Sentinel-1 Interferometry using the Integrated Wide Area Processor (IWAP) – First Experiences

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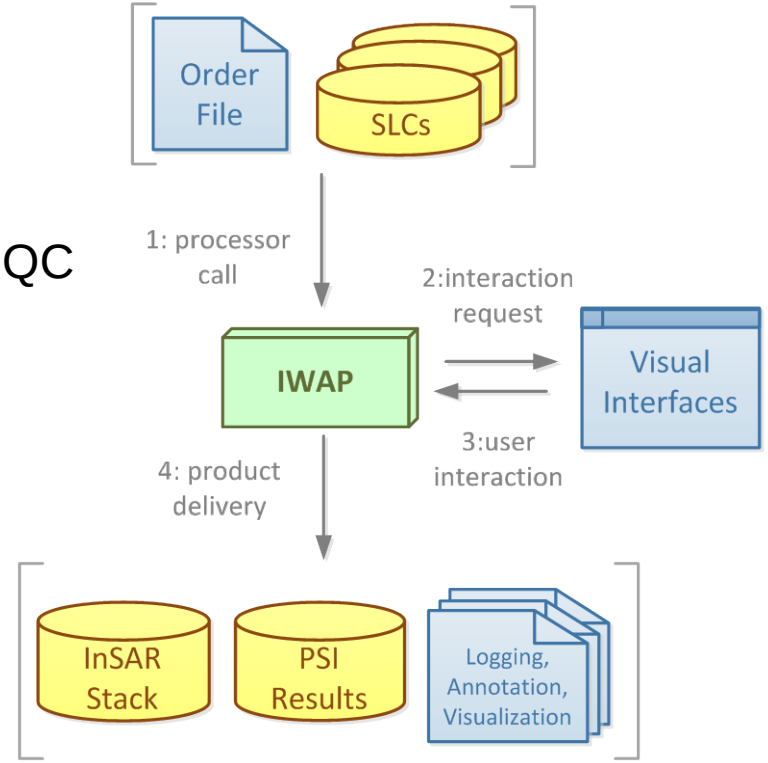
Overview

- Design of IWAP Burst-Mode
- Sentinel-1 Experiments
  - Standard Approach
  - Full Exploitation of Spectral Diversity in ESD
  - Experiments (Genoa, Istanbul)
- Slice Mosaicking
- TerraSAR-X ScanSAR PSI

Integrated Wide Area Processor (IWAP)

A multi-mode multi-sensor PS-InSAR processor

- Based TMSP, ITP, PSI-GENESIS
- Flexible modular approach
- Automated
  - User notified when intervention necessary
  - Visual interfaces aid decision process and QC
- Computationally efficient
  - Multi-threading
  - Parallel processing
- Easy archival, packaging of important results
- Version control
- Snapshot of processor can be exported



Design Requirements

- SM and SL modes are **single burst modes**
  - Single contiguous SLC
  - Doppler centroid continuous over scene
- TOPSAR and ScanSAR are **(multi) burst modes**
  - Multiple discontiguous SLCs
  - Doppler centroid continuous over a burst but discontinuous between bursts or over a scene

Design Requirements

- Enable processing of all modes with IWAP
  - SM
  - SL
  - TOPSAR
  - ScanSAR
- Introduce workflows for
  - non-burst mode (SM, SL)
  - burst mode (TOPS, ScanSAR)
- Allows unified approach of burst mode acquisitions regardless of configuration (# beams, # bursts, burst size)

Burst-Mode Structure

Three level hierarchical structure

Scene Level

Parameter Pool → **Mosaics (interferogram, amplitude)**

Beam Level

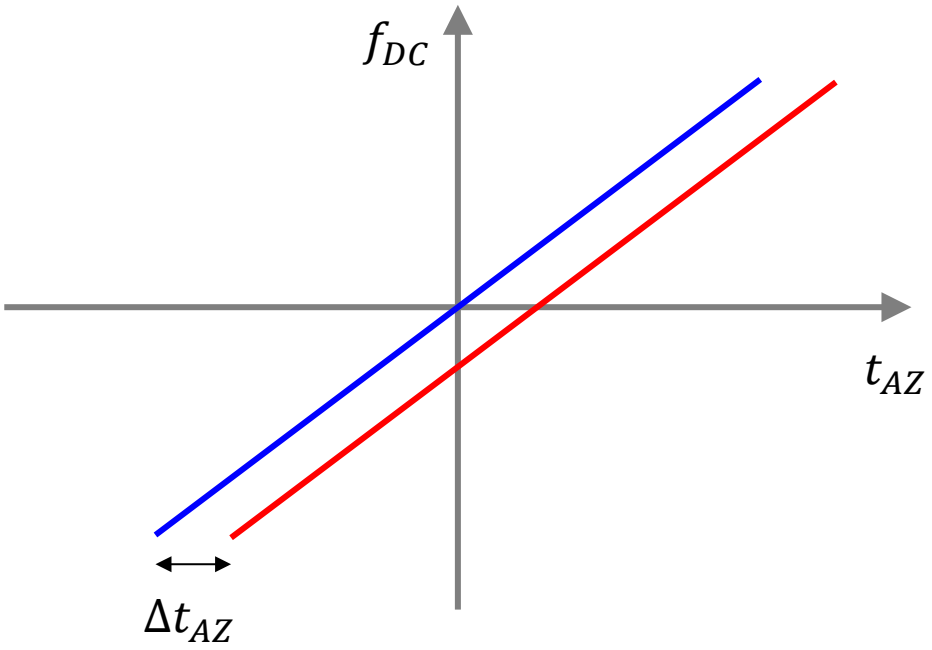
Parameter Pool → **Mosaics (interferogram, amplitude)**

Burst Level

Parameter Pool → **SLCs and Valid Pixel Masks (interferogram, amplitude)**

Coregistration

- Azimuth coregistration accuracy requirement for TOPS is **1/1000** pixels
- Limits azimuth phase ramp to **1/100** cycles



$$\phi_{err} = 2\pi f_{DC} \Delta t_{AZ}$$

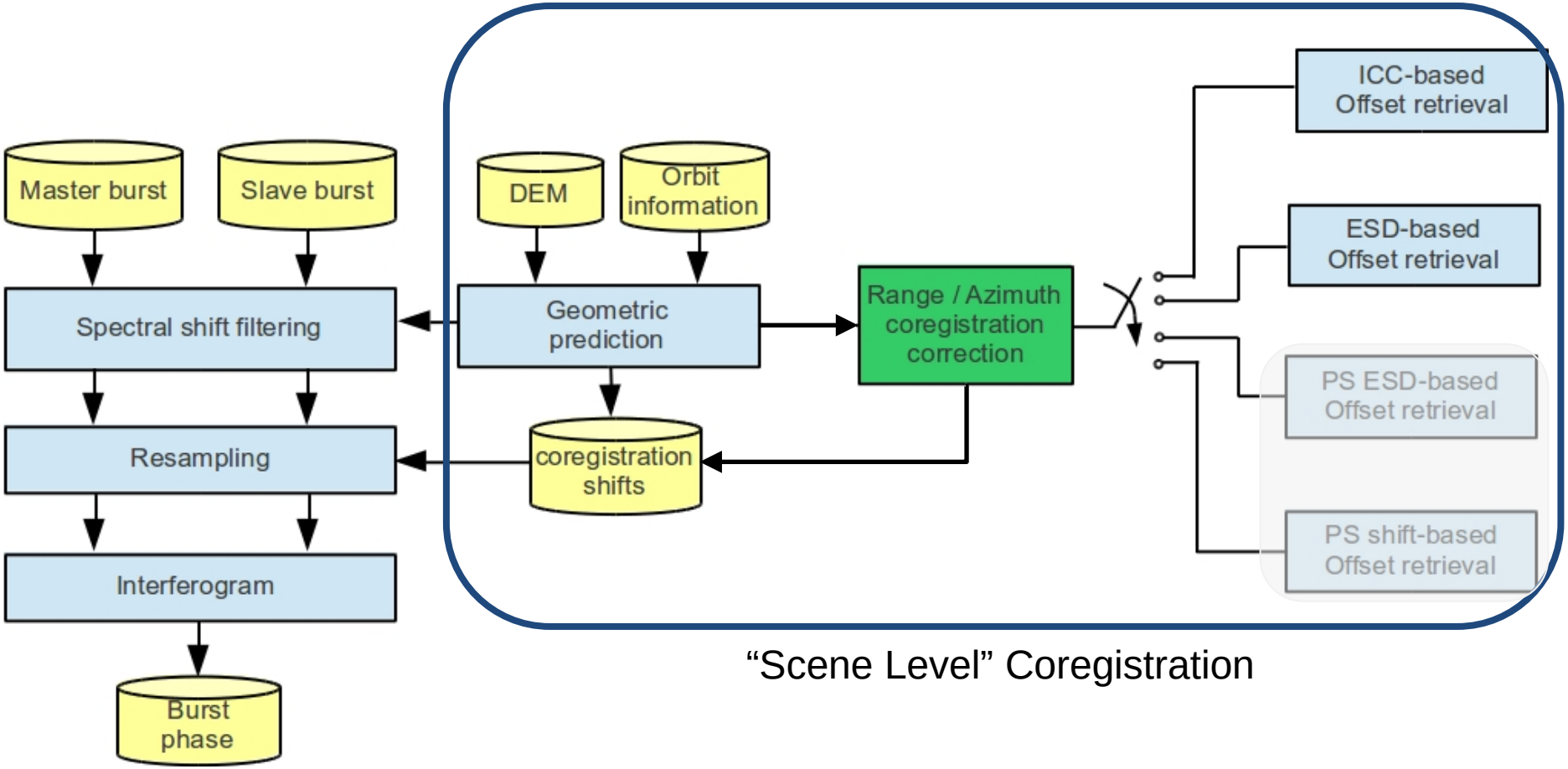
Coregistration

- Coherent Cross-Correlation (CCC)
  - MLE for distributed Gaussian scatterers, requires DEM
- **1. Incoherent (Amplitude) Cross-Correlation (ICC)**
  - Robust (speckle tracking, no phase)
  - Time consuming (oversampling, detection)
- PS-Geometric Coregistration (standard SM approach)
  - Quick but insufficient accuracy for TOPS
- **2. Enhanced Spectral Diversity (ESD)**
  - Best accuracy
  - Requires a priori coregistration to ambiguity band of 1/10 pixel
- PS-ESD

Coregistration

- ICC if orbits uncertain, refined by or checked with ESD
- ESD if orbits are of sufficient quality (< 1/10 azimuth pixel)
- ICC and ESD are run beam-wise
  - **Apply independent beam-wise corrections**
  - Combine beam-wise estimates for a single global correction

Coregistration Workflow



"Scene Level" Coregistration

Mosaicking at burst, beam or scene level +
Quality Control (ESD)

IWAP Sensor and Imaging Mode Support

- Before: 5 combinations

Sensor and Format	Imaging Mode	Status		
		Import	InSAR	PSI
ERS-1/2 (CEOS, Envisat)	SM	Operational		
Envisat (Envisat)	SM	Operational		
ALOS-PALSAR	SM	Operational		
TerraSAR-X*	SM	Operational		
TerraSAR-X*	SL (+ HS)	Operational		

* TerraSAR-X includes TSX and TDX

IWAP Sensor and Imaging Mode Support

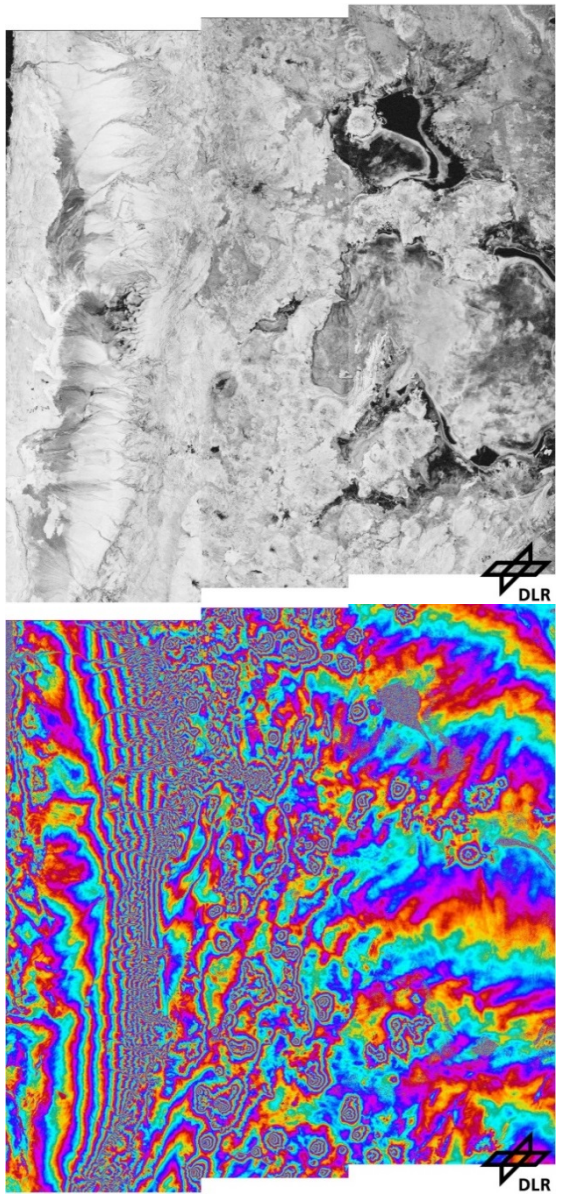
- After: 10 combinations

Sensor and Format	Imaging Mode	Status		
		Import	InSAR	PSI
ERS-1/2 (CEOS, Envisat)	SM	Operational		
Envisat (Envisat)	SM	Operational		
ALOS-PALSAR	SM	Operational		
TerraSAR-X*	SM	Operational		
TerraSAR-X*	SL (+ HS)	Operational		
TerraSAR-X*	ScanSAR (+ Wide ScanSAR)	Operational		Prototype
TerraSAR-X*	TopSAR	Operational		Untested
Sentinel-1	IM (+ EW)	Operational		Untested
Sentinel-1	SM	Operational		Untested
Sentinel-1	WV	Operational	NA	NA

* TerraSAR-X includes TSX and TDX

Experiments

- **RadarSAT-2** (11 infs)
  - **IW TOPSAR**: 2 (InSAR Pairs) + 10 (InSAR Stack)
- TerraSAR-X (~98 infs)
  - TOPSAR: 2
  - ScanSAR: ~95 (PSI Stack)
  - Wide ScanSAR: 1
- Sentinel-1 (~55 infs *from Commisioning Phase*)
  - IW TOPSAR: ~50
  - EW TOPSAR: 2
  - SM: 3
- **Totaling more than 160 burst-mode interferograms**



RadarSAT-2 IW
Salar de Uyuni, 285x302 km

Experiments

- RadarSAT-2 (11 infs)
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- **TerraSAR-X** (~98 infs)
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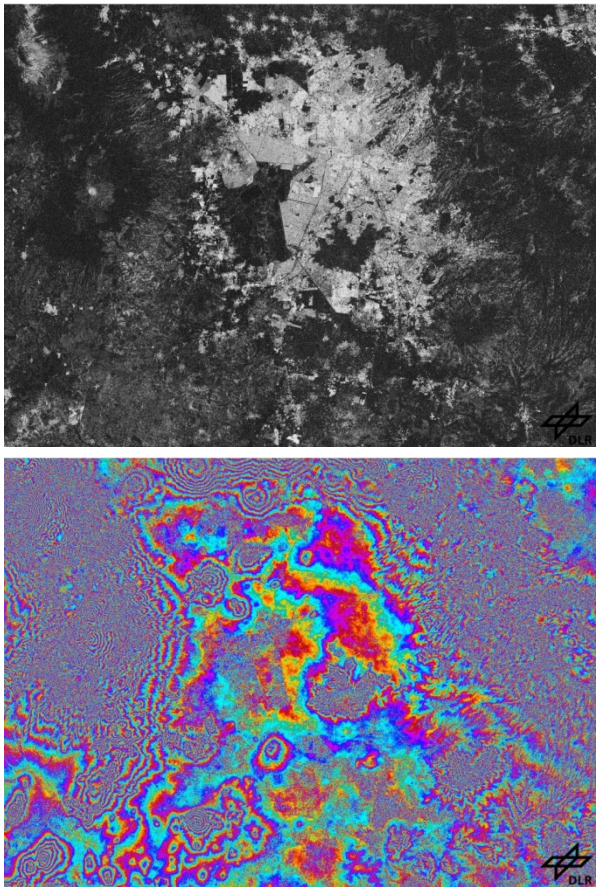

TerraSAR-X TOPSAR
Mexico City, 107x81 km

Experiments

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- **TerraSAR-X** (~98 infs)
  - TOPSAR: 2
  - **ScanSAR**: ~95 (PSI Stack)
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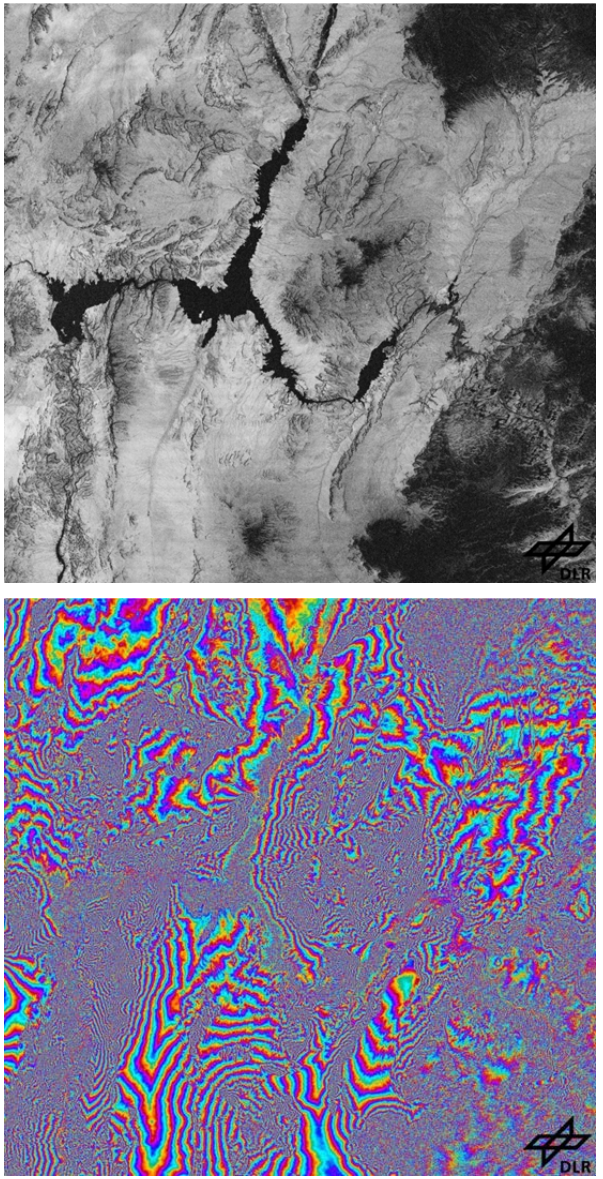

TerraSAR-X ScanSAR
Hoover Dam, 103x99 km

Experiments

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- **TerraSAR-X** (~98 infs)
  - TOPSAR: 2
  - ScanSAR: ~95 (PSI Stack)
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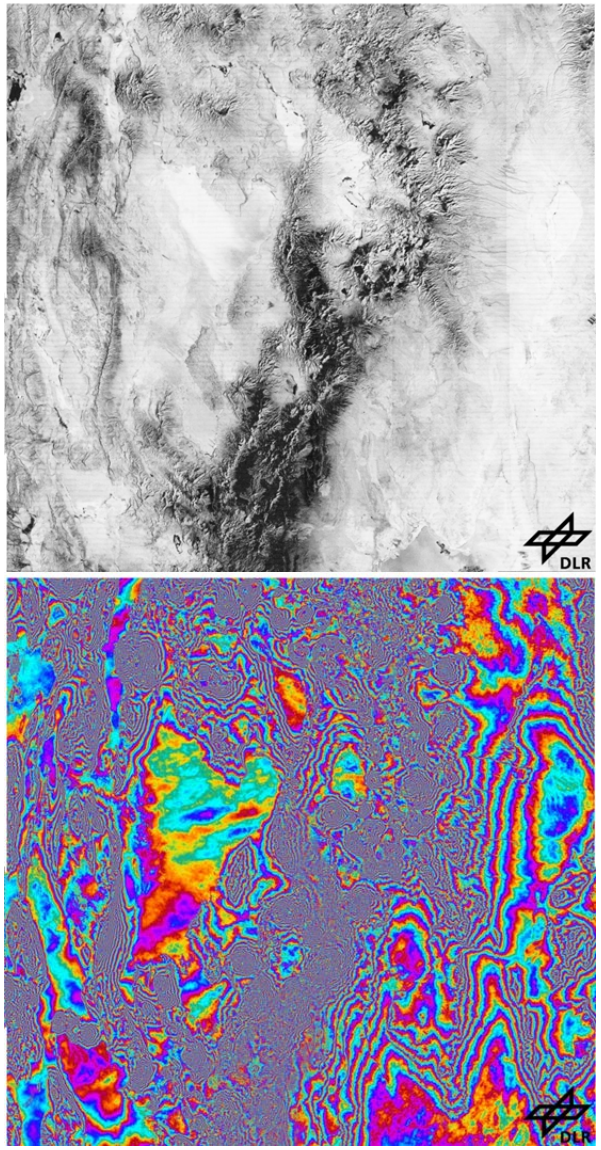
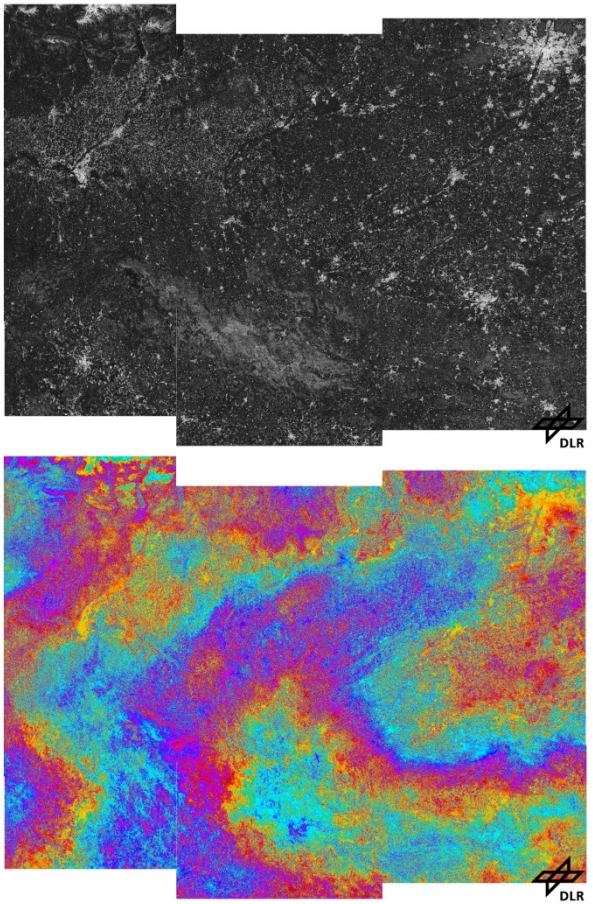


TerraSAR-X Wide ScanSAR
Salar de Arizaro, 220x206 km

Experiments

- RadarSAT-2 (11 infs)
  - IW TOPSAR: 2 (InSAR Pairs) + 10 (InSAR Stack)
- TerraSAR-X (~98 infs)
  - TOPSAR: 2
  - ScanSAR: ~95 (PSI Stack)
  - Wide ScanSAR: 1
- **Sentinel-1** (~55 infs *from Commisioning Phase*)
  - **IW TOPSAR**: ~50
  - EW TOPSAR: 2
  - SM: 3
- **Totaling more than 160 burst-mode interferograms**



Sentinel-1 IW
Munich, 250x170 km

Experiments

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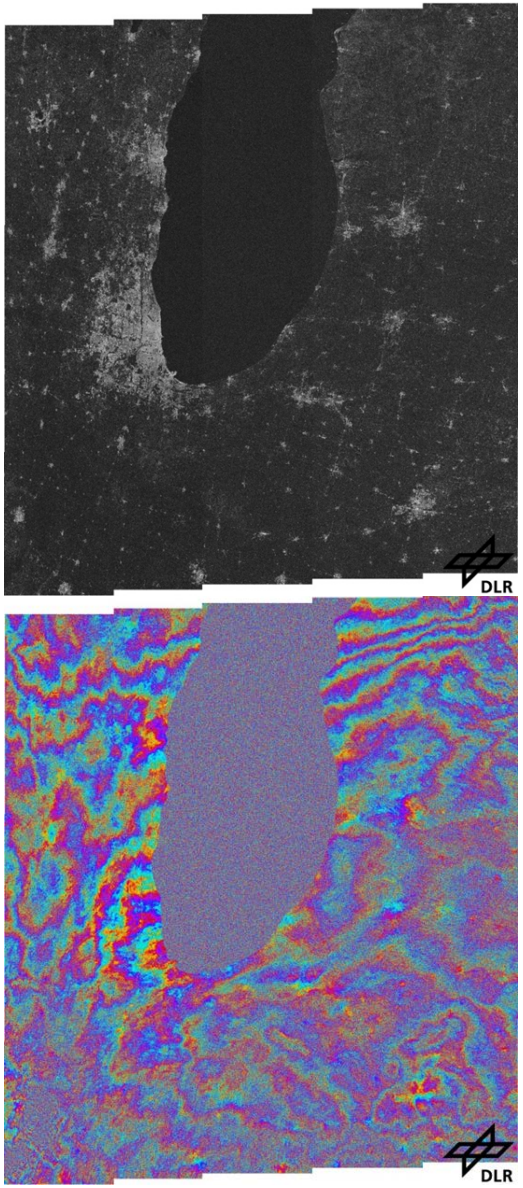
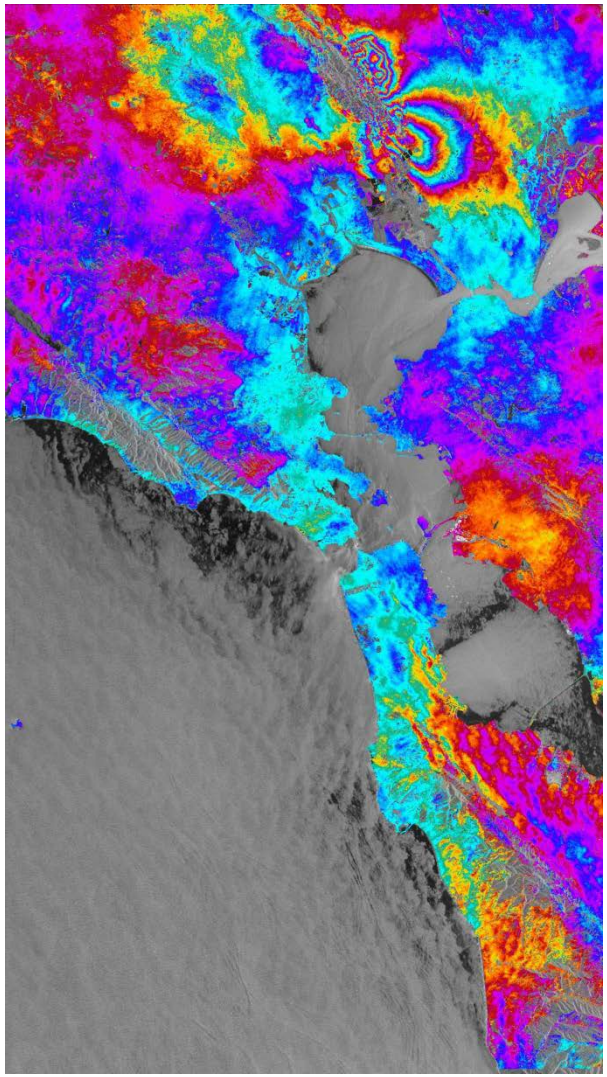
  - IW TOPSAR: 2 (InSAR Pairs) + 10 (InSAR Stack)
- TerraSAR-X (~98 infs)
  - TOPSAR: 2
  - ScanSAR: ~95 (PSI Stack)
  - Wide ScanSAR: 1
- **Sentinel-1** (~55 infs *from Commisioning Phase*)
  - IW TOPSAR: ~50
  - **EW TOPSAR**: 2
  - SM: 3
- **Totaling more than 160 burst-mode interferograms**



Sentinel-1 EW
Chicago, 384x431 km

Experiments

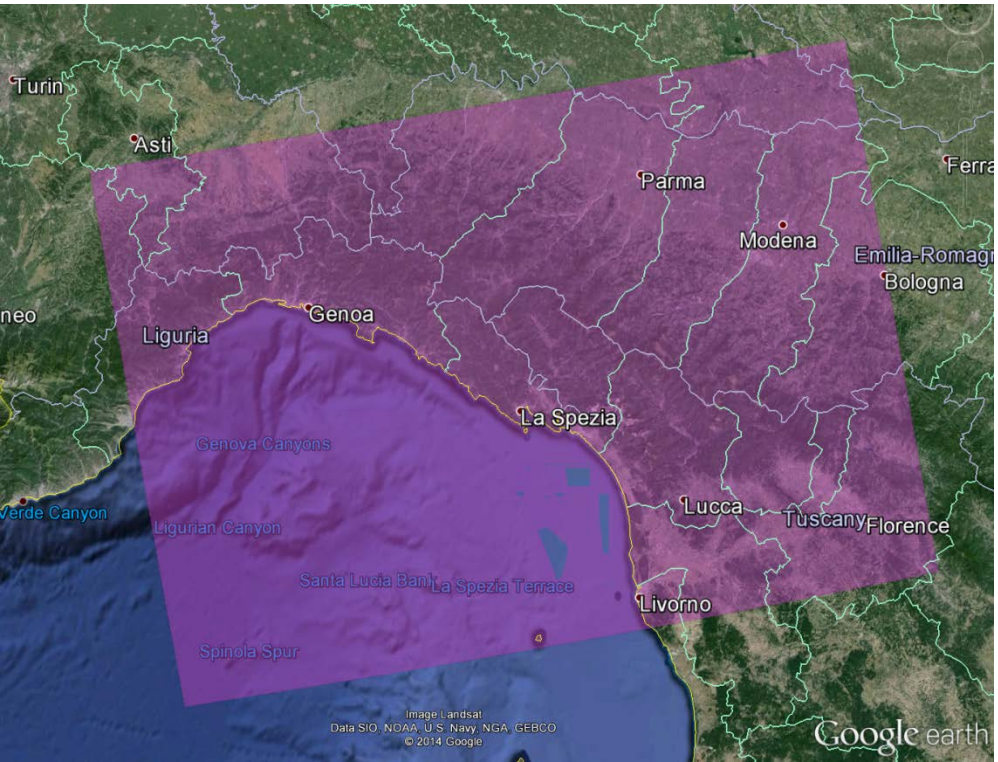
- RadarSAT-2 (11 infs)
  - IW TOPSAR: 2 (InSAR Pairs) + 10 (InSAR Stack)
- TerraSAR-X (~98 infs)
  - TOPSAR: 2
  - ScanSAR: ~95 (PSI Stack)
  - Wide ScanSAR: 1
- **Sentinel-1** (~55 infs *from Commisioning Phase*)
  - IW TOPSAR: ~50
  - EW TOPSAR: 2
  - **SM**: 3
- **Totaling more than 160 burst-mode interferograms**

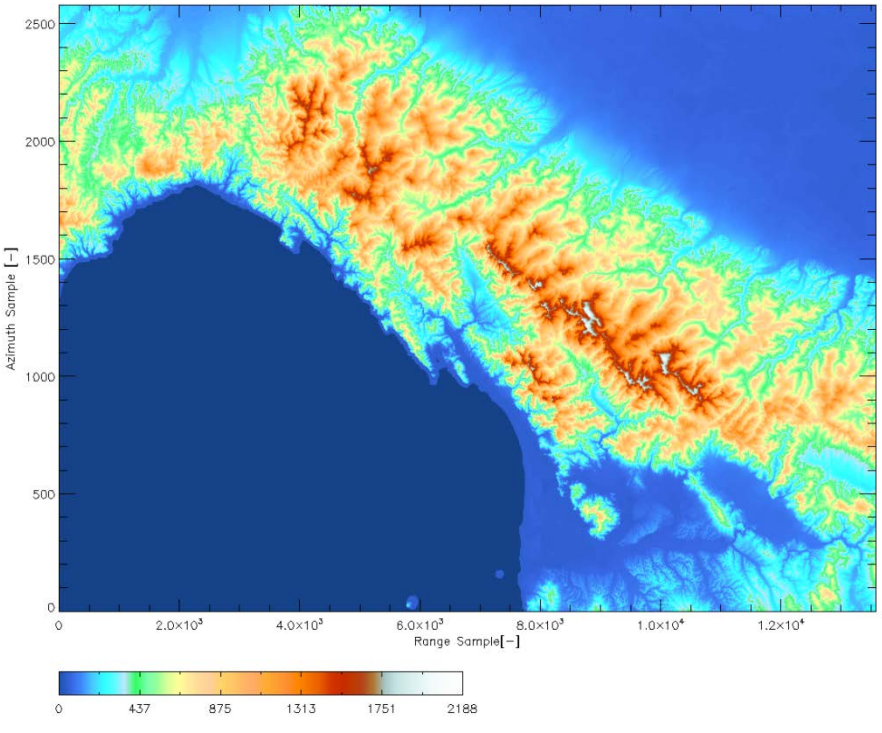


Sentinel-1 SM
Napa Earthquake, 80x130 km

Sentinel-1 – IW TOPSAR, Genoa

- Acquisition lies over north-west Italy
- Elevation reaches 2000 m
- Urban areas, plains, ocean, forested mountains



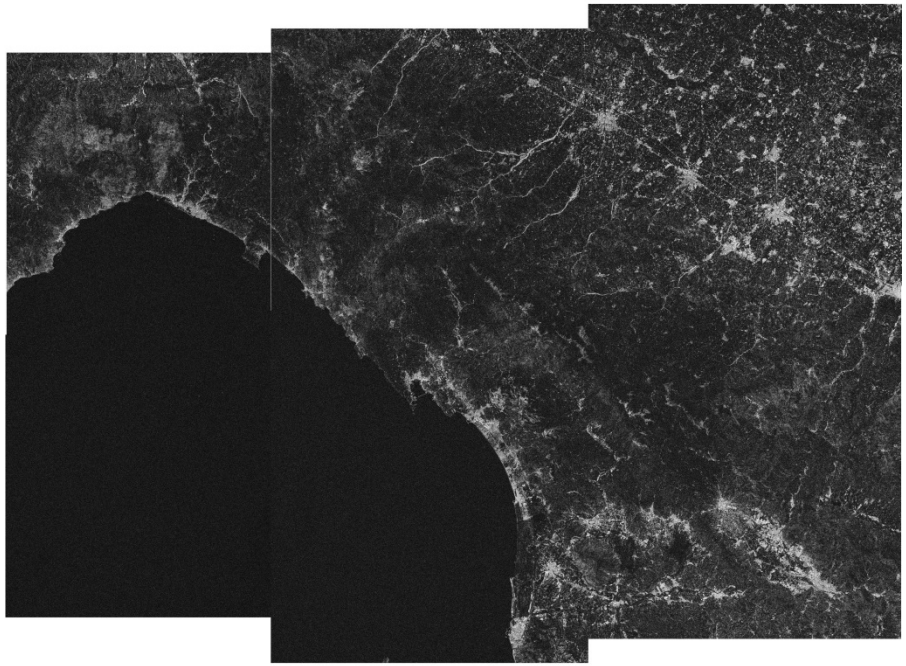


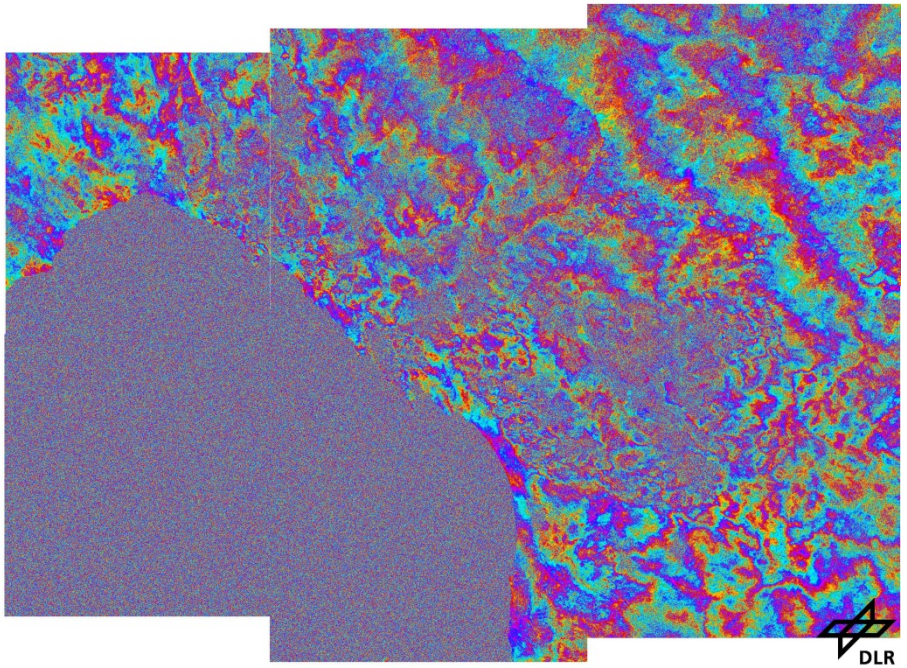
Sentinel-1 – IW TOPSAR, Genoa

- 3 Beams, 9 Bursts
- ICC coregistration + ESD quality control
- No visible discontinuities

Master Date	19-08-2014
Slave Date	07-08-2014 (12 days)
Mode	IW
Resolution	4.5 m x 20.9 m (Burst 1, Beam 1)
Extension	249 km x 179 km
Polarisation	VV
Orbit Direction	Ascending
Effective Baseline	121.4 m avg.
Height of Ambiguity	128.5 m avg.
Incidence Angle	30.5° – 45.9° (15.4°)
Average Coherence	0.17

DEM Corrected Interferometric Coherence and Phase

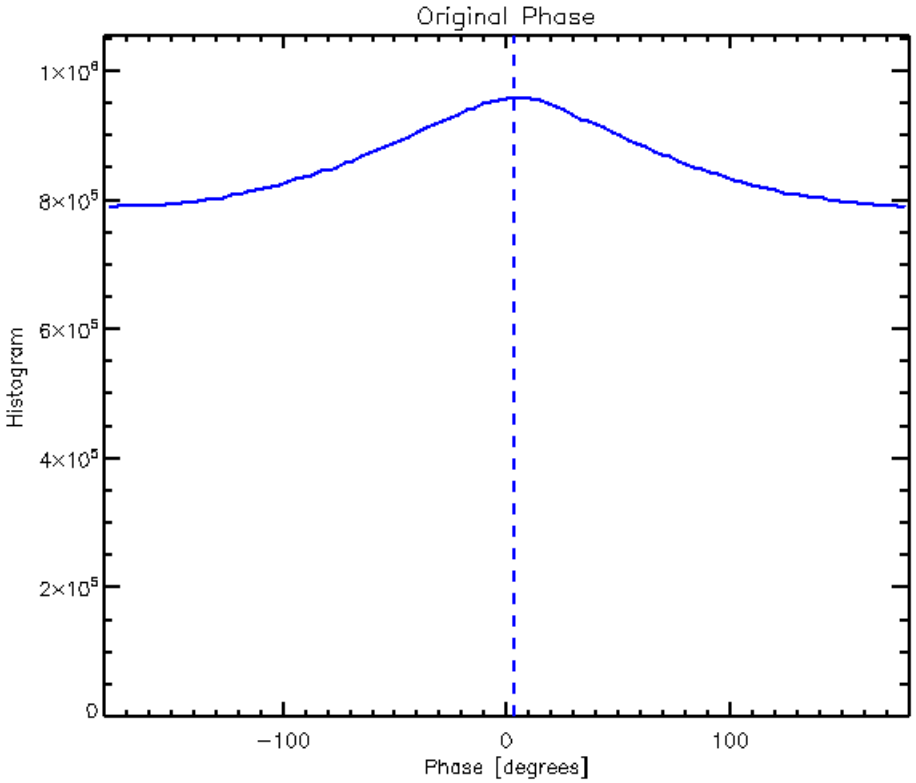


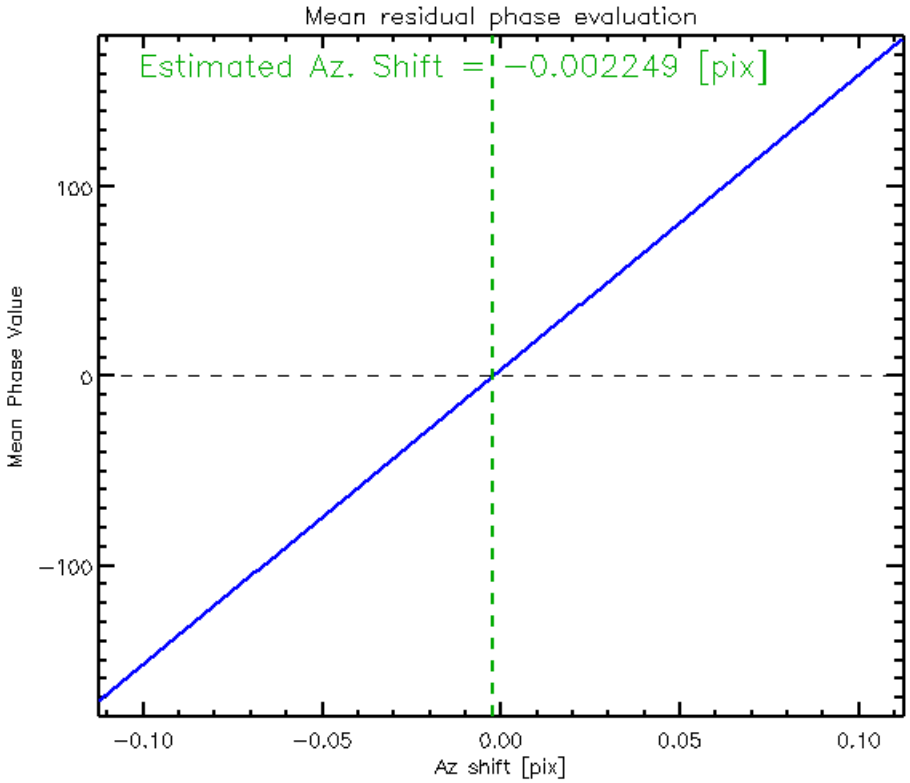


DLR

Sentinel-1 – IW TOPSAR, Genoa

- ESD Quality Control runs after ICC
- Agreement to 1 milli-pixel (OSF=2)

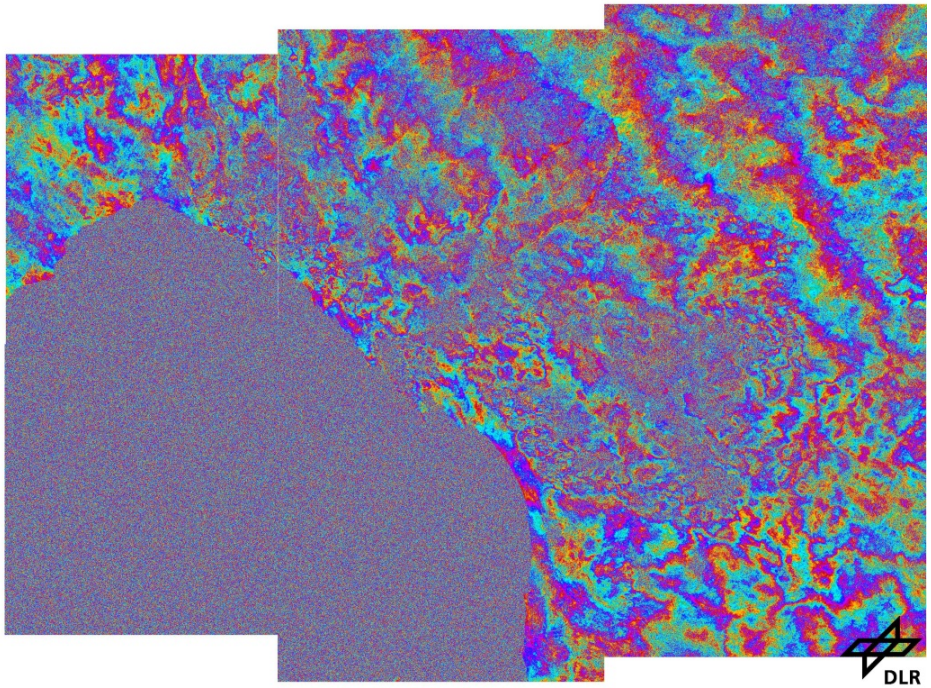




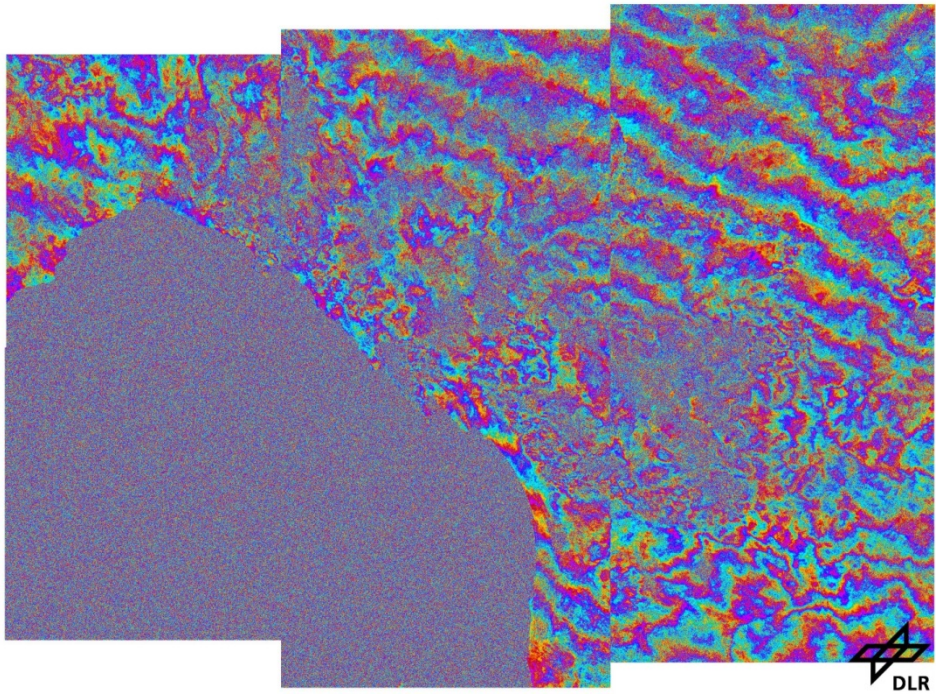
Sentinel-1 – IW TOPSAR, Genoa

DEM Corrected Interferometric Phase

ICC Coregistration



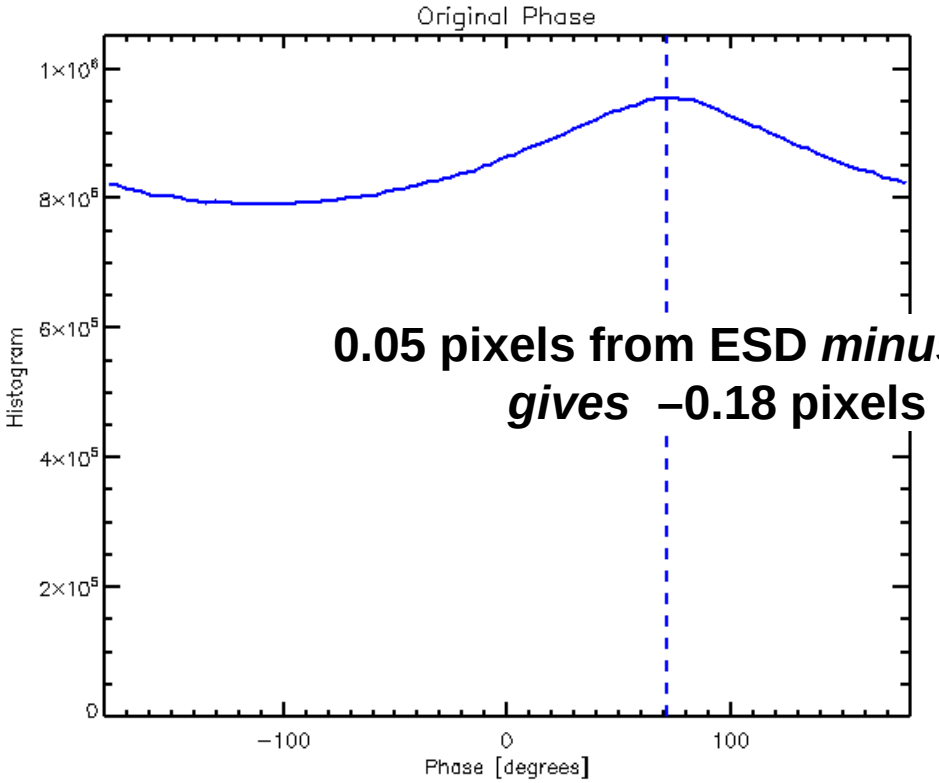
ESD Coregistration

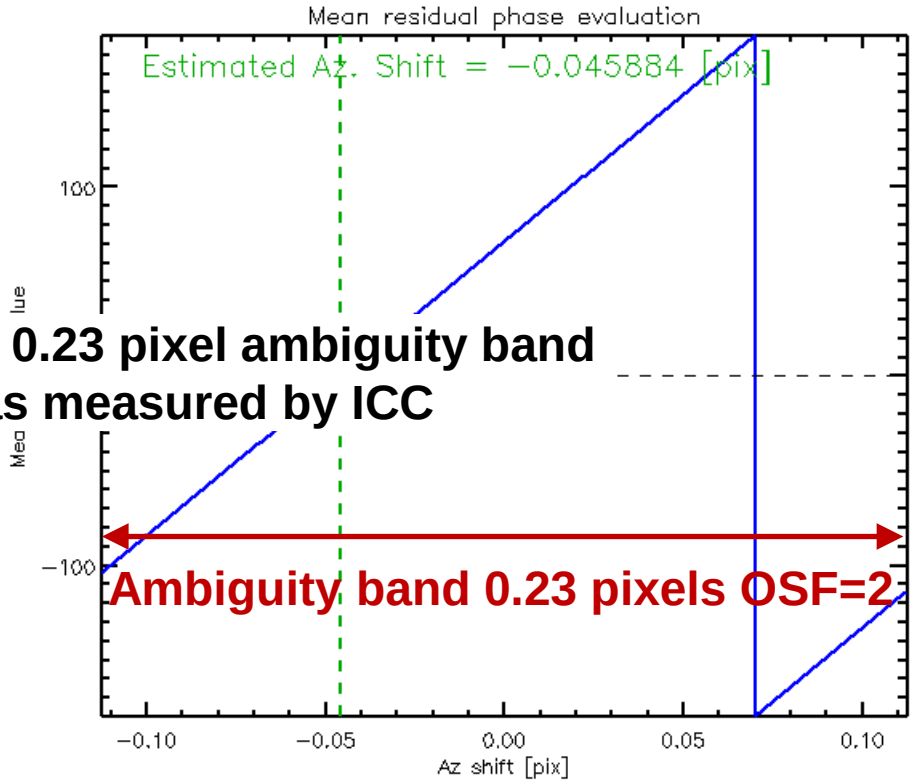


Sentinel-1 – IW TOPSAR, Genoa

ICC Coregistration, ICC Shift = -0.18 pixels

ESD Coregistration, ESD Shift = 0.05 pixels





0.05 pixels from ESD *minus* 0.23 pixel ambiguity band
***gives* –0.18 pixels as measured by ICC**

Ambiguity band 0.23 pixels OSF=2

Enhanced Spectral Diversity Ambiguity Band

- Phase of differential interferogram between bursts **within burst overlap area**

$$\phi = \frac{2\pi \Delta f_{DC} \Delta_{AZ}}{PRF}$$

P. Prats-Iraola, R. Scheiber, L. Marotti, S. Wollstadt, A. Reigber, *"TOPS Interferometry with TerraSAR-X,"* IEEE TGRS, vol. 50, no. 8, 2012.

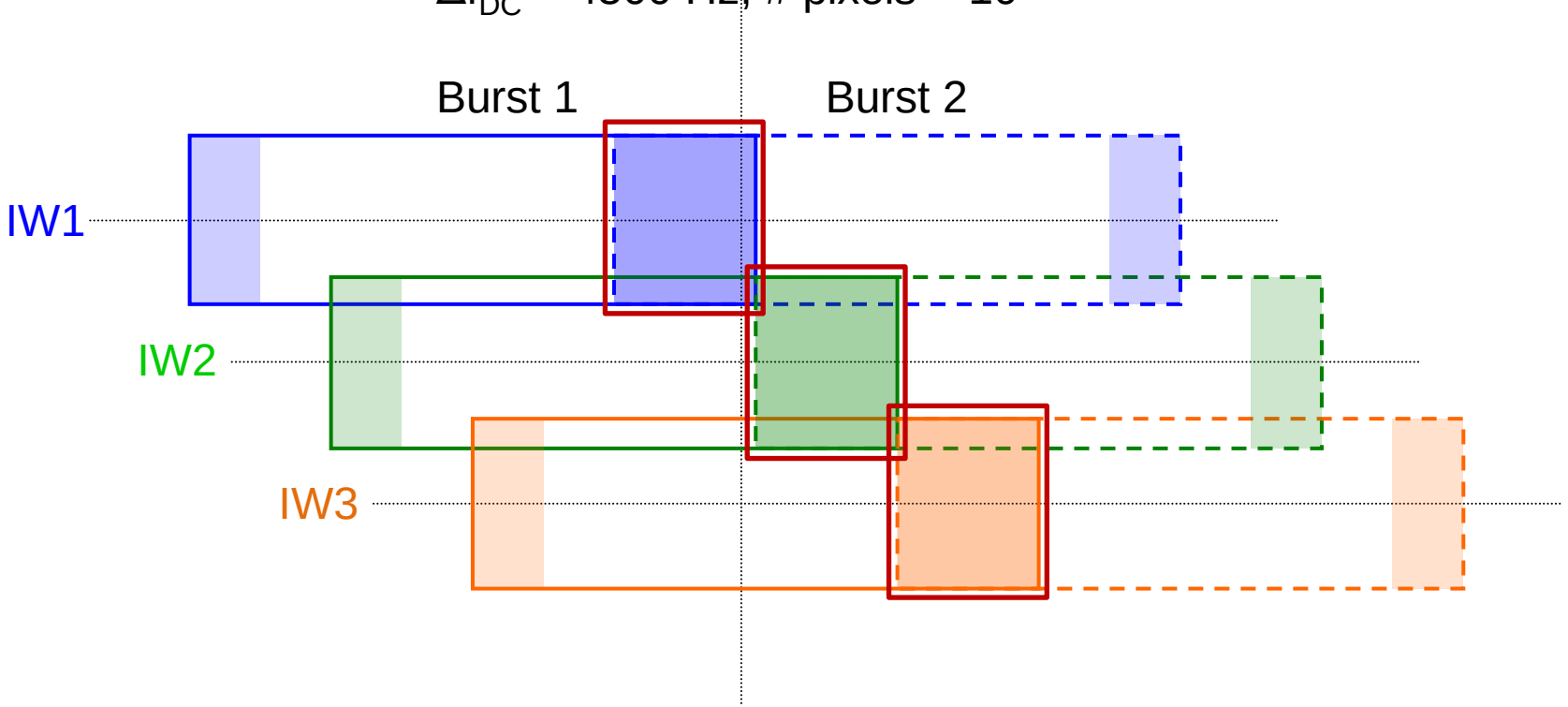
- Δf_{DC}: Doppler centroid difference between bursts
- Δ_{AZ}: Azimuth pixel misregistration
- PRF: Pulse repetition frequency

- ESD ambiguity band for Sentinel-1 IW mode ~ **0.1** azimuth pixels

- Requires *a priori* coregistration to better than **1/10 pixels**

ESD: Overlap Between Bursts 1

“Burstwise”
consecutive bursts within a beam
Δf_{DC} = 4500 Hz, # pixels = 10^7

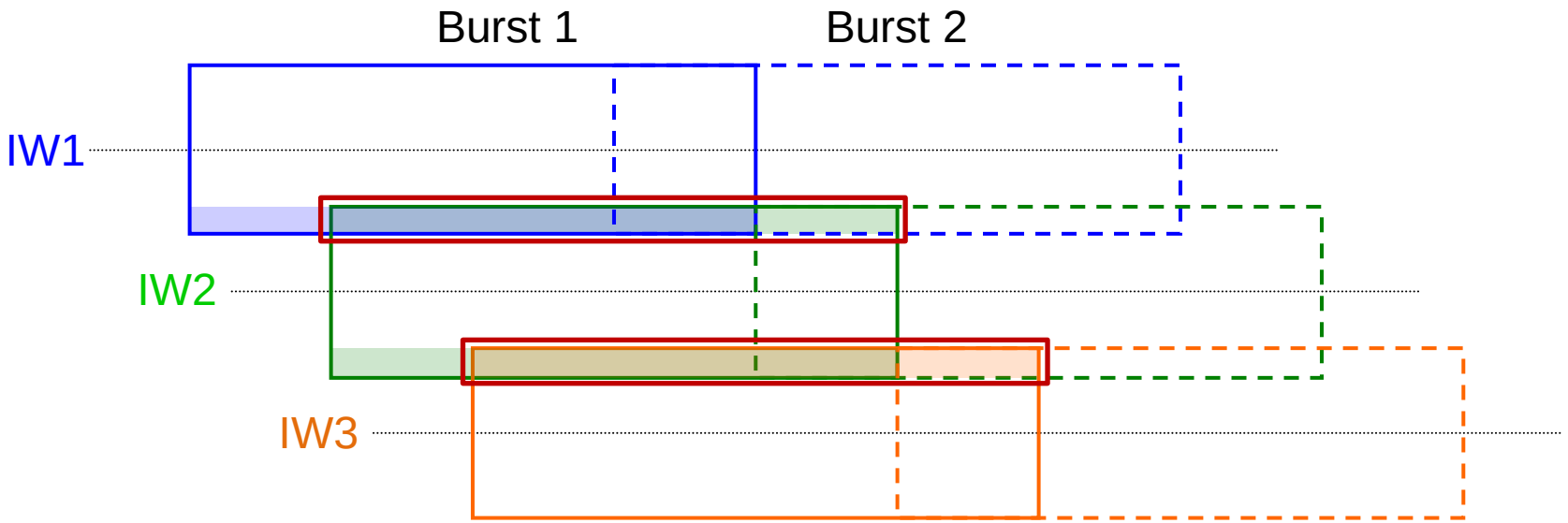


ESD: Overlap Between Bursts 2

“Beamwise Forward”

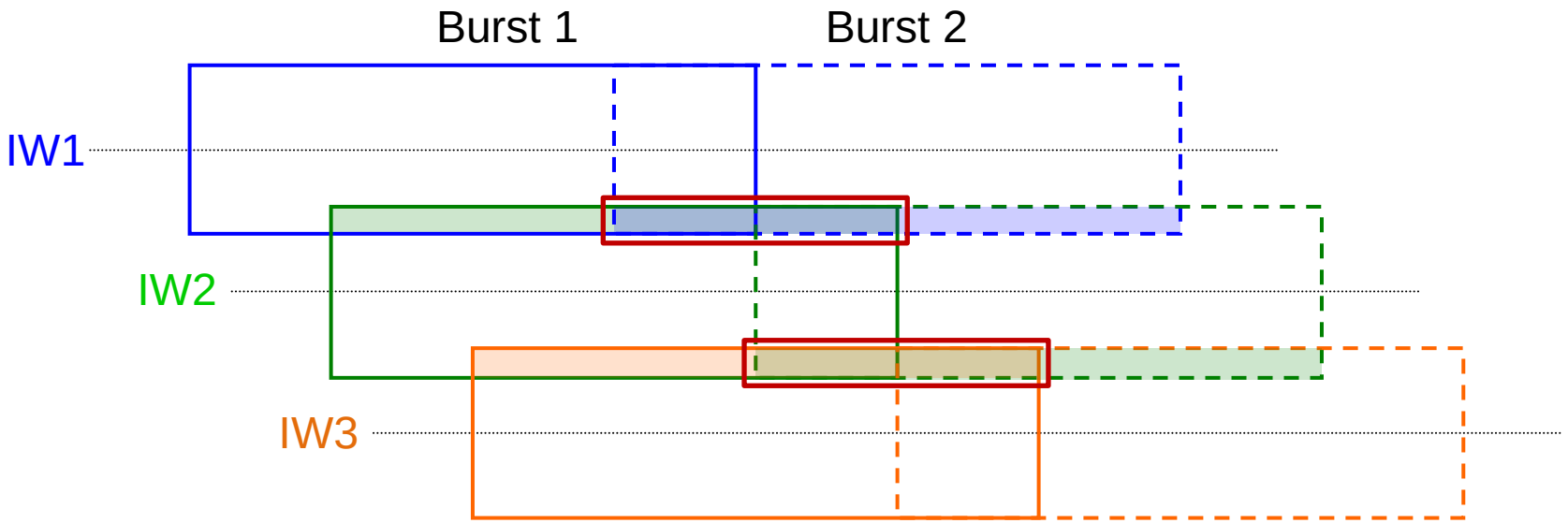
“same” bursts in consecutive beams

Δf_{DC} = 1500 Hz, # pixels = 10^6



ESD: Overlap Between Bursts 3

“Beamwise Backward”
consecutive bursts in consecutive beams
Δf_{DC} = 3000 Hz, # pixels = 10^6



ESD: Resolving the Ambiguity Band

- Basic ESD relation

$$\phi_i = \frac{2\pi \Delta f_{DC,i} \Delta_{AZ}}{PRF}$$

- Method 1: applied pixelwise to any type/combination of burst overlap

$$\widehat{\Delta_{AZ}} = \underset{\Delta_{AZ}}{\operatorname{argmin}} \left| \arg \sum_i e^{-j\tilde{\phi}_i} \right| \qquad \tilde{\phi}_i = \phi_i - \frac{2\pi \Delta f_{DC,i} \Delta_{AZ}}{PRF}$$

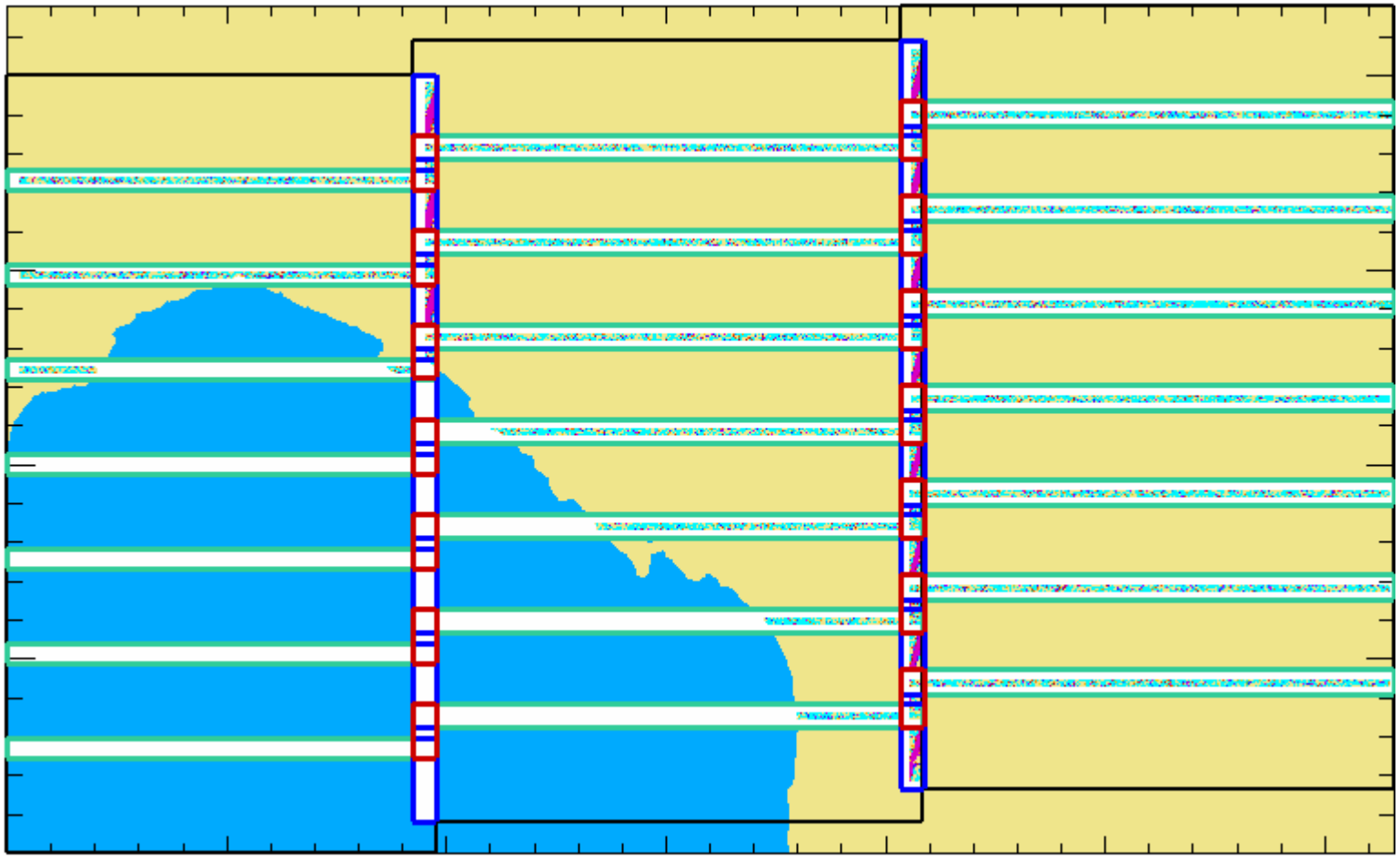
- Method 2: only to combine estimates from Method-1 from different burst overlap types, e.g. IW1 between bursts + IW1/IW2 between beams

$$\widehat{\Delta_{AZ}} = \underset{\Delta_{AZ}}{\operatorname{argmin}} \sum_i W^2\{\tilde{\phi}_i\}$$

- Combining different types of burst overlap, *each with a different ambiguity band*, leads to a larger ambiguity band.

Genoa Revisited

ICC Shift 0.18, Ambiguity Band ±0.1 (OSF=2)



Genoa Revisited

ICC Shift 0.18

Burstwise

IW1	IW2	IW3	All	Ambiguity Band
-0.016	-0.058	-0.046	-0.045	**~0.2**

Wrapping

Beamwise Forward

IW1/IW2	IW2/IW3	All	Ambiguity Band
0.18	0.18	0.18	**~0.6**

Correct

Beamwise Backward

IW1/IW2	IW2/IW3	All	Ambiguity Band
0.097	-0.11	-0.081	**~0.3**

Wrapping

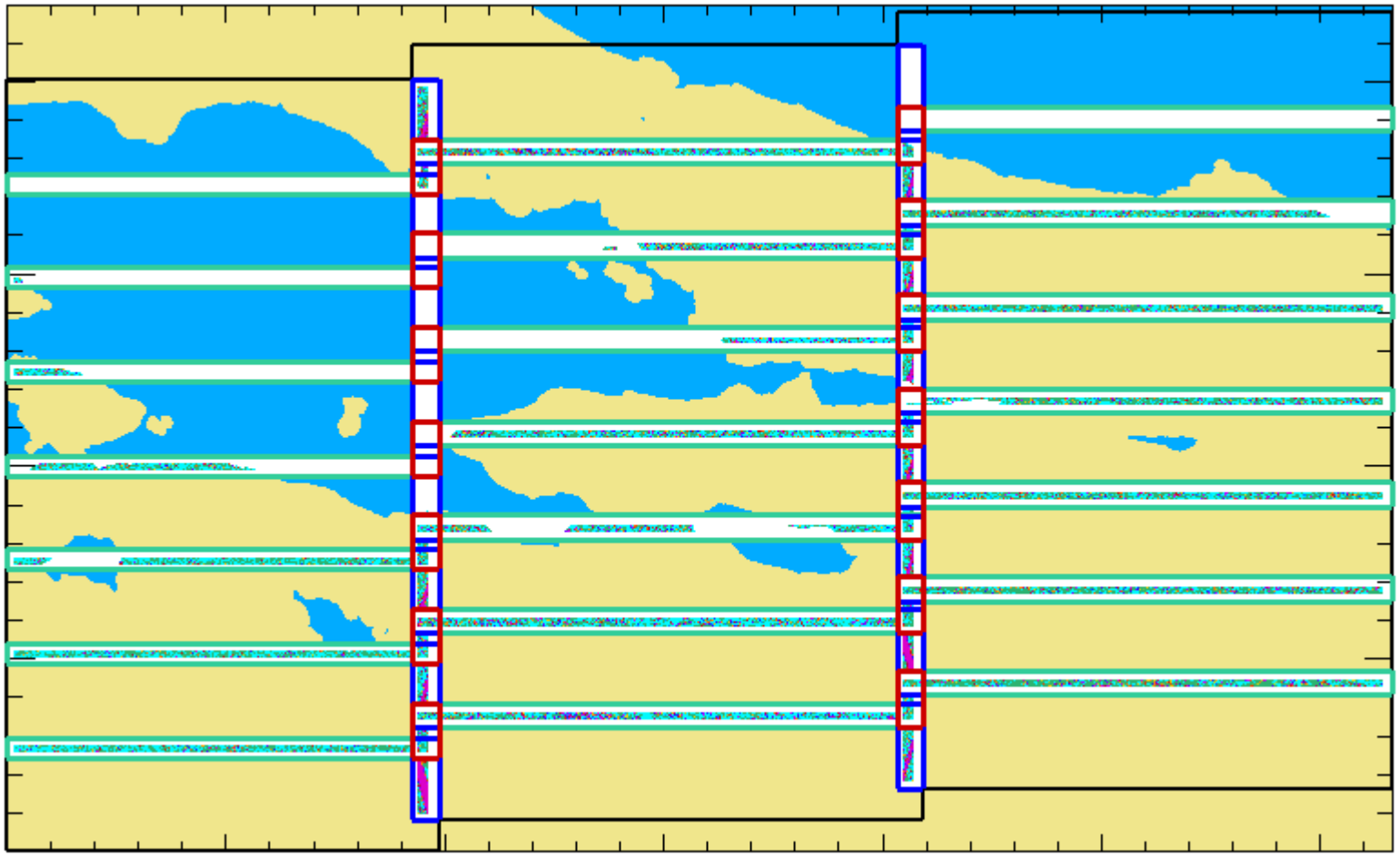
All overlap areas in Beam / Scene

IW1	IW2	IW3	All	Ambiguity Band
0.19	0.19	0.19	0.19	**N/A**

Correct

Istanbul

ICC Shift 0.71, Ambiguity Band ±0.1 (OSF=2)



Istanbul

ICC Shift 0.71

Burstwise

IW1	IW2	IW3	Ambiguity Band
-0.098	-0.015	0.022	**~0.2**

Wrapping

Beamwise Forward

IW1/IW2	IW2/IW3	Ambiguity Band
0.068	0.035	**~0.6**

Wrapping

Beamwise Backward

IW1/IW2	IW2/IW3	Ambiguity Band
0.026	-0.050	**~0.3**

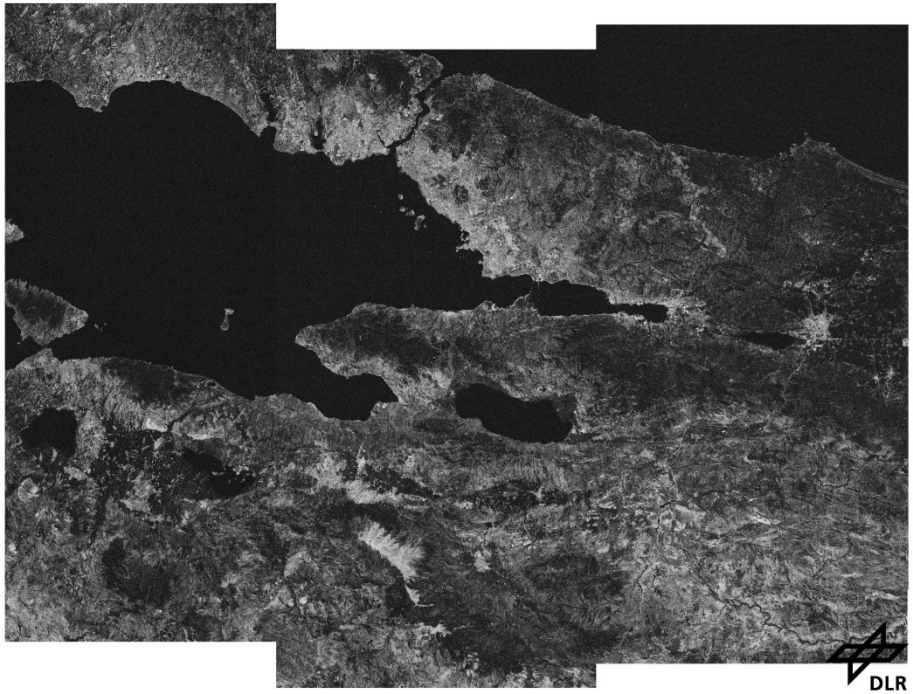
Wrapping

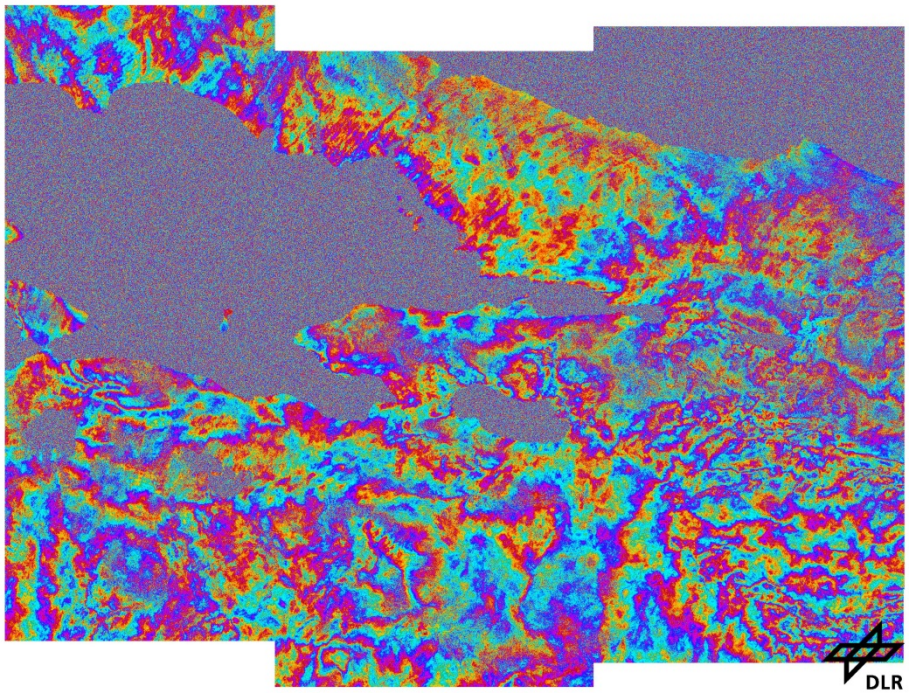
All overlap areas in Beam / Scene

IW1	IW2	IW3	Ambiguity Band
0.71	0.71	0.71	**N/A**

Correct

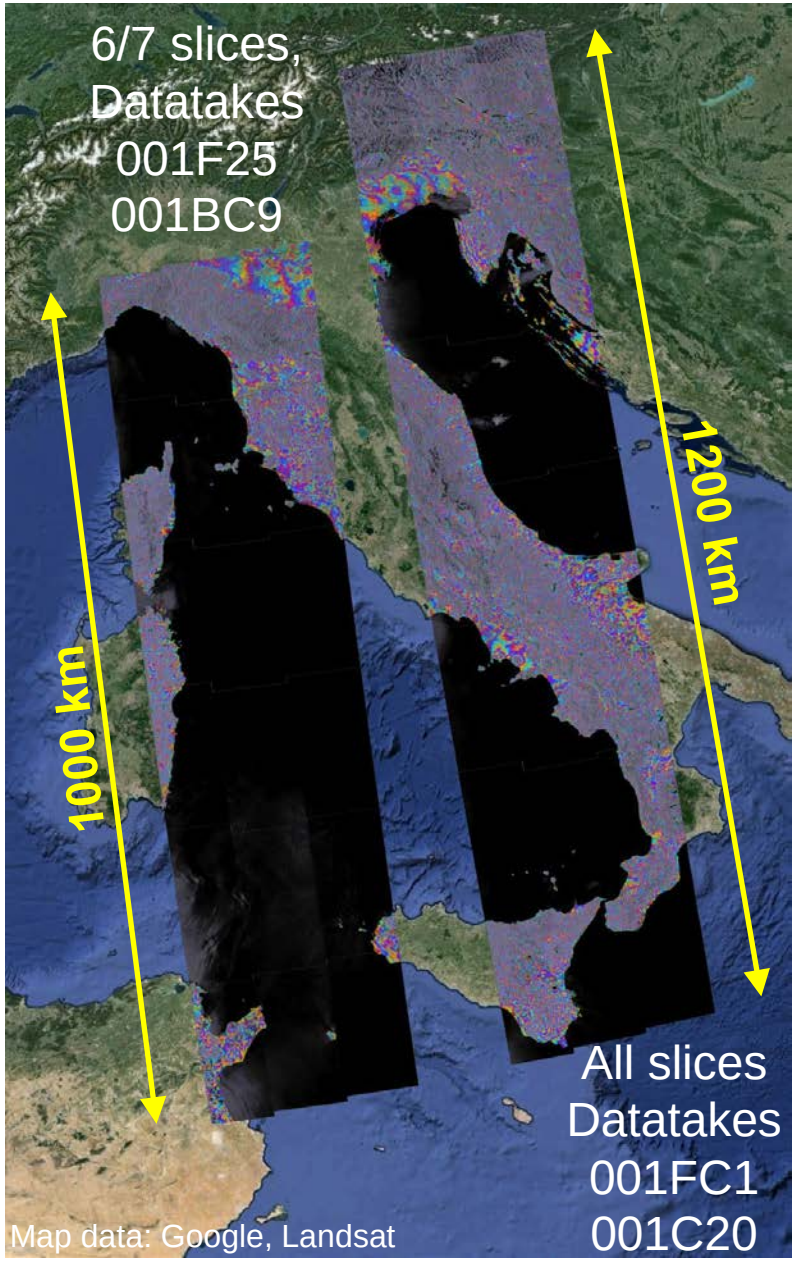
Istanbul – DEM Corrected Interferogram





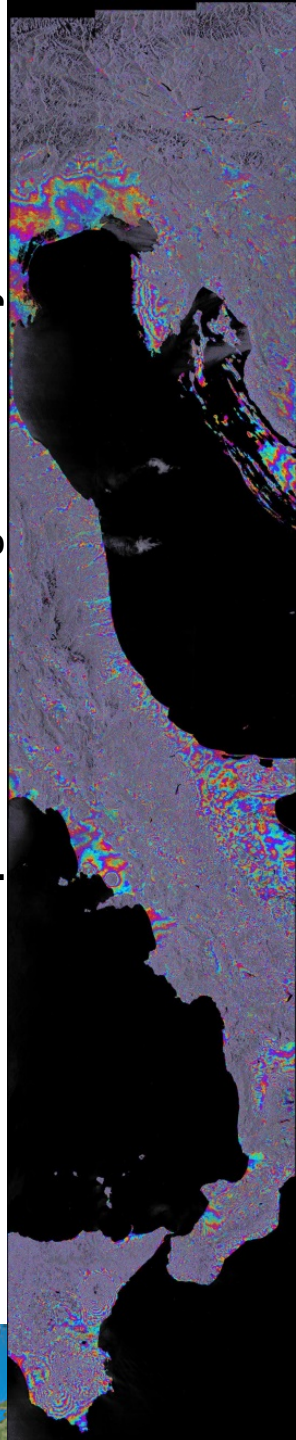
Slice Mosaicking

- An L0 datatake may be packaged as L1 slice products (IW mode)
- All slices are processed with the same parameters on a common grid
- IW slice products were interferometrically processed using IWAP and then mosaicked
- Could also mosaic L1 slice products and then perform InSAR processing → datatake level coregistration

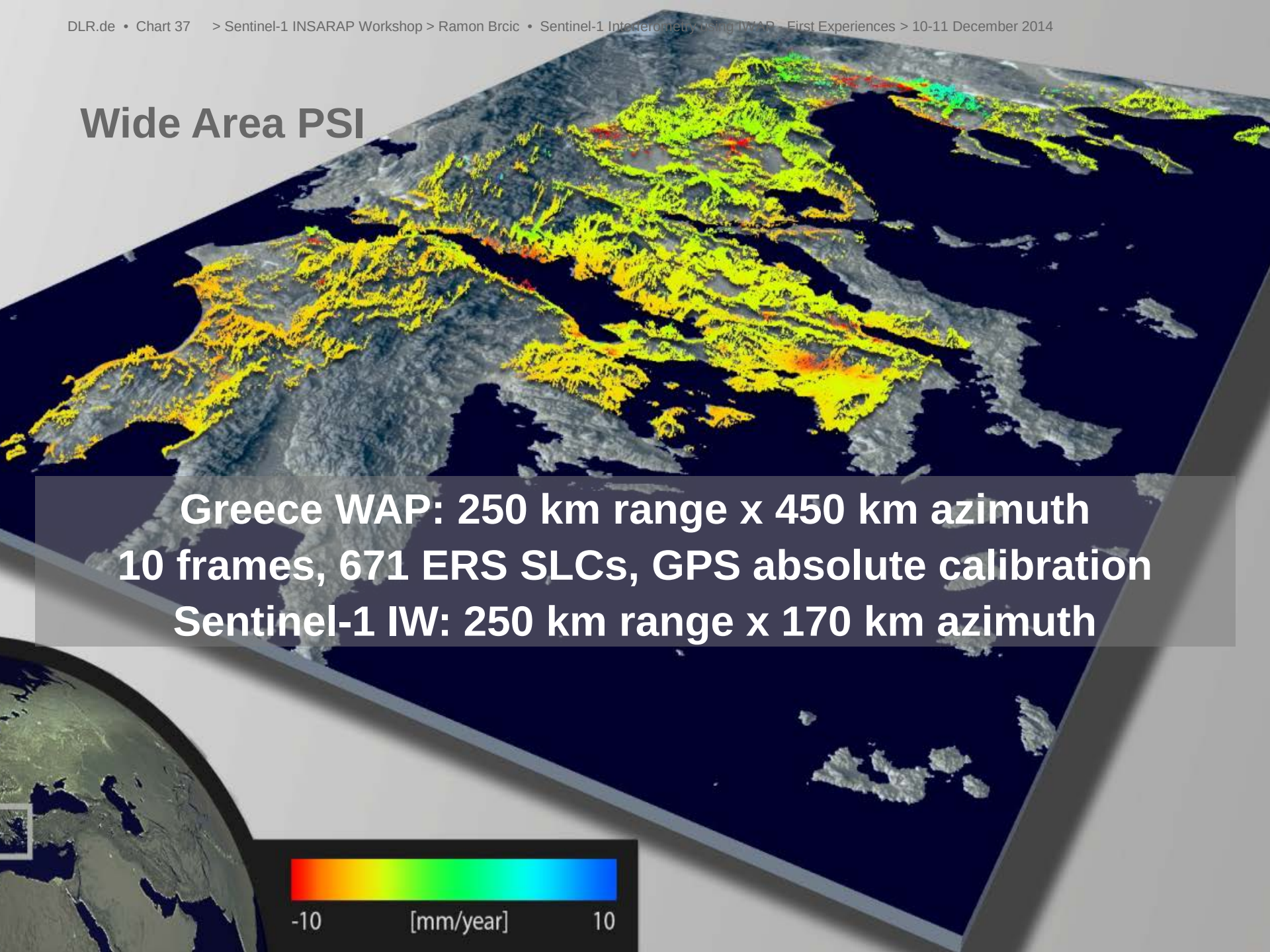


Remarks

- Correction of FEP or DEM phase must be consistent
- Varying local height between slices for FEP calculation → phase jumps
- No approximations in DEM corrected interferogram → no phase jumps



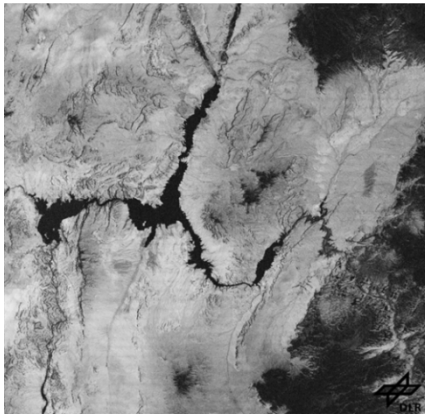
Wide Area PSI

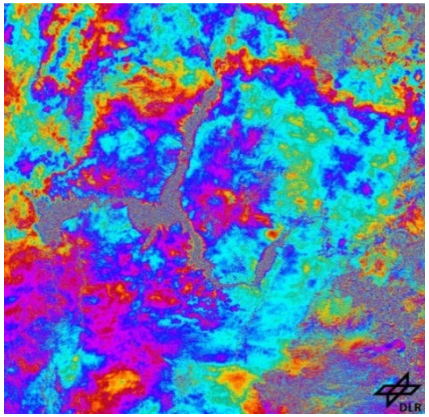


Greece WAP: 250 km range x 450 km azimuth
10 frames, 671 ERS SLCs, GPS absolute calibration
Sentinel-1 IW: 250 km range x 170 km azimuth

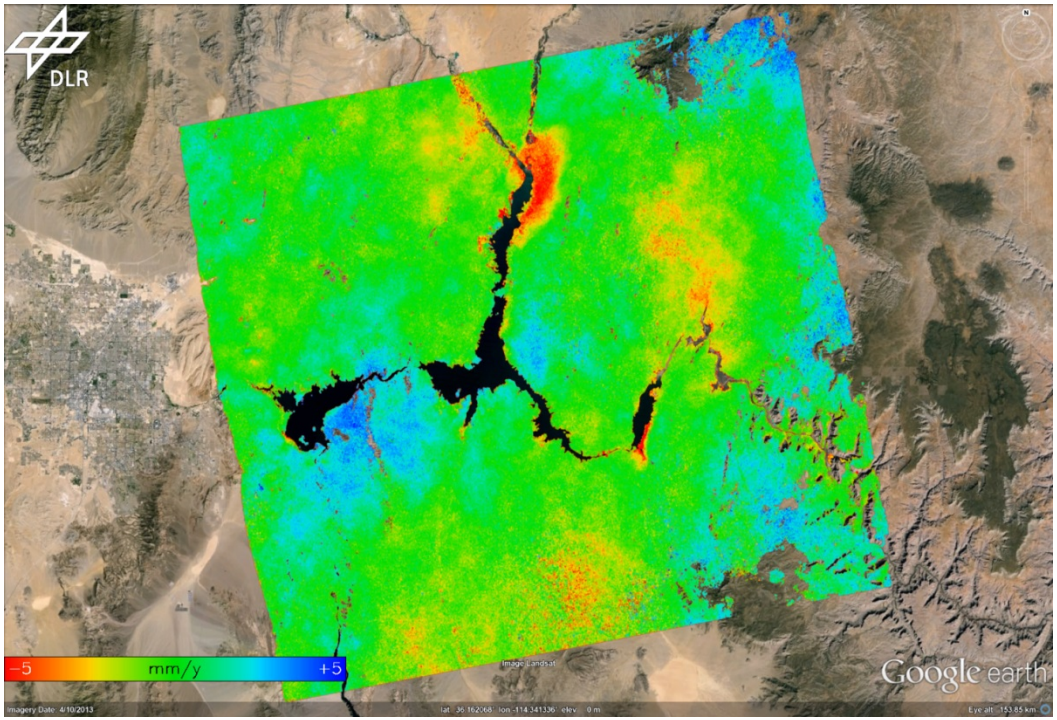
TerraSAR-X ScanSAR PSI – Hoover Dam, USA

- 65 images
- Timespan: Aug 2008 – Jan 2011
- Ground res: 3.8 m x 15.0 m
- Extension: 103 km x 99 km
- Polarisation: VV
- Incidence angle: 19.7° – 30.3°





DEM corrected coherence and phase
Master: 10-12-2009, Slave: 29-11-2009



Linear deformation (ramp compensated)

Conclusion

- IWAP adapted to process burst-mode acquisitions
  - TOPSAR
  - (Wide) ScanSAR
- Uses a combination of ICC and ESD coregistration
- Successful InSAR processing for all burst-modes on more than 160 interferograms
- Proposed method for ESD ambiguity band determination to make coregistration simpler and more robust

Future Work

- Use all slices within a datatake for a better coregistration?
- Further investigate the potential of ESD using all burst overlap regions
  - Sufficient for all orbit types (annotated, restituted, precise)?
  - Is ICC still necessary?
  - Is a simple a priori coregistration (aside from geometric) still necessary?
- Sentinel-1 IW PSI on a sufficiently sized stack