Введение в спутниковую радиолокацию:
Радиолокаторы с синтезированной апертурой (РСА)

Introduction to satellite radars:
Synthetic Aperture Radars (SAR)

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Outline

1. Intro to SAR basic principles
2. Range resolution
3. Phase history of a point target
4. Azimuth (along-track) resolution
5. Unfocused SAR
6. Focused SAR
7. Ocean applications
SAR = Synthetic Aperture Radar

An active instrument that transmit/receive EM radiation, store data in amplitude and phase (real and imaginary part)

- Works in the presence of clouds, day and night
- Operates at microwave (or radar) frequencies
- Fine resolution is independent of the platform height, so images with the same geometric resolution (order of 10 m) can be obtained from satellites as from airplanes
SAR principles:

- SAR is carried out on satellite with usually near-polar orbit, at an altitude ~600-800 km
- Antenna size is ~ 10 by 1 m
- Incidence angle between 15° and 60°
ANGLES AND RANGES

- Radar
- Elevation angle
- Depression angle
- Slant range
- Incidence angle
- Normal to earth surface
- Ground range
- Earth
A short pulse is emitted by the antenna and then the **amplitude and phase** of the backscattered signal is recorded as a function of time.

This is repeated over again while the platform is moving.

Thus a 2-dimensional image is generated.
SAR principles

Short (microsecond) high energy pulses are emitted and the returning echoes recorded, providing information on:

- magnitude (or attenuation)
- phase
- time interval between pulse emission and return from the object
- polarization
- Doppler frequency

The same antenna is often used for transmission and reception.
SAR concept:

- SAR receives and records the echoes coherently – this needs a detector with a very high sampling rate

- Coherent recording of the echoes enables the phase history of individual scattering elements to be tracked

- Analysis of this coherent record from many echoes delivers very fine resolution in azimuth and range directions
\[ \lambda = c \cdot T = c \cdot \frac{1}{f} \]
Azimuth resolution
SLAR systems

- The spatial resolution in the along-track direction (i.e. the azimuth) is determined by the angular width (or aperture) of the azimuth beam pattern ($\beta$)

**ENVISAT case**

$\lambda_{\text{radar}} = 5.6 \text{ cm}$
$L = 10 \text{ m}$
$R = 850 \text{ km}$

$\Rightarrow \delta_{az} = 4.25 \text{ km}$
Azimuth resolution
Improving azimuth resolution: from SLAR to SAR

• Azimuth resolution is determined by the angular width of the azimuth beam pattern
  – resolution increases with range
  – smaller resolution means larger antennas ($\beta = \lambda/L$)
  – antennas became too large to realistically mount on an airplane

• This can be solved by using a small antenna to “synthesize” what a larger antenna would have collected, thus generating a synthetic antenna or aperture
Azimuth resolution
Synthetic Aperture Radar

• An artificial larger antenna is synthesized using displacement of the antenna along the track
• Finer azimuth resolution is achieved keeping track of the history of the Doppler frequency caused by the relative displacement of the target w.r.t. to the antenna.
• Best achievable resolution

\[ \delta_{az} = \frac{L}{2} \]
Figure 6-15. Imaging radars typically use antennas that have elongated gain patterns that are pointed to the side of the radar flight track. The pulse sweeps across the antenna beam spot, creating an echo as shown in this figure.
Phase history of a point target

Sensor moves along x-axes (azimuth) and emits radar pulses to the ground.

The distance between the sensor at position $x$ and the target can be expressed as

$$r = \sqrt{x^2 + r_0^2}$$

where $r_0$ denotes the minimum distance between them at $x=0$.

As the extension of the radar footprint on the ground is much smaller than the target distance ($x \ll r_0$), the following approximation can be made:

$$r = r_0 \sqrt{1 + \frac{x^2}{r_0^2}} \approx r_0 + \frac{x^2}{2r_0}$$
Along-track resolution

Consider a radar system flying at a constant speed along a straight and level trajectory as it views the terrain.

For a point on the ground the range to the radar and the radial velocity component can be determined as a function of time.

Radar position = \( (0, v \cdot t, h) \), Target position = \( (x_o, y_o, 0) \), Range to target, \( R(t) \)

\[
R(t) = \sqrt{(0 - x_o)^2 + (v \cdot t - y_o)^2 + (h - 0)^2}
\]

\[
R(0) = \sqrt{x_o^2 + y_o^2 + h^2}
\]

\[
\frac{dR}{dt} = \dot{R}(t) = \frac{v (v \cdot t - y_o)}{\sqrt{x_o^2 + (v \cdot t - y_o)^2 + h^2}}
\]

\[
\dot{R}(0) = \frac{-y_o v}{\sqrt{x_o^2 + y_o^2 + h^2}}
\]

\[
f_D = -\frac{2}{\lambda} \dot{R}(0) = \frac{2 y_o v}{\lambda \sqrt{x_o^2 + y_o^2 + h^2}}
\]
Phase history of a point target

The phases of the received echoes, resulting from the two-way distance $r$, are:

\[ \varphi(x) = 2 \frac{2\pi}{\lambda} \left( r_0 + \frac{x^2}{2r_0} \right) = \frac{2\pi x^2}{\lambda r_0} + \text{const.} \] (10)

Assuming a constant sensor velocity $v$ and the abbreviation $k = \frac{2\pi v^2}{\lambda r_0}$, a quadratic phase behaviour in time is resulting, neglecting the constant phase term, which has no time dependency.

\[ \varphi(t) = kt^2 \]

The quadratic phase behaviour corresponds to a linear change in the received azimuth frequency $f(t)$, the so-called DOPPLER-effect.

\[ f(t) = \frac{1}{2\pi} \frac{\partial \varphi(t)}{\partial t} = \frac{k}{\pi} t \] (12)
The maximal illumination time of a point target is defined by the extension of the antenna footprint in azimuth. This length, equal to the length of the synthetic aperture, is determined by:

\[ t_{max} = \frac{L_{sa}}{v} = \frac{\theta_{ta} r_0}{v} \]

The bandwidth of the signal in azimuth \( B_\alpha \) is, therefore,

\[ B_\alpha = f(-t_{max}/2) - f(+t_{max}/2) = \frac{2v \theta_{ta}}{\lambda} \]

This bandwidth in azimuth sets also the lower limit of the pulse repetition frequency (PRF) of the radar, with which the radar pulses are emitted to the ground. After eliminating the carrier frequency (demodulation in the receiver hardware), frequencies between \(-B_\alpha/2\) and \(+B_\alpha/2\) are present in the complex signal.
Unfocused SAR

Processing SAR phase data to achieve a fine-resolution image requires elaborate signal processing.

In some cases trading off resolution for processing complexity is acceptable.

In these cases a simplified *unfocused* SAR processing is used wherein only a portion of the azimuth phase history is used resulting in a coarser azimuth resolution.

In unfocused SAR processing consecutive azimuth samples are added together (in the slow-time domain).

Since addition is a simple operation for digital signal processors, the image formation processing is much easier (less time consuming) than fully-focused SAR processing.
Unfocused SAR

Summing consecutive samples, also known as a *coherent integration* or *boxcar filtering*, is useful so long as the signal’s phase is relatively constant over the integration interval.

**Example**
For a 20-sample interval the central portion of the chirp waveform (zero Doppler) is relatively constant. For the outer portions of the chirp the phase varies significantly and integrating produces a reduced output.

Figure 5.21: Boxcar filtering applied to linear FM signal.
Example (cont.)
Over a 38-sample interval phase variations within the central portion of the chirp waveform results in a reduced output (0.8 peak vs. 1). The magnitude of the first sidelobe is also larger (0.4 vs. 0.3). The width of the main lobe is narrower.

Figure 5.21: Boxcar filtering applied to linear FM signal.
Unfocused SAR

The resolution improves with increased integration length up to a point when oscillations in the signal are included in the integral.

The maximum synthetic aperture length for unfocused SAR is \( L_u \) which corresponds to a maximum phase shift across the aperture of 45°.

\[
L_u = \sqrt{R \lambda / 2}, \quad (m)
\]

The azimuth resolution for \( L = L_u \) is

\[
\Delta y = \sqrt{R \lambda / 2}, \quad (m)
\]

Notice the range- and frequency-dependencies of \( \Delta y \).
To realize the full potential of SAR and achieve fine along-track (azimuth) resolution requires matched filtering of the azimuth chirp signal.

Stretch chirp processing, correlation processing, tracking Doppler filters, as well as other techniques can be used in a matched filter process.

However the range processing is not entirely separable from the azimuth processing as an intricate interaction between range and azimuth domains exists which must also be dealt with to achieve the desired image quality.
Focused SAR

In SAR systems a very long antenna aperture is synthesized resulting in fine along-track resolution.

For a synthesized-aperture length, \( L \), the along-track resolution, \( \Delta y \), is

\[
\Delta y = \frac{\lambda R}{2L}
\]

\( L \) is determined by the system configuration.

For a fully focused stripmap system, \( L_m = \beta_{az} \cdot R \) (m), where

- \( \beta_{az} \) is the azimuthal or along-track beamwidth of the real antenna (\( \beta_{az} \approx \frac{\lambda}{\ell} \))
- \( R \) is the range to the target

For \( L = L_m \), \( \Delta y = \ell/2 \) (independent of range and wavelength)
Processing in azimuth

The echo of a single point target is contained in many received radar pulses and appears defocused.

The aim of SAR processing, or compression, is to focus all received energy of a target on one point at \( t=0 \).

To achieve this, phase history is used. The received signal in the azimuth direction can be rewritten as

\[
S_a(t) = A_0 \exp(i\varphi(t)) = A_0 \exp(ikt^2)
\]

Where \( A_0 \) denotes the backscatter amplitude of a point target (complex).

The idea of azimuth compression is to adjust all phase values to the same value followed by coherent summation.

To achieve this, a correlation of \( S_a(t) \) with a reference function \( R(t) = \exp(-ikt^2) \) is performed.

The reference function has exactly opposite phase.
The result of the correlation is then

\[ V(t) = \int_{-\infty}^{\infty} S_\alpha(\xi) R(t + \xi)d\xi \]  \hspace{1cm} (18)

\[ = \int_{-\infty}^{\infty} A_0 \exp(ik\xi^2) \exp(-ik(t + \xi)^2)W(t + \xi)d\xi \]  \hspace{1cm} (19)

\[ = A_0 \exp(-ikt^2) \int_{-\infty}^{\infty} W(t + \xi) \exp(-2ik\xi t)d\xi \]  \hspace{1cm} (20)

Or after applying FT:

\[ \Longrightarrow \quad V(t) = A_0 t_{max} \sqrt{2\pi} \exp(-ikt^2) \left[ \frac{\sin(kt_{max}t)}{kt_{max}t} \right] \]  \hspace{1cm} (25)

The result of this correlation is the image. The principal shape of the resulting impulse response corresponds thereby to the FOURIER-transform of the weight function.
In Fig. 3.2 this process is illustrated.

**Figure 3.2:** Signal compression. Real part of the complex signal of an ideal point target response (left) and amplitude of the compressed signal (right).

Defining the resolution as the half distance between the first minima of the main peak at $t = \pm \pi/kt_{\text{max}}$, a synthetic aperture consequently has an azimuthal resolution of:

$$
\delta_{sa} = \frac{\pi v}{kt_{\text{max}}} = \frac{v}{B_a} = \frac{l_{ra}}{2}
$$

(26)
Along-track resolution

Figure 4.10: Azimuth beam pattern and its effect upon signal strength and Doppler frequency.
Figure 3.5: Block-diagram of a simple SAR processor
SAR processing example

Reading and visualizing raw data

\[ \rho(E) = \frac{1}{2\pi} \left( \frac{2m_r}{\eta^2} \right)^{\frac{3}{2}} (E)^{\frac{1}{2}} \]
STAGES IN SAR IMAGE COMPRESSION

(a) Raw SAR data
- Samples within echoes
- Individual pulses
- Echo when SAR is at azimuth \( a_0 \)
- Field within the SAR raw data containing information about the power reflected from ground cell \( (R_0, a_0) \)
- Range-compress each echo individually

(b) Range compression process
- Chirp Replica pulse
- Correlation scans across whole echo
- SAR demodulated raw data echo (IF)
- Discrete time samples
- Range-binned Complex signal
- \( R_0 \) Discrete range values

(c) Part processed SAR data
- Individual pulses
- Range binned signal
- Echoes containing information about \( a_0 \)
- \( R_0 \) Range compressed but with information from a single azimuth spread through many pulses

(e) SAR Image
- Range cells
- \( (R_0, a_0) \)

(d) Azimuth compression process
- Doppler phase history for range \( R_0 \)
- Correlation scans over sequence of echoes
- Complex signal in range bin \( R_0 \) (IF)
- Values from discrete echoes
- Complex reflected power for range \( R_0 \)
- \( a_0 \) Discrete azimuth values

OUT
Ocean applications
New Ocean Waves
Algorithm/Product

SAR Ocean Images

Real Part

Imaginary Part

Level 1
A decisive breakthrough: the cross-spectral analysis

- Based on ERS Image products, G. Engen and H. Johnsen (NORUT) proposed the use of Single Look Complex (SLC) imagettes using cross-spectra methodology (*Engen et al., 1995, TGARS*)

**Improvements:**
- Direct uncorrelated noise removal
- Hands-off resolved wave propagation ambiguity in most cases (85%)
New algorithm philosophy

Level 1 Product

Processing Set-Up File

Cross Spectra Estimation

Clutter & SNR Estimation

Wind Speed Retrieval

Ocean Wave Spectra Retrieval

Level 2 Product Generation

Level 2 Product

Inversion Model:

\[ \chi^{nlin}(k; U_{10}) \]

where

\[ T(k) = \left\{ ik_y \frac{R}{V} \omega_k + 2k_{rad} k_x \nabla \sigma \right\} G(\theta) \]

\[ G(\theta) \equiv \frac{k_x}{k} \sin \theta + i \cos \theta \]

\[ \nabla \sigma \equiv \frac{\Delta \sigma_{c mod}}{\Delta \theta} \frac{1}{\sigma_{c mod}} \frac{1}{2k_{rad} \cos \theta} \]
Figure 18: HIMAGE cross-spectrum. Image intensity (top), real part of cross spectra (left), imaginary part of cross-spectra (right).
Sequence of ERS Wave Mode orbit processed into ASAR Wave Mode Level 2 product
Fireworks
• Ocean currents retrieved from SAR Doppler shifts
Partial contribution of different type of facets to the total
C-band Doppler velocity at wind speed 10 m/s for VV (left) and HH (right) polarizations.
- Solid lines are for Bragg-facet,
- dash-dotted lines are for mirror points,
- dashed lines are for breakers.

C-band Doppler velocities for VV (solid line) and HH (dashed line) vs. incidence angle at 10 m/s wind speed
• Doppler shift: Main equation

Фасетная модель :

$$\frac{\pi f_D}{k_R} = \frac{(u \sin \theta - w \cos \theta) \sigma_0 (\theta + \Delta \theta)}{\sigma_0 (\theta + \Delta \theta)}$$

$$V_D = \pi f_D / k_R \sin \theta = \bar{c} + u_s - \frac{1}{\tan \theta} \frac{\partial \Theta_0}{\partial \sigma_0} + \frac{\bar{c}}{\sigma_0}$$

$$V_D = u_s + \sum P_j^P (\bar{c}_j + c_j^{TH})$$

$$c_j^{TH} = \int_{k<k_z} \left[ (-\cot \theta \times M_j' + M_{1f}' \cos (\phi_R - \phi) + \cot \theta \times M_{2f}') \cos k^2 B(k) \right]$$

Тип фасетов :

- Бре́гговская ря́бь
- Гребень обрушающейся волны
- "Зеркальные" точки

$\bar{c}_j$ - скорость фасета

$c_j^{TH}$ - добавка за счет модуляции фасетов длинными волнами

$P_j^P$ - вклад механизма рассеяния в полную УЭПР
Background characteristics of Doppler shifts

Figure 2. Observed WM (color) and simulated (solid) wind dependence of C-band Doppler shift for VV polarization in (A) and (C) and HH polarization in (B) and (D) at (top) 23° and (bottom) 33° incidence angles. The color represents the spread in number of observation points. The open circles mark the mean fit to the observations. Upwind corresponds to positive radial velocity.
Figure 1. Time series of the Doppler velocity from the ascending ASAR wide swath (420 km) images on (right) 16, (middle) 19 and (left) 22 September 2007 covering the greater Agulhas Current region. The color bar marks the radial velocities from $-3$ m/s to $+3$ m/s. Positive speed is directed towards the SAR look direction. Black curve marks position of the maximum geostrophic current derived from altimetry 7-day mean.
Поле геострофической скорости по данным альтиметрии

Geostrophic current from altimeter

Поле Доплеровской скорости

Doppler velocities
To obtain direct ocean surface velocities from space: 
A speed-gun principle (Doppler analysis)

SRTM 2-Antenna Interferometry

Ultra-high resolution
Limited to line-of-sight direction
To obtain direct ocean surface velocities from space
RADARSAT-1 modes (1/2)

- Standard
- Fine
- Wide
- Extended (low incidence)
- Extended (high incidence)
- ScanSAR

Satellite Ground Track

- 250 km
- 500 km
- 425 km

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SAR training to improve analysis in oil spill emergency context
### RADARSAT-1 modes (2/2)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Swath width (km)</th>
<th>Resolution Dist x Az (m)</th>
<th>Incidence angle (°)</th>
<th>Looks</th>
<th>Polarization</th>
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<tbody>
<tr>
<td>FINE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>15 positions, 60% overlap</td>
<td>37 - 56</td>
<td>8 x 8</td>
<td>36 - 48</td>
<td>1</td>
<td>HH</td>
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<tr>
<td>STANDARD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 positions, &gt; 10% overlap</td>
<td>100</td>
<td>25 x 28</td>
<td>20 - 50</td>
<td>4</td>
<td>HH</td>
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<tr>
<td>WIDE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 positions, 3% overlap</td>
<td>150</td>
<td>25 x 28</td>
<td>20 - 40</td>
<td>4</td>
<td>HH</td>
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<tr>
<td>SCANSAR - Narrow</td>
<td>300</td>
<td>50 x 50</td>
<td>20 - 40</td>
<td>2</td>
<td>HH</td>
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<tr>
<td>SCANSAR - Wide</td>
<td>500</td>
<td>100 x 100</td>
<td>20 - 50</td>
<td>2</td>
<td>HH</td>
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<tr>
<td>EXTENDED - High</td>
<td>75</td>
<td>25 x 28</td>
<td>50 - 50</td>
<td>4</td>
<td>HH</td>
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<tr>
<td>EXTENDED - Low</td>
<td>170</td>
<td>25 x 28</td>
<td>10 - 20</td>
<td>4</td>
<td>HH</td>
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</table>
RADARSAT-2 Features

- **High resolution:**
  - 3 m
  - multi-look 10 m
- **Polarimetric modes**
  - single/dual polarization
  - quad-pol
- **Right and left-looking capability**
- **Enhanced ground system providing:**
  - efficient satellite tasking (12 - 24 hours routine)
  - faster data processing
  - data encryption
# RADARSAT-2 modes

<table>
<thead>
<tr>
<th>Modes</th>
<th>Swath width (km)</th>
<th>Resolution Dist x Az (m)</th>
<th>Incidence angle (°)</th>
<th>Looks</th>
<th>Polarization</th>
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<tr>
<td>FINE</td>
<td>50</td>
<td>10 x 9</td>
<td>37 - 49</td>
<td>1 x 1</td>
<td>HH, HV or VV, VH</td>
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<td>STANDARD</td>
<td>100</td>
<td>25 x 28</td>
<td>20 - 49</td>
<td>1 x 4</td>
<td>HH, HV or VV, VH</td>
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<tr>
<td>WIDE</td>
<td>150</td>
<td>25 x 28</td>
<td>20 - 45</td>
<td>1 x 4</td>
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<td>50 x 50</td>
<td>20 - 46</td>
<td>2 x 2</td>
<td>HH, HV or VV, VH</td>
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<tr>
<td>SCANSAR - Wide</td>
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<td>100 x 100</td>
<td>20 - 49</td>
<td>4 x 4</td>
<td>HH, HV or VV, VH</td>
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</table>
Sentinel 1 (ESA)

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SAR training to improve analysis in oil spill emergency context
### Sentinel-1 modes

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<th>Modes</th>
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<th>Resolution Dist x Az (m)</th>
<th>Incidence angle (°)</th>
<th>Polarization</th>
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<td>Wave (WV)</td>
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<td>23 / 36</td>
<td>HH or VV</td>
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<td>Strip Map (SM)</td>
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<td>10 x 10</td>
<td>20 - 49</td>
<td>HH-HV or VV-VH</td>
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<td>Interferometric wide swath (IWS)</td>
<td>250</td>
<td>20 x 20</td>
<td>30 - 45</td>
<td>HH-HV or VV-VH</td>
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<td>Extra Wide Swath (EWS)</td>
<td>400</td>
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<td>20 - 46</td>
<td>HH-HV or VV-VH</td>
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