→ 6th ESA ADVANCED TRAINING COURSE
ON LAND REMOTE SENSING

Synthetic Aperture Radar (SAR): Principles and Applications

Marwan Younis

German Aerospace Center (DLR)
Microwaves and Radar Institute
82230 Oberpfaffenhofen, Germany

e-mail: marwan.younis@dlr.de / Web: www.dlr.de/HR

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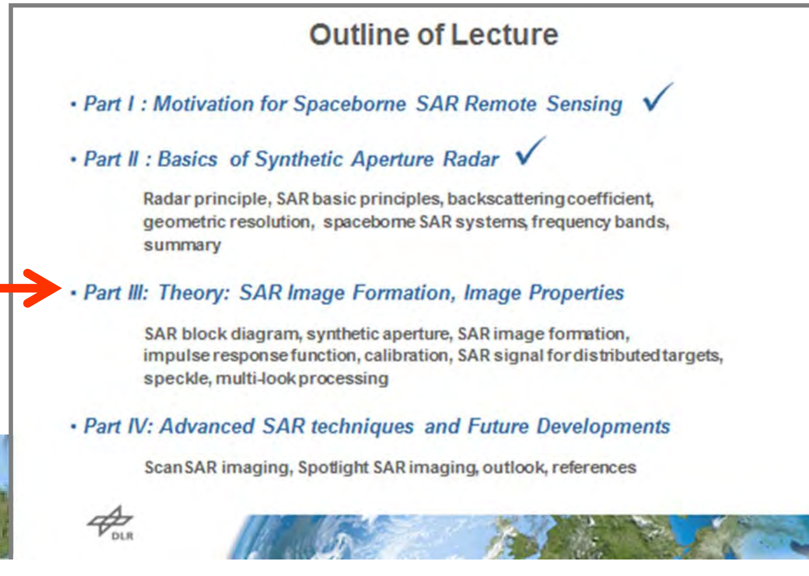
PART III

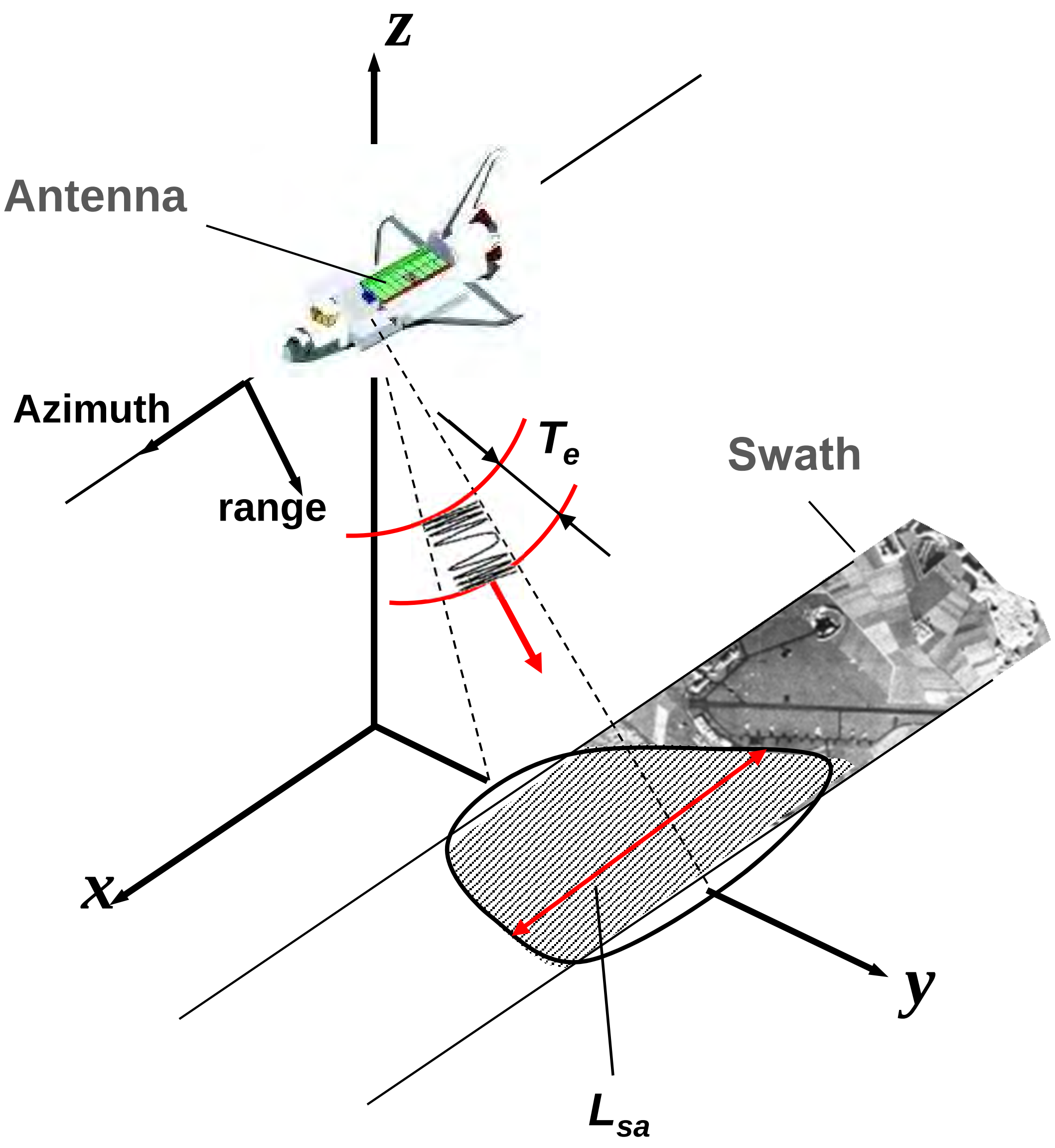
Theory: SAR Image Formation and Image Properties



DLR

SAR Image Formation

SAR Basic Principle



1) pulsed radar system
(PRF = Pulse Repetition Frequency)

2) two dimensional imaging
(range x azimuth)

3) range resolution

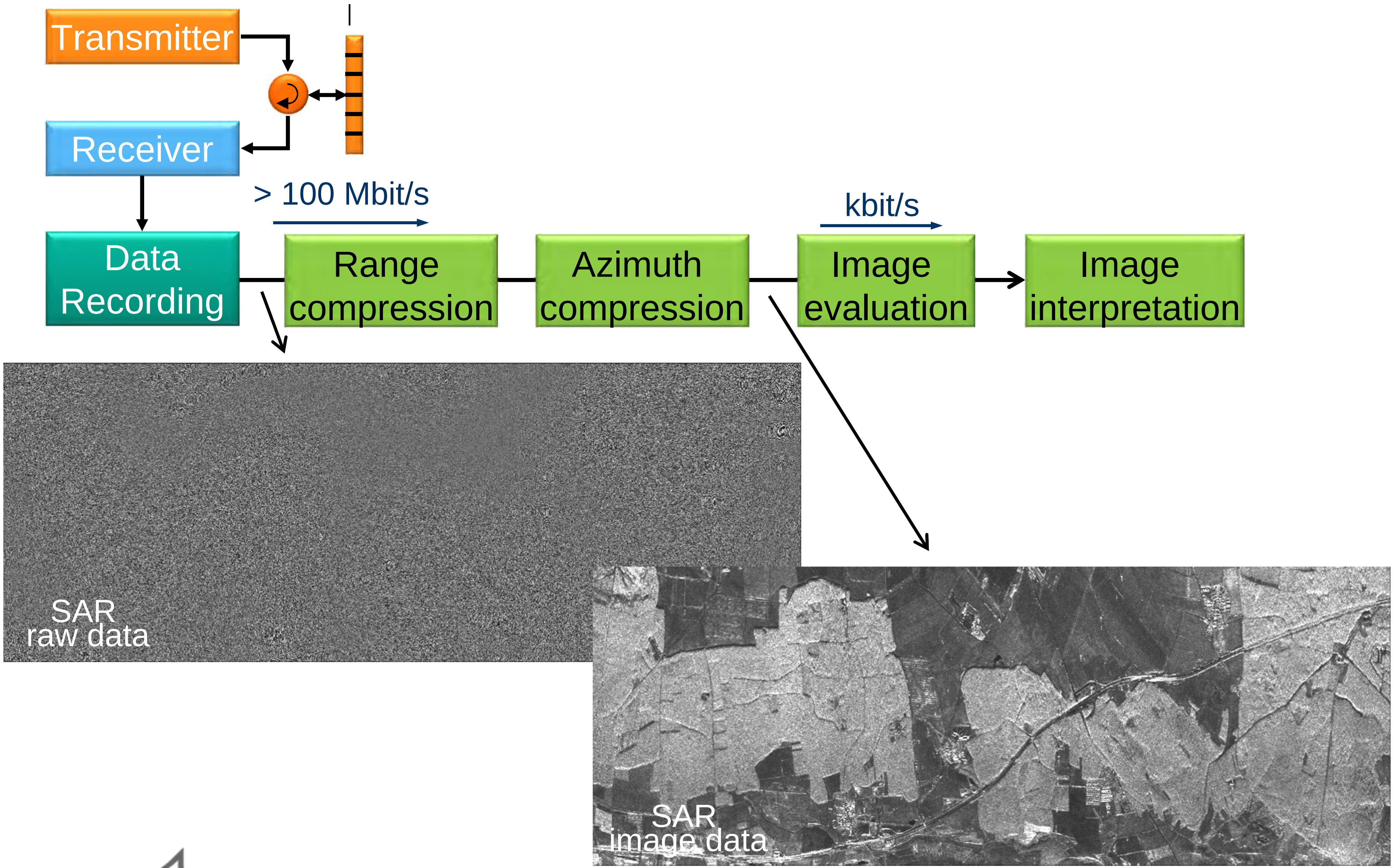
$$\delta_r = \frac{c_o}{2B_p}$$

4) azimuth resolution

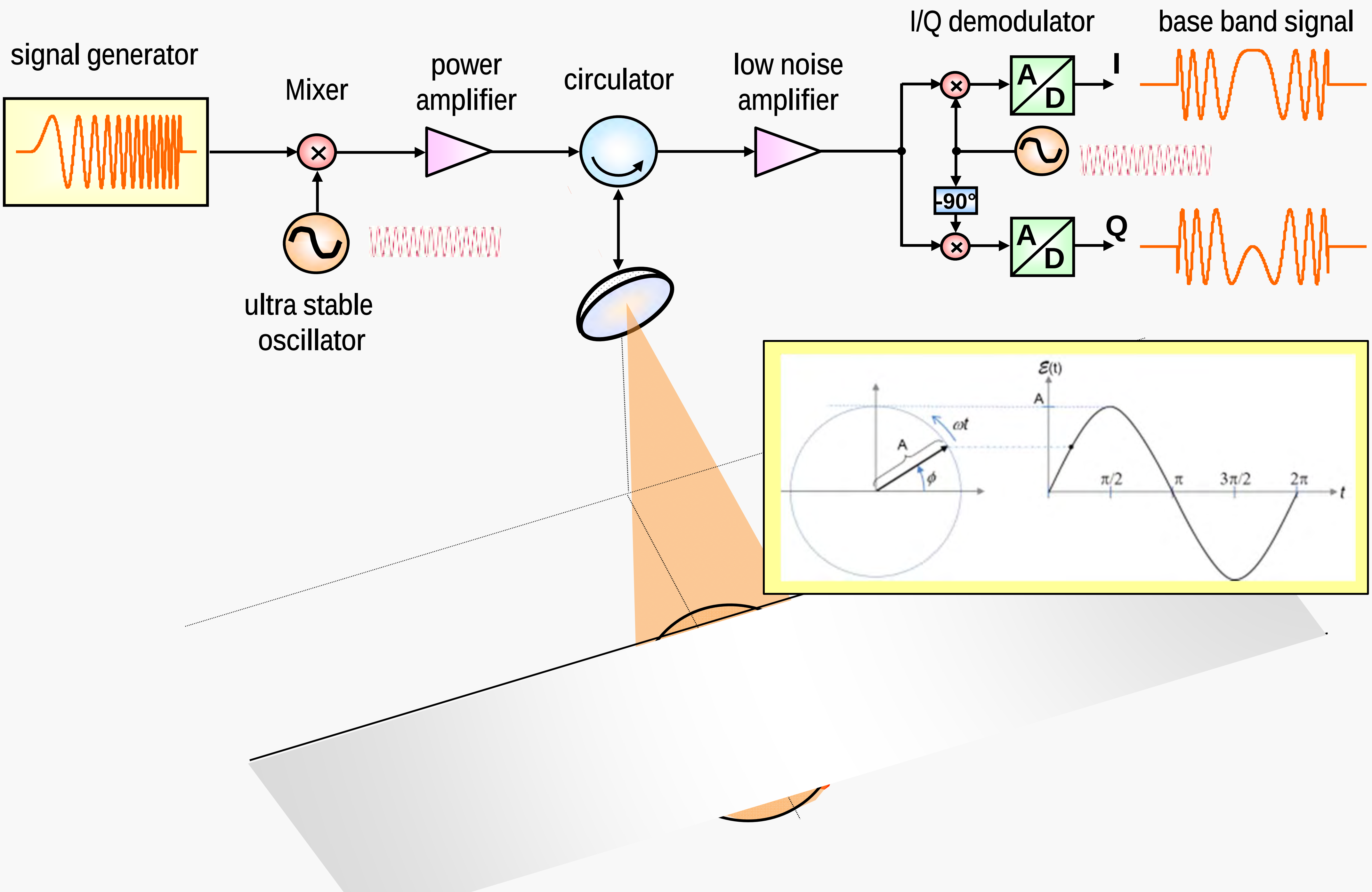
$$\delta_a = \frac{d_a}{2}$$

5) Radar system must be coherent!

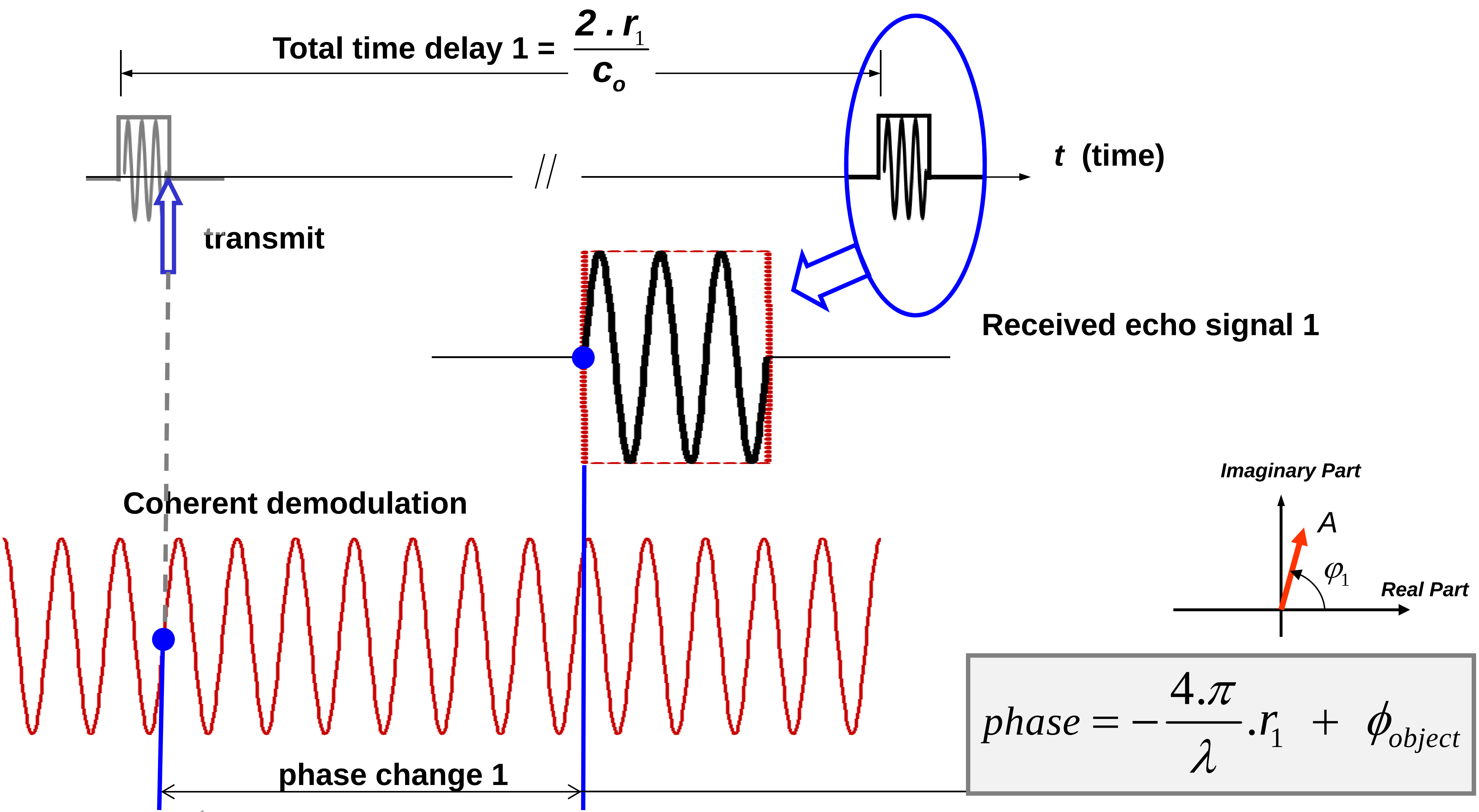
SAR Data Flow



Synthetic Aperture Radar (SAR)

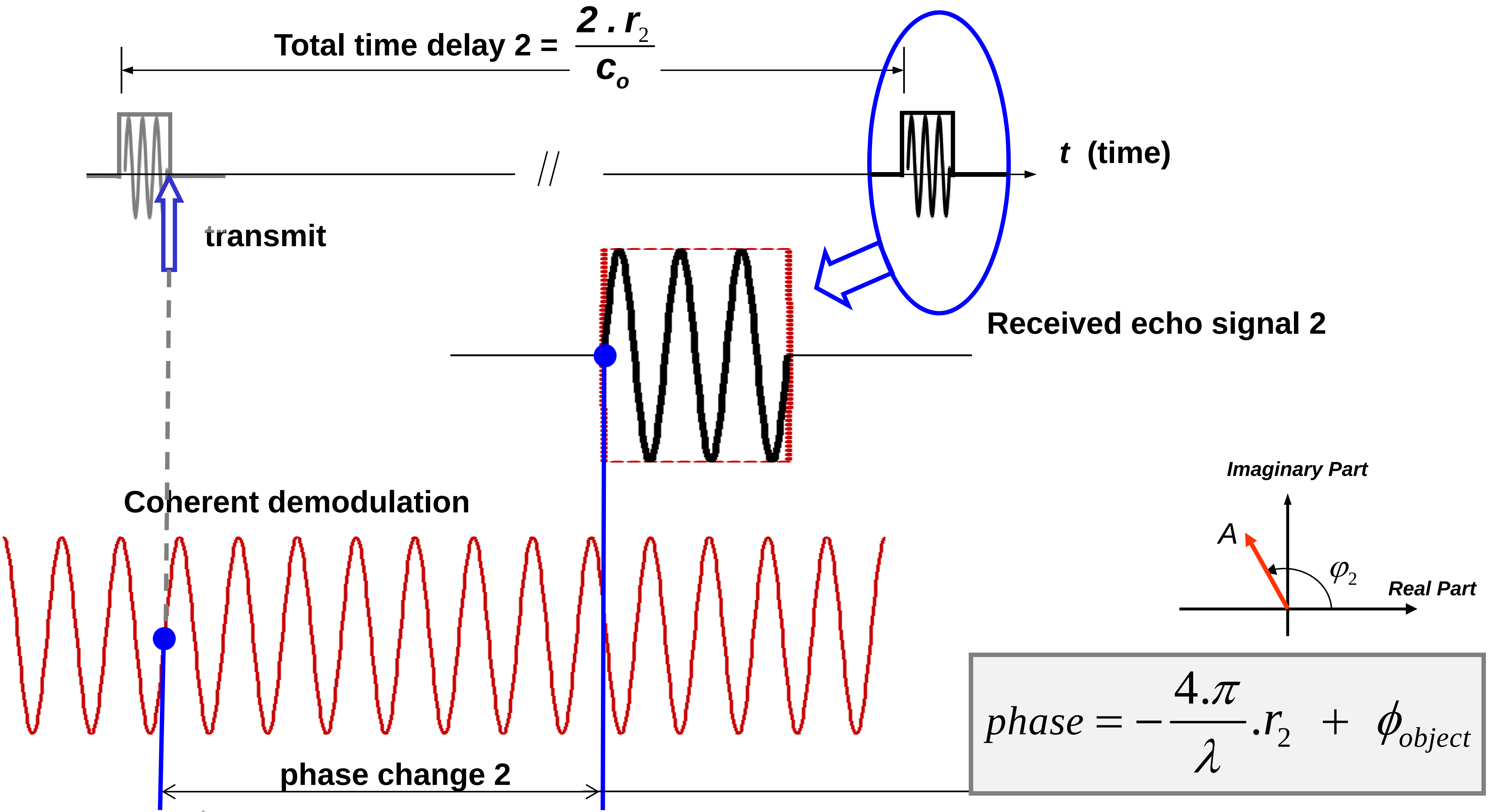


Coherent Measurement Principle



$$phase = -\frac{4.\pi}{\lambda}.r_1 + \phi_{object}$$

Coherent Measurement Principle



$$phase = -\frac{4.\pi}{\lambda}.r_2 \;+\; \phi_{object}$$

Phasor Representation of SAR Signal

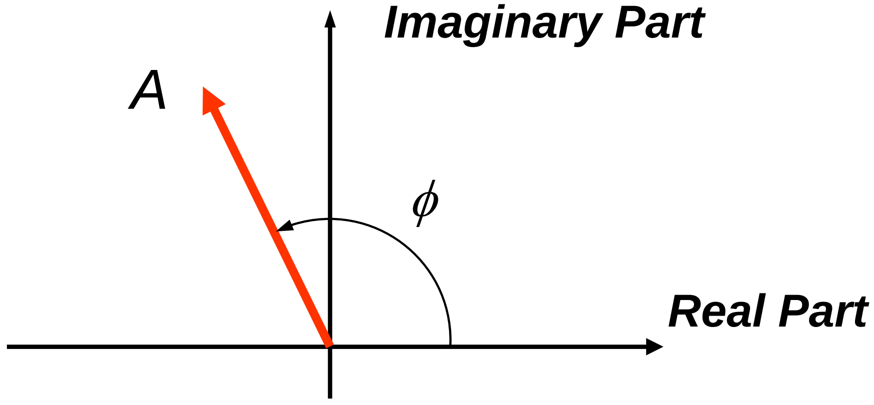
complex representation: $A \cdot \cos(2\pi f_0 t + \phi) \quad \rightarrow \quad A \cdot \exp\left[j\left(2\pi f_0 t + \phi\right)\right]$

after demodulation: $A \cdot \exp\left[j \cdot \phi\right]$

amplitude: A

intensity, power: A^2

phase: ϕ



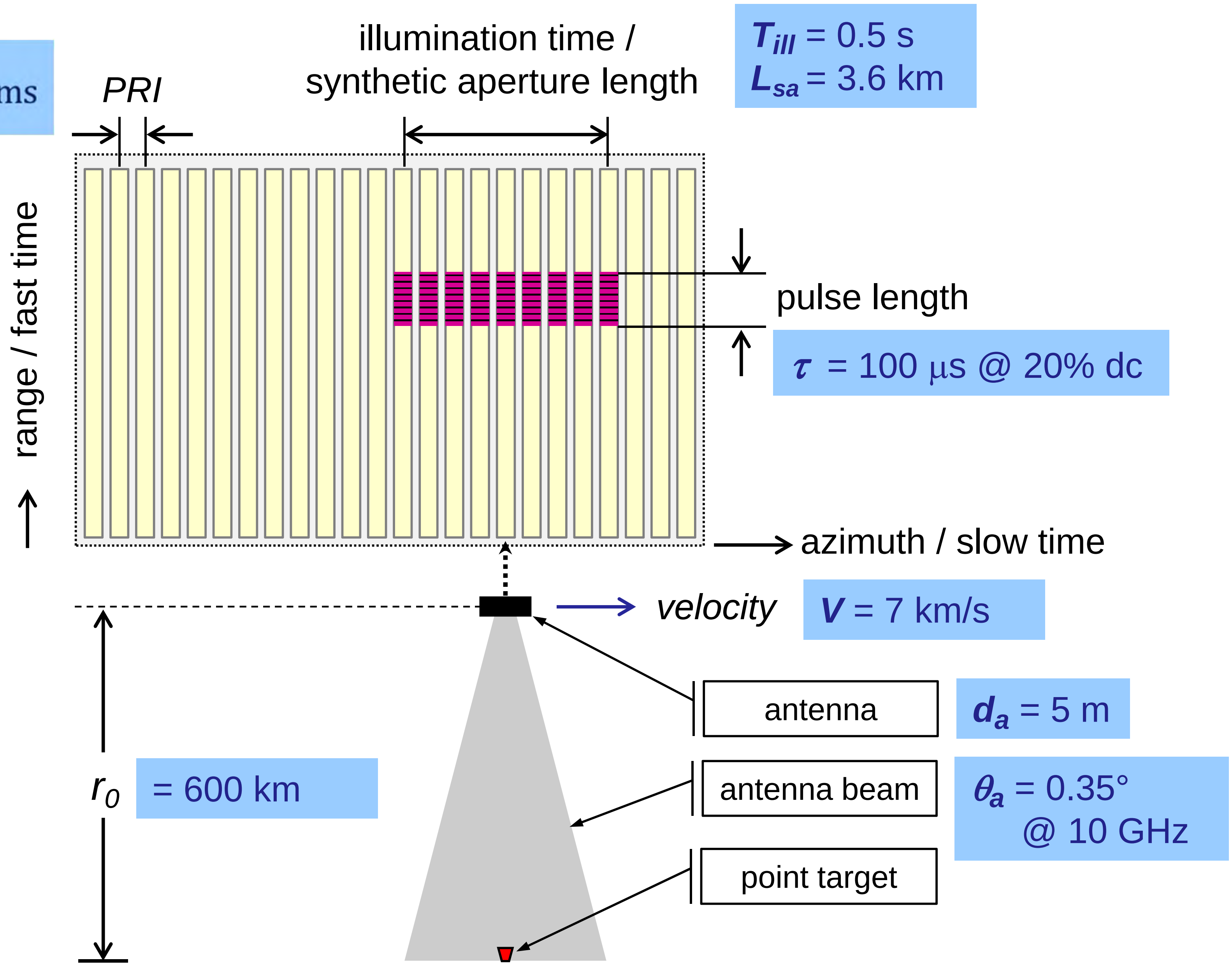
Every pixel of a complex SAR image consists of a real and an imaginary part, i.e. it is a phasor and contains amplitude and phase information.

$$\textit{amplitude information} \rightarrow \textit{backscattering coefficient} \;\; \sigma_o$$

$$\textit{phase information} = -\frac{4.\pi}{\lambda}.r + \phi_{object}$$

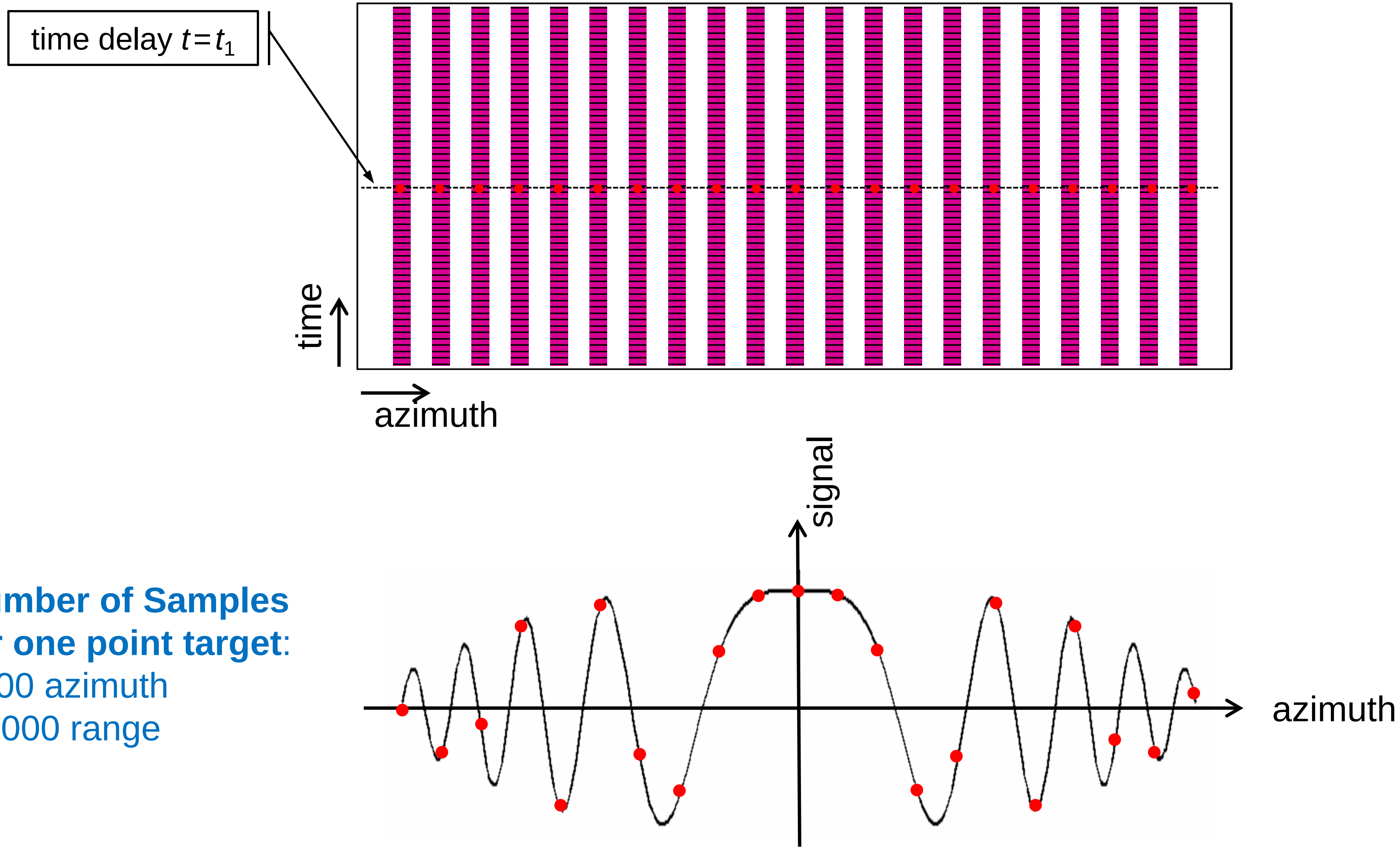
2-D Raw Data Matrix

$$PRI = \frac{1}{PRF} = \frac{1}{3\ \text{kHz}} = 0.33\ \text{ms}$$



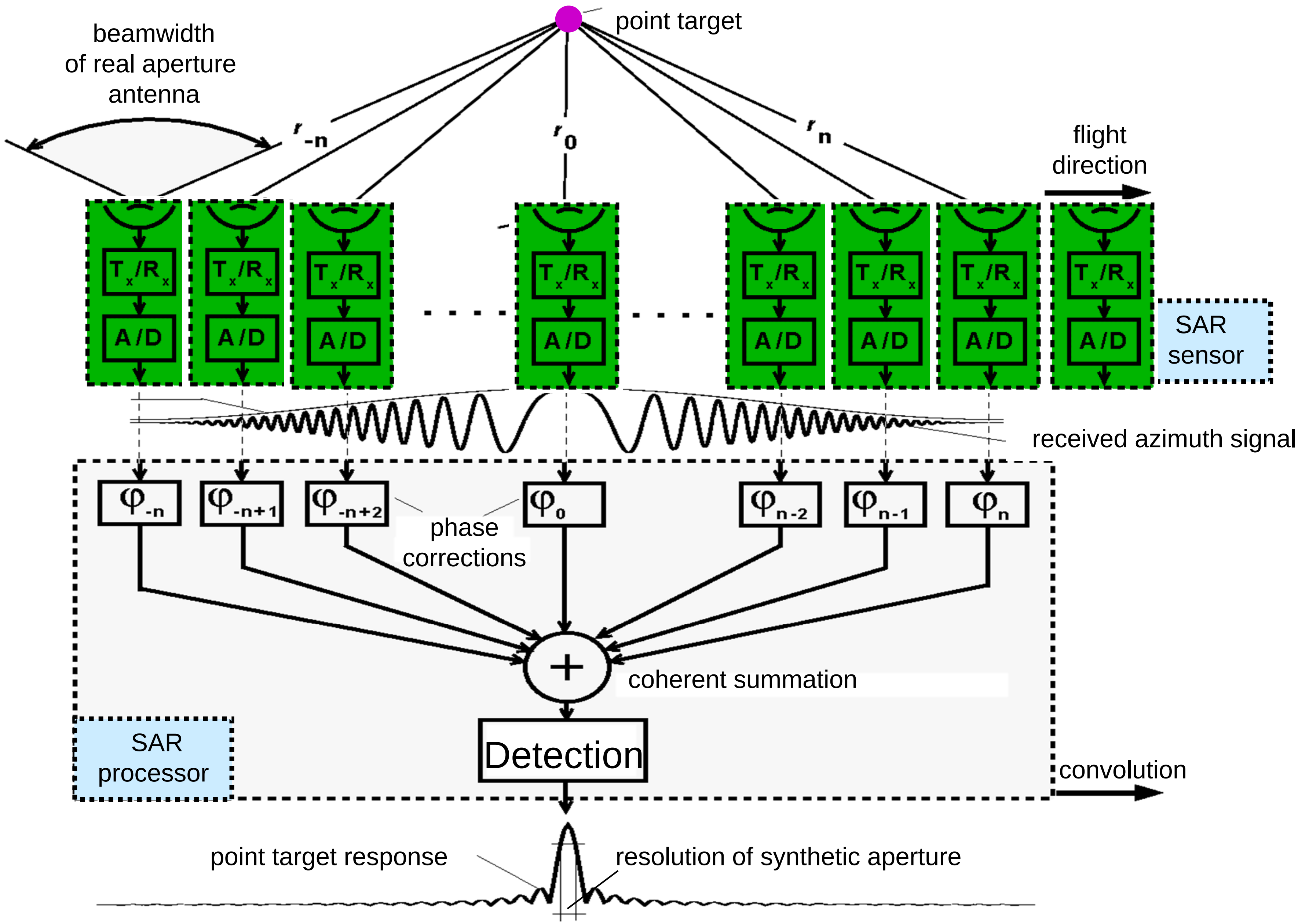
Number of Samples for one point target:
1500 azimuth
30 000 range

Formation of Azimuth Chirp Signal

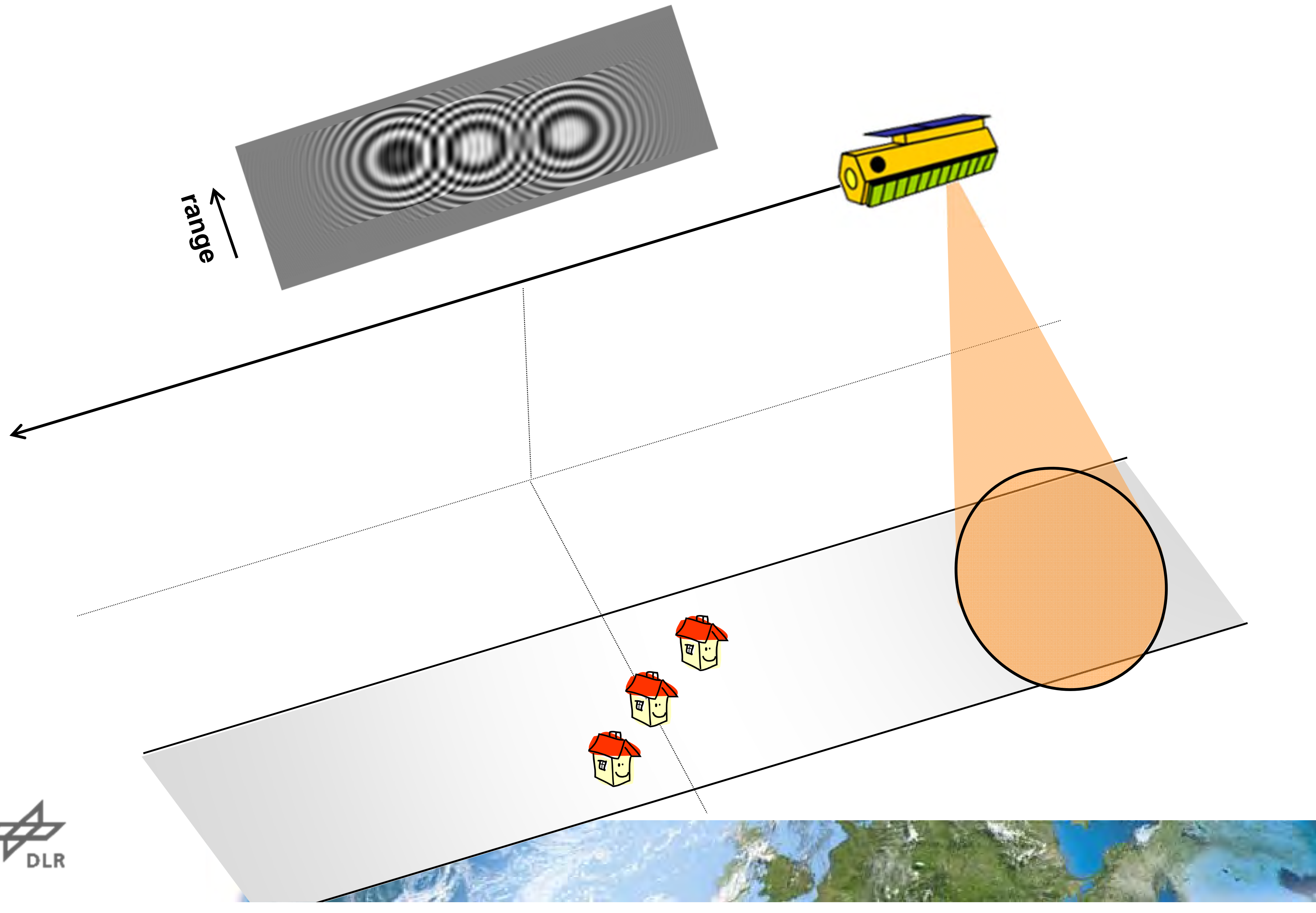


Number of Samples for one point target:
1500 azimuth
30 000 range

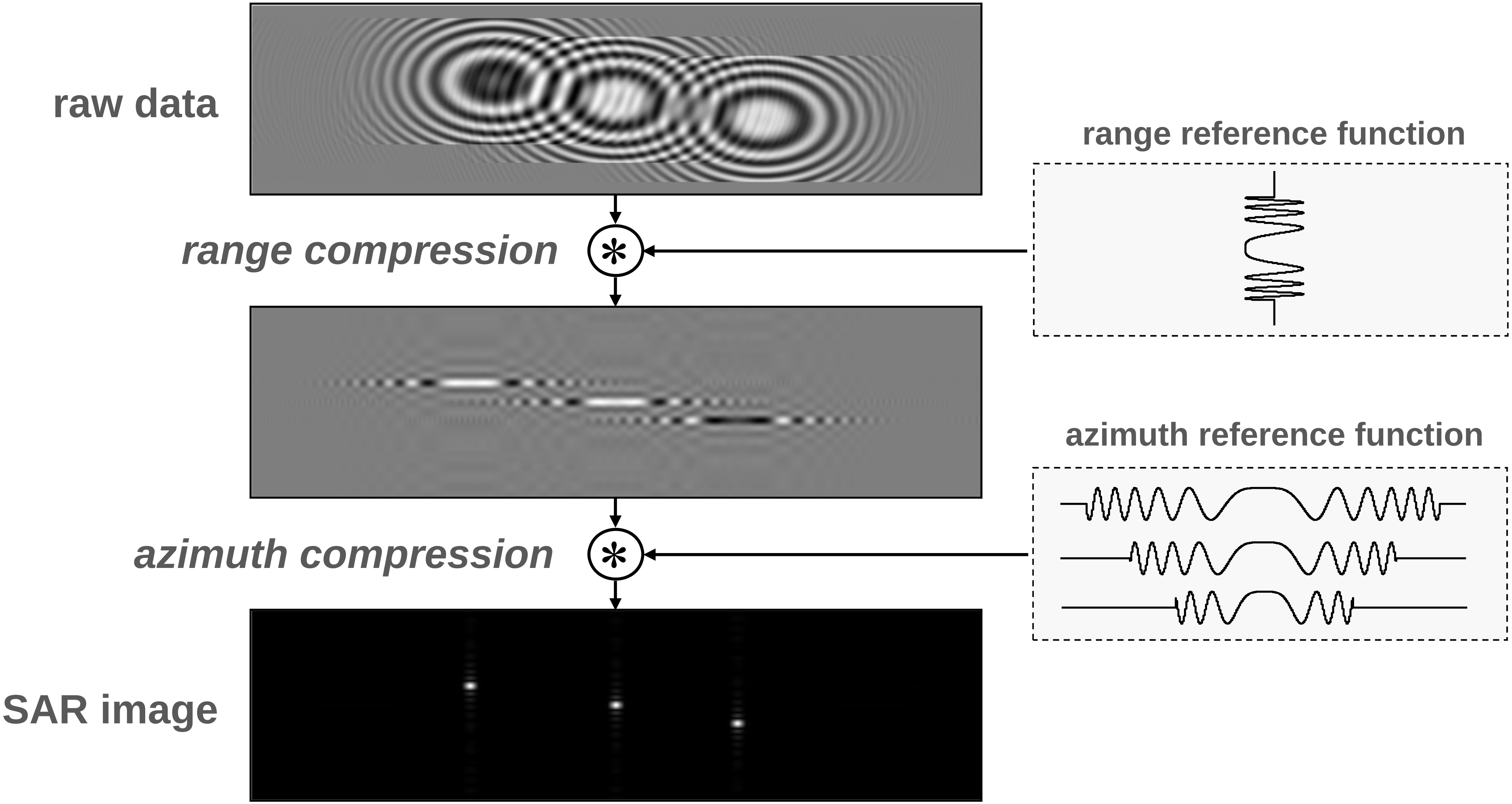
Synthetic Aperture Formation and Processing



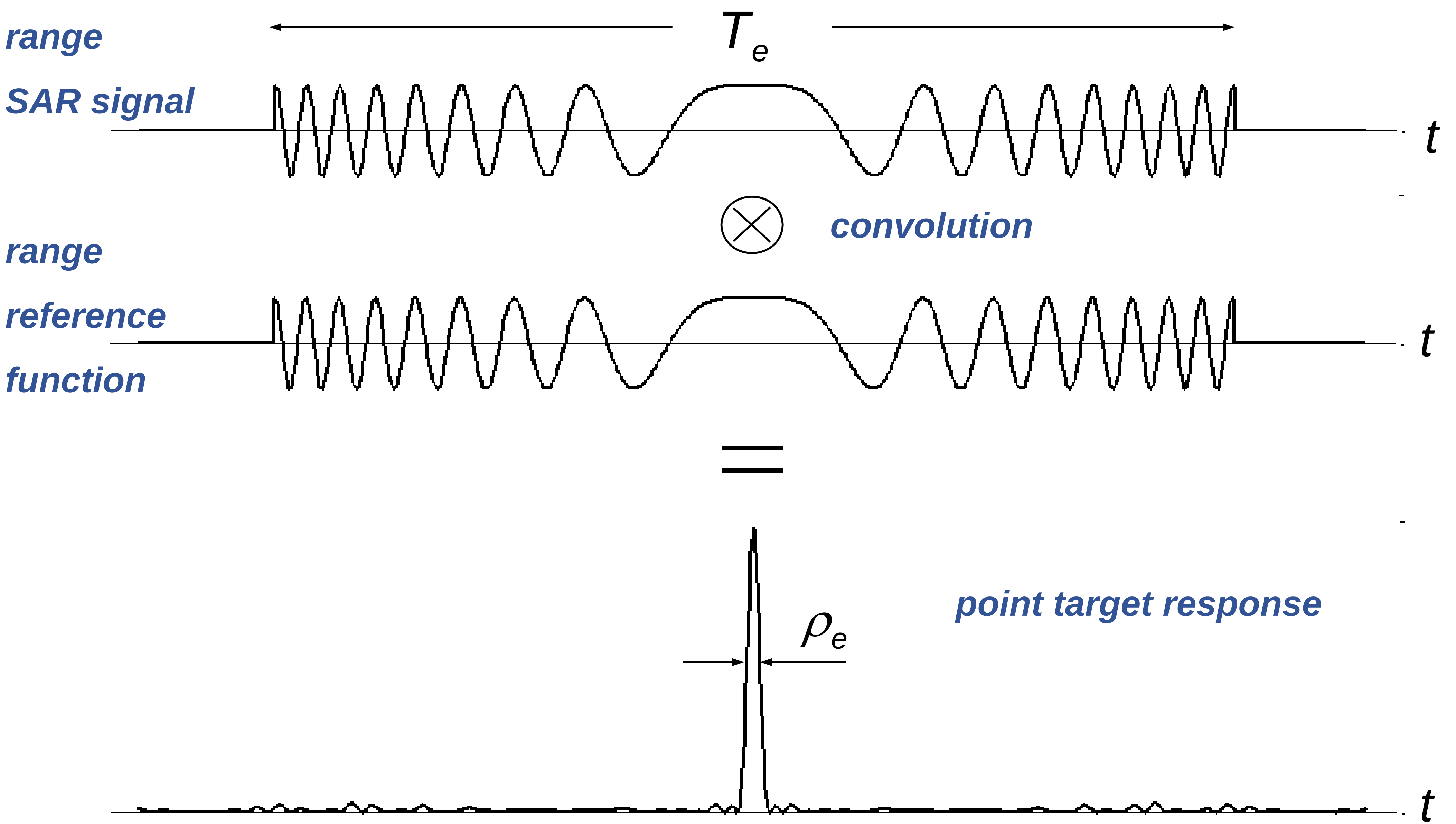
Synthetic Aperture Radar (SAR)



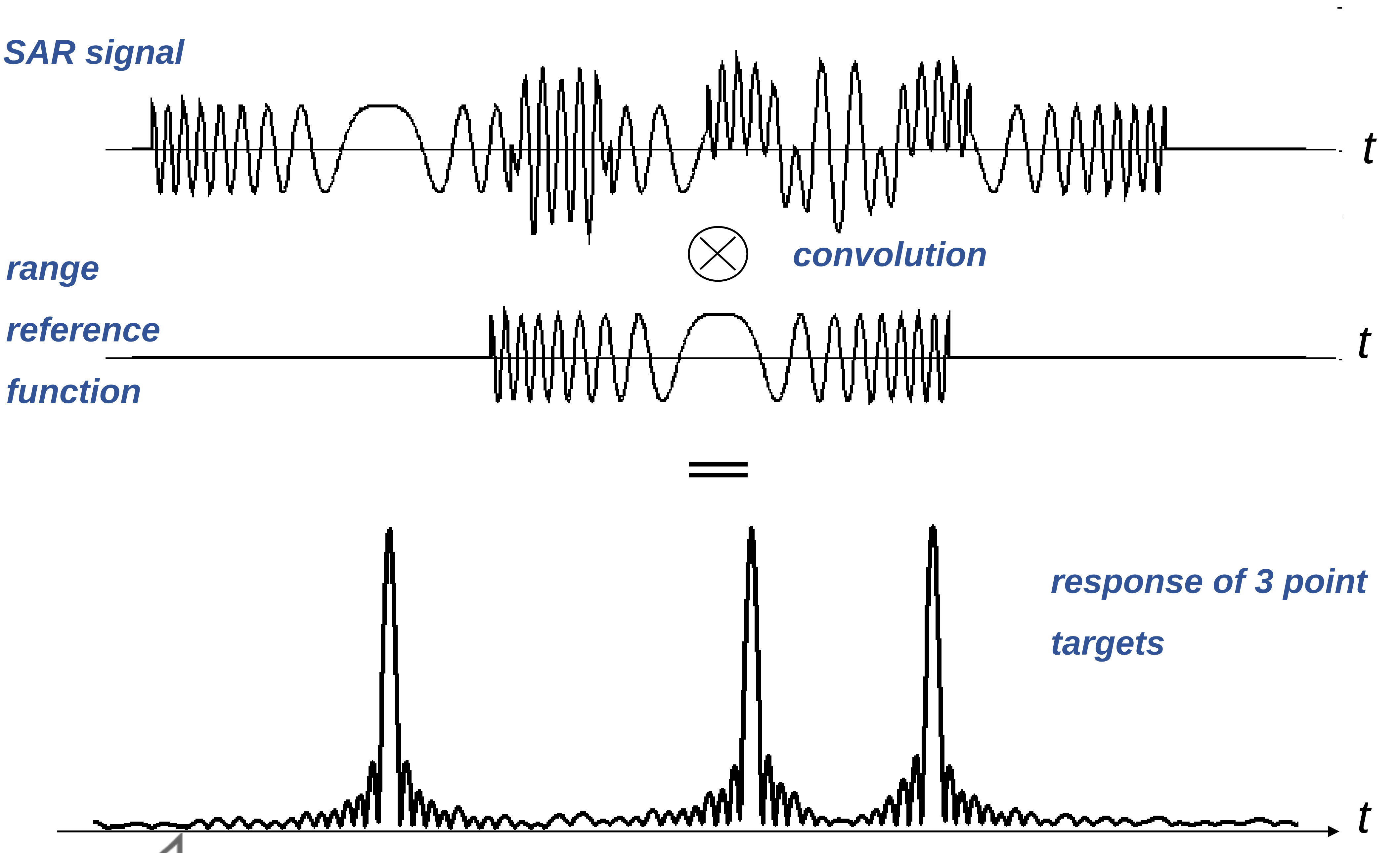
SAR Processing (Image Formation)

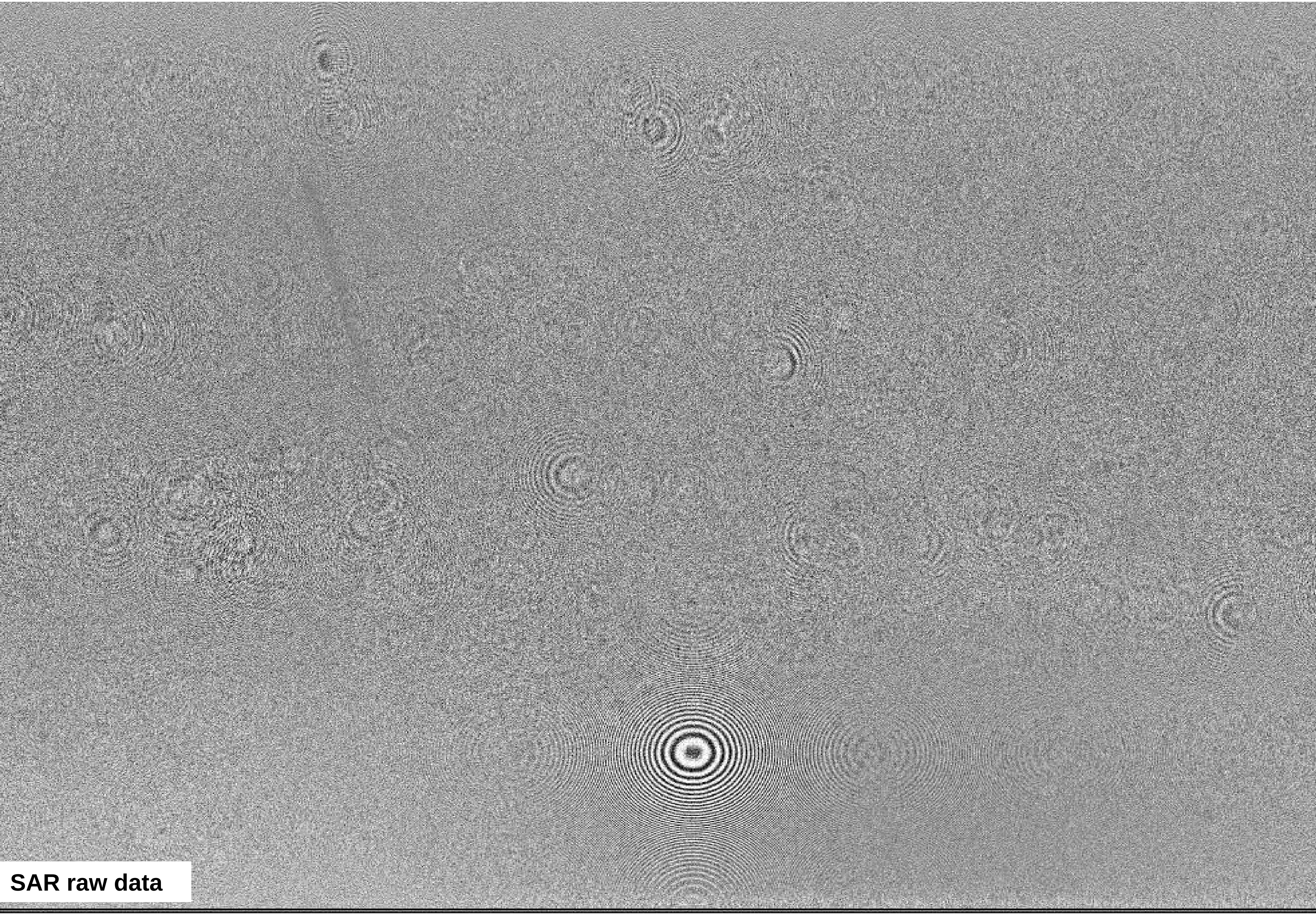


Pulse Compression by Convolution



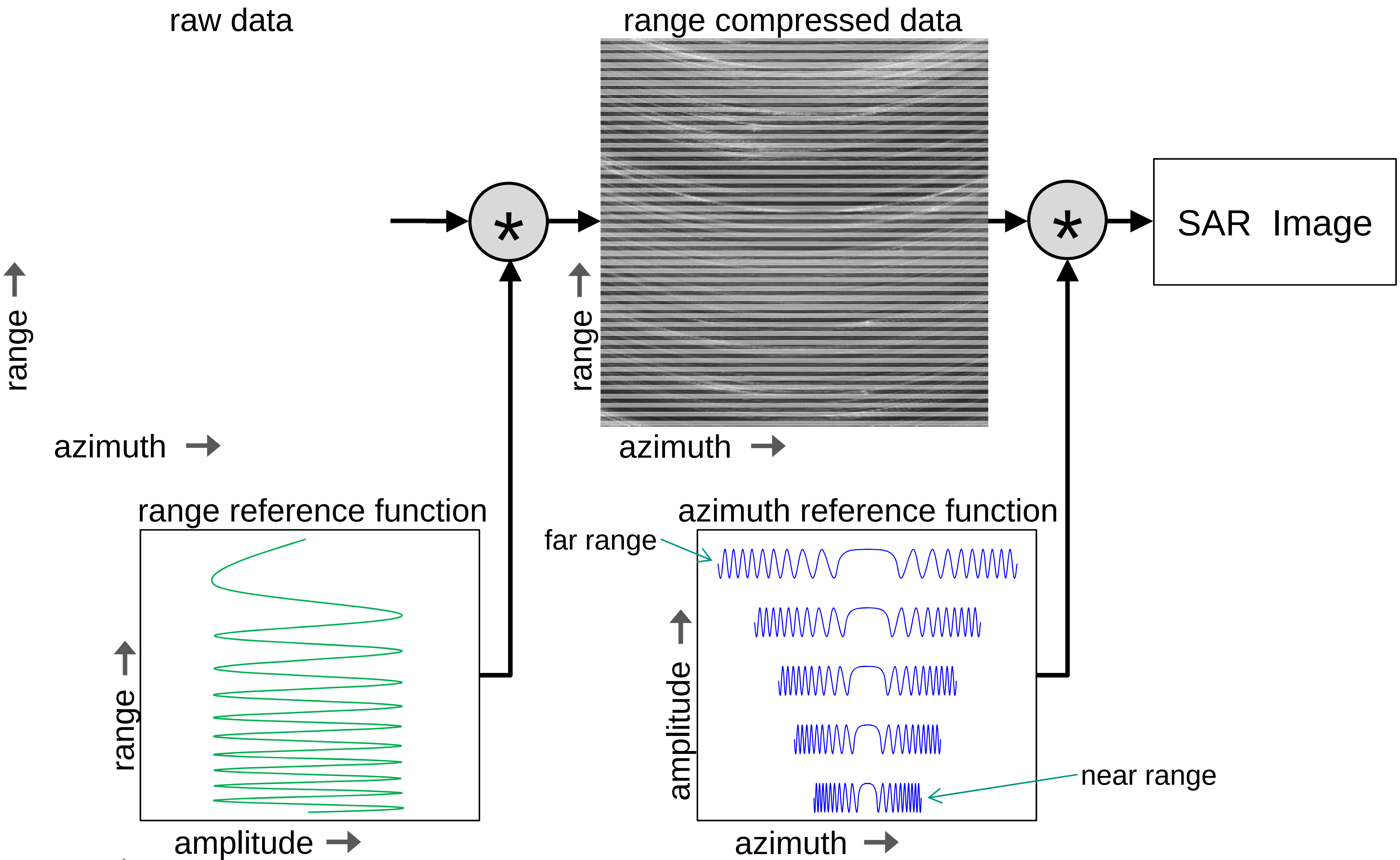
Linear Superposition of Chirps





SAR raw data

SAR Processing (Image Formation)



SAR Processing (Image Formation)

Summary: SAR Processing

1. Step: Range compression

- Generation of range reference function
- Matched filtering using convolution of range signal with range reference function

2. Step: Azimuth compression

- Generation of azimuth reference function
- Matched filtering using convolution of azimuth signal with azimuth reference function

3. Step: Calculation of the modulus of the SAR image (detection)

- This step is not required in case that the phase information is used (e.g. polarimetry, interferometry etc.)

Normally the convolution is carried out in frequency domain

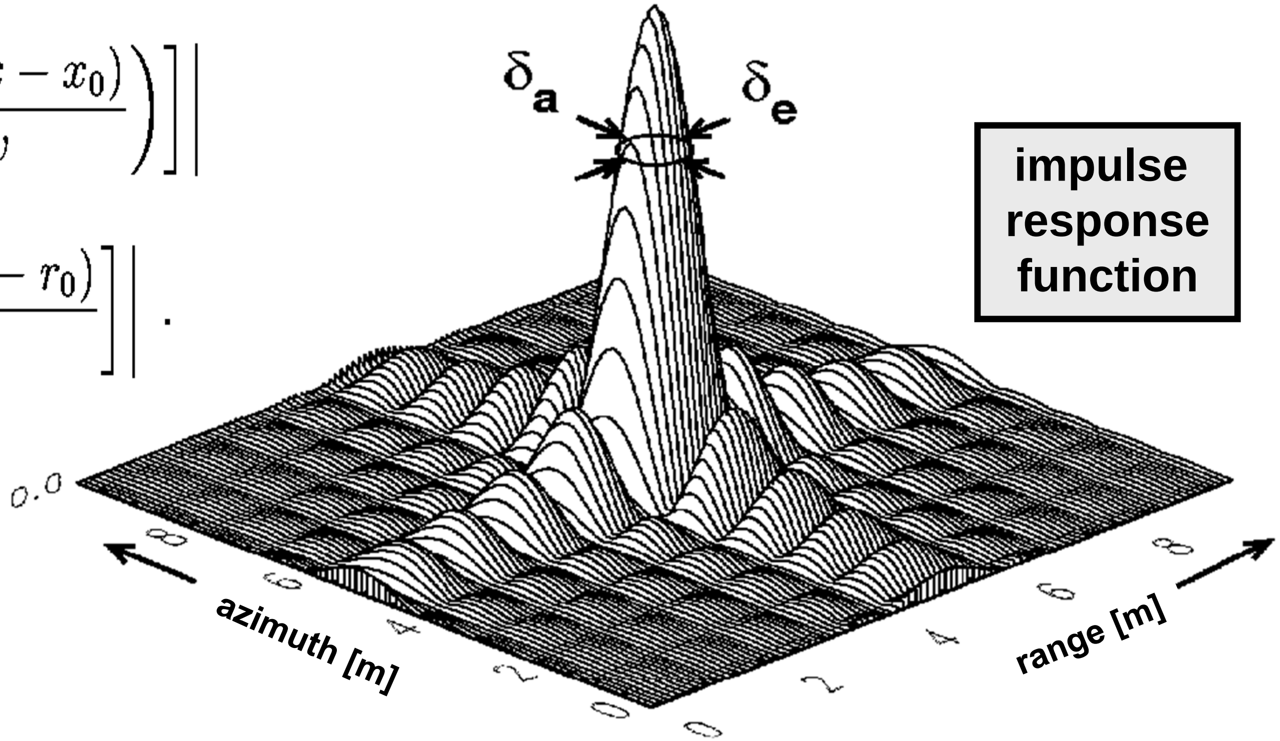
SAR Processing: 2D Matched Filter

$s_o\,(x, r)$ → **range compression** $h_e\,(x, r)$ → **azimuth compression** $h_a\,(x, r)$ → **detection** $\sqrt{u_i^2 + u_q^2}$ → **2D pulse** $|u_o\,(x, r)|$

SAR Processing

$$|u_a(x)| = \left| \sqrt{B_a \cdot T_a} \cdot \text{sinc}\left[\pi \cdot \left(\frac{B_a \cdot (x - x_0)}{v}\right)\right]\right|$$

$$|u_e(r)| = \left| \sqrt{B_e \cdot T_e} \cdot \text{sinc}\left[\frac{2\pi \cdot B_e \cdot (r - r_0)}{c_0}\right]\right| .$$



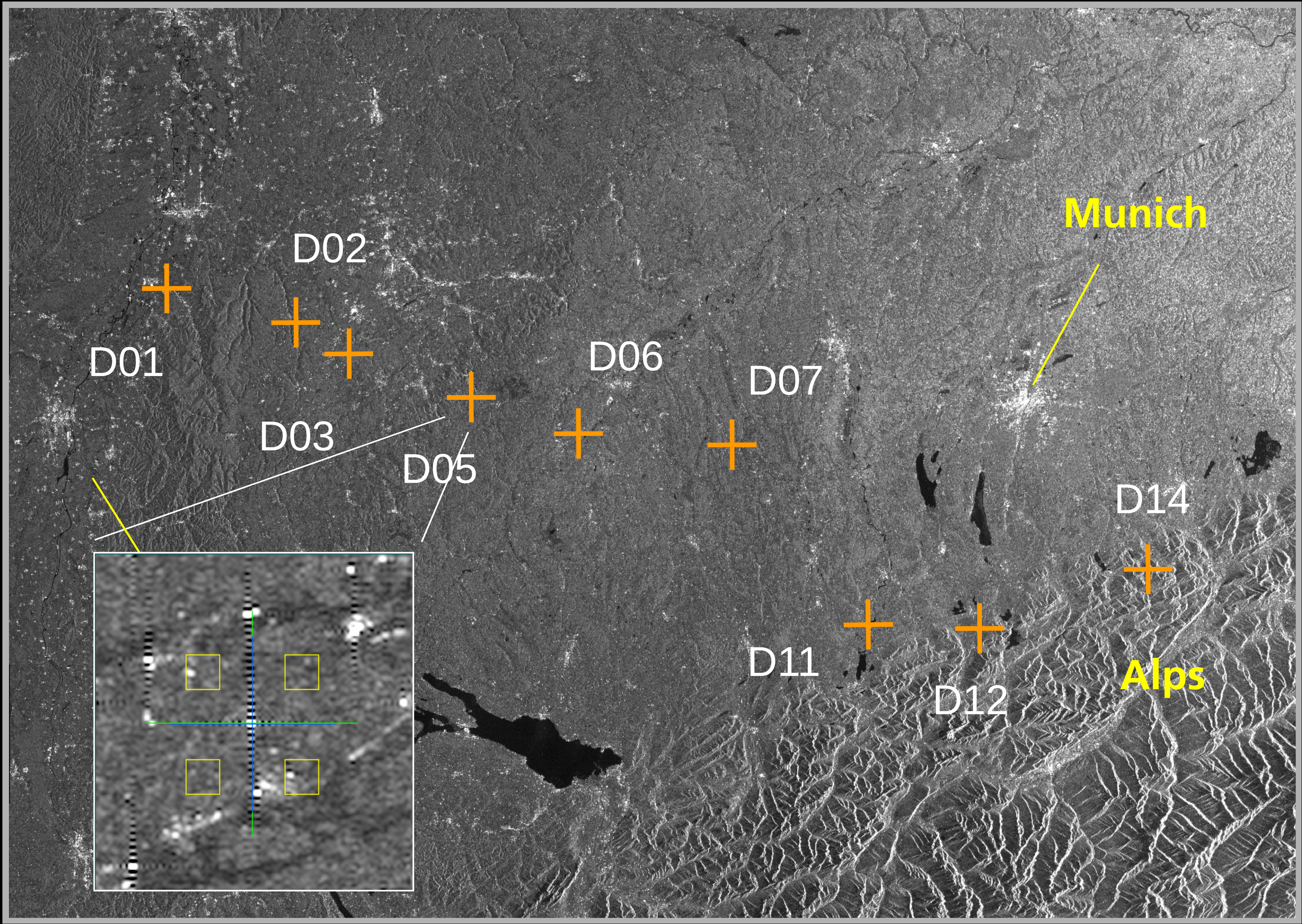
impulse response function

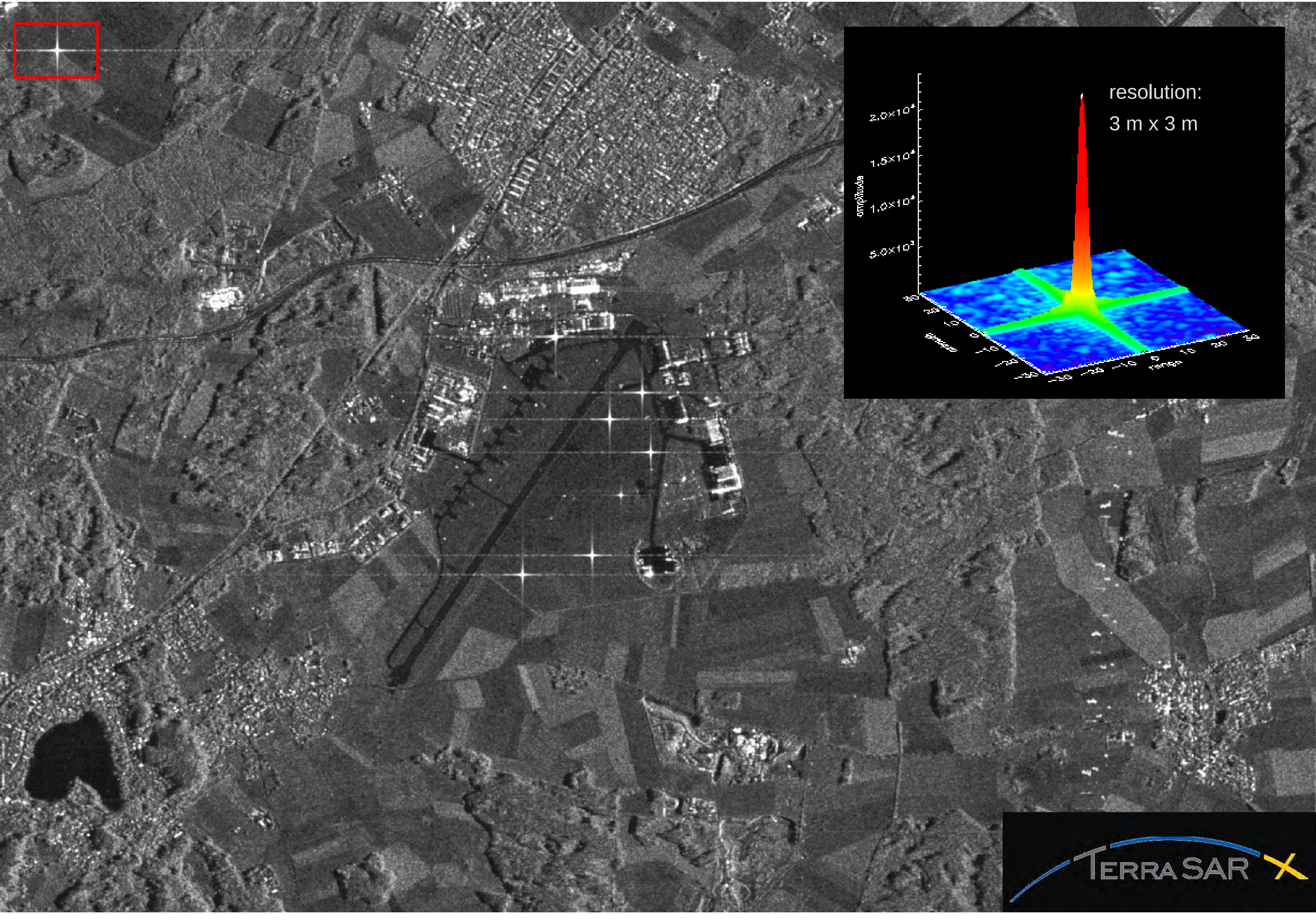
Calibration of SAR Images

Calibration Devices

- **Examples of calibration targets with well-known reflectivity (Radar Cross Section) for external calibration of the SAR system**

SAR Image of ASAR/ENVISAT, 12-10-02



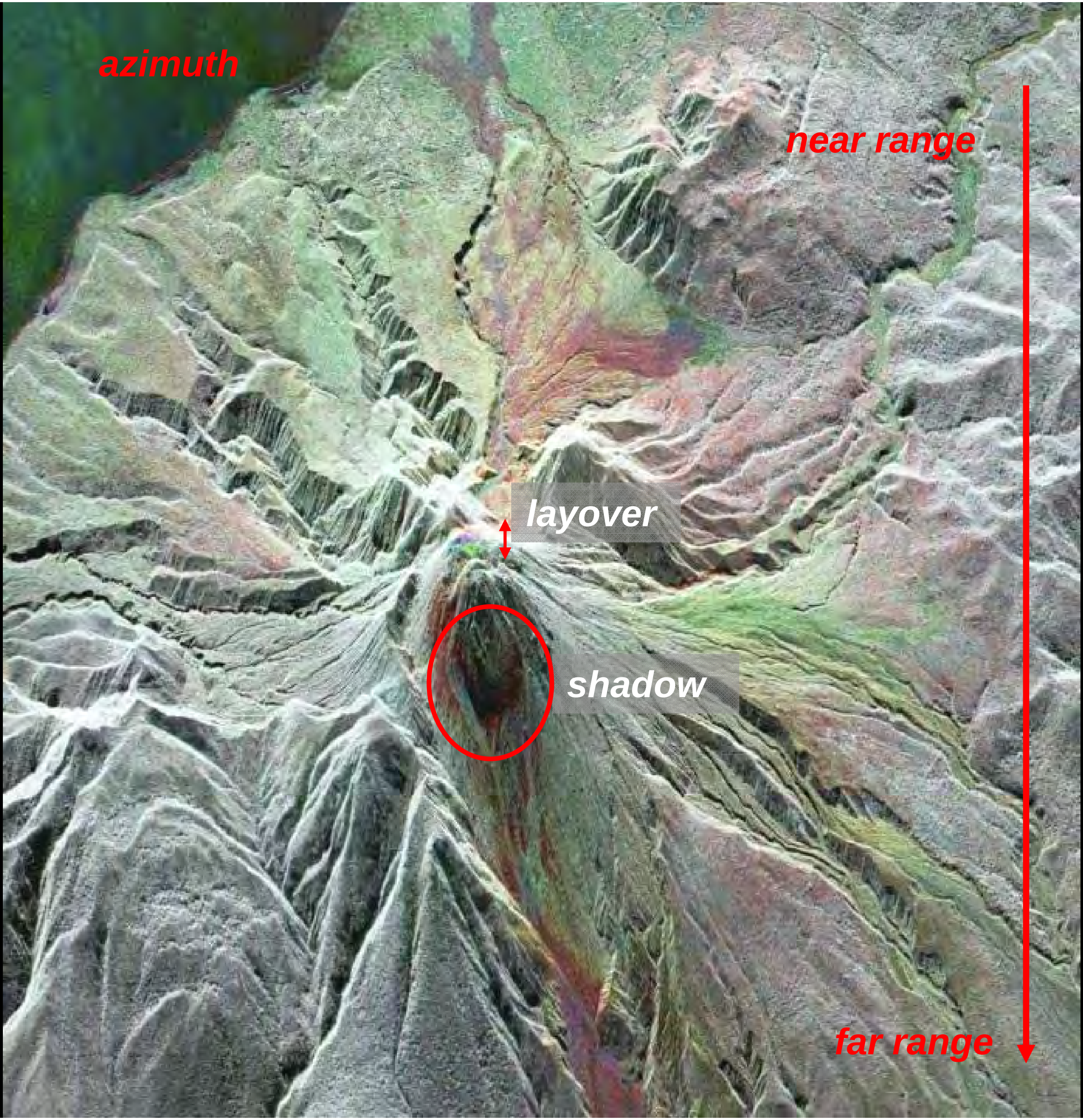

resolution:
3 m x 3 m
TERRA SAR

SAR Image Properties
– Geometric Distortions –

Montserrat Volcano

Stripmap

VV-pol.



- **9. Oct. 2007**

Eruption: 29. July 2008

- **1. Aug. 2008**
- **12. Aug. 2008**

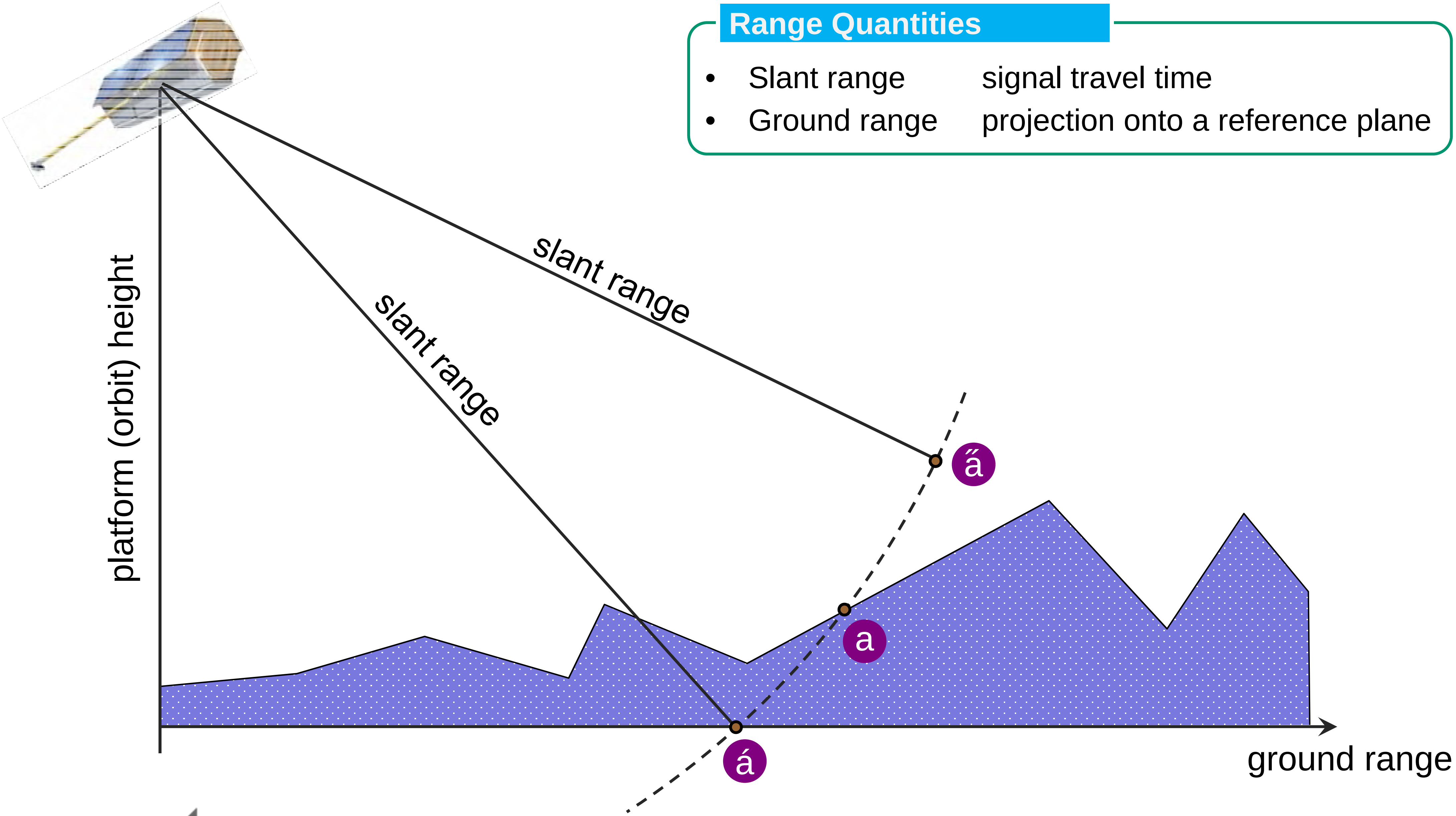
DLR

TERRASAR X

Slant-to-Ground-Range Conversion

Range Quantities

- Slant range — signal travel time
- Ground range — projection onto a reference plane



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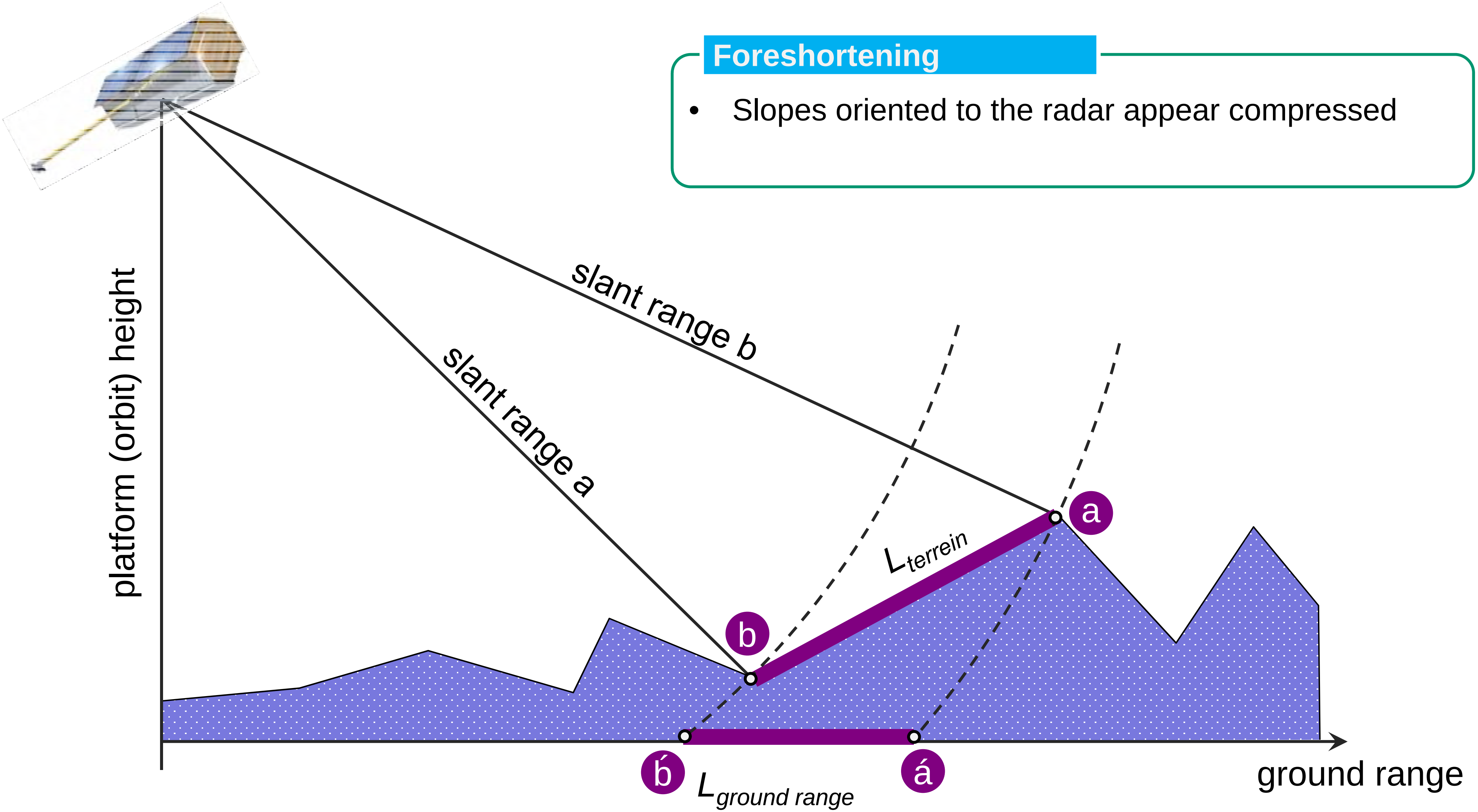
Geometric Distortion: Foreshortening

Foreshortening

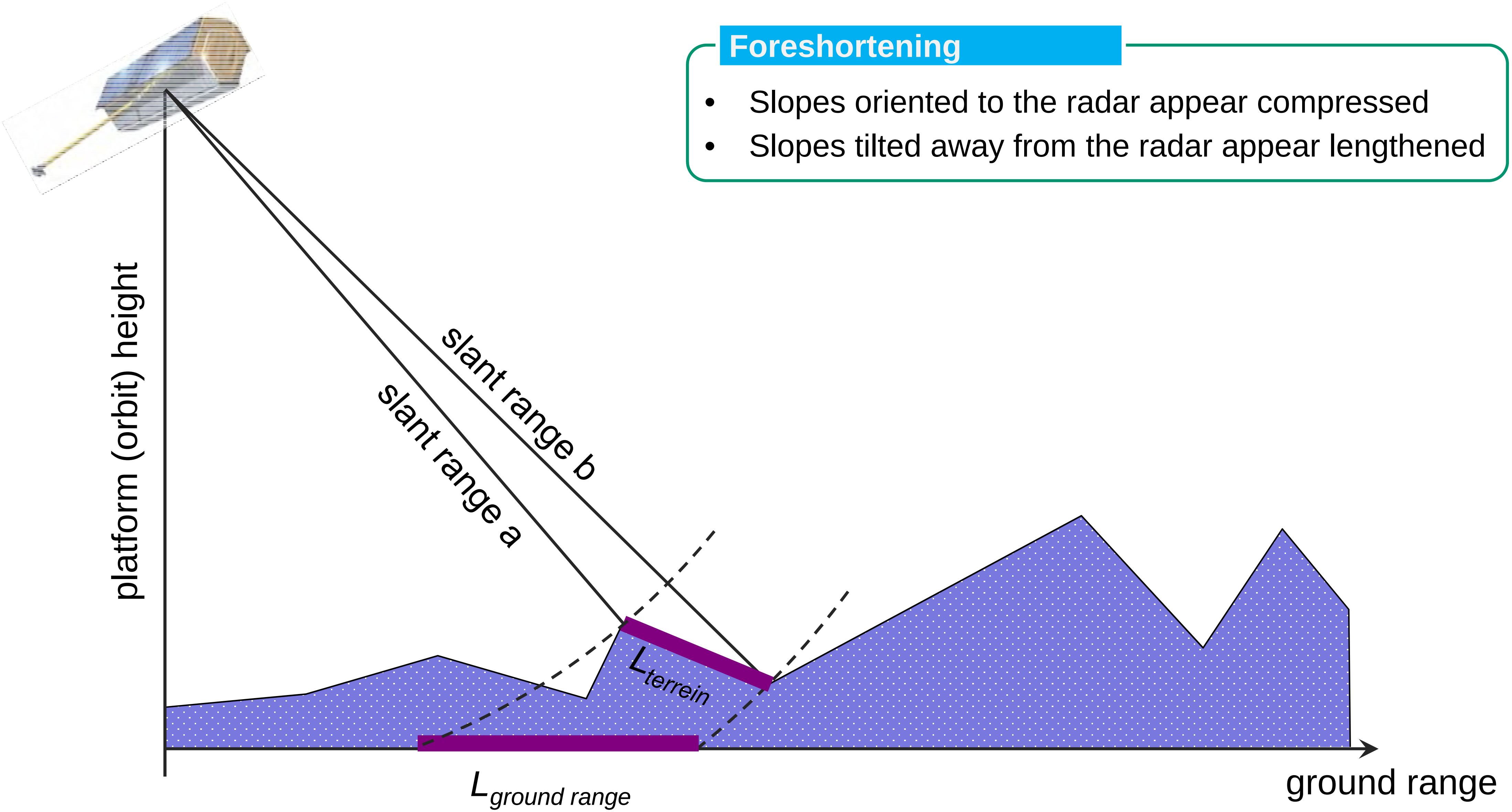
- Slopes oriented to the radar appear compressed



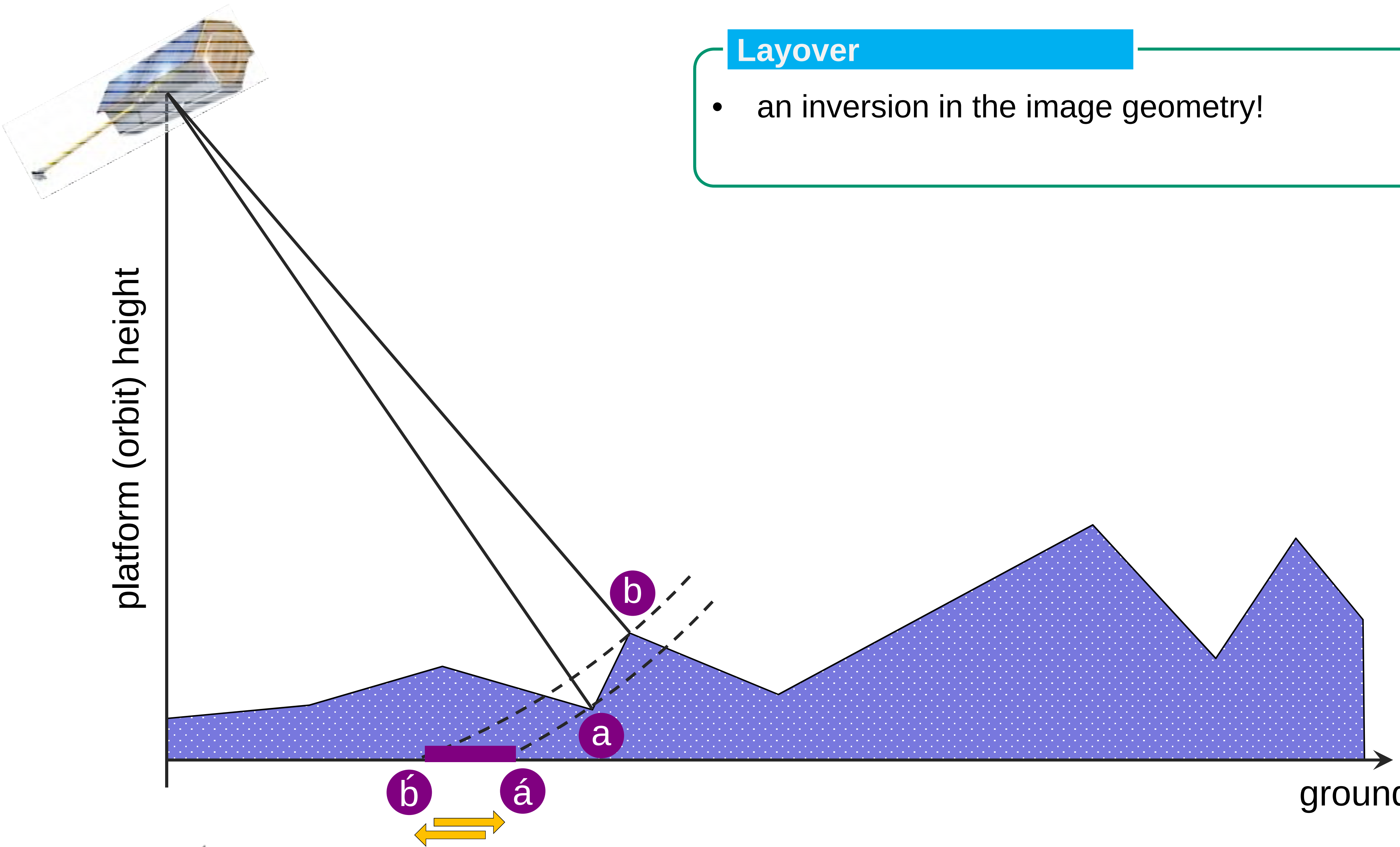
Geometric Distortion: Foreshortening

Foreshortening

- Slopes oriented to the radar appear compressed
- Slopes tilted away from the radar appear lengthened



Geometric Distortion: Layover



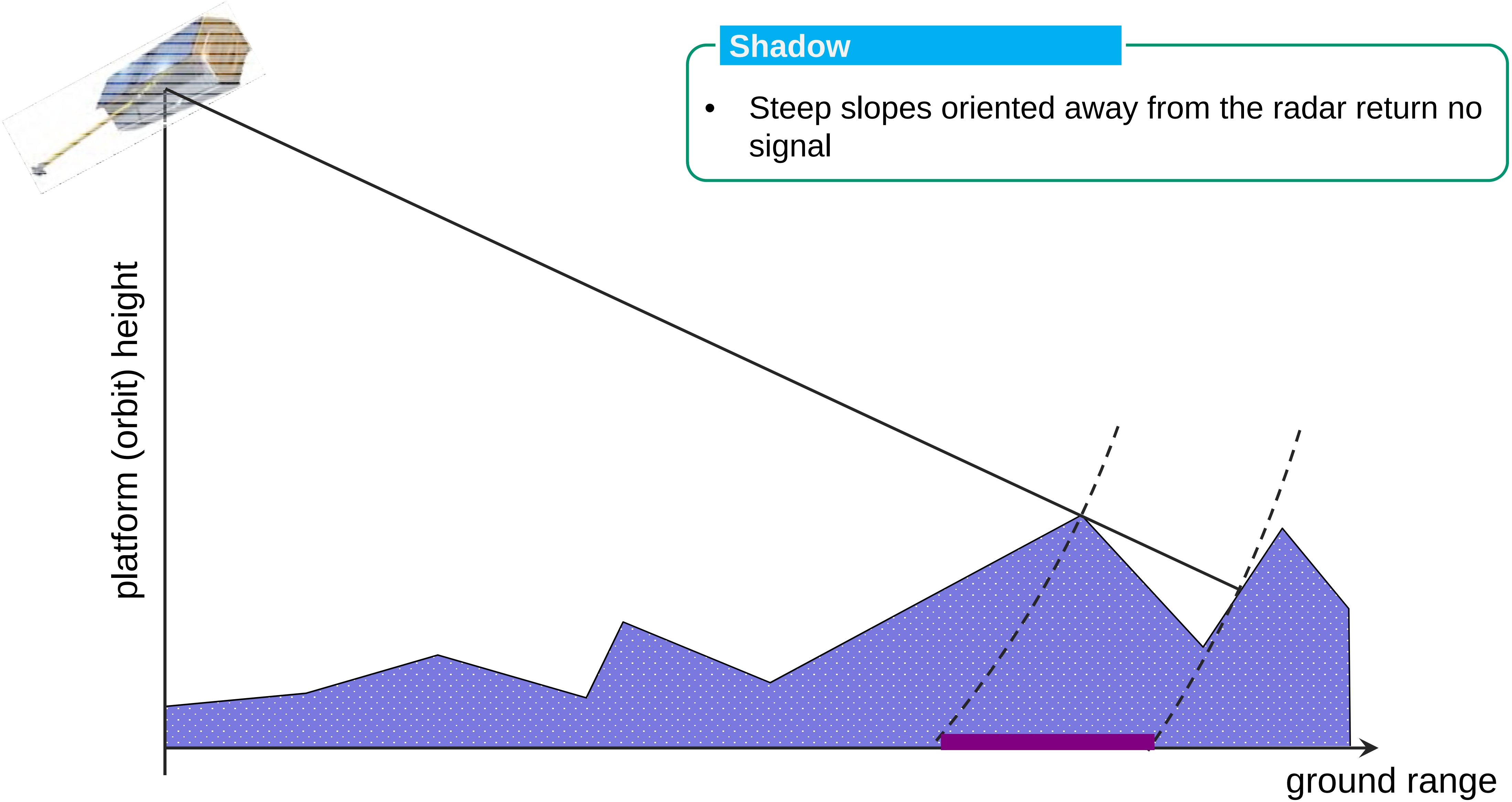
Layover

- an inversion in the image geometry!

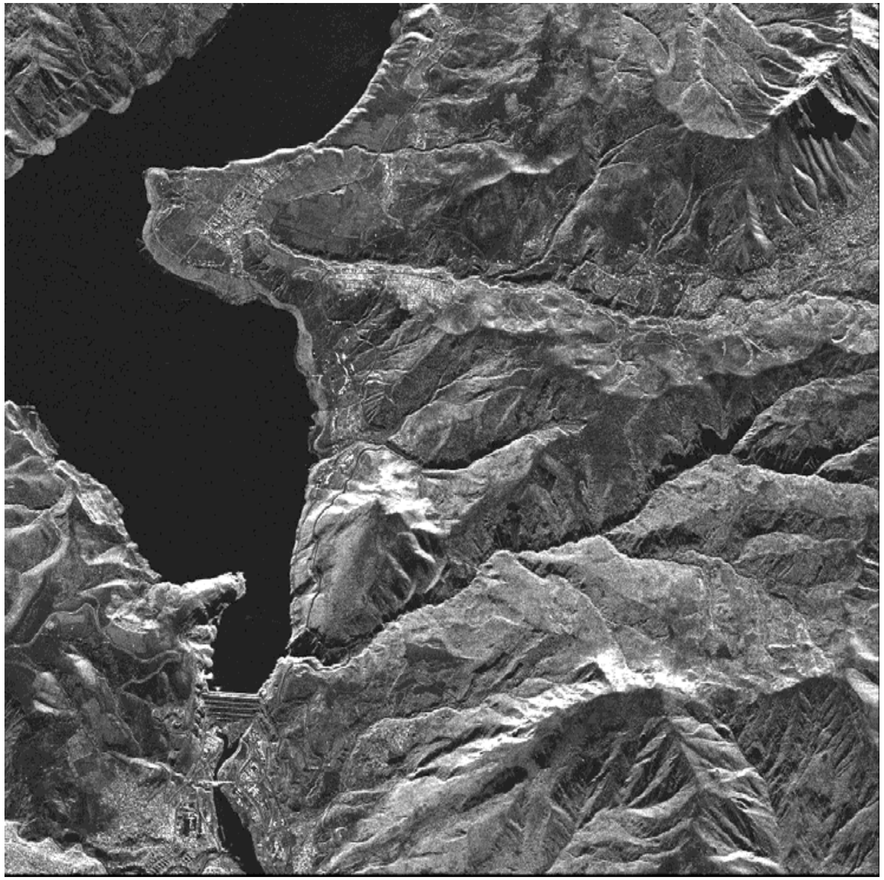
Geometric Distortion: Shadow

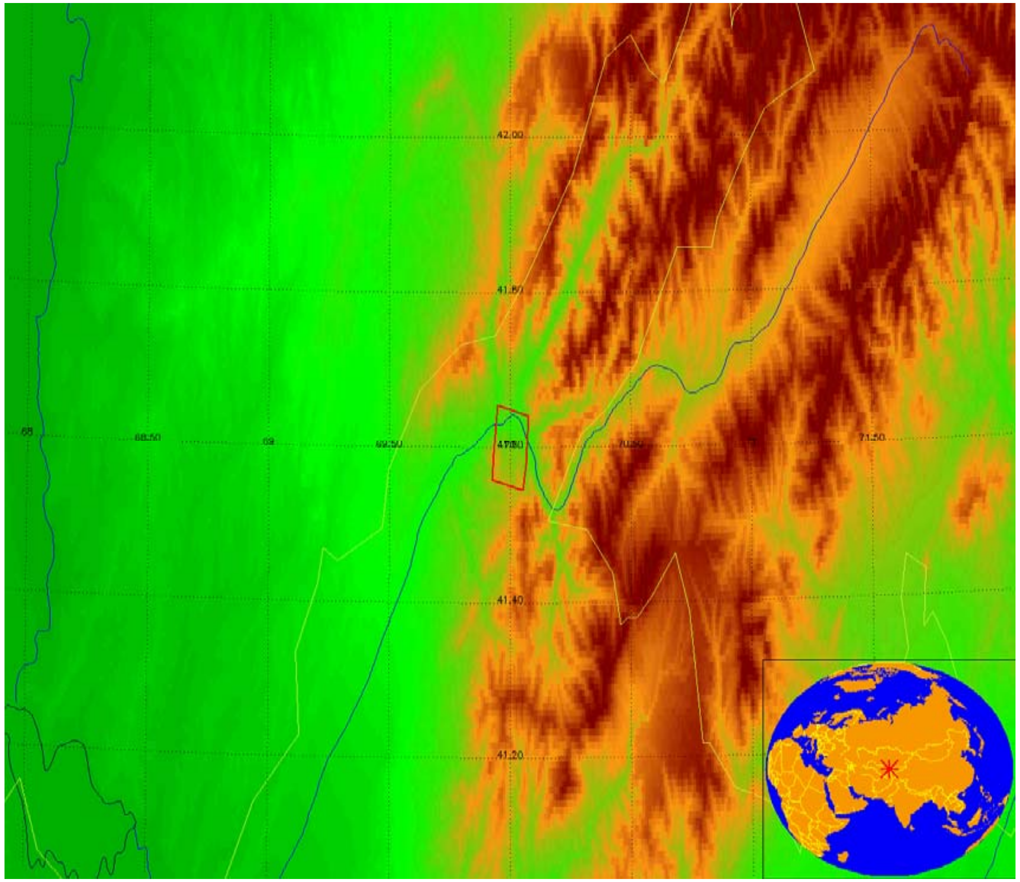
Shadow

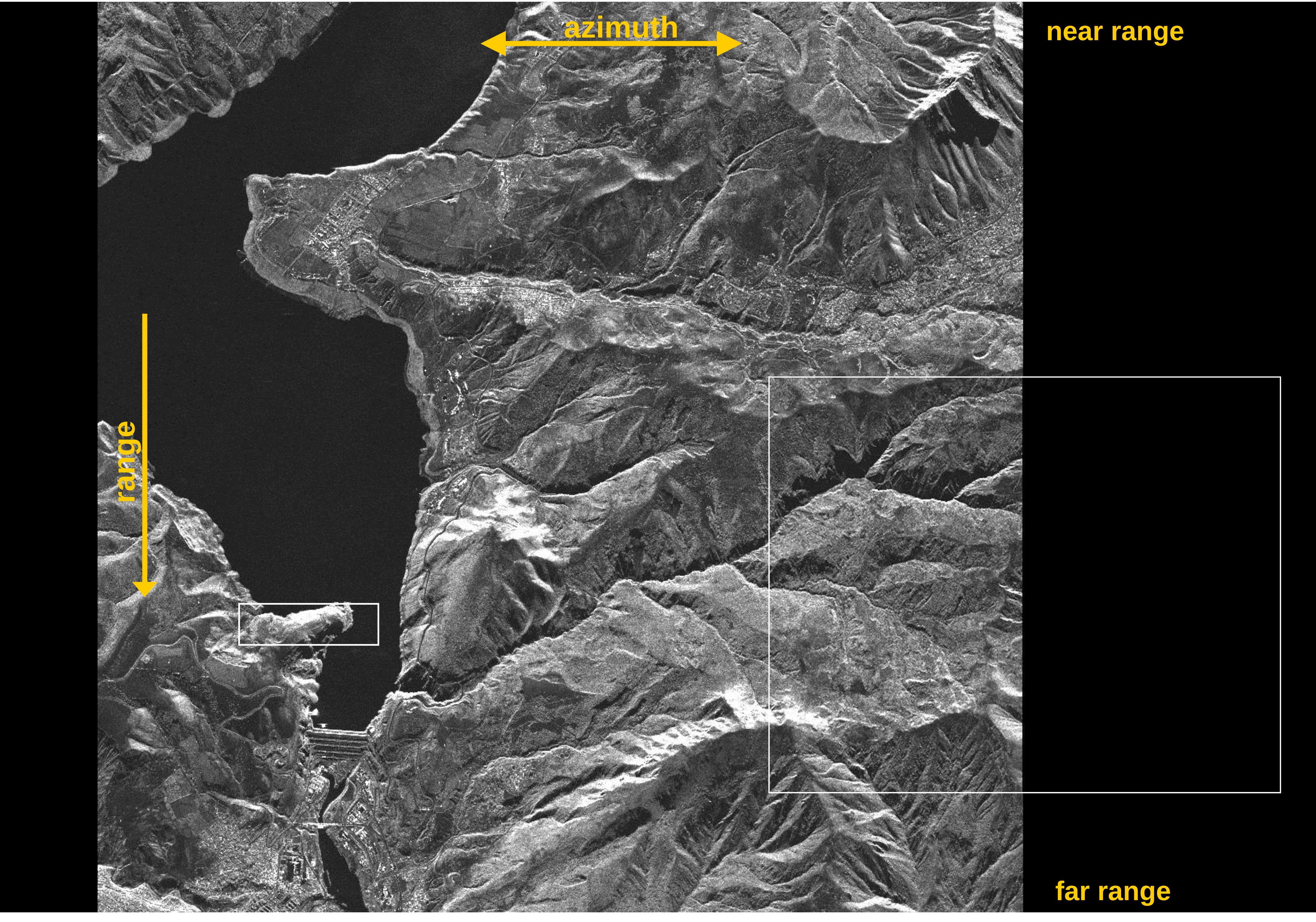
- Steep slopes oriented away from the radar return no signal



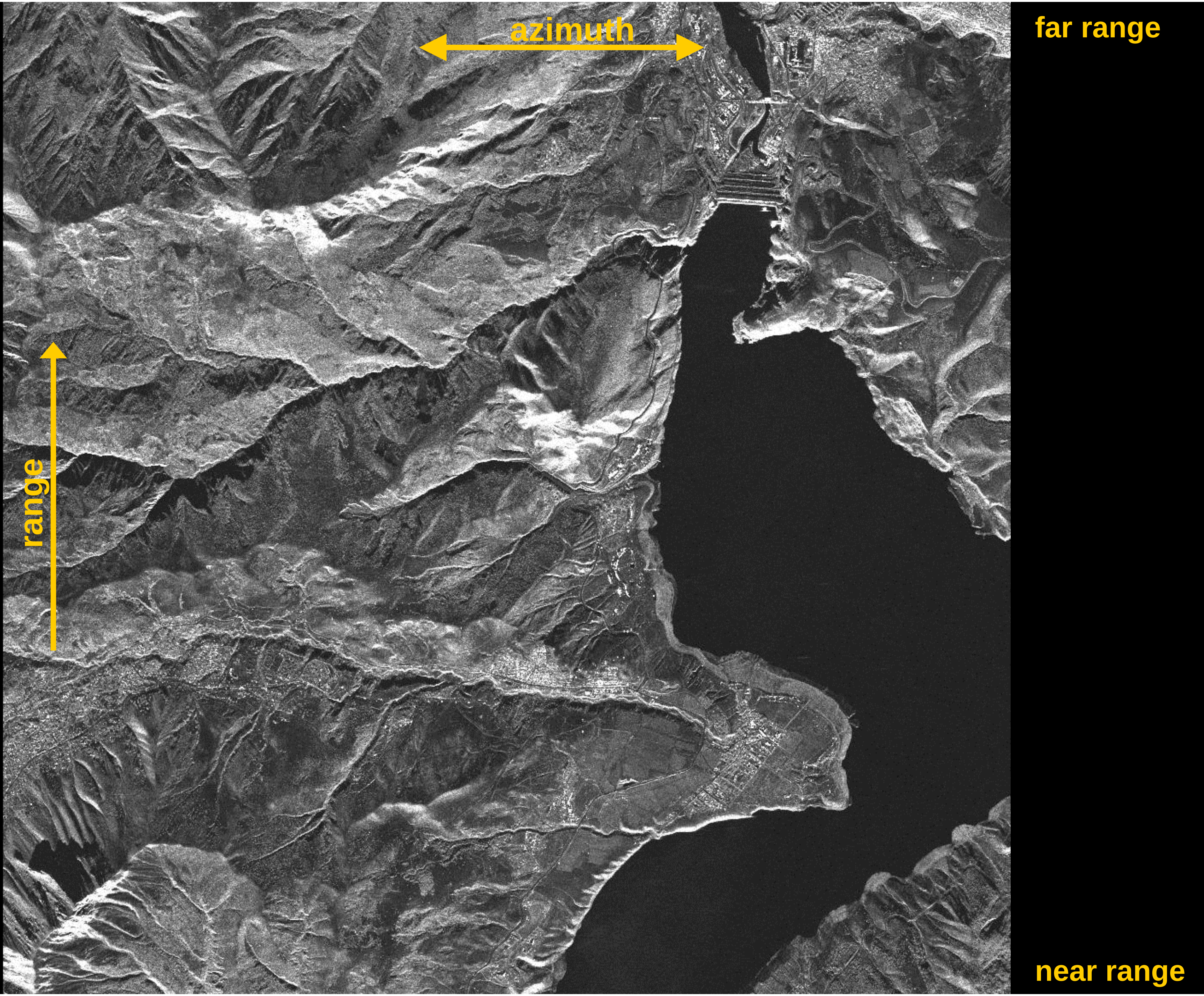
Consider the radar image below. What is the illumination direction of the radar?







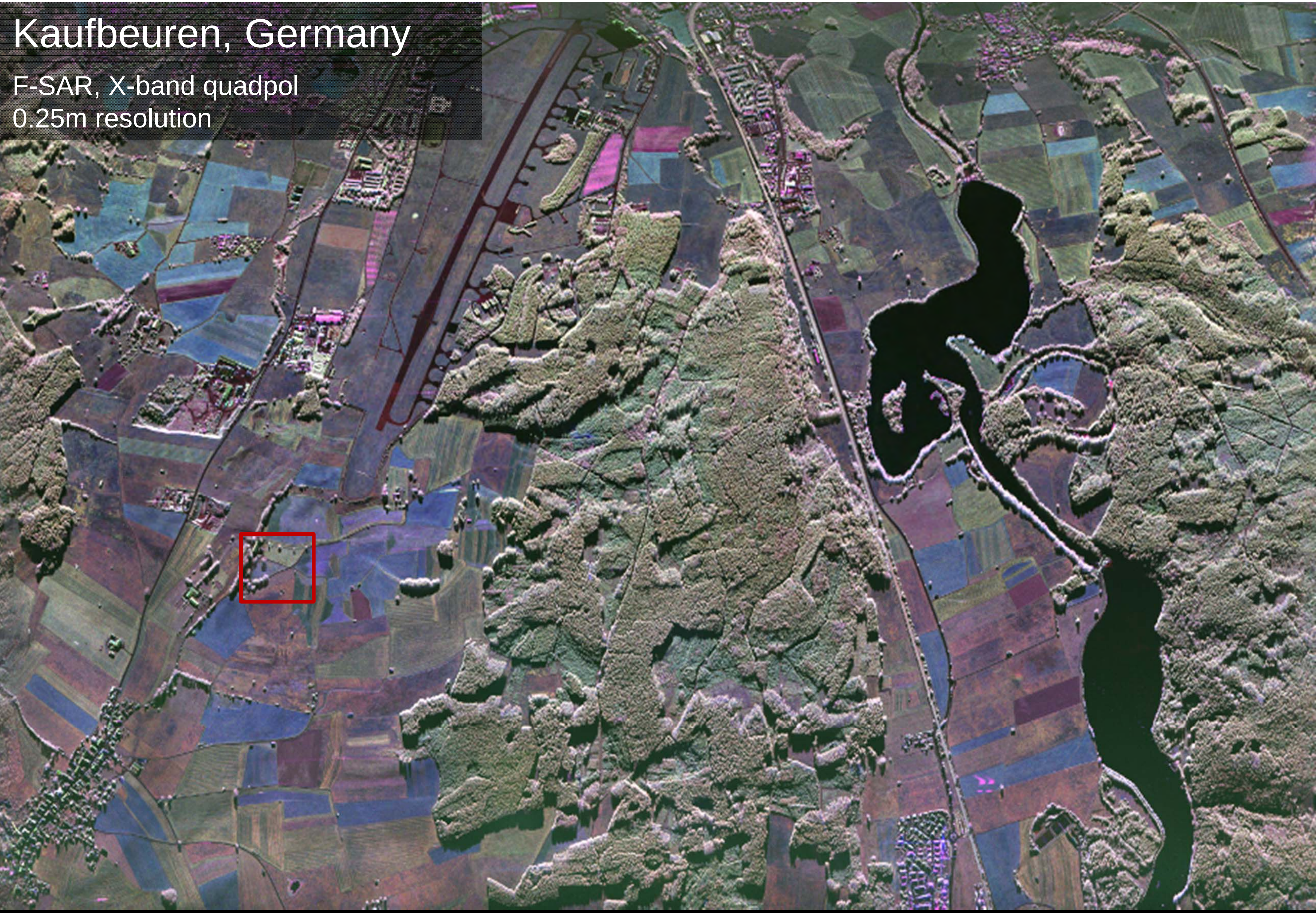
azimuth
range
near range
far range

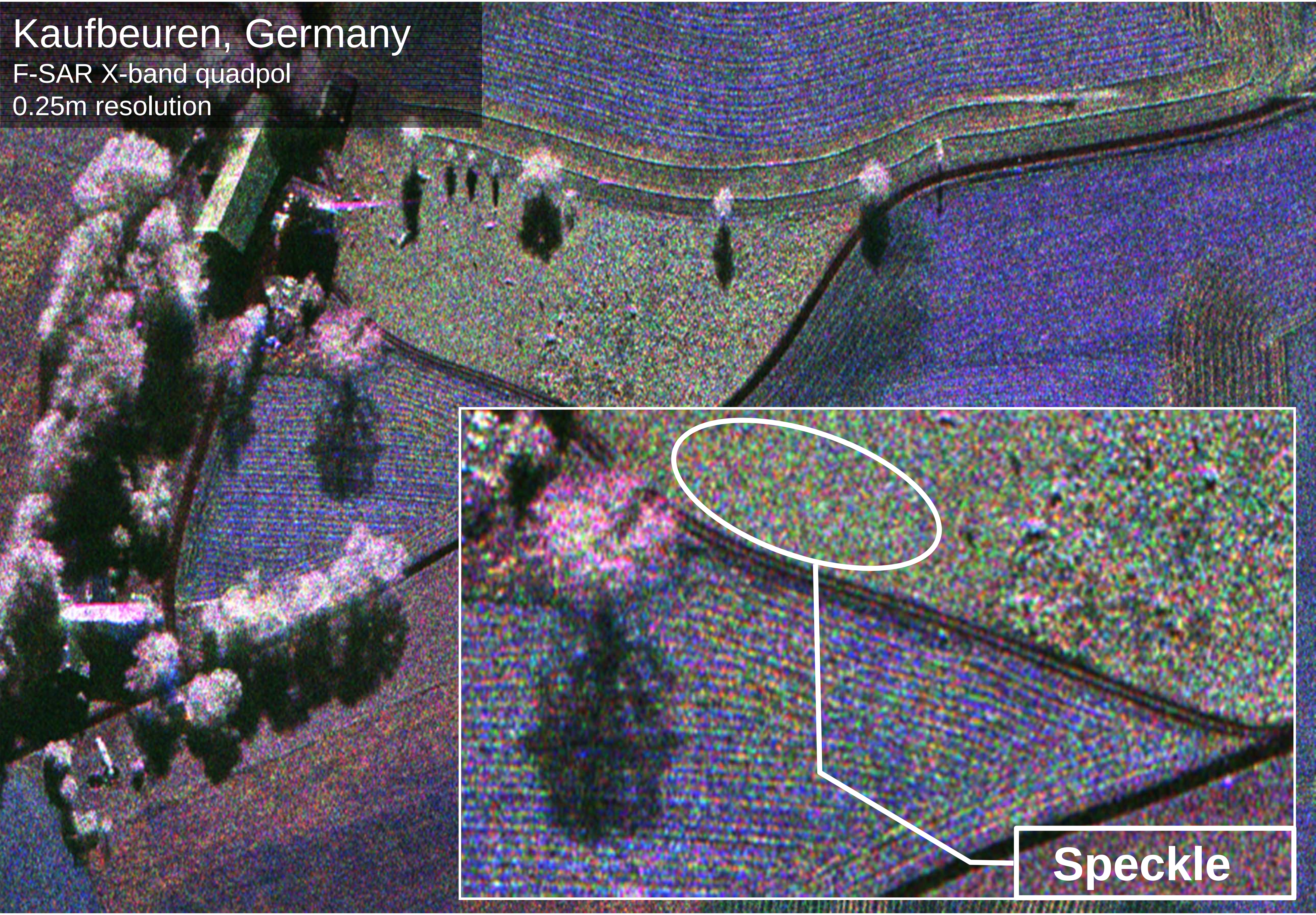

azimuth
range
far range
near range

SAR Image Properties

– Speckle –


ERS-1 image /© ESA


Kaufbeuren, Germany
F-SAR, X-band quadpol
0.25m resolution


Kaufbeuren, Germany
F-SAR X-band quadpol
0.25m resolution
Speckle

SAR signal modeling

- SAR image can be modeled as:

$$|u(x, r)| = |\, \gamma\,(x, r) \otimes u_o\,(x, r)\,|$$

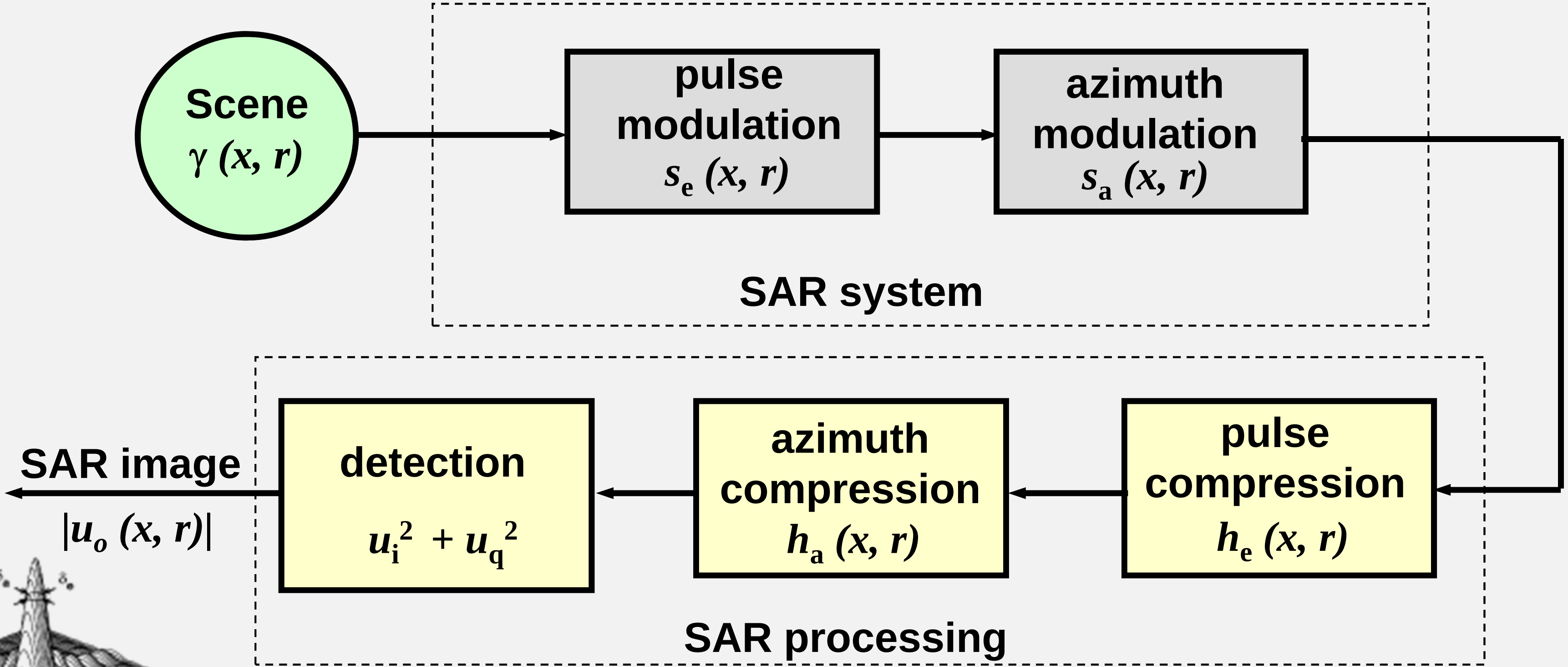
- For a point target: $\gamma = 1$

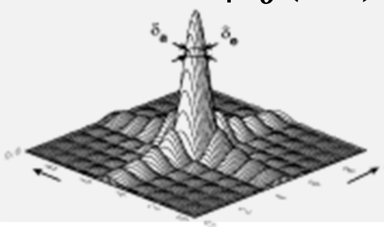
where

$|u(x, r)|$ *SAR image*

$\gamma\,(x, r)$ *scene complex reflectivity*

$u_o\,(x, r)$ *SAR impulse response*





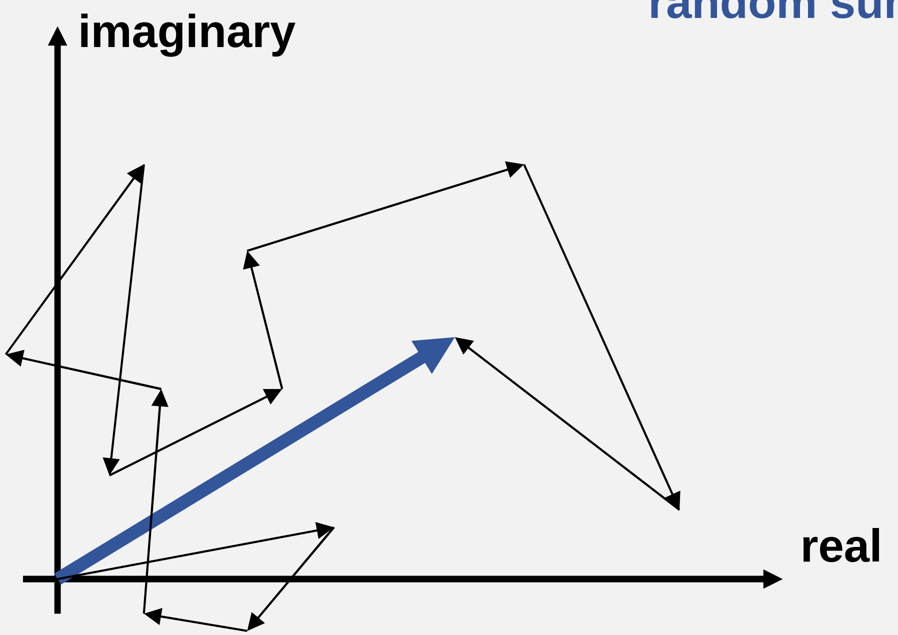
SAR signal modeling

- Distributed targets have surface roughness comparable or smaller than radar wavelength

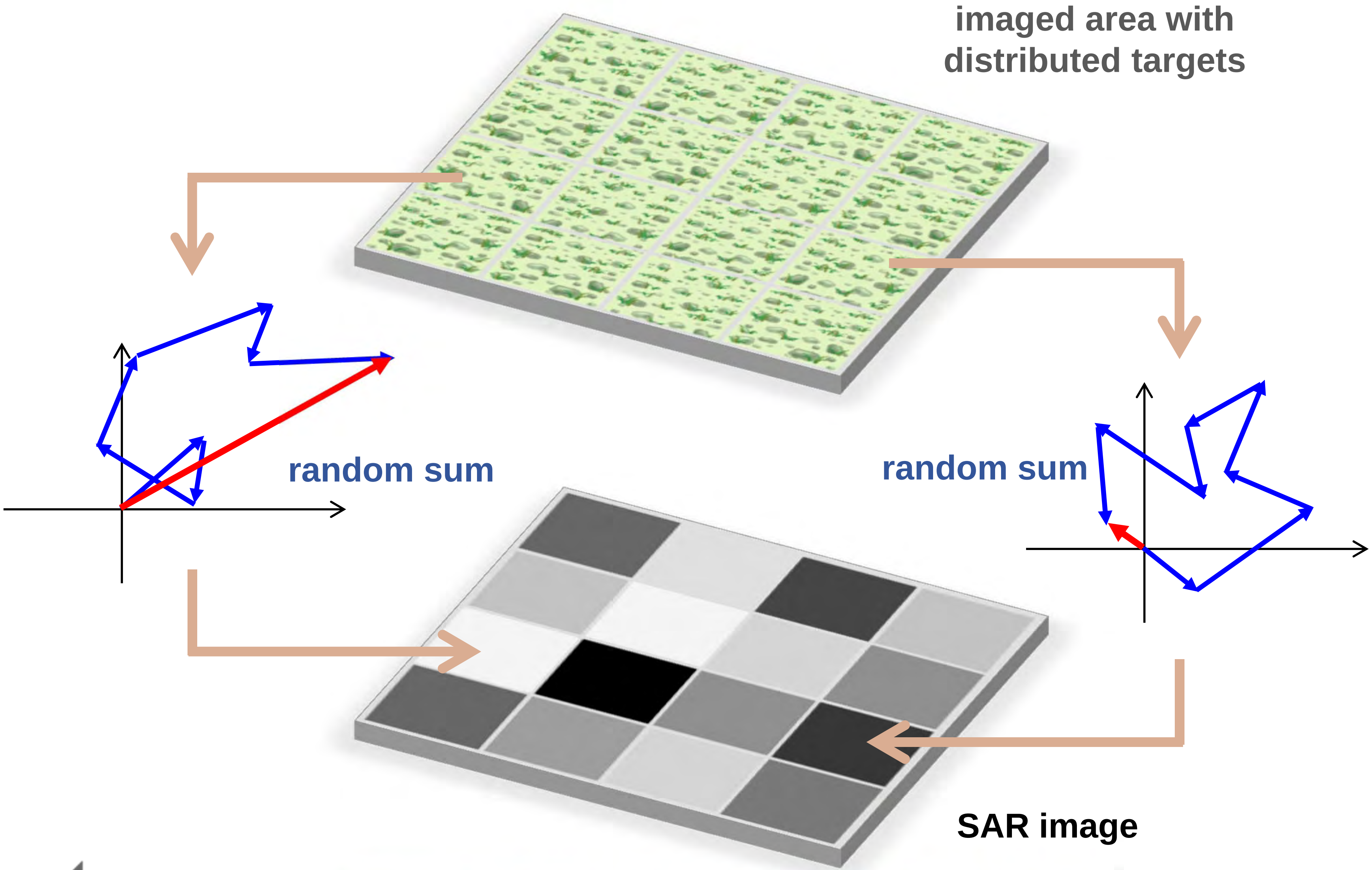
- Resolution of the SAR sensor cannot resolve individual scatterers

- For each resolution cell, $\gamma\ (x, r)$ is equal to the sum of all scatterers contributions i. e.

$$|u(x_o, r_o)| = |\ \gamma\ (x_o, r_o) \otimes u_o\ (x, r)\ | = |\ \underbrace{\sum \gamma_i\ (x_o, r_o)}_{\text{random sum}} \otimes u_o\ (x, r)\ |$$



Speckle

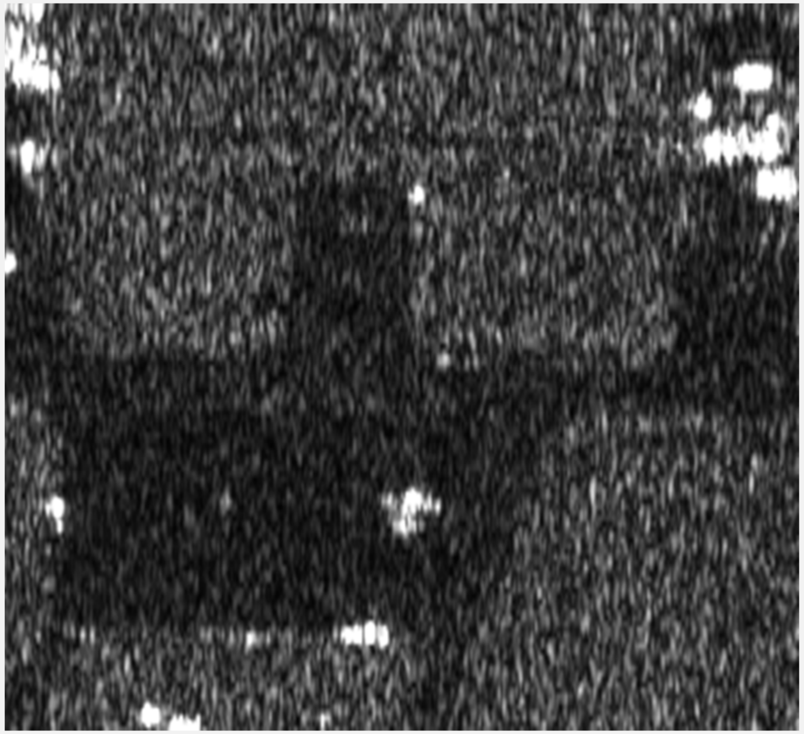

imaged area with
distributed targets
random sum
random sum
SAR image

Speckle

- Inherent to coherent systems
- Probability distribution function has a exponential distribution, i.e.

average value = standard deviation

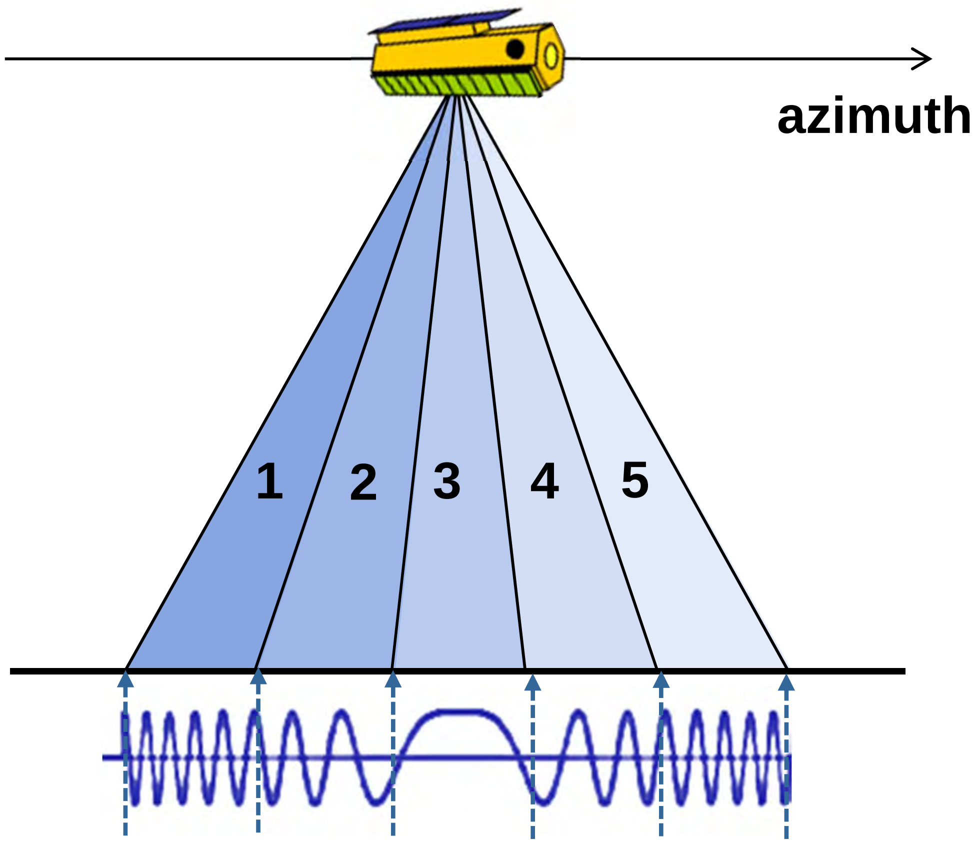
- Speckle makes SAR image interpretation more difficult



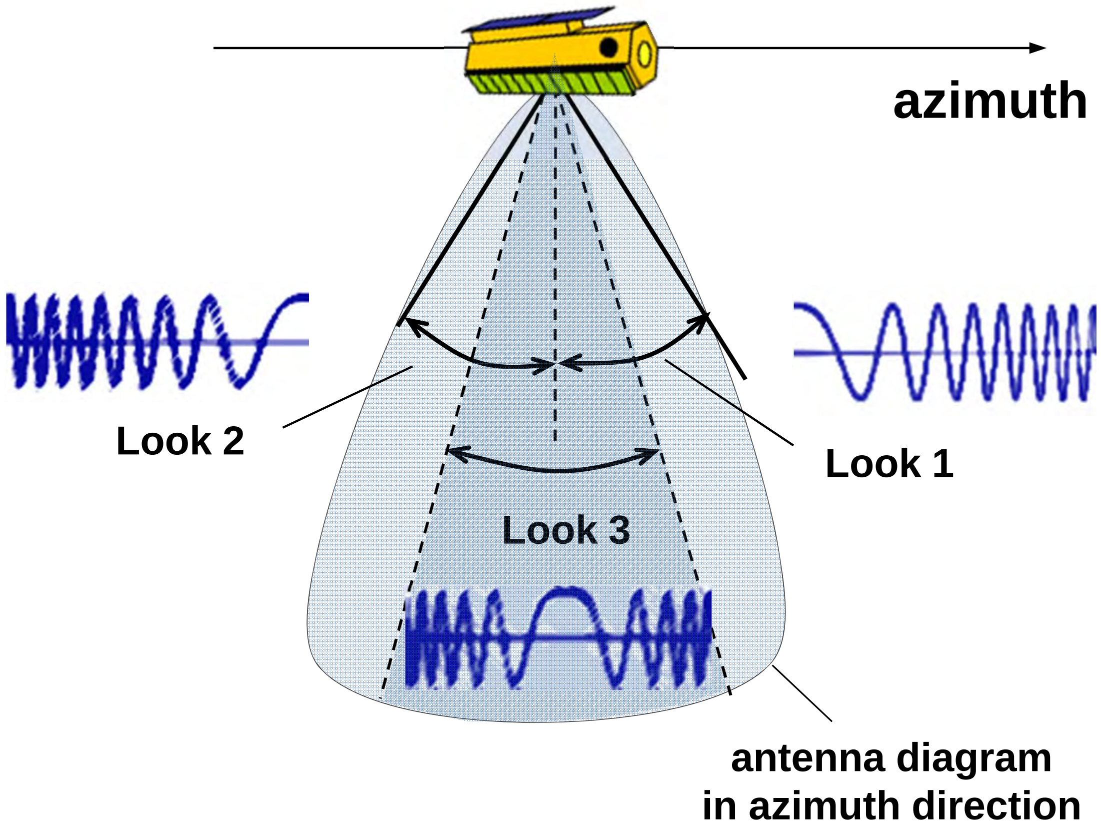
E-SAR high resolution image
(0.6 m x 2 m)

Multi-Look Processing

5 azimuth looks

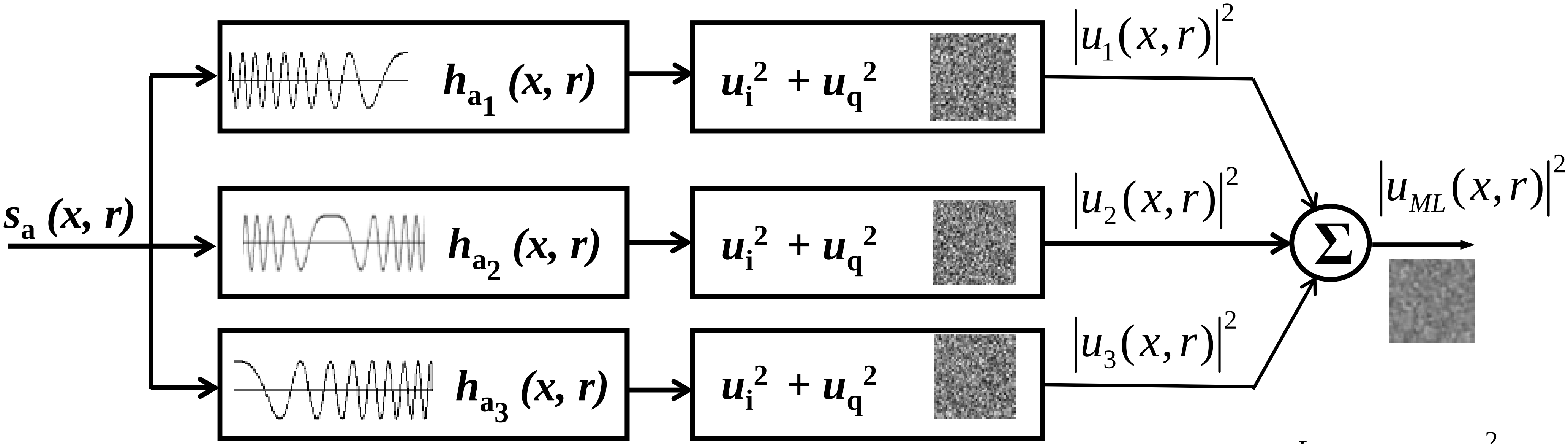


3 looks with 50% overlap



→ overlap of 50% between the looks is commonly used.

Multi-Look Processing (@ SAR Processor)



• **SAR impulse response function with multi-looking (L looks):** $|u_{ML}(x,r)|^2 = \dfrac{\sum_{i=1}^{L} |u_i(x,r)|^2}{L}$

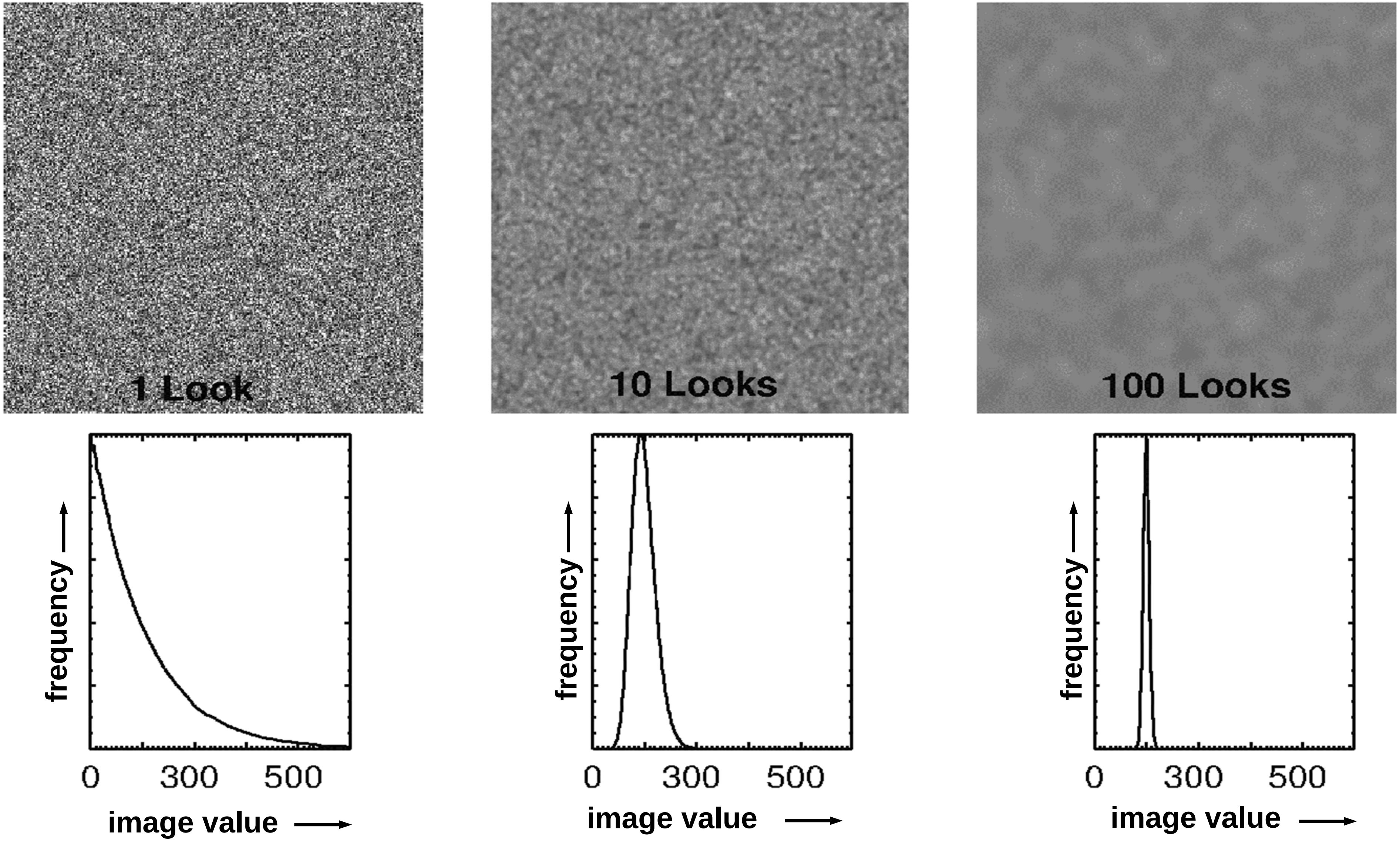
• **azimuth resolution deteriorates:** $\delta_{a,ML} = \delta_a . L$

• **Standard deviation of the speckle noise is reduced by the square root of the number of looks:**

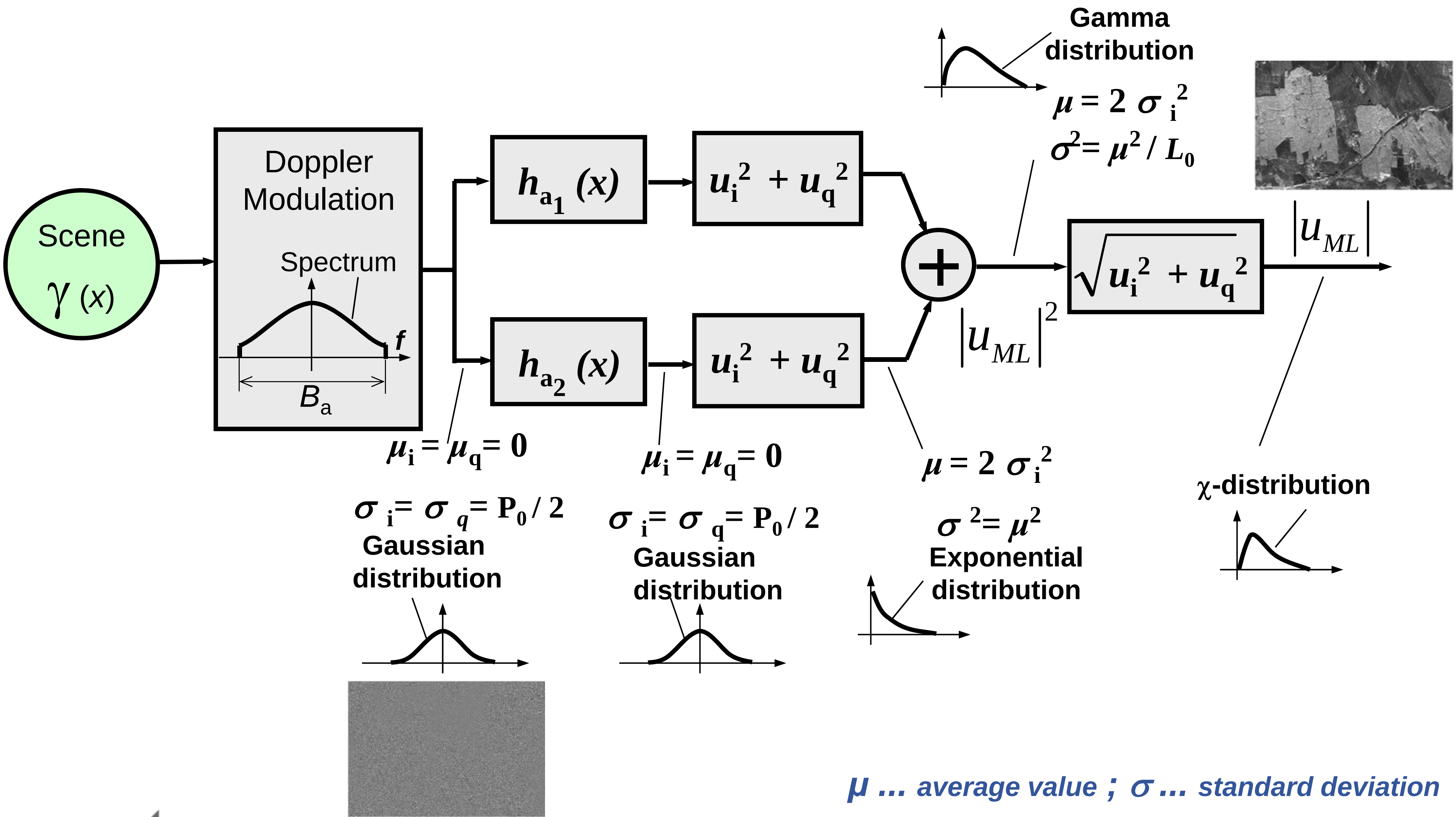
standard deviation = average value / sqrt(L)

DLR

Multi-Look Processing

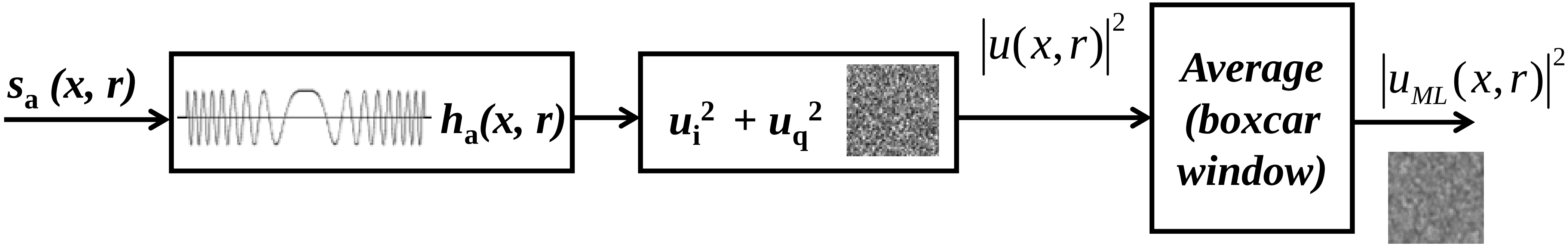


Statistics of SAR Signal for Distributed Targets



μ … average value ; σ … standard deviation

Multi-Look Processing (@ SAR Image)



• SAR impulse response function with average of L image pixels: $$|u_{ML}(x,r)|^2 = \frac{\sum_{n,m=1}^{n+m=L} \left|u\left(x_n, r_m\right)\right|^2}{L}$$

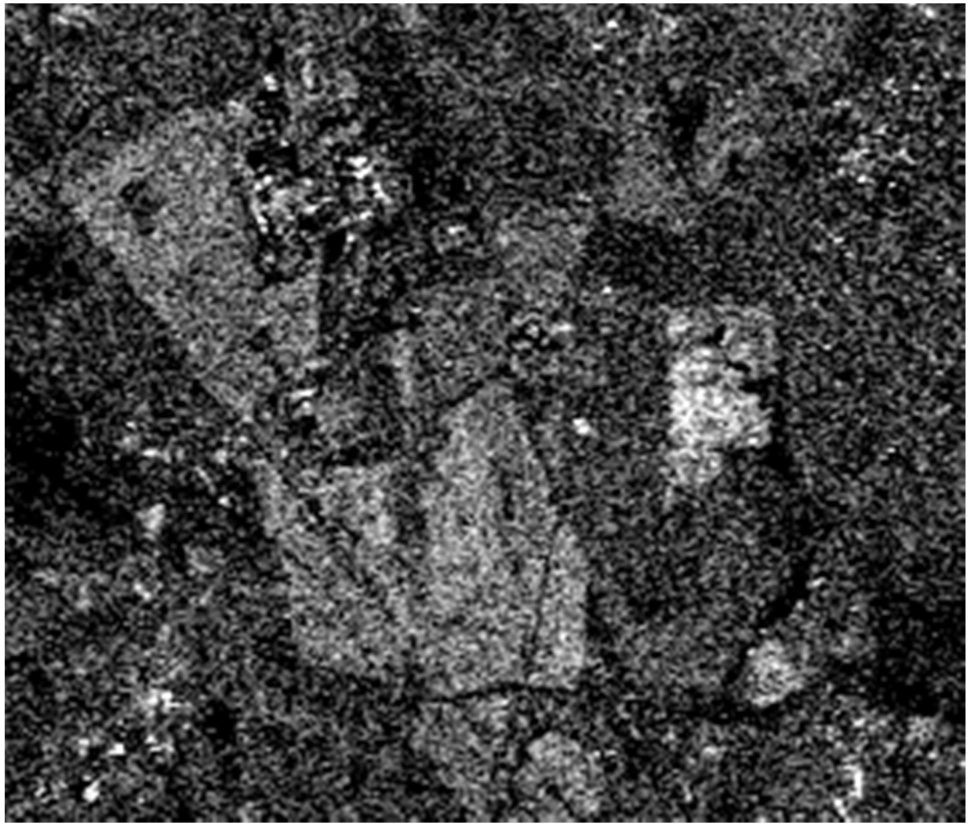
• azimuth resolution deteriorates: $\delta_{a,ML} = \delta_a . L$

L = number of looks

• Standard deviation of the speckle noise is reduced by the square root of the number of looks:

standard deviation = average value / sqrt(L)

Single-Look and Multi-Look Processing



5 looks

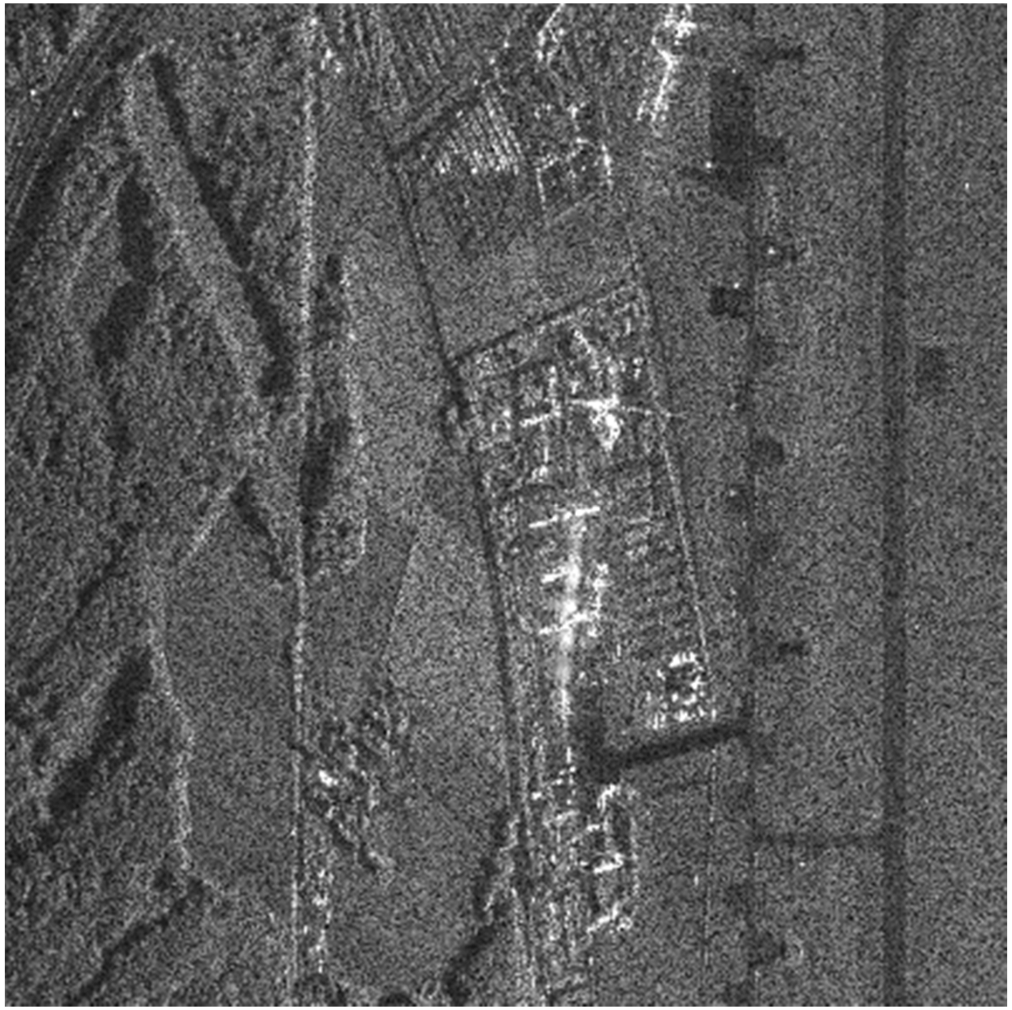
20 m x 20 m resolution

320 looks (average of 64 images)

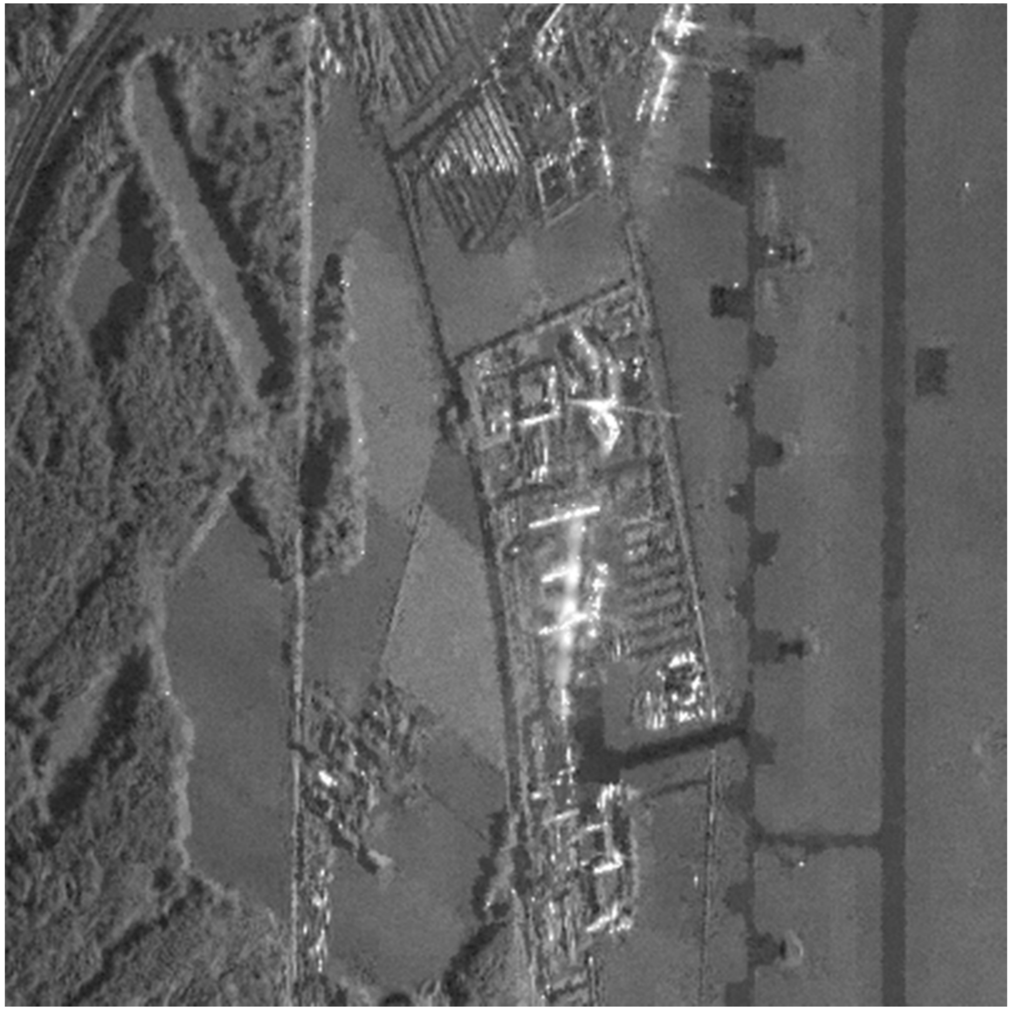
20 m x 20 m ground resolution

ERS-1 satellite images (processing DLR-IMF)

Speckle Reduction with Image Filtering



original SAR image (1 look)
Airborne SAR AeS-1



speckle filtered
Adaptive Filtering
(Model based approach)

Summary: Speckle

• SAR image of distributed targets contains speckle noise.

• Speckle noise is inherent in coherent radar systems.

• The average value of the speckle amplitude is equal to its standard deviation (exponential distribution).

• Multi-look processing or spatial averaging is used to reduce the speckle noise. Standard deviation decreases with $\sqrt{L_{eff}}$.

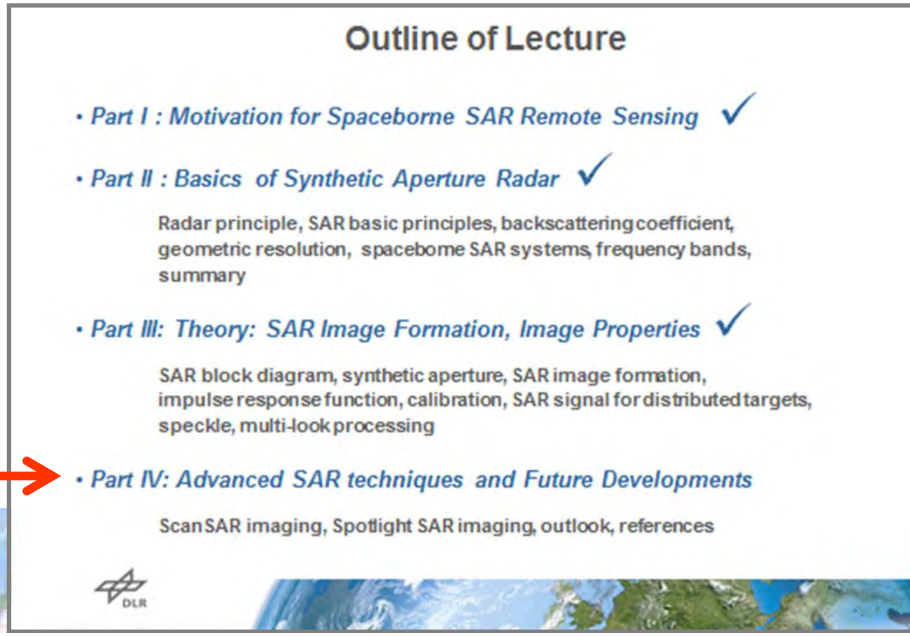
• An overlap of 50% between the looks is commonly used.

• Speckle noise can also be reduced by averaging the final image

PART IV

Advanced SAR Techniques

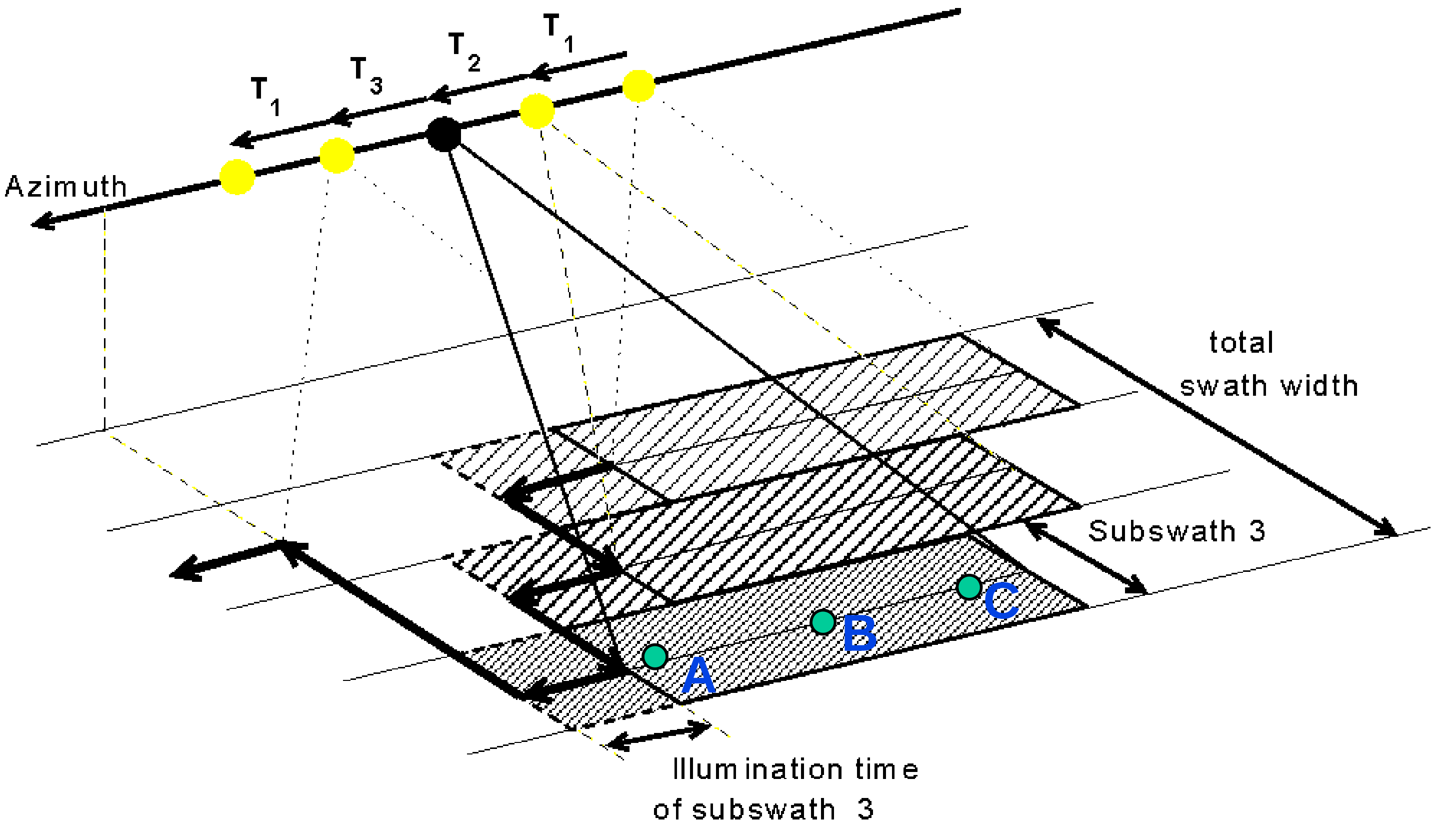
and Future Developments



DLR

Advanced SAR Imaging Modes
- ScanSAR Mode -

ScanSAR Imaging

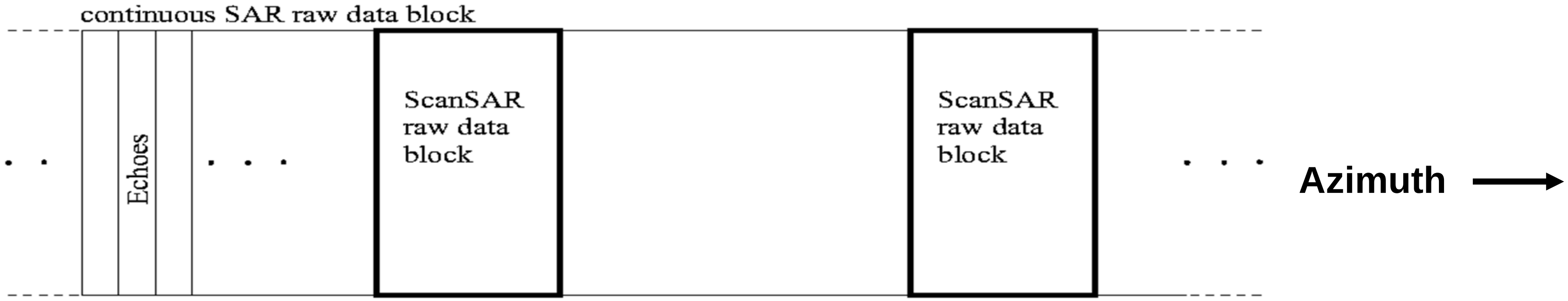


- Synthetic aperture is shared between the subswaths (not contiguous within one subswath)
- Mosaic Operation is required in azimuth and range directions to join the azimuth bursts and the range sub-swaths

ScanSAR Main Properties

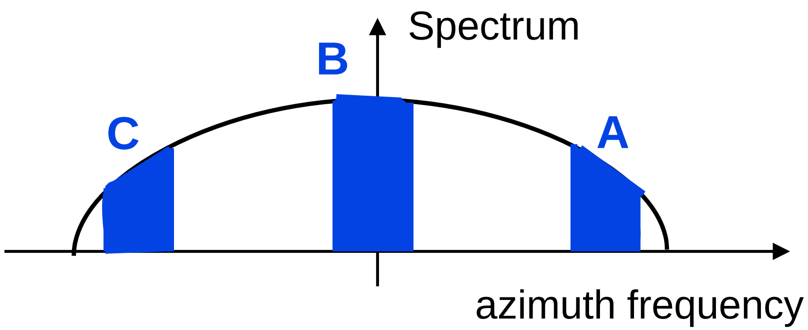
• **ScanSAR leads to a large swath width**

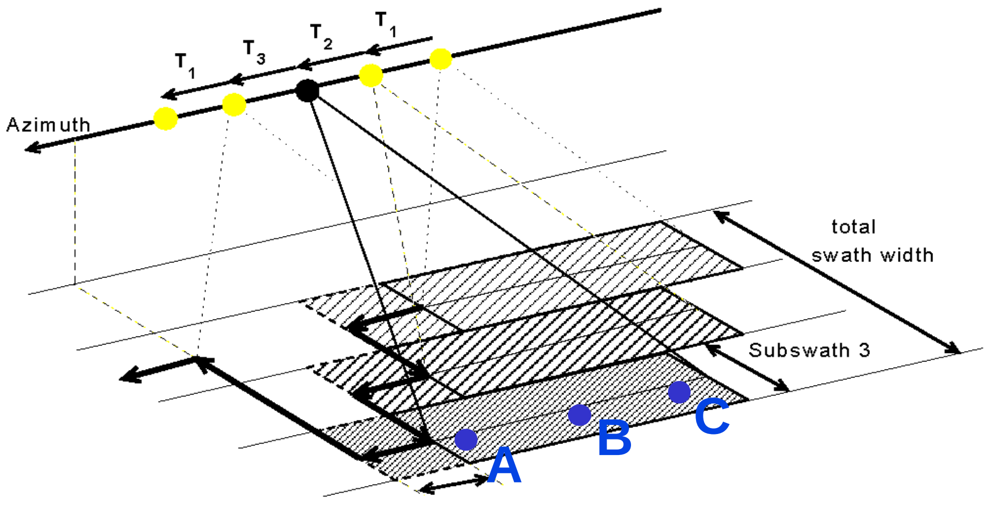
•**The azimuth signal consists of several bursts**



• **Azimuth resolution is limited by the burst duration**

• **Each target has a different frequency history depending on its azimuth location**





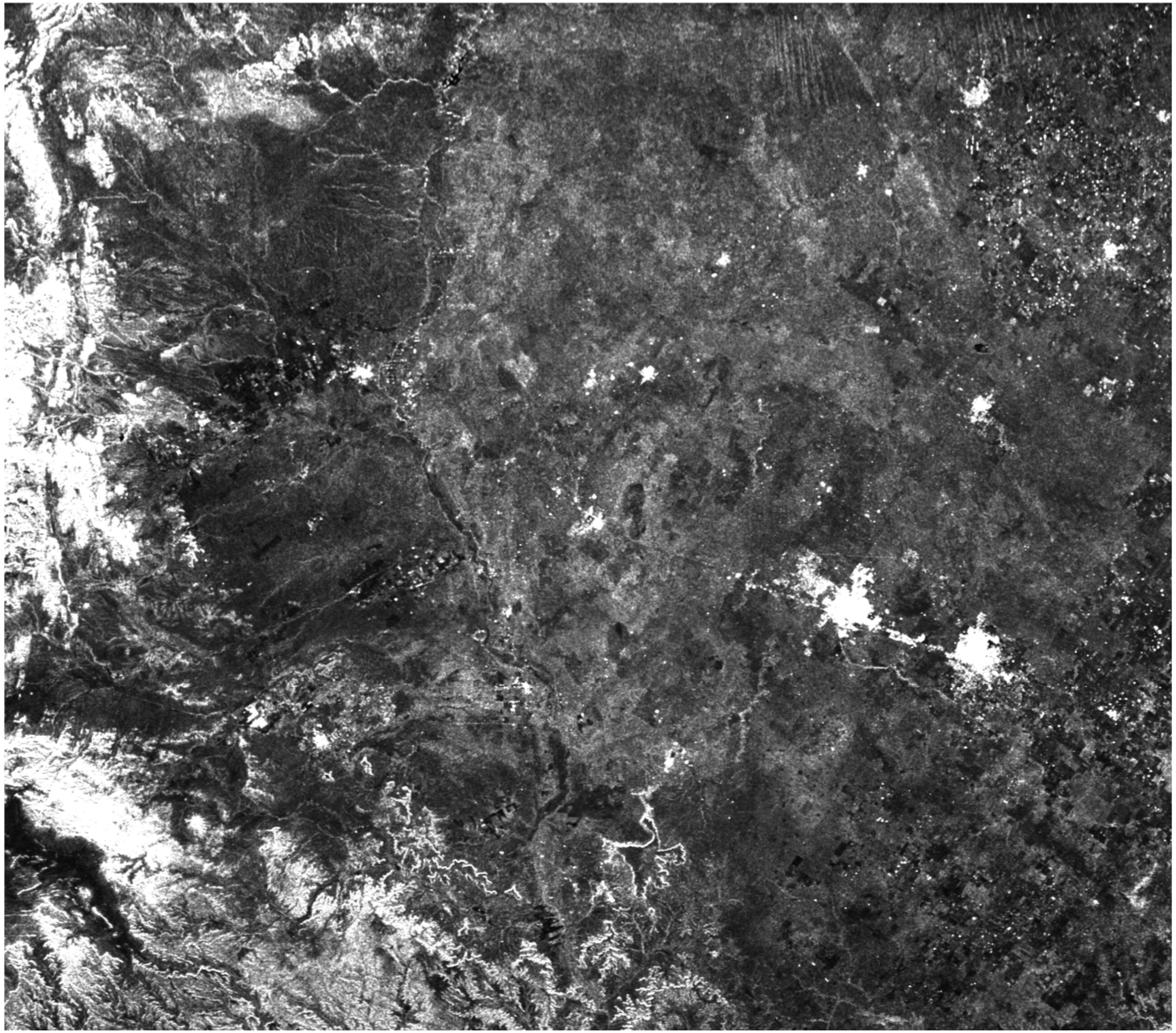
ScanSAR Imaging (Chickasha, Oklahoma, USA)

Subswath 1 (near range)

Subswath 2

Subswath 3

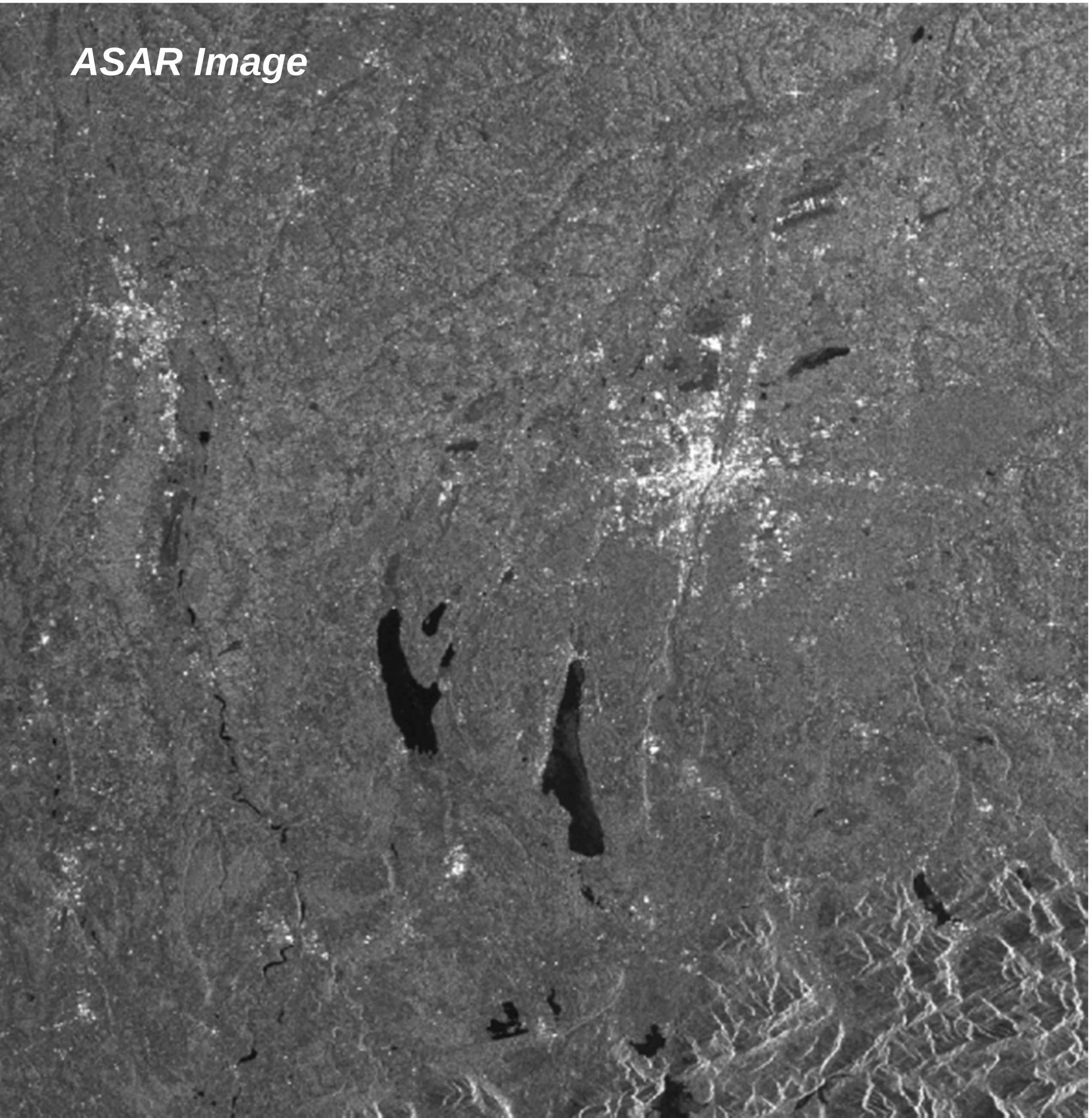
Subswath 4 (far range)

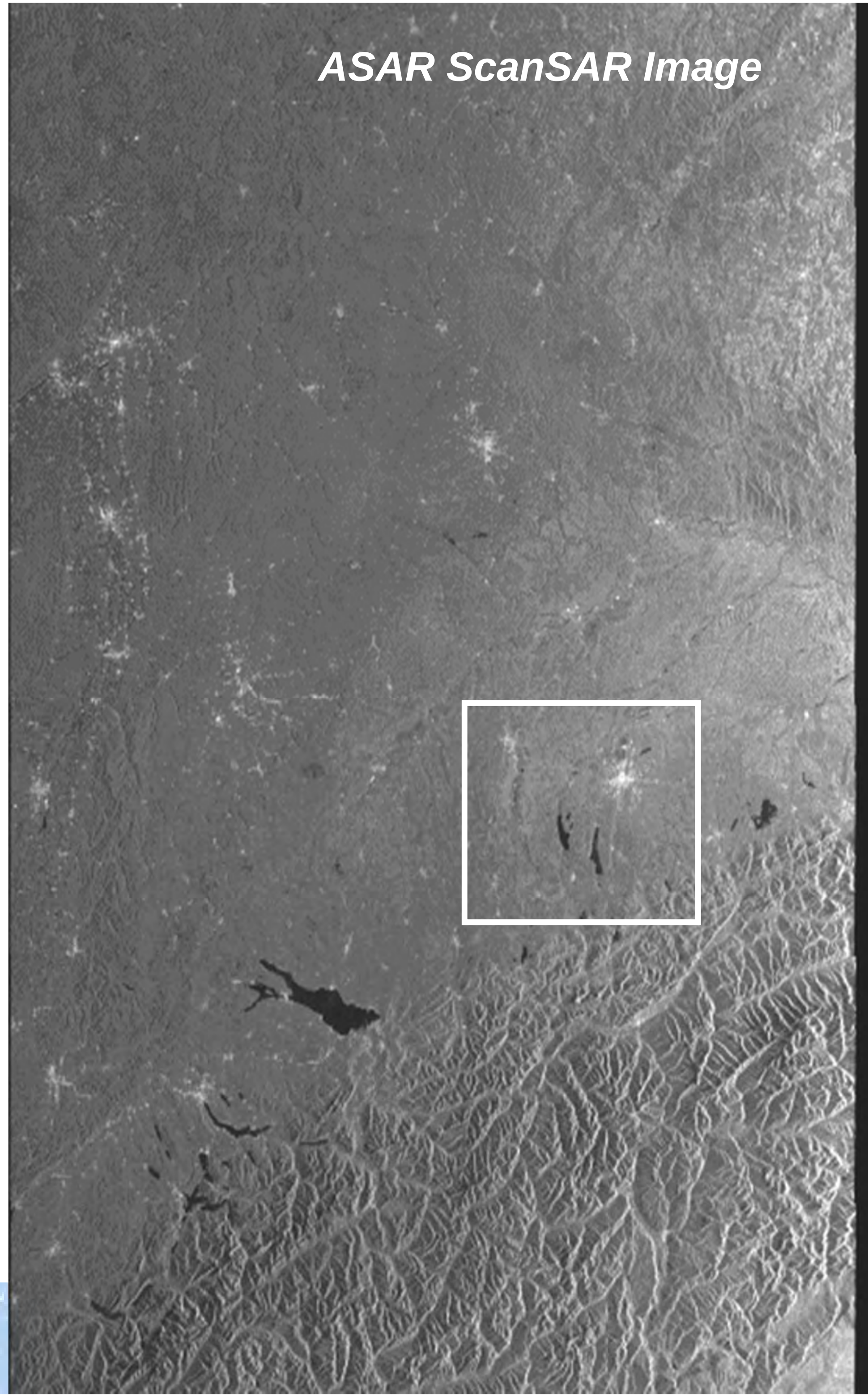


azimuth →

SIR-C image L-band, VV

ASAR SCANSAR Image (Munich Area)





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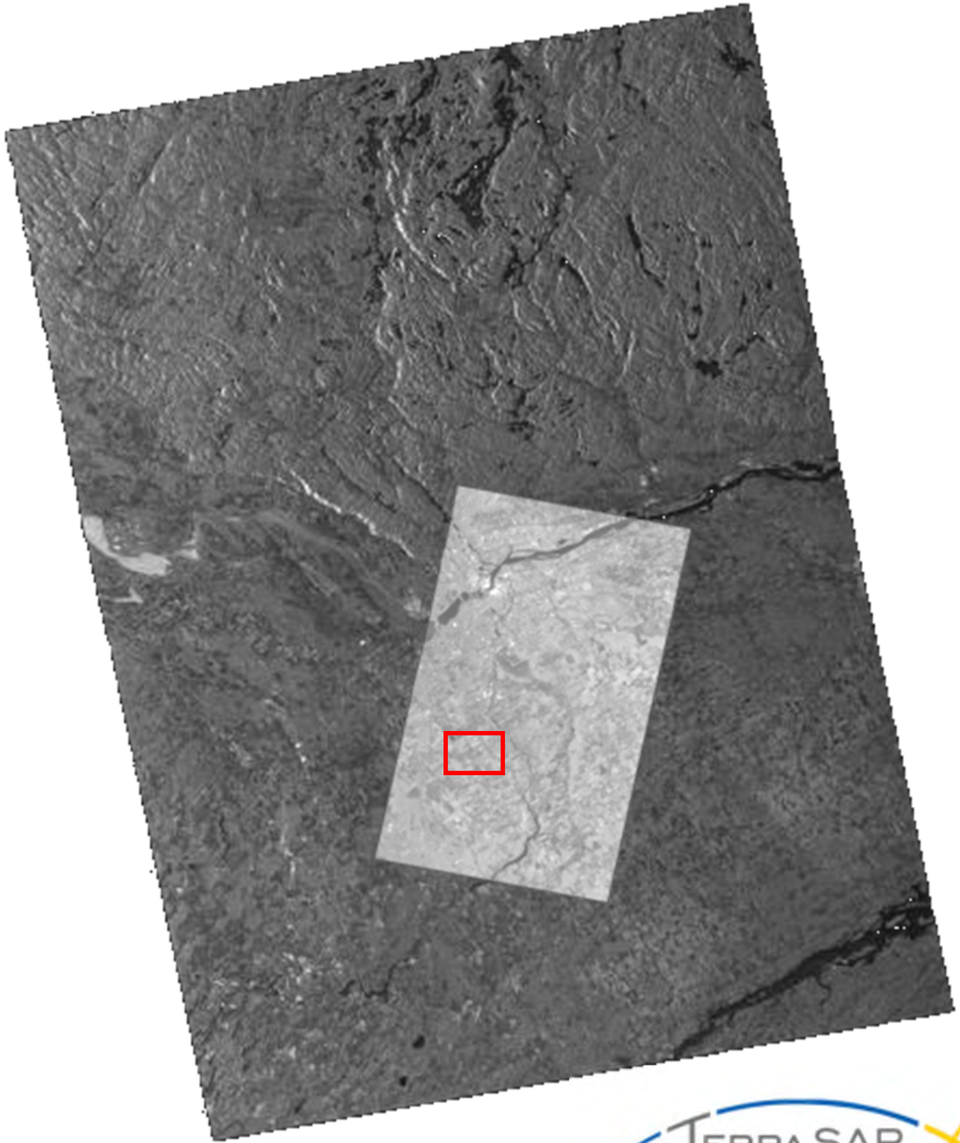
Comparison: ScanSAR vs. Stripmap (TerraSAR-X)



- ***ScanSAR (HH)***
  - 150 MHz
  - 17 m resolution
  - 1 (az) x 6.9 (rg) looks
  - ascending orbit
- ***Stripmap (HH)***
  - 150 MHz
  - 7 m resolution
  - 2.9 (az) x 3.4 (rg) looks
  - descending orbit
- ***3 days time separation***

ScanSAR

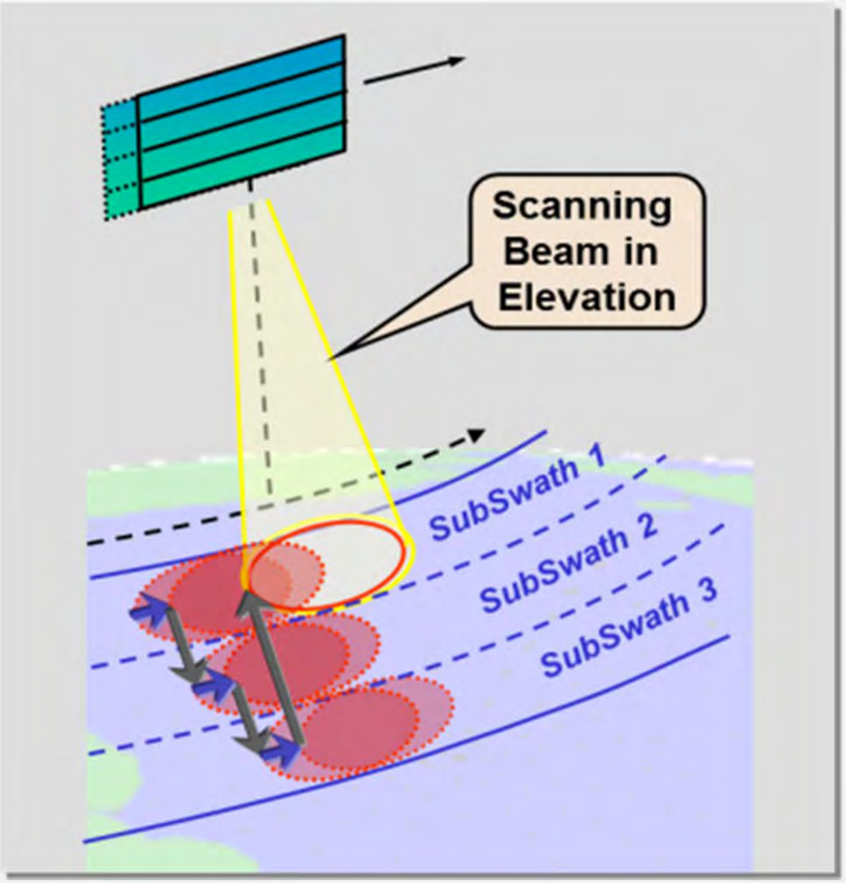
Stripmap

TerraSAR-X

TOPS-SAR (Terrain Observation by Progressive Scan)

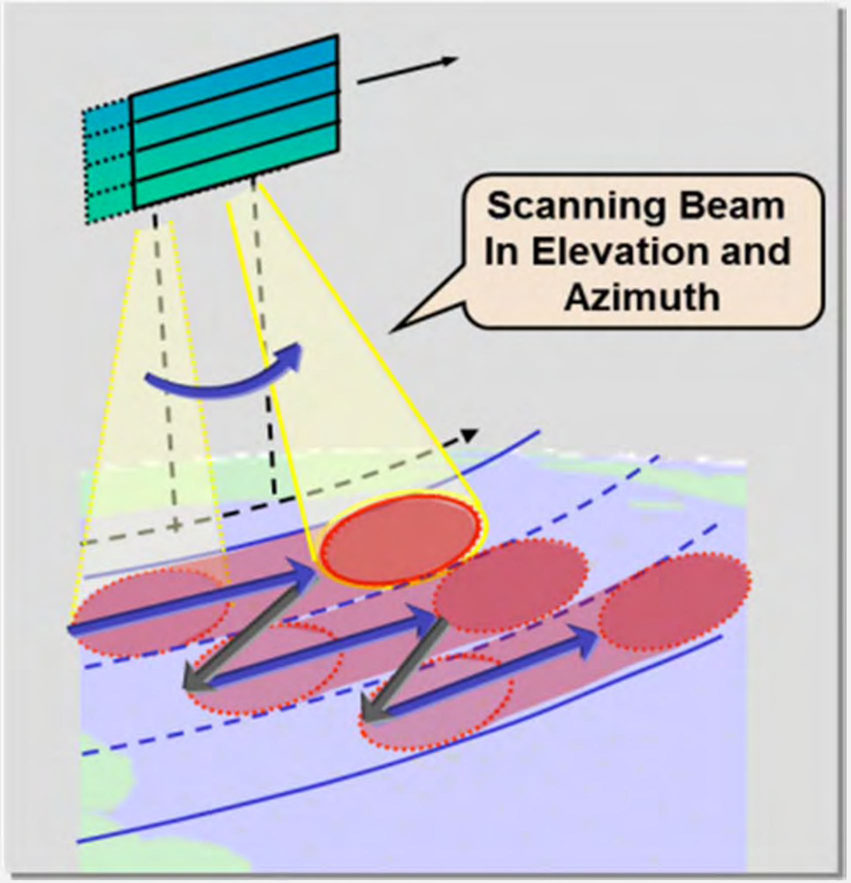
ScanSAR

- Shares illumination time between multiple swaths



TOPS-SAR

- Shares illumination time between multiple swaths
- Improved image quality



Advanced SAR Imaging Modes
- Spotlight Mode -

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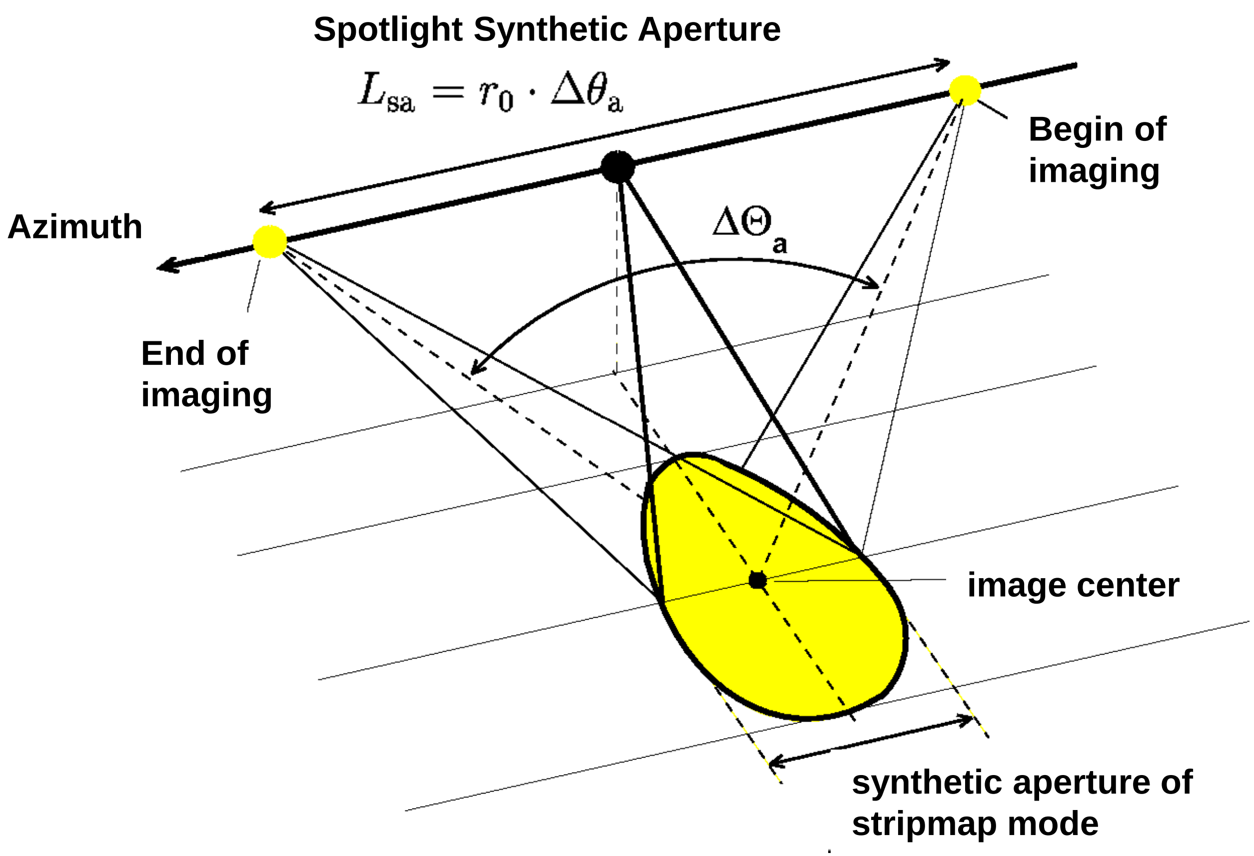
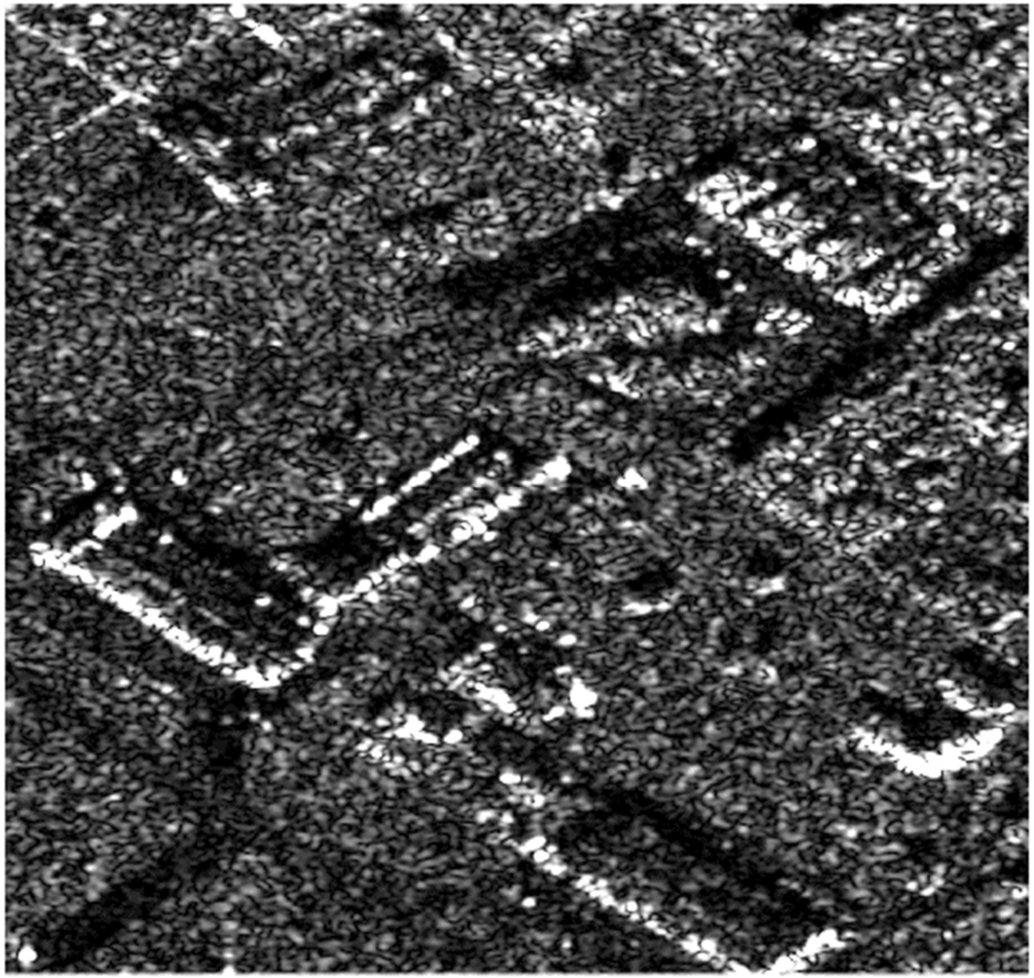
Spotlight SAR Imaging



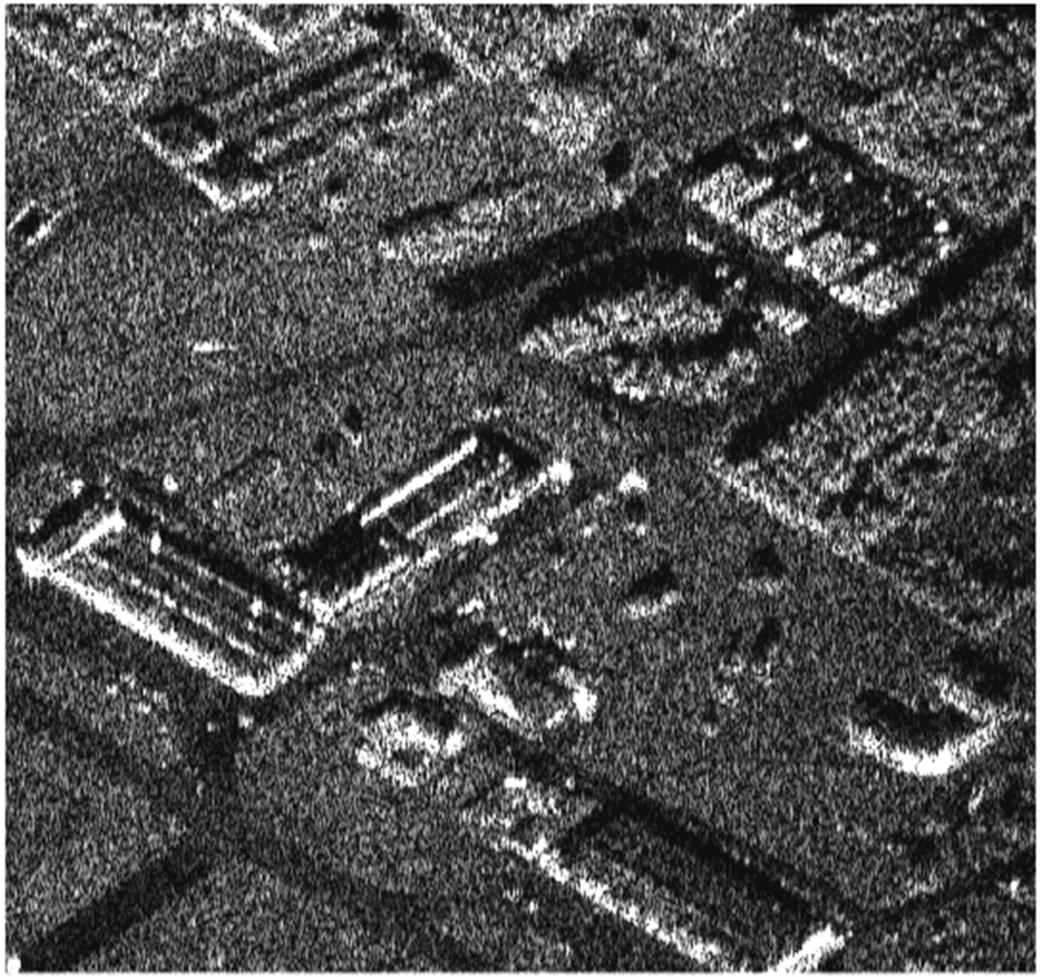
- Non continuous imaging mode, but very high azimuth resolution
- Spotlight azimuth resolution

$$\delta_a = \frac{\lambda}{2 \cdot \Delta\theta_a}$$

Spotlight SAR Imaging



Stripmap image
3 m azimuth resolution



Spotlight image
0.46 m azimuth resolution

E-SAR System, X-Band, Oberpfaffenhofen, Germany

Chuquicamata, Chile

Spotlight Imaging Mode

Oberpfaffehofen

Outlook

SAR Application Trends

Trends in Earth Science & Applications:

- ✓ Day / night, all-weather coverage of the Earth's surface
- ✓ Frequent revisit times (time series):
  - ✓ hours to 1 day: coastal zones, ocean, traffic and disaster monitoring
  - ✓ days to weeks: differential interferometry, soil moisture, agricultural areas
  - ✓ months to year: tropical, temperate and boreal forests, differential interf.
- ✓ Variable resolution (1 to 100 m) and wide coverage (25 to 450 km swath width)
- ✓ High (2 m) and medium resolution (10-15 m) global topography
- ✓ Information products of key inputs to global change models:
  - ✓ above ground biomass, soil moisture, wetland areas, land cover types
  - ✓ ocean surface & currents, ice mass balance, glacier velocity
- ✓ Calibrated and geo-coded data products are required (e.g. compatibility to GIS)
- ✓ Model based inversion algorithms are needed for reliable information extraction

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Summary: SAR Principles and Applications

- High resolution capability (independent of flight altitude)
- Weather independence by selecting proper frequency range
- Day/night imaging capability due to own illumination
- Complementary to optical systems
- Polarization signature can be exploited (physical structure, dielectric constant)
- Terrain Topography can be measured by means of interferometry
- Innumerous applications areas
- Great interest in the scientific community as well as for commercial and security related applications

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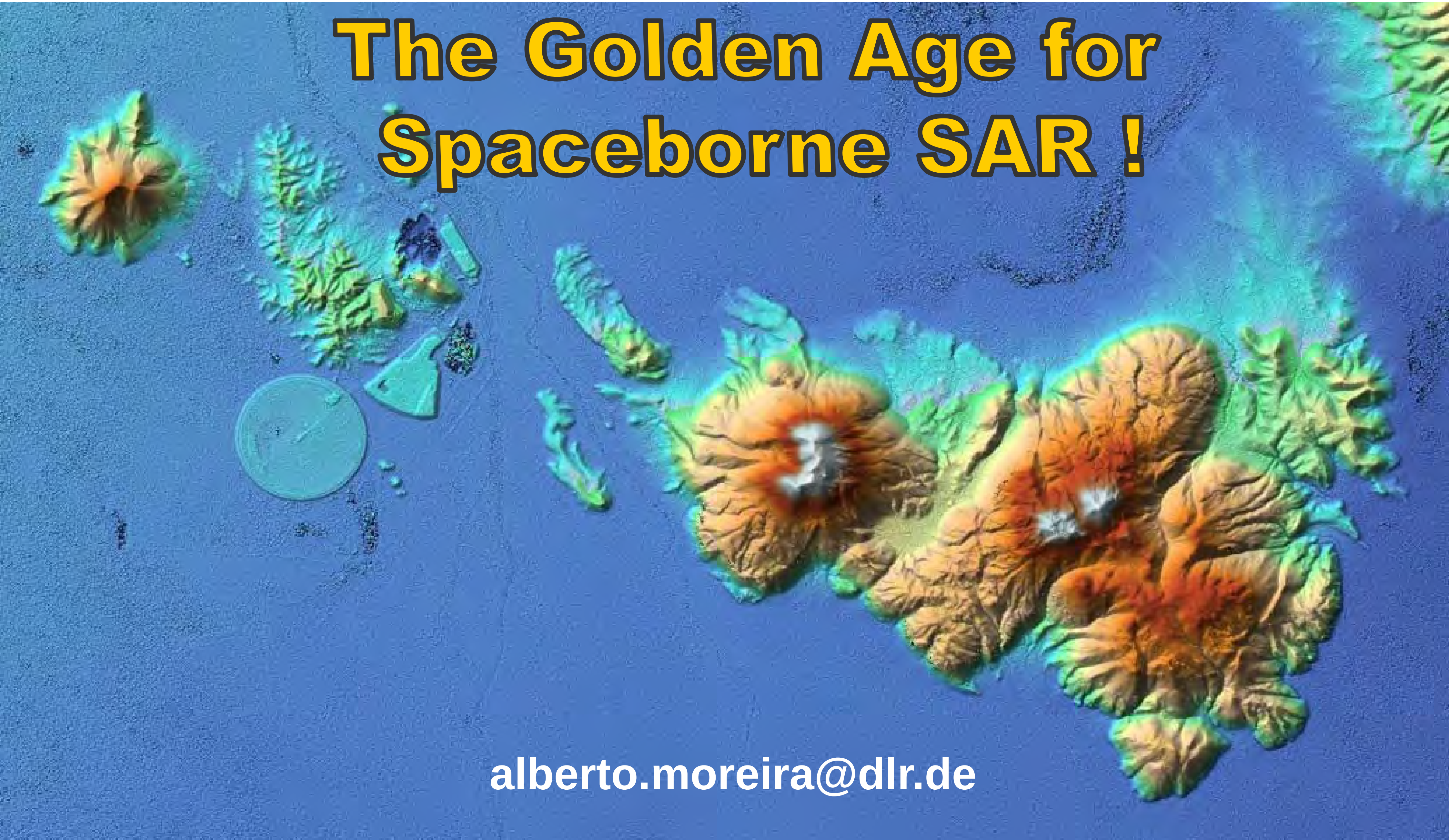
The Golden Age for Spaceborne SAR !



alberto.moreira@dlr.de

TanDEM-X, Kori Kollo, Bolivia