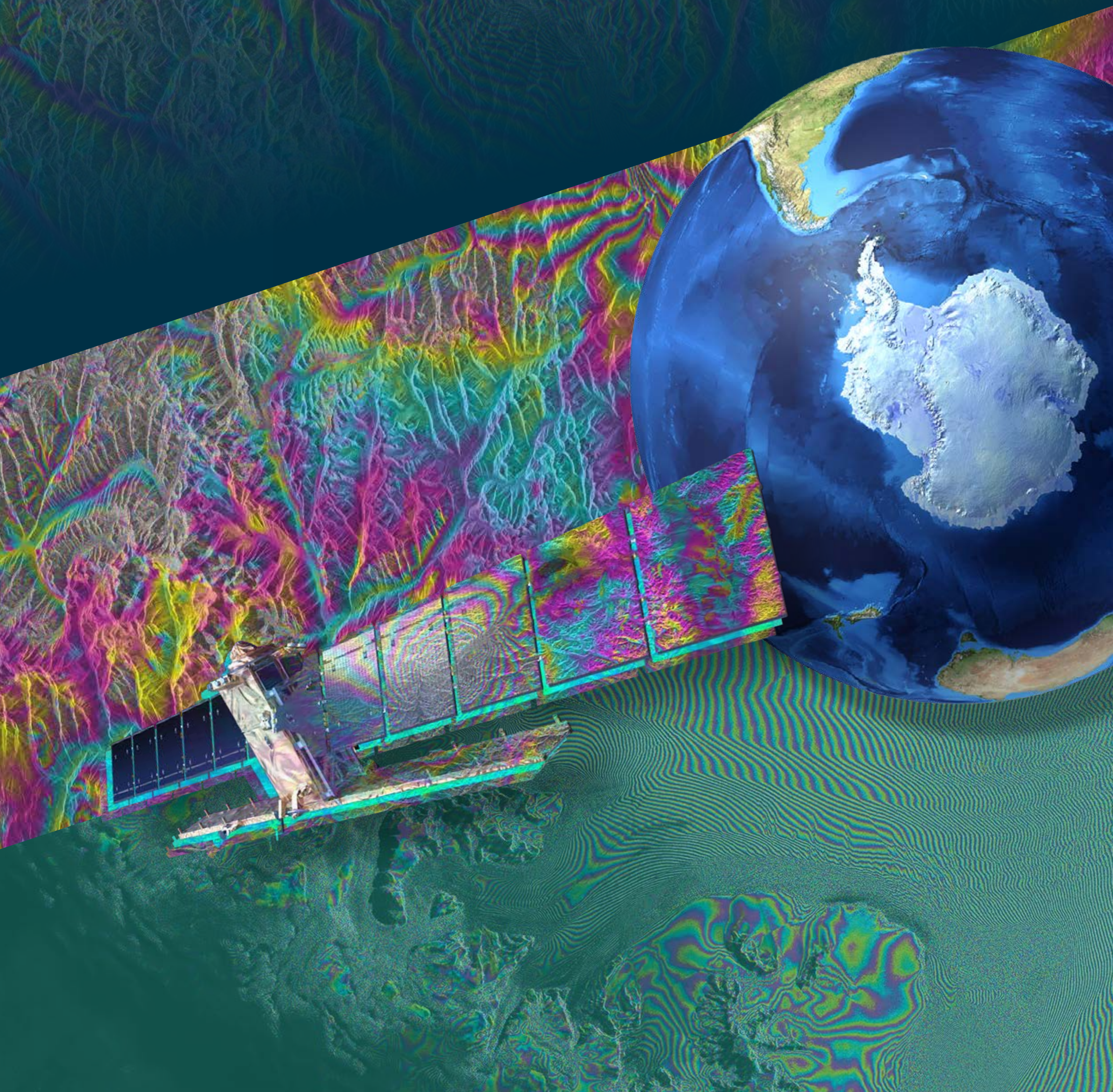
FRINGE 2023 WORKSHOP

Session Summaries and recommendations



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This document contains summaries and recommendations of the Fringe 2023 Workshop, *"Advances in the Science and Applications of SAR Interferometry and Sentinel-1 InSAR"* that was organised on 11 - 15 SEPTEMBER 2023 in Leeds, UK.

Chairs: Muriel Pinheiro, ESA-ESRIN/ Nuno Miranda, ESA-ESRIN

The session provided an overview on S1 mission status, S1 cal/val activities and data quality. It has also provided details on the monitoring of baseline and burst synchronization, which are currently slightly impacted by solar activity and on recent evolutions such as burst ID/burst ID map and on the activation of the RFI correction.

Recommendations:

- To reprocess data from the beginning of the mission (2014/2015) which show degraded quality with possible impact for certain applications.
- In general, to reprocess archive data making full use of newest algorithmic developments and ensuring homogeneity of the data.
- To provide data which have only recently started to be generated (e.g., burst ID and ETAD product) also for the archive.
- To reprocess data with anomalous burst ID annotation.
- To foster the characterization of RFI signals, for example, by exploiting information from RFI detection/correction, to create open databases.
- To extend data quality flagging, in particular w.r.t orbit quality
- To improve communication of anomalous data processing events.

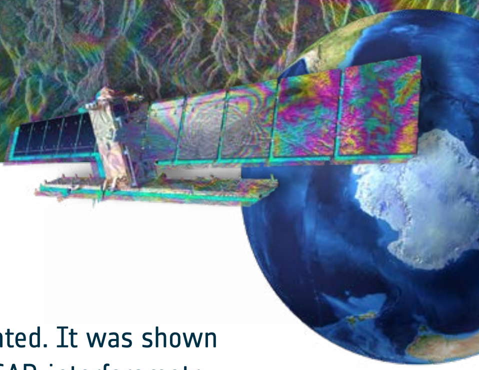
Chairs: Falk Amelung, University of Miami / Giovanni Nico, Consiglio Nazionale delle Ricerche

This session focused on mitigating troposphere/ionosphere artifacts in the interferometric products and SAR meteorology. The main topics presented during the session include:

- A new autofocus algorithm for the polarimetric calibration and correction of ionospheric artifacts on P-band products of the future Biomass mission.
- A methodology to mitigate atmospheric artifacts in space and airborne L-band SAR interferograms based on the Independent Component Analysis technique for the estimation of water level changes in wetlands.
- It was shown how SAR meteorology could contribute to the updating of Digital Twins of the atmosphere.
- Development of a new model of propagation delay into the atmosphere for the mitigation of turbulent and stratified components of the delay and application to a long time series of S1 data of the post seismic deformation after the 22 May 2021 Maduo earthquake (China).

Recommendations:

- To define and use methods to quantify atmospheric signal reduction, e.g. by range variability of a corner reflector or InSAR phase variograms etc.
- Consider the validity of algorithms (especially ionosphere) for ROSE-L (side discussions after the session).



Chairs: Michael Eineder, DLR/ Riccardo Lanari, IREA-CNR

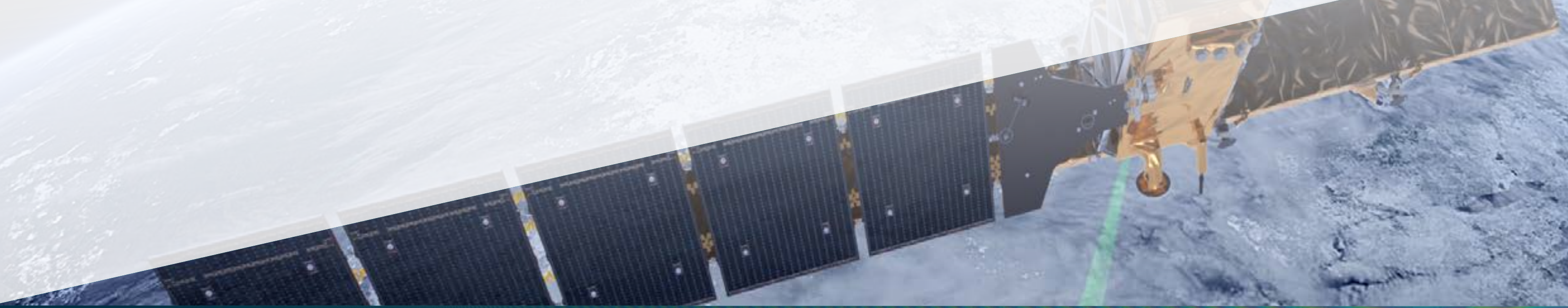
During this session the ESA's new ETAD product and its evolution was presented. It was shown how the ETAD product can be used to reduce atmospheric phase errors in SAR interferometry. Due to different sampling grid in different SLC products, artifacts may appear in rugged terrain. Two contributions demonstrated how to remove/reduce these artifacts, either by improving the grid interpolation using a phase/height gradient determined from the data of each ETAD data set, or, by exploiting the phase statistics from multiple SAR/ETAD data sets to reduce the artifacts significantly.

It was shown how NASA uses an equivalent (to ETAD) approach to improve geocoding accuracy with good results. More work to quantify the potential of atmospheric InSAR phase reduction will be done in the future by all teams involved.

Application to tectonic / earthquake signals: the power of ETAD-like reduction of ionospheric effects based on CODE TEC maps was shown. It seems that the correction is more effective in ascending orbit passes. The split band method provides better results than the ETAD one (based on TEC maps) but is only applicable to interferometry. Application to volcanoes: a comprehensive approach to automatically detect volcanic activity was shown with improvements on many processing steps.

Recommendations - important

- One of the questions from the scientific community was whether it would be possible to have in the future an external sensor (e.g. ENVISAT/MERIS), ideally simultaneous to SAR, to measure water vapor?
- Define / provide test areas (supersites) together with SAR and auxiliary data sets for the cross-comparison of algorithms.
- Discussion on the grid of complex SLC products. Should ESA stay with slant range or change/add a fixed geographic grid? Decision/recommendation is postponed. Experiences (e.g. that at NASA/JPL) shall be monitored. Many open questions remain, e.g. which DEM should be used and how to handle changing DEMs.
- To provide ETAD products rapidly (latency is currently limited by POD orbit generation time); request to publish ETAD corrections and restituted orbits within 48 hours from the acquisition of the SAR image (side discussion after the session).
- ESA to publish algorithms (e.g. RFI removal) instead/additionally to data corrections so that the user can do the corrections individually.
- All corrections by ESA should be reversible.
- Longer interferometric across track baselines are required by certain applications.



DATA PRODUCTS AND SERVICES I AND II SESSION

Chairs: Nuno Miranda, ESA-ESRIN/ Jose Manuel Delgado Blasco, RHEA Group
Chairs: Marcus Engdahl, ESA/ Jean-Philippe Malet, CNRS / EOST

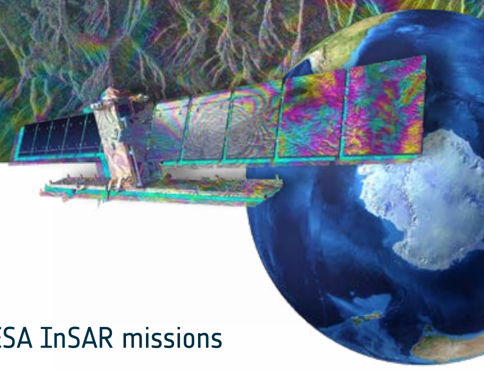
During the two parts of the session a wide variety of presentations were seen, namely:

- TimeSAT - Ground Motion Pattern Detection and Classification in massive Satellite Image
- Time Series by A. Déprez et. al.
- OPERA Analysis-Ready SAR and Optical Products for Mapping Water Extent, Disturbance, and Displacement at Continental to Near-Global Scales by D. Bekaert et. al.
- Supporting Civil Protection Activities with Spaceborne and Airborne InSAR Products in Volcanic and Seismic Regions by F. Casu et. al.
- Nationwide Sentinel-1 PSI Surface Motion of Greece Using On-Demand SNAPPING Service of the Geohazards Exploitation Platform by M. Foumelis et. al.
- Land Motion Monitoring Service of Switzerland Through Interferometric Multi-Temporal Analyses of Sentinel-1 SAR Data by G. Tessari et. al.
- InSAR Capabilities and Outlook of the ESA SNAP Toolbox by C. Brockmann et. al.
- SNAP2StaMPSv2: Increasing Features and Supported Sensors in the Open Source SNAP2StaMPS Processing Scheme by J. M. Delgado Blasco et. al.
- ALUs Toolbox: GPU-Accelerated Sentinel-1 and ALOS PALSAR Processing Tools by M. Jüssi et. al.
- SAR2CUBE - an Open Framework for an Efficient Setup of InSAR Application in Analysis Ready Data CUBES Presenting author by G. Centolanza et. al.

Recommendations

- Geocoded SLC:s should become standard products.
  - They should be delivered as stacks co-registered to a reference geometry/grid.
  - Alternatively sets of corrections to be provided to facilitate stacking at the user end.
- The InSAR community should move forward from single-master processing approaches to multi-master ones, especially now that the time series (S-1) are getting long.
- Space agencies should coordinate and set up test sites, with ground truth, and SAR stacks at multiple wavelengths.
- Big processing power and storage needed for global applications, and only a few big players can do this today. ESA should provide resources and support to smaller players to reduce entry barriers.

FUTURE INSAR ESA MISSIONS SESSION



Chairs: Björn Rommen, ESA/ESTEC/ Malcom Davidson, ESA-ESTEC

In this session mission managers and scientists from ESA presented future ESA InSAR missions describing the main features of BIOMASS, ROSE-L, Sentinel-1 NG and Harmony.

- **Biomass** – there was some discussion regarding polarization capabilities of this mission.
- **ROSE-L & Sentinel-1** Next Generation – similarly to BIOMASS the polarization capabilities for S1NG and ROSE-L have been discussed. It has been explained that orbit time will be limiting factor, however consideration on how to use QP data is still open. Other topics discussed during this presentation were: ionospheric mitigation in L-band (ITT for ionospheric study to be issued soon), burst overlap for 3D deformation retrieval, 2-look scatter for ROSE-L, modes will be limited to a strict minimum to serve different communities.
- **Harmony** – For this mission level 3 algorithms have been discussed. Although it's an Earth Explorer mission, ESA will try to serve open science and the community which should be able to use these algorithms and products in the future. There were discussions about useful parameterizations for Harmony and possible scenario of Harmony flying together with S1 and S1NG (still under investigation). In the last presentation of the session the performance analysis for Harmony land applications was shown.

Recommendations

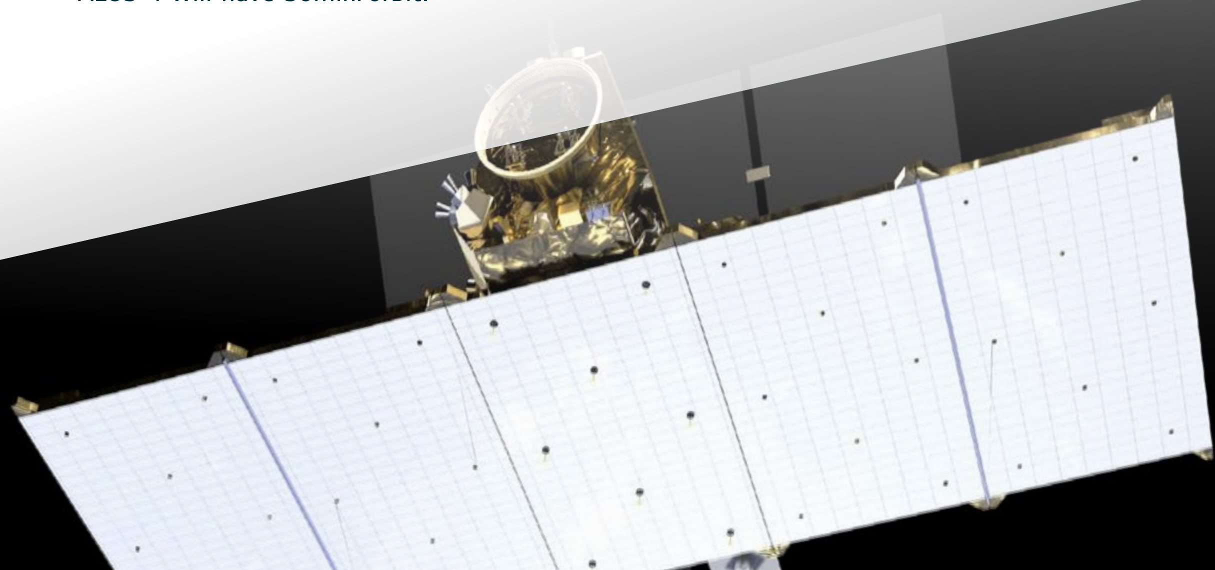
Three days spacing between S1NG and ROSE-L (still under discussion at ESA; ice community is opting for convoy concept).

C- AND L-BAND SYNERGIES: ESA/JAXA COOPERATION AND BEYOND SESSIONS

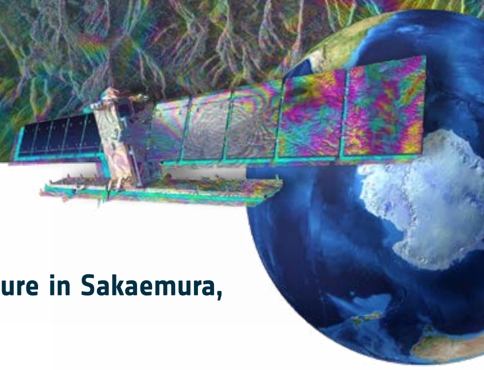
Chairs: Julia Kubanek, European Space Agency (ESA)/ Takeo Tadono, JAXA

ESA and JAXA initiated cooperation to acquire L-band data to be used in synergy with Sentinel-1 data to better understand synergies and limitations for both missions. There are few studies that run in parallel to help development of ROSE-L and ALOS-4. Results from the following studies have been presented during the session:

- **Characterization of C- and L-band: A DInSAR dataset in the Saar Mining Area:**
  - Focusing on Ground motion in a mining area in Germany.
  - PS density increased also in rural areas for ALOS-2 compared to Sentinel-1.
  - Similar long-term positive trends for time series for ALOS-2 and S-1 could be seen, however it's difficult to obtain good long term time series due to the orbit limitation of ALOS-2 (not so many acquisitions).
  - In the future it is expected to have more repeat acquisitions available with ALOS-4 and even NISAR.
- **Soil Moisture Derived from InSAR: Experiments at C-band and Contributions from L-band:**
  - Backscatter vs. coherence in different frequencies has been studied together with the correlation of InSAR derived soil moisture with land surface temperature.
  - Backscatter change vs. InSAR vs. Sentinel-2 - features visible in InSAR also visible in Sentinel-2. This might be interesting for weather forecast in the future.
  - ALOS-2 data time-series of 3 years in Puglia in Italy has been acquired together with ground truth data (over test fields).
  - Good results for the soil moisture retrieval over undisturbed terrain have been obtained but still more studies are needed.
- **Status of ALOS-2 Mission Operation and Cal/Val Plan of ALOS-4:**
  - ALOS-2 status, ALOS-4 Overview and example of possible applications.
  - Jaxa emphasized that collaboration with international agencies and private sectors is expanded (e.g. ESA, CSA, NASA, ASI).
  - ALOS-4 will have 50min/orbit.



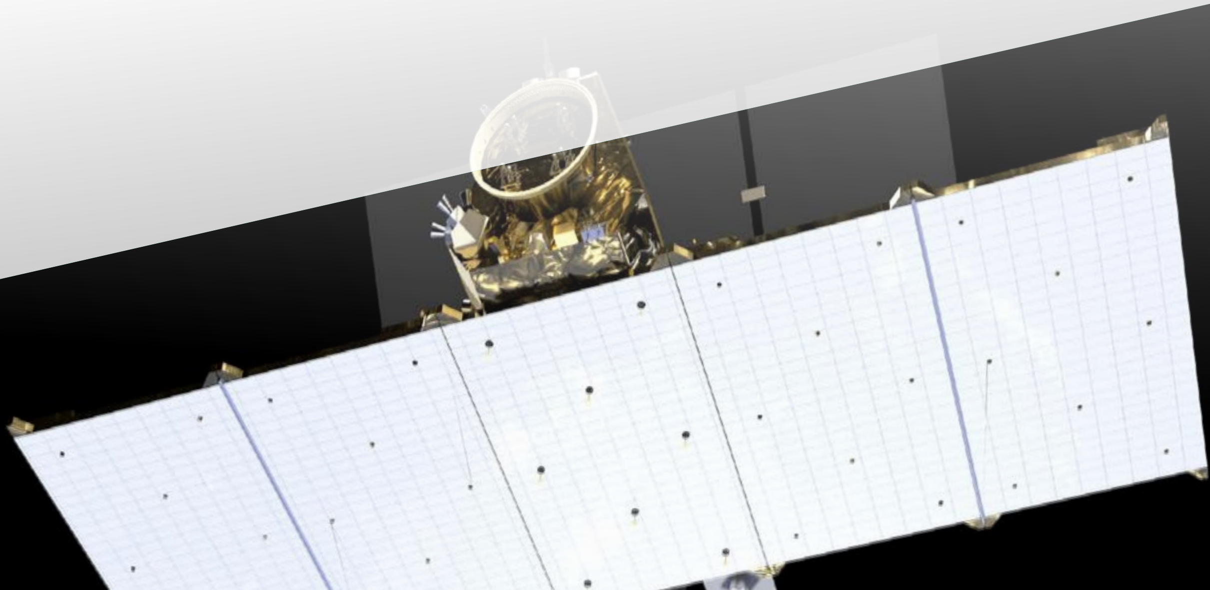
C- AND L-BAND SYNERGIES: ESA/JAXA COOPERATION AND BEYOND SESSIONS



- **A case study of ALOS-2 Emergency Disaster Prevention for Slope Failure in Sakaemura, Simominochi-gun, Nagano Prefecture, Japan:**
  - Overview of Landslide pre- and post-disaster PALSAR intensity images.
  - ALOS-2 and S1 for InSAR analysis (DInSAR & SBAS).
  - Higher frequency of data needed; L-band shows deformation, S-1 could to some extent be used but it's difficult to maintain coherence.
- **On the P-SBAS Processing Chain New Developments for the Generation of SAOCOM-1 Advanced DInSAR Products - Large scale monitoring service implementation with SAOCOM:**
  - More accurate orbits are only released 18 days after the acquisition.
  - Displacement time-series generation over Campi Flegrei caldera, Tuscany region (landslides).
  - C- and L-band comparison, comparison of X- and L-band for metallic bridge.
  - Some advice for the use of SAOCOM data has been presented.

Recommendations

- Acquisitions over Antarctica and Greenland are necessary e.g. with different snow types and topography. To organize a joined calibration/validation campaign cooperation for arctic sites.
- To have C- and L-band data acquired close by in time to study atmospheric and ionospheric effects.
- Dense temporal acquisitions/long time and time series are necessary in several areas.
- Collaboration needed for validation/ground truthing.
- New application in soil moisture estimation by InSAR using phase closure.



ICE AND SNOW I AND II SESSIONS

Chairs: Thomas Nagler, ENVEO IT GmbH/ Anna Hogg, University of Leeds, UK

Chairs: Othmar Frey, Gamma Remote Sensing / ETH Zurich/ Line Rouyet, NORCE Norwegian Research Centre

There were two sessions on ice and snow presenting Sentinel-1 and other SAR sensors to study ice velocity, grounding line location, permafrost and snow. The following seed questions have been discussed during the session:

What are the most important science questions that should be addressed using SAR data in the Polar and mountain regions?

- The community is happy to use dense repeat sampling of ice speed measurements to understand short term variability in ice speed. However, the sampling is not dense enough.
- We shall add commercial datasets (e.g. Iceye, TSX) and provide community access, especially to the data with interferometric coherence preserved. Support from space agencies for acquiring commercial data would be required.

Which are the scientific and technological gaps in monitoring parameters of ice sheets, glaciers, snow?

- 1-day repeat acquisitions still missing since ERS. This is a big gap. Sentinel-1 acquisition strategy for frequent observation of grounding lines in Antarctica is required. Sentinel-1 Extended Timing Annotation Dataset might be useful.
- From the water sector perspective better SWE products would be useful. Existing products are not frequent enough or products are not reliable enough.
- Snow density is a missing product, and the community needs it for a range of applications. Long wavelengths and denser coverage would help, however current instruments aren't optimized for these kinds of acquisitions. More frequencies are needed, for example L-band.
- Snow thickness / snow structure. Mid-latitude alpine areas: melt-freeze crusts hinder the typical approaches delta SWE and others. Multi-static mission concepts (SAR tomography) should be studied further.
- Timeseries of DEM's are missing. Great that we have it from TDX, but there is nothing planned in the future.
- Uncertainties in surface elevation measurements. Suggestion to consider changing the orbit/ mission strategy towards the end of the mission to have a longer mission lifetime.
- BIOMASS mission 3-day baseline or 9-month baseline. Acquisitions plans in Antarctica seem to be promising but the community needs to discuss further how we will use it.
- For permafrost studies a short acquisition temporal baseline is needed. For thaw slumps: higher frequency single-pass or multi-static mission required.

- PIG and TW will still be incoherent with NISAR, so still there will be no grounding line datasets.
- The community wants a 6-day repeat back from Sentinel-1 as soon as Sentinel-1C is launched. Don't decommission S1A until Sentinel-1D is launched and working.

How can we coordinate and optimize SAR acquisition strategy over ice sheets, glaciers and snow with current (and upcoming) satellite missions? (Sentinel-1, NISAR, SAOCOM, ROSE-L). Which are the priority regions?

- Polar space task group exists as a model. Within ESA coordination should be more straightforward. ESA shall get input from the science community on a regular basis.
- How should ROSE-L acquisitions be connected to S1 acquisitions? Currently the plan is to have both satellites in the same orbital plane, or should there be differences? Both will provide good coverage, but having dual frequency SAR is even better. Better coverage vs. contemporaneous dual frequency?
- S and L (NISAR) are quite similar, so it won't help so much. L and C would be better, or c and x. For SWE products and for topography dual frequency should be prioritized over coverage
- Decrease of data availability in permafrost regions (outside Europe) since S1B failure. The community needs systematic data coverage at Pan-Arctic scale.

What cal val campaigns are required to produce accurate error estimates for core SAR products (e.g ice speed, GLL and snow mass/extend), and understand differences between multi-frequency SAR (eg C, X vs L-band, Ku-/Ka-band)?

- Cal/val supersites needed, especially when ROSE-L will be available.
- Cal val on ice sheets and ice shelves are needed.

Recommendations

- Resume acquisition of 6-day repeat data from Sentinel-1 across Antarctica and Greenland as soon as S1c is launched.
- Validation campaigns are required now in Antarctica, to characterize error and improve algorithm performance on important measurements such as ice velocity.
- On SWE retrievals with InSAR; the methods are physically understood; however we need reference points for SWE phase relationship, accurate ATM phase correction in mountains. Further development needed.
- Volume changes from InSAR can be calculated, but need continuation of TanDEM-X acquisitions to generate these products, and preparation for Harmony
- Fly ROSE-L and S-1 in close formation to learn about SAR retrievals at different frequencies, and to develop new multi frequency products

INSAR METHODS SESSION

Chairs: Michele Crosetto, CTTC/ Dinh Ho Tong Minh, INRAE

The main topics discussed during this session were:

- How discontinuities in a decorrelated time series could be bridged by considering the measurements of nearby similarly behaving regions (Estimating Peatland Surface Motion with Discontinuous InSAR Time Series Data Philip Conroy et al.).
- Methodology to unmix reliable pixels from those affected by the non-closure phase in 2-looks (Spatial Unmixing of Pixels for More Accurate Displacement Time Series Obtained with a Small Baseline Strategy: Application on France Aya Cheaib et al.).
- A Novel Algorithm for Identification of Persistent Scatterers in comparison to classical methods like amplitude dispersion (Mario Costantini et al.).
- Estimator for updating InSAR displacement time series based on the phase linking technique (Scott Staniewicz et al.)
- Deep Learning (DL) perspective: the available models are well-known so the DL can have limited contributions. However, DL can help to speed up the processing faster and more efficiently. There is a potential to use DL for phase unwrapping, an outlier in time series, and assist in postprocessing in providing alarm-related information.
- How do we better understand the signal related to the non-closure phase? The soil moisture application exploits the physical aspect. For the deformation applications, it is necessary to eliminate this non closure phase based on the phase linking. The open-source phase linking tool such as TomoSAR is encouraged.

Recommendations

- For deformation applications, working on statistical phase linking or PSI techniques is essential to eliminate the non-closure phase. Support to make open-source tools (i.e., TomoSAR and StaMPS) available in Python is necessary.
- To extract the physical signal in the non-closure phase, a complete study must be required to understand its mechanism under many scenarios.
- Reduce the delivery time of precise orbits to 24h can improve InSAR processing.
- Systematical atmospheric correction products are essential to reduce the artifacts in InSAR results.

GROUND MOTION SERVICE SESSION

Chairs: Philippe Bally, ESA/ Michele Crosetto, CTTC

The session concerned the exploitation of Sentinel-1 using InSAR techniques for wide areas, typically pan-European, terrain motion monitoring such as with the Copernicus EGMS and other services like national services. There were five presentations; one was an intercomparison between EGMS and another (national) service. Two presentations were given about EGMS validation and other two about downstream applications of wide area terrain motion mapping with one concerning monitoring the cultural heritage in Italy. Last presentation concerned a standard deformation detection service called ADA that is exploiting the Copernicus EGMS to detect and characterize terrain motion patterns. In the session on Data Products and services there were some additional presentations showing other than the EGMS wide area mapping solutions for instance; the Sentinel-1 SNAPPING coverage over the entire territory of Greece (by Aristotle University of Thessaloniki) alongside with a presentation of the TimeSAT post-processing developed by CNRS EOST using the Geohazard Exploitation Platform GEP that is able to exploit the Copernicus EGMS results to detect an characterize terrain motion patterns with interesting complementarity with the ADA techniques presented in this session.

The main conclusions from the round table discussions were:

- There is a general consensus that the EGMS is meeting the goals of providing a regular, EU wide, validated and standardized full resolution terrain motion mapping. It is considered a valid starting point considering that the capability should gradually improve, and that user community feedback is intended to be used for this purpose. It is also noted that there are open issues that should be addressed, as some terrain motion phenomena are not mapped in an optimal fashion with the current service, notably earthquakes and volcanic eruptions.
- It was discussed that such limitations are beyond reach of the standard Copernicus EGMS and require tailored InSAR techniques by industrial providers or geoscience centers and academia. Some session participants requested that for some events such as earthquakes and volcanic unrest or volcanic eruption, the event be flagged in some sort of fashion in the EGMS results.
- It was also discussed whether the loss of Sentinel-1B is affecting the ability of the EGMS to deliver and there is a general agreement that the annual terrain motion products using 12-day temporal sampling are considered fit for purpose.
- It was also discussed how well the EGMS is able to combine with the (EO and non EO) geospatial services currently used for ground motion monitoring applications and whether it can be integrated with these services. Session participants indicated that there lacks an API to access EGMS and support further exploitation and post-processing.

- It was explained that there is a collaboration between EEA and ESA and there are APIs on the Geohazards Exploitation Platform GEP to access EGMS products. The time series visualization function provided by the GEP is intended to be accessible to any user registering to the system to support the visualization (and download) of measurements from EGMS products and help to conduct further analysis. For instance, there is a link in place between the Copernicus EGMS and the GEP to allow complementary processing using radar (PSI, SBAS, D-InSAR) and Optical (e.g. correlograms using time series).
- It was also discussed that user communities need to be carefully informed about the fact that EGMS results are combining InSAR with GNSS while InSAR products of the community generally are just non calibrated InSAR measurements not which may be confusing. It is essential to explain to the users the contribution of InSAR measurements versus the contribution of GNSS.

Recommendations

- It would be useful to visualize the Basic Product in the EGMS Explorer and the background layers used for visualization in the EGMS Explorer should be improved. Users should be able to download a time series over any customized AOI; the phase unwrapping with non-linear motion needs to be improved; the atmospheric filtering needs to be improved; intermittent or partial scatterers could be used to derive measurements; the geocoding accuracy of measurement points needs to be increased (e.g. scatterers found offshore).
- Evolving scope of the EGMS service regarding EO missions to be used, observing strategy, processing, etc. The following was considered: the use of amplitude data to derive change detection products should be considered, not just InSAR based deformation measurements; InSAR measurements based on L-band data should be delivered; the North-South deformation component should be better tackled in the future.
- ESA to provide open-source processing chains for the service so that experts and users can achieve greater impact with the Copernicus Sentinel terrain motion technique.
- R&D: tools should be available, and experiments should be conducted to enable and promote the combined access and visualization of soil moisture data in correspondence with InSAR terrain motion data (such as Sentinel-1 based soil moisture data and EGMS measurements); methods should be developed and tested to enhance phase unwrapping using both C-band and L-band data.

ADVANCES IN INSAR THEORY I AND II SESSIONS

Chairs: Pau Prats-Iraola, German Aerospace Center (DLR)/ Yngvar Larsen, NORCE

Chairs: Ramon Hanssen, Delft University of Technology, Faculty of Civil Engineering and Geosciences/ Howard A Zebker, Stanford University

There were two session slots dedicated to the most recent advances in the field of InSAR theory. Presentations and posters in this session addressed mainly topics of non-closure phases / soil moisture retrieval. The main topics discussed were related to the phase bias evaluation for different land covers, phase bias removal for short-term multilooked interferograms, soil moisture retrieval, soil moisture modelling and evaluation, improvement of the phase linking algorithm, 3-D phase unwrapping of time series, efficient time-series processing of large.

Recommendations

- **Phase closure**
  - ESA should contribute to establishing supersites related to the research on (and interpretation of) phase closure signals. Important aspects: availability of ground truth, observations in different wavelengths potentially combinations with GNSS-R
  - Distinguish the different driving mechanisms behind phase closure signal, i.e., soil moisture, vegetation, sub-pixel displacements.
  - Support organizing the science community working on phase closure signal
  - et up a special session on phase closure signal during next Fringe
- **L-Band / C-Band Combination**
  - Have ROSE-L in the same orbit as Sentinel-1 NG, ensuring the same viewing geometry, repeat orbit, and resolution.
  - Involve the science community in the planning of the temporal separation of the acquisitions (e.g., ROSE-L acquisition either 1 day or 3 days after S1-NG).
  - Facilitate L-band/C-band combination experiments by providing SAOCOM/Sentinel-1 acquisition schemes and data availability.
- **Orbits**
  - Currently, precise orbits are available two weeks after image acquisition. This hampers several high-performance applications (absolute range positioning, geolocation precision)
  - Investigate the possibility to have precise orbit information available earlier. Ideally simultaneously with the image availability (<24h). Consider different options and trade-offs.
- **Baselines**
  - In order to have better estimation of the elevation of scatterers in the built environment consider having 3 or 4 repeat orbits with larger baselines, only during the CAL/VAL period of Sentinel-1C and Sentinel-1D.

DISPLACEMENTS AND DEFORMATION I AND II SESSION

Chairs: Mario Costantini, B-Open Solutions/ Rachel Holley, CGG Satellite Mapping

Chairs: Deodato Tapete, Italian Space Agency (ASI)/ John F. Dehls, Geological Survey of Norway

During this session the following topics with seed questions have been discussed:

- What different requirements are there for small-scale infrastructure use cases, compared to wider-scale Earth and environmental applications? How can these be accommodated alongside all the communities' needs?
- The discussion with delegates recognised the potential for conflicting requirements from user communities which value wide-scale pre-processed data products and those who rely on accuracy at city to building scales for applications such as civil defence and critical infrastructure monitoring.
- One mechanism to help accommodate different users' needs is to continue strengthening the complementarity between the Sentinels and the Copernicus Contributing Missions (e.g., COSMO-SkyMed, TerraSAR-X, ICEYE), which can provide higher spatial resolutions and extended capabilities.
- However, they don't currently provide the coordinated global consistency and temporal continuity which makes Sentinel so valuable, and accommodating the needs of both communities in future mission plans would be very valuable where this is practical.

What complementarity is there between satellite and ground-based systems and ancillary data?

- Complementarity between satellite, ground-based systems and ancillary data is intrinsic and obvious. It is not just a matter of improving the spatial scale of observation and investigation, it is also the fact that satellite, ground-based systems and ancillary data address different tasks of the whole process of investigation e.g., of a landslide or an infrastructure.
- Ground-based systems and ancillary data have also the benefit of increasing the time revisit.
- The discussion highlighted that it is recommended to support a greater use of CRs for validation and defining guidelines building upon the experimental tests that have been run by the community in the past years.

What are the main issues for making InSAR more operational and respond to user needs, e.g. revisit time, spatial resolution etc.?

- Users call for availability of long-term SAR data.
- A key property is shortest revisit time which would be beneficial and an enabling factor to support a variety of displacement and deformation applications, not only disaster response.

- Therefore, it is recommended either investing in SAR constellations or allowing for more flexibility in acquisition plans or a mixture of the two approaches, to achieve shortest revisit time.
- This would couple with the requirement of shorter baselines - see answer to Q1.

Is it necessary to invest in post-processing to extract information for warnings and alarms to make results more useful for end-users?

- The debate on post-processing methods for warning and alarm systems revealed two contrasting viewpoints among delegates: Some prioritize the InSAR scientific community's role in enhancing processing methods and ensuring data quality, without the direct responsibility of distributing derived products to end-users; Others advocate for multidisciplinary cooperation with geologists, engineers, administrations in charge of infrastructure management, civil protection etc. to stimulate InSAR derived products exploitation
- Investing in post-processing tools and methods is essential to enhance the capability of extracting valuable information and generating user-friendly products from InSAR data, including the extensive data within the EGMS. This aims to make EGMS valuable not only to the scientific community but also to end-users.

Should ESA fund any R&D projects to support development of methods and tools for post-processing?

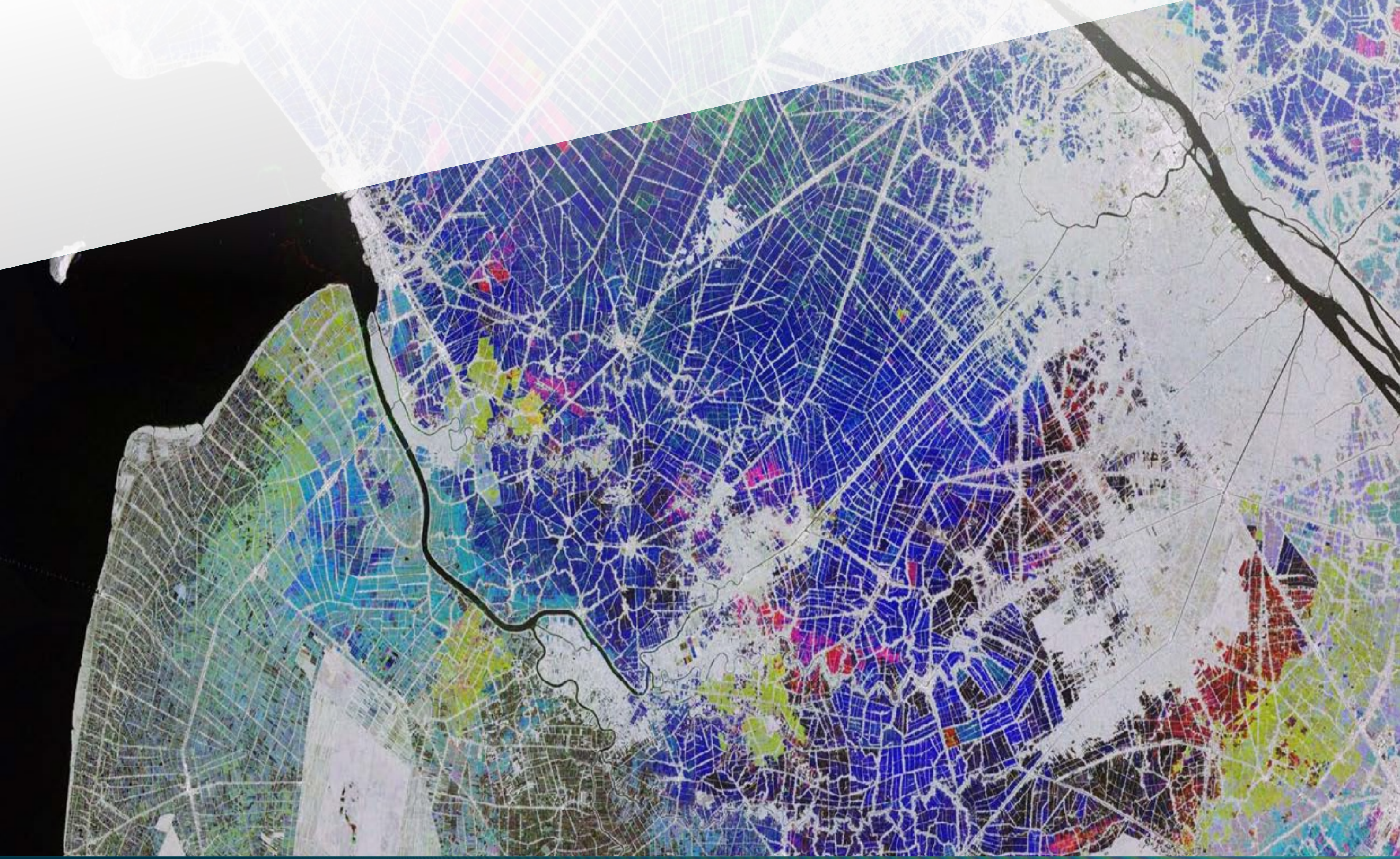
- Some investments towards this direction would be very positive to increase the use of InSAR data and derived products by end-users, the latter being e.g., non-InSAR experts, geologists, engineers, technical officers of local administrations.

Which role should platforms hosting InSAR processing services (e.g. ESA's Geohazards Exploitation Platform, Earth Console) play, and what is the future roadmap?

- Processing platforms are certainly advantageous and a resource that ESA should continue investing in.
- Probably at this stage, an overall discussion would be needed to define a roadmap towards a unified approach leading to a lower number of platforms than they currently are and collecting the various processing routines into a platform as a unique hub.

Recommendations

- Ensuring Sentinel-1 observation continuity - Prefer a constellation approach to optimize revisit times and minimize intervals.
- Allowing for more flexibility in acquisition plans in future missions.
- Harness the accumulated expertise of the scientific community in L-band SAR data processing to prepare for upcoming L-band missions. Suggested coordination between agencies operating L-band sensors (JAXA, CONAE, in future ESA with ROSE-L and NASA with NISAR) and distributing L-band data (ASI with SAOCOM data) to maximize observational capacity across these sensor platforms.
- Optimizing Data Collection Parameters: Ensure new observations adhere to optimal parameters, such as orbital tube and short baselines, to maximize the utility of SAR data for interferometry.
- Making these data accessible to the scientific community and investing on working groups so processing capability is further strengthened.
- Emphasize research on ionospheric correction for L-band SAR data (e.g., ROSE-L) to align with preparations for NISAR.
- Allocate funds for small studies and/or organising dedicated workshops to accelerate the understanding of what could be achieved with BIOMASS.



EARTHQUAKES AND TECTONICS I, II AND III SESSIONS

Chairs: Ekaterina Tymofyeyeva, NASA Jet Propulsion Laboratory/ Tim J Wright, University of Leeds

Chairs: Andy Hooper, University of Leeds/ David Thomas Sandwell, UCSD

Chairs: Qi Ou, University of Leeds/ Sang-Ho Yun, Earth Observatory of Singapore

The amount of satellite data especially from Sentinel-1 has revolutionized our ability to study earthquakes and tectonics, improving our ability to observe, monitor, and understand active tectonic processes. The scientific community has now the capability now to monitor earthquakes and tectonic processes using satellites on a routine basics.

During these sessions the following topics have been presented and discussed:

- Applying Sentinel-1 data to investigate fault properties in a variety of tectonic environments.
- Seismic hazard assessment using InSAR strain measurements.
- Addressing challenges in applying InSAR to research in tectonics.
- Large scale processing of InSAR data.
- Observing earthquakes.
- Automated detection of earthquakes.
- Earthquake event response with Damage Proxy Maps.

How do we separate tectonic deformation from soil moisture effects in multilooked InSAR time series? Are there best practices for selecting interferograms for different types of surfaces?

- One way to enhance recovery of deformation and reduction of soil moisture effects is to weight errors on individual pixels in an image based on loop non-closure.
- Removing shortest and second shortest interferograms could reduce soil moisture effects, but we would lose revisit time. If more frequent revisit time becomes available from future missions, will it be even more problematic in terms of contributing to "noise" from soil moisture effects?
- Soil moisture can be viewed not as noise but rather as a signal that we need to understand.
- Analysis of sequential pairs can help us increase our understanding of soil moisture signals.

What scientific advances do you envision driving the FRINGE community in the future?

- We need to make progress in understanding North-South deformation.
  Need a left-looking SAR?
- We can form more connections with other sciences for interdisciplinary studies. Examples of other datasets to integrate seismology, optical data, damage, intensity, and exposure data for urgent disaster response.

- For urgent response to disasters, we need to push to decrease processing time.
- For consistent coverage and continuity, we need more satellites, more missions, more coordination, so that we can have a system of systems and not rely on just one satellite.
- Rather than focusing on static velocity maps, we need to focus on time series, time dependent deformation signals, time dependent strain rates.

What challenges do we face in earthquake and tectonics research today when implementing existing InSAR datasets? What changes do we need from the SAR data / mission to help push forward the science?

- The reference frame issue is important, and different studies address it differently. We need to make sure we have good GPS datasets that have a unified reference frame, and that we apply them correctly.
- How do we continue to update our products in a timely way, and especially to accommodate changes in approaches when we have already processed large volumes of data and have large archives?
- We need more access to analysis-ready datasets.
- Will larger baselines for Sentinel-1A affect coherence?

What measurements or observations are missing from current and planned missions?

- Recovering 3D deformation is very important, so having co-flyers will probably become very popular in future missions, as they add great value. They will also help mitigate artifacts due to propagation delays through the atmosphere.
- Continuity and global coverage are very important for our observations. Commercial constellations will never have the global coverage that we need to successfully study tectonics.

What aspects of disaster response are being facilitated by SAR data? How effective has it been? What are the pain points and opportunities for improvement? Is it data limitation, technical challenges, or unclear route to impact?

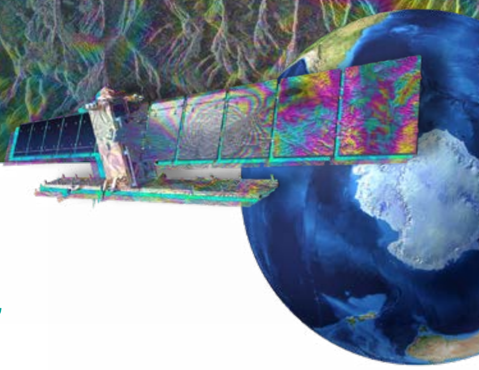
- Disaster response requires more satellites, more publicly available datasets, more frequent revisit, and reduced latency. Some data can be provided by the Commercial constellation or achieved with a Geosynchronous SAR, which can repoint for disasters, and can also get more components of deformation.

Recommendations

- Have a workshop regarding soil moisture effects in InSAR time series and best practices for selecting interferograms for different types of surfaces.
- ESA to launch Sentinel-1C as soon as possible.
- To promote continued research, it is important not to delete the archive and do not change the format of the archived data.

- ESA can fund a comparison study to address differences in InSAR processing and interpretation methods, perhaps in collaboration with the SCEC Community Geodetic Model exercise, to address specific challenges and best practices in the estimation of InSAR deformation time series and velocities.
- For Sentinel-1A and future generations, keep short baselines (within the original 300m tube) despite the trade-off with mission duration.
- For Sentinel-1 NG, or ROSE-L should have bigger overlap between bursts to allow for better recovery of North – South deformation.
- Do not immediately park Sentinel-1A when Sentinel-1C is launched.

  Recommendation for Harmony: make level-3 products available quickly and easily.
- As a contingency plan for the case that Sentinel-1A fails before 1C is launched, begin to negotiate a pre-emptive deal with RADARSAT to provide additional coverage to fill in the gaps and not break the continuity.
- Negotiate with Commercial SAR constellation to provide regular (minimal useful) background coverage to make it possible to have pre-event imagery.
- Form a formal, international SAR tectonics advocacy group for negotiations with space agencies to support science needs.
- Whenever possible, pursue "boring" but continuous and sustainable acquisition strategies.
- Pursue more coordination with commercial constellation and negotiate access to CSK data.
- The more datasets ETAD can provide the better. Keep the format of the datasets consistent and simple. Provide uncorrected raw data along with optional correction layers.
- Add a land cover map as a layer in the InSAR datasets.
- Other recommendations for targeted R&D activities in the short and medium term, and in preparation for the BIOMASS, ROSE-L, Harmony and Sentinel-1 NG missions:
  - Make sure to provide open SAR data with transparent licensing.
  - Ask the military if it is possible to release old datasets.
  - Explore the possibilities of adding other instruments to SAR missions, e.g., MERIS-like instrument for water vapor estimation. -Explore improving revisit time for disaster response, e.g., 1 hour revisit.
  - Study the best approach to launch Sentinel 1C and 1D if 1A stays in orbit and continues to take measurements.
  - Make a good case for unique science to keep Sentinel 1A in orbit as 1C and 1D are launched.
  - Explore possibilities involving 1-day gap between one pair of the satellites, to explore the scientific utility of an architecture that gets very short revisit time occasionally (e.g., 1 day or shorter).



VOLCANOES I, II AND III SESSION

Chairs: Fabien Albino, ISTerre, Université Grenoble-Alpes/ Julia Kubanek, European SpaceAgency (ESA)

Chairs: Paul Randall Lundgren, Jet Propulsion Laboratory/ Juliet Biggs, University of Bristol

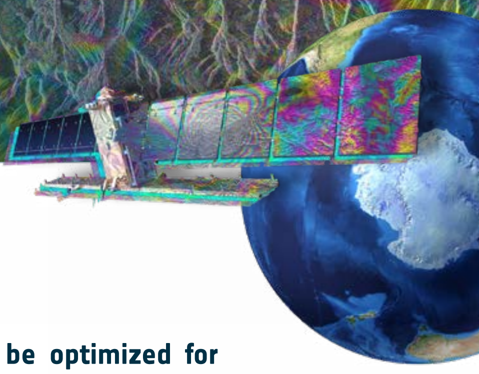
Chairs: Susanna Ebmeier, University of Leeds/ Adriano Nobile, KAUST

The session dedicated to volcanoes addressed many technical points such as: monitoring of eruption and unrest, monitoring ground deformation related to volcanic activity, effects of climate change- on seismic and volcanic activity, the use of machine learning in volcanoes deformation monitoring, operational InAR based monitoring systems for volcanoes. The main findings from the session:

- Sentinel-1 time series is a key for surveying and monitoring individual volcanoes; many examples were presented during Fringe2023 (e.g. Galapagos, Mauna Loa, Askja, Tullu Moye, Chiles).
- Short time revisit of Sentinel-1 enables to better constrain the temporal evolution of magmatic systems -> it provides information about rheology as well as coupling processes.
- Large amount of Sentinel-1 data collected for almost 10 years worldwide provides a good dataset to develop and to test AI algorithms, or blind separation method to discriminate between atmospheric noise and ground deformation -> the final objective is to perform automatic detection of new unrest or changes in behaviour.
- Sentinel-1 datasets are often used for modelling magmatic sources -> the objective is to better understand the volcanic processes; although the discrimination between magmatic and hydrothermal sources is still difficult and it requires additional information.
- In addition to ground deformation studies, there is a need for high-resolution topography products for hazards management and mitigation (e.g. volcanic domes, lava flows) -> our community starts to prepare for the next radar missions (ESA Harmony, NASA STV) by looking at the effect of spatial resolution and DEM's errors on the retrieval of topographic changes.

The community also defined some challenges:

- Discrimination between mixed signals (atmospheric noise vs deformation signals, magmatic vs. hydrothermal sources).
- Understanding coupling processes such as the interactions between volcanoes or the effect of external processes.
- Tracking with accuracy the topographic changes related to eruptive activity.
- Preparation for the next missions NISAR, ROSE-L, Harmony (reproducibility/transferability of existing algorithms).



The following seed questions have been discussed:

How can the future radar missions (Harmony, ROSE-L, Sentinel-1NG) be optimized for volcanoes? What about conjunction with external space agency missions (e.g. ALOS-4, SAOCOM, NISAR, …)?

- Future Missions - NS Motion (two looks everywhere).
- Continuity in Time Series – keep S1A running even when S1C+D are up.
- ROSE-L will be important for vegetated volcanoes (comparison/complementarity with C-band).
- SA shall try to ensure that there are no gaps between existing S-1 observations and observations from future S-1 satellites, in order to provide high temporal resolution of observations

What about the complementary of non-deformation observations (e.g. Harmony topography, optical, hyperspectral, including commercial data)?

- Harmony: benefit of ascending + descending track.
- Up-to-date DEM is important for InSAR processing – could be Harmony, but it would need to make global coverage a requirement.
- Pathway for commercial operators to contribute (e.g. ICEYE, Capella, Umbra etc.).

Do we need benchmarking for performance of automated data processing, time series, machine learning applications?

- Benchmarking studies are important, but it needs to be done centrally (e.g. by/funded by ESA).
- There could be several test sites with different environmental conditions (vegetation, topography, etc) to test for algorithm development (unwrapping, time series analysis, anomaly detection, AI).

What data or methods are most important for volcano monitoring and therefore for Disaster Risk.

Reduction? Are there remaining inequities in geographic distributions of data acquisitions?

- Community can develop new algorithms (machine/deep learning) but it depends on quality and continuity of data.

Chairs: Irena Hajnsek, ETH Zurich / DLR/ Björn Rommen, ESA/ESTEC
Chairs: Marco Lavalle, NASA/JPL/ Nestor Yague-Martinez, Capella Space

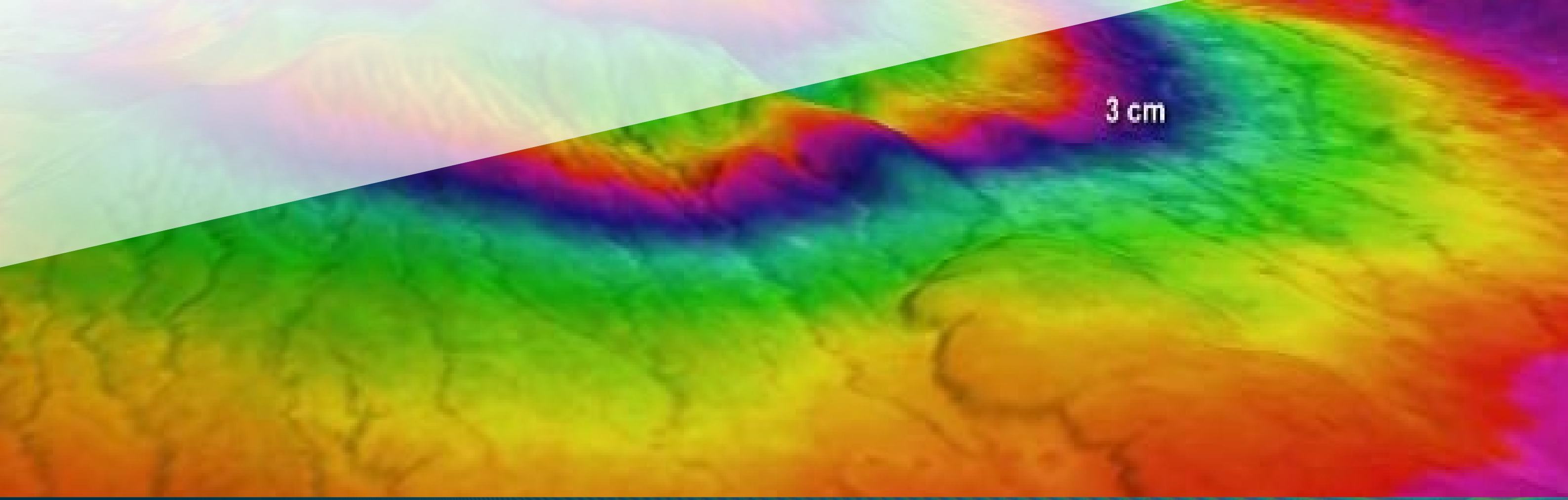
These sessions focussed on the current and future InSAR missions. Several presentations showed recent InSAR developments with commercial SAR constellations of low-cost small satellites. Presentations provided in Missions I session focused on 3D deformation following different approaches:

- New mission design using co-fliers (passive followers).
- Using mid-inclination orbits combined with Sun-Synchronous Orbits (SSO).
- Enabling squint-angle diversity on current missions in development (i.e. ROSE-L). This comes at a certain cost on mission design parameters/requirements (such as NESZ). Question arose whether approaches could be developed that have minimum impact on mission specifications.
- For ATI-SAR enabled systems (e.g. Harmony), one presentation focused on mitigation methods of coherent ambiguities.

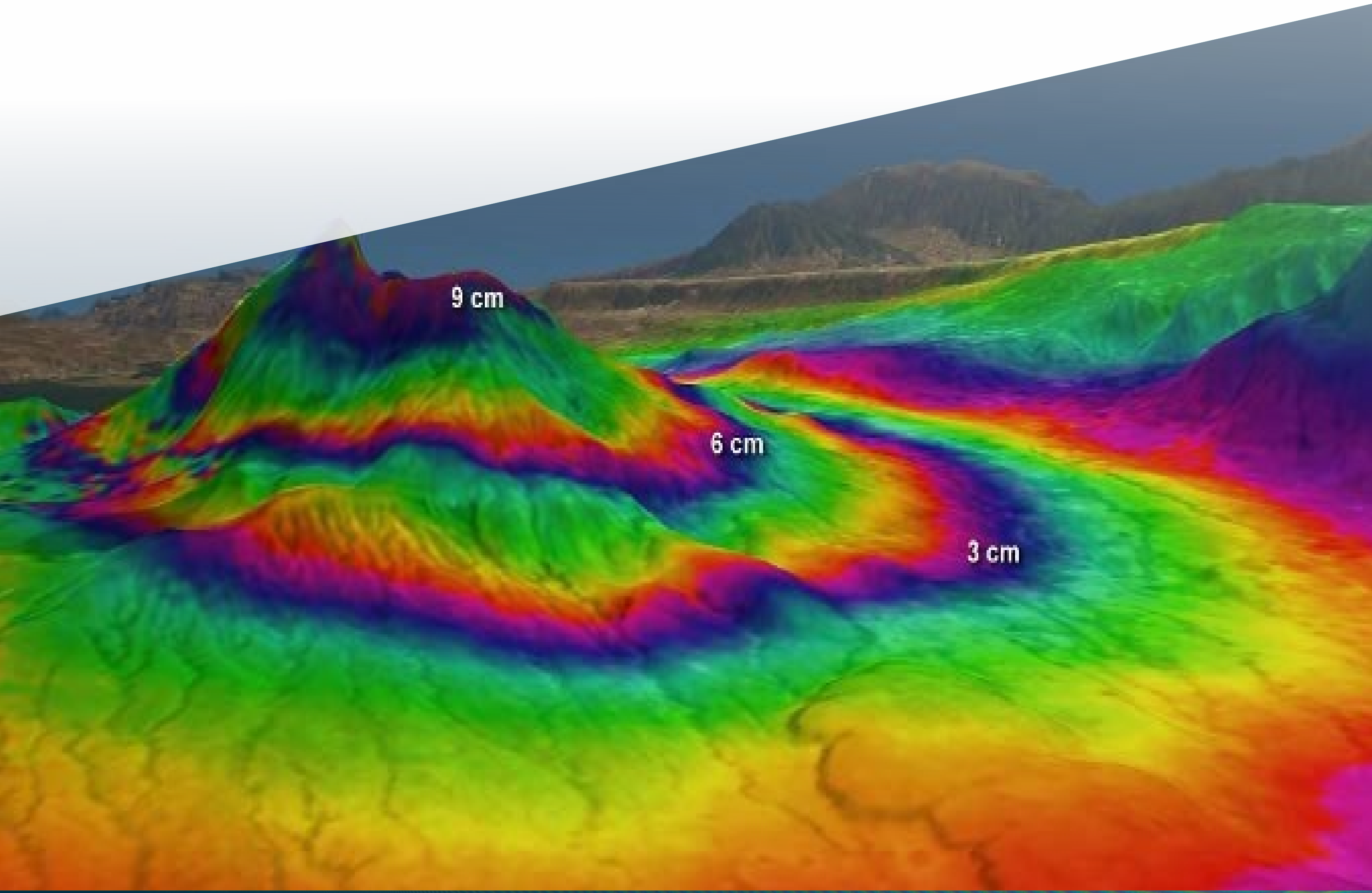
The time-series results were presented with the Chinese SAR constellation GaoFen-3, indicating a reliable use for interferometry. A Ka-band mission proposal to measure topography with an unprecedented accuracy and focusing on the cryosphere was presented. An overview of the InSAR data assessment of the ICEYE and SAOCOM missions in the ESA's EDAP+ project was presented.

Recommendations

- It is recommended to include Chinese missions into ESA Third Party Missions, especially the geosynchronous SAR data from LuTan-4 that was recently launched. The European scientific community would benefit significantly from its high revisit. The connections between ESA and the Chinese are already in place (e.g., through the Dragon project), which will hopefully facilitate the exchange of data.
- ESA should consider using commercial SAR constellations, for processes that require fast revisit (~1 day), e.g., for emergencies or disaster response, to fill the gaps of S1 acquisitions
- ESA should work with the private sector (i.e., SAR constellation providers) to acquire additional data with consistent geometry, and similar to their S-1 (and future ROSE-L) time-series geometry, as far as the orbital constraints allow.



- The use of mid-inclination orbits will lead to a time-varying local acquisition time for the same scene. This might represent a challenge for time-series analysis (specially infrastructure monitoring). More work is needed to investigate this aspect further. More multi-static experiments are needed with multiple airborne platforms, as previous campaigns have only considered bistatic configurations.
- Missions employing co-flier satellites are exciting because they can unlock, in an easy way, new science aspects, that are not possible with current missions.
- The combination of S-1 NG and ROSE-L is important because it will provide useful data about the weather, overcoming the limitation of the coarse temporal sampling. Recommendation to ESA is to increase collaboration with atmospheric scientists for InSAR meteorology.
- To tackle the availability of updated DEMs, possibly by looking at DEM-change missions, such as Harmony.
- Very high vertical height accuracies with a frequent time update are requested to monitor dynamic earth processes. The difference DEMs should have the same or a better performance than current available single pass InSAR derived DEMs.



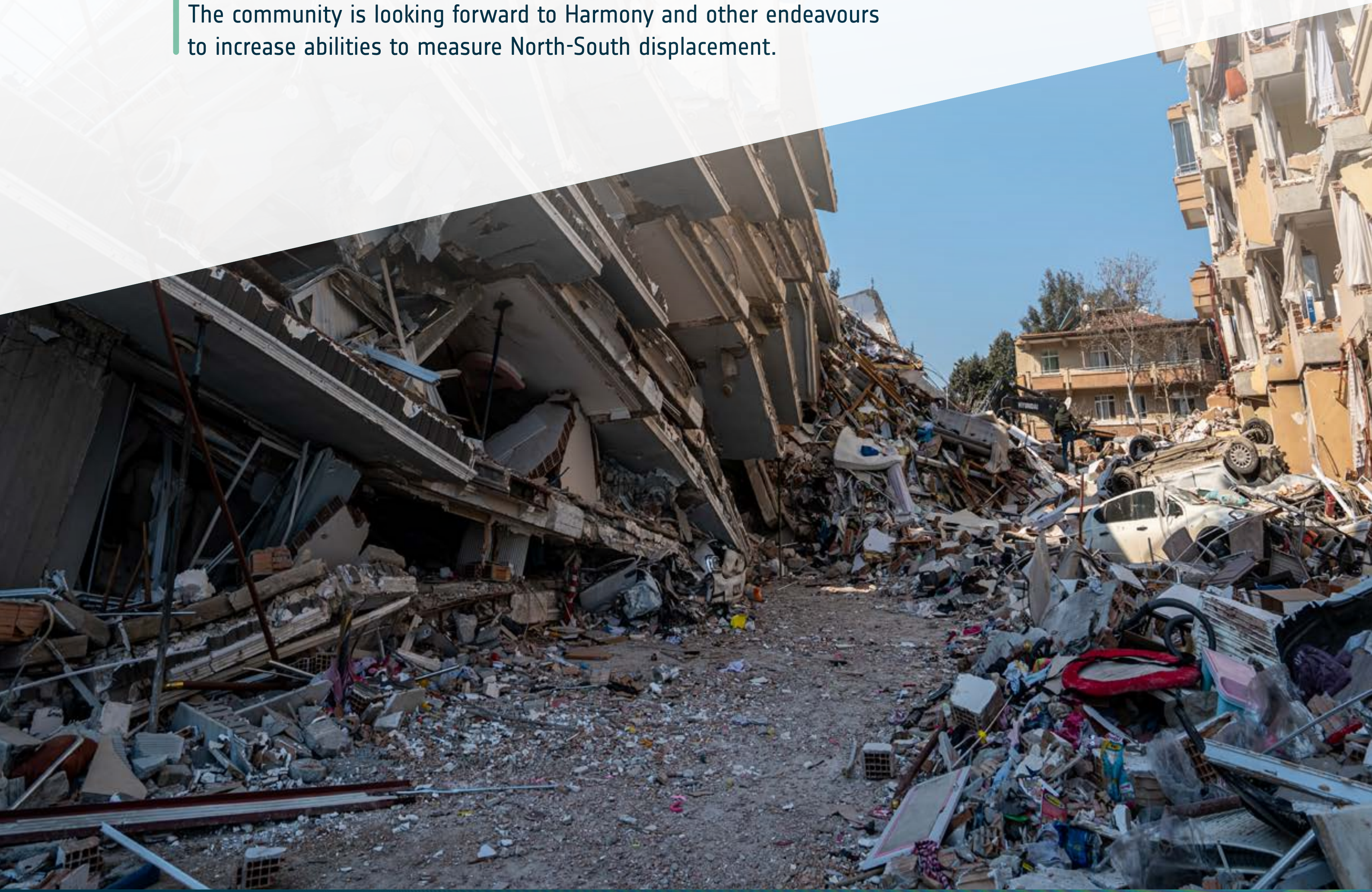
Chairs: Henriette Sudhaus, Kiel University/ Mustapha Meghraoui, University of Strasbourg

For the tectonic and earthquake community the response after this disaster is a milestone. Detailed mapping of the very long surface rupture based on InSAR and pixel offset tracking was shared a few days after the earthquake, less than two days after the necessary secondary image acquisition. There has been very good uptake by the media (e.g. in Germany the pixel offsets showing the surface deformation made it into the channel One 8 pm evening news!) However, the first postseismic SAR imaging over the affected area was acquired 4 days after the two major earthquakes. The community discussed a role of scientists in emergency response in terms of closer cooperation and communication with civil protection and disasters management.

During the session one of the topics discussed was the detailed 3D imaging of fault zone damage. These observations provide us with data to test hypotheses on crustal fault properties and behaviour. Off-fault localized deformation at preexisting secondary faults could be observed to large detail, particularly near the rupture termination location, that highlight the fault zone complexity to be further studied. The North component of surface motion was a well sought observation in the presentations. The community is a bit puzzled by relatively little early and afterslip/postseismic at the activated fault with respect to the large magnitude of the earthquake.

Recommendations

The community is looking forward to Harmony and other endeavours to increase abilities to measure North-South displacement.



Chairs: Carlos López-Martínez, Universitat Politecnica de Catalunya/ Alberto Refice, Consiglio Nazionale delle Ricerche

The main topics discussed during this session were:

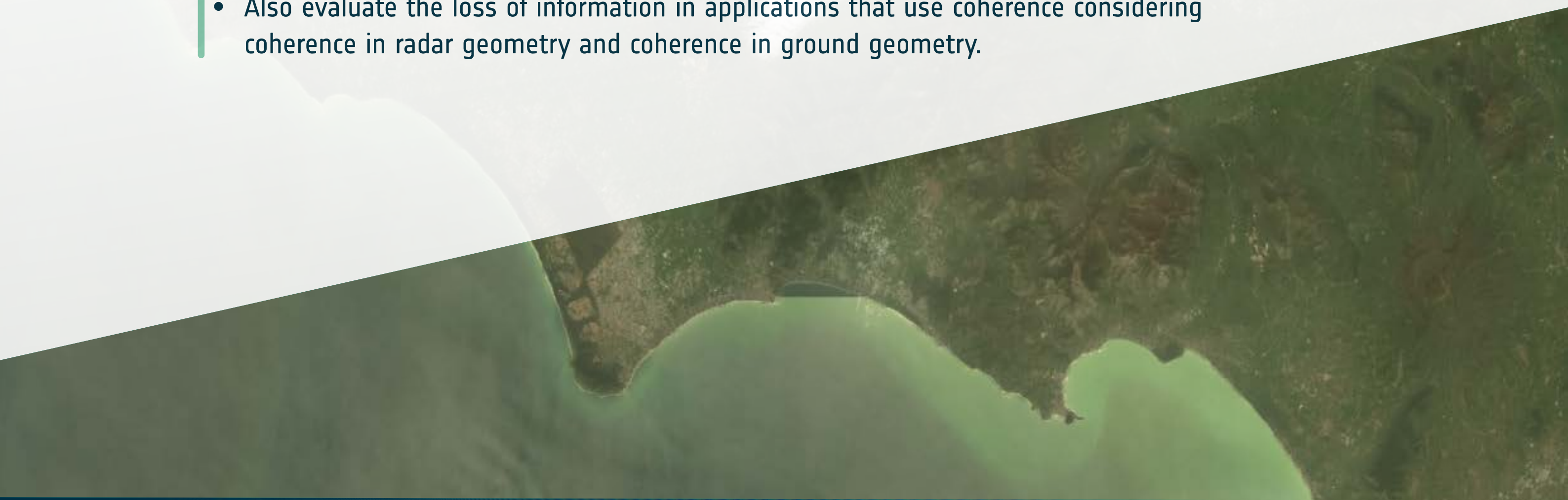
- The TanDEM-X DEM Change Maps Product and Their Application.
- Combination of Multi-Track Sentinel-1 Multitemporal InSAR Coherence and Sentinel-2 data in Land Cover and Vegetation Mapping: the SInCohMap project.
- Improving the Versatility of Post-Disaster Damage Mapping Algorithms by Combining InSAR Coherence and SAR Intensity Correlation.
- Innovation in InSAR Processing and Analysis of C-, X- and L-Band SAR Data for Natural Hazards, Agriculture, Marine and Coastal Applications in the framework of ASI's "Multi-Mission and Multi-Frequency SAR" Program.
- InSAR Coherence Analysis: A Proxy for Change Detection of Pavements.

The main topics emerging from this session are:

1. Interferometric InSAR coherence & multitemporal DEM changes, in the context of multitemporal analysis, as product providing information about the targets under study and their dynamics.
2. Coherence as complementary product to existing products in mapping and change detection, but better understanding of its behaviour and dependencies is needed.
3. DEM changes analysis for change detection, but uncertainty exists in interpreting DEM changes.
4. InSAR, multitemporal series, as technology for Earth's surface dynamics analysis

Recommendations

- Strengthen synergies between new missions (ROSE-L, S1NG, BIOMASS). Provide collocated, coregistered Analysis Ready Data datasets of these missions if possible.
- Provide geocoded SLC as Analysis Ready Data product to facilitate coherence use. It is necessary to evaluate the loss of information when geocoding SLC data to produce coherence.
- Also evaluate the loss of information in applications that use coherence considering coherence in radar geometry and coherence in ground geometry.



- Promote studies to determine theoretical models for temporal coherence at different frequency bands, polarizations, etc... The objective is to see if that there are other models possible beyond the exponential model.
- Promote additional studies on existing test-sites to evaluate the information content and the dynamic behaviour of temporal InSAR coherence.
- Advertise applications that benefit from the use of temporal coherence to raise awareness on people non experts in remote sensing for Earth observation.
- Focus on the exploitation of coherence for civil applications/infrastructures monitoring where spatial resolution is crucial.
- Keep investing in the SNAP software.

AI AND MACHINE LEARNING SESSION

Chair: Michele Martone, German Aerospace Center

Papers presented in the session described Machine Learning exploited for different SAR/InSAR applications:

- Monitoring and interpreting deformation of linear infrastructure using Deep Clustering of MTInSAR.
- Learning displacement signals from wrapped interferograms using Sentinel-1 and AI.
- The use of Deep Transformers ML method to improve spatial coverage of InSAR velocity maps.
- Exploitation of ML for performance-optimized SAR raw data compression.
- Potential of Deep Learning for the monitoring of the Amazon Forest with Sentinel-1 InSAR data.

ML represents a promising solution to support existing (physical-based) models for InSAR.

Applications for improving the currently achievable performance, increasing the computation efficiency (e.g. matrix inversion), filling the gaps due to missing/noisy data, creation of reference data and tool benchmark for machine learning purposes, SAR data compression and on-board SAR processing play an important role considering the increasing data volume to be acquired in the context of present and future missions.

Recommendations

- Given the increasing availability of freely available SAR/InSAR data, the potentials of methods exploiting ML for InSAR applications should be further investigated and benchmarked with respect to currently used (well-established) physical models, in terms of achievable accuracy and efficiency.
- ESA should support the curation of reference training (labelled) and test benchmark data sets to be exploited by the scientific community for ML/AI applications.
- Develop benchmarking algorithms that are more suitable for specific applications and use them as reference.
- ESA should support the creation of standardized data formats generated by different sensors and that can more easily be labelled; also, define standardized approach (e.g. pre-processing) when working with machine learning and complex SAR data.
- On-board SAR processing represents an attractive solution to potentially reduce the data storage and/or for fast information extraction, but it poses also challenges in terms of system complexity and for the generation of reliable products. Dedicated studies aimed at understanding potentials and limitations should be initiated.
- SAR data compression plays an important role for present and future missions; opportunities for suitable algorithms for data compression should be investigated in dedicated studies, especially but not only in relation to current ESA missions.

Chairs: Jose Manuel Delgado Blasco, RHEA Group/ Maya Ilieva, UPWr

This session focussed on the use of InSAR for landslide detection and monitoring. One of the topics discussed weather and in which cases shall optical data be used to complement landslides analysis, and whether that kind of analysis be proposed also for the next EGMS contract. The potential of exploiting "New Space" for systematic monitoring over landslides areas was also tackled, however, the conclusion was that this is still very limited and very localized data for InSAR applications. There was also discussion about slope failure prediction maps and the potential of producing such maps operationally. The conclusion was that current prediction methods are still not mature enough for an operational service.

One of the conclusions was that the new ESA missions (ROSE-L, BIOMASS, etc) data will be very useful for the landslide community.

Recommendations

- To integrate the coherence maps as a new layer, also NDVI for optical extra information, amplitude images as well that were not exploited yet.
- To improve the spatial resolution of the soil moisture layer – currently it is 1 km.
- Community would like to advice ESA to launch another constellation of small satellites, also with free available data, dedicated to landslides.
- The community needs to include L and P-band from the new ESA satellites to complement Sentinel-1 operationally, especially to map fast and very fast landslides events.
- ESA to push the other agencies to open their data policy (SAOCOM, ALOS-2, etc.).