Report of: Miami InSAR for atmosphere workshop of March 2018

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1. Introduction

Motivated by the upcoming NISAR mission, more than 30 participants convened for two days in Miami in March 2018 to discuss lower atmosphere-related signals in Interferometric Synthetic Aperture Radar (InSAR) observations. The goals were (1) to spotlight the possible atmospheric science value of InSAR observations, (2) to review opportunities for improved atmospheric correction for geodesy, and (3) to seek a nexus between these interests that might serve to motivate the complex efforts required.

This report summarizes opportunities identified in the wide-ranging presentations and breakout session notes. It expands upon and updates the lower-atmospheric aspects of the prior 2009 TIGIR workshop report. Much of the workshop's discourse necessarily centered on the challenges and difficulties of utilizing InSAR as a salient atmospheric observing system. What could it add to existing estimates of the atmosphere's state, generated by multiple other observational data streams and advanced data-assimilating models?

Geodesy presentations emphasized how crucial atmospheric corrections are to achieving goals in volcano and earthquake science. Detailed estimation of the atmospheric component of InSAR's signal stream *must* be done, both in near real time for hazard warnings, and in retrospect for geodetic research. Given that fact, mustn't there be *some* atmospheric science value to be gained? The difference between the InSAR observation and an atmospheric model *ipso facto* comprises new information for atmospheric science, albeit in an already information-rich context.

Since the workshop, a JPL-led project was initiated to address goal 2 (atmospheric corrections). As a report is being drafted for this project [Zhong, Bekaert et al., AGU 2020], this topic is not addressed in this document.

The workshop website, available from this wordpress URL, has more details on the agenda and attendees. The presentations archive is located in this Box folder.

2. Sessions & themes: back and forth, crosscuts

The workshop opened with sessions reviewing Foundations (of both InSAR and atmospheric science) and the existing skyscape of atmospheric observations. One session focused specifically on Global Navigation Satellite System (GNSS) data, which contain a column-integrated water vapor measurement that is comparable to the wet-delay atmospheric signal in InSAR data. Further sessions surveyed opportunities for collaboration: *What can InSAR do for Meteorology? What can Meteorology do for Geodesy (Atmospheric Corrections)?* A session on *Data Infrastructure and Product Design* discussed the challenges and practicalities of data processing. Breakout groups pondered *New Opportunities in the Physics of the Measurement, Water Vapor Retrievals/Corrections, Data stream Processing*, and a *Tiger Team on Atmospheric Product designs* for a possible JPL-led reprocessing workflow using existing InSAR data archives.

3. Recurrent issues from stubborn challenges

A unique strength of InSAR for atmospheric science is that it measures vapor *over land* where the passive microwave constellation is hobbled by surface emissivity complications. The main weaknesses are the sparse coverage in time and the modest swath width. The sampling interval is long relative to atmospheric decorrelation time, which means that the necessary time differencing of InSAR phase acquisitions blends two almost unrelated atmospheric situations, complicating interpretation. Sampling could be improved with constellations, and is more frequent at high latitude, but temporally unresolved atmospheric pattern evolution still thwarts InSAR's perhaps greatest strength: high horizontal resolution.

The limited coverage reduces InSAR's value in ways that are obvious for any single-source data studies, but also affect multi-source work like data assimilation. Data sources with only occasional availability can be so tricky to utilize that their impact is not necessarily unambiguously positive, or may require prohibitively complex tailored efforts to exploit. Another potential problem is diurnal-cycle undersampling and aliasing by sampling from sun-synchronous orbits. The impact of these limitations remains to be quantified in studies. Geostationary InSAR could someday solve these temporal and spatial coverage weaknesses, while sacrificing only the horizontal resolution from polar orbiters (which is excessively fine anyway). That would be a game-changer for atmospheric science users.

The salient horizontal features in atmospheric column-integrated water vapor are on kilometer scales, and thus are grossly oversampled by InSAR's pixel lengths of 10s of meters. InSAR's nominal strength of spatial resolution is thus a burden for atmospheric applications because of unwanted data volume. But this hurdle can easily be removed by the production of down-sampled global grid data products, preferably with phase ambiguities pinned by absolute wet delay measurements (e.g. from GNSS sites).

An easy challenge is the fact that InSAR phase delay mixes information from different atmospheric state parameters: dry air mass, temperature, condensed water, and water vapor and soil moisture. Dry air mass is well analyzed and predicted as surface pressure, whose dynamics are relatively smooth in space and time and well covered by the weather enterprise, a success true also of temperature to some extent. Temperature and condensed water effects are quantitatively small. For all these reasons, the *wet delay* component can be isolated quite reliably.

Workshop presentations suggest that the pixels in *water vapor path difference maps* (interferograms) are typically accurate to the order of +/- 1 kg m^{-2} (equal to mm of liquid equivalent or “precipitable” water PW). This is roughly a 1% error bar in Earth’s total dynamic range of about 0-70 mm in zenith column integrals. If atmospheric vapor in one map of the difference pair (called the reference acquisition) is known to be low, or smooth (weakly patterned), interpretation can focus more clearly on the other one. For instance, convective-scale vapor patterns in an unstable patch of atmosphere can be usefully obtained as a difference from the same area under a smooth stable airmass from another season, synoptic weather state, or time of day. Once a suitable smooth and/or dry reference scene is selected, however, *time series* of difference maps can use the same reference scene, facilitating interpretation.

Beyond water vapor, the workshop also considered other atmospheric science-relevant InSAR measurables, such as surface conditions. For instance, SAR observations of phase incoherence, indicating surface water in inundated lands, or ponding or leads in ice scenes, could inform surface boundary conditions to which atmospheric models are importantly sensitive. Relatedly, soil moisture information is contained in SAR phase budget closure residuals. SAR’s high-resolution surface observations can also inform retrieval challenges in other data sources, such as beam-filling problems for passive microwave sensors. Less directly, marine wave estimates contain integrated information about past wind fields in the atmosphere.

Some useful numbers and facts to keep in mind include:

- 1 mm of PW corresponds to about 6 mm in phase delay, and the entire terrestrial atmosphere’s range of variation of PW is about 0-70mm.
- InSAR senses a slanted (25-45 degrees from nadir) path integral through the atmosphere, blending information from a range of altitudes at horizontal locations a few km apart, since the depth of the water vapor-bearing layer is several km.
- Volcanic hazard forecasting applications require estimating differences of 1-2 centimeters (2-3 mm PW), with time trends no larger than meteorological PW trends from day to day, and longer-term differences no larger than atmospheric differences from season to season or year to year.
- The horizontal scale of crustal deformations of interest is of order 10s-100s of km. This falls in the atmospheric *mesoscales,* between convective and synoptic

scales. In these scales, the types of geodesy-confounding vapor structures needing correction include filaments along the direction of a wind strain field, cross-wind wavy patterns due to internal waves forced by flow over surface topography, or lumps in unstable (convecting) conditions.

4. Main opportunities and recommendations

This section summarizes some opportunities identified in the workshop materials and notes, in somewhat descending order of promise. For each opportunity, exploit requirements are summarized. Those are translated into recommendations and suggestions, ordered roughly by increasing cost and difficulty.

a. Marine wind and sea/ice surface conditions

Value: SAR already provides valuable information, with stakeholders including wind farming, sea ice, oil spills, shipping, etc.

Exploit requirements: Operational (NOAA SAROPS) exploits are in place. Wind speed is well measured, especially up to high speeds where scatterometry saturates. High resolution allows direction to be inferred from streaks and rolls, and extends data into the coastal zone and down to fine scales.

Suggestion: Ocean wave spectra contain a convoluted blend of surface wind that in principle might be used to back out winds earlier and elsewhere.
Suggestion: Passive microwave retrievals could be improved based on InSAR backdrop scene information, like sea ice leads or sea state.
Suggestion: High latitude applications are especially strong, because overlapping satellite swaths provide good temporal coverage.

b. Column water vapor (CWV or PW) in the atmosphere

i. General spectrum of variability by scale

Value: Documenting the climatological spatial-scale spectrum could utilize SAR's high resolution as a strength. Such an effort could help to justify and showcase whole-dataset scale InSAR processing efforts, despite the spatial and temporal sampling limitations. Results can serve as statistical validation targets for high-resolution atmospheric simulations to try and emulate. This climatological variance spectrum could provide spectral scale-aware uncertainties for corrected geodetic data. Differences in local spatial spectra (textures) can serve as indicators of important atmospheric regime distinctions, such as more-convective vs. more-laminar weather, even if absolute values remain challenging to retrieve.

Exploit requirements: A continental or global, km-scale InSAR time-series data product with a well-chosen (smooth, dry conditions) reference acquisition is the baseline requirement for most atmospheric applications of wet delay data. Once such a dataset exists, atmospheric science challenges such as spectral estimation in gappy data, and the task of making salient comparisons to high-resolution atmospheric model grids (e.g. by InSAR-like masking of model grids), will be student-tractable efforts.

Suggestion: Slant-delay time series are the desired data products, since zenith estimation can be simple (cosine correction) or complex (slant assimilation). Expanding on our modest pilot effort over CONUS, where high-resolution weather model data (HRRR, on a 3km grid) are available to compare and contrast with InSAR data, could further clarify challenges and opportunities.

ii. Site-specific microclimate studies

Value: Site-scale comparisons utilize SAR's extremely fine resolution as a strength. Such work feeds into site-scale science for which the comparison combinations of multiple datasets are a strength, despite the hyperlocal sampling weakness. Such an effort could entrain SuperSite data communities to InSAR work, opening collaborations in both U.S. interagency (like DOE ARM community) and international directions.

Exploit requirements: Geographically localized time series data products for a set of sites/regions.

Suggestions: USA examples discussed at the workshop included DOE/ARM sites at SGP (Oklahoma/Kansas), NSA (Alaska), and mobile deployments. Other mentions included: ENA (eastern US), Ascension, Azores, Svalbard, S-band ground radar sites, Hawaii, Lisbon, Basilicata, Finland (Nico), VLBI antennas (Onsala, Japan), Taiwan, Polar, China, Mexico city SAR calibration site, India and other tropical climates with humidity-dependent moist convection.

iii. Atmospheric convection and wave process studies

Value: Column vapor (CWV or PW) is a key interactive field in important moist convection processes in the atmosphere. Internal waves are another process producing CWV structure on similar scales, by thickening and thinning the moisture bearing layers of air. Assuming these fast waves are adiabatic, associated temperature changes can be inferred, although the slant-path integral nature of the measurement makes interpretation only semi-quantitative and ambiguous. Studies of both processes, or their interaction, could therefore be undertaken with mesoscale-resolving InSAR data.

Exploit requirements: The atmospheric science effort would be to combine detected wave signals with ancillary data, both remotely sensed (satellite imagery, precipitation radar, GNSS for time resolution, radio occultation for vertical resolution) and in situ (especially if some are near research super-sites as above in item ii.). Interpretive case study analysis, perhaps bolstered by model simulation or assimilation efforts, would be the capstone scientific activity.

Suggestion: Strong cases of atmospheric features could be identified by applying machine learning techniques to global InSAR time series data products. Limited availability of InSAR should drive study case selection; weather models have total coverage and can match it.

iv. Atmospheric correction failure and bust studies

Value: In the absence of earthquakes and rapid tectonic deformation, corrected InSAR time series are a measure of the quality of the atmospheric model products used for the correction. A focus on well-measured failures of those model products could attract a larger atmospheric science community to this new data source.

Exploit requirements: A collection of rich datasets could be assembled around particularly illustrative busts (poor performances) of atmospheric correction systems, as determined after the fact.

Suggestion: Automated search (including machine learning and AI systems) can easily identify outliers and poor correction performances in a global data set.

v. Assimilation testbed

Value: To explore InSAR's atmospheric information value thoroughly, in the realistic context of other existing datasets, a testbed is needed for model-based assimilation research (including the mesoscales where InSAR provides unique information).

Exploit requirements: An atmospheric model forecast system (with assimilation capabilities, and hindcast skill evaluation protocols to measure better vs. worse outcomes) would need to be available to run in a data-proximate setting. Ideally, this should be a 4DVAR assimilation system, capable of feature relocation -- a common form of error at fine scales where InSAR's high resolution adds the most value. All other routine data sources would have to be available in this computation environment too, in order to demonstrate the (hypothesized) *added* value of InSAR's unique information content.

Suggestion: Such an effort would probably have to be a funded collaboration at an NWP or experimental forecast center (like NASA's GMAO) where serious data assimilation capabilities exist.

c. **Surface state as a boundary condition to the atmosphere**

Exploit requirements: InSAR-based ice cover information, including narrow openings or "leads" and surface water ponds or inundation fraction, could be directly usable as lower boundary information under atmospheric models. Inferences about vegetation could similarly have value, but would require expert land surface modeling community involvement since the state-variable space is not easy to map InSAR observables into.

Soil moisture detected from "phase closure" error in acquisition triplets, is a promising variable for initializing land subsurface models. However, this was too tangential to our workshop for a thorough assessment of its value in light of other soil moisture missions (SMAP, SMOS). A different expert community would be needed to assess this opportunity in any detail.

Prospects for low-latency products:

The workshop discussions considered whether low-latency products should be prioritized for atmospheric purposes. Low latency would be essential for InSAR to make an impact on the Numerical Weather Prediction (NWP) enterprise -- and then only if all the other challenges of data use can be tackled.

The greatest strengths of InSAR (high spatial resolution) are especially hard to exploit for weather prediction, because fine scales have a short predictability horizon. The market niche for InSAR's unique information contribution is slender. In light of these challenges, a realtime InSAR delay product intended for NWP assimilation of its water vapor information is hard to prioritize very highly, in the view of workshop discussions.

General data product recommendations

The breakout group on data product design concluded that column-integrated water vapor maps over land, on a horizontal mesh fine enough to resolve the atmospheric mesoscale (of order 1 km), could be a unique contribution of InSAR to atmospheric science. The suggested Level 3 products are:

- Global land InSAR time series at 0.33 km and 1 km resolution, with carefully selected reference acquisitions (seeking uniform dry air masses) to maximize interpretability of patterns.

- Soil moisture products.

In light of the inescapable weaknesses of InSAR data for atmospheric science (sparse time coverage and narrow swath width), the prospects for uptake or utilization of such atmospheric data products hinges on ease of data access.

Appendix A: agenda and presentations links

box of presentations is here

Thursday. Rapporteurs: https://tinyurl.com/InsarMiami2018

8:45 Introduction and workshop goals *(10 min)*, Welcome from NASA (15 min)

Session 1: Foundation – InSAR

09:10 – The NISAR mission *(30)* – Paul Rosen Rapporteur: Foster

09:40 – InSAR for atmosphere *(45 min)* – Ramon Hanssen Rapporteur: Mapes

10:25 – SAR data issues *(15 min)* – Paul Rosen Rapporteur: Igel

Coffee – 10:40-11:00

Session 2: Foundations – Atmospheric Sciences

11:00 – Scales in the atmosphere *(15 min)* – Brian Mapes Rapporteur: Nico

11:15 – CWV and oceanic convection *(30)* – Matthew Igel Rapporteur: Zuidema

11:45 – CWV & continental convection *(30)* – David Adams Rapporteur: Kursinski

12:15 –Impact of Assimilating Moisture … *(30)* – Shu-Hua Chen Rapporteur: Adams

Breakout intro and Lunch – 12:45 – 14:00

Session 3: Existing Observations

14:00 – Existing remote sensing obs *(30)* – Paquita Zuidema Rapporteur: Kursinski

14:30 – GPS Met 25 years later: *(30)* – Bevis à James Foster Rapporteur: Hunter

15:00 – Title TBD *(30 min)* – Robert Kursinski Rapporteur: Rodrigues Gonzalez

Coffee – 15:30-15:45

Session 4: What can InSAR do for Meteorology?

15:45 – Keynote: Examples of InSAR PWV – Giovanni Nico Rapporteur: Amelung

16:15 General Discussion – *Leading to 3 Breakout groups*

Posters – 17:30,

Reception – 18:00

Dinner – 19:00

Friday: **Breakfast** – 08:30 – 09:00

Session 5: What can Meteorology do for Geodesy? InSAR Atmospheric corrections

09:00- Motivation: Terrestrial applications of InSAR *(20 min)* – Amelung

09:20 – Generic Atmospheric Correction Online Service *(30 min)* – Zhenhong Li

09:50 – Operational weather modelling & atm corrections (Mapes , Foster)

10:20 – Towards automated robust correction - David Bekaert *(15 min)*

10:35 –InSAR atmospheric noise (Rodrigues Gonzalez , Fielding)

10:50 – Ionosphere: one geodesists learned to deal with *(5 min)* – Eric Fielding

Coffee – 11:05-11:20

Session 6: GNSS Applications

11:20 – Estimation of water vapor from ground-based GNSS – Gunnar Elgered

11:50 – Impact on Short-to-Medium-Range Forecasts – Avelino Arellano

12:10 – Occultation *(15 min)* – Robert Kursinski

Lunch – 12:30-13:30

Session 7A: What can SAR and InSAR do for Meteorology?

13:30 – Understanding mountain-wave phases – Ye Yun

13:50 – SAR & Marine Atmospheric Phenomena – Frank Monaldo and Xiaofeng Li

14:10 – Meteo-Marine w/ interferometric and dual-pol SAR Data – Susanne Lehner

Session 7B: Data Infrastructure and Product Design

14:30- NISAR data products – Eric Fielding

14:40 –numerical weather prediction, weather observing system – Robert Atlas

14:50 – Data infrastructure for GNSS Met – Gunnar Elgered

Coffee – 15:00 – 15:15

15:15 Summary of breakouts so far, more breakout time

17:00 Ignite talks (5 min each), Panel Discussion (17:15),

Appendix B: Scientific Committee

David Adams	UNAM
Falk Amelung	U Miami
John Braun	UCAR Boulder
James Foster	U Hawaii
Ramon Hanssen	TU Delft
Matthew Igel	UC Davis
Robert Kursinski	PlanetiQ
Zhenhong Li	Newcastle University

Brian Mapes	U Miami
Giovanni Nico	CNR Bari
Jens Wickert	GFZ Potsdam
Paquita Zuidema	U Miami