The limits of spaceborne SAR geolocation: Can we attain the 1 cm level?

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5 Geoscience Australia
Overview on SAR geolocation

1. **Orbit determination**
   - Very high requirements [1-2 cm]
   - Realizes reference frame (ITRF)

2. **Image formation**
   - Accurate SAR processor
   - 0-Doppler geometry
   - SAR payload → GNSS time → UTC

3. **Point target analysis**
   - \( t_A, t_R \) at sub-pixel level
   - Proportional to SNR

4. **Observation perturbations**
   - Atmosphere
   - Geodynamic effects

5. **Applications**
   - Calibration
   - Geolocation

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Talk by U. Balss in S32, Consideration of Inter-Pulse and Intra-Pulse Motion in Zero Doppler SAR Processing
Reference Frames and the SAR Observations

When using satellites, two frames are involved:

- International Celestial Reference Frame (ICRF) → set of Quasar coordinates
- International Terrestrial Reference Frame (ITRF) → set of Cartesian station coordinates

Linked by transformation and time dependent Earth Orientation Parameters (EOPs)

Satellite orbits in ICRF

Orbit in ITRF

Observations (Range, Azimuth, ...)

Comparison, atmosphere

Instantaneous ITRF coordinates at epochs

Epoch 1  Epoch 2  ...  Epoch n
X₁, X₂, ...  X₁, X₂, ...  ...  X₁, X₂,

Regularized ITRF coordinates at epochs

X₁, X₂, ...  X₁, X₂, ...  ...  X₁, X₂,

Linked by linear movements \( \dot{X}_1, \dot{X}_2, \ldots \)

Range-Doppler Equations

\[ |X_S - X| - t_R \cdot c / 2 = 0 \]

\[ \frac{\dot{X}_S \cdot (X - X_S)}{|\dot{X}_S| \cdot |X - X_S|} = 0 \]
Geodetic SAR Ground Infrastructure

Permanent CRs (1.5 m & 0.7 m) at geodetic observatories with local ties and reference coordinates (ITRF) → accuracy better than 5 mm

- Metsähovi (Oct. 2013):
  - 1 CR - D

  - 1 CR - A, 1 CR - D

  - 1 CR - A, 1 CR - D

- GARS O’Higgins (March 2012):
  - 1 CR - A, 1 CR - D

- Surat Basin (Nov. 2014):
  - 40 CR – A by Geoscience Australia
  - Coordinates from DGPS survey (< 4 cm)

Geodynamic Corrections for Solid Earth Deformations

The models are linked to the ITRF and are documented in the IERS conventions\(^1\)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Horizontal [mm]</th>
<th>Vertical [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Earth tides</td>
<td>± 50.0</td>
<td>± 200.0</td>
</tr>
<tr>
<td>Ocean tidal loading</td>
<td>± 10.0</td>
<td>± 50.0</td>
</tr>
<tr>
<td>Pole tides</td>
<td>± 1.5</td>
<td>± 6.0</td>
</tr>
<tr>
<td>Atmospheric tidal loading</td>
<td>± 0.2</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Ocean pole tide loading</td>
<td>± 0.3</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Atmospheric non-tidal loading</td>
<td>± 3.0</td>
<td>± 15.0</td>
</tr>
<tr>
<td>Secular trends</td>
<td>up to 100 mm/y</td>
<td>up to 15 mm/y</td>
</tr>
</tbody>
</table>

1 Petit and Luzum (eds.) *IERS Conventions (2010)*, IERS Technical Note No. 36, 2010. Online: [www.iers.org](http://www.iers.org)
Atmospheric corrections

Two concepts of computation: **zenith delay** vs. **slant integration**

- Direct slant range integration (ray-tracing) using 4-D atmospheric state model
- Vertical modelling/integration + mapping function (e.g. VMF1, SLM-MF)

**Atmosphere**

**Troposphere** (neutral, 0-100km)

- ECMWF Integration
- VMF1 grid with vertical delays
- GPS ZPD with VMF1

**Ionosphere** (dispersive, 100-1200km)

- GNSS GIMs with SLM-MF
- Single GNSS with SLM-MF

**VMF1 Zenith-Delay, 2017-06-01, 18:00 UTC**

**Global Ion. Map, 2017-06-01, 18:00 UTC**

[Maps showing VMF1 Zenith-Delay and Global Ion. Map with isarithmic lines and color bars indicating values in meters or TECU.]
Atmospheric corrections

Two concepts of computation: **zenith delay** vs. **slant integration**

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### Atmosphere

- **Troposphere** (neutral, 0-100km)
  - ECMWF Integration
  - VMF1 grid with vertical delays
  - GPS ZPD with VMF1

- **Ionosphere** (dispersive, 100-1200km)
  - GNSS GIMs with SLM-MF
  - Single GNSS with SLM-MF

#### Impact of 20 TECU on a 55° beam

<table>
<thead>
<tr>
<th>Band</th>
<th>X-band</th>
<th>C-band</th>
<th>L-band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.149 m</td>
<td>0.482 m</td>
<td>9.758 m</td>
</tr>
</tbody>
</table>

#### Impact of 2.4 m ZPD on a 55° beam

<table>
<thead>
<tr>
<th>Band</th>
<th>X-band</th>
<th>C-band</th>
<th>L-band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.174 m</td>
<td>4.174 m</td>
<td>4.174 m</td>
</tr>
</tbody>
</table>
Geometric calibration of TerraSAR-X and TanDEM-X

Difference of SAR observation and geometric prediction

- Observations corrected for the atmospheric delays
- Prediction from orbit and CR reference at epoch of the pass

Metsähovi, 11/13 – 12/16: 182 DTs

1 CR - D (27° 37° 46°)

\[ s_R = \pm 0.011 \text{ m} \]

\[ s_A = \pm 0.017 \text{ m} \]

Sentinel-1A Analysis at the Surat Basin, Australia

TOPS IW data (56 passes) 10/14 – 08/17
- Orbit 111: IW1 and IW2 cover whole array
- Orbit 9: IW3 covers West part of the array
- Reprocessed with IPF v2.84 and AUX_POEORB
- Azimuth bistatic residual correction\(^1\) applied

Sentinel-1A Analysis at the Surat Basin, Australia

Range offsets versus the CR positions in the TOPS burst:
- Linear behavior
- Individual CRs are much better than the overall result
Range offsets versus the CR positions in the TOPS burst:

- Linear behavior
- Individual CRs are much better than the overall result

**Mean and Standard Deviation:**

- Range STD is between ± 4 cm and ± 8 cm
- Agrees with SCR limit and the accuracy of the coordinates

**Reason for the trend:** Intra-pulse\(^1\) motion?

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TerraSAR-X Analysis of the Surat Basin, Australia:

- Calibrated TSX and TDX confirm the high quality of the Surat CR array
- The limits are indeed the 4 cm accuracy of the CRs and the SCR of the SAR

ScanSAR (8 scenes, 04/17 – 10/17)

Stripmap (21 scenes, 09/14 – 09/15)
The limit of spaceborne SAR geolocation

TerraSAR-X and TanDEM-X analysis at Wettzell and Metsähovi

- In total 337 high-resolution spotlight products between 01/12 – 12/15
- Precise science orbit distributed with products
The limit of spaceborne SAR geolocation

TerraSAR-X and TanDEM-X analysis at Wettzell and Metsähovi

- In total 337 high-resolution spotlight products between 01/12 – 12/15
- Precise science orbit distributed with products
- New precise orbit* (improved dynamic modeling; GPS ambiguities fixed)

1.5 m WTZ_A (63)

\[ \Delta R \text{ [mm]} = -10.2 \pm 7.6 \]
\[ \Delta A \text{ [mm]} = -6.1 \pm 13.4 \]

1.5 m WTZ_D (141)

\[ \Delta R \text{ [mm]} = -9.1 \pm 9.9 \]
\[ \Delta A \text{ [mm]} = 12.8 \pm 22.8 \]

1.5 m MET_D (133)

\[ \Delta R \text{ [mm]} = 0.0 \pm 9.1 \]
\[ \Delta A \text{ [mm]} = -0.4 \pm 15.0 \]

* by Stefan Hackel, GSOC, DLR
The limit of spaceborne SAR geolocation

TerraSAR-X and TanDEM-X analysis at Wettzell and Metsähovi

- In total 337 high-resolution spotlight products between 01/12 – 12/15
- Precise science orbit distributed with products
- New precise orbit (improved dynamic modeling; GPS ambiguities fixed)
- New precise orbit * (outliers removed by 2σ test)

1.5 m WTZ_A (57)

```
<table>
<thead>
<tr>
<th>TSX1 - 34°</th>
<th>TSX1 - 46°</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
```

```
| R [mm]     | -10.0 ± 6.6 |
| A [mm]     | -7.6 ± 11.3 |
```

1.5 m WTZ_D (124)

```
<table>
<thead>
<tr>
<th>TSX1 - 33°</th>
<th>TSX1 - 45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
```

```
| R [mm]     | -9.3 ± 8.2 |
| A [mm]     | 12.5 ± 17.4 |
```

1.5 m MET_D (120)

```
<table>
<thead>
<tr>
<th>TSX1 - 27°</th>
<th>TSX1 - 46°</th>
</tr>
</thead>
<tbody>
<tr>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
```

```
| R [mm]     | -0.4 ± 8.2 |
| A [mm]     | -0.7 ± 11.2 |
```

* by Stefan Hackel, GSOC, DLR
Conclusions:

Best quality SAR geolocation/calibration requires meticulous care in
• Precise orbit determination (ICRF/ITRF standards)
• Image formation in SAR processor (consistent 0-Doppler geometry)
• Proper consideration of the atmosphere
• Accounting for the periodic geodynamic signals

Given that, the absolute 1 cm geolocation becomes possible if
• The point target has sufficient SCR (~ 45 dB)
• The atmospheric corrections are good enough

Every SAR satellite can do this, geolocation (range, azimuth) does not depend on wavelength → all missions can measure the same target → straight forward joint analysis

Funded by ESA-ESRIN through the FRM4SAR project


Backup: TerraSAR-X SCR Estimate

- The GSA array has trihedral CRs with 1.5m, 2.0m (4,8,9), and 2.5m (3,5,14).
- Observed SCR values and nominal product resolution allow an estimate for the radiometric-based precision of the geolocation.

<table>
<thead>
<tr>
<th>CR size [m]</th>
<th>SCR [dB]</th>
<th>$s_R$ [±cm]</th>
<th>$s_A$ [±cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TSX Stripmap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>42</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>2.0</td>
<td>48</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>TSX ScanSAR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>37</td>
<td>1.0</td>
<td>9.8</td>
</tr>
<tr>
<td>2.0</td>
<td>41</td>
<td>0.6</td>
<td>6.3</td>
</tr>
<tr>
<td>2.5</td>
<td>45</td>
<td>0.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

$s_{R,A} \approx \frac{0.39}{\sqrt{SCR}} \cdot \rho_{R,A}$

→ Only the ScanSAR azimuth should be limited by the radiometry.
Backup: Sentinel-1 SCR Estimate

- The GSA array has trihedral CRs with 1.5m, 2.0m (4,8,9), and 2.5m (3,5,14)
- Sentinel-1 IW TOPS

<table>
<thead>
<tr>
<th>CR</th>
<th>SCR [dB]</th>
<th>theoretical ALE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>10</td>
<td>31.0</td>
</tr>
<tr>
<td>2.0 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>9</td>
<td>34.1</td>
</tr>
<tr>
<td>2.5 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>14</td>
<td>38.6</td>
</tr>
</tbody>
</table>

\[ s_{R,A} \approx \frac{0.39}{\sqrt{SCR}} \cdot \rho_{R,A} \]