SIMULATING SATELLITE RADAR MEASUREMENTS OF VOLCANIC ERUPTIONS IN PREPARATION FOR ESA's HARMONY MISSION

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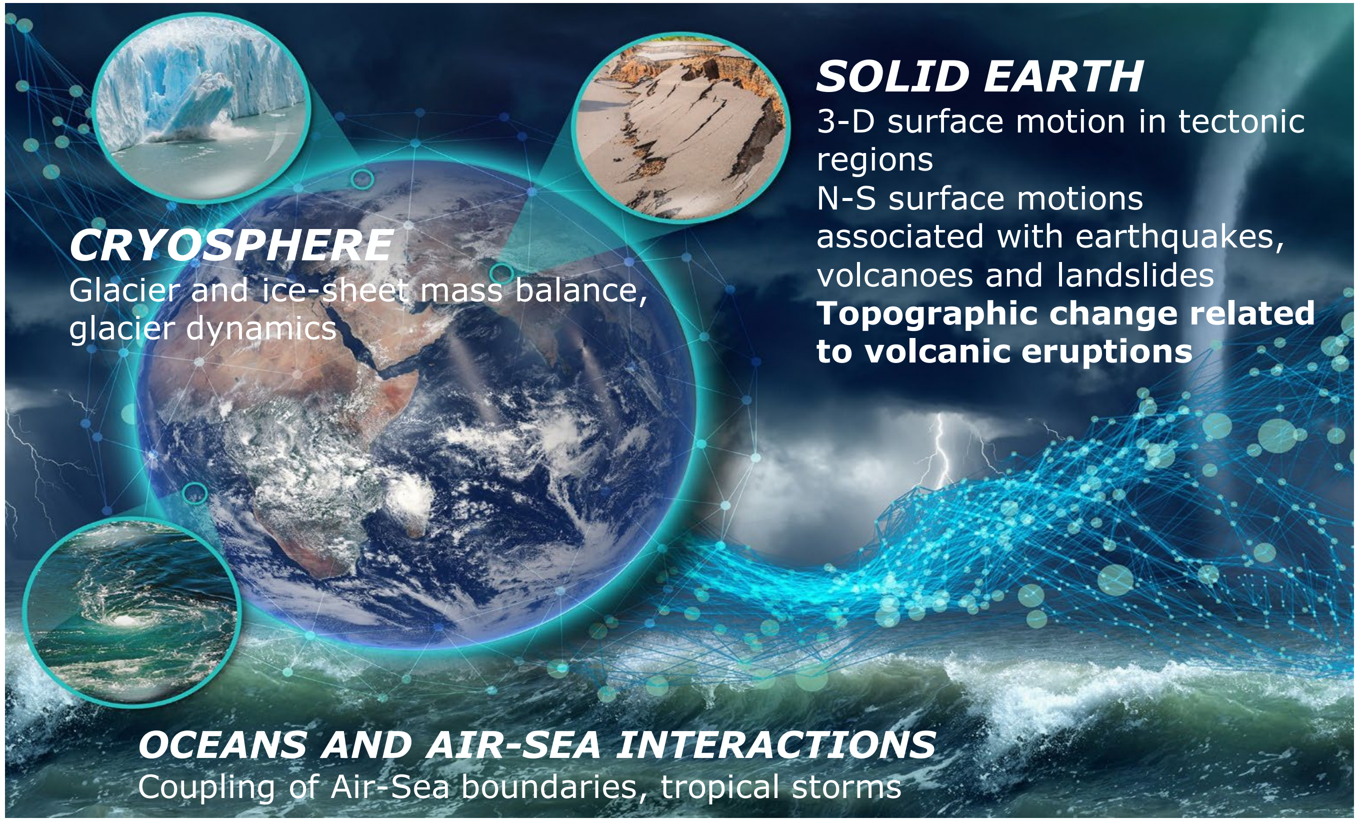
The Harmony Mission

Harmony has been selected by the European Space Agency as the 10th Earth Explorer mission[1,2] (expected launch date in 2029) and is dedicated to the observation and quantification of small-scale deformation to address scientific questions related to ocean, ice and land dynamics.



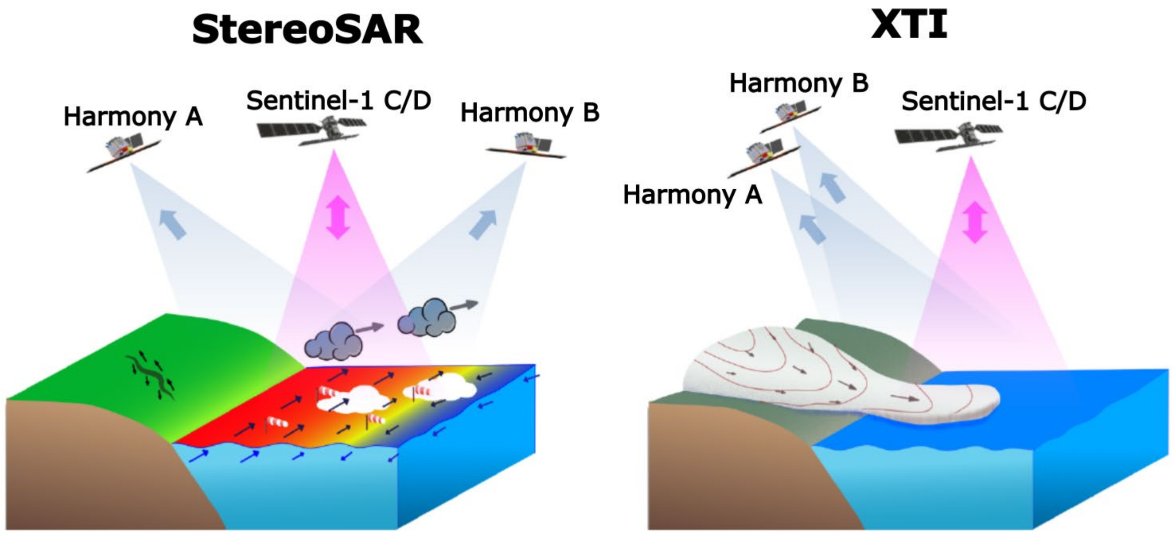
The Harmony Mission

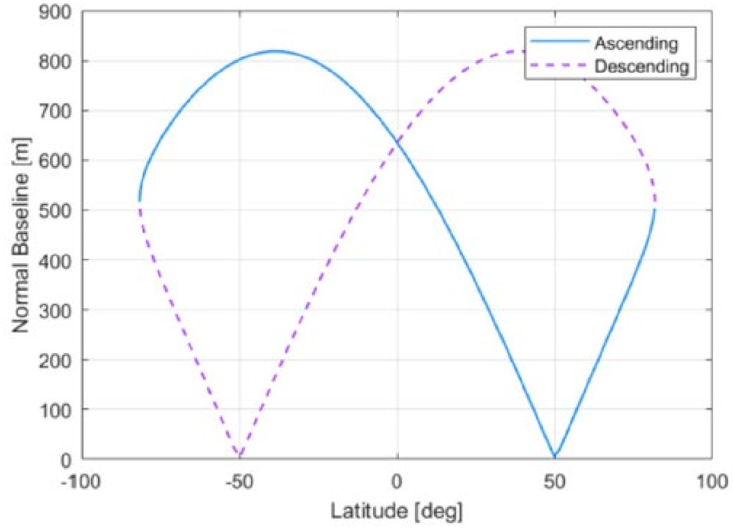
The Harmony mission will consist of 2 spacecraft, orbiting in formation with Sentinel-1 and equipped with a receive-only SAR instrument, providing bistatic, single-pass InSAR capabilities.

StereoSAR mode: the line-of-sight diversity will allow the retrieval of 3-D surface motion vectors

Across-track interferometry (XTI): dense time series of surface elevation models while retaining 3-D InSAR capabilities

Perpendicular baseline varies across orbit - latitude dependent

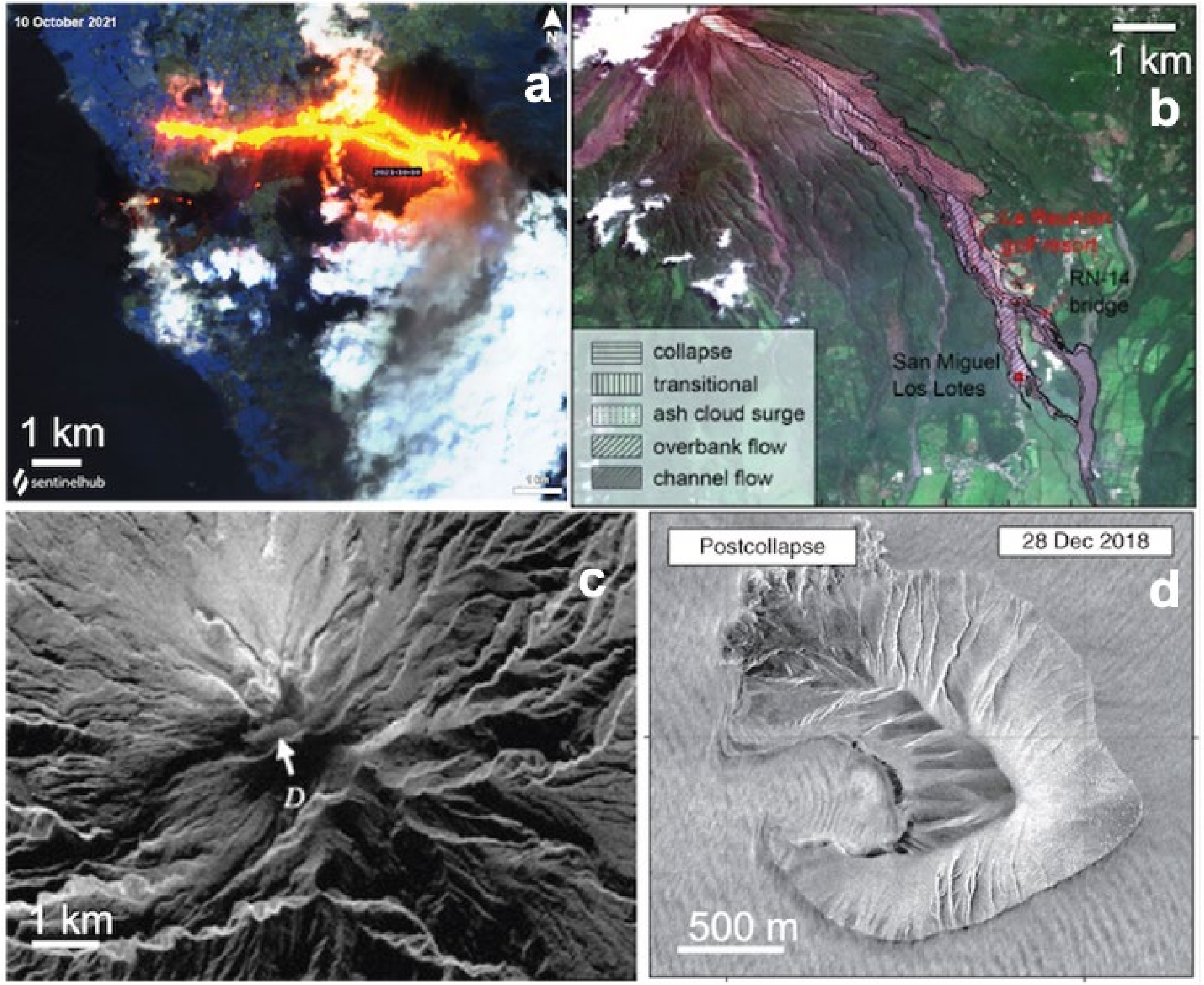




Volcanic Topographic Change

Lava Flow
(La Palma)

Pyroclastic Flow
(Fuego)



Lava Dome Growth
(Merapi)

Collapse
(Anak Krakatau)

TOC Case Study - Objectives

Utilise high-resolution bistatic InSAR data (TanDEM-X CoSSC) to produce interferograms and generate TOC maps of volcanic eruption (St. Vincent La Soufriere)

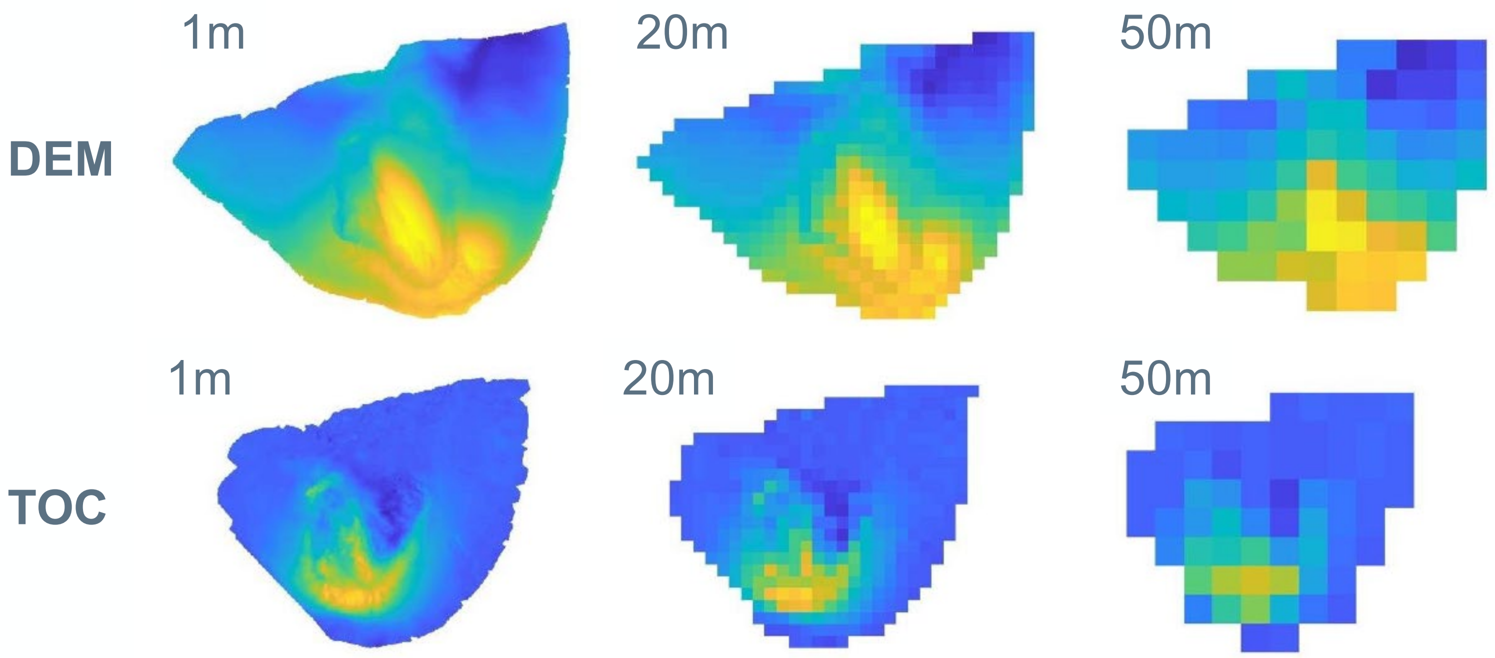
- Demonstrate the effects of challenging topography
- Demonstrate the need for qualitative masking of the DEM/TOC maps
- Demonstrate the need for both ascending and descending passes over volcanic regions

Provide input/ground truth to the Harmony end-to-end simulator (HEEPS/Terra) developed at DLR.

Simulating HRM20 Resolution

Resolution is key!

Examples of St. Helen's DEM and TOC over dome growth phase in 2004.



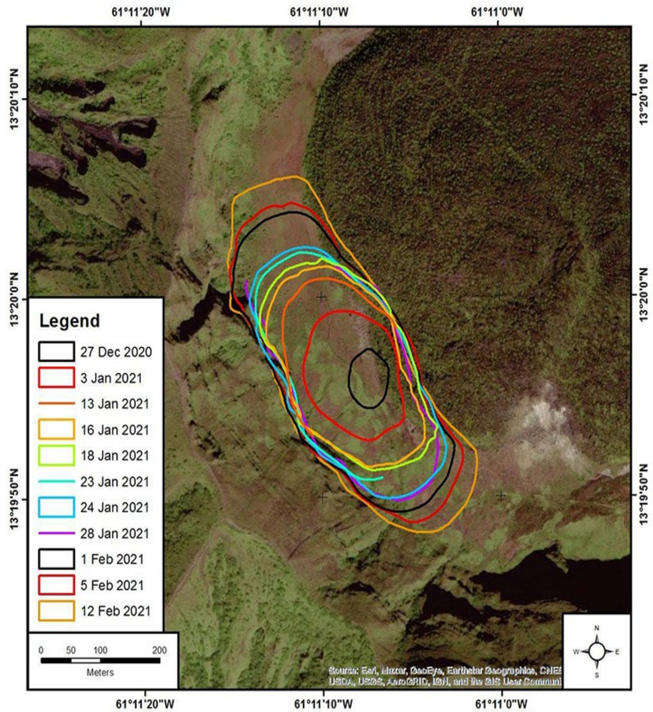
Produce a set of lower-resolution measurements (matching that of Harmony) by sub-sampling high-resolution data to simulate Harmony's performance (separate from HEEPS/Terra)

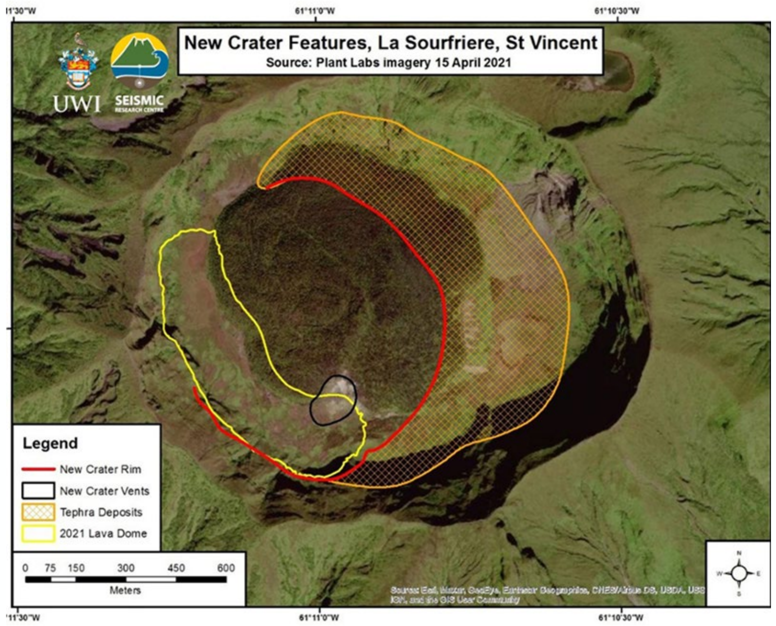
St. Vincent La Soufriere

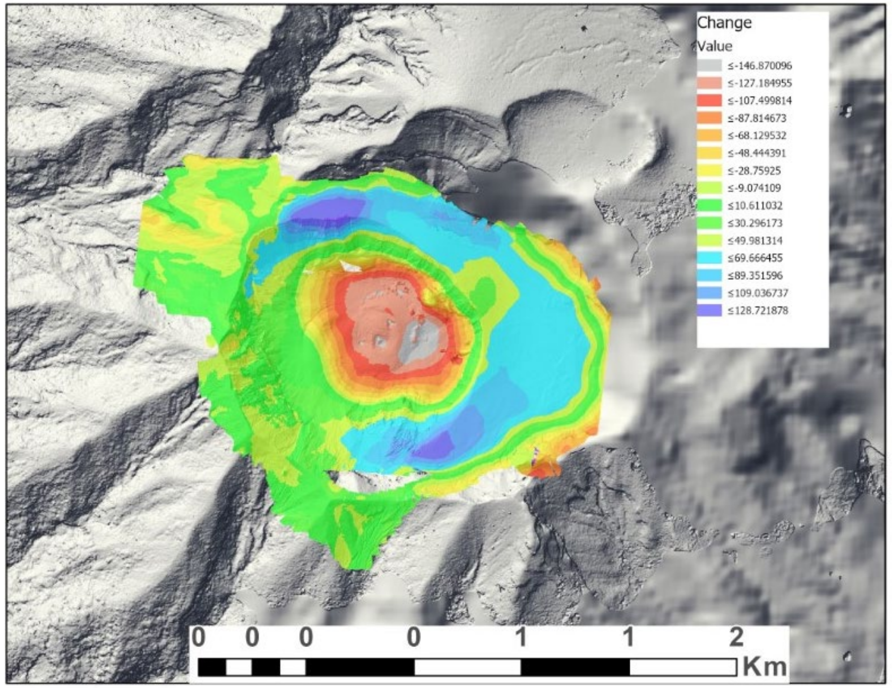
La Soufriere is an active stratovolcano located on the northern part of the island of St. Vincent, in St. Vincent and the Grenadines, with a summit elevation of 1220m.

27th December 2020: Effusive eruption – creation & growth of new lava dome[3]

9th April 2021: Explosive eruption – destruction of lava domes, formation of new crater and tephra deposits[4]



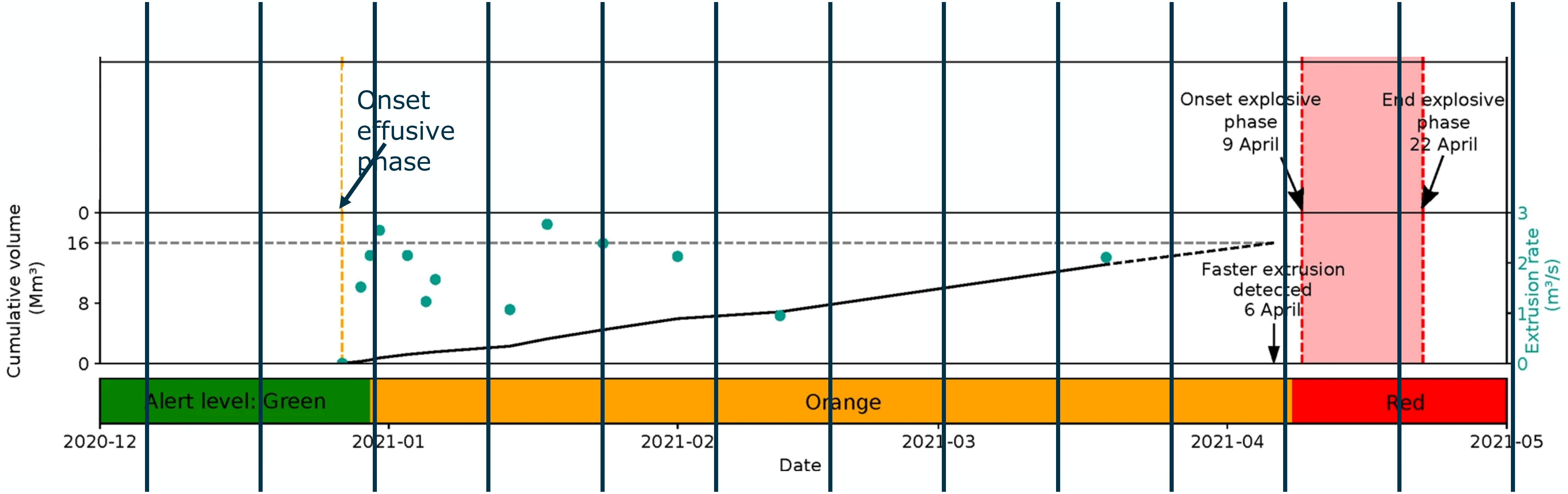




Harmony Temporal Resolution

Harmony will provide regular acquisitions in 12-day intervals.

At least 12 DEMs produced over this particular eruption!



TanDEM-X CoSSC Data

Two pre-eruptive TanDEM-X CoSSC data products, one in ascending and one in descending orbit.

One post-eruptive TanDEM-X CoSSC data product, in ascending orbit.

No data covering the period of effusive eruption / dome growth.

Dataset	1	2	3
Acquisition Date	17/01/2017	26/05 2019	10/10/2021
Pass	Ascending	Descending	Ascending
Heading	349°	190°	349°
Incidence Angle	33.6°	46.2°	34.7°
Range Pixel Spacing	1.36m	1.36m	0.91m
Azimuth Pixel Spacing	1.97m	2.17m	1.98m
Baseline	110m	196m	176m

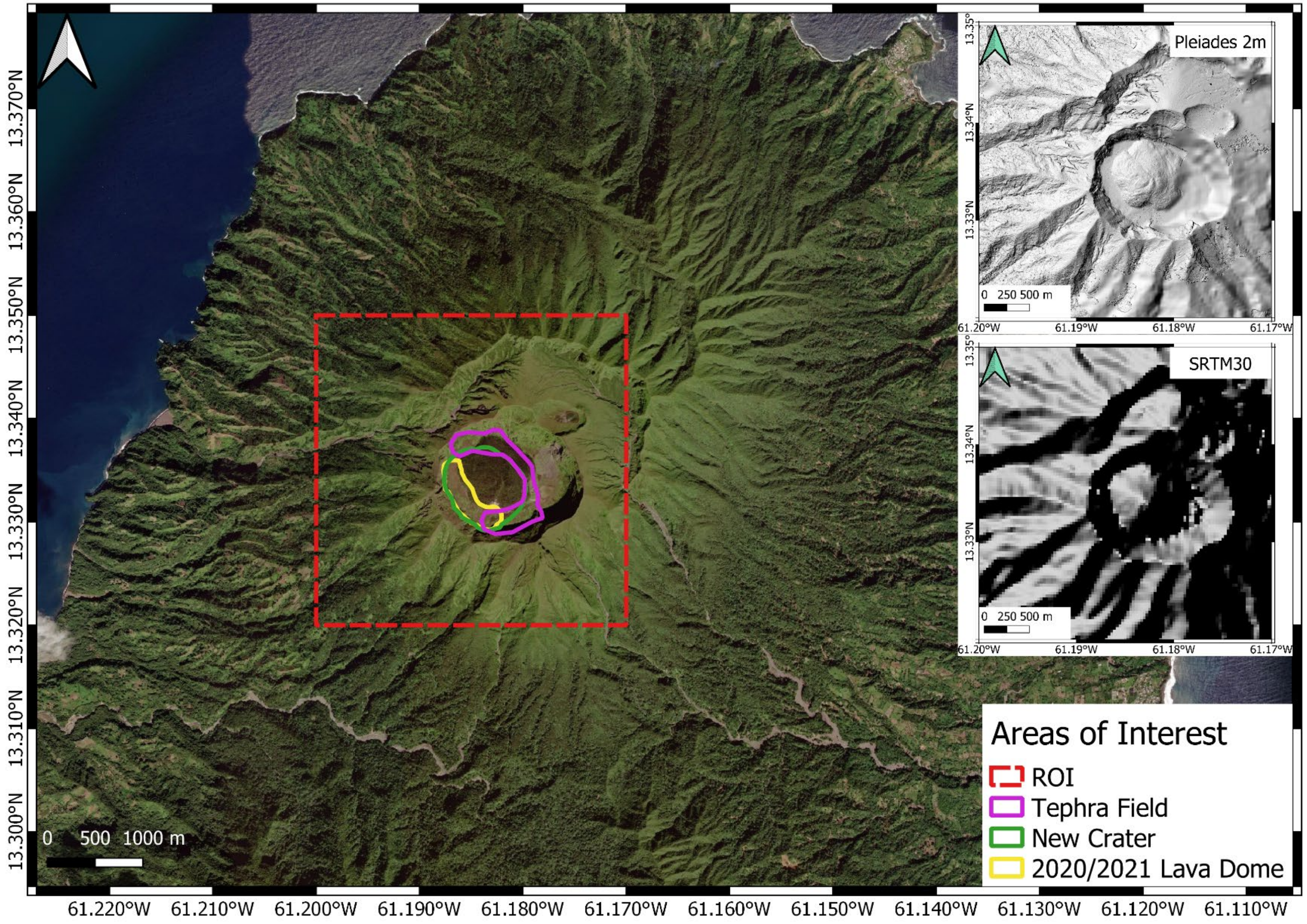
Specifications of the available TanDEM-X CoSSC Products

St. Vincent DEMs

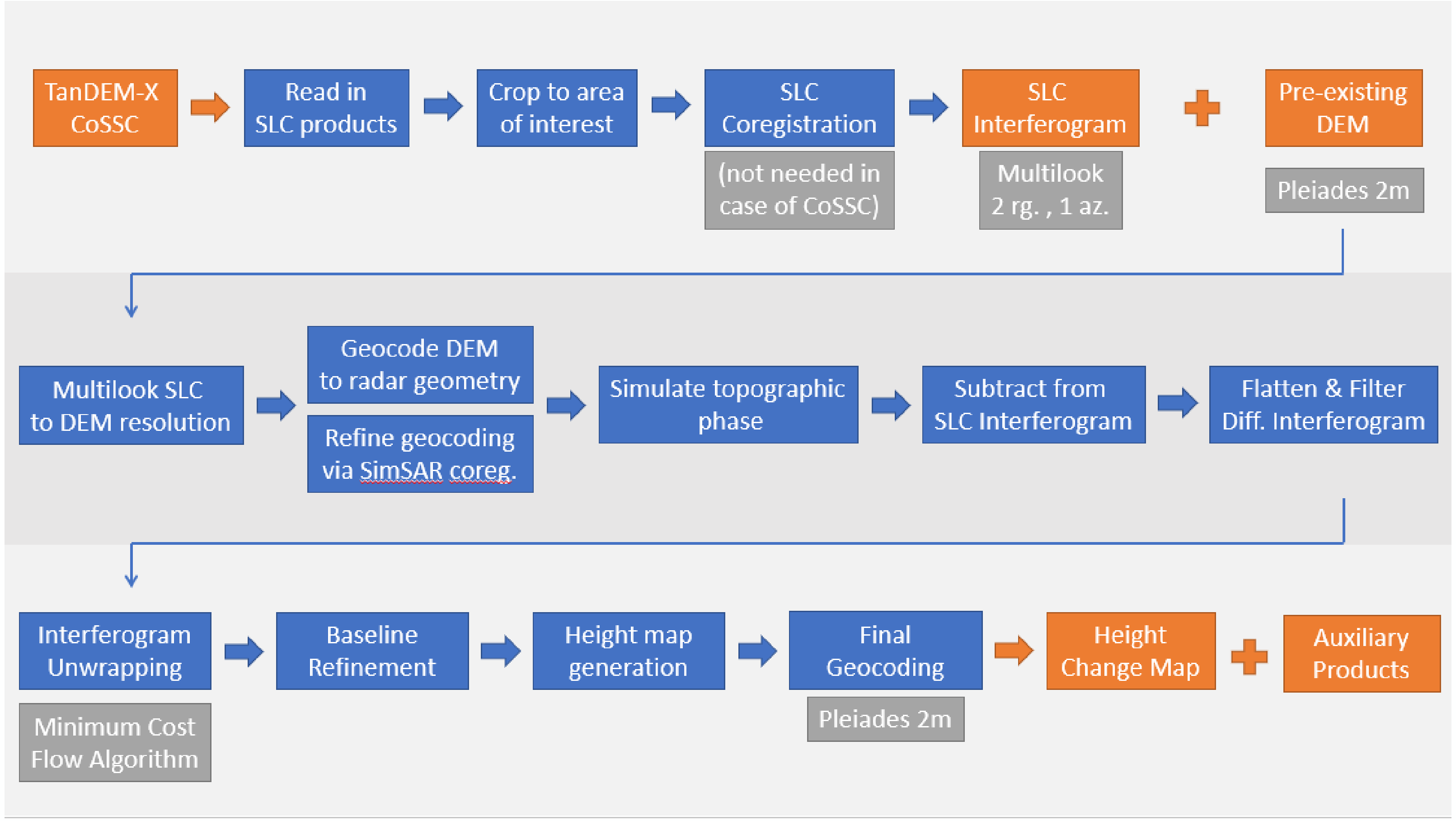
- Globally available DEM:
  SRTM 30m

- Best available DEM:
  Pleiades optical imagery (2014) at 2m, gap filled using oversampled Copernicus 30m[5]

Pleiades 2m results shown here

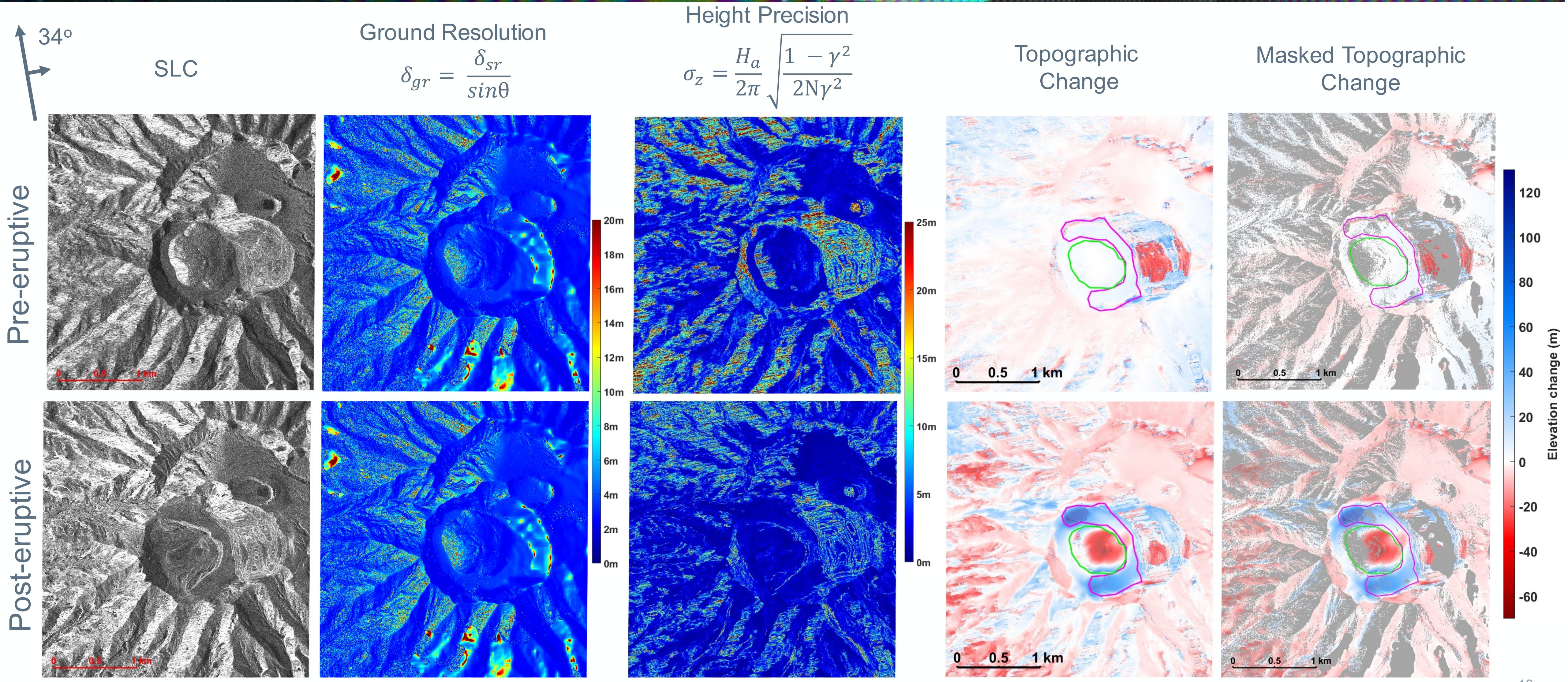


Processing Workflow – TanDEM-X

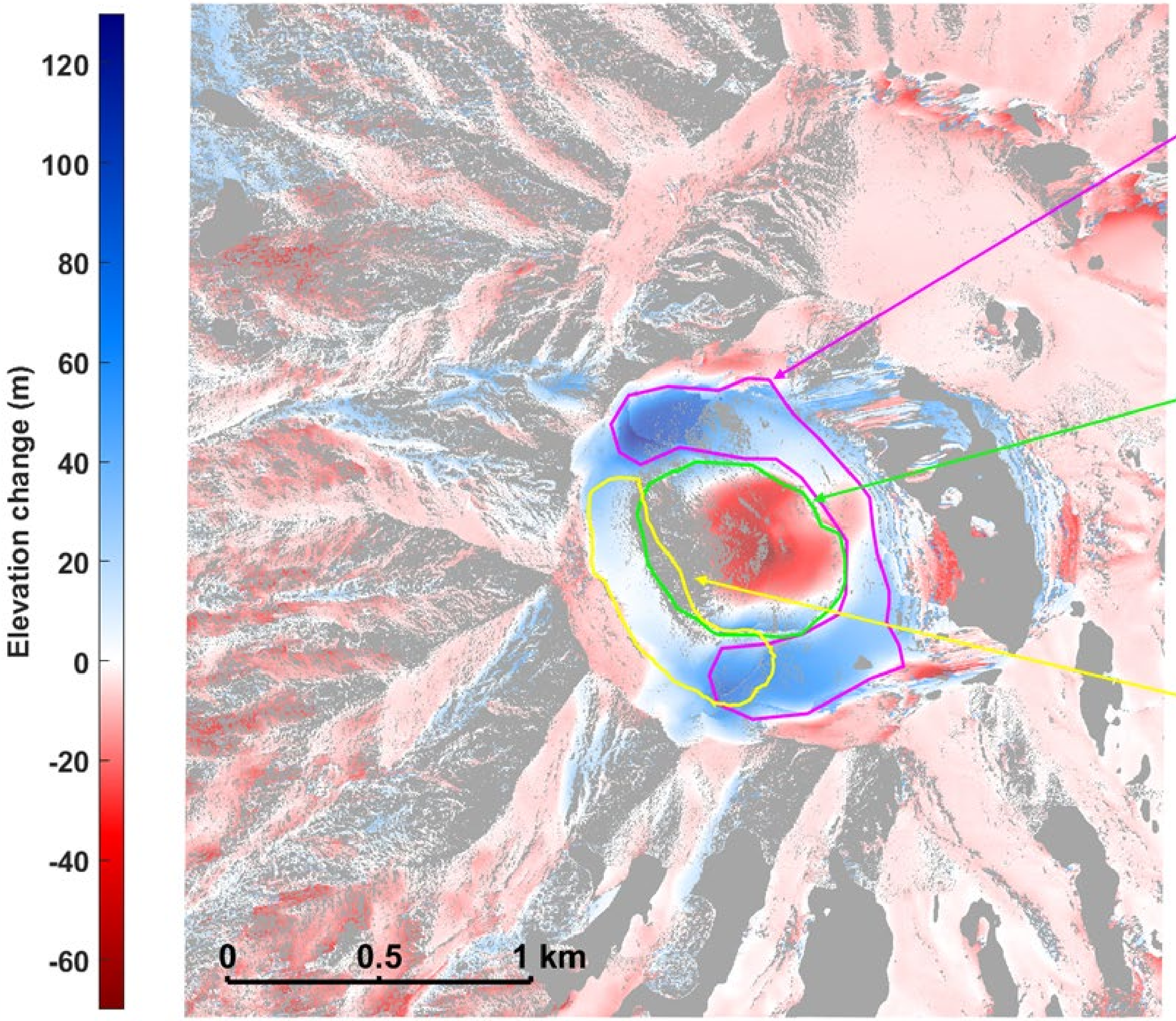


GAMMA Processing workflow for full-resolution TanDEM-X data.

St. Vincent – TanDEM-X TOC



St. Vincent – TanDEM-X TOC



Tephra deposits – two major ponds/slumps North and South of the new crater, with additional deposits along the Eastern edge.

New crater – significant depression occupying part of the old 1979 lava dome (destroyed during the eruption).

New lava dome formed between December 2020 to eruption completely destroyed – little topographic change visible.

TanDEM-X Subsampling to HRM20

GAMMA

TDX SLC

↓

Convert to MATLAB format → 2D FFT → FFT Shift → FFT Filtering → Inverse FFT

Optional FFT Decimation

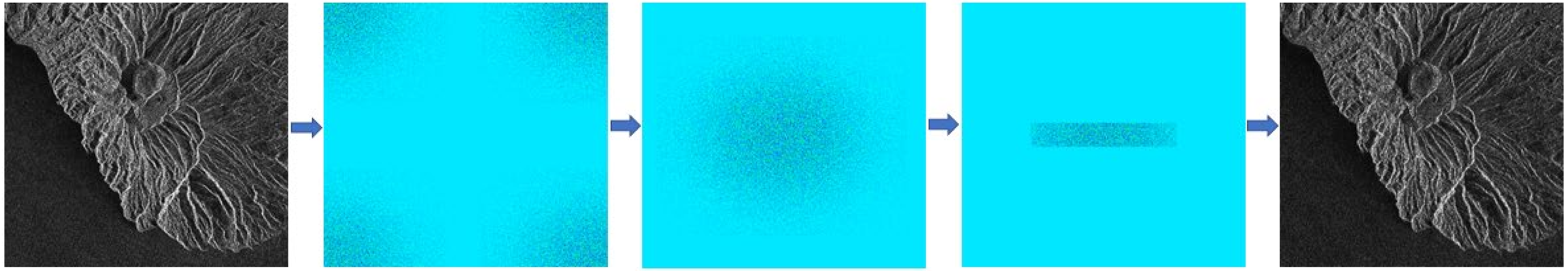
$$N_{rg}^{S1} = B_{rg}^{S1} \frac{N_{rg}}{f_s}$$

$$N_{az}^{S1} = B_{az}^{S1} \frac{N_{az}}{PRF}$$

↑

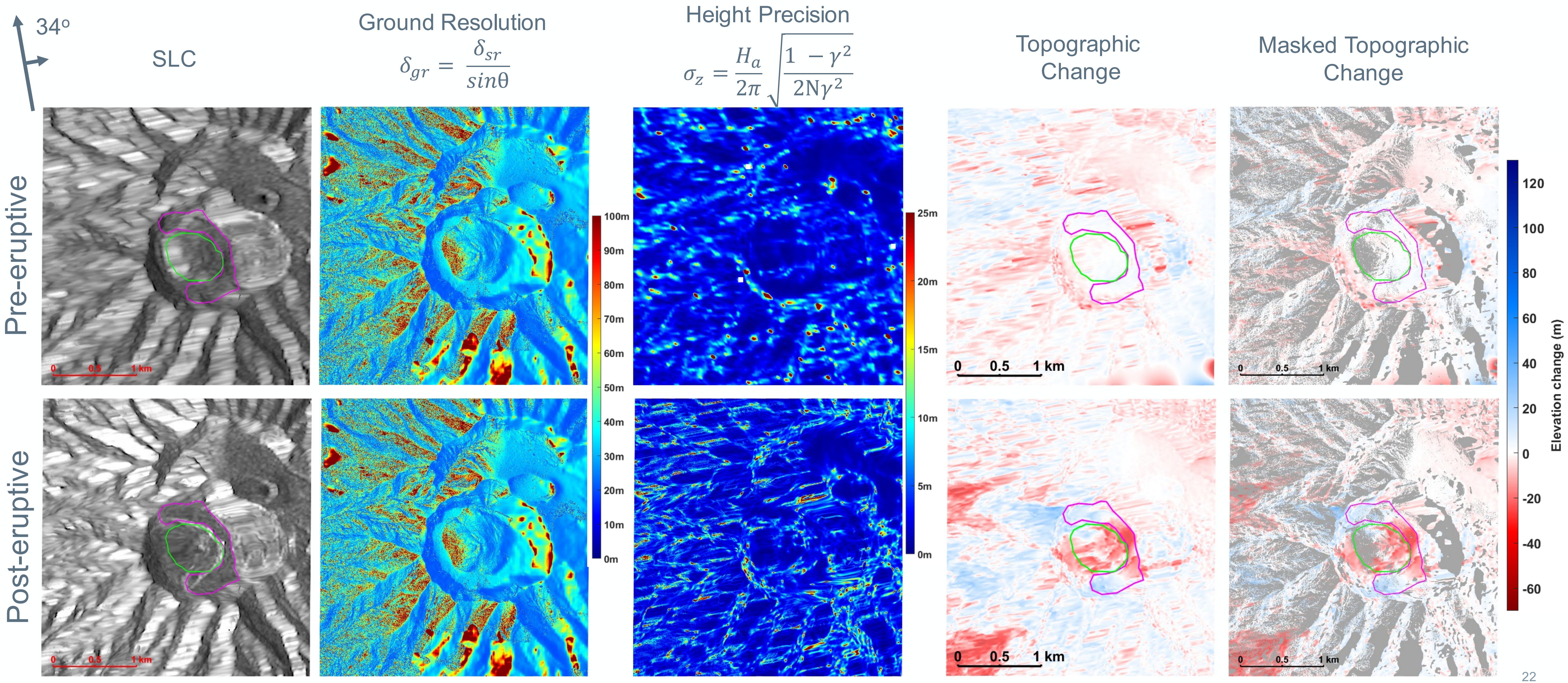
HRM SLC

GAMMA

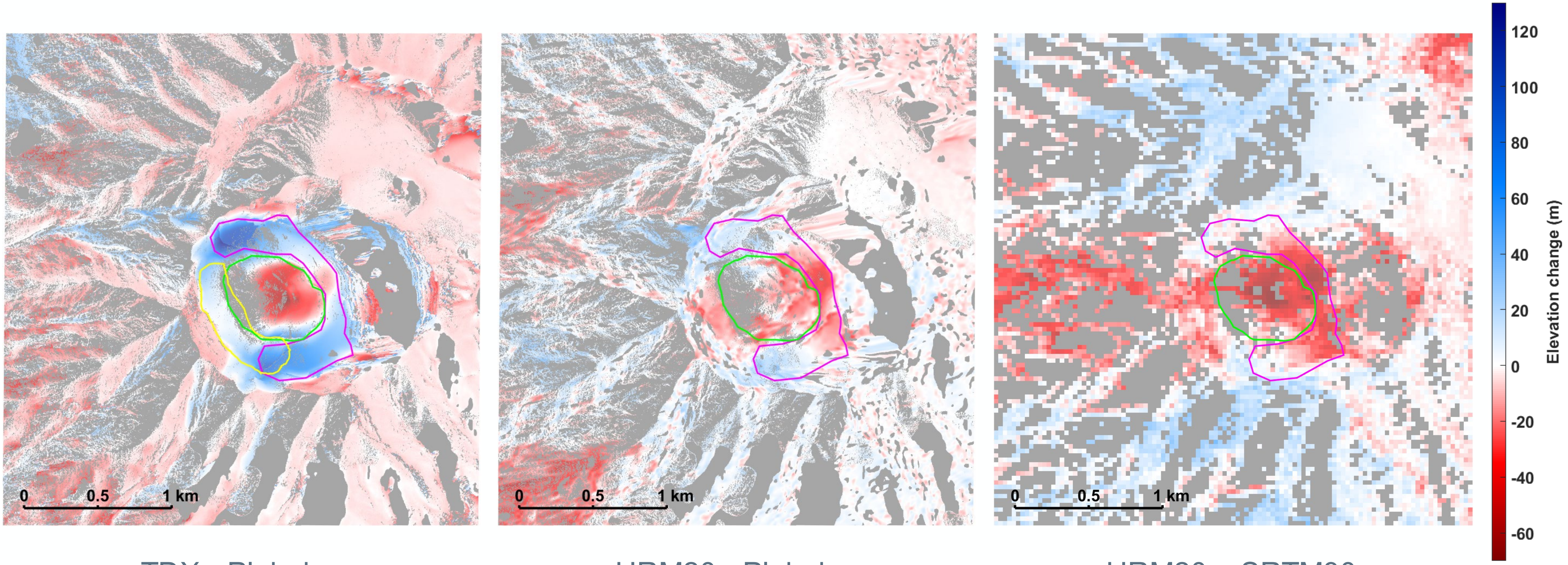


Original SLC → *Frequency Spectrum* → *Shifted Frequency Spectrum* → *Cropped Frequency Spectrum* → *Low-resolution Subsampled SLC*

St. Vincent – HRM20 TOC



TanDEM-X vs HRM20 TOC

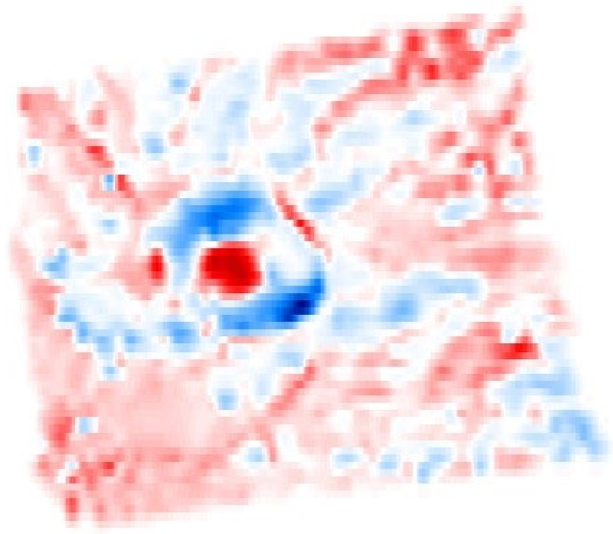


TDX - Pleiades

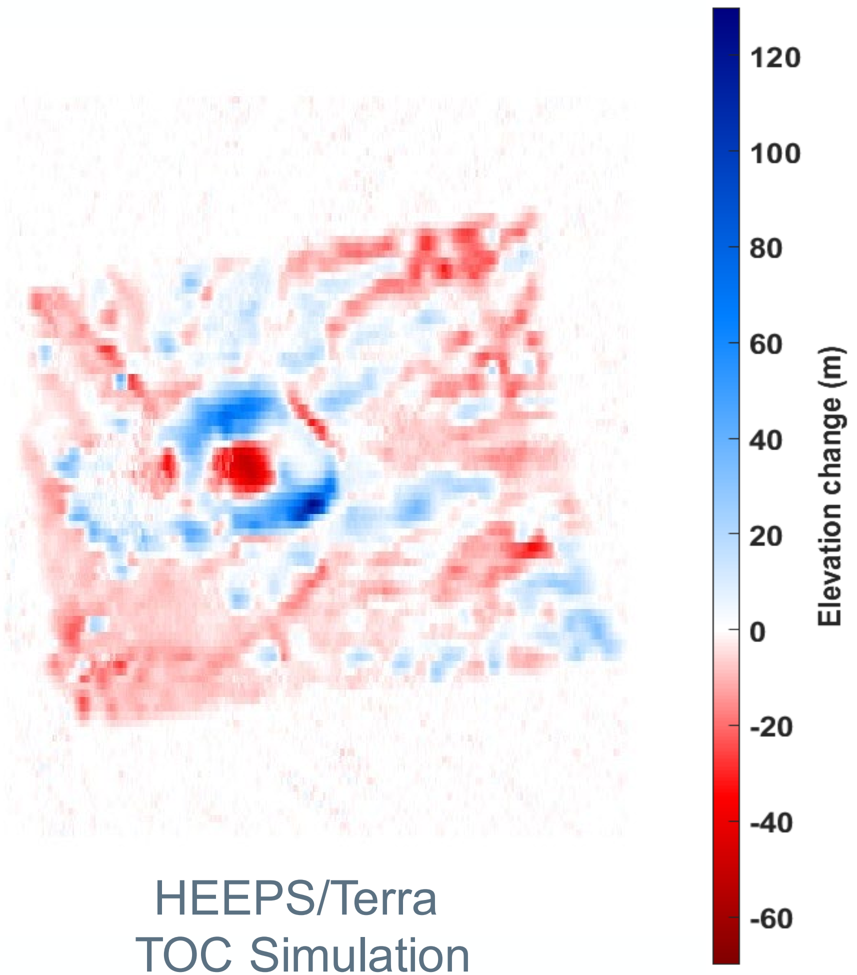
HRM20 - Pleiades

HRM20 – SRTM30

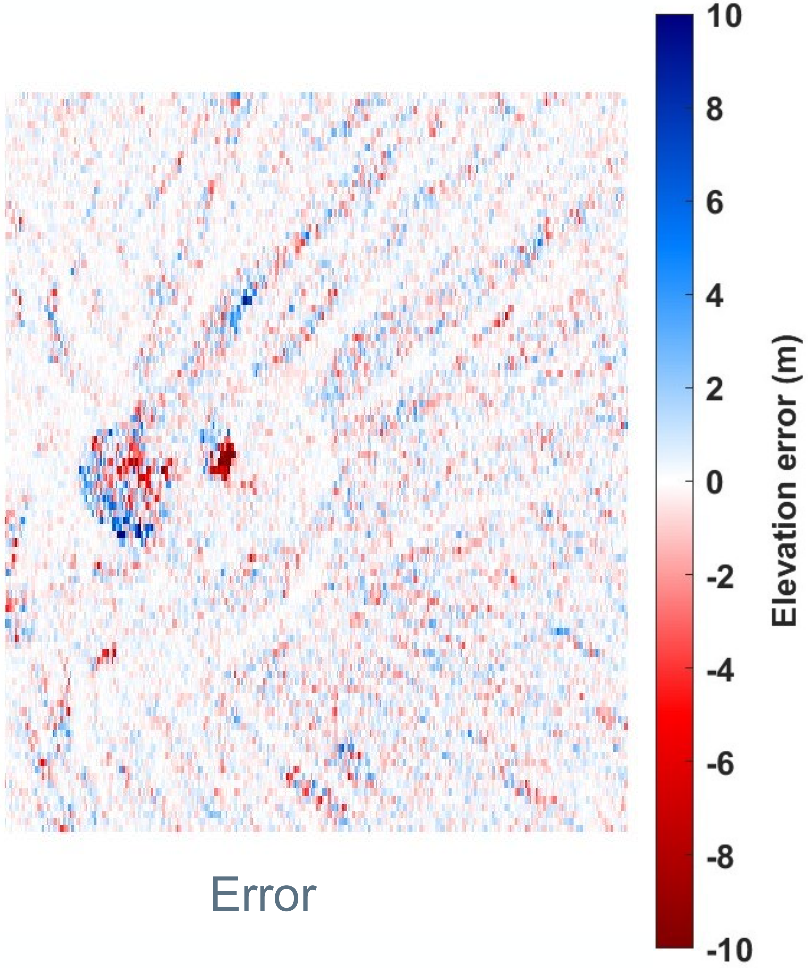
St. Vincent DLR HEEPS/Terra



TOC Ground Truth



HEEPS/Terra
TOC Simulation



Error

Further Studies

Phase I

May 2022 – October 2022

St. Vincent La Soufriere case study, development of HRM20 simulation

Phase II

August 2023 – January 2024

Improvement of HRM20 simulation performance, further case studies

Additional case studies:

- Reventador Volcano, Ecuador, exhibiting evolving lava flows[6]
- Fuego Volcano, Guatemala, exhibiting pyroclastic flows[7]

Different latitudes!

Different topographic change!

Thank you for your time!

References

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[4] Joseph, E.P., Camejo-Harry, M., Christopher, T. et al. Responding to eruptive transitions during the 2020–2021 eruption of La Soufrière volcano, St. Vincent. Nat Commun 13, 4129 (2022). https://doi.org/10.1038/s41467-022-31901-4

[5] Grandin, R., Delorme, A., 2021. La Soufriere Volcano (Saint Vincent) – Fusion of Pleiades (2014, 2 m) and Copernicus (2018, 30 m) Digital Elevation Models. Dataset on Zenodo. doi:10.5281/zenodo.4668734.

[6] Arnold, D. W. D., Biggs, J., Anderson, K., Vallejo Vargas, S., Wadge, G., Ebmeier, S. K. Mothes, P. (2017). Decaying lava extrusion rate at El Reventador Volcano, Ecuador, measured using high-resolution satellite radar. Journal of Geophysical Research: Solid Earth, 122, 9966–9988. https://doi.org/10.1002/2017JB014580

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Abstract

Harmony has been selected by ESA as the 10th Earth Explorer Mission, with an expected launch date in 2029. Comprising of two satellites carrying passive (receive-only) Synthetic Aperture Radar (SAR) instruments as well as Thermal-Infrared Spectrometers (TIR), Harmony will operate in tandem with Sentinel-1 and monitor changes in the Earth's surface and cryosphere, as well as monitor ocean surface conditions.

Harmony will revolutionise the way we measure the rapid topographic changes associated with volcanic eruptive activity. More than 800 million people across the world live within 100km of a volcano and monitoring is key to mitigating the threat of volcanic eruptions to human life. Maps of surface displacement and topographic change are vital for understanding the geometry and activity of underlying magma storage areas and the stability of steep volcanic edifices. Harmony will provide such high temporal-resolution views of topographic change and yearly DEM updates at actively erupting volcanoes. This will improve the modelling and forecasting of volcanic dome growth, collapse, and emplacement of volcanic flows, all of which can pose significant threat to nearby populations.

As part of the Harmony science studies, we have investigated a number of recent volcanic eruptions and the associated topographic change with the aim of providing both ground-truth topographic change measurements as well as simulating the resolving capabilities of Harmony. Interferometric pairs of TanDEM-X high-resolution SAR images were processed to produce high-resolution digital elevation models (DEM) which were used to assess topographic change after volcanic eruptive activity. These SAR images were then subsampled to simulate the imaging resolution achievable by the Harmony mission, and the subsampled imagery was in turn similarly processed to produce digital elevation models and topographic change maps indicative of Harmony's capabilities.

Our case studies include a) the 2020-2021 eruption of St. Vincent La Soufriere, where the explosive eruption completely destroyed the lava domes and significantly changed the crater topography; b) the Reventador volcano in Ecuador, which has been continuously erupting since 2008, producing tens of lava flows; and c) the June 2018 explosion of the Fuego volcano in Guatemala, which caused pyroclastic density currents that destroyed the nearby town of San Miguel Los Lotes. These three case studies present variations in both local terrain and volcanic hazard that can provide a broad picture of Harmony's resolving capabilities.

These studies have allowed us to better understand and quantify the effects of topography on the resolution and accuracy of Harmony's interferometric measurements. In areas of steep terrain (such as most volcanos), layover and shadow artefacts often occur. Layover manifests as compression/foreshortening along steep slopes facing the radar line of sight, while shadowing refers to the complete lack of a return signal from parts of the terrain obscured from the radar beam's illumination. These lead to artefacts and erroneous data appearing in the generated interferograms, which in turn complicate and introduce errors during the unwrapping process (whereby phase cycles in the interferogram are re-interpreted as continuous phase change directly translatable to displacement in physical units). Identifying and modelling the effects of local topography on the produced interferograms, as well as identifying the optimal processing and unwrapping techniques for such locales have allowed us to identify areas of particular challenge for Harmony.

Additionally, the Harmony measurements simulated during this project via sub-sampled TanDEM-X data have also been compared to the Harmony end-to-end system simulator developed by the German Aerospace Agency (DLR); this has proven beneficial to the validation and further development of both systems. Finally, the full-resolution TanDEM-X -generated topographic change maps themselves serve as valuable input to the DLR simulator, as it is dependent on ground-truth data of topographic change in order to simulate Harmony measurements.