InSAR Meteorology Workshop

March 1 and 2, 2018
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami.

Summary

The InSAR Meteorology workshop will assemble a small (20-40) group of domain experts in atmospheric science and experts in the InSAR and GNSS techniques with interest in atmospheric sciences. The goals of the workshop are (1) to make the atmospheric community aware of the potential and value of InSAR data, (2) to scout out particular research opportunities in atmospheric sciences that could benefit from InSAR data, and (3) to link communities in order to make advances in atmospheric sciences readily available to the space geodesy communities. The workshop is motivated by the forthcoming NASA-ISRO SAR mission (NISAR), which is scheduled for launch in 2021. The workshop organizers (Amelung and Mapes) are members of the NISAR science team with the explicit task of developing atmospheric applications of InSAR. The deliverables of the workshop will be a report entitled "Research Opportunities in InSAR Meteorology" that will also contain suggestions for an atmospheric correction strategy for the NISAR mission.

1. Overview

Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) are remote sensing techniques aimed to study the Solid Earth (tectonics and volcanoes), the cryosphere and the vegetation coverage of the planet. The largest impediment to these aims in the InSAR measurements are electromagnetic wave delays due to lateral patterns in the tropospheric water content. "Corrections" for this unwanted signal are an important stage of InSAR data processing, estimating and discarding this information about the atmospheric state. Might it have some value to atmospheric research, or potentially to operations if future InSAR missions are engineered to deliver their data in real time? We propose to organize a workshop bringing together the InSAR and relevant atmospheric sciences communities with the aim of raising awareness of the opportunities this data source may present to atmospheric science.

We must acknowledge at the outset that there are challenges and shortcomings to the use of these data in meteorology: the measurement is a slant-path column integral, and is a double difference in both space (pattern only, no absolute value) and time (relative to a reference chosen or derived from prior observations). Data are at a very fine native resolution (<1 km) that is both inconvenient in its sheer data volume and incommensurate with the column-integrated (~5km vertical scale) nature of the signal. Data latency (many hours) is much longer than the predictability time for these fine scales in the atmosphere, so the value currently will mainly be to research about past events, not real-time operational forecasting.

On the other hand, column water vapor (CWV) is a quantity with significant importance to the hydrological cycle, and in particular to storms that draw their energy from its condensation. Passive microwave measurements of CWV are accurate and abundant over the oceans at about 0.25 degree resolution, but over land passive techniques are badly fouled by the finely patterned and state dependent emissive backdrop, in infrared as well as microwave bands. In contrast, land surface *elevation* is a very stable background pattern at the relevant accuracy (cm or finer) outside a few areas of extremely active geology. Limb sounding such as by GNSS receiver constellations measures water vapor with quantitative accuracy, but involves horizontal integrals over >100km path lengths. Spaceborne profiling water vapor lidars are still a dream, with only airborne proofs of concept. In short, InSAR does occupy a unique niche of observational specification space (high relative accuracy at fine horizontal scales), albeit imperfectly (with very sporadic time sampling). What value can be extracted from these unique, quantitative glimpses, viewed in the context of the suite of other available measurements?

Aim: Bring together the water vapor and InSAR communities. The basic specifications of the NiSAR mission are little known to atmospheric scientists, while NISAR designers have limited intuition about the atmosphere on the space, time, and accuracy scale regimes the instrument will sample. An in-person encounter is considered essential to evoke the necessary opportunistic spirit to maximize this scientific opportunity.

2. Background SAR and InSAR

2.1 SAR missions. Space-based Synthetic Aperture Radar plays an increasing role for Earth Observations. The information provided is the amplitude of the signal backscattered from the Earth's surface and the interferometric phase obtained by combining two images acquired at different times. Currently there are 5 orbiting SAR missions or constellations comprising a total of 9 satellites (Sentinel-1A,B Cosmo-Skymed-1,2,3,4, TerraSAR-X, ALOS-2, Radarsat-2) that provide data for scientific and/or commercial applications. Another two SAR constellations are scheduled for launch in 2018 (SAOCOM, Radarsat-C) and the NASA ISRO SAR mission (NISAR) is scheduled for launch in 2021.

2.2 Interferometric SAR.

Coherent SAR measures phase: the fractional number of radar wavelengths along the two-way slant path to the target and back. Time differences in this quantity reflect both the change in slant path (due to ground motion), and the changes in wavelength at the transmitter's frequency induced by the index of refraction in the intervening medium, the so-called *phase delay*. Due to orbital considerations, the time differences are over days or longer, many many decorrelation times for the atmospheric state (the weather, mainly the water vapor content field). Furthermore, there are Nyquist ambiguities about whether the number of wavelengths has changed by an integer number as well as the fraction of a wavelength reflected in the data (that the data gives a *modulo 1* operation on the fractional number of wavelengths). At pixel scale, there would be no hope for resolving this ambiguity, but spatial structure (spatial coherence of interferometric fringe patterns) offers a way forward -- if we can sufficiently understand, estimate, and utilize the expected spatial patterns of both ground motions and atmospheric structure.

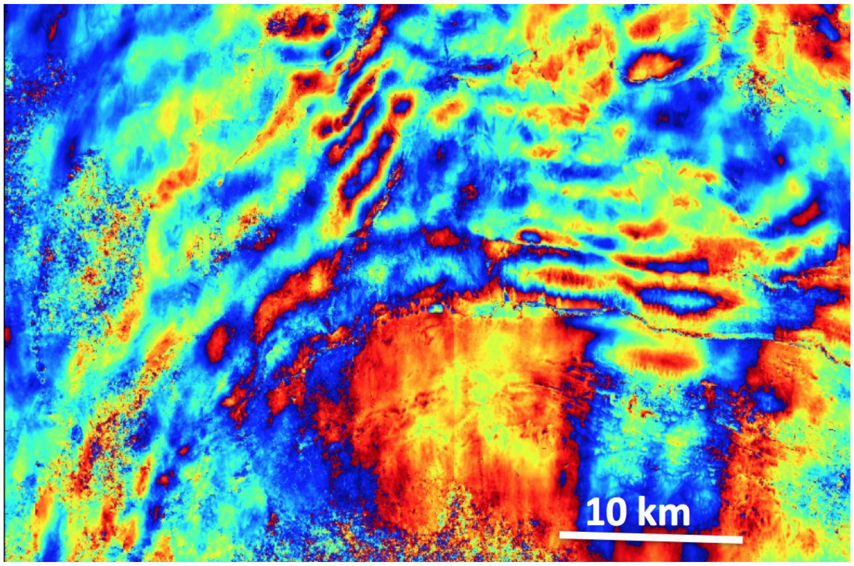

Figure 1. C-Band SAR interferogram showing the atmospheric variations related to gravity waves. One color cycle corresponds to 3 cm delay of the radar signal due to variations in water content. One limitation of InSAR is that it records only relative variations of PWV.

2.3 SAR Backscatter. Well-established marine SAR applications include sea-ice and oil-spill monitoring. A marine meteorological application is the measurement of wind speeds that can be compared with model predictions. *SAR polarimetry* derives information on land, snow, ice, and urban surfaces based on the measurement of the polarimetric properties of the ground scatterers.

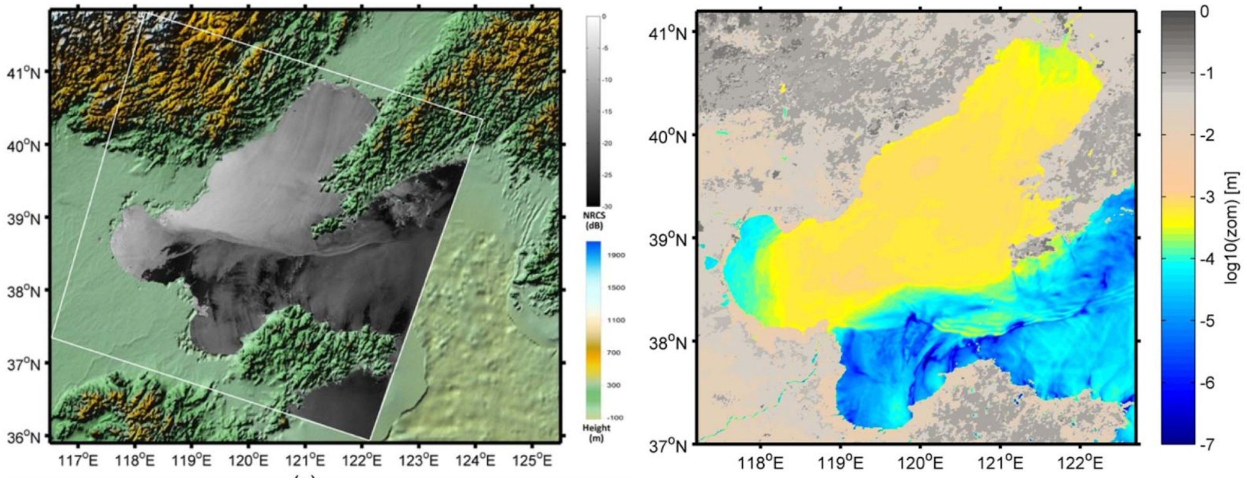

Figure 2. Marine meteorological application of SAR backscatter for surface winds. (Left) SAR backscatter measuring the roughness of the ocean surface, (right) Surface roughness length from a WRF simulation (from Li et al., 2016)

2.4 Atmospheric sciences: InSAR as a tropospheric measurement tool.

Background. Zenith phase delay *d* due to tropospheric mass (measured by surface pressure P), and due to the water vapor partial pressure profile e(z), are given by Doin et al. (2009) as:

$$d_{tropo} = 10^{-6}\left[\frac{k_1 R_d}{g_m}P(z_0) + \int_{z_0}^{\infty}\left(\left(k_2 - \frac{R_d}{R_v}k_1\right)\frac{e}{T} + k_3\frac{e}{T^2}\right)\mathrm{d}z\right]$$

The hydrostatic delay term (the first term) is larger (~3m), but much less variable (+/- a well-estimated, smooth pattern of ~1% amplitude) than the wet delay (the second term, of magnitude ~30cm +/- a complex, rapidly changing, and often poorly measured field with ~100% amplitude).

That second term can be approximated in terms of an estimate of column water vapor (CWV):

*d ~ CWV *6 /cos(zenith angle)*

CWV is a quantity of great meteorological interest (see Sherwood et al. 2010 for a broad review), with a dynamic range of 0-7 cm over the Earth. With the factor of 6 above, and the ~6cm wavelength of SAR, CWV variations thus translate into a few wraparounds (fringes) if interferometric phase. CWV is poorly measured over land by the passive microwave methods that observe it accurately over water. This is because water's high reflectivity in the microwave implies a low emissivity, so that water is a cold brightness temperature backdrop for upward emissions by water vapor that the satellites sense. When d is measured to the specifications needed for geodesy (to sense changes in surface elevation slope of ~1cm/100km between satellite overpasses), the implied accuracy of the CWV measurement (again, as part of a double difference in both space and time) is on the order of 1-2 mm. Such a measurement of CWV horizontal pattern structure is clearly precise enough to be of interest to atmospheric science, even if the differencing means that the absolute value has to pinned down by other methods.

For near-nadir measurements, and assuming a smooth past reference for the time differencing is available, the quantity InSAR presents to atmospheric scientists is essentially a high-resolution field of (CWV mod L/6), where L is the wavelength of NiSAR and mod is the modulo operator. Mockups of this quantity can be made from simulated CWV fields in order to motivate use cases. Because of the mod operation, it has a wraparound value (color) scale as in the image above.

Opportunities. Parallel efforts in Europe are indicative of the opportunities: The ESA Sentinel-1 mission has a relatively short (6-day) revisiting time and wide swath. A set of interferograms can be converted into a time-series (see Fig. 3) of accurate information on the tropospheric physical properties (refractivity) which can in principle be assimilated into Numerical Weather Models (NWMs) for more accurate weather forecast and (in a retrospective reanalysis context) climate studies. Merging InSAR data with the traditional GNSS tomography of atmosphere (whether

inside a model assimilation procedure, or in offline retrievals) is expected to provide significant information content (in a Bayesian sense) to atmospheric state estimates
Measurements offset in time can only be utilized will in the context of an atmospheric model which can evolve the pattern of CWV (and the other variables) in time according to the laws of motion and the other physical laws for sources and sinks (cloud condensation, mixing, evaporation from clouds and precipitation and from the surface, etc.). This process is known as data assimilation, and is an art as well as a science. For this reason, experts need to be brought together to frame the problem at its most general, although simpler approximate approaches may suffice in light of the uncertainties and errors that prevent the full daydream implementation where models and data are assumed perfect.

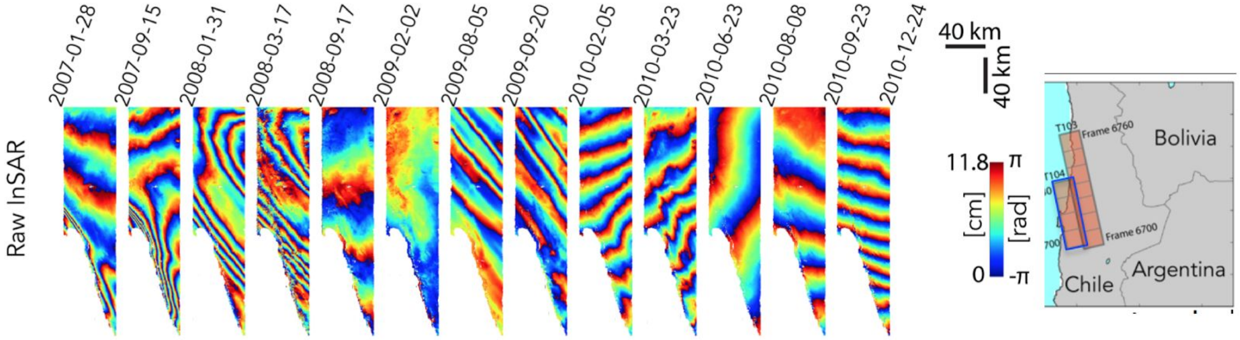

Figure 3: Example of an InSAR time-series for a location in Northern Chile, showing changes in radar range (phase) with respect to the first acquisition [from Fattahi et al., 2017]. In this example the changes due to ionospheric variations are shown. Tropospheric contributions are similar but of smaller magnitude (ionospheric contributions are less a concern for geodesy because they can be estimated and corrected for from the data). Ground deformation is inferred from time series of several tens of SAR acquisitions.

2.5 *Geodetic science: Atmospheric corrections for InSAR*

The simplistic Saastamoinen model (using only surface RH to estimate the column moisture) has errors of 2-5 cm in the ZWD, which is inadequate for geodetical purposes. It is clear that the CWV pattern in the free troposphere, away from the surface, must be estimated or measured more accurately in order to meet the specs for capturing geodetic phenomena of interest.

The InSAR community has devised various correction schemes, largely relying on ready-accessible global weather models (Fig. 4). Popular models are the ERA-interim and ERA5 global re-analysis models provided by the European Center for Medium Range Weather Forecasting (ECMWF) and the HRES ECMWF forecast model. The GACOS project aims to refine information from HRES with GNSS zenith delays if available. An *open question* is whether heterogeneous, nested atmospheric models with temporal and spatial spacing adopted to a particular SAR mission would lead to improved InSAR corrections.

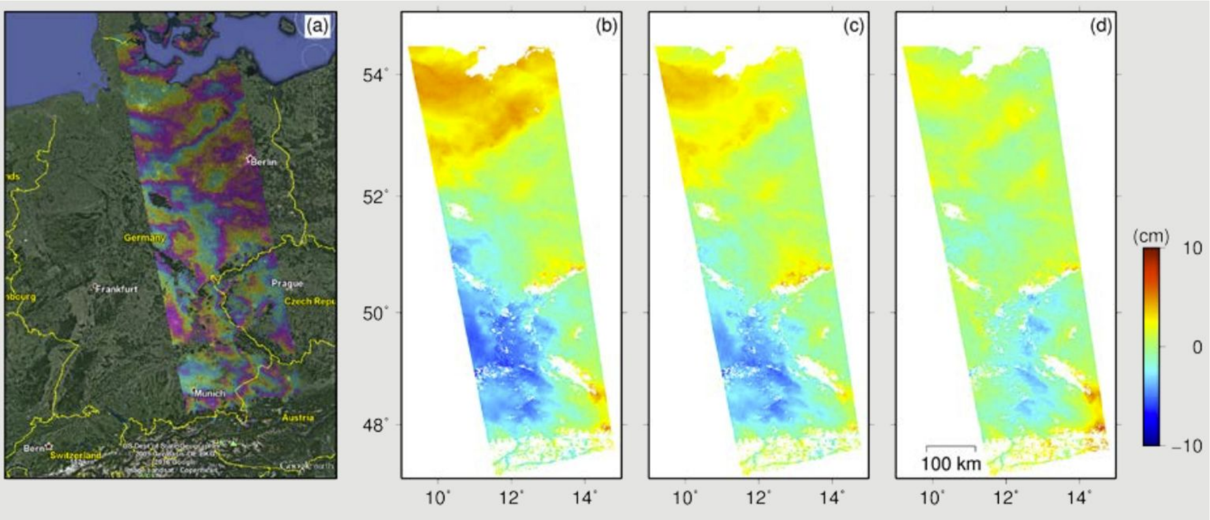

Figure 4: (a) 900-km long Sentinel-1 interferogram between 7 and 19 January 2016 across Germany, (b) unwrapped phase of the interferogram, (c) and (d) unwrapped phase corrected for atmospheric water vapor with ERA-Interim and GNSS atmospheric models (from Haghshenas Haghighi and Motagh, 2017). (d) shows lateral CWV variations at a scale not detected by GNSS.

3. Deliverable: Workshop Report

The output of the workshop will be summarized in a report. The audience are atmospheric scientists, InSAR scientists and the NISAR Science team, and NASA program managers interested in bringing together the NISAR and atmospheric communities. The contents of our report will cover:

- State-of-the-art of water vapor measurements in the atmosphere (satellite and in-situ assets and their temporal and spatial resolution)
- Description of atmospheric measurements gaps or opportunities that could be filled by InSAR.
- Potential applications of InSAR for atmospheric sciences (exciting new science that was unthinkable)
- Action plan including data processing and access recommendations necessary to realize the opportunities.
- Consideration of future joint atmospheric-geodetic science SAR missions.

This report will be a more focused and updated revisit of the issues touched in the 2009 TIGIR workshop held at the Jet Propulsion summary (see references). It will also address some of the recommendations coming out of the atmosphere/ionosphere session of the European Space Agency's Fringe 2017 workshop held in June 2017 in Helsinki Finnland (see Appendix A)

4. References:

Alshawaf, Fadwa, Stefan Hinz, Michael Mayer, and Franz J. Meyer. "Constructing accurate maps of atmospheric water vapor by combining interferometric synthetic aperture radar and GNSS observations." *Journal of Geophysical Research: Atmospheres* 120, no. 4 (2015): 1391-1403.

Haghshenas Haghighi and Motagh, 2017. Sentinel-1 InSAR over Germany:Large-Scale Interferometry, Atmospheric Effects, and Ground Deformation Mapping. Zeitschrift fuer Vermessungswesen, 142, DOI 10.12902/zfv-0174-2017

GACOS (Generic Atmospheric Correction Online Service for InSAR) developed at Newcastle University: http://ceg-research.ncl.ac.uk/v2/gacos/

Li, X., Zheng, W., Yang, X. and Pietrafesa, L.J., 2017. Sea Fetch Observed by Synthetic Aperture Radar. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(1), pp.272-279.

Mateus, P., Catalão, J. and Nico, G., 2017. Sentinel-1 Interferometric SAR Mapping of Precipitable Water Vapor Over a Country-Spanning Area. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(5), pp.2993-2999.

Sherwood, S., R. Roca, T. Weckwerth, and N. Andronova, 2010: Tropospheric water vapor, convection and climate. Rev. Geo- phys., 48, RG2001, doi:10.1029/2009RG000301.

Yu, C., N. T. Penna, and Z. Li (2017), Generation of real-time mode high-resolution water vapor fields from GPS observations, J. Geophys. Res. Atmos., 122, 2008–2025, doi:10.1002/2016JD025753. [Link]

Yu, C., Z. Li, and N. T. Penna (2017), Interferometric synthetic aperture radar atmospheric correction using a GPS-based iterative tropospheric decomposition model, Remote Sens. Environ., doi:10.1016/j.rse.2017.10.038.

TIGIR 2009 workshop documents:

Proposal:https://www.unavco.org/community/publications_and_reports/proposals/2009/TIGIR-Workshop-proposal.pdf

Report: https://miami.box.com/s/yxq29nel309j8uhzf2k73ceq0y3fnkb6

Appendix

The European Space Agency's (ESA's)Fringe 2017 workshop held in June 2017 in Helsinki featured an Atmosphere/Ionosphere session including a 45 minutes moderated open-discussion session with the objective of providing recommendation to ESA. The recommendations, which will be partly addressed by the Miami workshop were:

Troposphere:

Recommendation 1: ESA should provide a tropospheric correction product for Sentinel-1. This should be based on either the HRES ECMWF forecast model or the ERA5 reanalysis model . A community recommendation may come out the Miami workshop in March 2018.

Recommendation 2: ESA should facilitate access to regional models (e.g. Unified Model for UK, Harmonie LAM) (Z Li can provide list of models for Europe)

Recommendation 3: ESA should develop with ECMWF a heterogeneous Sentinel-1-adapted atmospheric reanalysis model (moving window-type with high spatial resolution model output at SAR acquisition times).

Recommendation 4: ESA should establish InSAR Meteorology Supersites in collaboration with sister agencies (e.g. Radarsat-C 1-2 SAR images/day)
Recommendation 5: ESA should promote funding for InSAR Met research and organize joint workshops between Meteorologists and the InSAR community.

Ionosphere:
Recommendation 6: ESA should organize an InSAR ionosphere workshop preferably in collaboration with the GNSS and ionosphere communities.

Recommendation 7: ESA should work with the community to implement state of the art ionospheric correction technology (split-spectrum InSAR) into software tools such as SNAP to enable users to include ionospheric correction steps into their InSAR workflows.

Recommendation 8: ESA should provide correction layer for ionosphere. Ionospheric correction would be calculated by ESA (e.g. using SNAP) (long term goal).