TanDEM-X Performance Analysis

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Across-Track SAR Interferometry

- SAR images are acquired in standard strip map mode
- Interferometric phase measurement corrupted by errors
- Phase error translates to height error proportional to orthogonal baseline

\[ u_1 u_2^* = |u_1| |u_2| \exp(j \phi) \]

\[ \phi = \phi_0 + \Delta \phi \]

\( \phi_0 \) : topographic phase

\( \Delta \phi \) : phase error

\[ h = h_{\text{amb}} \frac{\phi}{2\pi} \]

\[ h = h_0 + \Delta h \]
### TanDEM-X: DEM Specifications

<table>
<thead>
<tr>
<th>Spatial Resolution</th>
<th>Absolute Vertical Accuracy (90%)</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; 20 m</td>
</tr>
<tr>
<td>DTED-2</td>
<td>30 m x 30 m</td>
<td>&lt; 12 m</td>
</tr>
<tr>
<td>HRTI-3</td>
<td>12 m x 12 m</td>
<td>&lt; 2 m</td>
</tr>
<tr>
<td>HRTI-4</td>
<td>6 m x 6 m</td>
<td>&lt; 0.8 m</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Absolute height error**
- **Relative height error**
- **Point-to-point errors** (90% confidence interval)
- **Single point errors**

**Equations:**
\[
\Delta h_i, \quad \Delta h_j, \quad p_{\Delta h}(\Delta h, \gamma, L)
\]
Performance Model

Measure for quality of interferogram:

\[ \gamma = \frac{\text{E}\{u_i u_i^*\}}{\sqrt{\text{E}\{u_i u_i^*\} \text{E}\{u_j u_j^*\}}} \]

Assumptions for error sources:
- Additive and uncorrelated

<table>
<thead>
<tr>
<th>Coherence</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_{\text{SNR}} )</td>
<td>Thermal receiver noise &amp; quantization</td>
</tr>
<tr>
<td>( \gamma_{\text{AASR}} )</td>
<td>Azimuth ambiguities</td>
</tr>
<tr>
<td>( \gamma_{\text{RASR}} )</td>
<td>Range ambiguities</td>
</tr>
<tr>
<td>( \gamma_{\text{rg}} )</td>
<td>Range-coreg. &amp; baseline</td>
</tr>
<tr>
<td>( \gamma_{\text{az}} )</td>
<td>Azimuth-coreg. &amp; doppler shift</td>
</tr>
<tr>
<td>( \gamma_{\text{vol}} )</td>
<td>Volume decorrelation</td>
</tr>
<tr>
<td>( \gamma_{\text{proc}} )</td>
<td>Processing errors</td>
</tr>
</tbody>
</table>

\[ \gamma \approx \gamma_{\text{SNR}} \gamma_{\text{AASR}} \gamma_{\text{RASR}} \gamma_{\text{rg}} \gamma_{\text{az}} \gamma_{\text{vol}} \gamma_{\text{proc}} \]
Definition of Dedicated TanDEM-X Beams

Phase A Study

- 10 swaths
- 2 m
- 240 km
- standard TSX swaths:
  - constant width: 30 km
  - 6 km overlap
  - performance degradation at far range

New Scenario

- 9 swaths
- 2 m
- 240 km
- variable swath width (28 - 32 km)
- 4 km overlap
- constant performance
- less data takes

Reduced data acquisition time & more balanced performance
Increase of Phase Errors for Different BAQ Settings

- prediction
- simulation
Reduction of Instrument Data Rate

**Phase A Study**

- Standard TerraSAR-X Settings
  - variable bandwidth with constant range resolution (up to 150 MHz)
  - 165 MHz sampling rate for many swaths
  - 4+4 bit BAQ
  - 6 km mutual swath overlap

  650 Mbit/s → 700 Mbit/s

**New Scenario**

- New Instrument Settings
  - constant range bandwidth of 100 MHz
  - **110 MHz** sampling (minimum possible)
  - 3+3 bit BAQ
  - new beams with **4 km** swath overlap
  - select PRFs as small as possible (> 3.05 kHz for azimuth ambiguities)

  350 Mbit/s → 470 Mbit/s

substantial reduction of instrument data rate mitigates memory and downlink constraints
Use of Displaced Beams with Different Baseline Lengths

- Improved & more balanced performance
- Less critical with regard to "data loss" at swath border

Height: 2 m

Swath width: 240 km

Mutual swath displacement: ~15 km

Performance after swath combination
Performance Reference Scenario

Motivation
- rough estimate of the global height accuracy

Global land cover classification map
- 14 land cover types
- (1x1)km$^2$ resolution
- considered latitude extension: ±70°
Impact of Vegetation & Slopes

\( h_v \)

\( \theta_i \)

\( \alpha \)

Relative Height Accuracy (90% Point-to-Point)

- 20 m
- 10 m
- 5 m

-20 %
+20 %

Ground Range [km]

Incident Angle [deg]

Height Error [m]
Height Performance

90% height error for soil & rock

histogram for soil & rock
Height Performance for sloped terrain

- 90% height error for soil & rock
- 20% terrain slope facing away from the radar
Global height error distribution

\[ p_{\Delta h}(\Delta h) = 0.134 p_1 + 0.170 p_2 + 0.183 p_3 + 0.204 p_4 + 0.306 p_5 \]

Vegetated areas can significantly increase height errors due to volume decorrelation.
Conclusion

- Reduced number of beams relaxes mission time constraint
- 3 Bit quantization good compromise between performance & data rate
- Performance in low coherent regions can be improved by additional acquisitions
DEM Performance & Calibration

Markus Bachmann
Jaime Hueso González
Outline

- Additional height error sources
  - Instrument errors
  - Baseline errors
- Error Modeling
- Absolute height references
  - ICESat data
- Conclusion
**Height Error Nature**

- **Phase error (after instrument calibration)**
  - Low frequency error (like drifts)
  - High frequency error (noise)

- **Graph:**
  - 90% height error for combination
  - Time in s: 10, 20, 30, 40, 50
  - Height error
  - Flight direction
  - Range
**Height Error Nature**

**Phase noise, De-correlation**

**Instrument errors**

**Baseline errors**

- Multi-looking & Multi acquisitions
- Minimization in the Calibration Processor
- Determination in the Commissioning Phase
**Instrument Error Sources**

**Internal Calibration**
- Determination of the actual instrument state
- Elimination of drifts of the instrument electronics and amplifiers

**Synchronisation link**
- Determination relative oscillators drifts

**Residual errors**
- Bi-static Internal Calibration
- Synchronisation link drifts

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![Diagram of instrument error sources](image)

- TSX
- Central Electronics
- Leaf Amplifier
- TRM
- Internal Calibration
- SAR Antenna
- Sync link

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**Determination of the actual instrument state**

**Elimination of drifts of the instrument electronics and amplifiers**

**Synchronisation link**

**Determination**

**Relative oscillators drifts**

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**Graph showing phase error vs. time**

- Phase error in deg
- Time in s

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**Deutsches Zentrum für Luft- und Raumfahrt e.V.**

in der Helmholtz-Gemeinschaft

**Microwaves and Radar Institute - TanDEM-Xscience Meeting -**

**Slide 5**

24-11-2008
Baseline Estimation

Both satellites are exposed to almost identical orbit perturbations

- Negligible azimuth modulation / twisting of DEM swaths
- Vertical bias and tilt of raw DEM swaths due to initial baseline estimation errors

Precise baseline estimation by

- Double-difference GPS carrier-phase measurements
- Accurate orbit propagation model

=> several studies predict a relative 3-D accuracy in the order of 1-2 mm
**TanDEM-X Baseline Error**

**Baseline bias**

- Would lead to geo-referencing error
- Will be calibrated during the commissioning phase

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Image: Graph showing the relationship between real topography, resulting DEM, and geo-referencing error. The image illustrates how baseline bias affects the accuracy of the DEM, leading to geo-referencing errors. The commissioning phase will be used to calibrate these biases.
Error Modeling

Statistical study

- of the residual height error behaviour
- 2D height error evolution modeled by functional descriptions
- derive coefficients of the mathematical model to be implemented/tested in the MCP

\[ g(x, y) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + b_1 \cdot y + k \cdot x \cdot y \]

<table>
<thead>
<tr>
<th>Height error evolution</th>
<th>Azimuth</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting function</td>
<td>3rd order polynomial</td>
<td>linear</td>
</tr>
</tbody>
</table>
DEM Calibration Simulation

Principle DEM calibration simulation

- Least-squares adjustment
- Overlapping regions of DTs and height references were used

- RMS Combination with the Phase Noise Errors of 1.8 m:

\[
\Delta h_{tot} = \sqrt{(\Delta h_{phase})^2 + (\Delta h_{res\_cal})^2} \\
= 1.86m < 2.0m
\]

~ 250 km
# Height References

## Requirements:
- Coverage on all significant isolated land masses
- Adequate distribution
- Controlled accuracy

<table>
<thead>
<tr>
<th>Function</th>
<th>GCP source</th>
<th>Coverage</th>
<th>Accuracy</th>
<th>Quality parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRELIMINARY absolute height calibration</td>
<td>SRTM</td>
<td>C-Band: (56°S-60°N) X-Band: 56°S-60°N, but big gaps</td>
<td>8.5 m ~ surface slope and roughness</td>
<td>Height specifications</td>
</tr>
<tr>
<td>MAIN absolute and relative height calibration</td>
<td>ICESat</td>
<td>Global</td>
<td>0.1 m - 1 m (weather/terrain)</td>
<td>Accuracy info/sample HRTI-3 (even HRTI-4) – after pre-selection</td>
</tr>
<tr>
<td>SECONDARY absolute and relative height calibration</td>
<td>Ocean-land transitions</td>
<td>restricted to optimal AT-distance and no currents</td>
<td>0.5 m</td>
<td>TBD</td>
</tr>
<tr>
<td>Crossing orbits</td>
<td></td>
<td>Where planned</td>
<td>0.5 m</td>
<td>Tie points</td>
</tr>
<tr>
<td>VALIDATION</td>
<td>GPS tracks</td>
<td>SRTM campaigns; selected regions</td>
<td>0.5 m</td>
<td>Height specifications HRTI-3</td>
</tr>
</tbody>
</table>
**ICESat Data Application**

- Spaceborne laser altimeter
- Over 1 bill. data points acquired
- Global coverage
- Pulse characteristics: 6 Gaussian peaks

**ICESat Data Packet**

- **DEM height**
- **SRTM height**
- **N. Peaks**
- **Sigma width/saturation**
- **Slope**
- **Cloud layers**
- **Surface properties**
- **Region type**

![Map of data distribution]

- High amount of valid ICESat points (> 5 / km²)
- Low amount of valid ICESat points (< 0.5 / km²)

![Graphs and data points]

- 47 m
- 61 m
- 16 Raw DEM pixel
**Miesbach Campaign to Determine Selection Criteria**

- Experimental Airborne Radar System (E-SAR)
- Acquisition region Miesbach: flat land, forests and mountainous areas
- 2 interferometric acquisitions/strip, with different flight heights
- ICESat height references available over this area – several tracks

**Selection criteria of ICESat Data for TanDEM-X mission:**

1. Outlier pre-selection with SRTM C-Band
2. Only good echoes with 1 peak
3. Narrow sigma threshold
   
<table>
<thead>
<tr>
<th></th>
<th>BASIC</th>
<th>EXTREME</th>
<th>OPTIMAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8ns</td>
<td>3.2ns</td>
<td>4.9ns</td>
</tr>
</tbody>
</table>

4. Threshold vegetation coverage < 20% OPTIMAL
Conclusion

- Error investigation
  - performed to determine the main error sources
  - Error models established

- Height references
  - ICESat data sets were examined to find selection criteria

- Height error requirement will be successfully fulfilled!
Thank you for your attention!