Sentinel-1 Constellation SAR Interferometry Capabilities: Results of Sentinel-1C & D In-Orbit Commissioning

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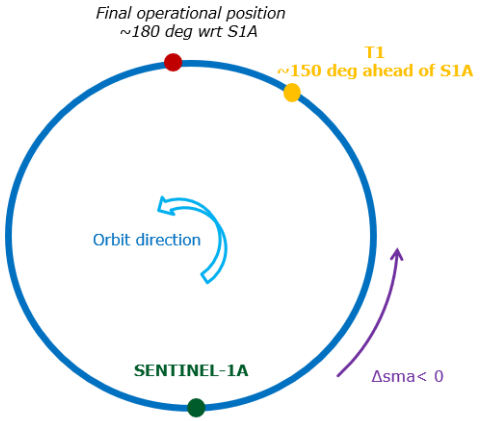
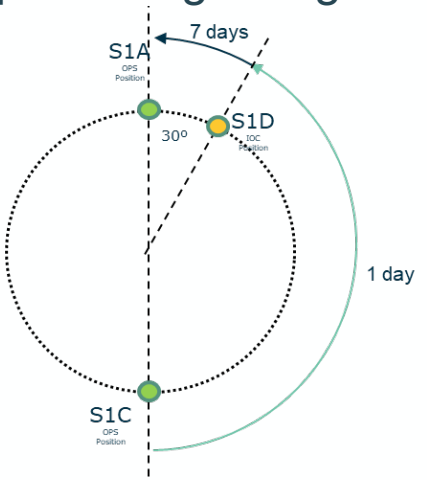
Sentinel-1C & D In-Orbit Commissioning (IOC) Phases

- **Sentinel-1C (S1C)** was *launched* on *Dec. 5th, 2024*, and its ***IOC*** was successfully completed on *May 7th, 2025*
- **Sentinel-1D (S1D)** was *launched* on *Nov. 4th, 2025*, and its ***IOC*** was successfully completed on *April 29th, 2026*

- ***S1C IOC*** was grouped in *two* phases regarding **S1C's** *repeat orbit* w.r.t. ***S1A***



- ***S1D IOC*** had only *one* phase regarding ***S1D***'s *repeat orbit* w.r.t. ***S1C***



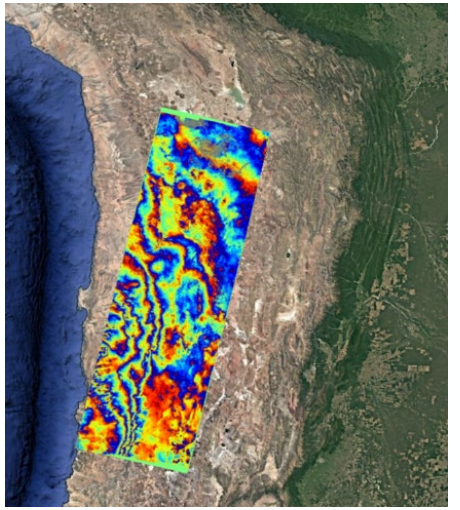
- ***Phase I***: ***S1C*** was *temporarily positioned* on an orbital node with a **1-day** *repeat orbit* w.r.t ***S1A*** (150 deg. ahead of S1A) for *4 repeat orbit cycles*
- ***Phase II***: ***S1C*** was transferred on 25/03/2025 to its nominal orbital node with a **6-day** repeat orbit w.r.t ***S1A*** (180 deg. phased orbit position) for *3 repeat orbit cycles*

- ***S1D*** was positioned on an orbital node with a **1-day** *repeat orbit* w.r.t ***S1C*** *(S1D* is *1 day later* than *S1C),* and
- ***7-day*** *repeat orbit* w.r.t ***S1A*** (*S1D* is *7 days later* than *S1A* in *same orbit cycle*, or *S1A* is *5 days later* than *S1D* w.r.t. *next orbit cycle*)

⇒ enabled Cross-Calibration and **formation of co - and cross-InSAR data (interferograms)**

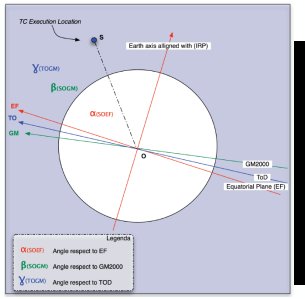
SAR Interferometry (InSAR) Verification

- ***InSAR verification*** involved analysis of ***S1C-S1C & S1D-S1D co-InSAR,*** and ***S1C-S1A*** & ***S1D-S1C*** & ***S1D-S1A cross-InSAR*** data pairs (*IW*, *SM*, *EW* modes) with specific ***repeat –pass intervals***
  - ***S1C-S1DC*** *co-InSAR* with ***12-day*** repeat-pass interval
  - ***S1C-S1A*** *cross-InSAR* with ***1-day*** and **6-day** repeat-pass interval
  - ***S1D-S1D*** *co-InSAR* with ***12-day*** repeat-pass interval
  - ***S1D-S1C*** *cross-InSAR* with ***1-day*** repeat-pass interval ***(S1D*** is ***1 day later*** than ***S1C)***
  - ***S1D-S1A*** *cross-InSAR* with ***7-day*** repeat-pass interval **(*S1D* is 7 days later** than ***S1A*** in **same orbit cycle, or *S1A*** is **5 days later** than ***S1D*** w.r.t. next orbit cycle**)**

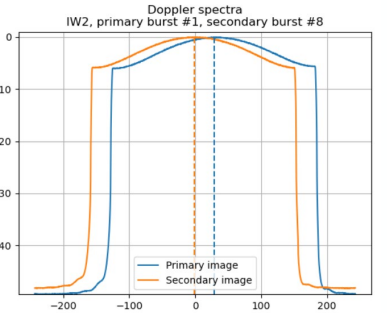


- Analysis involves **End-to-End verification** of **co-and *cross-InSAR* performance**:
  - *SAR instrument* ***phase stability*** (repeat orbit cycles)
  - *Compatibility* of ***S1D & S1C & S1A*** SAR instruments for ***burst synchronization***
  - *Stable* and *accurate* ***platform*** & ***SAR antenna pointing*** (Doppler centroid diff.)
  - Accurate ***orbit control*** (orbital tube) - ***InSAR orbital baseline***
  - Satellite ***on-board timing*** and ***GNSS solution*** for ***Position-tagged commanding*** (*OPS* angle)
  - *Mission Planning* system using ***burst cycle time grid*** for ***datatake start time*** determination

Azimuth spectral alignment = *Common Doppler BW*







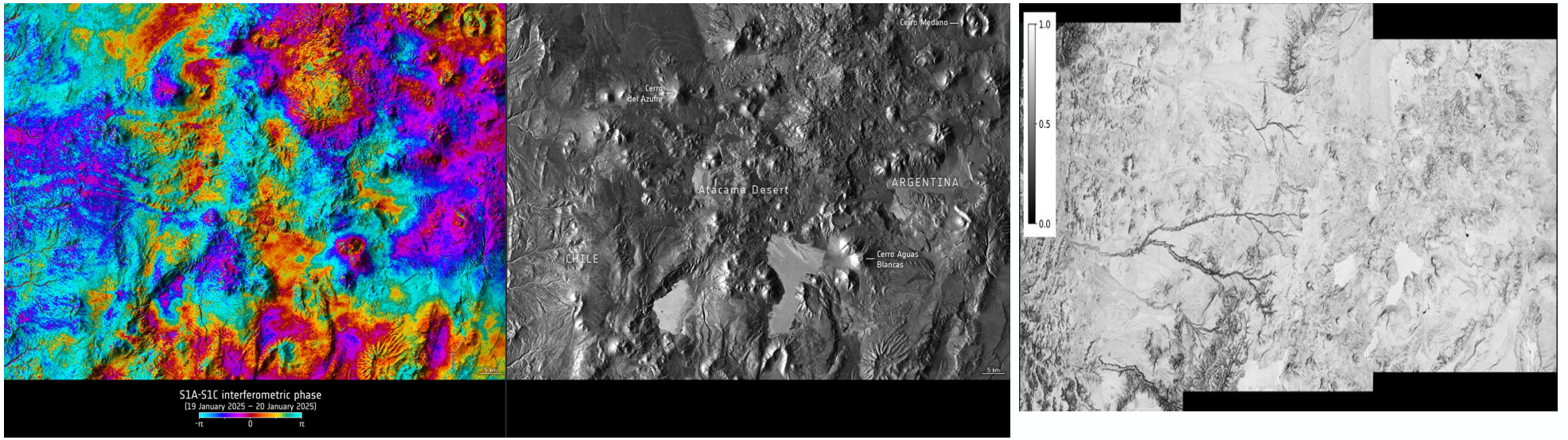
S1C SAR Interferometry (InSAR) Verification

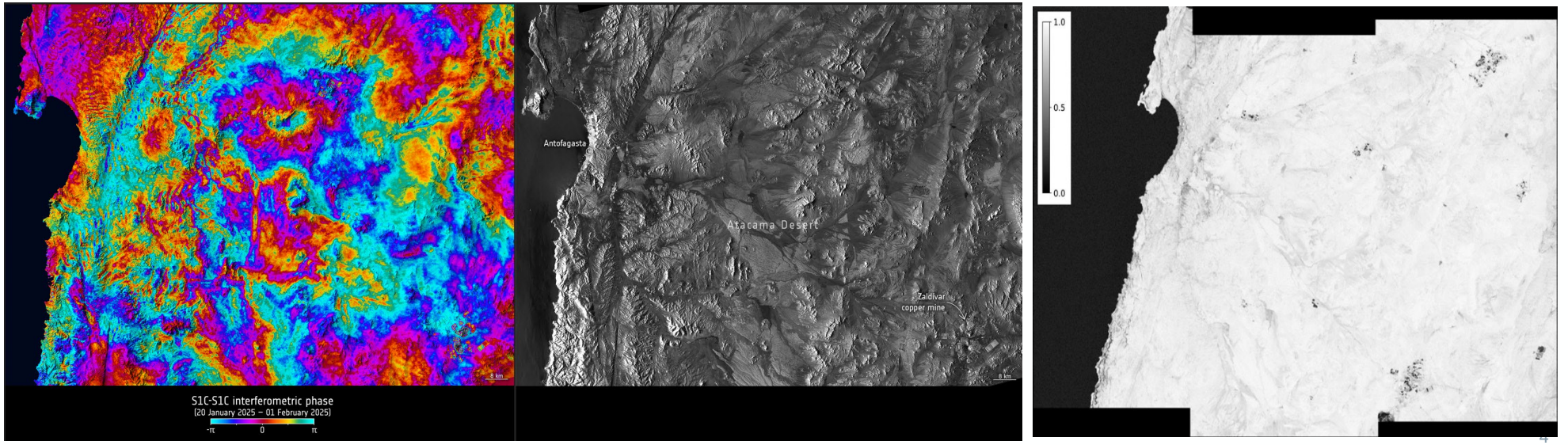
***S1A - S1C* IW 1-day** repeat-pass cross-interferogram of **Atacama Desert** (Chile), acquired on **19 Jan.25 (S1A) & 20 Jan.25 (S1C)**

Atacama desert: *flat* region, *non-vegetation* coverage providing *stable backscatter* and *phase* characteristics over InSAR repeat-pass interval

***S1C - S1C* IW 12-day** repeat-pass cross-interferogram of **Atacama Desert** (Chile), acquired on **20 Jan.25 & 01 Feb.25**

*Images processed by DLR-HR





S1D SAR Interferometry (InSAR) Verification

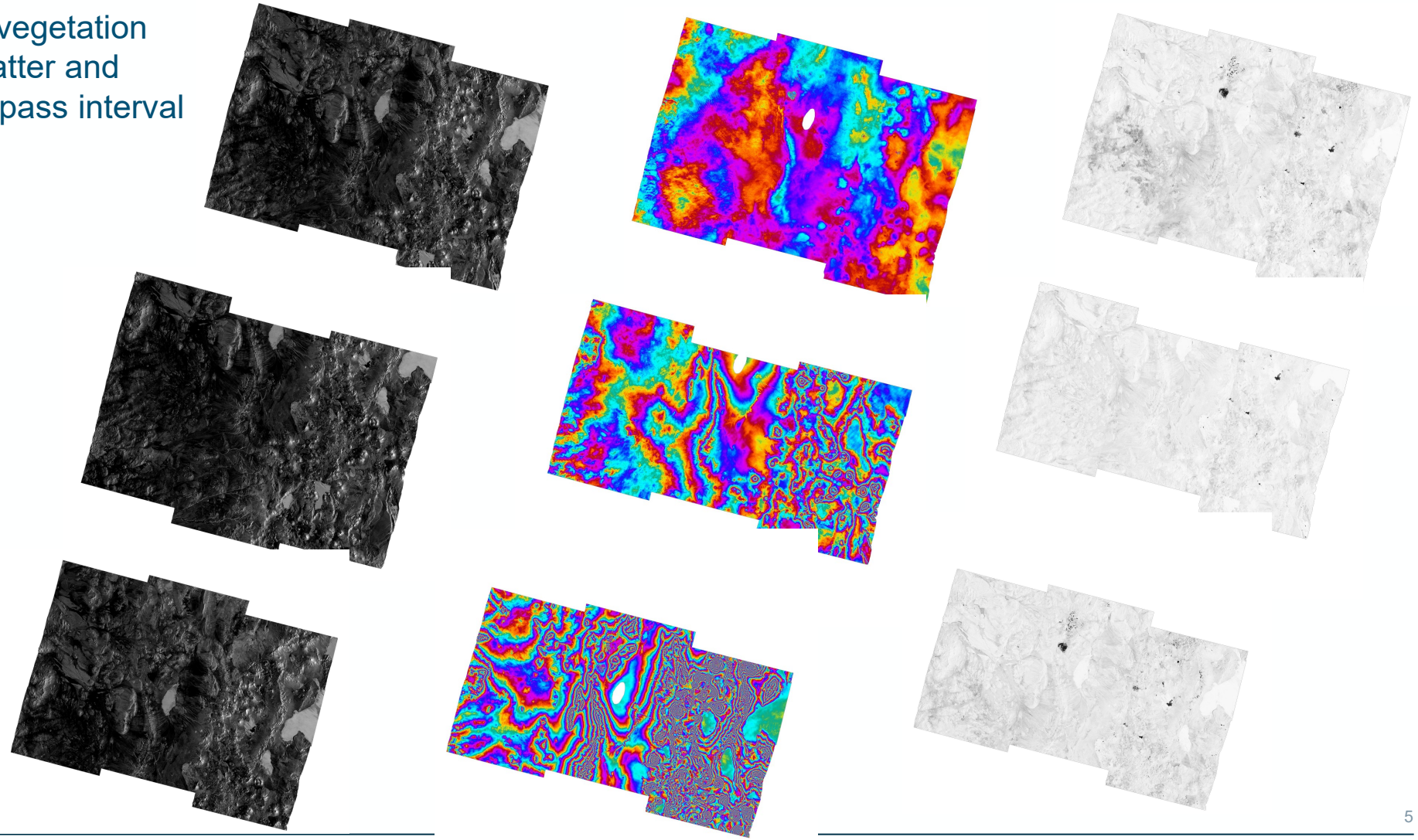
- ***Generation*** of ***S1D-S1D co-InSAR ,*** as well as ***S1D-S1C*** *and* ***S1D-S1A cross-InSAR*** data pairs

Atacama desert: flat region, non-vegetation coverage providing stable backscatter and phase characteristics over repeat-pass interval

S1D - S1D **IW mode** ***12-day*** **co-interferogram** of ***Atacama & Salar de Uyuni,*** acquired on *6 &* ***18 Mar. 26***

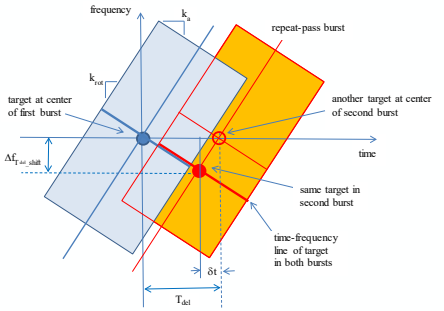
S1C - S1D **IW** ***1-day*** **cross-interferogram** of ***Atacama & Salar de Uyuni***, acquired on *17 &* ***18 Mar. 26***

S1A - S1D **IW** ***7-day*** **cross-interferogram of Atacama & Salar de Uyuni,** acquired on *11 &* ***18 Mar. 26***

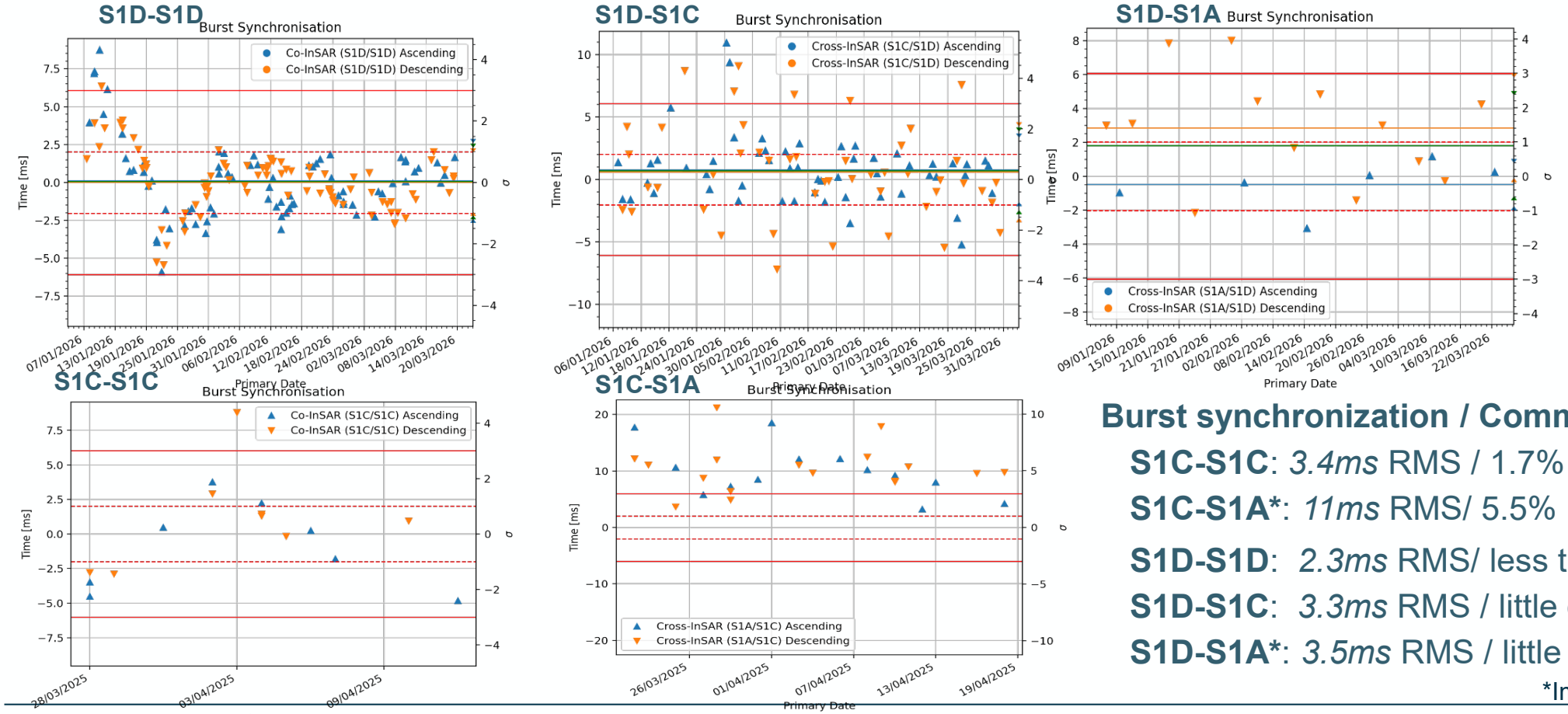


Burst Time Synchronization

- **Burst mis-synchronization** is deviation in *along-track* (azimuth) *time* (position) between *zero-Doppler time* of *Primary* and *Secondary* repeat-pass *InSAR bursts (pair-wise burst synchronization* analysis)
- **Burst time (*Tdel*) mis-synchronization** would cause **relative shift** of **Doppler spectra**
  ⇒ would lead to a **loss** in *attainable* ***InSAR* azimuth BW** = ***common Doppler BW***



$$\Delta f_{T_{del_shift}} = k_a \left| \frac{k_{rot}}{k_a - k_{rot}} \right| T_{del} < 1$$



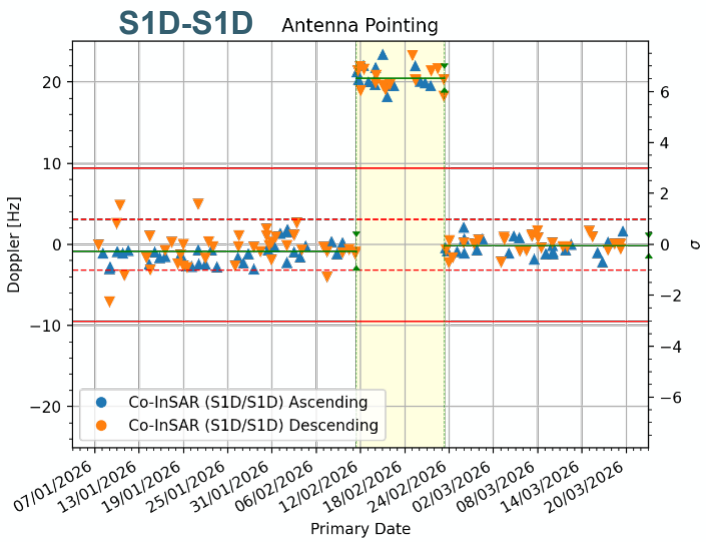
Burst synchronization / Common Doppler BW loss:

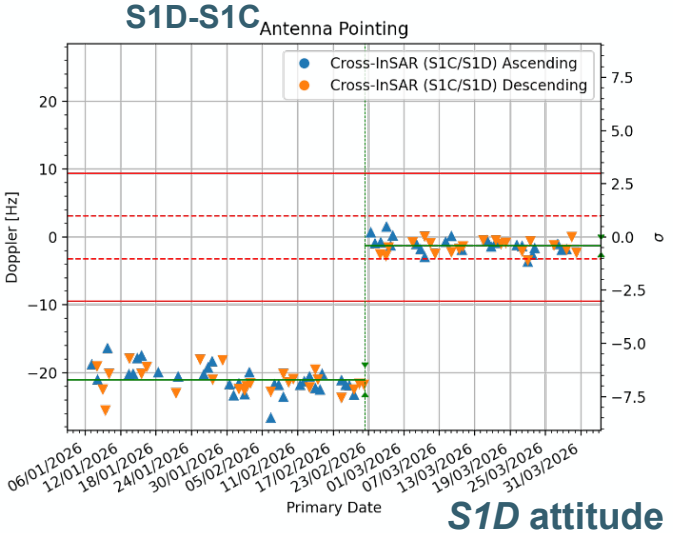
- **S1C-S1C**: *3.4ms* RMS / 1.7%
- **S1C-S1A***: *11ms* RMS/ 5.5%
- **S1D-S1D**: *2.3ms* RMS/ less than 1%
- **S1D-S1C**: *3.3ms* RMS / little over 1%
- **S1D-S1A***: *3.5ms* RMS / little over 1%

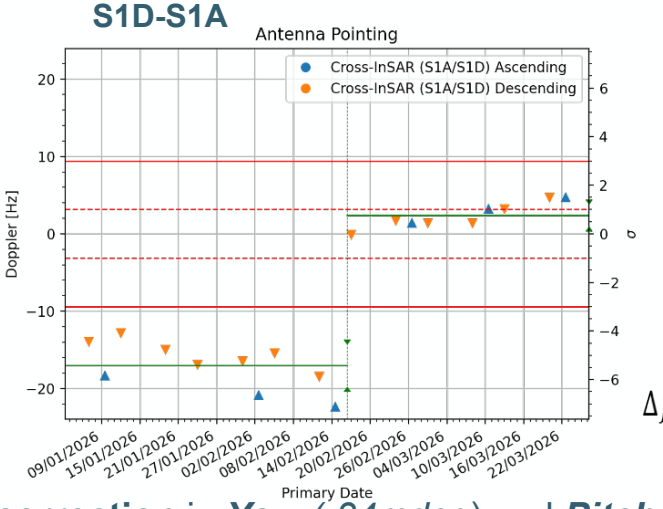
*Impact of S1A relaxed orbit control

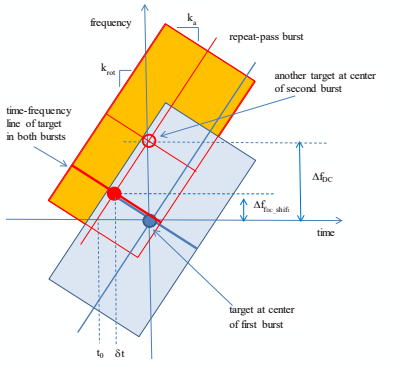
Impact of SAR Pointing on Azimuth Spectral Alignment

- ***Different* pointing *offsets*** due to ***platform attitude*** and ***SAR antenna pointing*** in **co-InSAR *S1C-S1C* & *S1D-S1D***, and **cross-InSAR *S1C-S1A* & *S1D-S1C* & *S1D-S1A*** pairs cause ***difference*** in ***Doppler Centroid*** *frequency*





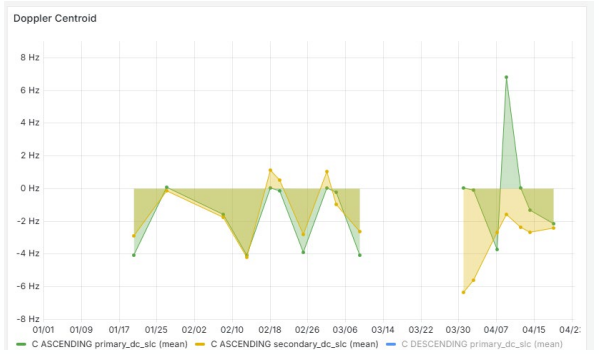




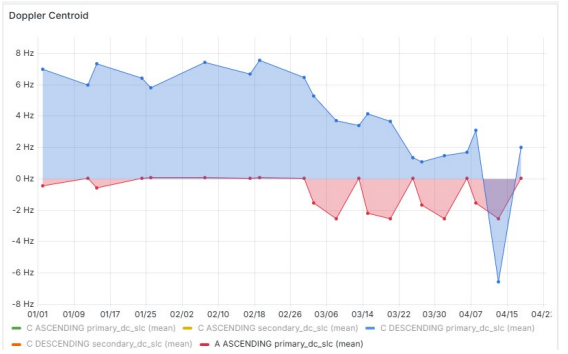
$$\Delta f_{f_{DC_shift}} = \frac{k_a}{k_a - k_{rot}} \Delta f_{DC} = \frac{\Delta f_{DC}}{\alpha}$$

S1D* attitude correction** in ***Yaw *(-34mdeg)* and ***Pitch*** *(-19.5mdeg)* on 23 Feb.26
⇒ ***minimizes S1D absolute Doppler Centroid frequency*** *on* from ***-90Hz*** to ***-10Hz***

S1C- S1C

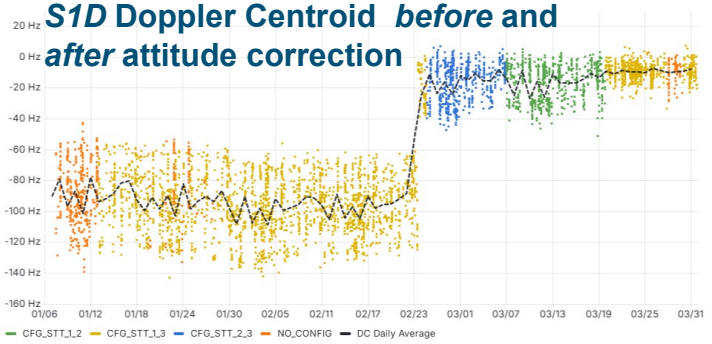


S1C (red) - S1A (blue)



- **Azimuth spectral alignment:** *average* ***BW RMS loss***
  - **S1D-S1D:** ***0.3%***
  - **S1D-S1C:** ***0.5%***
  - **S1D-S1A:** ***0.8%***
  - **S1C-S1C:** ***0.8%***
  - **S1C-S1A:** ***2.5%***

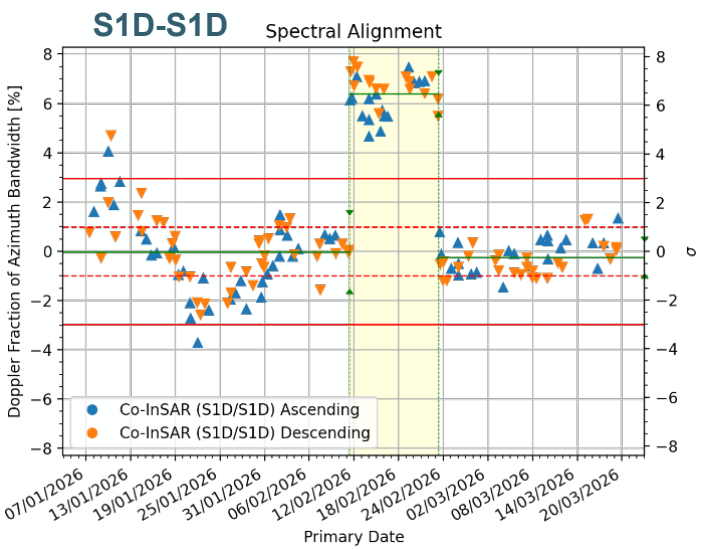
***S1D* Doppler Centroid *before* and *after* attitude correction**

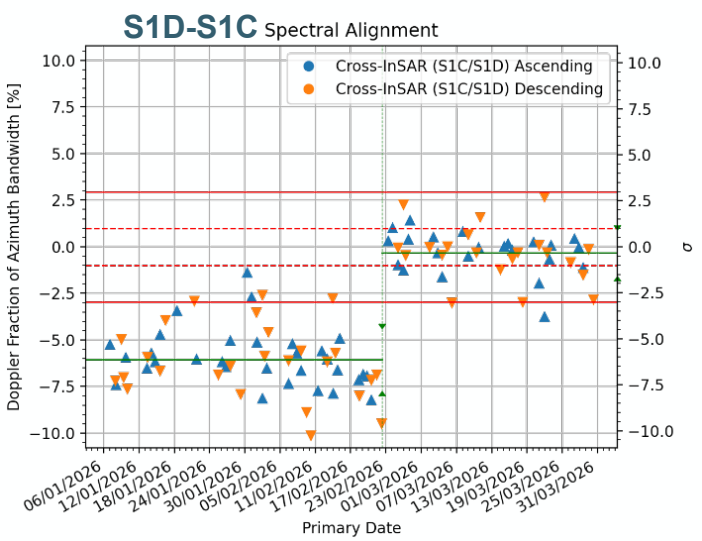


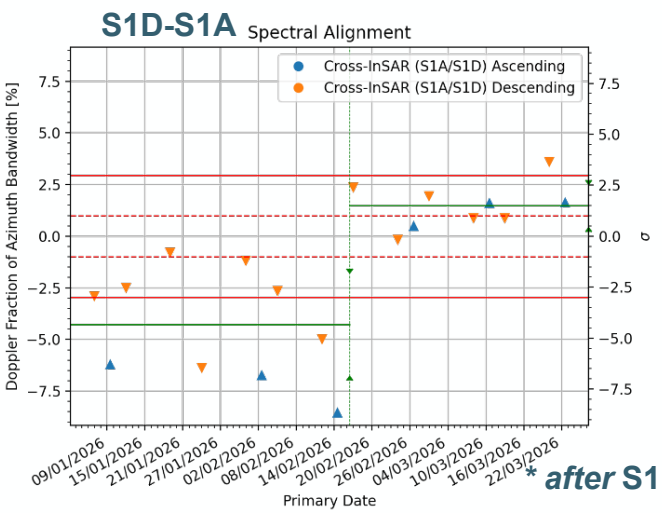
S1A has ***larger*** **pointing offset than *S1C*** causing **Doppler spectra shift ~ *20 Hz*** (scaled)

Total Azimuth Spectral Alignment – Common Doppler BW

- **Total Azimuth Spectral Alignment** – ***Common Doppler BW*** considers contributions from both: ***Burst (mis-) Synchronisation*** and ***SAR*** (mis)-***Pointing*** (measured as ***difference*** in ***Doppler Centroid frequency***)

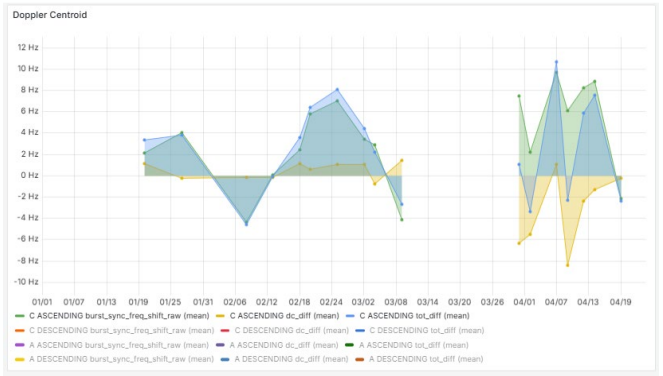




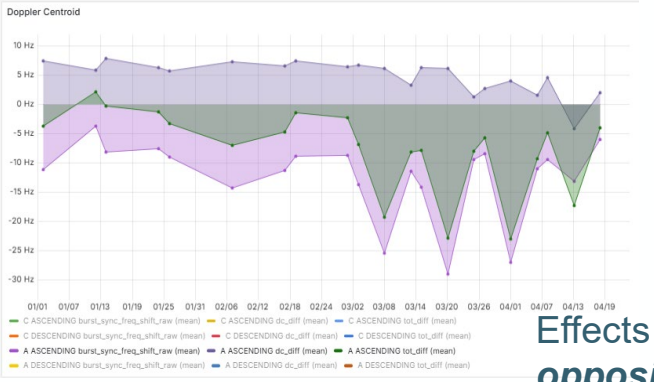


* ***after*** **S1D attitude correction**

S1C-S1C total Doppler Centroid shift (blue)



S1C-S1A total Doppler Centroid shift (green)



Total *Common Doppler* BW :

- **S1D-S1D*:** more than **99%**
- **S1D*-S1C:** about **99%**
- **S1D*-S1A:** more than **98%**
- **S1C-S1C:** more than **98%**
- **S1C-S1A:** about **97%**

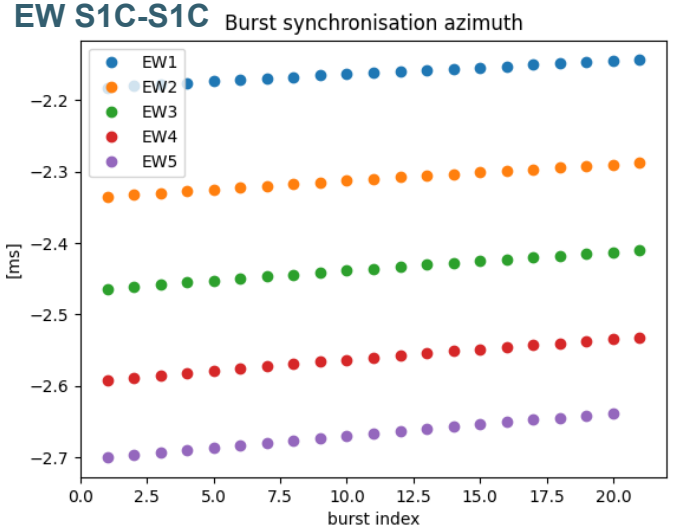
Effects of ***burst synchronisation*** and ***SAR pointing*** can be **in *opposite directions*** ⇒ *partially cancel* each other when combined

Extra Wide Swath Data InSAR Capability

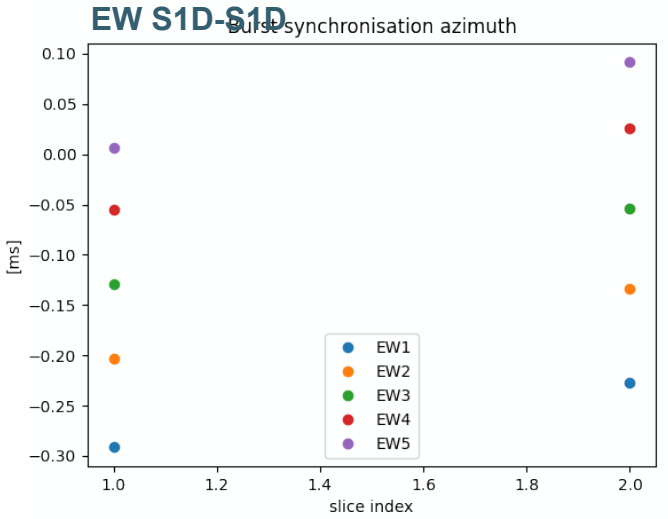
- Demonstration of *InSAR capability* for ***S1C-S1C & S1D-S1D EW*** **InSAR data** pairs (*5 sub-swaths* covering *400km)*
- ***EW SLC data*** are <u>only</u> available during the Commissioning phase

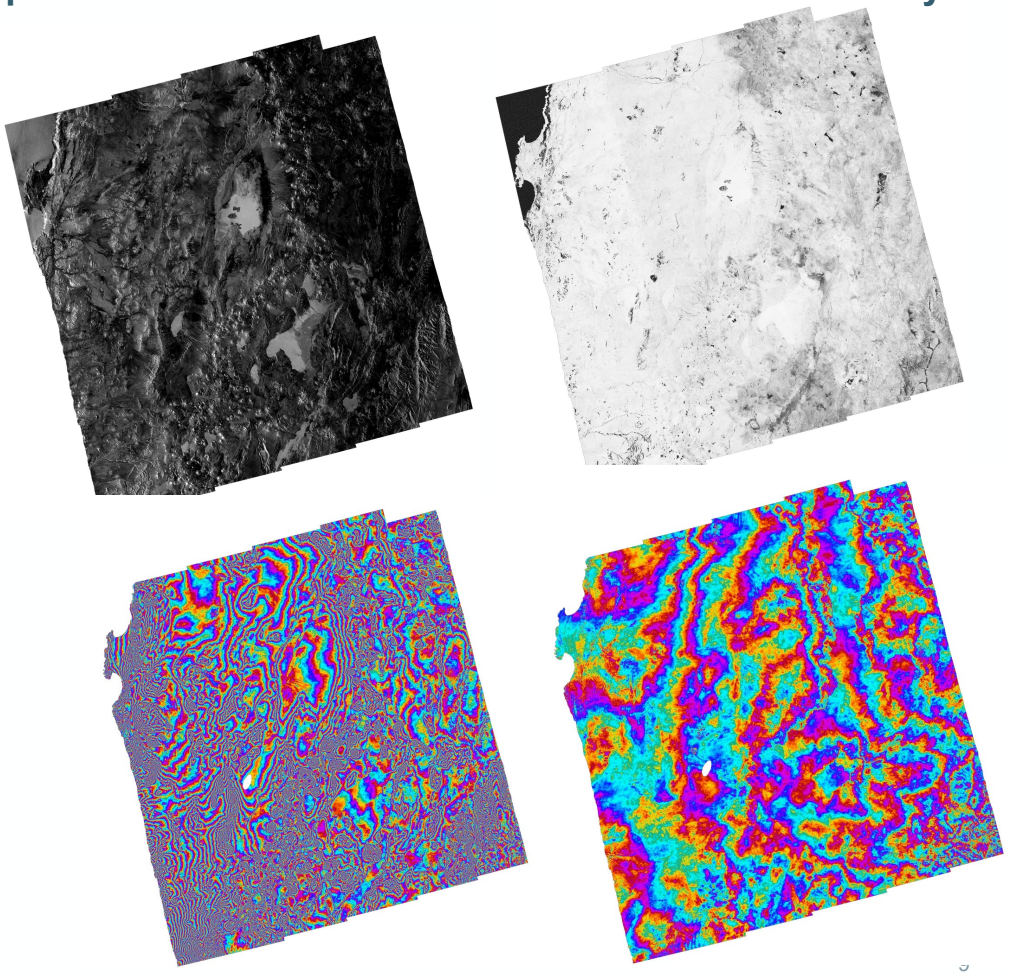
Example: EW S1C 2025-01-27 / S1C 2025-02-08 Salar de Uyuni

EW S1C-S1C



EW S1D-S1D



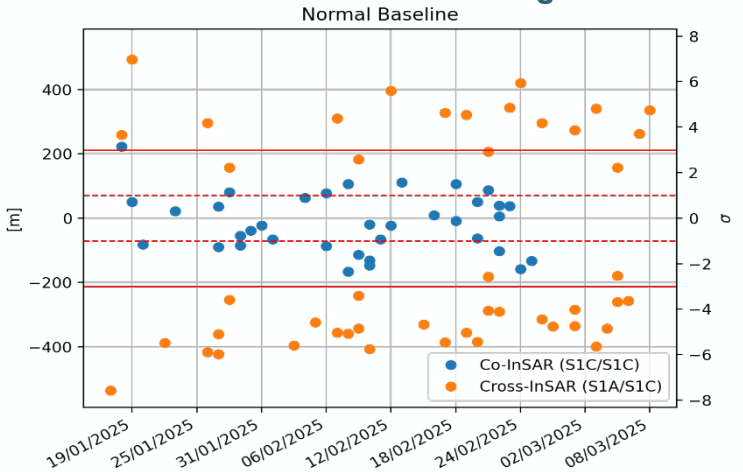


- **Very good EW InSAR burst synchronization < 1ms** despite *5 EW sub-swaths* with *shorter burst duration* (0.5s – 0.6s) than in *IW* data (0.8s -1.05s)
- **Very good** *azimuth spectral alignment* with ***98% (S1C)*** and **more than *99% (S1D)*** of **Common Doppler BW**
- **Demonstrates capability of repeat-pass InSAR using large number of sub-swaths for wide area mapping**

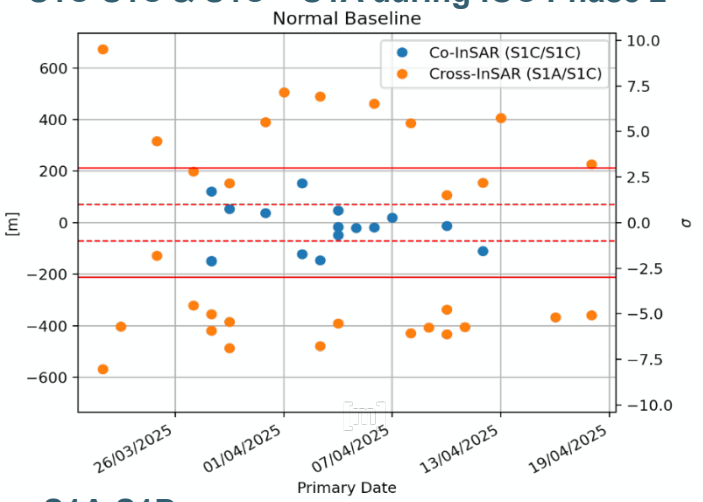
InSAR Orbital Baseline

- **InSAR baselines** for ***co-InSAR S1C-S1C & S1D-S1D,*** and ***cross-InSAR S1C-S1A & S1D-S1C*** & ***S1D-S1A*** *pairs*

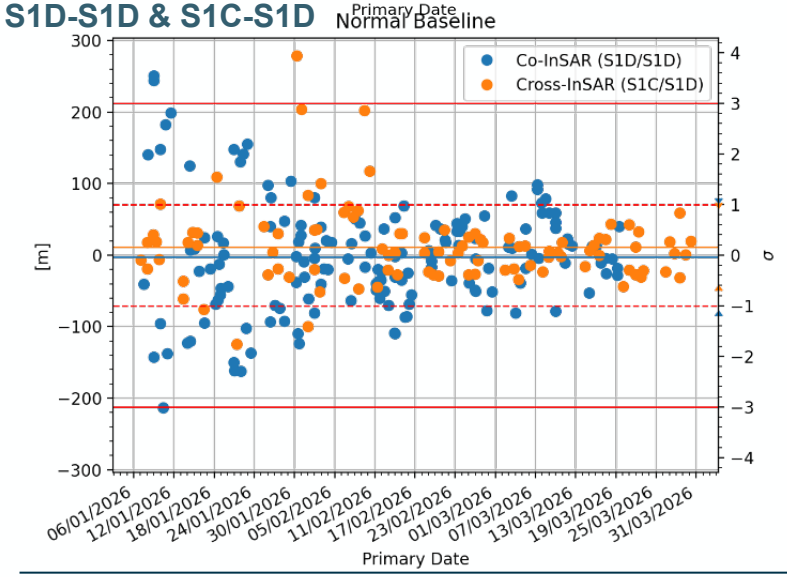
S1C-S1C & S1C – S1A during IOC Phase 1



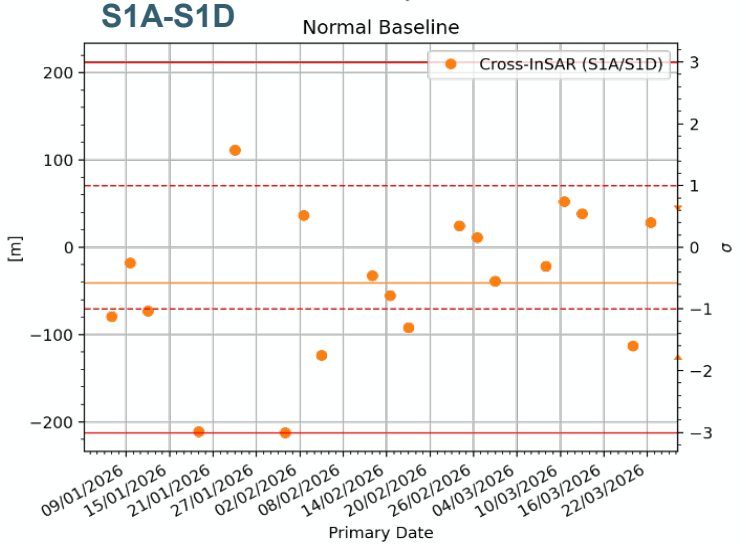
S1C-S1C & S1C – S1A during IOC Phase 2



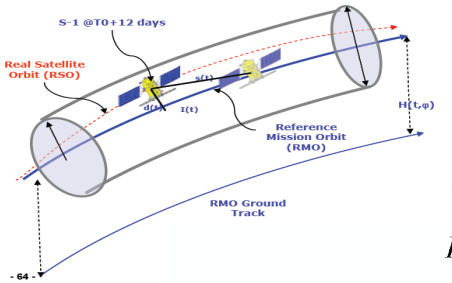
S1D-S1D & S1C-S1D



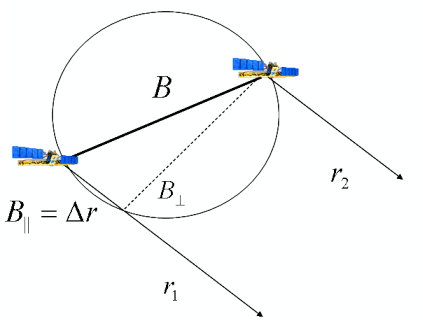
S1A-S1D



Sentinel-1 Orbital Tube



InSAR orbital Baseline



Orbital baseline for **co- and cross-InSAR** is **very well-controlled**

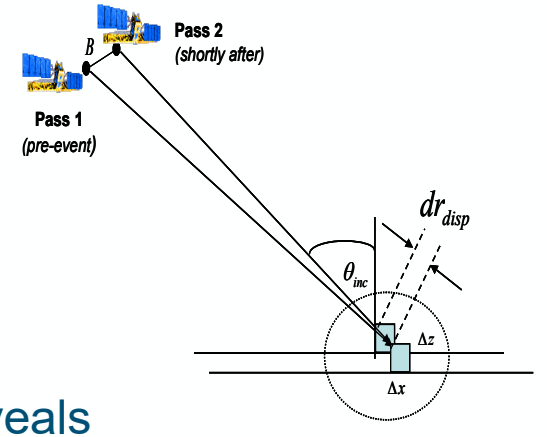
- **S1D-S1D co-InSAR**: 47m RMS
- **S1D-S1C cross-InSAR**: 42m RMS
- **S1D-S1A cross-InSAR**: 62m RMS
- **S1C-S1C co-InSAR**: 92 m RMS
- **S1C-S1A cross-InSAR**: 362m RMS

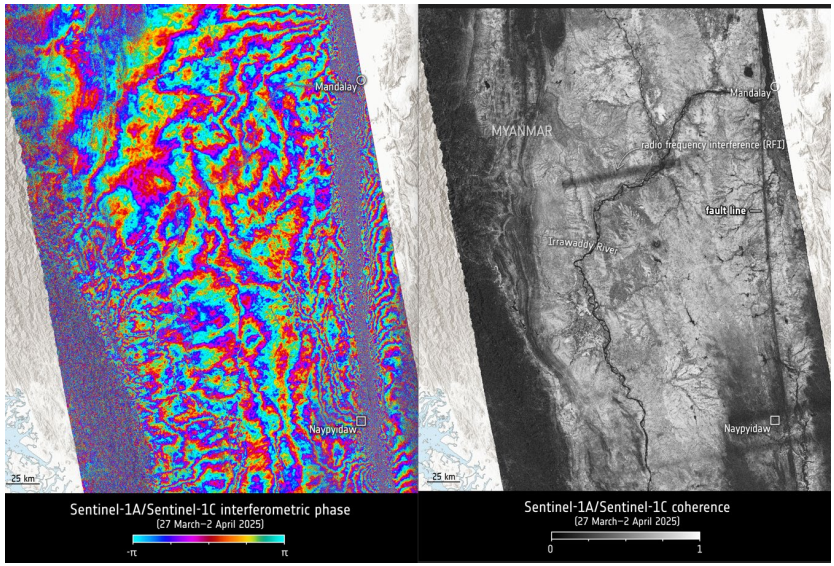
* ***S1A-S1D*** cross-InSAR normal baseline is affected by ***S1A's*** relaxed orbit control, thus showing a larger spread

S1A-S1C InSAR for Surface Deformation Mapping: Myanmar Earthquake

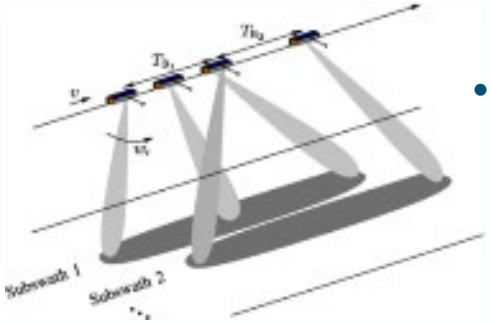
Powerful ***7.7 magnitude earthquake*** struck central Myanmar on ***28 March 2025***

- *pre-earthquake* **S1A IW mode image** taken on ***27 March 2025***, thanks to *global* and *systematic S1* acquisition plan
- **S1C** was immediately tasked to image earthquake site with an **IW mode** acquisition taken on ***2 April 2025***

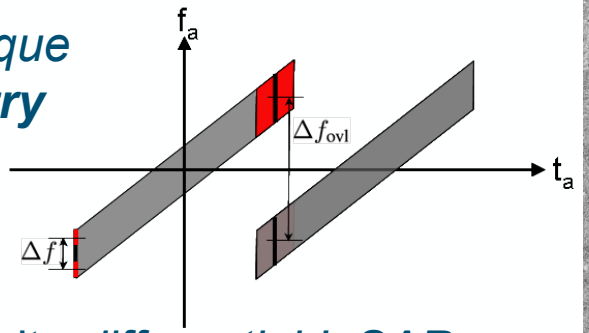


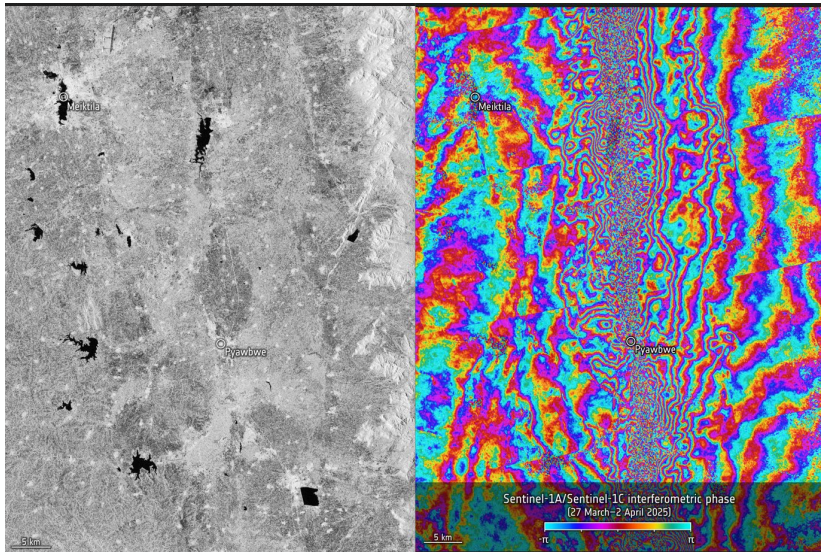


⇒ ***cross-S1A-S1C* differential interferogram** reveals **surface deformation** in ***across (E-W)*** and ***along*** the ***N-S Sagaing Fault***



- ***S1 TOPS* mode** enables *unique* ***Burst Overlap Interferometry*** capability





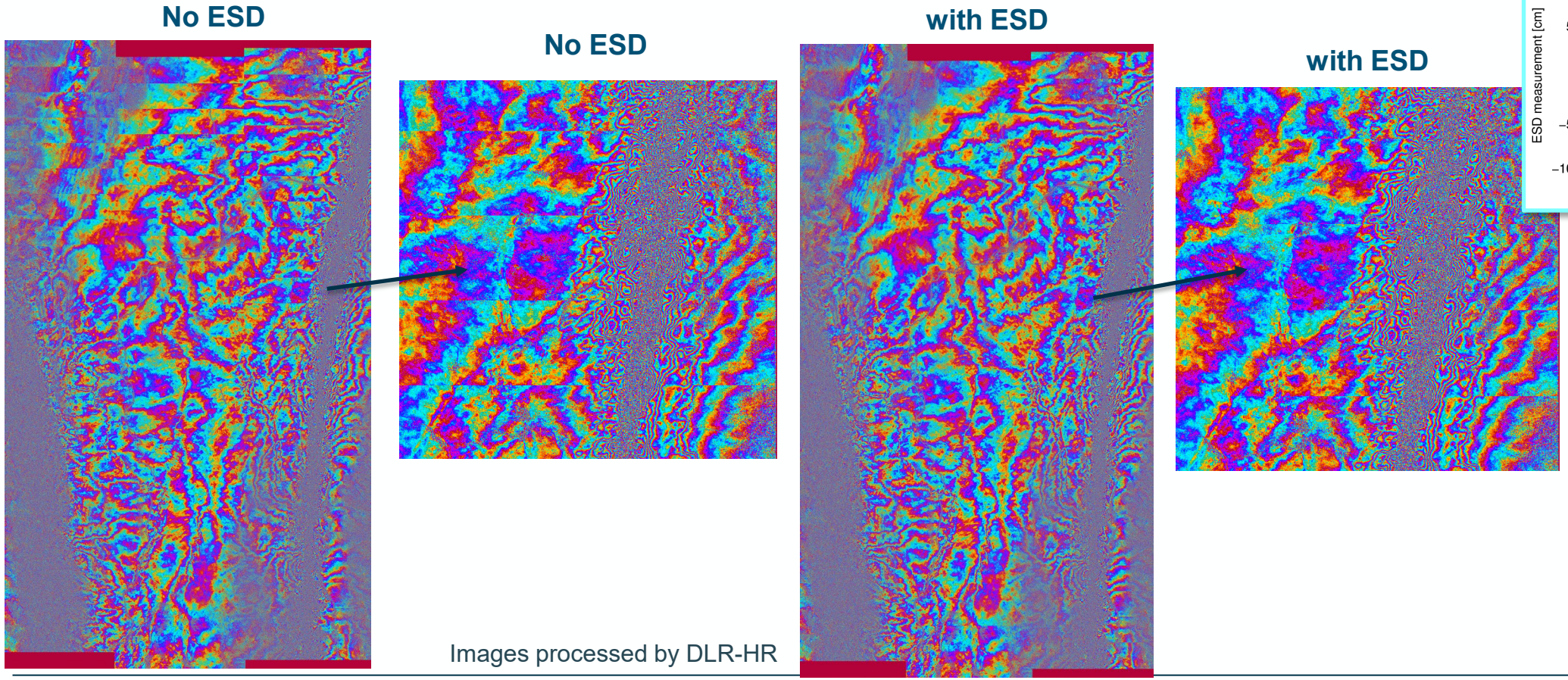
- ***Enhanced Spectral Diversity (ESD)** method* exploits *differential InSAR phase* in **overlap region of bursts** to measure **along-track surface shifts**

Images processed by DLR-HR

S1A-S1C InSAR for Surface Deformation Mapping: Myanmar Earthquake

- *Azimuth shifts* due to ***surface deformation*** occur mostly in ***IW-3*** *sub-swath*
- Estimation of ***co-registration shifts*** only in ***IW-1*** and ***IW-2*** using *ESD*
- Application of co-registration shifts to all sub-swaths to avoid flattening of *geophysical signal* in *IW-3*

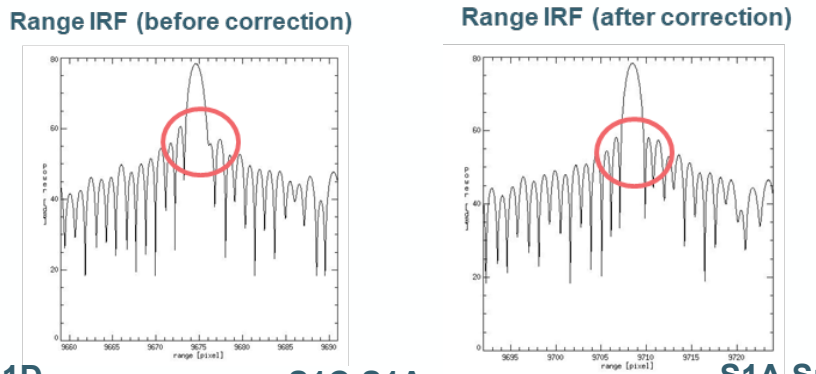
⇒ ***Separate ESD measurements*** in ***IW-3*** *yield azimuth shift* related to *surface deformation*

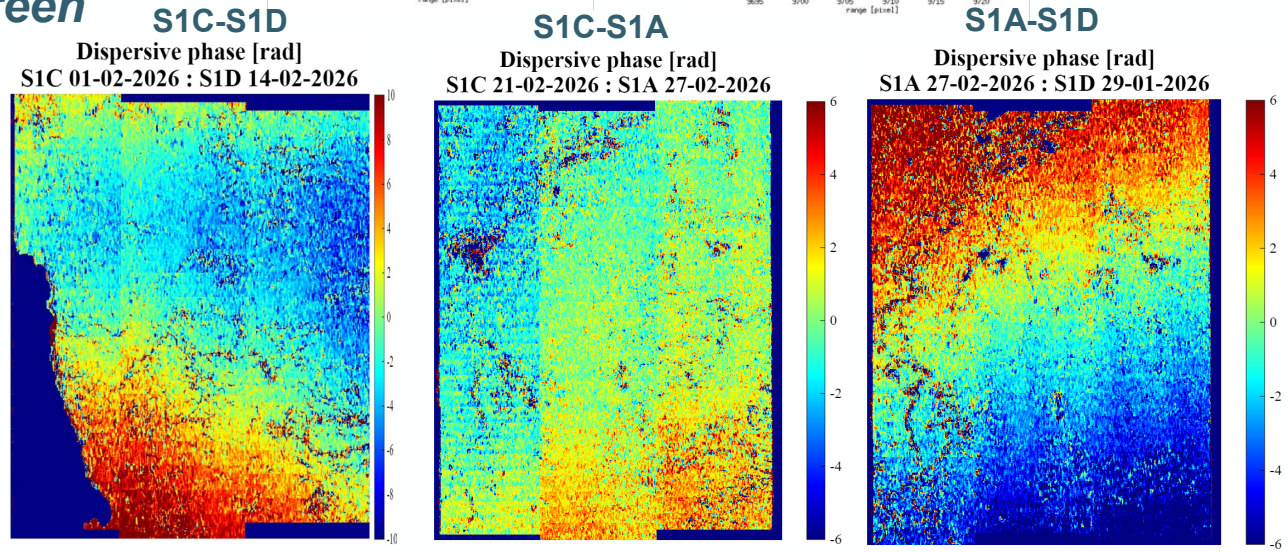


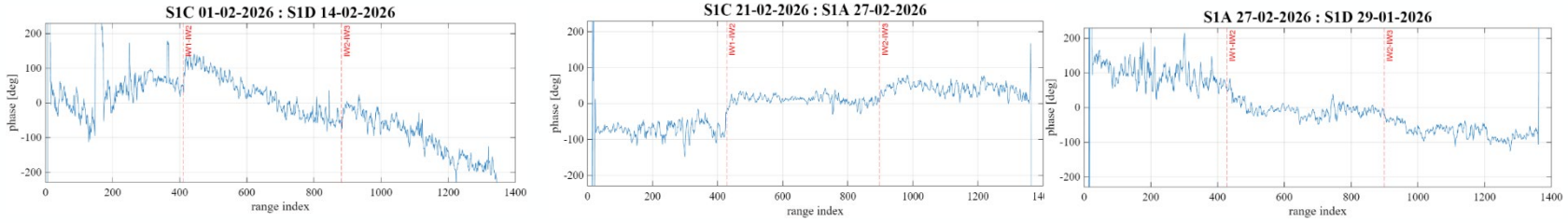
Images processed by DLR-HR

InSAR Dispersive Phase Analysis

- Slight *asymmetry* in *sidelobes* of ***S1C*** and ***S1D range IRF*** caused by a *residual phase* in SAR instrument radar chirp generator
- **Phase correction** was implemented in **IPF** for ***each S1C IW sub-swath*** and ***polarization*** using 5th-7th order polynomials
- *Delta-k* ***dispersive phase*** is *sensitive* to ***distortions*** in ***range spectral phase*** profile ⇒ ***ionospheric phase screen***
- ***Dispersive phase*** shows a ***small phase jump*** of *about 0.5 deg.* (scaled) between *IW1* and *IW2* in ***S1C-S1D*** and ***S1C-S1A***, but **not** in ***S1D-S1A*** **cross-interferograms ⇒ S1C SAR** causes *dispersive phase*
- ***Disperse phase*** is **consistent** in ***S1D-S1D*** and ***S1C-S1C*** **co-InSAR** interferograms ⇒ ***no phase jumps***
- *Phase jumps* are **not** *noticeable* in **regular *S1C-S1D* cross-InSAR** interferograms, only when estimating ***ionospheric phase screen***

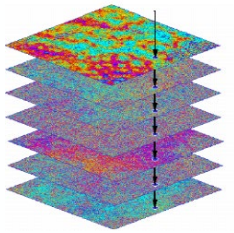




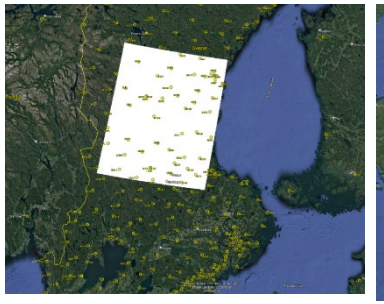


InSAR Stack Data Analysis

- Verification of **phase stability** of **co-** ***S1C-S1C*** & ***S1D-S1D*** and **cross-** ***S1C-S1A & S1D-S1C*** interferogram stacks
- InSAR stacks were analyzed: *Atacama desert* (flat, dry), and *Central Sweden and Le Mans* (large number of Persistent Scatterers (PS))





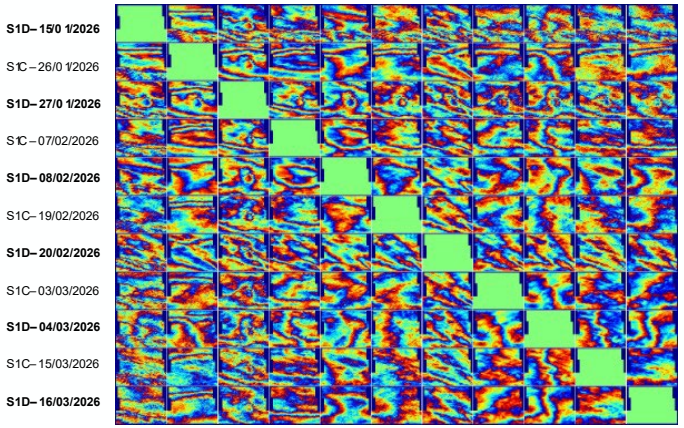




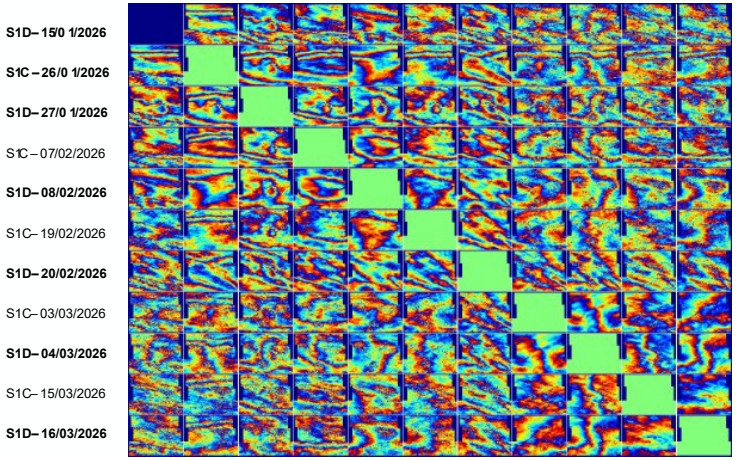
- **Phase Linking** approach measures ***phase stability*** of ***each* interferogram** by *comparing its phase* with the one estimated from **jointly processed *entire InSAR stack***

⇒ Enables fast assessment of *InSAR image quality*

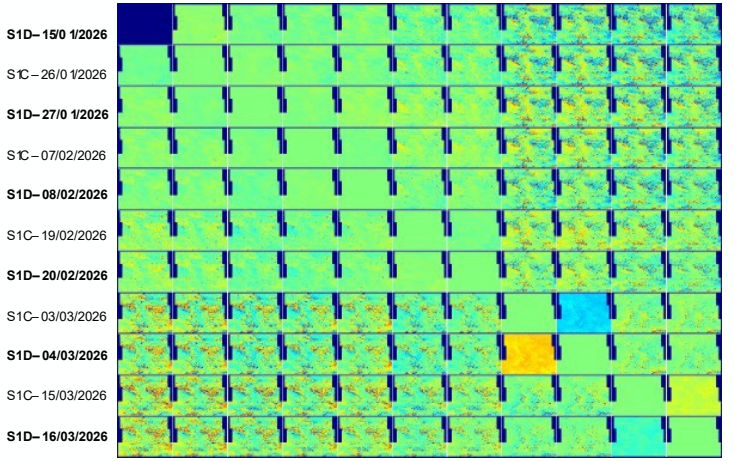
Original Interferograms



Linked Interferograms



Residuals

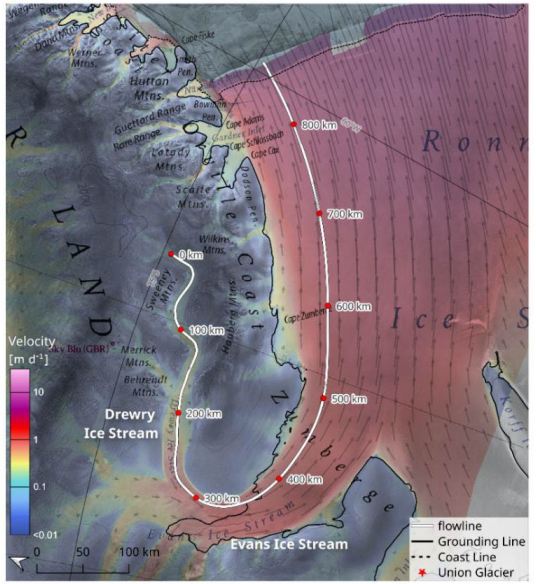


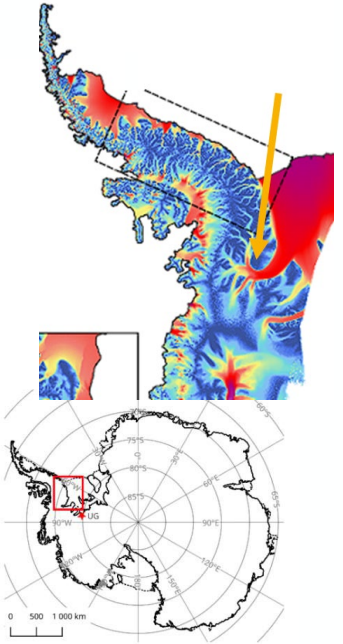
- **No anomalies** have been found in all processed ***S1C*** and ***S1D*** *co-* and *cross interferograms*
- Decorrelation and volumetric scattering make the residual interferometric phase noisy at long temporal baselines (known repeat-pass InSAR limitation)

S1C-S1D InSAR Ice-Flow Mapping of Antarctic Stream

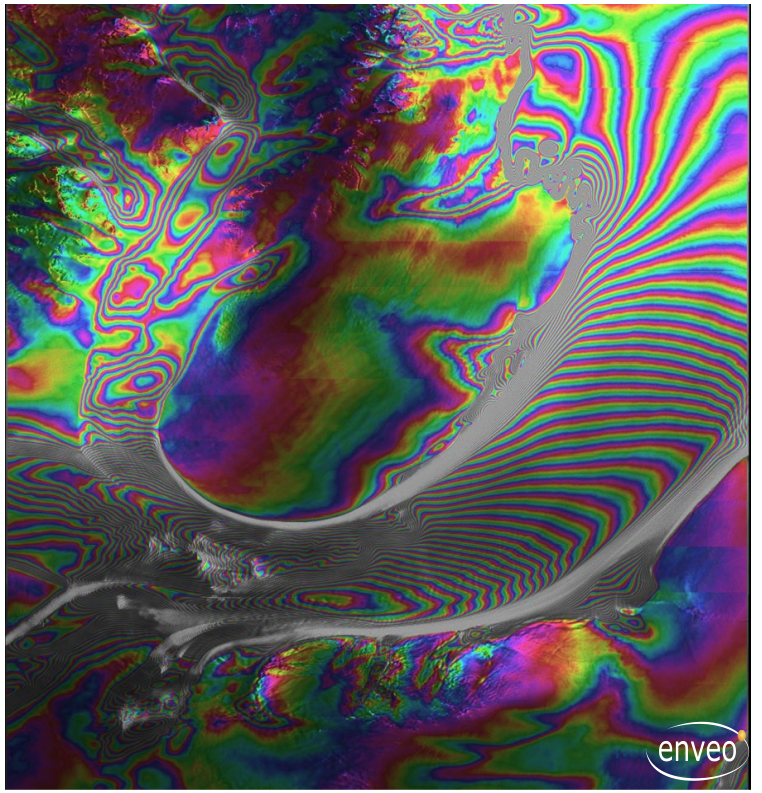
- ***S1C-S1D,* 1-day cross-interferogram** demonstrates capability to measure ***ice-flow velocity*** and ***Grounding line*** of ***Antarctic ice streams***, e.g., the ***Evans Ice Stream*,** data acquired on ***13 & 14 Feb. 2026***

- ***Evans Ice Stream*** is a prominent *outlet glacier*, located in *West Antarctica*
- Channels *ice* from *intersection* between ***Peninsula*** and ***West Antarctic Ice Sheet*** into ***Ronne Ice Shelf*** with velocities of *3-4m/day*









Data processed by ENVEO, images courtesy of Thomas Nagler

- Proposed ***Cal/Val*** *site* for ***ROSE-L*** *Polar Ice Sheets* products

Conclusions

- ***Sentinel-1 mission***, previously with ***S1A*** & ***S1B***, has already set a benchmark for achieving a ***high-quality end-to-end SAR*** and ***InSAR performance***
- Demonstration of ***co-InSAR*** and ***cross-InSAR*** capabilities, including combinations of ***S1C***, ***S1D***, and ***S1A*** *InSAR pairs*, for mapping of *surface deformation* (e.g., *Myanmar* earthquake) and *flow* of *ice streams* (e.g., *Evans Ice Stream* in Antarctica)
- Verification of key *InSAR performance* parameters :
  - Accurate **burst synchronization < 5ms**
  - Stable **platform and SAR pointing** yielding small Doppler centroid differences (~10Hz),

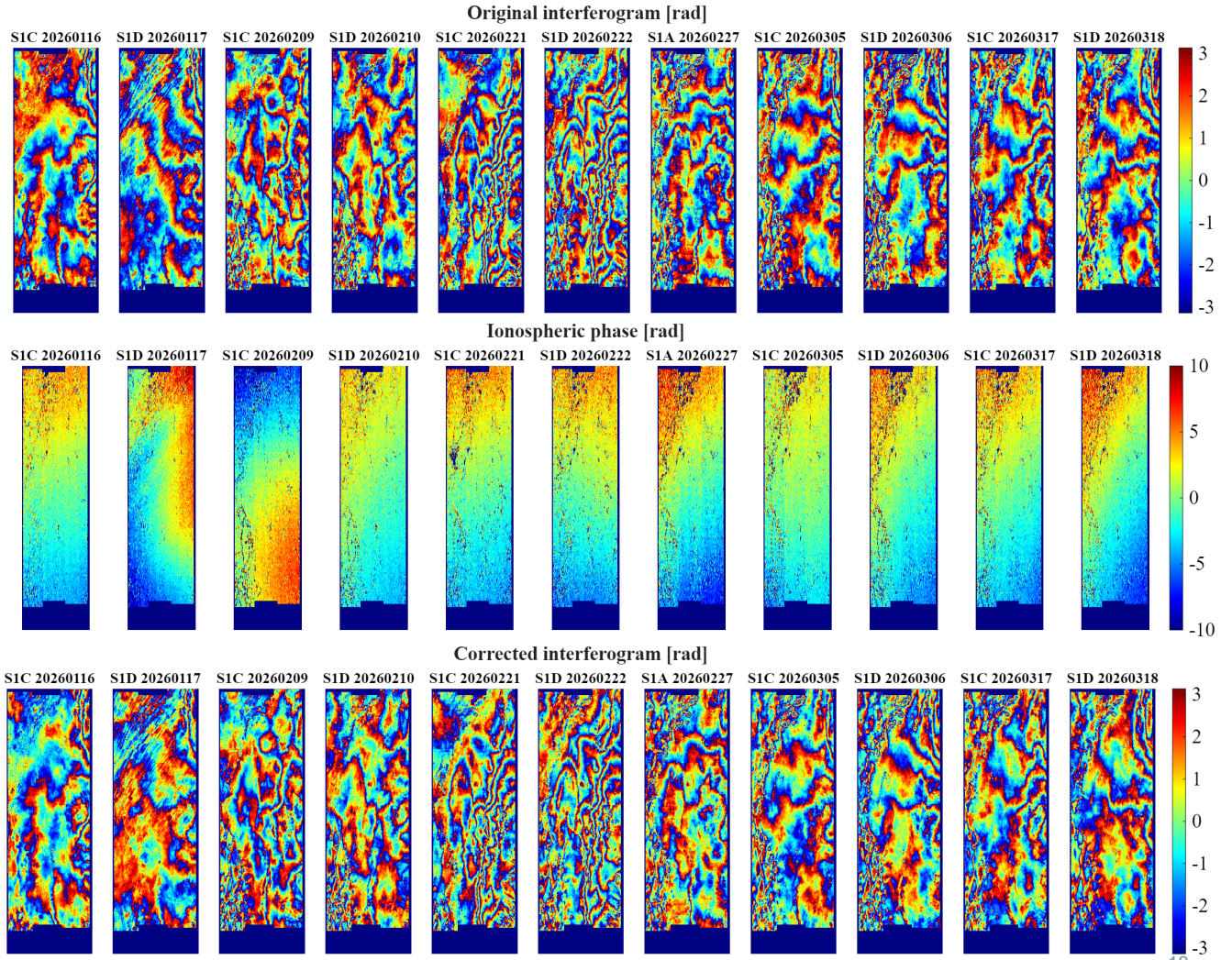
  ⇒ **Large common Doppler BW: *99%* - 97% of azimuth BW**
  - ***Small*** orbital **InSAR baselines < *100m*** RMS**, except for *S1A-S1C*** with about ***360m*** RMS
- *Consistent* ***dispersive phase*** in ***S1D-S1D*** and ***S1A-S1D*** interferograms, but a small *dispersive phase jump* of 0.5 deg. in ***S1C-S1D*** (unnoticeable in regular interferograms)
- High **phase stability** of **co- *S1C-S1C & S1D-S1D*** and **cross- *S1D-S1C & S1C-S1A stacks*** (time series) of interferograms
- Demonstration of **EW** (5 sub-swaths) ***S1D-S1D*** *co-InSAR* **capability** incl. accurate **burst synchronization**

⇒ Following the completion of *S1C* and *S1D IOCs*, the ***Sentinel-1C/D*** **mission** provides an ***improved, continuous*** **support for *routinely*** **InSAR monitoring the Earth system**

Backup Slides

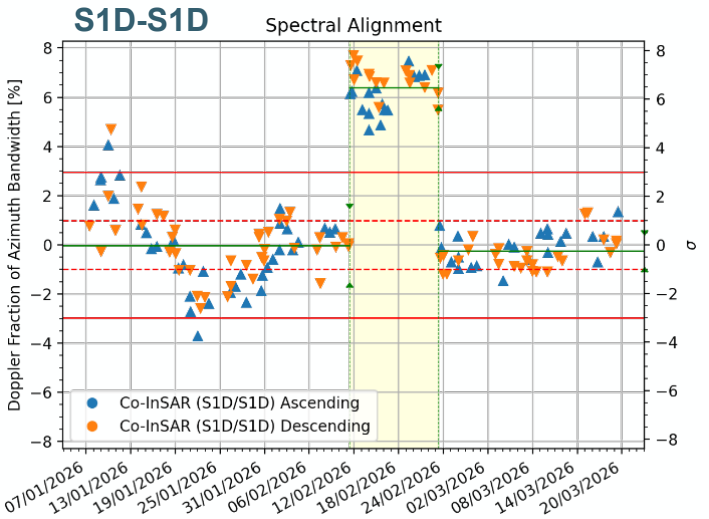
Ionospheric Phase Screen Estimation

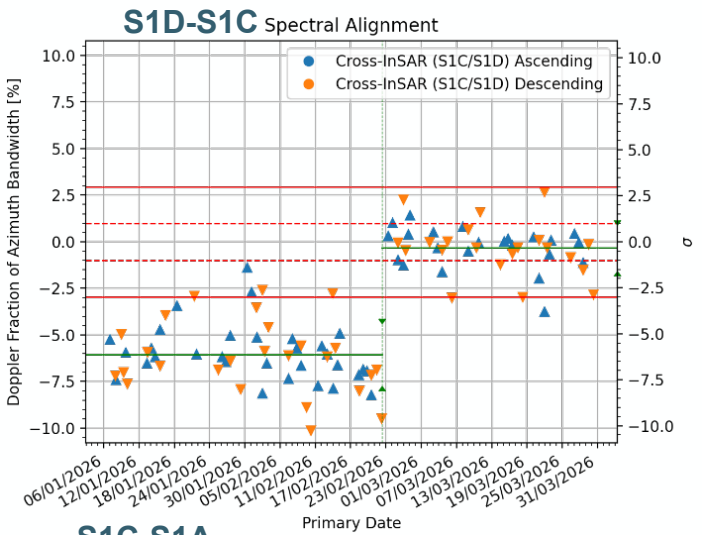
- Exploit *dispersive nature* of **EM wave propagation** through ***Ionosphere layer*** to separate its effect from other contributions (troposphere, topography, surface movement…)
- Calculation of ***delta-k dispersive phase***
- *Sensitive* to any ***distortions*** in ***slant-range spectral phase*** profile, but low resolution due to noise amplification
- Estimation of ***ionospheric phase screen***
- ***Strong solar activity*** at *beginning* of ***S1D*** commissioning phase introduced ***ionospheric phase scintillations*** to SAR data (latitude dependent)
- Required application of ***ionospheric phase correction*** *to* some SAR interferograms

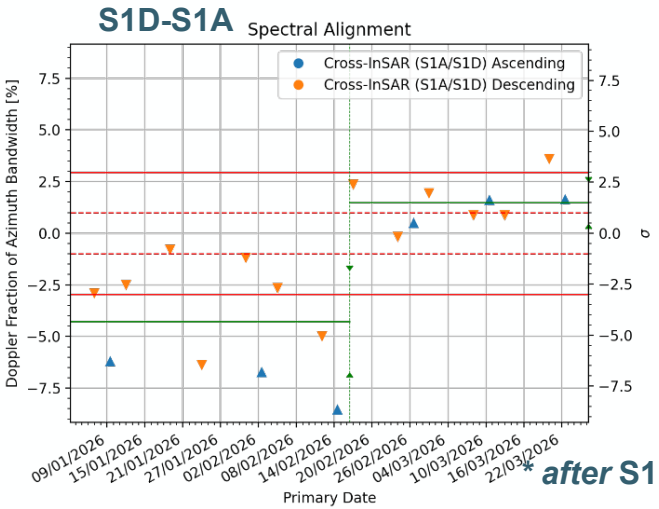


Total Azimuth Spectral Alignment – Common Doppler BW

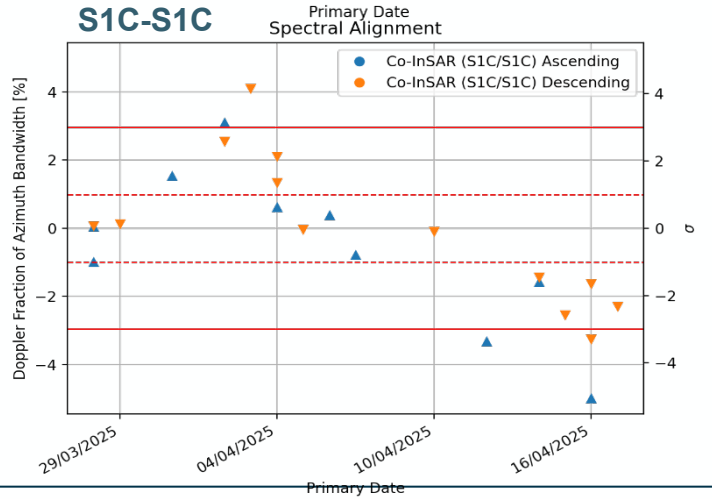
- **Total Azimuth Spectral Alignment** – ***Common Doppler BW*** considers contributions from both: ***Burst (mis-) Synchronisation*** and ***SAR*** (mis)-***Pointing*** (measured as ***difference*** in ***Doppler Centroid frequency***)

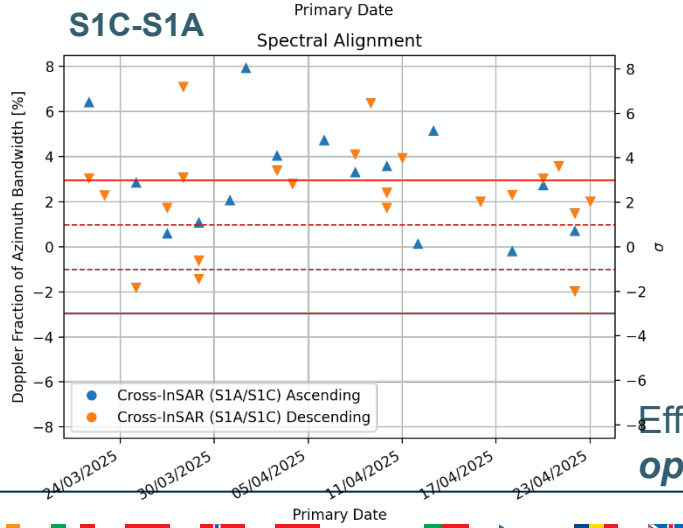






* ***after*** **S1D attitude correction**





Total Common Doppler BW :

- **S1D-S1D*:** more than **99%**
- **S1D*-S1C:** about **99%**
- **S1D*-S1A:** more than **98%**
- **S1C-S1C:** more than **98%**
- **S1C-S1A*:** about **97%**

Effects of ***burst synchronisation*** and ***SAR pointing*** can be **in *opposite directions*** ⇒ *partially cancel* each other when combined