Universität Hamburg
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MIN-Fakultät
Fachbereich Informatik
Arbeitsbereich SAV/BV (KOGS)

IP2: Image Processing in Remote Sensing

7. Sensors II: Microwave Sensors and SAR Systems

Summer Semester 2014

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Agenda

- General Microwave Sensors
  - Passive Systems
  - Active Systems
    - Altimeter
    - Scatterometer
- SAR-Sensors
  - Design
  - From Low- to High-Resolution Systems
  - Challenges for Image Processing
- Other Sensors

Microwave Systems

- Strong differences in Imaging compared to former (visible light and infrared) sensors!
- Nearly no interference when passing the atmosphere and some atmospheric phenomena:
  - Clouds
  - Dust
  - Smoke
  - Snow
  - Light rain
- Allows (nearly) weather independent observation
- Wavelengths are between 1 mm – 1 m, which corresponds to 300 GHz – 300 MHz

Passive Microwave Sensors

- (Main) emit of the earth at microwave wavelengths: material temperature
- Signals at these spectral ranges may contain information about
  - Snow coverage
  - Soil moisture
  - Soil composition
- But: Signals are of low intensity!

  Low geometric resolution (mainly Push Broom Scanners)

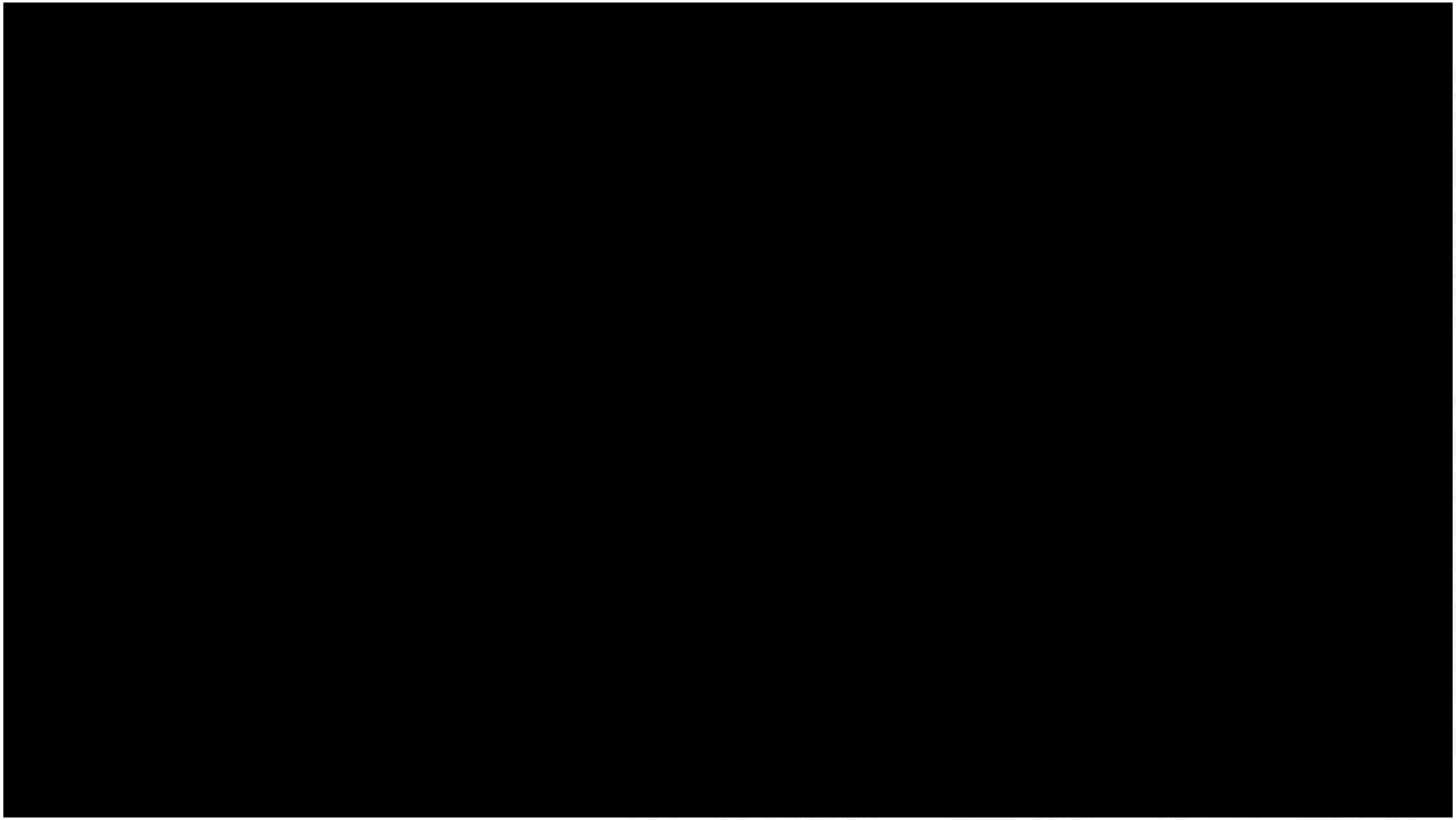
  No Synoptical image generation
- High construction efforts to enhance signal to noise ratio (SNR)

Example: SMOS

- SMOS = Soil Moisture and Ocean Salinity
- ESA Satellite launched on 2009/11/02
- Sensor: MIRAS (Microwave Imaging Radiometer using Aperture Synthesis)
  - a radiometer that operates between 1400-1427 MHz (L-band).
  - central structure and three deployable arms
- There are 69 antenna elements – the so-called LICEF receivers, which are equally distributed over the three arms and the central structure.
- The signal is then transmitted to a central correlator unit, which performs interferometry cross-correlations of the signals between all possible combinations of receiver pairs.

SMOS Satellite: ESA's Water Mission

http://www.youtube.com/watch?v=Kw0umICWXuU



Active Microwave Systems

- Categorization:
  - Real vs. Synthetic Aperture Radar (SAR)
  - Push broom vs. Side looking
  - Single vs. Multi/Cross-Polarization
  - Single vs. Multi-Band Systems
- Active Systems!
  - Formerly high energy consumption -> additional batteries needed
  - Nowadays: Solar panel power sufficient!
- Different bands for different observations
- Not every configuration available:
  - currently not multi-band SAR in orbit
  - some systems allow cross- or single polarization

Satellite based Altimetry

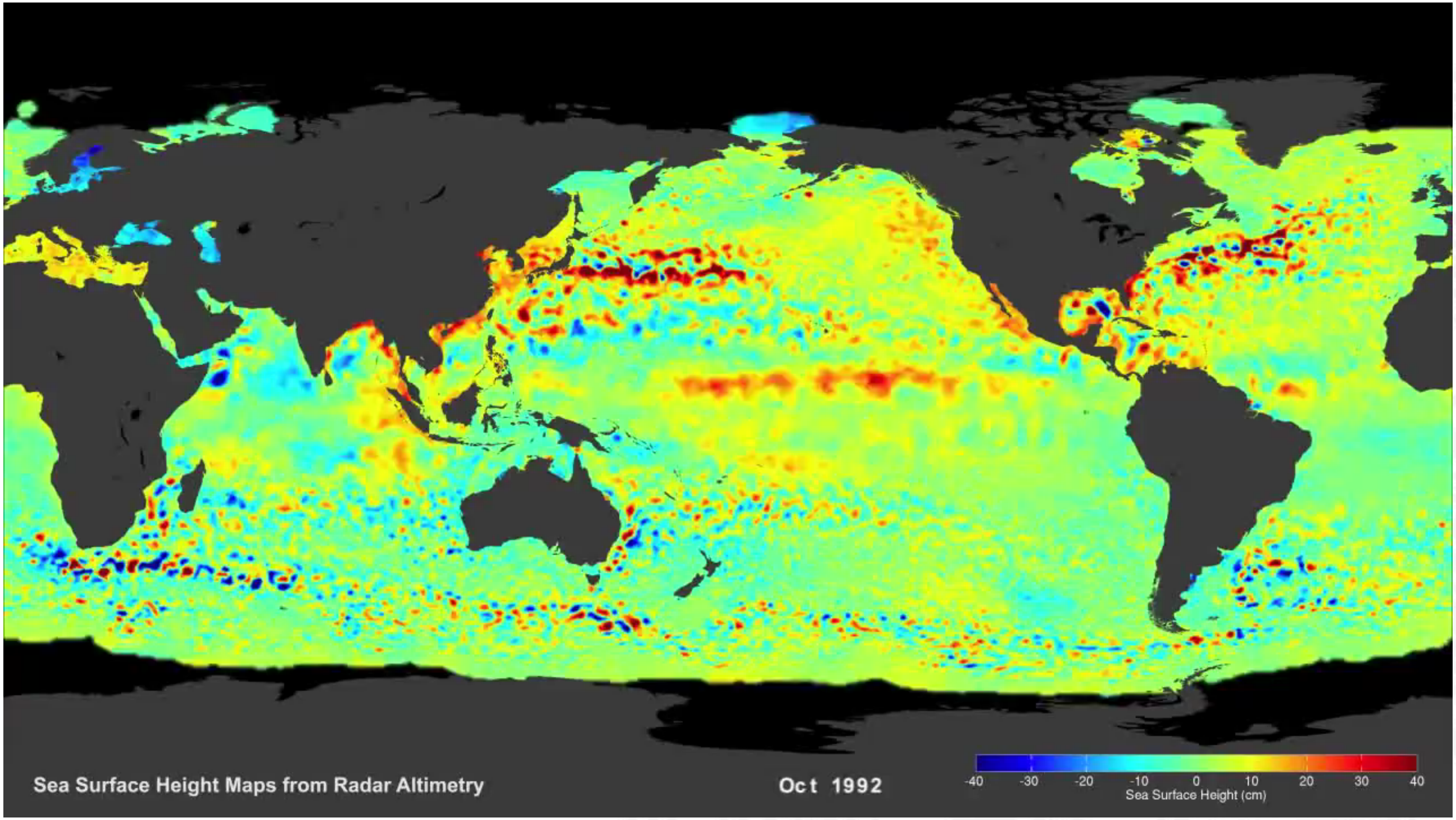
- Typical applications:
  - Earth surface height
  - Ocean water level/distribution (important climate parameter)
- Push broom/point wise measurements
- System design – down-facing:
  1. Emit Microwaves of certain power
  2. Measure backscattered energy and runtime
  3. Derive Altimetry from measured data
- Note:
  - Measured altitude needs to be normalized w.r.t the earths geoid (gravity distribution is non-uniform)
  - IFOV (Footprint) size/resolution depends on aperture size of the antenna
  - Typical Sensors achieve low spatial but high measurement precision!

Example: TOPEX/POSEIDON

- Successful Altimeter: 1992 – 2006
- Technical details:
  - Bands: Ku- and C-Band
  - Footprint: 3 – 5 km
  - Precision: 3.3 cm!
  - Distance between two measures: 8 km
- Mainly ocean topography measurements
- Problems at coastal regions
- Large efforts in different disciplines:
  - Climate Research
  - Hurricane Forecasting
  - El Niño & La Niña Forecasting
  - Ship Routing
  - …
- Yet, over 2100 publications based on the data!

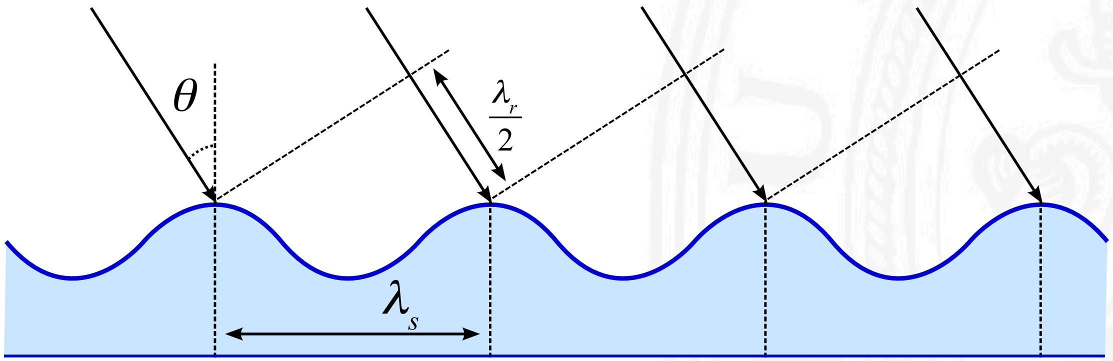
Sea Surface Height Maps from RADAR Altimetry

http://www.youtube.com/watch?v=F8zYKb2GoR4



Satellite based Scatterometry

- Backscattering of emitted microwave radiation allows a measurement of related phenomena.
- Example: Wind velocity and direction over sea surface:
  - Estimation indirectly over the sea surface roughness
  - Through small (ripple) waves modulation of ~ 1 cm
  - Waves become visible through Bragg-Resonance:



θ Incidence angle

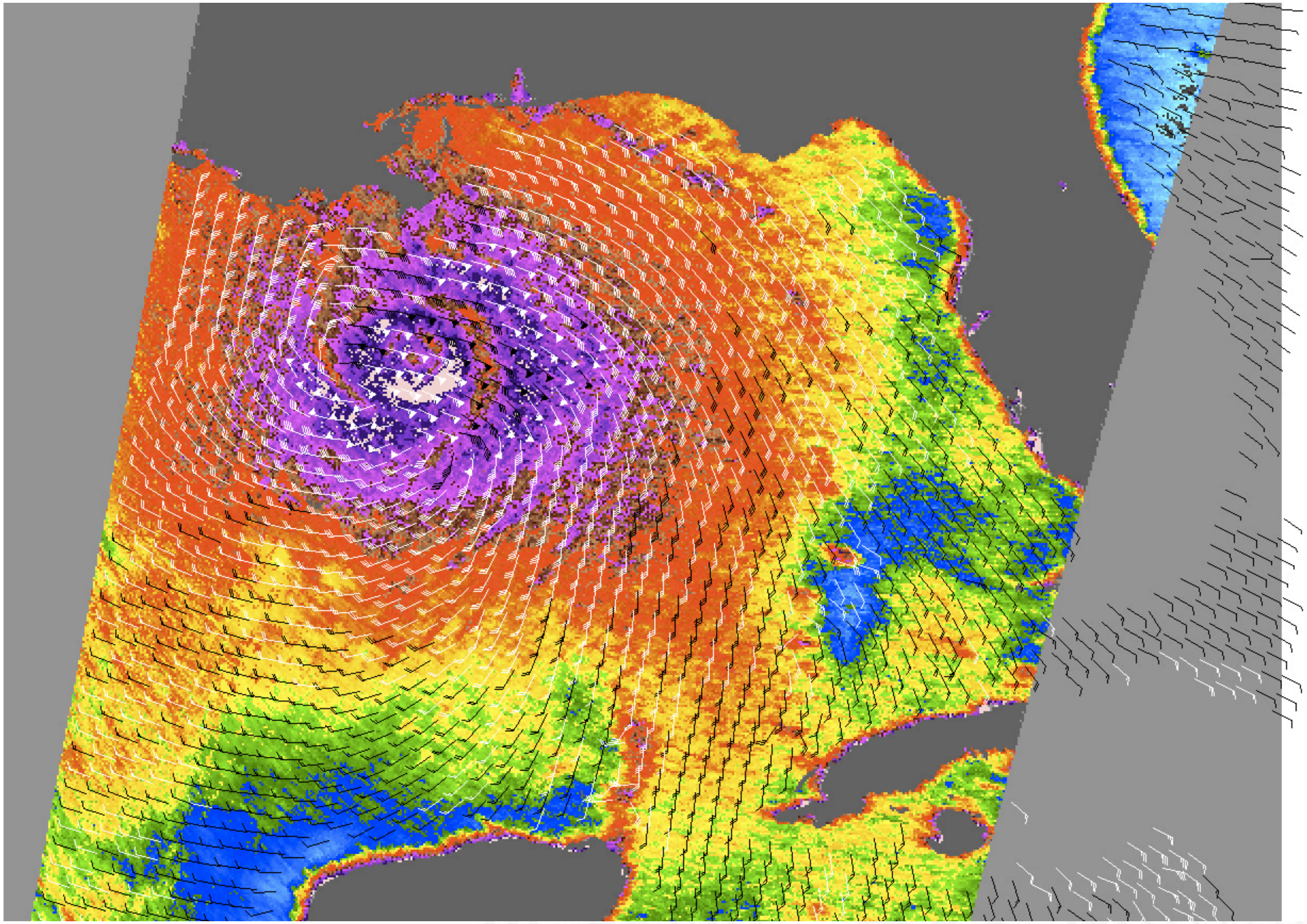
λ_r RADAR wavelength

λ_s Wave's wavelength

Example: QuikSCAT

- NASA Scatterometer 1999 – 2009
- Main purpose: Wind measurement (over sea surface)
- Sensor characteristics:
  - 2 rotating dish antennas: 1 m aperture with a circular sweep
  - Resolution: 25 km
  - Measurement height: 10 m above sea surface
  - Wind-speed measurements of 3 to 20 m/s (accuracy: 2 m/s)
  - Wind-direction with an accuracy of 20°
  - Swath width: 1800 km
  - Band: Ku-Band
- Collected much more wind measurements than ground stations!

Example: Hurricane Katrina (2005)



RADAR vs. Photometric Resolution

The angular resolution depends on:

- λ the wavelength
- D the aperture and
- R the distance:

$$\delta = \frac{\lambda}{D} R$$

- Example:

  D=3 m, R=900 km

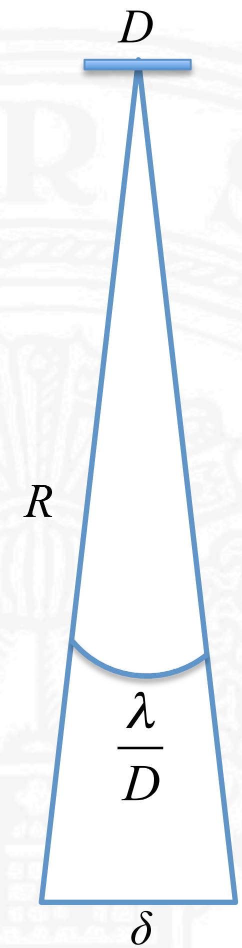
  - Visible Spectrum ($\lambda=7\ 10^{-7}$ m):

    $\delta = 0.21$ m

  - RADAR ($\lambda=7\ 10^{-2}$ m):

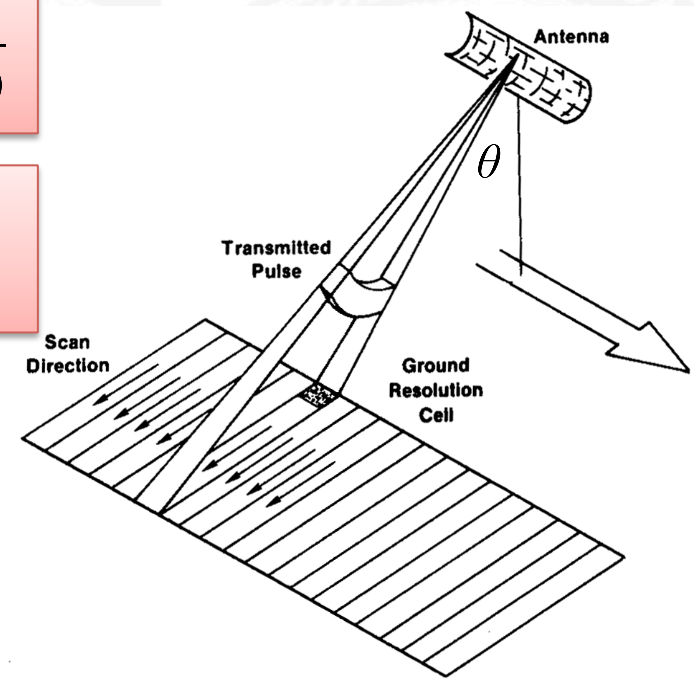
    $\delta = 21000$ m

- Worse angular resolution compared with spectral imaging methods!



Side Looking RADAR (SLAR)

- From "basic" RADAR to imaging radar!
- Side looking (incidence angle θ) is necessary for image creation/range resolving.
- Ground range resolution (with pulse length τ): $\delta_r = \frac{c \cdot \tau}{2\sin(\theta)}$
- Azimuth resolution is: $\delta_a = \frac{\lambda}{D} R$
- The shorter the pulse and the larger the antenna, the higher the resolutions!



From Real to Synthetic Aperture I

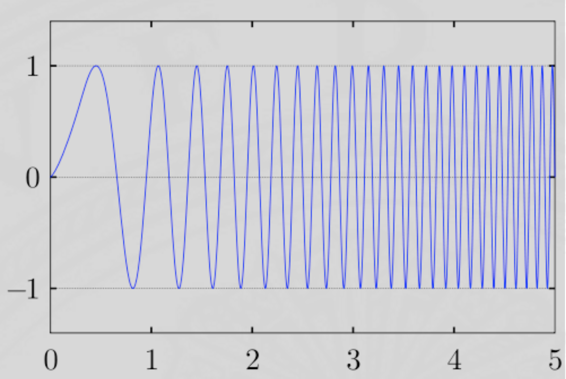
- Unrealistic to have either large antennas or very short pulse lengths!
- Example: ERS-Satellite (R=850 km, λ=5.5 cm, D=10 m)
  - To achieve an azimuth resolution of 10m, a 5 km large antenna is needed!
  - At a pulse length of τ=20 µs and inclination angle θ=35°, the range resolution is ≈ 5227 m
- Two different problems:
  - Shorter impulses (practically) cannot carry as much energy
  - Larger antennas not possible in orbit

⇒ SAR-Technique has been developed to simulate a large antenna!

From Real to Synthetic Aperture II

Step 1: Solving the pulse length problem:

- Use pulse compression instead of a single pulse
- Also called (by its sound) chirp
- Instead of a single wavelength λ, a complete bandwidth is used: B_c



- Procedure
  1. Emit chirp
  2. Reconstruct the response by correlation with the "chirped" signal
- Advantages: Compression factors of ~ 600 in praxis
- Example of last slide:
  - Range resolution changes!
  - Formerly 5227 m, with pulse compression 8 m!
- At the cost of higher processing!

From Real to Synthetic Aperture III

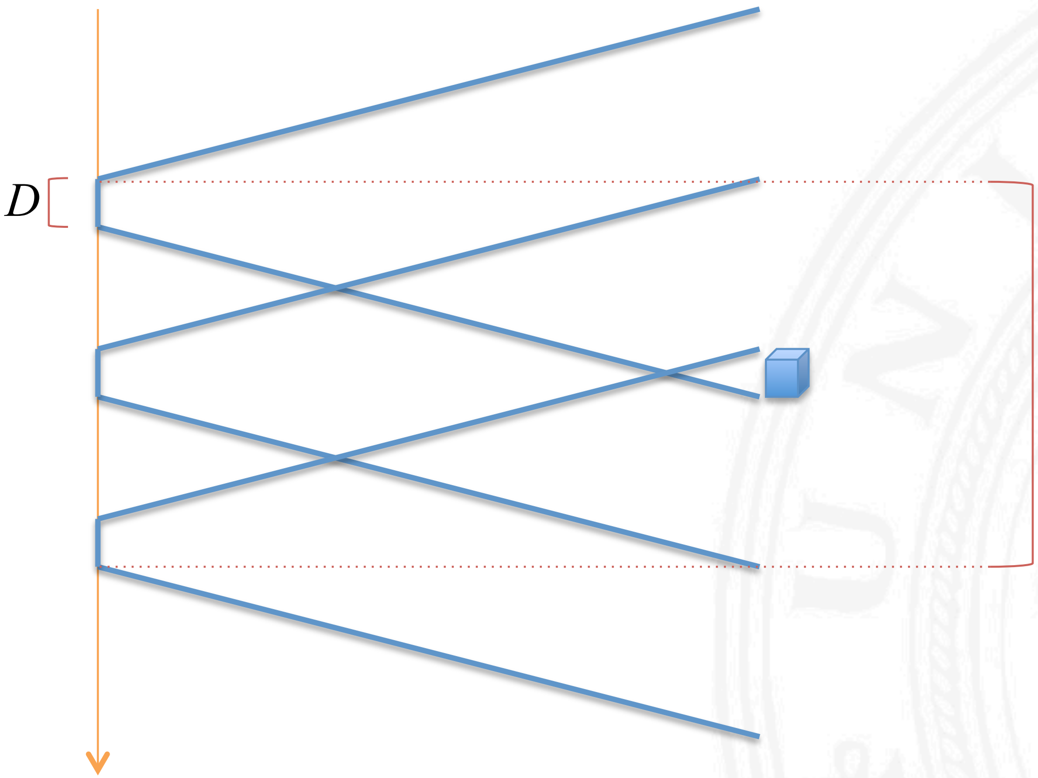
Step 2: Enhancing the azimuth resolution:

- Idea: Make the RADAR system work coherently. Knowledge needed about phase shifts between
  - sender and receiver and
  - pulse to pulse
- Repeat measurements along-track and "synthesize" the short antennas to a large antenna!
- SAR synthesis step requirements
  - exact knowledge of position and
  - exact orientation of the sender.

From Real to Synthetic Aperture IV

Step 2: Enhancing the azimuth resolution:

- Recall the RADAR azimuth resolution equation: $\delta_a = \frac{\lambda}{D} R$



$$D_{syn} = \frac{\lambda}{D} R \Rightarrow \delta'_a = \frac{D}{2}$$

Note: Factor ½ origins from doubled phase shift!

From Real to Synthetic Aperture V

Step 2: Enhancing the azimuth resolution:

- To resolve the synthetic aperture the Doppler shift is used:
  - Assumption: Moving Satellite and non-moving objects
  - Equation on last slide: result of Doppler Bandwidth and signal theory

Note: the SAR azimuth resolution is independent of the microwave's wavelength and altitude!

- Real aperture RADAR:
  Larger Antenna, better resolution
- Synthetic aperture RADAR:
  smaller Antenna, better resolution

⇒ Results in complex processing schemes!

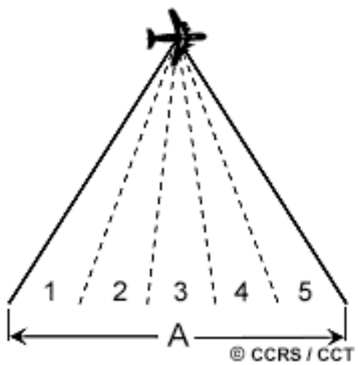
Properties of Synthetic Aperture RADAR (SAR) Systems

- **Remember:** Microwave Imaging ≠ Photometric Imaging!
- Classical Radar: Target vs. Clutter
- SAR: No equivalent to clutter but point and area objects → normalized backscatter coefficient σ_0
- Multiple scattering/reflection of microwaves
- Direct backscattering on metal/artificial objects
- Length distortion in range direction
- SAR: Coherent Imaging → Coherent pixel value assignment
  → Speckle "Noise"

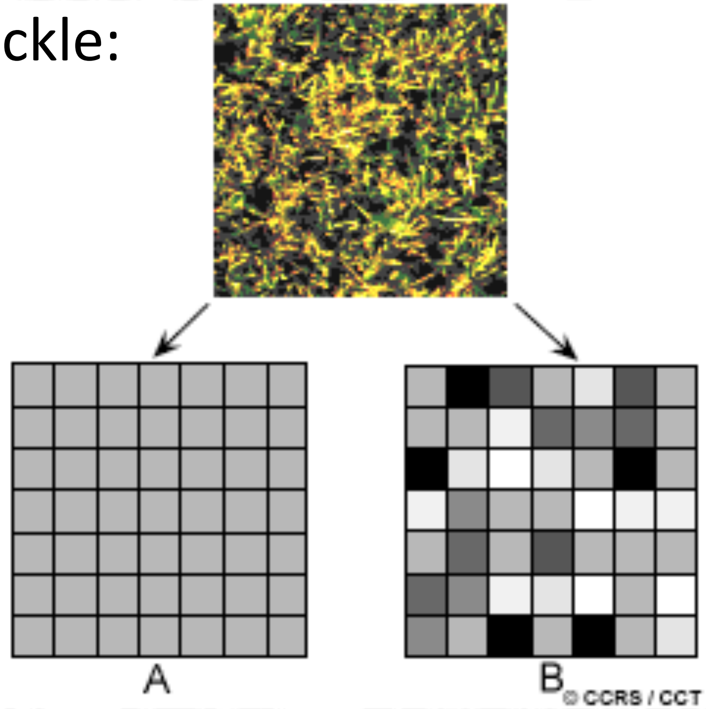
Speckle "Noise"

- Speckle seems to cover the interesting measurements, e.g. the characteristic backscatter coefficient of an area class.

- Two strategies to decrease the speckle:
  1. Multi-Look processing



  2. Image filters



Note: Speckle is the signal!

Speckle Filters as Moving Window Filters

- Definition by means of "Moving Window Filters":
  - The filtered value is computed based on the surrounding window
  - Window size has to be determined by the user

$$\forall_{\frac{f_w}{2} \leq x \leq w - \frac{f_w}{2} - 1} \quad \forall_{\frac{f_h}{2} \leq y \leq h - \frac{f_h}{2} - 1} \quad I'\left(x, y\right) = f\left(W_{x,y}\right)$$

- Important values (for most filters):
  - Variance and mean of **the intensity inside the current window** (can be computed easily)
  - Variance and mean of the **speckle** (unknown, has to be approximated)

$$c_I^2 = \frac{\mathrm{var}(W_{x,y})}{\left(\bar{W}_{x,y}\right)^2}$$

$$c_u^2 = \frac{\mathrm{var}(u) \approx n^{-1}}{\bar{u}^2 \approx 0.523^2}$$

- Non-linear/adaptive behavior (due to non-linear speckle)

Median, Lee & Kuan Filters

- The Median Filter is an adaptive (edge-preserving) filter!
  - Easy to understand and to implement
  - No statistics of the speckle need to be known
  - But: Sorting has to take place for each window!
- Lee & Kuan Filter are quite similar

$$f\left(W_{x,y}\right) = I\left(x,y\right)w + \left(\bar{W}_{x,y}\right)(1-w)$$

Lee: $w = 1 - \frac{c_u^2}{c_I^2}$ Kuan: $w = \left(1 - \frac{c_u^2}{c_I^2}\right) \Big/ \left(1 + c_u^2\right)$

weighting coefficient is a function of local target heterogeneity measured with the coefficient of variation.

Gamma MAP Filter

- The Gamma Filter is a Maximum A Posteriori (MAP) Filter
  - based on a Bayesian image statistics analysis.
  - Assumption: the radar reflectivity and the speckle noise follow a Gamma distribution.
  - The superposition of these distributions yields a K-distribution:

$$f\left(W_{x,y}\right) = \frac{l\,\overline{W}_{x,y} + \sqrt{\left(\overline{W}_{x,y}\right)^2 l^2 + 4\alpha n \overline{W}_{x,y}}}{2\alpha}$$

  - with: $\alpha = \frac{1+c_u^2}{c_I^2 - c_u^2}$ and: $l = (\alpha - n - 1)$

Note: The K-distributions are recognized to match a large variety of radar return distributions of land and ocean targets.

The Frost Filter

- Can be considered as an adaptive Wiener Filter:
  - Fixed window size
  - Convolution of the image with an exponential function:

$$f\left(W_{x,y}\right) = \frac{\sum_{x,y \in W_{x,y}} I(x,y)w(x,y)}{\sum_{x,y \in W_{x,y}} w(x,y)}$$

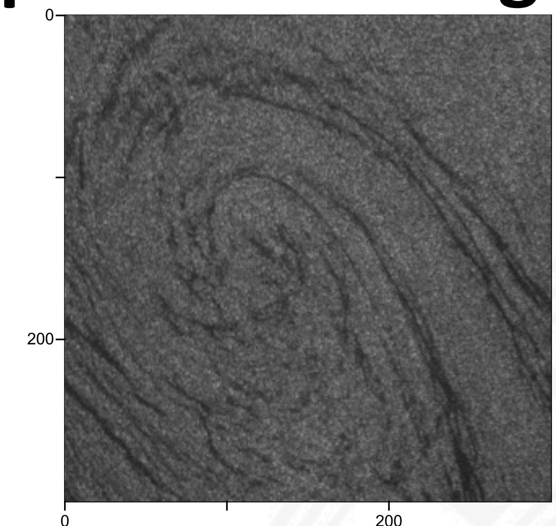
with:

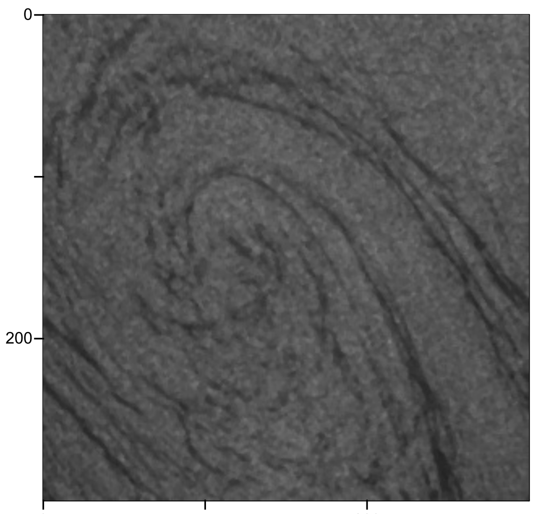
$$w(x,y) = e^{-k\, c_I^2\, d(x,y)}$$

$$d(x,y) = \sqrt{\left(x - {}^{f_w}\!/\!_2\right)^2 + \left(y - {}^{f_h}\!/\!_2\right)^2}$$

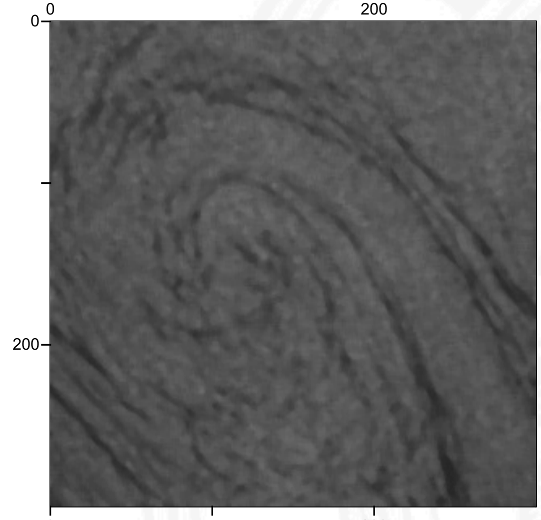
- Observations: Response is depending on
  - The position inside the window,
  - The ratio of the mean (squared) and variance of the window and
  - The free parameter k.

Examples of Speckle Filtering: Median Filter

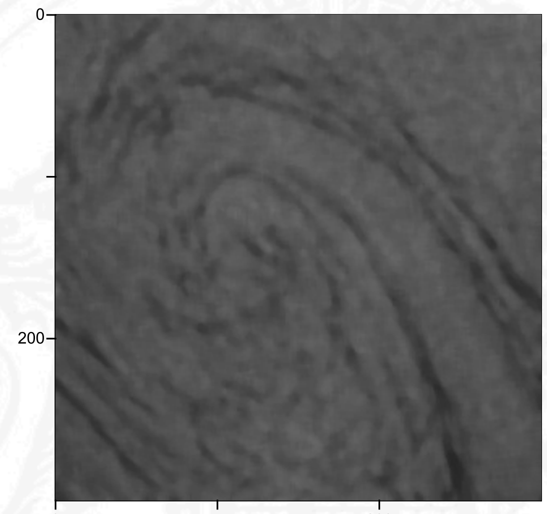




3x3 Filter size

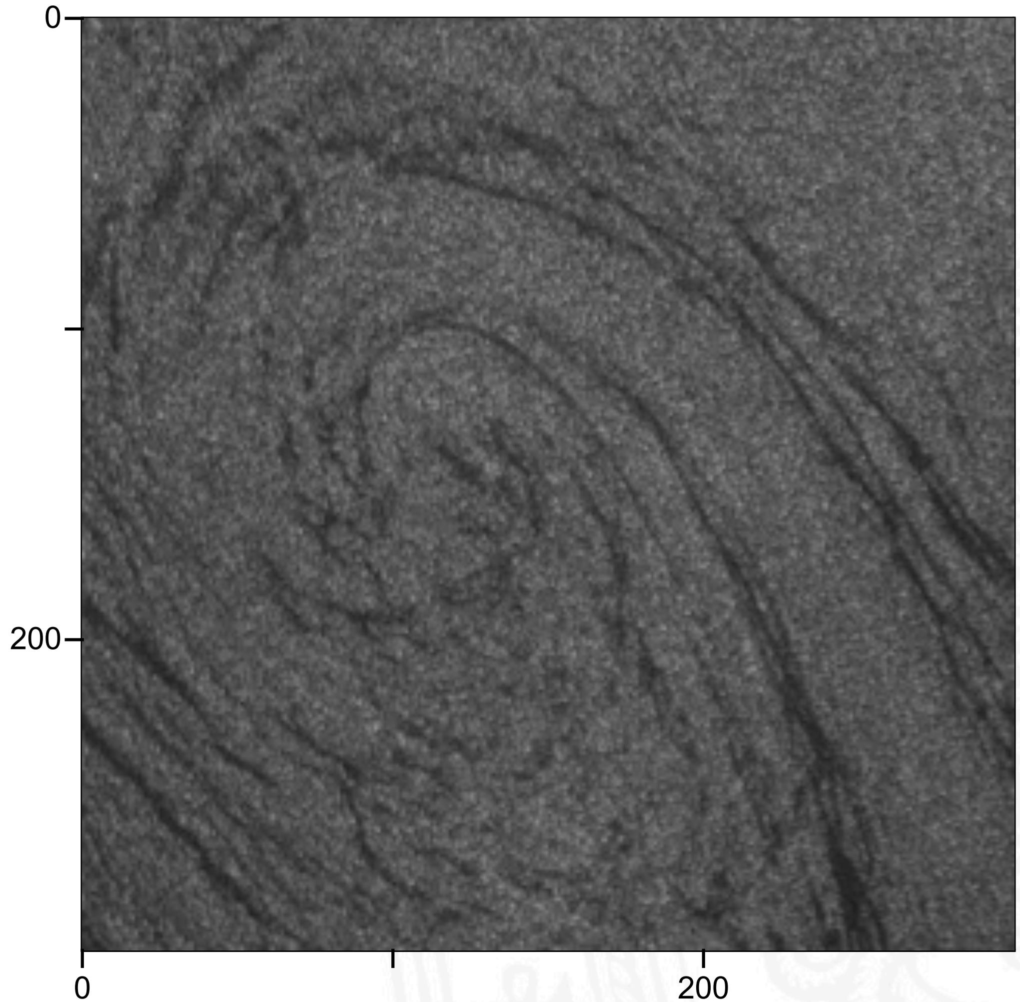


5x5 Filter size

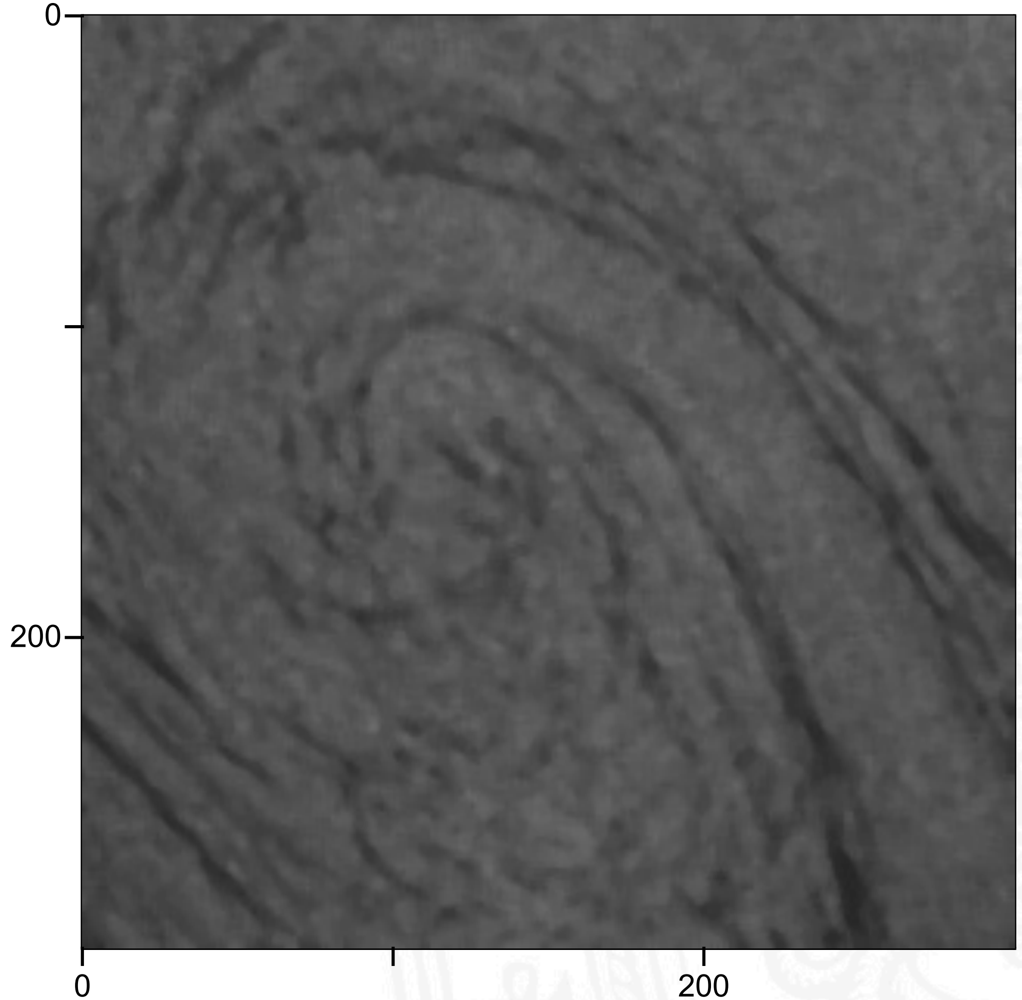


7x7 Filter size

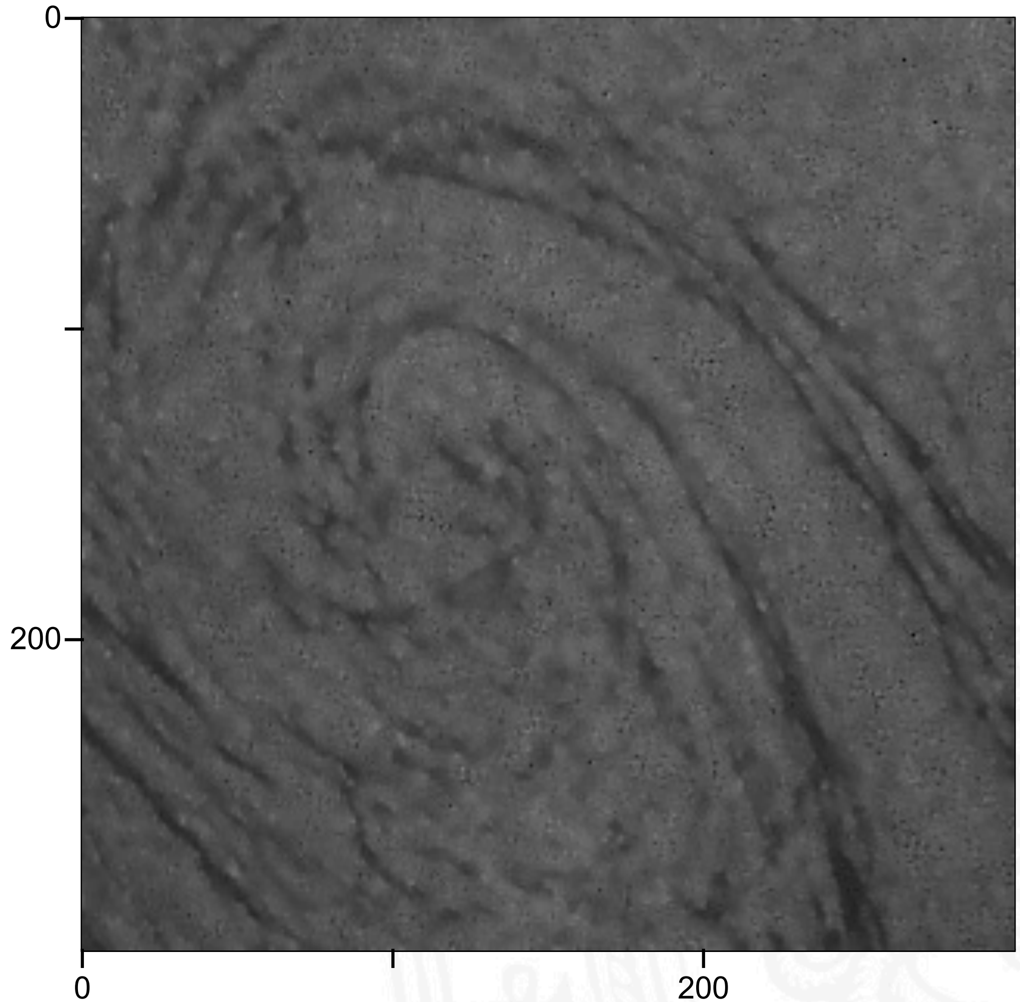
Original Image



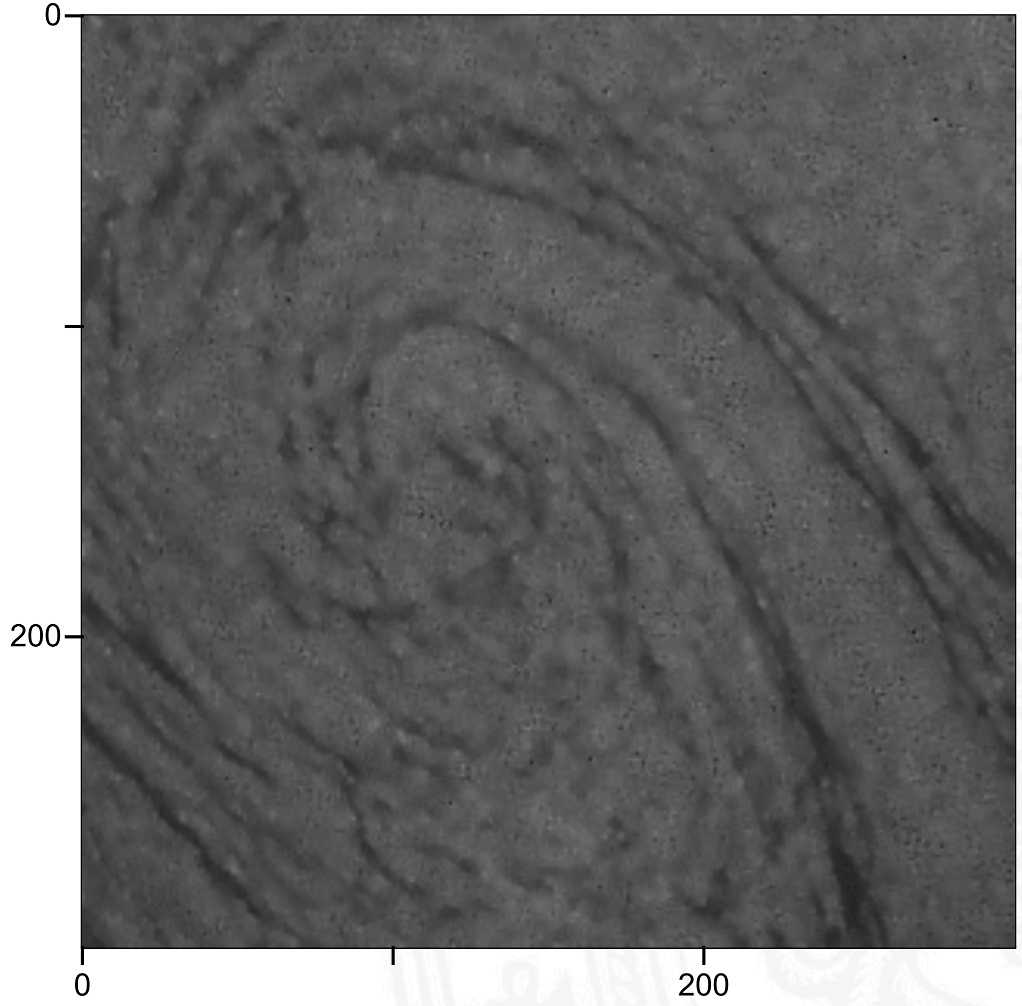
Median Filter (Filter size: 5x5)



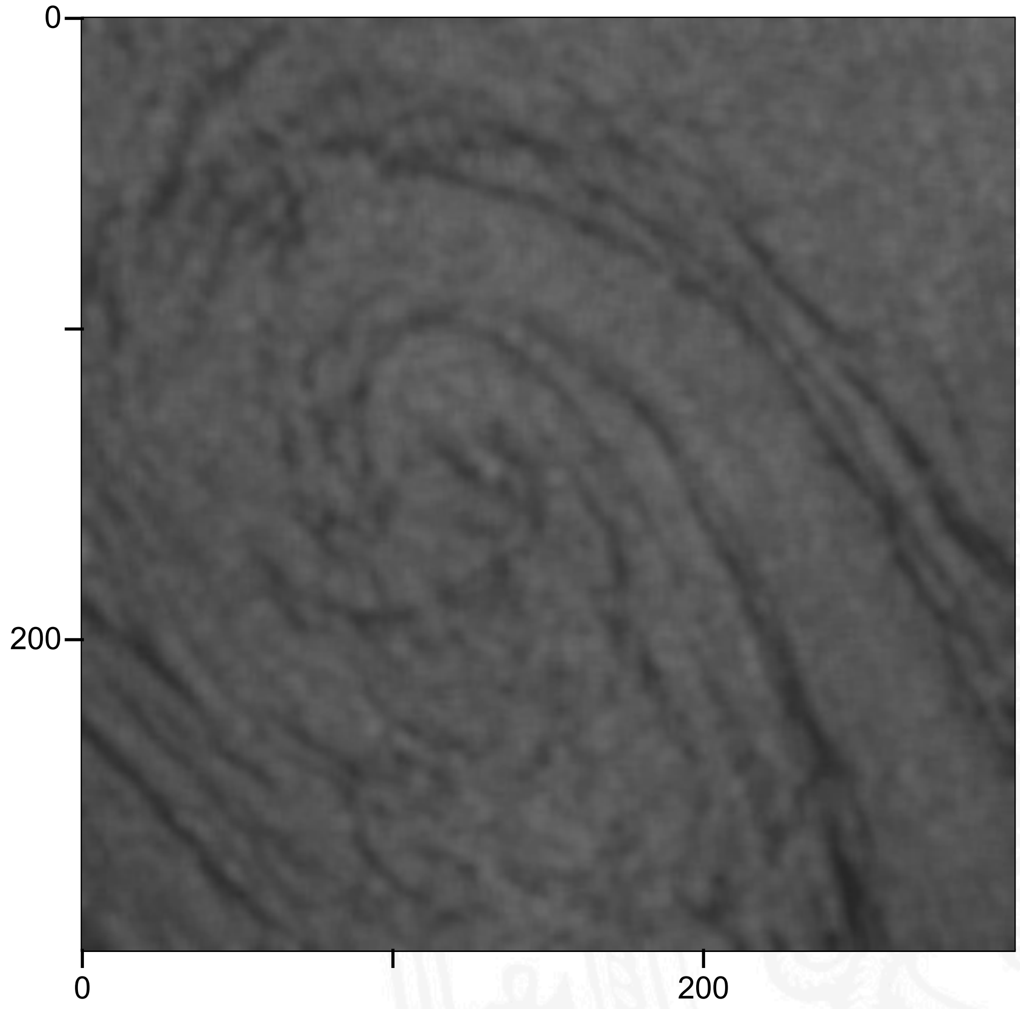
Lee Filter (Filter size: 5x5)



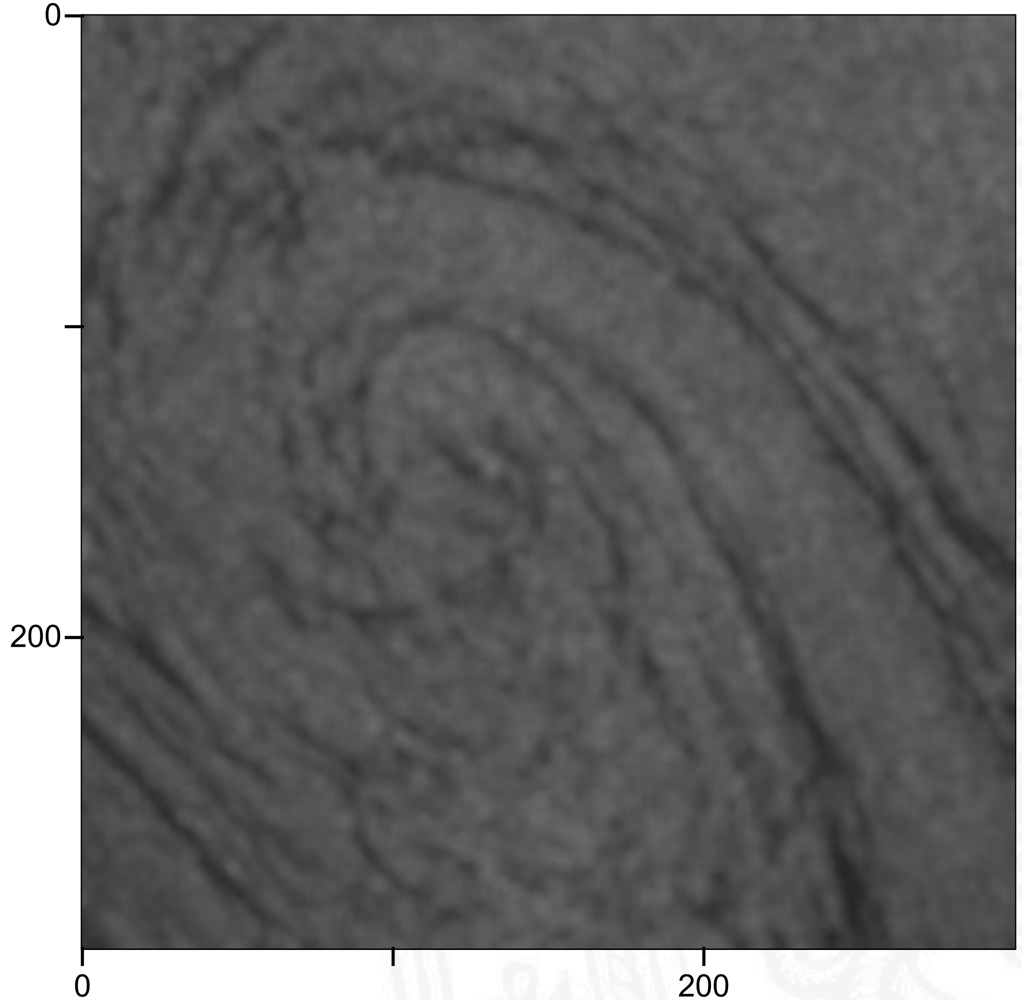
Kuan Filter (Filter size: 5x5)



Gamma MAP Filter (Filter size: 5x5)



Frost Filter (k=1, Filter size: 5x5)



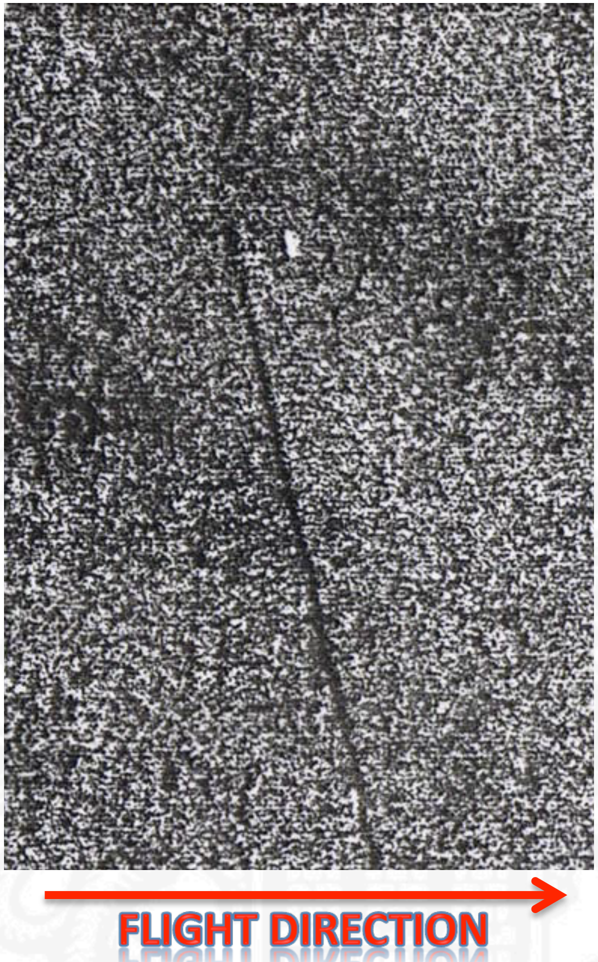
Example on Doppler-Effects: Ship-off-Wake (Alpers et al. 2008)

Seasat SAR image of a fast traveling ship crossing the English Channel

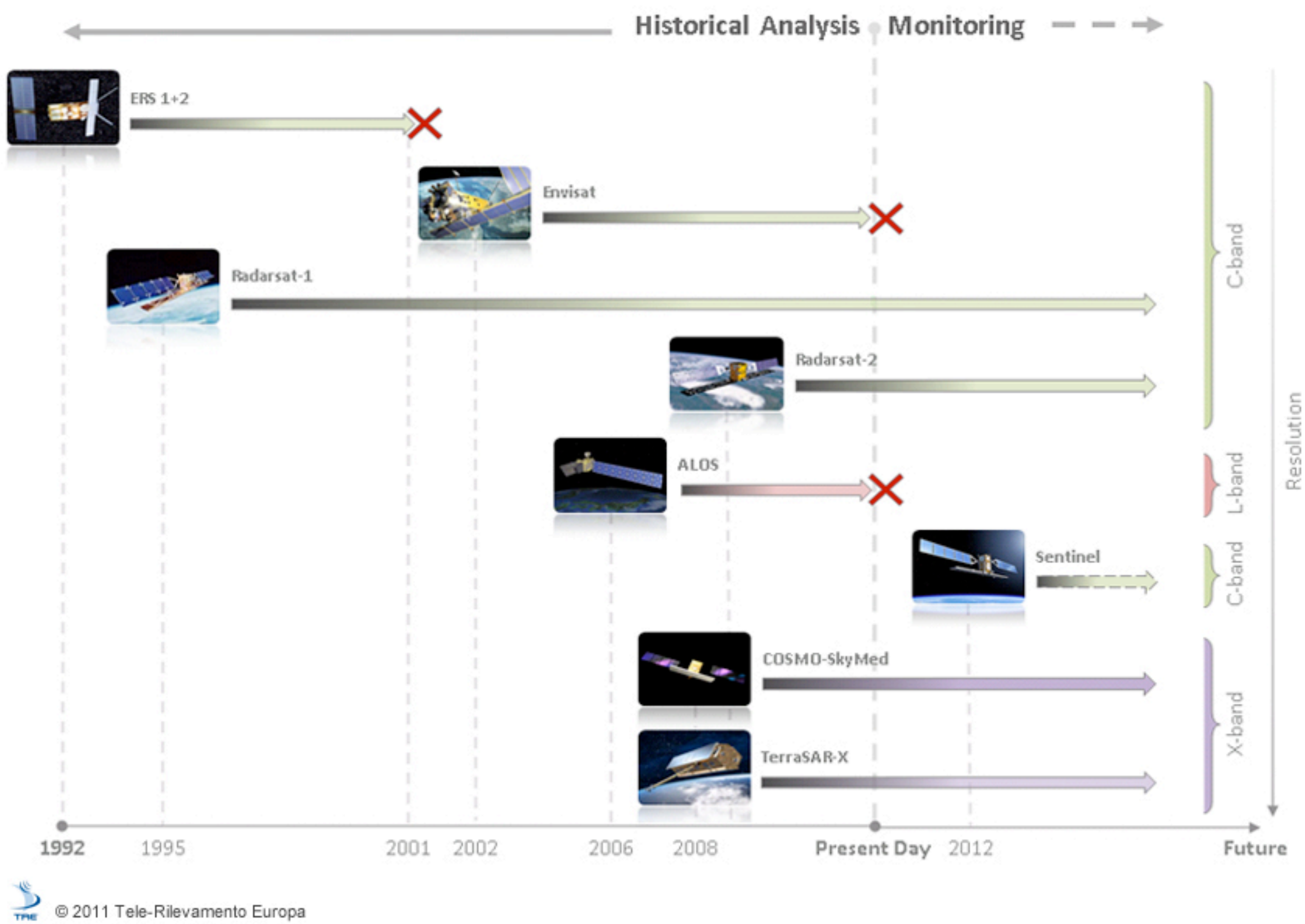
- Ship speed u can be computed from:
  - v satellite speed over ground
  - h altitude of the satellite
  - d displacement to the closest point of the extrapolated wake in azimuth direction
  - θ incidence angle
  - α angle between ship's heading and range direction

$$u = \frac{d \cdot v}{h \cdot \cos(\theta) \cdot \cos(\alpha)}$$

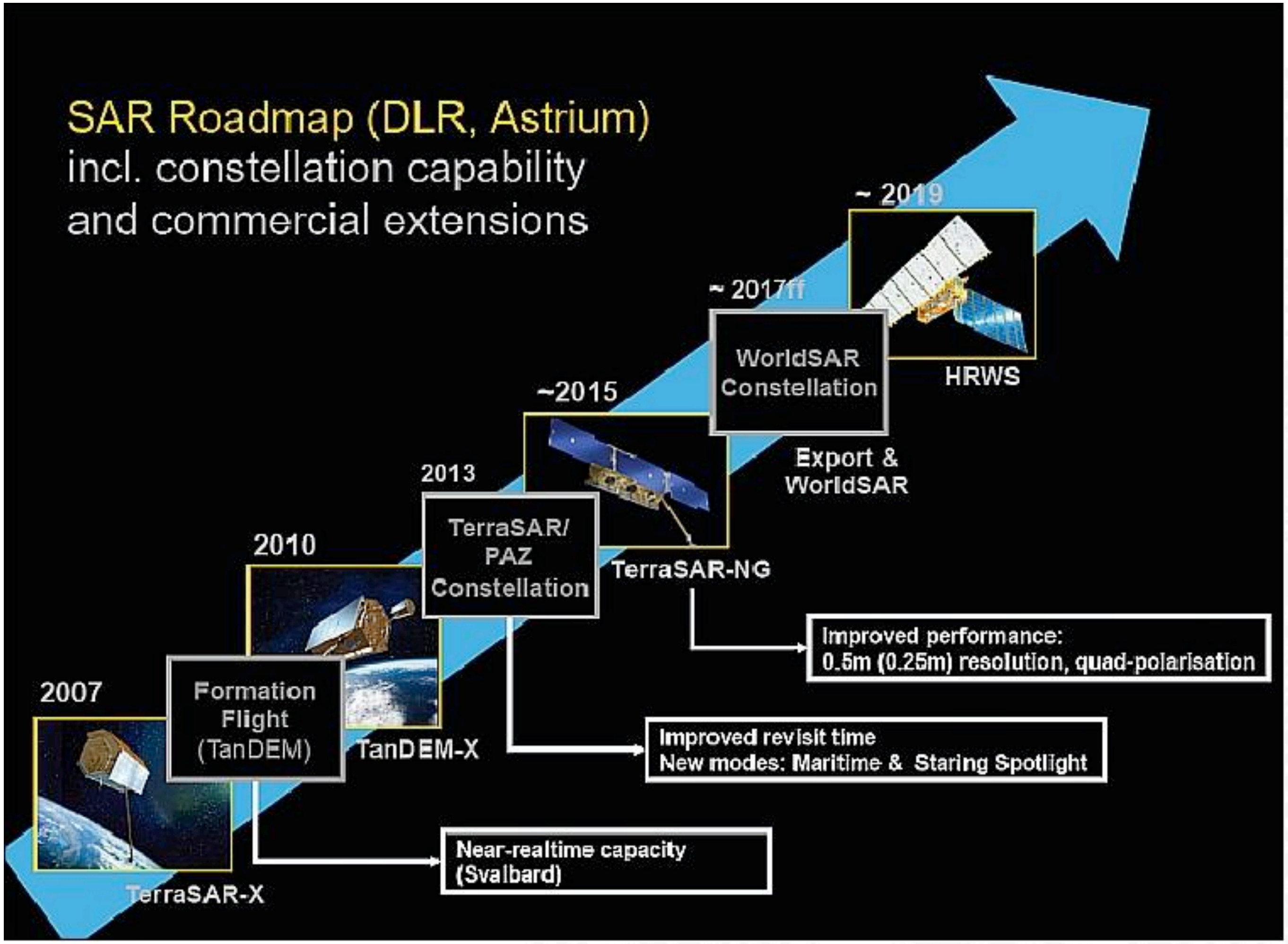
But: only possible when the ship speed is very high (typically larger than 12 m/s)



Overview of SAR Systems



German (DLR) SAR Systems



Issues for High-Resolution SAR Imagery

- New SAR Systems achieve resolutions of < ½ m!
- Formerly unknown details become visible
- Direct backscattering "paints" the scene
- Huge impact on observation of man-made scenes, like:
  - Cities / Buildings
  - Ships
  - Infrastructure
- Weather independent observation of these structures is of high military interest

  → German Bundeswehr: SAR-Lupe (5 equal hi-res SAR)

Example: High-Resolution SAR Imagery

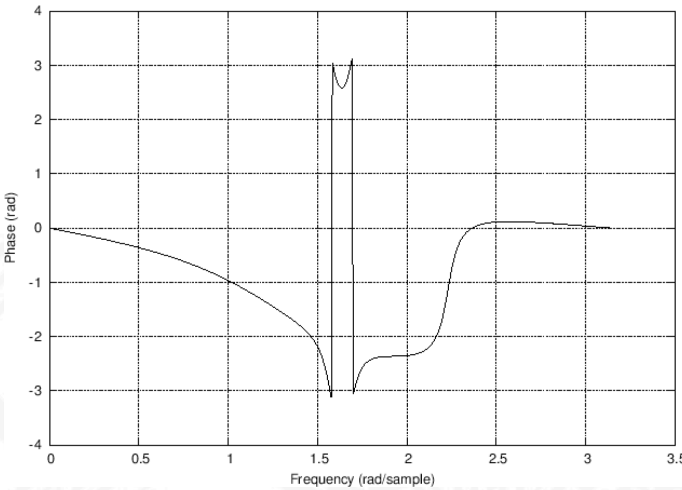
Stadium in Barcelona

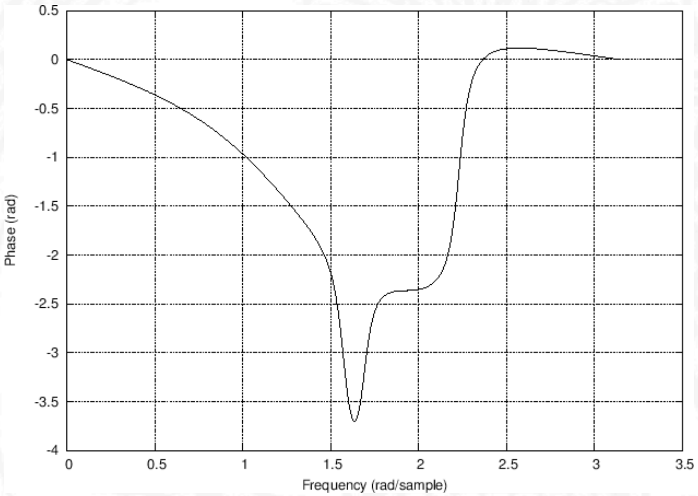
Interferometric SAR (InSAR)

- Uses the phase instead of using the magnitude image
- Distance between two acquisitions: baseline
- Requirements of the baseline
  - needs to be small for a high correlation of the “persistent” scatterers!
  - needs to be large enough to actually determine phase shifts!
- Former: Use of two or more different satellites!
- Now: Special configurations allow the derivation of InSAR images with comparable sensors or with a single platform.
- Basic measurement:
  (Changes in the) Terrain of the surface

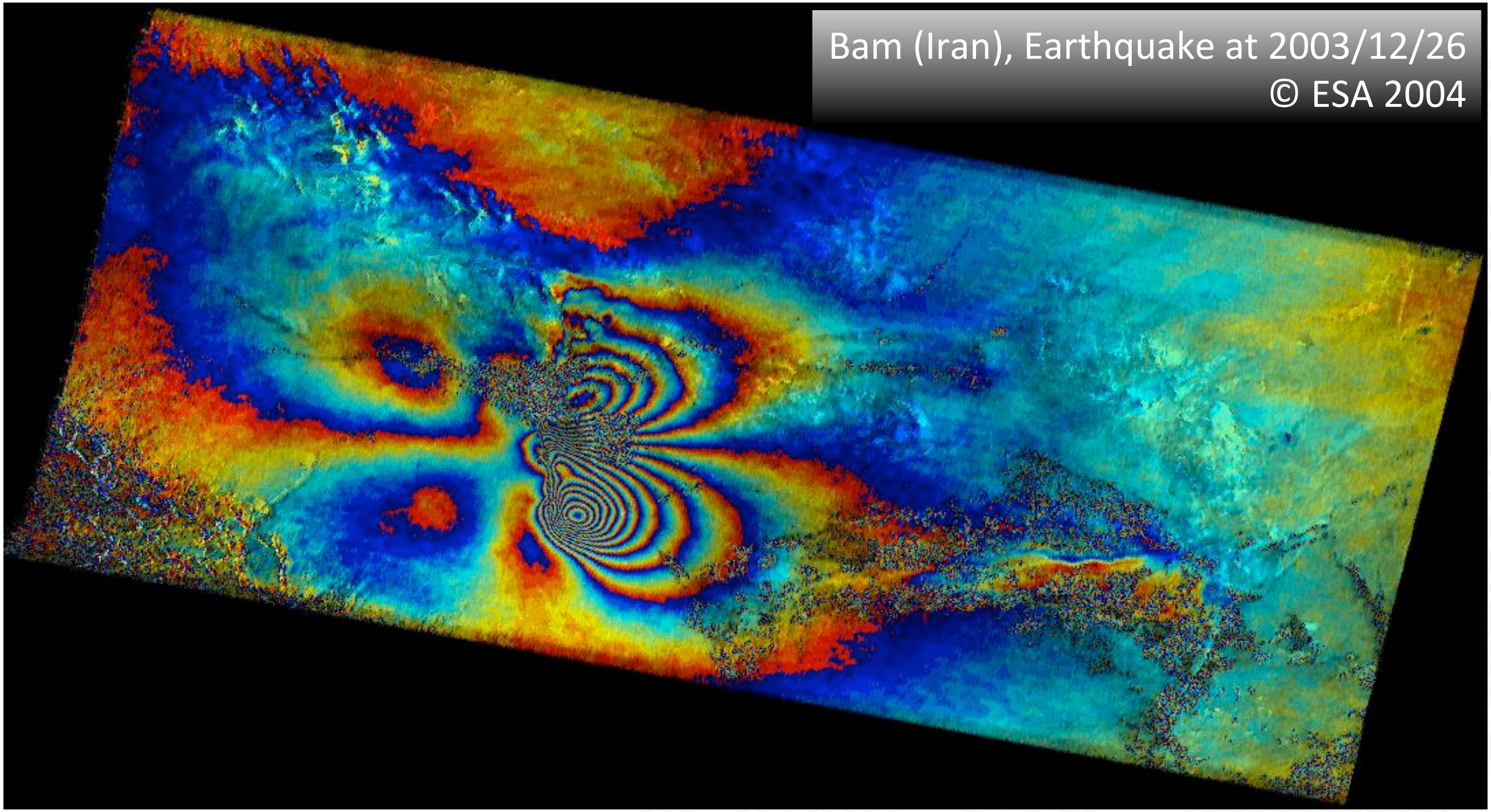
Phase Unwrapping

- Phase Information is given at
  0 … 2π or -π … π
- 1D example is shown at right images
- But: 2D-variant needed for InSAR images!
- Ill-posed problem!
- Many (heuristic) algorithms exist
- Still a lot of research on this topic!
- Digital Elevation Model (DEM) is fused in some algorithms!

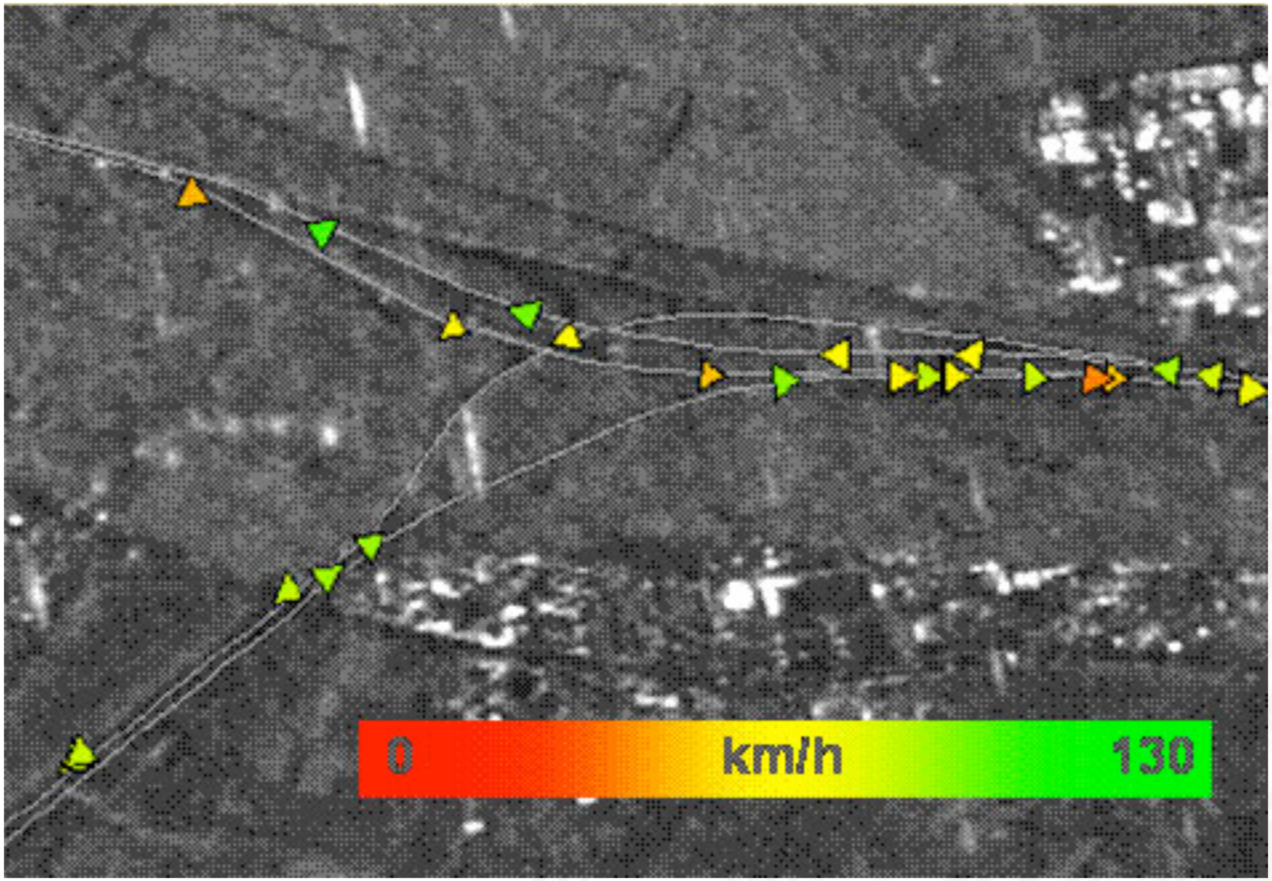




Example 1: Earthquake Monitoring



Example 2: Traffic Monitoring



Operational: TerraSAR-X Traffic Processor (TTP) ©DLR, 2014

Mount Etna InSAR Time Series Animation

http://www.youtube.com/watch?v=6qAu-NHudp4