# GEOS 657 – MICROWAVE REMOTE SENSING

GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

**Lecturer:**
Franz J Meyer, Geophysical Institute, University of Alaska Fairbanks, Fairbanks; fjmeyer@alaska.edu

**Lecture 12: InSAR for Deformation Monitoring, Automatic Processing Services & Limitations of Traditional InSAR**

UAF Course GEOS 657

---

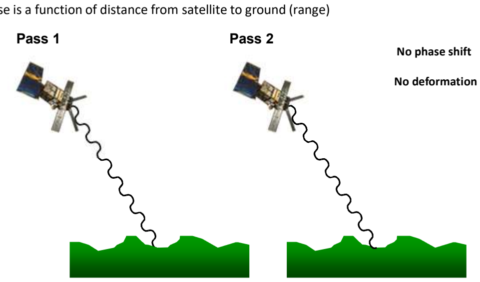
- https://avo.alaska.edu/images/image.php?id=194280
- https://avo.alaska.edu/images/image.php?id=194281



---

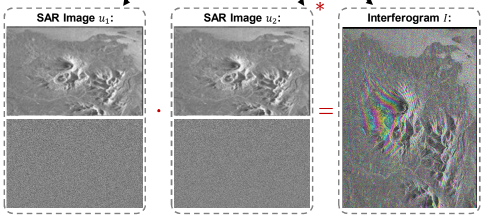
## How InSAR Works

- InSAR phase is a function of distance from satellite to ground (range)



## InSAR Processing – Steps 1 – 7:
**Find and Download Images, Co-Register & Form Interferogram**

- **To form interferogram, we calculate:** $I = u_1 \cdot u_2^*$ (where * is complex conjugate)

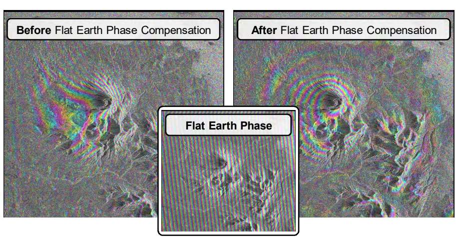



**Example**: Mt. Peulik volcano, Alaska

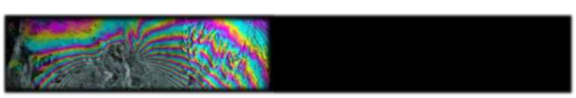


## InSAR Processing – Step 8:
**Subtraction of Flat Earth Phase**

- **Example:**
  - ERS-2 Interferogram of Mt. Peulik volcano, Alaska

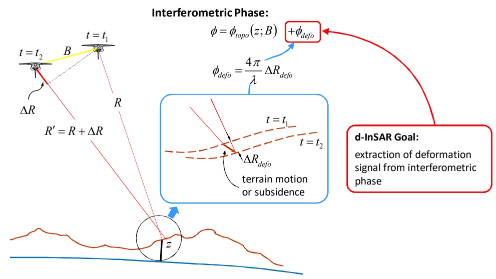




DIFFERENTIAL INSAR – A METHOD FOR CM-SCALE DEFORMATION MONITORING

## The Concept of Differential InSAR (d-InSAR)






## How to Separate Topographic and Deformation Phase?

**1. If reliable DEM is available, use DEM to compensate for topography.**

**2. Else, ≥ 3 complex SAR images at times $t_1, t_2, \ldots, t_n$ are required:**

- Form several interferograms:
  - time lag: $\Delta t_{n-m} = t_n - t_m$
  - baseline: $B_{\perp,n-m}$
  - phase: $\phi_{n-m}$
- For constant velocity: $\phi_{n-m}^{defo} = \phi_{n-m} \propto \Delta t_{n-m}$ and $\phi_{n-m}^{topo} = \phi_{n-m} \propto B_{\perp,n-m}$

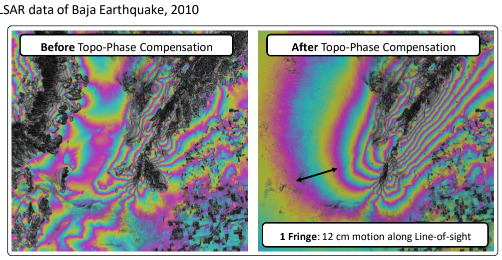
**For signal separation consider:**
- Deformation phase changes only with time
- Topography phase changes only with Baseline

**3. For singular displacement event:** use $\phi_{n-m} \propto B_{\perp,n-m}$ to derive topography



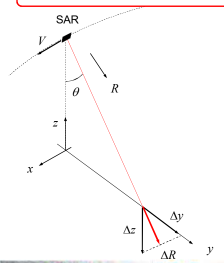
## Example of Topography Compensation

- Compensation using available DEM
- ALOS PALSAR data of Baja Earthquake, 2010



## How well can we measure deformation?

**How to measure surface motion from the InSAR phase:** $\phi_{defo} = \frac{4\pi}{\lambda}\Delta R_{defo}$




**$\Delta R$ is motion in sensor look direction**

$$\Delta R = \Delta y \sin\theta - \Delta z \cos\theta$$

**For previous PALSAR example:**

1 fringe ($2\pi$) corresponds to

**12.5 cm** in R

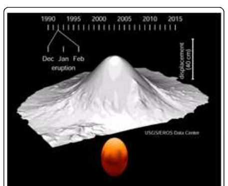
**14.5 cm** in z (e.g. subsidence)

**25.0 cm** in y (motion)



## Monitoring Volcanoes with InSAR
**Principle**

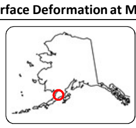
- InSAR is capable of observing inflation and deflation of volcanoes
- Inflation and deflation is triggered by changes of magma pressure in magma chamber (see animation)
- These phenomena precede volcanic eruptions and are potentially interesting for predicting eruptive behavior



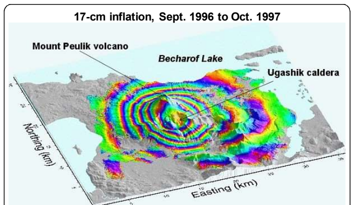

**Westdahl Volcano Deformation Movie**



## Interferometric Phase Interpretation
**Example: Surface Deformation at Mt. Peulik, Alaska**

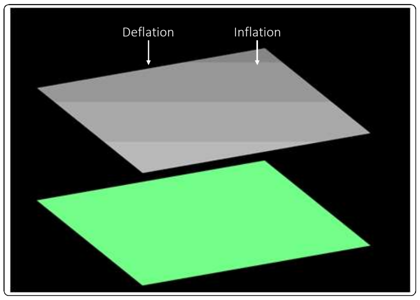


**17-cm inflation, Sept. 1996 to Oct. 1997**




Zhong Lu, et al. (2001)

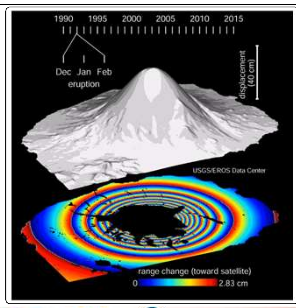
## Representation of Interferometric Phase





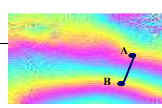

## Representation of Interferometric Phase

**The Westdahl Case**

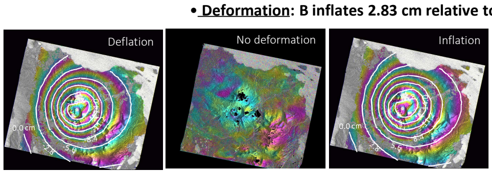





## Interpretation of Interferometric Phase



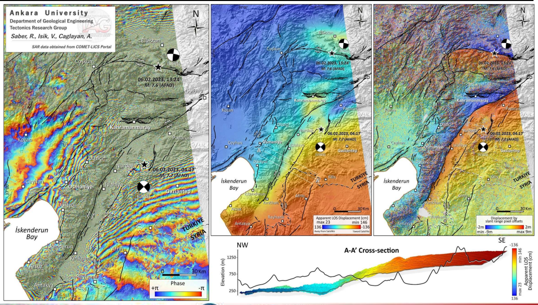

- **<u>Phase Difference from A to B</u>: -2π (one fringe)**
- **<u>Deformation</u>: B inflates 2.83 cm relative to A.**




Dr. Z. Lu, USGS

## Interferograms in Support of Emergency Management
**Example: 2023 M7.8 Turkey–Syria Earthquake**

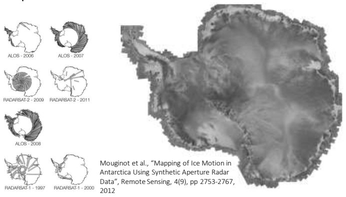
Modern SAR Sensors such as Sentinel-1 and the upcoming NISAR mission can provide InSAR data within 2-3 days of an event



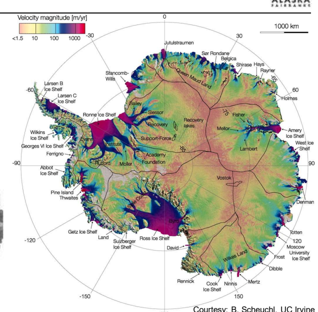



## Continent-Wide Deformation Mapping from InSAR
**Example: Antarctica**

- First Antarctic-wide glacier velocity map in history
- Full coverage by merging data from a wide range of satellite systems
- Accuracy varies with number of multiple coverage per area and coherence



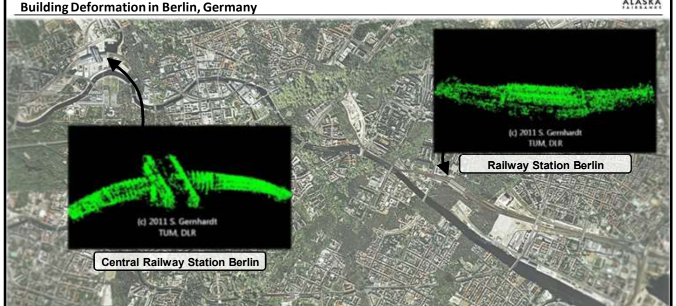

Mouginot et al., "Mapping of Ice Motion in Antarctica Using Synthetic Aperture Radar Data", Remote Sensing, 4(9), pp 2753-2767, 2012




Courtesy: B. Scheuchl, UC Irvine

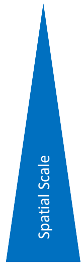


## Sub-Milimeter Surface Analysis
**Building Deformation in Berlin, Germany**



## Typical Applications of Differential InSAR

| Application | Notes |
|---|---|
| • Infrastructure (buildings; roads; levees) deformation | X-band |
| • Sink holes | X-band |
| • Landslides | X- or C-band |
| • Oil/gas extraction | |
| • Glacier motion mapping | |
| • Volcano monitoring | |
| • Permafrost-related surface deformation | C- or L-band |
| • Soil moisture variation | L-band |
| • Co-seismic earthquake deformation | L-band |
| • Post & inter-seismic deformation | L-band |
| • Ice sheet monitoring | C- or L-band |





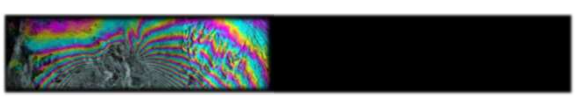

## Think – Pair – Share

Picking the right data for your InSAR analysis:

- Okmok is a volcano in Alaska's Aleutian Chain.
- Since its last eruption in 2008, the volcano has been re-inflating at a rate of ~10cm/year
- Activity: Pick the most suitable interferogram for measuring this deformation. Motivate your answer!
  a) L-band data; $\Delta t = 24$ days; June - July
  b) L-band data; $\Delta t = 48$ days; June - August
  c) L-band data; $\Delta t = 144$ days; July – December
  d) C-band data; $\Delta t = 24$ days; June - July
  e) C-band data; $\Delta t = 48$ days; June - August
  f) C-band data; $\Delta t = 144$ days; July - December
- Please consider the expected coherence $\gamma$ and phase noise $\sigma_\phi$ in your answer


Okmok Volcano, Alaska





## Typical InSAR Processing Workflow

## A Typical InSAR Processing Workflow

1. **Select and order InSAR-capable SAR data** from a data server
2. **Import SAR data into an InSAR processing system**
3. **Calculate spatial baseline & apply spectral (wavenumber) shift filtering** (not discussed in the lectures – applied automatically by most available tools)
4. **Determine co-registration parameters**:
   - cross-correlate >100 image chips spread over image
   - use over-sampling and interpolation to locate correlation peaks
   - apply regression to parameterize co-registration (e.g. affine transform)
5. **Co-register images:**
   - Resample slave image(s) to match master image
   - Required accuracy: << 1/10 resolution element
   - More on required co-registration accuracy on Slides 20 & 21



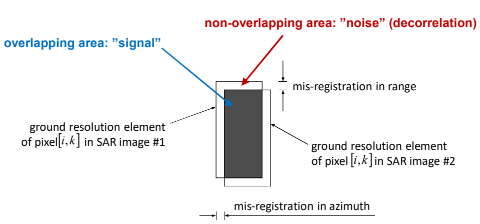
## A Typical InSAR Processing Workflow

6. **[Optional Orbit improvement:** If precise orbit information is available.**]**
7. **Interferogram formation:** $I = u_1 \cdot u_2^*$; optional multi-looking may be applied.
8. **Flat Earth phase removal:** Simulate and subtract phase trend due to the geometry changes from near range to far range.
9. **Coherence Calculation:** Coherence is calculated as described in Lecture 12.
10. **For differential InSAR (d-InSAR):** Using a DEM, simulate and subtract interferogram replicating topography-related phase.
11. **Apply phase filter:** A phase filter is applied to reduce InSAR phase noise and reduce phase unwrapping complexity (see next section).
12. **Phase Unwrapping:** Turns originally ambiguous interferometric phase into unambiguous absolute phase.
13. **Geocoding and Terrain Correction:** Note that flat earth phase needs to be added before geocoding to obtain absolute phase.



## Effects of Coregistration Errors on Coherence

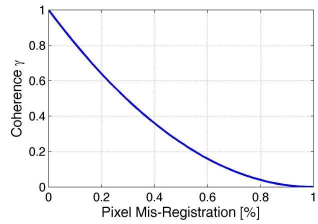
- **How accurately must the two SAR images be co-registered before interferogram formation?**




**Stripmap rule-of-thumb:** 1/10 of a resolution element mis-registration is usually acceptable

## Coherence Reduction Caused by Image Mis-Registration

- **Here a plot how coherence drops with pixel misregistration:**
  - **Assumption:** Mis-registration is only cause of de-correlation
  - Mis-registration expressed in fractions of pixels






## Tips for Selecting Suitable Images for InSAR

<u>**How to select a suitable image pair for successful InSAR processing**</u>

- **Required conditions:**
  - Images from identical orbit direction (both ascending or both descending)
  - Images with identical incidence angle and beam mode
  - Images with identical resolution and wavelength (usually: same sensor)
  - Images with same viewing geometry (same track/frame combination)
- **Recommended conditions:**
  - For topographic mapping: Limited time separation between images (temporal baseline)
  - For deformation mapping: Limited spatial separation of acquisition locations (spatial baseline)
  - Images from similar seasons / growth / weather conditions



## AUTOMATIC (INSAR) PROCESSING SERVICES

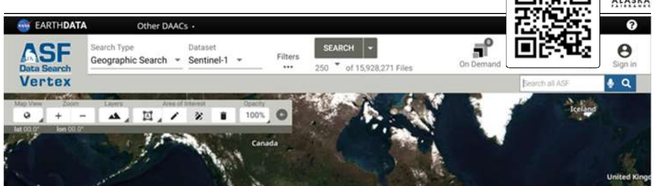
## Why Is There a Need For Automatic SAR Processing Services?

- **Processing Flows for Generating Value-Added Products Are Often Complicated**
  - Difficult and heterogeneous data types and data formats
  - SAR data typically do not come geocoded and have strong geometric distortions
  - Strong noise effects require complex filtering approaches
  - InSAR processing is complicated and error prone
- **Large Data Volume of SAR Requires Powerful Processing Machines**
- **SAR Processing Software is Often Not User Friendly**

**→Several automatic processing tools are in development to make SAR data more accessible especially to new users from the disaster monitoring communities**

Franz J Meyer, UAF
GEOS 657 Microwave RS - 28

## Search and Process (In)SAR Data with Vertex




- **Search & discover** ASF's holdings over your AOI
- Use our baseline and SBAS tools to **configure your perfect InSAR stack**
- Submit Sentinel-1 scenes for **on-demand processing** to RTC or InSAR
- **Download** data for additional processing using convenient interface options

Franz J Meyer, UAF
GEOS 657 Microwave RS - 29

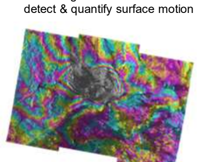
## HyP3 On-Demand Processing

**HyP3: On-demand processing service for analysis-ready SAR data**

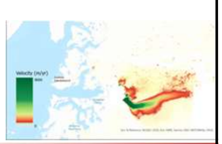
- Available to anyone at no direct cost
- DAAC managed L1 → L2 workflows

### RTC
- Radiometric Terrain Correction
- Corrects geometric and radiometric distortions caused by the terrain

### InSAR
- SAR Interferometry
- The phase measurements of 2 SAR images are differenced to detect & quantify surface motion



### autoRIFT
- Glacier velocity tracking
- Measures surface displacements between two SAR images
- Part of NASA MEaSUREs ITS_LIVE project



Franz J Meyer, UAF
GEOS 657 Microwave RS - 30

## Order an SBAS InSAR Stack in Vertex and Analyze it in OpenSARLab

A demo on how to generate an SBAS InSAR Stack in Vertex and then Analyze the data using MintPy in OpenSARLab can be found here:

https://youtu.be/tq8nZpsWK6k

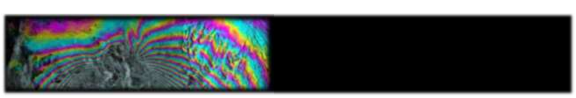


## Creating Product Subscriptions over your AOI on HyP3

**Example of a Sentinel-1 SAR Image Time Series:**

- Mekong River Delta
- Time frame: 2019



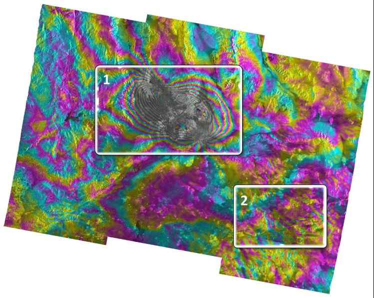


## LIMITATIONS OF CONVENTIONAL INSAR

## Think – Pair – Share: Take 1

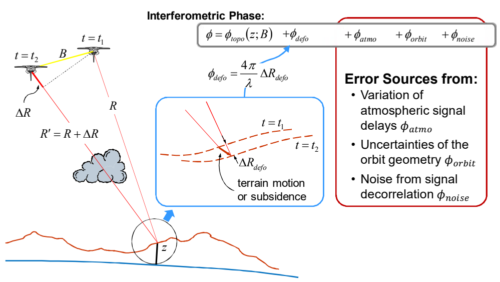
Phase Interpretation: Analyze the phase content of this interferogram

- Activity 1: What do the phase patterns in Area 1 represent?
  a) Displacement phase most likely related to an earthquake
  b) Topographic signal
  c) Atmospheric delay
- Activity 2: What is the main phase contribution in Area 2?
  a) Displacement phase most likely related to an earthquake
  b) Topographic signal
  c) Atmospheric delay






## Recap of InSAR Acquisition Scenario






## The Complete InSAR Phase Equation

- **Phase of an interferogram:**

$$\phi = W\{\phi_{topo} + \phi_{defo} + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\}$$

$$= W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot sin(\theta)}h + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}$$

($W$: wrapping operator $\rightarrow \phi$: $[-\pi, \pi[$)

- **Phase of a differential interferogram** (after compensation of topography phase):

$$\Delta\phi = W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot sin(\theta)}h_{err} + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}$$

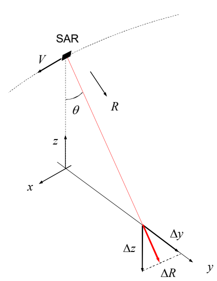
(where $h_{err} = h_{true} - h_{DEM}$ is a residual topography phase due to errors in the DEM)

## Limitations and Error Sources of InSAR
**Overview**

1. **Only sensitive to motion in sensor's line-of-sight → does not provide 3D motion fields**
2. **Temporal baseline is limited, leading to limited sensitivity to very slow surface motion:**
   – Limitation is due to temporal decorrelation, leading to increase of phase noise with time
3. **Spatial baseline is limited, limiting number of interferograms that can be formed from a stack of SAR data** [advanced topic – not as relevant with sensors such as Sentinel-1 and NISAR]
4. **Atmospheric phase patterns may mask signal of interest, limiting sensitivity of InSAR to very small motion (or topography) signals**
5. **Orbit errors may cause ramp-like phase distortions** [usually small]



## Limitations of InSAR:
**1. Only Line-of-Sight Motion Sensitivity**




$$\Delta R = \Delta y \sin\theta - \Delta z \cos\theta$$

**for ERS:**

**1 fringe ($2\pi$) corresponds to**

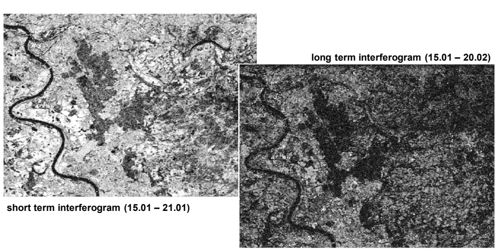
**2.8 cm in R**
**3.0 cm in z (e.g. subsidence)**
**7.2 cm in y (motion)**

! **only 1 dimension of 3-d motion accessible**
! **no sensitivity to motion in x direction**



## Limitations of InSAR:
**2. Temporal Signal Decorrelation**

- **Changes of the ground scattering properties are main source of signal decorrelation with time**
  – **Example:** Airborne C-band SAR over vegetated environments

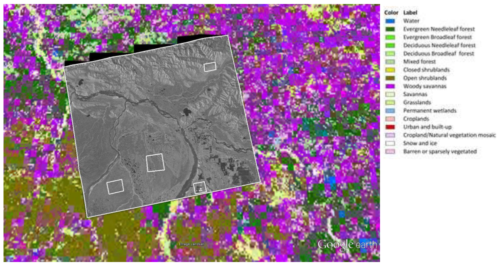


long term interferogram (15.01 – 20.02)

short term interferogram (15.01 – 21.01)

## Examples of Coherence Change with Time
**Boreal Dry Climate**

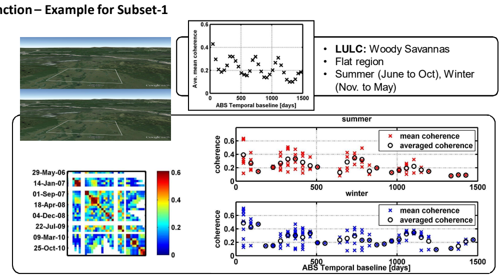
- **Example**: Delta Junction – L-band SAR (ALOS PALSAR)






## Examples of Coherence Change with Time
**Boreal Dry Climate**

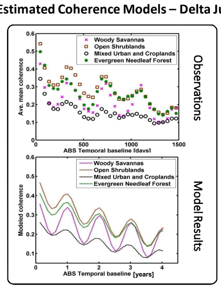
- **Delta Junction – Example for Subset-1**






## Examples of Coherence Change with Time
**Boreal Dry Climate**

- **Estimated Coherence Models – Delta Junction; L-band**




| LULC type | A | λ (1/yr) | ϕ | B | d (1/yr) | $R^2$ |
|---|---|---|---|---|---|---|
| 1. Woody Savannas | 0.08 ± 0.01 | 0.99 ± 0.01 | 0.00 ± 0.17 | 0.31 ± 0.01 | 0.18 ± 0.02 | 0.89 |
| 2. Open Shrublands | 0.06 ± 0.01 | 0.99 ± 0.02 | 0.03 ± 0.23 | 0.44 ± 0.01 | 0.23 ± 0.02 | 0.92 |
| 3. Urban & Croplands | 0.03 ± 0.01 | 1.01 ± 0.03 | 0.00 ± 0.47 | 0.25 ± 0.01 | 0.26 ± 0.03 | 0.80 |
| 4.Evergreen Forest | 0.05 ± 0.01 | 0.99 ± 0.03 | 0.00 ± 0.43 | 0.39 ± 0.02 | 0.21 ± 0.03 | 0.76 |

– **Coherence Model Characteristics:**

$$\bar{\gamma}(t) = \boldsymbol{A} \cdot \boldsymbol{cos}(2\pi\lambda \cdot t + \phi) + \boldsymbol{B} \cdot \boldsymbol{exp}(-\boldsymbol{d} \cdot \boldsymbol{t})$$

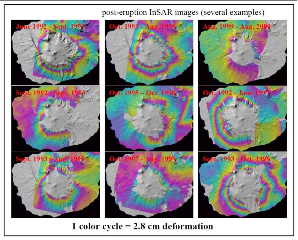
- Different exponential decay parameters ($d$ & $B$)
- **Significant** & similar **periodic cycle** $\lambda$ for analyzed land covers
- Differences in amplitude $A$ of periodic signal
- Periodicity $\lambda$ closely one year → near-seasonal signatures
- Good model fit (high $R^2$)

## Limitations of InSAR:
**2. Temporal Signal Decorrelation**

Caldera of Westdahl Peak is decorrelated in all interferograms

**Example**: Volcano Monitoring

- Often, caldera of active volcanoes is decorrelated due to constant change (snow and ice melt; ash fall; lahars; lava flows; …).
- **Consequence**:
  - Area with strongest signals inaccessible
  - In modeling, shape of source model as well as horizontal location of source hard to define
  - combination with GPS is advised

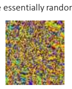




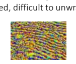

## Decorrelation and Fringe Washing

**Gorkha Earthquake, Nepal, April 2015**

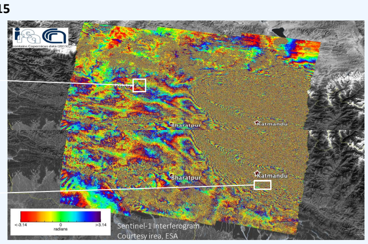
**Decorrelation:**
phase essentially random



**Fringe Washing**
Large strain: fringes closely spaced, difficult to unwrap



Can decrease coherence



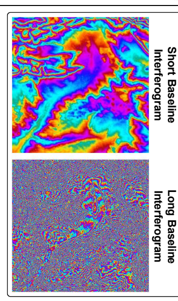

InSAR Time Series Analysis is mitigating the impact of signal decorrelation



## Limitations of InSAR:
**3. Limited Spatial Baselines**

Advanced Material

- **Long spatial baselines lead to decorrelation of interferograms**
- **Figure:** Fringe density increases with baseline length!
- **At certain baseline length (critical baseline $B_{\perp,crit}$) the fringes become closer than the pixel size:**
  → phase jump from pixel to pixel > $2\pi$
  → phase image becomes random



## Limitations of InSAR:
### How to Calculate the Critical Baseline $B_{\perp,crit}$

Advanced Material

- **We can calculate the fringe frequency in the interferogram from:**

$$\Delta f(\alpha) = -\frac{c \cdot B_{\perp}}{R \cdot \lambda \cdot t \quad (\theta - \alpha)} \quad \left[\frac{1}{s}\right] \qquad \alpha\text{: terrain slope}$$

- **Critical baseline if we have one fringe of phase change per pixel, corresponding to $\frac{2\Delta f(\alpha)}{c} = \frac{1}{\rho_r}$ (with range resolution $\rho_r$):**

$$\frac{1}{\rho_r} = -\frac{2 \cdot B_{\perp,crit}}{R \cdot \lambda \cdot tan(\theta - \alpha)} \quad \Rightarrow \quad B_{\perp,crit} = \left|\frac{R \cdot \lambda \cdot tan(\theta - \alpha)}{2 \cdot \rho_r}\right| \quad [m]$$

- **Dependencies:**
  - Higher range resolution (smaller $\rho_r$) → $B_{\perp,crit}$ increases
  - Steeper slopes (larger $\alpha$) → $B_{\perp,crit}$ decreases
  - Longer wavelength $\lambda$ → $B_{\perp,crit}$ increases



## Critical Baseline $B_{\perp,crit}$ for Various Sensors

Advanced Material

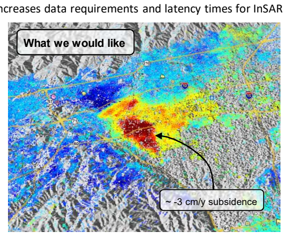
- **Assumptions:**
  - Surface slope $\alpha = 0^{\circ}$
  - Incidence angle $\theta = 25^{\circ}$
  - Range to ground $R \approx 800{,}000m$

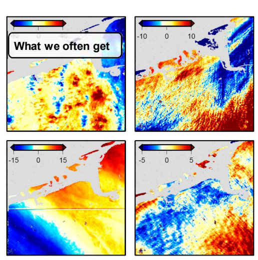
- **$B_{\perp,crit}$ for various sensor systems @ $\theta = 25^{\circ}$ :**
  - **ERS-1/2 & Envisat Stripmap mode**: $B_{\perp,crit} \approx 1{,}100m$
  - **ALOS PALSAR**:
    - FBS mode: $B_{\perp,crit} \approx 8{,}500m$
    - FBD & PLR mode: $B_{\perp,crit} \approx 4{,}250m$
  - **TerraSAR-X Stripmap mode**: $B_{\perp,crit} \approx 5{,}800m$



## Limitations of InSAR:
### 4. Atmospheric Distortions

- **Atmospheric propagation influence:**
  - Masks deformation signals in InSAR
  - Increases data requirements and latency times for InSAR analyses



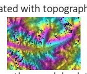
## Limitations of InSAR:
**4. Atmospheric Distortions**

**Coquimbo Earthquake, Chile, April 2018, M6**

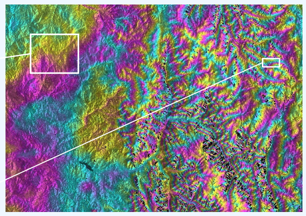
**Turbulent Troposphere:**
Horizontal variation in refractive index, esp. in water vapor
Variable across spatial scales
Can mask small earthquake

Correction:
- Regional scale: weather model, GPS, etc.
- Small scale: filtering in space and time

**Stratified troposphere**
Signal path decreases with elevation
Phase correlated with topography



Correction: weather models, data-driven

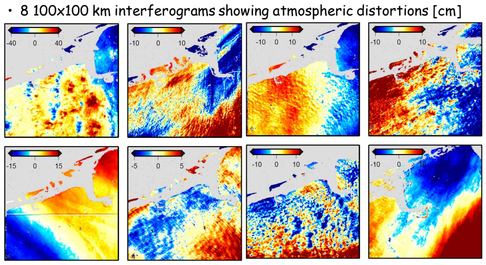


Sentinel-1 Interferogram
Courtesy SARVIEWS, ESA

Franz J Meyer, UAF
GEOS 657 Microwave RS - 49

## Examples of Turbulent Atmospheric Phase Distortions in InSAR Data

- 8 100x100 km interferograms showing atmospheric distortions [cm]

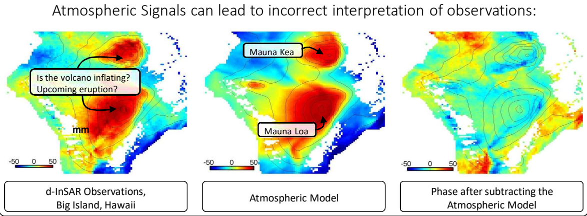



Courtesy: R. Hansen, TU Delft

Franz J Meyer, UAF
GEOS 657 Microwave RS - 50

## Example and Impact of Stratified Atmospheric Phase Distortions

Atmospheric Signals can lead to incorrect interpretation of observations:




Franz J Meyer, UAF
GEOS 657 Microwave RS - 51

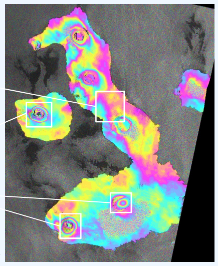
## Limitations of InSAR:
### 4. Atmospheric Distortions

**Isabela Island, Galapagos, Ecuador, September 2019, M6**

Troposphere or volcanic origin?

Stratified troposphere or volcanic origin?

How could you quantify the relative contributions?



Sentinel-1 Interferogram
Courtesy SARVIEWS, ESA

InSAR Time Series Analysis is mitigating the impact of atmospheric phase delay



## What's Next?

- **This is what awaits next:**
  - **Thursday March 30: Lab on Interpreting InSAR data**
  - **Tuesday April 04: Polarimetric SAR**



## Think – Pair – Share: Take 2

Quantify What's in the Interferogram

- Activity: Based on the interferogram and following the instructions above, what is the amount of line-of-sight deformation contained in the image?
  a) 0-25 cm
  b) 60-80 cm
  c) 100-150 cm