High Resolution Geodetic Earth Observation with TerraSAR-X: Measurements on the Obtained Pixel Localization Accuracy and Results

Ulrich Balss¹, Christoph Gisinger², Stefan Hackel³, Xiao Ying Cong⁴, Ramon Brcic¹, Michael Eineder¹,⁴

¹Remote Sensing Technology Institute (IMF), German Aerospace Center (DLR), Oberpfaffenhofen, Germany

²Institute for Astronomical and Physical Geodesy (IAPG), Technische Universität München (TUM), Munich, Germany

³German Space Operation Center (GSOC), German Aerospace Center (DLR), Oberpfaffenhofen, Germany

⁴Remote Sensing Technology (LMF), Technische Universität München (TUM), Munich, Germany
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  - Test sites
  - Acquisition geometry of SAR
  - Influence of signal path delays and geodynamic effects

- Measurement Results
  - Measured localization accuracy
  - Analysis of residual error sources

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Introduction

- **unprecedented pixel localization accuracy** of German SAR satellites TerraSAR-X (TSX-1) and TanDEM-X (TDX-1) at **centimeter level**

- **Preconditions for this accuracy:**
  - **Already fulfilled by data provider (i.e. the TerraSAR mission):**
    - precise orbit determination
    - avoidance of several SAR processor approximations
      - in particular: stop-go approximation
  - **To be done by data user (when aiming at centimeter level):**
    - thorough correction for
      - all **signal path delays**
      - **geodynamic effects**
Test Sites (near IGS reference stations)

- **Wettzell, Germany:**
  - 1 CR installed
    - ascending geometry (34°, 46°)
    - datatake acquisition started at 2011-07-12
    - 40+10 datatakes (as at 2013-09-22)
  - 1 CR in progress
    - descending geometry (32°, 44°)

- **GARS O'Higgins, Antarctic Peninsula:**
  - 2 CRs installed
    - 1 for ascending geometry (30°, 38°, 45°)
    - 1 for descending geometry (35°, 42°)
    - datatake acquisition started at 2013-03-27
    - 44 datatakes (as at 2013-09-22)

- **Metsähovi, Finland (in progress):**
  - cooperation with the Finnish Geodetic Institute (FGI)
  - 1 CR

source: www.fgi.fi
Radar Time Coordinates of a Target

Under zero Doppler conditions:
slow time: $t$

fast time: $\tau = 2 \cdot \frac{R}{c_0}$
Radar Time Coordinates of a Target

**Under zero Doppler conditions:**

- **slow time:** $t$  
  
- **fast time:** $\tau = 2 \cdot \frac{R}{c_0} + \Delta T_{TD} + \Delta T_{ID}$

**Ionospheric delay** $\Delta T_{ID}$  
(introduced by electrons)

**Tropospheric delay** $\Delta T_{TD}$  
(introduced by dry air and water vapor)

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**Diagram:**
- Flight path
- Signal path
- Corner reflector (CR)

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Radar Time Coordinates of a Target

Under zero Doppler conditions:
slow time: \( t \rightarrow t + \Delta t_{SET} + \Delta t_{CD} + \Delta t_{APL} + \Delta t_{OTL} + \Delta t_{PT} + \Delta t_{OPT} + \Delta t_{ATL} \)
fast time: \( \tau = 2 \cdot \frac{R}{c_0} + \Delta t_{TD} + \Delta t_{ID} + \Delta t_{SET} + \Delta t_{CD} + \Delta t_{APL} + \Delta t_{OTL} + \Delta t_{PT} + \Delta t_{OPT} + \Delta t_{ATL} \)

- Ionospheric delay \( \Delta t_{ID} \) (introduced by electrons)
- Tropospheric delay \( \Delta t_{TD} \) (introduced by dry air and water vapor)
- Continental drift \( \Delta t_{CD}, \Delta t_{CD} \) (moves true position of CR)
- Solid earth tides \( \Delta t_{SET}, \Delta t_{SET} \)
- Atmospheric pressure loading \( \Delta t_{APL}, \Delta t_{APL} \)
- Ocean tidal loading \( \Delta t_{OTL}, \Delta t_{OTL} \)
- Pole tides \( \Delta t_{PT}, \Delta t_{PT} \)
- Ocean pole tides \( \Delta t_{OPT}, \Delta t_{OPT} \)
- Atmospheric tidal loading \( \Delta t_{ATL}, \Delta t_{ATL} \) (move true position of CR)
Correction of Signal Path Delays and Geodynamic Effects

- **Tropospheric Delay:**
  - Zenith Path Delay (ZPD)
    - *IGS* measurements where available, otherwise
    - *Weather Model* (e.g. by ECMWF)
  - Transform from zenith path to slant range

- **Ionospheric Delay:**
  - vertical Total Electron Content (vTEC)
    - *Local measurements* where available, otherwise
    - *Global TEC map* (e.g. by CODE)
  - Transform to slant range and conversion to delay value

- **Geodynamic Effects:**
  - International Earth Rotation and Reference System Service (IERS):
    - *IERS conventions*, 2010 edition
      (http://tai.bipm.org/iers/conv2010)
  - Exception: atmospheric pressure loading
    - *NASA atmospheric pressure loading service* (http://lacerta.gsfc.nasa.gov/aplo_eph)
Localization Accuracy of TerraSAR-X (TSX-1)

Wettzell Test Site

TSX-1, 34° Ascending:

after correction of signal path delays and geodynamic effects
(current TMSP version 4.9)

azimuth offset $= +14.0 \pm 35.5$ mm
range offset $= -315.4 \pm 17.6$ mm
Localization Accuracy of TerraSAR-X (TSX-1)

Wettzell Test Site

Range offset of about 31 cm:

Reason:
Instrument calibration constants of TerraSAR-X were determined on base of a simplified model for the atmospheric delays. Thus, they also contain atmospheric information.

Mention:
The used approach suffices to over fulfill the specified requirement (1 m).

To be done:
High accuracy measurements require a recalibration of the instrument constants.

Range offset = +14.0 ± 35.5 mm
Range offset = -315.4 ± 17.6 mm
Localization Accuracy of TerraSAR-X (TSX-1)

Wettzell Test Site

TSX-1, 34° Ascending:

after correction of signal path delays and geodynamic effects
(current TMSP version 4.9)

azimuth offset = +14.0 ± 35.5 mm
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Localization Accuracy of TerraSAR-X (TSX-1)  
Wettzell Test Site

TSX-1, 34° Ascending:

after correction of signal path delays and geodynamic effects  
(current TMSP version 4.9)

azimuth offset = +14.0 ± 35.5 mm
range offset     = -309.8 ± 11.4 mm
Localization Accuracy of TerraSAR-X (TSX-1)

Wettzell Test Site

TSX-1, 34° Ascending:

After correction of signal path delays and geodynamic effects
(TMSP version 4.9)

- Localization accuracy in range is much better than in azimuth.
- Reason: Azimuth accuracy is limited by clock rate of annotated raw data acquisition time (18.6 µs).
- Mention: TerraSAR-X had been originally designed for a localization accuracy better than 2 meters.

Azimuth offset = +14.0 ± 35.5 mm
Range offset = -309.8 ± 11.4 mm
Localization Accuracy of TerraSAR-X (TSX-1)

Wettzell Test Site

TSX-1, 34° Ascending:

after correction of signal path delays and geodynamic effects

(SW development for upcoming TMSP versions)

azimuth offset = $+17.3 \pm 12.7$ mm
range offset = $-309.8 \pm 11.4$ mm
Localization Accuracy of TerraSAR-X

GARS O’Higgins Test Site

TSX-1 and TDX-1, all geometries:

after correction of signal path delays and geodynamic effects

(SW development for upcoming TMSP versions)

azimuth offset = -77.0 ± 24.7 mm
range offset = +1.3 ± 13.7 mm

Offsets are recalibrated on base of the Wettzell measurement series.
Temporal Progression of Range Offset (Wettzell Test Site)
Temporal Progression of Range Offset (Wettzell Test Site)
Temporal Progression of Range Offset (Wettzell Test Site)
The distinct, approximately annual pattern in the range offset is confirmed by Satellite Laser Ranging (SLR). Thus, it cannot be a SAR effect.

Hypothesis: It might result from the residual orbit error (which is much lower than specified: requirement 20 cm, goal 10 cm)

Nevertheless, further improvements of the orbit accuracy are subject of ongoing investigations.
Conclusions and Outlook

- **TerraSAR-X** enables **localization accuracies** of about 1 cm.
- However, **high precision** pixel localizations require a **recalibration** of the geometric instrument constants.
- A **strong temporal correlation** in the residual range position offset (maybe an orbit effect) reveals that there is still the **potential for further improvements**.

**Topics of ongoing investigations:**
- **angular dependencies** of the localization results
- verification of the **world-wide reproducibility** of our results
- further improvements in **azimuth localization** and **orbit determination**

**Possible application areas:**
- **geometric calibration** of SAR sensors
- **annotation** of SAR products
- **new application areas** for SAR get possible (e.g. **Stereo SAR**)
Thank you for your attention!
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