Ship Detection and Motion Parameter Estimation with TanDEM-X in Large Along-Track Baseline Configuration

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Mission Goals

- Global DEM → Level-3 standard
- Local DEMs → Level-4 like quality
- Demonstr. of innovative techniques applications (formation flying, bistatic acquisition, Pol-InSAR, GMTI, ...)

Launched on 21st June 2010
### TanDEM-X Data Acquisition Modes

<table>
<thead>
<tr>
<th>Pursuit Monostatic</th>
<th>Bistatic</th>
<th>Alternating Bistatic</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Pursuit Monostatic**
  - Both satellites transmit and receive independently
  - Temporal decorrelation & atmospheric disturbances
  - Backup solution

- **Bistatic**
  - One satellite transmits and both satellites receive simultaneously
  - Dual use of signal energy
  - Requires synchronisation

- **Alternating Bistatic**
  - Transmitter alternates between PRF pulses
  - Provides two baselines
  - Enables synchronisation, calibration & verification
Moving targets in conventionally processed SAR images appear ...

- **Displaced** from their true positions
  - Large azimuth displacement (slow ship → up to 600 m; fast car → up to 2 km and more)
  - Small range displacement (≤ 5 m for line-of-sight velocities ≤ 100 km/h)
  - Reason: Doppler shift due to across-track velocity

- **Blurred** in azimuth direction
  - Reason: Along-track velocity and across-track acceleration
Ground Moving Target Indication (GMTI)

Objectives of GMTI
- Detection (at “wrong“ position!)
- Parameter estimation
  - „true“ position
  - absolute velocity
  - moving direction

Spaceborne GMTI so far ..
- Single platform
- Along-track interferometry
  (→ small baseline)
- A priori knowledge-based GMTI
  (→ Road database)
The **RX antennas** are separated in flight or along-track (azimuth) direction, respectively.
Classical Along-Track Interferometry (ATI) Principle

The RX antennas are separated in flight or along-track (azimuth) direction, respectively.

Range Difference
\[ \Delta r = r_1 - r_2 = v_{r0} \Delta t \]

Interferometric Phase
\[ \Delta \phi = \frac{4\pi}{\lambda} \Delta r = \frac{4\pi}{\lambda} v_{r0} \Delta t \]

Azimuth displacement
\[ \Delta x \approx -r_0 \frac{v_{r0}}{v_p} \Delta t \]

- ATI phase \( \Delta \phi \rightarrow v_{r0} \rightarrow \Delta x \)
- Problems: Noise + Clutter
- \( \Rightarrow \) Re-displacement errors (10s to 100s of meters)
Along-Track Baseline

Small baseline $\Rightarrow \Delta t \approx \text{ms}$
- Moving target keeps in res. cell
- Only sensitive to $v_{r0}$ (1D)
- „Classical ATI“

Large baseline $\Rightarrow \Delta t \approx \text{s}$
- Moving target leaves res. cell
- 2D velocity estimation
- Large-Along Track Baseline GMTI
Along-Track Baseline

- **Small baseline** $\Delta t \cong ms$
  - Moving target *keeps in res. cell*
  - Only sensitive to $v_{r0}$ (1D)
  - "Classical ATI"

- **Large baseline** $\Delta t \cong s$
  - Moving target *leaves res. cell*
  - 2D velocity estimation
  - Large-Along Track Baseline GMTI
Large Along-Track Baseline GMTI → Principle

- Large along-track baseline \( \cong 20 \, \text{km} \) \( \Rightarrow \) time lag \( \cong 2.5 \, \text{s} \)
- Monostatic pursuit mode
- Moving target \( \Rightarrow \) displaced in both SAR images
- Displacement difference \( \Rightarrow \) true geographical position, velocity, heading (and acceleration)
- No a priori knowledge required!
- Detection of vehicles moving on open land and open sea!

Large Along-Track Baseline GMTI → Algorithm (II)

Ocean

(→ no clutter suppression)

Image 1

Reference Patch

2D Correlator

Result

Image 2

Preprocessing

Clutter Suppression

Detection + Clustering

2D Correlation

Parameter Estimation

Georeferencing

Visualization

Land

Image 1

Image 2

DPCA

Reference Patch

Without Reference Patch

2D Correlator

Result
Large Along-Track Baseline GMTI → Algorithm

Ocean
(→ no clutter suppression)

Land
(→ clutter suppression necessary)

Superposition of single-channel images
red: TerraSAR-X image (fore)
green: TanDEM-X image (aft)

Superposition of single-channel images
DPCA
Clutter-suppressed DPCA image
Experiments and First Results
Overview TanDEM-X Commissioning Phase

- Monostatic TDX commissioning phase
- Large along-track baseline → 20 km → 2.5 s time lag
- Acquisition of 20 GMTI data takes
Test Sites for Traffic Monitoring

**Interstate 15**
- NE of Las Vegas
- Monitoring of road vehicles
- Low clutter contribution

**Strait of Gibraltar**
- Monitoring of ships
- Always traffic
- AIS data available
Verification Using AIS Data as Reference → Principle

- **Automatic Identification System**
  - Standardized VHF transceiver
  - Ships with GT ≥ 300 tons
  - ID, position, speed, moving dir., ...
  - Available via internet (≈ real-time)

- Different acquisition times
  - \( t_{\text{AIS}} \neq t_{\text{SAR}} \) (sec. → min)
  - Extrapolation of the AIS data
  - Const. velocity & heading assumed

**AIS:** Position ⇒ GPS antenna / AIS

**SAR:** Area centroid ⇒ geocoded position

- Acquired at \( t_{\text{SAR}} \)
- Position Difference

- Extrapolation

\( \text{time} \ t_{\text{AIS}} \)
First Results: Vessel Monitoring in the Strait of Gibraltar

- Coordinates: 35.949 N, -5.712 E
  - Velocity: 16.7 kn

- Coordinates: 35.953 N, -5.704 E
  - Velocity: 9.5 kn

- Coordinates: 35.960 N, -5.694 E
  - Velocity: 12.7 kn

- Coordinates: 35.964 N, -5.700 E
  - Velocity: 8.9 kn

- Coordinates: 35.964 N, -5.659 E
  - Velocity: 8.8 kn

- Coordinates: 35.963 N, -5.657 E
  - Velocity: 9.8 kn
Ship Detection and Motion Parameter Estimation with TanDEM-X in Large Along-Track Baseline Configuration

Stefan Baumgartner

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Verification Using AIS Data as Reference → First Results (I)

- Vessels have moved mainly in range direction
  - Northing pos. difference ~ azimuth re-positioning error
  - „True azimuth position is more difficult to estimate than range position!“
Verification Using AIS Data as Reference → First Results (II)

Velocity Difference

- Velocity Difference [kn]
- Target ID
- ≈ 0.15 m/s → 0.54 km/h
- bad correlation (→ RCS change)

Moving Direction Difference

- Heading Difference [°]
- Target ID
- bad corr.
Verification Using Road Database as Reference ➔ Principle

- Absolute Geographical Position „Error“
  - Estimated target position ↔ closest road point
- Target Moving Direction
  - Compared with known road direction
- Detection / False Alarm Rate
  - Unfortunately no ground truth available!
Verification Using Road Database as Reference → Results

Absolute Position Difference

- MEAN: 10.97 m
- STDDEV: 13.28 m

<table>
<thead>
<tr>
<th>Occurrence</th>
<th>Position Difference [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
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<tr>
<td>2</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>

- Simple detector → fixed threshold
- False detections skipped manually
  - 31 remaining "true" targets (SCNR 10 to 24 dB)

Moving Direction Difference

- MEAN: 0.55°
- STDDEV: 3.82°

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>5</td>
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<tr>
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<td>10</td>
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<tr>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>

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Conclusions and Outlook

- Large Along-Track Baseline Algorithm
  - Proof of concept provided
  - Targets: point-like (small cars) ↔ extended (ships) ↔ „other“ movers / non-movers?
  - Excellent parameter estimation performance
  - You get both with one pass: High resolution SAR images + GMTI data

- Reference Data ↔ „Data Fusion“
  - „Traffic Monitoring“ → assignment to certain roads (automatically)
  - „Ship Monitoring“ → comparison / fusion with AIS data (automatically)

- Outlook
  - Not all acquired data takes evaluated so far; no robust (CFAR) detector implemented
  - Principally applicable for „future“ platforms ...
State-of-the-Art and Future?

Airborne
- Global Hawk
- F-SAR

Spaceborne
- TerraSAR-X
- SAR-Lupe
- Turtle Airship

Differences / selection criterions:
- Spatial / temporal coverage
- Endurance / range
- Applications

„High Altitude Airships (HAAs)“?