Sentinel-1 InSAR Performance: Results from the Sentinel-1A In-Orbit Commissioning

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Sentinel-1 TOPS InSAR Pre-Studies

- Sentinel-1 TOPS InSAR study based on *TerraSAR-X TOPS data* for mapping of stationary and non-stationary scenarios focusing on TOPS image co-registration techniques.

- Experimental implementation of TOPS mode on *RADARSAT-2* to mimic the Sentinel-1 IW mode SAR and InSAR performance and to generate Sentinel-1-like IW SLC products.
Repeat-pass TOPS InSAR using *Interferometric Wide Swath (IW)* data pairs worked on the ‘spot’

*S-1A IW interferogram* of data pair acquired 7-19 August, 2014 (\(2\pi\) height = 128.82m)

**Verification of:**

- SAR instrument phase stability
- Satellite on-board timing and GNSS solution to support *position-tagged commanding* (OPS angle)
- Mission Planning system using *TOPS cycle time grid points* for datatake start time estimation
- Accurate orbit control (orbital tube)
Sentinel-1A Instrument Stability
Internal Calibration

• Network of Cal pulses monitors potential drifts in SAR instrument’s (internal) Transmit (Tx) and Receive (Rx) signal path:

• Each DT starts and ends with sequences of 6 types of Cal pulses both at nominal signal BW and at 100MHz BW:

- APDNCal
- TACal
- EPDNCal
- RxCal
- TxCal

Product (complex) of Transmit power and Receive gain

\[ PG = \frac{\text{TxCal} \cdot \text{RxCal}}{\text{EPDNCal}} \cdot \frac{\text{TACal}}{\text{APDNCal}} \]

- PG product is applied to Raw SAR data (in operational SAR processor (IPF)) to correct for instrument amplitude and phase variations:
  - Internal electronic instrument delay correction
  - Radiometric correction
**Sentinel-1A Instrument Stability during long Datatakes (25min)**

**Variation over 25 min:**

- **Gain:**
  - 0.31 dB (VV)
  - 0.37 dB (VH)

- **Phase:**
  - -13.6° (VV)
  - -14.3° (VH)

- **Variations in amplitude < 0.6 dB**
- **Discrete jumps in phase and internal delay occur when the SES is restarted**
Sentinel-1A Orbital Tube

• Reference orbit was reached on August 7th, 2014
• Satellite is kept within an Orbital Tube around a Reference Mission Orbit (RMO)
• Specified Orbital Tube radius of 50 (rms) ⇒ equivalent to Ground-track dead band of 60m
• During S-1A Commissioning: Relaxation of Ground-track dead band to 120m ⇒ Orbital Tube radius of better than 100 (rms)

RMS of Orbital Tube w.r.t. Reference Orbit expressed in baseline coordinates
Sentinel-1A Orbital InSAR Baseline

**Average (daily) absolute Baseline for consecutive repeat passes**

- $B_{\text{perpendicular}}$
- $B_{\text{parallel}}$
- $B_{\text{along\:track}}$

During S-1A Commissioning

Perpendicular Baseline $< 150m$

**Average (5 cycles) absolute Baseline for consecutive repeat passes**

- Effective baseline [m]

Latitudes and Effective Baseline values

- Ascending
- Descending

worst case
Sentinel-1A SAR Timing Calibration

Measurement of *Range-Doppler geolocation* of known reference Point target in SAR image for estimation of *systematic SAR timing offsets* in:

- **Slant range** (residual internal electronic path delay and Sample Window Start Time)
- **Azimuth** (radar time and spacecraft GPS time)

⇒ Absolute Location Error (ALE) = predicted – measured (PTs)

*Reference Point Targets (PTs)*

- 4 Corner Reflectors (CRs) deployed at Torny-le-Grand, Switzerland
- 3 ESA transponders deployed in the Netherlands
- 3 DLR CRs and 3 DLR transponders

Geolocation accuracy may be affected by:

- Accuracy of orbital state vector
- Survey accuracy of reference targets
- Atmospheric path delay of radar signal
Data analyzed over **Torny-le-Grand corner reflector** site by University of Zurich, RSL
- 19 SM and 3 IW and use of **Precise Orbit Data (POD)**

**Applied corrections:**
- Internal path delay
- Tectonic motion
- Solid Earth tides motion
- Atmospheric path delay

<table>
<thead>
<tr>
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<th>ALE Slant range offset</th>
<th>ALE Azimuth offset</th>
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<tbody>
<tr>
<td>SM</td>
<td>1.28 ± 0.07 m</td>
<td>2.09 ± 0.49 m</td>
</tr>
<tr>
<td>IW</td>
<td>1.31±0.37 m</td>
<td>0.53±0.74 m</td>
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8x10^{-9} sec | 3.08x10^{-4} ± 6.79x10^{-5} sec

7.7x10^{-5} ± 1.1x10^{-4} sec
Burst Azimuth Spectral Alignment

Burst Timing Mis-synchronization: \( T_{\text{del}} \)

Antenna Mis-pointing (squint): \( \Delta f_{DC} \)

**TOPS:**
\[
\Delta f_{T_{\text{del,shift}}} = \frac{k_a \ k_{\text{rot}}}{k_a - k_{\text{rot}}} T_{\text{del}}
\]

**ScanSAR:**
\[
\Delta f_{T_{\text{del,shift}}} = k_a T_{\text{del}}
\]

\( \Rightarrow \) TOPS is more robust than ScanSAR
Datatake Start Time Estimation for Burst Synchronization – Position-tag Commanding

- Data acquisition (repeat orbit cycle) over the same ground location uses on-board schedule execution (OPS) based on **Orbit Position angle** (instead of timing)

**Advantage**: more accurate DT start time estimation
no need for precise orbit prediction or frequent update of on-board command queue

Calculation of OPS angle $\alpha_{\text{start\_plan}}$ based on:
- S-1A Reference orbit
- use of an orbital point grid based on **burst cycle time**

Spacecraft Avionics converts (on-board) planned OPS angle ($\alpha_{\text{start\_plan}}$) to time ($t_{\text{start}}$) by analytical propagation of GPS PVT data

PVT
(on-board GPS)

Instrument executes measurement according to $t_{\text{start}}$

First imaging PRI $t_{\text{echo}}$

Warm-up
Preamble
Imaging
Verification of S-1A IW DT Start Time Estimation for Burst Synchronization

- 498 IW measurements between Aug. 7th, 2014 (Reference Orbit reached) and Sept. 6th, 2014
- Measured performance includes:
  - Accuracy of the on-board conversion from OPS angles to instrument start time
  - Accuracy of instrument in achieving the requested start time

**Average = 1.32 ms**
**Std dev = 1.28 ms**

**Duration of IW bursts:**
- IW1: 0.8s
- IW2: 1.06s
- IW3: 0.83s
Sentinel-1A Burst Synchronization Results

48 InSAR product pairs
- 28 ascending geometry
- 20 descending geometry
- 46 in IW mode
- 2 in EW mode

Estimation of along-track burst synchronization:
- Orbital state vectors (POD, restituted orbits)
- Annotated raw start azimuth time (sensing time) of the bursts
- Fine Co-registration using cross-correlation and ESD techniques

Datatake-Level (Italy DT)

Burst (along-track) synchronization < 2.83 ms

Mean AT mismatch [ms] | Ascending | Descending |
-----------------------|-----------|------------|
IW1                    | 2.03      | 2.12       |
IW2                    | 2.12      | 2.47       |
IW3                    | 2.16      | 2.47       |

AT mismatch variation [ms] | IW1 | IW2 | IW3 |
---------------------------|-----|-----|-----|
IW1                        | 2.41| 2.42| 2.47|
IW2                        | 2.42| 2.47|     |
IW3                        | 2.47|     |     |
Sentinel-1A Burst Spectral Alignment Results

**Mean Doppler Centroid difference < 20 Hz**
due to stable attitude and antenna pointing

**Common Doppler bandwidth > 95%**

Satellite Pitch angle adjustment of 0.025 deg in Oct. 2014

⇒ Reduced mean Doppler centroids
Backup Slides
Demonstration of *Differential* and *Multi-Aperture (Squint)* SAR Interferometry

M6.0 South Napa Valley earthquake on August 24\(^{th}\), 2014

Use of Stripmap (SM-1) data pairs acquired on August 7\(^{th}\) and 31\(^{st}\), 2014

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**D-InSAR**

**MAI (MS-InSAR)**

*Image courtesy, DLR-IMF*

*Image courtesy, Andrea Monti Guarnieri, POLIMI*
Sentinel-1 SAR TOPS Mode

TOPS (Terrain Observation with Progressive Scans in azimuth) for Sentinel-1 Interferometric Wide Swath (IW) and Extra Wide Swath (EW) modes

- **ScanSAR-type** beam steering in *elevation* to provide large swath width (IW: 250km and EW: 400km)
- Antenna beam is steered along *azimuth* from *aft* to the *fore* at a constant rate

- All targets are observed by the entire azimuth antenna pattern eliminating scalloping effect in ScanSAR imagery
- **Constant SNR** and *azimuth ambiguities*
- Reduction of azimuth resolution due to decrease in dwell time

- S-1 IW TOPS mode parameters:
  - ±0.6° azimuth scanning at Pulse Repetition Interval rate with step size of 1.6 mdeg.

Sentinel-1A IW dual-pol image, acquired over Namibia
Sentinel-1A Instrument Stability during long Datatakes (25min)

**IW VV-VH**

**IW HH-HV**

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