

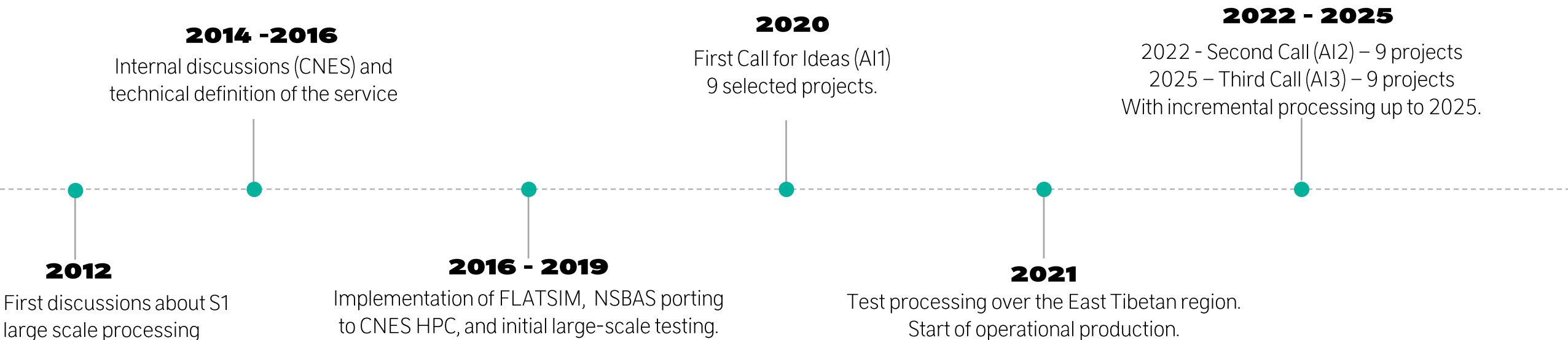
FLATSIM: A SERVICE FOR LARGE-SCALE GROUND MOTION MONITORING WITH SENTINEL-1 DATA

**RAIMBAULT B., DURAND P., BONIFACE C., GAUGAIN S., SCHAEITTEL C., MAESEN E.,
ZEMIRI F., DOIN M-P., PATHIER E., THOLLARD F., LOVERY B., HENRIOT O.,
LASSERRE C., DAOUT S., GRANDIN R., DESCHAMPS-OSTANCIAUX E., POINTAL E.**

FLATSIM - FORMATERRE LARGE-SCALE MULTI-TEMPORAL SENTINEL-1 INTERFEROMETRY

- Process Sentinel-1 data on the CNES HPC for large areas ($> 250,000 \text{ km}^2$), beyond the capabilities of researchers alone.
- Generate time series using the NSBAS MT chain (Doin et al., 2011) and other derived products.
- Automatic workflow with minimal parameterization and validated by InSAR experts.
- First to support scientific usage in France and then opened widely after restriction/usage period.
- Enable incremental processing for future calls – way to go S1C and S1D!

**INITIAL
OBJECTIVES**



PROCESSED AREA SO FAR (2014 - 2021)



After two Calls : ~170,000 products generated, ~650 Tb of data stored, ~12 million km² of geographic area processed, ~20 million km² of product area processed.

INSAR FOR AND FROM THE GEOSCIENCE COMMUNITY

Areas covered on Call for Ideas

Location	Themes	Project leaders	Products
■ Call for ideas 2020 (data October 2014 - end of April 2021) -			
Afar	Landslides, Tectonics, Volcanology	R. Grandin (IPGP)	Access to products
Central Andes, Peru-Chile	Landslides, Tectonics, Volcanology	M. Chlieh (ISTerre)	Access to products
Okavango Delta	Hydrology, Tectonics	M. Jolivet (Géosciences Rennes)	Access to products
Ozark aquifer	Hydrology	K. Chanard (IPGP, IGN)	Access to products
Tarim	Tectonics	M. Simoes (IPGP)	Access to products
The Balkan region	Anthropogenic and climatic hazards, Tectonics	M. Métois (LGLTPE)	Access to products
Turkey	Tectonics	R. Jolivet (Laboratoire de Géologie, ENS Paris)	Access to products
■ Call for ideas 2022 (data October 2014 - end of May 2022) -			
Caucasus	Hydrocarbon Reservoir Dynamics, Mud Volcanoes, Tectonics	F. Masson (ITES)	Access to products
Central Chile	Erosion, Tectonics, Volcanism	A. Socquet (ISTerre)	Access to products
Himalaya and western Tibet	Glaciers, Hydrology, Landslides, Permafrost, Tectonics	M.-P. Doin (ISTerre) , C. Lasserre (LGLTPE) , R. Jolivet (Laboratoire de Géologie , ENS Paris)	Access to products
Levant	Anthropogenic and gravitationnal hazards, Hydrology, Tectonics	S. Michel (Laboratoire de Géologie , ENS Paris)	Access to products
Maghreb	Hydrocarbon Reservoir Dynamics, Hydrology, Landslides, Tectonics	C. Doubre (ITES)	Access to products
Makran	Tectonics	S. Chevrot (GET) , D. Remy (GET)	Access to products
Mozambique	Tectonics	M. de Michele (BRGM) , A. Fuenzalida (BRGM)	Access to products
South Mexico	Hydrology, Tectonics, Volcanism	E. Pathier (ISTerre)	Access to products
Tian Shan	Landslides, Permafrost, Tectonics	M. Rizza (CEREGE)	Access to products

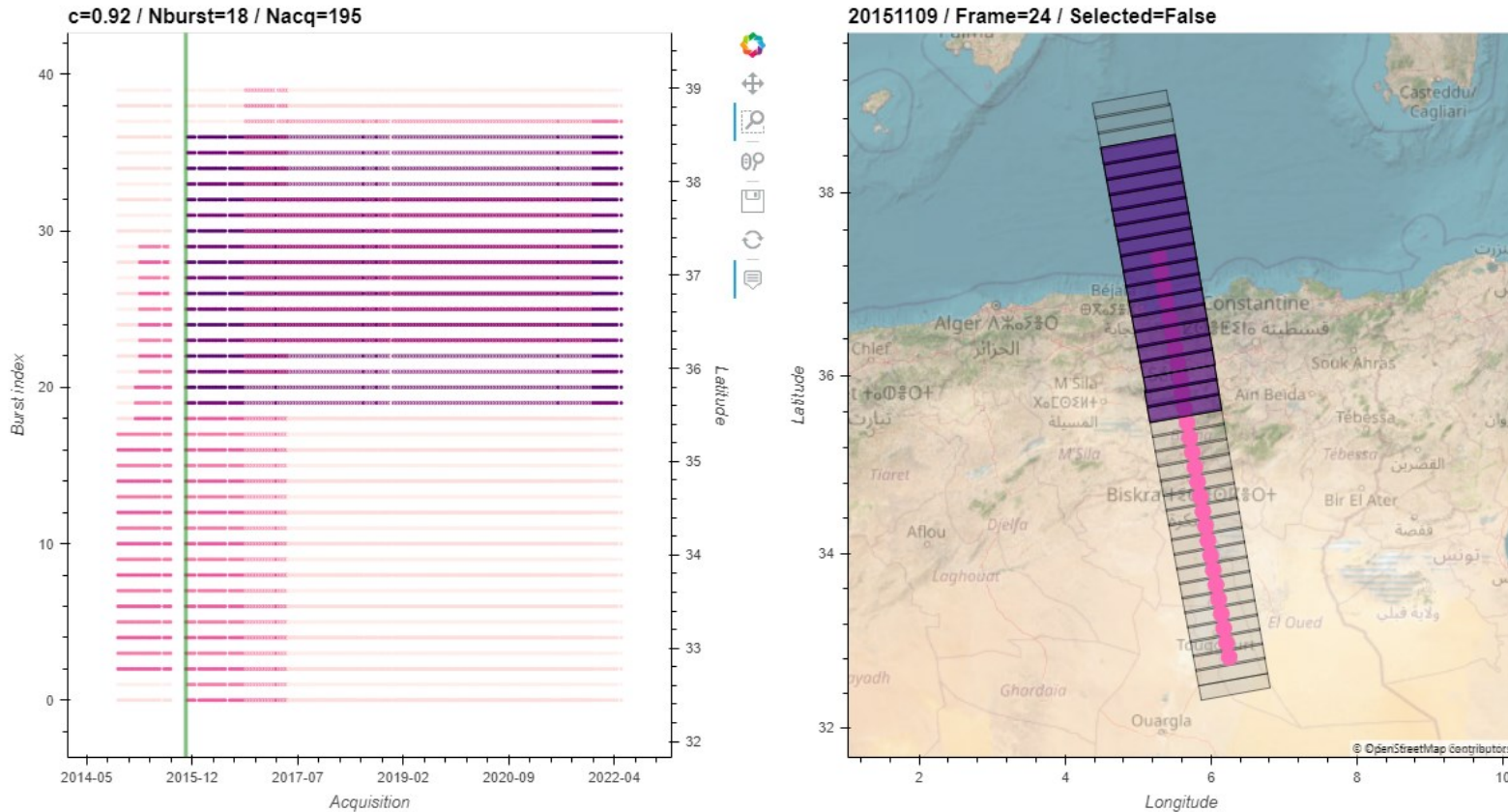
3RD CALL OF PROPOSAL - ONGOING



2014 - 2025

Will result in up to ~1 Pb of products, mainly incremental up to 2025 from previous calls, resulting in ~15 million km² of unique geographic area processed

FLATSIM - NSBAS ALGORITHM



- Burst selection strategy, SAFE archives are often inhomogeneous, check all SAFE files overlapping the region of interest.

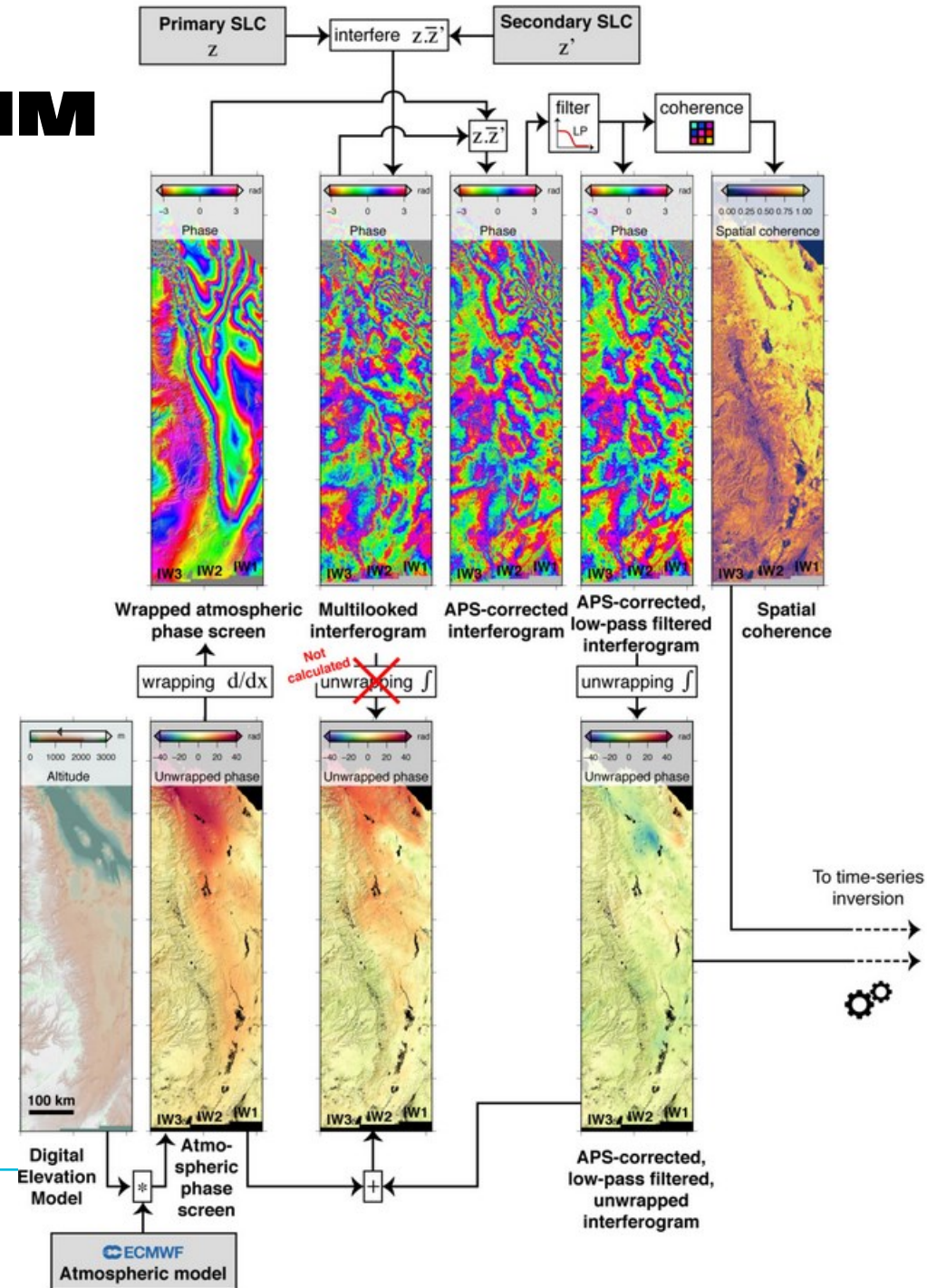
- NSBAS MT InSAR Processing Chain (Doin et al., 2011, Grandin, 2015): Heritage from ROI_PAC (Rosen et al., 2004) with state-of-the-art development over the years..
- Processing scale are over large azimuthal distances which enable long-wavelength deformation signal extraction independent from GNSS.

Maximize spatial coverage and temporal consistency for large-area processing.

FLATSIM - NSBAS ALGORITHM IMPROVEMENTS

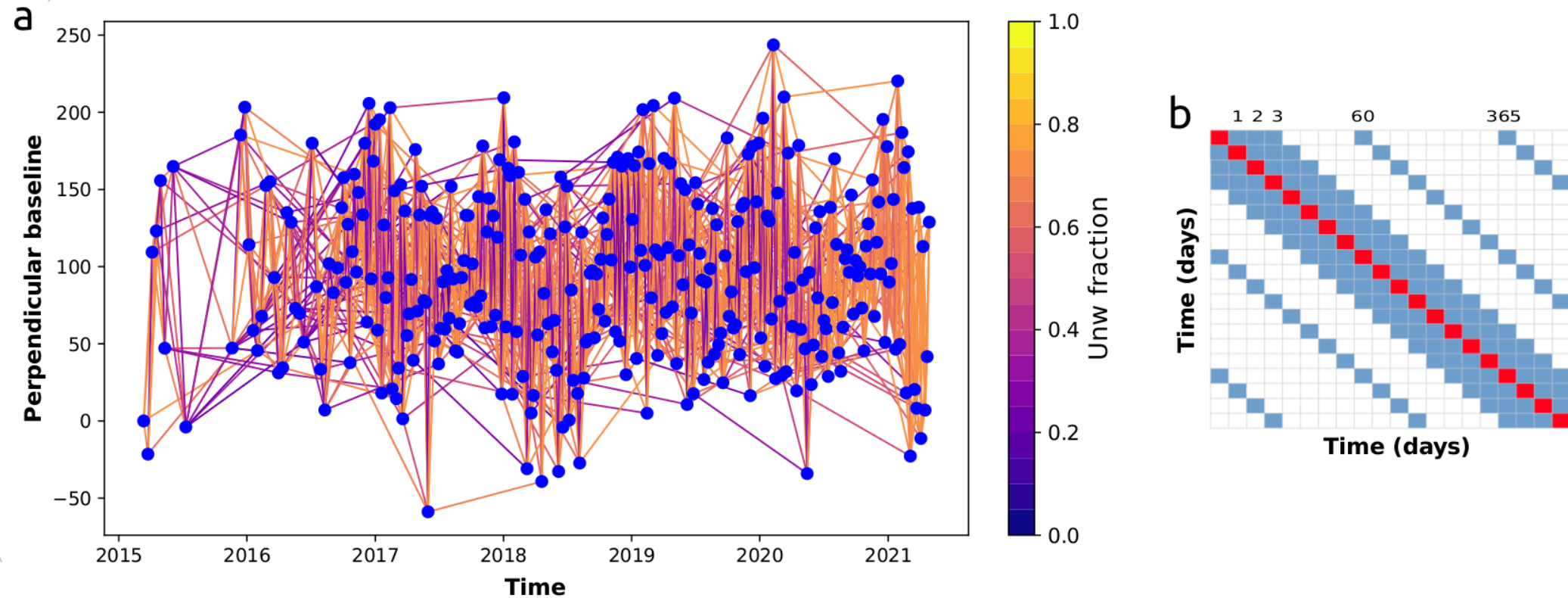
- ERA-5 atmospheric data to remove strong phase gradients caused by topography and atmospheric delays, facilitating subsequent unwrapping by reducing phase discontinuities
- Implements a region-growing unwrapping algorithm that starts from high-quality pixels (derived from filtered phase amplitude) and prioritize them, to minimize error propagation
- Automatically bypass areas affected by layover to ensure accurate unwrapping
- Priority queue system that process pixels by quality (highest first) with $O(\log n)$ complexity for insertions and deletions, eliminating the need for quality map quantization and enabling fast unwrapping of large images (Doin et al., 2023)

Thollard et al., 2021 – FLATSIM: the ForM@Ter Large-scale multi Temporal Sentinel-1 InterferoMetry service -- Remote Sens., 2021, doi: 10.3390/rs13183734

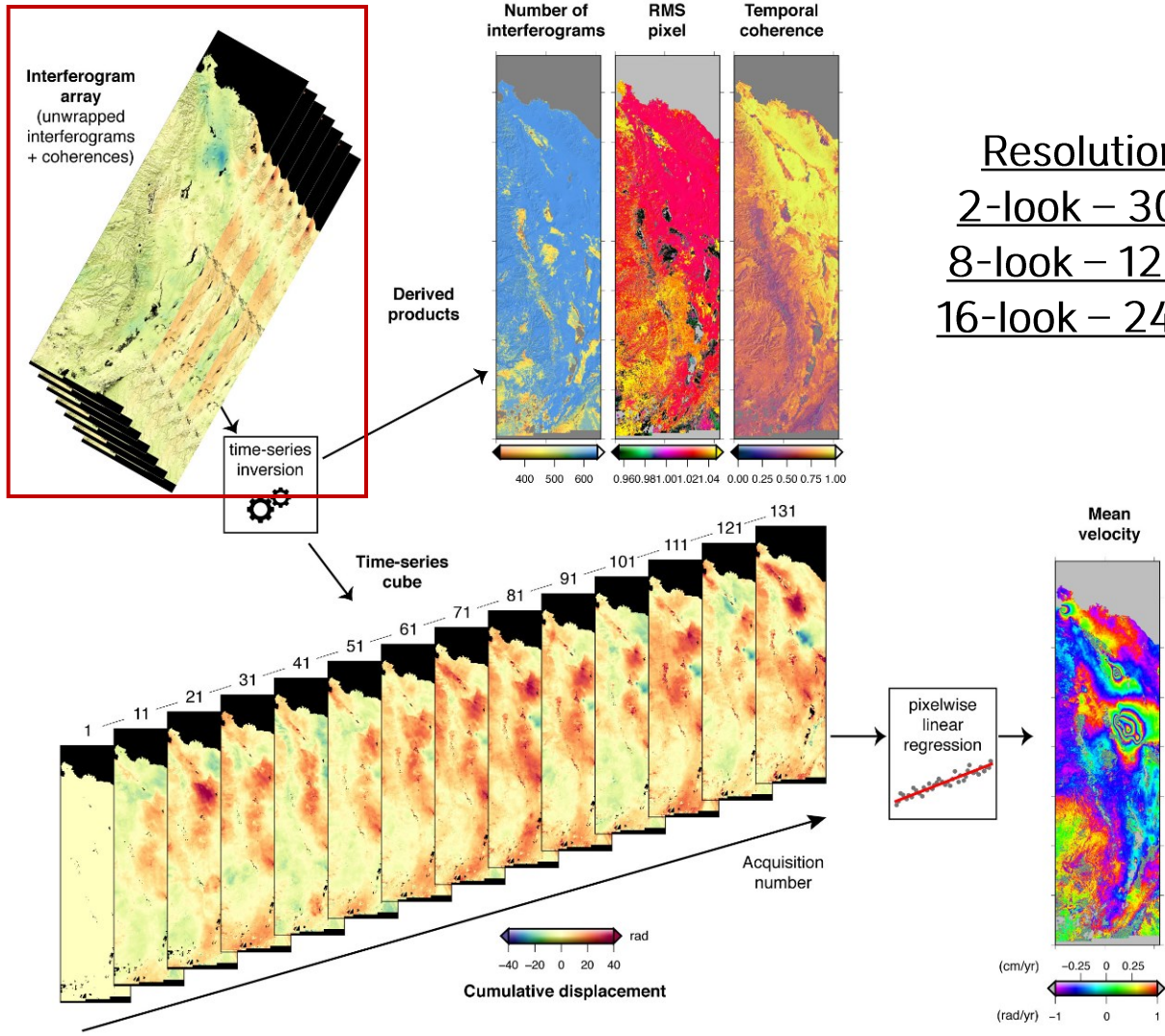


NETWORK INVERSION STRATEGY

- Long temporal baselines to limit phase biases and integrate noise (Ansari et al., 2020; De Zan et al., 2015).
- Pixel per pixel inversion that enables mapping of residuals for each link which is use as weight ($1/\epsilon$) for a second inversion iteration. Weight and a value ($n2\pi$) are applied from iterations on the incriminated residuals/links to reduce potential phase bias or unwrapping error.



DATA PRODUCTS AND FORMAT



Resolution:
2-look – 30m
8-look – 120m
16-look – 240m

1. Interferogram Package (Per Date Pair)

Wrapped Differential Interferograms (InW): Raw phase data, corrected for atmospheric phase screen (APS) and spectral diversity.

Filtered Wrapped Interferograms (InWF): Triangularly filtered version of InW weighted by spatial coherence.

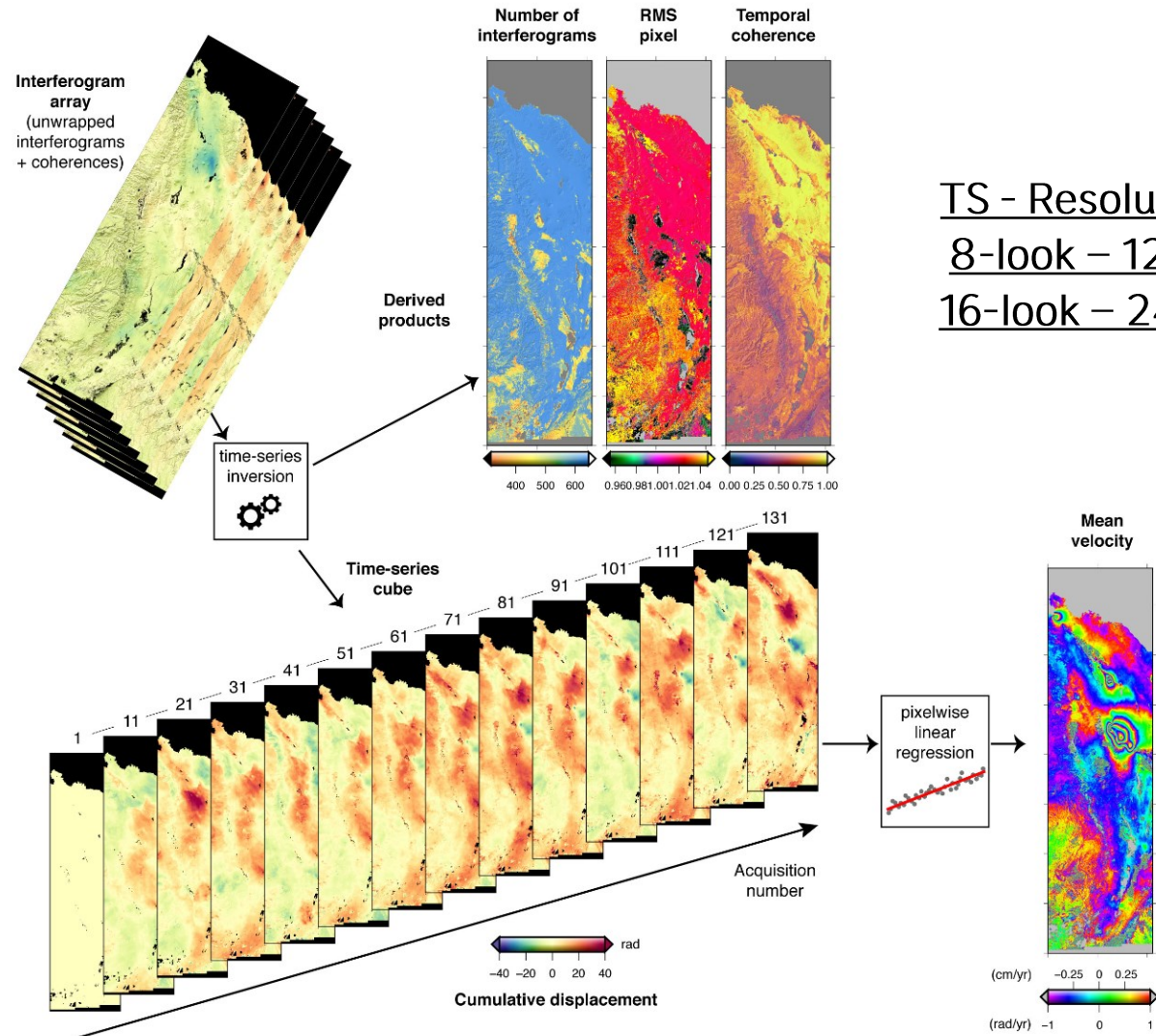
Unwrapped Interferograms (InU): Phase unwrapped using a quality-guided region-growing unwrap algorithm.

Auxiliary: Atmospheric Phase Screen (**APS**) from ERA-5 models and Spatial Coherence (**Coh**) maps for quality assessment.

<https://formater.pages.in2p3.fr/flatsim/index.html>

Thollard et al., 2021 – FLATSIM: the ForM@Ter Large-scale multi Temporal Sentinel-1 Interferometry service -- Remote Sens., 2021, doi: 10.3390/rs13183734

DATA PRODUCTS AND FORMAT



TS - Resolution:
8-look – 120m
16-look – 240m

2. Interferogram Quality Indicators (Net)

RMS misclosure (network consistency).
Temporal coherence proxy.
Number of images/interferograms used.

3. Time Series Package

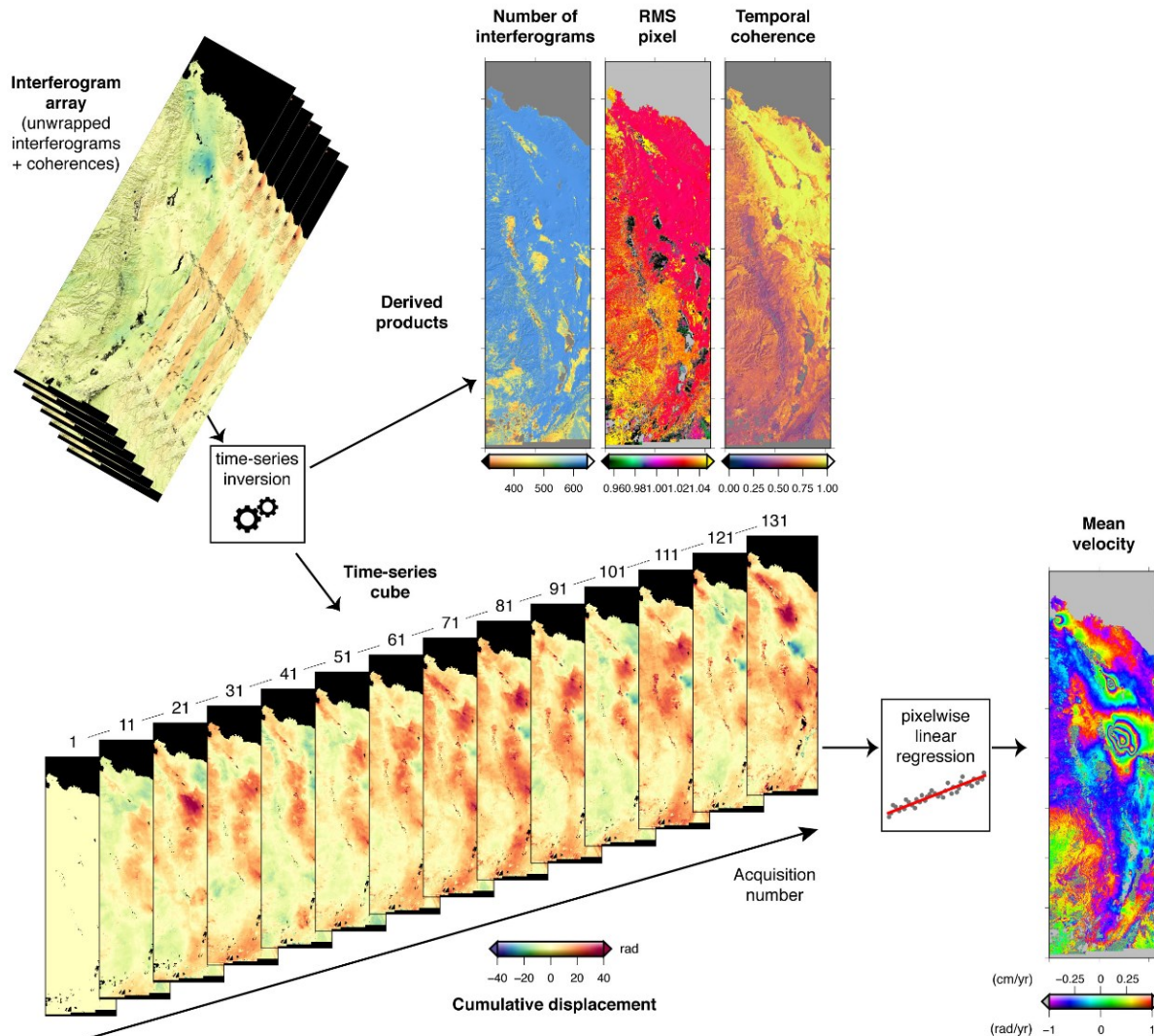
Displacement Cube (DTs): Cumulative phase delay (in radians) at each time step.

Mean LOS Velocity (MV-LOS): Linear velocity estimate (rad/yr).

<https://formater.pages.in2p3.fr/flatsim/index.html>

Thollard et al., 2021 – FLATSIM: the ForM@Ter Large-scale multi Temporal Sentinel-1 InterferoMetry service -- Remote Sens., 2021, doi: 10.3390/rs13183734

DATA PRODUCTS AND FORMAT



Auxiliary Data Package

DEM: Digital Elevation Model (radar geometry).

CosENU: LOS unit vector components (East, North, Up).

LuT: Lookup tables for radar-to-geographic coordinate transformation.

TCoh: Temporal coherence proxy for the entire stack.

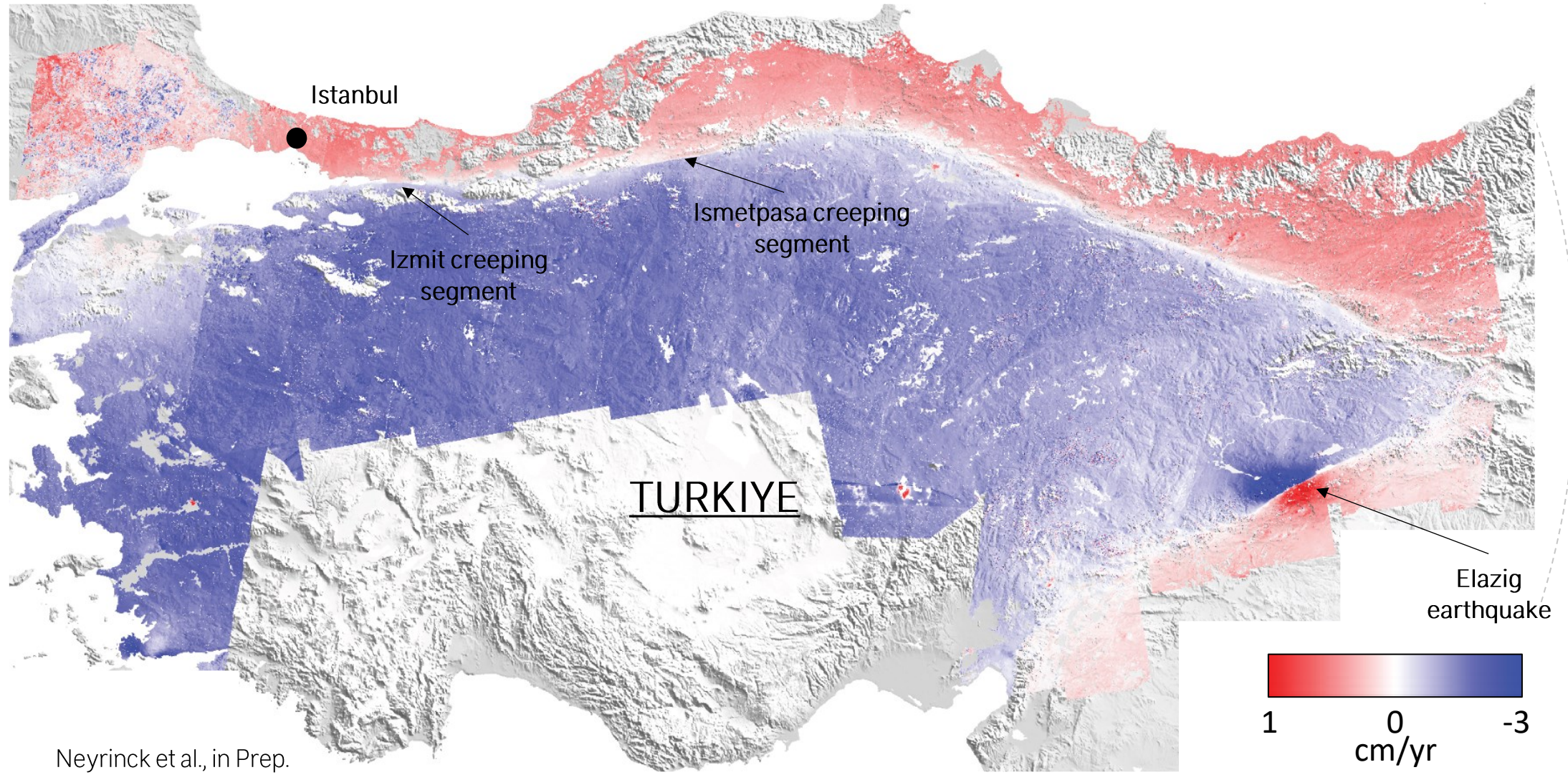
Most products are available in both Radar and Geographic (Lat/Lon) geometries, with preview PNGs and metadata.

→ **GEOTIFFS**

<https://formater.pages.in2p3.fr/flatsim/index.html>

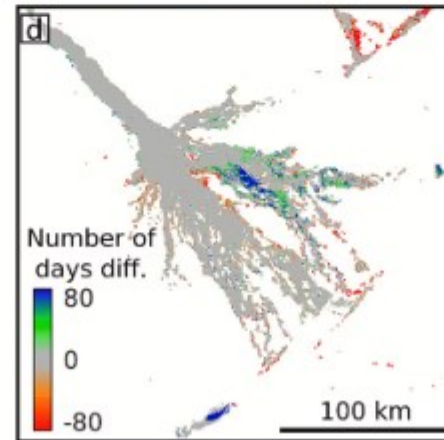
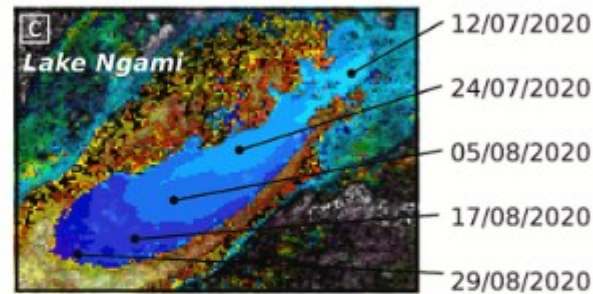
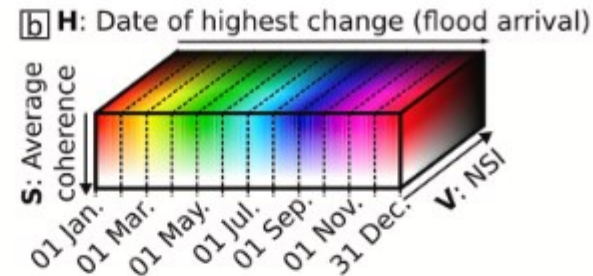
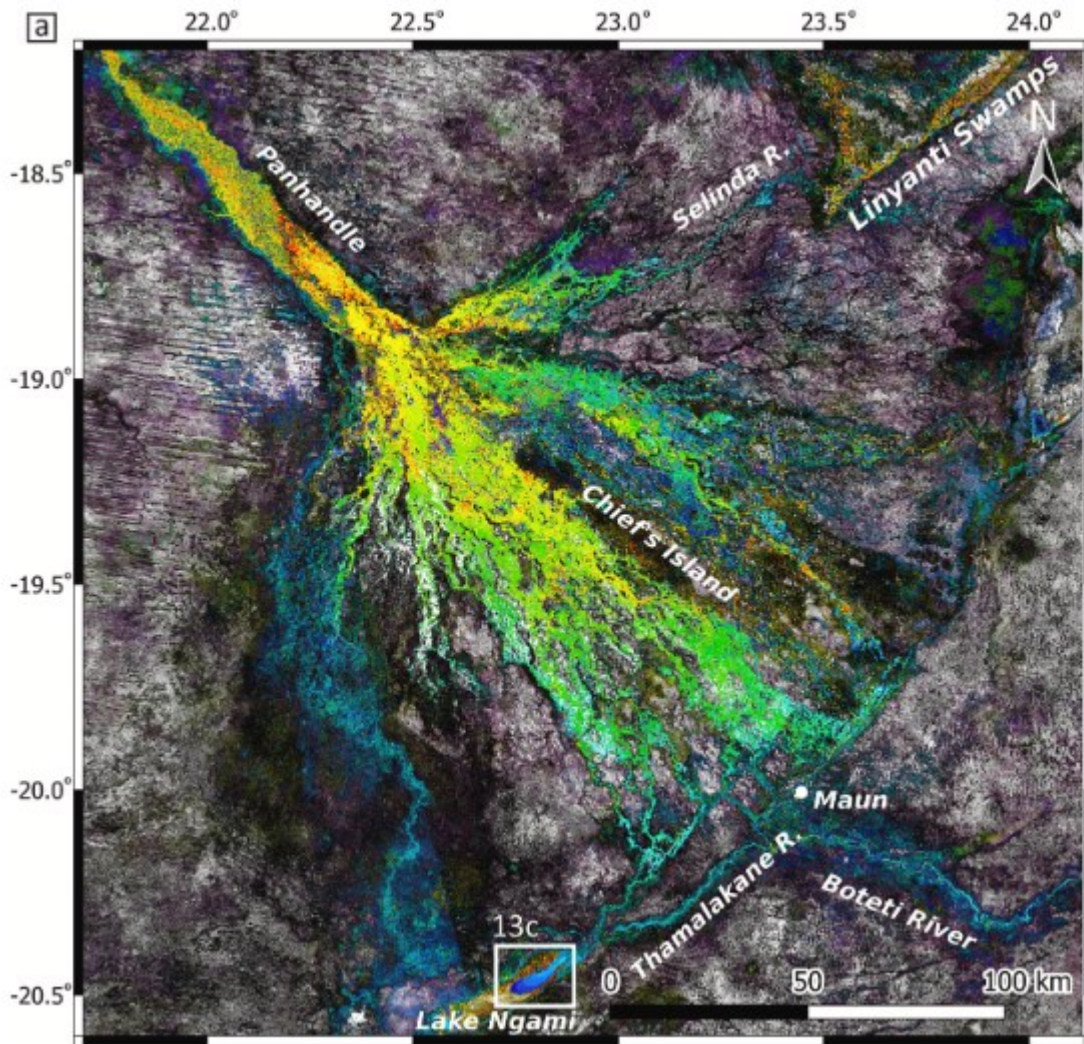
Thollard et al., 2021 – FLATSIM: the ForM@Ter Large-scale multi Temporal Sentinel-1 InterferoMetry service -- Remote Sens., 2021, doi: 10.3390/rs13183734

LARGE SCALE CONTINENTAL COVERAGE



Neyrinck et al., in Prep.

EXTRACT KNOWLEDGE FROM DIFFICULT AREAS



Example of Okavango Delta (Botswana)

Flood mapping detection method:
Change detection in coherence time series to identify flood pulse arrival.

- Hue: Represents the date of flood arrival.
- Saturation: Decreases as coherence increases (higher reliability).
- Value (Brightness): Decreases as NSI (Non-Surface Inundation) increases.

Comparison with reference inundation maps confirms accuracy of detected arrival dates!

Gaudaré et al., 2024 -Remote Sensing of Environment

OPEN ACCESS OF THE FIRST CALL

What? Sentinel-1 SAR interferometry products covering 2014 to 2021.

Where? Seven areas: Ozark, Central Andes, Balkans, Türkiye, Tarim, Afar, and Okavango -- Spanning 5 million km² -- 300 Tb of products.

Who? -- Research and non-commercial entities under CC BY-NC license.

When? -- Available starting Q4 2026.

Applications / What For?

Seismotectonics, Landslide, Flood monitoring, Hydrology... It's up to you now!!

AI/ML integration workflows on wrapped interferograms (e.g., Burrows et al., 2026).



How can you access the data ????

How to cite :

ForM@Ter (2020): FLATSIM Data Products. CNES. (Dataset).

[doi:10.24400/253171/FLATSIM2020](https://doi.org/10.24400/253171/FLATSIM2020)

RIS Citation

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5000 km
3000 mi

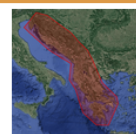
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- Spatial extent
- Time slot
- Repository
- Provider
- Discipline
- Platform
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Sort by Popularity

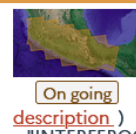
Sentinel-1 Interferograms and time series collection on the Balk



Completed

Oct 1, 2014 → May 1, 2021
The Balkan region is one of the most seismic zones in Europe, with intense industrial and demographic development. This project aims to better quantify the deformations of tectonic origin in this region (kinematics).

Interferograms and time series collection on South Mexico 201



On going

Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed description](#)).
- "INTERFEROGRAM": this brings together the differential interferograms, wound and unwound, in radar or terrain geometry, filtered or not at different resolutions as

Interferograms and time series collection on Himalaya and weste



On going

Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed description](#)).
- "INTERFEROGRAM": this brings together the differential interferograms, wound and unwound, in radar or terrain geometry, filtered or not at different resolutions as

Interferograms and time series collection on Central Chile 201



On going

Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed description](#)).
- "INTERFEROGRAM": this brings together the differential interferograms, wound and unwound, in

Sentinel-1 Interferograms and time series collection on Ozark aq



Completed

Oct 1, 2014 → May 1, 2021
This project focuses on the study of the deformations associated with the Ozark aquifer (south of the Mississippi basin) subjected to strong variations in groundwater level, and in neighboring regions where significant seismicity is observed at strong

Sentinel-1 Interferograms and time series collection on the Okav



Completed

Oct 1, 2014 → May 1, 2021
This project aims to better understand the deformations of tectonic origin in the area of the Okavango Delta (associated with the functioning of the Okavango rift and the East African rift), or of hydrological origin (linked in particular to the flood cycle.), and the possible interactions between tectonics and

Interferograms and time series collection on Tian Shan 2014-202



On going

Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed description](#)).
- "INTERFEROGRAM": this brings together the differential interferograms, wound and unwound, in radar or terrain geometry, filtered or not at different resolutions as

Sentinel-1 Interferograms and time series collection on eastern



Completed

Oct 1, 2014 → Jan 1, 2021
The objective of the project is to quantify and model the current deformations on the eastern edge of the Tibetan plateau. It focuses on deformations of tectonic origin, at the scale of active faults as

Sentinel-1 Interferograms and time series collection on Central



Oct 1, 2014 → May 1, 2021
This project aims to better understand the seismic cycle of the Andean subduction zone in Peru

Sentinel-1 Interferograms and time series collection on Tarim 20



Completed

Oct 1, 2014 → May 1, 2021
This project focuses on the analysis of tectonic deformations along the Western Kunlun Range, on

Interferograms and time series collection on Mozambique 2014-2



On going

Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed](#)

Interferograms and time series collection on Makran 2014-2022



Oct 1, 2014 → May 1, 2022
Three types of products are made available for each orbit portion processed (see [detailed](#)

SOME USAGES AND STATISTICS

- Supported ~10 Postdocs, ~8 PhD students, ~5 Interns across France.
- >15 permanent researchers from 15+ French institutions.
- ~10 scientific papers since the 2021 initial release.
- Latency of the publication pipeline; results from the first call are now arriving.
- Led to the development of tools like InSARviz (doi: 10.21105/joss.06440) for data cube visualization – POSTER!



- Organized dedicated national events (e.g., Flatsim Day).
- Dynamic scientific discussions around InSAR in France.

And many more to come !!

Flood pulse monitoring in wetlands with multi-temporal Sentinel-1 interferometric coherence data: Application to the Okavango Delta (Botswana)

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2022JB026251

Referencing of Continental-Scale InSAR-Derived Velocity Fields: Case Study of the Eastern Tibetan Plateau

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2024JB030796

Slip Modes Along a Structurally-Driven Earthquake Barrier in Chile

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2022JB026251

Referencing of Continental-Scale InSAR-Derived Velocity Fields: Case Study of the Eastern Tibetan Plateau

Geophysical Research Letters*

RESEARCH LETTER
10.1029/2025GL118843

Long-Wavelength Ionospheric Compensation of InSAR Time-Series Based on Global Ionosphere Maps

The slow slip event cycle along the Izmit segment of the North Anatolian Fault

FLATISM'S USER PRESENTATION @ FRINGE 2026

Don't miss out our talented PhDs and Postdocs!!!

Orals:

4:50pm - 5:10pm

Oral_20

Widespread Slope Processes Across the Tibetan Plateau: Insights from Large-Scale InSAR Processing Using FLATSIM

Hugo Watine¹, Simon Daout¹, Jérôme Lavé¹, Marie-Pierre Doin², Philippe Durand³, Flatsim Working group⁴

Thursday 18/06 – 3:10-3:40pm

3:20pm - 3:40pm

Oral_20

Present-Day Kinematics of Western Greece and the Balkans Revealed by Sentinel-1 In SAR Data

Aïmine Meridi¹, Cécile Lasserre¹, Marianne Métois¹, Marie-Pierre Doin², Philippe Durand³

Wednesday 17/06 – 4:10-5:50pm

Posters:

Water-driven deformation over the Dinaric karst : insights from Sentinel 1 InSAR time series

Zoé Dubois¹, Cécile Lasserre¹, Marianne Métois¹, Aïmine Meridi¹, Kristel Chanard²

Tuesday 16/06 – Poster Session

GDM-SAR-In: an on-demand service for Sentinel-1 InSAR processing

Erwan Pathier¹, Claude Boniface², Emilie Deschamps-Ostanciaux³, Marie-Pierre Doin¹, Philippe Durand², Sébastien Gaugain², Oliver Henriot¹, Cécile Lasserre⁴, Bertrand Lovery¹, Eric Maesen⁵, Elisabeth Pointal³, Bryan Raimbault², Clément Schaettel⁵, Franck Thollard¹

Tuesday 16/06 – Poster Session

InsarViz : An Open-Source Tool to Visualize InSAR time series

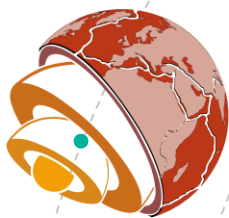
Marc Coiffier¹, Erwan Pathier¹, Franck Thollard¹, Renaud Blanch²

Tuesday 16/06 – Poster Session

Slip dynamics and morphology of a major creeping fault step-over at the eastern end of the Tianzhu seismic gap (Haiyuan fault, China), as seen by 33 years of ESA InSAR missions

Farès Mokhtari¹, Cécile Lasserre¹, Romain Jolivet², Olivier Cavalié³, Simon Daout⁴, Sun Jianbao⁵, Marie-Pierre Doin⁶, Philippe Durand⁷

Thursday 18/06 – Poster Session



FormaTerre
DATA TERRA

THANK YOU FOR YOUR ATTENTION!

THIS PROJECT HAS BEEN A JOURNEY MADE POSSIBLE BY THE EFFORTS OF MANY PEOPLE FROM DIFFERENT INSTITUTIONS ACROSS FRANCE. TODAY, I STAND HERE ON BEHALF OF ALL OF THEM WITHOUT WHOM THIS PROJECT WOULD NOT EXIST.

THANK YOU TO ALL THE PERSON INVOLVED IN THIS ADVENTURE:

CLAUDE BONIFACE, KRISTEL CHANARD, AYA CHEAIB, SEBASTIEN CHEVROT, MOHAMED CHLIEH, DOMINIQUE CLESSE, SIMON DAOUT, MARCELLO DE MICHELE, EMILIE DESCHAMPS-OSTANCIAUX, MARIE-PIERRE DOIN, JOËLLE DONADIEU, CÉCILE DOUBRE, PHILIPPE DURAND, HUGO FOURNIER, MARION FRESNE, AMAYA FUENZALINDA, SEBASTIEN GAUGAIN, RAPHAEL GRANDIN, OLIVER HENRIOT, PATRICE HENRY, BENJAMIN HUSSON, EMILIE KLEIN, MARC JOLIVET, ROMAIN JOLIVET, MARIE-FRANCE LARIF, CECILE LASSERRE, CHRISTOPHE LAURENT, JEAN-PAUL LELAY, LAETITIA LEMRABET, BERTRAND LOVERY, ERIC MAESEN, LÉO MARCONATO, FRÉDÉRIC MASSON, MARIANNE METOIS, SYLVAIN MICHEL, JEAN-MATHIEU NOCQUET, ERWAN PATHIER, FÉLIX PEROSANZ, VIRGINIE PINEL, ELISABETH POINTAL, CATHERINE PROY, DOMINIQUE REMY, MAGALI RIZZA, MARJORIE ROBERT, BAPTISTE ROUSSET, CLEMENT SCHAETTEL, MARTINE SIMOES, ANNE SOCQUET, BERNARD SPECHT, FRANCK THOLLARD, FLAVIAN ZEMIRI,...