Constellation & Formation Flying Concepts for Radar Remote Sensing

H. Fiedler, G. Krieger, M. Zink
### Future SAR Systems: Motivation

#### Application Areas for SAR Data Products

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<td>Reconnaissance Inventory</td>
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<td>Oil Seep Detection</td>
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<td>Ship Detection Service</td>
<td>Dynamic Traffic Monitoring</td>
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<tr>
<td>Oil Spill Monitoring</td>
<td>Maps of Roads, Channels, ...</td>
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<td>Sea Ice Monitoring</td>
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### System Requirements

- **short response time**
- **high revisit frequency**
- **wide area coverage**
- **high radiometric and geometric resolution**
- **imaging with multiple**
  - polarisations
  - wavelengths
  - view angles (e.g. interferometry)
  - time intervals (change detection)
- **high reliability**
- **cost efficiency**
Future SAR Systems: Paradigm Shift to Satellite Clusters

Paradigm Shift

Large, multi-functional satellites

- Smaller, simpler satellites → reduced cost & time
- Modular design → upgradable, improved reliability
- Spatially distributed → improved revisit time / coverage / adaptability
- Separated, sparse apertures → improved performance and resolution

Virtual satellite - web of cooperating satellites
Bistatic and Multistatic SAR Systems

Definitions:
• Radar systems with a spatial separation between transmitter and receiver are called bistatic.
• Systems with multiple receivers are called multistatic.

Fully active system
(TechSAT21, Radarsat 2/3, TanDEM-X)

- two monostatic & two bi-static images
- phase synchronisation in ping/pong mode
- higher redundancy & increased flexibility

Partially active system
(BISSAT, Cartwheel, Cross-Track Pendulum)

- reduced costs & low weight of passive receivers
- increased sensitivity (no Tx/Rx switches)
- DBF on receive with MMICs in the antenna
Changeable Orbital Parameters
How Do They Look Like?

Two satellites orbit behind each other with
• different ascending nodes:
  - collision risks
  - no cross track baselines at high latitudes
• additional different eccentricities (HELIX)
  - safe operation
  - arbitrary shift in along track
Twin Satellite Formation: HELIX

- Two satellites with different right ascensions of the ascending node
- Equal inclination for both satellites
- Two completely spatially separated orbits avoid collision (e/I vect)
- Along-track displacement selectable at desired latitude
- Shift of ascending nodes or expansion of eccentricity required for cross track interferometry at high latitudes
- First implementation of operational close formation flight expected in spring 2009 with TanDEM-X for global DEM-derivation

- TerraSAR-X Add-on for Digital Elevation Measurements
- PPP Astrium/DLR
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Possible Formations

Variation of Eccentricity

Inclination

Right asc. of the asc. node

Argument of perigee

Eccentricity

Pendulum

Drift

Trinodal Pendulum

Cartwheel

Drift

CarPe

Drift

Techsat Circle

Drift

HELIX
Example: TechSat Circle

Co-ordinate System is co-rotating in barycentre of formation

- Radial
- Along-track
- Cross-track
- Flight direction
## Baselines & Critical Issues

<table>
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<tr>
<th></th>
<th>CT-Pendulum</th>
<th>TN-Pendulum</th>
<th>CarPe</th>
<th>CartWheel</th>
<th>TechSAT-C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross</strong></td>
<td>One stable baseline for all orbital positions</td>
<td>Two scalable baselines with constant baseline ratio</td>
<td>One stable baseline for all orbital positions</td>
<td>One stable baseline for all orbital positions</td>
<td>One stable baseline for all orbital positions</td>
</tr>
<tr>
<td><strong>Along</strong></td>
<td>Two different baselines independently selectable</td>
<td>Two different baselines independently selectable</td>
<td>One baseline selectable</td>
<td>Constant baseline change</td>
<td>Constant baseline change</td>
</tr>
<tr>
<td><strong>Critical</strong></td>
<td>Fuel required to compensate nodal drift</td>
<td>Along track separation of satellites may be critical w/o autonomous control or e/i-vector separation</td>
<td>Reduced common Doppler bandwidth for large baselines at high latitudes</td>
<td>Reduced common Dop. bandwidth for large baselines at all latitudes and along track displacement requires frequent manoeuvring</td>
<td>Reduced common Dop. Bandwidth for large baselines</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Displacements &amp; nodal drift require frequent manoeuvring</td>
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Bistatic Scattering Coefficient

Bistatic scattering depends on:

- Incident angle $\theta_{Tx}$
- Scattering angle $\theta_{Rx}$
- Out-of-plane angle $\phi$
- Frequency
- Polarization

Extended Observation Space:

- improved detection
- improved segmentation
- improved classification
Polarimetric Interferometry

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

$h_v, \sigma, \phi_0, m_{1-3}$

(from K. Papathanassiou & S. Cloude, 2001)
Polarimetric SAR Interferometry: Performance Example for TerraSAR-L

Monostatic Repeat Pass System
\( (\gamma_{\text{temp}} = 0.7) \)
- Height Error and Height Bias
- Poor Inversion Accuracy

Bistatic Single Pass System
\( (\gamma_{\text{temp}} = 1.0) \)
- Height Error and Height Bias
- Good Inversion Accuracy

\( \mu_{\text{min}} \) and \( \mu_{\text{max}} \) polarisations

\textbf{sufficient separation of phase pdfs}
Tomography with Micro-Satellite Array

Basic Idea: Cluster of receiver satellites forming a sparse aperture in cross-track

- enables real three-dimensional imaging
- allows accurate measurement of vertical scatterer distribution
- reliable extraction of biophysical parameters (e.g. forest height, ground topography, ...)
- does not rely on a priori model assumptions
- not affected by layover or foreshortening
- cross-track distance between the individual satellites defines the height of ambiguity
- total tomographic baseline defines the height resolution

(from A. Reigber & A. Moreira, 2000)
Ambiguity Reduction and Wide Swath Imaging with Multiple Receivers

- single transmitter illuminates **wide image swath**
- multiple receivers record scattered signal simultaneously
- N receivers allow reduction of PRF by a factor of 1/N without raising azimuth ambiguities:
  - increase of swath width by factor N at **full azimuth resolution** (as opposed to ScanSAR)
  - great variability in optimum receiver displacement:
    \[ x_i - x_j \approx \frac{2 \cdot v \cdot (i-l)}{PRF \cdot N} + k_i \] for \( i \in \{1,2,...,N-1\}, k_i \in \mathbb{Z} \)
  - reconstruction also possible for other displacements
  - performance can be optimized by PRF adaptation
  - requires stable oscillators or RF synchronization and accurate measurement of relative displacement
- major application: **high resolution** imaging of a **wide image swath** with **small antennas** (e.g. distributed L-Band SAR with multiple microsatellites)
Super-Resolution with Passive Receivers

Increased geometric resolution of SAR images by:

- along-track displacement of parasitic satellites:
  ⇒ different Doppler centroids
  ⇒ super-resolution in azimuth by coherent combination of shifted Doppler spectra

- across-track displacement of receiving satellites:
  ⇒ different incidence angles
  ⇒ super-resolution in range by coherent combination of images with different ground range spectra
**Geostationary Illuminator / LEO Receivers**

**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

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

**Receivers:**
- low-cost micro-satellites
- small antennas
- passive (receive only)
- low earth orbit
Example: Orbit optimized for short revisit times of dedicated area (h=404 km, 31 orbits/2 days)

⇒ up to 5 observations per repeat cycle

Average Revisit Time

- ~ 1 h
- ~ 17 min
Digital Beamforming in Passive Receivers

Digital beamforming on receive makes effective use of the total signal energy in the large illuminated footprint:

⇒ **mapping of a wide swath**
  or multiple spots
  (in spite of extended antennas in elevation)

⇒ **very long synthetic apertures**
  (also with long receiver apertures)
  – high azimuth resolution
  – more independent looks
  – improved sensitivity

⇒ **interference suppression**

⇒ **ambiguity reduction**

⇒ **multiple phase center MTI**
  (e.g. STAP)

**Transmitter Footprint**
125 km x 250 km
(X-Band, $d_{\text{ant}}=10\text{m}$, $\Theta=48^\circ$)

**Receiver Footprint**
Ø ≤ 10 km
(X-Band, $d_{\text{ant}}=2\text{m}$, $h=400\text{ km}$)
Challenges in Bi- and Multistatic SAR

Oscillator Phase Noise

Pulse Synchronization

Antenna Pointing & Calibration

Orbit Control & Relative Position Sensing

Bistatic Processing
Conclusions

Future SAR systems must provide
  • broad coverage and short revisit times
  • multiple view angles, polarisations, baselines, and frequencies

New and affordable concepts are
  • 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
Vision

Continuous Global Monitoring for Environment and Security by a Reconfigurable SAR Satellite Constellation
Questions