DLR

TUM

Introduction into Microwave and SAR Remote Sensing

II. Synthetic Aperture Radar (SAR)

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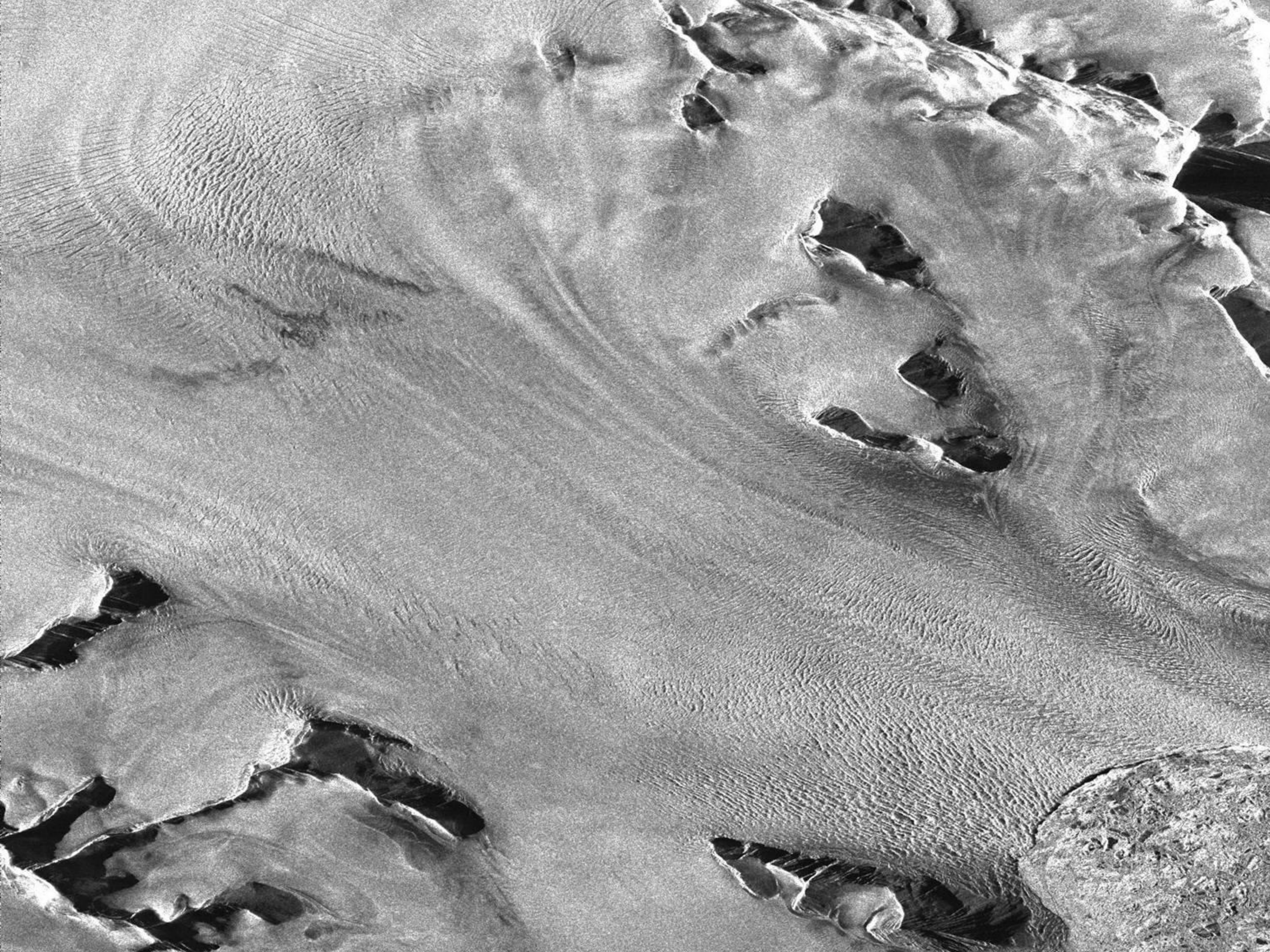
Remote Sensing Technology

Microwave Satellite Remote Sensing



Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar - SAR

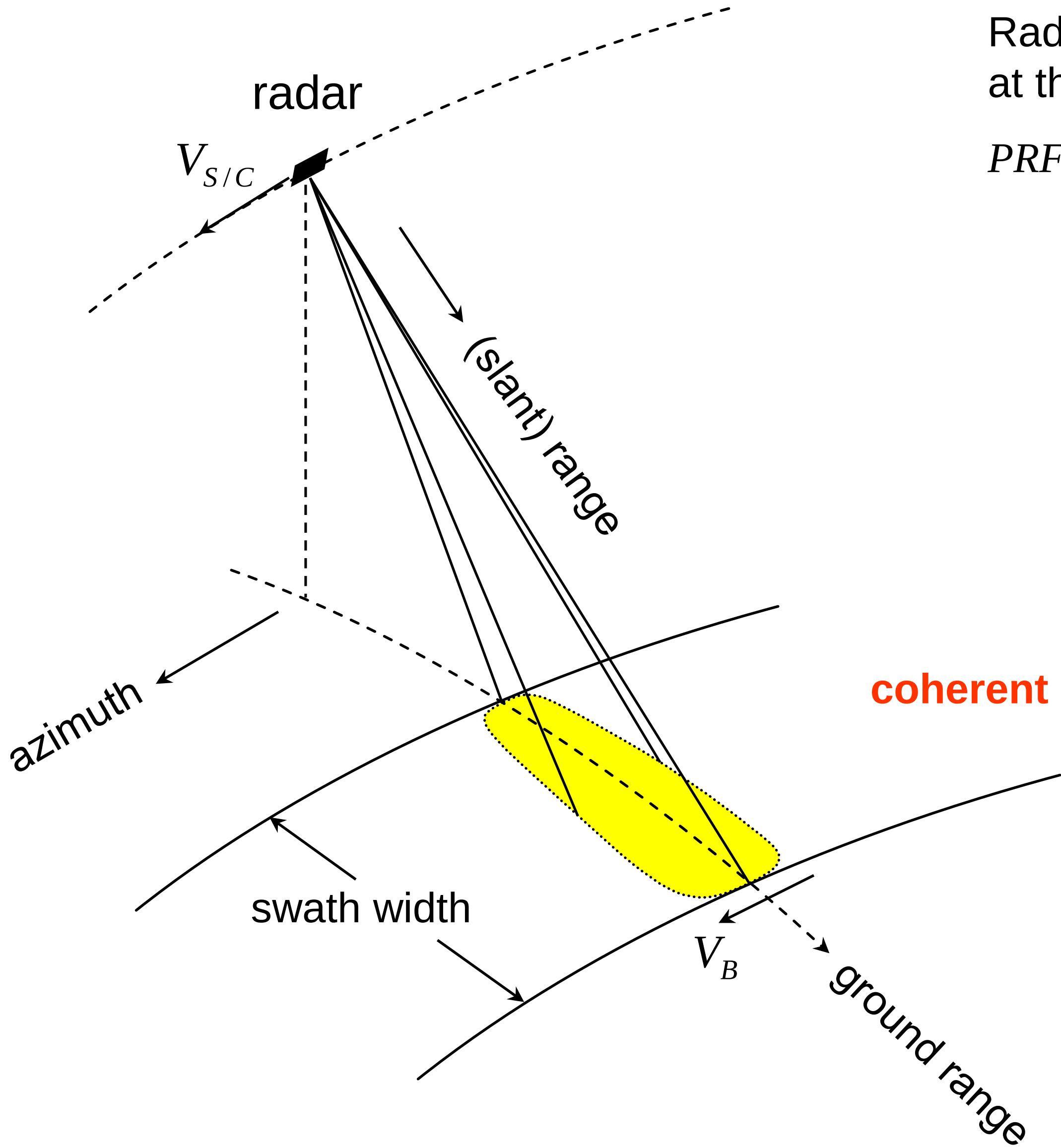
- active ⇒ independent of sun illumination
- microwave ⇒ penetrates clouds and (partially) canopy, soil, snow

wavelengths:	X-band:	3 cm
	C-band:	6 cm
	L-band:	24 cm

- coherent ⇒ interferometry, speckle
- polarization can be exploited
- spatial resolution:

space-borne:	5 m - 100 m	(TerraSAR-X: 1 m)
air-borne:	> 0.2 m	

SAR Imaging Geometry



Radar transmits pulses and receives echoes at the rate of the pulse repetition frequency:

PRF @ 1000 - 4000 Hz

range: radar principle = scanning at speed of light

azimuth: scanning in flight direction at V_B plus aperture synthesis (holography)

coherent imaging: complex-valued pixels contain amplitude (brightness) and **phase** information

for this lecture: straight flight path

$$\Rightarrow \quad V_{S/C} = V_B = V$$

SAR – A Two-Step Imaging Process

SAR is a two-step imaging process:

1. data acquisition

Illumination of a scattering **object** and collection of received echoes

$\Rightarrow$ **raw data**

contribution of a single point is dispersed over $10^4 \ldots 10^7$ samples

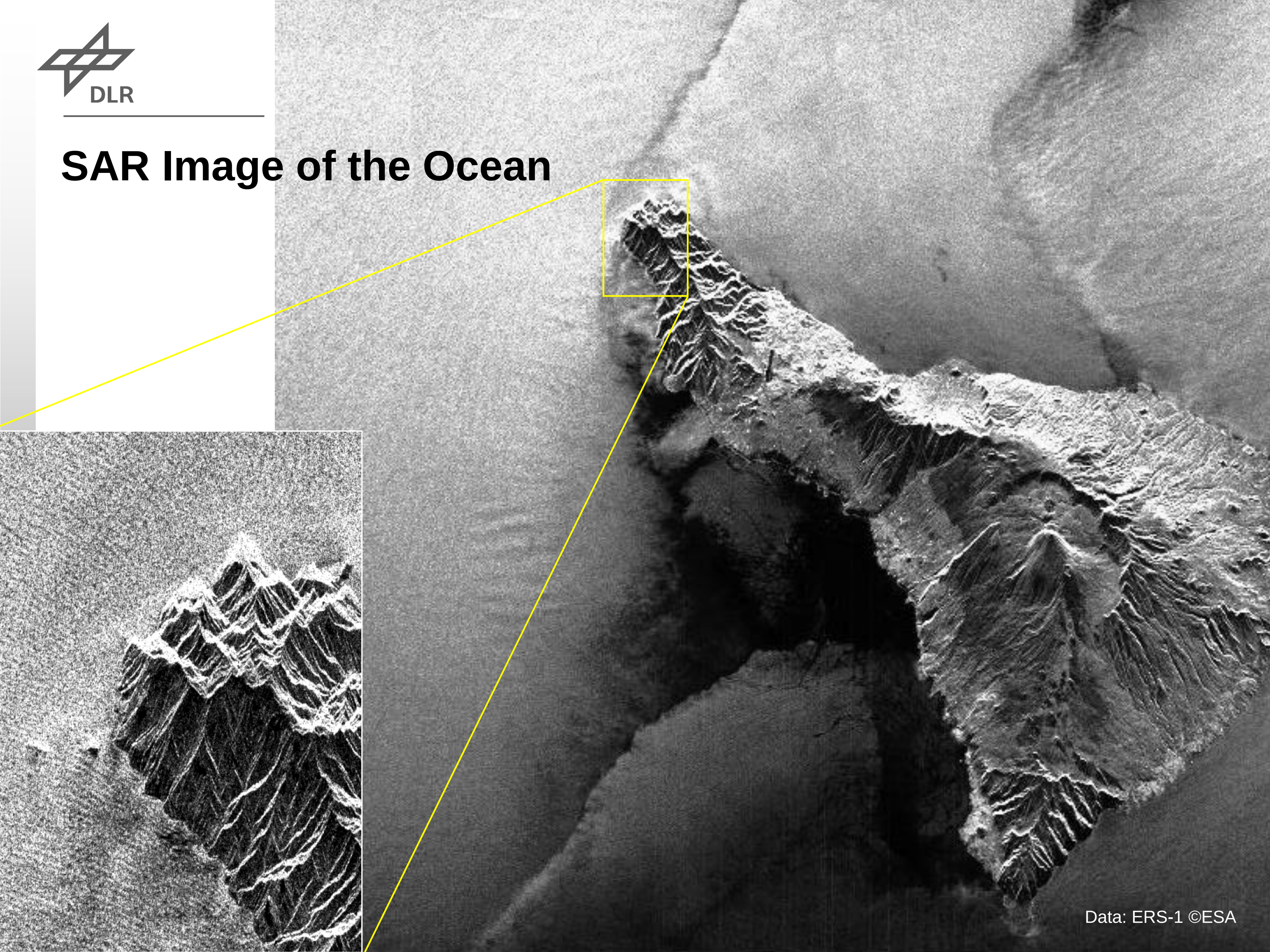
2. processing

raw data focusing $\Rightarrow$ **image** of the object

Airborne X-band SAR image

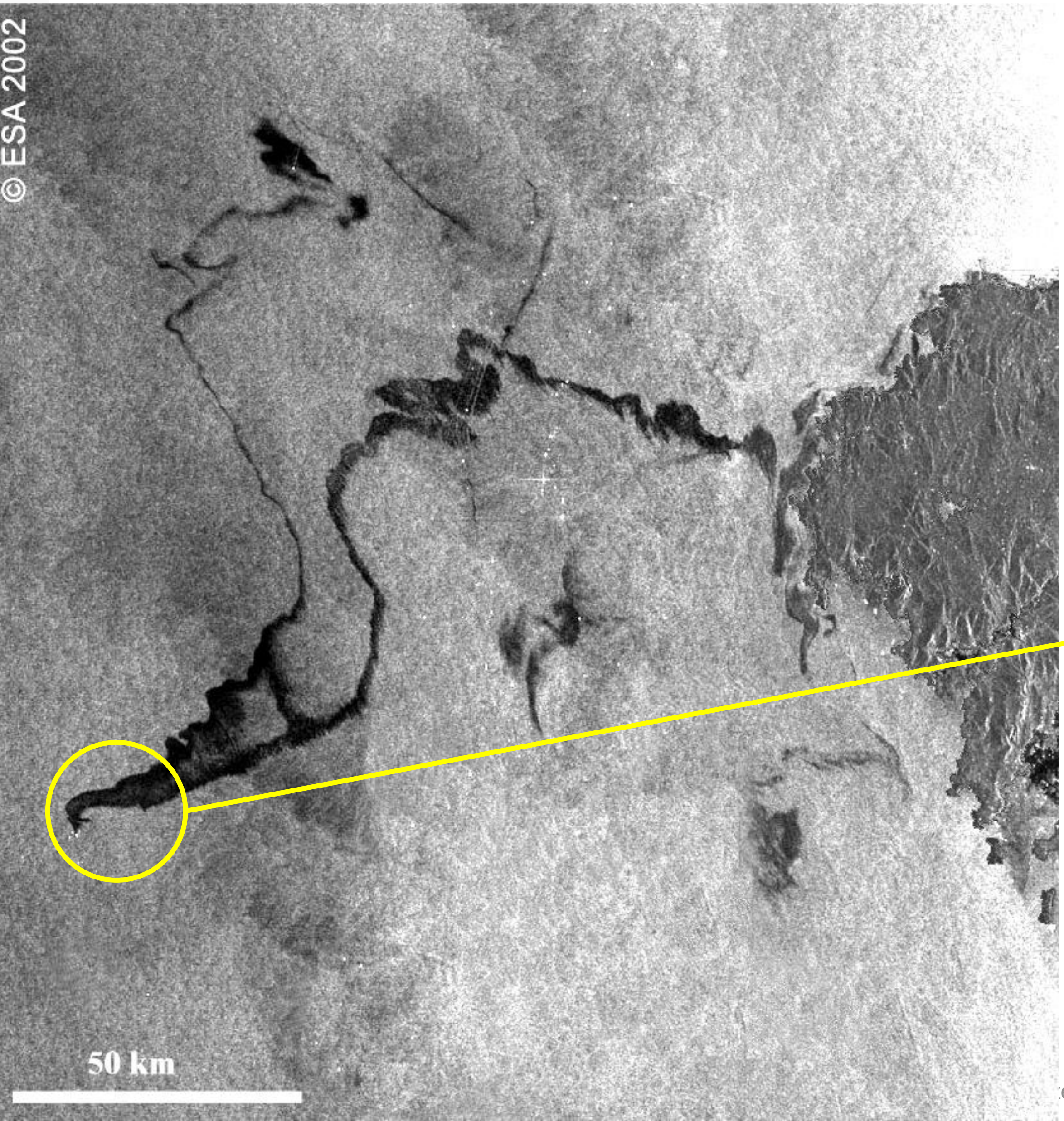
1 m resolution

SAR Image of the Ocean



Data: ERS-1 ©ESA

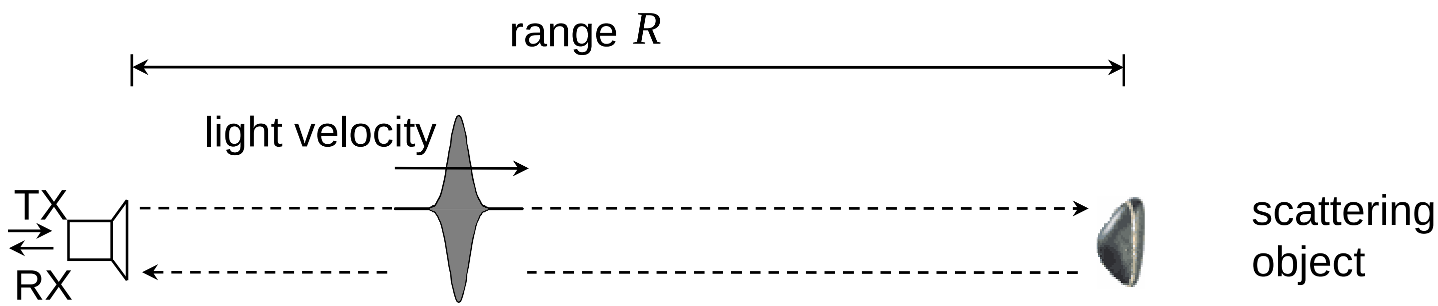
“Prestige” Oil Tanker Disaster Off the Spanish Coast



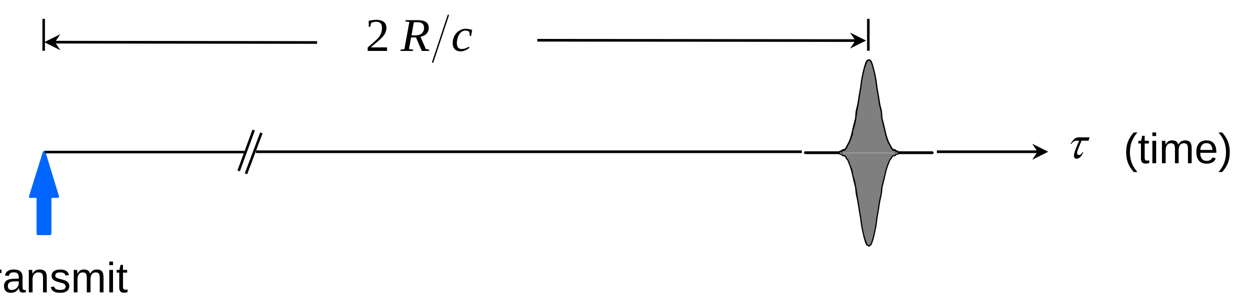
Envisat/ASAR
20 November 2002

Synthetic Aperture Radar (SAR)

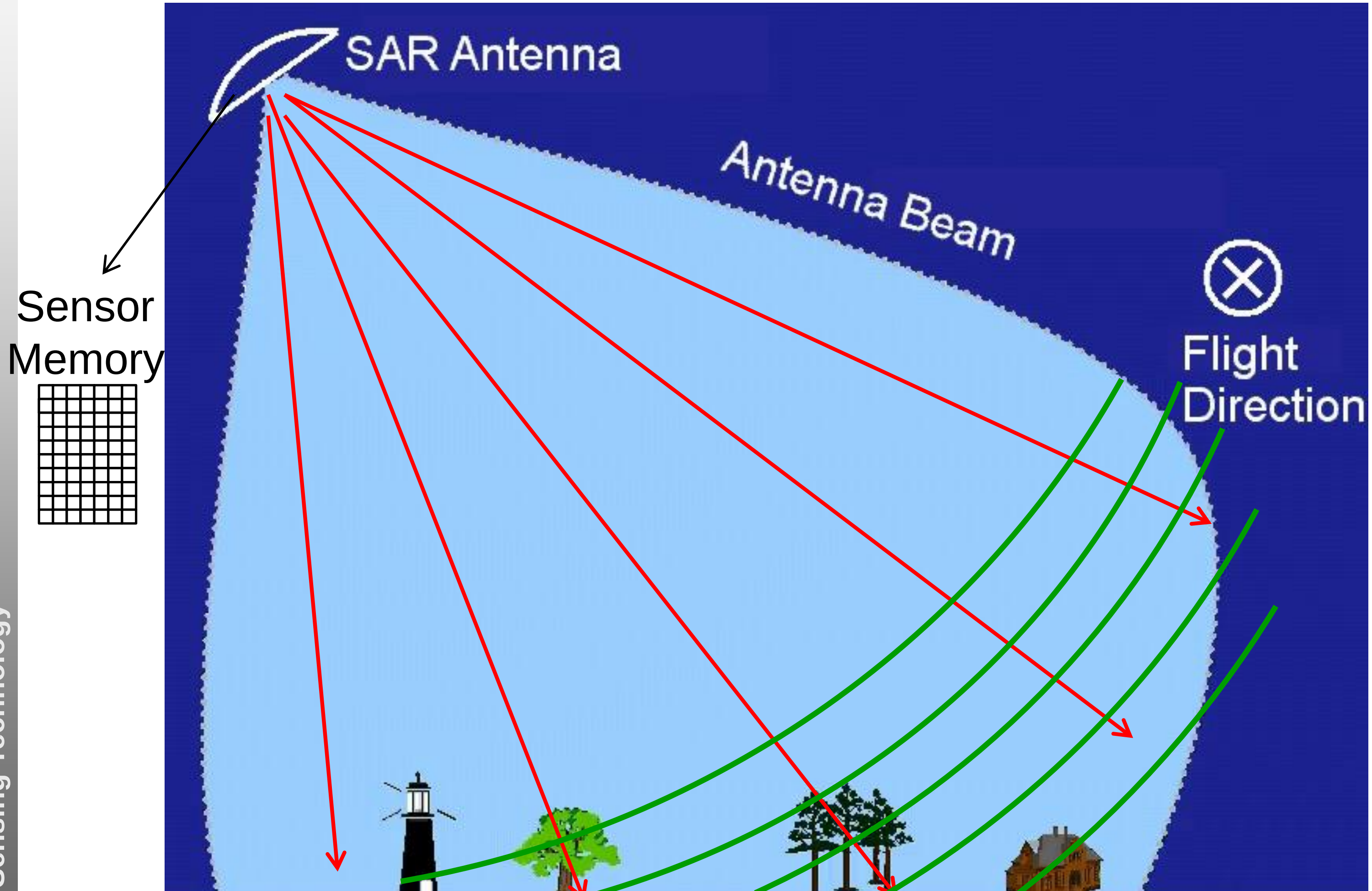
Radar Principle



received echo:



Range Imaging Principle

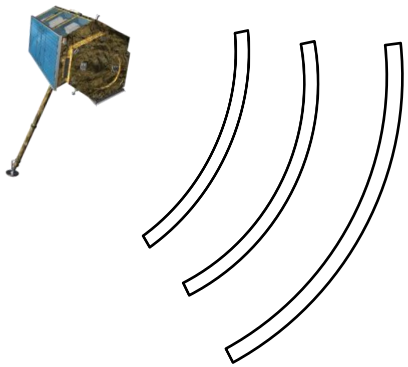


Angular imaging geometry of a camera: resolution determined by aperture, wavelength, distance

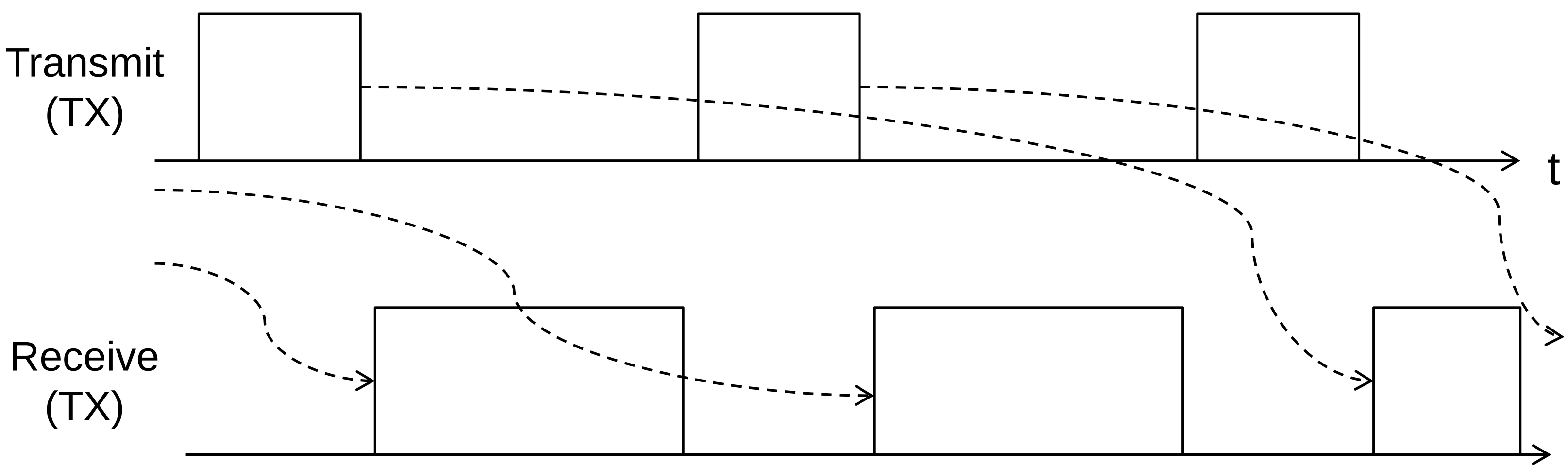
Radial imaging geometry of a RADAR: resolution determined by light vel., pulse (band)width and sampling

→ sampling and storing echoes of transmitted pulse

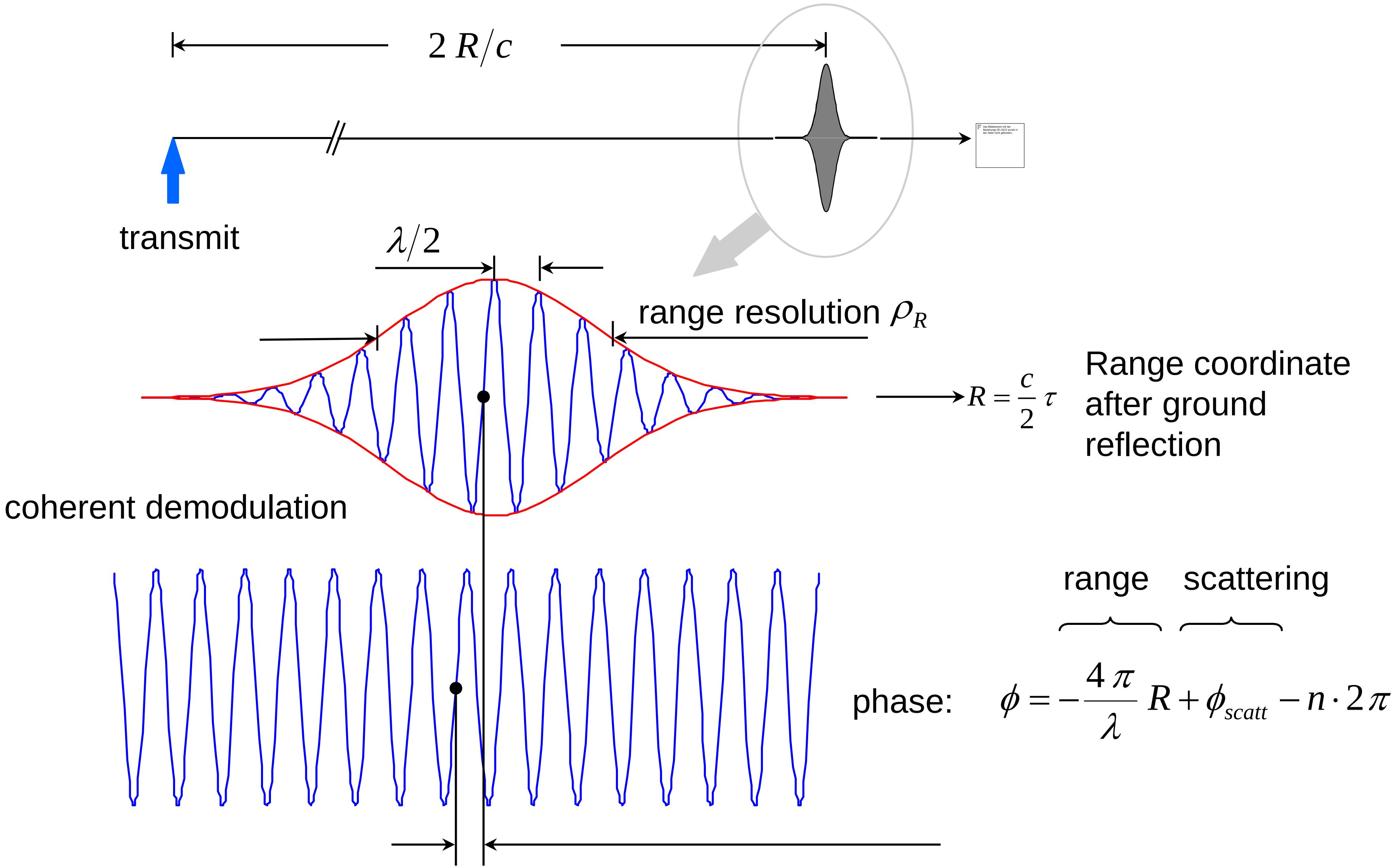
Timing Constraints of a Space-borne SAR



- SAR cannot receive during transmit
- Several pulses “in the air” simultaneously



Coherently Received Echo of a Point Target



Phasor Representation of a Wave Signal

$$\left(\exp(j\,\alpha) = \cos(\alpha) + j\sin(\alpha)\right)$$

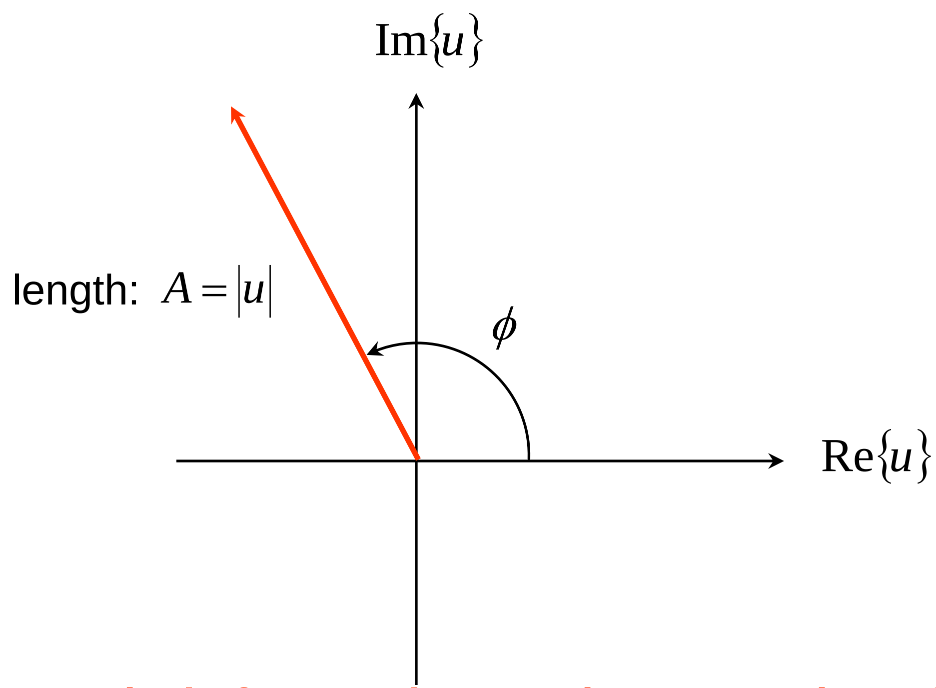
complex representation: $A \cdot \cos(2\pi\nu_0\tau + \phi) \quad \rightarrow \quad A \cdot \exp(j\,(2\pi\nu_0\tau + \phi))$

after demodulation: $u = A \cdot \exp(j \cdot \phi)$

amplitude: $A = |u|$

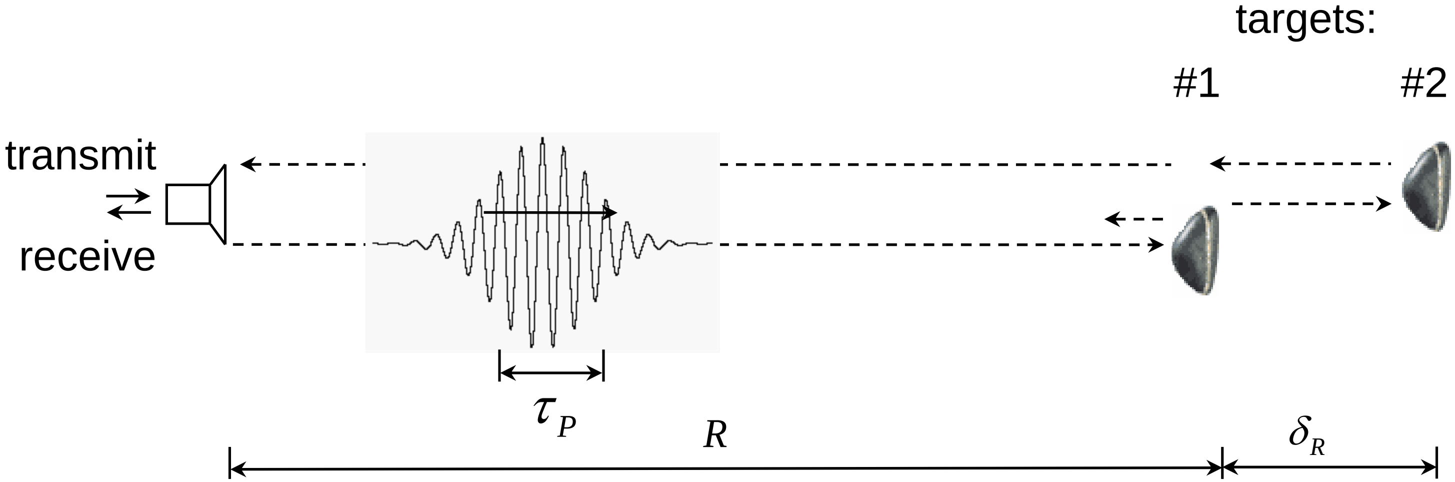
intensity, power: $A^2 = |u|^2$

phase: ϕ



Every sample of a SAR raw data set and every pixel of a complex SAR image consists of a real and an imaginary part, i.e. it is a phasor and contains amplitude and phase information.

Pulse Waveform and Range Resolution



radar frequency : ν_0

transmitted pulse: $g(\tau)\cdot\exp(j\,2\pi\nu_0\tau)$

received echo from target #1: $g(\tau-2\,R/c)\cdot\exp(j\,2\pi\nu_0(\tau-2\,R/c))$

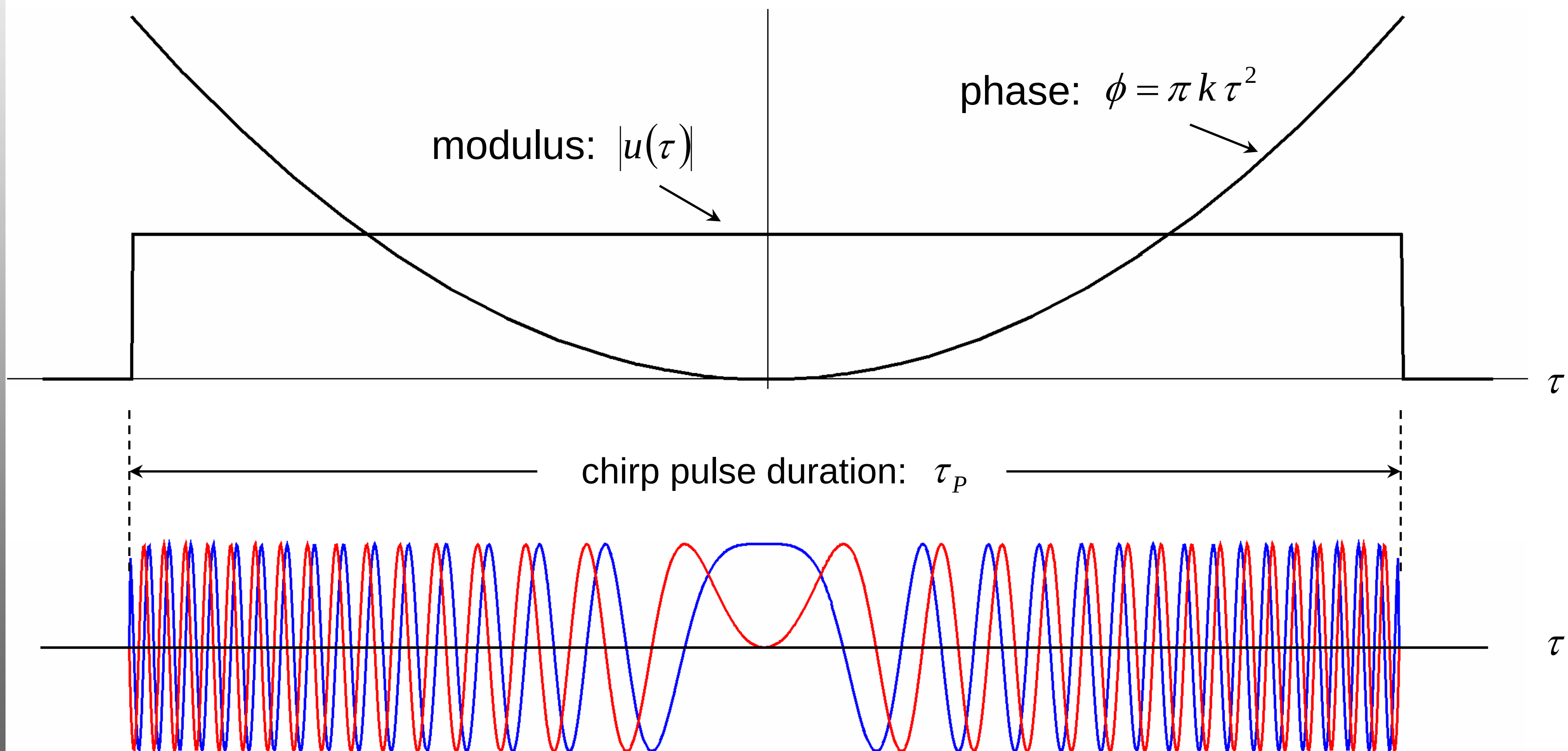
targets #1 and #2 easily separable, if $\delta_R \geq \rho_R = \tau_P\, c/2$ (range resolution)

for phase coded pulses, e.g. chirps, of bandwidth W_P : $\rho_R = \dfrac{c}{2\,W_P}$

Chirp Signal

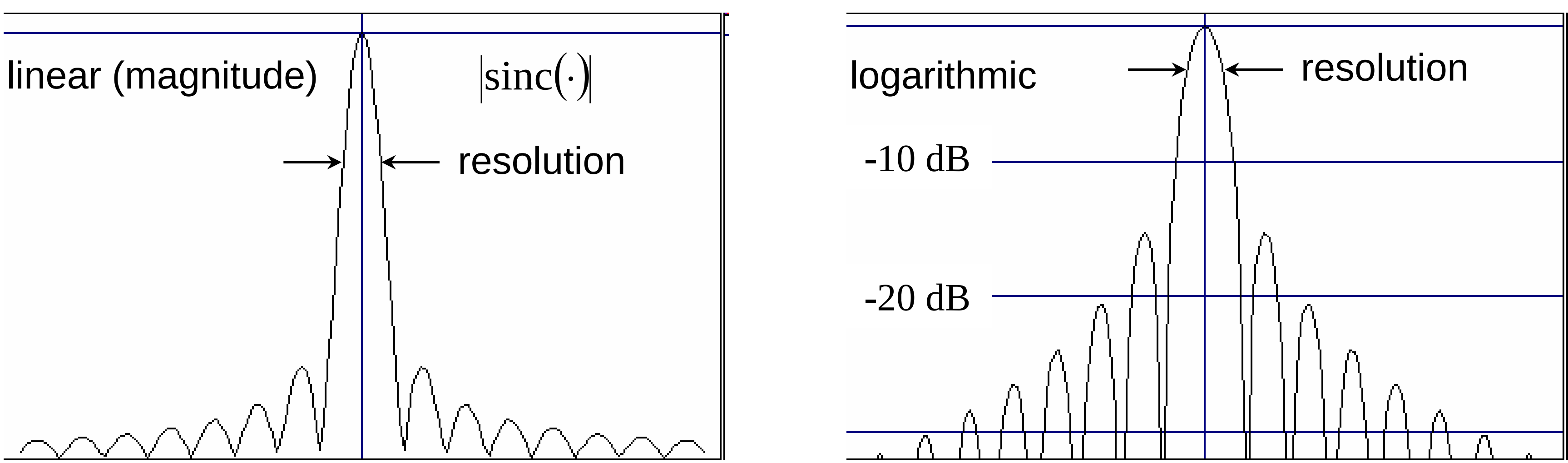
$$u(\tau)=\exp\left(j\pi k\tau^2\right)=\underbrace{\cos\left(\pi k\tau^2\right)}_{\text{real part}}+\underbrace{j\sin\left(\pi k\tau^2\right)}_{\text{imaginary part}} \quad \text{for} \quad -\frac{\tau_P}{2}\leq\tau\leq\frac{\tau_P}{2}$$

k : chirp rate

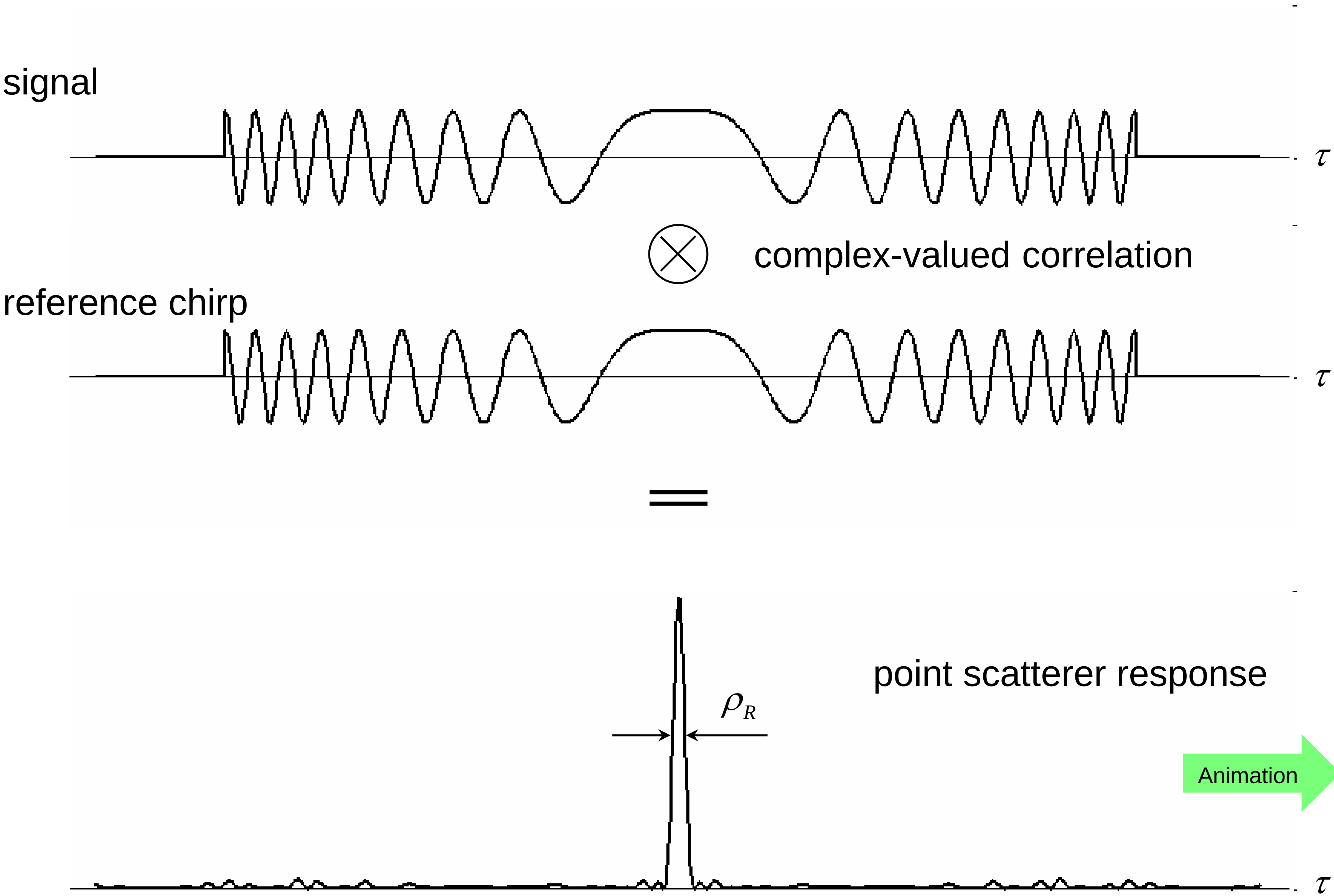


Range Compression

- transmit chirp instead of short pulse
- every point target will return chirp echo
- correlate received signal with replica of transmitted chirp
- final impulse response (approximation) with W_P chirp bandwidth: $\mathrm{sinc}(\tau \cdot W_P) = \dfrac{\sin(\pi \tau W_P)}{\pi \tau W_P}$
- final range resolution: $\rho_R \cong \dfrac{c}{2W_P}$ (exact value depends on definition)

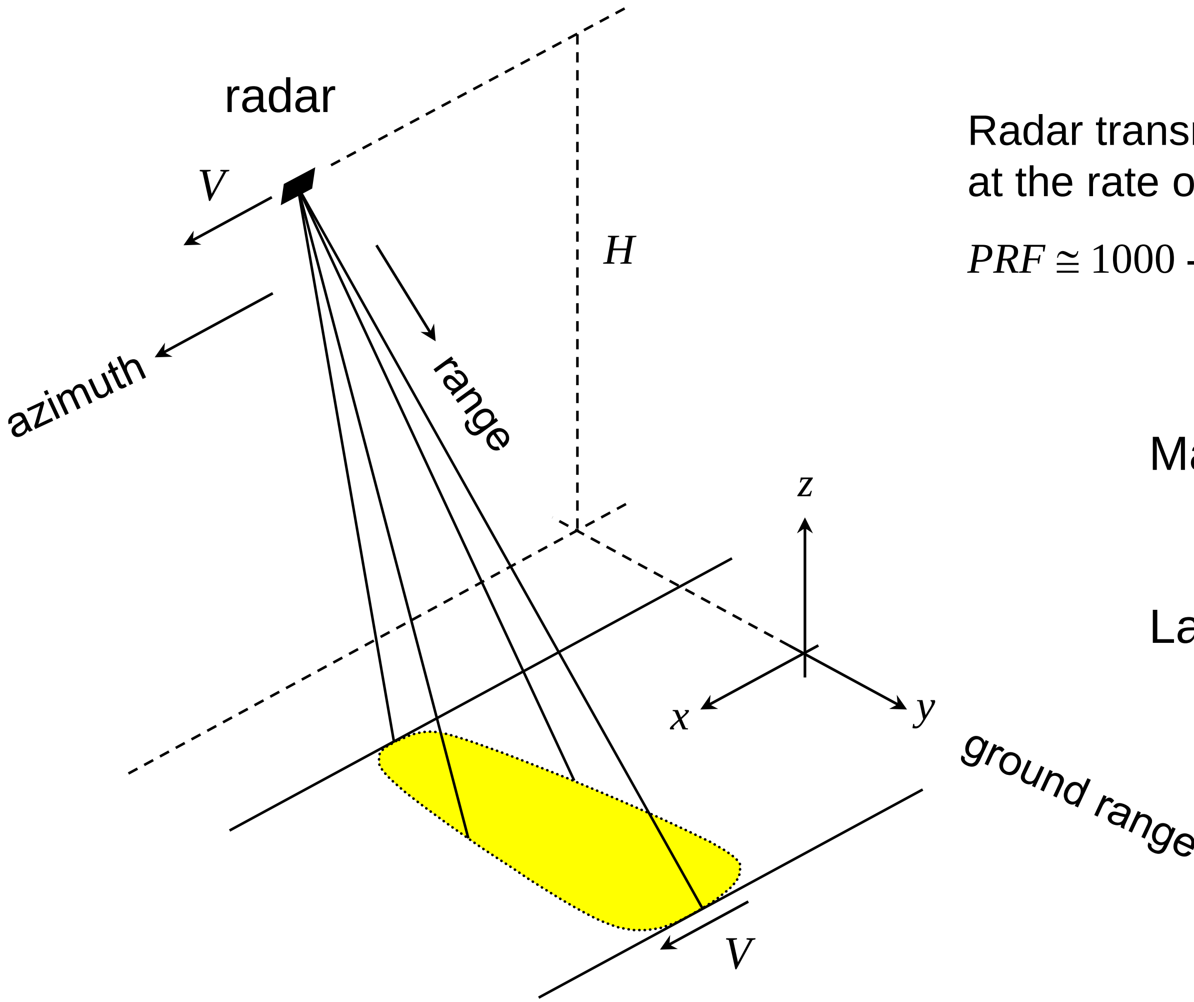


Range Compression by Matched Filtering



Synthetic Aperture Radar (SAR)

Side-Looking Radar Geometry



Radar transmits pulses and receives echoes at the rate of the pulse repetition frequency:

$PRF \cong 1000 - 4000 \text{ Hz}$

Main topic in the following:

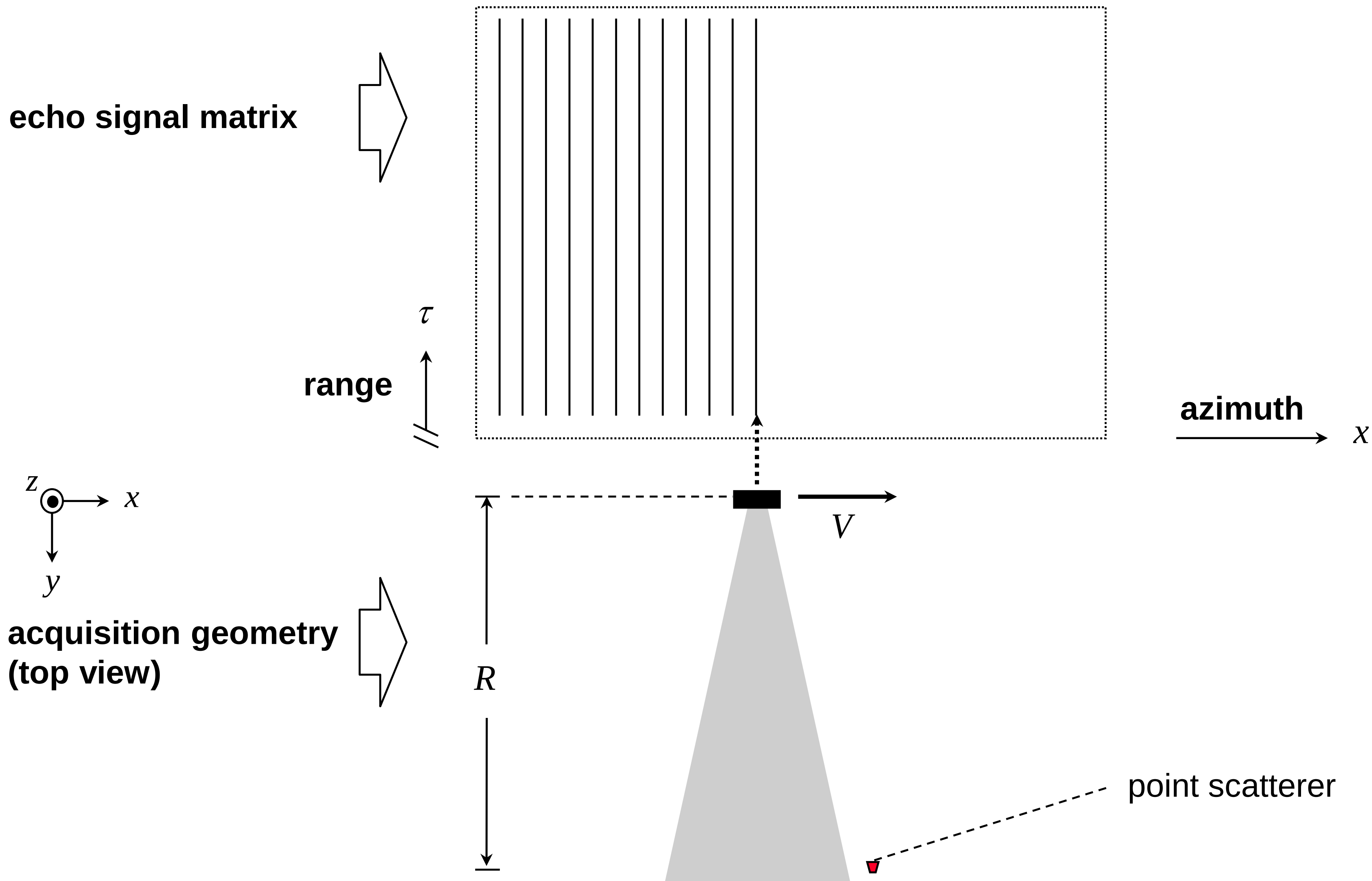
Stripmap-Mode SAR

Later:

Spotlight Mode SAR

ScanSAR

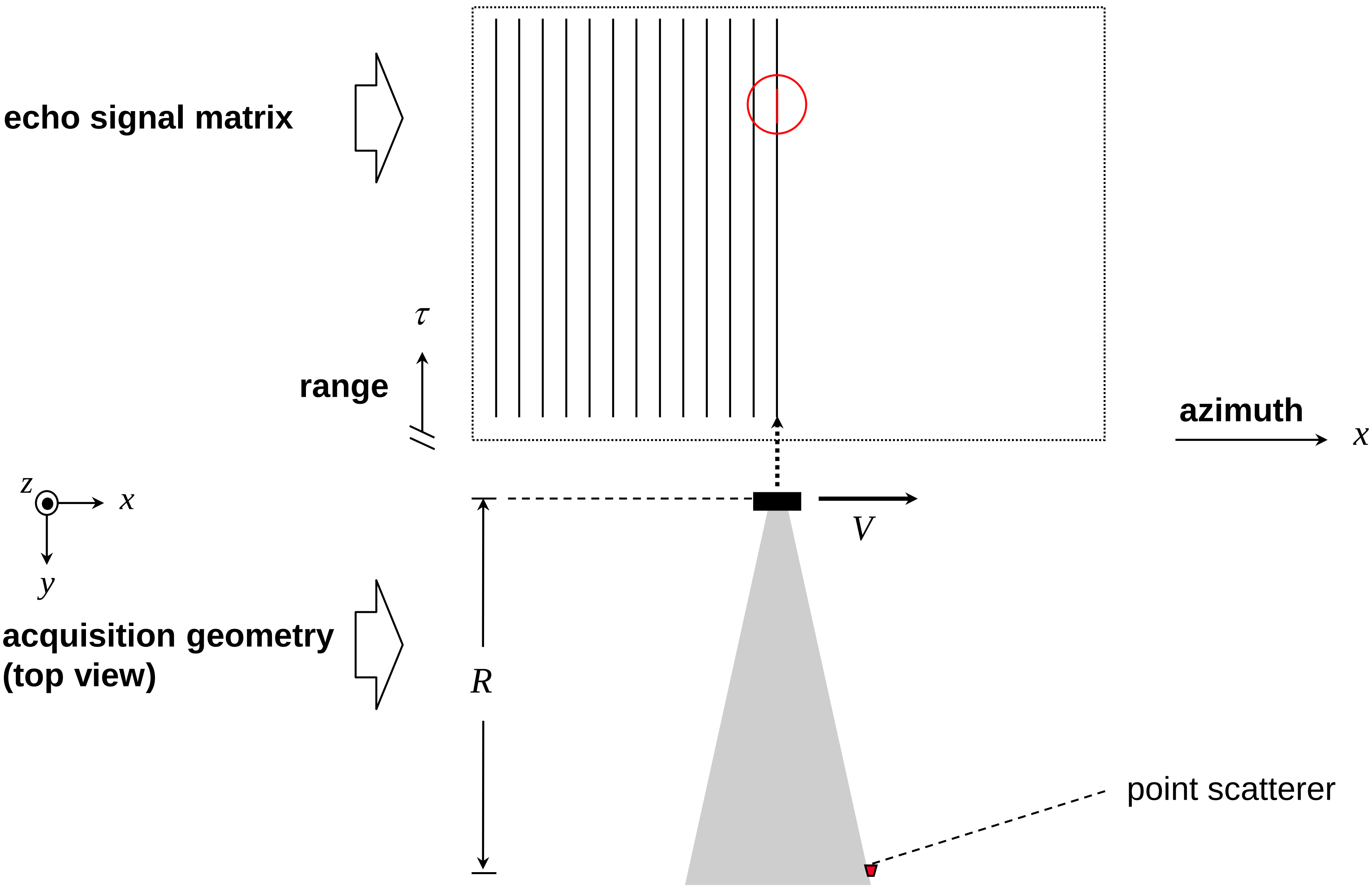
2-D Raw Data Matrix



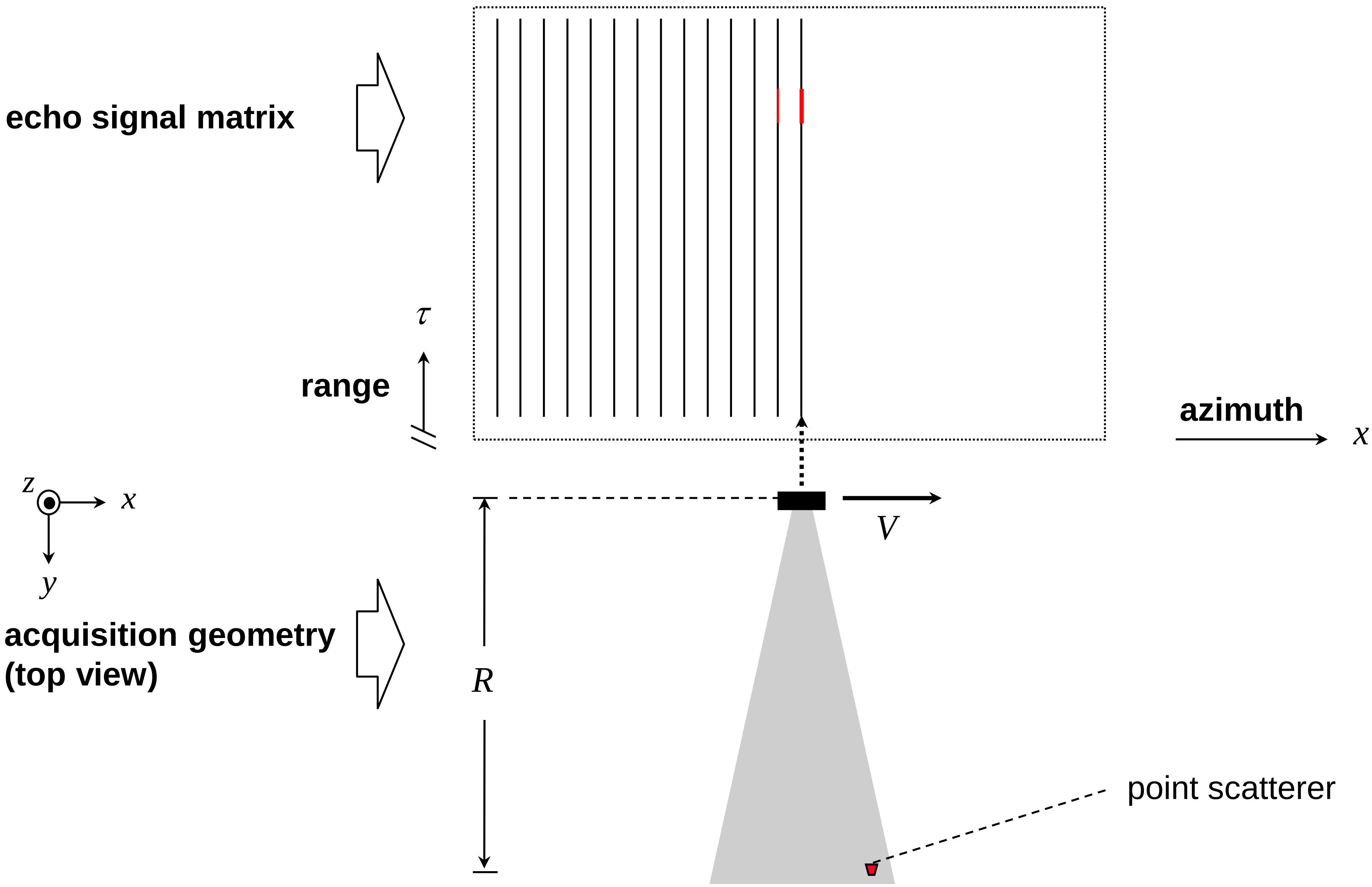
2-D Raw Data Matrix

echo signal matrix

acquisition geometry (top view)

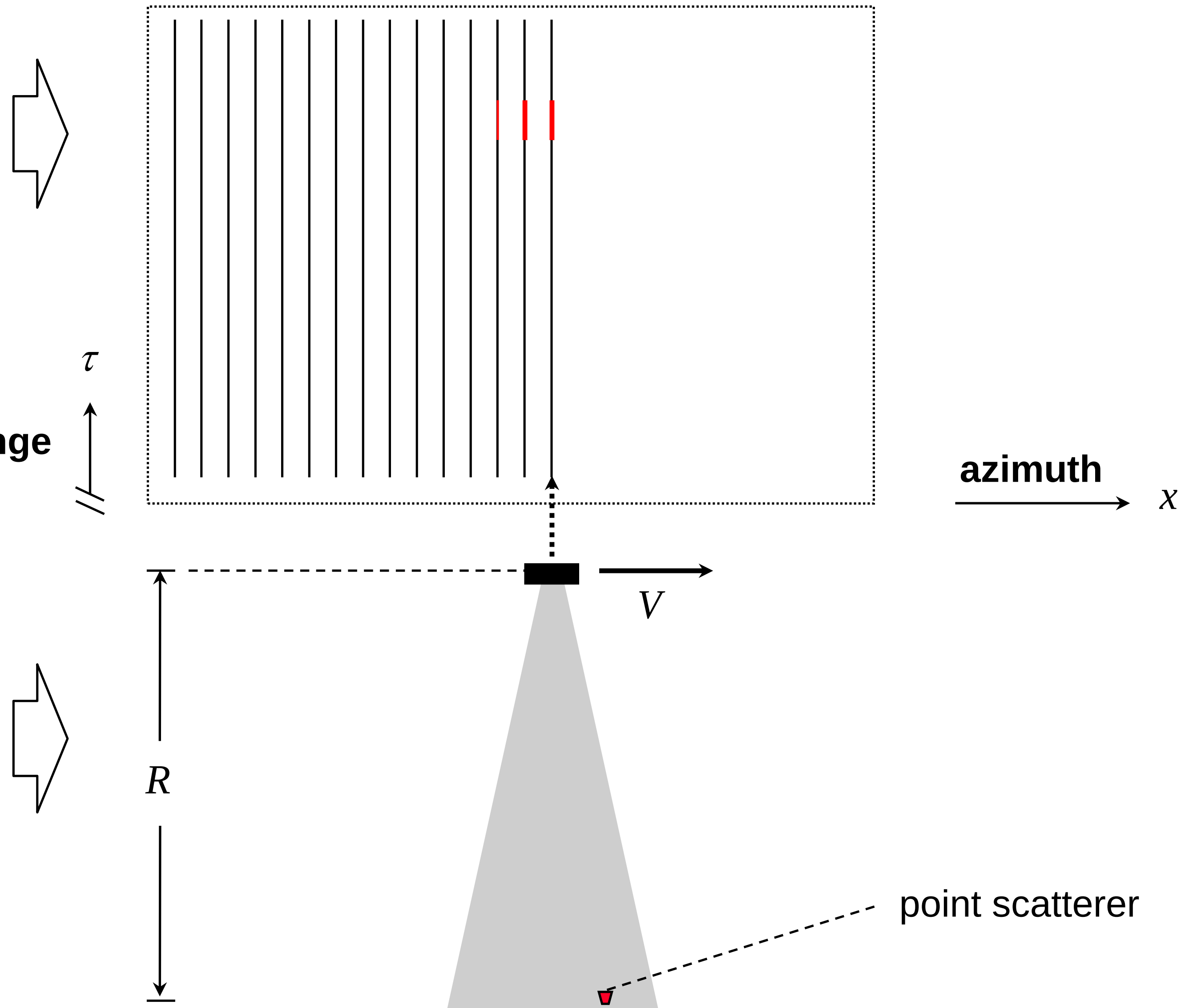


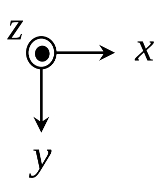
2-D Raw Data Matrix



2-D Raw Data Matrix

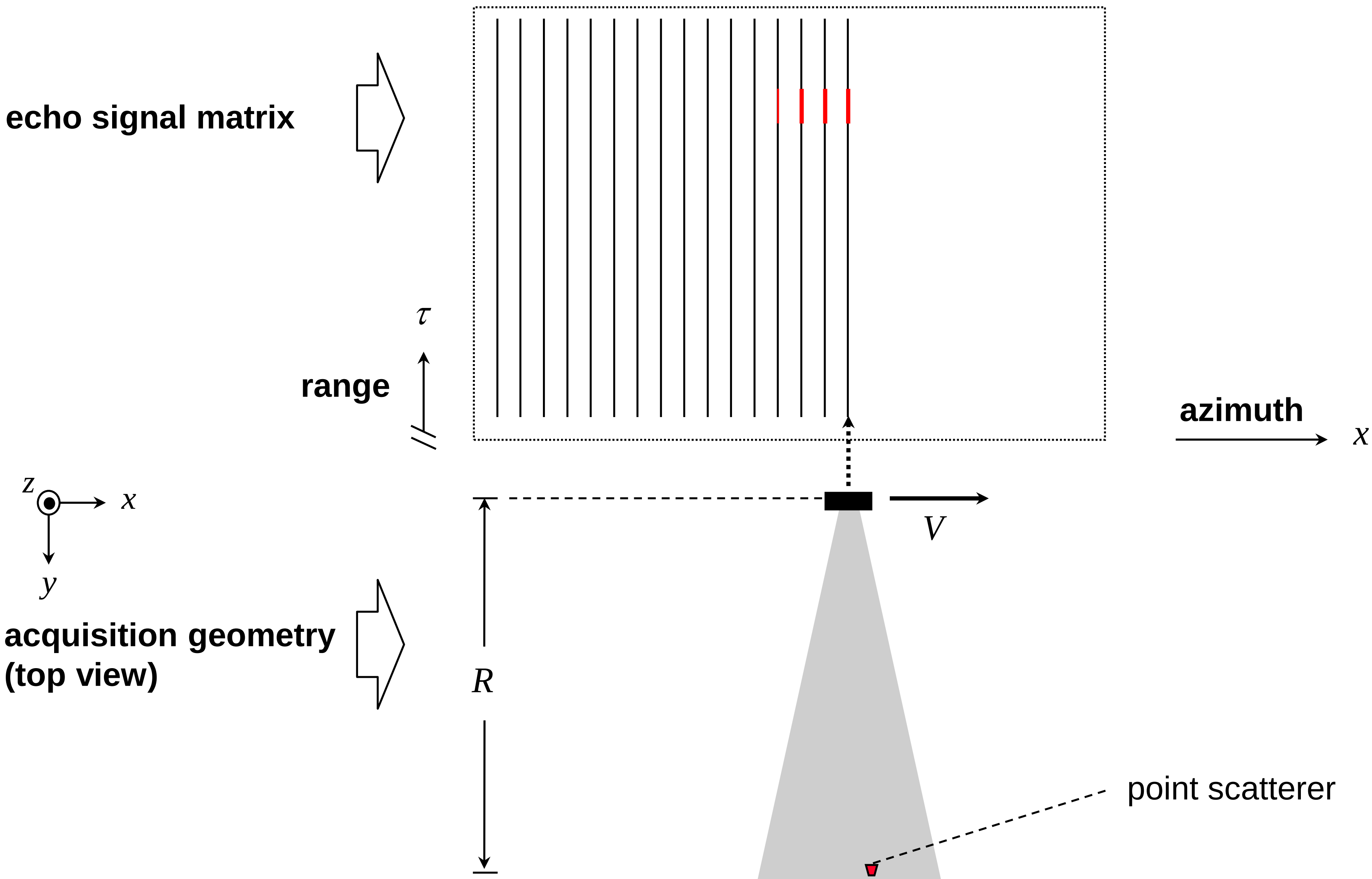
echo signal matrix



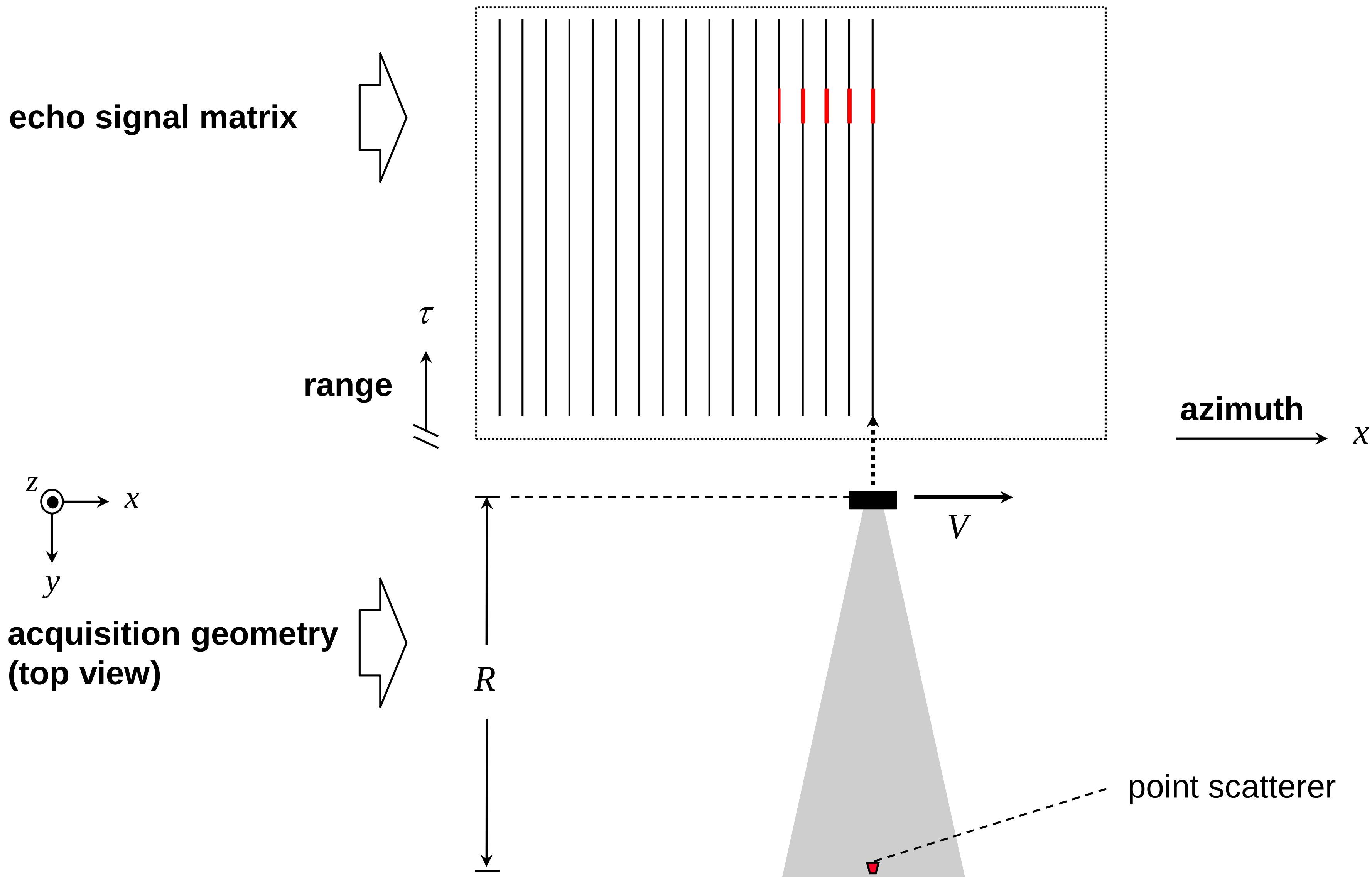


acquisition geometry (top view)

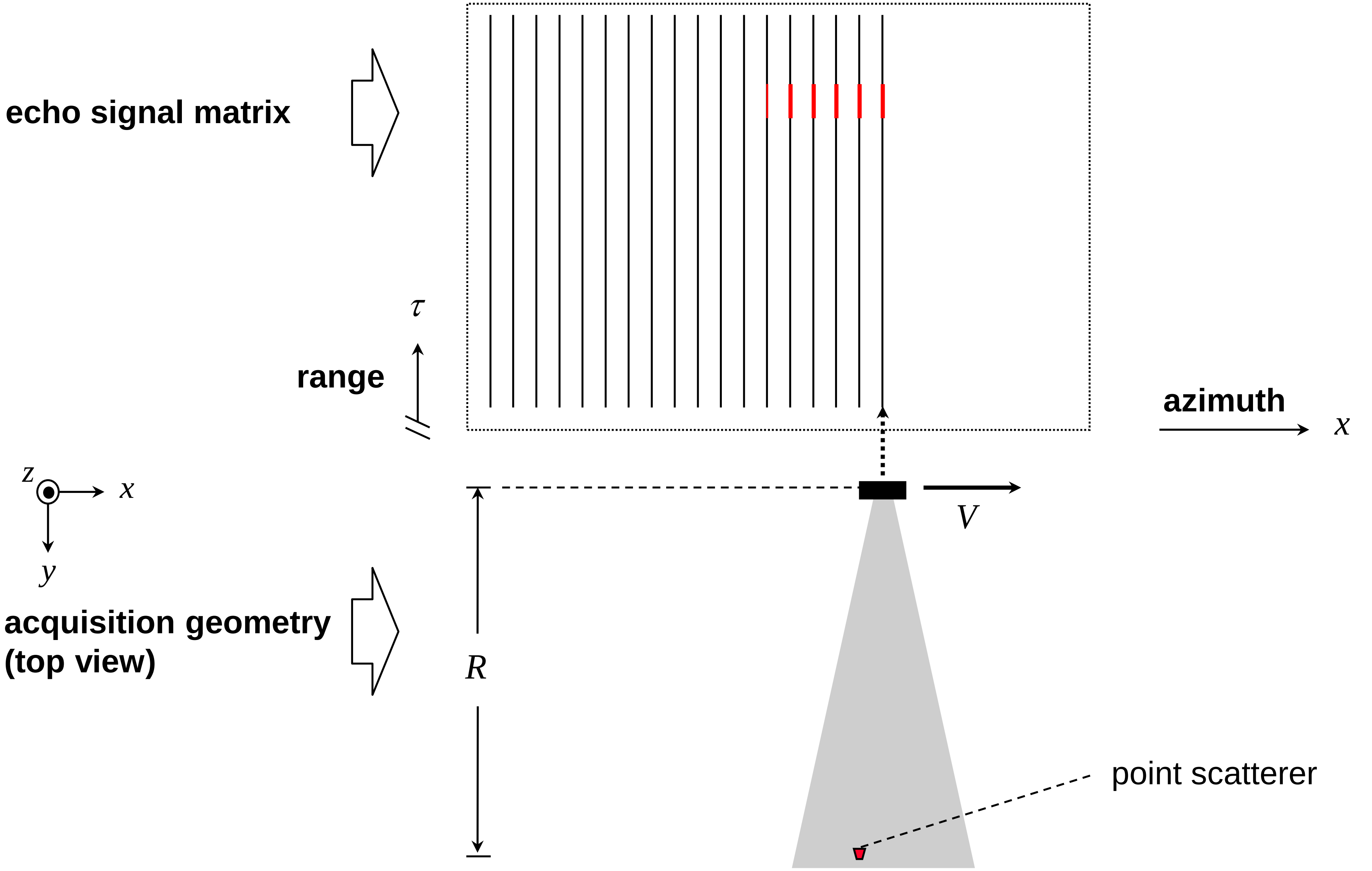
2-D Raw Data Matrix



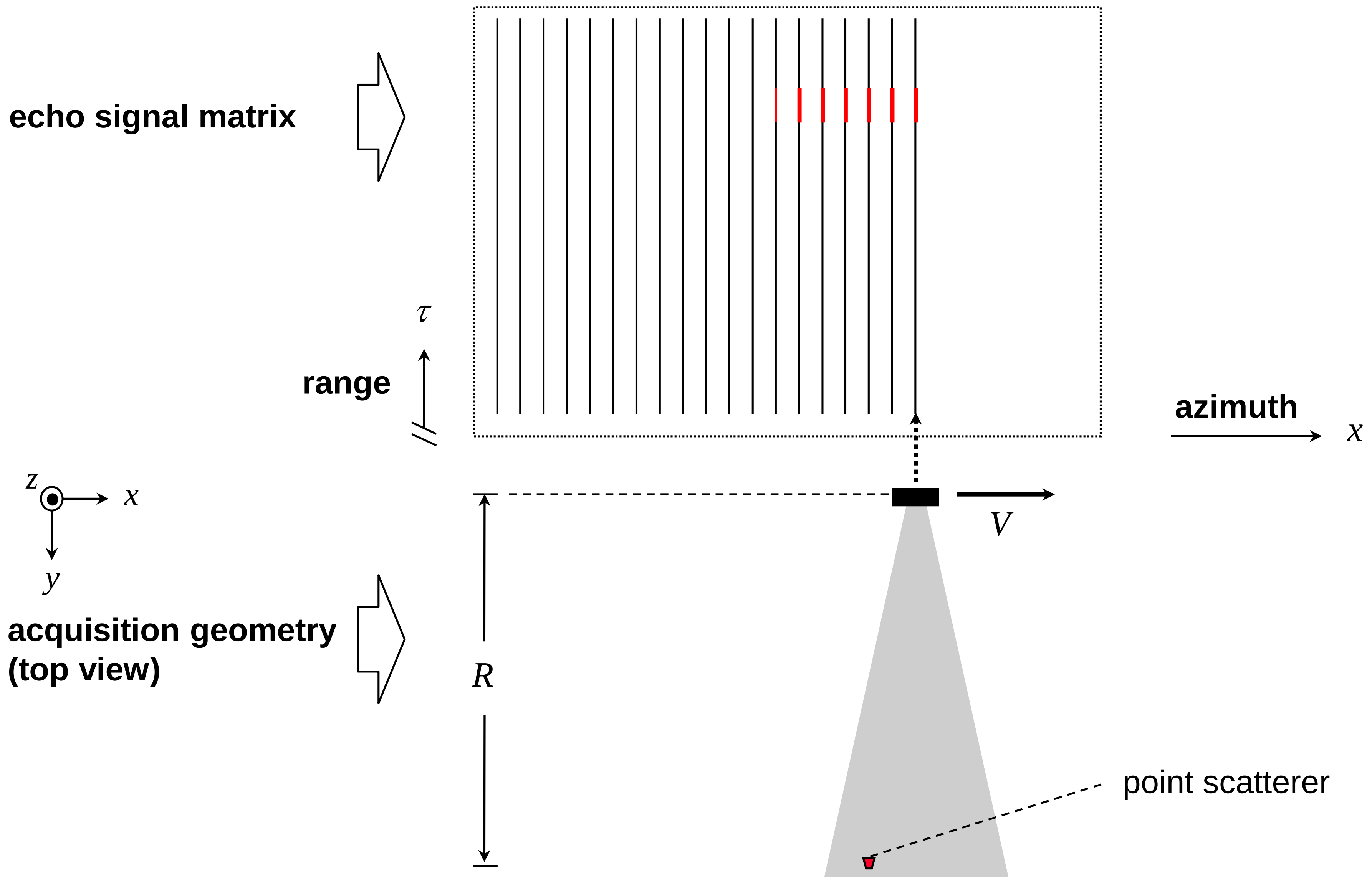
2-D Raw Data Matrix



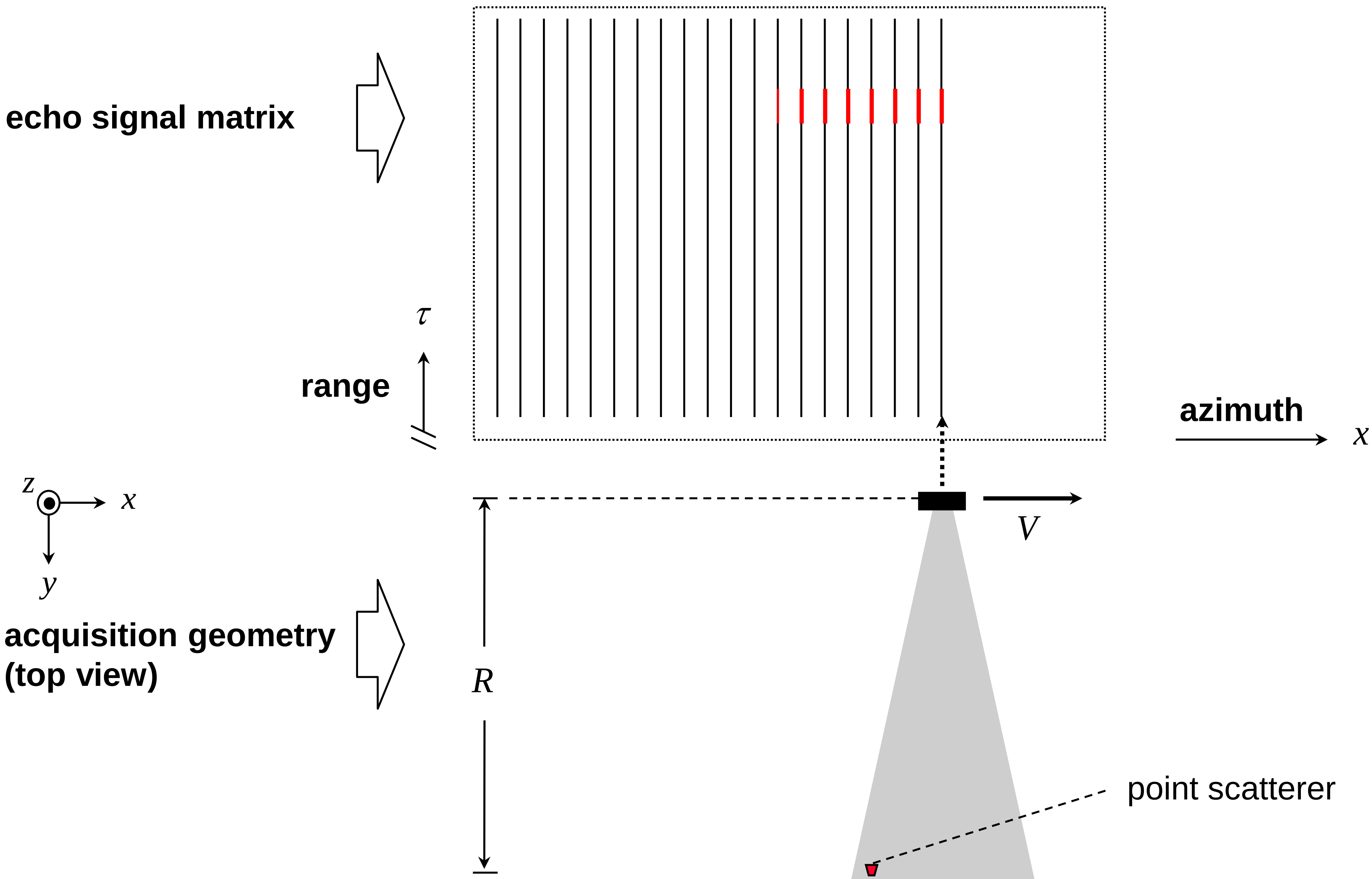
2-D Raw Data Matrix



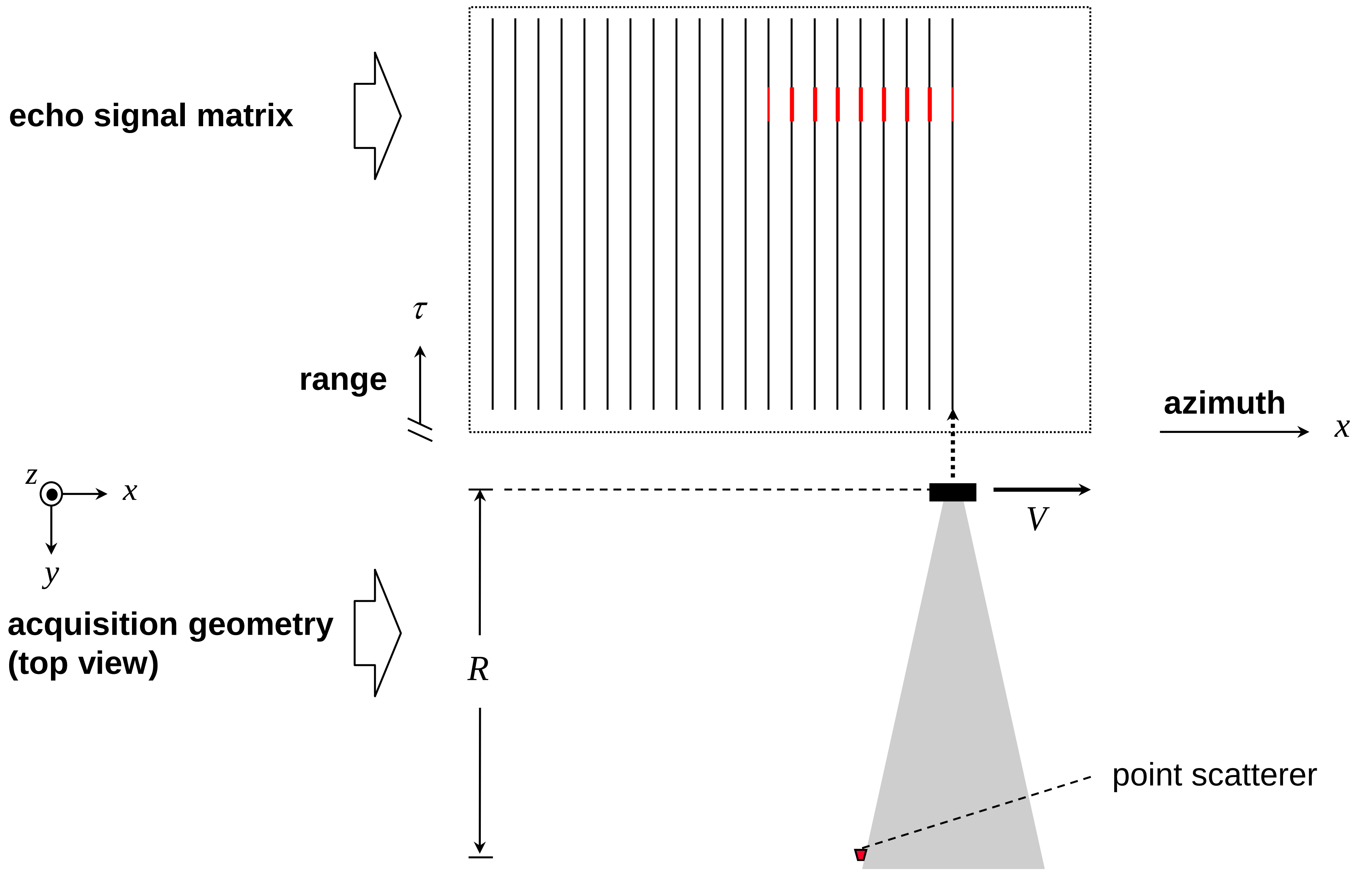
2-D Raw Data Matrix



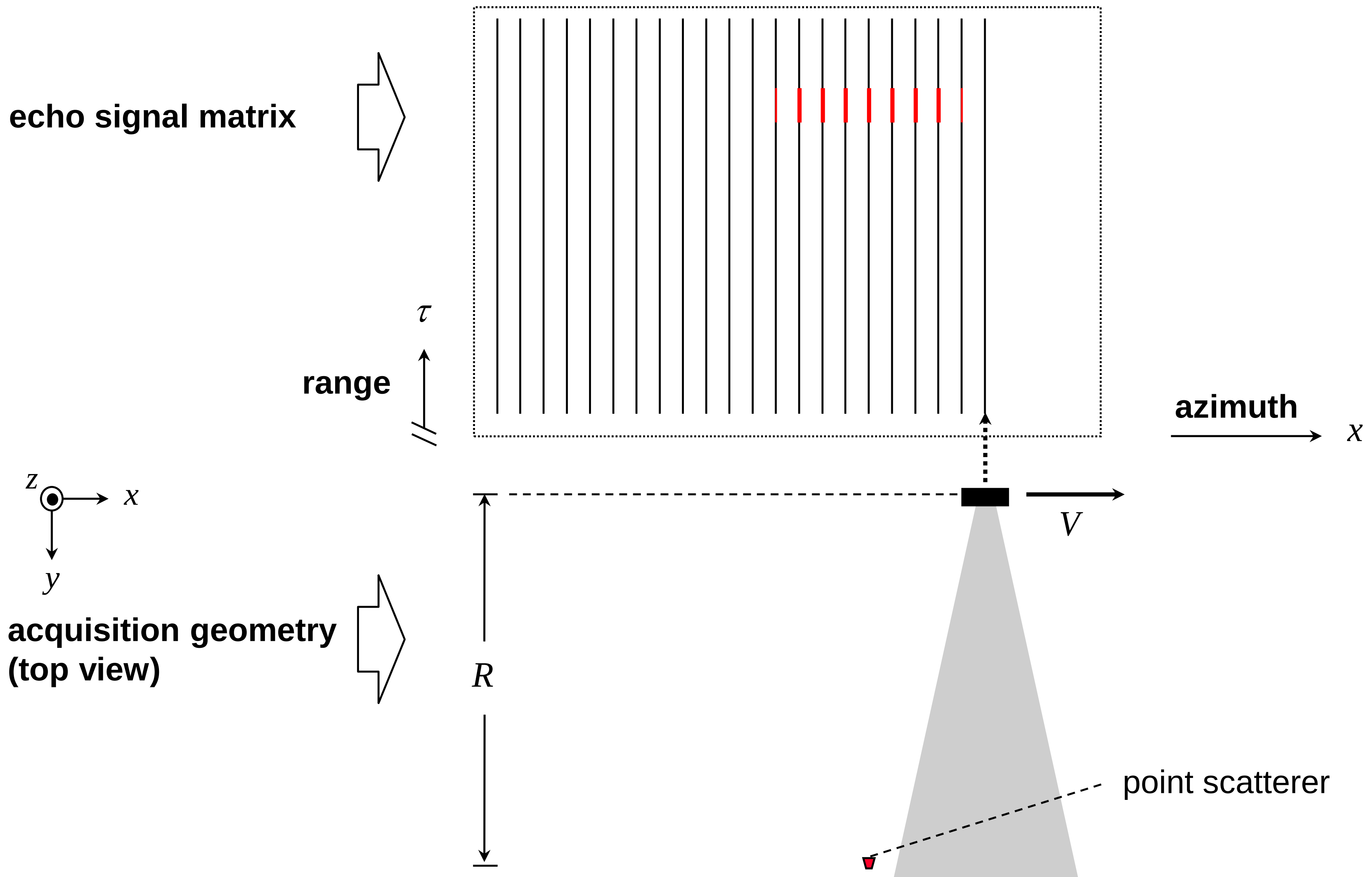
2-D Raw Data Matrix



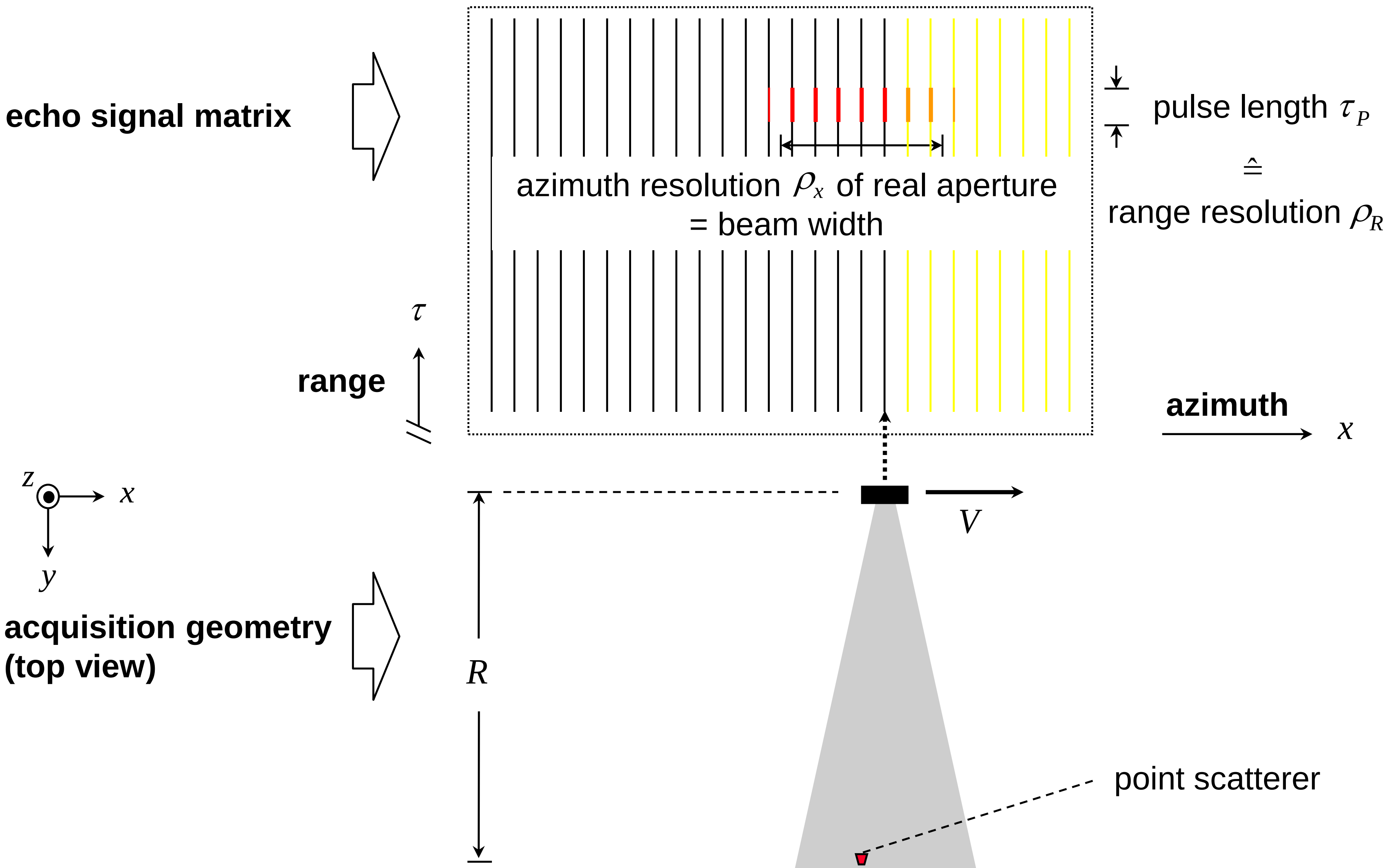
2-D Raw Data Matrix



2-D Raw Data Matrix



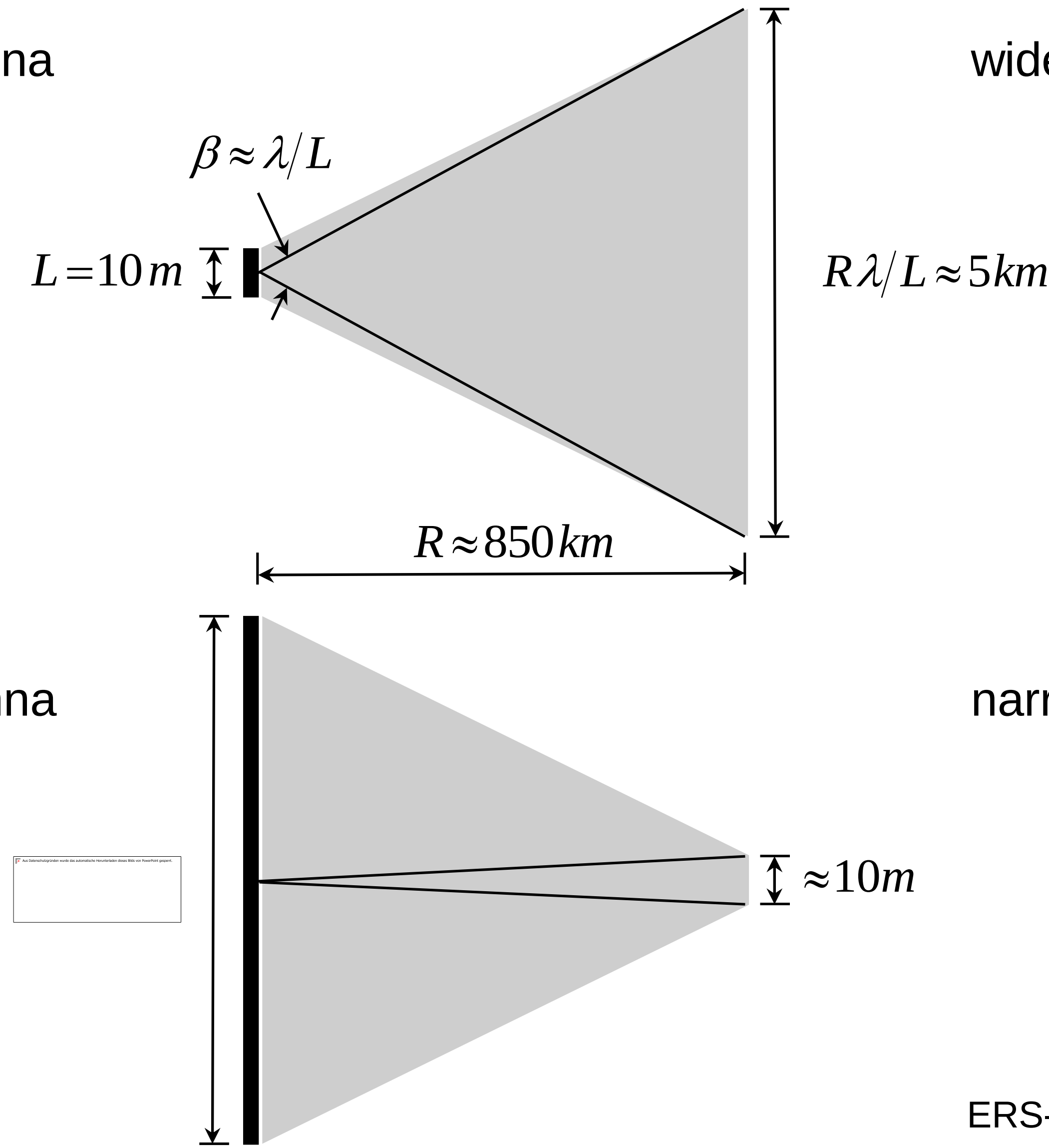
2-D Raw Data Matrix



Antenna Size vs. Beam Width

short antenna

wide beam

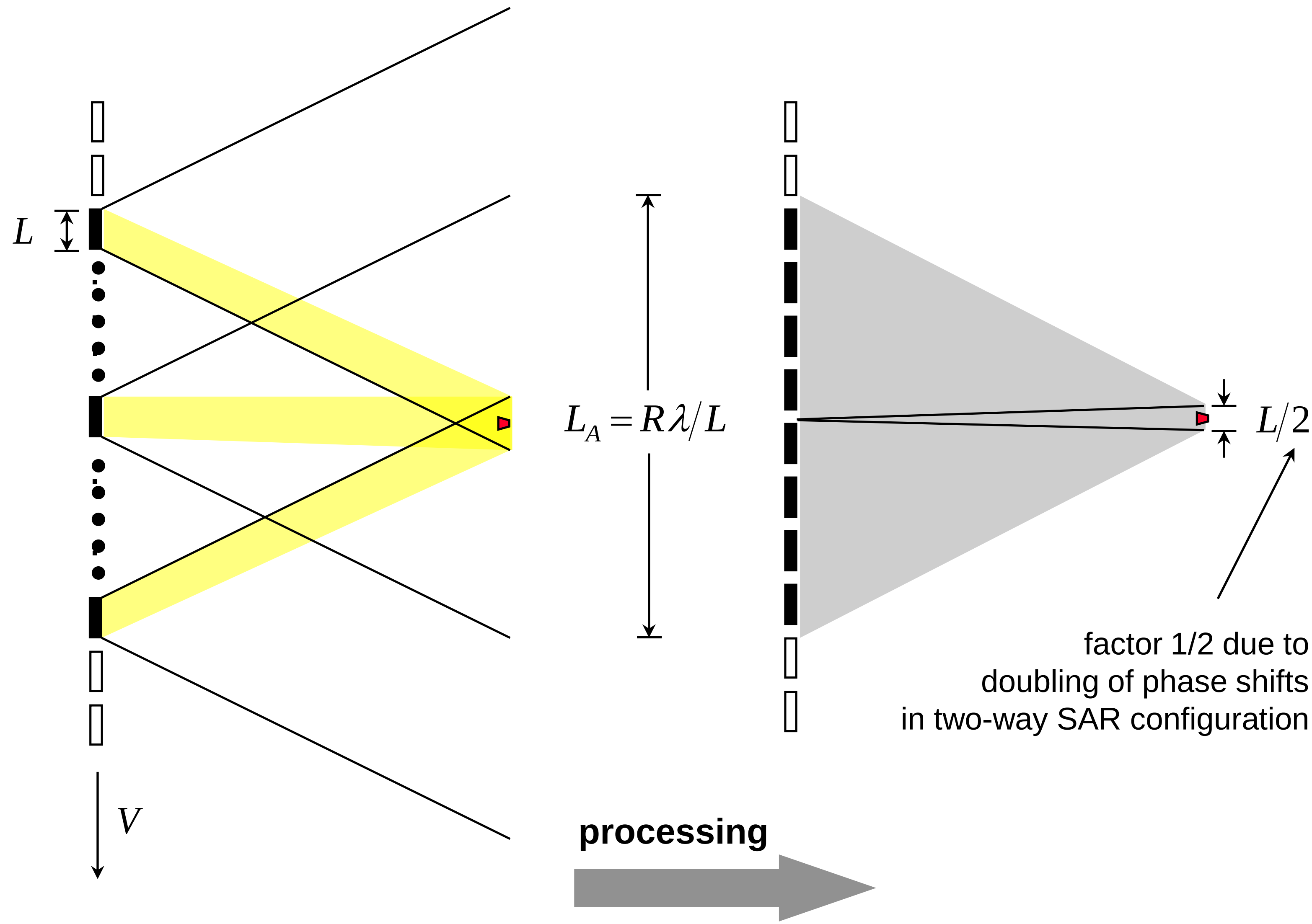


long antenna

narrow beam

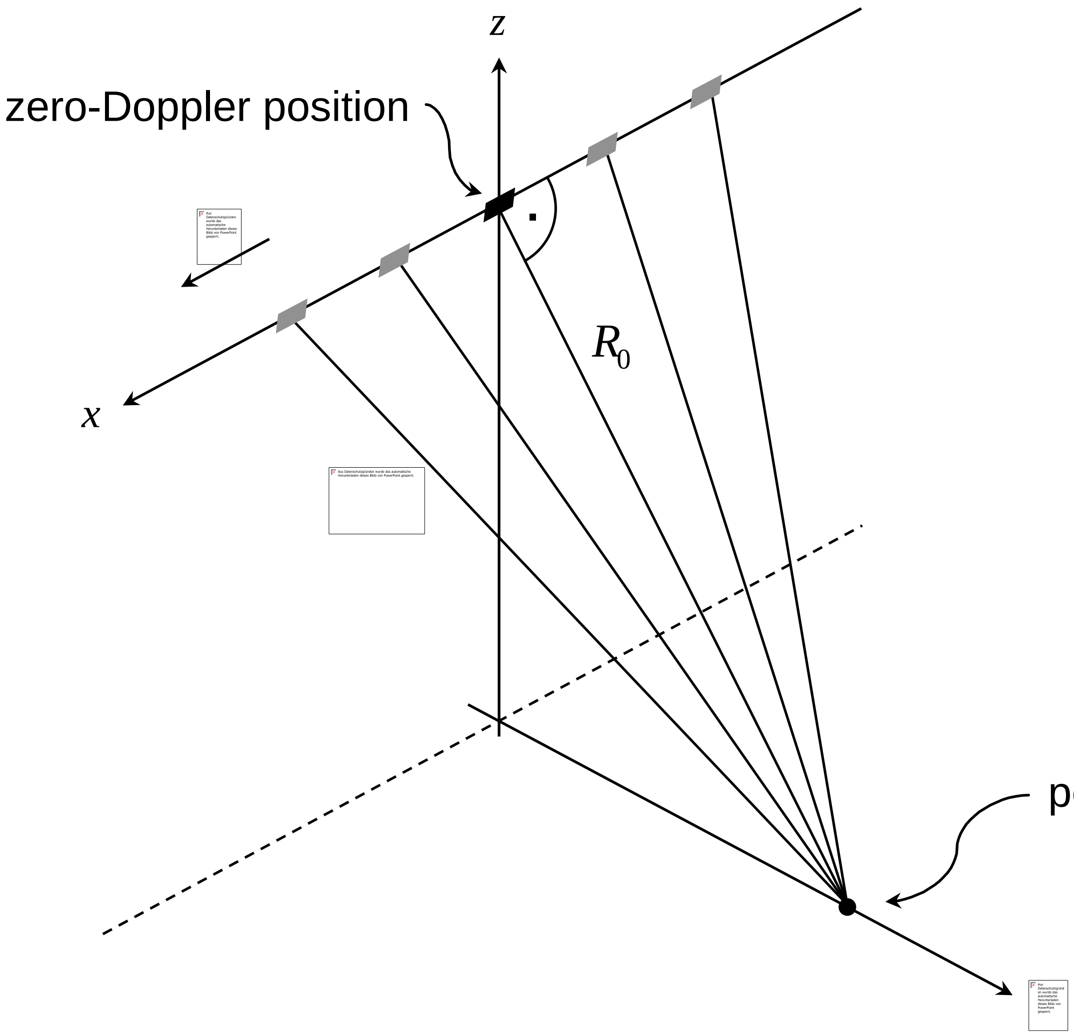
ERS-1/2 parameters

Formation of a Synthetic Aperture - SAR Principle



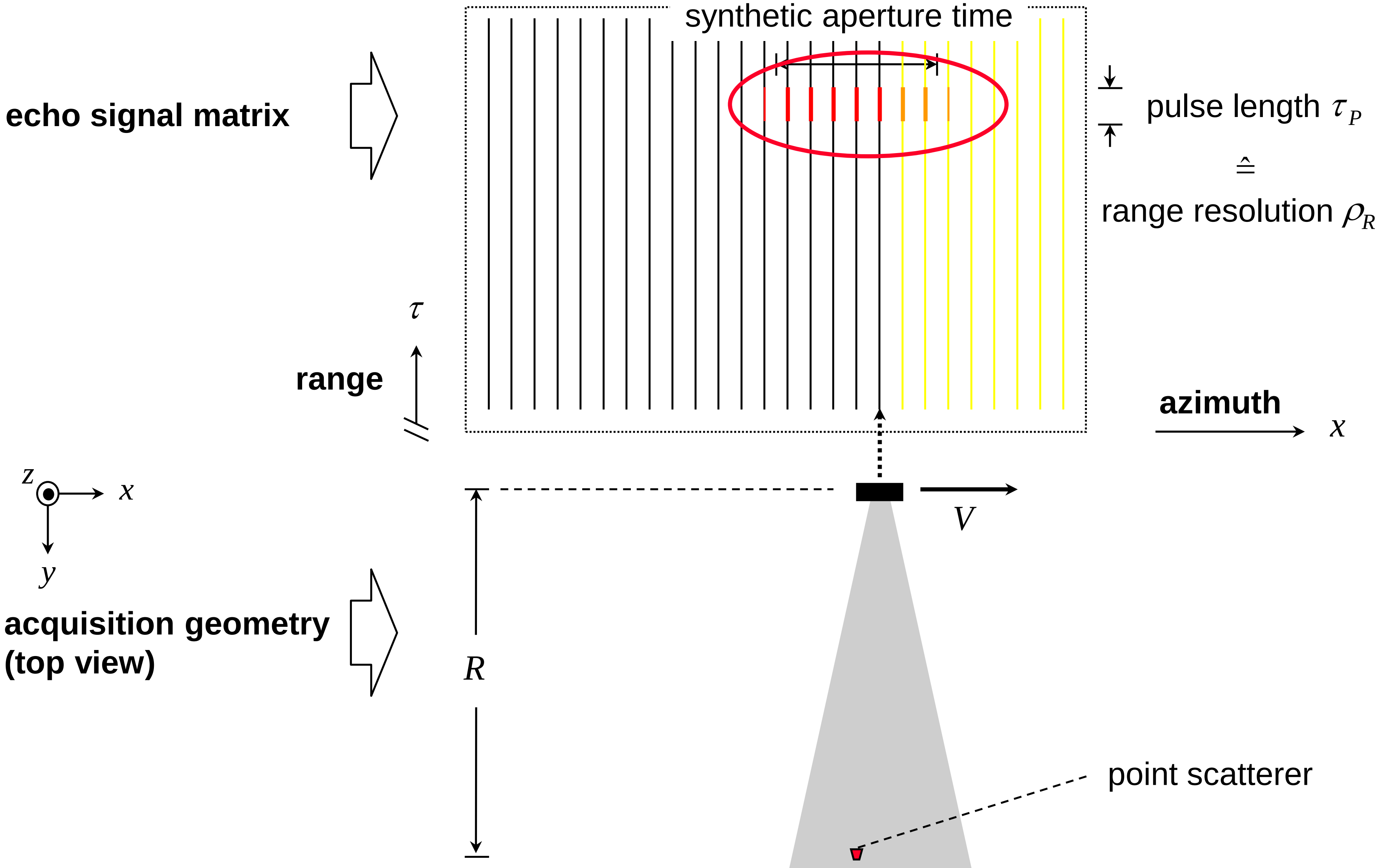
= phase corrected summation of echoes

Range History of a Single Point Scatterer

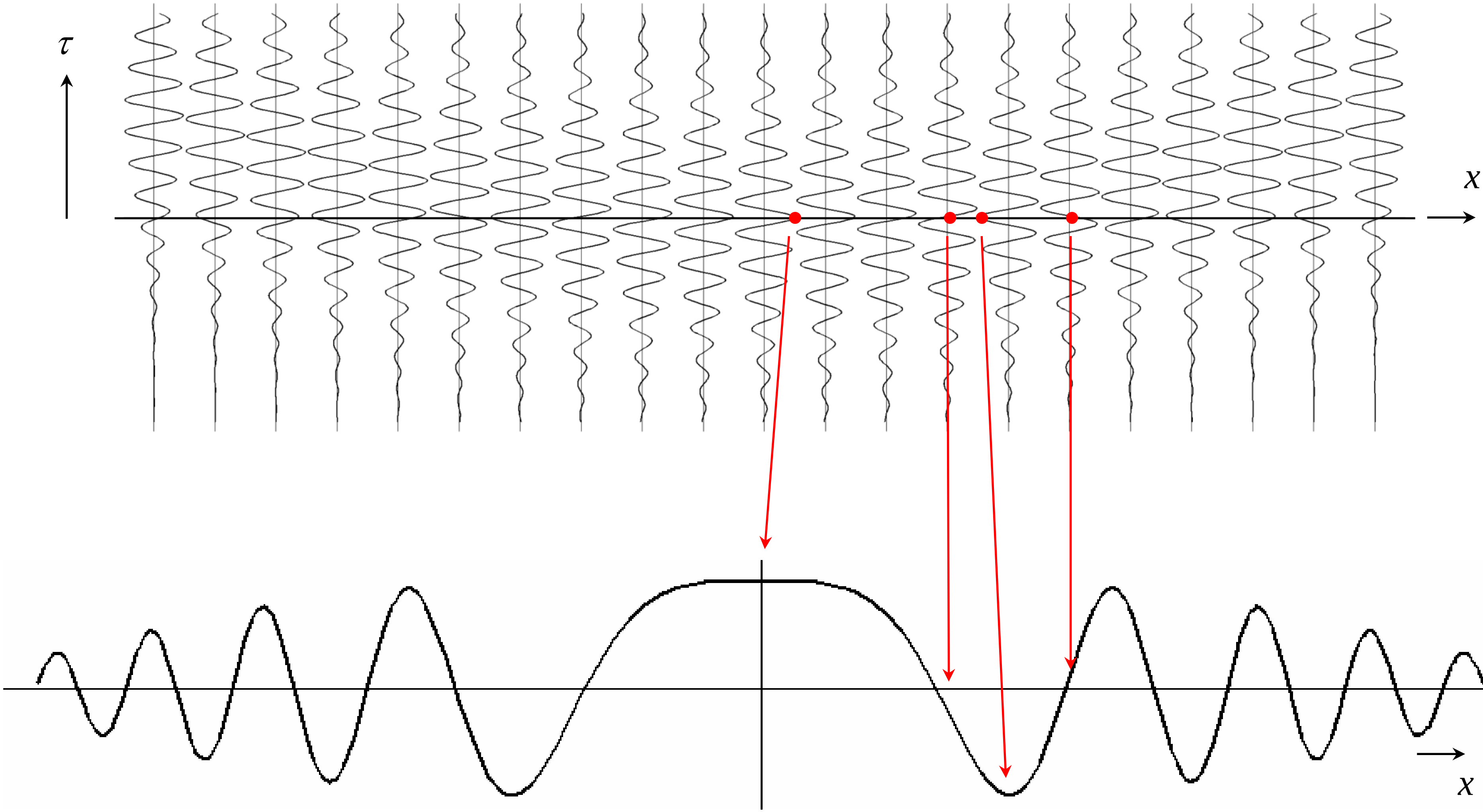


$$R(x) = \sqrt{R_0^2 + x^2} \cong R_0 + \frac{x^2}{2\,R_0}$$

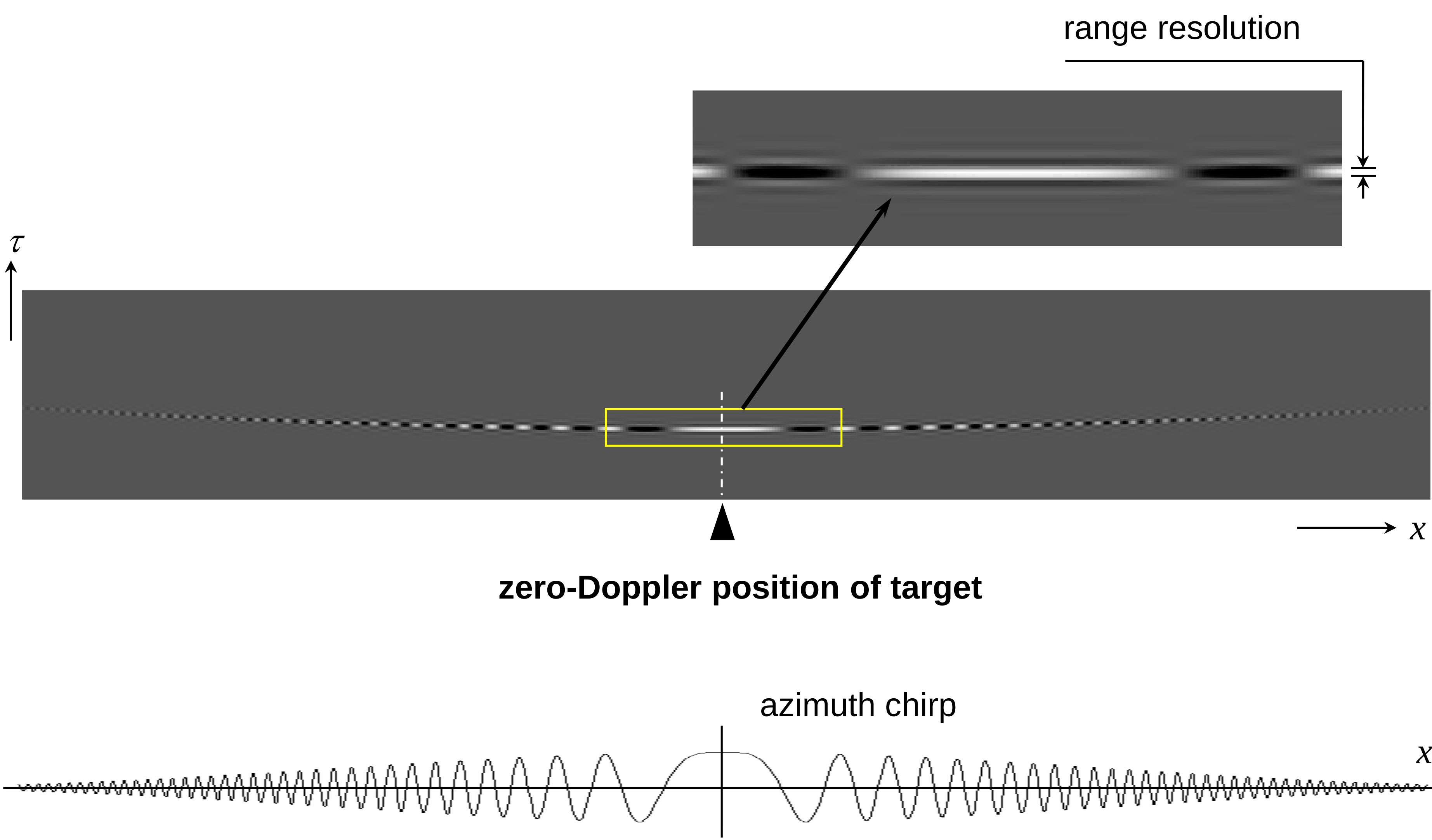
2-D Raw Data Matrix



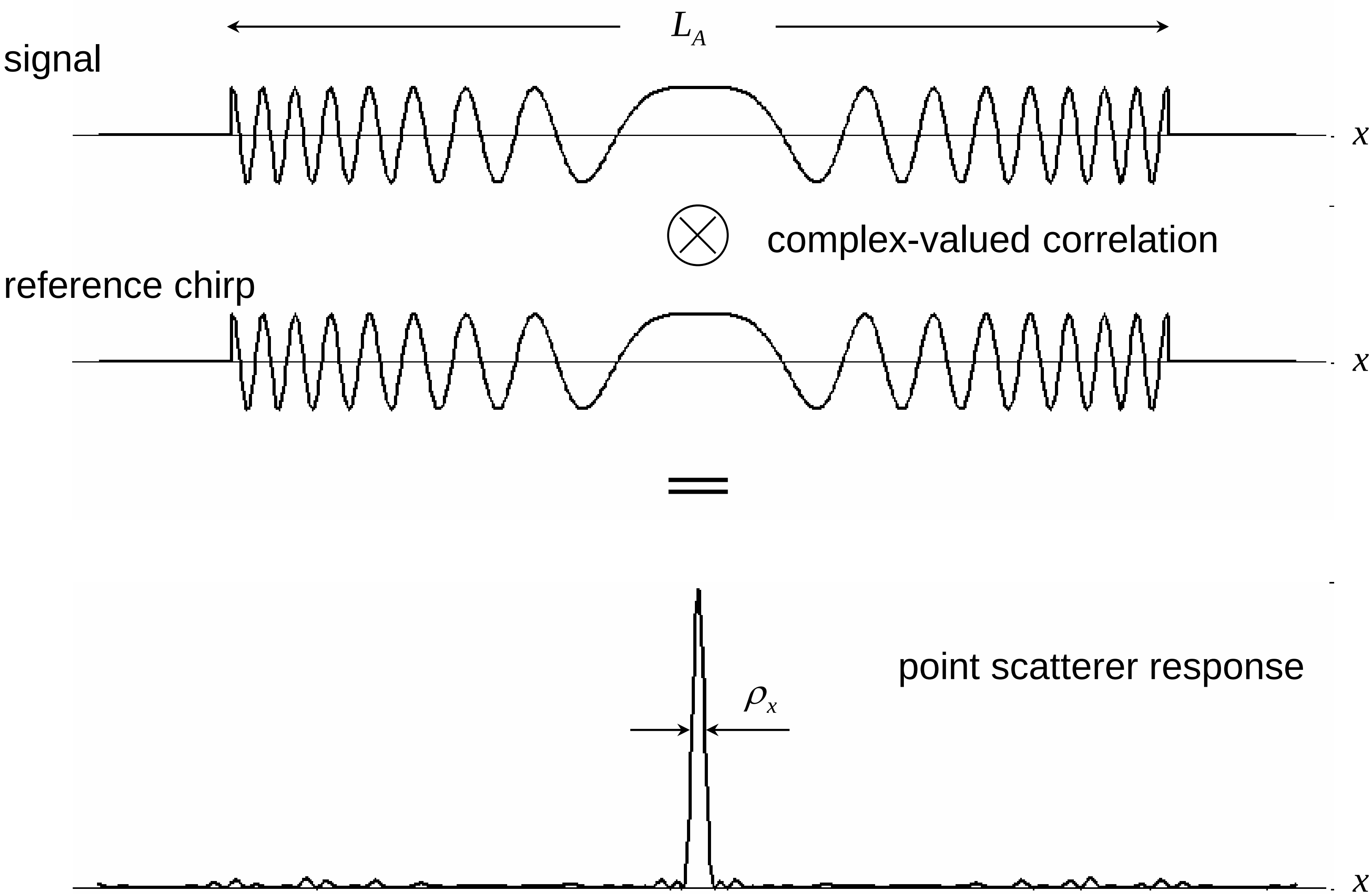
Formation of the Azimuth Chirp Signal



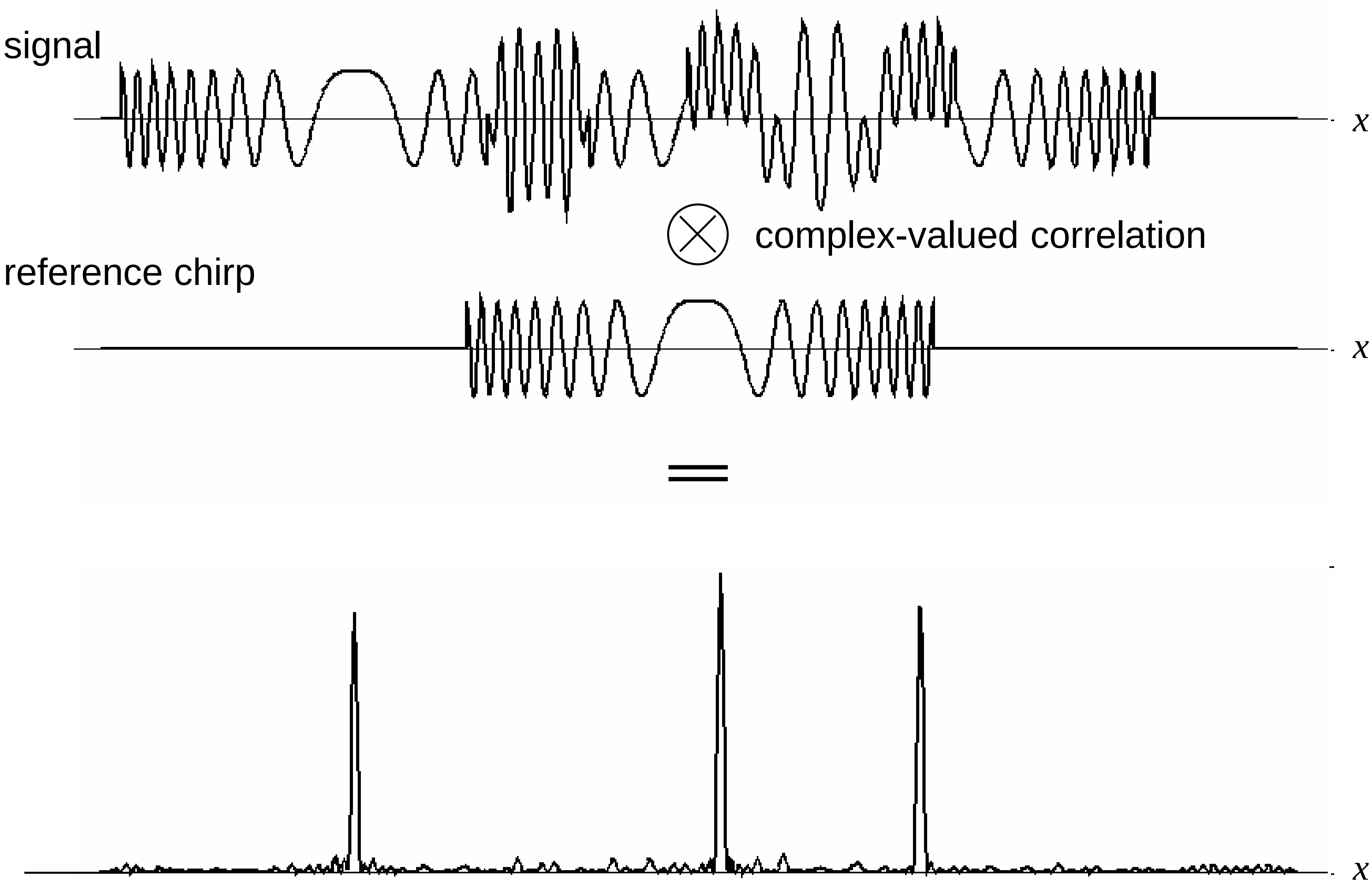
SAR Raw Data of a Point Scatterer (Simulation)



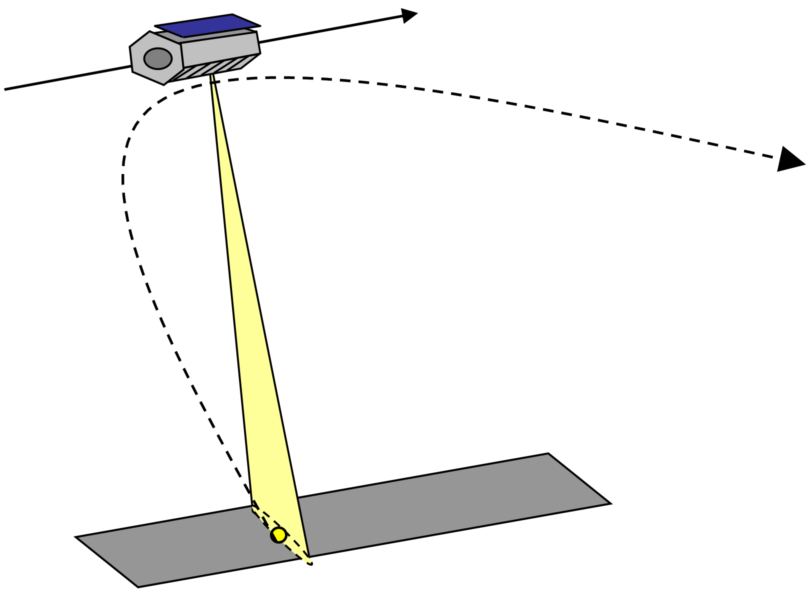
Azimuth SAR Processing by Correlation

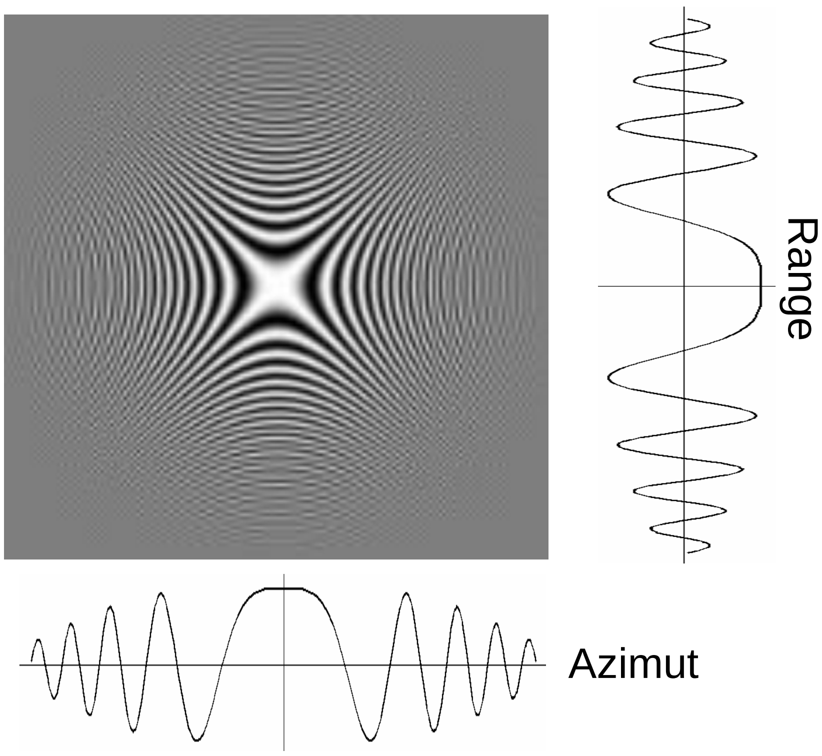


Linear Superposition of Chirps



Unfocussed (Raw) 2D SAR Point Response

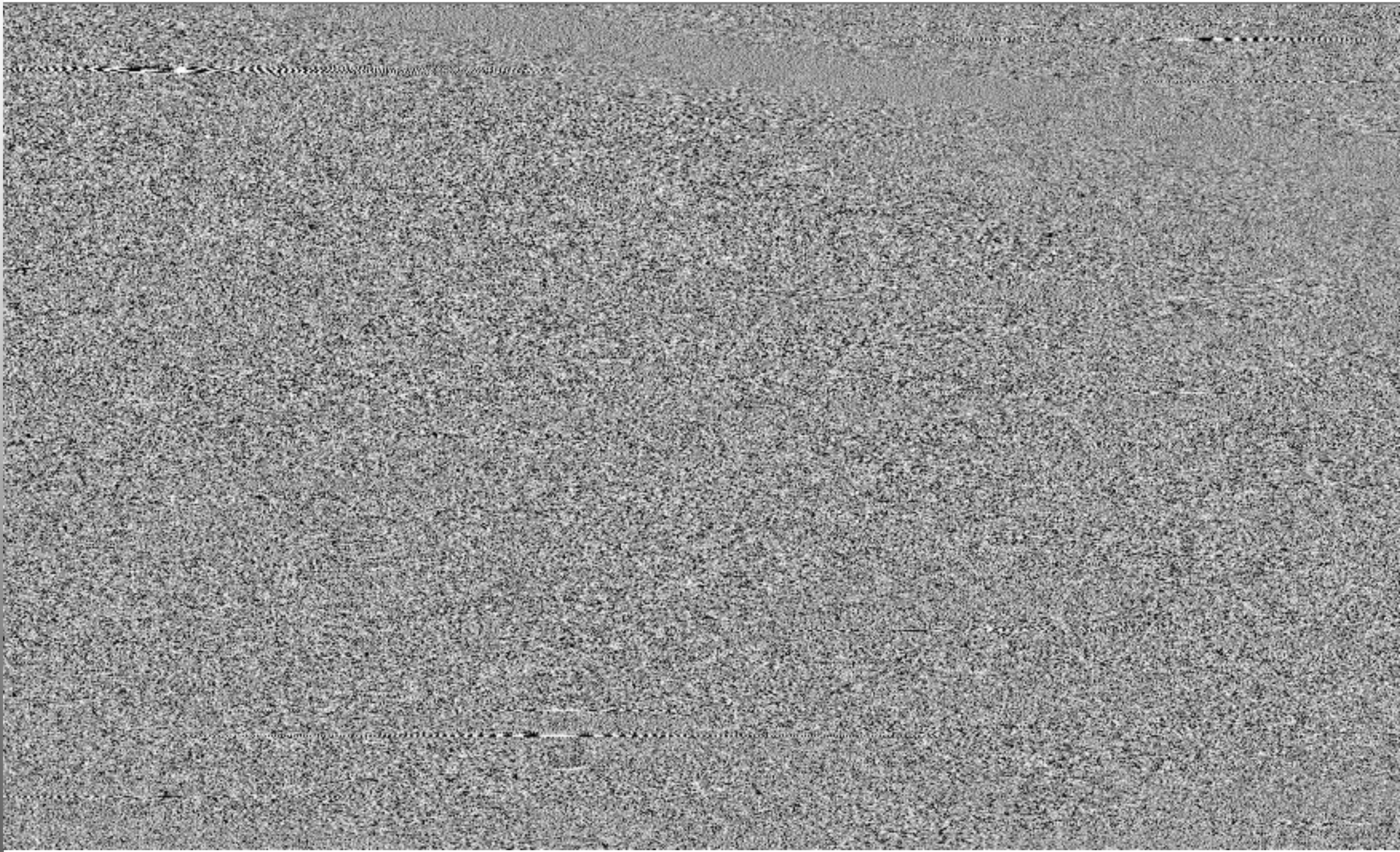




SAR Raw Data (After Range Compression)

→ azimuth

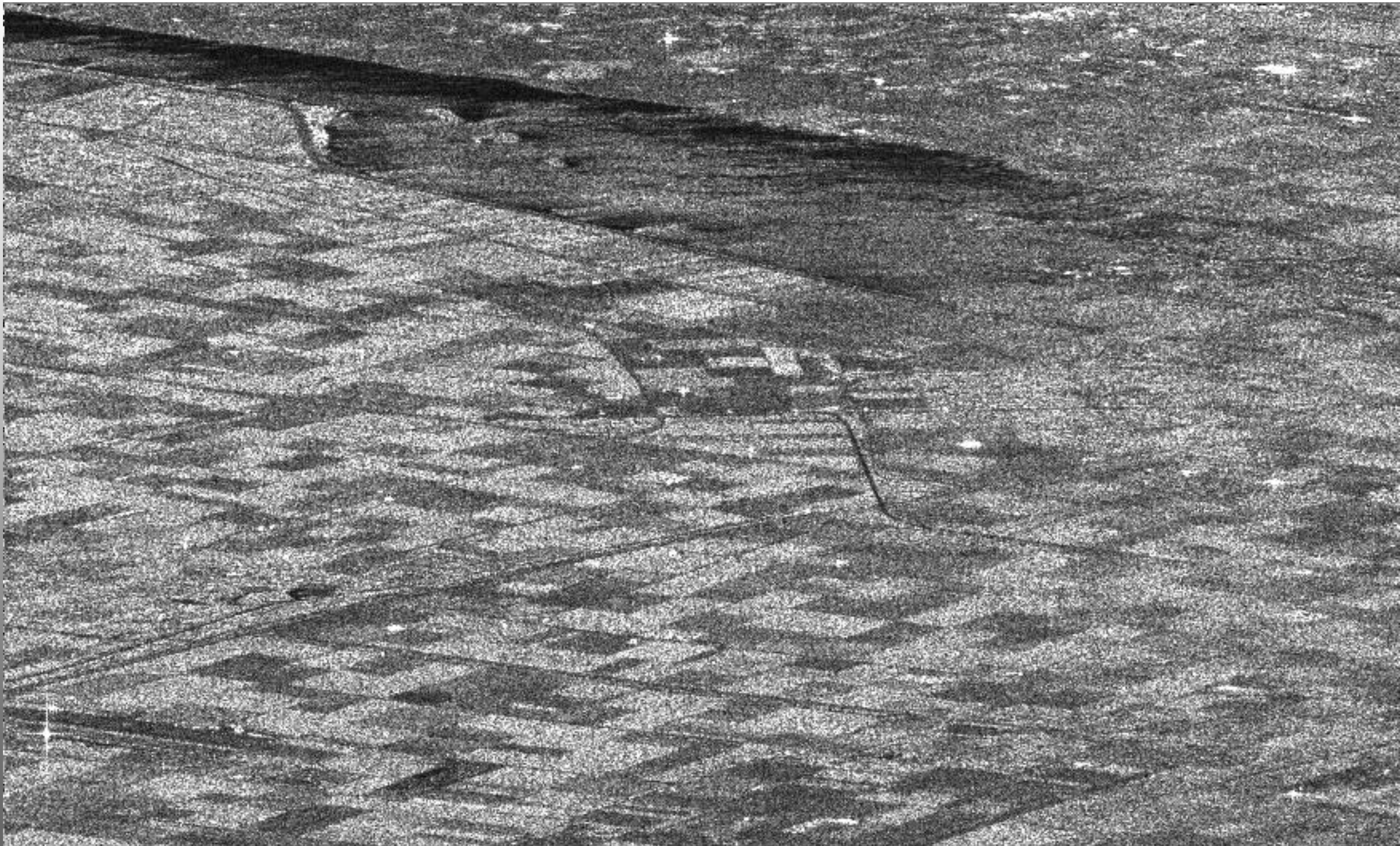
data ERS-1 © ESA



Focussed SAR Data

azimuth

data ERS-1 © ESA



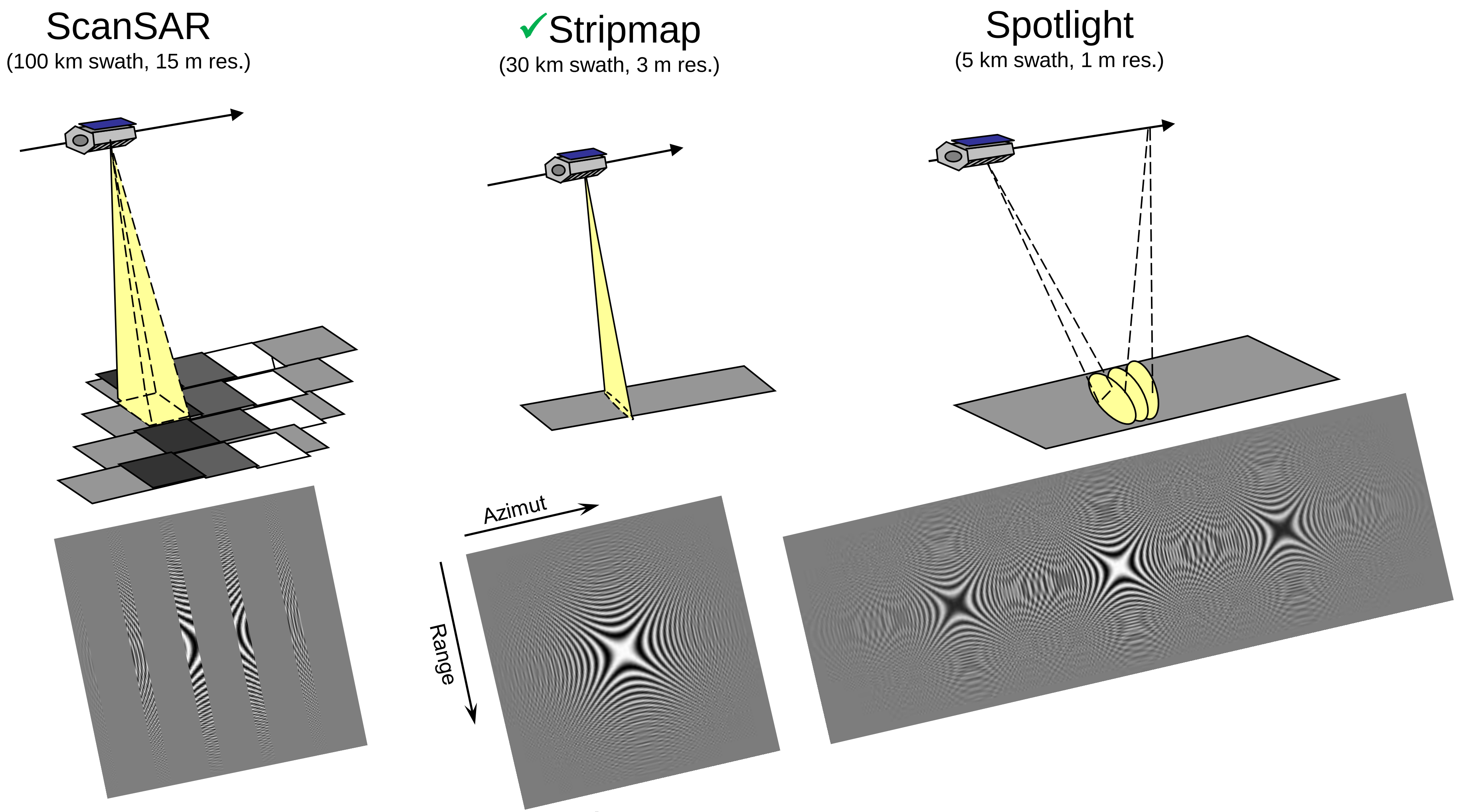
Focussed SAR Data

azimuth

data ERS-1 © ESA

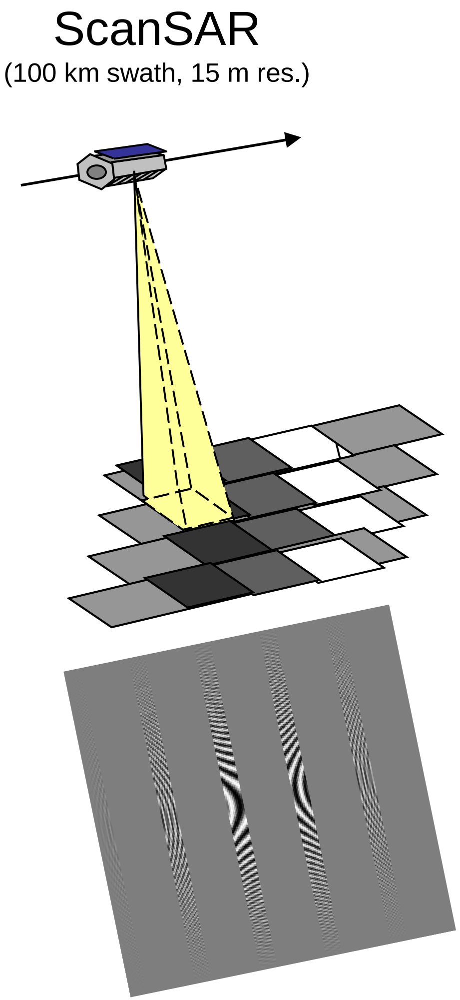
after
azimuth pixel averaging by 4
to achieve approximately
square pixels

Advanced SAR Modes: e.g. TerraSAR-X



Point target response

ScanSAR Mode

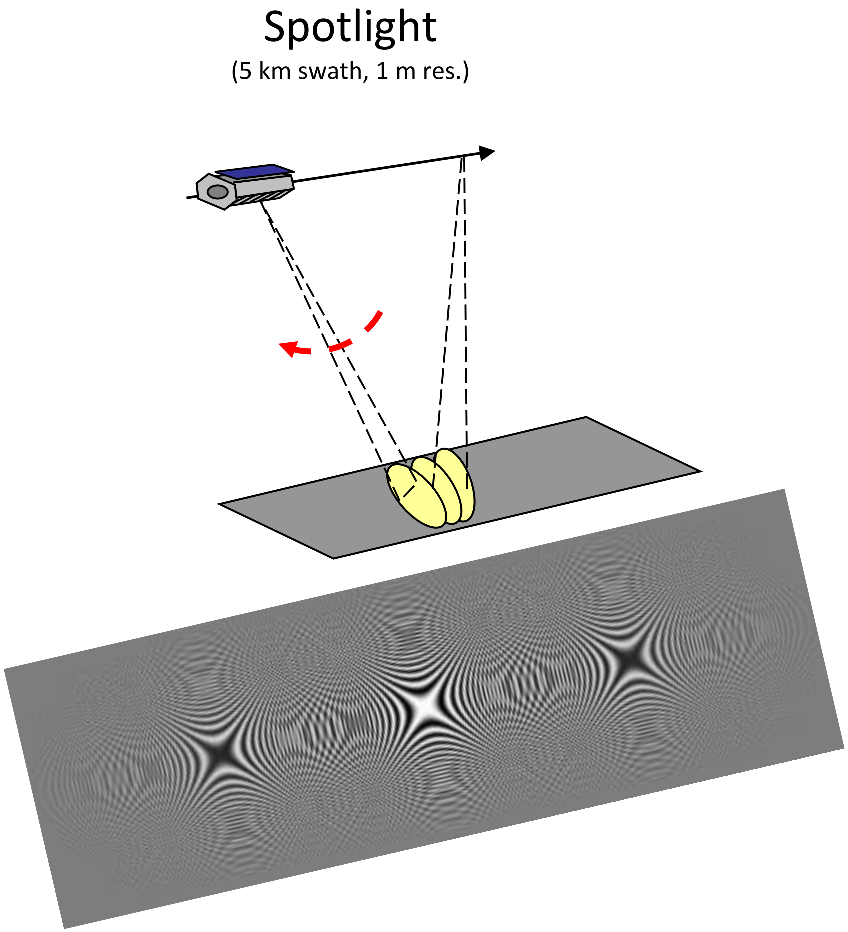


- Periodic switching of antenna elevation look direction:
- Illuminate/receive only part (e.g. ¼) of synthetic aperture with bursts
- Use remaining time to look („Scan“) at other ranges by steering the antenna electronically

→**+** increased swath width (e.g. × 4)

→ **-** reduced resolution (e.g. ÷ 4)

Spotlight Mode

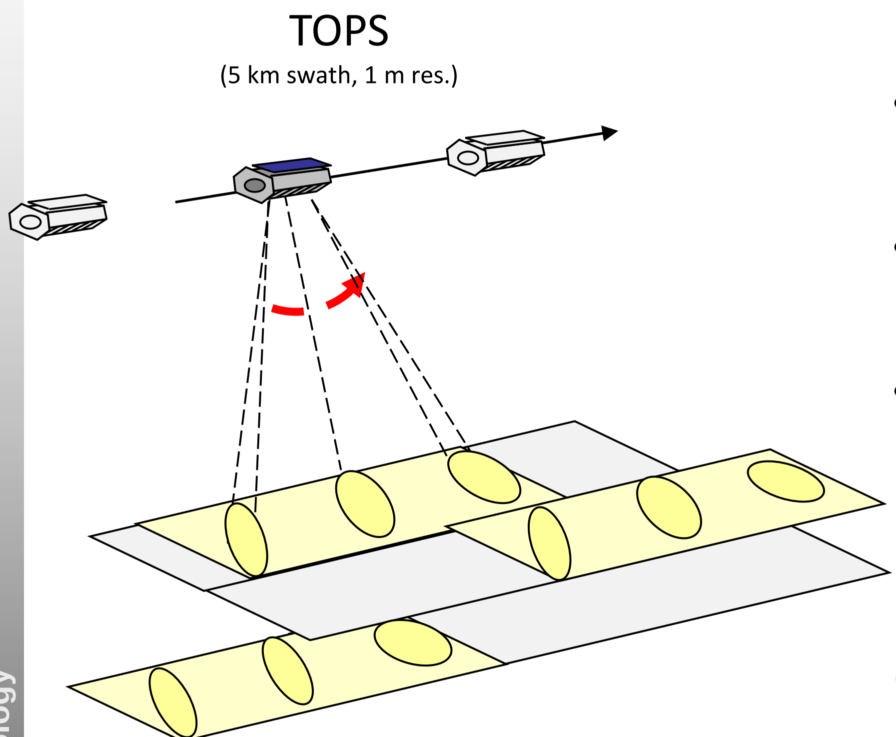


- Increase aperture time by steering the antenna ectronically **backward** in azimuth → longer illumination time, longer chirp
- Higher chirp frequencies & aliasing with PRF need special processing techniques

→ **+** increased resolution (e.g. × 3)

→ **-** continuous operation not possible, limited azimuth image size (e.g. 5 km)

TOPS Mode (e.g. Sentinel-1)



- Reduce aperture time by steering the antenna ectronically **forward** in azimuth
- More azimuth distance, less illumination time per target
- Saved time can be used to electronically steer the antenna to other elevation directions

→increased swath width (e.g. S1: 3 x = 250 km)

→reduced resolution (e.g. S1: 17 m)

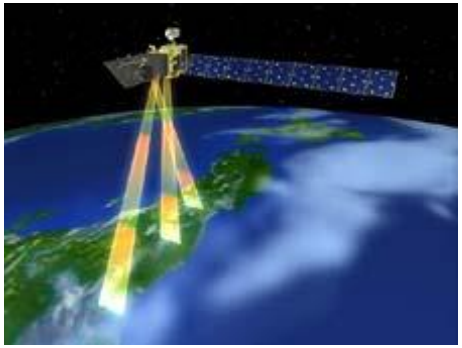
Current and Future Civil Spaceborne SARs

satellite	owner	band	resolution	look angle	swath	lifetime
ERS-1	ESA	C	25 m	23°	100 km	1991-2000
ERS-2	ESA	C	25 m	23°	100 km	1995-2012
Radarsat-1	Canada	C	10 m - 100 m	20°- 59°	50 - 500 km	1995-2013
ENVISAT	ESA	C	25 m - 1 km	15°- 40°	100 - 400 km	2002-2012
ALOS	Japan	L	10 m -100 m	35°- 41°	70 - 360 km	2006-2011
Cosmo	Italy	X	ca. 1 m - 16 m	…	…	2007-
TerraSAR-X & TanDEM-X	Germany	X	1 m - 16 m	15°- 60°	10 - 100 km	2007/2010-
Radarsat-2	Canada	C	3 m - 100 m	15°- 59°	10 - 500 km	2007-
ALOS-2	Japan	L	3 m – 100 m	8°-70°	25 – 350 km	2014?-
Sentinel-1a/b	ESA	C	5 m – 50 m	20°-46°	20 - 400 km	‘14/’16-

Sentinel-1A

Antarctica Peninsula from Sentinel-1A
Data © ESA

L-Band Systems: ALOS, ALOS-2



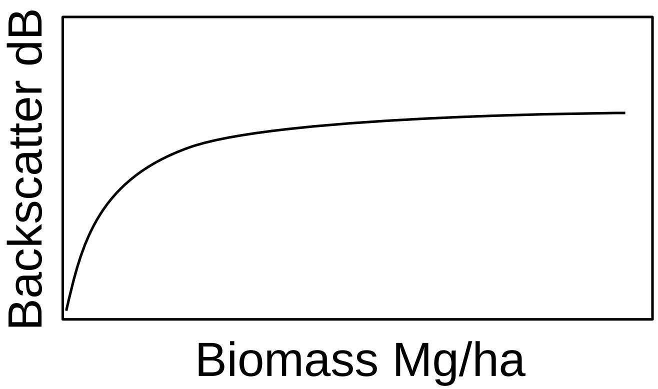
(image: © JAXA)

Observation parameter	**ALOS (launch 2006)**	**ALOS-2 (launch 2014)**
Observation frequency	- Revisit time: 46 days	- Revisit time: 14 days
	-Daytime observation is limited by sharing with optical observation	- No conflict
	- Incidence angle : 8-60º - Right-side looking	- Incidence angle: 8-70º - **Right- or left-side looking observation capability**
Spatial resolution	- Strip map: 10 m - ScanSAR: 100 m	- Strip map: 3 m /6 m /10 m - ScanSAR: 100 m - Spotlight: 1 m x 3 m

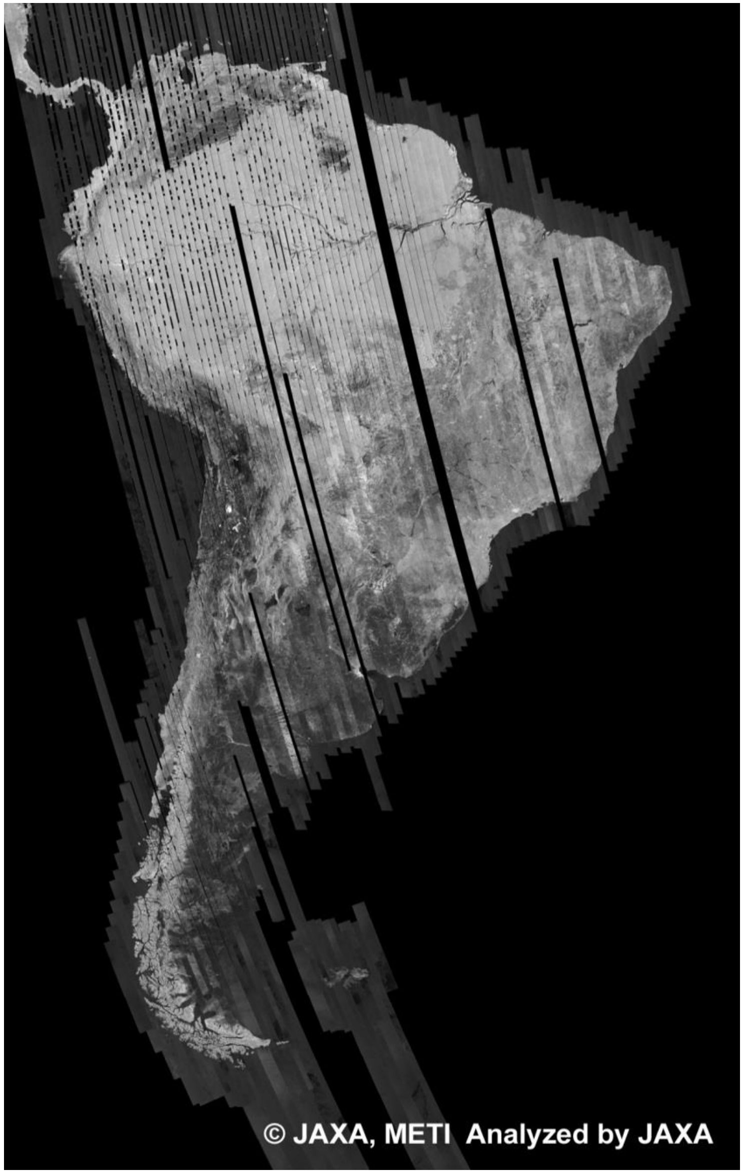
Biomass Mapping with ALOS – PALSAR

500m Browse Mosaic of South America
(FBS/HH Ascending)
for cycle40 (Dec. 16, 2010 ~ Jan. 30, 2011)

→ Forest / biomass mapping



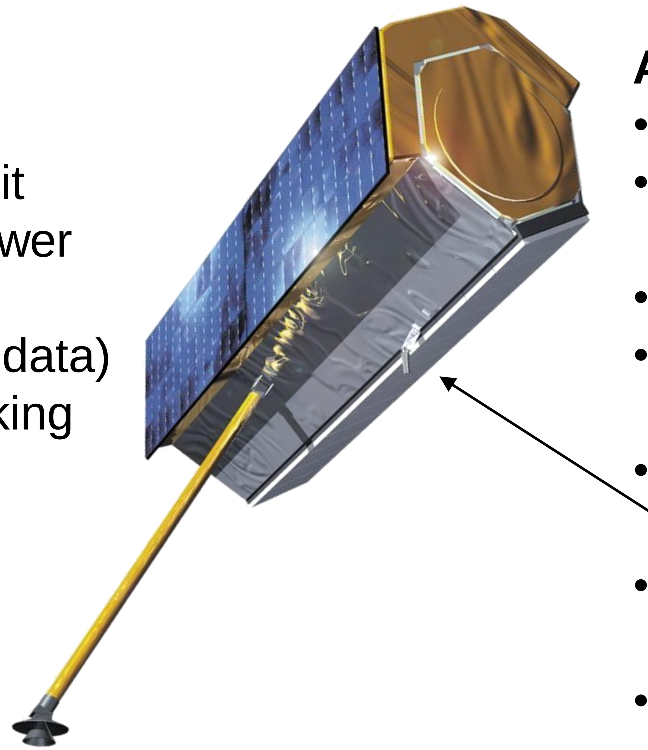
From: http://www.eorc.jaxa.jp/ALOS/en/img_up/mosaic_500_c40.htm



Remote Sensing Technology

TerraSAR-X Satellite

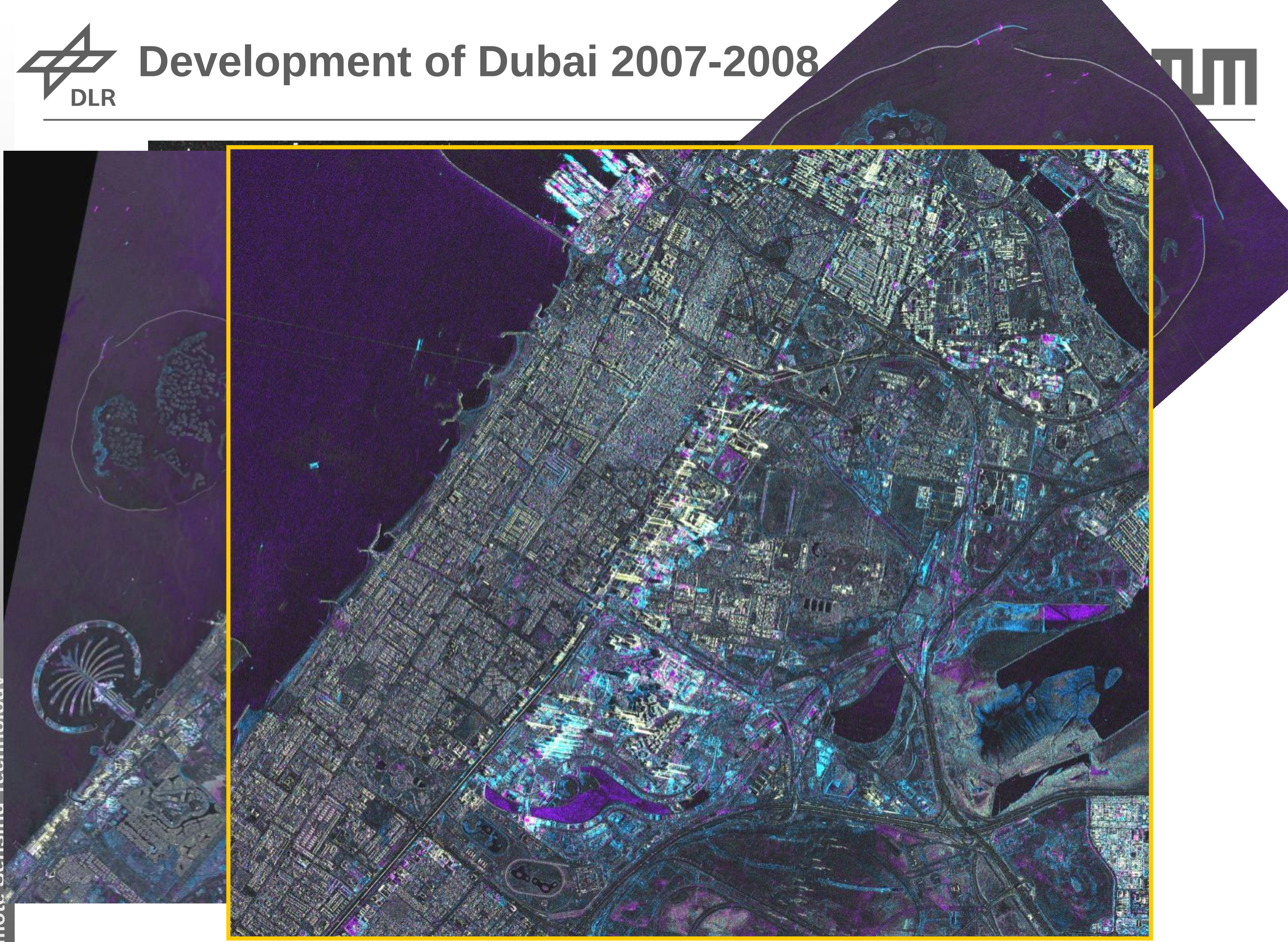
Satellite
- 514 km altitude
- 11 days repeat orbit
- 800 W average power
- 320 Gbit memory
  (600 s of stripmap data)
- Rollable to left looking



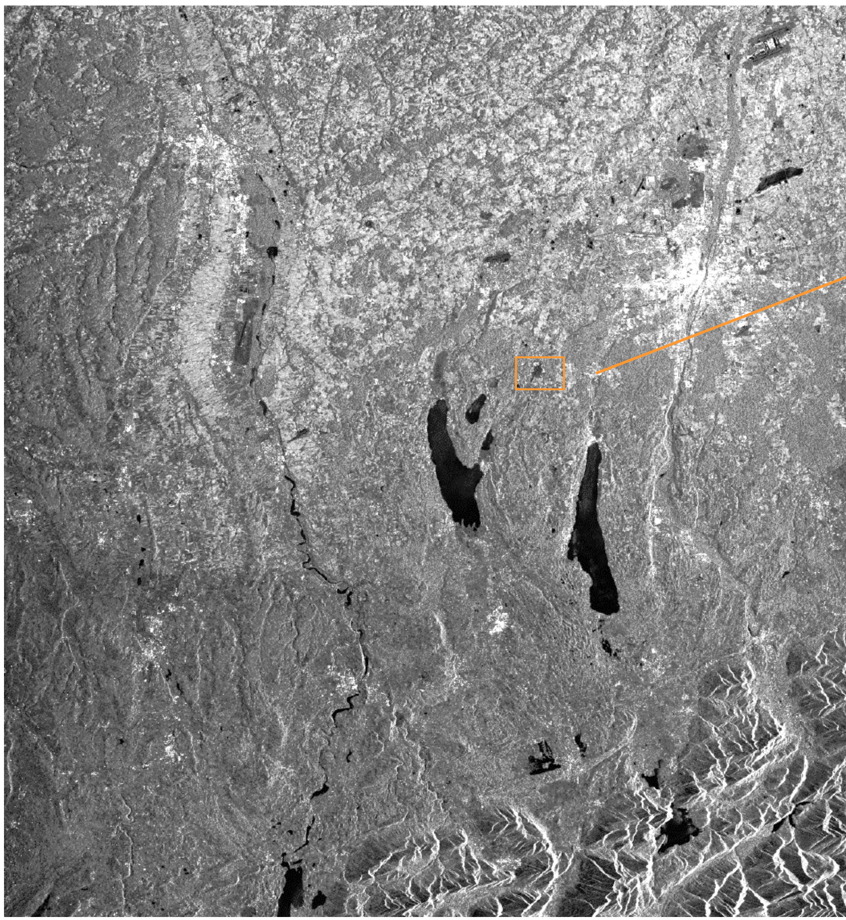
300 MBit/s downlink

Active array SAR antenna
- 384 sub-arrays
- 150 MHz bandwidth (300 MHz)
- right looking
- >100 elevation beams
  - ScanSAR
- > 100 azimuth beams
  - Spotlight
- transmit and receive in H or V
  - Dual polarization
- experimental dual receive antenna & redundant receiver
  - Quad polarization
  - GMTI

Development of Dubai 2007-2008



Application: Mapping of Urban Areas



ENVISAT / ASAR IM 2 Oberpfaffenhofen 100 km x 100 km;
25 m resolution (© ESA)

TerraSAR-X Spotlight Image
2 m resolution

Synthetic Aperture Radar (SAR)

5.1 Introduction

5.2 Radar Distance Measurement (Range-Component)

5.3 Formation of Synthetic Aperture (Azimuth-Component)

5.4 Characteristics of SAR Images

5.4.1 Radiometric and Backscatter Characteristics

5.4.2 Geometric Characteristics

SAR Image Characteristics

azimuth

range

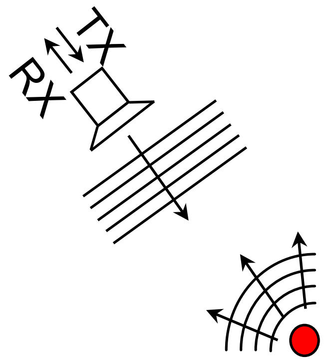
ERS-1 data © ESA

Issues:

- resolution (shape of point scatterer response)
- radiometry
- geometry
- polarimetry
- artifacts

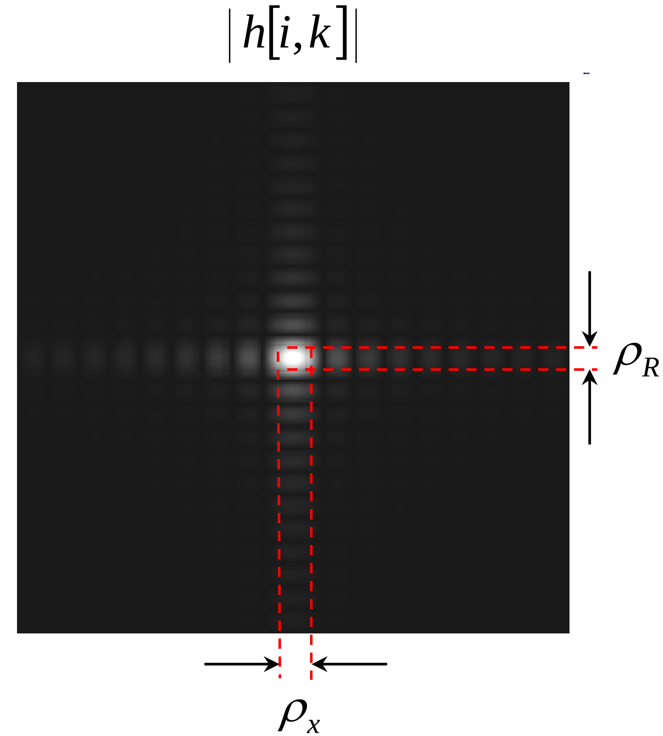
SAR Image Point Scatterer Response

point scatterer



size << $\rho_{x,R}$

SAR image of point scatterer (simulated)

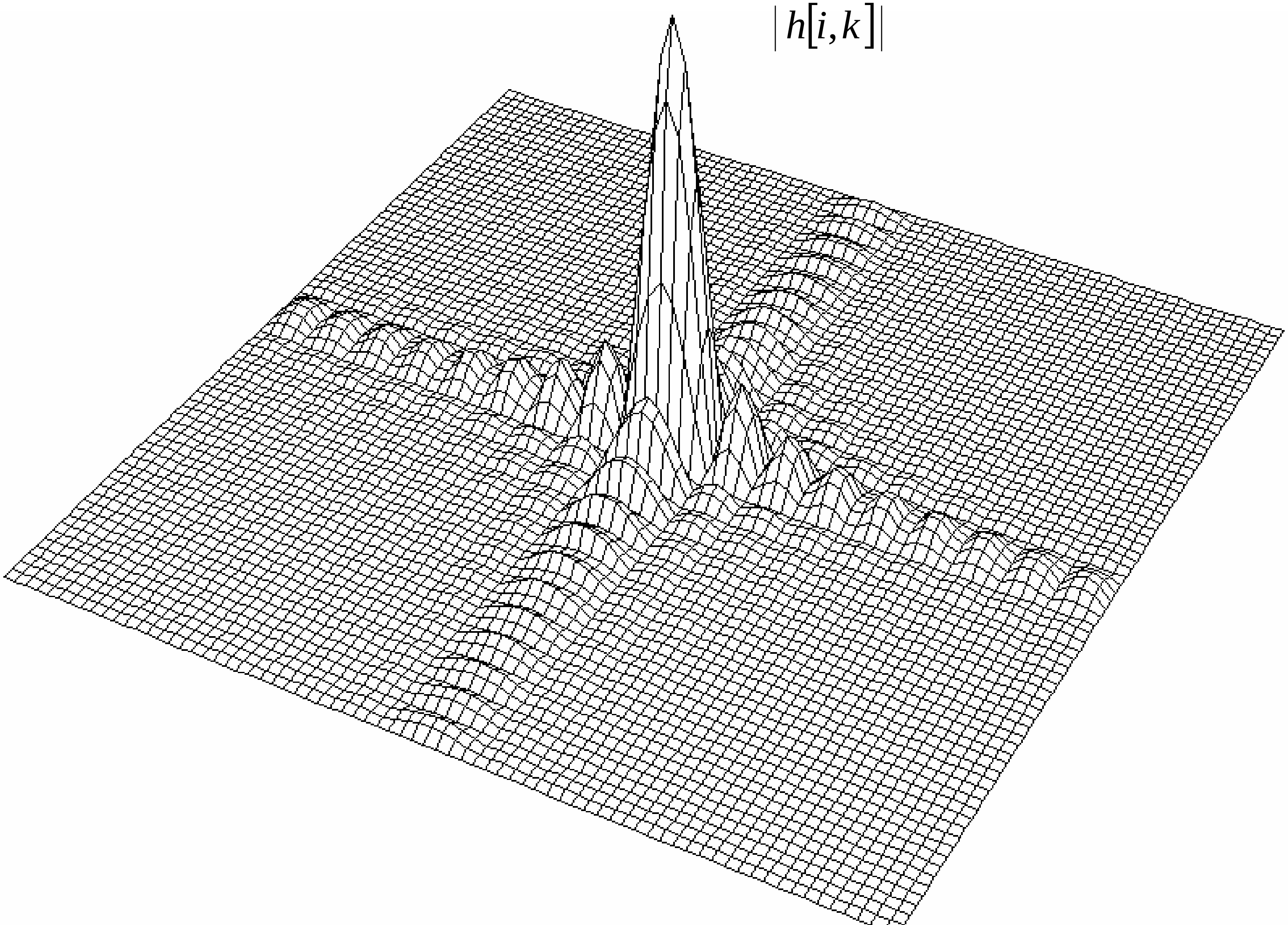


radar cross section: $\sigma \quad [m^2] \quad \text{or} \quad [dBm^2]$

energy: $\Delta x \, \Delta R \times \sum_i \sum_k |h[i,k]|^2 \propto \sigma$

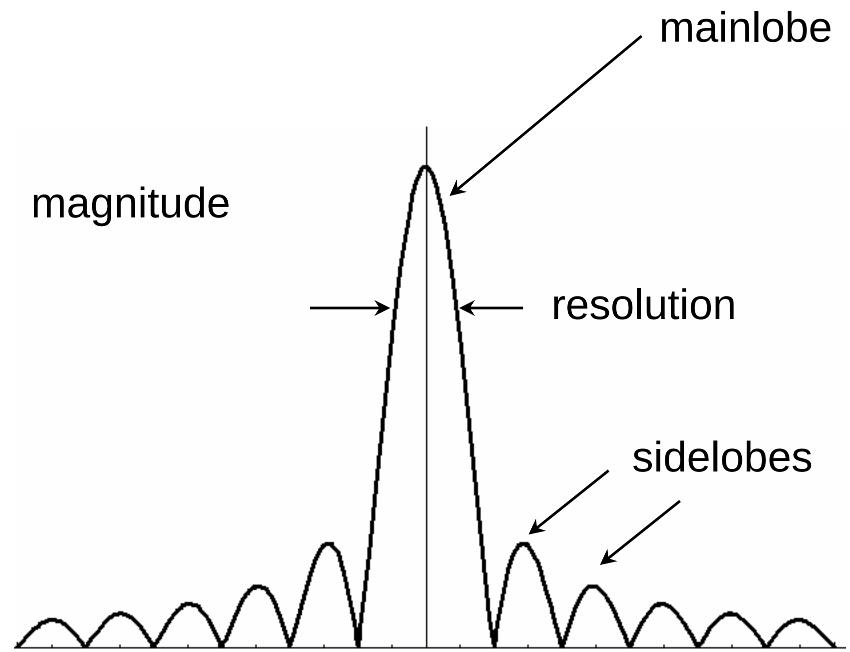
phase at peak: $\phi = -\frac{4\pi}{\lambda} R + \phi_{scat}$

3-D View of Point Response Function



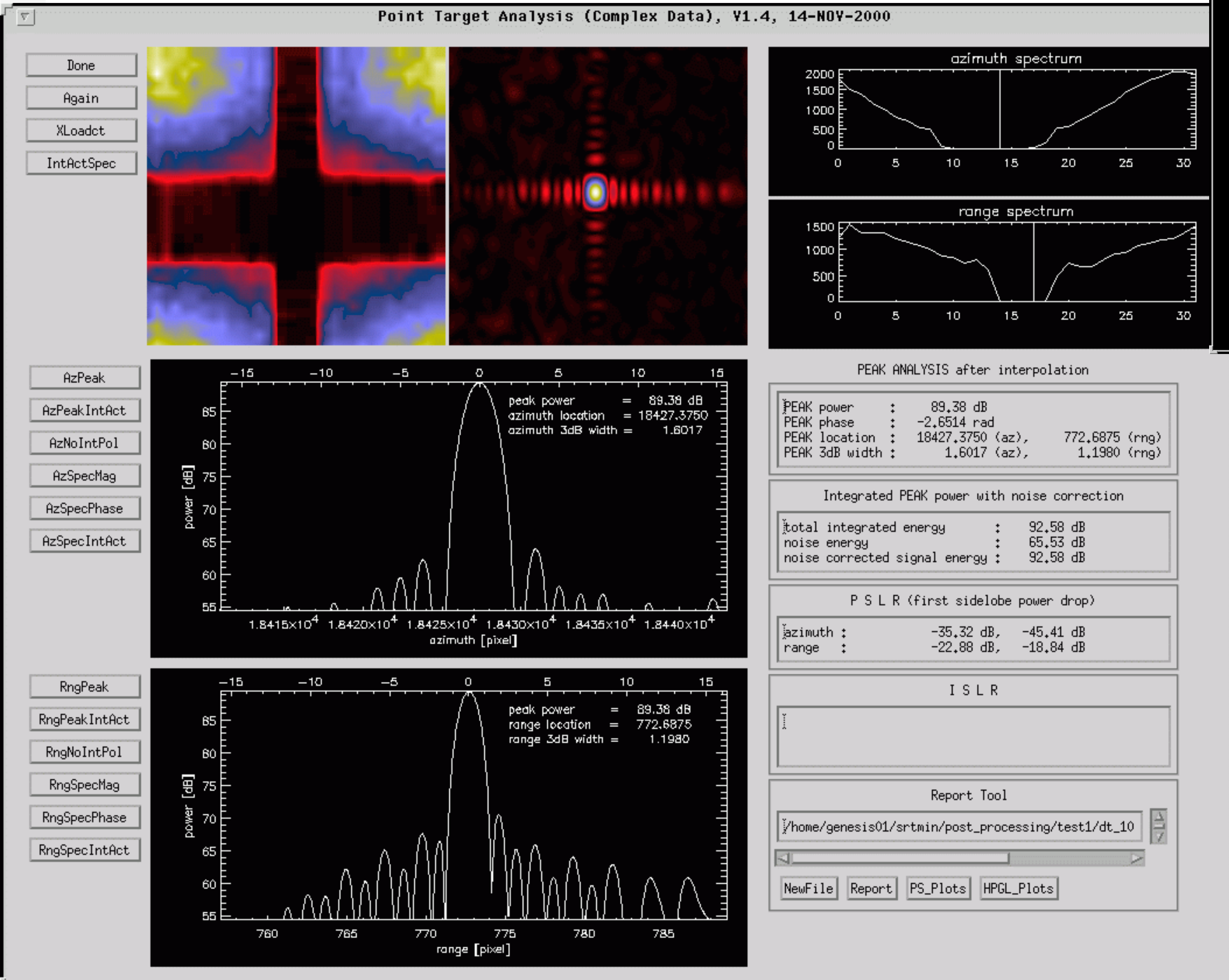
Characteristics of Point Scatterer Response

- resolution = width of mainlobe, often defined as 3dB-width (half power)
- location accuracy
- sidelobe structure:
  - PSLR: peak-sidelobe-ratio
  - ISLR (1-D or 2-D): integrated sidelobe-ratio, ratio of energy in sidelobes to energy in mainlobe
- phase at peak



1-D cut through 2-D point response function

Example of a SAR Point Target Analysis Tool



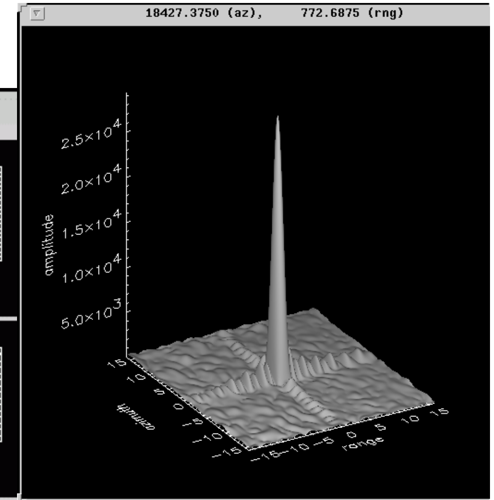


Image Analysis Software

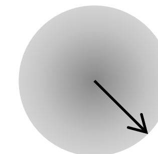
DLR

Radar Cross Section of Single Scatterers

- Metal sphere:

e.g. R=1 m → σ=3.1 m²

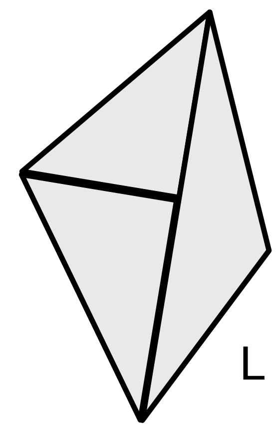
$$\sigma = R^2 \pi \quad \left[m^2\right] \longleftrightarrow$$



- Corner reflector:

e.g. L=1 m, λ=5.6 cm →σ=74 m²

$$\sigma = \frac{4\pi\, L^4}{3\,\lambda^2} \quad \left[m^2\right] \longleftrightarrow$$



Backscatter of Distributed Objects

- Natural scenes (rough surfaces, vegetation) contain ‘many‘ scatterers in every resolution element (often referred to as “clutter”).
- scatterer density = normalized radar cross section or **backscatter coefficient “sigma naught”**:

$$\sigma^0 = \frac{\sum\limits_{n \in \text{area}} \sigma_n}{\text{area}} \qquad \left[\frac{m^2}{m^2}\right]$$

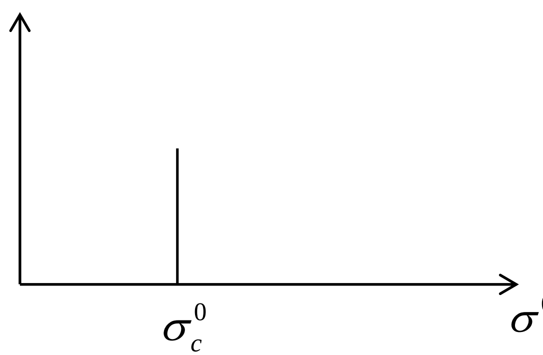
e.g. cornfield

$\sigma_c^0 = -10dB$

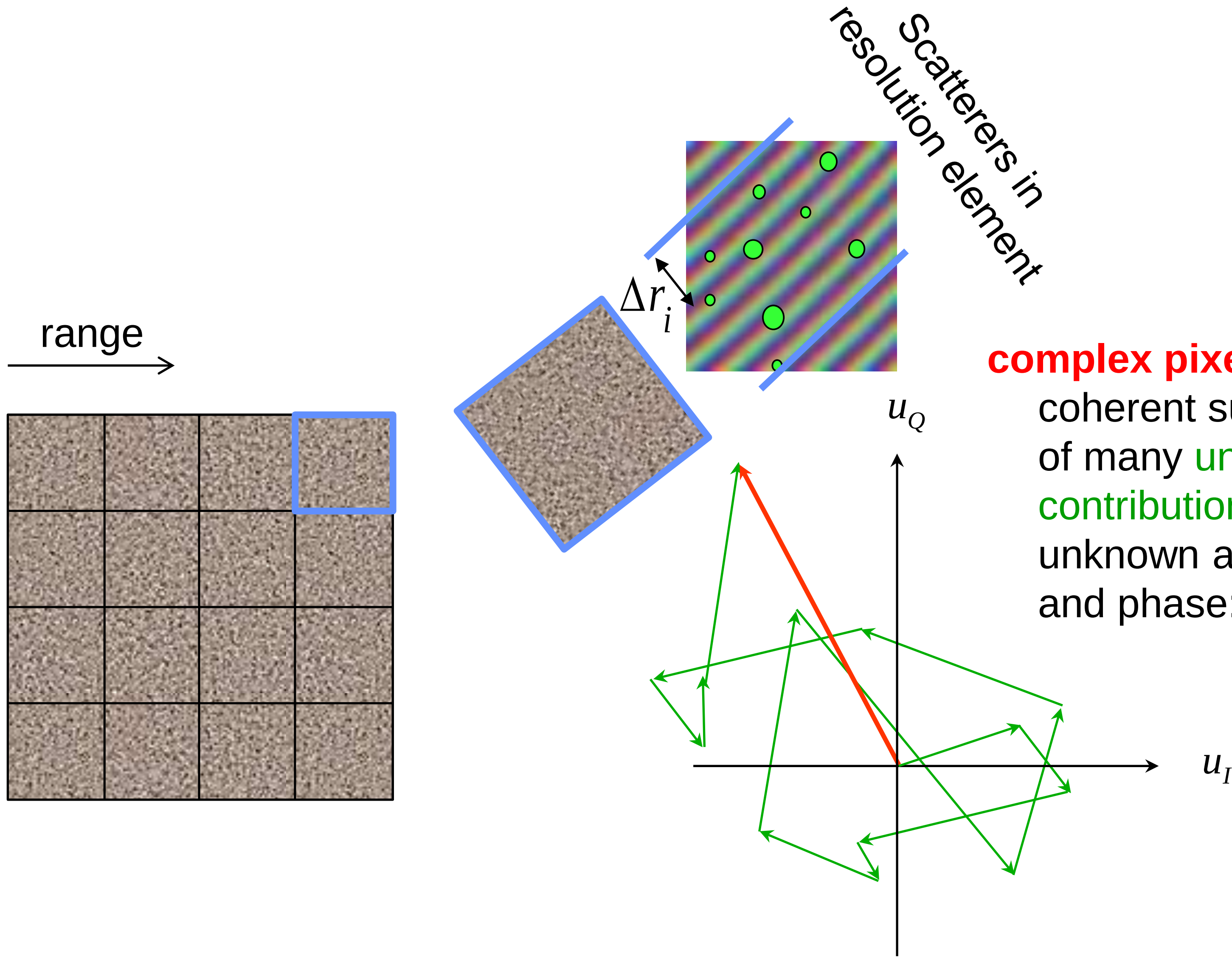
σ_c^0	σ_c^0	σ_c^0	σ_c^0
σ_c^0	σ_c^0	σ_c^0	σ_c^0
σ_c^0	σ_c^0	σ_c^0	σ_c^0
σ_c^0	σ_c^0	σ_c^0	σ_c^0

Resolution cells

Ideal Histogram

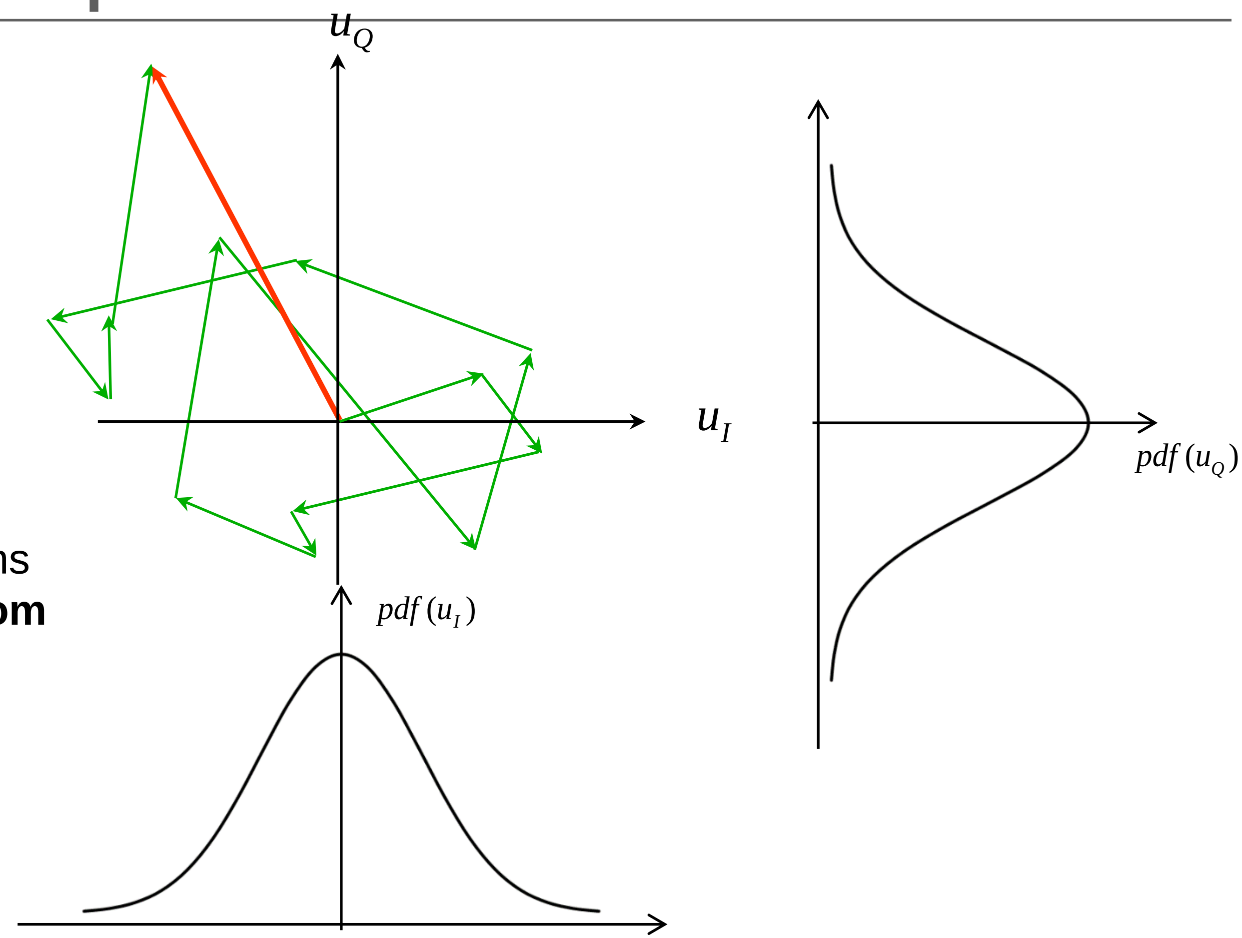


Speckle Effect within Resolution Element



complex pixel value =
coherent summation of many uncorrelated contributions of unknown amplitude and phase:

Speckle Statistics



large number of contributions
→**circular Gaussian random process**

- u_I and u_Q are zero-mean mutually uncorrelated Gaussian processes, where :

$$E\{\, u_I^2 + u_Q^2 \,\} \propto \sigma^0$$

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Consequences of Speckle Statistics

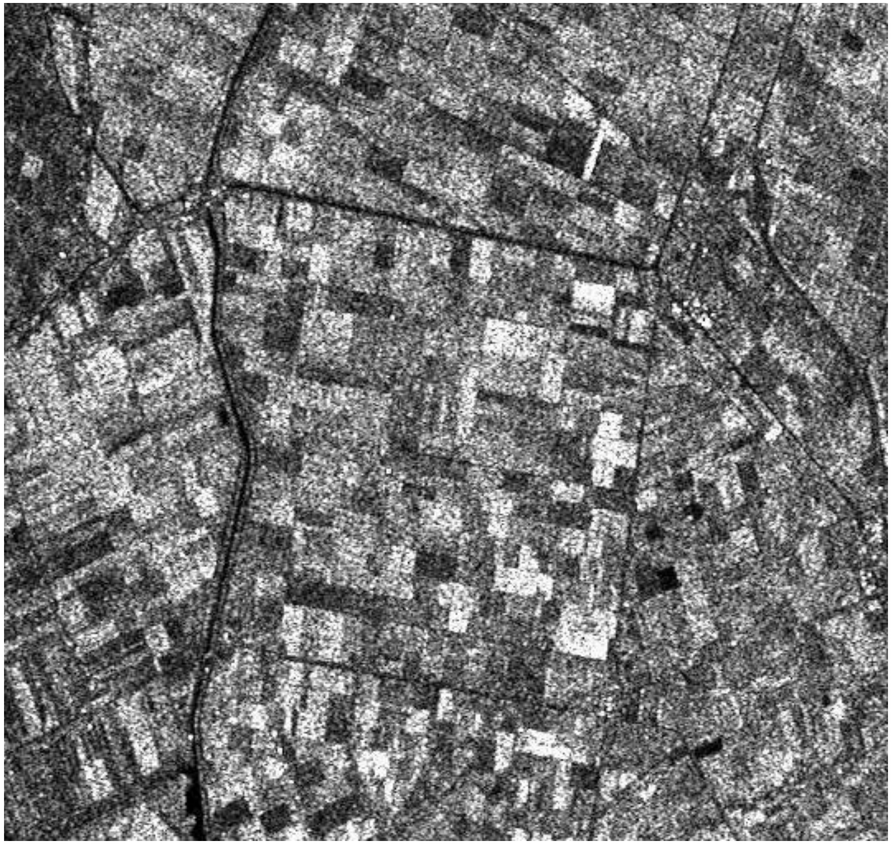
Random positive and negative interference of wave contributions from many individual scatterers within one resolution cell →

- varying brightness from pixel to pixel even for constant σ^0

$\Rightarrow$ granular appearance

- random equal distribution of phase:

$$\boxed{\phi_{scatt}} = \arg\left\{\sum A_i e^{\boxed{-j\frac{4\pi\Delta r_i}{\lambda}}}\right\}$$



ERS data © ESA

Speckle Intensity Statistics

	magnitude	intensity
quantity ⇨	$\sqrt{u_I^2 + u_Q^2}$	$I = u_I^2 + u_Q^2$
probability distribution ⇨	**Rayleigh**	**exponential**

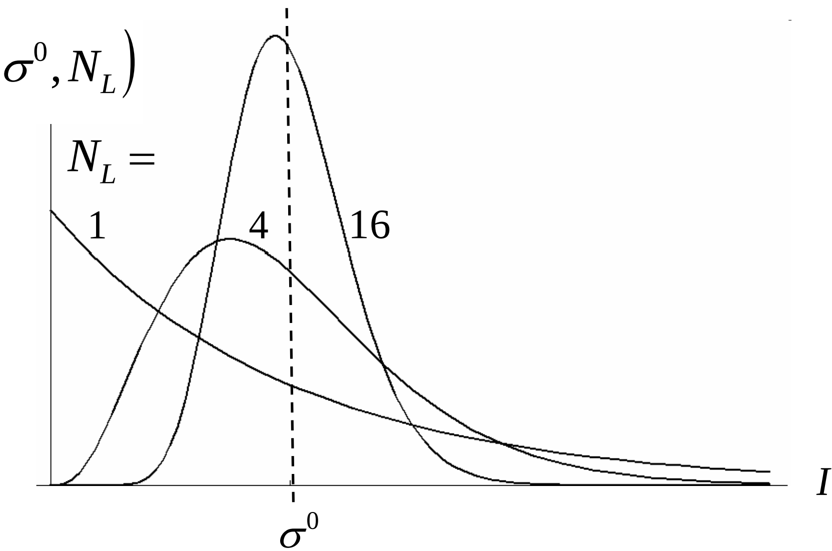
$$pdf_I\left(I \middle| \sigma^0\right) = \frac{1}{\sigma^0} \exp\left\{-\frac{I}{\sigma^0}\right\}$$

averaging of N_L independent samples (looks)

$$pdf_I\left(I \middle| \sigma^0, N_L\right) = \frac{I^{N_L - 1} {N_L}^{N_L}}{\Gamma(N_L)\sigma^{0 N_L}} \exp\left\{-\frac{I\, N_L}{\sigma^0}\right\}$$

Gamma function $\left(\Gamma(x+1) = x \cdot \Gamma(x)\right)$

$pdf_I\left(I \middle| \sigma^0, N_L\right)$



$N_L = 1 \;\Rightarrow\;$ standard deviation = mean !

Speckle Reduction

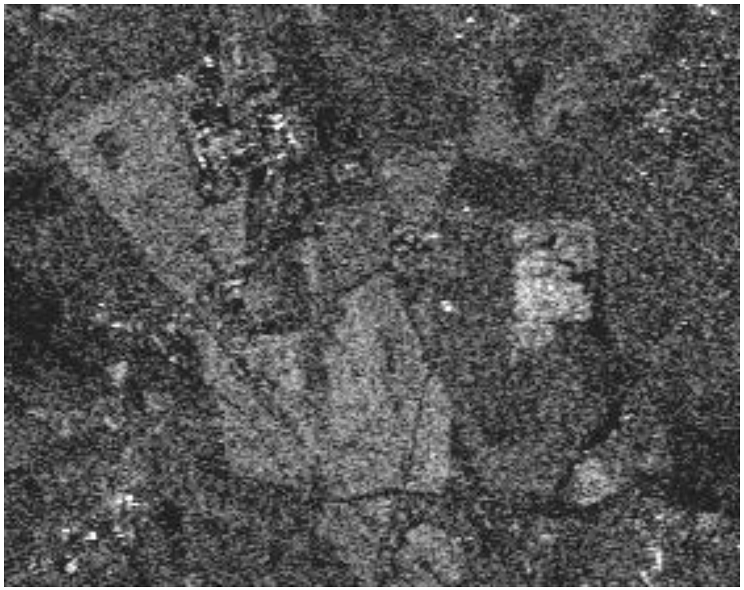
- speckle "masks" underlying σ^0-image

- speckle reduction = estimation of σ^0
  - $\Rightarrow$ assumptions (models) about the structure of σ^0 are required to separate it from speckle (Maximum A Posteriori estimation: MAP)

- optimum speckle reduction for simple model: σ^0 = const.:
  - averaging of adjacent pixels (box filter) or **multi-looking** $\Rightarrow$ **loss of resolution**

- more complex models (try to limit resolution degradation):
  - σ^0 Γ-distributed $\Rightarrow$ Gamma-Gamma-MAP filter
  - Gibbs random fields for describing textures
  - heuristic smoothness criteria $\Rightarrow$ e.g. wavelet denoising
  - full Bayesian approach allows for automatic selection between models of different complexity

Speckle Reduction by Temporal Multilooking (ERS)



L=5 looks
20 x 20 m ground resolution
2 dB radiometric resolution

L=320 looks
20 x 20 m ground resolution
0.3 dB radiometric resolution

Adaptive Speckle Reduction

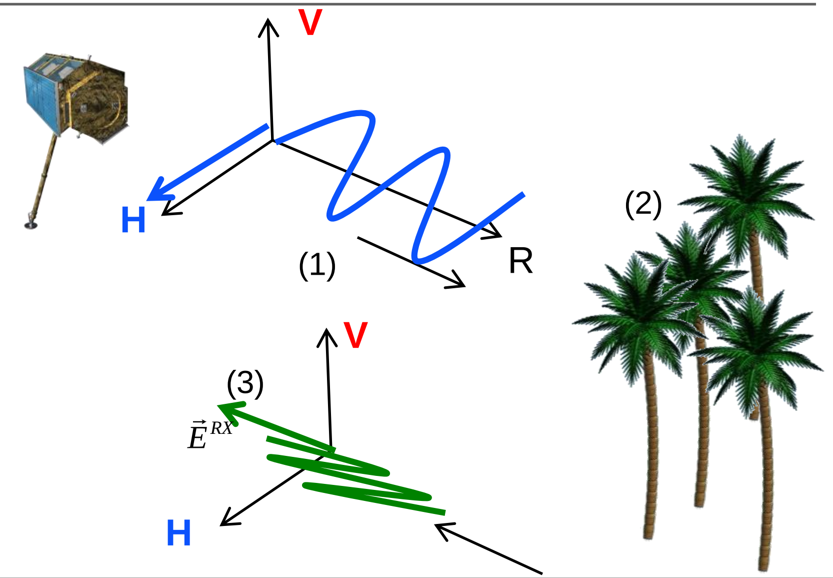
Example for Bayesian method. Others are *Lee* or *Frost* filter.

original SAR image
SAR data © AeroSensing GmbH

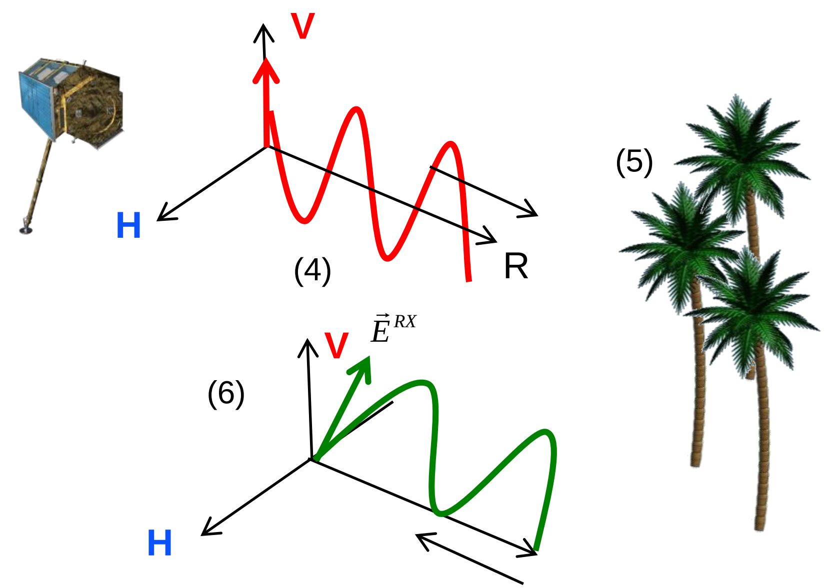
speckle filtered
Bayesian algorithm

SAR Polarimetry (I)

- (1) Sensor transmits horizontally (H) polarized pulse
- (2) H-Pulse is scattered and polarization angle may change
- (3) Sensor receives horizontal and vertical echo components in 2 channels → scattering vector



- (4) Sensor transmits vertically (V) polarized pulse
- (5) V-Pulse is scattered and polarization may change
- (6) Sensor receives horizontal and vertical echo components in 2 channels → scattering vector



SAR Polarimetry (II)

- **Result: 2 x 2 scattering matrix [S]**

$$\begin{bmatrix} E_H^{RX} \\ E_V^{RX} \end{bmatrix} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_H^{TX} \\ E_V^{TX} \end{bmatrix}$$

- **Describes polarimetric signature of scattering object**

- **Examples:**
  - **Single reflection on metallic plate (or odd number of reflections)**

$$S = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

  - **Random scattering of vegetation**

$$S = \begin{bmatrix} a & b \\ b & d \end{bmatrix}$$

Calibration of SAR Systems

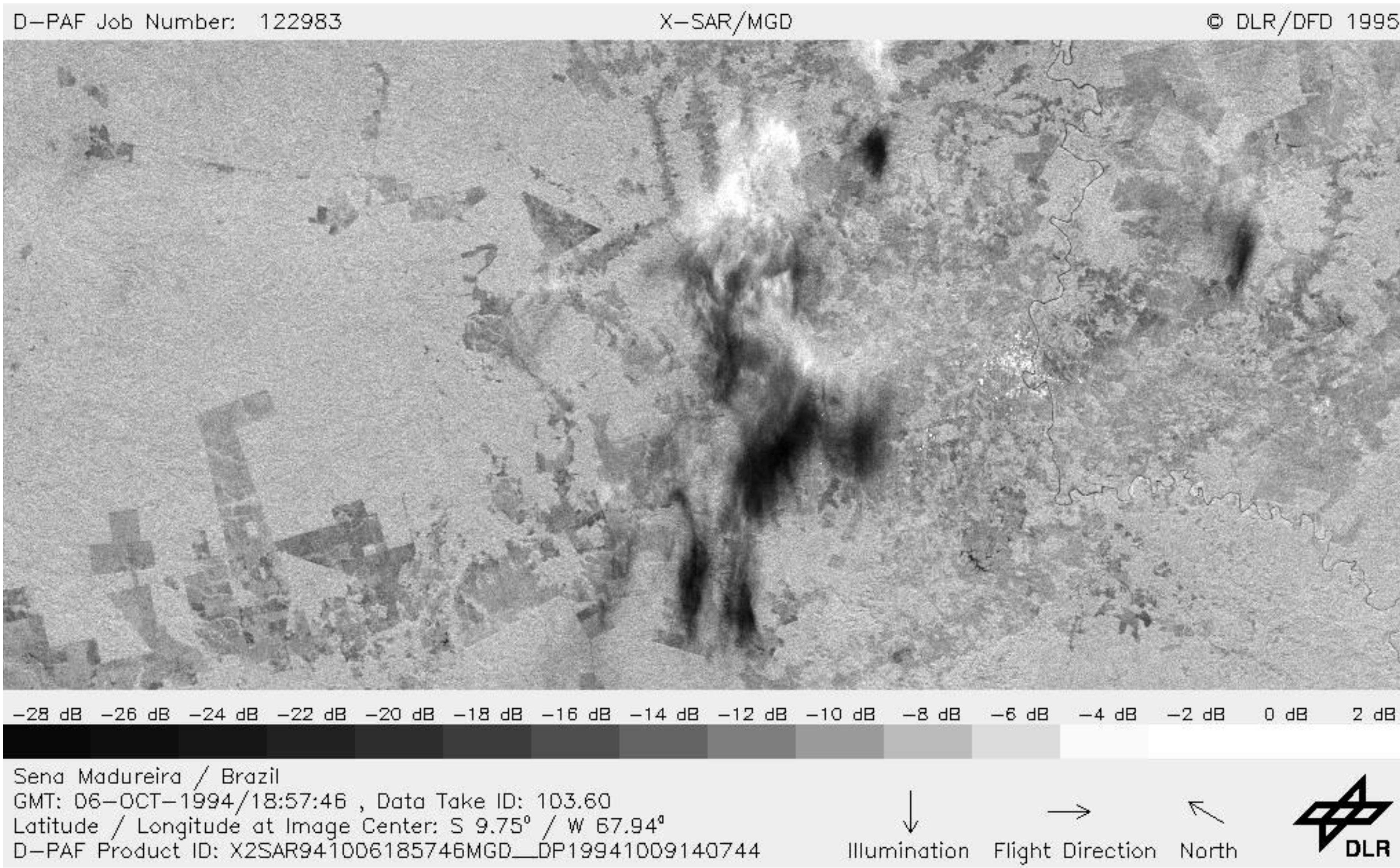
Instrument parameters to be calibrated:

- transmit power
- receiver gain
- elevation antenna pattern (roll angle !)

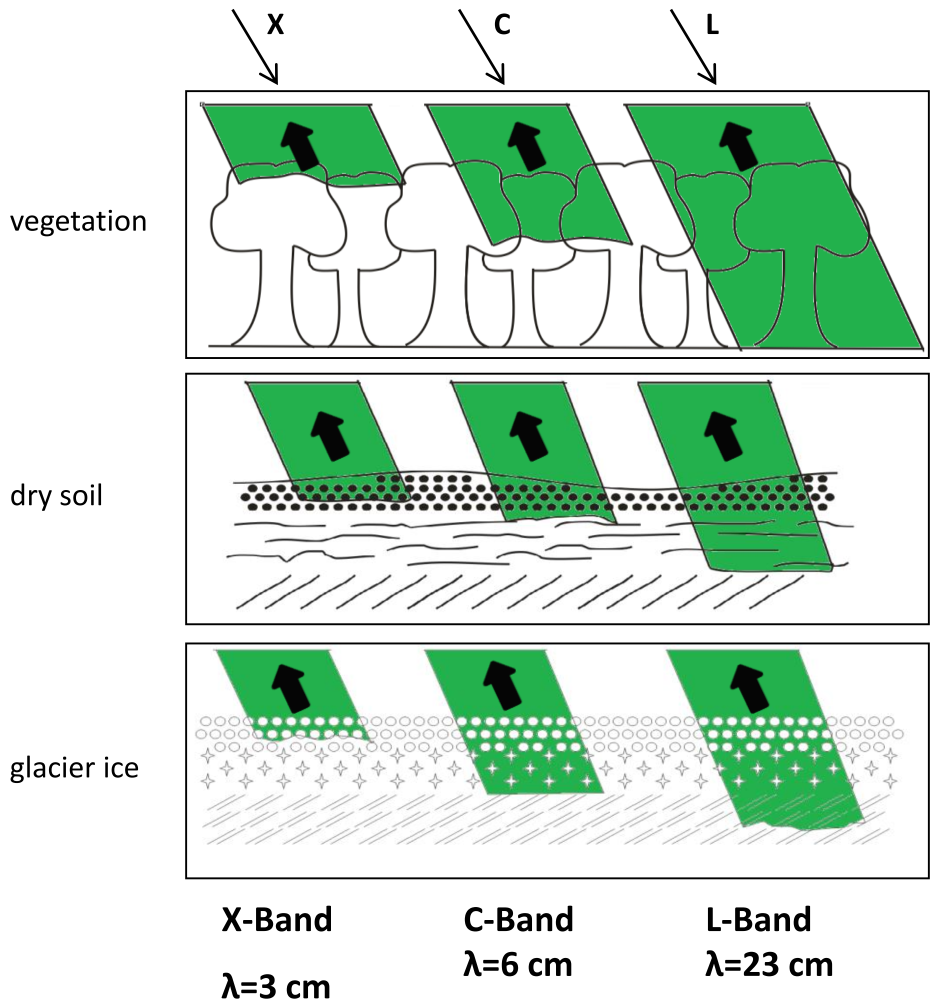
Calibration objects:

- corner reflectors
- active radar calibrators (ARCs)
- rain forest

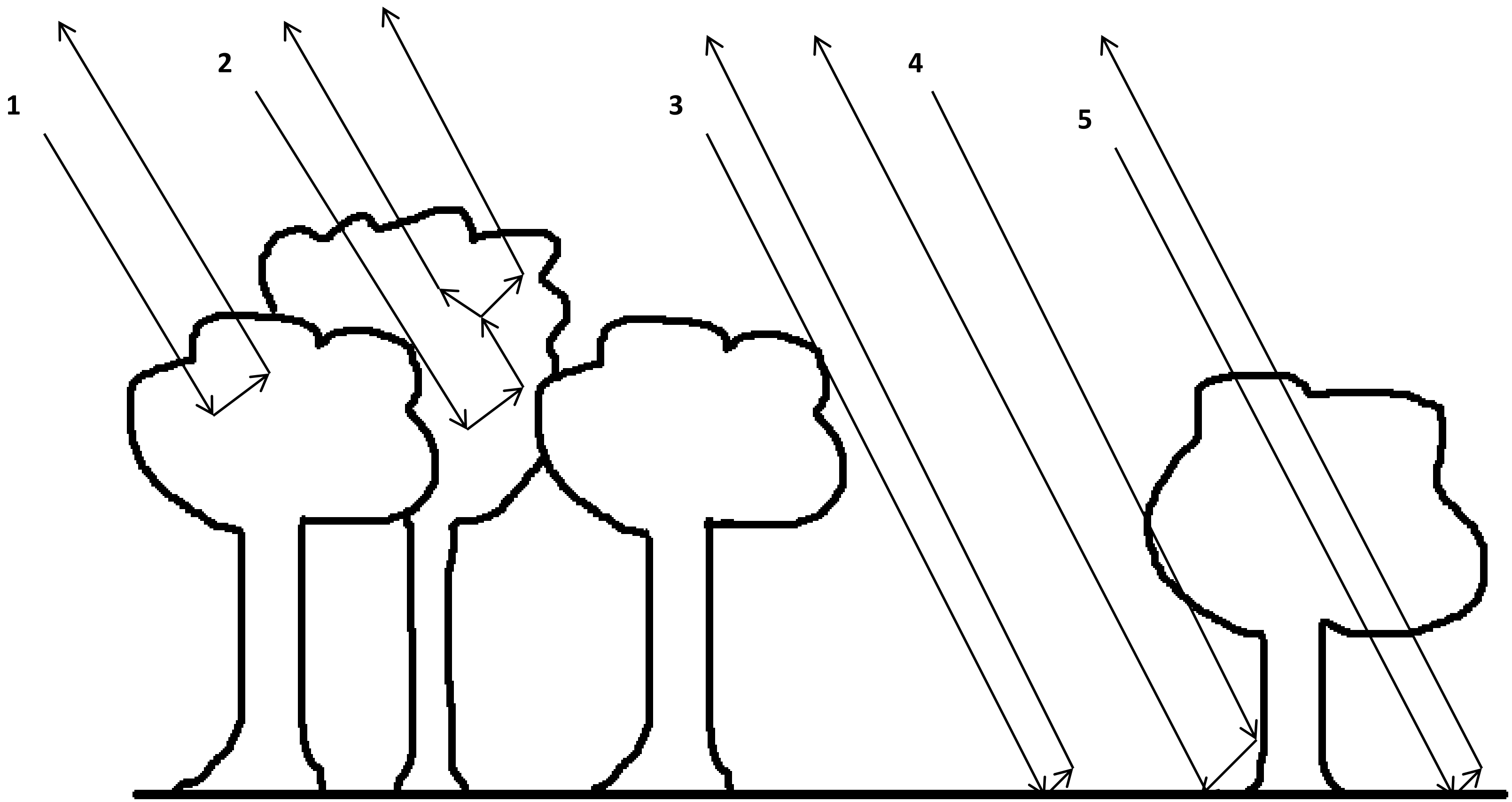
Heavy Clouds and Rain Cells in X-Band SAR Images



Penetration of Microwaves



Scattering Mechanisms in Forests



1: direct single scatter

2: multiple bounce

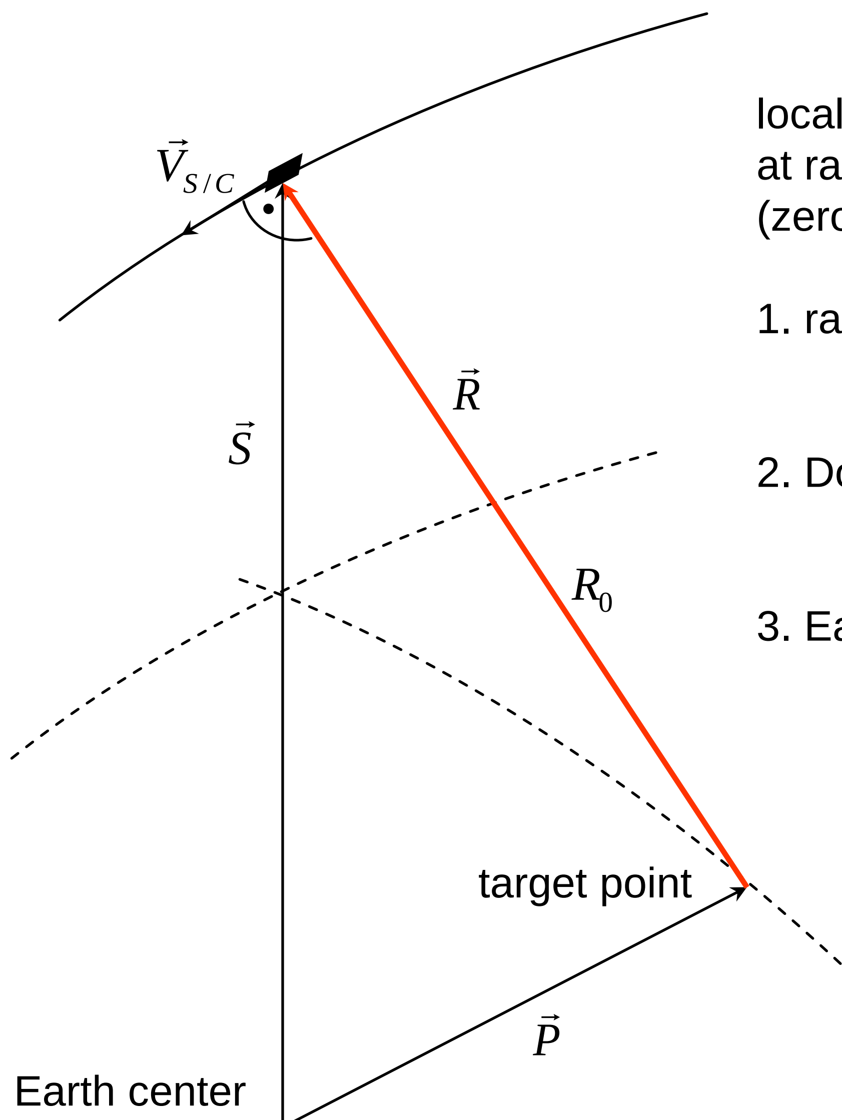
3: direct ground reflection

4: double bounce trunk - ground

5: attentuation of ground scatter by canopy

Synthetic Aperture Radar (SAR)

Geometry of SAR Images - Range-Doppler Equations



localization of a point $\vec{P}$ from a SAR image at range R_0 and azimuth t_0 with satellite position $\vec{S}(t_0)$ (zero-Doppler image geometry assumed):

1. range equation: $\left|\vec{S}-\vec{P}\right| = \left|\vec{R}\right| = R_0$

2. Doppler equation: $\left(\vec{S}-\vec{P}\right)\cdot\left(\dot{\vec{S}}-\dot{\vec{P}}\right) = 0$

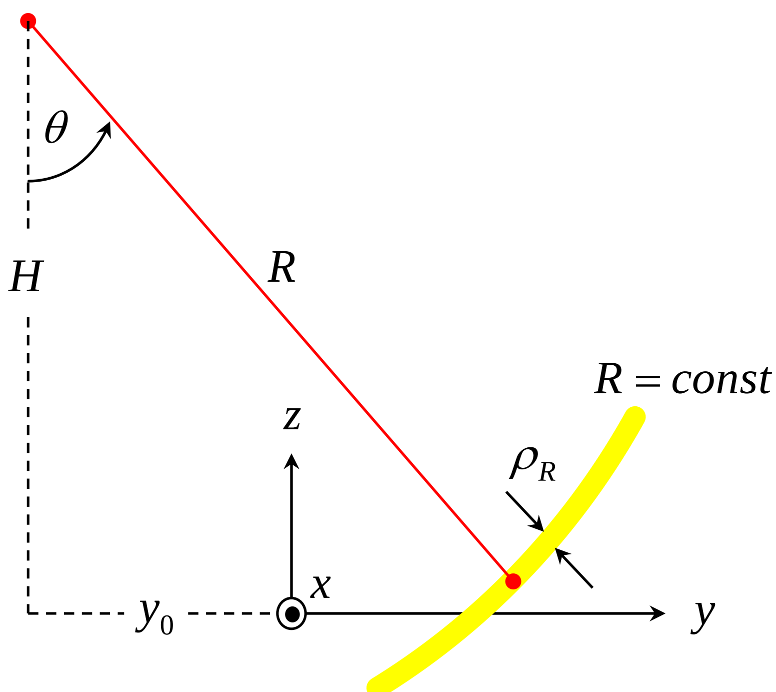
3. Earth equation: $\left|\vec{P}\right| = \text{local Earth radius}$

in Earth fixed co-ordinates: $\dot{\vec{S}}-\dot{\vec{P}} = \dot{\vec{S}} = \vec{V}_{S/C}$

Geometry of SAR Images - Radar Co-ordinates

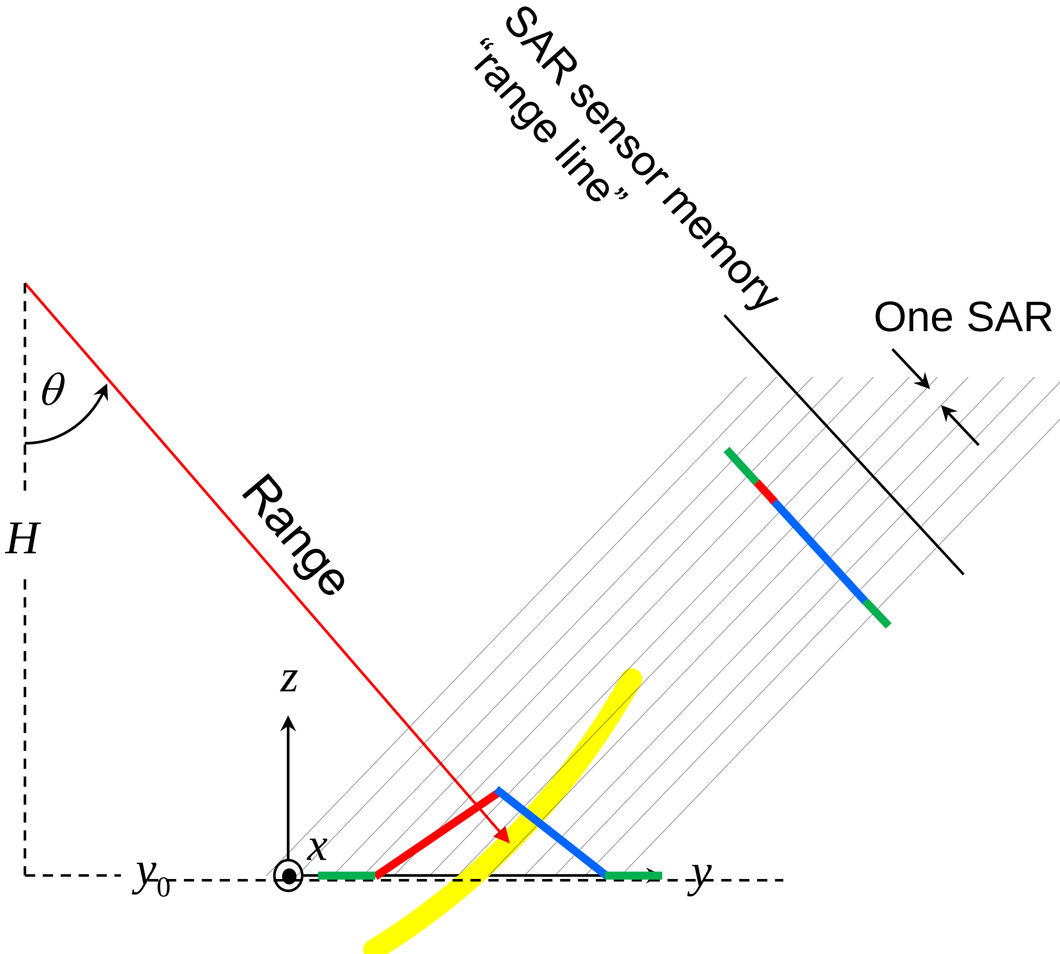
for SAR images processed to ‘zero-Doppler‘ geometry: $\begin{pmatrix} x \\ y \\ z \end{pmatrix} \Rightarrow \begin{pmatrix} x \\ R \end{pmatrix}$

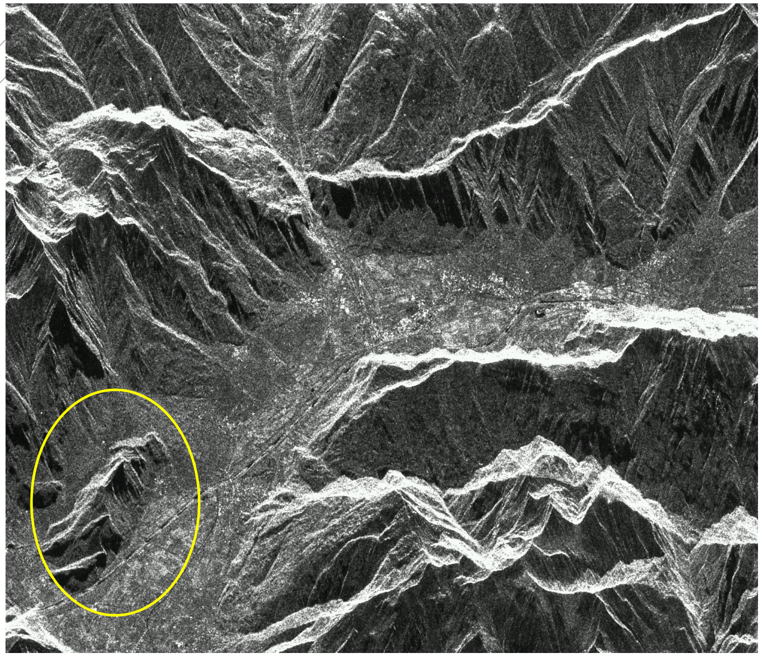
where $R = \sqrt{(y_0 + y)^2 + (H - z)^2}$



Geometry of SAR Images - Foreshortening

= geometric distortions of slopes from ground to "slant range"

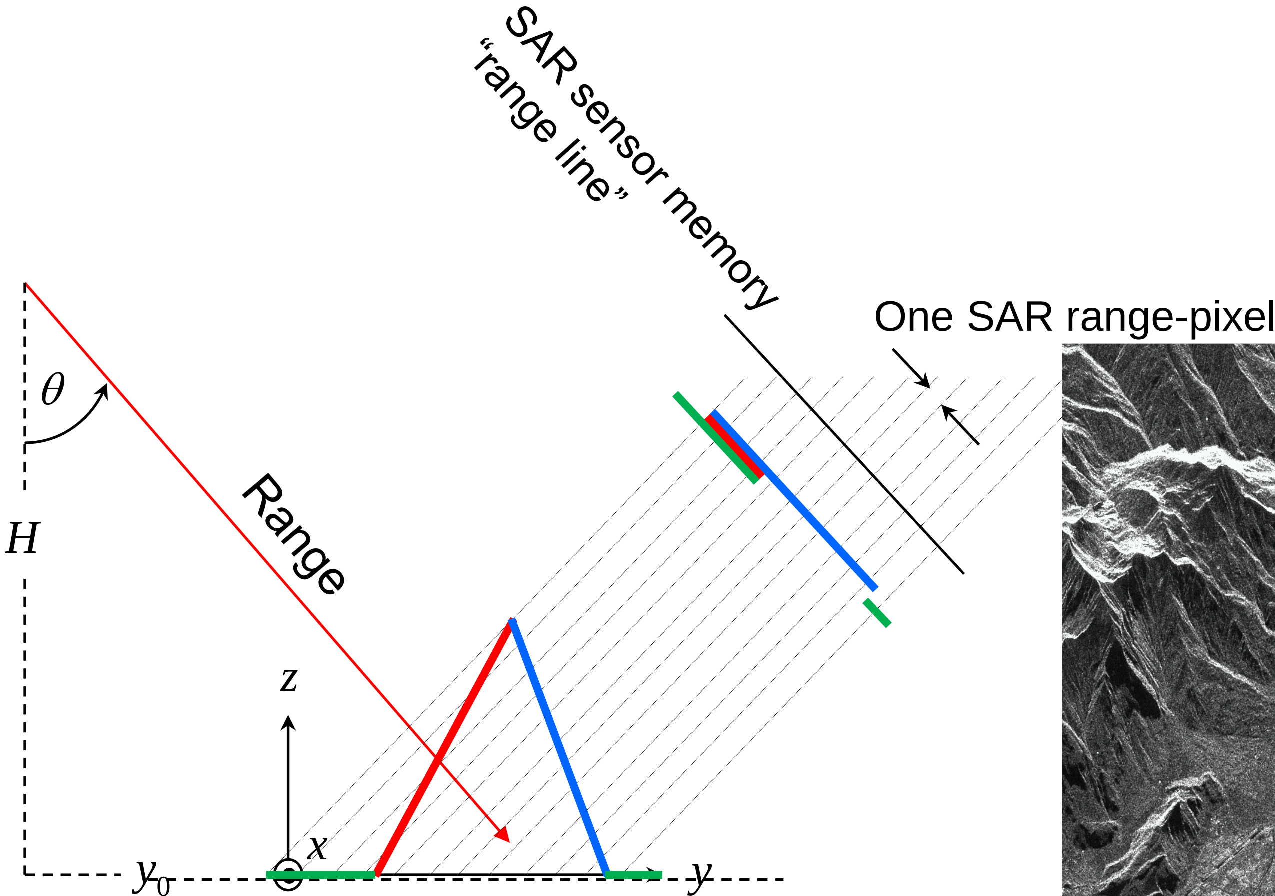


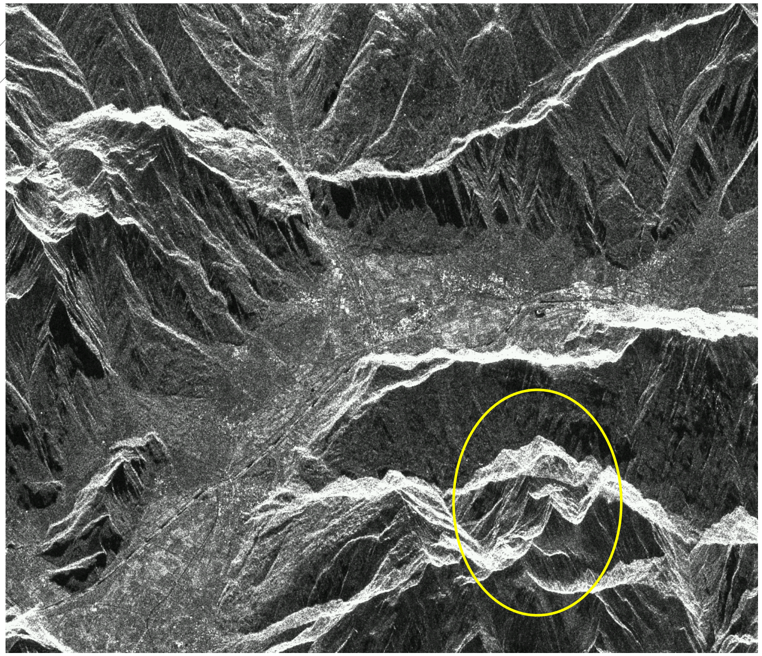


$\theta = 23\,\mathrm{deg}$ ERS-1

Geometry of SAR Images - Layover

= overlay of multiple areas from ground to slant range

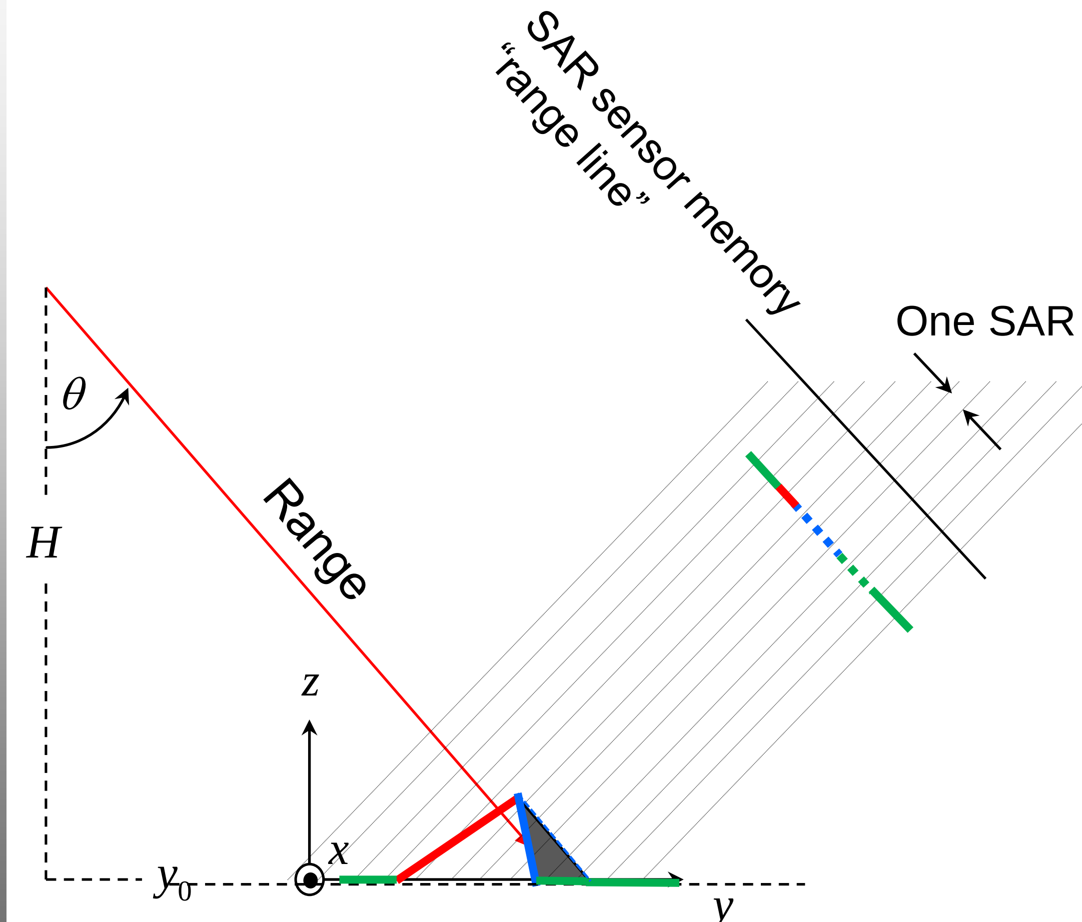


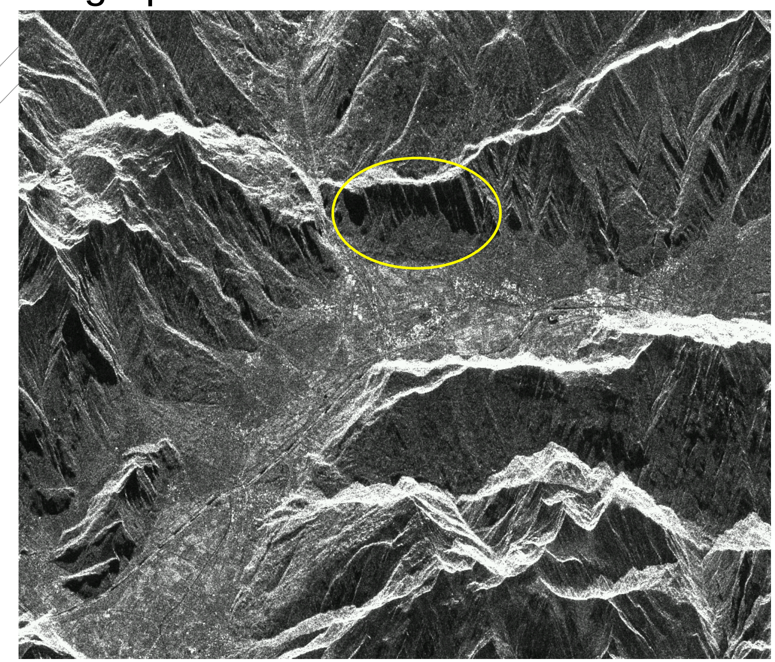


$\theta = 23\,\text{deg}$ ERS-1

Geometry of SAR Images - Shadow

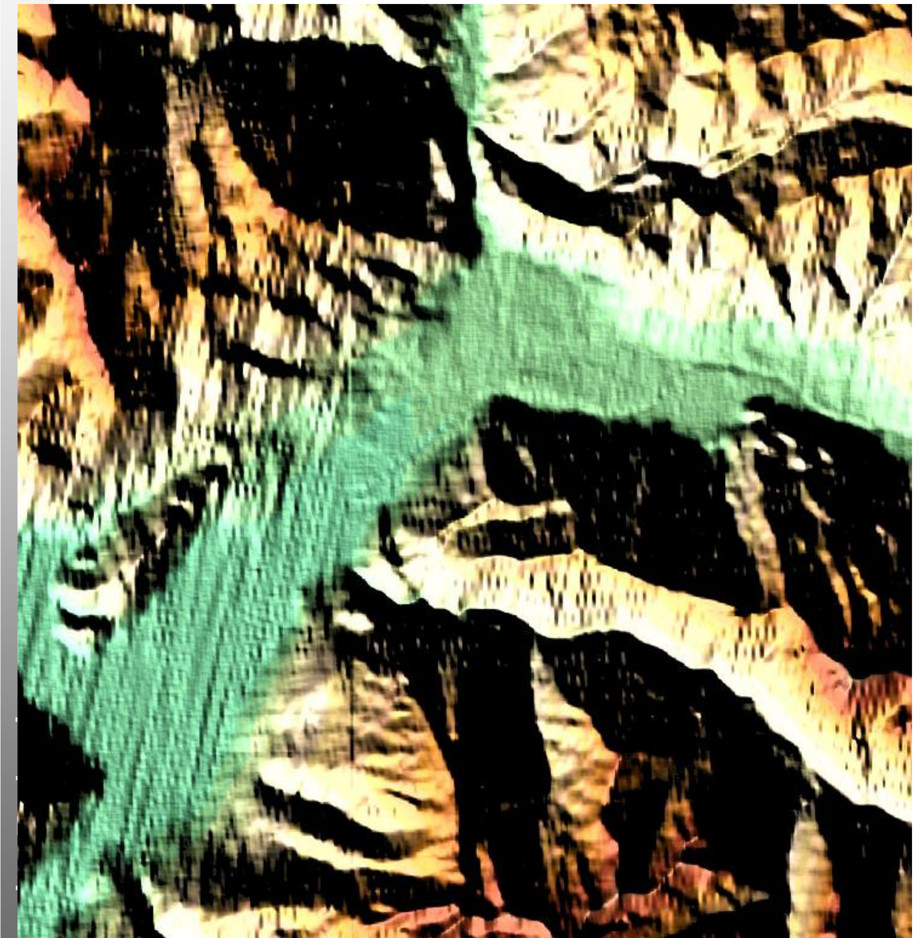
= no reflection from back-slopes which are not illuminated by radar



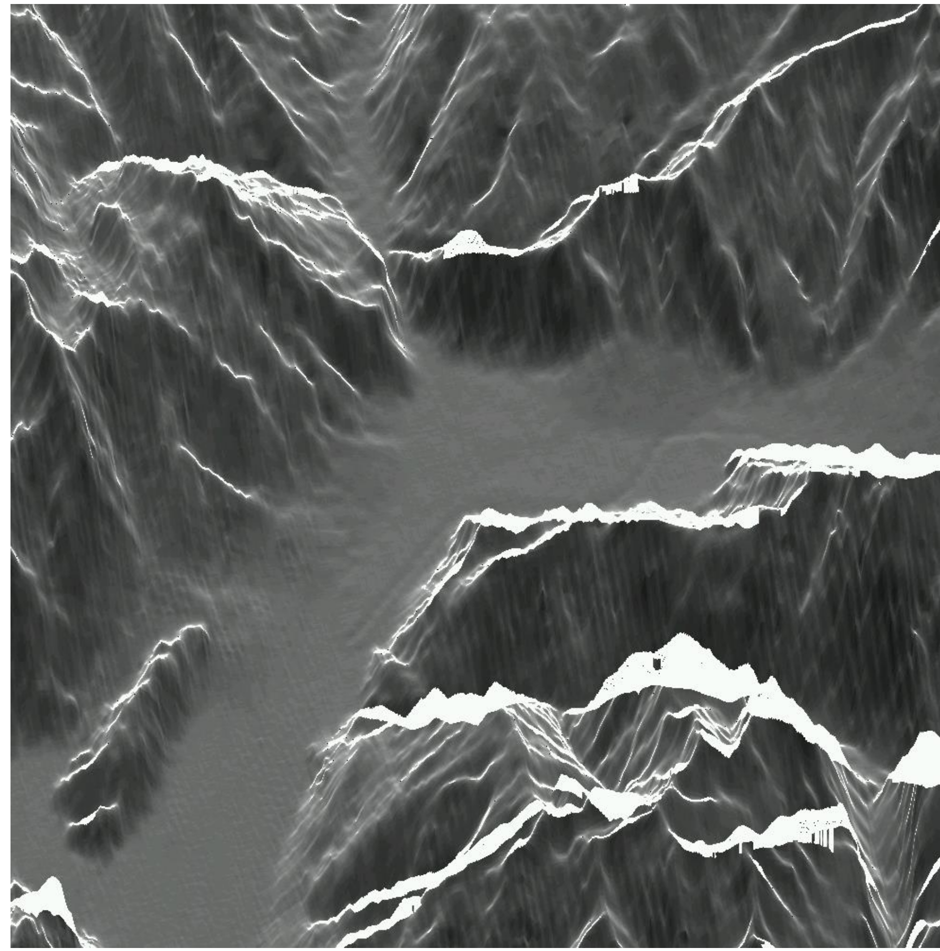


$\theta = 23\,\mathrm{deg}$ ERS-1

Lay-Over Mask Computed from DEM



100m DEM

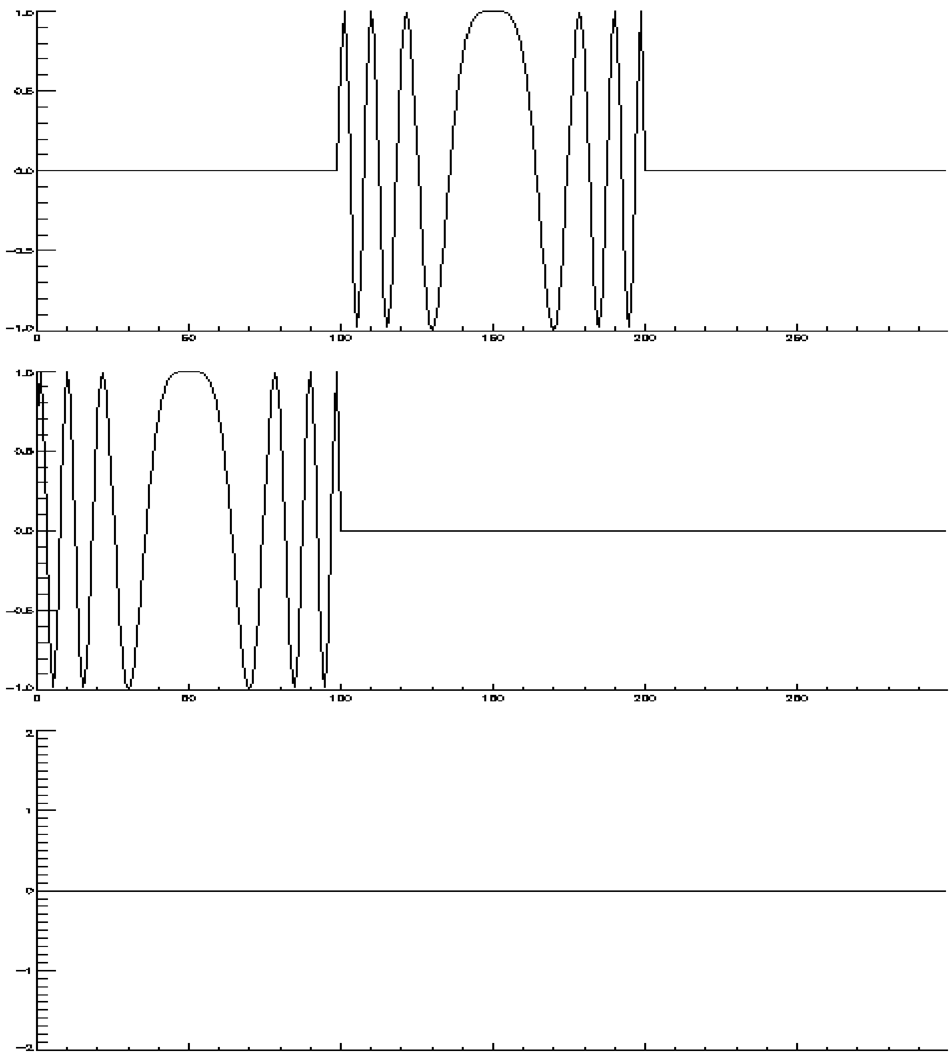


simulated ERS-Image
white: lay-over

Books on SAR

- John C. Curlander, „Synthetic Aperture Radar: Systems and Signal Processing“, Wiley-Interscience, 1991
- Ian G. Cumming, „Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation“, Artech House, 2005

Range Compression by Matched Filtering

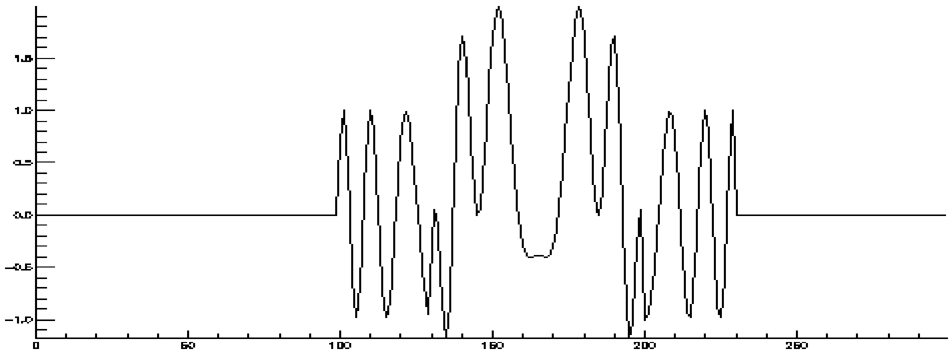


received signal $r(\tau)$

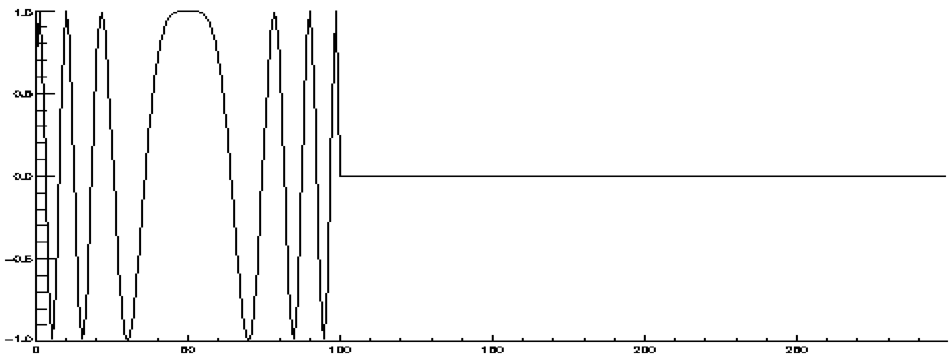
reference chirp $c(\tau)$

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

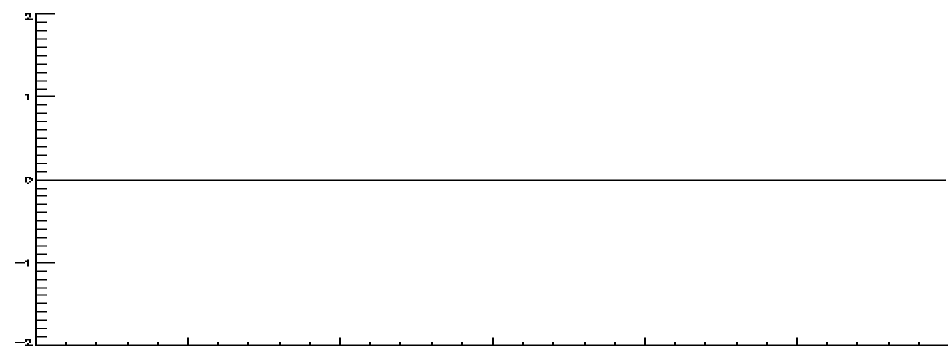
Linear System →Superposition Law



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



reference chirp $c(\tau)$



cross-correlation

$$\int (r_1^*(\tau) + r_2^*(\tau))\, c(\tau + s) d\tau =$$

$$\int r_1^*(\tau)\, c(\tau + s) d\tau + \int r_2^*(\tau)\, c(\tau + s) d\tau$$

Back

Remote Sensing Technology