sentinel-1

→ RADAR VISION FOR COPERNICUS

Sentinel-1 Constellation

SAR Interferometry Performance Verification

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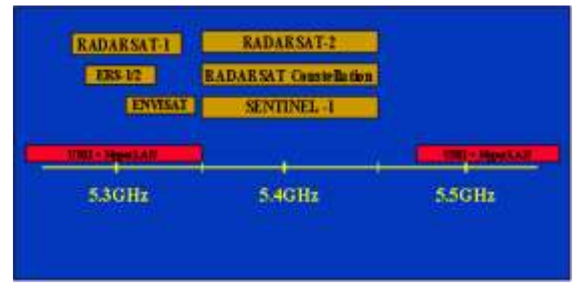
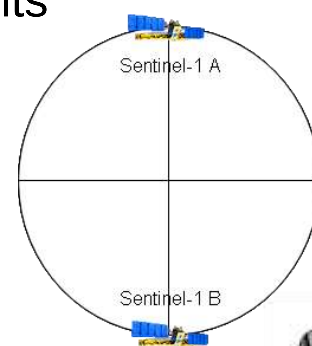
Sentinel–1 Mission Facts

- Constellation of two satellites (A & B units)
- Sentinel-1A launched on 3 April, 2014 & Sentinel-1B on 25 April, 2016
- C-Band Synthetic Aperture Radar Payload (at 5.405 GHz)
- 7 years design life time with consumables for 12 years
- Near-Polar, sun-synchronous (dawn-dusk) orbit at 698 km
- *12 days* repeat cycle (1 satellite), *6 days* for the constellation
- 3 X-band Ground Stations (Svalbard, Matera, Maspalomas) + one planned for Inuvik, Canada + Collaborative Ground Segments



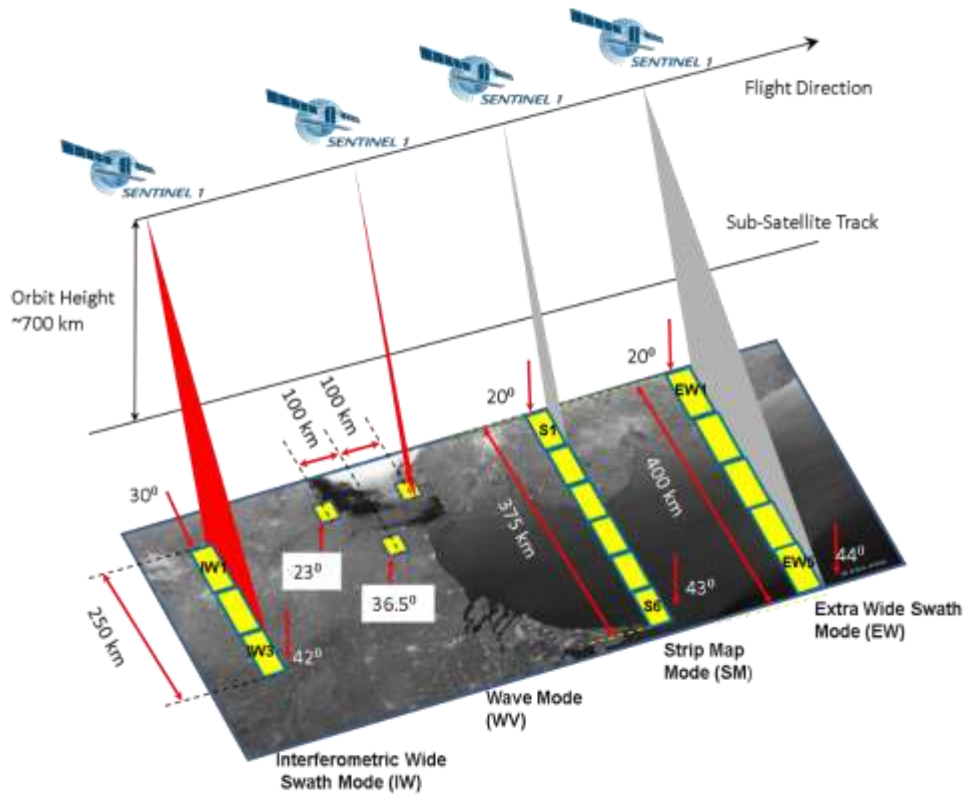
- On-board data latency (i.e. downlink):
  - max 200 min (2 orbits)
  - One orbit for support of near real time (3h) applications
  - Simultaneous SAR acquisition and data downlink for real time applications



- Optical Communication Payload (OCP) for data transfer via laser link with the GEO European Data Relay Satellite (EDRS)

Sentinel-1 SAR Imaging Modes

- SAR Instrument provides *4 exclusive SAR modes* with different resolution and coverage



- *Interferometric Wide Swath (IW) mode* for land & coastal area monitoring
- *Extra Wide Swath* (EW) mode for sea-ice monitoring and maritime surveillance
- *Wave (WV)* mode is continuously operated over open ocean

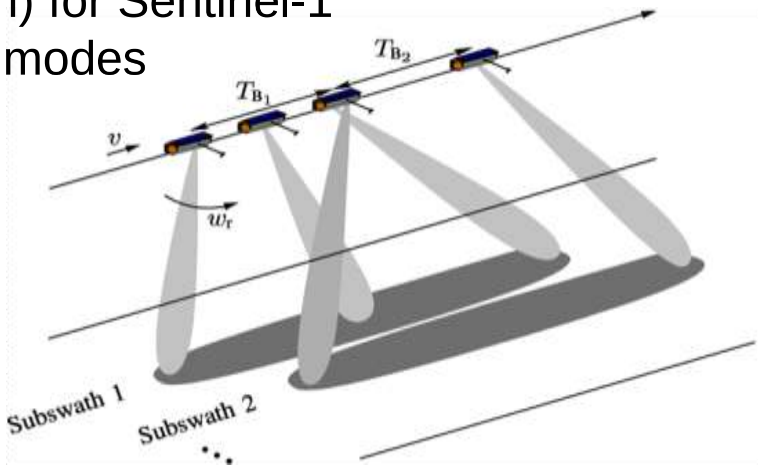
- SAR duty cycle per orbit:
  - ✓ up to *25 min* in any imaging mode
  - ✓ up to *74 min* in Wave mode

Mode	Incidence Angle	Single Look Resolution	Swath Width	Polarisation
Interferometric Wide Swath (IW 1-3)	30-42 deg.	Range 5 m Azimuth 20 m	250 km	HH+HV or VV+VH
Wave mode WV1 WV2	23 deg. 36.5 deg.	Range 5 m Azimuth 5 m	20 x 20 km Vignettes at 100 km intervals	HH or VV
Strip Map S1-S6	20-43 deg.	Range 5 m Azimuth 5 m	80 km	HH+HV or VV+VH
Extra Wide Swath (EW 1-5)	20-44 deg.	Range 20 m Azimuth 40 m	400 km	HH+HV or VV+VH

- Polarisation schemes for *IW, EW & SM*:
  - ✓ single pol: HH or VV
  - ✓ dual pol: HH+HV or VV+VH
- Wave mode (WV): HH or VV

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

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

Duration of IW bursts:

IW1: 0.8s

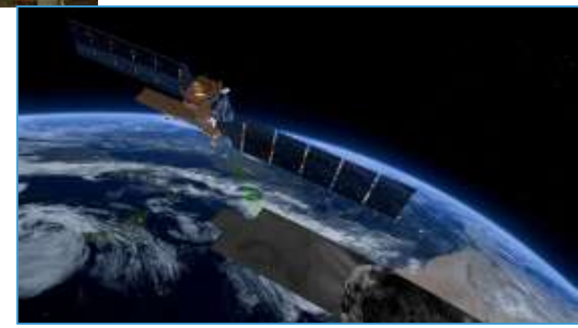
IW2: 1.06s

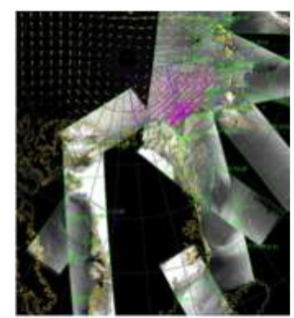
IW3: 0.83s

Sentinel-1A Mission Status

- Sentinel-1A launched on 3 April, 2014 on Soyuz from Kourou
- Nominal orbit reached on 7 August, 2014
- Sentinel-1A In-Orbit Commissioning completed on 23 Sept., 2014
- 12 orbit collision avoidance manoeuvres up to now
- 1 Electronic Front End (EFE) failure (out of 140)

  ⇒ negligible impact on overall radiometric (image) performance
- Data access (Raw, SLC, GRD data products) opened to all Users, worldwide, on 3 October, 2014
- EC Copernicus services, in particular the Marine and Emergency services operationally use Sentinel-1A data
- Sentinel-1B launched on 25 April, 2016





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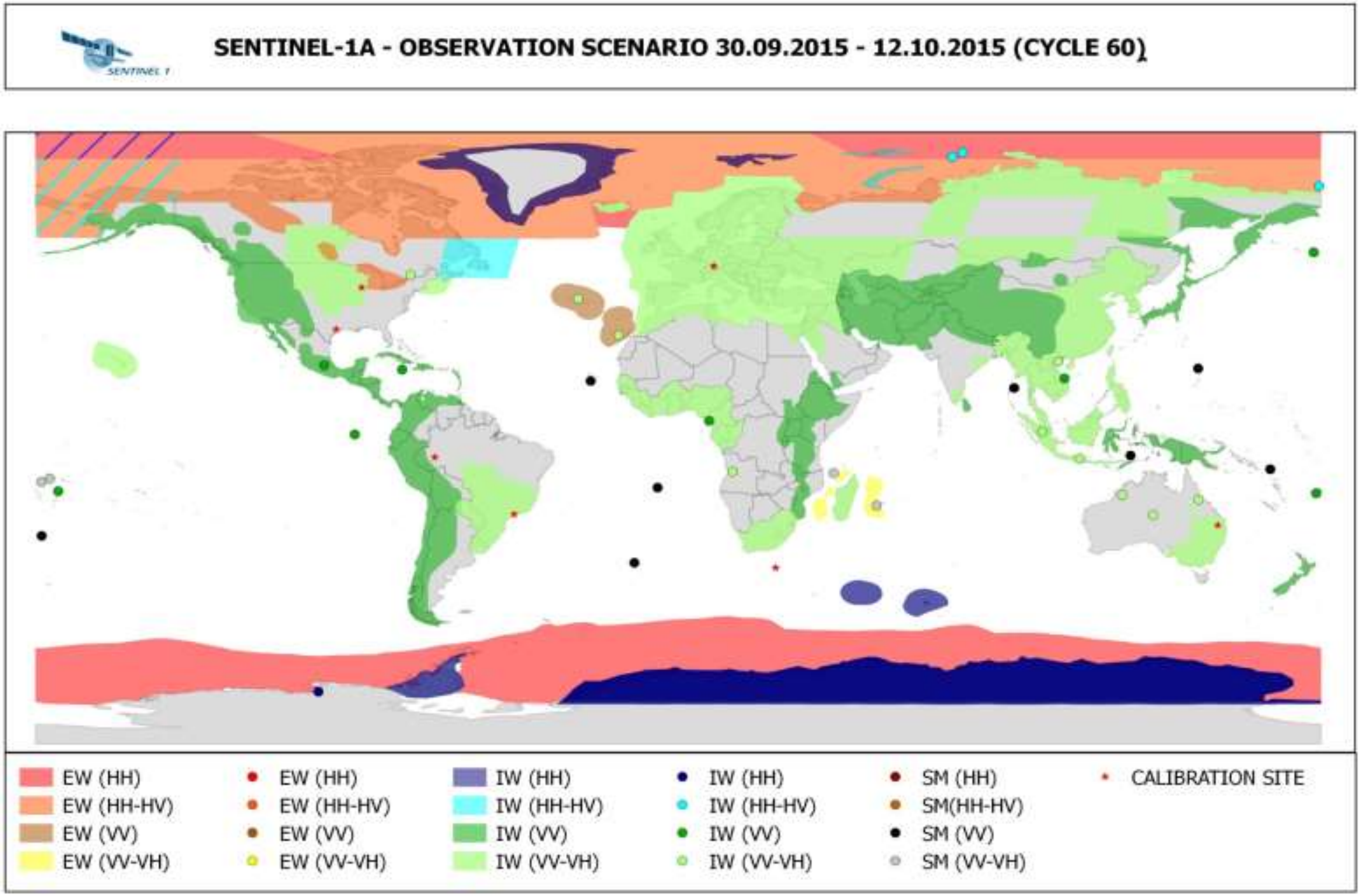
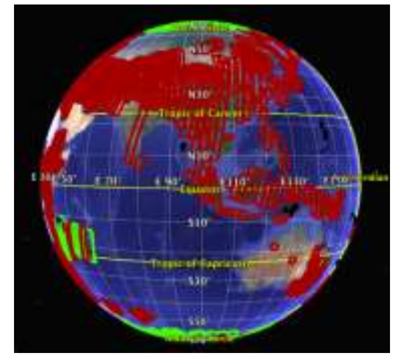
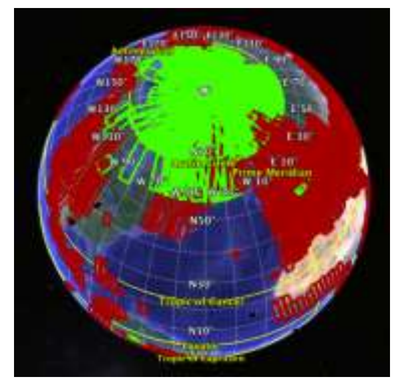
Sentinel-1A Observation Scenario regularly published online



Acquisition Segments



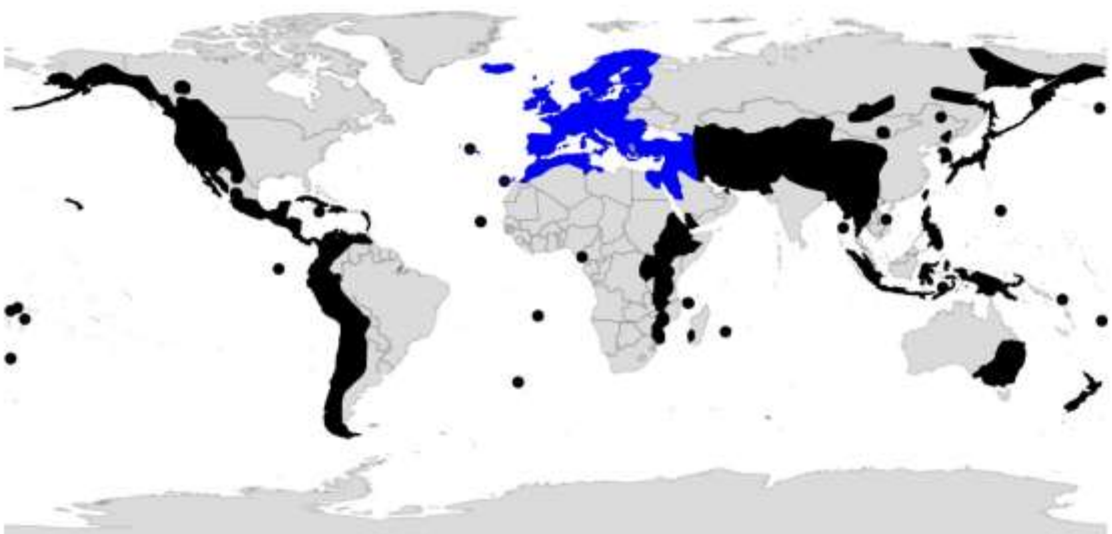


https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/observation-scenario/acquisition-segments

https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/observation-scenario

Sentinel-1A Observation Scenario Tectonic and Volcanic Areas

SENTINEL-1A - Tectonic active areas and volcanoes / subsidence and landslides



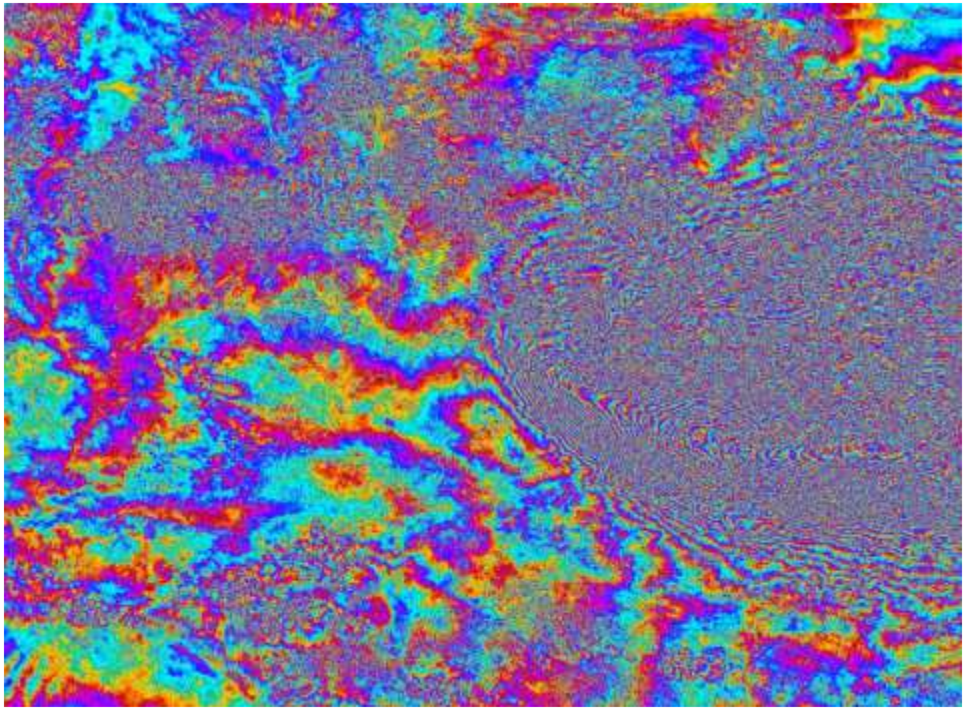
- All Land and Ice masses systematically provided as IW SLC data products
- Includes all global tectonic/volcanic areas
- About 1.4 TB of IW SLC data available daily

- **BLUE**: Acquisitions in *IW dual pol* mode, *VV+VH* polarisation, every 12 days *ascending* and *descending*
- **BLACK**: Acquisitions in *IW* mode, *VV* polarisation, every 12 days *ascending* or *descending*; *repeat* on the same track every *24 days*
- Stripmap mode (SM) acquisitions over selected small volcanic islands
- Increased sampling density over supersites outside Europe
- About one third of global landmass regularly covered, based on this acquisition strategy

Sentinel-1A IW Mode D-InSAR Earthquake Surface Deformation Mapping

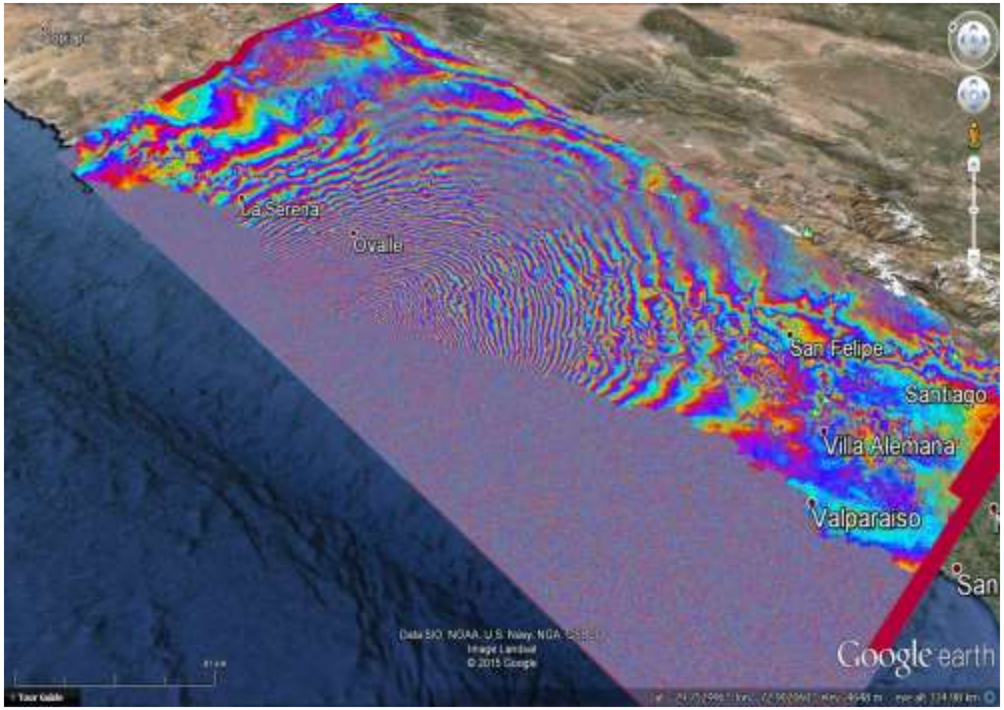
M7.8 Nepal earthquake on April 25th, 2015

Sentinel-1A IW (TOPS) mode acquisitions on 17 & 29 April, 2015



M8.3 Chile earthquake on Sept. 16th, 2015

Sentinel-1A IW (TOPS) mode acquisitions on 24 August & 17 September, 2015



Images courtesy: Contains Copernicus data (2015)/ESA/DLR Microwaves and Radar Institute/GFZ/e-GEOS/INGV–ESA SEOM INSARAP study

Sentinel-1B Status

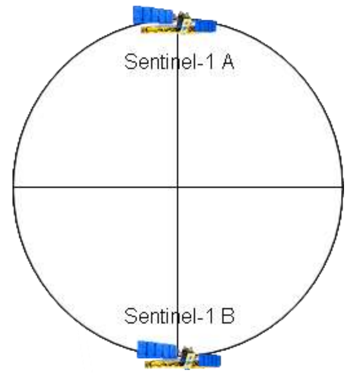
- Sentinel-1B launched on 25 April, 2016 on Soyuz from Kourou, French Guyana
- Very good injection orbit with a semi-major axis 1.9 km higher than reference orbit with an initial orbital drift of 2.1 deg./per day

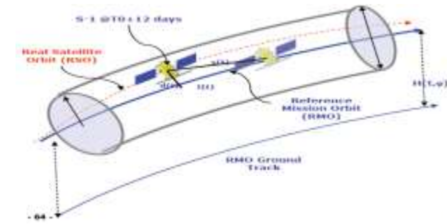
⇒ optimal situation to reach the orbital node of 180° phased with Sentinel-1A

- LEOP completed in less than three days as planned (25-28 April), including:
  - critical deployment of Solar Panels and SAR Antenna
  - SAR payload switched on and checked out
  - First SAR image acquisition as part of instrument check-out
- Commissioning started on 29 April, including spacecraft and SAR calibration activities, and will be completed by 14 September, 2016 (IOCR)

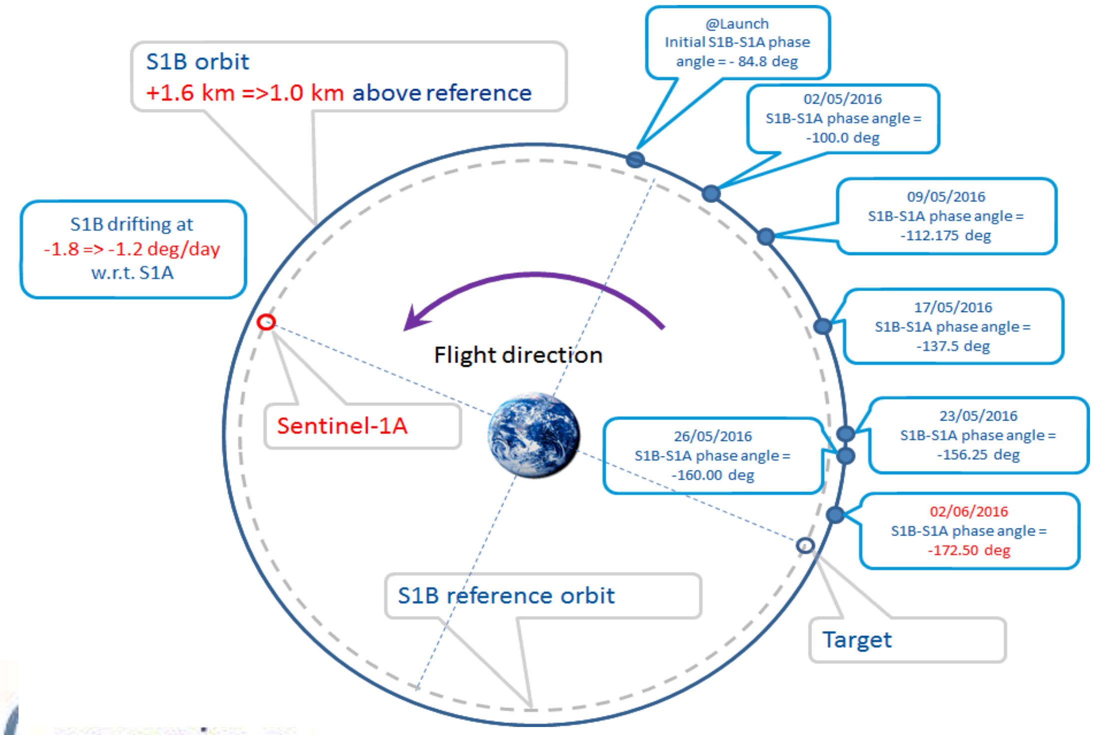
Sentinel-1B Reference Orbit Acquisition and Phasing with Sentinel-1A

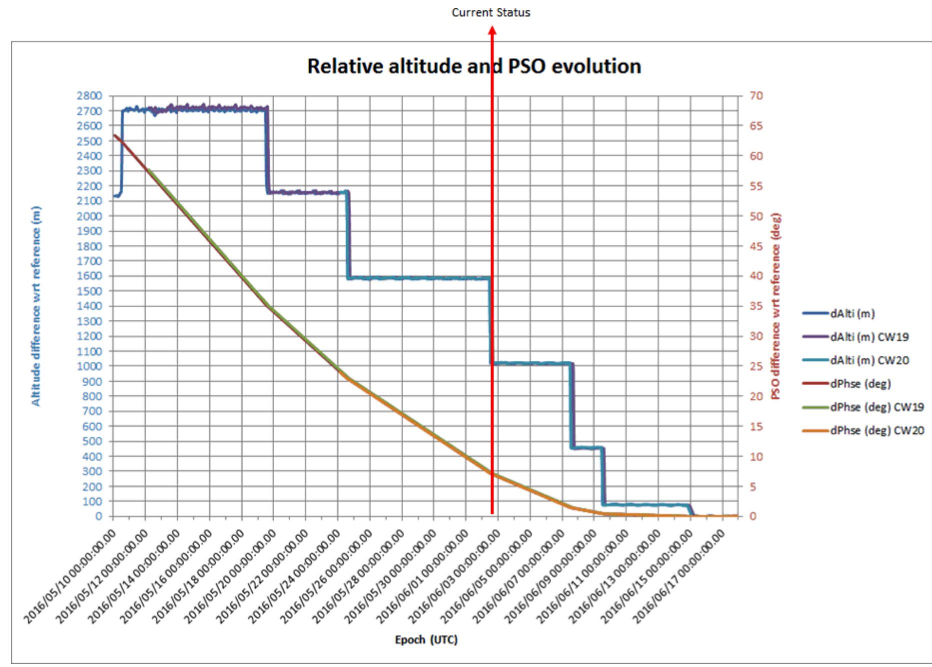
- Sentinel-1 A & B fly in the same orbital plane with *180 deg.* phased orbit positions
- Nominal S-1B orbital note reached on 15 June, 2016





Sequence of orbit manoeuvres (Yaw slew + OCMs)





- 1 orbit collision avoidance manoeuvre

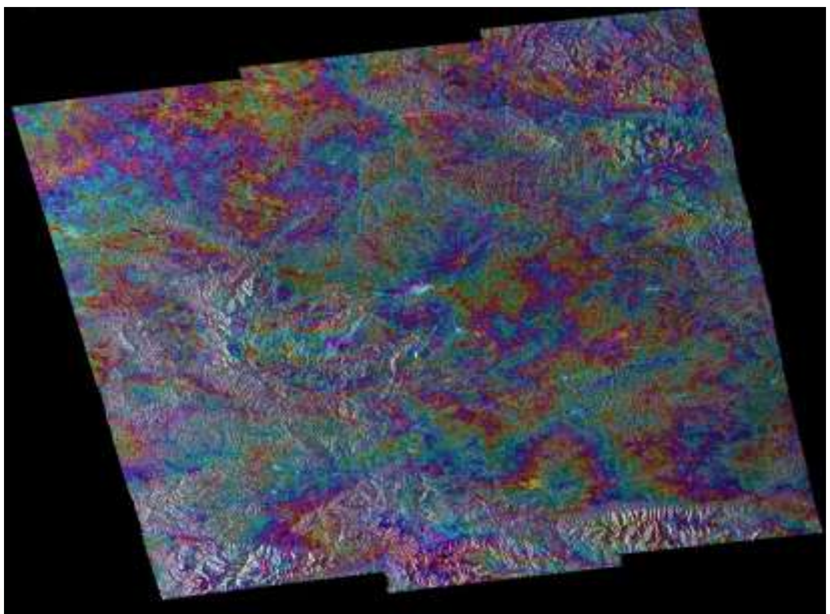
Sentinel-1A/B Cross-SAR Interferometry

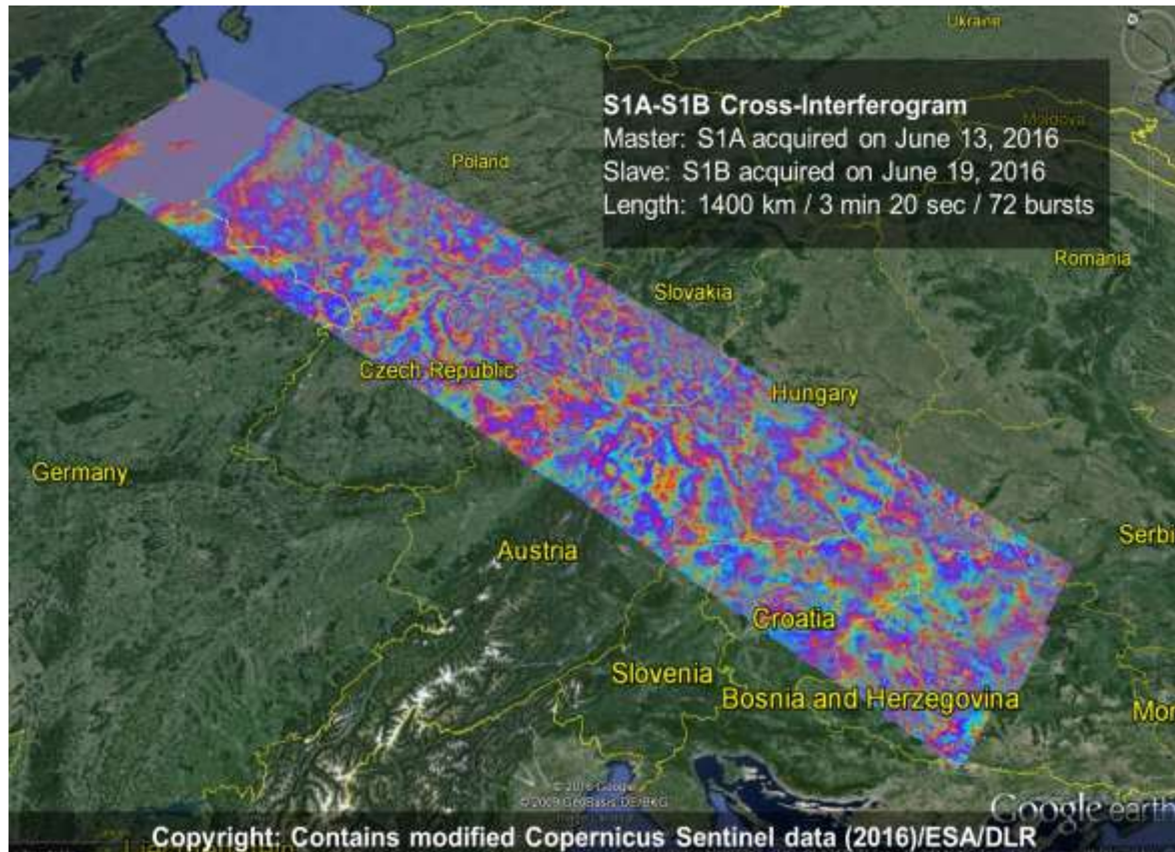
12-day repeat orbit cycle for each satellite ⇒ Formation of InSAR data pairs with *6-day* intervals

S-1A image: acquired on 10 June, 2016
S-1B image: acquired on 16 June, shortly after Sentinel-1B reached its designated orbital node phased 180° with Sentinel-1A

- Perpendicular Baseline: 54m
- Burst Synchronization: < 1.7ms

Long S-1A – S1B cross-interferogram demonstrates compatibility of both SAR instruments

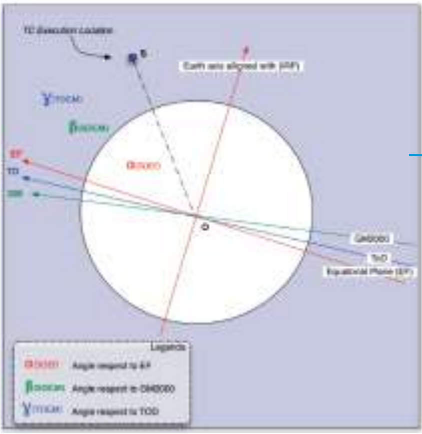


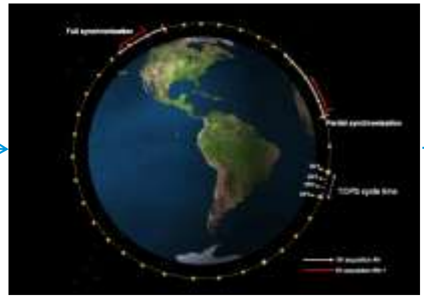


Images courtesy: P. Prats, N. Martinez, DLR

Datatake Start Time Estimation for Burst Synchronization – Position-tag Commanding

- Data acquisition (repeat orbit cycle) over the same ground location uses on *On-board Position 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

First imaging PRI
t_{echo}

α_{PVT} $\Delta\alpha$ α_{start_plan}

OPS angle

using actual S-1 orbit position

time

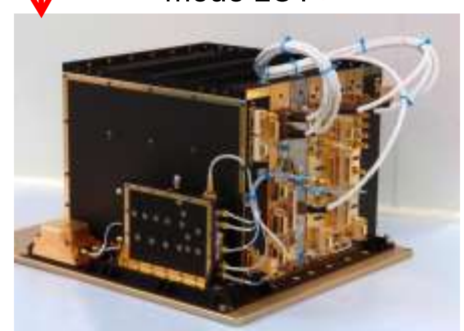
Δt ~20 s

Calculation of OPS angle α_{start_plan} based on :

- S-1 Reference orbit
- use of an orbital point grid based on 2 x *burst cycle time*

Spacecraft Avionics converts on-board the planned OPS angle (α_{start_plan}) to time (t_{start}) by analytical propagation of GPS PVT data

t_{start} using SAR mode LUT t_{echo}



PVT
(on-board GPS)

Instrument executes measurement according to t_{start}

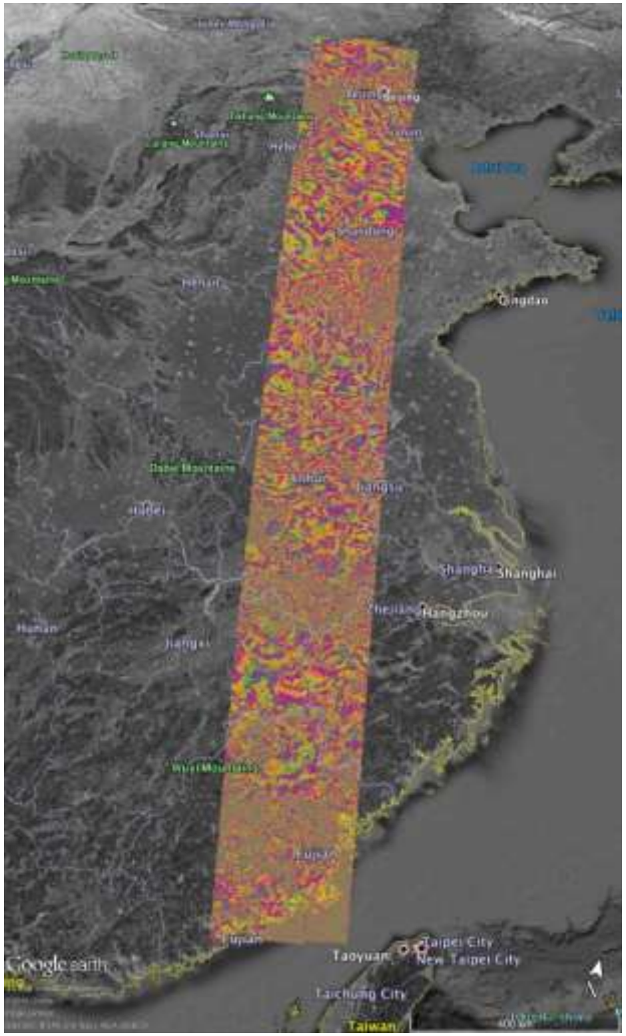
Sentinel-1B Burst Synchronization Results

Estimation of along-track burst synchronization at :

- Scene (slice)-level
- Long Datatake-level
- Sentinel-1A/Sentinel-1B InSAR data pairs

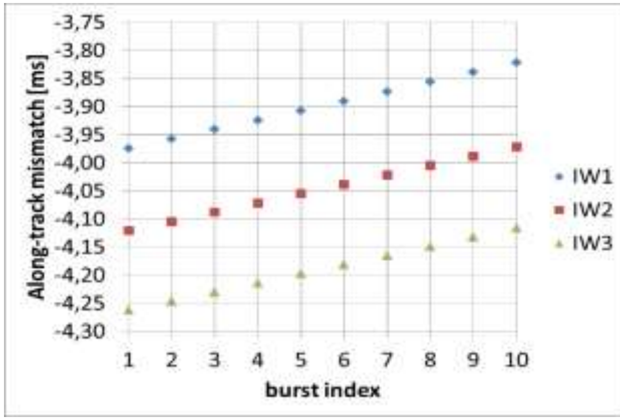
Using:

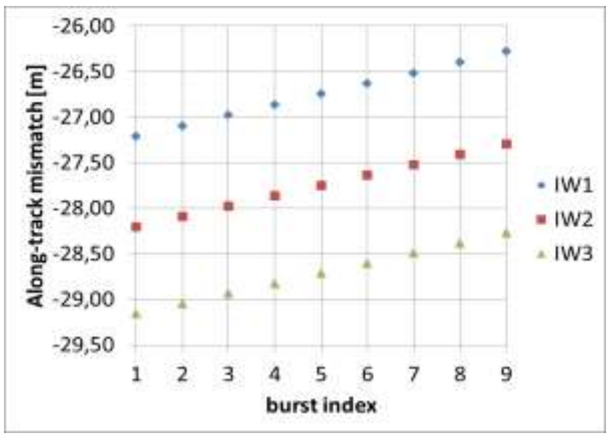
- Orbital state vectors (POD, restituted orbits)
- Annotated raw start azimuth time (sensing time) of the bursts
- Fine Co-registration using cross-correlation and Extended Spectral Diversity (ESD) techniques



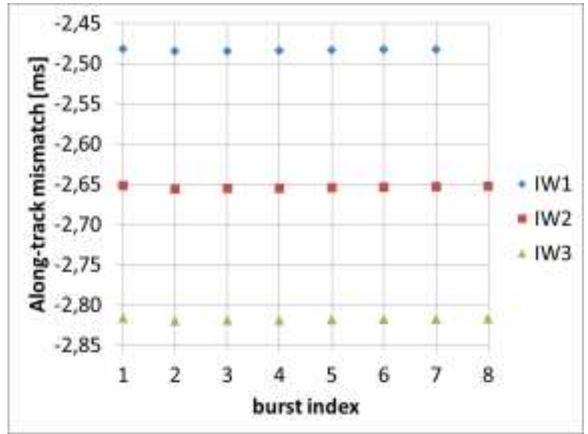
Burst Synchronization: Scene-Level

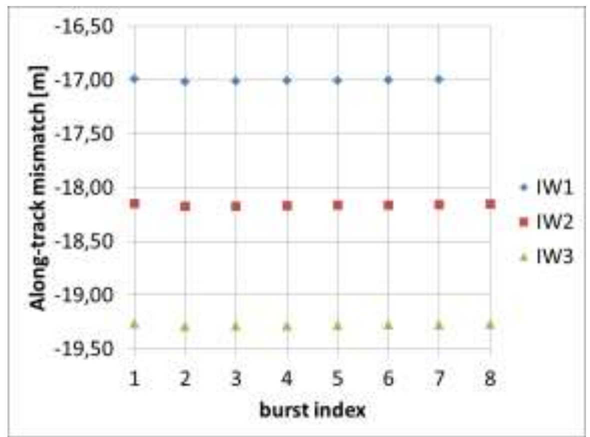
Sentinel-1B/-1B InSAR pair



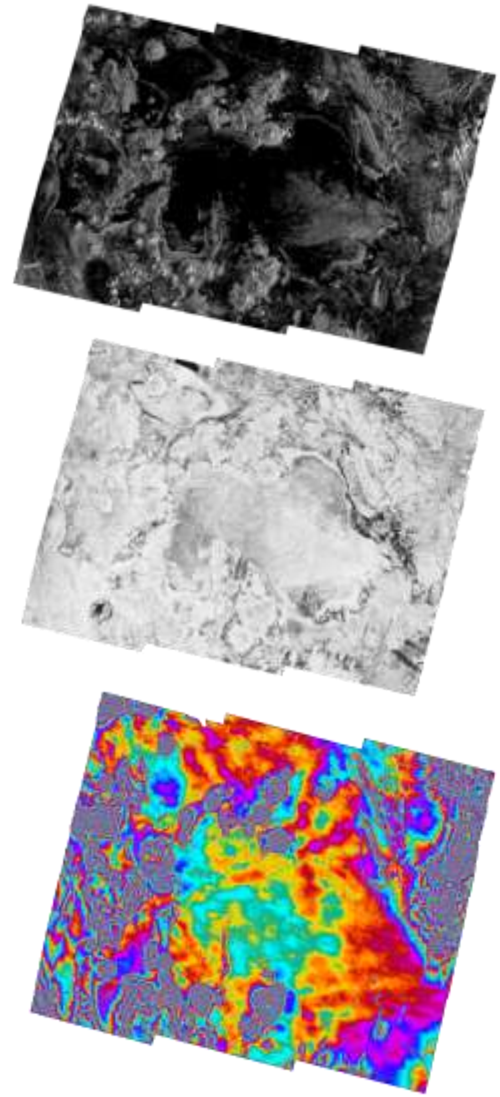


Sentinel-1A/-1B InSAR pair





Salar de Uyuni Scene



	IW1	IW2	IW3	IW1	IW2	IW3
Burst Synchronization variation [ms]	-0.15	-0.15	-0.15	0.0	0.0	0.0
Burst Synchronization (ground) variation [m]	-1.05	-1.02	-1.00	0.0	0.0	0.0

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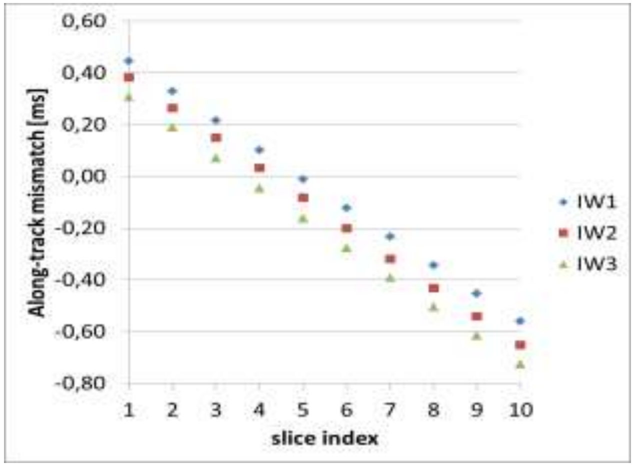
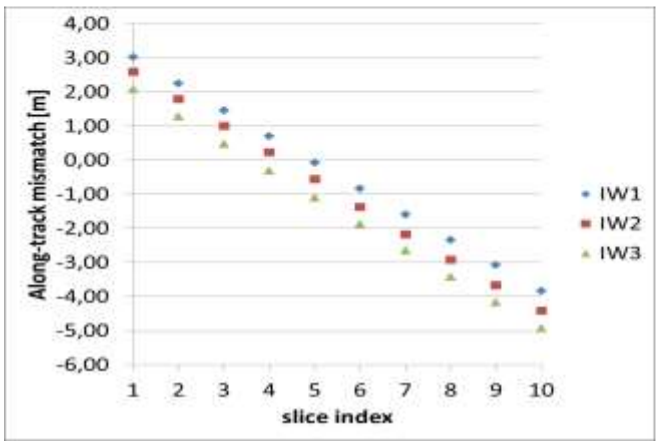
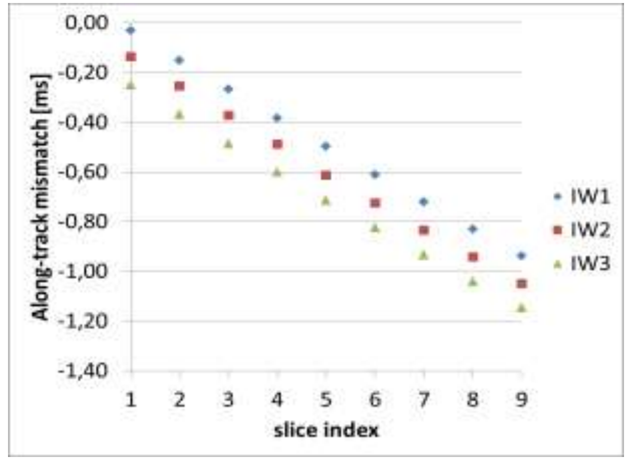
Burst Synchronization: Datatake-Level

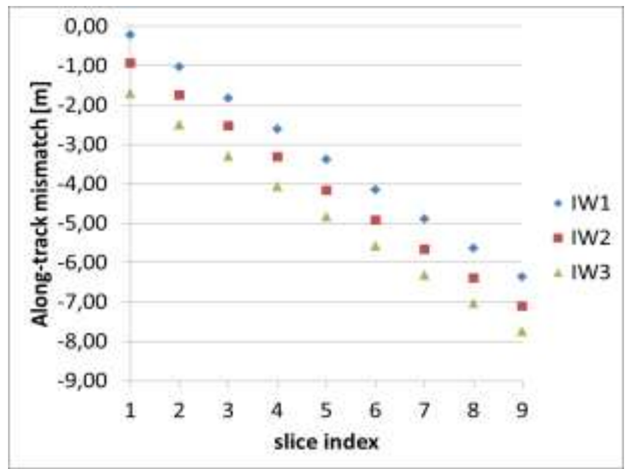
Sentinel-1B/-1B InSAR pair



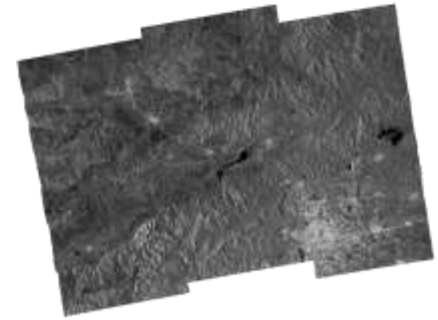


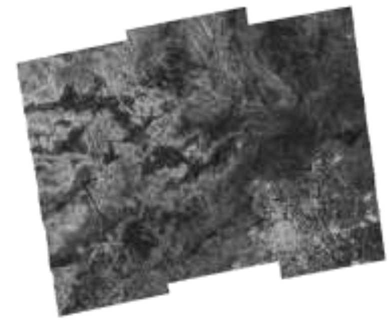
Sentinel-1A/-1B InSAR pair

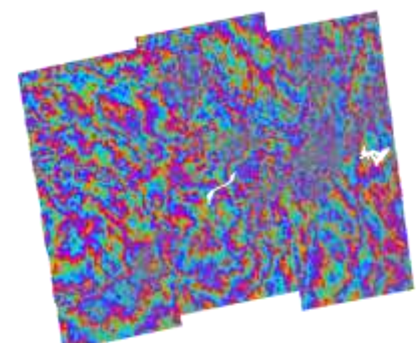




China DT



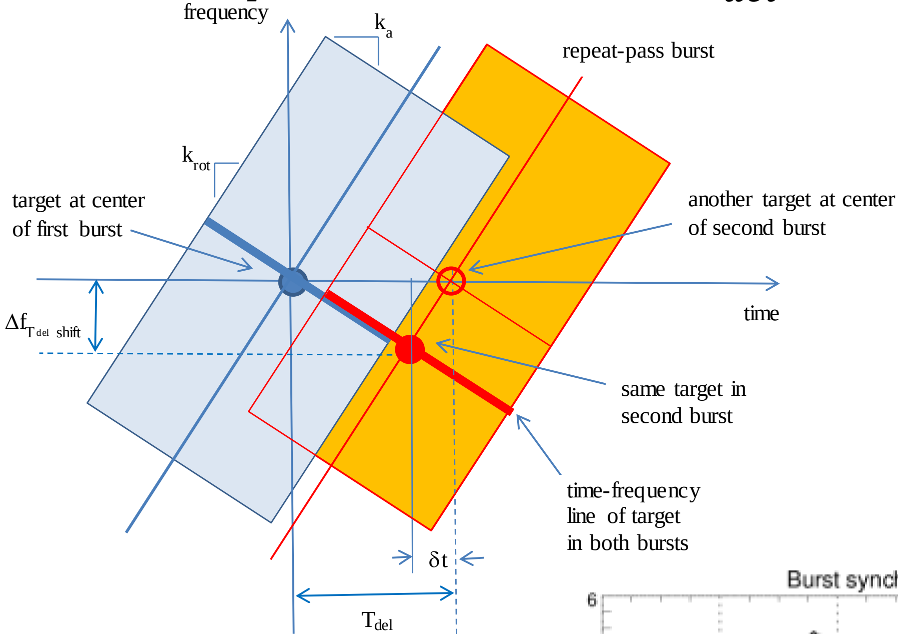




	IW1	IW2	IW3	IW1	IW2	IW3
Burst Synchronization variation [ms]	1.01	1.03	1.04	0.90	0.91	0.89
Burst Synchronization (ground) variation [m]	6.86	7.01	7.01	6.14	6.18	6.04

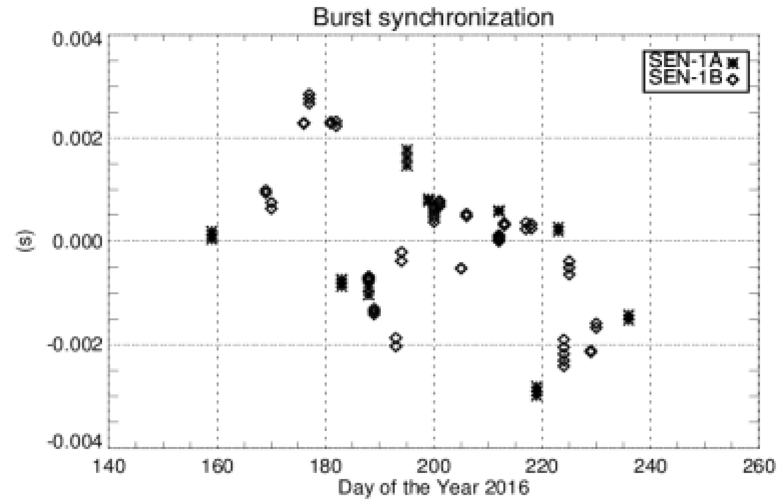
Burst (Mis) Synchronization vs Doppler Centroid Difference & Common Doppler Bandwidth

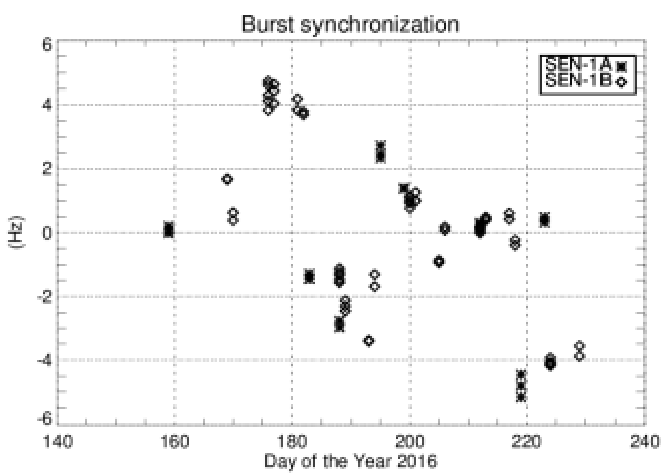
Burst Mis-Synchronization: T_{del}

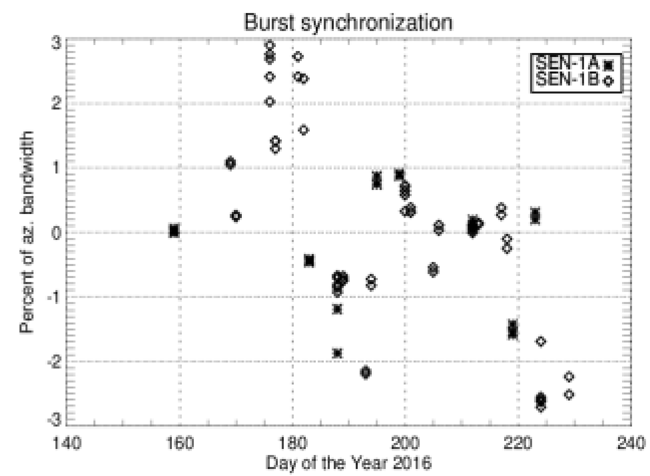


$$\Delta f_{T_{del\_shift}} = k_a \frac{k_{rot}}{k_a - k_{rot}} T_{del}$$

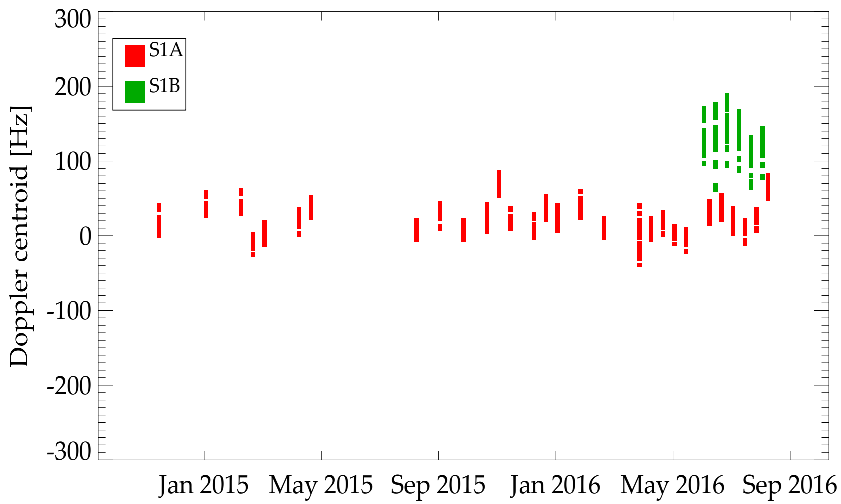
<1



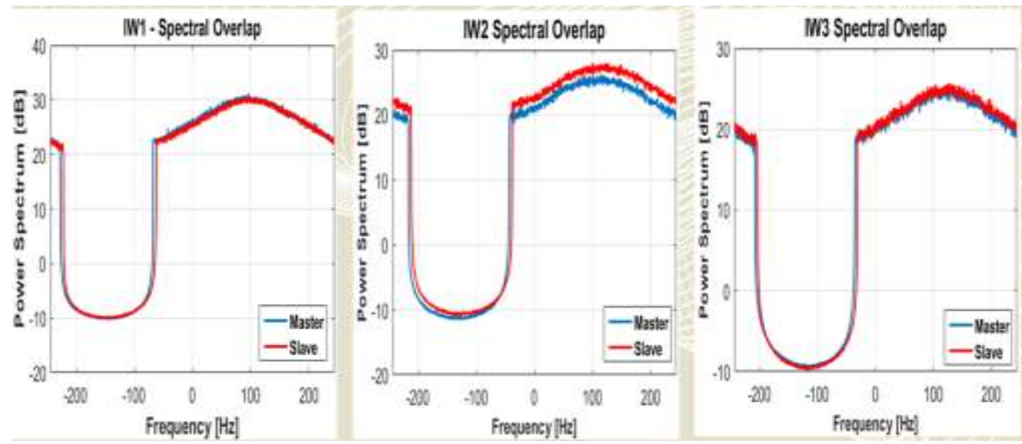


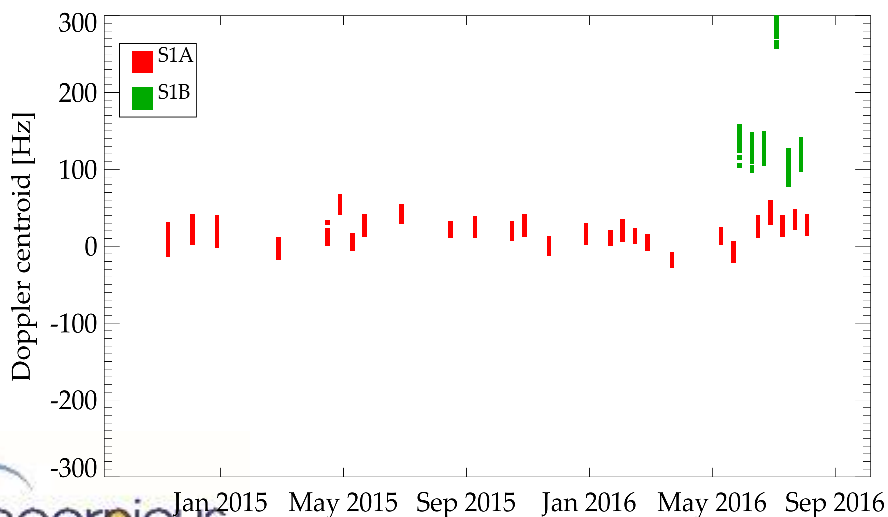


Mean Doppler Centroid Frequency Difference

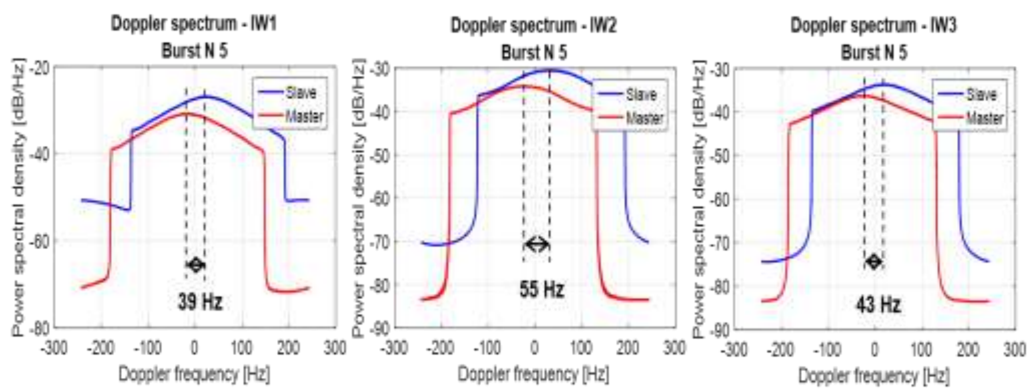


Sentinel-1B/Sentinel-1B InSAR pairs



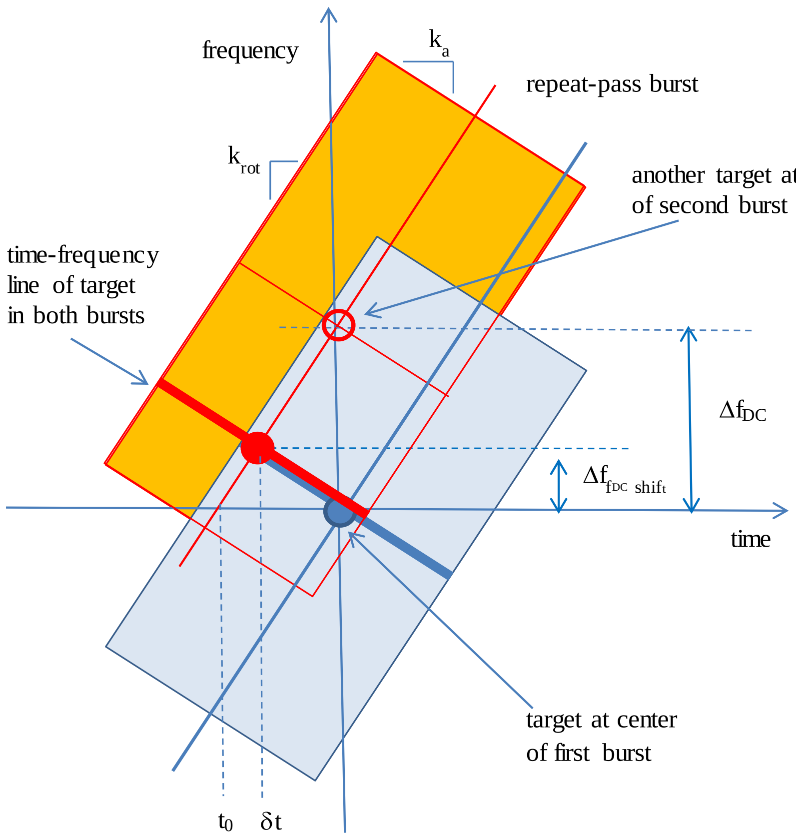


Sentinel-1A/Sentinel-1B InSAR pairs



Antenna (Mis) Pointing (squint) vs effective Doppler Centroid Difference

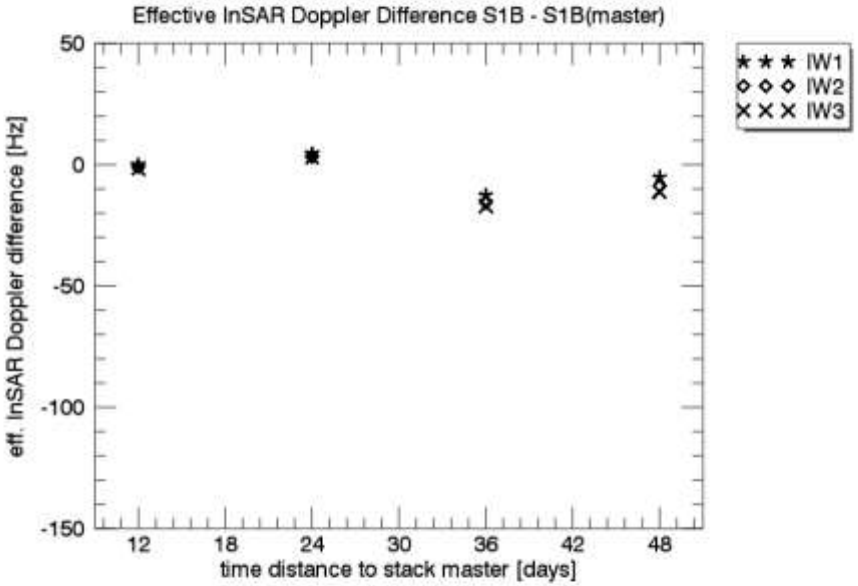
Doppler centroid difference Δf_{DC}

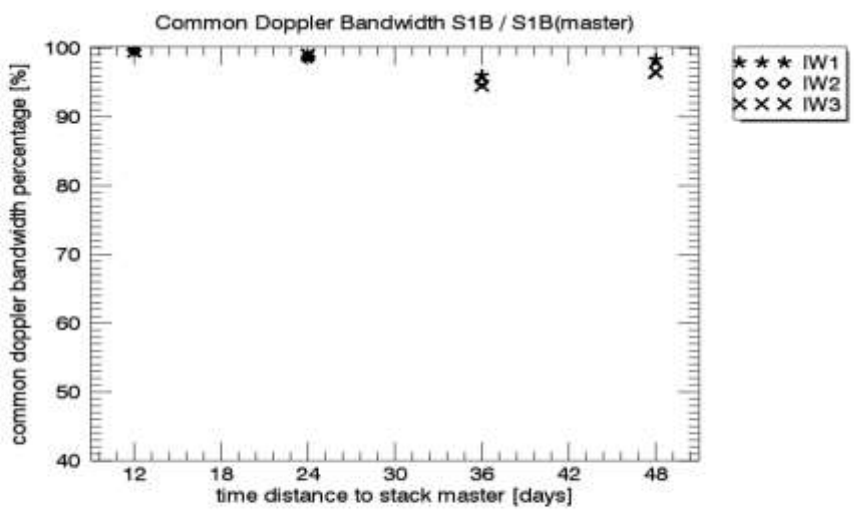


$$\Delta f_{f_{DC\_shift}} = \frac{k_a}{k_a - k_{rot}} \Delta f_{DC} = \frac{\Delta f_{DC}}{\alpha}$$

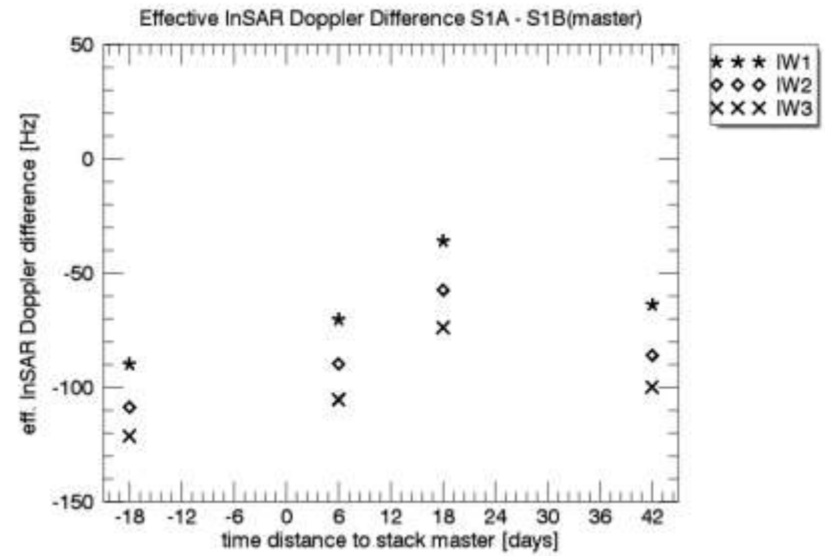
Mean Doppler Centroid Frequency Difference & Common Doppler Bandwidth

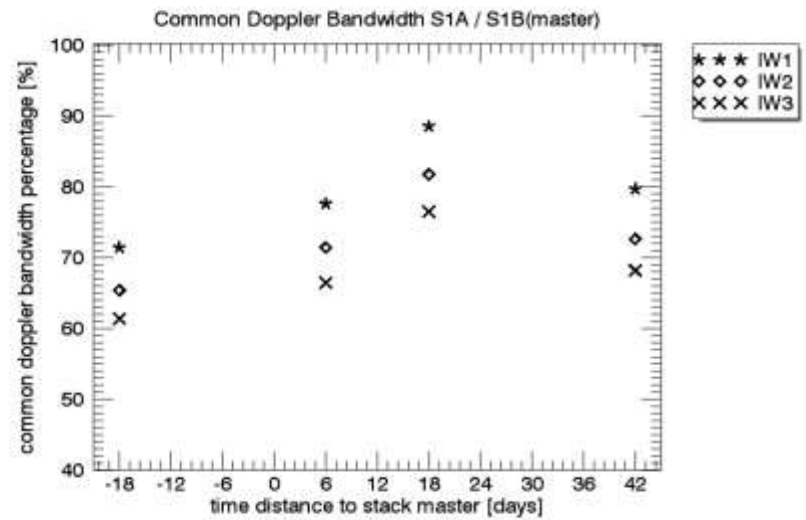
Sentinel-1B/Sentinel-1B InSAR pairs





Sentinel-1A/Sentinel-1B InSAR pairs

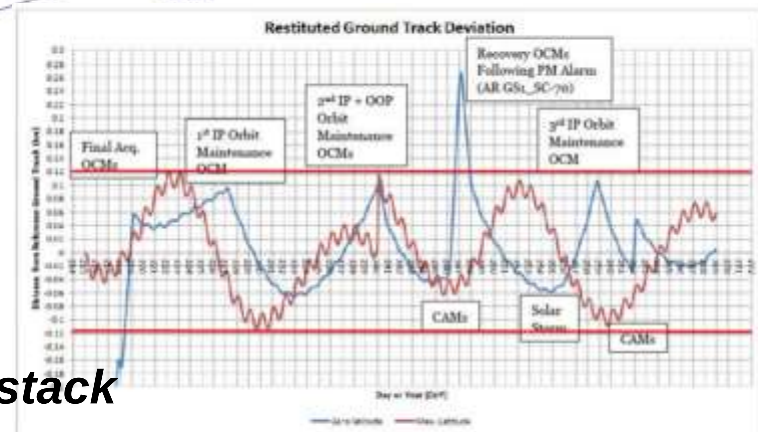




Sentinel-1 Orbital Tube and InSAR Baseline

- Sentinel-1 A & B are kept within an *Orbital Tube* around a *Reference Mission Orbit* (RMO)
- Initially specified *Orbital Tube* radius of 50 (rms)

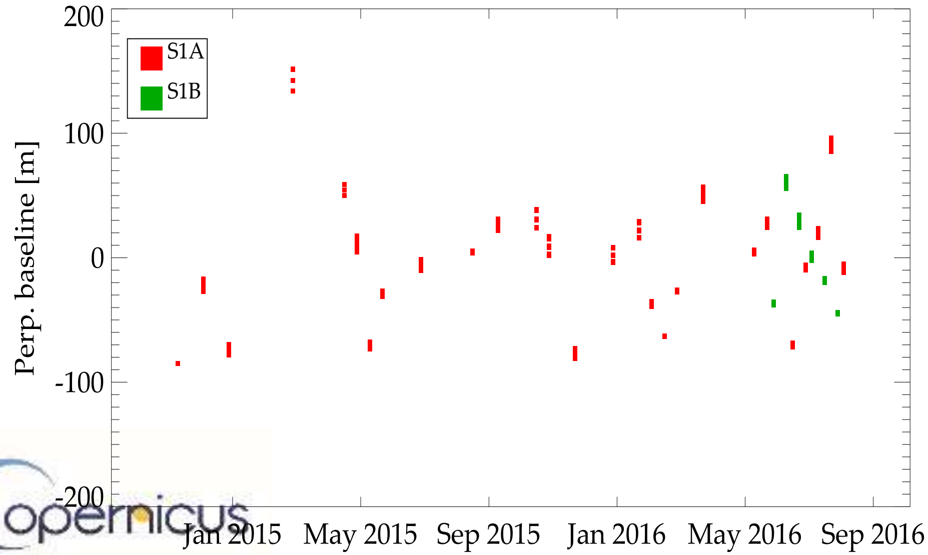
⇒ equivalent to *Ground-track* dead-band of 60m

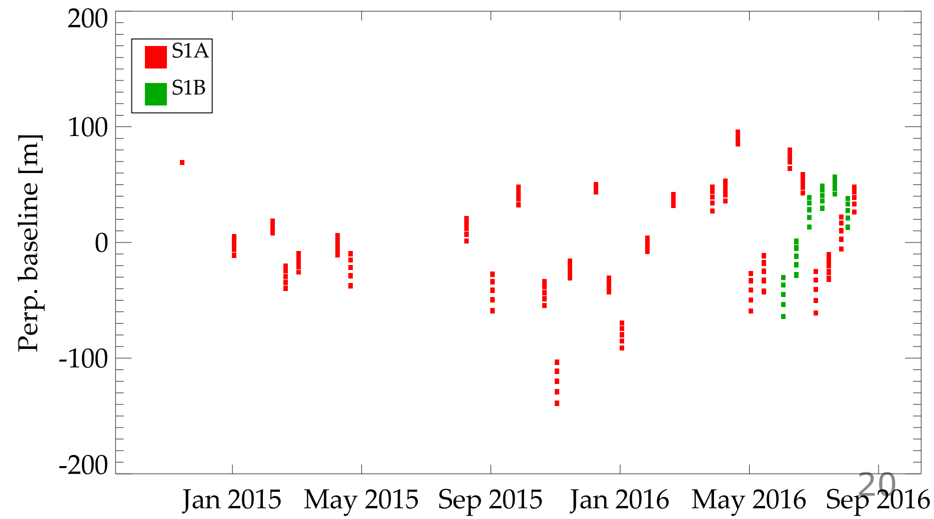


- During Sentinel-1A Commissioning: Relaxation of *Ground-track* dead-band to 120m remains

⇒ *Orbital Tube* radius of better than 100 (rms)

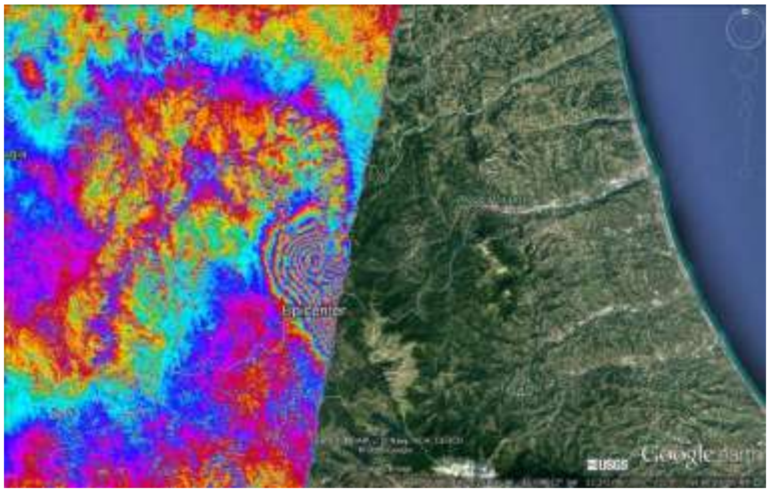
S1A/S1B perpendicular Baseline *for IW and EW data stack*

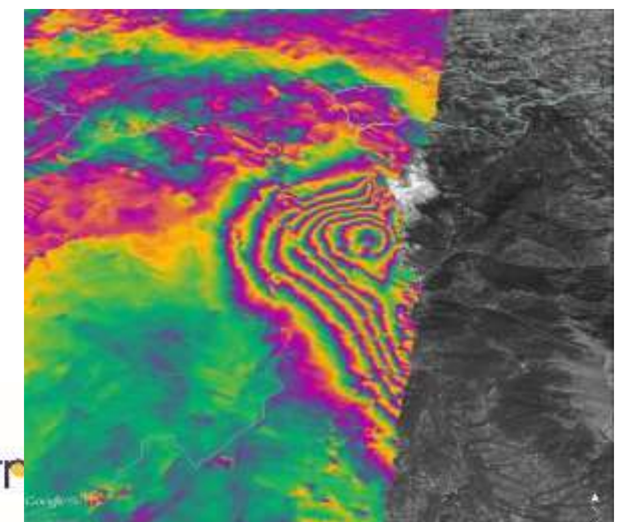


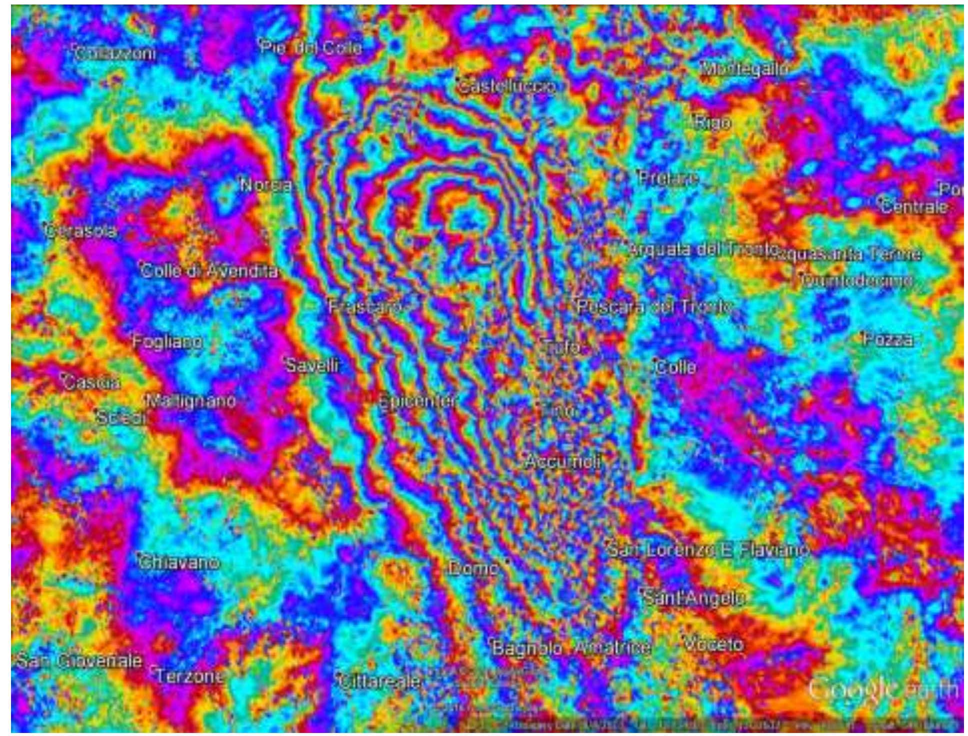


Results of Italy Earthquake

- M 6.2 central Italy earthquake on 24 August 2016 at 03:36:32 CEST
- Sentinel-1A and Sentinel-1B IW data pairs acquired on 20 & 26 Aug. and 21 & 27 Aug. for generation of coseismic differential interferograms







effective baseline: 28.1 m

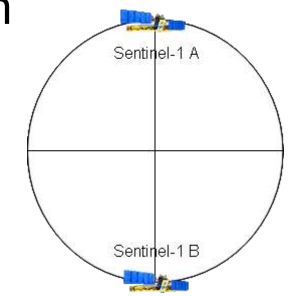
mean Doppler frequencies: 110 Hz (S1B) & 54 Hz (S1A)

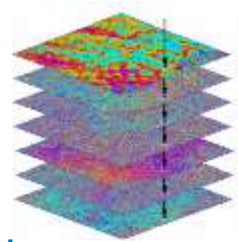
burst mis-synchronization: 3.12 ms

Conclusions

- Sentinel-1 acquires *systematically* and provide *routinely* SAR data for operational monitoring tasks for *Copernicus* and *national EO services*

- Using the same SAR imaging mode (instrument settings), *e.g.* ***IW mode***, enables the build-up of ***long data time series*** for continuous observations with ***equidistant*** and ***short time intervals*** *(interferogram stacks)*





- Sentinel-1 A & B fly in the same orbital plane with *180 deg.* phased in orbit, each with*12-day repeat* orbit cycle

  ⇒ Optimization of coverage offering global revisit time of *6-days*

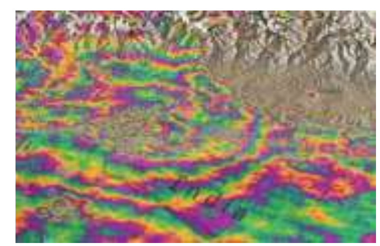
  ⇒ Formation of InSAR data pairs with 6-day intervals

- Small orbital tube with R < 100m (rms) provides small InSAR baselines

  ⇒ Differential InSAR for surface deformation monitoring

- Accurate TOPS burst synchronization + small Doppler centroid differences for S-1A and S-1B InSAR pairs, but requires improvement for S-1A/S-1B

  ⇒ Large common Doppler bandwidth = optimal azimuth spectral alignment



⇒ **Excellent performance for wide-area (250km) SAR + InSAR mapping**

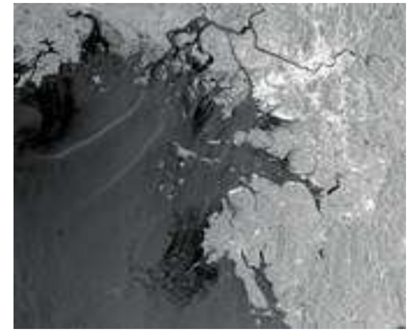

Thank you for your attention.

Outline

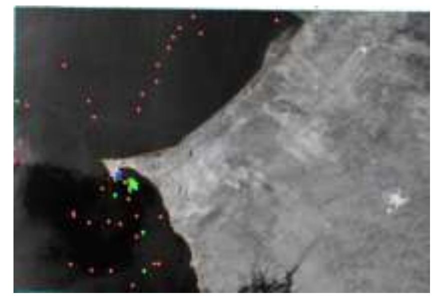
- Mission Facts and Objectives
- Overview of SAR Imaging Modes, with focus on novel TOPS mode
- Sentinel-1A Mission Status
- SAR Instrument Overview
- Methods for and Results from Sentinel-1A Calibration
- TOPS mode InSAR performance
- Sentinel-1B Mission Status
- Conclusions

Sentinel-1 Mission Objectives

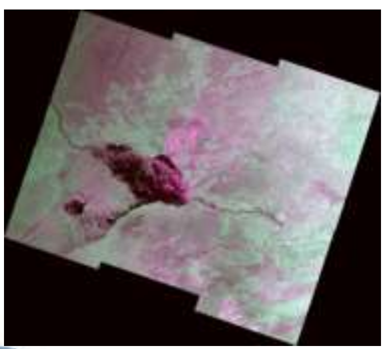
- Acquire systematically and provide routinely SAR data to operational *Copernicus* and *National services* focussing on specific applications:
  - ✓ Monitoring of marine environment (e.g. oil spills, sea ice zones)
  - ✓ Surveillance of Maritime Transport Zones (e.g. European and North Atlantic zones)
  - ✓ Land Monitoring (e.g. land cover, surface deformation risk)
  - ✓ Mapping in support of crisis situations (e.g. natural disasters and humanitarian aid)
  - ✓ Monitoring of Polar environment (e.g. ice shelves and glaciers)



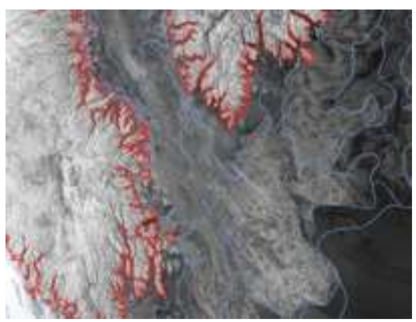
Oil spill monitoring



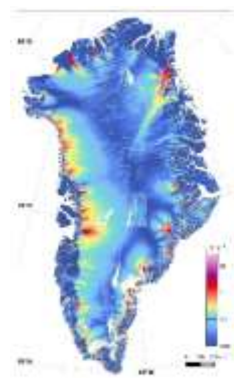
Ship detection



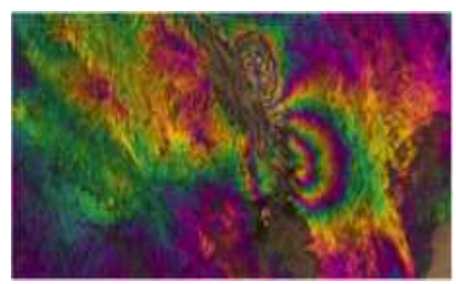
Flood monitoring



Sea ice mapping



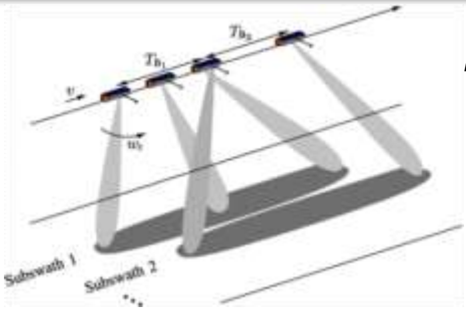
Ice sheet velocity



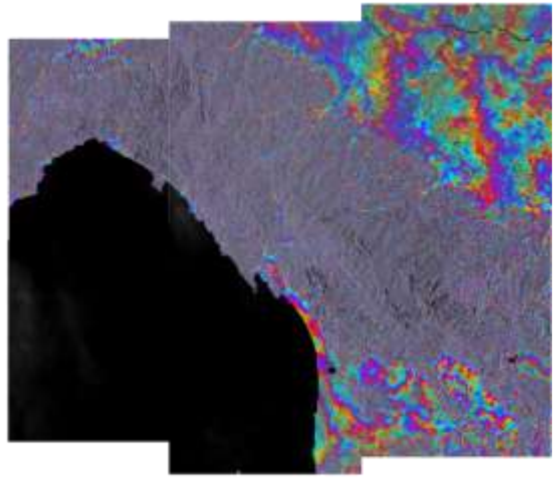
Surface deformation

Land cover mapping

Sentinel-1 IW TOPS InSAR



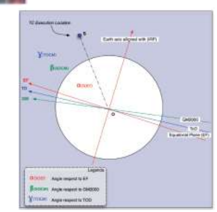
Repeat-pass TOPS InSAR using ***Interferometric Wide Swath (IW)*** data pairs worked on the 'spot'



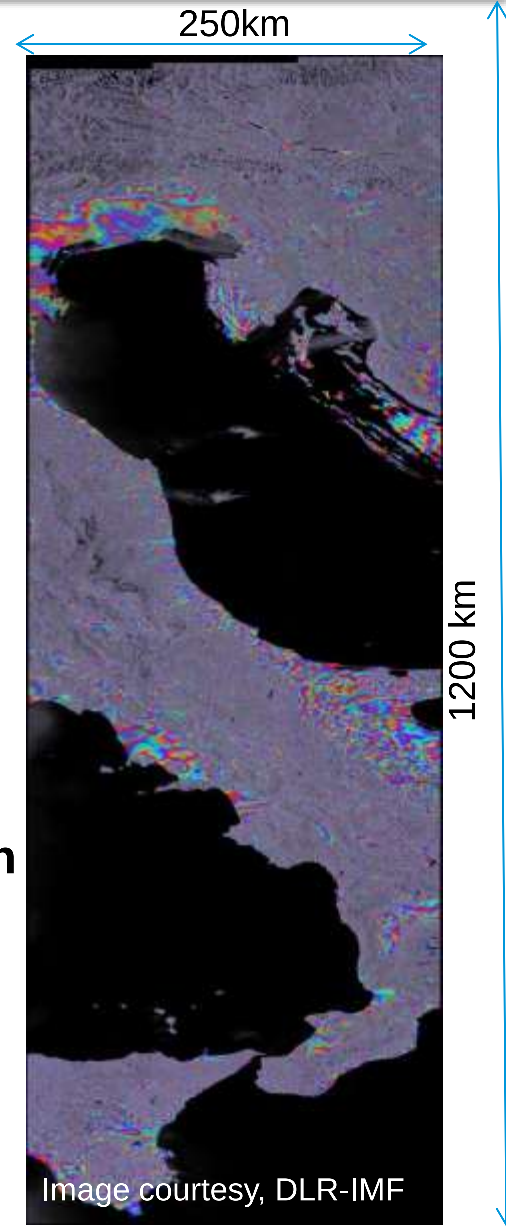
S-1A IW interferogram of data pair acquired 7-19 August, 2014 (2π height = 128.82m)

Verification of:

- SAR instrument phase stability
- Satellite on-board timing and GNSS solution to support *position-tagged commanding*
- Mission Planning system using *TOPS cycle time grid points* for datatake start time estimation
- Stable antenna pointing
- Accurate orbit control (orbital tube)



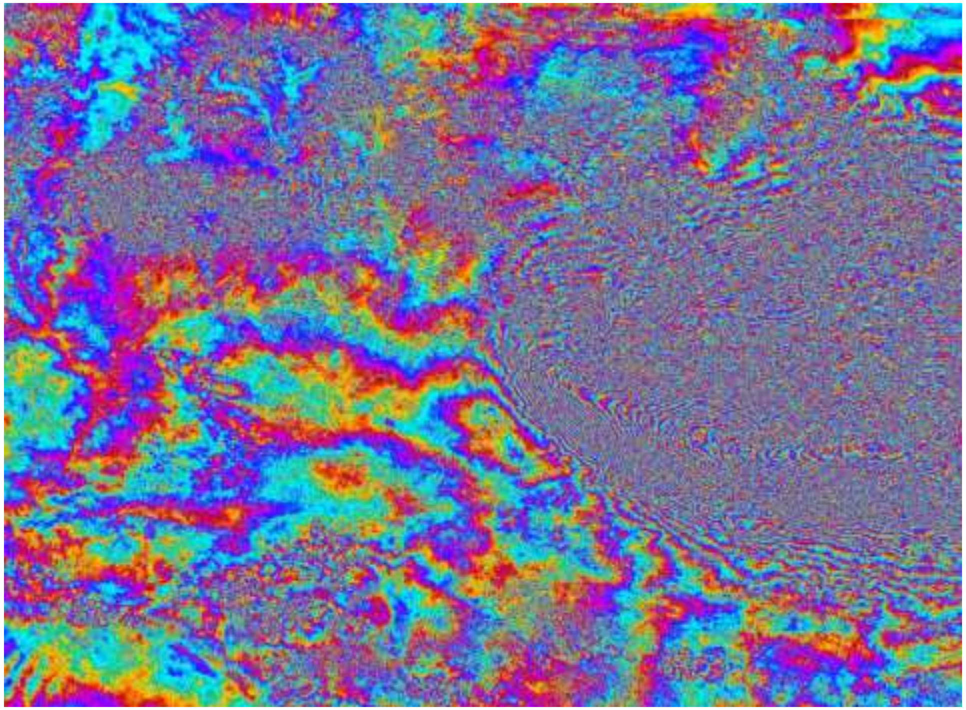
Burst synchronization



Sentinel-1A IW Mode D-InSAR Earthquake Surface Deformation Mapping

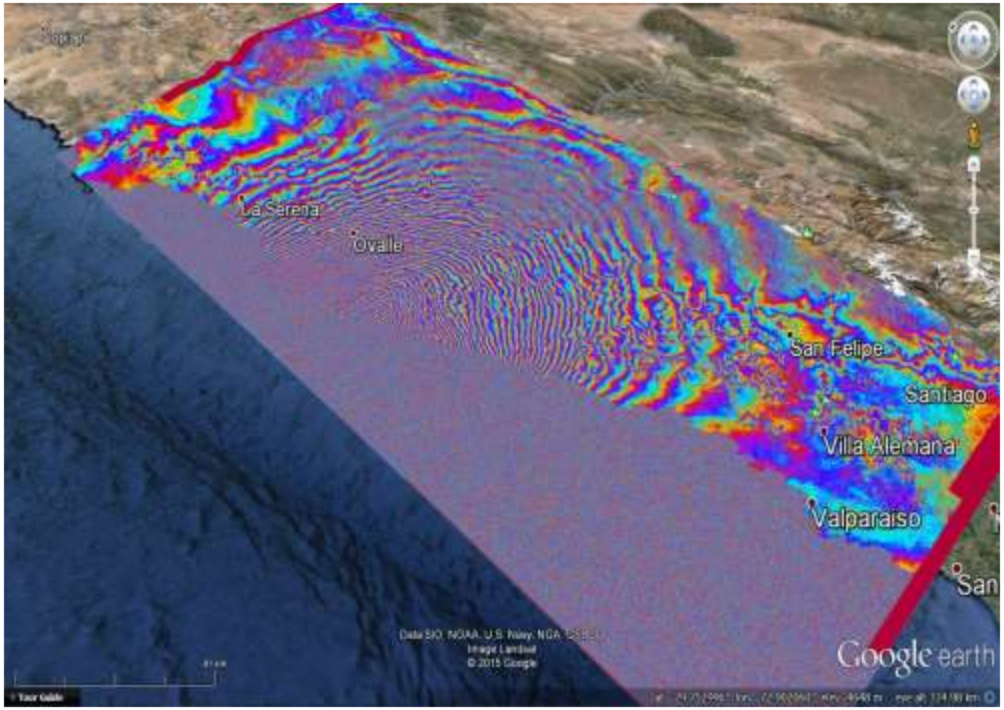
M7.8 Nepal earthquake on April 25th, 2015

Sentinel-1A IW (TOPS) mode acquisitions on 17 & 29 April, 2015



M8.3 Chile earthquake on Sept. 16th, 2015

Sentinel-1A IW (TOPS) mode acquisitions on 24 August & 17 September, 2015



Images courtesy: Contains Copernicus data (2015)/ESA/DLR Microwaves and Radar Institute/GFZ/e-GEOS/INGV–ESA SEOM INSARAP study

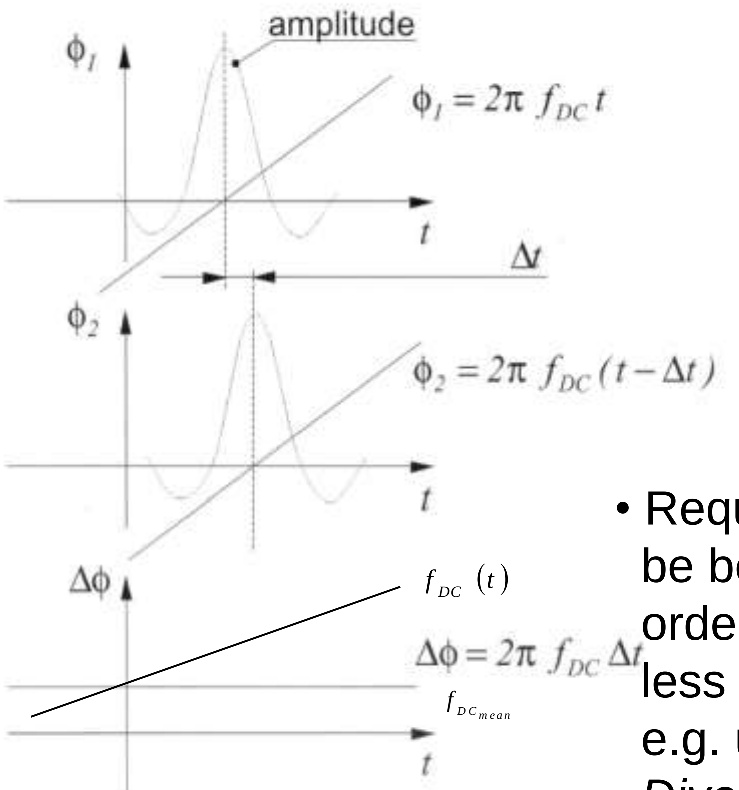
Sentinel-1B First Image

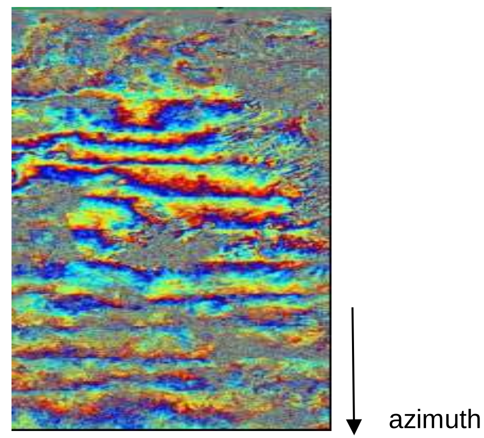
- Acquired on 28 April, 2016 as part of SAR instrument check-out just 2 hours after switch-on (54 hours after lift-off)
- Interferometric Wide Swath (IW) mode image (250km swath width) showing *Svalbard, the Norwegian archipelago* in the *Arctic Ocean* and *Austfonna glacier*

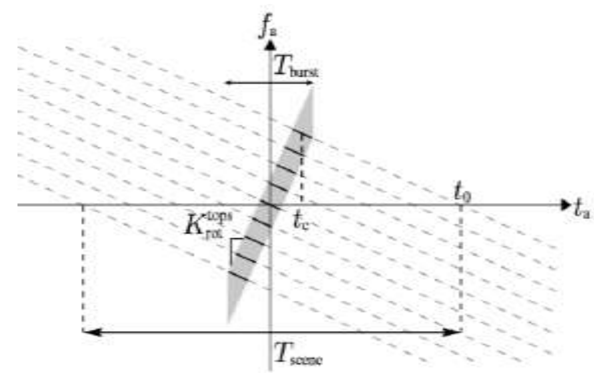
Sentinel-1 InSAR TOPS Image Co-Registration

- Antenna squint in Stripmap image pairs induces linear phase ramps in the *Impulse Response Function (IRF)* ⇒ small co-registration error causes *InSAR phase offset*
- TOPS mode: Azimuth *InSAR phase ramp* (azimuth fringes) introduced due to small co-registration errors (Δt) and Doppler centroid variations of about 5.2 kHz

$$\phi_{az_{err}} = 2\pi f_{DC} \Delta t$$







- Requires azimuth co-registration to be better than *0.001 samples* in order to obtain phase error less than 4° (~ 1.3.cm) , e.g. using Extended *Spectral Diversity (ESD)* approach (phase difference in burst overlap region)

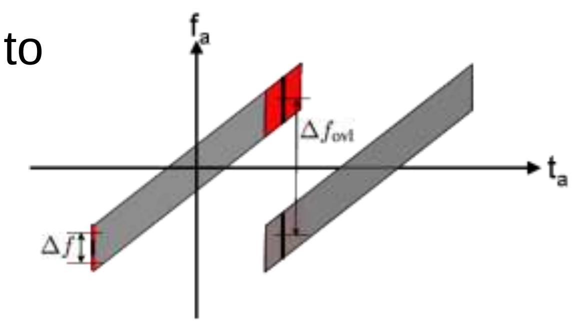


Image courtesy: P. Prats, DLR