Digital Beamforming and MIMO-SAR Systems

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German Aerospace Center - DLR
Microwaves and Radar Institute
Oberpfaffenhofen

Future SAR Systems: Motivation

<table>
<thead>
<tr>
<th>Application Areas for SAR Data</th>
<th>Future Demands</th>
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</thead>
<tbody>
<tr>
<td>Earthquakes</td>
<td>• wider coverage and shorter revisit times</td>
</tr>
<tr>
<td>Volcanoes</td>
<td>• higher geometric and radiometric resolution</td>
</tr>
<tr>
<td>Land &amp; Sea Ice</td>
<td>• new data products from coherent combinations of SAR images:</td>
</tr>
<tr>
<td>Ocean</td>
<td>- Delta-DEM (ice mass balance, ...)</td>
</tr>
<tr>
<td>Land Environment</td>
<td>- 3-D volume imaging (forest structure, ...)</td>
</tr>
<tr>
<td>Subsidence</td>
<td>- 4-D tomography (biomass dynamics, ...)</td>
</tr>
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<td>Traffic</td>
<td>• reliable data supply</td>
</tr>
<tr>
<td>Disaster</td>
<td>• cost efficiency</td>
</tr>
<tr>
<td>Reconnaissance</td>
<td></td>
</tr>
</tbody>
</table>
Future SAR Systems: Motivation

**New SAR Techniques and Technologies**
- Digital Beamforming
- MIMO-SAR
- Hybrid & Adaptive SAR

**New Data Acquisition Concepts**
- GEO - MEO - LEO
- Sparse Satellite Arrays
- Novel Platforms

**New Retrieval Algorithms and Products**
- Object Dynamics
- 3-D & 4-D Structure
- Data Fusion

**Future Demands**
- wider coverage and shorter revisit times
- higher geometric and radiometric resolution
- new data products from coherent combinations of SAR images:
  - Delta-DEM
  - 3-D volume imaging (forest structure, ...)
  - 4-D tomography (biomass dynamics, ...)
- reliable data supply
- cost efficiency

SAR System Design Constraints
Limitations of Conventional SAR Sensors

SAR is the ideal sensor for the observation of dynamic processes on the Earth surface, but...

<table>
<thead>
<tr>
<th>Imaging Mode (Single Pol.)</th>
<th>Resolution</th>
<th>Swath Width</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ScanSAR</td>
<td>16 m</td>
<td>100 km</td>
<td>3 minutes / orbit</td>
</tr>
<tr>
<td>Stripmap</td>
<td>3 m</td>
<td>30 km</td>
<td></td>
</tr>
<tr>
<td>Spotlight</td>
<td>1 m</td>
<td>10 km</td>
<td></td>
</tr>
</tbody>
</table>


SAR Systems: State of the Art and Future Requirements

<table>
<thead>
<tr>
<th>State of the Art (TerraSAR-X)</th>
<th>Imaging Mode (single pol.)</th>
<th>Resolution</th>
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</tr>
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Resolution  Swath Width  Repeat Cycle

<table>
<thead>
<tr>
<th>Future Requirements</th>
<th>Imaging Mode (quad pol.)</th>
<th>Mode X</th>
<th>Mode Y</th>
<th>Mode Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>5 m</td>
<td>2 m</td>
<td>1 m</td>
<td></td>
</tr>
<tr>
<td>Swath Width</td>
<td>500 km</td>
<td>200 km</td>
<td>100 km</td>
<td></td>
</tr>
<tr>
<td>Orbit Duty Cycle</td>
<td>&gt; 50 minutes per orbit</td>
<td></td>
<td></td>
<td></td>
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### SAR Systems: State of the Art and Future Requirements

#### State of the Art (Sentinel-1)

<table>
<thead>
<tr>
<th>Imaging Mode (single/dual pol.)</th>
<th>EW</th>
<th>IW</th>
<th>SM</th>
</tr>
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<tbody>
<tr>
<td>Resolution</td>
<td>40 m</td>
<td>20 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Swath Width</td>
<td>400 km</td>
<td>250 km</td>
<td>80 km</td>
</tr>
<tr>
<td>Orbit Duty Cycle</td>
<td>25 minutes per orbit</td>
<td></td>
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#### Future Requirements

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### SAR System Design Constraints (1)

- high azimuth resolution $\delta \alpha$ requires long synthetic aperture $L$:
  \[
  \delta \alpha = \frac{\lambda \cdot r}{2L} = \frac{d_{\text{ant}}}{2}
  \]

---

*Image and text indicate topics related to SAR systems, including state of the art and future requirements, with specific details on resolution, swath width, and orbit duty cycle.*
Limitations of Conventional SAR Sensors

- long synthetic aperture is provided by short antenna with broad azimuth beam
- large azimuth beamwidth implies wide Doppler spectrum:
  \[ B = \frac{2 \cdot \nu}{\delta \alpha} = \frac{\nu}{\delta \alpha} \]

SAR System Design Constraints (2)

Azimuth Ambiguity-to-Signal Ratio (AASR):

\[ \text{AASR} = \frac{\sum_{i=0}^{\frac{\text{Proc} / 2}{\text{PRF} / 2}} G^2(f + i \cdot \text{PRF}) \cdot df}{\int_{-\text{Proc} / 2}^{\text{Proc} / 2} G^2(f) \cdot df} \]

- sampling with PRF causes ambiguities (AASR)
- low AASR requires high PRF:
  \[ \text{PRF} > B = \frac{\nu}{\delta \alpha} \]
Azimuth Ambiguities: Example

SAR System Design Constraints (4)

- high azimuth resolution
- large Doppler bandwidth
- high PRF
- range ambiguities

Range Ambiguity-to-Signal Ratio (RASR):

\[
RASR = \frac{\sum_{i=0}^{\infty} \sigma^0(\theta_i) \cdot G^2(\theta_i) / (r^3 \sin(\theta_i))}{\sigma^0(\theta_0) \cdot G^2(\theta_0) / (r_0^3 \sin(\theta_0))}
\]

- $\sigma^0$: antenna gain
- $\sigma^0$: backscatter coefficient
- $r$: range
- $\theta$: incident angle
Range Ambiguities: Example

Limitations of Conventional SAR Sensors

SAR System Design Constraints (5)

- high azimuth resolution
- large Doppler bandwidth
- high PRF
- range ambiguities
- narrow swath

suppression of range ambiguities requires narrow antenna beam in elevation
Nadir
Return:
Example

TIMING ANALYSIS

- Ground Range [km]
- Incident Angle [deg]
- PRF [Hz]

- Green line indicates transmit event
- Blue line indicates nadir return
The Design Dilemma for SAR Systems

- High azimuth resolution
- Narrow swath
- Ambiguities & timing
- High PRF
- Large Doppler bandwidth

Swath \( < \frac{c(1 - 2\Delta_d)}{2v_{sat} \sin \theta_i} \cdot \delta_{az} \)

TerraSAR-X Spotlight

Sentinel-1 IW

Sentinel-1 Stripmap

TerraSAR-X ScanSAR

TerraSAR-X Stripmap

Sentinel-1 EW

Swath Width [km] vs. Azimuth Resolution [m]

5 m @ 500 km
2 m @ 200 km
1 m @ 100 km

State of the Art

Future SAR
Digital Beamforming for SAR

Digital Beamforming / Multichannel SAR

radar with phased array (state of the art)

radar with digital beamforming (future systems)
DBF-SAR Systems with Planar Arrays

<table>
<thead>
<tr>
<th>Scan-On-Receive</th>
<th>Digital Beamforming in Elevation</th>
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<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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- High sensitivity and less pattern losses at swath border
- Improved range ambiguity suppression

**Digital Beamforming in Elevation**

**United States Patent**

<table>
<thead>
<tr>
<th>Patent Title</th>
<th>Patent Number</th>
<th>Date</th>
</tr>
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**ABSTRACT**

A synthetic aperture radar system is provided in which the receive beam is controlled so as its directivity so that it remains over a required swath in accordance with the direction of reflection of an interrogating radar pulse; a good example is a rotating conical reflector.

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DBF-SAR Systems with Planar Arrays

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</tr>
<tr>
<td><img src="image3.png" alt="real-time beamsteering for high Rx gain" /></td>
<td><img src="image4.png" alt="scan-on-receive ( \theta (\tau) )" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="simultaneously arriving radar echoes" /></td>
<td><img src="image6.png" alt="real-time beamsteering for high Rx gain" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="DBF-SAR Systems with Planar Arrays" /></td>
<td><img src="image8.png" alt="DBF-SAR Systems with Planar Arrays" /></td>
</tr>
</tbody>
</table>

**Digital Beamforming in Elevation**

\[
\theta(\tau, f_c) = \sum w_1(\tau) + \sum w_2(\tau) + \sum w_3(\tau)
\]
DBF-SAR Systems with Planar Arrays

**Scan-On-Receive**
- High sensitivity and less pattern losses at swath border
- Improved range ambiguity suppression

**Digital Beamforming in Elevation**
- Real-time beamsteering for high Rx gain
- Time-variant beamsteering

---

DBF-SAR Systems with Planar Arrays

Scan-On-Receive

- high sensitivity and less pattern losses at swath border
- improved range ambiguity suppression

Digital Beamforming in Elevation

real-time beamsteering for high Rx gain

time-variant beamsteering

Losses from Beam Mispointing due to Topography (X-Band)

\[
h_{\text{ant}} = 1 \text{ m} \quad h_{\text{ant}} = 2 \text{ m} \quad h_{\text{ant}} = 3 \text{ m}
\]

\[ h_{\text{orbit}} = 700 \text{ km}, \theta_{\text{ant}} = 35^\circ, \lambda = 3.1 \text{ cm} \]

1. high antenna requires a beam steering law in accordance with topography (either via coarse onboard DEM or appropriate commanding from ground)
2. topography variations within a wide azimuth beam must also be considered
3. additional mispointing due to range cell migration (for high res. & ScanSAR)
Losses from Beam Mispointing due to Topography (L-Band)

\[ h_{\text{ant}} = 5 \text{ m} \quad h_{\text{ant}} = 7.5 \text{ m} \quad h_{\text{ant}} = 10 \text{ m} \]

\[ h_{\text{orbit}} = 700 \text{ km}, \quad \theta_{\text{ant}} = 35^\circ, \quad \lambda = 23.6 \text{ cm} \]

1. high antenna requires a beam steering law in accordance with topography (either via coarse onboard DEM or appropriate commanding from ground)
2. topography variations within a wide azimuth beam must also be considered
3. additional mispointing due to range cell migration (for high res. & ScanSAR)

DBF-SAR Systems with Planar Arrays

- high sensitivity and less pattern losses at swath border
- improved range ambiguity suppression

- real-time beamsteering for high Rx gain

- time-variant beamsteering
**DBF-SAR Systems with Planar Arrays**

### Scan-On-Receive

- High sensitivity and less pattern losses at swath border
- Improved range ambiguity suppression

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### Digital Beamforming in Elevation

- Time-variant beamsteering

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### DBF-SAR Systems with Planar Arrays

<table>
<thead>
<tr>
<th>DPCA</th>
<th>Multiple Rx Apertures in Azimuth</th>
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<tbody>
<tr>
<td><strong>Wide-swath SAR</strong></td>
<td></td>
</tr>
<tr>
<td>Equivalent conventional SAR Tx/Rx positions</td>
<td></td>
</tr>
<tr>
<td>Moves a distance $D/2$</td>
<td></td>
</tr>
<tr>
<td>Results in properly sampled equivalent synthetic aperture</td>
<td></td>
</tr>
</tbody>
</table>

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DBF-SAR Systems with Planar Arrays

- Enables high azimuth resolution and wide swath
- Requires dedicated multichannel SAR processing
DBF-SAR Systems with Planar Arrays

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| - enables high azimuth resolution and wide swath  
- requires dedicated multichannel SAR processing | ![Diagram](image)  
- Timing, Nadir  
- Ambiguities  
- \( PRF = \frac{2v}{l_{ant}} \)  
- nonuniform sampling  
- dedicated processing  
- Timing, Nadir  
- Ambiguities |

\( Rx1 \quad Rx2 \quad Rx3 \quad Rx4 \quad Tx \)
DBF-SAR Systems with Planar Arrays

**DPCA**

- enables high azimuth resolution and wide swath
- requires dedicated multichannel SAR processing

**Multiple Rx Apertures in Azimuth**

**System Model:**

\[ h_i(t; \Delta x_i) \]

\[ u(t) \]

\[ \text{Reconstruction & SAR Processing} \]

**Bistatic Azimuth Impulse Response:**

\[ h_i(t; \Delta x_i) \equiv A_{TX}(vt) \cdot A_{RX}(vt - \Delta x_i) \cdot \exp \left[ -\frac{2\pi}{\lambda} (r_{TX}(vt) + r_{RX}(vt - \Delta x_i)) \right] \]

---

**Coherent Reconstruction**

\[ u(t) \]

\[ U(f) \]

(Bandwidth B)

\[ P_1(f) \]

\[ P_2(f) \]

\[ P_3(f) \]

\[ \mathbf{A}(f) = \begin{bmatrix} H_1(f) & H_2(f) & H_3(f) \\ H_1(f + B/3) & H_2(f + B/3) & H_3(f + B/3) \\ H_1(f + 2B/3) & H_2(f + 2B/3) & H_3(f + 2B/3) \end{bmatrix} \]

\[ \mathbf{A}^{-1}(f) \]

\[ P_1(f) \]

\[ P_2(f + B/3) \]

\[ P_3(f + 2B/3) \]

---

### DBF-SAR Systems with Planar Arrays

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#### Multiple Rx Apertures in Azimuth

**DPCA**

Displaced phase centers and/or multiple azimuth beams

**Multiple Rx Apertures in Azimuth**

- $H_1(f)$
- $H_2(f)$
- $H_3(f)$
- $H_4(f)$

**Reconstruction in Frequency Domain:**

$U(f)$

- $P_1(f)$
- $P_2(f)$
- $P_3(f)$
- $P_4(f)$

Reconstruction by sum of linear filters $\sum P_i(f)$ can also be interpreted as a frequency dependent linear beamformer.

---

DBF-SAR Systems with Planar Arrays

- enables high azimuth resolution and wide swath
- requires dedicated multichannel SAR processing

Reconstruction from Nonuniform DPCA Sampling

- Single-Channel Image
- Demonstration with TerraSAR-X

Pulse-to-Pulse Antenna Phase Center Variation

Uniform Sampling of Synthetic Aperture

DBF-SAR Systems with Planar Arrays

HRWS

Combination of Scan on Receive with DPCA

• scan-on-receive with dispersive beam for high Rx gain
• DPCA for improved azimuth resolution in stripmap mode


DBF-SAR Systems with Planar Arrays

<table>
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<th>HRWS</th>
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<tr>
<td></td>
<td><img src="image1" alt="Diagram of System Components" /></td>
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- scan-on-receive with dispersive beam for high Rx gain
- DPCA for improved azimuth resolution in stripmap mode

**Combination of Scan on Receive with DPCA (SCORE) and DPCA (MAPS)**

- $h = 514\text{ km}$
- $\Delta_{\text{duty}} = 15\%$

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- scan-on-receive with dispersive beam for high Rx gain
- DPCA for improved azimuth resolution in stripmap mode

**Combination of Scan on Receive with DPCA (SCORE) and DPCA (MAPS)**

- $h = 700\text{ km}$
- $\Delta_{\text{duty}} = 15\%$

---

DBF-SAR Systems with Planar Arrays

**HRWS**

- improved scan-on-receive (SCORE) and DPCA (MAPS)

**Combination of Scan on Receive with DPCA**

- scan-on-receive with dispersive beam for high Rx gain
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<table>
<thead>
<tr>
<th>Swath</th>
<th>PRF</th>
<th>$l_{ant}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 km</td>
<td>≤ 1.6 kHz</td>
<td>≥ 10 m</td>
</tr>
<tr>
<td>200 km</td>
<td>≤ 800 Hz</td>
<td>≥ 20 m</td>
</tr>
<tr>
<td>400 km</td>
<td>≤ 400 Hz</td>
<td>≥ 40 m</td>
</tr>
</tbody>
</table>

$2 \cdot v_x \cdot PRI \leq l_{ant}/2$

DBF-SAR Systems with Planar Arrays

**Quad Array SAR**

- good azimuth resolution
- compact antenna
- range gap in the middle of the swath

**Suppression of Range Ambiguities by Null Steering**

### DBF-SAR Systems with Planar Arrays

<table>
<thead>
<tr>
<th>Burst-DBF-SAR</th>
<th>DPCA in Burst Mode Operation</th>
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<tbody>
<tr>
<td>combination of DPCA, SCORE and ScanSAR/TOPS</td>
<td>• Minimum PRF is determined by antenna length: $PRF \geq \frac{2 \cdot v_s}{\lambda_{ant}}$</td>
</tr>
</tbody>
</table>
| • enables mapping of ultra-wide swaths with high resolution | $\begin{array}{c|c|c}
\lambda_{ant} & PRF \\
10 \text{ m} & \geq 1500 \text{ Hz} \\
12.5 \text{ m} & \geq 1200 \text{ Hz} \\
15 \text{ m} & \geq 1000 \text{ Hz}
\end{array}$ |
| • suggested as Sentinel-1 successor system | • Minimum burst number is determined from timing |

### ScanSAR with Planar Array

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- enables mapping of ultra-wide swaths with high resolution
- suggested as Sentinel-1 successor system

**requires nadir echo suppression**

**New Nadir Suppression Technique**

- Raw SAR data (with nadir echo)
- Focusing matched to the nadir echo
- Removal of the nadir echo
- Inverse focusing
- Focusing matched to the useful signal

- nadir echo as well as house and tree echoes are smeared
- nadir echo is focused while house and tree echoes are additionally smeared
- nadir echo is removed while house and tree echoes remain smeared
- nadir echo is removed while house and tree echoes appear almost identical as in original data
- focused SAR image without nadir echo
### DBF-SAR Systems with Planar Arrays

#### Burst-DBF-SAR

- Enables mapping of ultra-wide swaths with high resolution
- Suggested as Sentinel-1 successor system

#### DPCA in Burst Mode Operation

<table>
<thead>
<tr>
<th>Burst Number (Nburst)</th>
<th>Minimum PRF (PRF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (with nadir)</td>
<td>1200 Hz</td>
</tr>
<tr>
<td>3 (w/o nadir)</td>
<td>1200 Hz</td>
</tr>
</tbody>
</table>

#### Minimum number of azimuth channels from azimuth resolution:

\[ N_{azi} \geq \frac{l_{ant}}{2\Delta_azi} (N_{burst} + 1) \]

#### Burst-DBF-SAR

- Enables mapping of ultra-wide swaths with high resolution
- Suggested as Sentinel-1 successor system

#### DPCA in Burst Mode Operation

- The high-resolution wide-swath ScanSAR mode may imply a notable squint angle change at the burst borders:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Bursts</th>
<th>(N_{azi})</th>
<th>(\Delta) Squint Angle ((\Delta\psi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-band</td>
<td>4</td>
<td>7</td>
<td>5.1°</td>
</tr>
<tr>
<td>C-band</td>
<td>7</td>
<td>7</td>
<td>1.2°</td>
</tr>
<tr>
<td>X-band</td>
<td>7</td>
<td>7</td>
<td>0.66°</td>
</tr>
</tbody>
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#### Challenges:

- Azimuth scalloping (AASR, NESZ)
- Line-of-sight variation (interferometry)
- Atmospheric discontinuities (ionosphere)
DBF-SAR Systems with Planar Arrays

- Enables mapping of ultra-wide swaths with high resolution
- Suggested as Sentinel-1 successor system

DPCA in Burst Mode Operation

Phase Jumps from Ionosphere

Sentinel-1
Mexico city, flattened phase

courtesy: P. Prats

F. De Zan et al., Interferometry with TOPS: coregistration and azimuth shifts, 10th European Conference on Synthetic Aperture Radar, Berlin, Germany, 2014.
DBF-SAR Systems with Planar Arrays

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<td>11-day TSX TOPS interferogram over the Lambert glacier, Antarctica. (Left) Reflectivity image and (right) flattened interferogram. The images show three consecutive bursts (9 km per burst in azimuth), where the top-right part is a stable rocky area showing no phase jumps at burst edges. The glacier, on the other hand, shows clear jumps at burst edges. The jumps are legitimate and correspond to the projection of the motion in the LOS direction, being the latter azimuth-dependent. At burst edges the LOS vectors have opposite azimuth directions, and therefore the jumps can be clearly seen. Range is horizontal and azimuth is vertical (from F. De Zan et al, EUSAR 2014).</td>
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- enables mapping of ultra-wide swaths with high resolution
- suggested as Sentinel-1 successor system


DBF-SAR Systems with Planar Arrays

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<tr>
<th>Burst-DBF-SAR</th>
<th>DPCA in Burst Mode Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>combination of DPCA, SCORE and ScanSAR/TOPS</td>
<td>Scalloping in Multichannel ScanSAR mode</td>
</tr>
</tbody>
</table>

- enables mapping of ultra-wide swaths with high resolution
- suggested as Sentinel-1 successor system

Deployable Reflector Antennas

DBF with Reflector Antennas

Large reflector enables:
• high sensitivity also at low frequencies
• improved ambiguity suppression
• innovative SAR modes
• multiple frequency SAR

DBF with Reflector Antennas

Variable Antenna Gain from Element Switching

Frequency Dependence of Antenna Patterns

Feed Blockage & Multipath

Redundancy Against Tx/Rx Module Failure

Modulation for Long Transmit Pulses
Synthetic Aperture Radar

low PRF $\rightarrow$ azimuth ambiguities

Multiple Swath Mapping

blind angles

Multiple Swath Mapping

Multiple Rx-Beams in Elevation

blind ranges for given PRF

blind ranges

swath echo

Key Challenges:

- **Blind ranges:**
  - bistatic SAR
  - PRI variation

- **Range ambiguities:**
  - large aperture
  - advanced DBF

**Range Ambiguity Suppression by Null-Steering**

- null-steering requires sufficient antenna height to avoid losses:
  \[
  h_{\text{ant}} = \frac{2\lambda \cdot r_{\text{far}} \cdot \tan(\theta_{\text{inc,max}})}{c \cdot \text{PRI}}
  \]

- null-steering is sensitive to:
  - antenna phase errors
  - topography
  - satellite mispointing
  - squint/Doppler variation

- possible mitigations:
  - larger antenna & tapered beams
  - advanced beamforming (e.g. real-time DBF with broad “nulls”)
  - cross elevation beam range ambiguity suppression (CEBRAS)
Minimum Antenna Height ($\theta_{l,max} = 50^\circ$, $h_{sat} = 700$ km)

- PRF $\sim$ 2 kHz for 5 m azimuth resolution
- PRF $\sim$ 10 kHz for 1 m azimuth resolution

G. Krieger et al., SIMO and MIMO System Architectures and Modes for High Resolution Ultra-Wide-Swath SAR Imaging, EUSAR 2016.

Tx-Rx Separation (Bistatic System)

- Simultaneous transmission and reception avoids blind ranges
- Direct signal can be suppressed by
  - Doppler filter
  - additional mitigation by waveform diversity and/or PRI variation
- Advantages
  - ultra-wide swaths with high resolution
  - compact antennas and satellites
  - no Tx/Rx switches, less losses, FMCW, ...
- Drawbacks
  - requires two satellites (3 for single-pass InSAR)
  - requires accurate time and phase synchronisation

**Tx-Rx Separation (Bistatic System)**

- Simultaneous transmission and reception avoids blind ranges
- Example:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath</td>
<td>500 km</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>3 m</td>
</tr>
<tr>
<td>Orbit Height</td>
<td>800 km</td>
</tr>
<tr>
<td>PRF</td>
<td>3.5 kHz</td>
</tr>
<tr>
<td>Tx Antenna Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Tx Antenna Height</td>
<td>&gt; 0.8 m (L-band)</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.1 m (X-band)</td>
</tr>
<tr>
<td>Rx Antenna Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Rx Antenna Height</td>
<td>&gt; 5.6 m (L-band)</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.7 m (X-band)</td>
</tr>
</tbody>
</table>

---

**Multi-Beam Concepts for Ultra-Wide-Swath Imaging**

- Strategies for Elimination of Blind Ranges -

**Continuous PRI Variation**

- Blind Ranges Move Across Swath
- Improved performance

**Multiple-Beam ScanSAR**

- Burst-Mode with Multiple Rx-Beams
- Gaps eliminated
Systematic Shift of Blind Ranges

Timing Options for SAR with Variable PRI

Slow PRI Variation

Fast PRI Variation

azimuth bursts

single pulse gaps
System Parameters Range-Dependent Burst Positions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.236 m (L-Band)</td>
</tr>
<tr>
<td>Satellite height</td>
<td>773 km</td>
</tr>
<tr>
<td>Incident angles</td>
<td>24° - 47.2°</td>
</tr>
<tr>
<td>Swath width</td>
<td>400 km</td>
</tr>
<tr>
<td>Reflector diameter</td>
<td>12 m</td>
</tr>
<tr>
<td>Focal length</td>
<td>12 m</td>
</tr>
<tr>
<td>Reflector offset</td>
<td>7.2 m</td>
</tr>
<tr>
<td>Azimuth elements</td>
<td>5 (0.6 (\lambda))</td>
</tr>
<tr>
<td>Elevation channels</td>
<td>45 (0.6 (\lambda))</td>
</tr>
<tr>
<td>Minimum PRF</td>
<td>3300 Hz</td>
</tr>
<tr>
<td>Maximum PRF</td>
<td>3444 Hz</td>
</tr>
<tr>
<td>Cycle time</td>
<td>3.54 s</td>
</tr>
<tr>
<td>Tx duty cycle</td>
<td>4%</td>
</tr>
<tr>
<td>Burst length</td>
<td>&gt; 3.35 s</td>
</tr>
</tbody>
</table>

Multiple Elevation Beam SAR with Slow PRI Variation

SAR with Slow PRI Variation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.236 m (L-Band)</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>5 m</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>12 m</td>
</tr>
<tr>
<td>Feed size</td>
<td>6.4 m x 0.71 m</td>
</tr>
<tr>
<td>Orbital altitude</td>
<td>773 km</td>
</tr>
<tr>
<td>Average Tx power (for NESZ = -25 dB)</td>
<td>883 W (610 W)</td>
</tr>
</tbody>
</table>
Multiple Elevation Beam SAR with Slow PRI Variation

System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda$)</td>
<td>0.236 m</td>
</tr>
<tr>
<td>Satellite height ($h_{sat}$)</td>
<td>773 km</td>
</tr>
<tr>
<td>Incident angles ($\theta_{inc}$)</td>
<td>24°-47.2°</td>
</tr>
<tr>
<td>Swath width ($\Delta s$)</td>
<td>400 km</td>
</tr>
<tr>
<td>Reflector diameter ($D$)</td>
<td>12 m</td>
</tr>
<tr>
<td>Focal length ($F$)</td>
<td>12 m</td>
</tr>
<tr>
<td>Reflector offset ($O$)</td>
<td>7.2 m</td>
</tr>
<tr>
<td>Azimuth elements ($N_{az}$)</td>
<td>5 (0.6 $\lambda$)</td>
</tr>
<tr>
<td>Elevation channels ($N_{el}$)</td>
<td>45 (0.6 $\lambda$)</td>
</tr>
<tr>
<td>Minimum PRF ($PRF_{min}$)</td>
<td>3300 Hz</td>
</tr>
<tr>
<td>Maximum PRF ($PRF_{max}$)</td>
<td>3444 Hz</td>
</tr>
<tr>
<td>Cycle time ($T_{cycle}$)</td>
<td>3.54 s</td>
</tr>
<tr>
<td>Tx duty cycle ($\Delta_{cycle}$)</td>
<td>4%</td>
</tr>
<tr>
<td>Burst length ($T_{burst}$)</td>
<td>&gt; 3.35 s</td>
</tr>
</tbody>
</table>

Range-Dependent Burst Positions

Extra Looks

- ~ 25 km
- ~3 ° (illuminated beamwidth)
- ~2.5 °
- ~1.5 °
- Extra looks for point C
- Synthetic aperture for point C

Bursts (shifted for different ranges)
Fast PRI Variation

Nonuniform PRI sequence

range

Tx

Fast PRI Variation

Nonuniform PRI sequence

range

Tx

Nonuniformly sampled SAR signal

BLU interpolation

resampled data

filtered data

Doppler filter

onboard decimation for data volume reduction


**Staggered SAR (400 km Single-Pol)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.236 m (L-Band)</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>15 m</td>
</tr>
<tr>
<td>Feed size</td>
<td>7.15 m x 0.86 m</td>
</tr>
<tr>
<td>Orbital altitude</td>
<td>773 km</td>
</tr>
<tr>
<td>Tx duty cycle</td>
<td>6%</td>
</tr>
<tr>
<td>Average Tx power</td>
<td>306 W</td>
</tr>
<tr>
<td>Polarisation</td>
<td>single-pol (400 km)</td>
</tr>
</tbody>
</table>

**Staggered SAR (200 km Quad-Pol)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.236 m (L-Band)</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>15 m</td>
</tr>
<tr>
<td>Feed size</td>
<td>7.15 m x 0.86 m</td>
</tr>
<tr>
<td>Orbital altitude</td>
<td>773 km</td>
</tr>
<tr>
<td>Tx duty cycle</td>
<td>2 x 3%</td>
</tr>
<tr>
<td>Average Tx power</td>
<td>177 W</td>
</tr>
<tr>
<td>Polarisation</td>
<td>quad-pol (200 km)</td>
</tr>
</tbody>
</table>

**Range Ambiguities (RASR)**

**Azimuth Ambiguities (AASR)**

![Graphs](image-url)
Smearing of Azimuth Ambiguities in Staggered SAR

Simulation to demonstrate the additional benefits from azimuth ambiguity smearing for a staggered-SAR system, based on a TerraSAR-X image, acquired over Barcelona, Spain. (a) Original image with accentuated azimuth ambiguities. (b) Simulated staggered-SAR image using the more elaborated sequence and best linear interpolation (BLI). (From Villano et al., *Staggered SAR: High-Resolution Wide-Swath Imaging by Continuous PRI Variation*, IEEE Transactions on Geoscience and Remote Sensing, July 2013).


Tandem-L

Systematic Monitoring of Earth System Dynamics

Staggered SAR with Multiple Azimuth Channels

- High azimuth resolution by multiple azimuth feeds/beams
- Wide swath imaging by multiple elevation beams and staggered PRI
- Blind ranges move across swath
Staggered SAR with Multiple Azimuth Channels

- Requires combination of:
  - multi-channel reconstruction
  - staggered SAR interpolation

- Novel virtual beam synthesis technique

- Key idea: multichannel SAR signal resampling to uniform grid using:
  - multiple Rx pulses (time-variant interpolation)
  - adaptive beams (time-variant aperture tapering)

F. Queiroz de Almeida et al., “Multichannel staggered SAR azimuth sample regularization”, Proc. EUSAR, June 2016 (TGRS paper in print)

### Multichannel Staggered SAR NESZ

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.236 m (L-Band)</td>
</tr>
<tr>
<td>Antenna diameter</td>
<td>18 m</td>
</tr>
<tr>
<td>Feed size</td>
<td>9.3 m x 0.76 m</td>
</tr>
<tr>
<td>Orbital altitude</td>
<td>773 km</td>
</tr>
<tr>
<td>Azimuth channels</td>
<td>4</td>
</tr>
<tr>
<td>Average Tx power</td>
<td>302 W</td>
</tr>
<tr>
<td>Polarisation</td>
<td>quad-pol (400 km)</td>
</tr>
</tbody>
</table>

### Range Ambiguities (RASR)

### Azimuth Ambiguities (AASR)
Spatiotemporally Non-Separable Waveform Encoding

\[ w(t, \theta) = h(t) \cdot a(\theta) \]

- separable
- orthogonal codes, different RF bands, delayed sub-pulses, ...

\[ w(t, \theta) \neq h(t) \cdot a(\theta) \]

- non-separable

Multidimensional Waveforms: Possible Implementation

Non-Separable Waveform: Example with 3 Sub-Pulses
High-Resolution Wide-Swath SAR Imaging (X-Band)

Classical SAR with 1 Tx/Rx aperture

Point Target Response

Displaced Phase Center Antenna (DPCA) Technique

Multi-aperture recording in azimuth

Point Target Response
Multidimensional Waveform Encoding (MIMO SAR)

4 Tx + 4 Rx
+ waveform Encoding
PRF = 1220 Hz

transfer of ambiguous energy from azimuth to range

Point Target Response

Multidimensional Waveform Encoding (MIMO SAR)

4 Tx + 4 Rx
+ Tx encoding
+ DBF on receive
PRF = 1220 Hz

residual ambiguities: - 30 dB

Point Target Response

MIMO-SAR with Reflector Antennas

Direct Radiating Arrays

Reflectors with Digital Feed Array

Additional Azimuth Phase Centers for Improved SAR Imaging & GMTI

Classic HRWS

Waveform Encoding

\[ d_{\text{max}} = \frac{n - 1}{2} \cdot d_{\text{ant}} \]

\[ d_{\text{max}} = (n - 1) \cdot d_{\text{ant}} \]
Fully Polarimetric Waveform Encoding

- transmit two sub-pulses with H and V → two polarisations in each Tx pulse!
- receive radar echo in two polarisations
- use DBF to separate Tx polarisations
- no increase of PRF → full swath width!

DBF on receive in elevation


g. krieger@dlr.de

Microwaves and Radar Institute
Orthogonal Waveforms for MIMO-SAR
(Examples from Recent IEEE Publications)

\[ \int s_i(t)s_j^*(t + \tau) dt = 0, \quad i \neq j, \forall \tau \in \mathbb{R}, \quad i, j = 1, 2, \ldots, L. \]

WQ Wang, IEEE AC 2007

\[ S_i(f) \cdot S_j^*(f) = 0 \quad \forall \quad f \in \mathbb{R} \]

→ no coherence for interferometry, polarimetry, azimuth ambiguity suppression, GMTI, ...

Orthogonal Waveforms for MIMO-SAR
(Examples from Recent IEEE Publications)

\[ \int s_i(t)s_j^*(t + \tau) dt = 0, \quad i \neq j, \forall \tau \in \mathbb{R}, \quad i, j = 1, 2, \ldots, L. \]

WQ Wang, IEEE AC 2007

\[ \int_0^{T_p} s_m(t)s_n^*(t) dt = \begin{cases} c_m, & m = n \\ 0, & m \neq n \end{cases} \]

WQ Wang, IEEE TGRS 2011

\[ \int_{T_p} s_m(t)s_n^*(t) dt = \delta_{mn}, \quad (m, n) \in [1, 2, 3, \ldots, K] \]

WQ Wang, IEEE GRSL 2012
Orthogonal Waveforms for MIMO-SAR: Up & Down-Chirps

Original Scene

Matched Filter Result (only matched channel present)

Matched Filter Result (also orthogonal channel present)
Orthogonal Waveforms for MIMO-SAR: Up & Down-Chirps

Original Scene

Matched Filter Result (only matched channel present)

Matched Filter Result (also orthogonal channel present)
MIMO SAR OFDM Chirp Waveform Diversity Design With Random Matrix Modulation

W. Qiu, Member, IEEE


Autocorrelation and Crosscorrelation
Short-Term Shift-Orthogonal Waveforms for MIMO-SAR

\[ \int s_a(t) \cdot s_b^*(t - \tau) \cdot dt = 0 \quad \forall \quad \tau \in [-a, a] \]
Information Cube

angle of arrival

frequency

time

Information Cube

angle of arrival

frequency

time
Information Cube

angle of arrival

time

Information Cube

angle of arrival

frequency

time

information space completely filled by distributed scatterers!
Information Cube

STSO waveforms: cyclic shift

angle of arrival

frequency
time

no unique separation between overlapping signal returns!
Information Cube

- DBF
- Angle of arrival
- Frequency
- Time

Sparsely populated information cube with DBF in elevation!

Information Cube

- MIMO (cyclic chirps)
- Angle of arrival
- Frequency
- Time

Cube filled with short-term shift-orthogonal waveforms!
Echo Separation in Multidimensional Waveform Encoding SAR Remote Sensing Using an Advanced Null-Steering Beamformer

Fan Feng, Shiqiang Li, Weidong Yu, Member, IEEE, Pingping Huang, and Wei Xu

Fig. 8. Block diagram of advanced null-steering beamformer on the satellite. \(\psi_{ij}\) denotes the element of the matrix \(\mathbf{V}_0^T\), where subscripts signify its position in the matrix, and \(\psi_{ij}\) represents the \((i,j)\)th element of the matrix \(V_0/(V^TV)^{-1}\). 
Digital Beamforming on Receive in Elevation for Multidimensional Waveform Encoding SAR Sensing

Feng He, Xile Ma, Zhen Dong, and Diannong Liang

In this letter, the performance of the separation approach employing a posteriori DBF in elevation is investigated in detail. It was originally suggested in [2] and was employed in [9] with a novel full polarimetric SAR mode. This way, useful information about the spatial structure in elevation will be preserved to enable flexible and adaptive beamforming on the ground. An

Fig. 3. RASR versus ground delay employing different elevation subapertures.

A Closer Look to Null-Steering
Example 1: Range Ambiguities for Planar Array

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna height $h_{ant}$</td>
<td>2.5 m</td>
<td></td>
</tr>
<tr>
<td>Antenna height $l_{ant}$</td>
<td>4 x 2.5 m</td>
<td></td>
</tr>
<tr>
<td>Wavelength $\lambda$</td>
<td>0.031 m</td>
<td></td>
</tr>
<tr>
<td>Satellite height $z_{sat}$</td>
<td>576 km</td>
<td></td>
</tr>
<tr>
<td>Height offset $dh$</td>
<td>1.5 km</td>
<td></td>
</tr>
<tr>
<td>Satellite velocity $v_{sat}$</td>
<td>7.5 km/s</td>
<td></td>
</tr>
<tr>
<td>Earth radius $r_e$</td>
<td>6378 km</td>
<td></td>
</tr>
<tr>
<td>Look angle $\theta_{look}$</td>
<td>32.4°</td>
<td></td>
</tr>
<tr>
<td>Sub-pulse delay $\Delta \tau$</td>
<td>50 $\mu$s</td>
<td></td>
</tr>
</tbody>
</table>

Iso-Range Contours on Earth Surface

- Iso-range contour of desired signal
- Iso-range contour of ambiguity (far range)
Null-Steering in Elevation for Zero-Doppler Position

- High gain for desired signal
- Null-steering for range ambiguity suppression

Null-Steering in Elevation for Zero-Doppler Position

- High gain for desired signal
- Null-steering for range ambiguity suppression
Null-Steering in Elevation: 2-D Pattern on Ground

Null-Steering in Elevation: Azimuth Patterns

At nominal height:  
- high gain for desired signal
- excellent suppression of ambiguities

range ambiguities < - 60 dB for all $f_{Dop}$

Null-Steering in Elevation: Impact of Topography

- Height of 1.5 km has:
  - Minor impact on main beam (< 1.5 dB)
  - Strong impact on nulling (-60 → -17 dB)

Diagram notes:
- Iso-range line for 1.5 km height offset
Example 2: Range Ambiguities for Reflector DBF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna diameter</td>
<td>$d_{ant}$</td>
<td>15 m</td>
</tr>
<tr>
<td>Feed elements</td>
<td>$n_{el}$</td>
<td>32</td>
</tr>
<tr>
<td>Wavelength</td>
<td>$\lambda$</td>
<td>0.236 m</td>
</tr>
<tr>
<td>Satellite height</td>
<td>$z_{sat}$</td>
<td>745 km</td>
</tr>
<tr>
<td>Height offset</td>
<td>$d_h$</td>
<td>3 km</td>
</tr>
<tr>
<td>Satellite velocity</td>
<td>$v_{sat}$</td>
<td>7 km/s</td>
</tr>
<tr>
<td>Earth radius</td>
<td>$r_e$</td>
<td>6378 km</td>
</tr>
<tr>
<td>Steering angle</td>
<td>$\theta_{steer}$</td>
<td>7.864°</td>
</tr>
<tr>
<td>PRI</td>
<td>$\Delta r$</td>
<td>150 $\mu$s</td>
</tr>
</tbody>
</table>

Null-Steering in Elevation: Pattern in Ground Plane

- high gain for desired signal
- null-steering for range ambiguity suppression
Null-Steering in Elevation: Azimuth Patterns

At nominal height:
- only -27 dB suppression for some $f_{Dop}$
- challenges fully polarimetric mode

Null-Steering in Elevation: Impact of Topography

Iso-range line for 3 km height offset
Null-Steering in Elevation: Impact of Topography

Height of 3 km has:
- negligible impact on main beam
- strong impact on nulling

$\Delta h = 3 \text{ km}$
Cross Elevation Beam Range Ambiguity Suppression

- On-board scan-on-receive with multiple elevation beams
  - dispersive beams to account for extended pulses
  - beams follow topography (MVDR beamformer and coarse DEM)

- On-ground range ambiguity suppression by combining beam signals
  - beamforming in range-Doppler domain to account for topography changes in azimuth (based on high-res. DEM)
  - can take into account auxiliary data (platform orientation, calibration data, refined beam patterns, ....)

Down Link

G. Krause and C. Kämmerer, CEBRAS: Cross elevation beam range ambiguity suppression for high-resolution wide-swath and MIMO-SAR imaging, IGARSS 2015.
Beamforming Weights: Simple Solution

- Cancellation weights can be approximated by
  \[ w_{lkj}(t, \tau) = \frac{A_l(\theta_i(\tau + \tau_{kl}), \varphi_i(\tau + \tau_{kl}); t, \tau)}{A_k(\theta_k(f_l), \varphi_k(f_l); t, \tau)} \]
  with \( \theta_k(\tau) = \theta_i(\tau + \tau_{kl}) \)

- Computation of beamforming weights \( w_{lkj}(\tau) \) requires knowledge about
  - complex antenna patterns after real-time scan-on-receive beamforming \( A_{kj}(\theta, \varphi; t, \tau) \)
  - antenna look angles \( \theta_{(k,l)} \) and azimuth angles \( \varphi_{(k,l)} \) of arriving wavefronts
    (derived from DEM together with a posteriori satellite attitude and position estimates)

Estimation of Antenna Patterns / Cancellation Weights

- Option 1: A Priori Antenna Model
  - employ 2-D model for computation of beam patterns
  - accuracy may be challenging for reflector system

- Option 2: Calibration Data Takes
  - illuminate with low PRI and receive with multiple beams
  - topography can be emulated by varying beam trigger times

- Option 3: Cross-Correlation
  - cross-correlate signals from multiple beams
  - prone to “self-cancellation”

- Option 4: Blind Source Separation
  - unmix signals as in cocktail party effect
  - requires use of higher-order statistics
Option 2: Dedicated Calibration Data Takes

- Acquire multi-beam data without range ambiguities
  - MIMO-SAR: employ e.g. single Tx channel/sub-pulse

\[
\begin{align*}
    w_{12}(t, \tau) &= \frac{A_1(\theta_2, \varphi_2; t, \tau, f_j)}{A_2(\theta_2, \varphi_2; t, \tau, f_j)} \\
    &= \frac{u_1(t, \tau, f_j)}{u_2(t, \tau, f_j)}
\end{align*}
\]

Option 3: Pattern Ratios from Cross-Correlation

- Operate SAR in nominal multiple beam mode

\[
\begin{align*}
    c_{ik}(t; \tau) &= \int u_k(t; \tau, f_j) \cdot u_i(t; \tau, f_j) \cdot dt \\
    \Rightarrow w_{ik}(t; \tau)
\end{align*}
\]
Option 4: Blind Source Separation

- Operate SAR in nominal multiple beam mode

\[
\begin{bmatrix}
  u_1(t; ...) \\
  u_2(t; ...) \\
  \vdots \\
  u_N(t; ...) \\
\end{bmatrix} =
\begin{bmatrix}
  a_{11} & \cdots & a_{1N} \\
  \vdots & \ddots & \vdots \\
  a_{N1} & \cdots & a_{NN} \\
\end{bmatrix}
\begin{bmatrix}
  s_1(t; ...) \\
  s_2(t; ...) \\
  \vdots \\
  s_N(t; ...) \\
\end{bmatrix}
\]

- Each recorded signal can be regarded as a linear superposition of statistically independent source signals.
- Independent component analysis can be used to separate the source signals:
  - entropy maximization
  - minimize mutual information
  - higher-order decorrelation (cumulants)
  - infomax
  - ...

I like IGARSS.

zebras eat grass

zebras like cocktails

I prefer cocktails
Option 4: Blind Source Separation

- Operate SAR in nominal multiple beam mode

\[
\begin{pmatrix}
    a_{11} & \cdots & a_{1N} \\
    \vdots & \ddots & \vdots \\
    a_{N1} & \cdots & a_{NN}
\end{pmatrix}
\begin{pmatrix}
    s_1(t; \ldots) \\
    \vdots \\
    s_N(t; \ldots)
\end{pmatrix}
\]

MIMO SAR Design Example
MIMO-SAR Systems with Planar Arrays

<table>
<thead>
<tr>
<th>MIMO-SAR</th>
<th>Acquisition of Additional Phase Centers for Each Tx-Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRWS</td>
<td></td>
</tr>
<tr>
<td>MIMO-SAR</td>
<td></td>
</tr>
</tbody>
</table>

- additional phase centers for reduced antenna length
- requires high antenna to separate waveforms

Parameter Symbol Value

- Azimuth Resolution $\delta x$ 1 m
- Swath Width $W$ 240 km
- Orbit Height $h_{\text{sat}}$ 693 km
MIMO-SAR Systems with Planar Arrays

- Additional phase centers for reduced antenna length
- Requires high antenna to separate waveforms

Acquisition of Additional Phase Centers for Each Tx-Pulse

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<td>Azimuth Resolution</td>
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</tr>
<tr>
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<td>( W )</td>
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<td>Orbit Height</td>
<td>( h_{sat} )</td>
<td>693 km</td>
</tr>
<tr>
<td>Incident Angle</td>
<td>( \theta_i )</td>
<td>30° - 45°</td>
</tr>
<tr>
<td>PRF</td>
<td>( PRF )</td>
<td>610 Hz</td>
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MIMO-SAR Systems with Planar Arrays

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<td>Sub-Aperture Length</td>
<td>$l_{sub}$</td>
<td>1.64 m</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>$\Delta _{duty}$</td>
<td>20 %</td>
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DBF for waveform separation (CEBRAS)

STSO waveforms
MIMO-SAR Systems with Planar Arrays

**Parameter** | **Symbol** | **Value**
--- | --- | ---
Azimuth Resolution | $\delta a$ | 1 m
Swath Width | $W$ | 240 km
Orbit Height | $h_{sat}$ | 693 km
Incident Angle | $\theta_i$ | 30° - 45°
PRF | $PRF$ | 610 Hz
Azimuth Channels | $N_{az}$ | 8
Antenna Length | $l_{ant}$ | 13.12 m
Sub-Aperture Length | $l_{sub}$ | 1.64 m
Duty Cycle | $\Delta_{duty}$ | 20% 
STSO Interval | $\tau_{STSO}$ | 164 $\mu$s 

$\tau_{STSO} = (\Delta_{duty}/2) \cdot PRI$

MIMO-SAR Systems with Planar Arrays

**Parameter** | **Symbol** | **Value**
--- | --- | ---
Antenna Height [m] | | 2.25 m @ C-band
PRF [Hz] | | 5000 to 500
Pulse Separation [ms] | | 0.02 to 2.00

**DBF for waveform separation (CEBRAS)**

**STSO waveforms**

Additional phase centers for reduced antenna length

Requires high antenna to separate waveforms
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---

HRWS (SCORE + DPCA) | MIMO-SAR (with DPCA) | Multiple Azimuth Channel ScanSAR | Multiple Elevation Beam SAR

- Displaced phase center antenna scan on receive
- STSO waveforms
- DBF for waveform separation (CEBRAS)
- DPCA & SCORE in burst mode
- Multiple Rx beams in elevation

Bistatic SAR (Tx-Rx Separation) | SAR with Slow PRI Variation | Staggered SAR (1 azimuth ch.) | Staggered SAR (N azimuth ch.)

- Multiple elevation beams
- Fast PRI variation for stripmap-like imaging
- Multiple azimuth beams
- Blind ranges for given PRF
- Multi Rx beams across swath
- Blind ranges move slowly across swath
Outlook

Data Bottleneck
Adaptive & Cognitive MIMO-SAR Systems

- maximize information gain for a given power & data budget
- optimized distribution of system resources

Saccadic Eye Movements
(Yarbus, 1967)
Thank you for your attention