Copernicus SAR Analysis-Ready Data: Products, Algorithms, and Processors

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SAR Analysis Ready Data (ARD)

Objective: Develop advanced processors for a new generation of SAR products, guaranteeing easy data access while maintaining state-of-the-art scientific quality.

CSLC

Co-registered Single Look Complex

- Aligned on a common radar grid with timing corrections.
- Preserves full measurement fidelity.
- Model-based + data-driven co-registration
- Interferometry-ready foundation for generating other ARDs.

GMLP

Geocoded MultiLooked Phase

- Geocoded to standard UTM coordinates (50 m posting).
- Reduces speckle and improves coherence.
- Phase consistency
- Regular updates with each 6 to 12-day acquisition.

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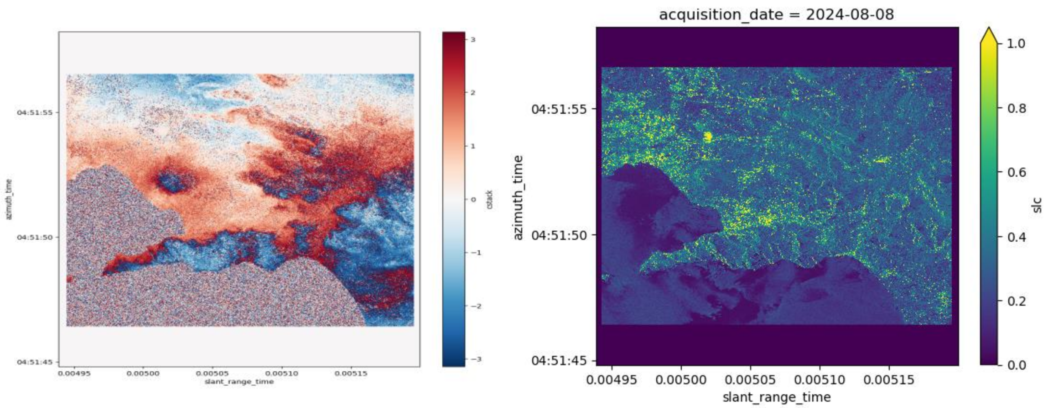
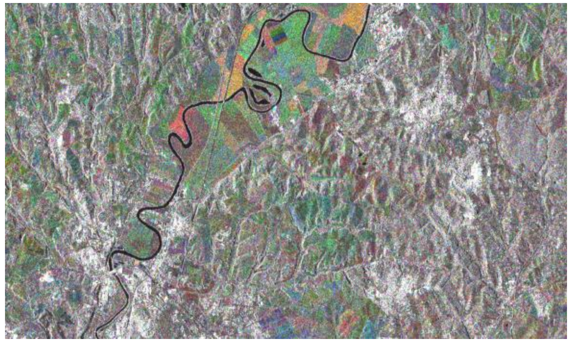
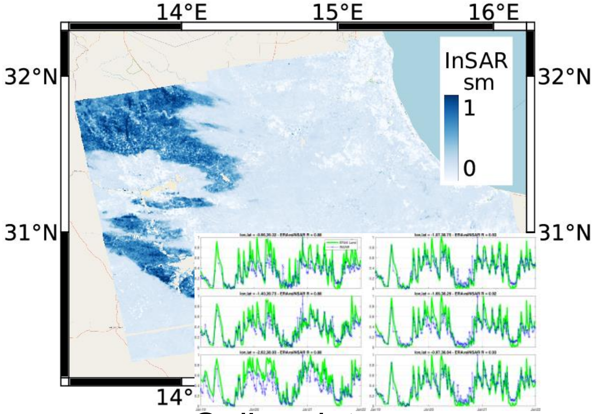
Applications



Phase & Coherence

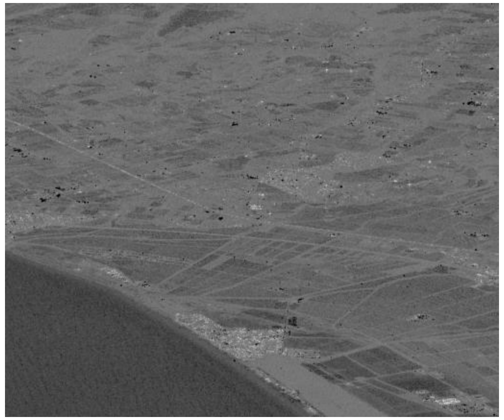


Change detection

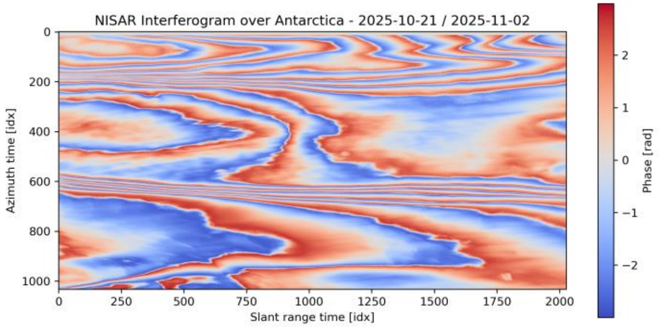


Soil moisture

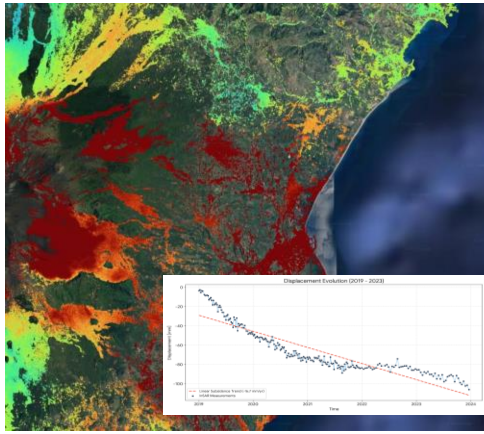
Temporal despeckling



Amplitude dispersion



Cryosphere



Persistent scatterers

Processor Implementation & Scalability

Cloud-Native Architecture

- Native Python ecosystem.
- **Xarray** & **Dask**: Chunked, lazy, and parallel computation.
- **Zarr:** Cloud-optimized format for highly efficient I/O.

Modularity & Extensibility

- Built for massive, systematic data volumes (**Sentinel-1**, **ROSE-L**).
- Pluggable framework for alternative corrections and new sensors.

Open Source Commitment

The complete processing pipeline will be released as *Open Source Software* to foster community collaboration, reproducible research, and transparent scientific validation.

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Quality Analysis

Different land cover

Point/Distributed scatterers

Artificial reflectors

- Co-registration accuracy
- Resolution
- ISLR/PSLR

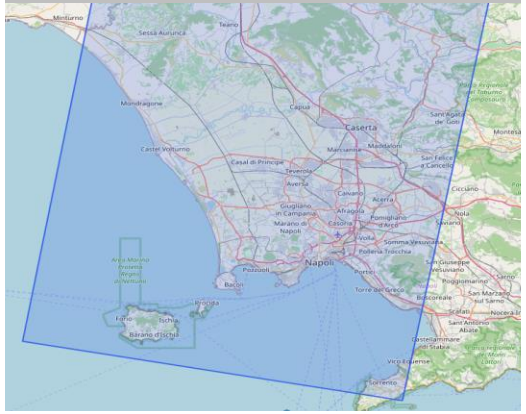
Burst overlap

- Residual azimuth shift
- Phase continuity

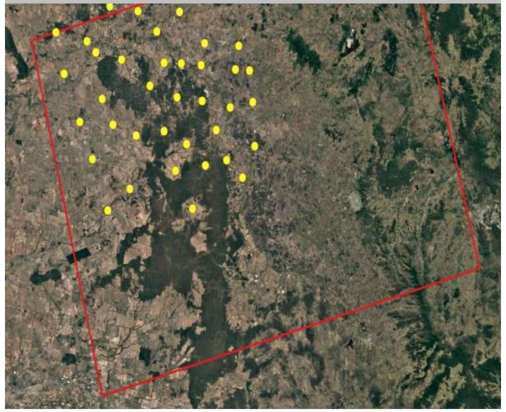
Persistent scatterers

- Phase drift in long time-series

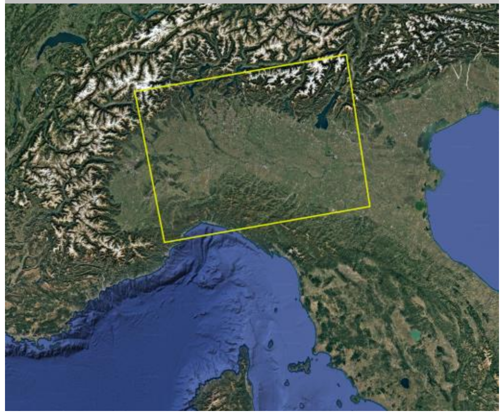
Campi Flegrei, Italy
SAOCOM, S4,
2020 - 2025



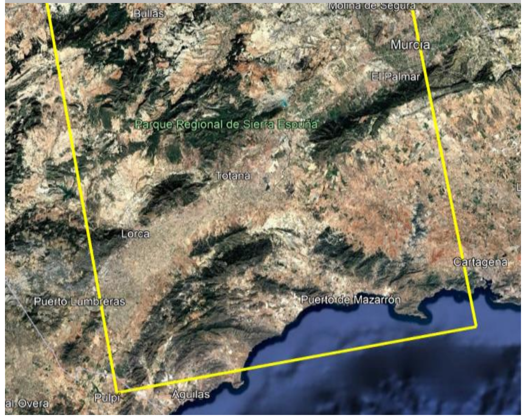
Surat Basin, Australia
Sentinel-1A, Track 111,
2024



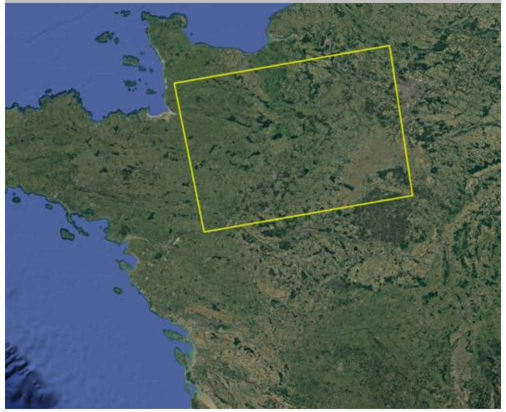
Milan, Italy
Sentinel-1C, Track 15,
2025 - 2026



Murcia, Spain
SAOCOM, S4,
2023 - 2026



Le Mans, France
Sentinel-1C, Track 132,
2025



Common Reference Grid

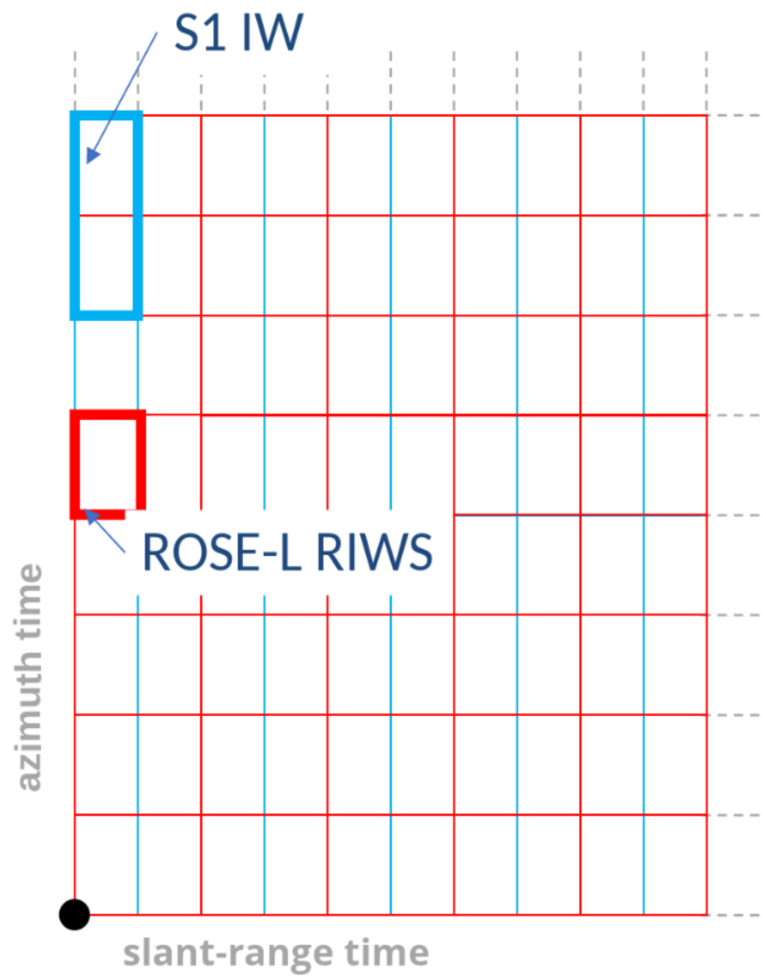
The Problem: Sentinel-1 and ROSE-L share orbits, but their native bursts are not comparable.

Proposed solution: A unified radar reference grid that projects and resamples every burst from both sensors onto a shared coordinate system.

Anchor Node: Uses a single shared point.

Spacing Optimization: Grid intervals are mathematically optimized to preserve the finest resolution of each sensor, with an integer ratio constraint.

Grid size: defined starting from the expected footprint, the reference orbit, and the application of zero-Doppler equations.



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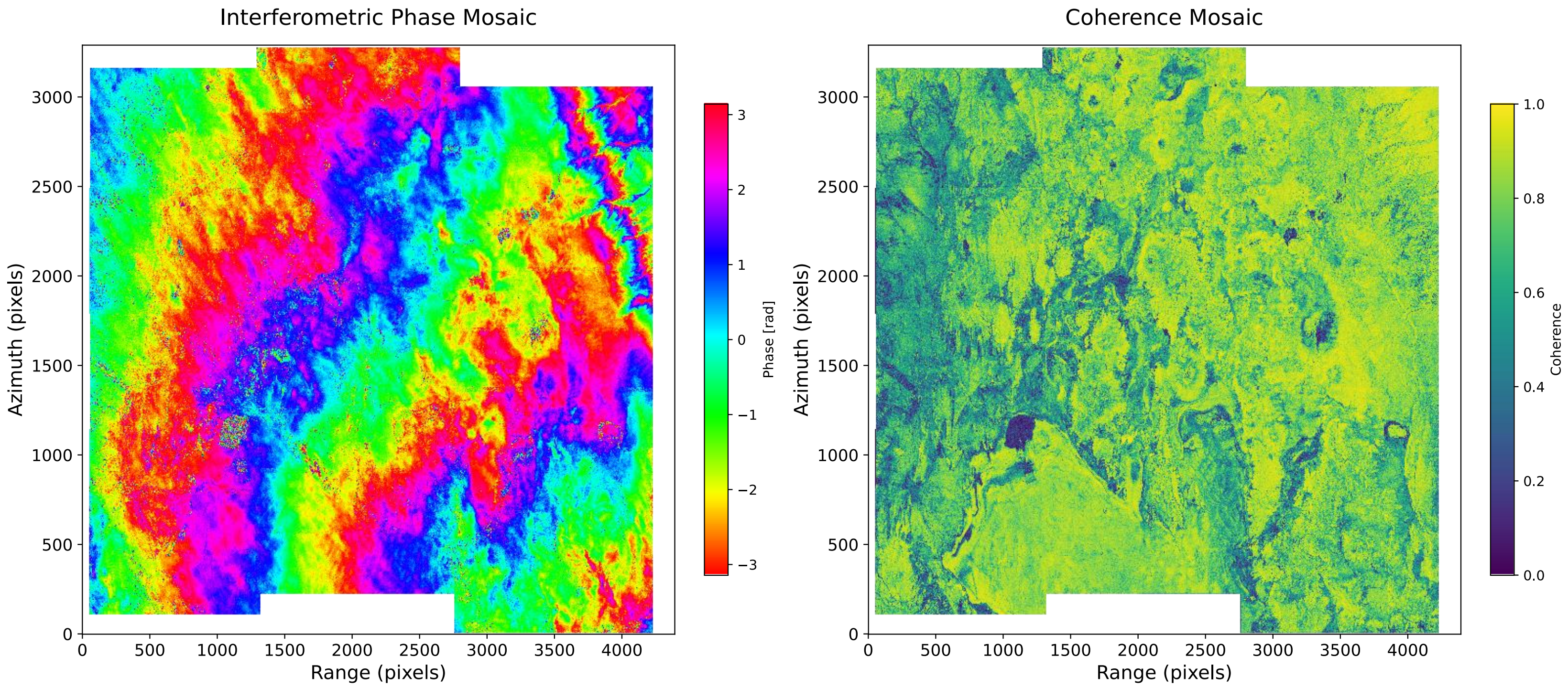
Model-based Co-registration

Geometric Alignment

- Uses DEM, orbital data, and timing corrections (ETAD).
- Applied independently on each individual burst.
- Generally sufficient for C-band sensors like the **Sentinel-1** mission.
- Small residual phase discontinuities between bursts can be easily recovered through ESD.



S1C Atacama: 2025-09-18 vs 2025-12-11

Why data-driven …

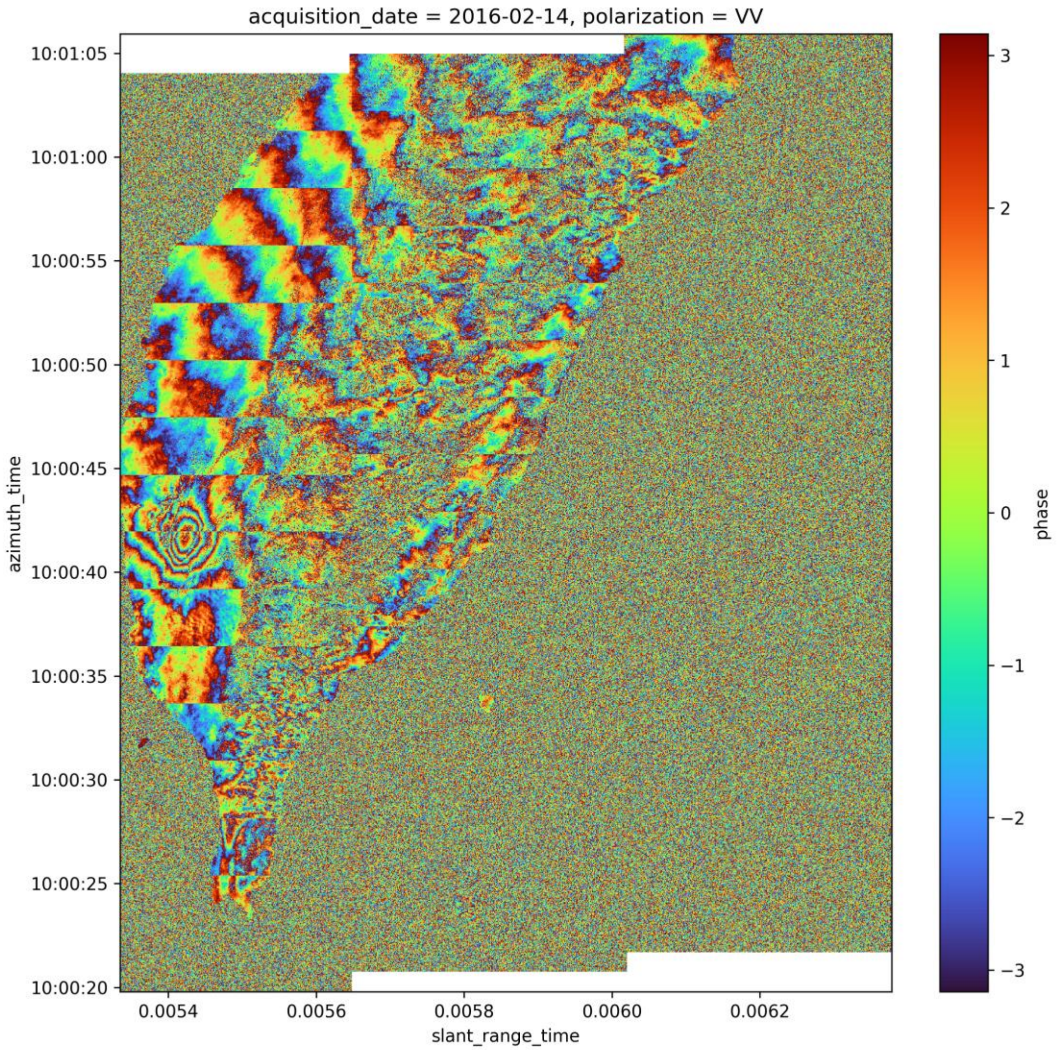
Signal offsets in L-Band are 18x larger than in C-Band.

Required to achieve sub-pixel accuracy and phase continuity in L-Band.

Taiwan: 2016-02-02 vs 2016-02-14

Model-Based Co-registration

Residual phase ramp + phase discontinuities



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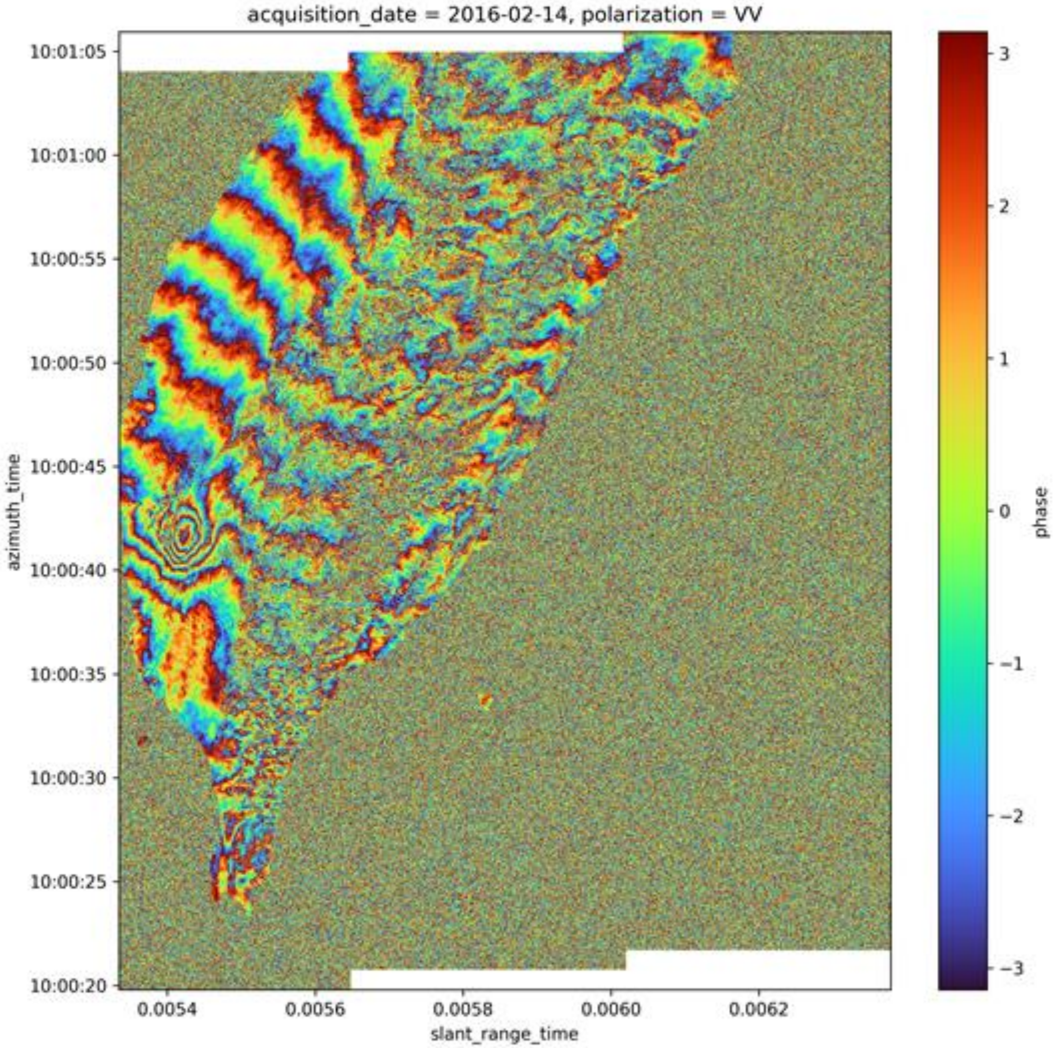
Why data-driven …

Taiwan: 2016-02-02 vs 2016-02-14

Image Matching & ESD: Refines range and azimuth alignment to absolute sub-pixel precision.

Residual phase ramp



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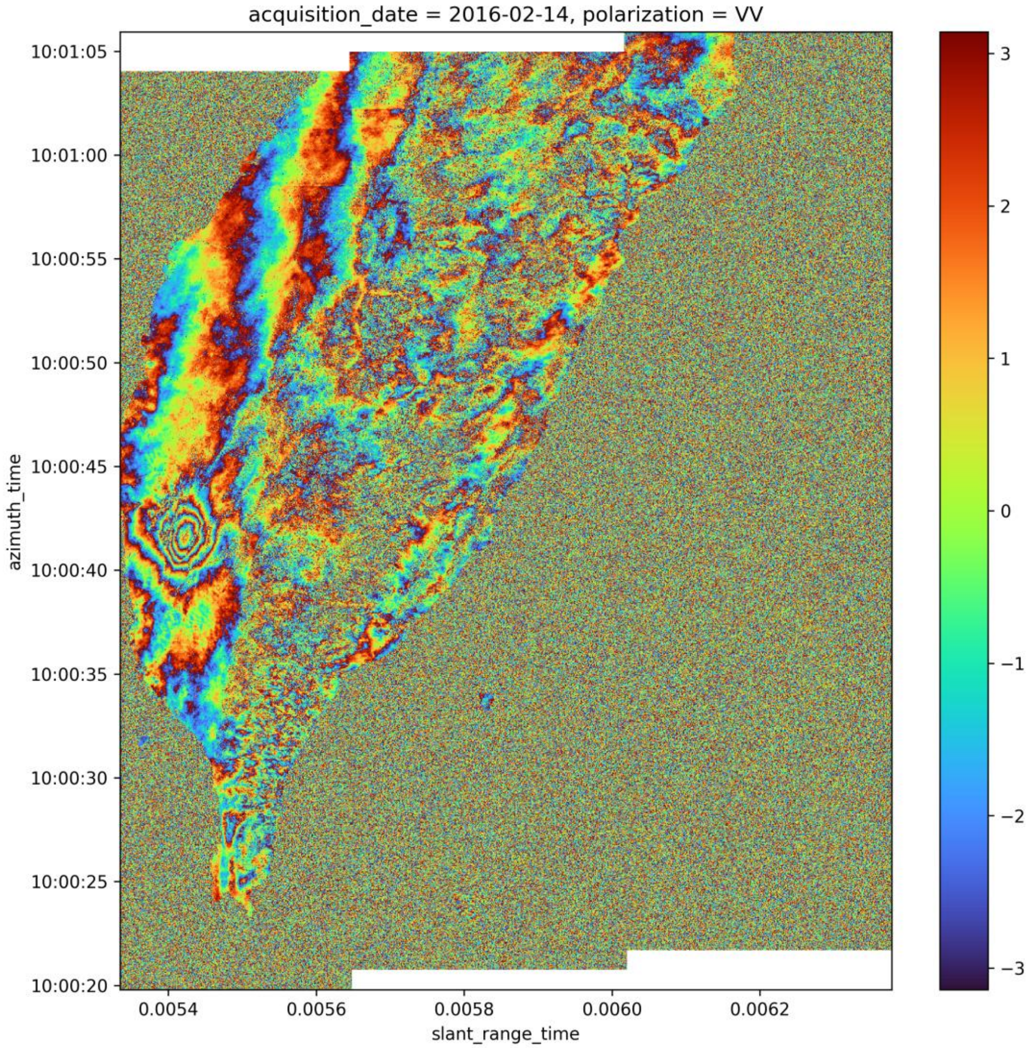
Why data-driven …

Taiwan: 2016-02-02 vs 2016-02-14

Image Matching & Split-Spectrum: Corrects ionospheric phase screens.

Corrected phase



CSLC Data Structure

Main Variables

- **cslc**: The coregistered Single Look Complex measurements.
- **phase_model**: Model-based phase corrections (e.g., from DEM and orbit).
- **phase_iono**: Ionospheric phase screen estimations.
- **phase_tropo**: Tropospheric phase delay components.
- **phase_lowres**: Phase contributions due to tides and system corrections.

xarray.Dataset

▸ Dimensions: (**polarization**: 2, **acquisition_date**: 54, **azimuth_time**: 1495, **slant_range_time**: 21825)

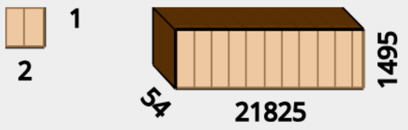
▾ Coordinates:

polarization	(polarization)	<U2	'V
acquisition_date	(acquisition_date)	object	'2
azimuth_time	(azimuth_time)	datetime64[ns]	1!
slant_range_ti...	(slant_range_time)	float64	0.

▾ Data variables:

cslc	(polarization, acquisition_date, azimuth_time, slant_ran...	complex64	d.

	Array	Chunk
Bytes	26.25 GiB	23.36 MiB
Shape	(2, 54, 1495, 21825)	(1, 1, 1495, 2048)
Dask graph	1188 chunks in 1 graph layer	
Data type	complex64 numpy.ndarray	



phase_model	(polarization, acquisition_date, azimuth_time, slant_ran...	float64	d.
phase_iono	(polarization, acquisition_date, azimuth_time, slant_ran...	float32	d.
phase_tropo	(polarization, acquisition_date, azimuth_time, slant_ran...	float32	d.
phase_lowres	(polarization, acquisition_date, azimuth_time, slant_ran...	float32	d.

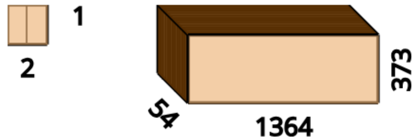
How to Use CSLC: interferometry

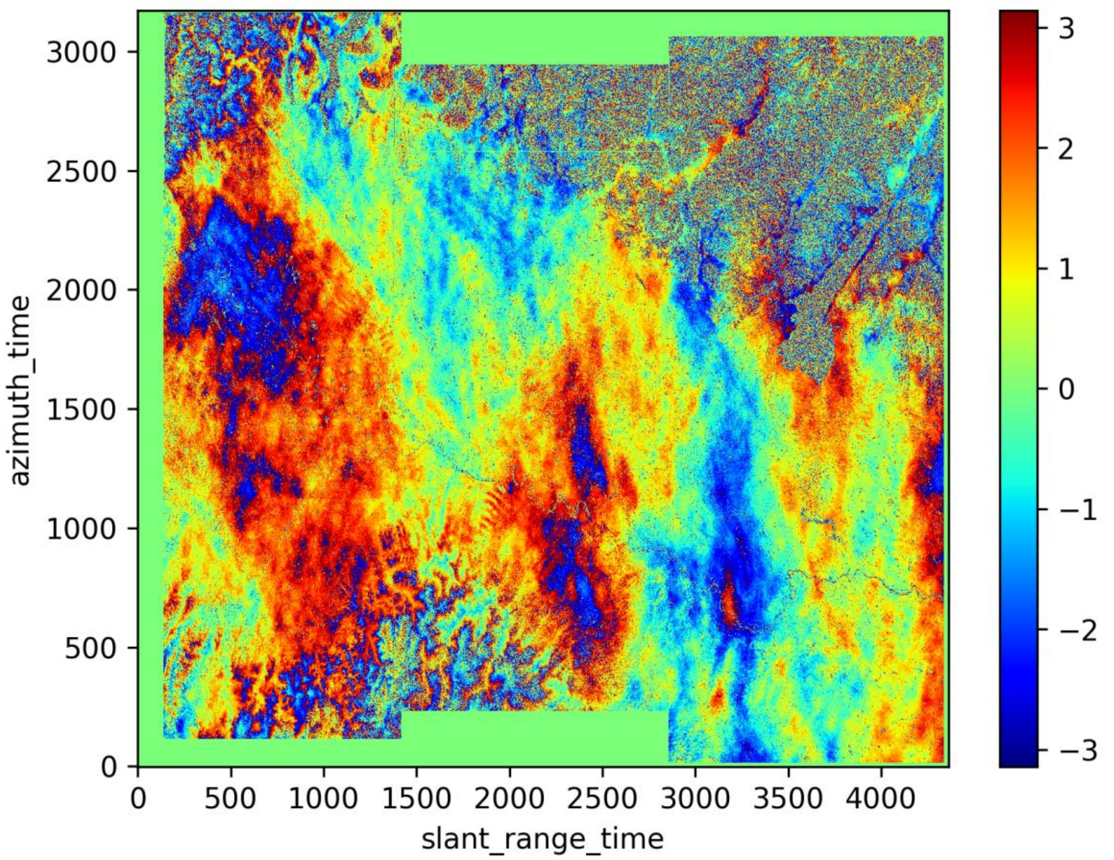
```
multilook = {"azimuth_time": 4, "slant_range_time": 16}
reference = coreg.sel(acquisition_date=reference_date)
interf = (
    (coreg.cslc * reference.cslc.conj())
    .coarsen(multilook, boundary="trim")
    .mean()
    .chunk({"slant_range_time": 2048, "azimuth_time": 2048})
)
phase = xr.apply_ufunc(np.angle, interf, dask="parallelized")
phase
```

✓ 0.3s

xarray.DataArray 'cslc' (**polarization**: 2, **acquisition_date**: 54, **azimuth_time**: 373, **slant_range_time**: 1364)

	Array	Chunk
Bytes	209.61 MiB	1.94 MiB
Shape	(2, 54, 373, 1364)	(1, 1, 373, 1364)
Dask graph	108 chunks in 15 graph layers	
Data type	float32 numpy.ndarray	





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… Temporal filtering

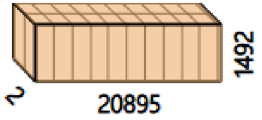
A single operation to compute the geometric mean over all the stack of co-registered images

```
n_dates = coreg.acquisition_date.size
gmean_amp = np.abs(coreg.cstack).prod(dim='acquisition_date')**(1/n_dates)
gmean_amp
```

Last executed at 2026-06-08 14:43:03 in 44ms

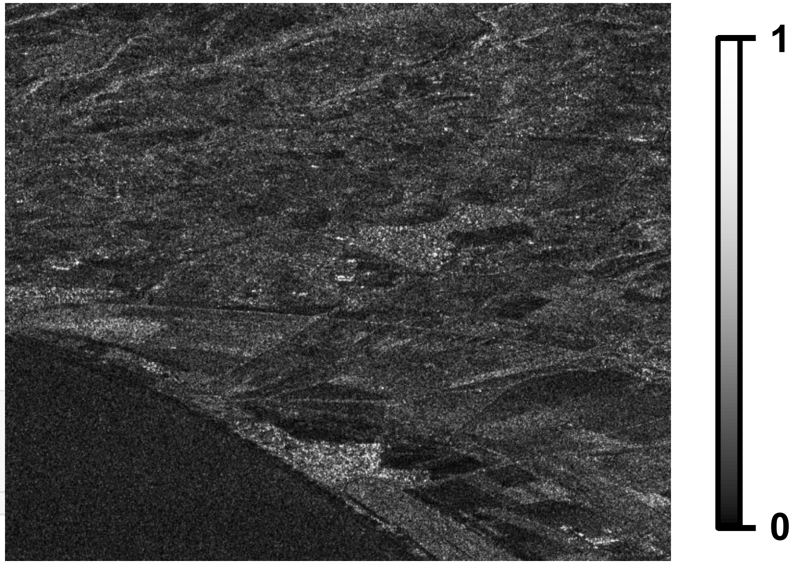
xarray.DataArray 'cstack' (**polarization**: 2, **azimuth_time**: 1492, **slant_range_time**: 20895)

	Array	Chunk
Bytes	237.85 MiB	11.66 MiB
Shape	(2, 1492, 20895)	(1, 1492, 2048)
Dask graph	22 chunks in 10 graph layers	
Data type	float32 numpy.ndarray	



▾ Coordinates:

polarization	(polarization)	<U2	'VV' 'VH'
azimuth_time	(azimuth_time)	datetime64[ns]	2016-02-02T10:00:19.695196962 .....
slant_range_time	(slant_range_time)	float64	0.005332 0.005332 ... 0.005657



Reference image intensity

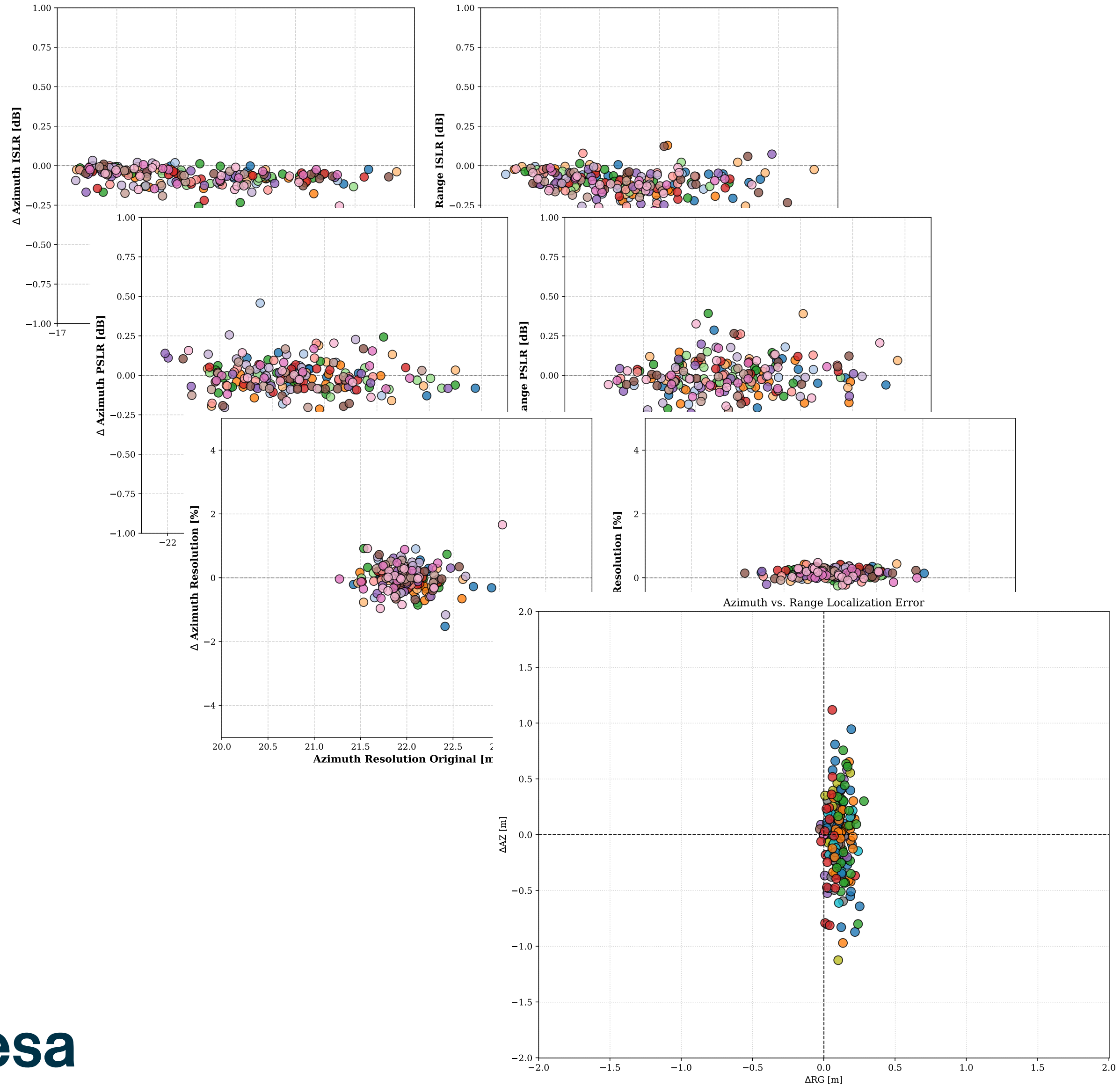
Temporal despeckling (+200 images)

CSLC Quality Analysis (ISLR, PSLR, Resolution)

The processor ensures that all Radar **Figures of Merit** remain unchanged and **consistent** with the original input Level-1 SLC product.

Consistent with S-1 Annual Performance Report for 2024

https://sar-mpc.eu/product-performances



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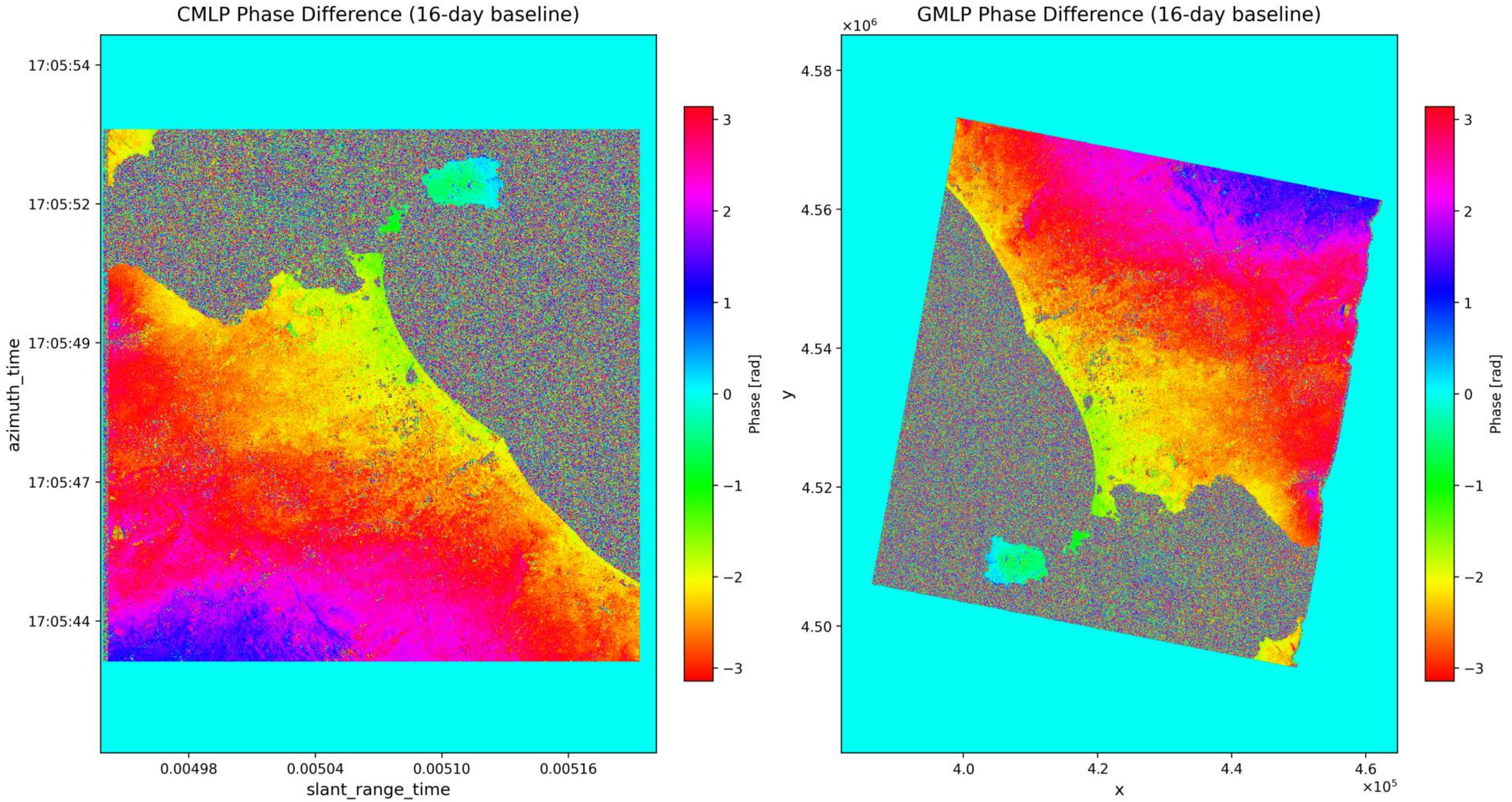
GMLP Key concepts

- Simplify interferometric processing for both single interferometric pairs and full time-series
- Provide consistent MultiLooked interferometric phase, with a drift-correction mechanism
- Data reduction (e.g. 50x)
- Fast update in correspondence of each new acquisition without need for full-stack reprocessing
- It contains some coherence layers to assist further processing (e.g. unwrapping)

F. De Zan, "Recursive and robust InSAR Phase Estimation," *EUSAR 2022; 14th European Conference on Synthetic Aperture Radar*, Leipzig, Germany, 2022, pp. 1-5.

Interferometric Phase

Naples DSC S4 2020-2025

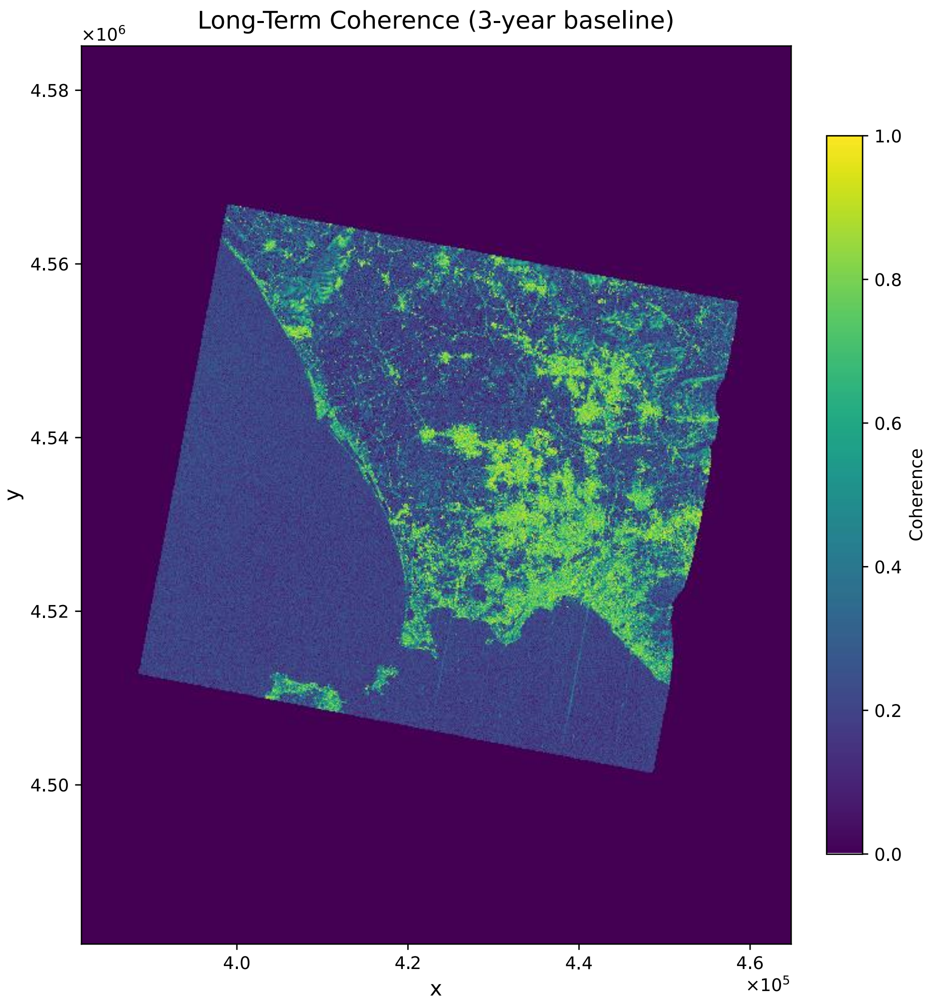


Long-term Coherence

It is one of the quality layers that accompanies the phase layer

It provides an indication of the reliability of long-temporal baseline phase measurements

It provides information that can be exploited for classification



GMLP Data Structure

Main Variables

- **phase**: Geocoded multi-look phase.
- **short_term_coh**: Short-term coherence with the current reference.
- **long_term_coh**: Long-term coherence with past references.

xarray.Dataset

▸ Dimensions: (**acquisition_date**: 1, **polarization**: 2, **y**: 1435, **x**: 3175, **past_reference_date**: 3)

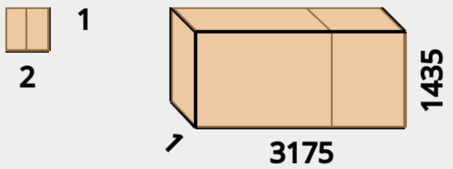
▾ Coordinates:

acquisition_date	(acquisition_date)	<U10	'2025-1...
polarization	(polarization)	<U2	'VV' 'VH'
y	(y)	float64	6.842e+...
x	(x)	float64	6.141e+...
past_reference...	(past_reference_date)	<U10	'2022-1...

▾ Data variables:

phase	(polarization, acquisition_date, y, x)	float32	dask.ar...

	Array	Chunk
Bytes	34.76 MiB	11.21 MiB
Shape	(2, 1, 1435, 3175)	(1, 1, 1435, 2048)
Dask graph	4 chunks in 2 graph layers	
Data type	float32 numpy.ndarray	



short_term_coh	(polarization, acquisition_date, y, x)	float32	dask.ar...
long_term_coh	(polarization, acquisition_date, past_reference_date, y, x)	float32	dask.ar...

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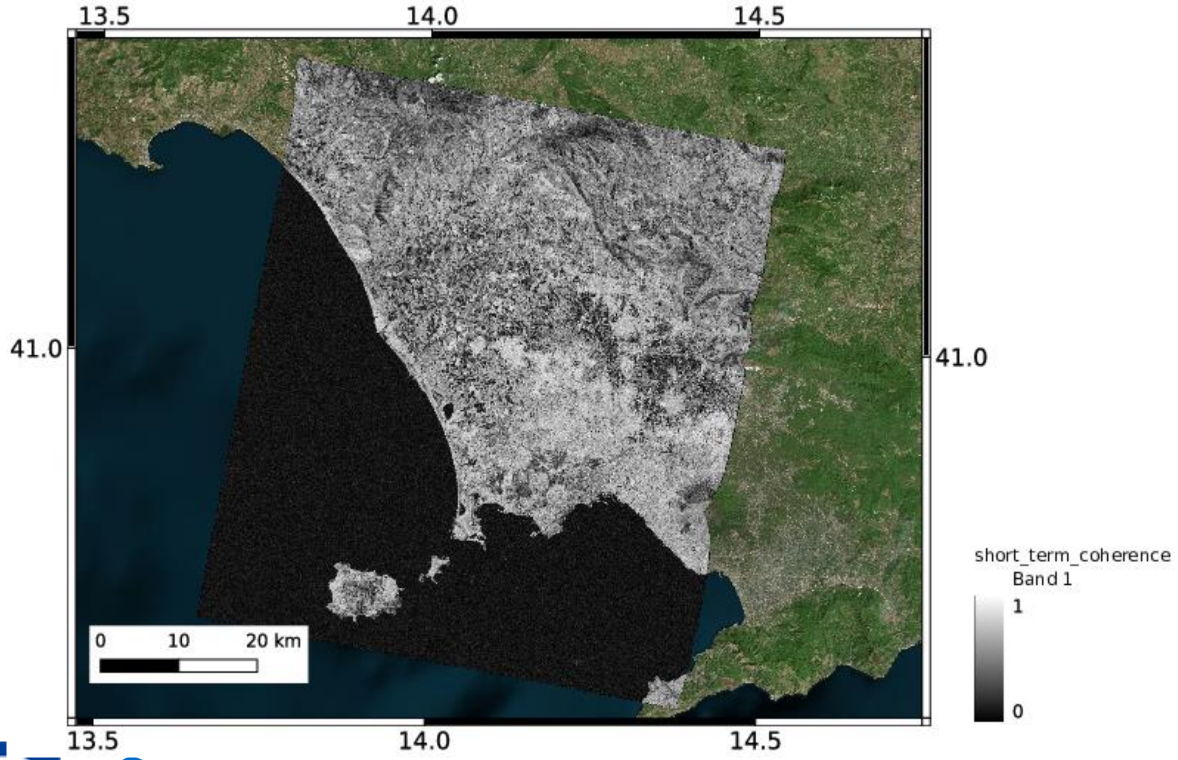
How to Use GMLP

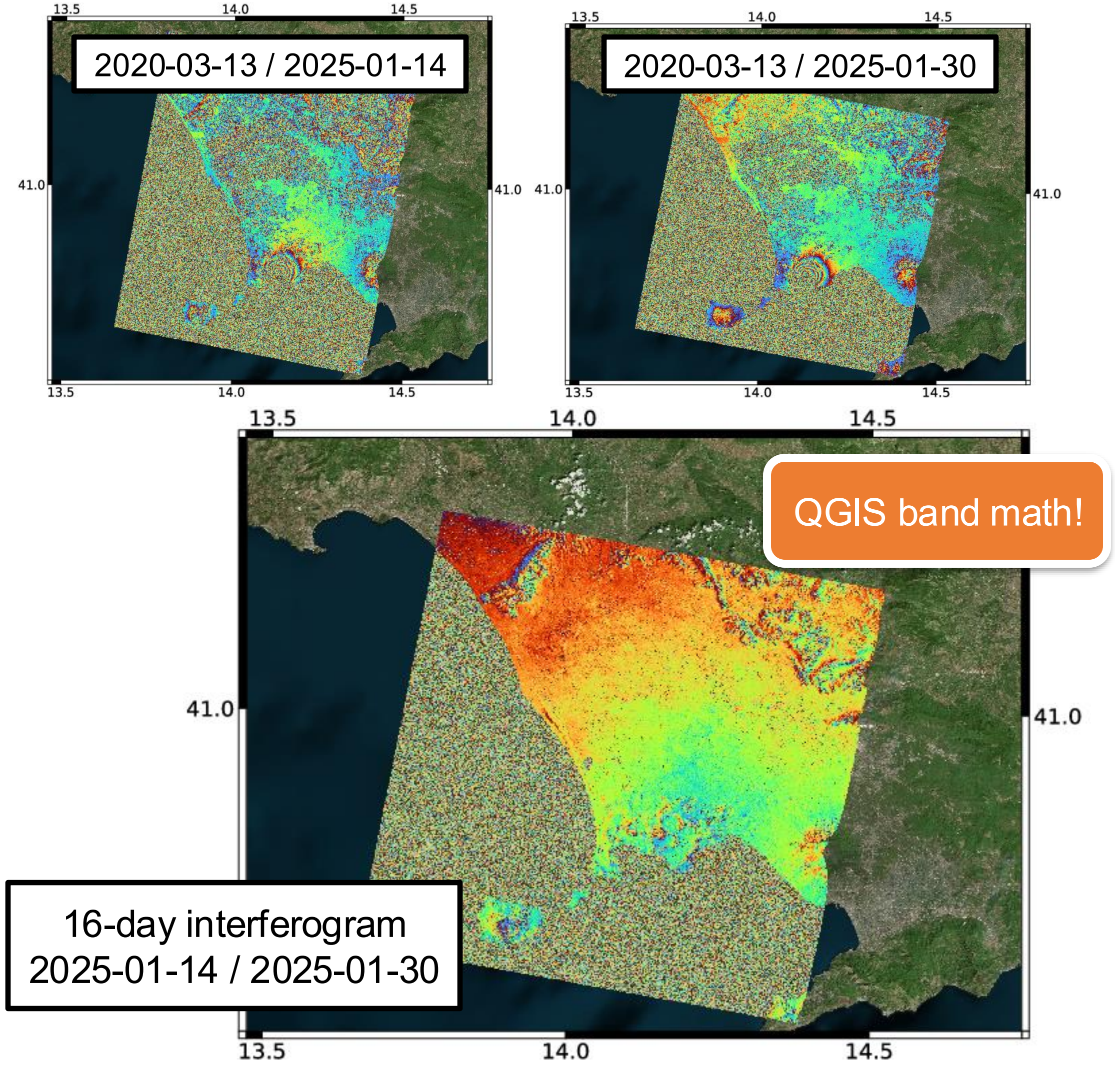
- Computing arbitrary interferograms directly in GIS

$$\varphi = \operatorname{atan2}\left(\sin(\phi), \cos(\phi)\right) = 2\operatorname{atan}\left(\frac{\sin(\phi)}{1+\cos(\phi)}\right)$$

Good short-term coherence

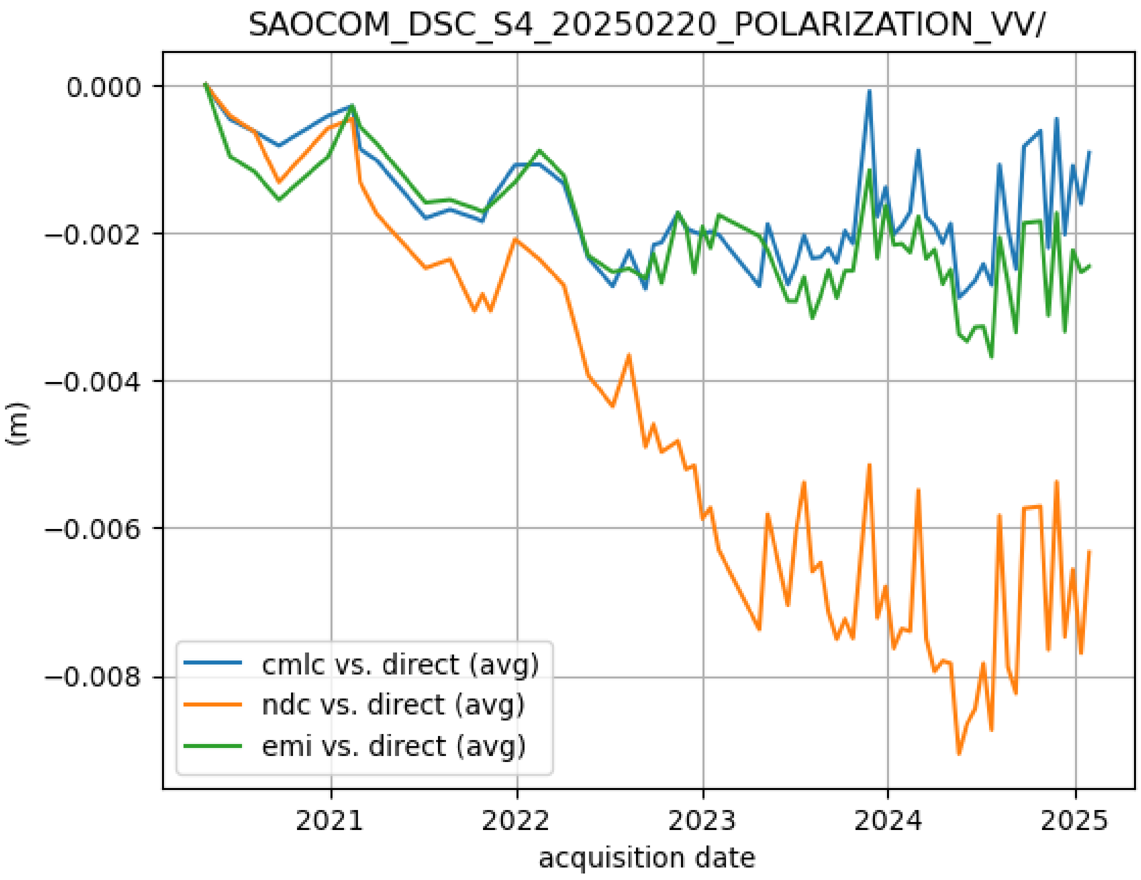


2x 5-year interferograms

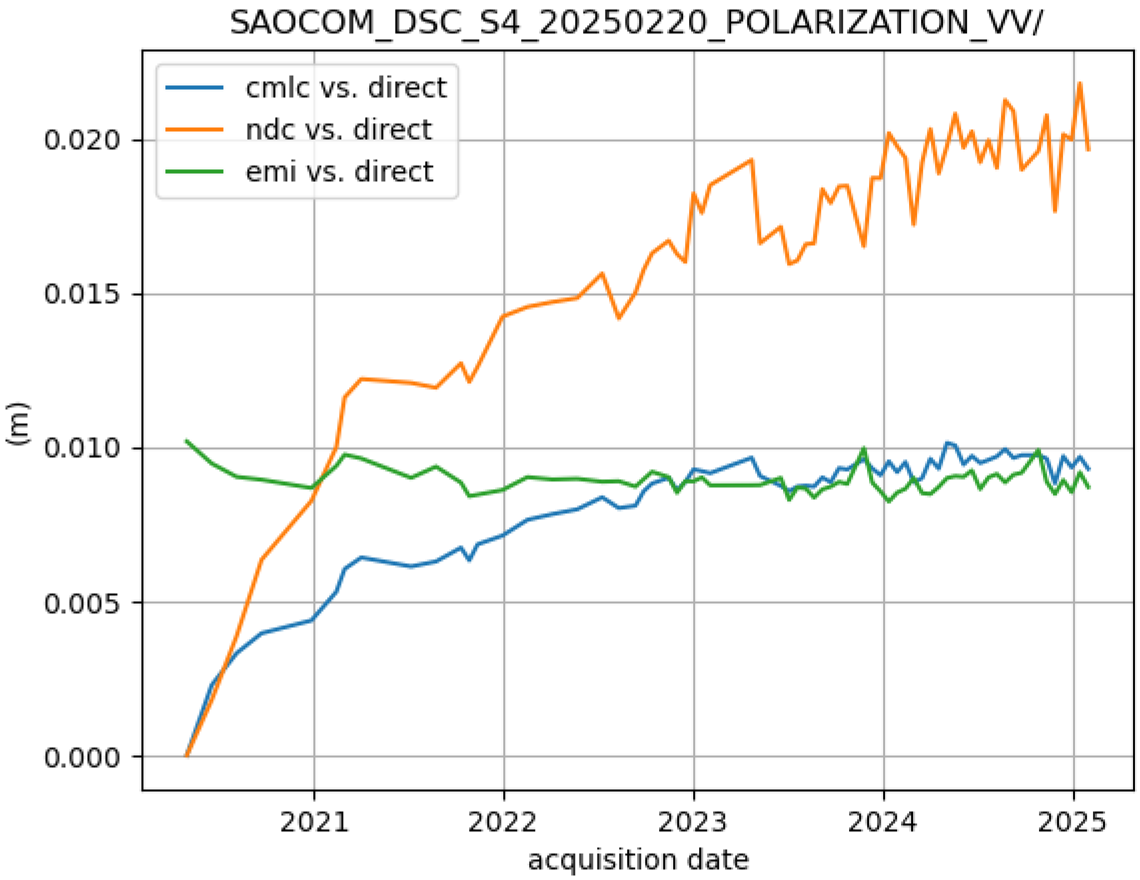


GMLP Quality Analysis

Average



Standard Deviation



Conclusions

Simplify processing maintaining rigorous information quality:

- CSLC: Full-resolution products in radar geometry to enable flexible processing workflows
- GMLP: innovative ARD inheriting all CSLC corrections while simplifying interferometric processing for both single interferometric pairs and full time series

Efficient exploitation of multiple SAR missions (Sentinel-1, ROSE-L, …)

Prototype processors for the generation of Analysis Ready Data (ARD):

- Leveraging cloud-native technologies
- Open-source

Scientific validation of the products

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Q&A

- Are you interested in these products?

- Suggestions for improvements

Thank you

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