Synthetic Aperture Radar

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International School on SAR Polarimetry: From Theory to Applications

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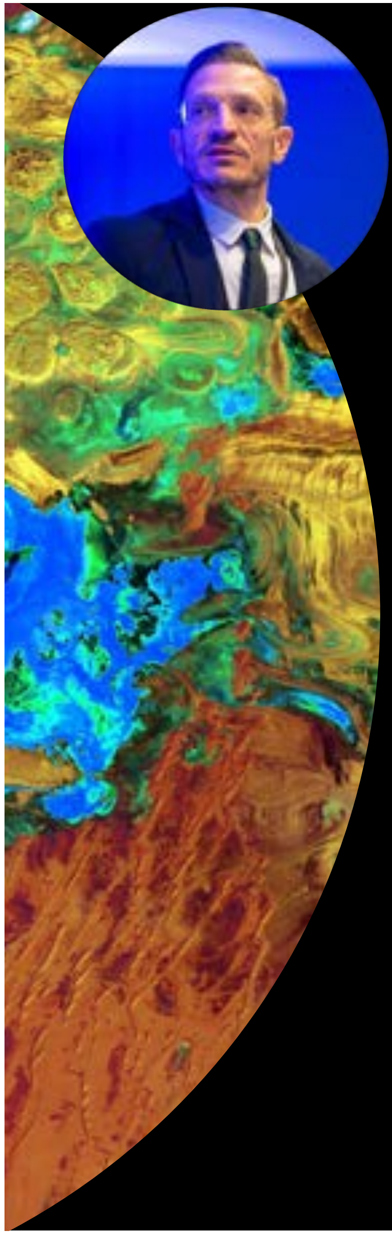

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Summary

- **Introduction**
- **One Dimensional SAR Systems**
- **Multidimensional SAR Systems**
- **SAR Polarimetry**

Introduction

Synthetic Aperture Radar Imaging

Why to use Synthetic Aperture Radar (SAR) to perform remote sensing?

- Active system providing its own illumination source. Day/night imaging capability (x2)
- Imaging capability independent of weather conditions (~ x5)
- High spatial resolution
- Sensitive to a wide range of Earth surface properties, especially in the case of multichannel or multidimensional SAR systems
  - Interferometry, differential interferometry, polarimetry, polarimetric interferometry, multifequency, multitime, etc…

SAR technology has been considered in different applications

- Topography, agriculture, forestry, hydrology, oceanography, glaciology, environment monitoring, MTI, etc…

Complementary to optical remote sensing systems

Data Models

What do they mean and which advantages provide data models ?

- A (better) description of the data acquired by the SAR system, making possible the (better) extraction of useful information
- Data can be systematically interpreted
- Allow a generalization of the observations
- Make possible to deal with the complexity associated with the scattering process

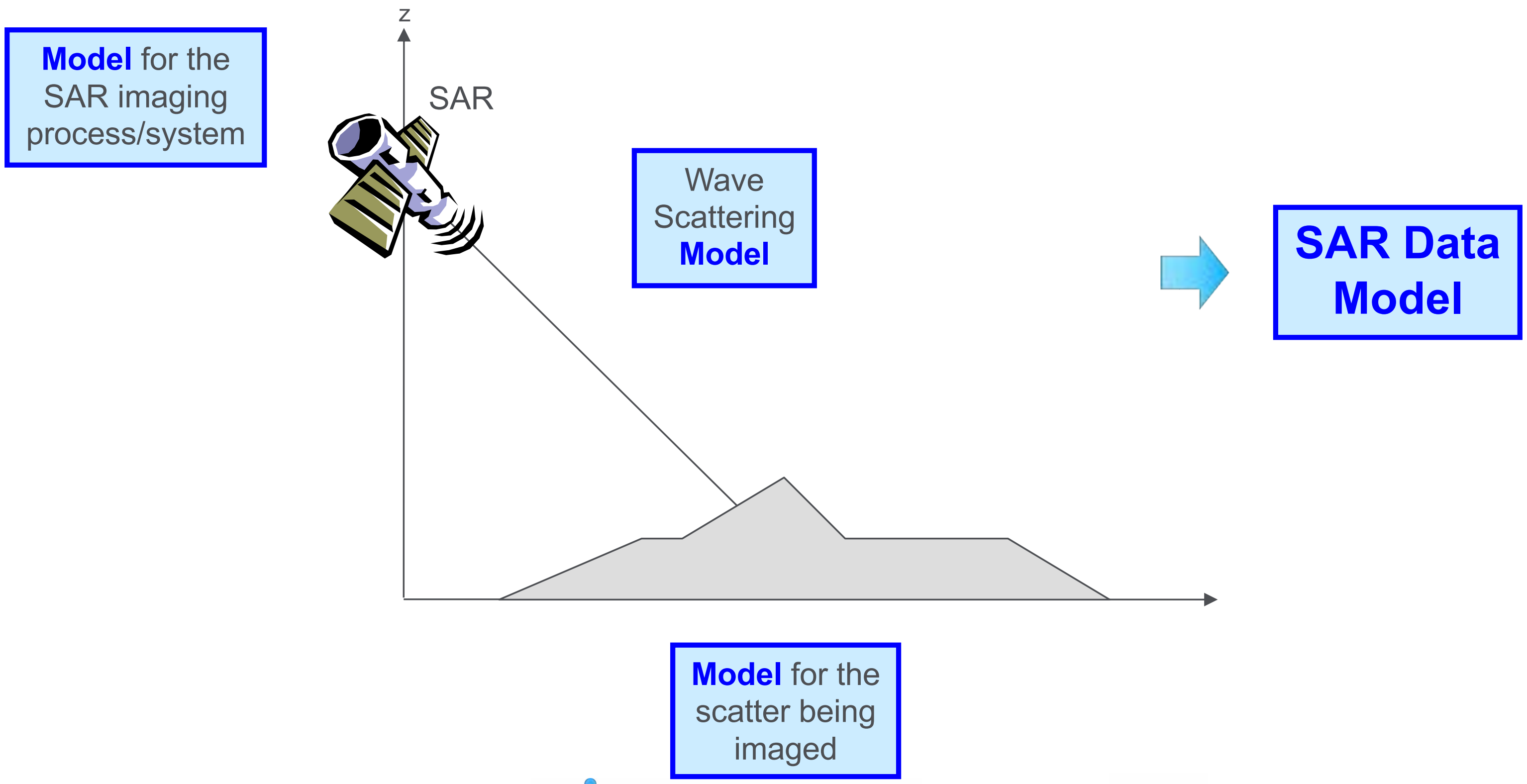
- In the lack of data models, only a phenomenological interpretation is possible

SAR data models are:

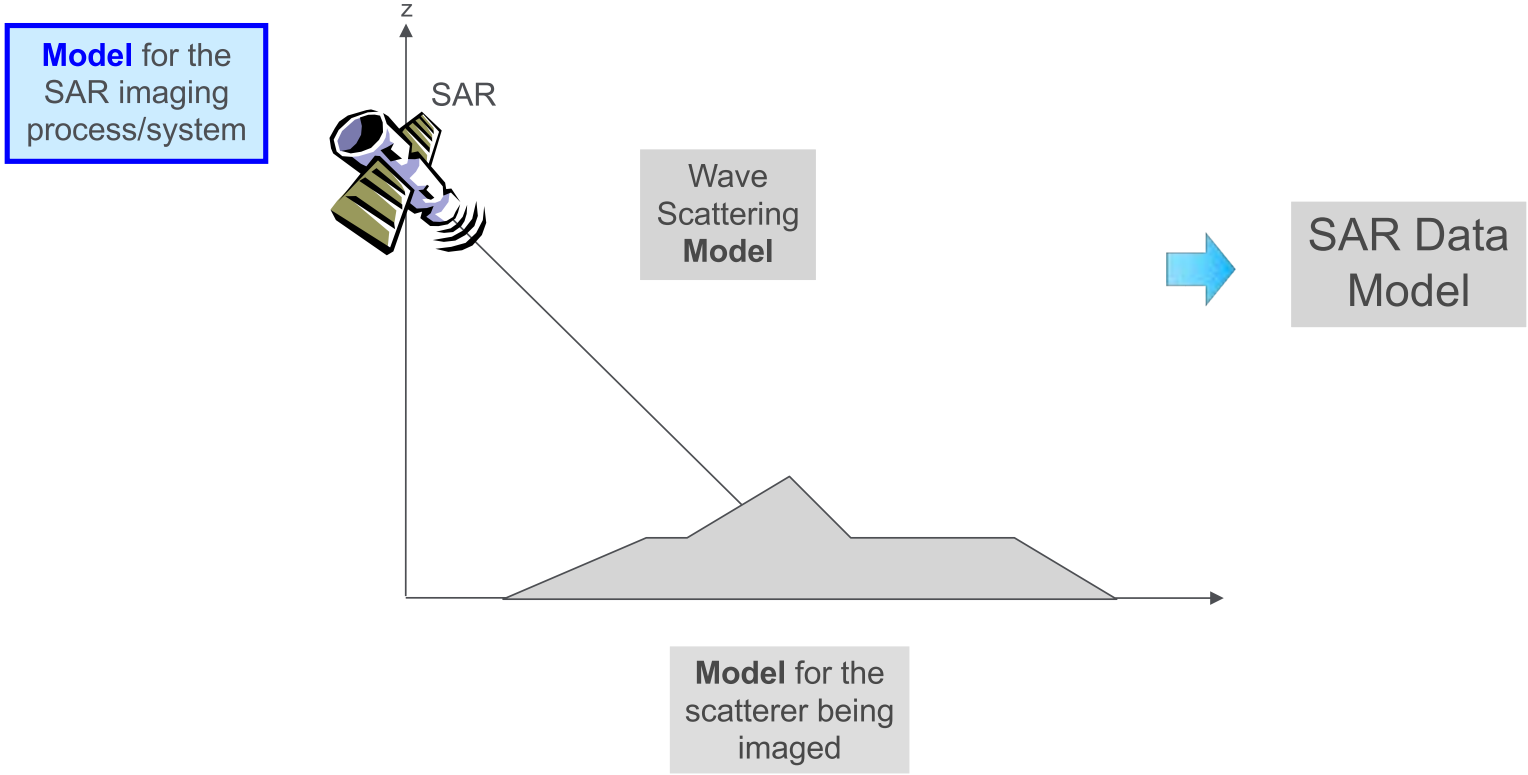
- Controlled by a set of parameters
- Stochastic in nature

Data Models

The analysis and understanding of data acquired by a SAR system needs from the following considerations

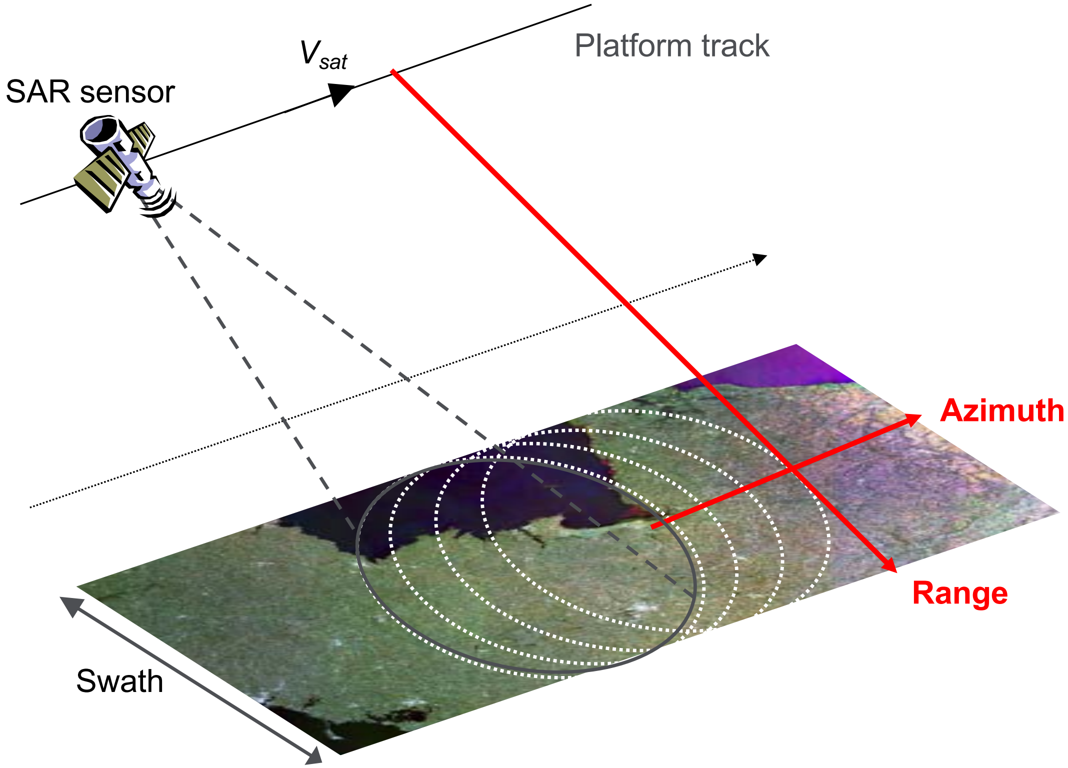


One Dimensional SAR Systems



Synthetic Aperture Radar Principles

Synthetic Aperture Radar Principles



Side looking geometry

Two-dimensional imaging system: Range vs. Azimuth

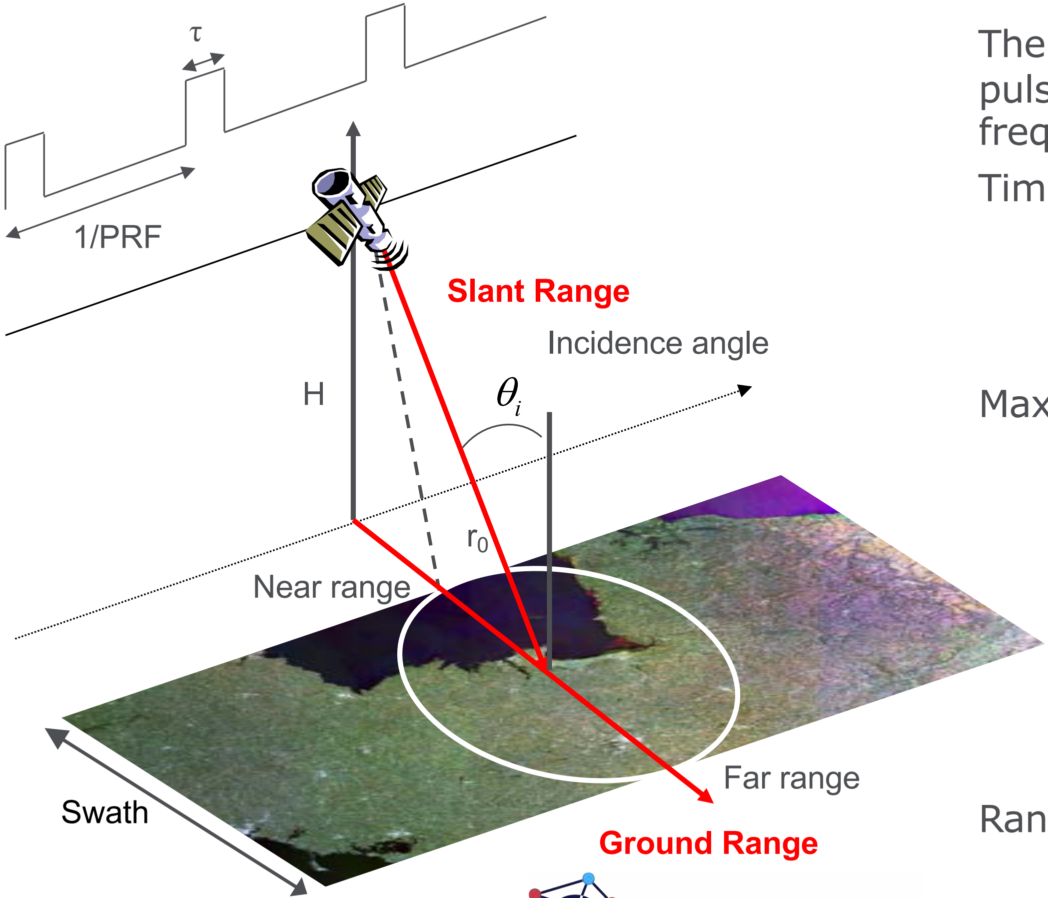
Different imaging modes. Compromise between resolution and swath coverage

- Stripmap
- Scansar
- Spolight

SAR images present a complex nature

Range Analysis

In range a SAR system operates as a conventional radar



The SAR system transmits pulses of duration τ at PRF frequency

Time delay

$$t_d = \frac{2r_0}{c}$$

Maximum swath

$$SW_{\max} \approx \frac{c}{2\,PRF\,\sin(\theta_i)}$$

$$\theta_i \in \left[20^0..60^0\right]$$

Range resolution $\boxed{\delta_r = \frac{c\tau}{2} = \frac{c}{2B}}$

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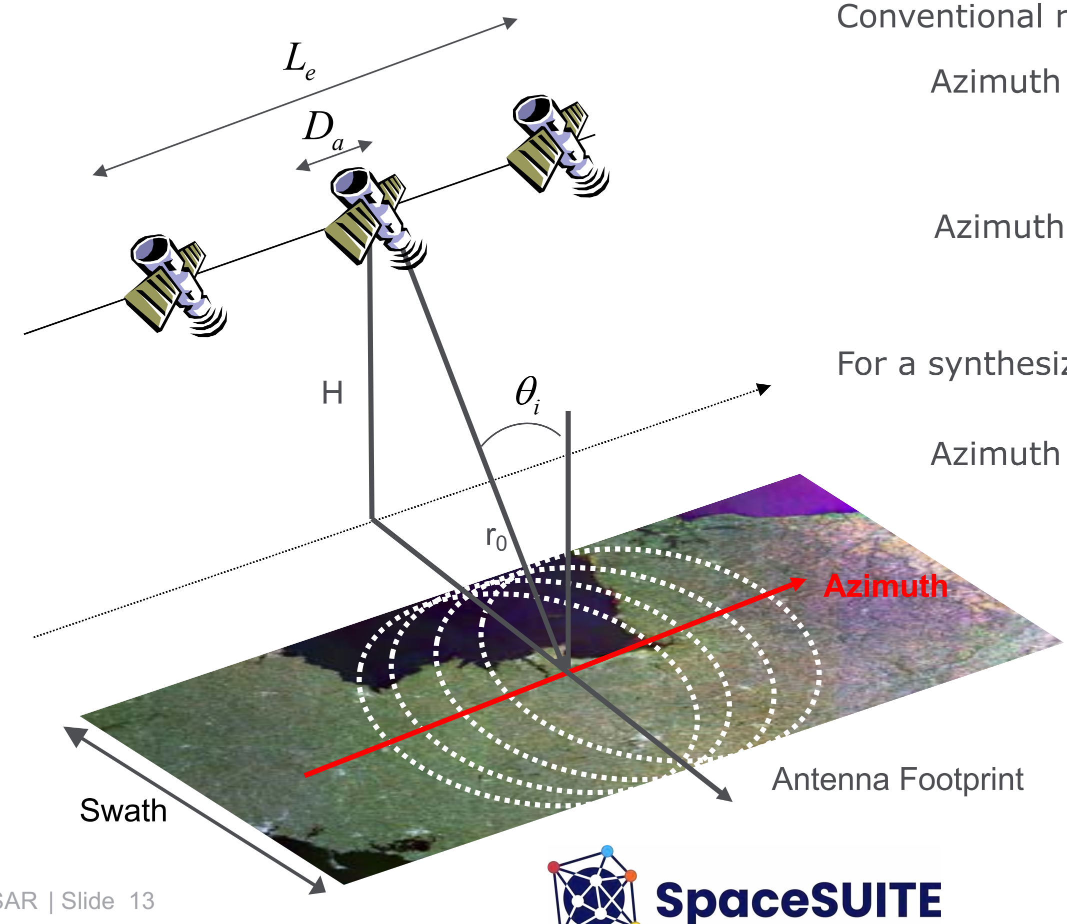
Azimuth Analysis

Difference between SAR system and conventional radars



Conventional radar

Azimuth angular spread $\theta_a \propto \dfrac{\lambda}{D_a}$

Azimuth resolution $\delta_a = r_0\theta_a = r_0 \dfrac{\lambda}{D_a}$

For a synthesized aperture

Azimuth angular spread $\theta_{sa} \propto \dfrac{\lambda}{2L_e}$

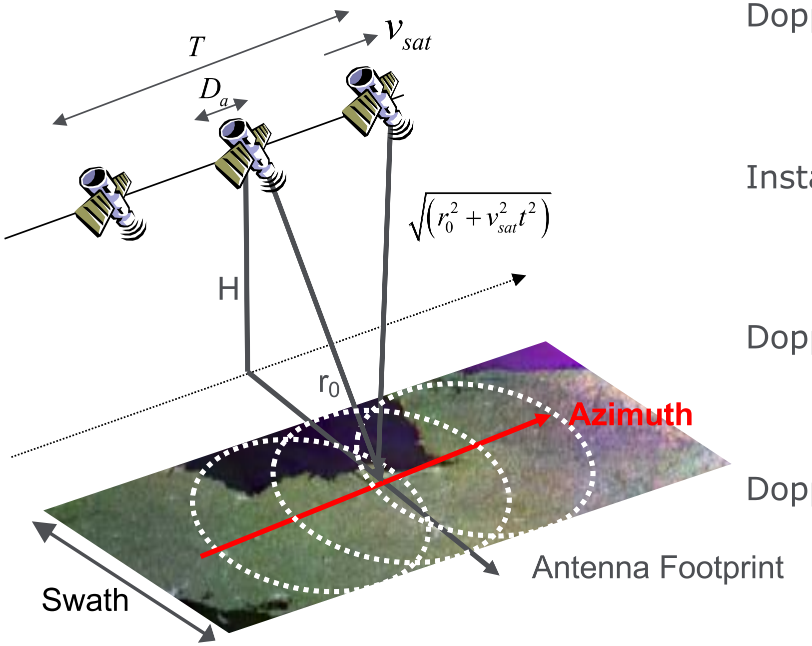
Two-way

Azimuth resolution $\delta_a = r_0 \dfrac{\lambda}{2L_e}$

$L_e < \dfrac{\lambda R}{D_a}$ $\boxed{\delta_a > \dfrac{D_a}{2}}$

Azimuth Analysis

Azimuth processing is based on the fact that a given target is observed all the time that it is within the antenna footprint. The different observation points are labelled through the Doppler frequency



Doppler frequency definition $$f_{dop} = \frac{1}{2\pi}\frac{d\phi}{dt}$$

Instant phase $$\phi = \phi_0 + 2\frac{2\pi}{\lambda}\sqrt{\left(r_0^2 + v_{sat}^2 t^2\right)}$$

Doppler frequency $$f_{dop} = 2\frac{v_{sat}^2 t}{\lambda r_0} \qquad B_{dop} = 2\frac{v_{sat}^2 T}{\lambda r_0}$$

Doppler bandwidth $$T \approx R\frac{\lambda}{L_e}\frac{1}{v_{sat}} \qquad B_{dop} \approx 2\frac{v_{sat}}{D_a}$$

Azimuth resolution $$\boxed{\delta_a \approx \frac{D_a}{2}}$$

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SAR Impulse Response

SAR data processing, i.e., SAR image formation process comprises

- Data acquisition process
  - Raw data generation. Data recorded by the SAR system
- Image formation process
  - Raw data compression
    - Generation of the synthesized aperture
    - Collecting/Focusing all the contributions of a given target
  - Non-separable/Non-homogeneous bi-dimensional problem

Consider all the process as a linear system

Phase information

$$\sigma_s(x_0,r_0) \longrightarrow \boxed{h(x,r)} \longrightarrow S(x,r)$$

Complex scattering amplitude

$$\sigma_s(x_0,r_0) = \sqrt{\sigma_0}e^{j\theta}\delta(x-x_0,r-r_0)$$

SAR impulse response or Point Spread Function (PSF)

Complex SAR image

Finite bandwidth impulse response $\delta_a \times \delta_r = \frac{D_a}{2} \times \frac{c}{2B_{pulse}}$

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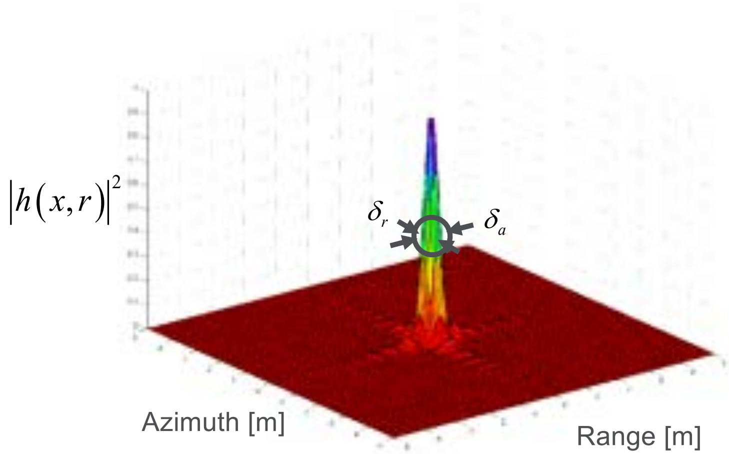
SAR Impulse Response

SAR impulse response function

$$h(x,r) \propto \mathrm{sinc}\left(\frac{\pi x}{\delta_a}\right)\mathrm{sinc}\left(\frac{\pi r}{\delta_r}\right)$$



$\delta_a = \delta_r = 1m$

Point scatterer

How it appears in the SAR image $S(x,r)$

Distributed scatterer

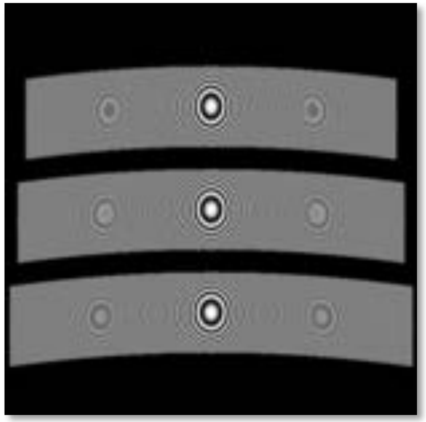
Idea of resolution cell $\delta_a \times \delta_r$

The resolution cell is not the pixel of the SAR image. The pixel properties depend on how the SAR impulse response is sampled

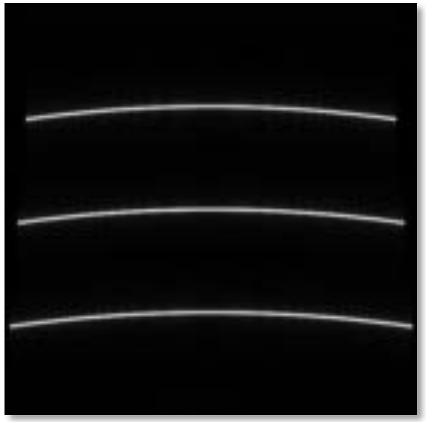
- Over-sampling induces image spatial correlation

SAR Impulse Response & SAR Focusing

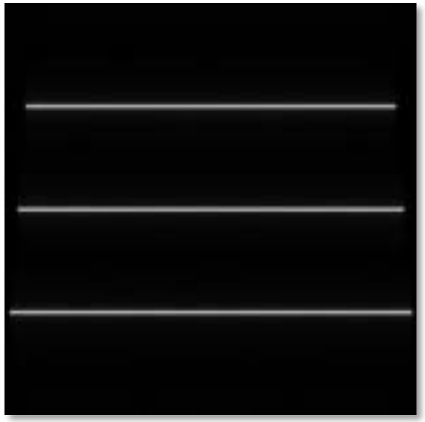
Focusing process of three point scatters varying in range



Real part of the raw data



Amplitude of
range-compressed data

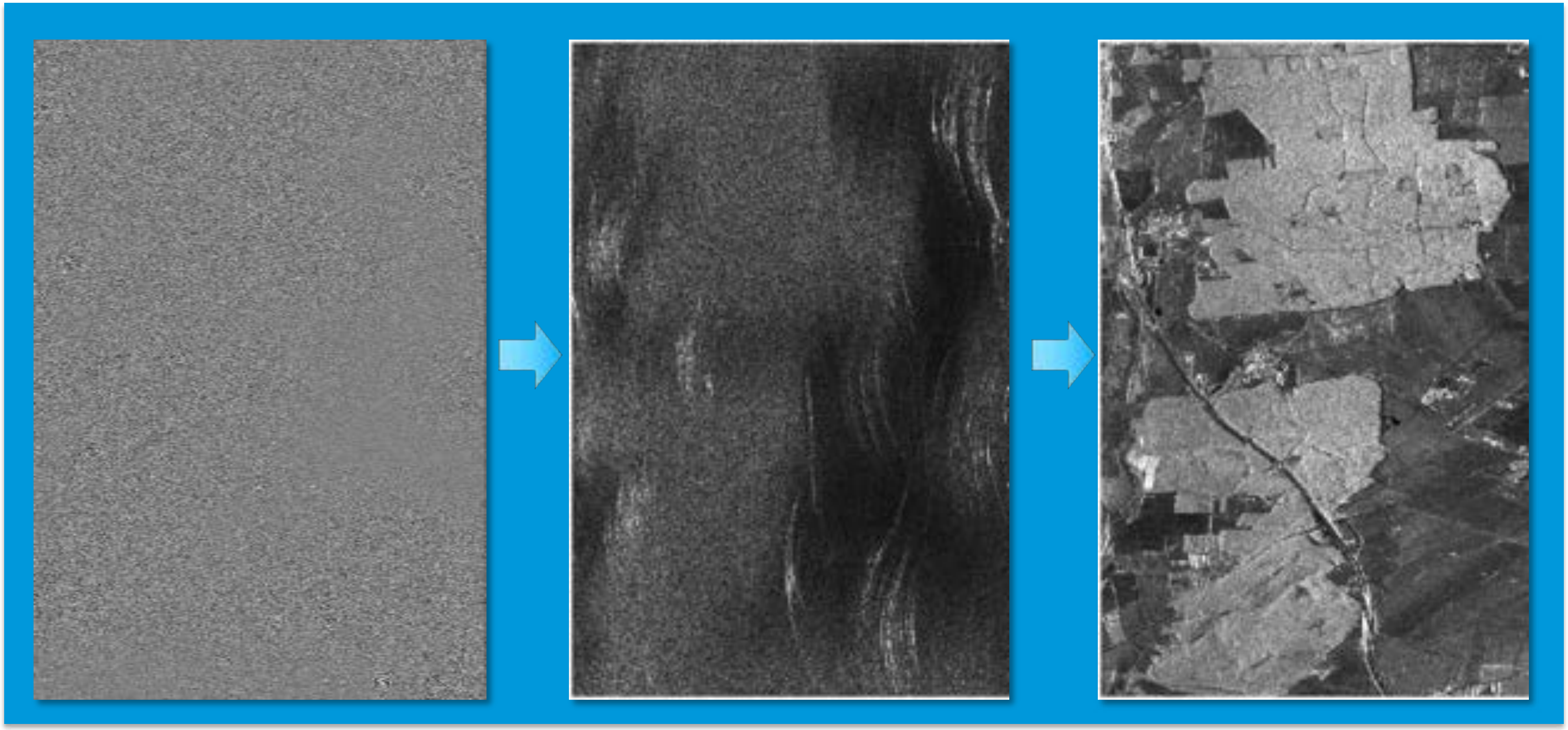


Amplitude of range-compressed
data after RCMC

Amplitude of the final
compressed image

SAR Impulse Response & SAR Focusing

Focusing process of a real SAR image



SAR raw data as measured by the system

SAR data after range compression

Focused SAR image

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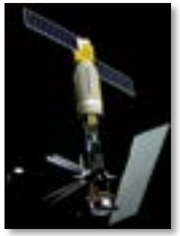
Platforms

Spaceborne: Orbital systems

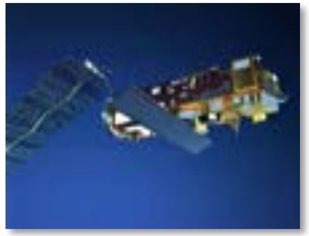


SEASAT
L-band
HH Pol
NASA/JPL (USA)

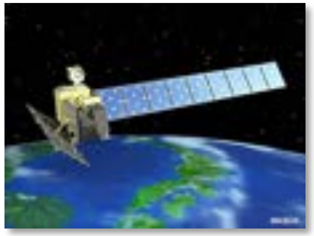
J-ERS-1
L-band
HH Pol
JAXA (J)

SIR-C/X-SAR
L, C, X-band
C&L FullPol, X VV
NASA/JPL (USA), ASI (I), DLR (G)

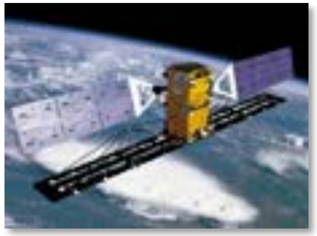
ERS-1/2
C-band
VV Pol
ESA (EU)



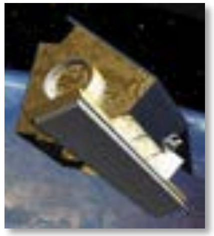
ENVISAT / ASAR
C-band
HH&HV, HH&VV, VH&VV
ESA (EU)



ALOS / PALSAR
L-band
FullPol
JAXA (J)

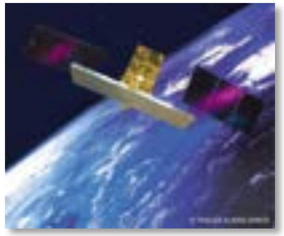


RADARSAT 2
C-band
FullPol
CSA - MDA (CA)

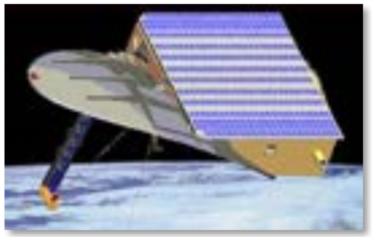


TERRASAR
X-band
FullPol
BMBF / DLR / ASTRIUM (G)

TanDEM-X
X-band
FullPol
BMBF / DLR / ASTRIUM (G)



Cosmo-Skymed
X-band
FullPol
ISA (I)



SAR-Lupe
X-band
BWB (G)

Sentinel-1
C-band
HH&HV, VH&VV
ESA (EU)

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Platforms

Airborne: Aerial or UAV systems

AES1
X-Band (HH), P-Band (FullPol)
InterMap Technologies (D)

AIRSAR
P, L, C-Band (FullPol)
NASA / JPL (USA)

AuSAR – INGARA
X-Band (FullPol)
D.S.T.O (Aus)

DOSAR
S, C, X-Band (FullPol), Ka-Band (VV)
EADS / Dornier GmbH (D)

ESAR
C, X-Band (Sngl)
P, L, S-Band (FullPol)
DLR (D)

EMISAR
L, C-Band (FullPol)
DCRS (DK)

MEMPHIS / AER II-PAMIR
Ka, W-Band (FullPol) / X-Band (FullPol)
FGAN (D)

STORM
C-Band (FullPol)
UVSQ / CETP (F)

PHARUS
C-Band (FullPol)
TNO - FEL (NL)

PISAR
L, X-Band (FullPol)
NASDA / CRL (J)

RAMSES
P, L, S, C, X, Ku, Ka, W-Band (FullPol)
ONERA (F)

SAR580
C, X-Band (FullPol)
Environnement Canada (CA)

Platforms

Ground Based: Linear mouvement

UPC-Balamis GB-SAR
P, L, S, C & X-band
(FullPol)
UPC (SP)

GBInSAR Lisa
LisaLab (I)

CNEAS Tohoku University GB-SAR
TU (J)

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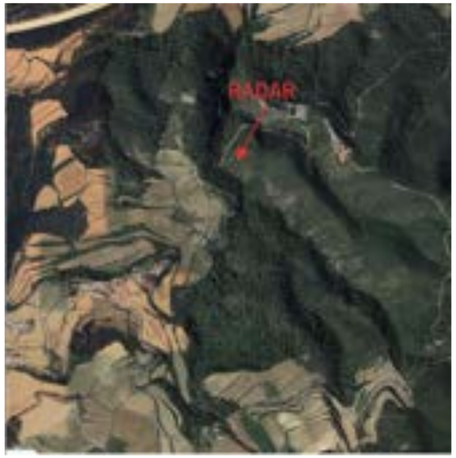
Platforms

Multifrequency GBSAR in collaboration with the company MWSE (Barcelona, Spain)



Technical specifications					
Frequency bands	X	C	S	L	P
Central frequency	9.6 GHz	5.4 GHz	3.2 GHz	1.27 GHz	435 MHz
Electrical bandwidth	200 MHz	150 MHz	150 MHz	150 MHz	50 MHz
Maximum operating range (1)	3 km				
Displacement accuracy (2)	0.01 mm	0.02 mm	0.03 mm	0.1 mm	0.3 mm
Range resolution	0.75 m	1 m	1 m	1 m	3 m
EIRP	25 dBm				
Modulation	Frequency Modulated Continuous Wave (FMCW)				
Power consumption	40W				
Power supply	220V AC				
Software specifications					
Operation	Web application for control via web browser. Remote operation (3). Real time status information. Real time data availability.				
Data processing	Included a basic software for data interpretation: - Power amplitude maps. - Displacement speed maps. - Absolute displacement maps. - Spatial and temporal coherence maps. - Automatic atmospheric compensation based on reference scatter. - Automatic geocoding of the maps with distortion correction (4).				

(1) Extensible on demand.
(1) Accuracy measured in the line-of-sight direction. The accuracy has been measured using a stable target with a high Signal to Noise Ratio (SNR).
(2) Standard connectivity with the GBSAR is done via WiFi. Remote operation is available on-demand and runs under mobile public infrastructure.
(3) For automatic geocoding of the maps, the maps of the operation area need to be provided.

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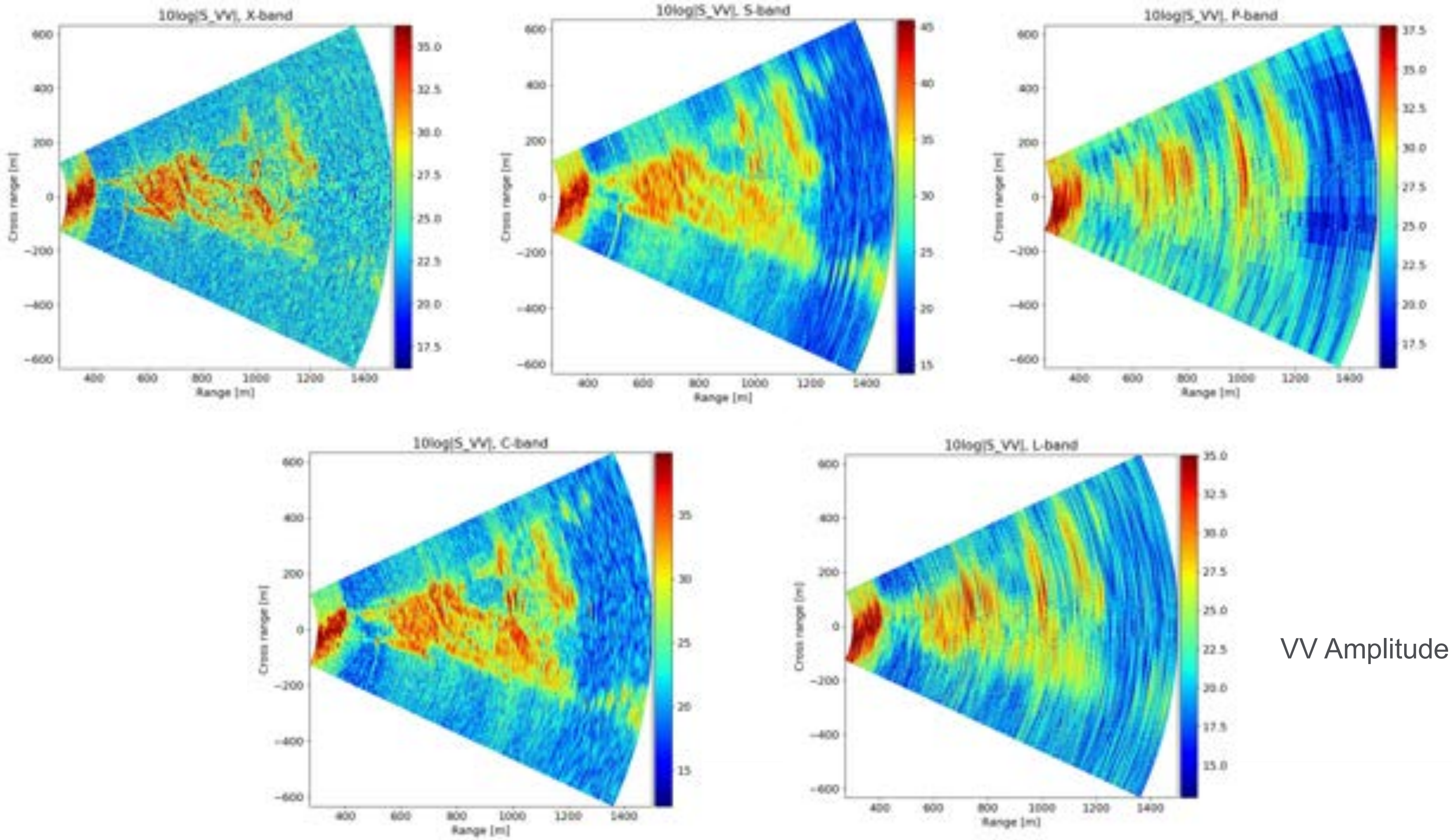
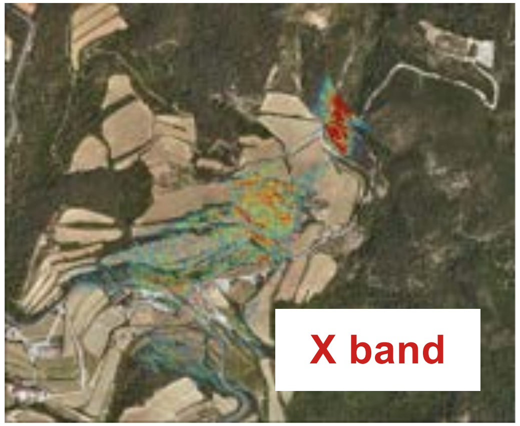
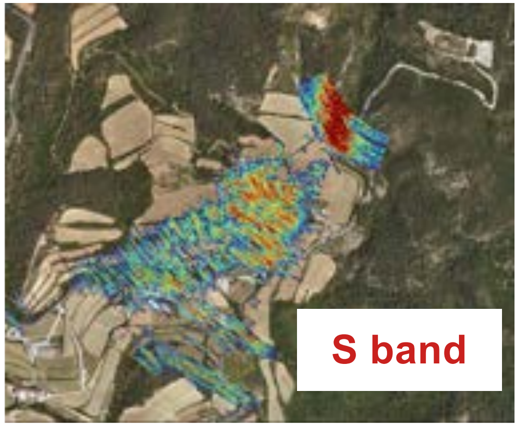
Platforms

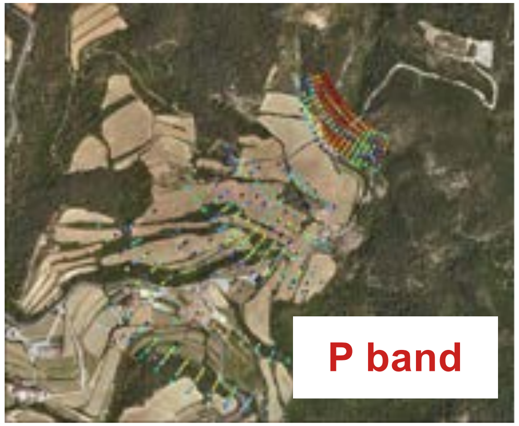


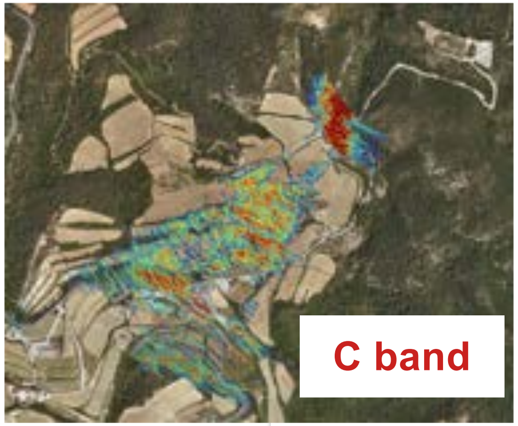
VV Amplitude measurements

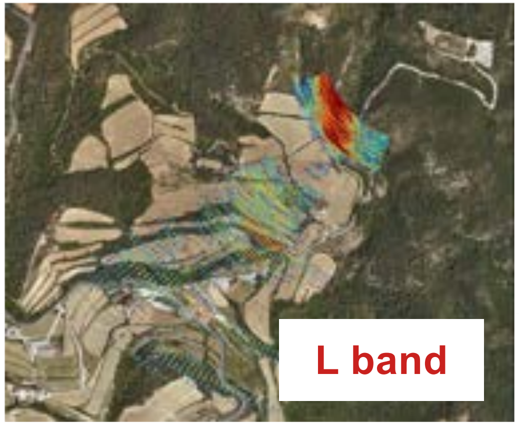
Platforms







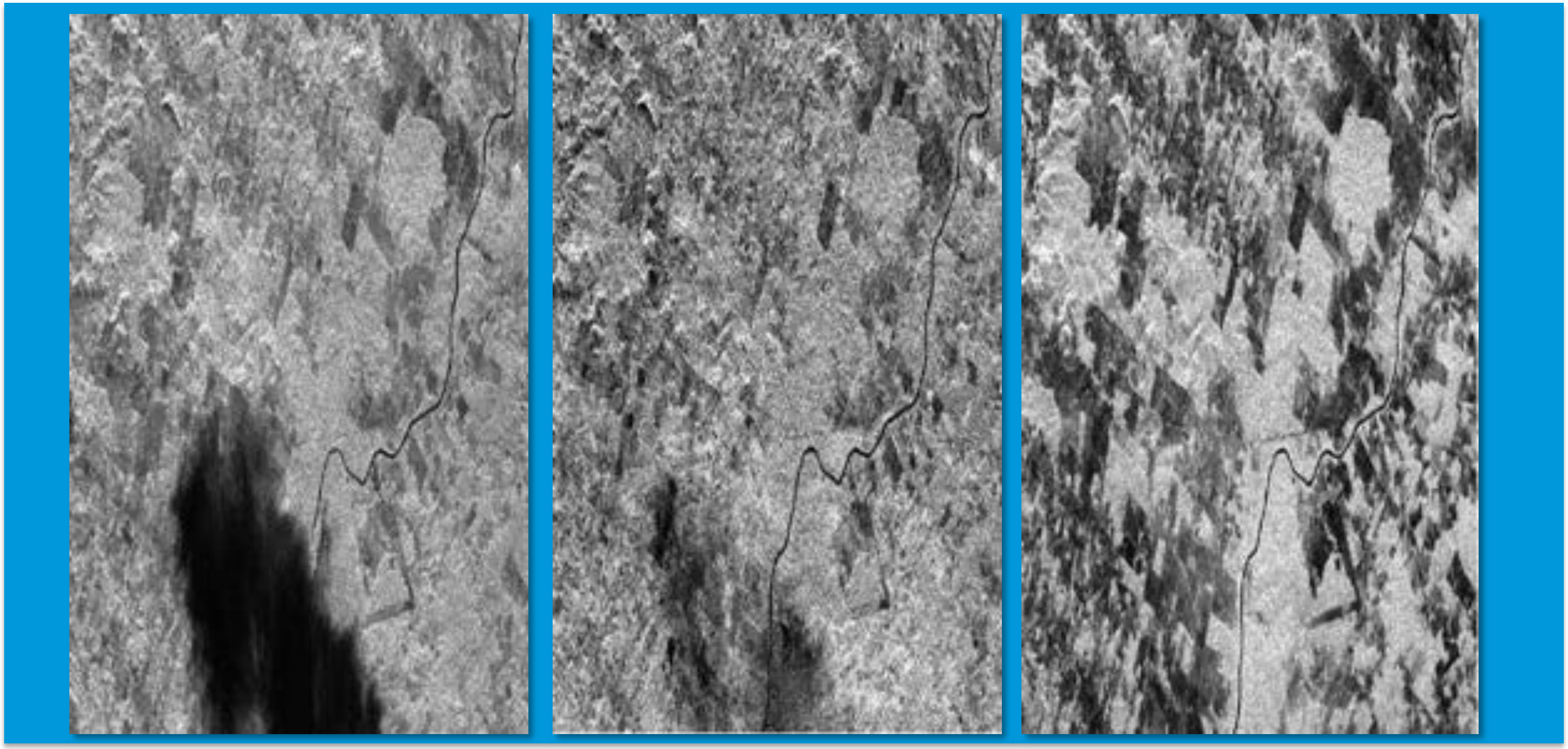




Geocoded VV amplitude measurements

Examples

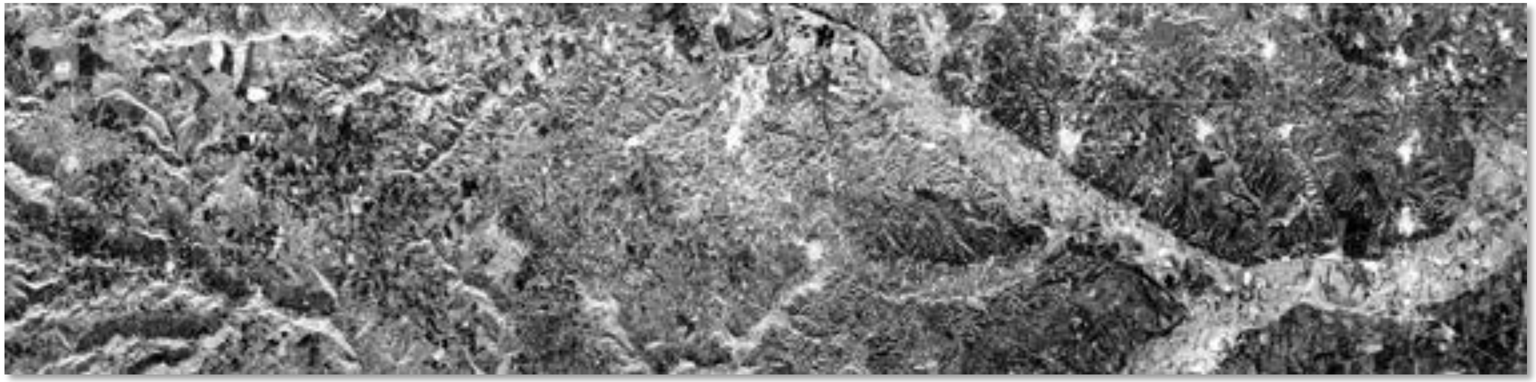
Amazonian Forest (Brazil)



X-band C-band L-band

Examples

Madrid (Spain). SIR-C Sensor



L-band

C-band

Range x Azimuth resolution: 25 x 25 m

PRF: 1620 Hz B_w : 12.5 MHz

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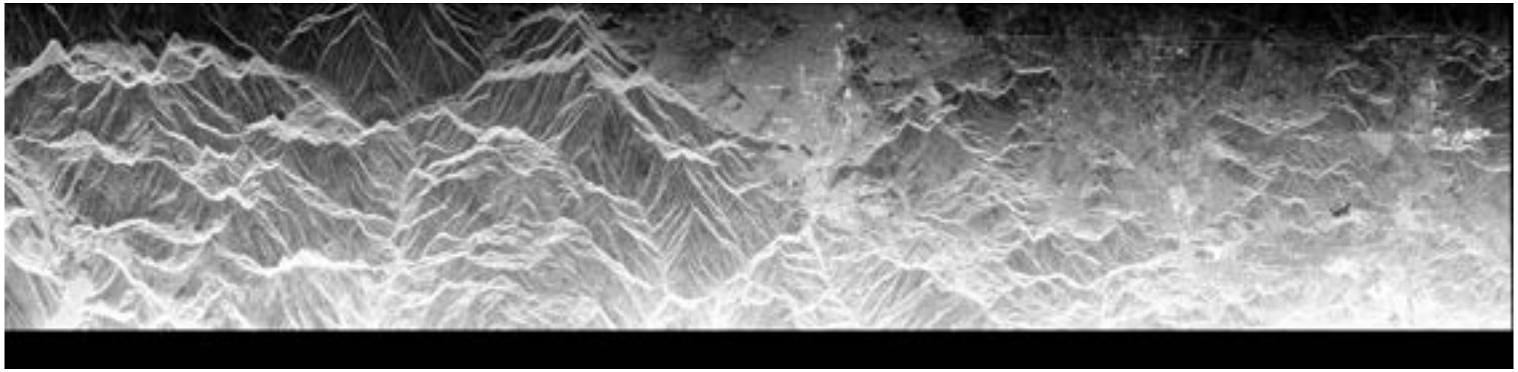
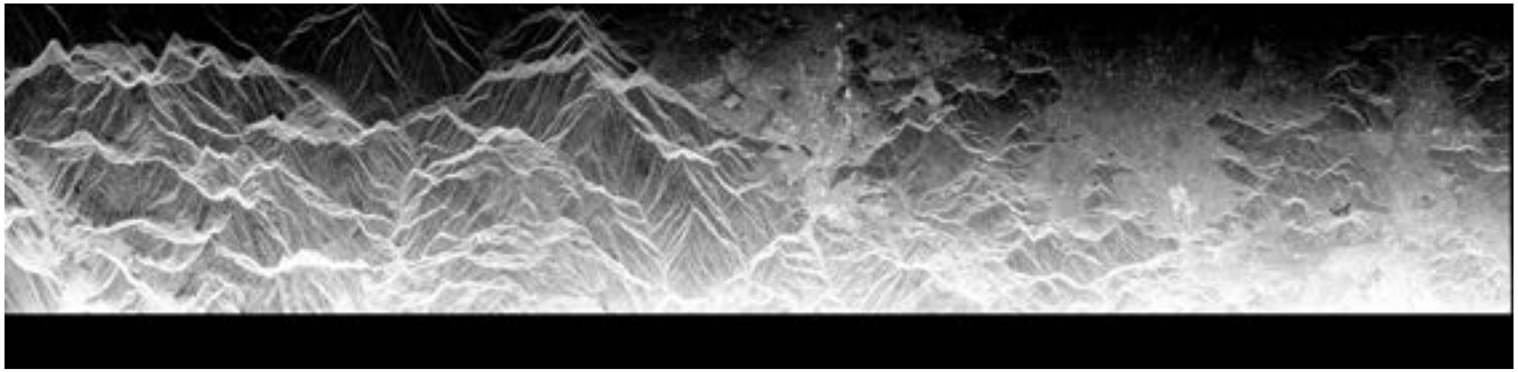
Examples

Santiago de Chile (Chile). SIR-C Sensor. 19/4/1994



L-band



C-band

Range x Azimuth resolution: 25 x 25 m

PRF: 1440 Hz B_w : 10.4 MHz

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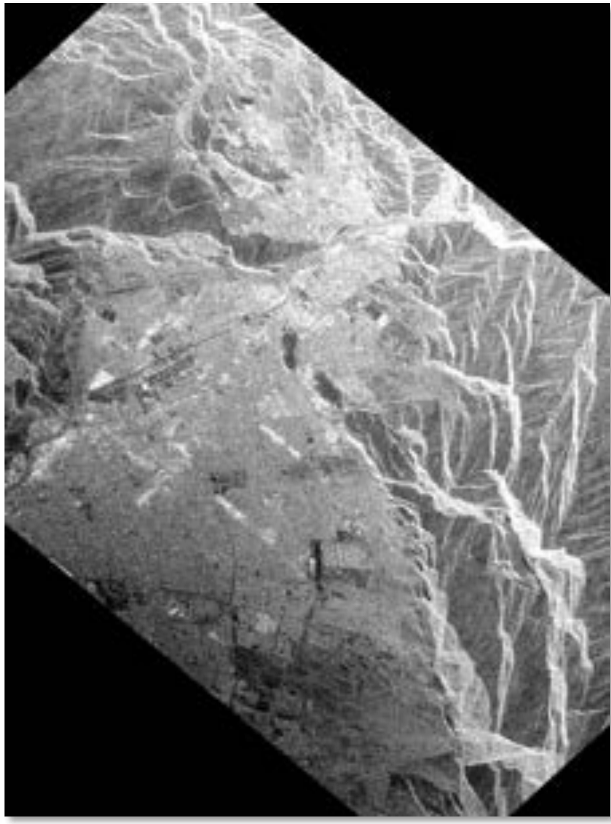
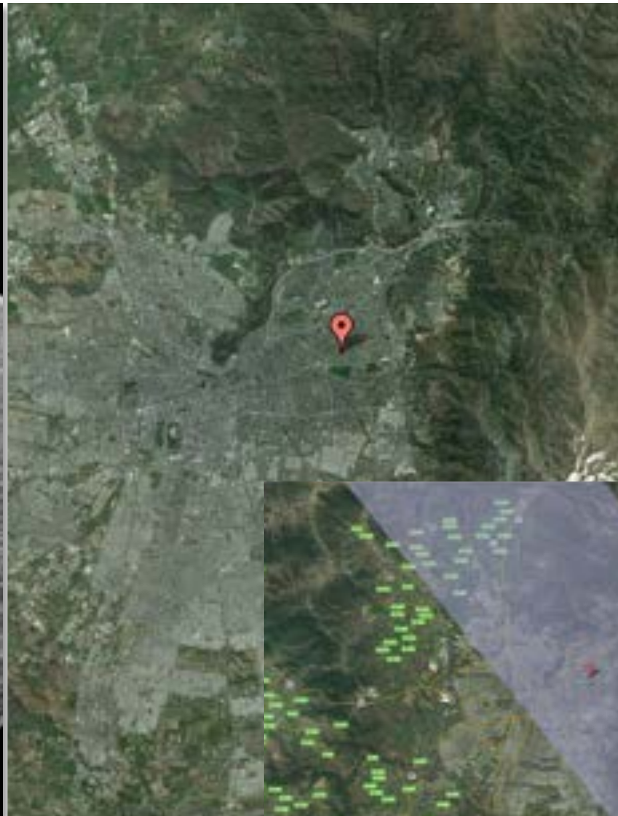
Examples

Santiago de Chile (Chile). SIR-C Sensor. 19/4/1994

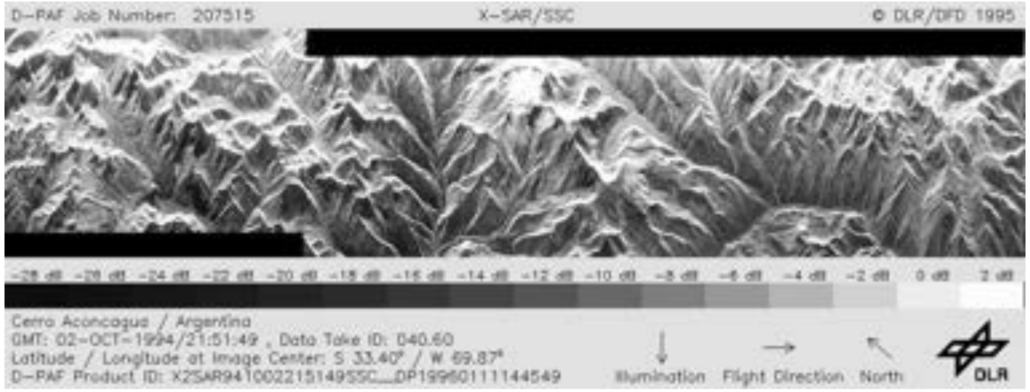


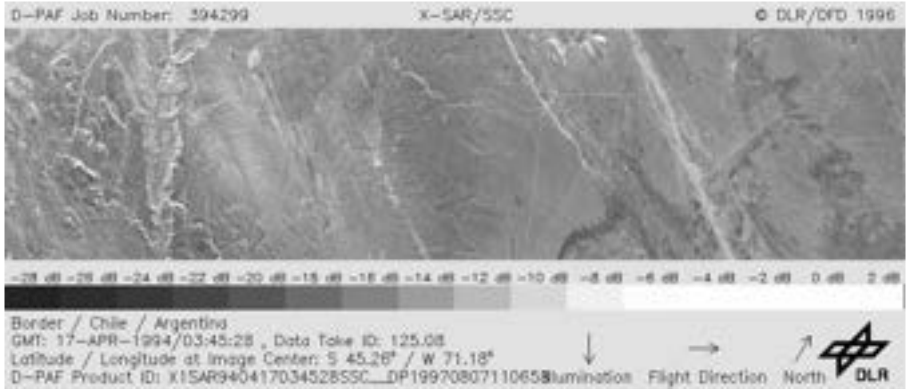


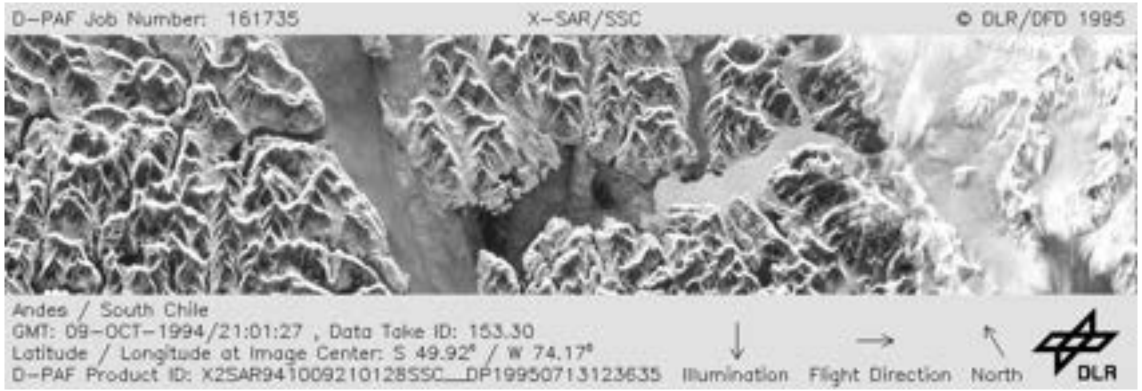
GoogleEarth image

Range x Azimuth resolution:
25 x 25 m
PRF: 1440 Hz B_w : 10.4 MHz

L-band

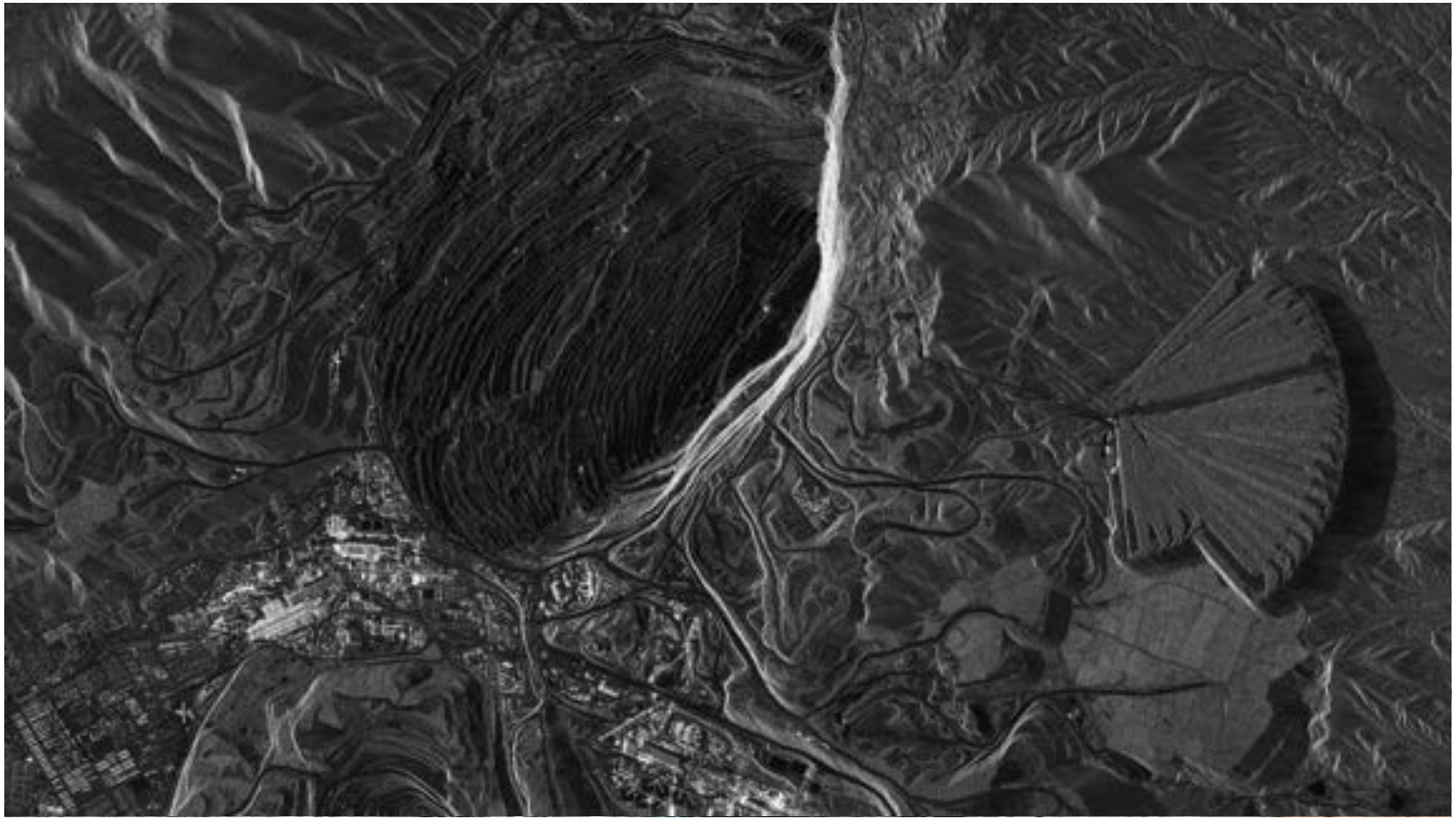






Chile. X-SAR Sensor

Examples



DLR; July 1, 2007, 23:00 UTC; Resolution: 1 meter
High Resolution Spotlight Mode, Polarization: HH.

Examples

Sandia National Laboratories

Ka-band (35 GHz)

4 inches spatial resolution

Examples

Sandia National Laboratories

Ka-band (35 GHz)

4 inches spatial resolution

Examples

Sandia National Laboratories. Washington DC area

Ku-band (15 GHz)

1 m spatial resolution

Examples

Global coverage by ALOS-PALSAR

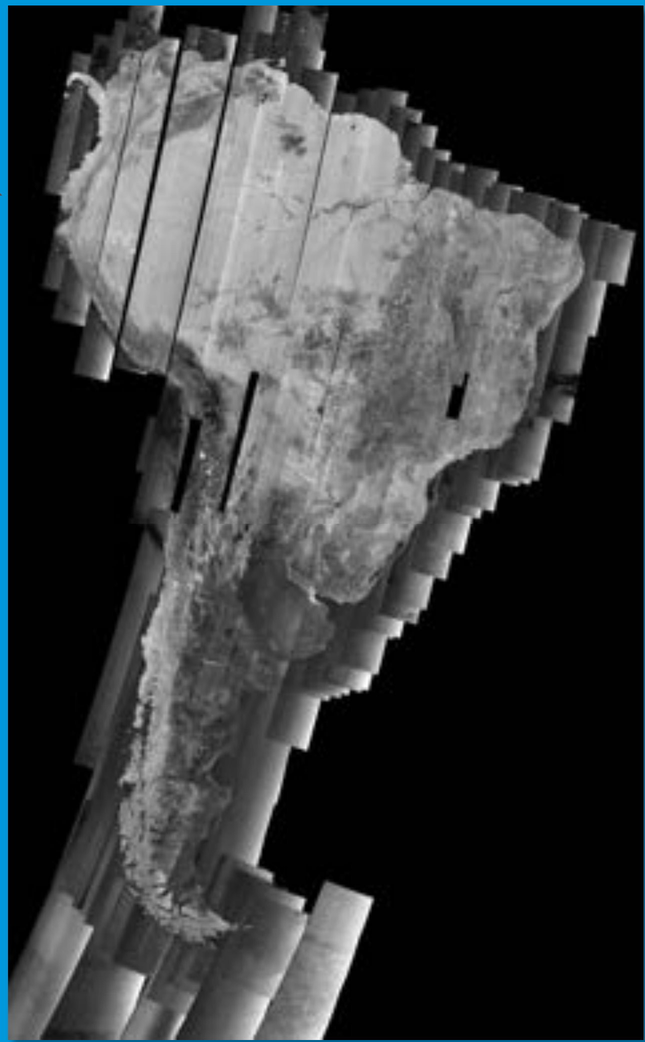
ALOS Kyoto & Carbon Initiative

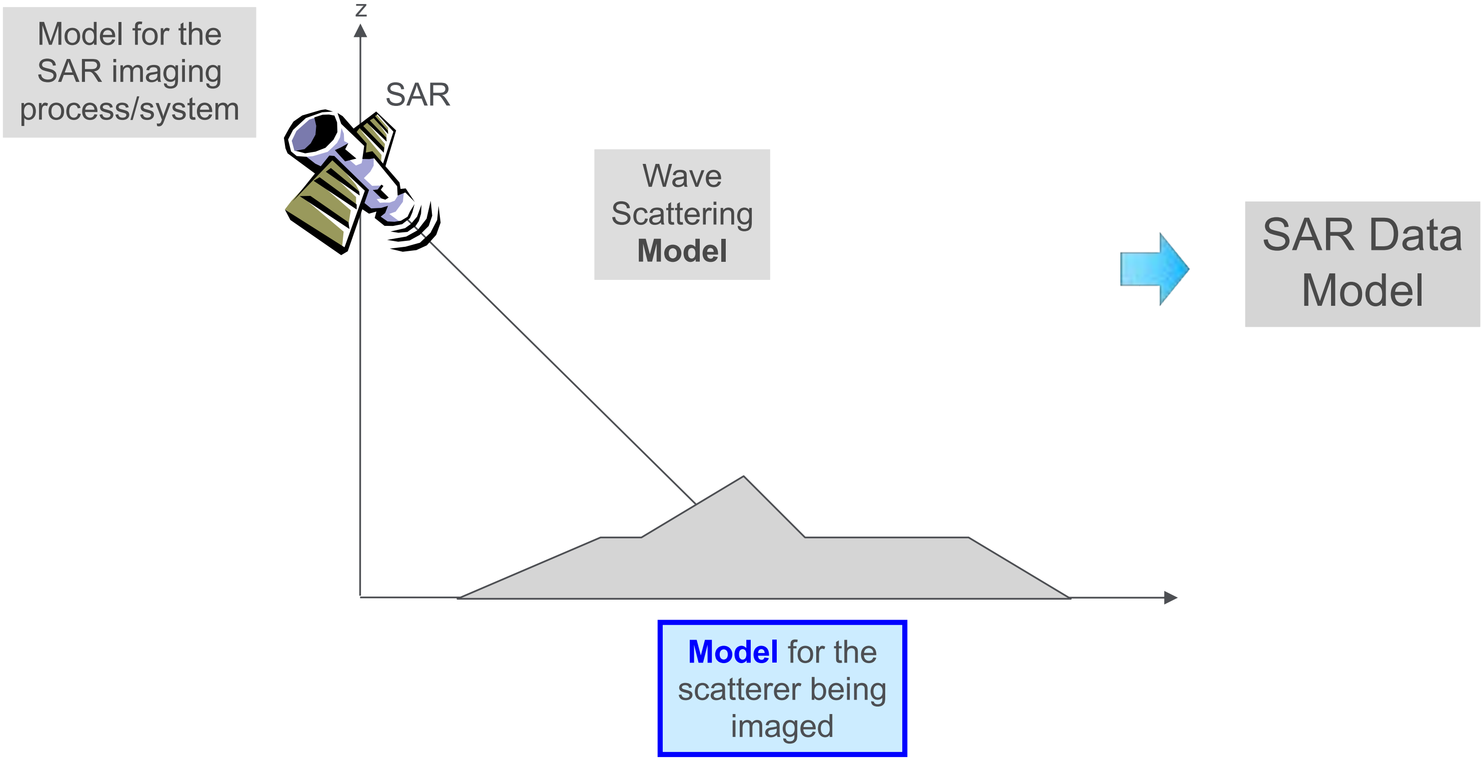
PALSAR 500m

Browse Mosaic Product

PALSAR Acquisition Mode: ScanSAR (WB1)

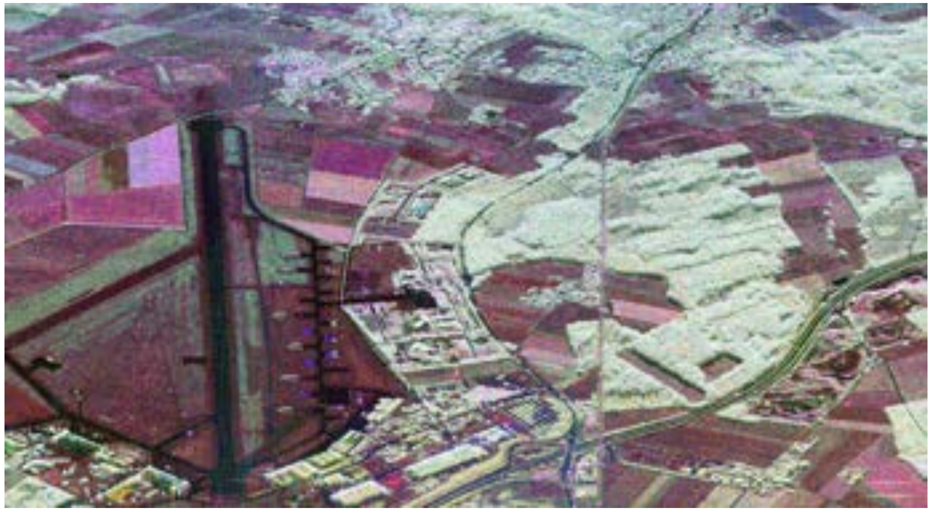
Central Frequency	1270 MHz
PRF	1500 - 2500 Hz (discrete stepping)
range Sampling Frequency	16 MHz
Chirp bandwidth	14 MHz
Polarisation	HH or VV
Off-nadir angle [deg]	20.1-36.5
Incidence angle [deg]	18.0-43.3
Swath Width [Km]	250-350
Bit quantization [bits]	5
Data rate [Mbps]	120 or 240





Scatterer Models

Scatterers Heterogeneity



|Shh+Svv| |Shh-Svv| |Shv|

SAR images reflect the Nature's heterogeneity

L-band (1.3 GHz) fully PolSAR data
E-SAR system. Oberpfaffenhofen test area (D)

Optical Image
Oberpfaffenhofen test area (D)

Scattering from Point Scatterers

Examples of point targets imaged by SAR systems

Power lines | Vehicles | Railways | Houses

Types of microwave scattering
- Point scattering
- Complex scattering

Man-made media present a strong point scattering behaviour

↓

Scattered field dominated by canonical scattering mechanisms

Point Scatterers Description

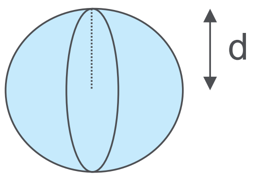
These scatterers make reference to canonical bodies as plates, cylinders, etc... the properties of which can be determined. Each body is finite in extent, and because in the far field zone, the scattered field appears to originated at a point, the body is described as a point target. [Ulaby'90]

$$\sigma_{i,j} = 4\pi \left| S_{ij} \right|^2 \qquad i, j = h, v$$

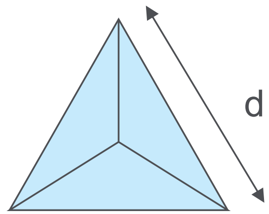
Radar Cross Section (RCS) of a body. Scattered power as a function of the incident power. Depends on the imaging geometry

$$\sigma_s\left(x_0, r_0\right) = \sqrt{\sigma} e^{j\theta} \delta\left(x - x_0, r - r_0\right)$$

Object description (Deterministic description)



$$\sigma_{\max}\left(m^2\right) = \pi d^2$$



$$\sigma_{\max}\left(m^2\right) = \frac{4\pi d^4}{3\lambda^2}$$

Scattering from Natural/Distributed Scatterers

Examples of natural targets imaged by SAR systems

Types of microwave scattering
- Surface scattering
- Volume scattering

Geophysical media present complicate structures and/or compositions

Exact knowledge of the scattered field very difficult

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Distributed Scatterers Description

Radar scattering from terrain involves complicated interactions because the scattering elements have complicated geometries and are randomly distributed in space. (...) Hence, we usually focus our attention on the development of generic models that can help to understand the nature of wave propagation and scattering in random media (...) allowing to interpret radar observations and extract useful information. [Ulaby'90]

$$u(\vec{r})$$

Object scattering function. (Random function - *microscopic structure*) NOT ACCESSIBLE

Distributed scatterers have complex geometries and are randomly distributed

$$\left\langle u(\vec{r}) \cdot u(\vec{r})^* \right\rangle = \sigma^0 \cdot \delta(\vec{r} - \vec{r}\,')$$

Object description. (2nd order descriptor - *macroscopic structure*)

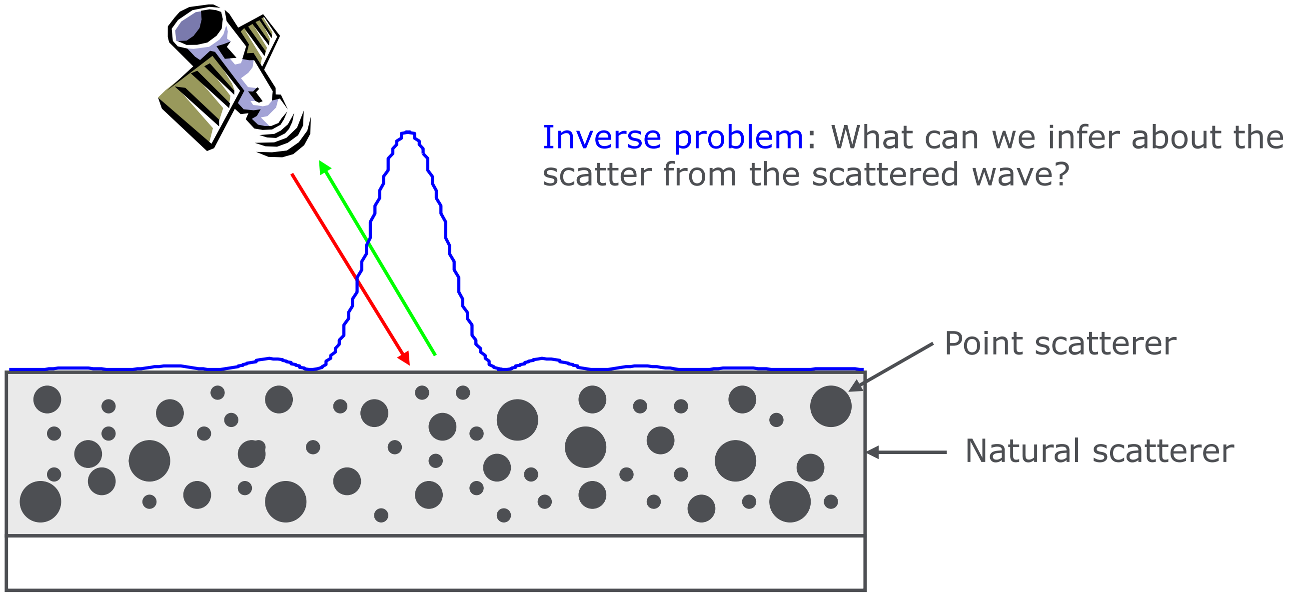
$$\sigma^0 = E\left\{\frac{\sigma}{A}\right\}$$

Average scattering coefficient or Differential backscattering coefficient. Does not depend on the area of the cell of resolution. This normalisation is necessary as a distributed target can occupy more than one cell of resolution.

Description of Distributed Scatterers

Real scatterers present a very complex structure

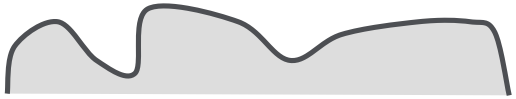
- Consider real scatterers as a collection of point or individual scatterers, randomly located
- The internal structure, i.e., microscopic structure, of the scatterer covered by the resolution cell can not be resolved
  - Partially solved by high dimensional SAR systems (PolInSAR)
- Scattered field results from the interaction of the incident wave with the individual scatterers

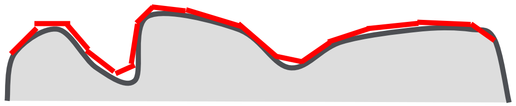


Description of Distributed Scatterers

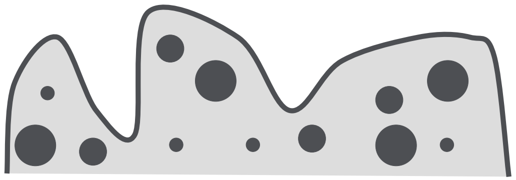
Types of complex scatterers

- Surface scatterer
  - The scattered wave is produced on the surface of the scatter (Conducting or homogeneous media)
  - The surface is considered as a set of facets. Discrete surface

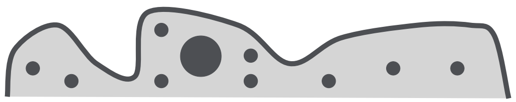


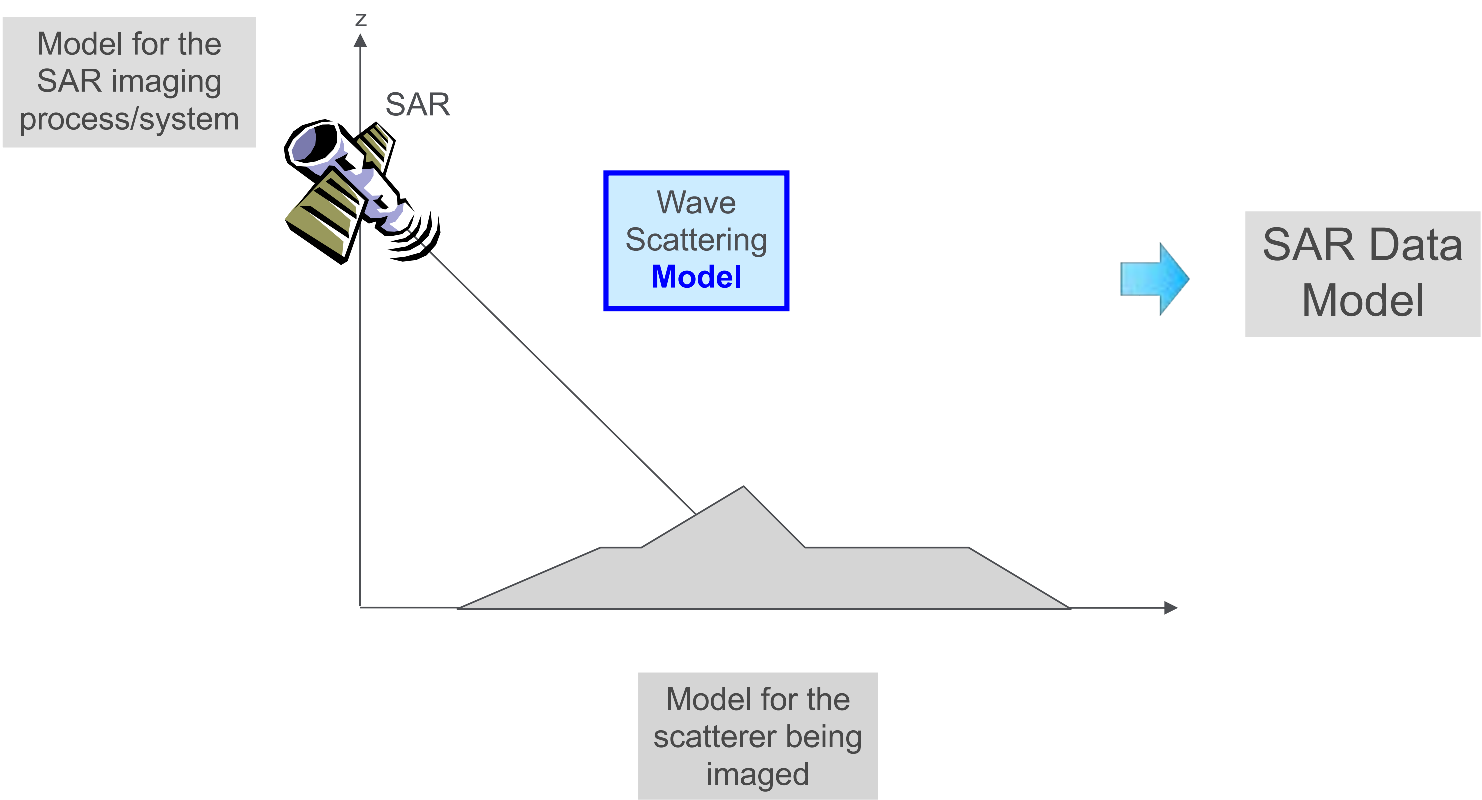


- Volume scatterer
  - The scattered wave is produced within the scatter (Inhomogeneous media)



- Point scatterer
  - The scattered wave is mainly produced by a dominant point scatter





Wave Scattering Models, Interaction with Matter

Scattering by Point Scatterers

The response of a point scatterer i.e., how it appears in a SAR image, can be considered as deterministic

$$\sigma_s(x_0,r_0)=\sqrt{\sigma}e^{j\theta}\delta(x-x_0,r-r_0) \qquad h(x,r)\propto \mathrm{sinc}\left(\frac{\pi x}{\delta_{\mathrm{a}}}\right)\mathrm{sinc}\left(\frac{\pi \mathrm{r}}{\delta_{\mathrm{r}}}\right)$$

$$S(x,r)=\sigma_s(x_0,r_0)**h(x,r)$$

Convolution in the Range-Azimuth space

$$\boxed{S(x,r)\propto \underbrace{\sigma_s(x_0,r_0)}_{\text{Target}}\underbrace{\exp\left(j2\frac{2\pi}{\lambda}(r-r_0)\right)}_{\text{Phase}}\underbrace{\mathrm{sinc}\left(\frac{\pi(x-x_0)}{\delta_{\mathrm{a}}}\right)\mathrm{sinc}\left(\frac{\pi(r-r_0)}{\delta_{\mathrm{r}}}\right)}_{\text{System}}}$$

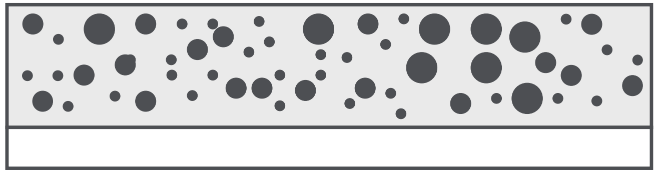
Complex SAR image

- Given the SAR image, it is possible to determine the properties of the scatterer from the image itself
- The pixel contains all the necessary information to characterize the scatterer

Scattering by Distributed Scatterers

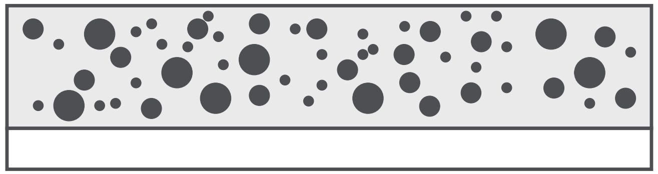
The complexity of a distributed scatterer is translated to the scattering process in the scatterer

Given a set of resolution cells/pixels, the internal structure (microscopic structure) changes from pixel to pixel, then, the scattering process changes from pixel to pixel



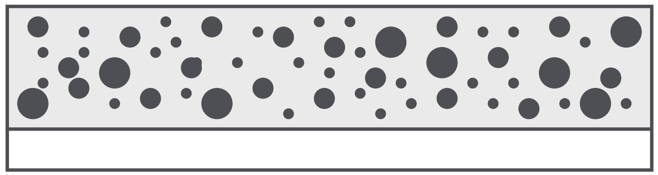
Pixel 1

Scattering processes can not be characterized by the value of single pixels as its values depend on the internal random arrangement



Pixel 2

Scattering processes must be characterized by global parameters common to all the pixels



Pixel 3

Characterization based on statistical parameters

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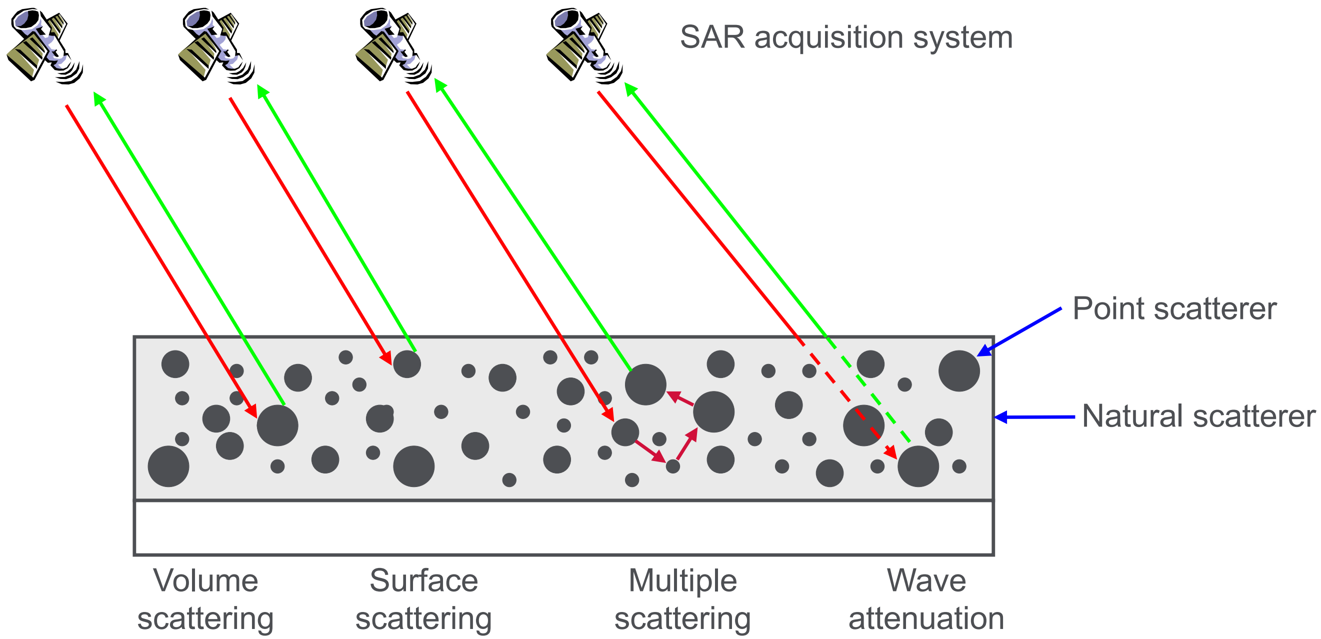
Born Scattering Approximation

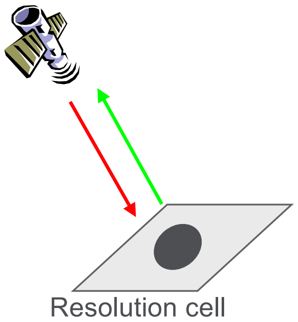
Scattering based on the Born approximation or single scattering approximation

- The scattering is supposed to be the linear coherent addition of the individual scattered waves from a set of discrete or point scatters



- The model does not consider attenuation or multiple scattering

SAR Imagery Analysis



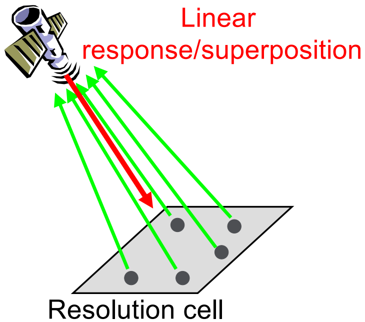
Deterministic Scatterer → Image formation process → DATA

Described in a **deterministic** way

Deterministic process

Can be studied using **deterministic** tools

↳ **Man Made Media**



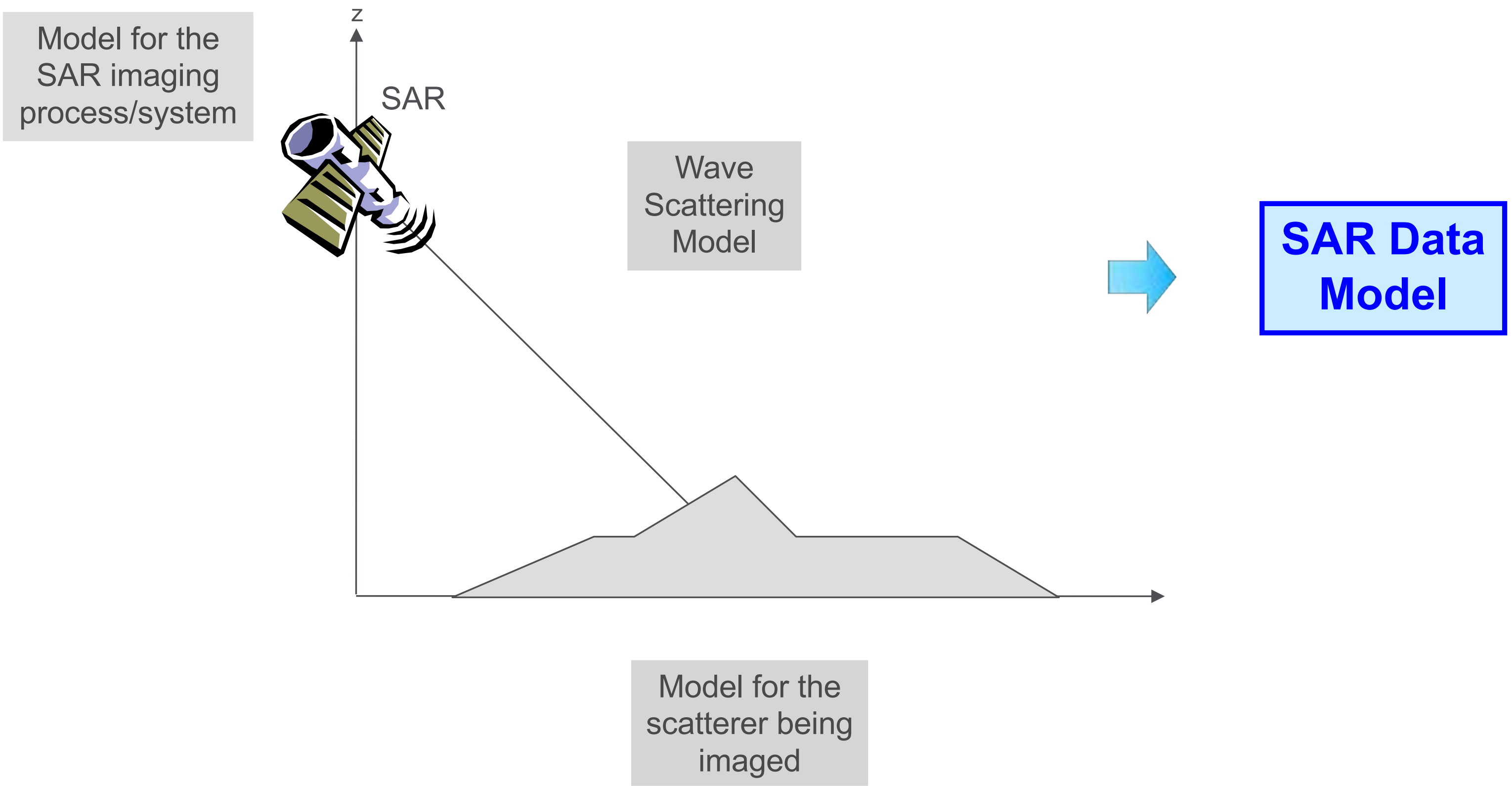
Distributed Scatterer → Image formation process → DATA

Described in a **stochastic** way

Deterministic electromagnetic process but can only be described in a **stochastic** way

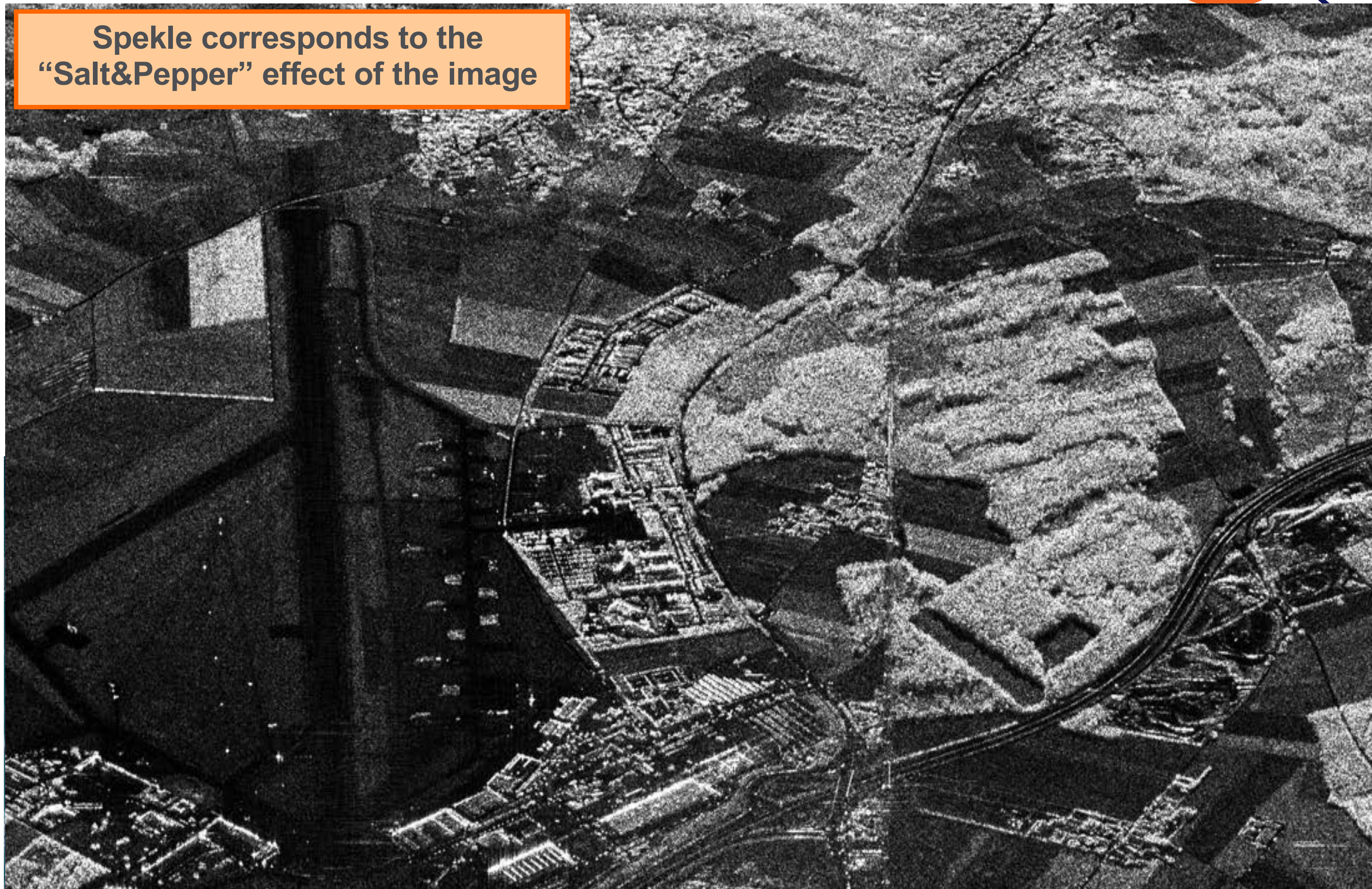
Can be studied using **stochastic** tools

↳ **Natural Media**



SAR Data Models and Speckle Noise

Speckle Noise



|Svv|

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Speckle Noise

On the basis of the discrete scatterer description

$$S(x,r)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}u(x',r')h(x-x',r-r')\mathrm{d}x'\mathrm{d}r' \Rightarrow S(x,r)=\frac{1}{\sqrt{L}}\sum_{k=1}^{L}\sqrt{\sigma_k}e^{j\theta_k}h(x-x_k,r-r_k)$$

Normalizing factor

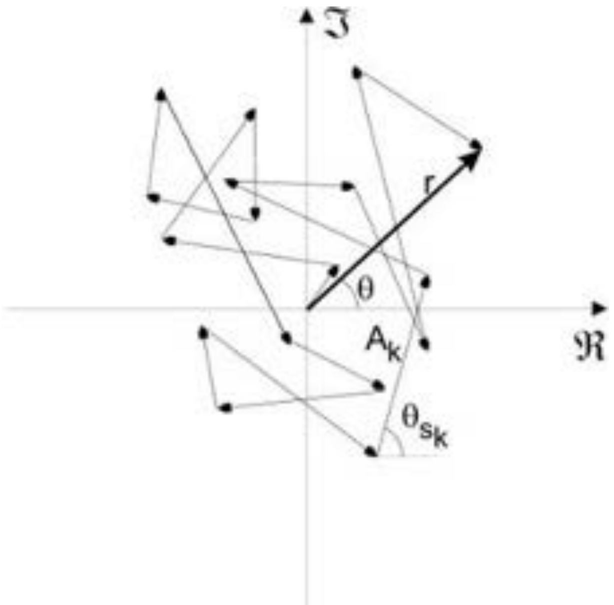
L: Number of point scatterers embraced by the resolution cell

- L as a deterministic quantity
  - L = 1: or a dominating point scatterer: Deterministic scattering
    - Rice/Rician model
  - L >1: Partially developed speckle
    - Not solved model. Even numerical solution difficult
  - L >>1: Fully developed speckle
    - Gaussian model
- L as a stochastic quantity
  - L characterized by a probability density function (pdf): Image texture
    - K-distribution model

Fully Developed Speckle Noise

- SAR image formation process

$$S(x,r)=\frac{1}{\sqrt{L}}\sum_{k=1}^{L}\sqrt{\sigma_k}e^{j\theta_k}h(x-x_k,r-r_k)$$



Random Walk Process

- Complex SAR data for L>>1

$$\begin{aligned}S(r(x,r),\theta(x,r))&=\Re\{S\}+j\Im(S)\\&=r(x,r)\exp(j\theta(x,r))\end{aligned}$$

  - Real part

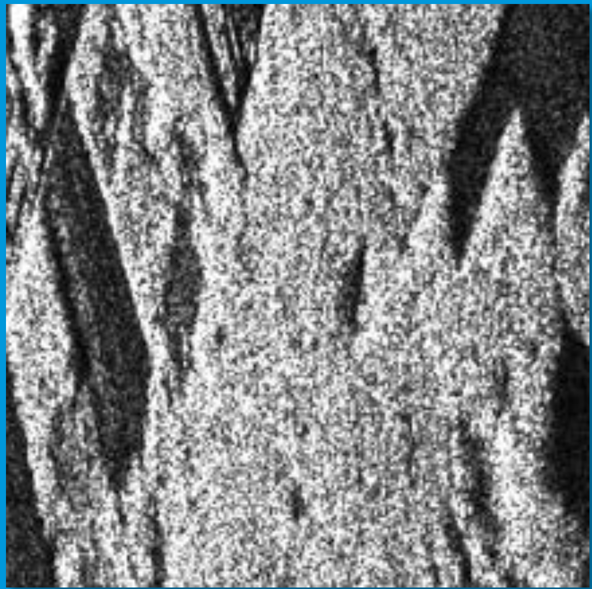
$$\Re\{S\}=\frac{1}{\sqrt{L}}\sum_{k=1}^{L}A_k\cos(\theta_{s_k})$$

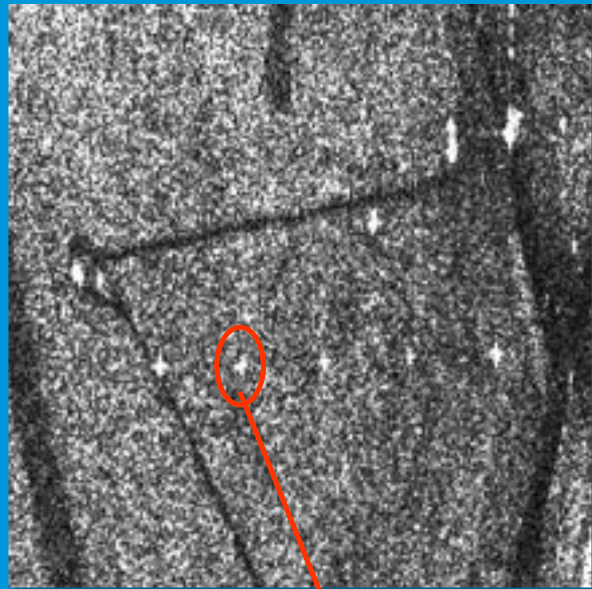
  - Imaginary part

$$\Im\{S\}=\frac{1}{\sqrt{L}}\sum_{k=1}^{L}A_k\sin(\theta_{s_k})$$

$$\boxed{r(x,r)\exp(j\theta(x,r))=\frac{1}{\sqrt{L}}\sum_{k=1}^{L}A_k\exp(j\theta_{s_k})}$$

Fully Developed Speckle Noise





Fully Developed speckle

Bright points: Points where the interference is constructive

Dark points: Points where the interference is destructive

Corner reflector
Dominant scatterer
No speckle

Speckle is the interference or fading pattern

S_{hh} amplitude
E-SAR L-band system

Fully Developed Speckle Noise

- Completely developed Speckle (large L and no dominant scatter)
  - Hypotheses
    - The amplitude A_k and the phase θ_{s_k} of the kth scattered wave are statistically independent of each other and from the amplitudes and phases of all other elementary waves (Uncorrelated point scatterers)
    - The phases of the elementary contributions θ_{s_k} are equally likely to lie anywhere in the primary interval *[-π, π)*

- Central Limit Theorem $\boxed{S = \mathrm{N}_{C^2}\left(0, \sigma^2/2\right)}$
  - Real Part

$$p_{\Re\{S\}}\left(\Re\{S\}\right) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2}\left(\frac{\Re\{S\}}{\sigma}\right)^2\right) \quad \Re\{S\} \in (-\infty, \infty)$$

Gaussian pdf

  - Imaginary Part

$$p_{\Im\{S\}}\left(\Im\{S\}\right) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2}\left(\frac{\Im\{S\}}{\sigma}\right)^2\right) \quad \Im\{S\} \in (-\infty, \infty)$$

Gaussian pdf

  - Real and imaginary parts are uncorrelated $E\{\Re\{S\}\Im\{S\}\} = 0$

Fully Developed Speckle Noise

- Amplitude: Rayleigh probability density function (pdf)

$$p_r(r) = \frac{r}{\sigma^2}\exp\left(-\frac{1}{2}\left(\frac{r}{\sigma}\right)^2\right) \quad r \in [0,\infty)$$

$$E\{r\} = \sqrt{\frac{\pi}{2}}\sigma$$

$$E\{r^2\} = 2\sigma^2$$

$$\sigma_r^2 = E\{r^2\} - E^2\{r\} = \left(2 - \frac{\pi}{2}\right)\sigma^2$$

- Intensity ($I=r^2$): Exponential probability density function

$$p_I(I) = \frac{1}{2\sigma^2}\exp\left(-\frac{I}{2\sigma^2}\right) \quad I \in [0,\infty)$$

$$E\{I\} = 2\sigma^2 \equiv \sigma$$

$$E\{I^2\} = 2\left(2\sigma^2\right)^2$$

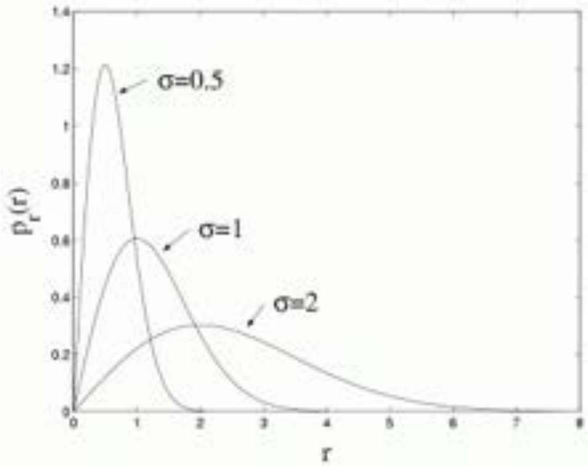
$$\sigma_I^2 = E\{I^2\} - E^2\{I\} = \left(2\sigma^2\right)^2$$

- Phase: Uniform probability density function .
  - Contains NO information

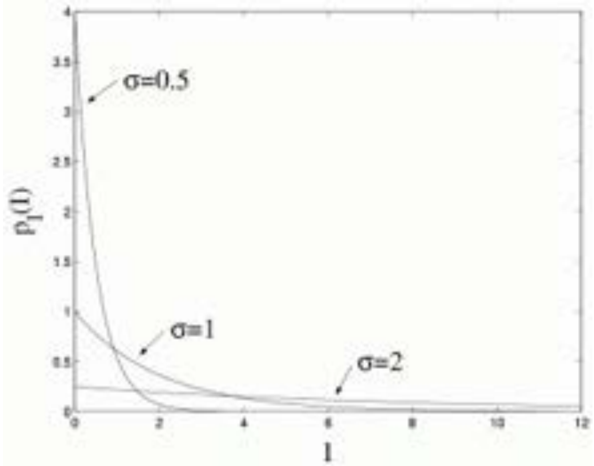
$$p_\theta(\theta) = \frac{1}{2\pi} \quad \theta \in [-\pi,\pi)$$

- Amplitude and phase are uncorrelated

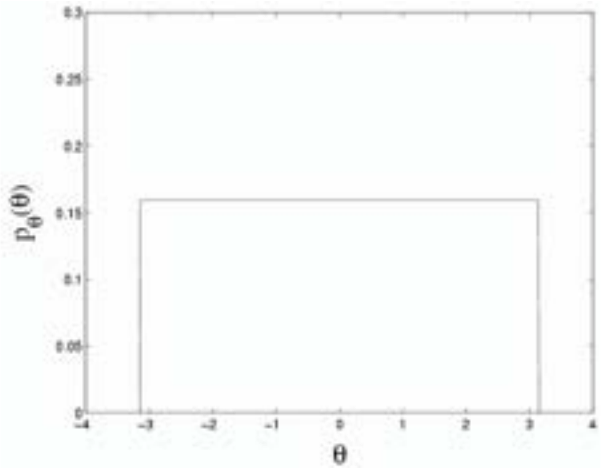
Fully Developed Speckle Noise



Amplitude: Rayleigh pdf



Intensity (I=r^2): Exponential pdf



Phase: Uniform pdf

Fully Developed Speckle Noise

Important considerations

- Speckle is a deterministic electromagnetic effect, but due to the complexity of the image formation process, it must be analysed statistically

- Considering completely developed speckle, a SAR image pixel does not give information about the target. Only statistical moments can describe the target or the process

Information

What does it mean information in the presence of Speckle?

- Phase contains no information
- Intensity exponentially distributed

$$p_I(I) = \frac{1}{2\sigma^2}\exp\left(-\frac{I}{2\sigma^2}\right) \quad I \in [0,\infty) \Rightarrow \begin{aligned} E\{I\} &= 2\sigma^2 \\ \sigma_I &= 2\sigma^2 \end{aligned}$$

Exponential pdf

First and second order moments

- Intensity, under the previous hypotheses, is completely determined by the exponential probability density function (pdf)
  - Pdf completely determined by the pdf shape
  - Pdf shape parameterized by σ $\Rightarrow$ INFORMATION $\Rightarrow$ RCS σ^0
- Not useful information is considered as NOISE

Fully Developed Speckle Noise Model

Objectives of a Noise Model

- To embed the data distribution into a noise model, that is, a function that allows identifying of the useful information to be retrieved, the noise sources, and how these terms interact
- Optimize the information extraction process, i.e., the noise filtering process

SAR image intensity noise model

SAR image intensity ($I=r^2$) $$p_I(I)=\frac{1}{2\sigma^2}\exp\left(-\frac{I}{2\sigma^2}\right) \quad I\in[0,\infty) \qquad E\{I\}=2\sigma^2 \quad \sigma_I=2\sigma^2$$

$$I=2\sigma^2 n \qquad p_n(n)=\exp(-n) \quad n\in[0,\infty) \qquad E\{I\}=1 \quad \sigma_I=1$$

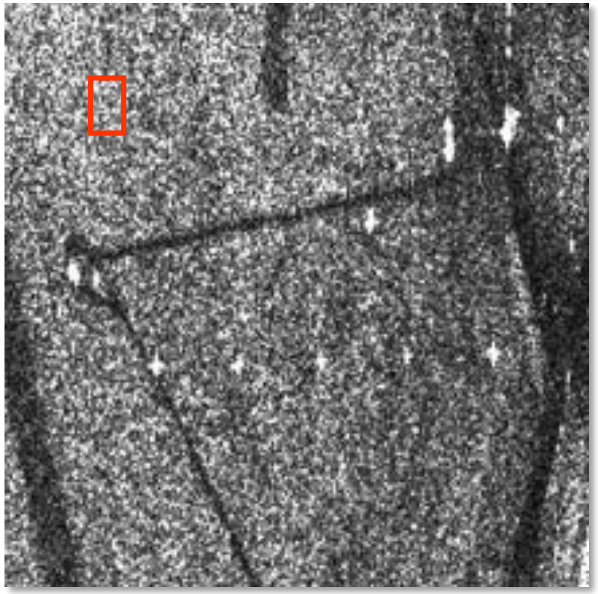
One dimensional speckle noise model (Model over the SAR image intensity - 2nd moment) $$\boxed{I(x,r)=\sigma(x,r)n(x,r)}$$

Multiplicative Speckle Noise Model

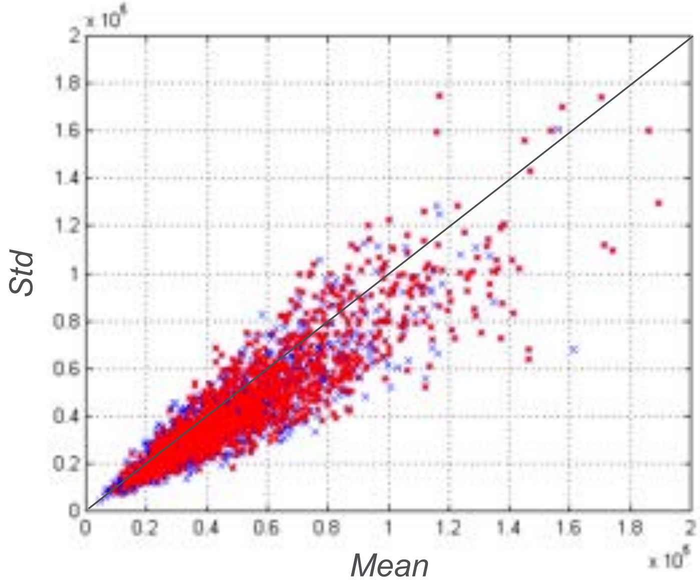
Fully Developed Speckle Noise Model

Moments calculated over local 7x7 local windows

Statistics area



Grass area



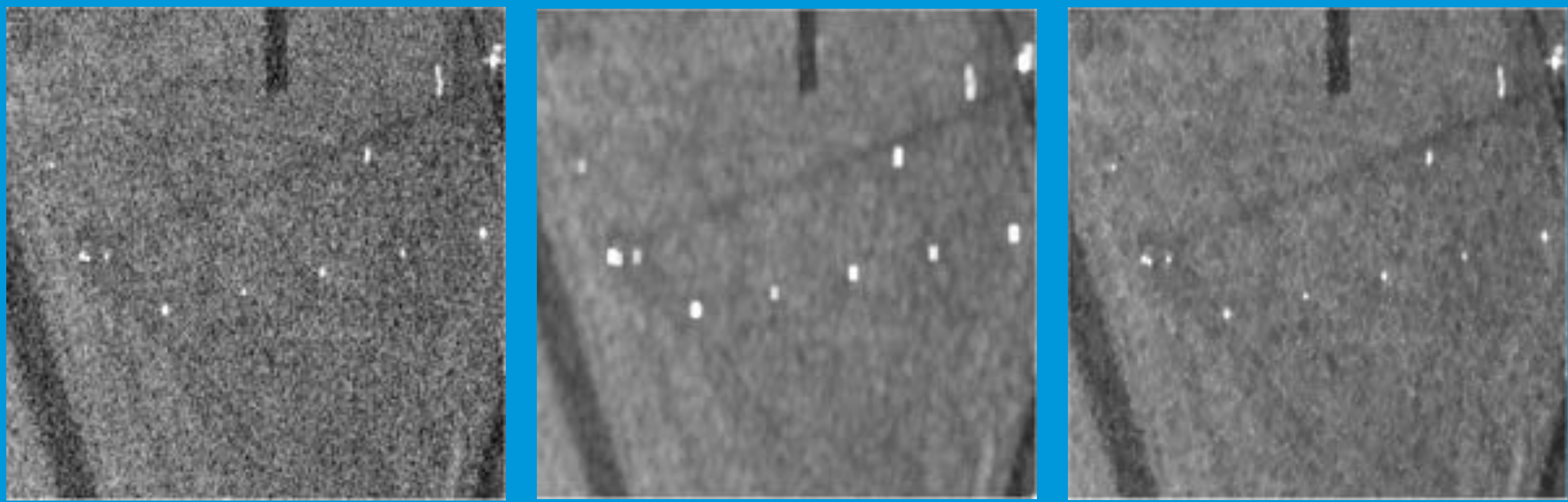
Blue: $|S_{hh}|^2$

Red: $|S_{vv}|^2$

S_{hh} amplitude
E-SAR L-band system

Speckle Noise Filtering

Speckle noise needs to be filtered for better data interpretation and information estimation



Original SAR intensity image

Filtered SAR intensity image
Boxcar Filter

Filtered SAR intensity image
Lee Filter

S_{hh} amplitude
E-SAR L-band system

Multidimensional SAR Systems

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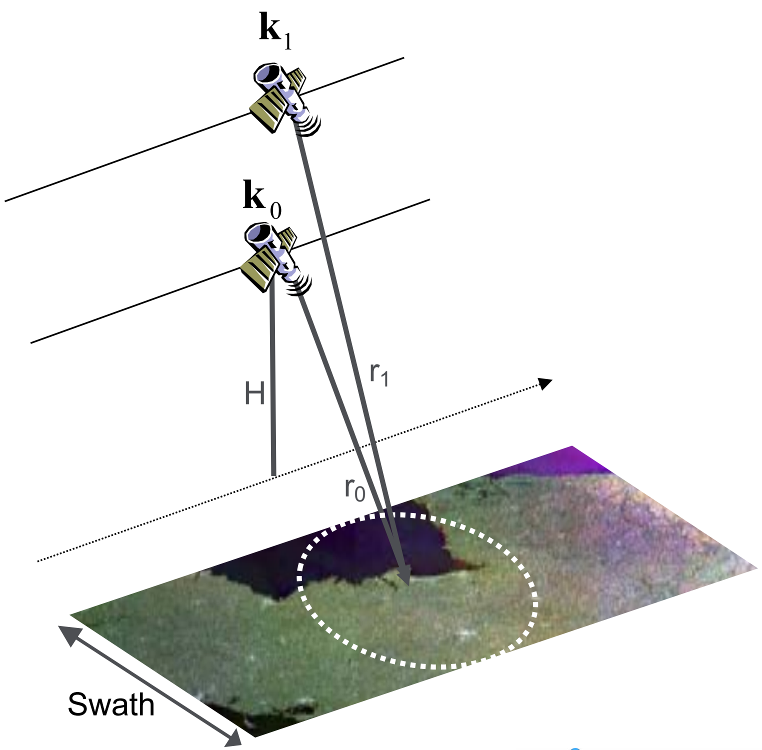
Multidimensional SAR Systems

The multidimensional SAR system acquires m complex SAR images

Target vector $\mathbf{k} = [S_1, S_2, \ldots, S_m]^T$



The properties of the target vector follow from the properties of a single SAR image

- **k** is deterministic for point scatterers. It contains all the necessary information to characterize the scatter
- **k** is a multidimensional random variable for distributed scatterers due to speckle. A single sample does not characterize the scatterer

SAR images characterized through second order moments

- Second order moments in multidimensional SAR data are matrix quantities

Multidimensional SAR Systems

- SAR Interferometry (InSAR): $m=2$. Topographic information
- Differential SAR interferometry (DInSAR): $m=3$. Topographic changes information
- SAR Polarimetry (PolSAR): $m=3,4$. Geometric characterization and classification of the scatterers being imaged
- Polarimetric SAR interferometry (PolInSAR): $m=6,8$. Study and characterization of volumetric structures
- SAR Tomography/Multibaseline: $m>2$. Vertical profiling
- Multitemporal SAR: $m>2$. Change detection and temporal analysis
- Multifrequency SAR: $m>2$. Characterization of the scatterers being imaged

Multidimensional SAR Systems

Important aspects to consider in Multidimensional SAR Imagery

- Physics
  - Depending on the configuration of the multidimensional SAR system, information is sensitive to one or several properties of the target being imaged
  - Data processing, and specially, data estimation can not be done without taking into account the physics behind de scattering process
  - The most clear example is the number of channels m. Represents a clear limitation for multidimensional SAR imagery

- Mathematical representation. Statistics
  - A mathematical description is necessary to systemize data description and understanding

Electromagnetic Signal Processing

SAR Polarimetry

SAR Polarimetry - PolSAR

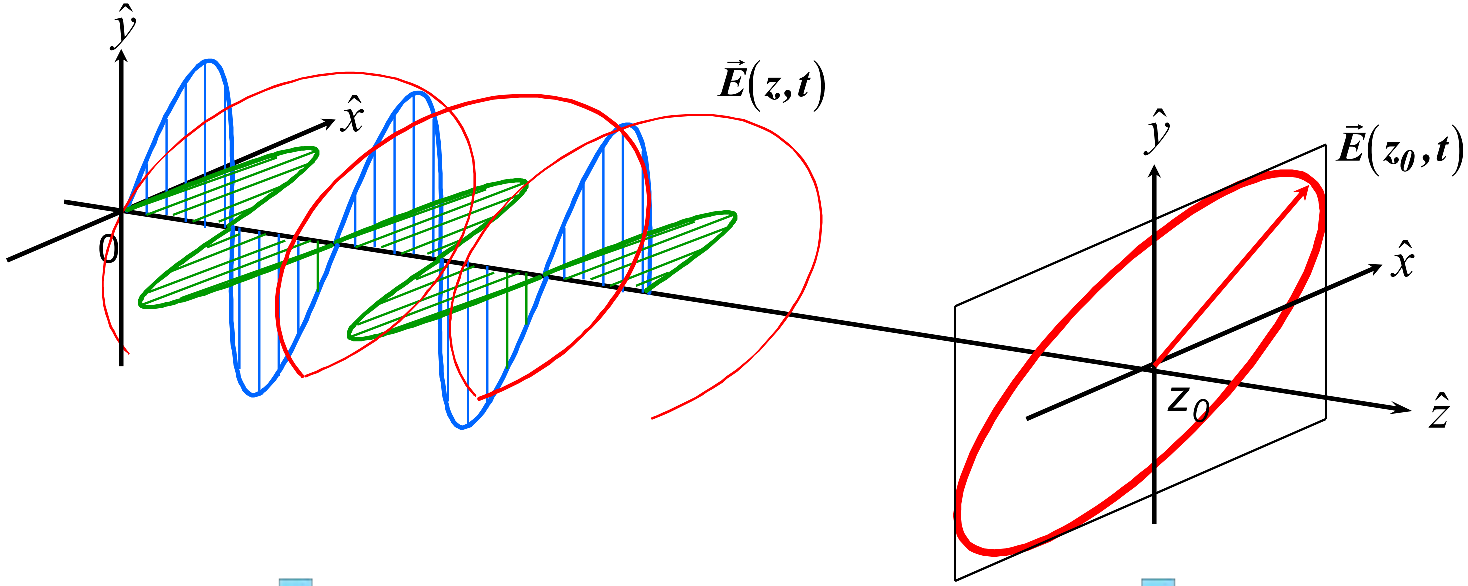
Polarimetry represents a cornerstone for the scatterers analysis

- Polarimetric data allows a better characterization of the scatter being imaged
- Polarimetric data is basically sensitive to the geometry and the electrical properties of the scatter being imaged
- Polarimetric synthesis allows, from the response of the scatterer to a particular polarization basis, the response to any polarization basis

SAR Polarimetry

- Extend the advantages of SAR systems, mainly, the high spatial resolution, to polarimetric data
- Considerations
  - Wave polarimetry
  - Wave scattering
  - Target Decomposition Theorems

Wave Polarimetry



Real electric field vector

$$\vec{E}(z,t) = \begin{cases} E_x = E_{0x}\cos(\omega t - kz - \delta_x) \\ E_y = E_{0y}\cos(\omega t - kz - \delta_y) \\ E_z = 0 \end{cases}$$

Polarization ellipse

$$\left(\frac{E_x}{E_{0x}}\right)^2 - 2\frac{E_x E_y}{E_{0x}E_{0y}}\cos(\delta) + \left(\frac{E_y}{E_{0y}}\right)^2 = \sin^2(\delta)$$

With: $\delta = \delta_y - \delta_x$

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Conclusions

- SAR systems allow to obtain Earth surface information at high spatial resolution, in the microwave of the electromagnetic spectrum, independently of the weather conditions or the day-night cycle
- SAR system can be boarded on space borne, air borne or ground based platforms.
- SAR imagery interpretation is different from optical imagery. Nevertheless, both technologies are complementary as they address different basic physics and target features
- SAR interferometry, based on spatial diversity, allows to obtain high resolution topographic information
- SAR polarimetry, based on polarimetric diversity, allows to obtain information about the geometry and moisture characteristics of the targets under observation