A Fractionated Space Radar for Bistatic, Multistatic, and High-Resolution Wide-Swath SAR Imaging


Microwaves and Radar Institute
German Aerospace Center (DLR)

Knowledge for Tomorrow

IGARSS
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Potentials of Bistatic and Multistatic SAR Systems

Bistatic Imaging

Cross-Track Interferometry

Along-Track Interferometry

Moving Target Indication

Frequent Monitoring

Wide Swath Imaging

Resolution Enhancement

SAR Tomography

4-D Tomography & Holography
MIMO-SAR Tomography
Double Differential InSAR
Increased Radiom. Sensitivity
Adv. Atmospheric Corrections
Interference Suppression
Challenges of Companion Satellite Missions

Safe Formation Flying

Phase Synchronisation

Baseline Estimation

Mode Compatibility & Performance

Master/Slave Acquisition Conflicts

Data Downlink Conflicts

Mutual Illumination Risk

Joint Operation & Commanding

Master/Slave Calibration

Development & Operation Schedule

Launch in Master Orbit

Ionospheric Jumps (Scan/TOPS)

Programmatic Aspects

Master Availability / Redundancy

...
MirrorSAR Concept
MirrorSAR: A New Concept for Multistatic SAR Systems

Pave the way for powerful and affordable multistatic SAR missions by

- Reducing weight, size and cost for each receiver satellite
  - no wide-band communication system for downlink of payload data
  - no full radar receiver, no on-board memory
  - no dedicated synchronization link
  - minimize overall power demands & simplify thermal design

- Mass and volume reduction enables launch of more receiver satellites
  - new applications: multibaseline interferometry, single-pass tomography, ...
  - opportunity for graceful degradation can further simplify Rx satellite design

- Use dedicated Tx-only satellite (if compared to companion mission)
  - highly efficient illumination (no TRMs, no circulators, TWTs, FMCW, ...)
  - continuous multistatic operation, free of operational conflicts
  - optimized Tx/Rx design and performance with dedicated acquisition mode
  - combination of multiple Rx signals provides new opportunity for data reduction
The MirrorSAR System Concept

On-ground post-processing:
- ambiguity reduction (e.g. CEBRAS)
- direct signal suppression (e.g. Doppler filter)
- nadir suppression (FMCW waveform diversity)

Tx/Rx separation enables:
- new modes and applications
- very wide swath (e.g. 500 km)
- high resolution (e.g. 1-2 m)

Dedicated Tx-only S/C:
- high efficiency (e.g. TWT, FMCW)
- less losses (e.g. no circulators)
- option for multi-satellite data compression

Cheap Rx-only S/C:
- transponder-like
- no memory
- no data downlink
- low power
- light weight

exclusion zones avoided by Tx/Rx along-track separation

Rx signal forwarding by phase-preserving modulation to avoid sync-link

scalability (e.g. MIMO)
MirrorSAR Data Acquisition

- **I/Q up-conversion (e.g. AM)**
- **low-cost radar mirror (space transponder)**
- **I/Q down-conversion**
- **analog space link**
- **up-conversion (e.g. AM)**
- **LNA**
- **Tx-only satellite**
- **Rx-only satellite**
up-conversion (e.g. AM)

Rx-only satellite

LNA

low-cost radar mirror (space transponder)

Commonalities with Trends in Mobile Communication

- Centralized RF signal generation and processing (headend)
- Multiple remote antenna units with minimum hardware effort
- RF signal distribution by Radio-over-Fibre (RoF)
Optical Space Link for MirrorSAR

- Wide bandwidth, no ITU restrictions
- Direct intensity modulation also for very high RF frequencies (up to Ka band)
- High SNR already for low laser power and very small telescope
- Less complex than space-to-ground link (relaxed pointing, no atmosphere)
- Will become very light, compact and low power (cf. CubeSat developments)

OsirisV3
(DLR/Tesat)
Mass: ~ 5 kg
DC power: < 50 W
Size: 30x30x15 cm³
Rate: 10-100 Gbit/s (to ground!)

OCSD
(NASA)
CubeSat (1.5 U)
Demo
(2017)

Future
Data Rate: 2.5 Gbit/s (to ground!)
MirrorSAR Synchronization / Baseline Estimation

- Radar echo forwarding causes time delay that depends on relative satellite position
- Relative satellite position varies smoothly
  - no high-frequency phase errors (in contrast to companion sat with separate Rx oscillator)
  - low-frequency phase errors can be corrected by knowledge of relative satellite position
- Relative satellite position can be estimated with high accuracy by double differential GPS measurements (TanDEM-X: \( \sim 1 \) mm)
- Dual-frequency GPS is anyway needed for accurate baseline determination
- Remaining phase errors are comparable to the effect of residual baseline errors in InSAR

\[ \Delta \varphi \sim \Delta t \sim \Delta r \]
MirrorSAR Example: Cost-Efficient Acquisition of DEMs with Unprecedented Accuracy
## Digital Elevation Models

<table>
<thead>
<tr>
<th>Spatial Resolution</th>
<th>Absolute Vertical Accuracy (90%, max. global offset)</th>
<th>Relative Vertical Accuracy (point-to-point in 1° cell, 90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTED-1</td>
<td>90 m x 90 m</td>
<td>&lt; 30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 20 m</td>
</tr>
<tr>
<td>DTED-2</td>
<td>30 m x 30 m</td>
<td>&lt; 18 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 12 m</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>12 m x 12 m</td>
<td>&lt; 10 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 2 m</td>
</tr>
<tr>
<td>Level 4</td>
<td>6 m x 6 m</td>
<td>&lt; 5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 0.8 m</td>
</tr>
</tbody>
</table>

Definition of 90% point-to-point errors:

\[
s_h < 0.35 \text{ m}!
\]

\[
\sigma_h = 2.33 \cdot \sigma_h
\]

\[
\Delta h_{P2P}^{90\%} \approx 2.33 \cdot \sigma_h
\]
Large Baseline DEM with TanDEM-X

- First TanDEM-X DEM (acquired before reaching 20 km formation)
- Large effective baseline (~ 2 km) from Earth rotation
- $h_{amb} \approx 3.8$ m!
TanDEM-X DEMs with Different Baseline Lengths

Phase Unwrapping Errors

$B_{eff} = 107.8 \text{ m, } h_{amb} = 49.2 \text{ m}$

$B_{eff} = 267.9 \text{ m, } h_{amb} = 19.7 \text{ m}$
TanDEM-X Interferograms with Different Baseline Lengths

$B_{\text{eff}} = 107.8 \text{ m}, \ h_{\text{amb}} = 49.2 \text{ m}$

$B_{\text{eff}} = 267.9 \text{ m}, \ h_{\text{amb}} = 19.7 \text{ m}$
Mission Concept

- Simultaneous interferometric data acquisition with two interferometric baselines
  - Small baseline (e.g. $h_{amb} = 75$ m):
    - avoid height ambiguities
    - high coherence for volume scatterers
  - Large baseline (e.g. $h_{amb} = 15$ m):
    - excellent relative height accuracy
      (e.g. $\Delta h = 0.4$ m for $\Delta \varphi = 10^\circ$)
    - excellent absolute height accuracy
      (e.g. $\Delta h = 0.5$ m for $\Delta B = 1$ mm in X band)
- No decorrelation and height changes between acquisition of two baselines (TanDEM-X)
- Phase unwrapping supported by radargrammetric evaluation of large baseline interferogram
X-Band Performance Example

- Design goal: minimize weight, costs, stowed volume and hardware effort
- 20 km swath can provide two global coverages (asc. & desc.) in 4.4 months

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>1.5 m x 1.5 m</td>
</tr>
<tr>
<td>Incident Angle</td>
<td>40°</td>
</tr>
<tr>
<td>Swath Width (no DBF)</td>
<td>20 km</td>
</tr>
<tr>
<td>Orbit Height</td>
<td>~ 500 km</td>
</tr>
<tr>
<td>Tx Antenna (Reflector)</td>
<td>3 m ∅</td>
</tr>
<tr>
<td>Rx Antenna (Reflector)</td>
<td>3 m ∅</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>9.65 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Avg. Tx Power w/o Rx DBF</td>
<td>500 W</td>
</tr>
<tr>
<td>(with Rx DBF)</td>
<td>(167 W)</td>
</tr>
<tr>
<td>Noise Figure / Losses</td>
<td>5 dB</td>
</tr>
</tbody>
</table>

![Graph showing NESZ and ASR performance](image)

**NESZ < -20 dB**

**ASR < -21 dB**

(ASR = RASR + AASR)
X-Band Performance Example

- Constant incident angle: 40°
  - good compromise between sensitivity, layover & shadow
- Two interferometric baselines:
  - $B_\perp = 870$ m ($h_{amb} = 15$ m, 5% of $B_{\perp,\text{crit}}$)
  - $B_\perp = 174$ m ($h_{amb} = 75$ m, 1% of $B_{\perp,\text{crit}}$)
- 20 km swath can provide total global coverage in less than 5 months
  - two coverages (asc. & desc.) possible
  - full coverage for $\Phi_{\text{lat}} > 60^\circ$ could be achieved already after 2 months
- Frequency selection
  - TanDEM-X: good results with X band
  - Ku/Ka band could be an alternative to reduce penetration for volume scatterers (cf. SIGNAL proposal)
  - MirrorSAR with reflector antennas is well suited for multi-frequency DEMs
## MirrorSAR: Cost and Reliability Considerations

<table>
<thead>
<tr>
<th></th>
<th>3 Tx/Rx</th>
<th>1 Tx/Rx + 3 Rx</th>
<th>1 Tx + 3 Rx</th>
<th>2 Tx + 4 Rx</th>
<th>2 Tx + 5 Rx</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Costs</strong></td>
<td>14 $</td>
<td>13 $</td>
<td>8 $</td>
<td>12 $</td>
<td>13 $</td>
</tr>
<tr>
<td><strong>Reliability (2 B)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0.95</td>
<td>0.86</td>
<td>0.81</td>
<td>0.81</td>
<td>0.98</td>
<td>0.996</td>
</tr>
<tr>
<td>p=0.90</td>
<td>0.73</td>
<td>0.66</td>
<td>0.66</td>
<td>0.94</td>
<td>0.982</td>
</tr>
<tr>
<td>p=0.85</td>
<td>0.61</td>
<td>0.52</td>
<td>0.52</td>
<td>0.87</td>
<td>0.951</td>
</tr>
<tr>
<td>p=0.80</td>
<td>0.51</td>
<td>0.41</td>
<td>0.41</td>
<td>0.79</td>
<td>0.904</td>
</tr>
</tbody>
</table>

**Note:** Costs are represented by dollar symbols ($), with $$$$$ for the highest cost and $ for the lowest cost. Reliability values are given in parentheses. The symbol $B$ represents the reliability measure.
Opportunities with Additional Receivers and Transmitters

- Additional receivers can be used to
  - improve DEM (triple-baseline interferometry with $h_{amb} = 4$ m enables $\Delta h = 0.2$ m @ 6 m)
  - resolve layover (enables DEM generation with steep incident angles in canyons, cities, ...)
  - demonstrate 3-D imaging (single-pass tomography for cities and semi-transparent scatterers)

- Additional transmitters can be used to
  - demonstrate new MIMO-SAR modes
  - increase number of virtual phase centers
    \[ n = n_{Tx} \cdot n_{Rx} \]
  - separate single-, double- and multiple-bounce scattering by MIMO-SAR tomography

- MIMO-SAR demonstrations require waveform separation that can be achieved by
  - choosing steeper incident angle (satellite roll)
  - adding a switchable feed network in transmitter and/or receiver to narrow beamwidth
MirrorSAR for High-Resolution Ultra-Wide Swath SAR Imaging
Simultaneous imaging of multiple swaths in stripmap mode

No blind ranges due to separate Tx and Rx satellites

Advanced range ambiguity suppression with CEBRAS enables compact Rx antenna (if compared to staggered SAR)

Advanced suppression of direct signal and nadir echo by Doppler filter and waveform diversity

Unique potential for imaging of ultra-wide swaths with very high resolution (even up to 500 km @ 1 m with 6 m² Rx antenna in X band (2 m² in Ka band) using FMCW illumination by Klystron)
Multichannel Mirror-SAR Transponder

- wide-swath imaging requires digital beamforming with multiple Rx beams
- phase integrity can, e.g., be preserved by
  - coherent demodulation
  - baseband DBF
  - coherent remodulation
- radar echoes from multiple Rx beams are simultaneously transferred to master satellite
  - use of different carriers
  - multichannel encoding

Digital Beamforming

up-conversion (e.g. multi-carrier AM)

coherent beamforming
Conclusions

- MirrorSAR is a new approach for the cost-efficient implementation of future multistatic SAR systems and missions
  - low-cost Rx satellites (no RFE, no DCE, no sync, no memory, no downlink, …)
  - highly efficient Tx satellites (no TRMs, no circulators, TWT, FMCW, …)
  - new opportunities for multistatic on-board data reduction before downlink
  - distributed redundancy concepts support further simplification of hardware

- MirrorSAR paves the way for new Earth observation products
  - decimeter-level DEMs and DEM time-series by multibaseline interferometry
  - 3-D structure maps by single-pass SIMO and MIMO tomography
  - 4-D structure change maps by differential tomography and holography
  - quasi-continuous Earth monitoring by new high-resolution wide-swath modes
  - multiangular images for better segmentation, classification and identification
  - resolution enhancement, measurement of object movements, …