Recent Advances in Pixel Localization Accuracy

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Outline

- Operational TerraSAR-X Absolute Pixel Localization Requirement and Achievement
- Submeter Accuracy Influences
  - Ionosphere and Troposphere
  - Earth Tides
  - Reference Frames and Continental Drift
- TerraSAR-X Absolute Accuracy
- Bistatic TanDEM-X Relative Accuracies
- High-Resolution Image Cross-Correlation Application Demonstrations
- Conclusion and Outlook
TerraSAR-X Pixel Localization Accuracy
Pre-Launch Requirement

Definition
Pixel localization accuracy defines how accurate a pixel in a TerraSAR-X basic product can be transformed to a ground position.

Requirement
2 m for complex products (SSC) assuming

- GPS orbit determination accuracy is major driver
- rapid orbit requirement: 2 m (3D, 1 sigma)
- science orbit requirement: 20 cm (3D, 1 sigma), aiming at 10 cm
- SAR timing in range and azimuth precise enough
- application of an approximate constant value for atmospheric delays (properly mapped to scene average height and incidence angle)
TerraSAR-X Pixel Localization Accuracy Measurements in 2007 (Commissioning Phase)

**Orbit Determination Accuracy**
- rapid orbit: 20 cm (TOR IGOR GPS with JPL real-time GPS RTG)
- science orbit: < 10 cm (TOR IGOR GPS with CODE from Univ. of Bern)

**Pixel Localization Accuracy**
- geometric calibration result: 0.5 m azimuth, 0.3 m range \((1 \sigma)\)
- requirement tightened to 1 m absolute for all imaging modes based on science orbits including all uncertainties on the signal path and along-track (azimuth) errors

**Pixel Localization Measurement Method**
- corner reflectors (different beams, angles) with precise GPS coordinates Oberpfaffenhofen test site with 6 corner reflectors
- compare point target peak locations against predicted point target location in SSC products

TerraSAR-X Basic Product Specification TX-GS-DD-3302
(Special Issue on TerraSAR-X: Mission, Calibration, and First Results)
Product Range Times Annotation Philosophy

- two-way radar pulse traveling time referring to zero Doppler location
- **corrected** for known instrument internal delays as annotated in the IOCS auxiliary product (calibration result)
- **not corrected** for atmospheric influences
- **additional** constant slant range delays annotated to correct for
  - average hydrostatic delay by troposphere (a few m)
  - ionospheric delay (a few cm)

see element signalPropagationEffects in GEOREF.xml:

```xml
<rangeDelay modelName="averageTECU_5" modelVersion="1.0" source="IONO">
  <validityRangeMin>3.6284400510285696E-03</validityRangeMin>
  <validityRangeMax>3.65775221316062740E-03</validityRangeMax>
  <referencePoint>3.64309613209459846E-03</referencePoint>
  <polynomialDegree>0</polynomialDegree>
  <coefficient exponent="0">1.54228486505132483E-10</coefficient>
</rangeDelay>

<rangeDelay modelName="hydrostatic" modelVersion="1.0" source="ATMOS">
  <validityRangeMin>3.6284400510285696E-03</validityRangeMin>
  <validityRangeMax>3.65775221316062740E-03</validityRangeMax>
  <referencePoint>3.64309613209459846E-03</referencePoint>
  <polynomialDegree>0</polynomialDegree>
  <coefficient exponent="0">1.64512872009106978E-08</coefficient>
</rangeDelay>
```
Product Azimuth Times Annotation Philosophy

- given in UTC and GPS referring to zero Doppler location
- **not corrected** for a systematic azimuth shift determined during geometric calibration, but not accountable to an instrument (either SAR or GPS) source
- geometric calibration measurements:
  average azimuth time offset $\Delta t_{shift} = -0.18$ msec ~ $-1.2$ m
  annotated as **additional constant delay in azimuth**

see element signalPropagationEffects in GEOREF.xml:

```xml
<azimuthShift modelName="external azimuth time shift" modelVersion="1.0" source="TIMING">
  <validityRangeMin>3.85752271532445890E-03</validityRangeMin>
  <validityRangeMax>3.89188252702577474E-03</validityRangeMax>
  <referencePoint>3.87470262117511682E-03</referencePoint>
  <polynomialDegree>0</polynomialDegree>
  <coefficient exponent="0">-1.80000000000000011E-04</coefficient>
</azimuthShift>
```

- source of azimuth time shift?
TerraSAR-X SAR System Update Spring 2010

- preparation of TSX recalibration campaign in spring 2010 and TDX commissioning

- SAR processor TMSP update: new version 4.5
  - refinement of stop/go approximation
    - previous: from PRI event to PRI event
    - now: also within focussed range line (more precise zero Doppler azimuth time)

- IOCS Auxiliary Product Update: new version 004.002
  Change of azimuth delay / azimuth shift
  from -180 microsec (~1.2 m) to -47.1 microsec (~0.3 m)
  to fit the TMSP approximations
Follow-On Systematic Assessment of Submeter Influences

Unprecedented high pixel localization accuracy of TerraSAR-X allows a systematic assessment of submeter accuracy influences


Discussed Range Influence Factors

- range sampling frequency accuracy / stability
- signal propagation: ionosphere and troposphere
- Earth tides
Atmospheric Influences – Ionosphere

- frequency-dependant phase advance and group delay
- group delay determination from VTEC (vertical total electron content)
- typical VTEC values: 5 – 10 TECU (total electron content unit)
- zenith (0º inc. angle) delay caused by moderate 5 TECUs

<table>
<thead>
<tr>
<th></th>
<th>L-Band 1.25 GHz</th>
<th>C-Band 5.6 GHz</th>
<th>X-Band 9.65 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionospheric delay</td>
<td>1.29 m</td>
<td>0.0642 m</td>
<td>0.0216 m</td>
</tr>
</tbody>
</table>

Beware: zenith delay of 0.0216 m - properly mapped to scene incidence angle - assumed and annotated in TerraSAR-X products

- sources for VTEC values
  - ground-based GNSS networks
  - space-based radio occultation measurements
Atmospheric Influences - Troposphere

- frequency-independant signal delays
  - larger hydrostatic (dry gases)
    ~ 2.3 m at sea level, modeled from known altitude and pressure
  - smaller „wet“ delay (precipitable water vapor)
    up to 0.4 m

- sources for actual delay values
  - ground-based GNSS measurements
    see e.g. Regional Reference Frame Sub-Commission for Europe (EUREF) permanent network
  - space-based water vapor measurements

- static model (2.0 m assumed for sea level) used and annotated – appropriately applied for current average scene height and mapped to incidence angle - in TerraSAR-X products
Zenith Path Delay from EUREF Permanent GPS Network

- around 202 permanent GPS stations in Europe
- ZDP measurements on station height
- temporal resolution: 30 min
- however: sparse location on a global basis

Wettzell, Bad Kötzting, Germany (WTZR)
Path Delay from Numerical Weather Model Data

- ERA-Interim reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF)
- Horizontal resolution: full T255 spectral truncation (grid size ~80 km)
- Available on 0h, 06h, 12h and 18h, since 1989 to current – 3 months
Validation of Centimeter-Level SAR Geolocation Accuracy after Correction for Atmospheric Delay using ECMWF Weather Data, Cong et al (TUM and DLR), Fringe 2011 Workshop (Sep), Frascati
Earth Tides

- **solid earth tides** caused by Earth deformations due to gravitational forces of Sun and Moon
  radial: up to 40 cm, horizontal: a few cm

- **pole tides** caused by changes in Earth’s rotational axis due to polar motion
  radial: up to 2.5 cm, horizontal: less than 1 cm

- **tidal ocean loading** caused by tidal changes of mass distributions of oceans
  radial: up to several cm near coast, < 1 cm for continental sites
Earth Tides and Reference Frames

**Characteristics:** Shifts up to ±20 centimeters

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TSX-1 / TDX-1 orbit in ITRF-2005/08 coordinates

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Honolulu, July 31th, 2010

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Graph showing deformation (up, north, east) over the course of the day (UTC) with peaks at certain times.
Further Follow-On Systematic Assessment of Submeter Influences

Unprecedented high pixel localization accuracy of TerraSAR-X and bistatic TanDEM-X configuration allows a further systematic assessment of submeter accuracy influences

Techniques for High Accuracy Relative and Absolute Localization of TerraSAR-X/TanDEM-X Data, Balss et al (DLR), IGARSS 2011 (July), Vancouver

Discussed Influence Factors

- reference frames and continental drift
- bistatic acquisition geometry and stop/go approximations in SAR processor

Further improvements on both absolute and relative localization accuracy
Continental Drift and Geodetic Coordinate Systems

GPS usually reported in a tectonic plate fixed system, e.g. ETRF89 for Europe

risk: misinterpretation of GPS coordinates

offset between expected and true CR position (e.g. approx. 60 cm if ETRS89 is taken for ITRF-2005)
Effect of Continental Drift on Radar Coordinates (e.g. corner reflector CR moved to northeast)

**ascending orbit (right looking):**

CR occurs more in *late azimuth* and *far range* than expected.
Effect of Continental Drift on Radar Coordinates (e.g. corner reflector CR moved to northeast)

descending orbit (right looking):
CR occurs more in *early azimuth* and *near range* than expected.
Effect of a Coordinate System Mismatch

Wrong: ETRS89 coordinates are misinterpreted as ITRS-2005

Correct: ETRS89 coordinates are transformed to ITRS-2005 system
Further TerraSAR-X SAR System Update
July 18, 2011

- SAR processor TMSP update: new version 4.6
  - range focusing module update (change of focusing reference)
  - removal of range bandwidth dependant systematic TMSP internal offsets (order ± 23 cm)
  - thus: further pixel localization accuracy improvement

- IOCS Auxiliary Product Updates
  - TSX IOCS Aux 004.009
  - TDX IOCS Aux 001.011

- calibrated instrument delays:
  no consideration of Earth tides (only continental drift considered)
Consideration of Earth Tides and Atmospheric Path Delay

Residual offsets as obtained with improved atmospheric path delay and operational instrument delay values

DLR discussions and measurements are confirmed by an independant very nice study from RSL, Univ. of Zurich:

Consideration of Earth Tides and Atmospheric Path Delay

Residual offsets as obtained with improved atmospheric path delay and operational instrument delay values

Improved residual offsets as obtained with improved atmospheric path delay and accordingly adopted instrument delay values
Absolute Localization Accuracy of TSX-1

\[ \sigma_{\text{azimuth}} = 6.3 \text{ cm} \]
\[ \sigma_{\text{range}} = 3.8 \text{ cm} \]

The following offsets are subtracted:
- azimuth offset: +8 cm
- range offset: -29 cm

Reprocessing done with
- actual TMSP version
- improved atmospheric delay
- improved instrument delay values
Relative Localization Accuracy of Bistatic TanDEM-X Acquisitions

mean value:

\[ m_{\text{azimuth}} = -18 \text{ mm} \]
\[ m_{\text{range}} = -2.1 \text{ mm} \]

standard deviation:

over all acquisitions:
\[ \sigma_{\text{azimuth}} = 40 \text{ mm} \]
\[ \sigma_{\text{range}} = 4.4 \text{ mm} \]

within an acquisition:
\[ \sigma_{\text{azimuth}} = 16 \text{ mm} \]
\[ \sigma_{\text{range}} = 1.0 \text{ mm} \]

different scaling of axes

azimuth: -100 \ldots +60 \text{ mm}
range: \ -10 \ldots +6 \text{ mm}
Glacier Velocity Measurements

Average Three-Year Velocity Map
Drygalski Glacier, Antarctica

W. Abdel Jaber, D. Floricioiu, M. Eineder
Co-Seismic Displacement Map at Sendai

Absolute disp histogram (m)

median = 2.81 m
mode = 2.74 m
sigma = 0.85 m

N. Yague-Martinez, C. Minet
Conclusions and Outlook

- operational TerraSAR-X pixel location accuracy well within in sub-meter range
- if atmospheric propagation effects (either from measurements or models) and Earth tides effects considered appropriately: pixel localization accuracy even in centimeter range
- TanDEM-X: relative pixel localization accuracy in range in sub-centimeter range
- TerraSAR-X may be used as geometric reference for other sensors (e.g. optical)
- high-resolution image correlation techniques open new areas of applications from single scene acquisitions, e.g. displacement measurements
- TerraSAR-X bears potential to be a precise geodetic measurement device
- future work:
  - refine methods for TerraSAR-X (towards a value-added product)
  - adopt methods and findings for other SAR missions, specifically Sentinel-1