Spaceborne SAR Systems for Polarimetric, Interferometric and PolinSAR Applications

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Spaceborne SAR Systems

**SEASAT**
NASA/JPL (USA)
L-Band, 1978

**ERS-1**
European Space Agency (ESA)
C-Band, 1991-2000

**J-ERS-1**
Japanese Space Agency (NASDA)
L-Band, 1992-1998

**SIR-C/X-SAR**
NASA/JPL, L- and C-Band (quad)
DLR / ASI, X-band
April and October 1994

**RADARSAT-1**
Canadian Space Agency (CSA)
C-Band, 1995-today

**ERS-2**
European Space Agency (ESA)
C-Band, 1995-today

**SRTM**
NASA/JPL (C-Band), DLR (X-Band)
February 2000

**ENVISAT / ASAR**
European Space Agency (ESA)
C-Band (dual), 2002-today

**ALOS / PALSAR**
Japanese Space Agency (JAXA)
L-Band (quad), 2005

**TerraSAR-X**
German Aerospace Center (DLR) / Astrium
X-Band (quad), 2006

**RADARSAT-II**
Canadian Space Agency (CSA)
C-Band (quad), 2006

**CosmoSkymed**
ASI / Alenia
X-Band (dual), 2006
ENVISAT/ASAR
ESA’s ENVISAT

- Most ambitious Remote Sensing satellite for environmental monitoring
- Unique combination of 10 instruments
Active Phased Array Antenna

ASAR Antenna consisting of 320 Transmit/Receive Modules in 32 rows and 10 elements per row
**ASAR Operation Modes**

**ASAR-Antenna (ca. 10 m x 1.33 m and 320 T/R-Modules)**

- 10 columns along track
- 32 rows across track

**ASAR imaging modes**

<table>
<thead>
<tr>
<th>Mode</th>
<th>IS 1</th>
<th>IS 2</th>
<th>IS 3</th>
<th>IS 4</th>
<th>IS 5</th>
<th>IS 6</th>
<th>IS 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF [Hz]</td>
<td>1678</td>
<td>1645</td>
<td>2096</td>
<td>1680</td>
<td>2082</td>
<td>1698</td>
<td>2097</td>
</tr>
<tr>
<td>ASAR center look angle</td>
<td>16.6°</td>
<td>20.1°</td>
<td>25.2°</td>
<td>29.5°</td>
<td>32.8°</td>
<td>35.6°</td>
<td>38.0°</td>
</tr>
<tr>
<td>ASAR swath width in ground range [km]</td>
<td>103.7</td>
<td>103.3</td>
<td>82.3</td>
<td>88.6</td>
<td>64.5</td>
<td>71.0</td>
<td>56.7</td>
</tr>
</tbody>
</table>
Electronic Beam Forming

RF-Unit
Pulse Generator, Up/Down-Conv., D/A-Conv., Data Storage, etc.
ASAR Operation Modes

Wave VV or HH
< 10m resolution (SLC)
5 x 5 km to 10 x 5 km vignettes

Alternating Polarisation
VV/HH or VV/VH or HH/HV
30m resolution
up to 100 km swath

Global Monitoring
VV or HH
1000m resolution
405 km swath width

Wide Swath
VV or HH
150m resolution
405 km swath width

Image VV or HH
< 30m resolution
up to 100 km swath
Oil Detection with ASAR
Single-Pol versus Polarimetric ASAR Image

German flood event (Summer 2002)
ASAR Alternating Polarization mode

© ESA
German flood event (Summer 2002)
ASAR Alternating Polarization mode
German flood event (Summer 2002)
ASAR Alternating Polarization mode

HH
HV
HH-HV

swath IS2
19 August 02
ALOS/PALSAR
**ALOS Satellite System**

- **Launch Date**: September 2005
- **Launch Vehicle**: H-IIA
- **Spacecraft Mass**: about 4,000kg
- **Generated Elec. Power at EOL**: about 7kW
- **Orbit**: Sun Synchronous
- **Altitude**: 691.65km
- **Repeat Cycle**: 46 days

**ACRONYMS**

- **PRISM**: Panchromatic Remote-sensing Instrument for Stereo Mapping
- **AVNIR-2**: Advanced Visible and Near Infrared Radiometer type 2
- **PALSAR**: Phased Array type L-band Synthetic Aperture Radar

© JAXA
ALOS / PALSAR

- Frequency: 1270 MHz
- Band Width: 28/14MHz
- Modes: FBS, FBD, POL, SCAN
- Antenna beams: 18 (STRIP) + 5 SCANs
- Image Width: 70Km
- Incidence: 7.7 - 60 degrees
- Tr. power: 2Kw
- Resolution: 9m (2L)
- Data rate: 240Mbps

ScanSAR mode (3scans - 5scans)

- Fine mode ( #1 - #18)
- Direct downlink mode ( #1 - #18)
- Polarimetric mode ( #1 - #12)

Subsatellite track

- Off-nadir: 20.1 deg. 36.5 deg.
- Incidence: 8 deg. 60 deg.

© JAXA

Incidence: 8 deg. 60 deg.

Off-nadir: 9.9 deg. 50.8 deg.
(nominal operation: 34.3 deg.)

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Single Pass
Polarimetric SAR Interferometry

Pol-InSAR

1 Step: Model and Validation Development

Coherent Scattering Model

Observables
3 Interferometric Coherences
3 Interferometric Phases
for one baseline and three polarisation states

Natural Scatterers

- Forest Parameters
- Surface Parameters
- Agricultural Parameters
- Land Ice Parameters

DLR
Single Pass
Polarimetric SAR Interferometry

Pol-InSAR
- Observables
  - 3 Interferometric Coherences
  - 3 Interferometric Phases
    for one baseline and three polarisation states

II Step: Model and Validation Inversion

Natural Scatterers
- Forest Parameters
- Surface Parameters
- Agricultural Parameters
- Land Ice Parameters

Coherent Scattering Model
Polarimetric Interferometric: Performance Estimation

Height Error and Height Bias

- $\mu_{\text{max}}$
- $\mu_{\text{min}}$
- $\Delta \phi$

Ground-to-volume range

Ground / Volume Ratio [dB]
ALOS/PALSAR ($\gamma_{tmp} = 0.7, 70 \text{ m} \times 70 \text{ m}$)

**B = 100 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5

**B = 200 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5

**B = 400 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5

**B = 700 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5

**B = 1000 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5

**B = 1600 m**

- Lambda: 23.8 m
- Slant Range: 691.0 km
- Theta Inc.: 35.0°
- NENC (H): -31.0 dB
- Swath Width: 14. MHz
- Rw Res.: 70.0 m
- Loops: 0.5
RADARSAT-II
Polarimetric modes will be available on Standard and Fine beams with a limited swath width of 25 km.

All modes will be available in selective single or dual polarization.

All modes will be available on either side of the satellite.
Comparison between RADARSAT-1 Fine beam (10 m resolution) and simulated RADARSAT-2 Ultra-fine beam (3 m resolution)
Polarimetric Application: Sea Ice

1- HH polarization image showing enhanced ice-type information.

2- HV polarization image showing enhanced ice-edge information.

3- H/A/\(\alpha\) Maximum Likelihood classification results after five iterations.

Data acquired from C-band Shuttle Imaging Radar (SIR) of the west coast of Newfoundland, April, 1994.

Study performed by MDA through the Earth Observation Application Development Program (EOADP) of the Canadian Space Agency.
TerraSAR-X
**TerraSAR-X**

- Private Public Partnership between DLR and ASTRIUM
- Goal is to establish a sustainable Global EO information service
- Technology demonstrators:
  - DESA: X-Band Front-End Demonstrator
  - TOPAS: on-board SAR Processing and Storage Demonstrator (1999-2002)
- Continuation of a successful X-Band technology program in Germany

Start: 2006
TerraSAR-X Imaging Modes

**Strip Map Mode**
- Resolution: $3 \text{ m} \times 1.5 \text{ m} ... 3.5 \text{ m}$
- Scene Size: $100 \text{ km} \times 30 \text{ km}$

**Scan SAR Mode**
- Resolution: $3 \text{ m} \times 1.5 \text{ m} ... 3.5 \text{ m}$
- Scene Size: $100 \text{ km} \times 100 \text{ km}$

**Spotlight Mode**
- Resolution: $1 \text{ m} \times 1.5 \text{ m} ... 3.5 \text{ m}$
- Scene Size: $5 \text{ km}...10 \text{ km} \times 10 \text{ km}$

- The data collection incidence angle range is from 15° to 60°
- Dual polarisation data acquisition is possible in all operational modes
- 300 MHz experimental mode with 0.5 m slant range resolution
- Further experimental modes are feasible due to the Dual Receiving Antenna
TerraSAR-L
The Spacecraft

- Snapdragon
- Mass: 2700 kg
  - 1800 kg p/l
  - 900 kg L-SAR
- Antenna: 32 m²
- Power: 5 kW
  - 4.5 kW L-SAR
- On-board Memory: 622 Gb @ EOL
- Data downlink: 300 MHz
- QS, DS, DW pol. + high radiometric performance
- IW, IS for interferometry – **IW as main mode**
- WV for wave spectra
Future SAR Systems
Future SAR Systems
**Bistatic and Multistatic SAR Systems**

- **Bistatic Systems**: spatial separation between transmitter and receiver

- **Multistatic Systems**: multiple transmitters/receivers

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**Fully active system:**
- TechSAT21, TanDEM-X, RADARSAT-2/3

**Partially active system:**
- ARGUS/FROMAGE, BISSAT, Cartwheel, Pendulum
Response to DLR Call for Proposals for the next National Earth Observation Mission
Interferometry with TanDEM-X

SRTM / X-SAR

DTED-2

E-SAR (Simulation TanDEM-X)

DTED-3
Polarimetric Interferometry:
Performance Estimation

B = 500 m
B = 1000 m
B = 2000 m
B = 3000 m
B = 4000 m
B = 6000 m
Micro-Satellite Concept
**Global High Resolution Interferometry**

**Interferometric Cartwheel**

**Cross-Track Pendulum**

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**Digital Elevation Model (DEM) from SRTM Mission**

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**Single-Pass Cross-Track Interferometry with Multistatic Satellite Configuration:**

- no temporal decorrelation (as opposed to repeat-pass interferometry)
- no atmospheric distortions (as opposed to repeat-pass interferometry)
- large interferometric baselines (as opposed to e.g. SRTM)
**Example: Interferometric Cartwheel**

**Master Satellite:**
- e.g. circular orbit

**Receiver Satellites:**
- elliptical orbits with equal eccentricities
- arguments of apogee differ by 120° for a Cartwheel with 3 satellites
- very stable maximum vertical baseline for all orbital positions
- relative movement of receivers may be approximated by CW-ellipse:

- coupling of along-track and across-track baselines
Polarimetric Interferometry with Passive Micro-Satellite Configuration

Inversion of Coherent Scattering Model
(e.g. Random Volume + Ground)

\[ h_V, \sigma, \phi_0, m_{1-3} \]

Estimated forest height
Multi-Baseline Approach
Basic Geometry for SAR Tomography

Measured Baseline with airborne experiment
First Demonstration of Airborne SAR-Tomography

Upper image: Polarimetric color composite (L-band) of a tomographic slice in the height/azimuth-direction
- **HH+VV**, **HH-VV**, **2*HV**

Lower image: Schematic view of the imaged area

High-Resolution Wide-Swath
• **Standard approach for wide swath imaging**

• **Basic idea:**
  - Divide wide swath in multiple subswaths
  - Scan subswaths in sequential order by appropriate beam steering in elevation (e.g. by using T/R modules)

• **Shares full aperture synthesis time between multiple swaths:**
  ⇒ *Reduced azimuth resolution*
## Solutions to Wide Swath SAR Imaging

<table>
<thead>
<tr>
<th>MultiBeam</th>
<th>DPC</th>
<th>Quad Array</th>
<th>HRWS</th>
</tr>
</thead>
</table>

- **MultiBeam**
  - Claassen & Eckerman (1983)
  - Jean & Rouse (1983)
  - Solutions to Wide Swath SAR Imaging

- **DPC**
  - Currie & Brown (1992)
  - Good azimuth resolution
  - Wide image swath
  - Long receiving antenna
  - Stringent PRF requirement

- **Quad Array**
  - Callaghan & Longstaff (1999)
  - Good azimuth resolution
  - Compact antenna
  - Range gap in the middle of the swath

- **HRWS**
  - Süß & Wiesbeck (2001)
  - Good azimuth resolution
  - High receive gain by real-time beamforming
  - Long receiving antenna

### Notes
- **MultiBeam**
  - Almost constant incident angle across whole swath
  - Wide swath imaging requires high squint

- **DPC**
  - Displaced phase centers and/or multiple azimuth beams

- **Quad Array**
  - Beamforming in elevation for range ambiguity suppression

- **HRWS**
  - Beamforming in elevation for high antenna gain

### Diagrams
- Squinted SAR illumination and narrow beams on receive
- Displaced phase centers and/or multiple azimuth beams
- Beamforming in elevation for range ambiguity suppression
- Beamforming in elevation for high antenna gain
### High Resolution with Dual Receive Antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>3.1 cm</td>
</tr>
<tr>
<td>Antenna Length (Tx)</td>
<td>2.4 m (4.8 m / 2)</td>
</tr>
<tr>
<td>Sub-Aperture Length (Rx)</td>
<td>2.4 m (4.8 m / 2)</td>
</tr>
<tr>
<td>PRF</td>
<td>3600 Hz</td>
</tr>
<tr>
<td>Velocity</td>
<td>7600 m/s</td>
</tr>
<tr>
<td>Channel SNR</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

**Response to Extended Scatterer**

**without reconstruction**

**with reconstruction**

![Graph showing response to extended scatterer with and without reconstruction](image)

Ch. 1  
\[ P_1(f) \]

Ch. 2  
\[ P_2(f) \]

\[ \text{SAR Proc.} \]
Satellite Constellations
**Basic Idea:**
- constant illumination by geostationary transmitter
- signal reception by multiple low-cost receivers

**Illuminator:**
- geostationary orbit
- high Tx power (CW)
- large antenna area
- optional: steerable antenna

**Receivers:**
- low-cost micro-satellites
- small antennas
- passive (receive only)
- low earth orbit

**Advantages:**
- substantially improved revisit times without cost explosion
- multiple missions may share one illuminator
**Geostationary Illuminator: Sensitivity**

- **Wavelength**: 3.1 cm
- **Max. Bandwidth**: 300 MHz
- **Average Transmit Power**: 1000 W
- **Antenna Size Tx**: 100 m²
- **Antenna Size Rx**: 6 m²
- **Noise Figure + Losses**: 5 dB
- **Receiver Altitude**: 400 km
- **Ground Range Resolution**: 3 m
- **Max. Res. Cell Diameter**: 6 m
An Alternative: MEO Orbits

- Example: Orbit with an inclination of 35° and 5 cycles/day (altitude: ~ 8000km)
- Integration time for 3m azimuth resolution: ~ 10 sec
- NESZ: ~ -30dB (X-Band, $P_{TX}= 1$ kW, $A_{Tx}=100$ m$^2$)
- Huge simultaneous access area
- Long observation times enable change detection in one pass

MEO SAR Constellations are an interesting alternative to the geostationary illuminator concept.
New Ways Forward

• **Multi-static SAR**
  – enables smaller and cheaper satellites
  – provides more information and increased sensitivity
  – benefits from advanced technologies

• **Digital beam forming**
  – makes full use of information at antenna array
  – improves performance

• **Satellite constellations**
  – may share common illuminator
  – symbiotic use of platforms (e.g. with Nav./Com.)
  – allow for decreased revisit times