TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry

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TanDEM-X
Mission Goals

→ acquisition of a global DEM according to HRTI-3 standard

→ generation of local DEMs with HRTI-4 like quality

→ demonstration of innovative bistatic imaging techniques and applications

TerraSAR add-on for Digital Elevation Measurements
TanDEM-X Timeline

- 2003: German Call for Proposals for a Future Earth Observation Mission
- 2004: Selection of TanDEM-X for Phase A Study
- 2005-2015: Phase A Study
- 2005-2015: Final Decision
- 2006-2015: Phase B/C/D
- 2009-2015: TanDEM-X Operation
- 2009-2015: TerraSAR-X Operation

All TanDEM-X mission objectives are achieved within 3 years of joint operation.
Investigations in Phase A Study

Derivation of User and Mission Requirements:

• Organisation of Science Team (currently 97 members)
• Scientific and Commercial User Survey
• Product Definition (DEM, radar data products, …)
• Performance Analyses (DEM, PolInSAR, GMTI, DBF, …)
• Mission Planning and Data Management
• PRF and Phase Synchronisation (design upgrade)
• Close Formation Flying (collision avoidance)
• Precise Baseline Determination (double difference GPS)
• Bi-Static and Interferometric Data Processing
• Interferometric Calibration (tie points, crossing orbits, …)
• …
User Survey:
- application areas
- basic user needs
- technical requirements
- ...

Product and Mission Definition

- system parameters:
  - $B_{\text{cross}} = \ldots \text{m}$
  - $B_{\text{along}} = \ldots \text{m}$
- deliverable data:
  - SLC SAR images
  - SAR raw data
  - TanDEM-X interferograms
  - orbit state vectors

Product and Mission Definition

- predefined accuracies:
  - $\Delta h = 2 \text{ m}$ @ $\Delta x = 12 \text{ m}$
  - $\Delta h = 4 \text{ m}$ @ $\Delta x = 6 \text{ m}$
  - $\Delta h = 1 \text{ m}$ @ $\Delta x = 25 \text{ m}$
  - $\Delta h = 0.5 \text{ m}$ @ $\Delta x = 50 \text{ m}$

- deliverable data:
  - standard DEM
  - detected SAR images
  - coherence maps
  - height error maps

- temporal requirements:
  - different seasons
  - different years

- deliverable data:
  - customised DEM
  - detected SAR images
  - coherence maps
  - height error maps

Compliance

- fully
- partially
- not

- 17%
- 7%
- 76%

Standard DEM
(globally HRTI)

- customised accuracies:
  - $\Delta h = \ldots \text{ m}$ @ $\Delta x = \ldots \text{ m}$
- temporal requirements:
  - different seasons
  - different years
- deliverable data:
  - customised DEM
  - detected SAR images
  - coherence maps
  - height error maps

Customised DEM
(local)

Radar Data Products

- system parameters:
  - $B_{\text{cross}} = \ldots \text{m}$
  - $B_{\text{along}} = \ldots \text{m}$
  - ...
- deliverable data:
  - SLC SAR images
  - SAR raw data
  - TanDEM-X interferograms
  - orbit state vectors
## HRTI-3 DEM Definition

<table>
<thead>
<tr>
<th></th>
<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>90m x 90m</td>
<td>&lt; 30 m</td>
<td>&lt; 20 m</td>
</tr>
<tr>
<td>DTED-2</td>
<td>30m x 30m</td>
<td>&lt; 18 m</td>
<td>&lt; 12 m</td>
</tr>
<tr>
<td><strong>HRTI-3</strong></td>
<td><strong>12m x 12m</strong></td>
<td><strong>&lt; 10 m</strong></td>
<td><strong>&lt; 2 m</strong></td>
</tr>
<tr>
<td><strong>HRTI-4</strong></td>
<td><strong>6m x 6m</strong></td>
<td><strong>&lt; 5 m</strong></td>
<td><strong>&lt; 0.8 m</strong></td>
</tr>
</tbody>
</table>

- SRTM / X-SAR ~ DTED-2
- E-SAR ~ HRTI-3
### Relative Height Accuracy ($B = 500$ m)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.031 m</td>
</tr>
<tr>
<td>Chirp Bandwidth</td>
<td>$\leq 150$ MHz</td>
</tr>
<tr>
<td>Peak Transmit Power</td>
<td>2260 W</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>18 %</td>
</tr>
<tr>
<td>Noise Figure TRM</td>
<td>4.3 dB</td>
</tr>
<tr>
<td>Losses (rad., atm.,...)</td>
<td>4.1 dB</td>
</tr>
<tr>
<td>Antenna Size (Tx, Rx)</td>
<td>4.8 m x 0.7 m</td>
</tr>
<tr>
<td>Antenna Tapering</td>
<td>linear phase</td>
</tr>
<tr>
<td>PRF (swath variant)</td>
<td>$\sim 3500$ Hz</td>
</tr>
<tr>
<td>Processed Bandwidth</td>
<td>2266 Hz</td>
</tr>
<tr>
<td>Mis-Registration</td>
<td>1/10 pixel</td>
</tr>
<tr>
<td>Quantization</td>
<td>4 bit (BAQ)</td>
</tr>
<tr>
<td>Sigma Nought Model (90% occurence)</td>
<td>Ulaby (X-Band, VV, Soil)</td>
</tr>
<tr>
<td>Baseline (perp.)</td>
<td>500 m</td>
</tr>
<tr>
<td>Along-Track Displ.</td>
<td>$&lt; 1$ km</td>
</tr>
<tr>
<td>Swath Width</td>
<td>30 km</td>
</tr>
<tr>
<td>Post Spacing</td>
<td>12 m x 12 m</td>
</tr>
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</table>

#### Diagram:

- **Relative Height Accuracy (90% Point-to-Point and Stdev)**
- **Bistatic Strip map**
  - $B = 500$ m
  - $\Delta x = 12$ m
- **90% point-to-point errors**
- **$\sigma$ (standard deviation)**
## Relative Height Accuracy ($B = 1000$ m)

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### Graphical Representation

![Relative Height Accuracy Graph](image)
Phase Unwrapping

TanDEM-X enables large baselines which allow for ultra high resolution DEMs with height accuracies in the sub-meter range, but …

\[ \Delta \varphi = 2\pi \]
(height of ambiguity)

Compromise on Accuracy for Global DEM
- use reduced baselines
- additional acquisitions for difficult terrain

Local/Regional Ultra High Resolution DEMs
- use multiple data acquisitions with large and small baselines

acquisition scenario for global DEM according to HRTI-3

regional DEMs with sub-meter resolution (e.g. HRTI-4)
## TanDEM-X Data Acquisition Strategy

<table>
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<tr>
<th>Terrain Type</th>
<th>Percentage of Total Landmass</th>
<th>Number of Acquisitions</th>
<th>Required Time (without RDP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderately Sloped Areas</td>
<td>50 %</td>
<td>1 (h&lt;sub&gt;amb&lt;/sub&gt; ~ 35 m)</td>
<td>~ 7 months</td>
</tr>
<tr>
<td>Hilly Areas, Tall Forests</td>
<td>30 %</td>
<td>2 (+ different h&lt;sub&gt;amb&lt;/sub&gt;)</td>
<td>~ 8 months</td>
</tr>
<tr>
<td>Mountainous Areas</td>
<td>&lt; 20 %</td>
<td>4 (+ asc. / desc.)</td>
<td>~ 11 months</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100 %</td>
<td><strong>1 - 4</strong></td>
<td>~ 26 months (incl. margin)</td>
</tr>
</tbody>
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### TanDEM-X Mission Scenario for 3 Years

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<td><strong>Global HRTI-3 DEM</strong></td>
<td>(incl. multiple acquisitions for difficult terrain)</td>
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<tr>
<td><strong>Additional Applications</strong></td>
<td>(local HRTI-4, ATI, new techniques, …)</td>
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**Total Landmass:**
- ~ 150 Mio km\(^2\)
- ~163 Mio km\(^2\)/year (stripmap, 140s/orbit)


**Helix Satellite Formation:**

**HELIX satellite formation enables safe operation**

- Horizontal cross-track separation at equator by different ascending nodes.
- Vertical (radial) separation at poles by orbits with different eccentricity vectors (periodic motion of libration is compensated by regular manoeuvres).

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Baseline Estimation and DEM Calibration

- Both satellites are exposed to almost identical orbit perturbations
  - negligible azimuth modulation / twisting of DEM swath (\(\Delta B < 0.25 \text{ mm} \) for 500 km swath and ‘unmodelled’ \(\delta a < 100 \text{ nm/s}^2\))
  - 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 3-D accuracy in the order of 1-2 mm
Impact of Oscillator Noise

Major effects:
- interferometric phase errors (azimuth ‘modulation’ of DEM)
- azimuth displacement
- increased azimuth sidelobes
- range drift (walk of receiving window)
Phase Referencing in TanDEM-X

Synchronisation Link

Analysis of Residual Errors

phase referencing can achieve a short term rmse below 1° in standard DEM acquisition mode by integrating multiple sync pulses (for B < 1 km)
Secondary Mission Goals & New Techniques

**Pol-InSAR**
(fully polarimetric !)

**Along-Track Interferometry**
(HELIX formation !)

**Digital Beamforming**
(4 phase centres !)

**Multi Baseline InSAR**
(flexible baselines !)

**Super Resolution**
(large bandwidth !)

**Bistatic Observations**
(bistatic angle !)
Along-Track Interferometry

**HELIX formation enables:**
- short along-track baselines
  (arbitrary satellite shifts along the orbits)
- vanishing cross-track baselines
  (for specified latitude/incident angle combinations)

**Example (bistatic mode):**
- $B_{\text{along}} = 100$ m
- posting = 10 m
- $\sigma^0 = -12$ dBm$^2$/m$^2$
- $\theta_{\text{inc}} = 45^\circ$
- $v_{\text{amb}} = 11$ km/h
  $\Rightarrow dv \sim 0.15$ km/h (stdv.)
SAR Imaging with four Phase Centres

- **short baseline**
  - $\Delta t \approx 0.2\text{ ms}$
  - Sensitive to fast movements

- **long baseline**
  - $\Delta t \approx 10\text{-}200\text{ ms}$
  - Sensitive to slow movements

**split antenna**

- **highly accurate velocity estimates for slow and fast object movements**
**SAR Imaging with four Phase Centres**

- **Ch. 1**: $P_1(f)$
- **Ch. 2**: $P_2(f)$
- **Ch. 3**: $P_3(f)$
- **Ch. 4**: $P_4(f)$

**Without reconstruction**

**SAR Proc.**

**With reconstruction**

- Enables High Resolution
- Wide Swath Imaging

**Ambiguity Suppression**

![Graphs showing amplitude vs. along track position for with and without reconstruction](image_url)
**PollInSAR Example: Sunflower**

**Parameters**

- $h = 1.2 \text{ m}$
- $\beta = 4.0 \text{ dB/m}$
- $\mu_{\text{min}} = -7.0 \text{ dB}$
- $\mu_{\text{max}} = 3.0 \text{ dB}$
- $B_\perp = 4 \text{ km}$
- $\theta_{\text{inc}} = 35^\circ$
- $\Delta x = 30 \text{ m}$

![Graph showing height error and height bias with pdf($\mu_{\text{min}}$) and pdf($\mu_{\text{max}}$) curves.](image)
“Double Differential SAR Interferometry”
e.g. difference between two single-pass cross-track interferograms

\[ \Delta h \sim \varphi_2 - \varphi_1 \]

→ *Grounding line detection, vegetation growth, snow/ice accumulation, ... ?*

**Relative Height Accuracy (Stdv)**

- Bistatic Strip map
  - \( B = 3000 \text{ m} \)
  - \( \Delta x = 12 \text{ m} \)

\( \Delta h < 10 \text{ cm} \)
TanDEM-X Summary

• TanDEM-X passed a phase A feasibility study with great success
• TanDEM-X has outstanding scientific and commercial potentials
• TanDEM-X will be implemented as a public private partnership
• TanDEM-X key technologies are:
  – bistatic radar operation and phase synchronisation
  – precise baseline determination
  – close formation flying capability
  – new algorithms for interferometric processing
• TanDEM-X plays a key role in the development of next generation SAR missions