Resolving 3D Deformation of Piton de la Fournaise

Enabled by Dense Multi-Geometry ALOS-2 Acquisitions

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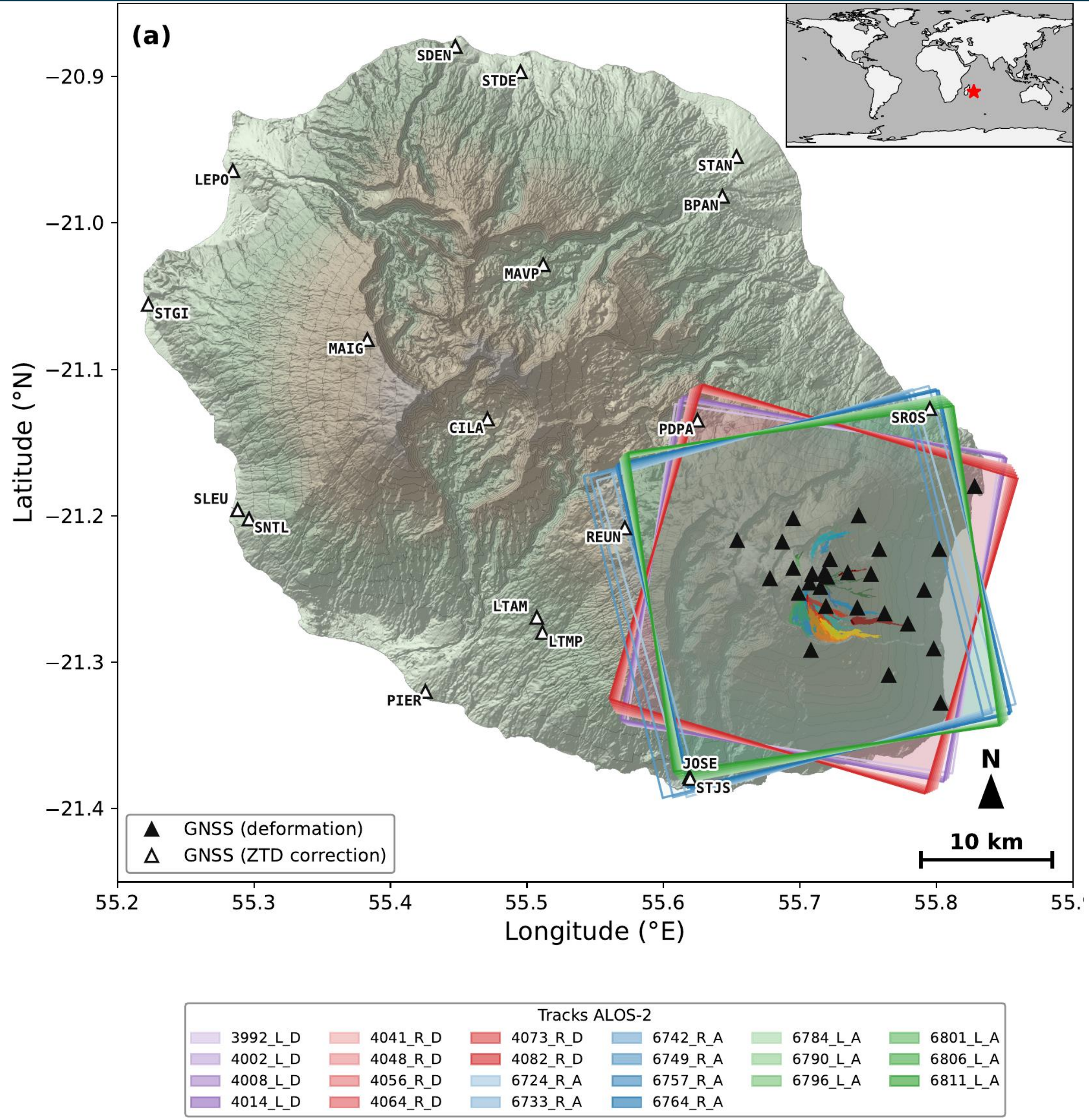
A natural geodetic laboratory

Piton de la Fournaise

- **One of the most active** basaltic volcanoes worldwide:
    - **Complex 3D kinematics:** eastward flank, rift zones, gravitational processes
    - **Frequent eruptions:** dyke intrusions, flank displacements, lava flows
- **One of the best monitored** basaltic volcanoes worldwide:
    - **Dense OVPF network:** continuous GNSS, seismology,…
    - **A unique SAR dataset:** acquired in the framework of a JAXA-ESA mutual collaborative project



Syn-eruptive 3D decomposition at Piton de la Fournaise: Peltier et al. (2015)

Syn-eruptive 3D from many LOS geometries

- Enough distinct LOS geometries to invert for full 3D displacement (E, N, U)
- **Key assumption:** all recorded deformation is sudden & syn-eruptive — interferograms at different dates capturing the same event are inverted jointly

The limitation we set out to overcome

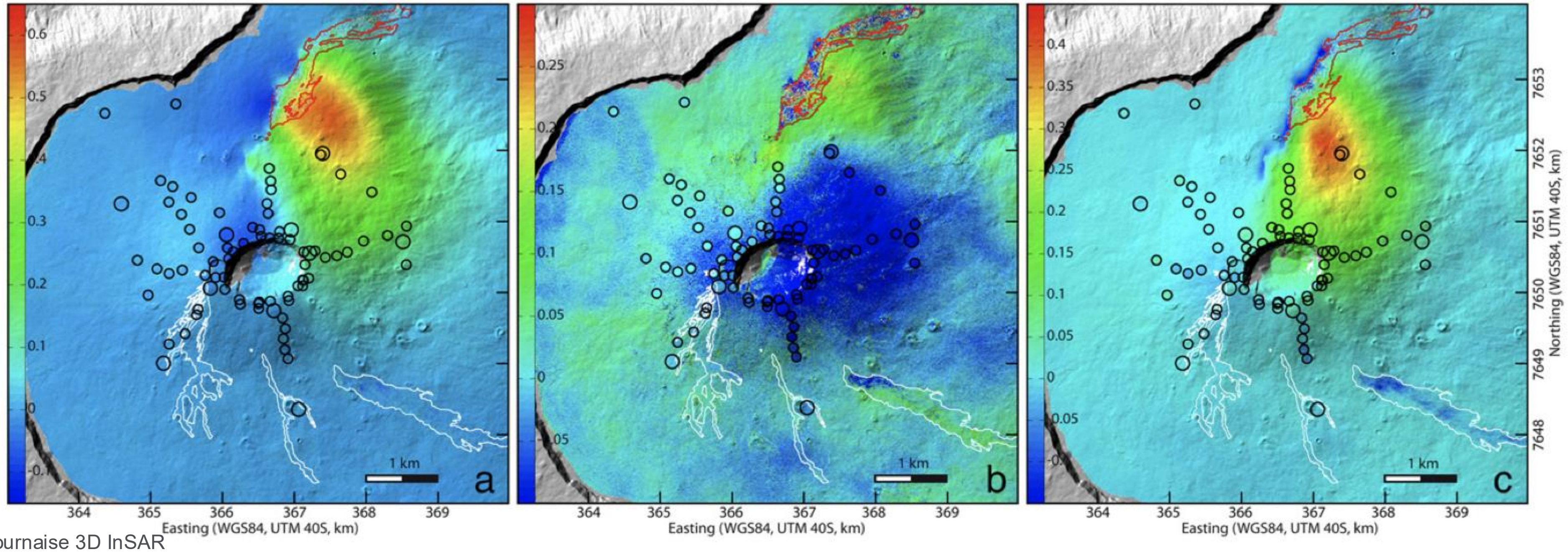
- Restricted to single, well-isolated eruptive events

⇒ No continuous 3D time series; inter-eruptive & transient signals not resolved

Case study: July 31, 2015 dike injection — 8 LOS acquisitions

From Peltier et al., 2015 (JVGR)

EW **NS** **UD**

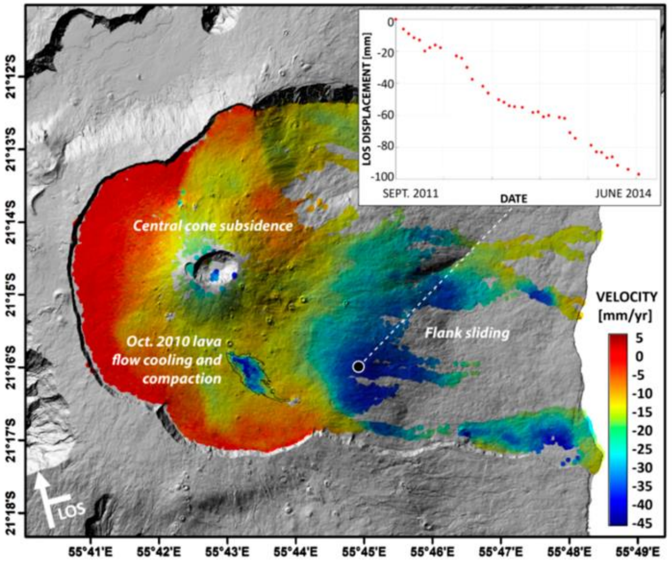


The limit of conventional InSAR Time series

Problem

1 — Single-LOS velocity

- One geometry measures motion projected along the line of sight only

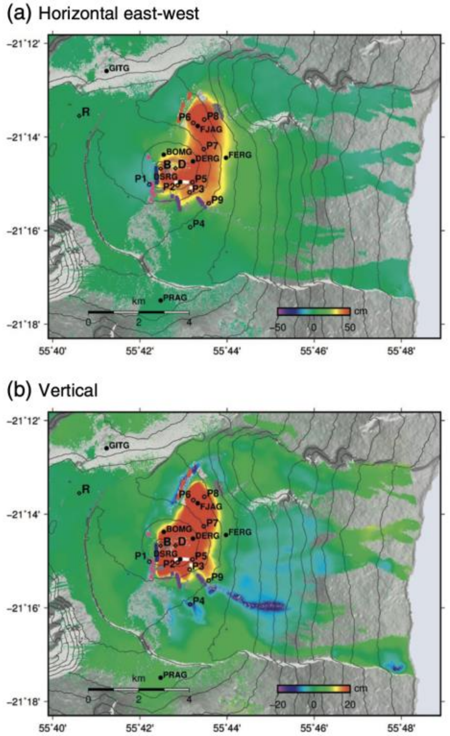


LOS velocities — ascending TSX SM

From Richter & Froger, 2020 (Remote Sensing)

2 — Quasi-2D (Asc + Desc)

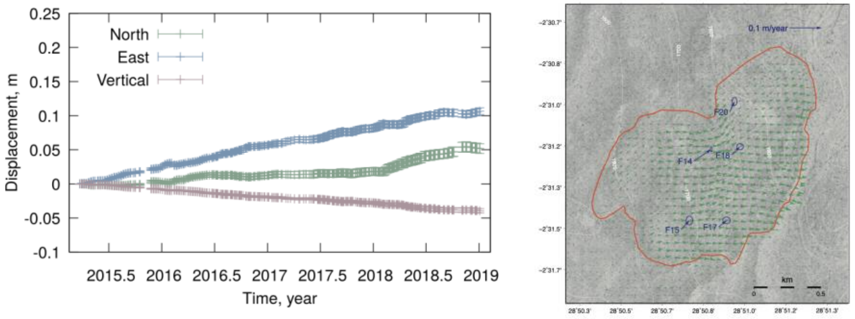
- One ascending + one descending LOS — resolves EW & Vertical, assumes N–S negligible



EW (a) & Vertical (b) — RadarSAT 2012–2016

From Samsonov et al., 2017 (JVGR)

3 — Pseudo-3D (+ slope gradients)



3D time series & displacement vector — Funu landslide (DRC)

From Samsonov et al., 2020 (Engineering Geology)

In a volcanic context

- Significant N–S motion from dike intrusions & flank dynamics
- No reason for along-slope displacements

⇒ biased EW/UD displacements?

An exceptional multi-geometry ALOS-2 dataset

Dataset

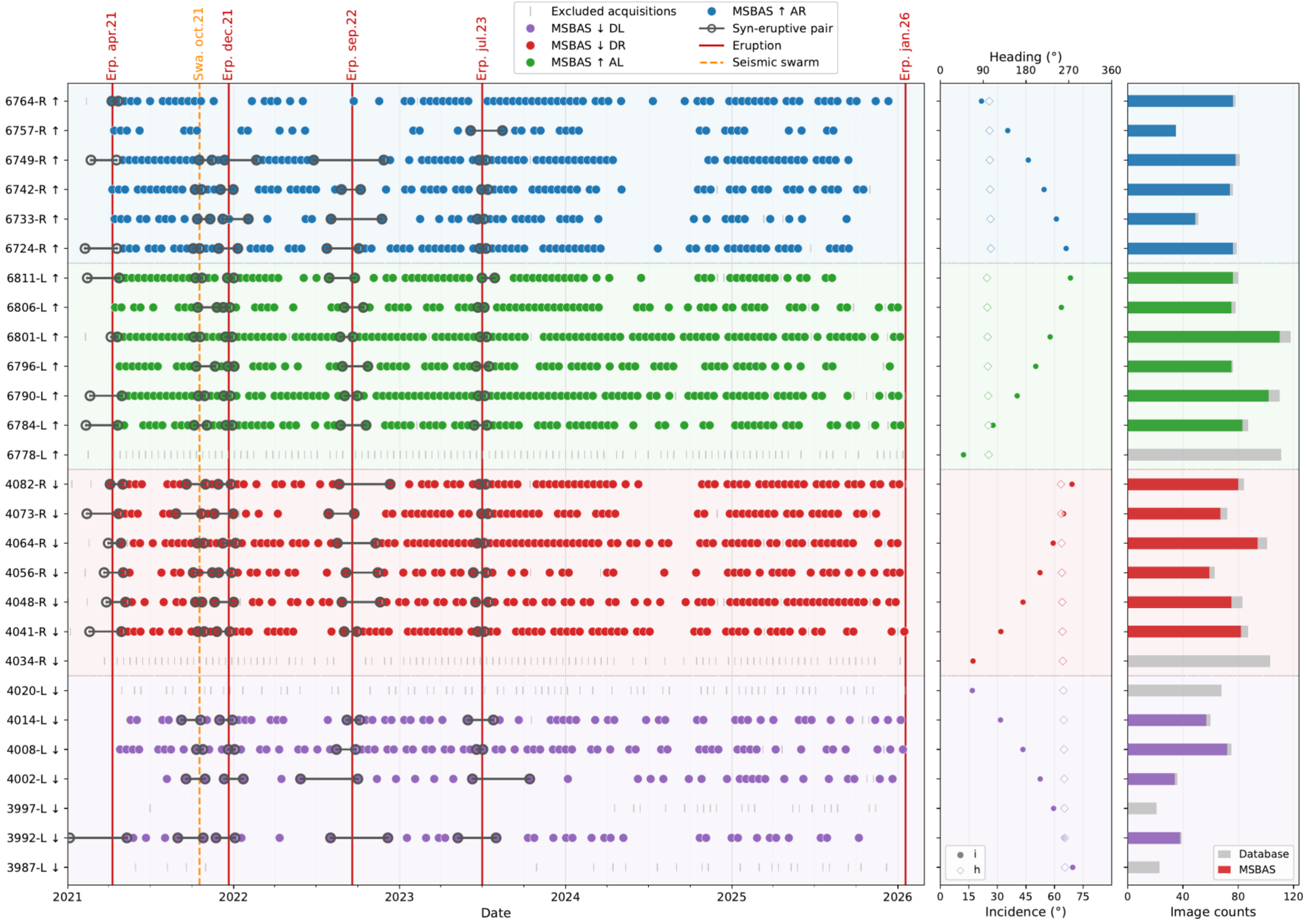
22
LOS geometries

>1,600
images

>7,700
interferograms

4.5 yr
Apr 2021 – Dec 2025

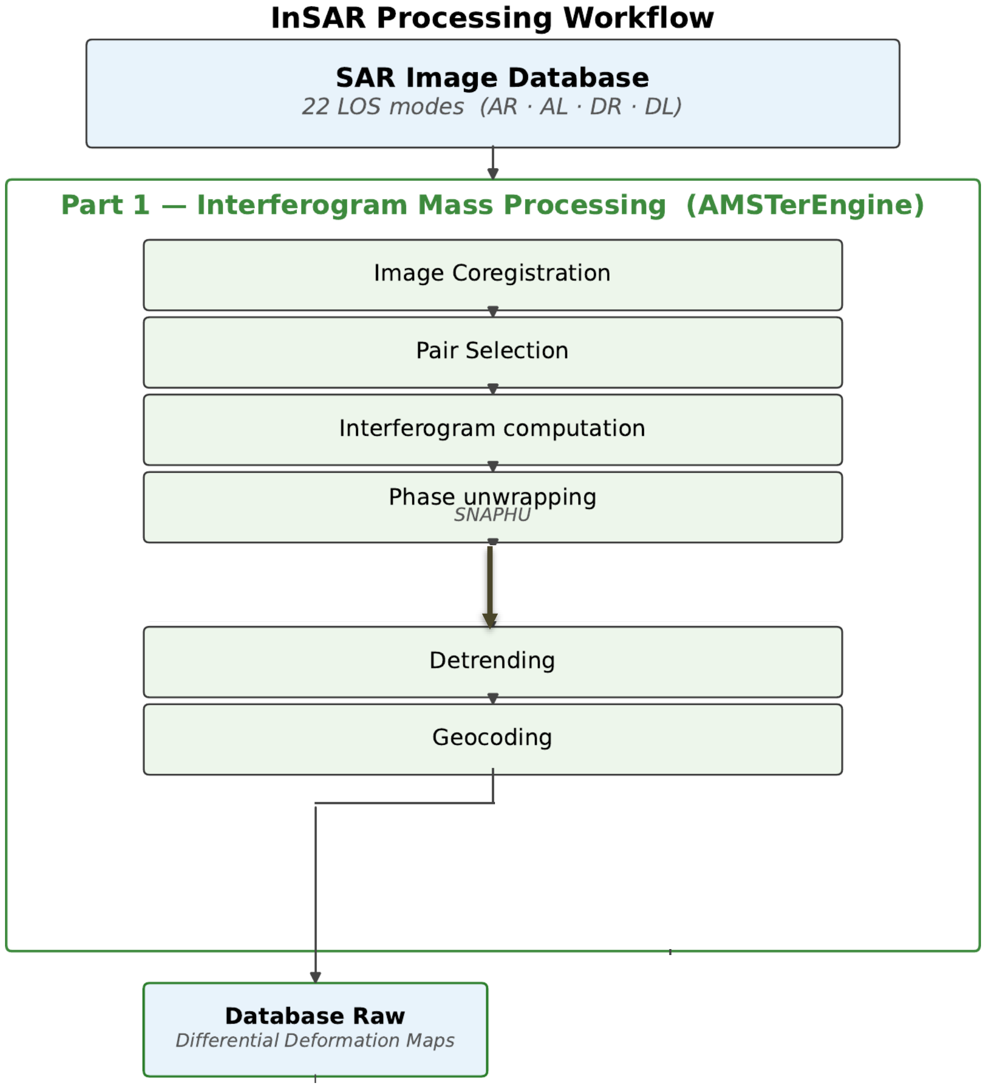
- **Right- & Left-**looking,
- **Ascending & Descending** LOS
- **L-band:** high coherence over vegetation
- **SpotLight:** high spatial resolution
- **Geometric redundancy** ⇒ True 3D inversion
- **Daily aquisitions** (14 day return time) ⇒ high temporal resolution



Processing workflow

AMSTer → SNAPHU → MANGO → geocoding

- **AMSTerEngine:** interferogram computation
- **SNAPHU:** phase unwrapping
- Geocoding to common grid



Processing workflow

AMSTer → SNAPHU → MANGO → geocoding → MSBAS

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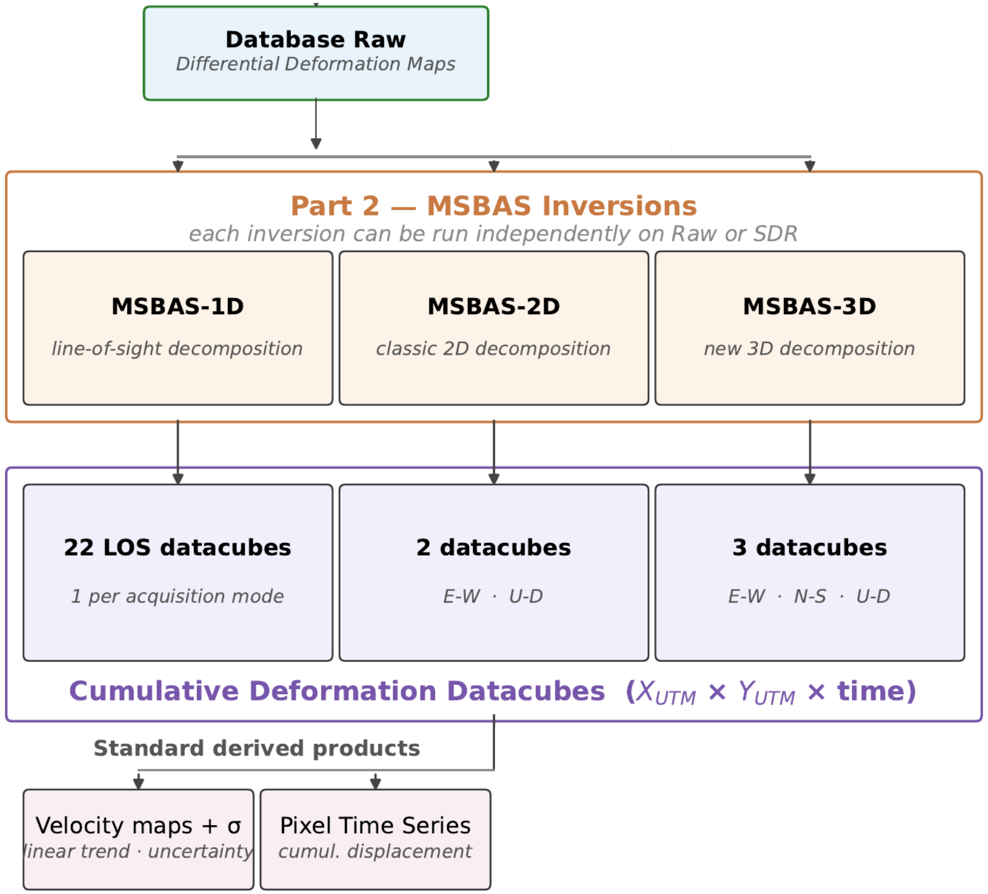
- **MSBAS:** multi-geometry time-series inversion



MSBAS inversion stability over time

Matrix meta-analysis · temporal conditioning

$$\hat{V} = \{V_1^E, V_1^N, V_1^U, \ldots, V_{n_t}^E, V_{n_t}^N, V_{n_t}^U\}$$

$$\hat{A}\,\hat{V}^{\mathsf{T}} = \hat{\Phi}$$

$$\text{ill-posed} \;\Rightarrow\; \text{regularization:}$$

$$\begin{pmatrix} \hat{A} \\ \lambda L \end{pmatrix} \hat{V}^{\mathsf{T}} = \begin{pmatrix} \hat{\Phi} \\ 0 \end{pmatrix}$$

- MSBAS inversion implements aTikhonov Regularization
- Regularized problem is fairly well constrained with 2 parameters:

  - Smoothing parameter λ and inversion order (0, 1 or 2)

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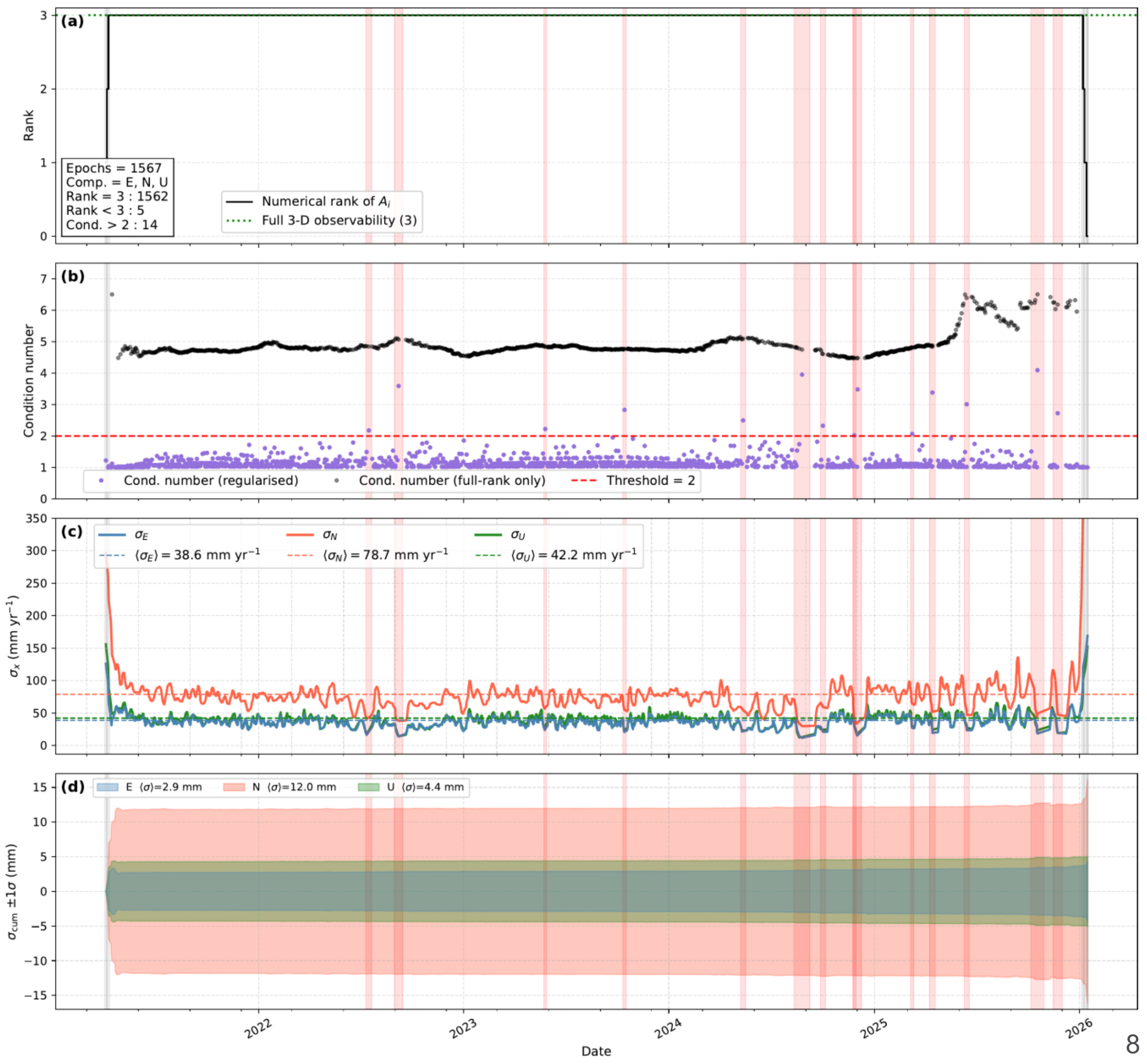
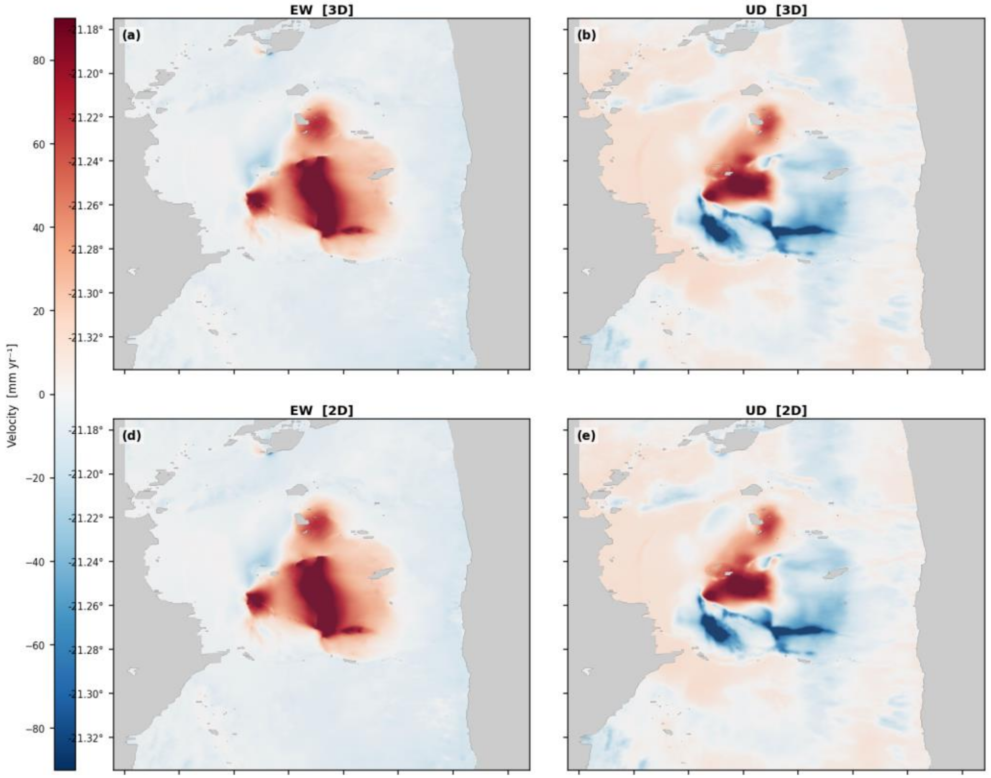


Added value of the full 3D inversion

2D (EW+UD) vs. 3D (EW+NS+UD)

- 3D vs. quasi-2D velocity maps
- N–S neglected in 2D



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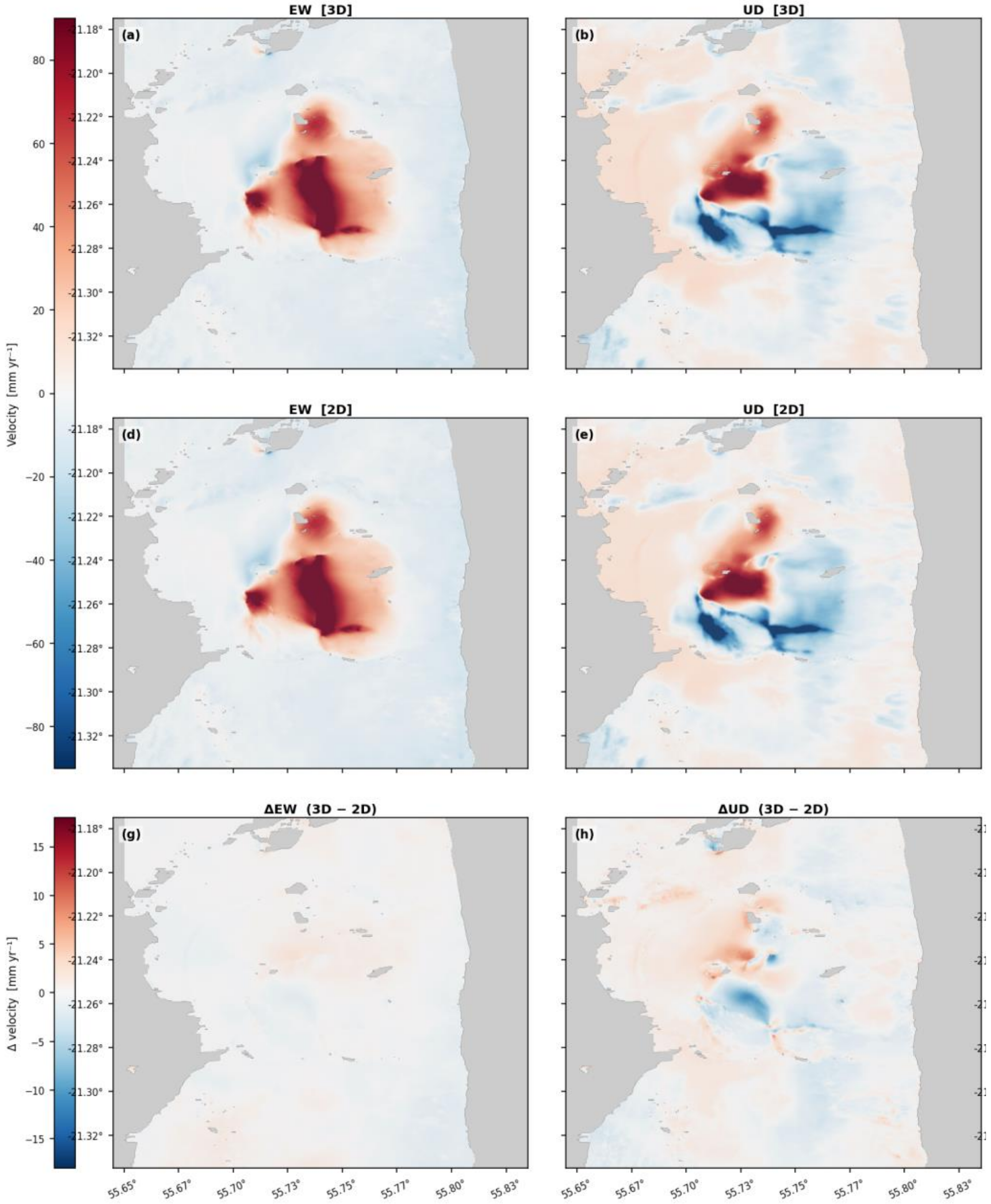

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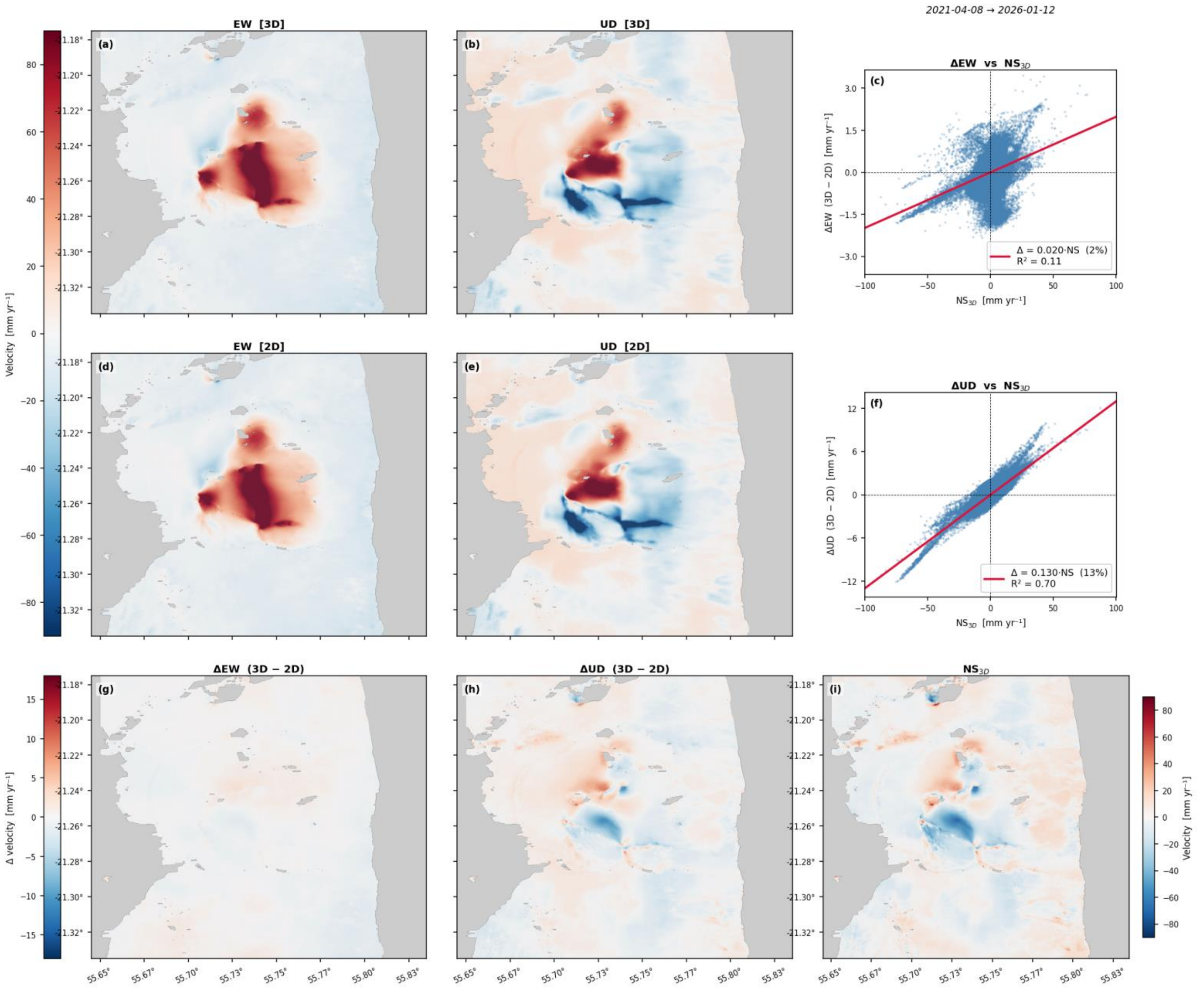

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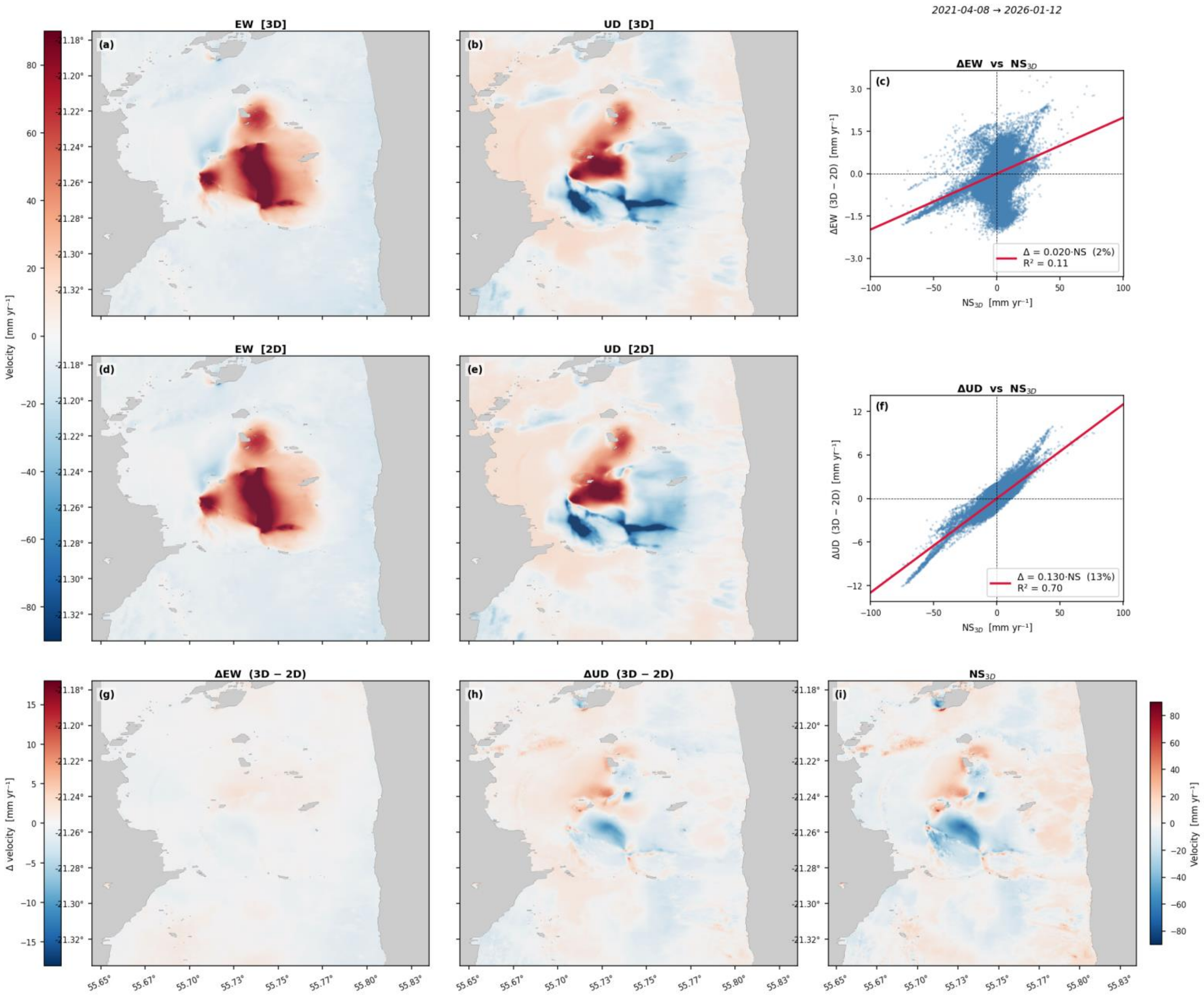
~13%

of N–S signal aliases into the vertical when N–S is neglected



Isolating long-term deformation

Raw vs. corrected (SDR) solutions

RAW solution

- Full set of interferograms ingested into MSBAS
- Dominated by large co-intrusive displacements

CORRECTED (SDR) solution

- Dyke displacements estimated, reprojected into each LOS, subtracted
- Syn-intrusive contribution removed before MSBAS inversion
- ⇒ reveals inter-eruptive signals

Processing workflow

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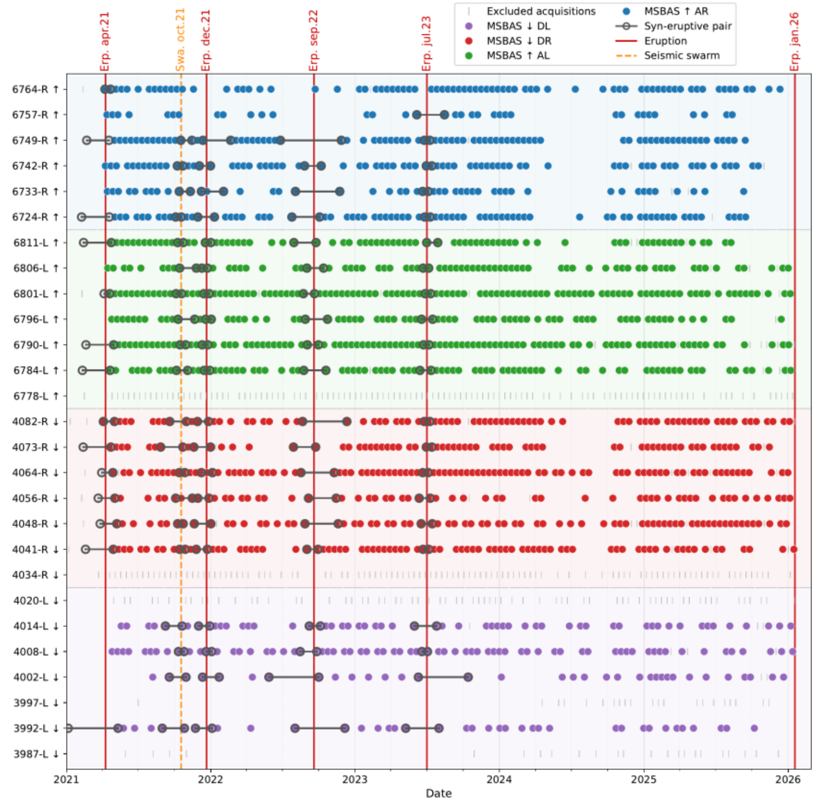
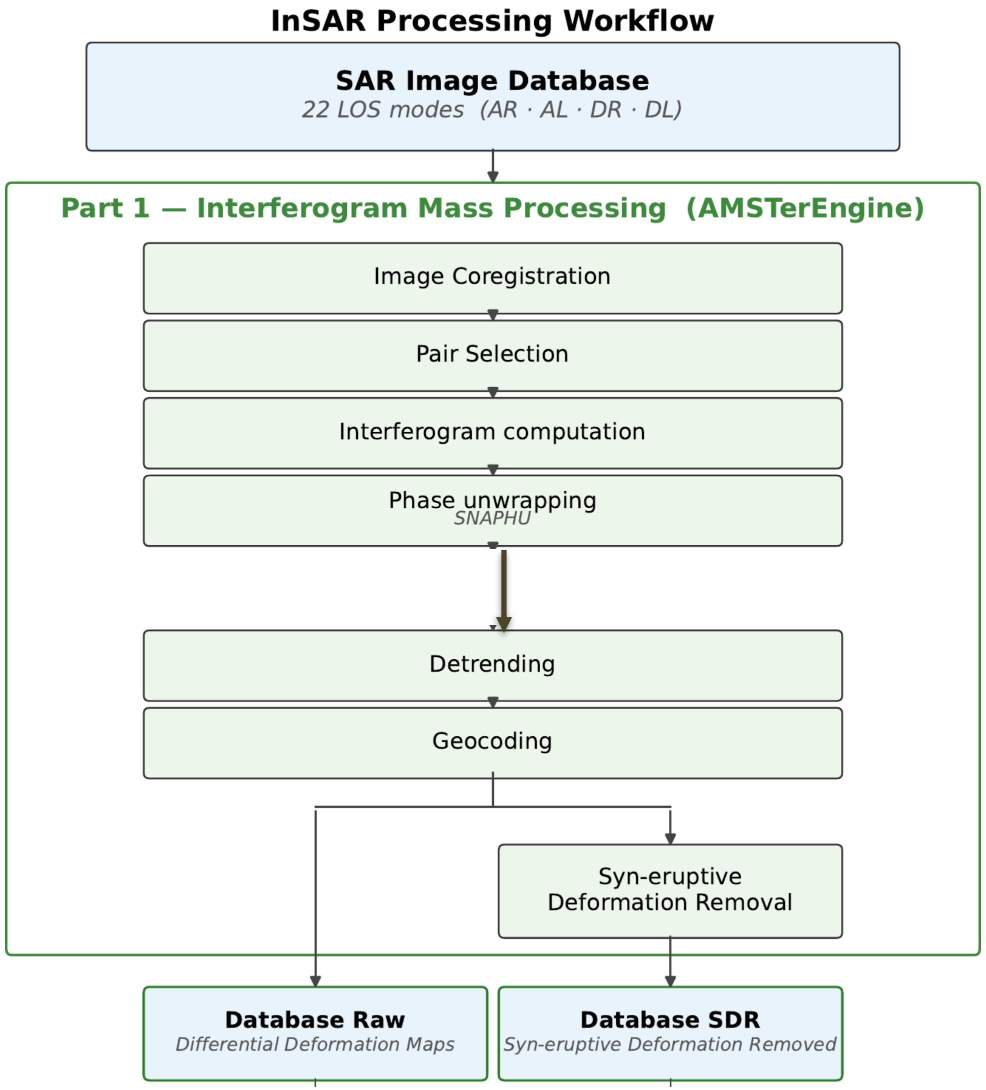


- **Syn-eruptive deformation computation using the shortest temporal baselines => 3D components displacement field**
- **3D components displacement field => Projection in each LOS**



3D linear velocity maps compared to GNSS

Raw vs. corrected · 2021–2026

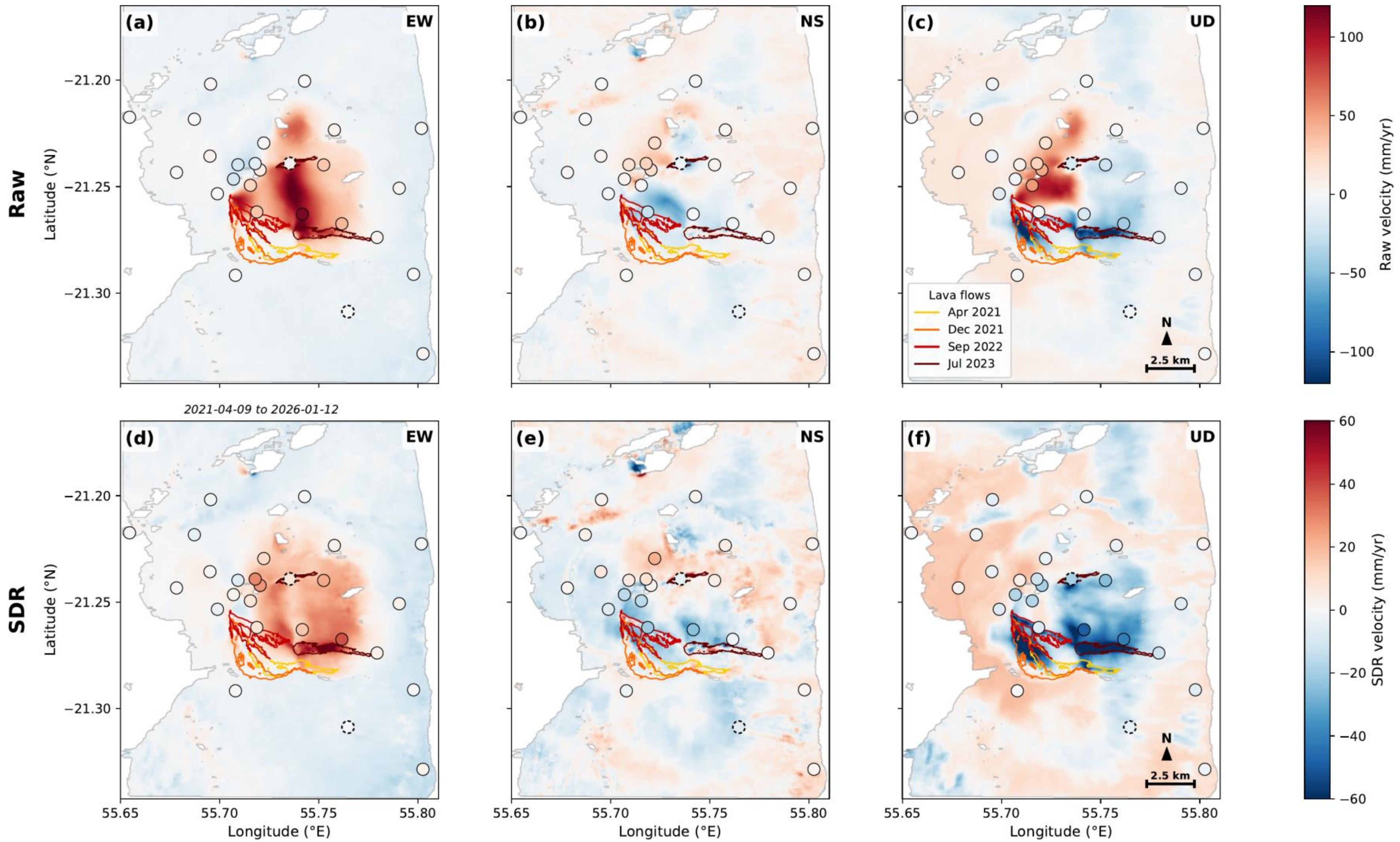
- **Large intermittent displacement due to magma intrusion dominate the long term velocity signal.**

- **After removal of syn-eruptive displacements :**

- **Eastern flank:** dominant eastward motion

- **Lava flows:** subsidence (compaction & cooling)

- **Rivière de l'Est:** prominent slope instability



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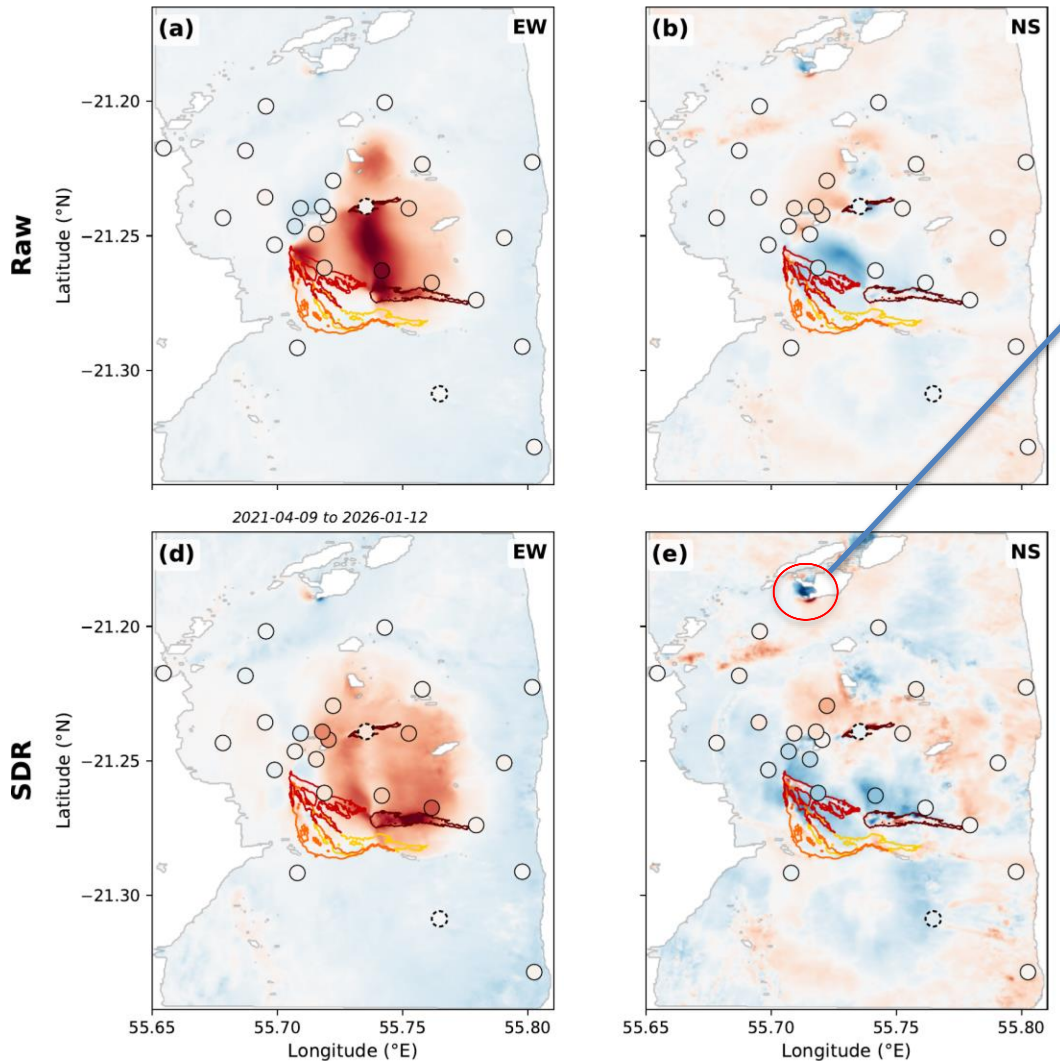


LINFO.RE LA REUNION OCEAN INDIEN FRANCE MONDE

Toute l'actu en direct ANNONCES LÉGALES AVIS & MARCHÉS PUBLICS

LINFO.re ▸ La Réunion ▸ Faits divers ▸ Rivière de l'Est : Un pan de falaise s'écroule

Rivière de l'Est : Un pan de falaise s'écroule

LINFO.RE – créé le 8.02.2020 à 09h04 - La rédaction

Partager X Post

La section aérienne de gendarmerie a photographié le résultat d'un éboulement de grande ampleur sur la fin du sentier de la Rivière de l'Est. L'abri installé au sommet de la falaise a failli être emporté.

Le communiqué de la Gendarmerie de La Réunion

"Ce jour, en retour de secours, les secouristes du PGHM survolent le cassé de la rivière de l'est et constatent un éboulement important survenu à la fin du sentier.

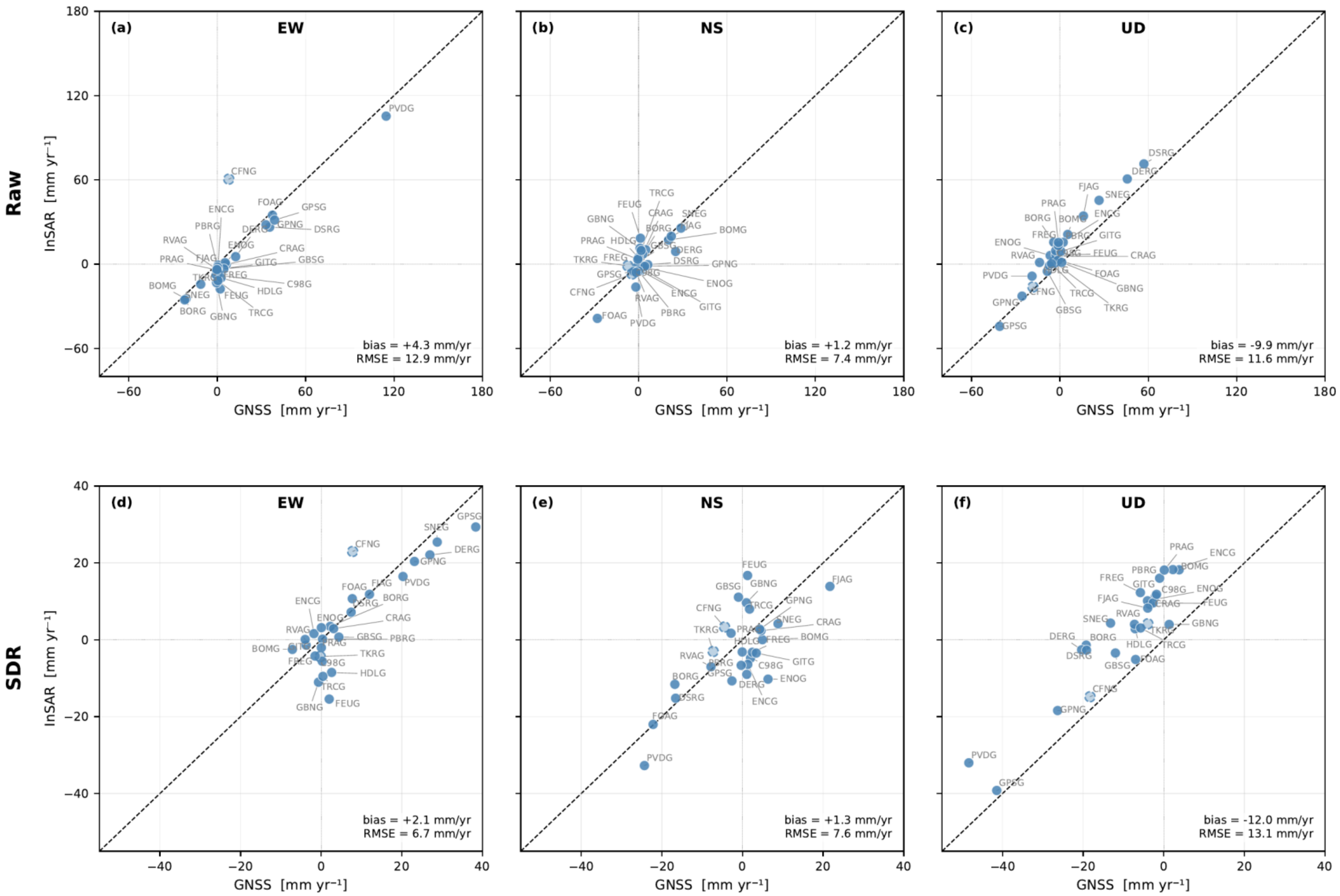
Un pan entier de falaise s'est décroché emportant les gardes corps en bois au niveau du point de vue, l'abri se trouvant normalement à environ 25 mètres du bord du cassé se situe maintenant en bordure de falaise.

Les secouristes ont également constaté d'importantes fissures dans le sol, un important éboulement est à prévoir rapidement dans le secteur.

Validation against independent GNSS

3D InSAR vs. GNSS E, N, U

- 3D InSAR velocities compared to GNSS velocities at each OVPF station

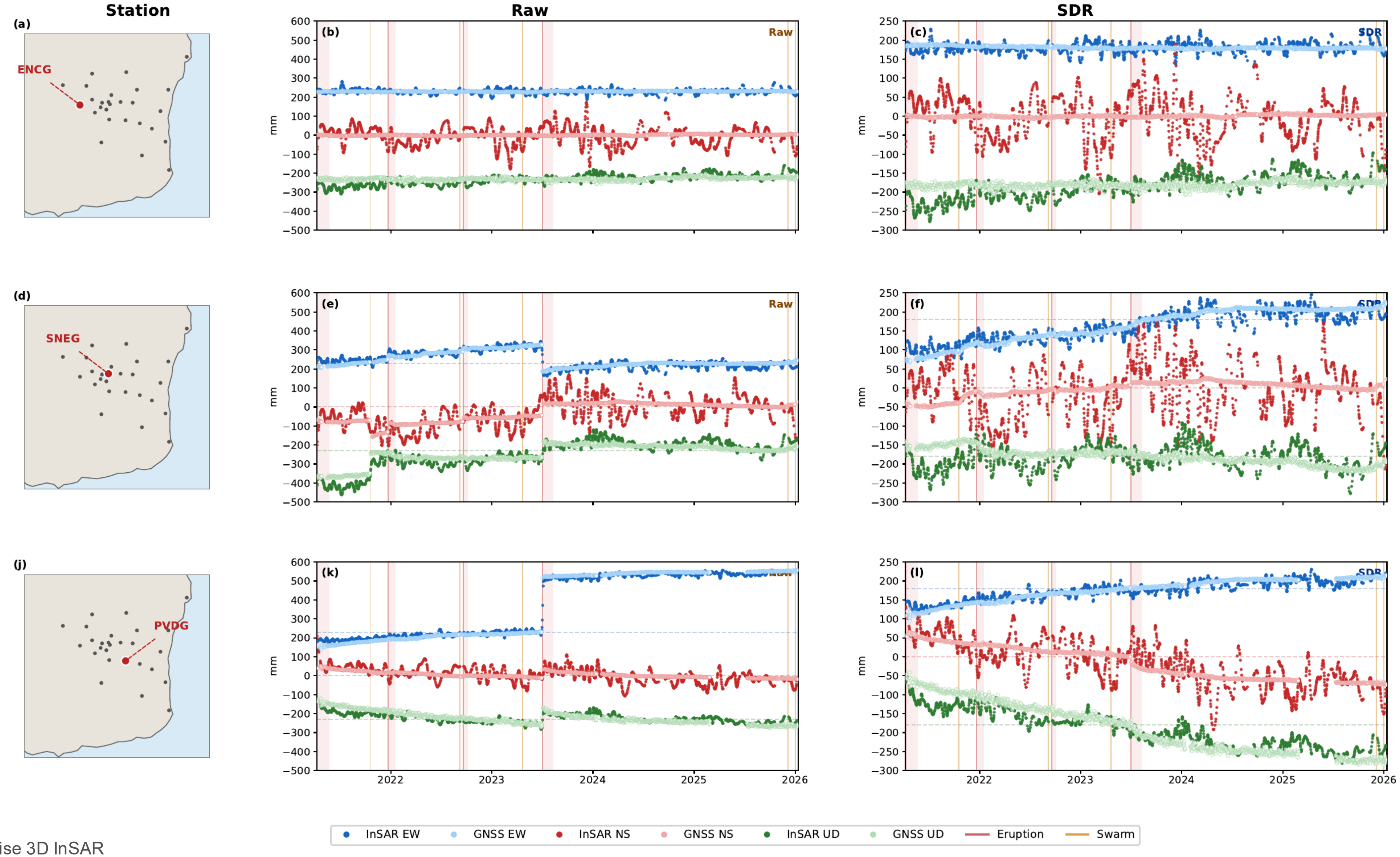


Very good agreement over the whole GNSS network

3D linear time series compared to GNSS

Raw vs. corrected · 2021–2026

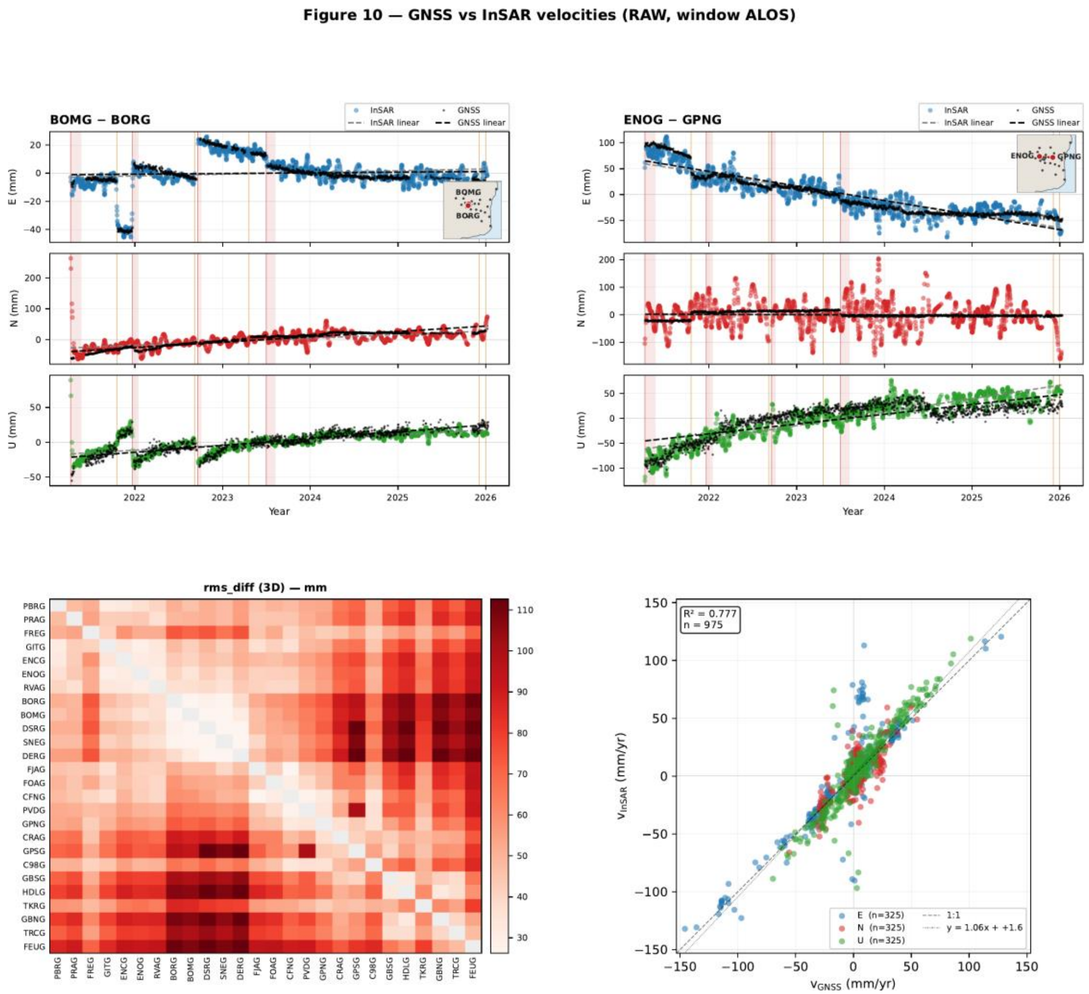
- Far field station
- Summit station
- East flank station



Validation against independent GNSS baselines

Raw vs. corrected (SDR)

Raw

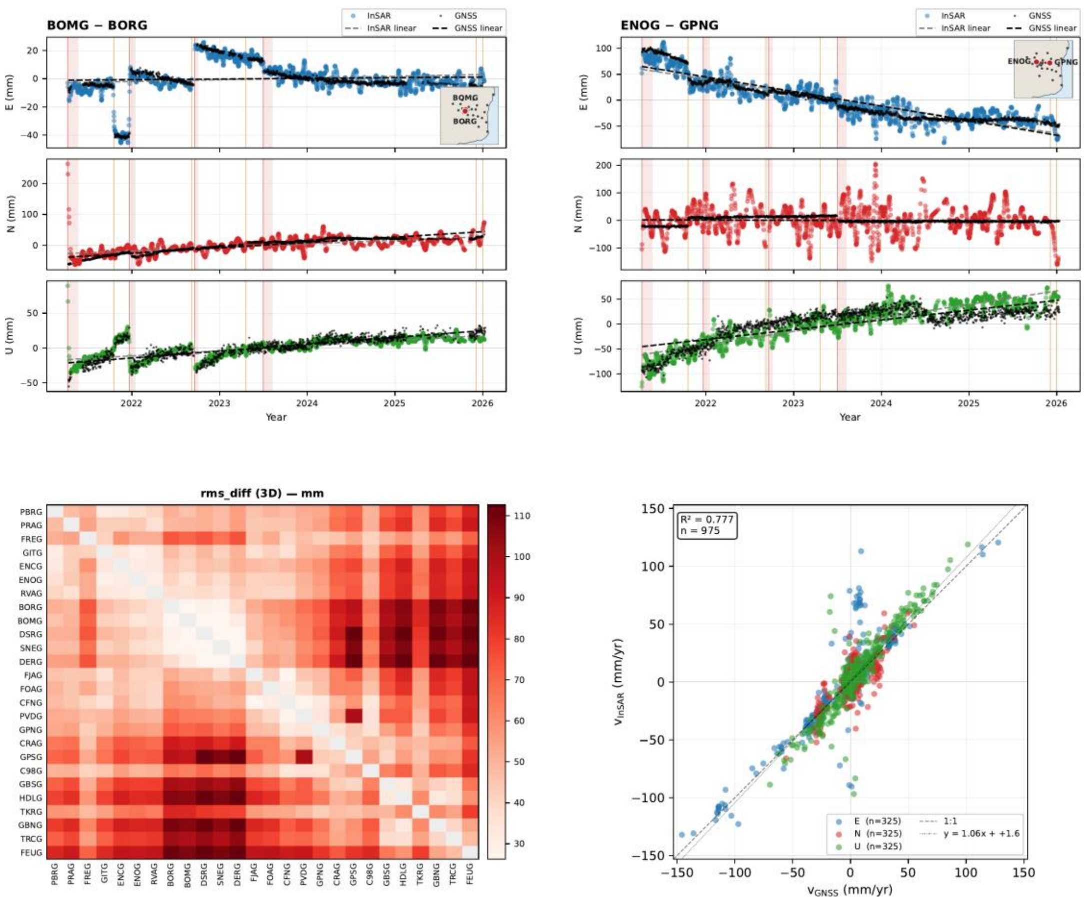


Validation against independent GNSS baselines

Raw vs. corrected (SDR)

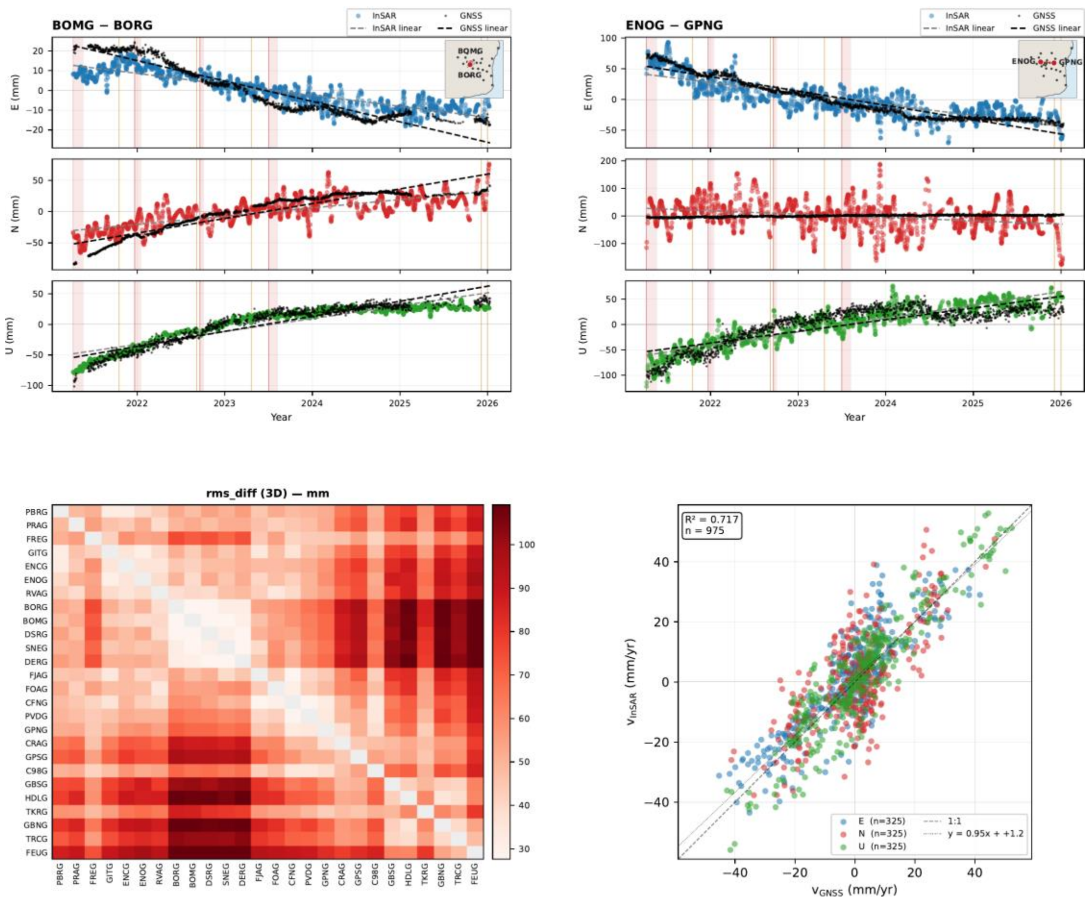
Raw

Figure 10 — GNSS vs InSAR velocities (RAW, window ALOS)



Corrected (SDR)

Figure 10 — GNSS vs InSAR velocities (SDR, window ALOS)



Conclusions

- **First true 3D InSAR time series** of Piton de la Fournaise — 22 ALOS-2 LOS geometries over 4.5 years
- **Syn-intrusive signal removal** is critical to reveal subtle long-term signals (rift zones, gravitational processes, post-intrusive relaxation)

- **3D reduces N–S leakage bias** — ~13% of N–S energy leaked into vertical in the quasi-2D solution
- **Combining diverse geometries is key to be able to access 3D**
- **SpotLight L-band really increase our capacity to monitor tropical volcanoes**

Work in Progress

- **MANGO atmospheric correction** (GNSS ZTD) in AMSTer should improves reliability, especially at grazing incidence angles

Thank you

delphine@ecgs.lu

ALOS-2 SpotLight images were acquired through the
JAXA 3rd Research Announcement on the Earth Observations Project ER3A2N008
and through the
ESA–JAXA 2019–2024 mutual cooperation project on Using Synthetic Aperture Radar Satellites In Earth Science and Applications.

The AMSTer Toolbox is available at https://github.com/AMSTerUsers/AMSTer_Distribution.

MSBAS is developed by S. Samsonov (https://insar.ca/multidimensional-small-baseline-subset-msbas/).

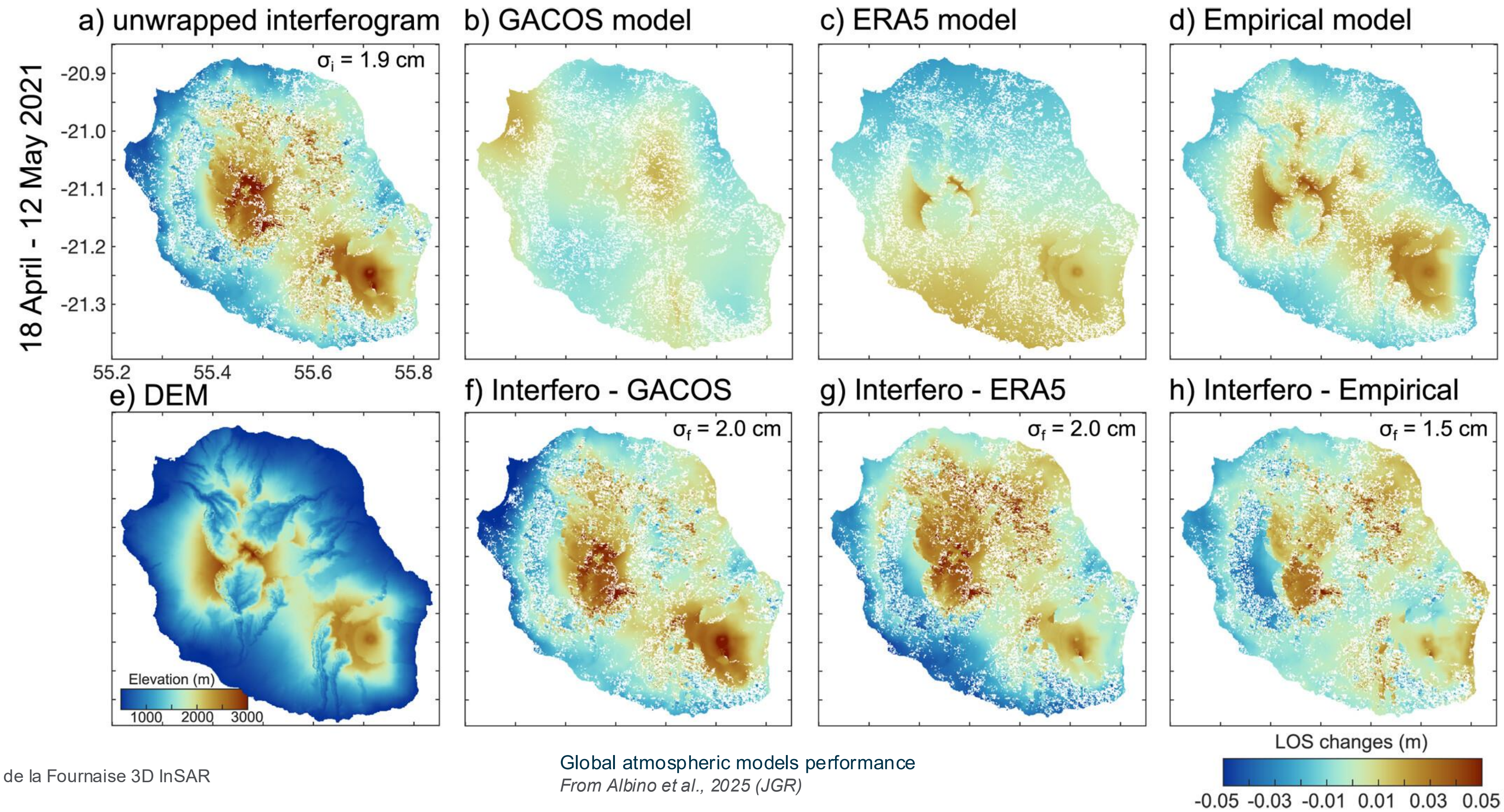
ECGS | CEGS

AMSTer

Which Atmospheric correction ?

Tropospheric delay

- Global models do not perform well on volcanic tropical islands



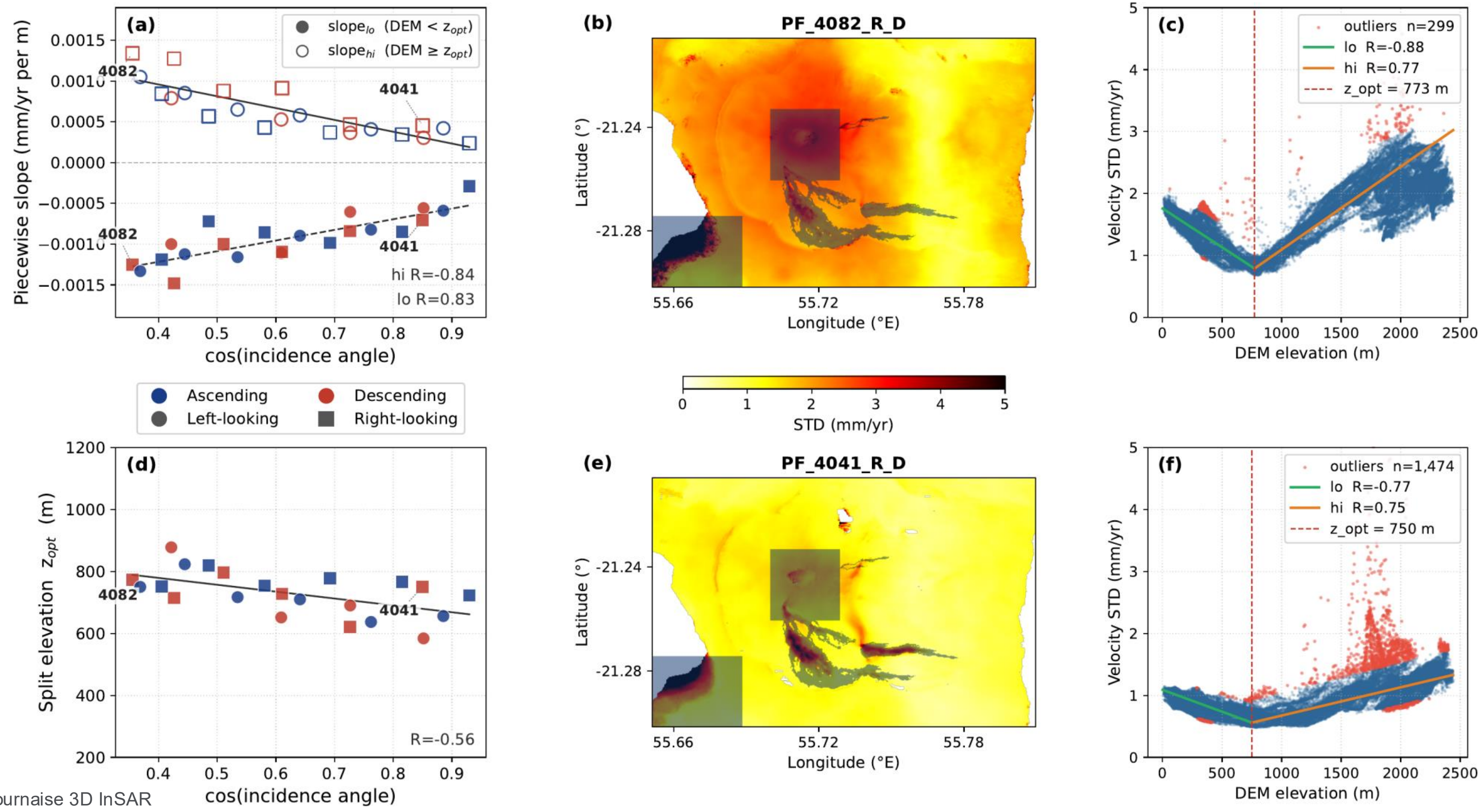
Global atmospheric models performance

From Albino et al., 2025 (JGR)

Need for Atmospheric correction

Tropospheric delay

- Grazing-incidence LOS (>55°) most sensitive to the stratified troposphere



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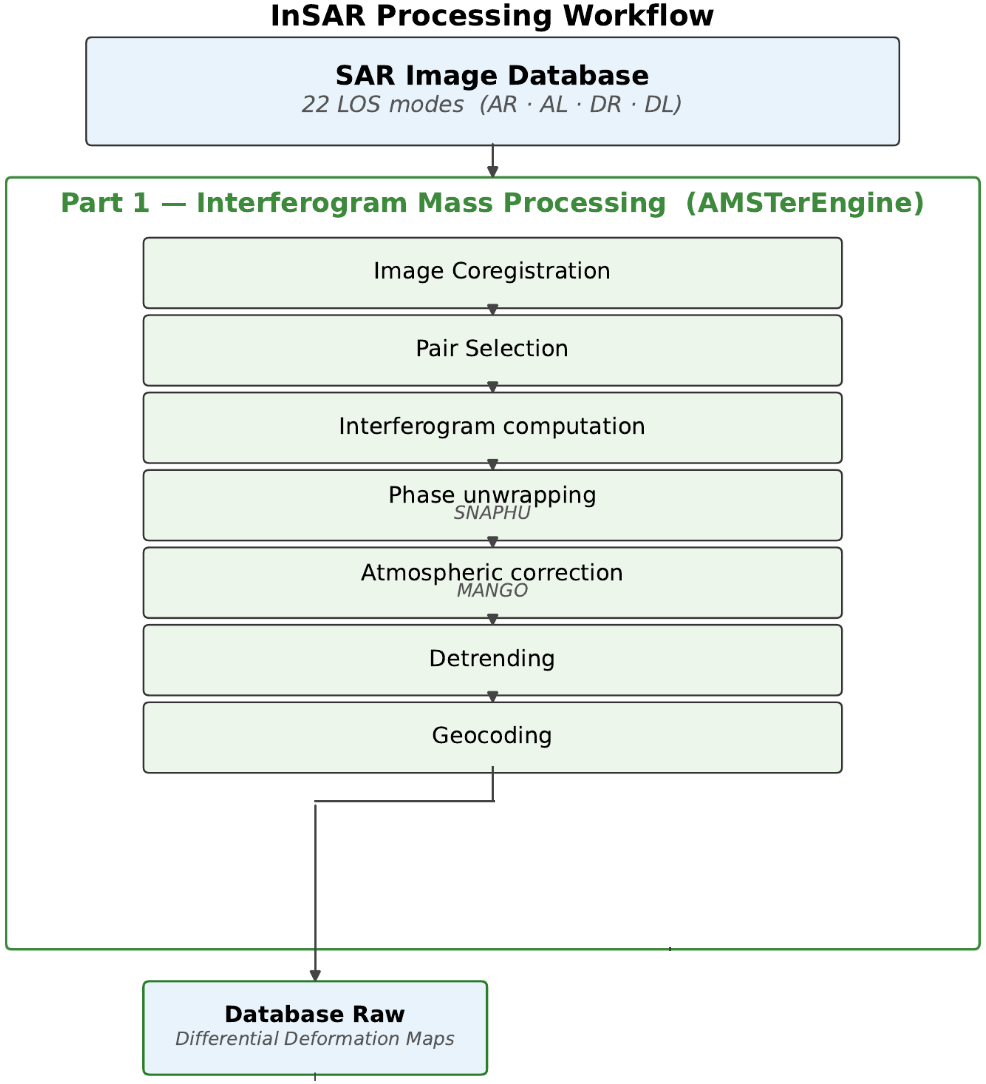
- **MANGO:** atmospheric correction (GNSS ZTD)
  (work in progress)
- Geocoding to common grid



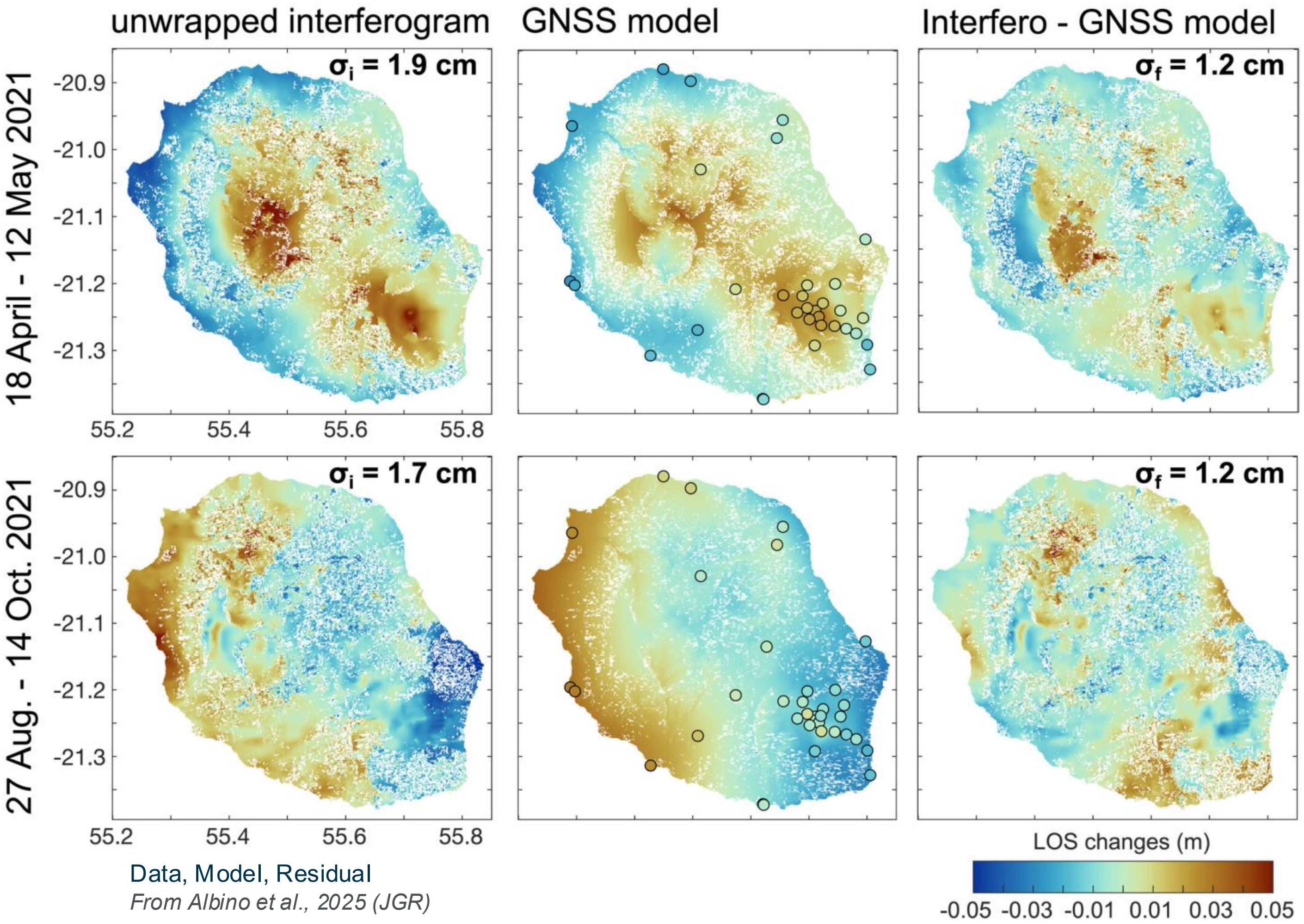
Atmospheric correction — MANGO in AMSTer

Tropospheric delay

- Grazing-incidence LOS (>55°) most sensitive to the stratified troposphere
- **MANGO toolbox** integrated into the automatic AMSTer workflow
- **APS from GNSS ZTD** (Zenith Total Delay) of the OVPF continuous network
- **Correction applied to each interferogram,** in slant range geometry, before detrending

Implementation in the AMSTer Toolbox
=> *Done*

Systematic Computation of 7700 corrected interferograms
=> *Work in Progress*



Data, Model, Residual
From Albino et al., 2025 (JGR)

Backup — GNSS station map

OVPF network for ZTD & validation