esa

FRINGE 2021

SUMMARIES AND RECOMMENDATIONS

CONTENTS

1. Introduction and background

This document contains the Session Summaries and Recommendations of the Fringe 2021 Workshop, "Advances in the Science and Applications of SAR Interferometry and Sentinel-1 InSAR" that was organised on 31.05 – 04.06 2021 at ESA-ESRIN (online). The contents have been compiled by the session chairpersons, and it has undergone minor editing in order to improve readability and clarity.

2. Contributors

Scientific Committee and contributors

Cigna Francesca, National Research Council (CNR)

Costantini Mario, e-GEOS, an Italian Space Agency / Telespazio company

Crosetto Michele, CTTC

De Zan Francesco, DLR (German Aerospace Center)

Dehls John, Geological Survey of Norway

Doin Marie-Pierre, CNRS

Duro Javier, DARES

Ebmeier Susanna, University of Leeds

Engdahl Marcus, ESA

Ferretti Alessandro, TRE ALTAMIRA

Fielding Eric, Jet Propulsion Laboratory, Caltech

Furuya Masato, Hokkaido University

Hanssen Ramon, Delft University of Technology

Holley Rachel, CGG Satellite Mapping

Ilieva Maya, UPWr

Jónsson Sigurjon, King Abdullah University of Science and Technology (KAUST)

Ketelaar Gini, Nederlandse Aardolie Maatschappij B.V.

Kubanek Julia, ESA

Larsen Yngvar, NORCE

Lasserre Cécile, CNRS

Lu Zhong, Southern Methodist University

Lundgren Paul, Jet Propulsion Laboratory

Mouginot Jeremie, CNRS

Nagler Thomas, ENVEO IT GmbH

Nico Giovanni, Consiglio Nazionale delle Ricerche (CNR)

Pasquli Paolo, sarmap sa

Pinel Virginie, IRD-ISTerre

Rignot Eric, University of California Irvine

Rocca Fabio, Politecnico di Milano

Rommen Bjorn, ESA

Rouyet Line Norce, Norwegian Research Centre

Strozzi Tazio, Gamma Remote Sensing

Sudhaus Henriette, Kiel University

Van Leijen Freek, Delft University of Technology

Wegmuller Urs, Gamma Remote Sensing AG

Zebker Howard, Stanford University

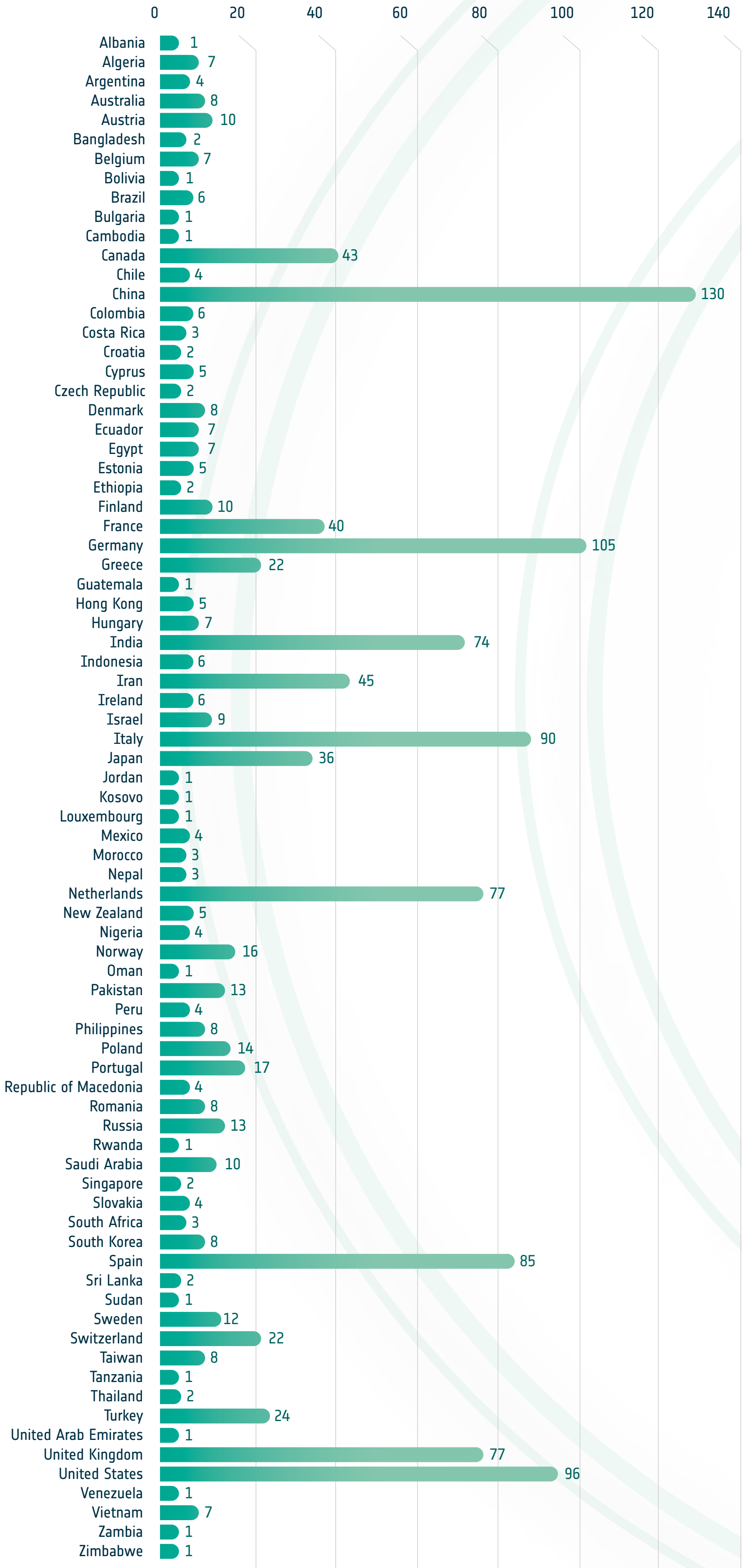
Editors (ESA): ***Marcus Engdahl, Magdalena Fitrzyk, Thibault Taillade***

3. List of acronyms

ARD	Analysis Ready Data
CSK	COSMO - SkyMed
DEM	Digital Elevation Model
DOY	Day Of Year
DS	Distributed Scatterers
ECV	Essential Climate Variable
EE10	Earth Explorer 10
EW	Extra Wide Swath
GNSS	Global Navigation Satellite System
GRD	Ground Range Detected
InSAR	Interferometric Synthetic Aperture Radar
LOS	Line Of Sight
MIMO	Multiple Input Multiple Output
ML	Multilooking
MRD	Mission Requirements Document
NESZ	Noise-Equivalent-Sigma-Zero
NG	Next Generation
NISAR	NASA-ISRO Synthetic Aperture Radar
OT	Offset Tracking
POLINSAR	Polarimetry Synthetic Aperture Radar (SAR) Interferometry
ROSE-L	Radar Observing System for Europe - L-Band
S1	Sentinel-1
S1 NG	Sentinel-1 Next Generation
SAOCOM	Satélite Argentino de Observación COn Microondas
SAR	Synthetic Aperture Radar
SDG	Sustainable Development Goal
SIMO	Single Input Multiple Output
SLC	Single Look Complex
SP-InSAR	Single-pass Interferometric Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
SWE	Snow Water Equivalent
TOPS	Terrain Observation by Progressive Scans
TS	Time Series
TDX	Tandem-X

4. Conference Statistics

The conference gathered **1296 participants** from **79 countries** (number of registrations to the workshop).



5. Advances In InSAR theory & methodological innovations

Interferometric SAR, or InSAR, allows with its coherent nature to accurately measure the electromagnetic travel path variations between the satellite and the earth surface. In the last decades, and more recently with the launch of Sentinel-1, InSAR has dramatically extended the ability of scientists to monitor earth surfaces and surface motions associated to natural phenomena or human activities. Unlike other techniques that rely on in-situ measurements over a few points, this technique has proven to be essential at remote locations and enables to obtain unprecedented large-scale information products globally.

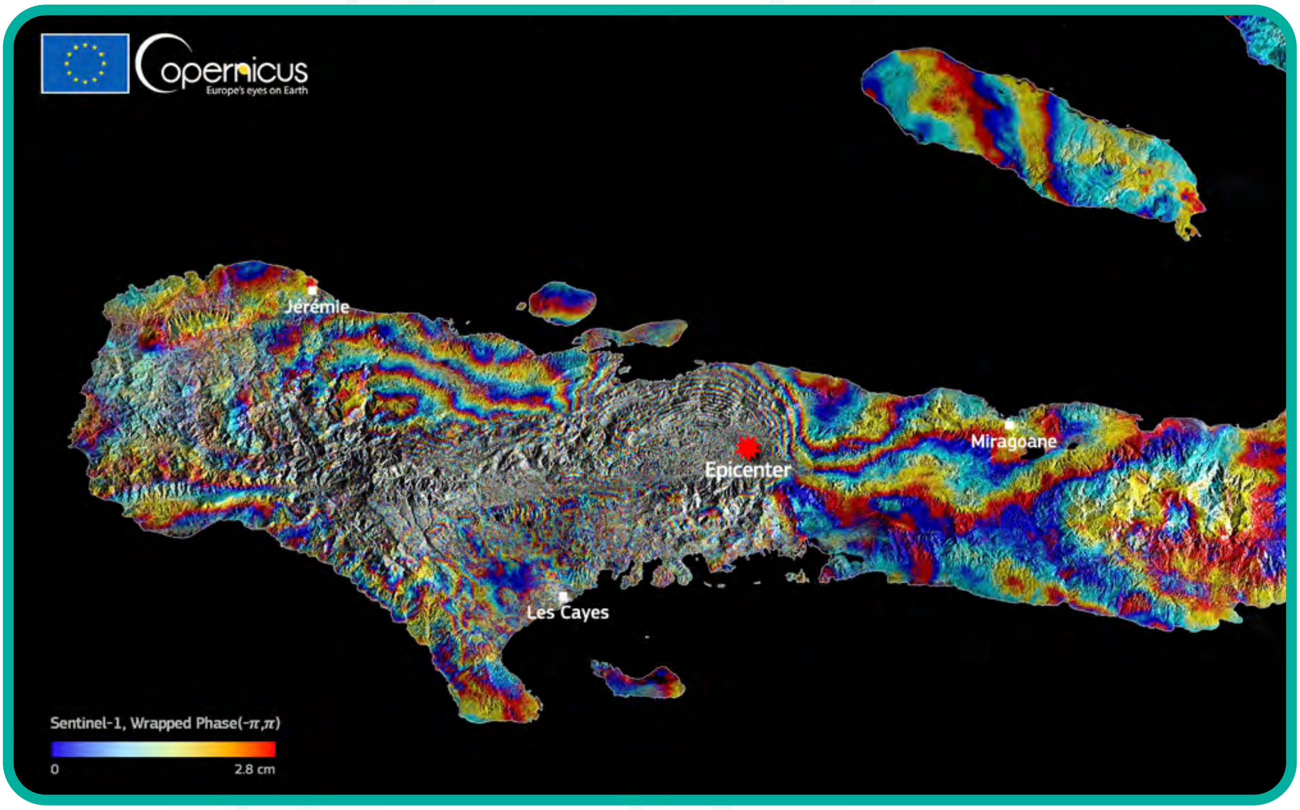


Figure 1: Land deformation interferogram generated using radar data from the Copernicus satellite Sentinel-1 taken on 3 and 15 August 2021 following a 7.4 magnitude earthquake in Haiti. Processed at INGV GeoSAR Lab.

This first group of three sub-sessions focused on the most recent theoretical and methodological advances in the field of InSAR theory and methods.

Advances in *InSAR* Theory & Methodological Innovations
SESSION I

Main topics discussed:

TOPIC 1 : Bias in InSAR-derived velocity maps

There is a fading signal that compromises the reliability of InSAR-derived deformation velocity maps. Two methods to mitigate this issue has been proposed - long term triangulation (Ansari), or measuring the bias and correct it (Zheng)

TOPIC 2: Methods for predicting and correcting phase unwrapping errors

Very effective methodology to identify areas where fast terrain uplift due to rainfall could lead to phase unwrapping errors was presented. Proposed methodology used simple neural network based on DOY, rainfall, soil type, to group terrain surfaces in lots, disjoint but with similar behaviour. This allowed to identify where phase unwrapping errors might have happened, and where there is a need to correct for them.

The problem of phase unwrapping errors, caused by other factors such as Ionosphere, troposphere, terrain slope in similar non-connected terrains was also presented in this session. Proposed methodology to mitigate this issue was based on the identification of cycle skips and their correction.

TOPIC 3: Dithered SA

The random dithering of the SAR pulses has been proposed, to widen the interpulse interval, at random. The impact on the interferometric coherence is proved to be small while the widening of the swath is significant.

Main recommendations

Regarding the bias in InSAR-derived velocity maps it has been proposed to take into account the proposal "A Proposal for Interferometric Time Series Product with Reduced Stochastic and Systematic Phase Errors" where Ansari et al. recommend a new intermediate product level for InSAR, namely the reconstructed consistent interferometric phase series

Product proposed by Ansari et al. would:

- Contain the consistent physical signals such as, but not limited to, atmospheric variations and surface displacements.
- Significantly reduce the interferometric phase bias and variance.
- Reduce the amount of interferometric data from the original pairwise interferograms within the data stack to a time series of higher quality and, optionally, subsampled interferograms.
- Ease the data transfer and provide a unified input to the user community.
- Enhance the reliability of InSAR for displacement analysis specifically for the retrieval of deformation velocity maps.

It was also recommended to study new SAR systems, like satellite formations (MIMO and SIMO), dithered SAR, that trade additional noise, likely to be acceptable for interferometric applications, with extended swath, higher reliability, lower costs.

Advances in InSAR Theory & Methodological Innovations *SESSION II*

Main topics discussed:

TOPIC 1: Use of range offsets to measure cm-level displacements

- The use of range offsets rather than phase for displacement measurement was presented. The main advantage is that primariliy no phase unwrapping needed. Disadvantages: requires much averaging to reduce errors to cm level. It has been proved that using the presented method for widespread and constant deformation rates it is possible to accurately map tectonic displacements. Map was accurate at the 1.5 cm level, could in theory approach mm level errors.

TOPIC 2: 1-D measurements and 3-D displacements

- Two of the presented papers examined mapping from 1-D LOS data to 3-D displacements.
- The fist solution was to use geophysical model constraints to reconstruct 3-D interpretations.
- Other paper presented examples from the literature where the authors are using loosely worded descriptions of how to overly interpret results - some were just unclear, others were incorrect.

Recommendation
researchers shall more carefully and fully explain results and assumptions.

TOPIC 3: Machine learning to find anomalies (events)

- Machine Learning approach to find anomalies or events in InSAR sequences was demonstrated. Presented method estimates background noise characteristics, deviation finds events. The conclusion is that these kind of solutions are needed as data volumes are too large for human interpretation these days.

TOPIC 4: Noise models

- Progress on estimation of the covariance matrix for sequences of InSAR measurements was presented.
- Better characterization of the noise in these data.
- Need such a model to find the right weight matrix for many inverse methods.

Advances in InSAR Theory & Methodological Innovations
SESSION III

Main topics discussed:

- It has been presented that the amplitude of the scatterers we use for monitoring displacements can really improve analysis and interpretation.
- It has been also shown that contextual information (in space or time) needs to be connected to the scatterers we use, and how a standardized database system can help querying.
- It has been also addressed that no scatterer is the same, and that we need to have agile methods to find the right model for each scatterer. He proposed using the Fuzzy Entropy for this purpose.
- Combination of InSAR information from different sensors, by clustering sets of displacements to find a unique solution was discussed.
- One author addressed the extraction of information from phase closures, and argued that phase closures are not special, but they are common, and contain useful information to be extracted.
- More and more InSAR products seem to focus on information from single scatterers, or single sets of scatterers, instead of the wide-area processes. This reshapes our view on the information products.

Main recommendation

It does not make sense for ESA to move from providing SAR SLC's and orbits to providing advanced InSAR products, such as interferograms. The reason is that there is not one single product that can be generated but a multitude of products. It depends on the application. The SLC's are the ingredients, but with the same ingredients we can make many recipes for meals.

6. Data products and services

Providing EO data products and services based on high-quality satellite data processing is one of the main elements supporting science, industry, and significant societal goals, such as Sustaibable Development Goals (SDG). One of the main priorities for stakeholders is to bring the potential of EO data to the end users through value-added services and applications, as well as the availabilty of satellite data products in a form of Analysis Ready Data (ARD) – processed for the easy extraction of information by non-expert users.

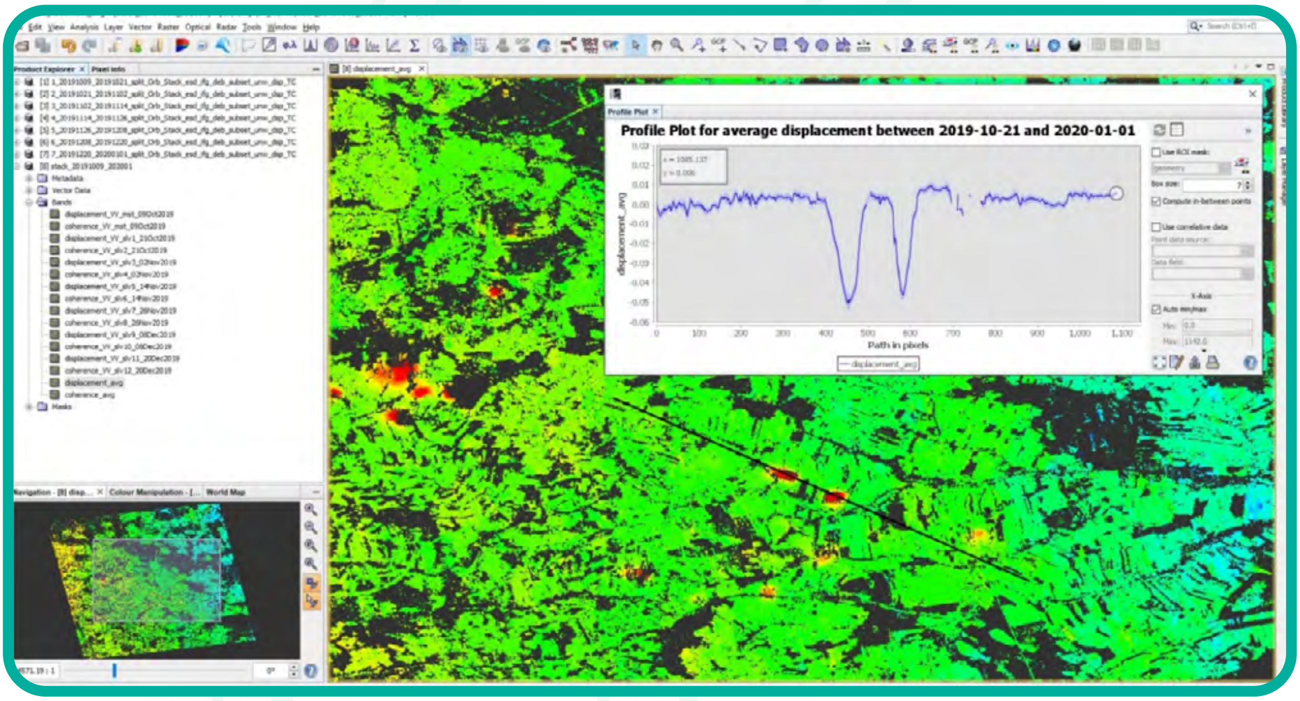


Figure 2: Example of displacement product generated with SNAP in the metropolitan area around Katowice, Poland.
Source: https://step.esa.int/docs/tutorials/S1TBX%20TOPSAR%20Interferometry%20with%20Sentinel-1%20Tutorial_v2.pdf

During the session some interesting solutions regarding SW, services and ARD were discussed:

- Updates on the continuous developments of ESA SNAP/Sentimel-1 Toolbox was presented.
- Different projects focused on development and provision of Analysis Ready Data were also demonstrated.
- Examples of interferometric ARD products were presented beside more conventional amplitude ones.
- Examples have been shown of higher-level products (coherence maps, interferograms, displacement maps) obtained with simple operations on pre-processed data cubes.
- Different variations have been shown, working on single bursts, full-frames, providing also interferograms, unwrapped products, time-series,....

The main discussion during the technical session was about how far these products are of interest and simplify users activities and how much high-level products can be accurate and reliable. Different opinions have been discussed.

Main recommendation

It has been been proposed to ESA to consider provision of higher-lever Interferometric ARD layers and access to single Sentinel-1 bursts.

7. ATMOSPHERE AND IONOSPHERE

This session focused mainly on the correction of interferometric products for the influence of the ionosphere and troposphere. In the main conclusions, the community emphasized that for the ionosphere the GNSS models are very helpful, especially at C-band, but we should not forget the top part of the ionosphere (we can use the GNSS on board for that). This issue is more challenging for L-band. Split-spectrum difficulties with Quasi-quad-pol mode for NISAR were mentioned.

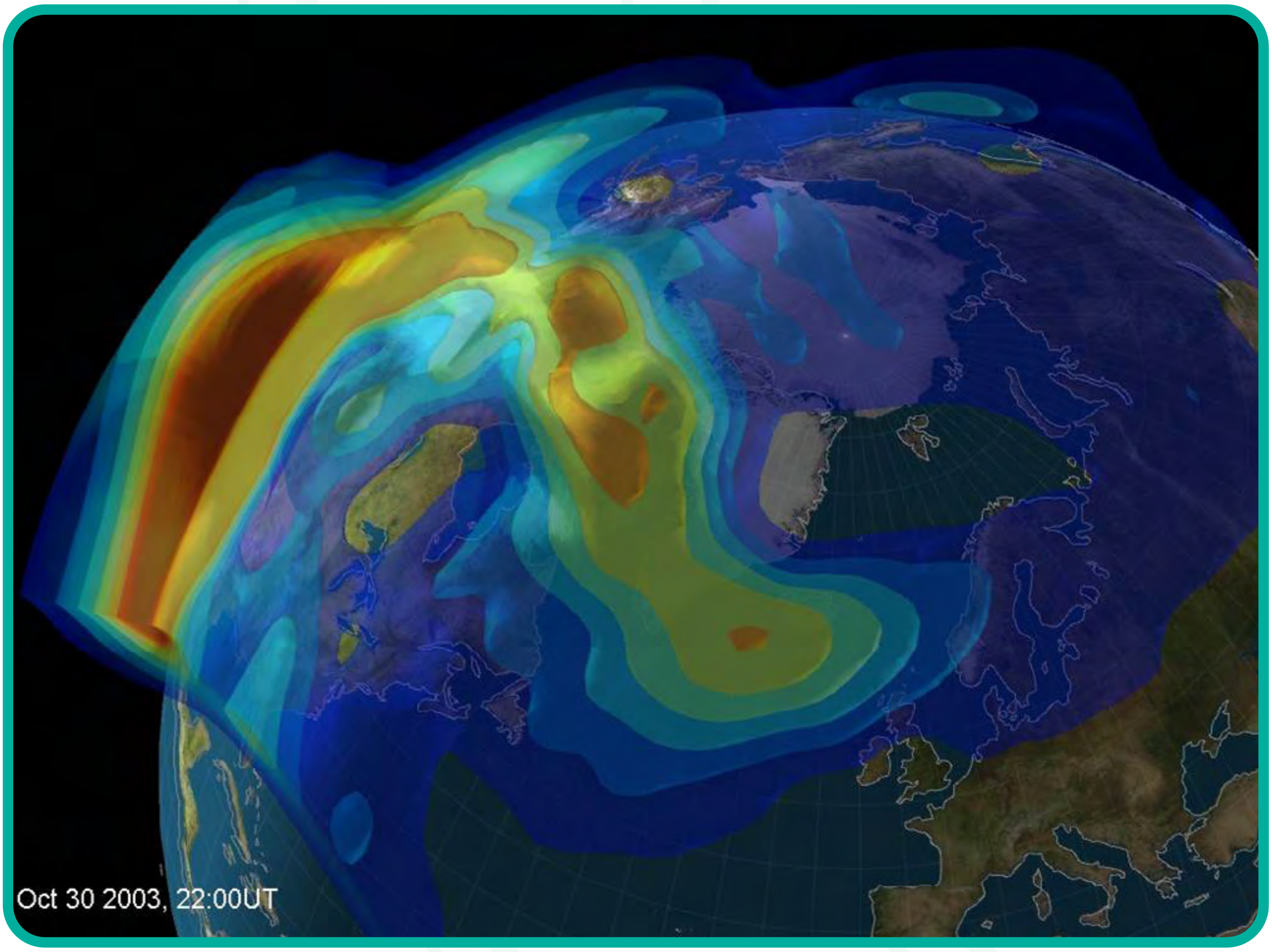


Figure 3: Stormy Ionosphere.
Source: https://www.esa.int/Applications/Navigation/Radio_astronomers_focus_on_ionosphere_for_sharper_satellite_navigation

For the troposphere, the global weather models to correct SAR is well-established technique. However there are possible dispersive effects with heavy rain at L-band - physical nature to be clarified looking at high frequencies, C & X-band. It shall be investigated how to improve offset estimation for ingestion into weather models

For all corrections (troposphere, ionosphere, tides, instrument) - decimeter level for Sentinel-1 or better for absolute geolocation

Main findings and recommendations

- Do not adopt Quasi Quad Pol if the goal is to apply split-spectrum for ionosphere mitigation (NISAR)
- If Quasi Quad Pol is adopted anyway, apply split spectrum to main bandwidth (NISAR)
- Extended Time Annotation Dataset (ETAD) would help both geolocation and interferometry (for Sentinel-1).
- Consider generation of blindly co-registered products for C-band Sentinel-1.
- Investigate solutions for L-band absolute geolocation (and phase) related to the ionosphere.

8. Ice and snow I&II

Ice and Snow dynamics are critical components and involve complex interactions with the atmosphere, cryosphere, hydrosphere, and lithosphere, with consequences on polar regions and, more generally, the Earth system. Monitoring processes with high revisit time and large scale such as ice velocity, grounding lines movement, ice shelfs and permafrost dynamics have been made possible by remote sensing technologies such as InSAR (DInSAR).

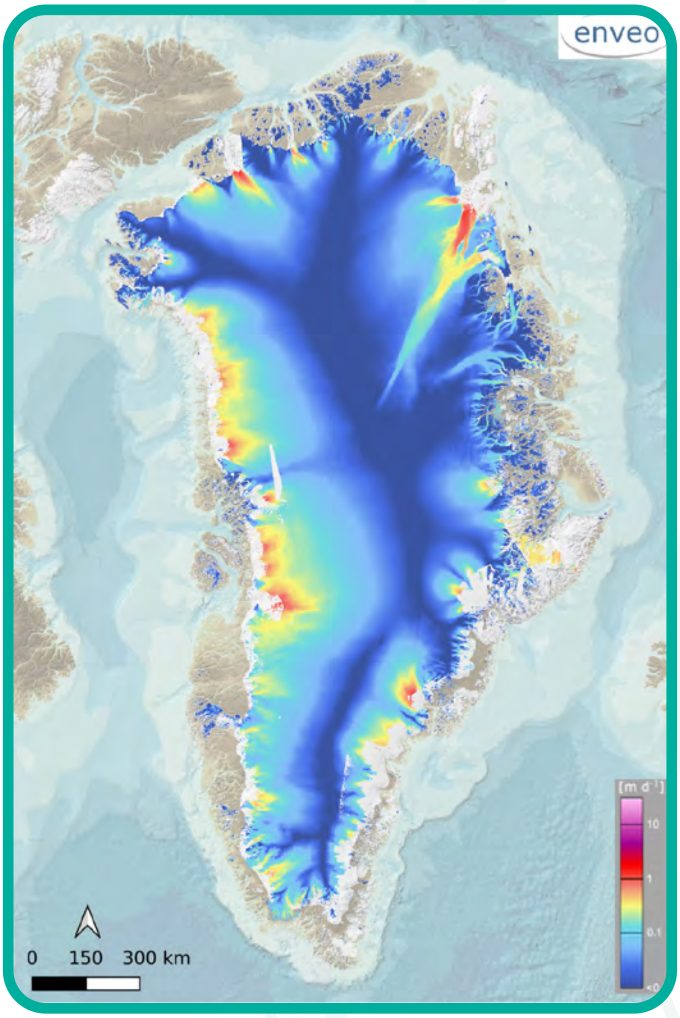


Figure 4: Greenland-wide ice velocity mosaic based on DInSAR applied to Sentinel-1 6-day image pairs acquired during the winter campaigns between 2017 and 2020. SAR data was processed by ENVEO.

Source: https://eo4society.esa.int/2021/07/01/a-breakthrough-in-the-quality-of-sentinel-1-ice-velocity-products/

The main topics discussed in the two "Ice and Snow" sessions were:

TOPIC 1: Ice velocity

- Sentinel-1 TOPS INSAR ice velocity, Greenland ice sheet wide InSAR map.
- Synergistic use of OT & INSAR (various SAR sensors) for Antarctica ice sheet wide velocity map.
- Single / Multi-sensor ice velocity maps (SAR, optical) for mountain glaciers.
- Preparations of ice velocity sheet monitoring with L-Band SAR.

TOPIC 2: Grounding lines

- Delineation by applying Deep Learning on InSAR data.
- Generation of time series of grounding lines for Antarctica, by INSAR from different SAR sensors.

TOPIC 3: Ice shelf crack propagation and calving

- Progress in automatic delineation using phase gradients in Sentinel-1 InSAR data.

TOPIC 4: Surface Elevation Change / Mass Balance

- Global inventory of Glacier SEC from TanDEM-X and SRTM, converted to Mass Balance.
- Modelled from ice velocity data.

TOPIC 5: Permafrost

- Time series of thaw subsidence / frost heave and coupling with modelling.
- InSAR mapping of key indicators related to ECV Permafrost.
- Permafrost degradation in mountain areas with InSAR.

TOPIC 6: Snow Water Equivalent

- Feasibility of multi-frequency InSAR SWE retrieval.
- Feasibility of POLINSAR for Snow depth and SWE retrieval with TDX data.

Main findings and recommendations

There is a gap in monitoring of fast processes using InSAR (tidal forcing of grounding lines, calving/cracking, velocity of outlet glaciers). This is not possible with current sensors, as short repeat pass data needed (1 day or even sub-daily). Currently, only CSK can offer 1 day repeat data.

Recommendation: Extend S1 systematic acquisitions for land cryosphere:

- Continuous full coverage of Antarctic margins with 6 days repeat to support retrieval of ice sheet parameters including ice velocity (as basis for ice discharge), grounding line, cracking/calving events. On a campaign basis (polar winter), crossing orbits should be acquired for InSAR velocity.
- Full coverage of Greenland and Arctic Ice caps by crossing orbits during winter campaigns for InSAR velocity.
- 6-days repeat-pass in for selected permafrost areas (e.g. Siberia).
- R&D studies to enhance synergistic use of offset tracking and InSAR for large scale monitoring.

Recommendation: Coordination of systematic acquisitions of current L-band SAR sensors for ice sheets, glaciers, permafrost regions and mountain areas with seasonal snow, and access to archives.

Recommendation: Study the retrieval of SWE using INSAR, investigate temporal decorrelation due to snow conditions / accumulation at C- and L-Band. Initiate R&D studies for SWE retrieval with access to suitable time series of repeat pass L-Band data (e.g. SAOCOM A&B), take synergy with S1 into account.

There is a gap in systematic observation of high resolution surface elevation change for outlet glaciers of ice sheets and mountain glaciers. Currently this is done by TANDEM-X, but continuation of this mission is not planned.

Recommendation: to initiate R&D studies to investigate the feasibility of C-band SP-InSAR to fill this gap (close formation of S1A & C).
Recommendation: Observations of 3D ice velocity with specific S1 acquisition campaign can be expected from EE10 candidate Harmony. But bistatic backscattering from different surfaces needs to be further investigated in preparation of EE10 candidate Harmony.

Recommendation: The community recommends operating the S1 A/B/C constellation with 1/5/6 days repeat. The 1 day pair will have an significant improvement of coherence and will also allow to monitor fast changing processes not observable by 6 or 12 days repeat. This constellation is seen as a game changer and a big step forward in monitoring land cryosphere.

Recommendation: It is also recommended to evaluate C-Band SP-INSAR capabilities for several months during the commissioning phase of S1C, this will provide important knowledge for preparation of Sentinel-1 NG and other future SAR missions.
Recommendation: The 4/4/4 constellation improves temporal sampling, but it will have no (or only minor) impact on coherence and retrieval of parameters and quality of the products.

Recommendation: Constellation of S1 and ROSE-L: Almost simultaneous acquisition of S1 and ROSE-L is the preferred constellation (S1 and ROSE-L in close formation). Dual frequency C/L-band data will improve the retrieval of ice and snow parameters and synergistic use will allow the development of significantly improved products and services.

Recommendation: Initiate R&D studies to develop concepts and algorithms for exploiting S1 / ROSE-L synergy.
Recommendation: SAOCOM A&B (8 days repeat) and ALOS-2 (14 days repeat pass) has similar repeat pass interval as ROSE-L with 6 / 12 days. Enable access to the SAOCOM and ALOS-2 archives for polar and mountainous areas.
Recommendation: Initiate R&D studies on coherence and other InSAR applications for ice and snow in preparation of ROSE-L, NISAR.

Recommendation: Investigate the potential of the opposite imaging geometry S1 (right looking) and NISAR (left looking) applying InSAR for various land cryosphere applications.

9. Land cover and vegetation

Land cover, land use and forest cover are considered priorities with direct impacts on different societal levels and area such as agriculture, ecosystems, and biodiversity. Land cover classification and vegetation mapping are also important indicators of the interaction between humans and the natural environment.

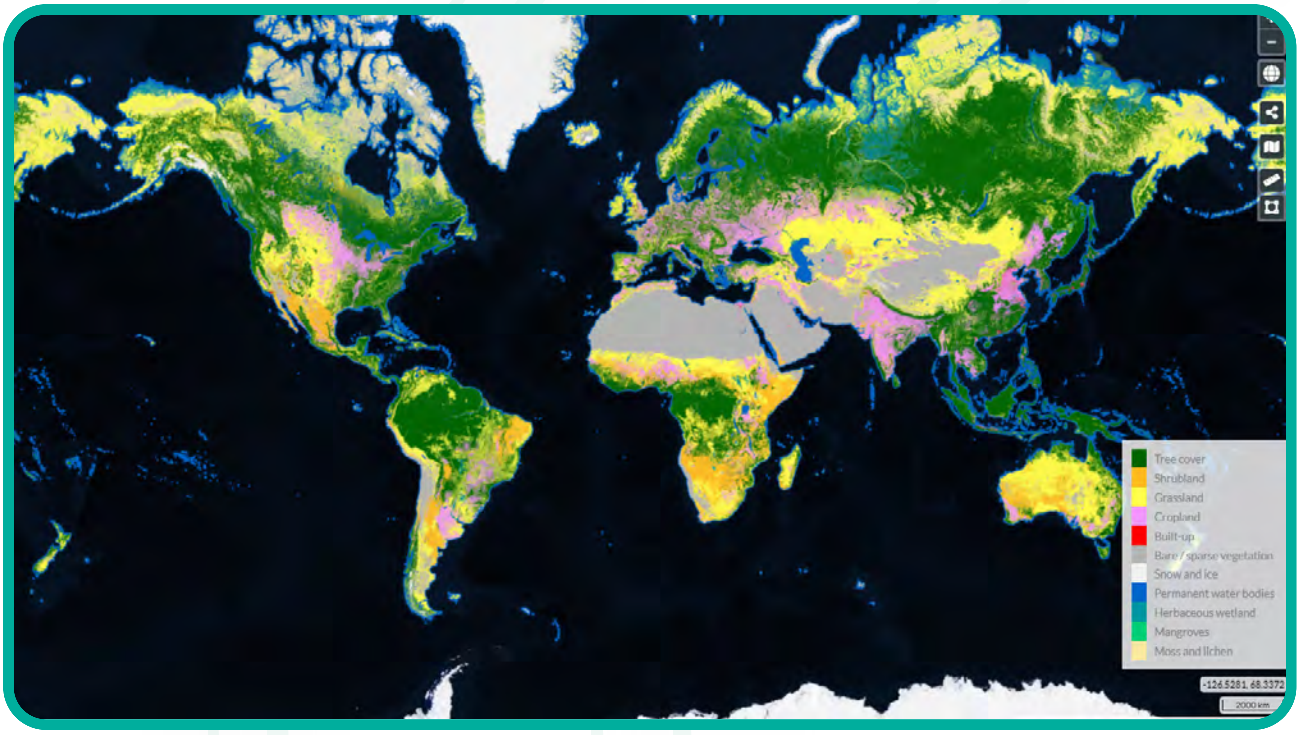


Figure 5: (From ESA) – World Cover 2020 – Source: https://esa-worldcover.org/en

Especially, the use of such indicators in land use management plays a major role in the sustainable management of natural resources. Therefore, the availability and accessibility of accurate and frequently updated land cover maps is of interest at global or regional levels for policy-making, and at for local infrastructures. This session aimed at reviewing the main advances in land cover and vegetation mapping applications using InSAR. More specifically, the presentations were focused on the following points:

- InSAR Coherence (and other phase related parameters such as the "closure phase") relate to land parameters (besides depending on SAR parameters as the wavelength, baseline, time interval, NESZ etc.).
- Coherence can contribute to classification type (e.g. landuse mapping, crop type mapping, forest mapping) and parameter retrieval type (e.g. vegetation biomass, crop phenology) applications.
- Thanks to Sentinel-1 C-band 6-/12- day coherence is available globally.
- Coherence and backscatter are complementary and should both be used.
- There is an interest in using multiple polarizations and wavelengths.

- Multi-temporal data sets are particularly useful for landuse and vegetation applications.
- Thanks to the systematic data acquisition with 6-days intervals and short spatial baselines Sentinel-1 has a high potential for landcover and vegetation applications.
- 6-day coherence performs clearly better than 12-day coherence.
- Many of the algorithms used (e.g. using machine learning) depend on access to training data. The algorithms work well for the area of the training data but cannot reliably be applied elsewhere

Main findings and recommendations:

For Sentinel-1A and 1B, systematic acquisitions with 6-day intervals (as much as possible and 12-day intervals elsewhere) are requested with a dual-polarisation mode preferred over single co-polarised data. Changing modes (e.g. polarization) should be avoided as much as possible. Taking into consideration the possible operation of Sentinel 1C (simultaneously with 1A and 1B), the configuration 1-5-6 day intervals and the operation with regular 4-4-4 day intervals are both attractive for the land cover and vegetation applications. The short 1 day interval can contribute additional (complementary) information, while the main multi-temporal rhythm remains at 6 days. The regular 4-day intervals would improve the temporal sampling to 4 days. There is a high interest in having „Sentinel-1 like data" also at other frequencies (e.g. L-band). Finally, the advantages / disadvantages of different S1-A,B,C schedules (1-5-6 day versus 4-4-4 day repeat) could be investigated in specific studies.

At present most algorithms depend on training data and can therefore not easily be scaled. It has pointed out by the community that physical model (scatter model, coherence model) based algorithms would be useful. ESA could support this through study contracts".

Preparations for L-band coherence could be addressed.

10. Volcanoes

In the last 20 years, several advances have been carried out to better monitor volcanic activities from space as well as their impact on the environment, economy, and people. SAR is an efficient technology to monitor eruption during a crisis since in most cases it can generate an image through the eruption plume. InSAR brings, in addition, the power to highlight surface deformations, which may give vital precursor information in case of chain events preceding or following an eruption.

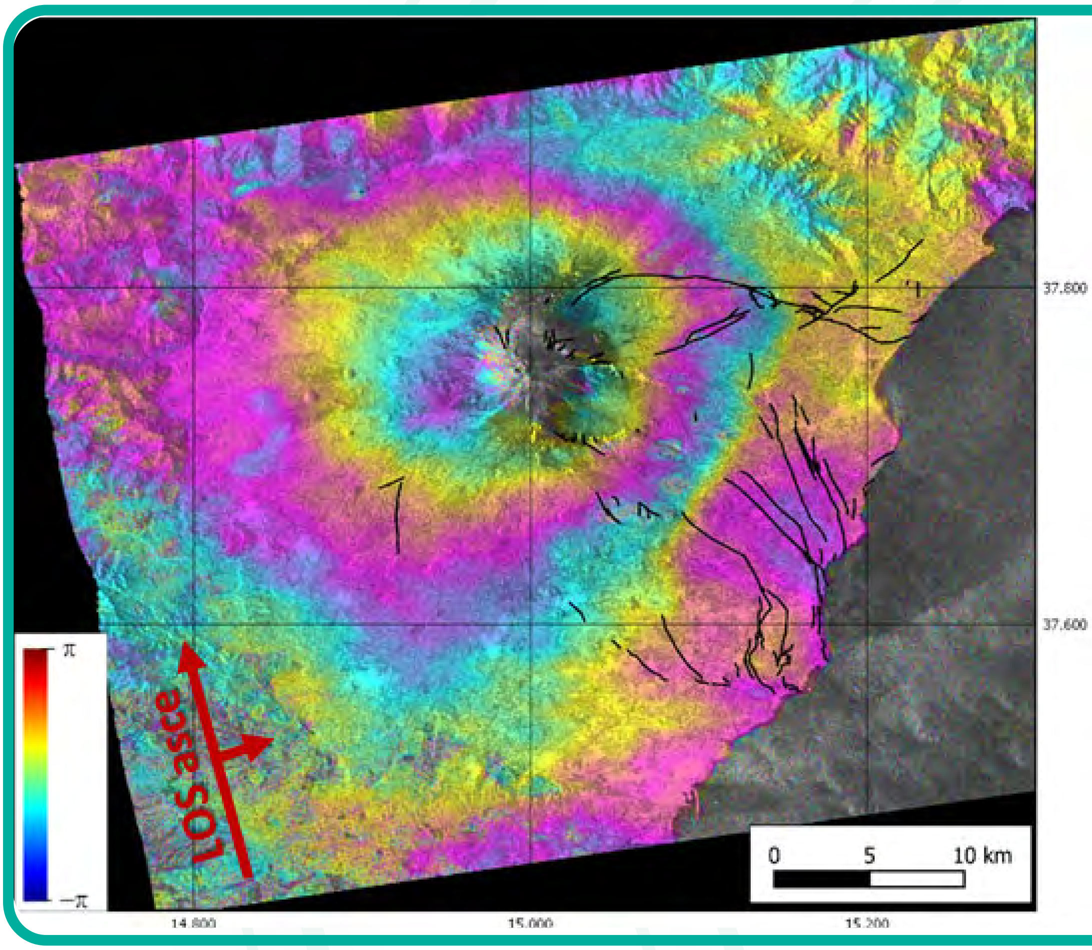


Figure 6: Etna eruption February 2021 - This interferogram was obtained using Copernicus Sentinel-1A and –B data and features the descending phase relative to 23 December 2020 and 27 February 2021. The volcanic edifice is affected by a diffused deflation of about 1.5 fringes.
Source: https://sentinel.esa.int/de/web/success-stories/-/copernicus-sentinel-1-shows-etna-s-deflation

The session dedicated to volcanoes addressed the following technical points:

- Monitoring of eruption and volcanic unrest.
- Research into mechanisms for caldera unrest and tracking eruption progression using diverse SAR methods.

Main findings and recommendations:

The volcanology community supports arguments for Sentinel-1C being activated, and especially request consideration for additional acquisitions during volcanic crises. In addition, the volcano community aspire to international community-led coordination for SAR tasking over volcanoes in unrest and eruption.

The acquisition of up-to-date DEMs is critical for InSAR in volcanology and for high quality automated processing, which should be done at higher spatial resolution for volcanoes where possible and applicable. Furthermore, commercial SAR imagery could have a role providing rapidly acquired images during volcanic crisis response, however routes need to be defined to obtain such imagery beyond the charter alone. The main recommendation regarding constellation configuration is to keep Sentinel-1A and B acquisition to retain the shortest achievable repeat time over active volcanoes (e.g., in particular six-day pairs would help for volcanoes in Southern Chile: descending track 83 and ascending track 91 where acquisitions have been intermittent since 2019.

11. Earthquakes and tectonics I, II, III, IV

The amount of satellite-geodetic measurements has increased over the past two decades, improving our ability to observe, monitor, and understand active tectonic processes. The scientific community has the capability now to routinely monitor earthquakes using satellites, and mapping surface ruptures of earthquakes on land.

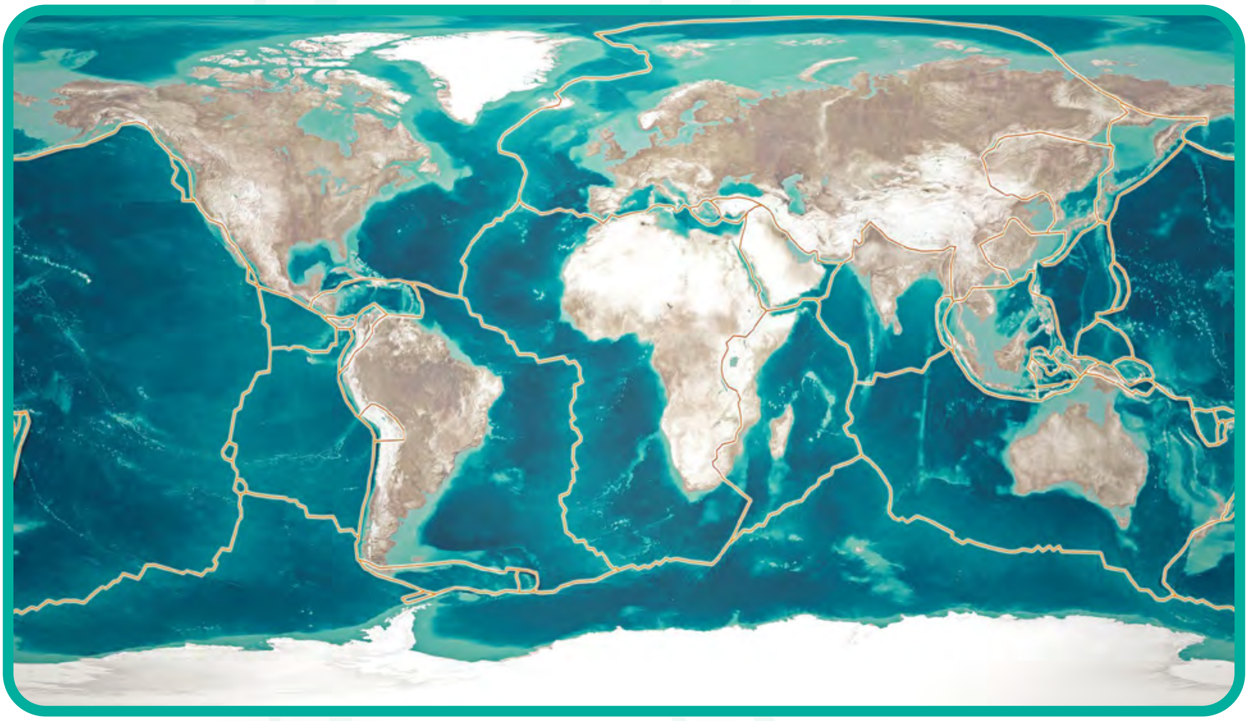


Figure 7: Tectonic Plate Map.
Source: https://www.nationalgeographic.org/encyclopedia/plate-boundaries

This space-based observation revolution pushes forward advances in models that can explain the surface deformation and the long-term evolution of fault areas and tectonic landscapes. During these sessions the following topics have been presented and discussed:

- Sentinel-1 data lifted the field of earthquakes and tectonics into a new era.
- Large scale and high-frequent revisits improved quantity and quality of our surface displacement maps. More and new phenomena of plate tectonics are being observed.
- We better see faults loading and creeping, but also folds folding!

- We get coseismic displacements in previously difficult areas in Europe and elsewhere due to more frequent visits and good coherence, which is very valuable for disaster response and hazard assessments.
- In former times we would see many studies about the same earthquake … not anymore.

Main findings and recommendations

Few studies that combine "old" mission data from ERS and Envisat with Sentinel-1 have been presented in the sessions. The community recommend to make the ERS and Envisat archive very easily assessable.

Recommendation

Re-assess the possibilities of a future spare S1-satellite in space.
Considering a scenario where three operating Sentinel-1 satellites are in space, the community advised that investigations should be carried out in the frame of Copernicus Mission objectives. For example, it could be of interest for emergency response and other possibilities as an on-off capability.

It has been highlighted as well that the accuracy of DS (Distributed Scatterer) time series products needs to be verified through different studies. More generally, it has been advised to ESA to launch studies regarding the comparison of different algorithms of time-series analysis over the same area in order to assess the reliability of products.

One objective in the near future is to work towards absolute measurements from InSAR data. The recommendation from the community is to include atmospheric corrections (also ionosphere), solid-earth tides etc. to fulfill this objective.

It has been recommended to keep the North-South sensitivity operational and not over to short-lived missions like Harmony. If Sentinel-1 NG is not acquiring in TOPS mode, alternatives have to be investigated for sensing the third dimension in the 2030s and beyond.

Single-burst downloads have to be enabled to save time and memory. ESA has been asked to provide coregistered images or meta-data for coregistration in order to skip coregistration step and have less data to store.

12. Subsidence and deformation I, II, II, IV

Interferograms from InSAR acquisitions represent maps of relative ground-surface motion in the radar line of sight direction. Exploiting the dense time-series of interferograms it is possible to reveal ground deformations, like subsidence, which cause major issues in terms of infrastructure damage. Monitoring techniques using interferometry can help to gain knowledge of ground deformation phenomena and deformation trends.

Figure 8: Subsidence in Pistoia – Source: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Monitoring_Earth_s_shifting_land

A wide range of deformation phenomena were presented during four oral sessions and one poster session. A short summary of the four oral sessions is provided below:

- Presentations on wide area processing – European GMS, IREA/CNR, Norway and Iran.
- Active reflectors – challenges and progress.
- Machine learning for post-analysis of large InSAR datasets.
- Concept for integration of InSAR with other geodetic data sources.
- Water management and ground water effects.
- Systematic and automated approaches to monitor sinkhole precursors were presented.
- The question about non-linear deformation models in sinkhole monitoring is still open.

- The contribution of the different types of deformation to the total subsidence cannot be clearly defined.
- Improved deep learning unwrapping procedure aiding InSAR processing.
- Increased efficiency of InSAR processing by focussing on small patches.
- Integrated monitoring of rock glaciers and landslides, using multi-sensor, multi-platform, phase and amplitude.
- Nation wide processing to detect a wide variety of deformation phenomena – access to multiple users.
- Piece-wise temporal processing to optimize detection of time series deformation patterns.
- Uncertainty assessment of 3D decomposition, depending a.o. on satellite constellation; taking potential North-South movements into account.
- The wide-area C-band processing is being increasingly applied. There will be an evolution towards new sensors, e.g.
    - L-band missions (SAOCOM, NISAR, ROSE-L).
    - Very-high resolution (COSMO-SkyMed Second Generation).
    - More viewing geometries (Harmony).
- A lack in standardized deformation data derived from InSAR was identified.

Main findings and recommendations

The following question have been asked to the community: « What can ESA do to stimulate the standardization of products from InSAR wide-area Ground Motion Services? Could ESA initiate a mechanism so that ground infrastructures with Corner Reflectors or Active Transponders would be acknowledged by satellite operators and their use and networking fostered? »

According to the scientific community, Sentinel-1 led to reach and unprecedented short-term coherence, but fading effects seem to be a limitation for multi-look processing. Approaches for areas where only short-term coherence is retained are also important, it has been noted as well that relying only on long-term interferograms is not always an option.

A proper processing approach allowing the identification of areas where phase data are affected by geophysical phenomena hindering ground motion estimation is needed, although effective solutions to achieve this task already exist. It is recommended to launch studies to advance the understanding of the physical scattering mechanisms and the proper processing approaches for short-term interferograms.

Stimulate deep learning initiatives, e.g. to better identify deformation patterns or handle large datasets. The requirement from many applications is the ongoing continuity for the Sentinel-1 constellation to have long time series of compatible data with consistent parameters. New features/flexibilities (e.g. larger baselines, longer burst overlap regions) have the risk to fragment the data. However, these new features should be considered for future complementary ESA missions.

13. InSAR for the built environment I & II

Infrastructures within cities (e.g. roads, tunnels, buildings) or in natural environment (e.g. pipelines, storage reservoirs, platforms) require generally dedicated in-situ equipment to monitor their state and aging. InSAR represents, therefore, a technological breakthrough to monitor infrastructures periodically from space.

Figure 8: Trans-Alaska Pipeline – Source: https://www.nationalgeographic.org/encyclopedia/pipeline/

During the two oral sessions and the virtual poster showcase, the following technical aspects have been presented and discussed:

- Types of infrastructure:
    - Transport (roads, highways, bridges, railways, surface and underground metro lines, airports).
    - Utilities (pipelines, power lines).
    - Oil & gas (storage reservoirs, offshore platforms).
    - Dams (tailing, embankment, hydroelectric).
    - Built-up areas (single building to city scale).
- Methodological steps for infrastructure monitoring: input data selection, image processing with advanced InSAR algorithms, post-processing, precision and accuracy assessment, field checks and validation, integration with geodetic surveys, geological and structural information, structural health monitoring, identification of anomalies and/or priority areas needing further investigation

Main findings and recommendations

The community confirms that high spatial and temporal resolutions are vital for built environment and infrastructure applications, and therefore encourages an "enhanced continuity" to be provided by S1-NG with respect to the current mission.

Regarding the maturity level of InSAR techniques within the infrastructure life-cycle (e.g. planning, construction, monitoring), the scientific community recommends to push forward and include InSAR technologies in the portfolio of infrastructure management workflows (e.g. during civil engineering courses).

When considering InSAR capability to provide information suitable for early-warning and alerting, the community identifies two main recommendations: (i) geophysical/geological/ground data are always to be accounted for when looking for precursors/anomalies; and (ii) early-warning triggering is to be supported by robust statistics and according to engineering standards.

In the field of infrastructure monitoring (as well as in other thematic applications), a crucial role is played by the step of communicating results and their uncertainty. Key recommendations in this regard are: (i) standardization of output products and (ii) error-bars and easy-to-understand statistics to accompany results and derived products for more rigorous analysis.

Regarding data related recommendations, the community considers that: (i) Sentinel-1B vs. Sentinel-1A geolocation offset requires investigation as it can lead to misinterpretations; and (ii) EW data for Arctic regions should be provided as SLC (in addition to GRD and RAW) to perform interferometric studies as well in this S-1 acquisition mode.

14. Future SAR missions

In the coming few years, we will witness an increasing number of SAR missions in space from ESA (BIOMASS, ROSE-L, S-1 NG, candidate EE Harmony), Third Parties and others (SAOCOM, NISAR, NOVASAR-S, RADARSAT Constellation Mission RCM, ALOS, TerraSAR-X NG, Newspace miniature SAR satellites....). This opportunity will offer a wide range of new, unique and complementary capabilities opening the door to new science and applications.

Figure 10: ROSE-L artist view – Source: ESA - Contract signed for new Copernicus ROSE-L mission

These new observation capabilities will provide data in different bands (P, L, S, C, X) and different polarizations, space resolutions, orbit configurations, acquisition modes, and acquisition incidence angles. It represents a significant challenge that has to be tackled: unprecedented unexplored synergistic capacity. Therefore, the preparation of joint data exploitation from those different missions should become an important field of investigation.

During this session, several topics have been approached taking into consideration synergies between missions:

- Synergies for Glacier monitoring.
- Synergies for Snow Water Equivalent retrieval.
- Synergies for Land use and vegetations.

Also, more general discussions on data, studies and mission schedule were held.

Main findings and recommendations

The discussion on synergies has been mainly focused on ROSE-L and S1 because sharing the same or similar acquisitions configurations would allow obtaining measurements at two different frequencies over the same area.

Regarding glacier monitoring, in the frame of InSAR applications, L-band can bridge incoherent measurements at C-band for fastest glaciers (where C-band decorrelates strongly). Actions can be taken by using SAOCOM A/B jointly with S-1 to investigate improvements brought by L-band for such measurements. The same comment applies for grounding line monitoring of tidewater glaciers.

The Snow Water Equivalent (SWE) have been a topic of interest during this session as well: Interferometric approaches are currently used for dry snow at C-band to derive the SWE. As it is not performing well for wet snow, acquisition at L-band may help significantly to fill in the gaps and improve the SWE retrievals where C-band does not provide accurate results. The same approaches and comments have been mentioned for sea ice monitoring.

Regarding land use and monitoring, the main improvement have been brought by coherent monitoring thanks to S1 instead of radiometry-only frameworks. The next major improvement could be brought by adding L-band simultaneously to have a frequency diversity and better classify the wide span of classes in land monitoring.

A more general recommendation on S1 and ROSE-L that have been mentioned several times through different sessions is the need for quasi-simultaneous measurements between the two sensors that could significantly improve the accuracy of mapping. Therefore the scientific community recommends having Sentinel 1 and ROSE-L acquisition times as close as possible to each other.

Geometric accuracy should be in the range of 10cm (for Geodesic reference). It is currently possible at C-band to fulfill this requirement, but it needs to be investigated at L-band. The absolute ionospheric phase at L-band needs to be accurately studied to reach the goal of 10cm. The main factor that impacts this accuracy is the ionospheric perturbation that currently leads to accuracy of few meters at L-band.

Analysis Ready Data (ARD) should become a standard in SAR applications and other remote sensing technologies to avoid disparities in results due to preprocessing frameworks.