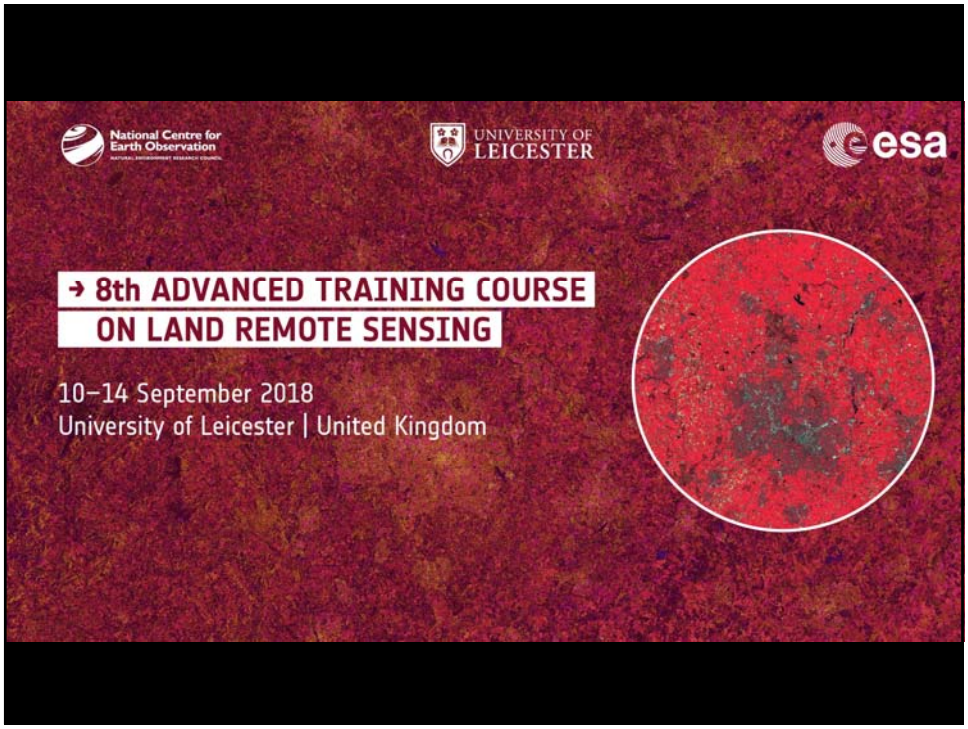


Introduction to SAR remote sensing

Ramon Hanssen

10-9-2018

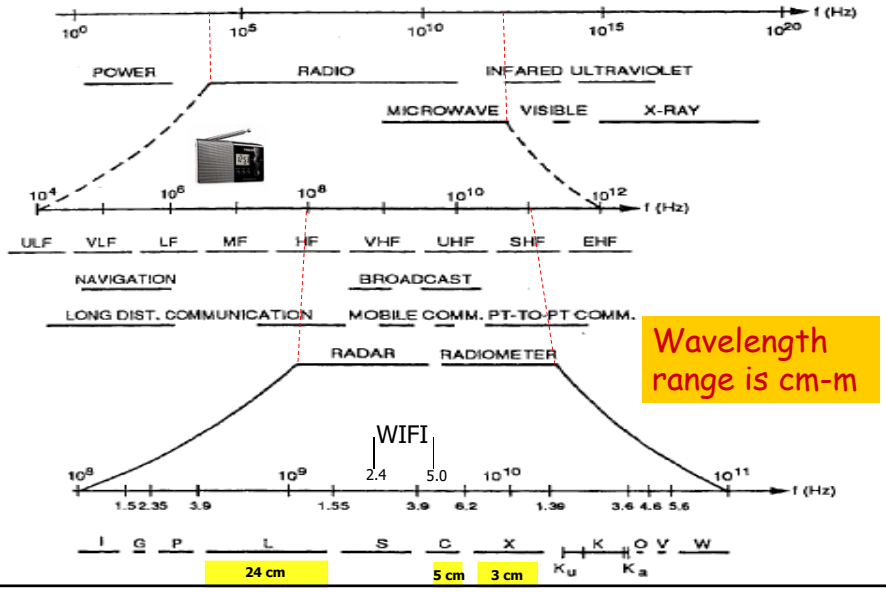
Obectives of the module

- Provide the basic essentials of SAR remote sensing, and understand the jargon
  - Radar
  - Physics
  - Geometry
  - SAR
  - Image coordinates and observables

Why radar?

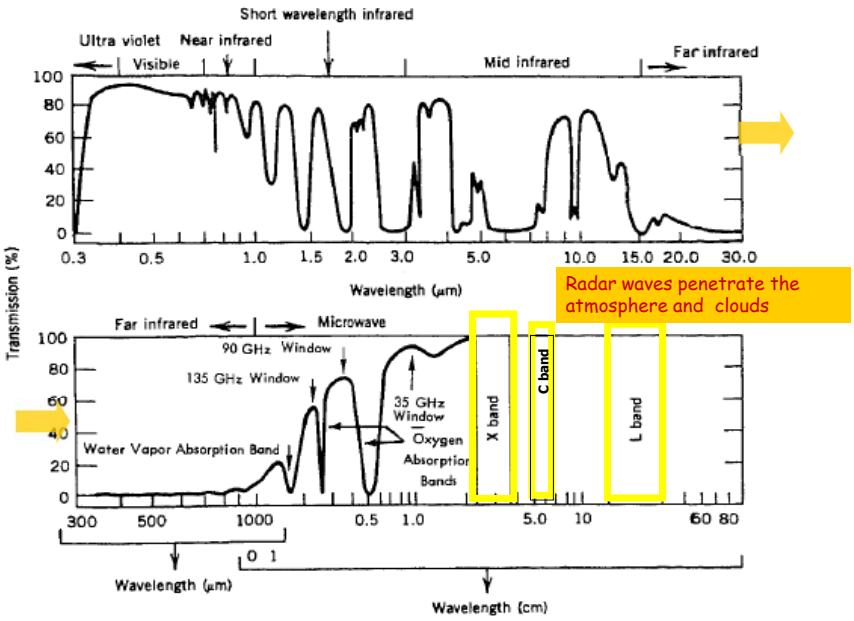
1. Active:
   - No sunlight necessary
2. Imaging properties
3. Longer wavelength than optical:
   - Penetration of clouds, canopy, soil
   - Coherent imaging (phase information)
4. Different physical properties (compared to optical)

Radar frequency bands



Wavelength range is cm-m

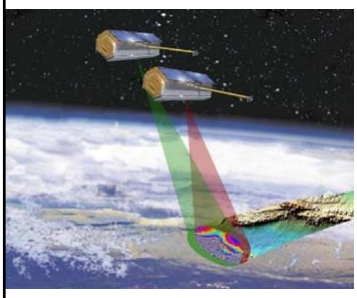
Radar frequency bands

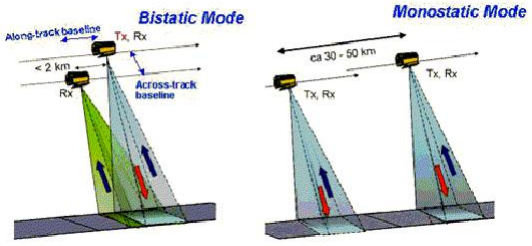


Radar waves penetrate the atmosphere and clouds

Radar types: bistatic – monostatic

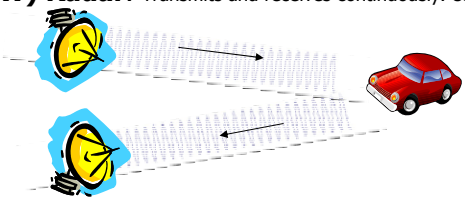
- Monostatic: same antenna for transmitting and receiving
- Bistatic: different antennas for transmitting and receiving



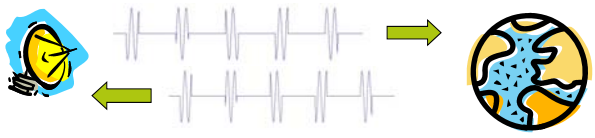


Radar Types: CW / pulsed

- **Continuous Wave (CW) Radar.** Transmits and receives continuously. Usually bistatic. Velocity measurements.

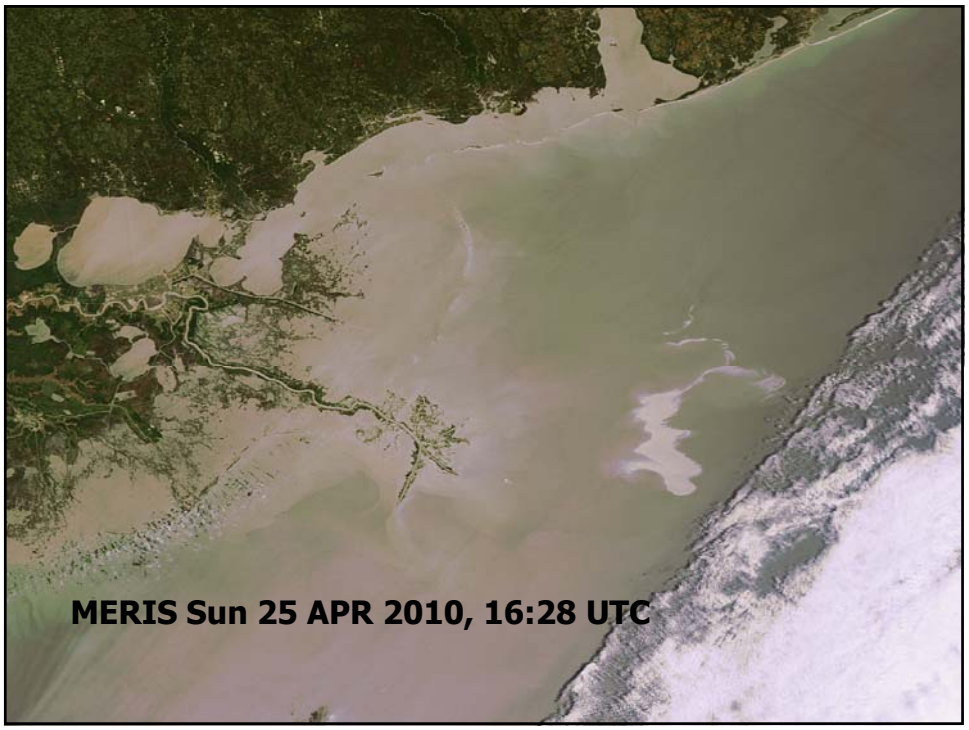


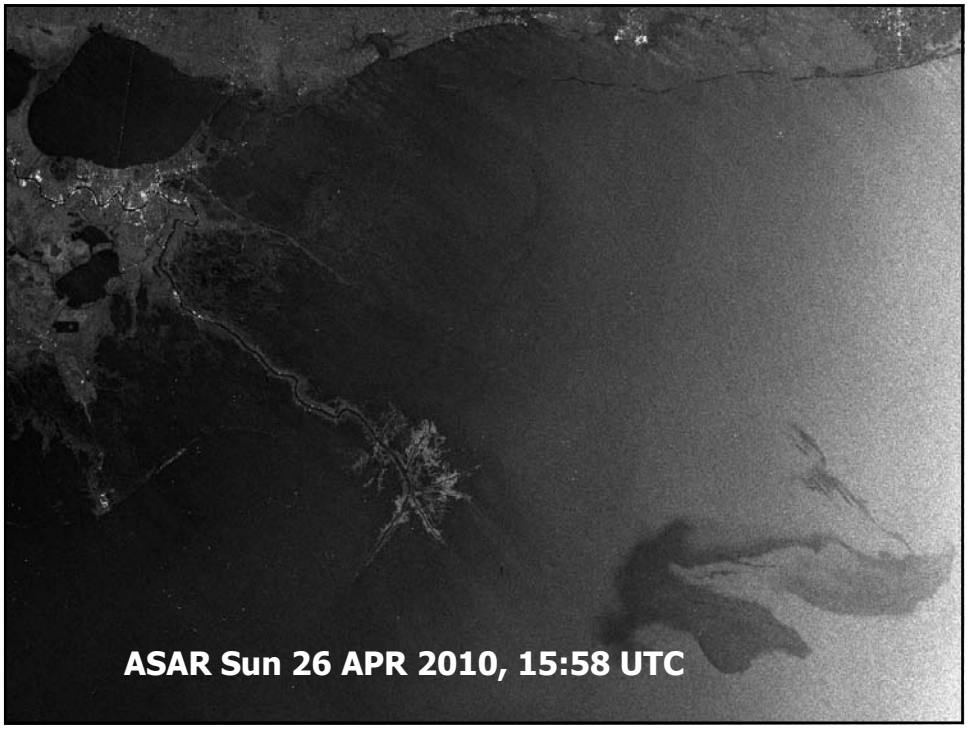
- **Pulse Radar.** The common radar type. It sends the signal in pulses. Measures range and velocities



Applications

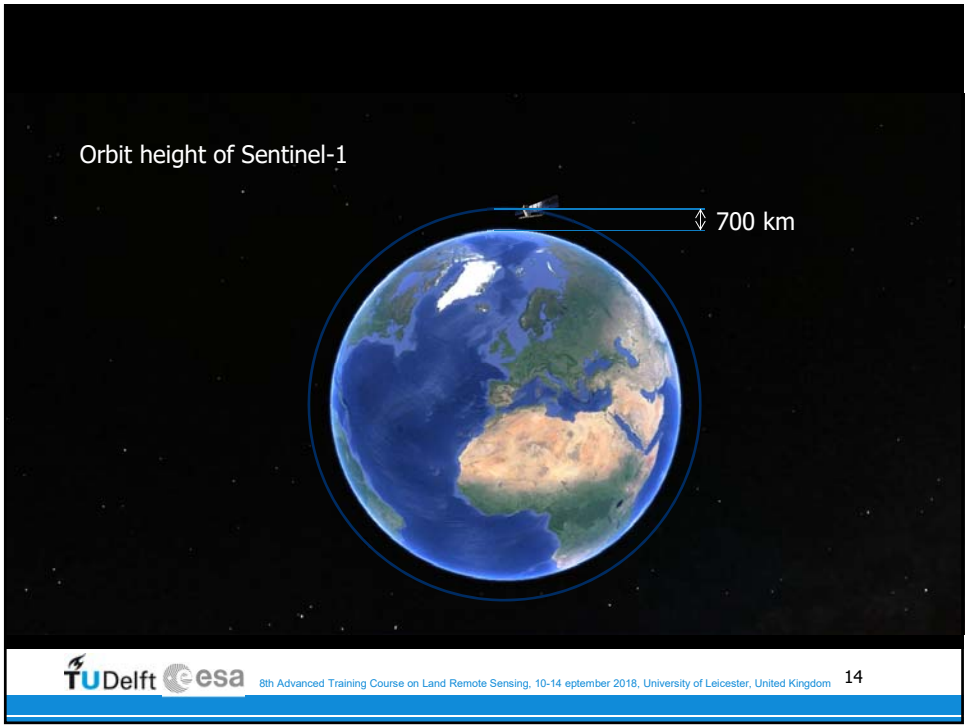
- Solid earth
  - Tectonics
  - Volcanoes
  - Surface movement
  - Forestry: Forest biomass / timber estimation, tree height
  - Agriculture: Crop classification, Soil moisture mapping, soil roughness mapping / monitoring, Crop yield, crop stress
  - Geology
  - Elevation models
  - Flood mapping, Snow mapping, Oil Slicks
  - Pipeline integrity
  - Landslide prediction
- Oceans
  - Spill detection
  - Natural seepage of oil
  - Wave strength for oil platforms
  - Ship detection
  - Wind and waves
  - Sea surface topography
  - Ocean currents
  - Bathymetry
  - Ice monitoring, Sea ice type,

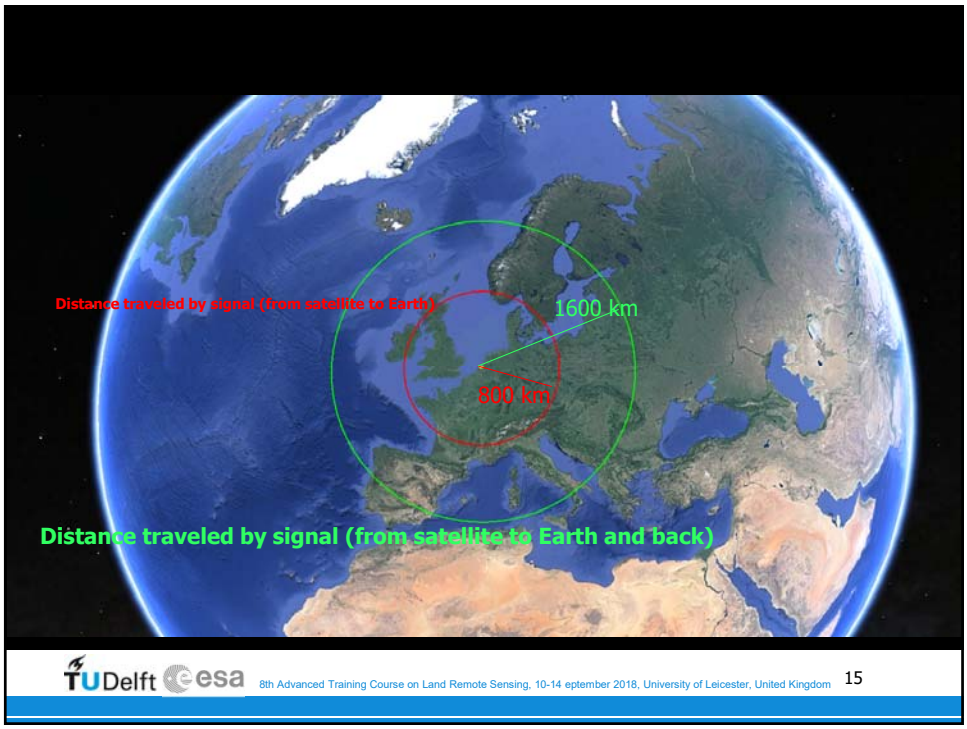




SAR Geometry

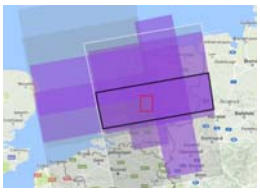
- Satellite orbit geometry
- Coordinates range, azimuth
- Side-looking
- Foreshortening, layover, shadow
- Incidence angle

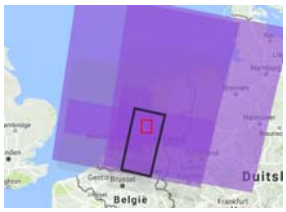

Orbit height of Sentinel-1
700 km

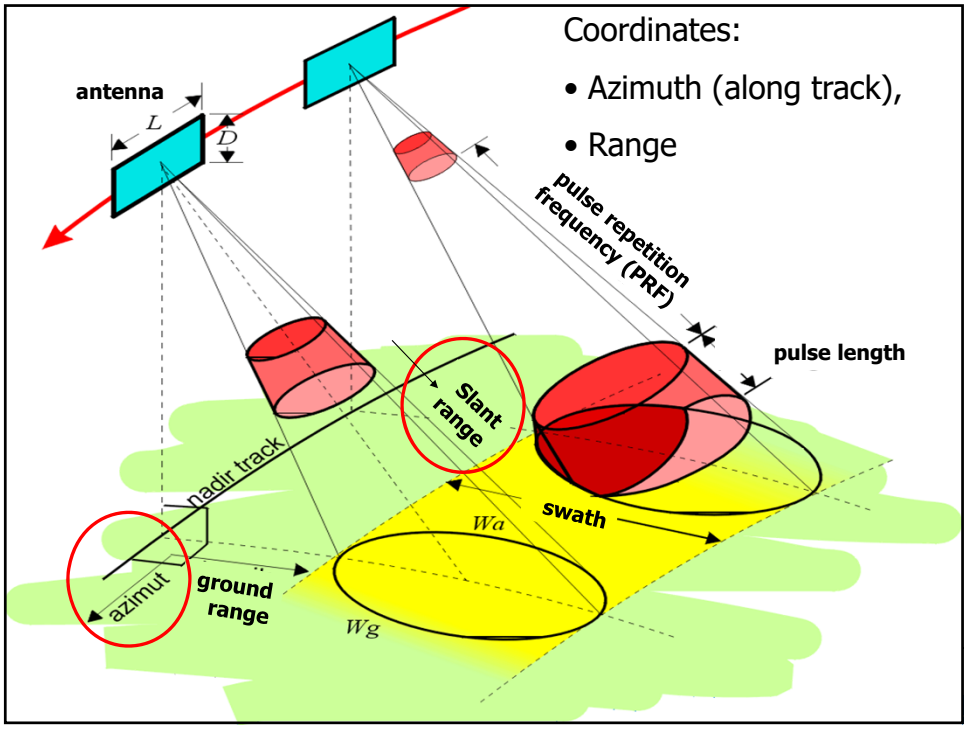

Distance traveled by signal (from satellite to Earth)
1600 km
800 km
Distance traveled by signal (from satellite to Earth and back)

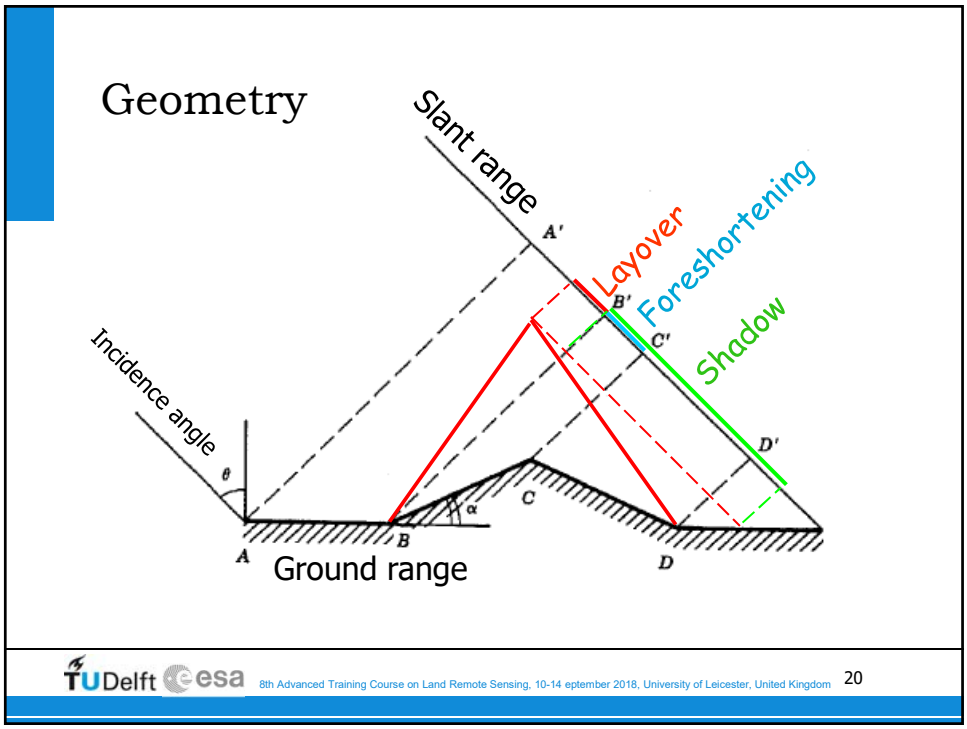
Orbital geometry

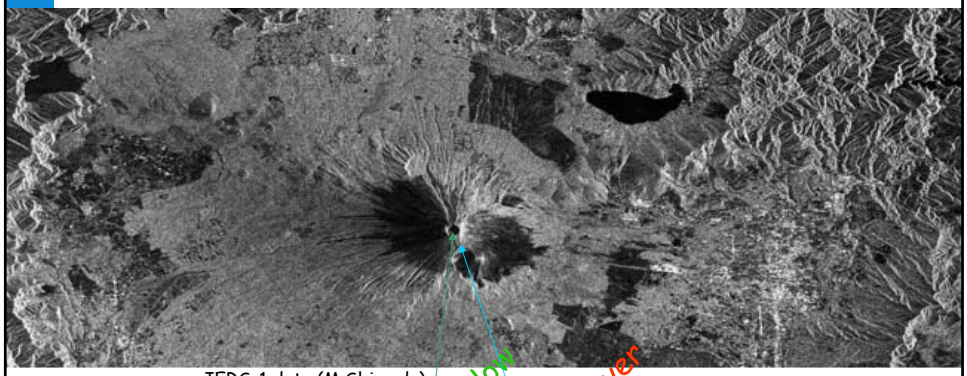
Near-polar, sun-synchronous, repeating, revisiting






Coordinates:
• Azimuth (along track),
• Range
antenna
L
D
pulse repetition frequency (PRF)
pulse length
Slant range
nadir track
swath
Wa
azimut
ground range
Wg


Geometry
Slant range
A'
Layover
Foreshortening
B'
C'
Shadow
D'
Incidence angle
θ
α
C
B
A
Ground range
D
TUDelft
esa
8th Advanced Training Course on Land Remote Sensing, 10-14 eptember 2018, University of Leicester, United Kingdom
20

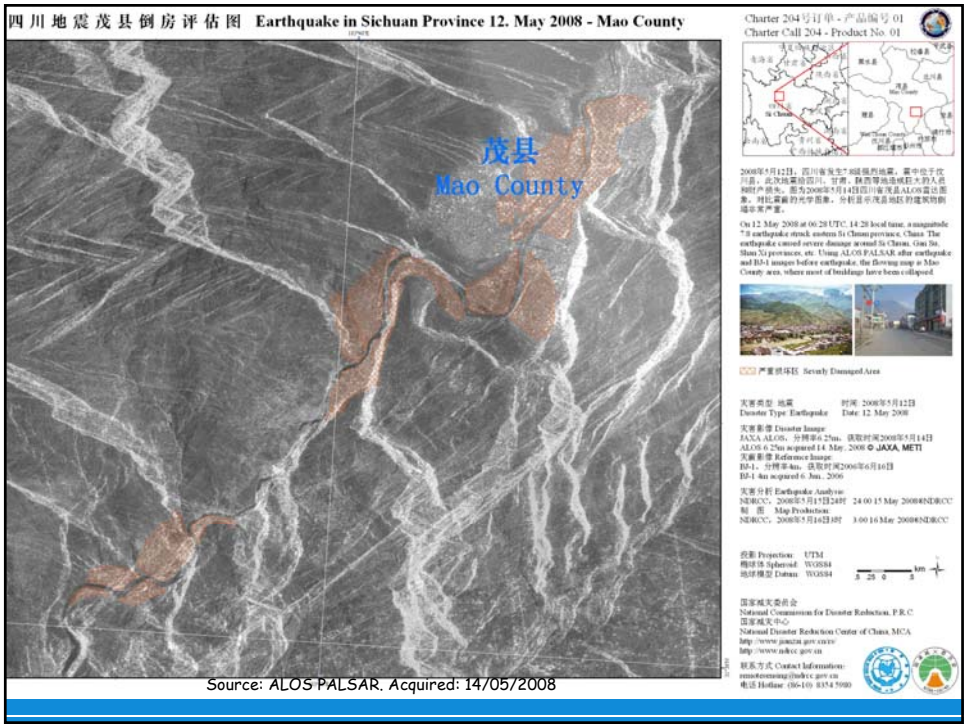


JERS-1 data (M.Shimada)

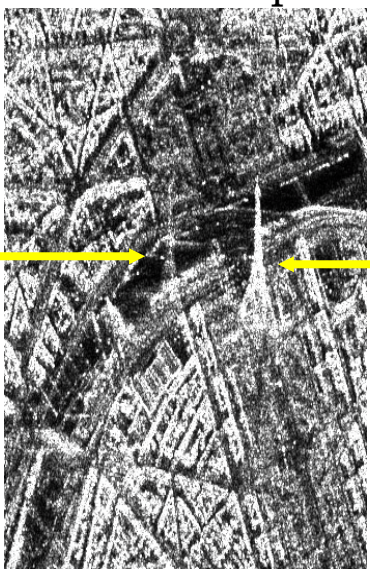
Shadow

Foreshortening

Layover

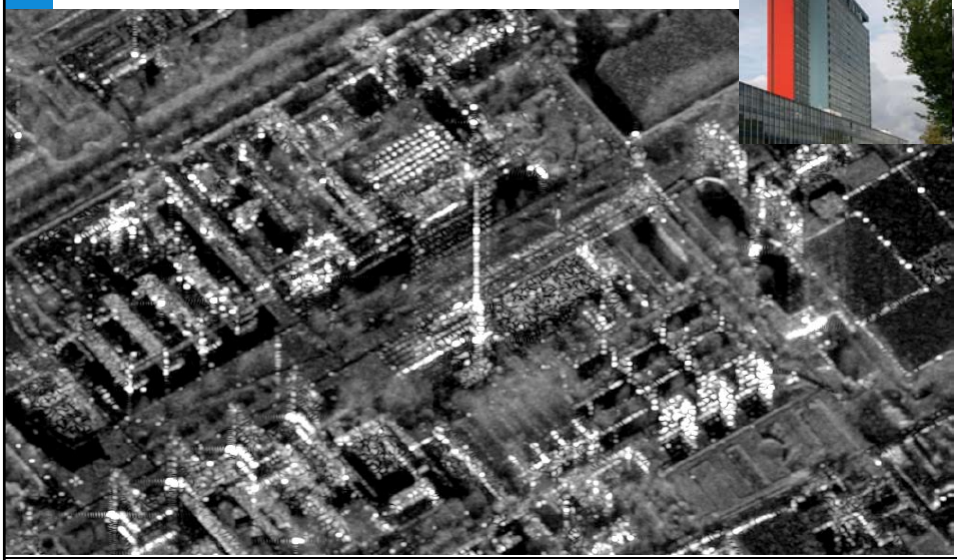


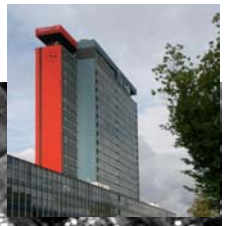
Lay-over: a real example

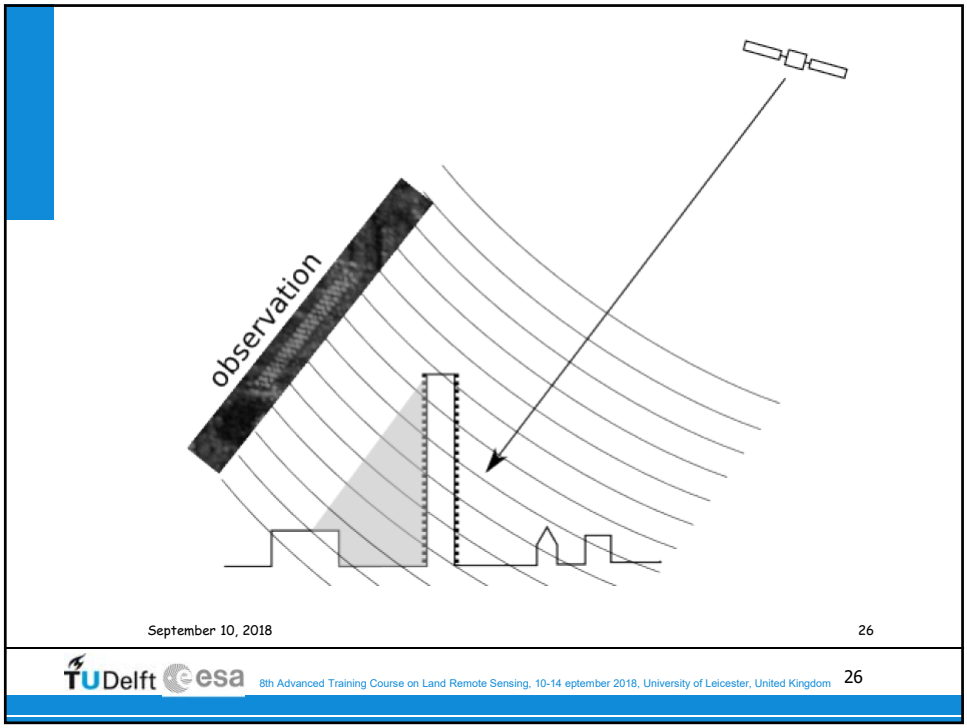


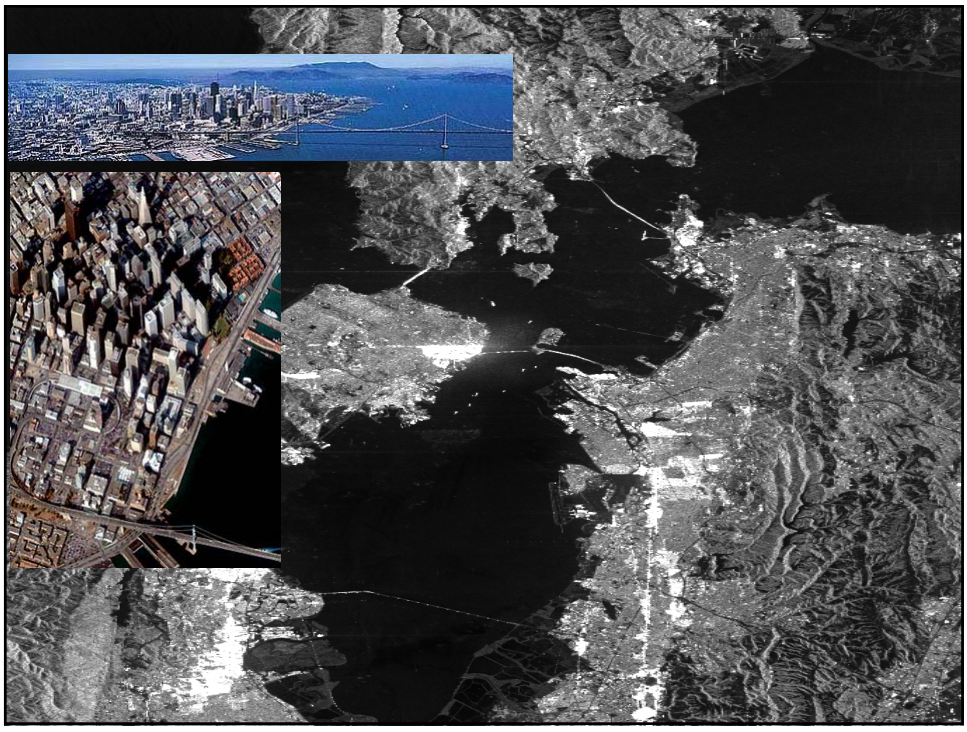
Data from SETHI, ONERA

EWI building, TU Delft

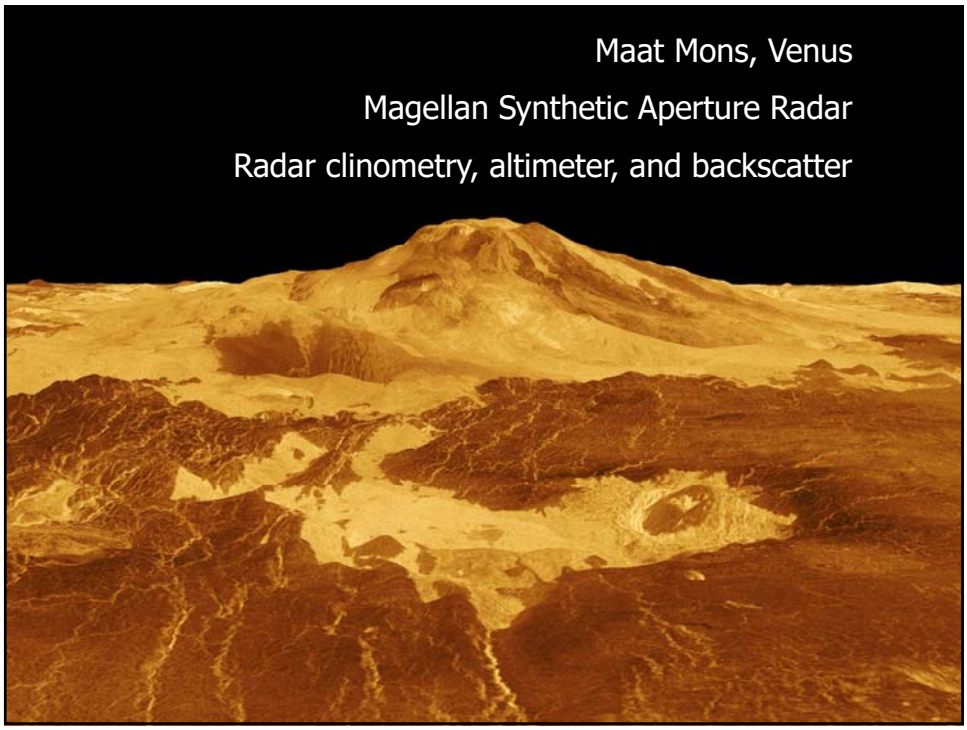


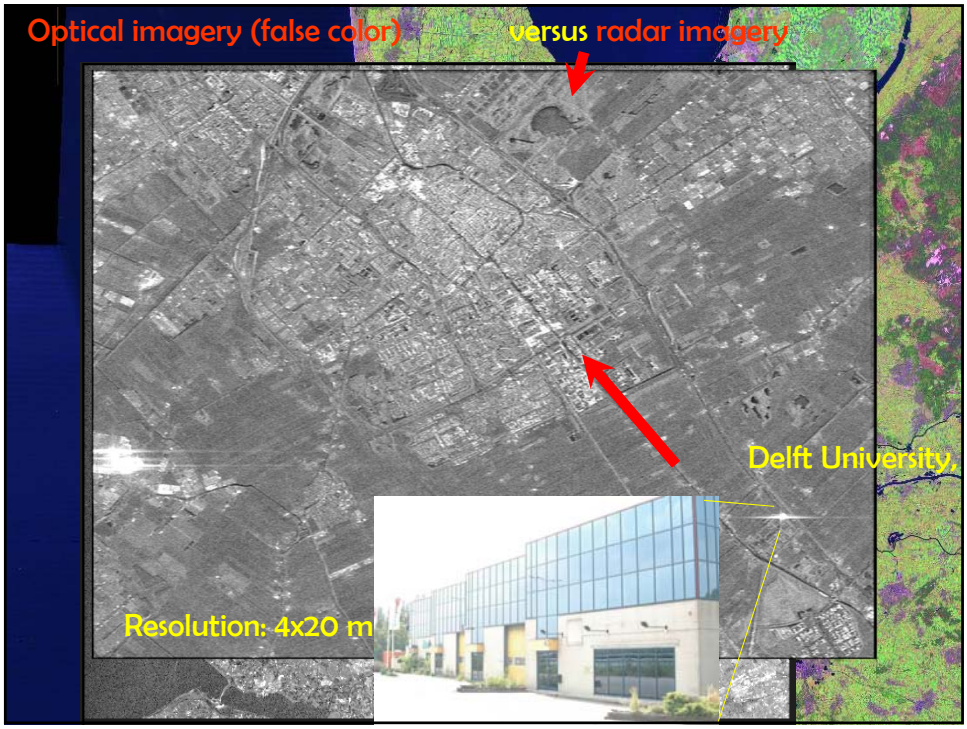



observation



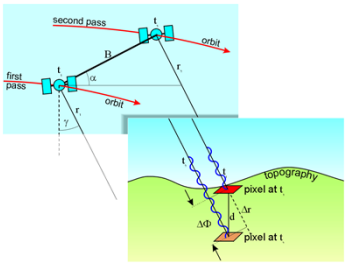
Magellan Synthetic Aperture Radar Mosai


Maat Mons, Venus
Magellan Synthetic Aperture Radar
Radar clinometry, altimeter, and backscatter

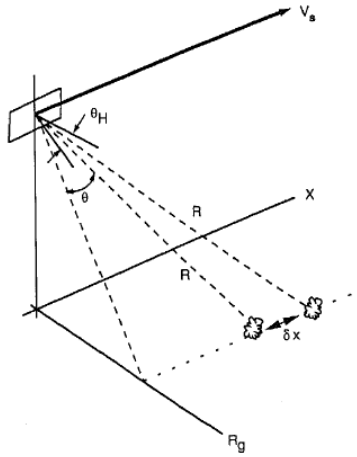


Imaging radar: Synthetic Aperture Radar (SAR)

- Angular Resolution (Beamwidth) is dependent on
  1. Antenna size
  2. Wavelength of the radar: C-band, X-band, L-band, S-band



Resolution I: RAR



- Real Aperture Radar
- Resolution dependent on antenna dimension/pulse length
- Beam width (half power width) is ratio wavelength over antenna size:

$$\theta = \alpha \frac{\lambda}{D} \text{ with } 0.9 < \alpha < 1.4$$

Figure 1.8 Illustration of real-aperture radar capability to resolve two targets separated in azimuth.

Calculate Ground Resolution

$$\theta = \frac{\lambda}{D}$$

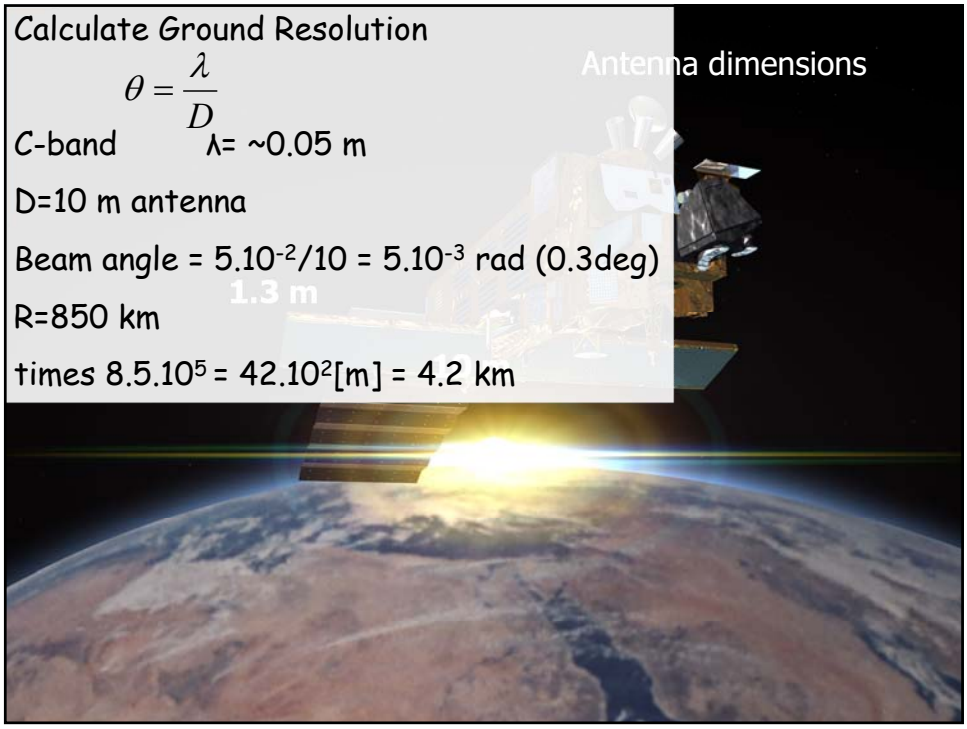
C-band λ= ~0.05 m

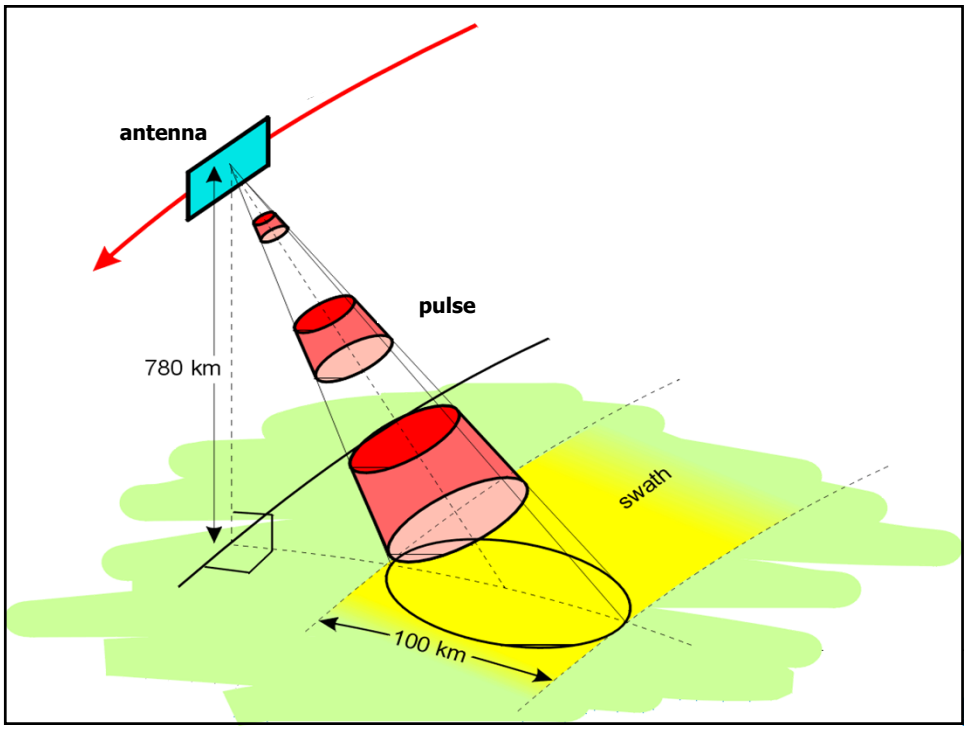
D=10 m antenna

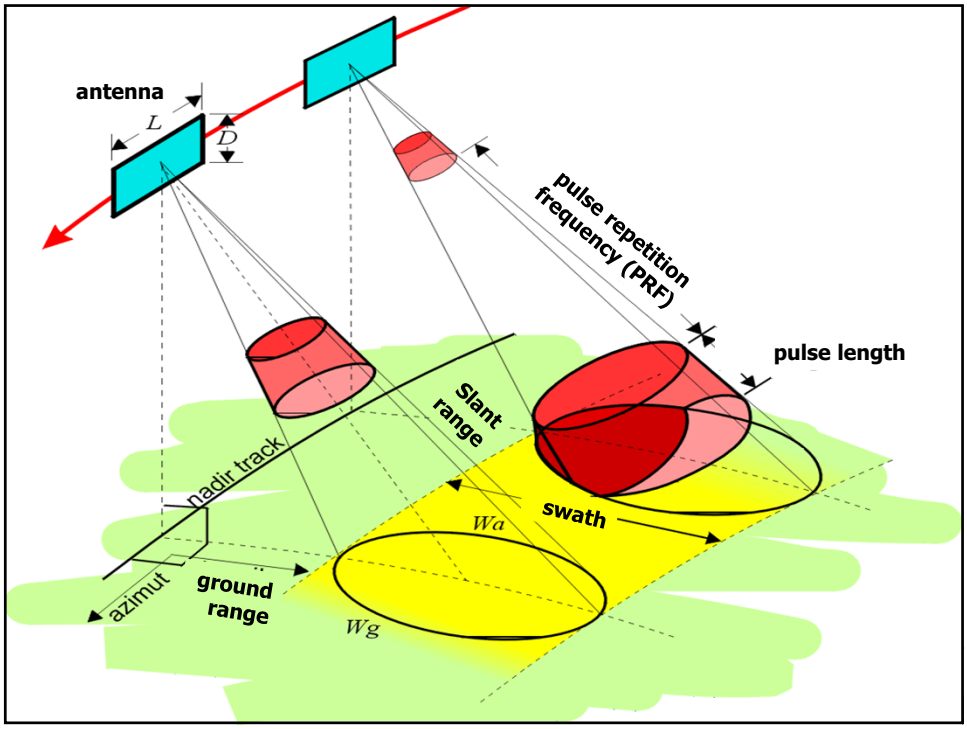
Beam angle = $5.10^{-2}/10 = 5.10^{-3}$ rad (0.3deg)

R=850 km

times $8.5.10^{5} = 42.10^{2}$[m] = 4.2 km



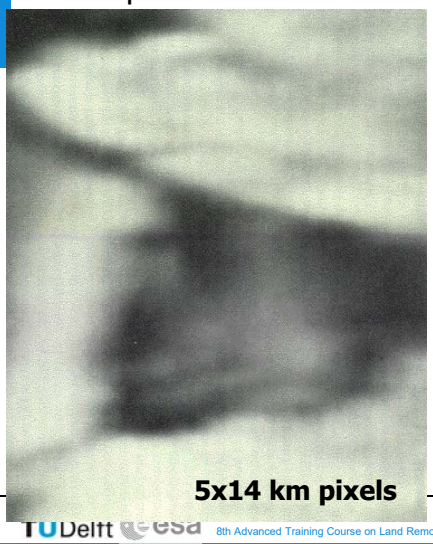




Improvement in Resolution

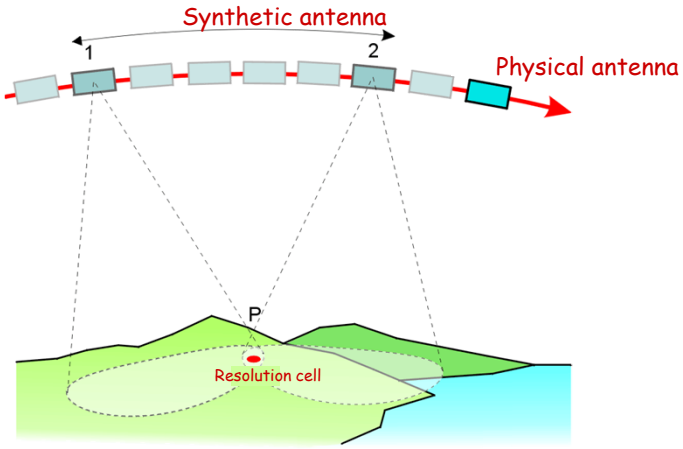
(Crimea, Ukraine)

Real Aperture Radar



Massonnet and Feigl, 1998

Improvement of along-track resolution: SAR

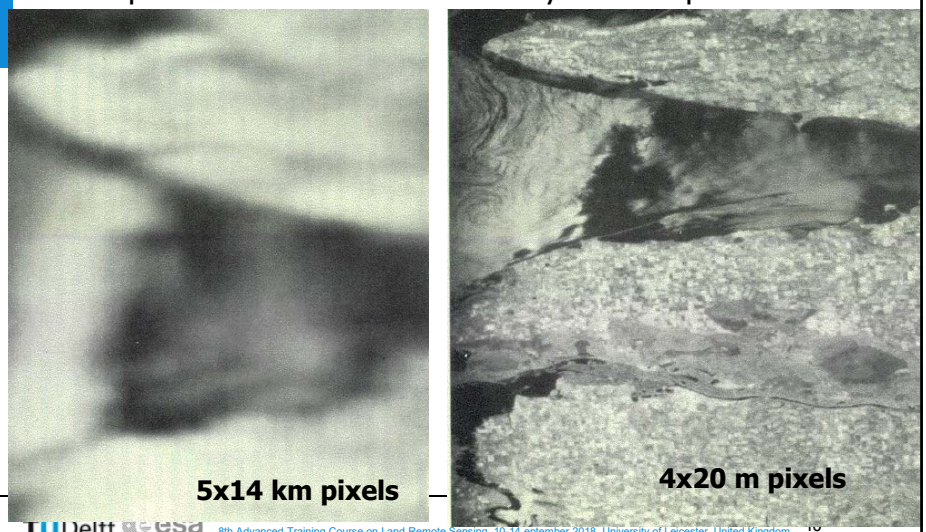


Improvement in Resolution

(Crimea, Ukraine)

Real Aperture Radar

Synthetic Aperture Radar



Massonnet and Feigl, 1998

The Radar Equation

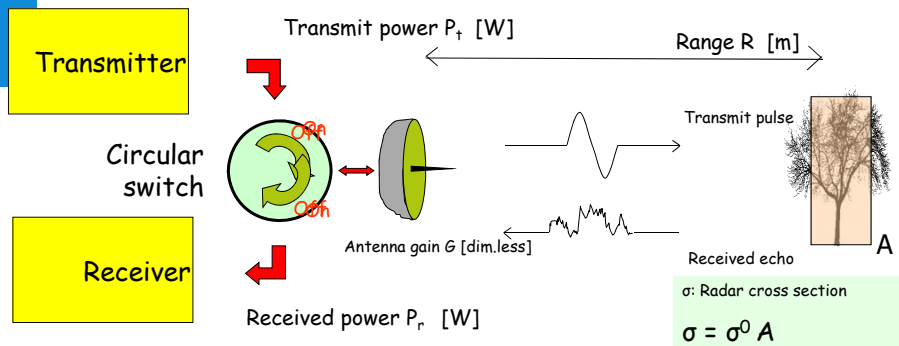
Radar equation (monostatic)

- Radar equation relates transmit power to received power, for a specific antenna and target:

$$P_r = \frac{A_e G P_t}{(4\pi)^2 R^4} \sigma^0 A$$

- The equation above is known as the radar equation.
- Note that power received by antenna is inversely proportional to the 4th power of distance.
- …derivation using radar block model:

Radar equation (monostatic)



σ: Radar cross section

$\sigma = \sigma^0 A$

σ^0: Normalized radar cross section
or 'sigma-naught'

A: scattering area [m^2]

A_e: Antenna size

sigma-naught: "a dimensionless quantity defining the ability of an object to scatter the incident microwave radiation back toward the radar instrument."

Radar equation step by step

Transmit power	: P_t	[W]
Power density (at distance R)	: $\frac{P_t}{4\pi R^2}$	[W/m^2]
Antenna directivity gain G concentrates energy	: $G = 4\pi A_e/\lambda^2$	[-]
Power density at scattering object	: $\frac{P_t}{4\pi R^2} \cdot G$	[W/m^2]
Fraction of power returned		[-]
Radiating isotropically back	: $\frac{1}{4\pi R^2}$	[m^{-2}]
Power density at receiving antenna	: $\frac{P_t}{4\pi R^2} \cdot G \cdot A \cdot \sigma^0 \cdot \frac{1}{4\pi R^2}$	[W/m^2]
Receive power at antenna with area A_e	: $\frac{P_t}{4\pi R^2} \cdot G \cdot A \cdot \sigma^0 \cdot \frac{A_e}{4\pi R^2}$	[W]

$$P_r = \frac{A_e G P_t}{(4\pi)^2 R^4} \sigma^0 A \qquad (9.3)$$

Radar equation step by step

Transmit power	: P_t	[W]
Power density (at distance R)	: $\frac{P_t}{4\pi R^2}$	[W/m^2]
Antenna directivity gain G concentrates energy	: $G = 4\pi A_e/\lambda^2$	[·]
Power density at scattering object	: $\frac{P_t}{4\pi R^2} \cdot G$	[W/m^2]
Power intercepted by area A	: $\frac{P_t}{4\pi R^2} \cdot G \cdot A$	[W]
Fraction of power returned to radar	: σ^0	[·]
Radiating isotropically back	: $\frac{1}{4\pi R^2}$	[m^{-2}]
Power density at receiving antenna	: $\frac{P_t}{4\pi R^2} \cdot G \cdot A \cdot \sigma^0 \cdot \frac{1}{4\pi R^2}$	[W/m^2]
Receive power at antenna with area A_e	: $\frac{P_t}{4\pi R^2} \cdot G \cdot A \cdot \sigma^0 \cdot \frac{A_e}{4\pi R^2}$	[W]

$$P_r = \frac{A_e G P_t}{(4\pi)^2 R^4} \sigma^0 A \qquad (9.3)$$

Radar equation (example ERS-2)

Peak transmit power P_t	4800 [W]
Range R	850.000 [m]
Antenna directivity gain G	40.000 [·]
Illuminated area A	70 [km^2]
Fraction of power returned to radar σ^0	4% [·]
Antenna area A_e	10 [m^2]

$$P_r = \frac{A_e G P_t}{(4\pi)^2 R^4} \sigma^0 A \qquad (9.3)$$
$$\approx 6.5 \cdot 10^{-9} \quad [W]$$

Transmit: 4.8 ·10^3 W

Receive: 6.5 ·10^{-9} W

Difference: ~10^{12} W

Echo is 120 dB below transmit power level!

Working with decibels

- Large power ratios

  $dB = 10 \cdot {}^{10}\log(P)$, and v.v. $P = 10^{(dB/10)}$

  where P is
  - Power ratio, or
  - A parameter related to a power unit (e.g. antenna gain)
- In equations, sometimes dB needs to be converted to numeric

Examples:

R	dB
1	0
2	3
100	20
31.6	15

Radar Cross Section

RCS depends upon:

1. The electrical properties of the target. High conductivity materials, e.g. metals, are good electromagnetic reflectors
2. The shape of the target
3. The size of the target

RCS, denoted as σ, can be given as

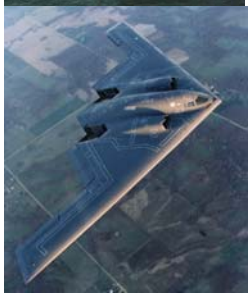
$$\sigma = \sigma^0 A$$

where σ^0 scattering coefficient or normalized radar cross section or 'sigma-naught' and A is the scattering area [m^2].

Radar cross sections

(@ microwave frequencies)

	m^2
Jumbo jet	100
Medium jet airliner	20
Helicopter	3
Pickup truck	200
Automobile	100
Man	1
Stealth fighter jet	< 1
Medium bird	10^{-3}
Small insect (fly)	10^{-5}



Signal and Noise

In the radar equation, we covered the 'signal': what we want to measure.

To determine whether it is measurable, we need to consider the 'noise' as well, since

The signal-to-noise ratio is a metric which tells us whether something is observable

So, we continue with the noise part

Sources of Noise

- The most important source of noise in a radar system is the one produced by the device itselft, i.e. **thermal noise** :

$$P_n = k \cdot T_{sys} \cdot B$$

  - P_n : Noise power
  - k : Boltzmann's constant (1.38 10^{-23} [J/K]
  - T_{sys} : Noise temperature [K]
  - B : System bandwidth [Hz]

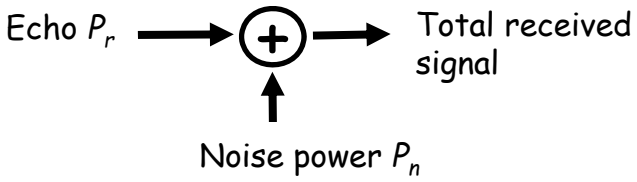
- Other sources only of concern when working at the edges of the microwave spectrum are Cosmic noise (<UHF) and Atmospheric absorption noise, (mm waves).

Signal to Noise ratio (SNR)

- SNR is an expression of the quality of a radar measurement
  - $SNR = P_r / P_n$
- For imaging radar, SNR > 10 is required

$$SNR = \frac{P_r}{P_n} = \frac{A_e G P_t \sigma^0 A}{(4\pi)^2 R^4 k \cdot T_{sys} \cdot B}$$

SNR



$$SNR = \frac{P_r}{P_n} = \frac{A_e G P_t \sigma^0 A}{(4\pi)^2 R^4 k \cdot T_{sys} \cdot B}$$

Exercise

Detect an oak tree at 10 km distance with SNR = 100
Given radar system:

- A = 8x20 m= 160 m^2

- Wavelength L-band = 0.25 m
- NRCS = 0.1
- B = 1 MHz

Assume for a start:

- P_t = 1000 W ;
- G = 50
- T_{sys} = 1000 K

Is this possible?
(use design table approach)

Working out the assignment: The *design table.*

Signal parameters

Parameter	Value	dB
Transmit Power	1000 W	30
Antenna gain	50	17
1/(4pi)	0.08	-11
$1/R^2$	$1/10000^2$	-80
A_{scat}	160 m^2	22
Sigma-zero	0.1	-10
A_r	0.248	-6
1/(4pi)	0.08	-11
$1/R^2$	$1/10000^2$	-80
Signal Power		**-129 dB**

x 3 + 5

-124

$A_r = G\lambda^2/(4\pi)$

Noise parameters

Parameter	Value	dB
Boltzmann	1.38×10^{-23}	-229
T_{sys}	1000 K	30
Bandwidth	1 MHz	60
Noise Power		**-139**

/ 3 - 5

-144

SNR = $P_r - P_n$ = -129 – (-139)

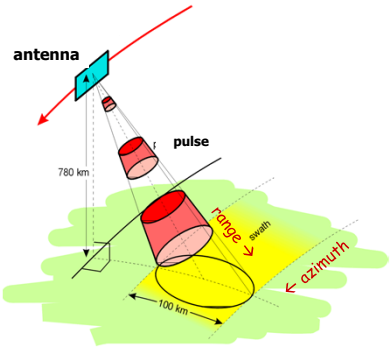
= + 10 dB, or 10:1

Not sufficient (SNR of 100 or 20dB was needed). How to change system?

Only parameters not fixed were transmit power, antenna gain, noise temperature

Imaging Radar
RESOLUTION (pixel size, posting)

- (Slant) Range and azimuth

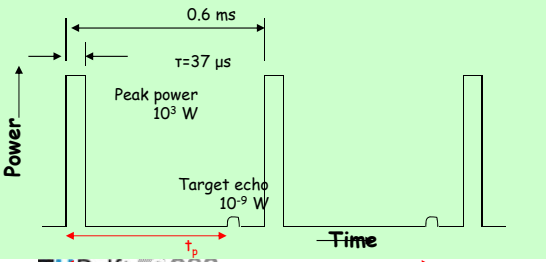


Material:
Hanssen, 2001, section 2.2, 2.3

Pulsed versus CW radar

- Continuous wave radars need to receive while transmitting → normally no range measurements
- Pulsed radars:

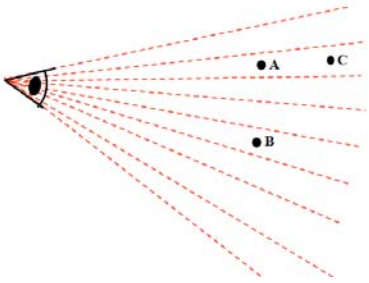
Pulse repetition frequency (PRF): 1680 Hz
Pulse period: 1/PRF=0.6 ms



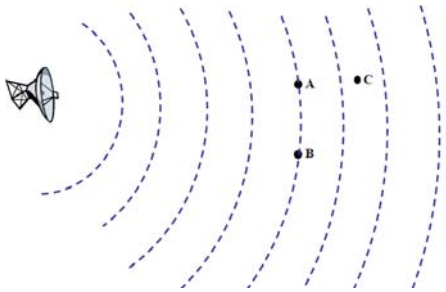
Skolnik,2001

Range ambiguity!!

Angular vision vs. Range Vision



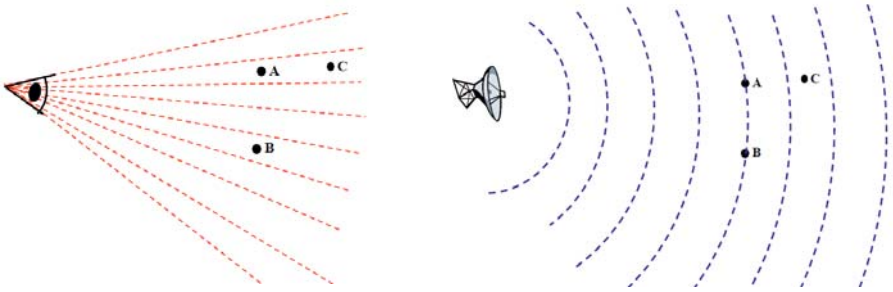
A et C are ambiguous



A et B are ambiguous

Jean-Claude Souyris, 2011

Angular vision vs. Range Vision



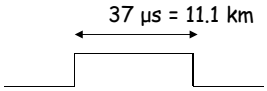
A et C are ambiguous

A et B are ambiguous

Why do we need a side-looking radar?
(Side-looking: the radar pointed at an angle instead of downwards)

Jean-Claude Souyris, 2011

Relation: pulse length – range resolution



- Pulse length of ERS satellite: τ [s] 37 μs
- Corresponds with distance:

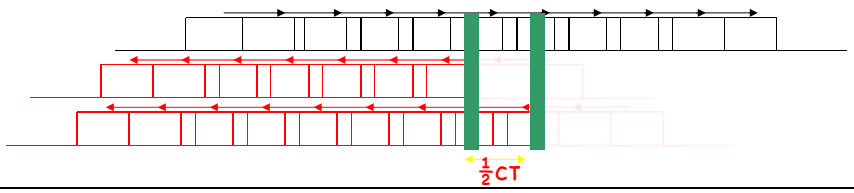
$c\tau$ [m] = 3e8 ·37e-6 = 11100 [m] = 11.1 [km]

- What is the smallest distance between two targets to be separated?

- Two targets can be recognized if separated

$\frac{1}{2}c\tau$ [m] = 5.5 [km]

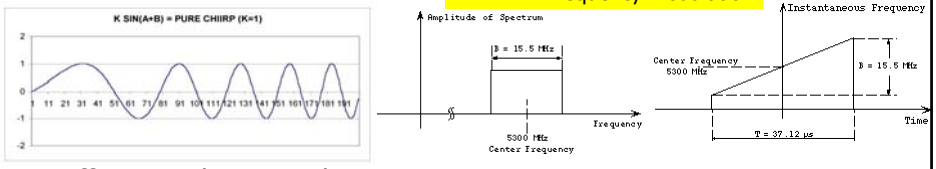
2-way travel



Synthetic shortening pulse length (matched filter)

- Transmit a 'chirp': signal with increasing frequency over pulse interval

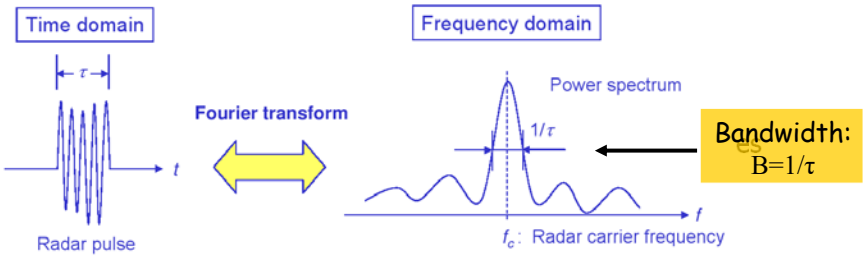
FM: frequency modulation



- Effective pulse interval:
  τ=1/bandwidth = 1/15.5 MHz = 64 $\cdot 10^{-9}$ [sec]
  64 ns
- Range resolution : ½cτ [m] = 9.6 [m]

Resolution and bandwidth

- RANGE BANDWIDTH ↔ RANGE RESOLUTION
- Resolution is inversely proportional with bandwidth of system



Take-home message:
Resolution is inversely proportional with bandwidth

Sidenote: Resolution and bandwidth

- Noise power scales with bandwidth!
- Trade off…

High range resolution = Large bandwidth

⇩

More noise power = Low sensitivity (low SNR)

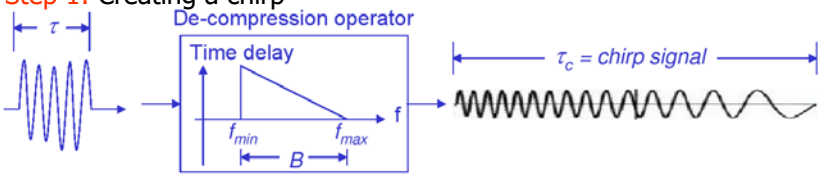
(Remember the Noise power calculation last lecture)

Pulse compression: 'chirping'

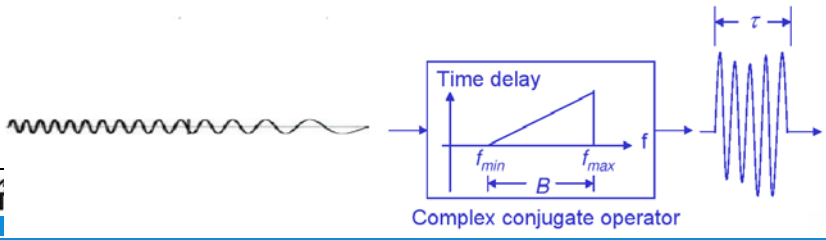
Resolution vs. Power

How can one have a short pulse (to still have a fine resolution) within the power limitations of the radar?

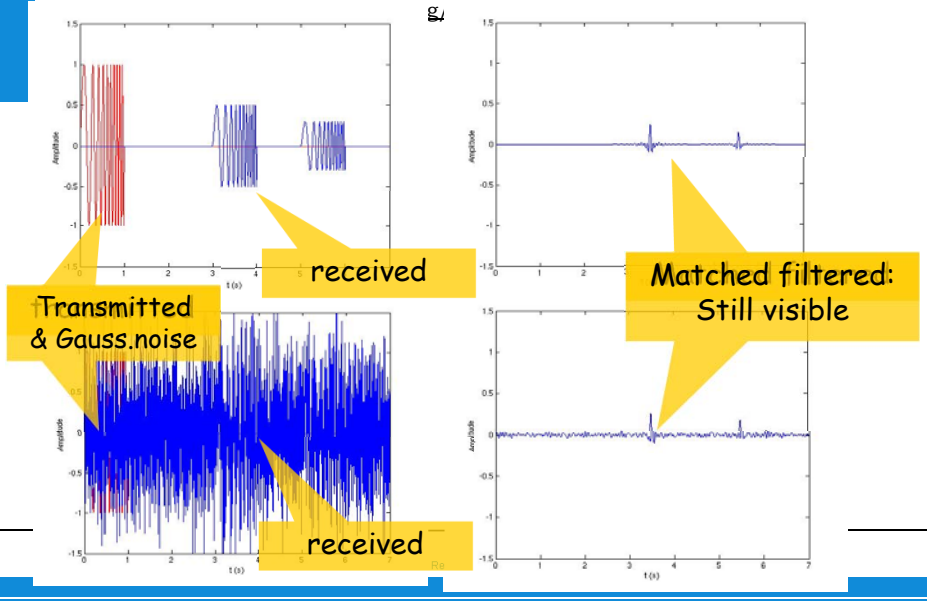
- Step 1: Creating a chirp



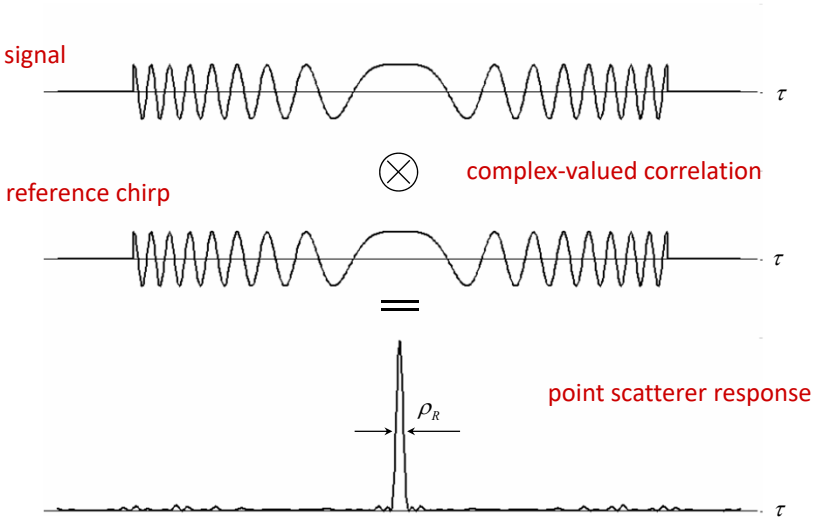
- **Step 2:** transmission
- **Step 3:** pulse dechirping



matched filtering and chirping

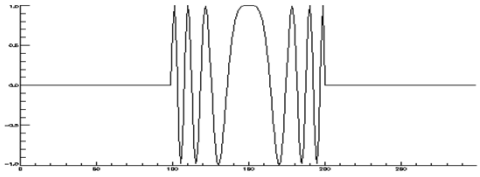


Range Compression by Matched Filtering

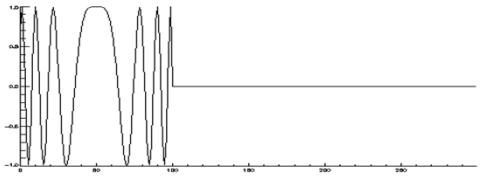


Source: https://sargeo.dlr.de/

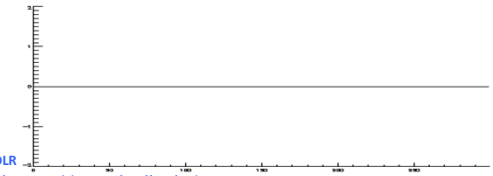
Range Compression by Matched Filtering



received signal $r(\tau)$



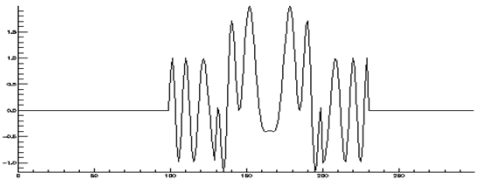
reference chirp $c(\tau)$



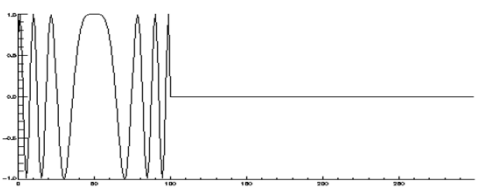
cross-correlation $\int r^*(\tau)c(\tau+s)d\tau$

s

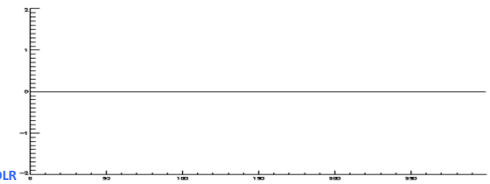
Range Compression by Matched Filtering
Superposition of two scatterers



received signal $r_1(\tau)+r_2(\tau)$

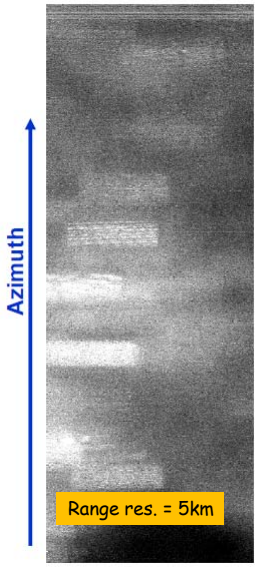


reference chirp $c(\tau)$



cross-correlation

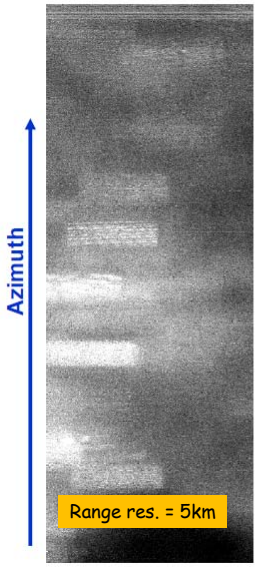
Resolution example: ERS image (Northridge, California, 1992)



Raw data

Jean-Claude Souyris, 2011

Resolution example: ERS image (Northridge, California, 1992)



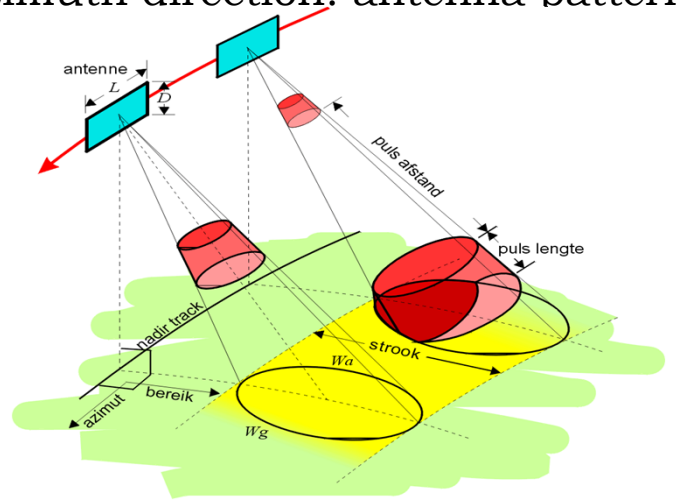
Raw data Range compression

Jean-Claude Souyris, 2011

Range resolution (Summary)

- Resolution is inversely proportional with bandwidth
- Range resolution dependent on pulse length, not on platform height
- However, shorter pulse length means less transmitted power, and therefore less received power, see Radar equation, leading to too low Signal-to-noise ratio. Therefore, indirectly related to platform height.
- Range resolution improvement using chirp waveform
  →No influence of satellite height on range resolution SAR image

Azimuth direction: antenna pattern



Antenna beam: Fraunhofer diffraction

Beam steering

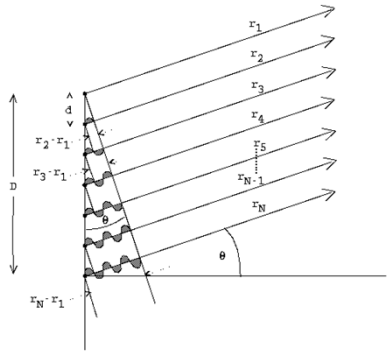
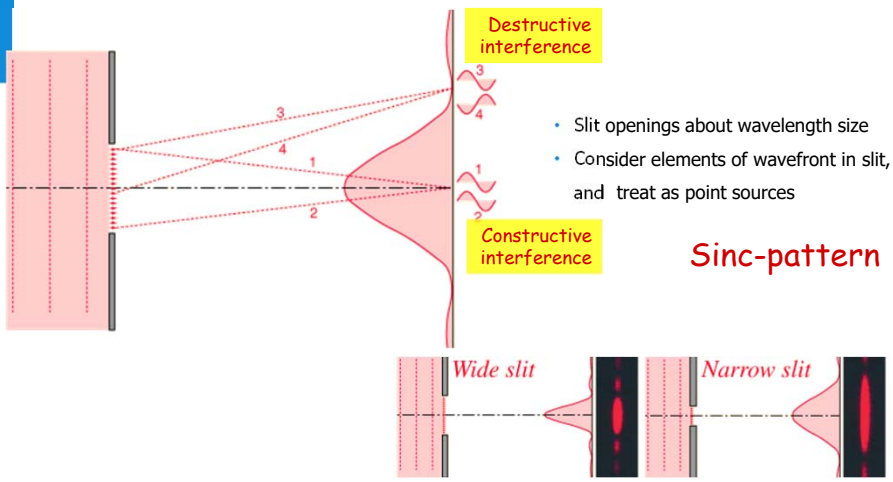


Figure 2.11: N-point sources forming a linear array of oscillators. Each oscillator emits waves which superimpose to form a diffraction pattern.

Fraunhofer single slit
(additive interferometry)



- Slit openings about wavelength size
- Consider elements of wavefront in slit, and treat as point sources

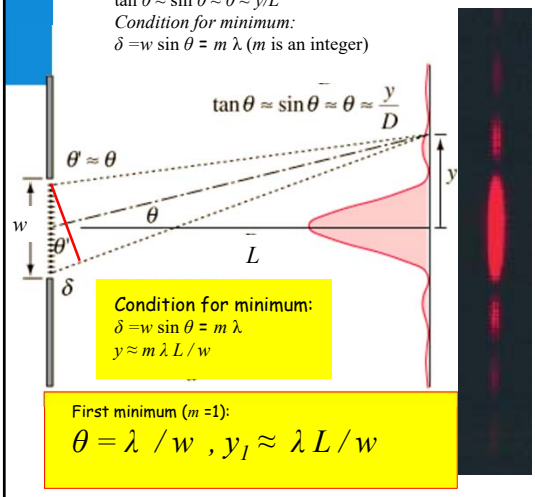
Sinc-pattern

MATLAB DEMONSTRATION IN CLASS

- Run the script interf_simulation.m
- Script is available on blacboard

Fraunhofer Diffraction

$\tan\theta = y / L$
$\tan\theta \approx \sin\theta \approx \theta \approx y/L$
Condition for minimum:
$\delta = w \sin\theta = m\,\lambda$ (m is an integer)



Condition for minimum:
$\delta = w \sin\theta = m\,\lambda$
$y \approx m\,\lambda\,L / w$

First minimum (m =1):
$\theta = \lambda / w$, $y_1 \approx \lambda L / w$

•Far-field approximation and $L >> w$:
- $\theta = \theta'$

Limits spatial resolution

Optical, 0.5 µm, lens 5 cm,
1000 km →10 m

Microwave, 3cm,
antenna 1m,
1000 km → 30 km !!

Take-home message:
RAR resolution in azimuth:

$$\theta = \lambda / w$$

Resolution I: RAR

- Real Aperture Radar
- Resolution dependent on
  - antenna dimension (in Azimuth)
  - pulse length (in range)
- Beam width (half power width) is ratio wavelength over antenna size:

$$\theta = \alpha \frac{\lambda}{D} \text{ with } 0.9 < \alpha < 1.4$$

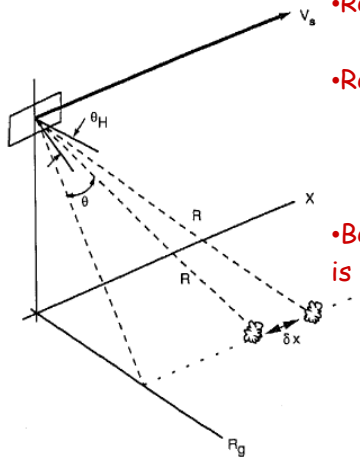


Figure 1.8 Illustration of real-aperture radar capability to resolve two targets separated in azimuth.

Calculate Ground Resolution

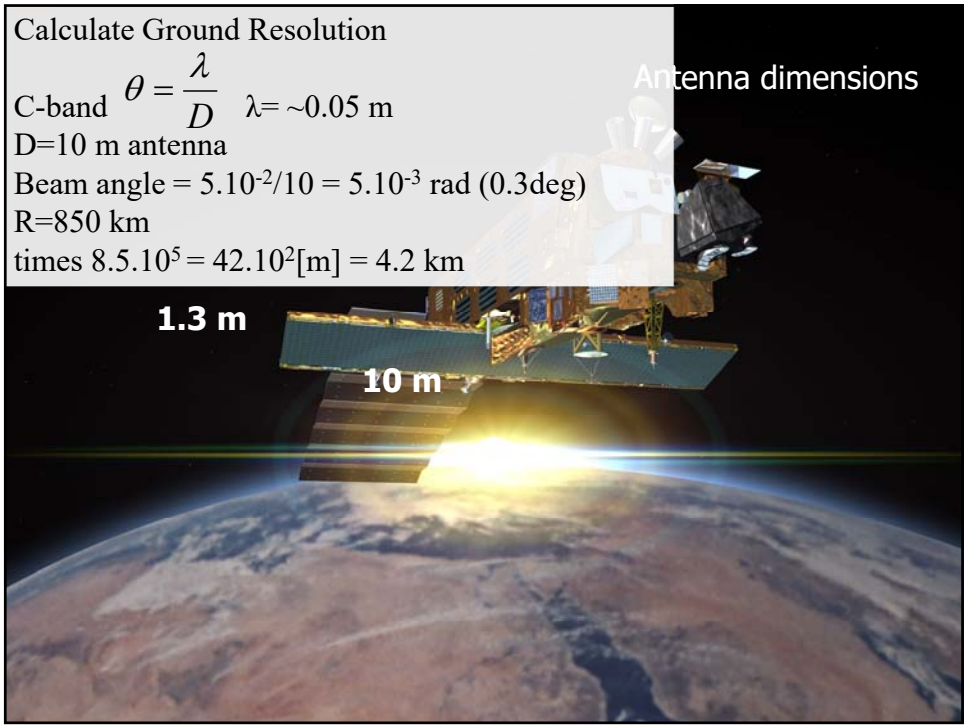
C-band $\theta = \frac{\lambda}{D}$ λ= ~0.05 m

D=10 m antenna

Beam angle = $5.10^{-2}/10 = 5.10^{-3}$ rad (0.3deg)

R=850 km

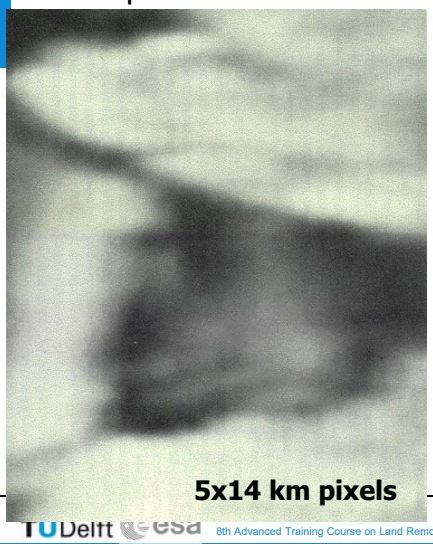
times $8.5.10^{5} = 42.10^{2}$[m] = 4.2 km



Resolution

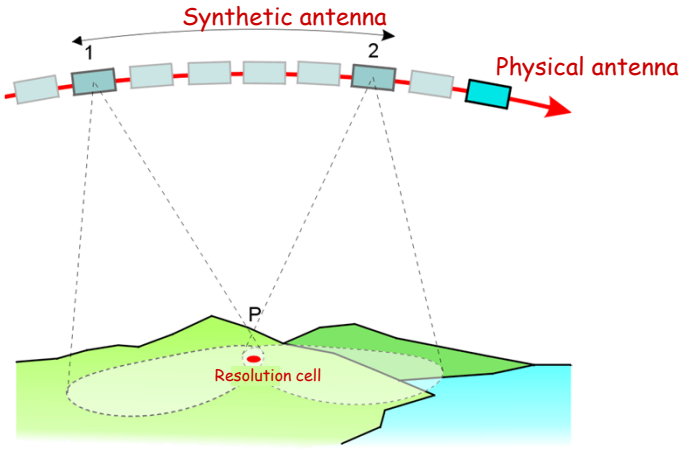
(Crimea, Ukraine)

Real Aperture Radar



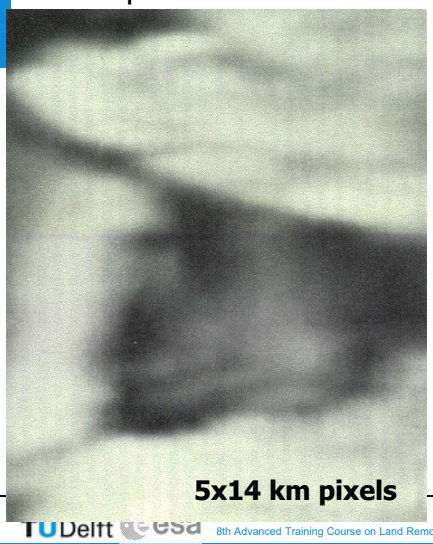
Massonnet and Feigl, 1998

Improvement of along-track (azimuth) resolution

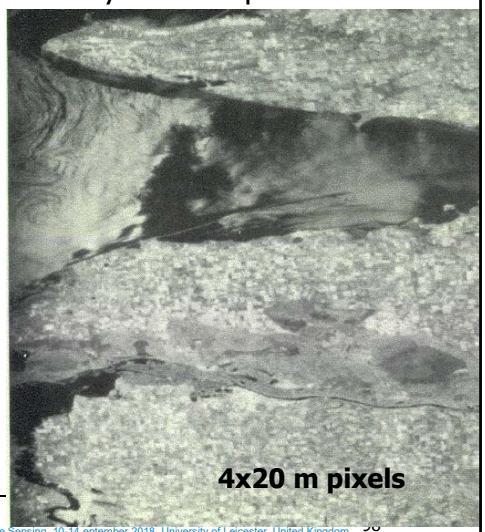


Improvement in Resolution (Crimea, Ukraine)

Real Aperture Radar

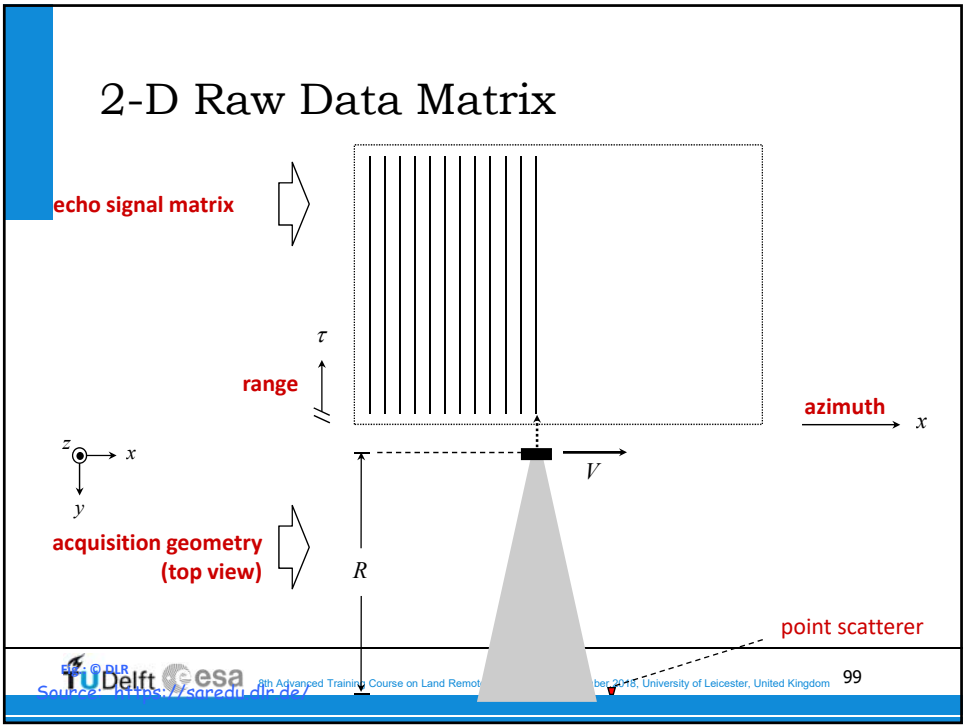


Synthetic Aperture Radar

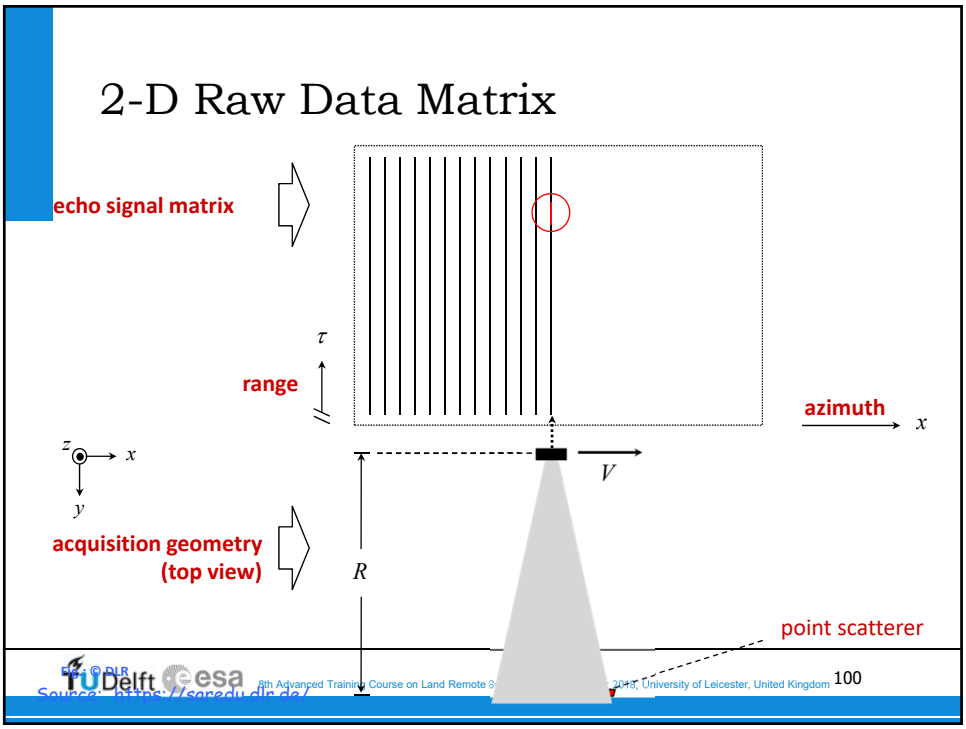


Massonnet and Feigl, 1998

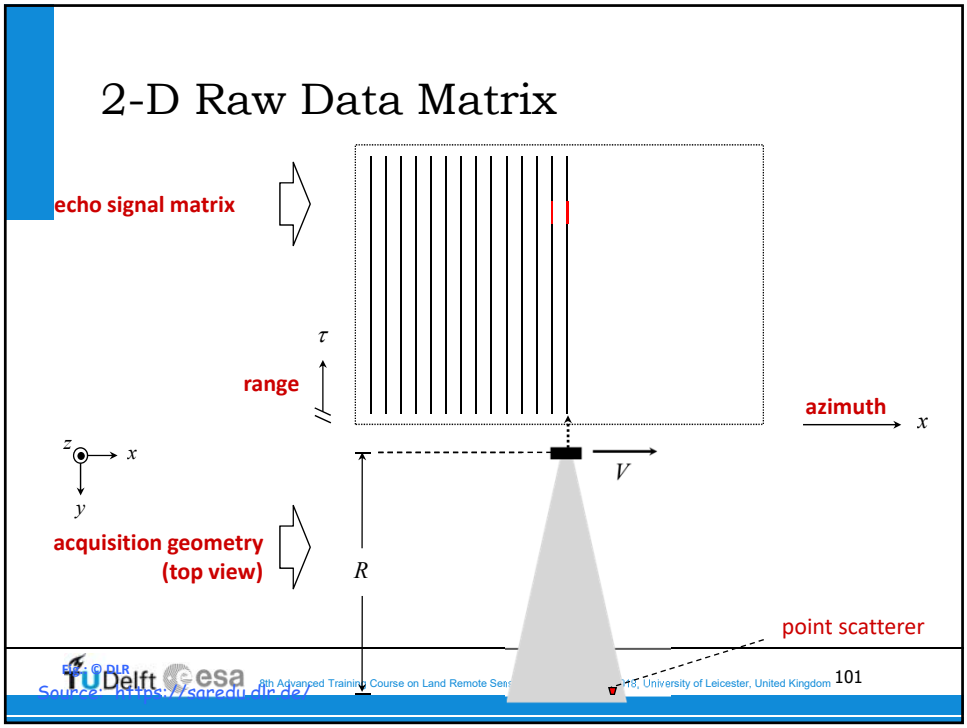
2-D Raw Data Matrix



2-D Raw Data Matrix

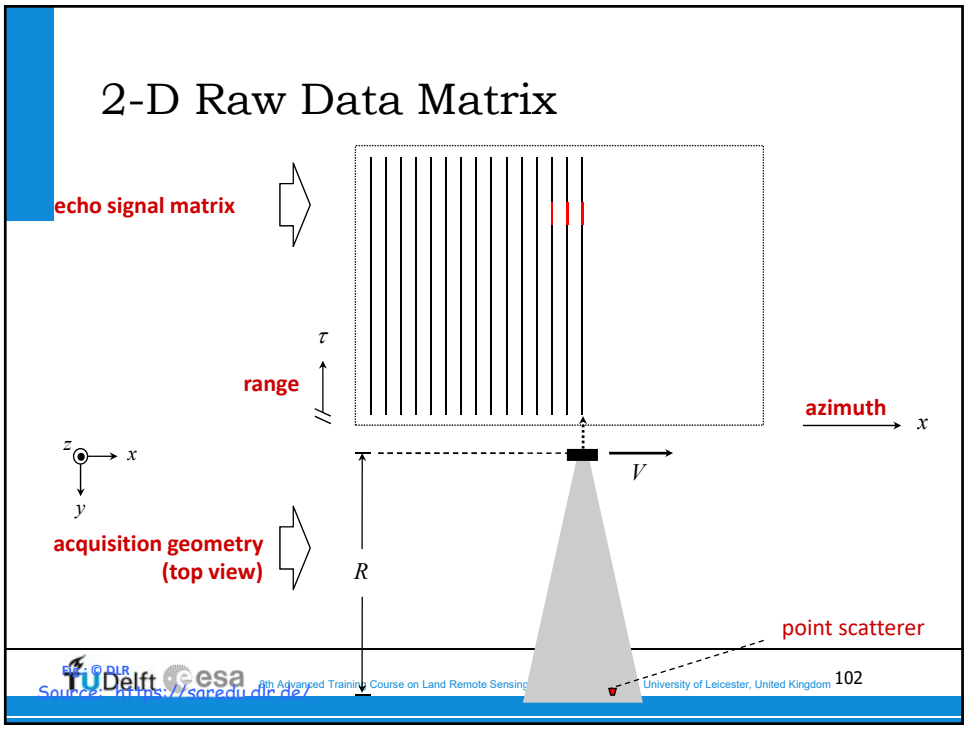


2-D Raw Data Matrix



Source: https://sargedu.dlr.de/

2-D Raw Data Matrix



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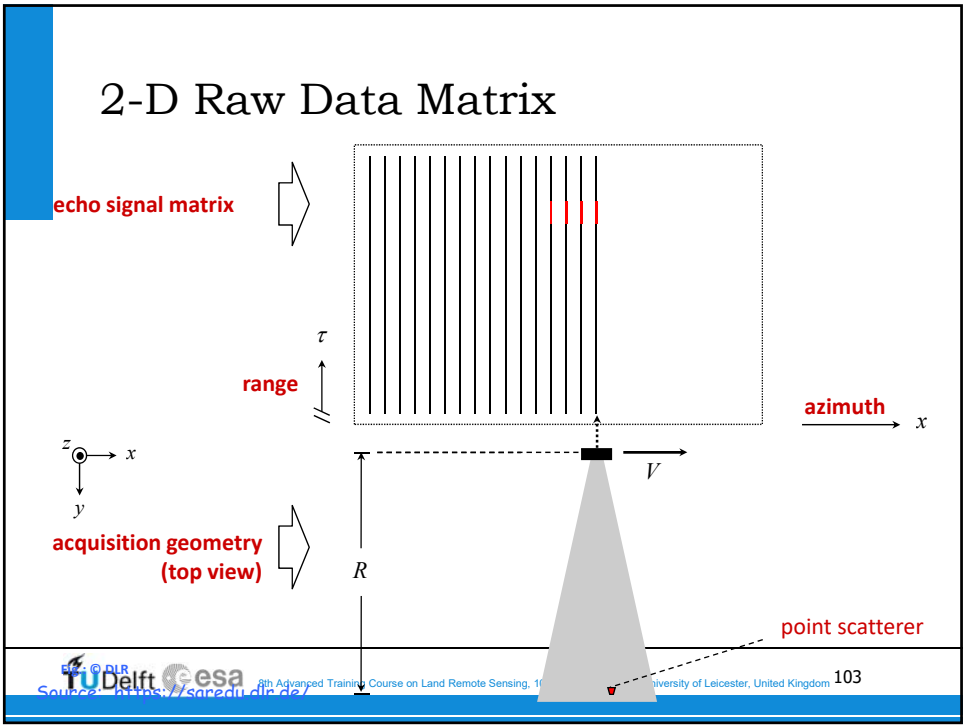
2-D Raw Data Matrix



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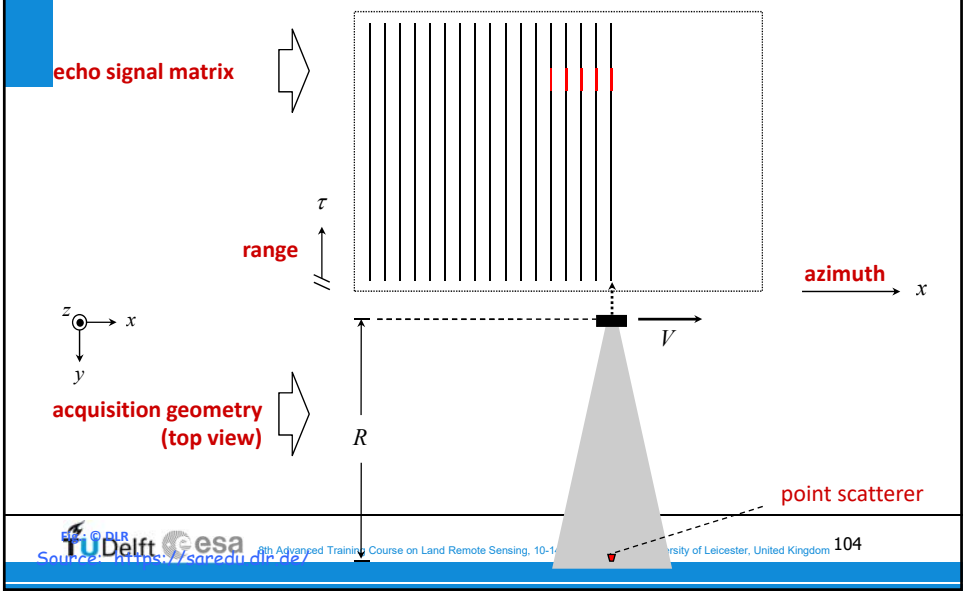
2-D Raw Data Matrix



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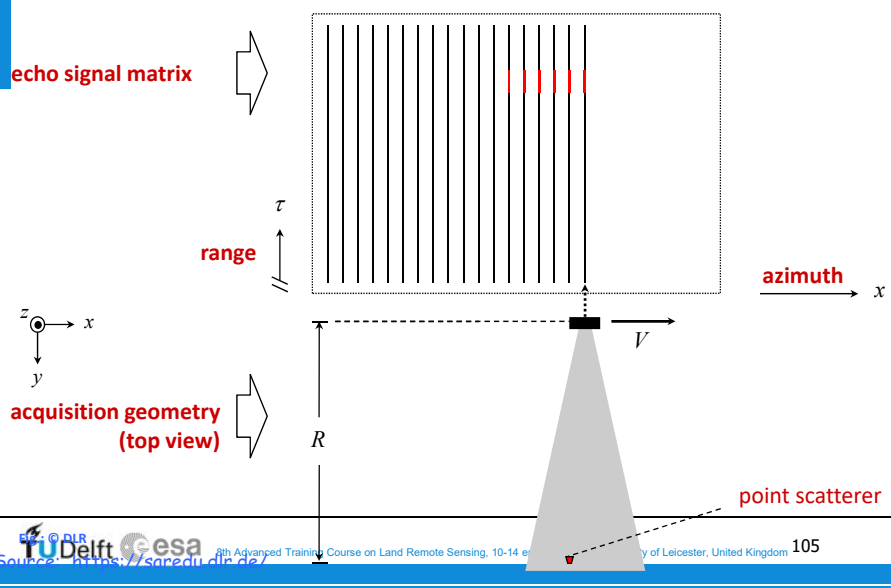
2-D Raw Data Matrix



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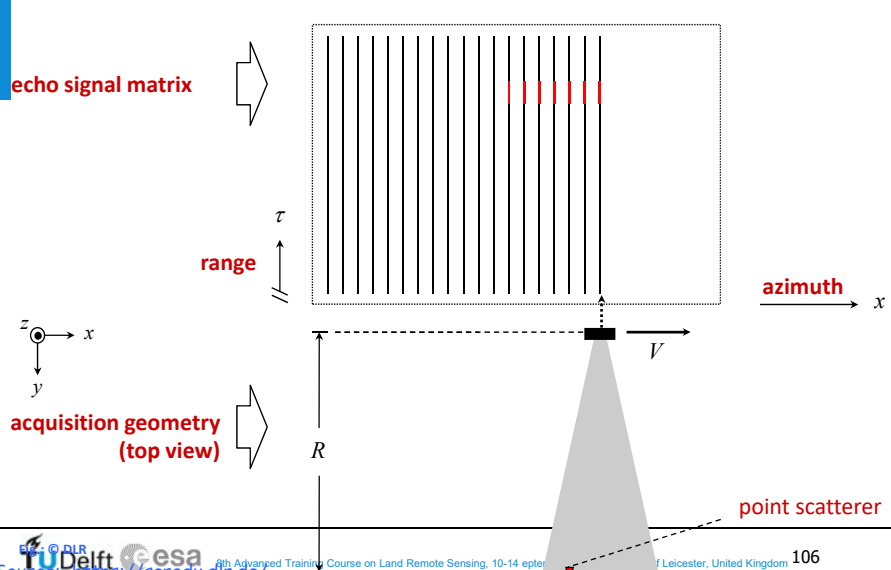
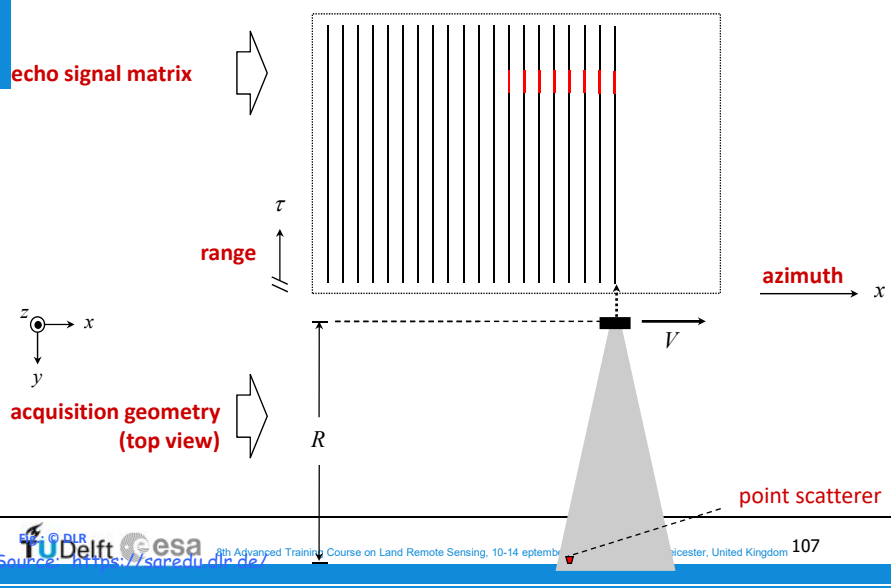
2-D Raw Data Matrix



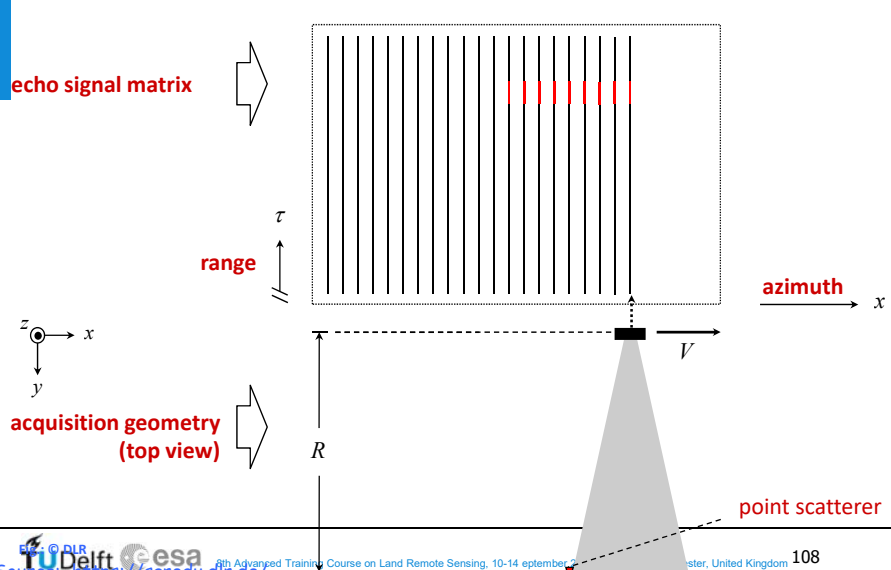
Source: https://sgredu.dlr.de/

2-D Raw Data Matrix



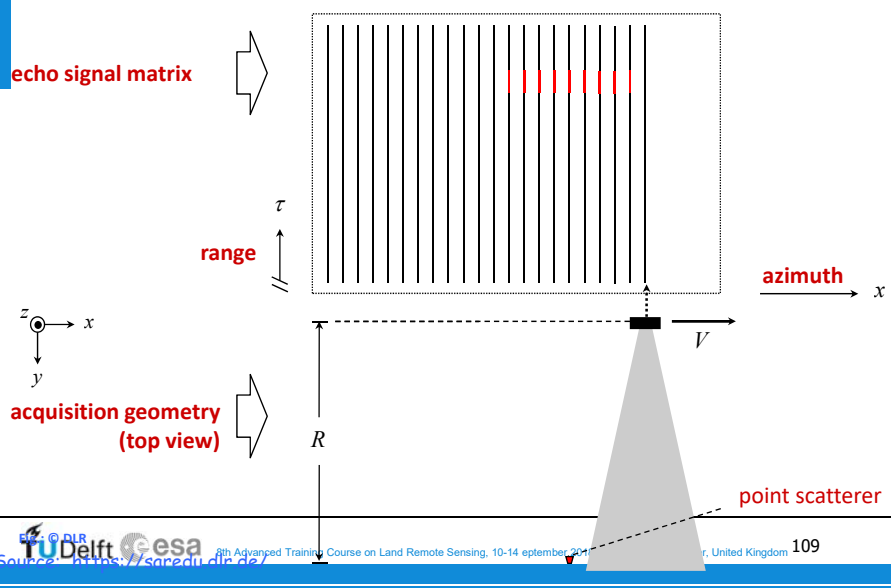
Source: https://sgredu.dlr.de/

2-D Raw Data Matrix



Source: https://sgredu.dlr.de/

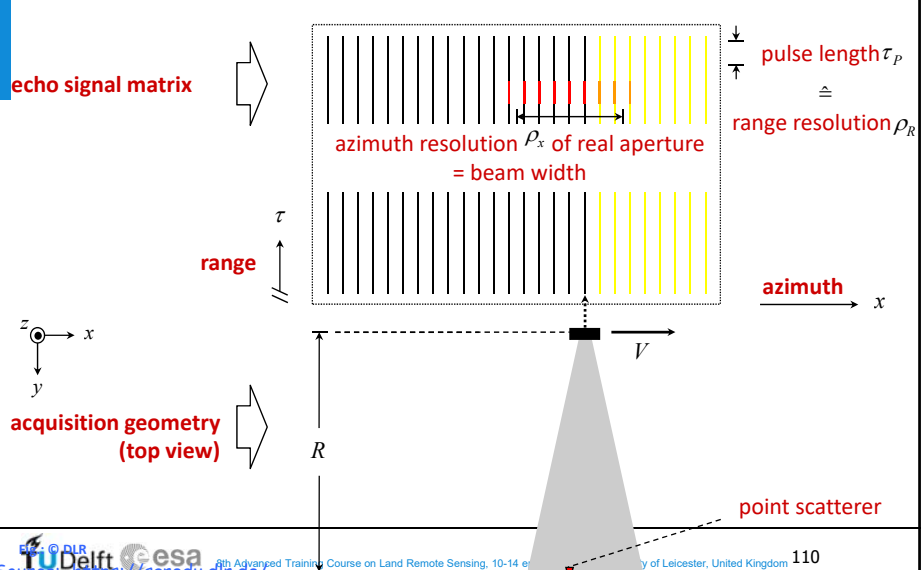
2-D Raw Data Matrix



EE - © DLR
TU Delft esa

Source: https://sgredu.dlr.de/

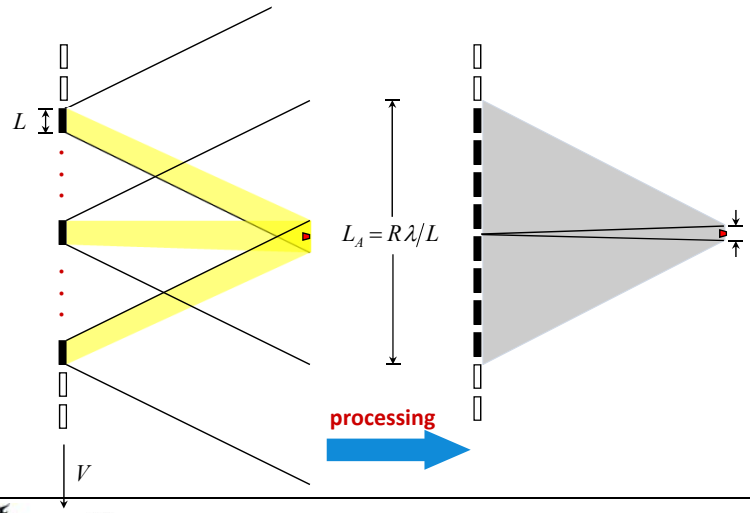
2-D Raw Data Matrix



EE - © DLR
TU Delft esa

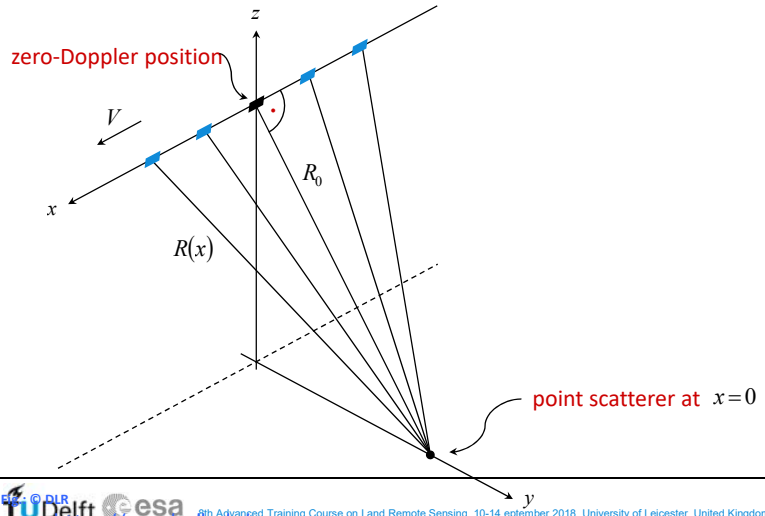
Source: https://sgredu.dlr.de/

Formation of a Synthetic Aperture SAR Principle



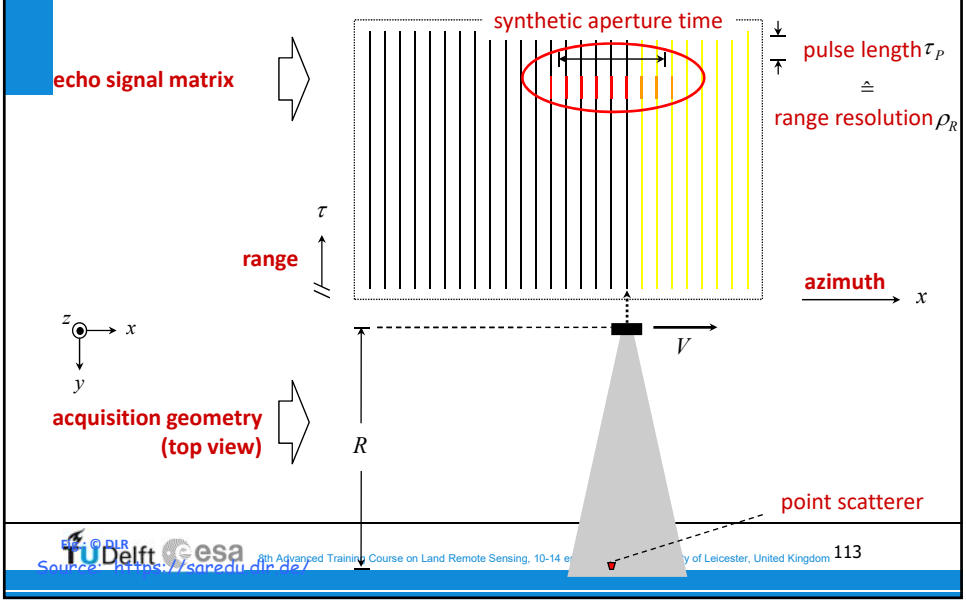
Source: https://sargedu.dlr.de/

Range History of a Single Point Scatterer

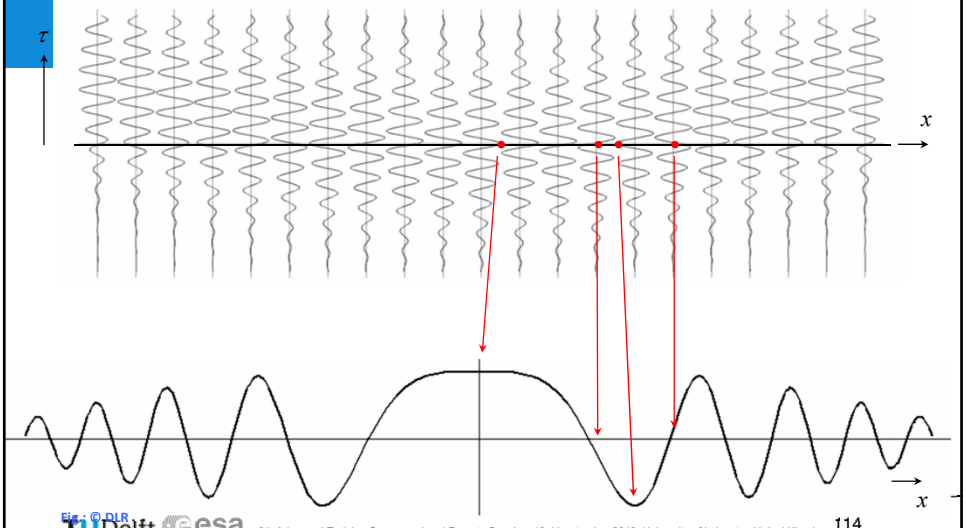


Source: https://sargedu.dlr.de/

2-D Raw Data Matrix



Formation of the Azimuth Chirp Signal



SAR Raw Data of a Point Scatterer (Simulation)

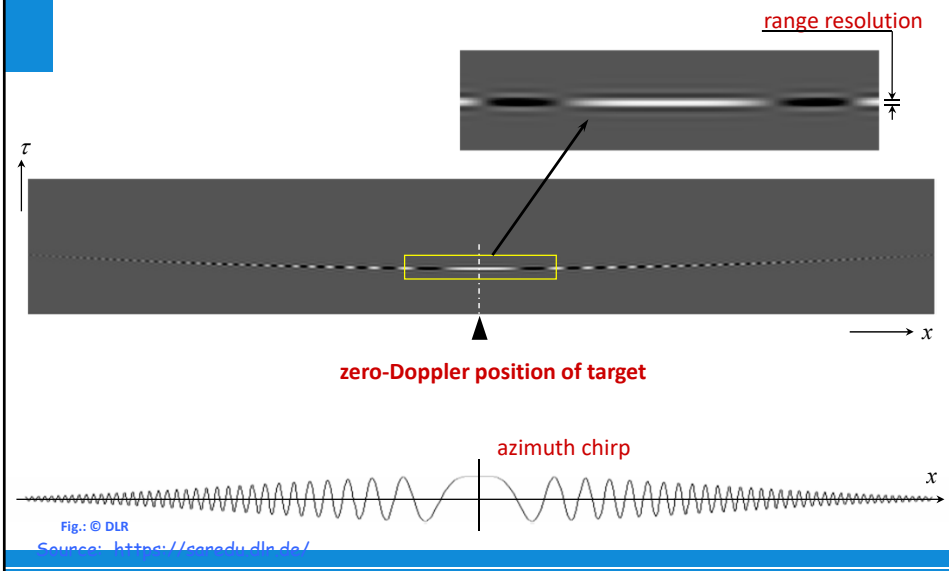
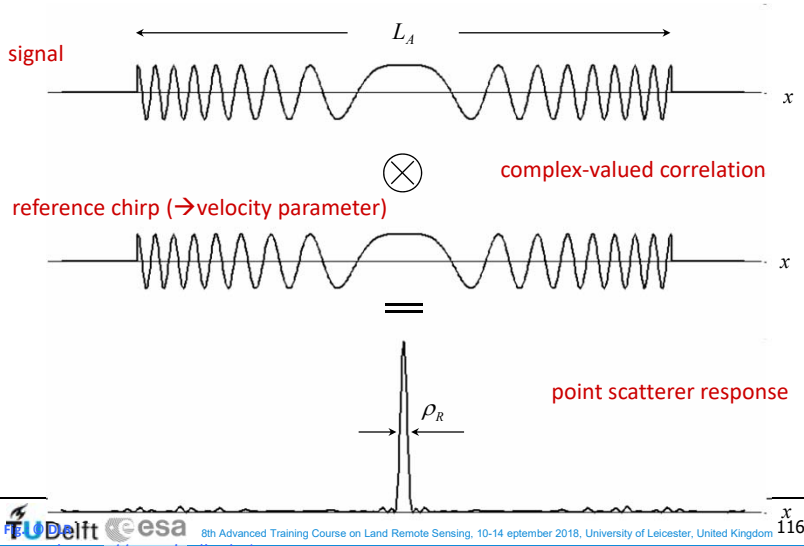


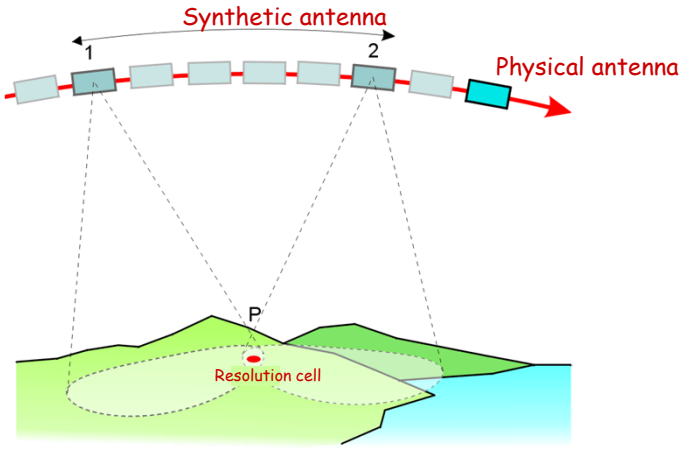
Fig.: © DLR

Source: https://geoedu.dlr.de/

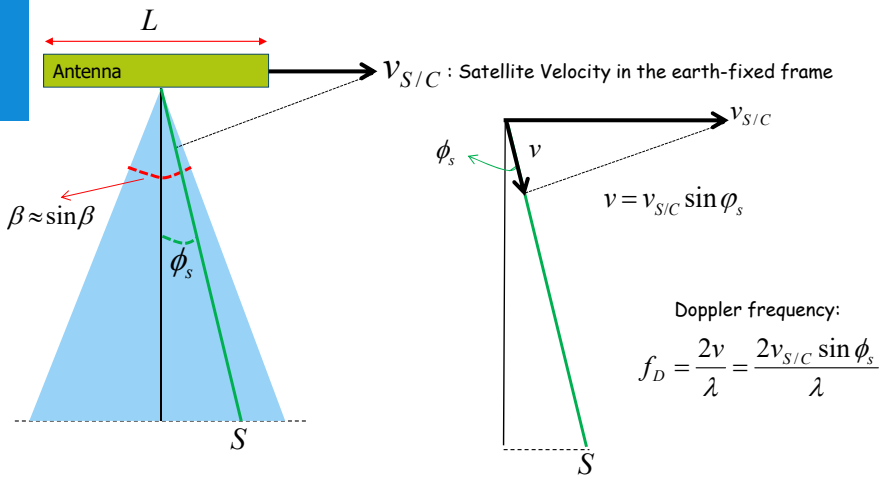
Azimuth SAR Processing by Correlation



Improvement of along-track (azimuth) resolution



Azimuth resolution SAR



Azimuth resolution SAR / bandwidth

•Similar to range direction: dependent on band width

$$\Delta_a = \frac{v_{S/C}}{B_{Dopp}}$$

• Doppler frequency

$$f_D = \frac{2v}{\lambda}$$

• Doppler frequency SAR

$$f_D = \frac{2v}{\lambda} = \frac{2v_{S/C}\sin\phi_s}{\lambda}$$

• Beam width:

$$\beta = \frac{\lambda}{L} \qquad \beta \approx \sin\beta$$

• Minimum Doppler:

$$f_{D,\min} = \frac{2v_{S/C}\sin\frac{-\beta}{2}}{\lambda} \approx \frac{2v_{S/C}\frac{-\beta}{2}}{\lambda} = \frac{-v_{S/C}\beta}{\lambda}$$

• Maximum Doppler:

$$f_{D,\max} = \frac{2v_{S/C}\sin\frac{+\beta}{2}}{\lambda} \approx \frac{2v_{S/C}\frac{+\beta}{2}}{\lambda} = \frac{+v_{S/C}\beta}{\lambda}$$

•Doppler bandwidth:

$$B_{Dopp} = \frac{2v_{S/C}\beta}{\lambda} = \frac{2v_{S/C}\lambda/L}{\lambda} = \frac{2v_{S/C}}{L}$$

• SAR resolution azimuth:

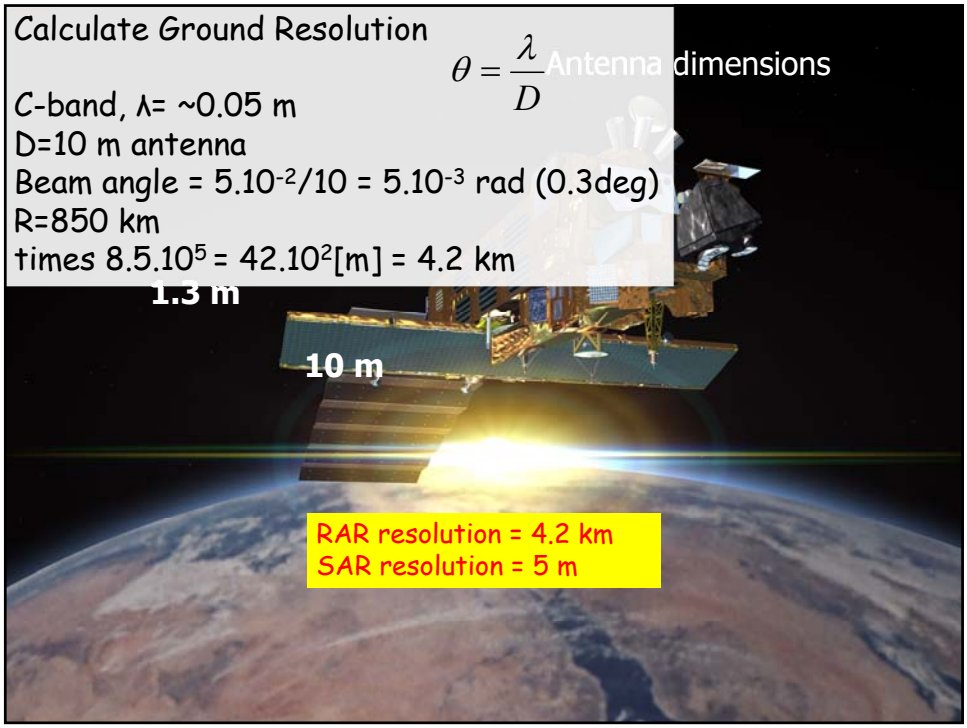
$$\Delta_a = \frac{v_{S/C}}{B_{Dopp}} = \frac{v_{S/C}}{\frac{2v_{S/C}}{L}} = \frac{L}{2}$$

Azimuth resolution SAR: Half the antenna size!

Calculate Ground Resolution

$$\theta = \frac{\lambda}{D}$$ Antenna dimensions

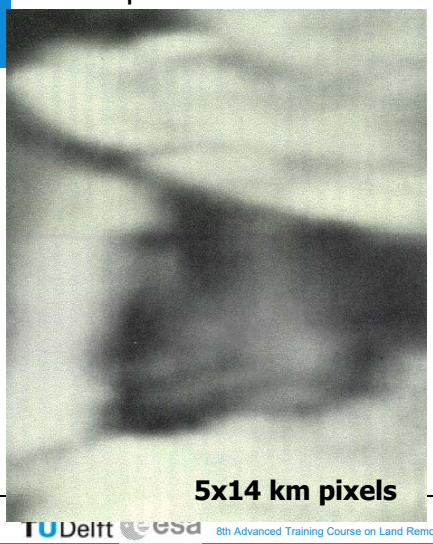
C-band, λ= ~0.05 m
D=10 m antenna
Beam angle = $5.10^{-2}/10 = 5.10^{-3}$ rad (0.3deg)
R=850 km
times $8.5.10^{5} = 42.10^{2}$[m] = 4.2 km



Improvement in Resolution

(Crimea, Ukraine)

Real Aperture Radar



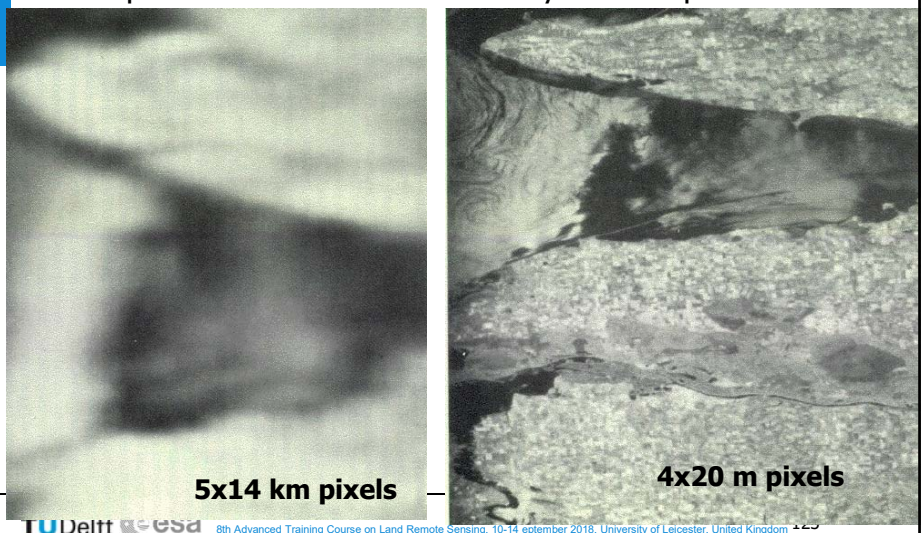
Massonnet and Feigl, 1998

Improvement in Resolution

(Crimea, Ukraine)

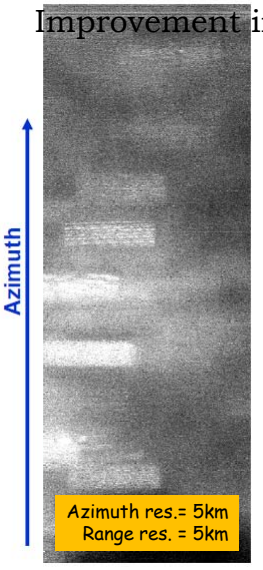
Real Aperture Radar

Synthetic Aperture Radar



Massonnet and Feigl, 1998

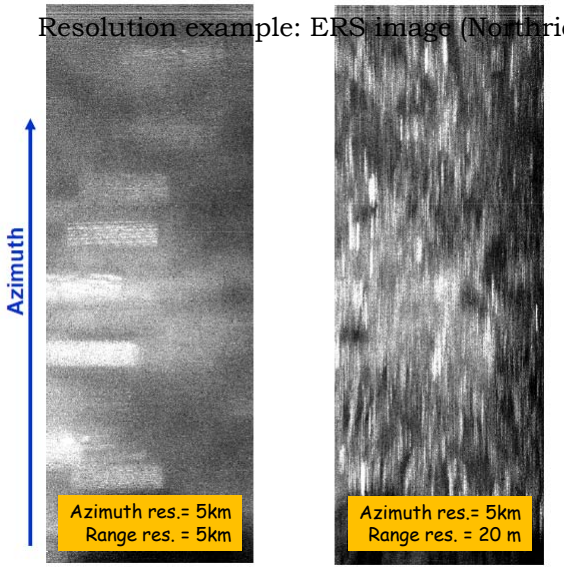
Improvement in Resolution



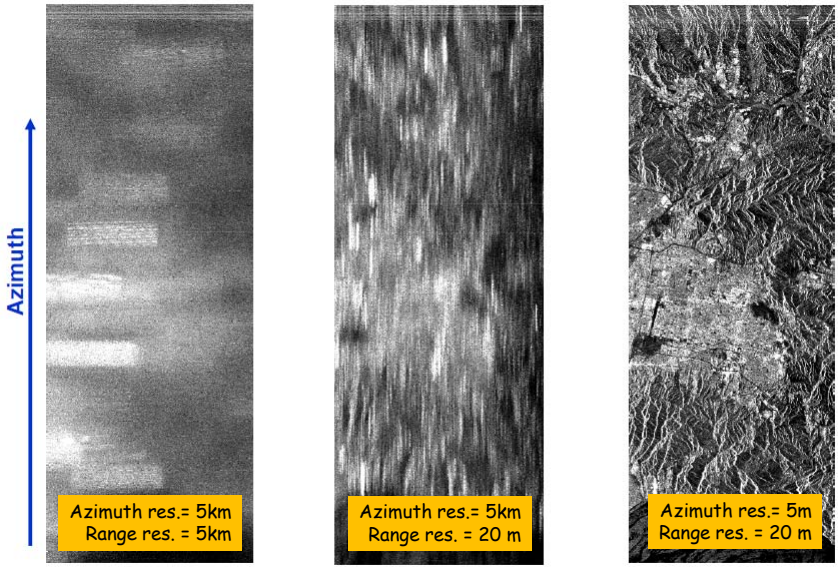
Raw data

Jean-Claude Souyris, 2011

Resolution example: ERS image (Northridge, California, 1992)



Resolution example: ERS image (Northridge, California, 1992)



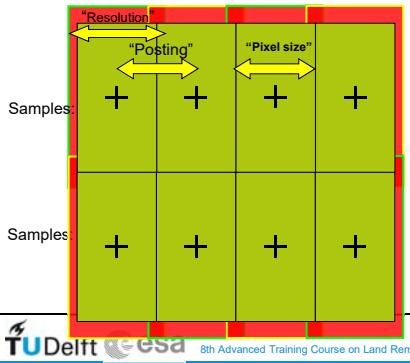
Resolution, pixel size, posting

Oversampling factor:

- Az_res = v_s/c / B_Dop = 7100/ 1380 = 5.14 m
- Az_pix = v_s/c / PRF = 7100/ 1680 = 4.22 m
- Ra_res = c / (2 B_R) = 3e8 / (2x1.55e7) = 9.68 m
- Ra_pix = c / (2 RSF) = 3e8/(2x1.86e7) = 7.91 m

1.22

1.22



SAR SLC observations

SLC: Single-Look Complex data
•Single-look: no averaging, finest spatial resolution
•Complex: both real and imaginary (In-phase and quadrature phase) stored

Coherent imaging

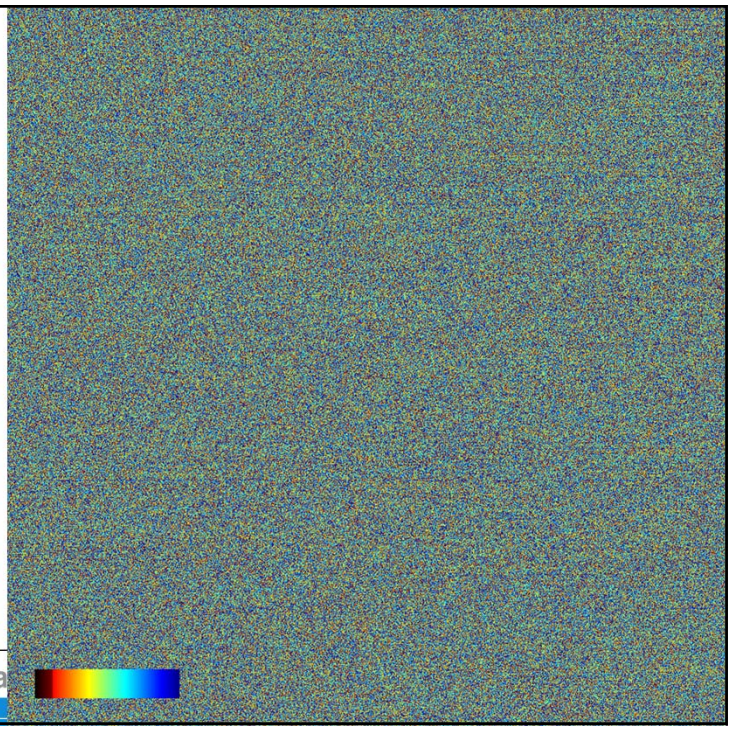
$$y_1 = |y_1| \exp(j\psi_1)$$

Amplitude Phase

Uninterpretable, due to scattering mechanism

Measurement of 2 quantities:
Reflection strength (amplitude) …

TU Delft esa



TU Delft esa

Resolution conclusions

- Improvement in resolution from RAR to SAR, and from pulse to chirp
- Resolution SAR is inversely proportional with bandwidth
- Azimuth resolution SAR: Half the antenna size!
  →No influence of satellite height on azimuth resolution SAR image
- Range resolution improvement using chirp waveform
  →No influence of satellite height on range resolution SAR image