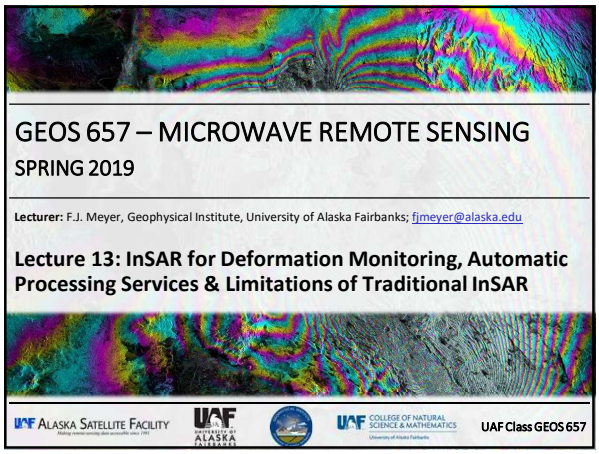


GEOS 657 – MICROWAVE REMOTE SENSING

SPRING 2019

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

Lecture 13: InSAR for Deformation Monitoring, Automatic Processing Services & Limitations of Traditional InSAR

UAF Alaska Satellite Facility | UAF College of Natural Science & Mathematics | UAF Class GEOS 657

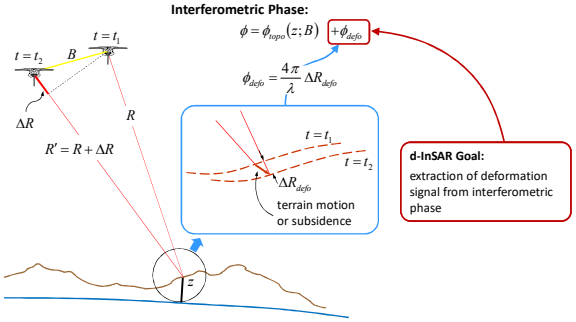
DIFFERENTIAL INSAR – A METHOD FOR CM-SCALE DEFORMATION MONITORING

The Concept of Differential InSAR (d-InSAR)

Interferometric Phase:

$$\phi = \phi_{topo}(z;B) + \phi_{defo}$$

$$\phi_{defo} = \frac{4\pi}{\lambda}\Delta R_{defo}$$



d-InSAR Goal:
extraction of deformation signal from interferometric phase

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, …, t_n are required:

- Form several interferograms:
  - time lag: $\Delta t_{n-m} = t_n - t_m$
  - baseline: $B_{\perp,n-m}$
  - phase: ϕ_{n-m}

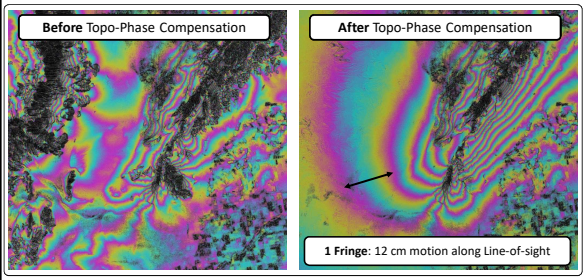
For signal separation consider:
- Deformation phase changes only with time
- Topography phase changes only with Baseline

- For constant velocity: $\phi_{n-m}^{defo} = \phi_{n-m} \propto \Delta t_{n-m}$ and $\phi_{n-m}^{topo} = \phi_{n-m} \propto B_{\perp,n-m}$

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

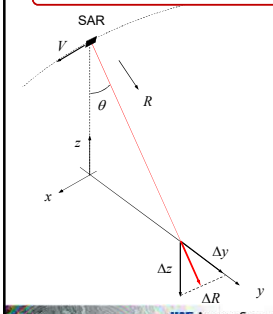
Example of Topography Compensation

- 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: $\phi_{defo} = \frac{4\pi}{\lambda} \Delta R_{defo}$



ΔR is motion in sensor look direction

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

For previous PALSAR example:

1 fringe (2π) corresponds to

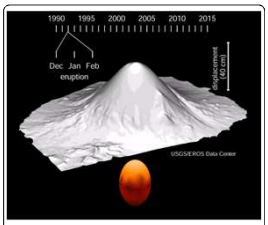
12.5 cm in R

14.5 cm in z (e.g. subsidence)

25.0 cm in y (motion)

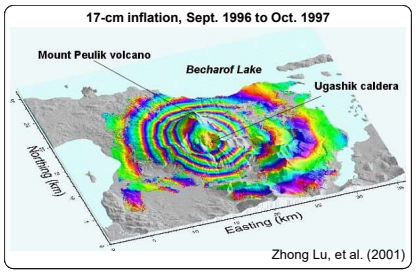
Monitoring Volcanoes with InSAR
Principle

- 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



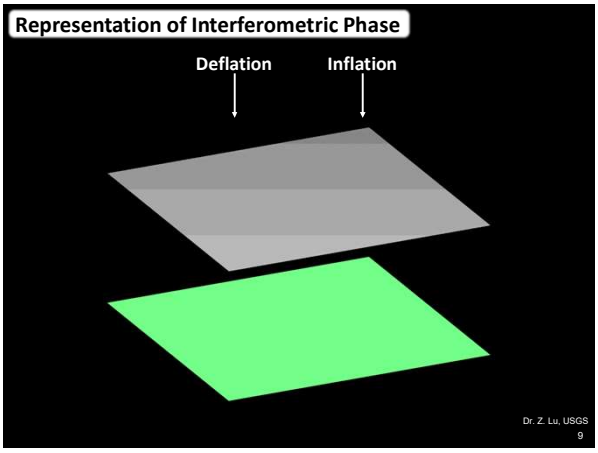
Westdahl Volcano Deformation Movie

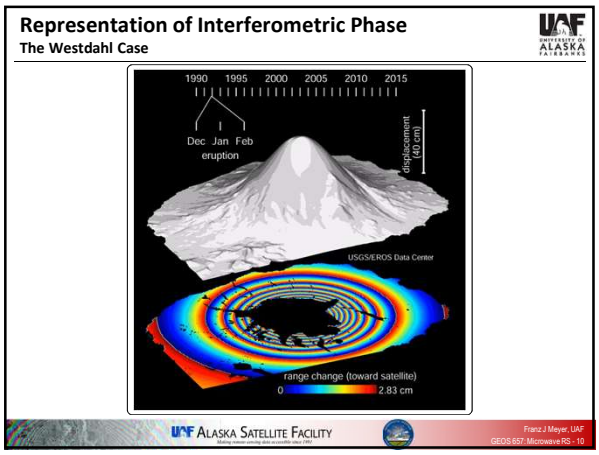
Interferometric Phase Interpretation
Example: Surface Deformation at Mt. Peulik, Alaska



Zhong Lu, et al. (2001)

Representation of Interferometric Phase




Representation of Interferometric Phase
The Westdahl Case
1990 1995 2000 2005 2010 2015
Dec Jan Feb
eruption
displacement (40 cm)
USGS/EROS Data Center
range change (toward satellite)
0
2.83 cm
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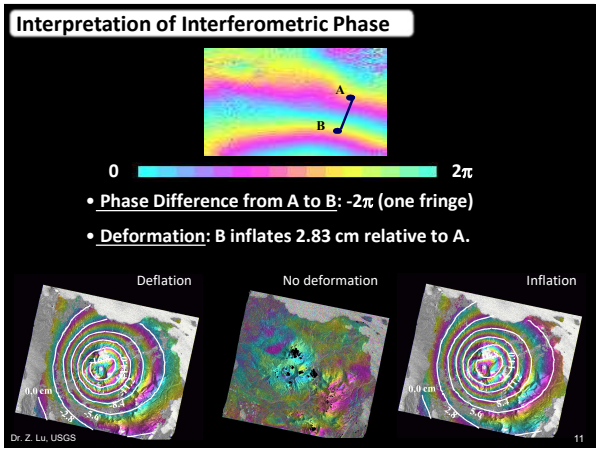
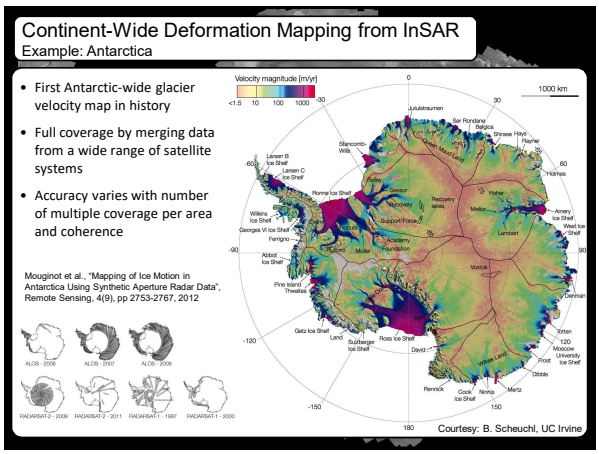
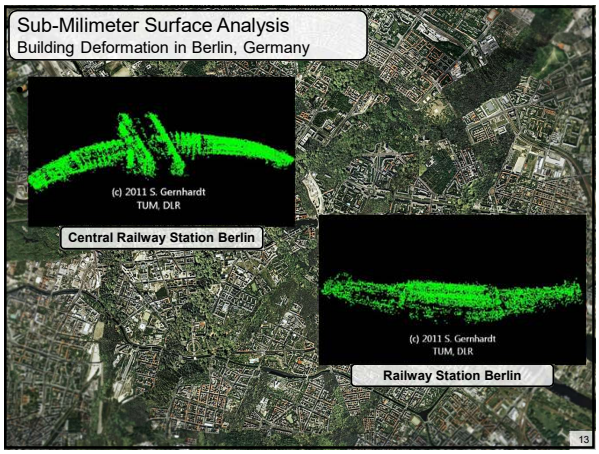

Interpretation of Interferometric Phase
A
B
0
2π
• Phase Difference from A to B: -2π (one fringe)
• Deformation: B inflates 2.83 cm relative to A.
Deflation
No deformation
Inflation
0.0 cm
Dr. Z. Lu, USGS
11


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
Velocity magnitude [m/yr]
<1.5 10 100 1000
1000 km
Courtesy: B. Scheuchl, UC Irvine



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

Spatial Scale

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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

Okmok Volcano, Alaska

- 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 γ and phase noise σ_ϕ in your answer

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TYPICAL INSAR PROCESSING WORKFLOW

A Typical InSAR Processing Workflow

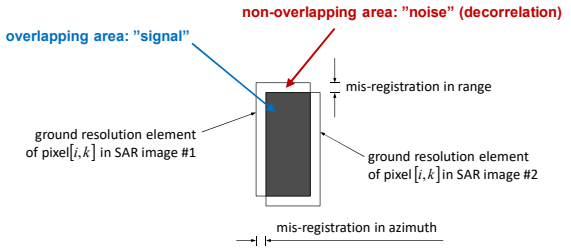
1. **Select and order InSAR-capable SAR data** from a data server
2. **Import SAR data into an InSAR processing system**
3. **Calculate spatial baseline & apply spectral (wavenumber) shift filtering** (not discussed in the lectures – applied automatically by most available tools)
4. **Determine co-registration 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

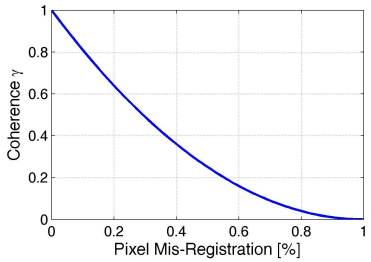
- **How accurately must the two SAR images be co-registered before interferogram formation?**



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

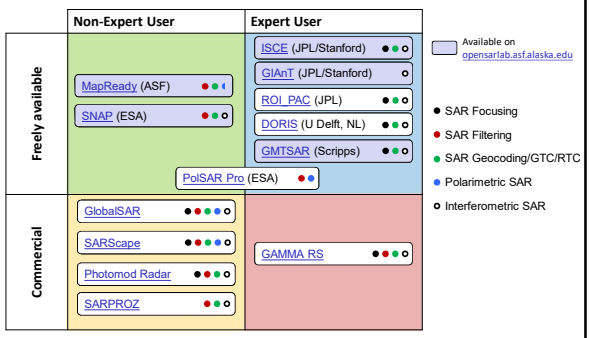


Tips for Selecting Suitable Images for InSAR

How to select a suitable image pair for successful InSAR processing

- **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

Available SAR Data Processing Tools



Non-Expert Free Software Packages

- **MapReady** (https://www.asf.alaska.edu/data-tools/mapready/)
  - Available from:
  - Sensors
    - ERS-1 (ASF & ESA format), ERS-2 (ASF & ESA format), Radarsat-1 (ASF format), ALOS PALSAR
  - Capabilities
    - Conversion of SAR data to Geotiff and JPG format
    - Data Visualization
    - Geocoding
    - Terrain Correction (Geometric and Radiometric)
    - Some Polarimetric tools

Non-Expert Free Software Packages

- **Sentinel Applications Platform** (SNAP; http://step.esa.int/main/download/)
  - Available from: European Space Agency (ESA)
  - Sensors
    - ERS-1, ERS-2, ENVISAT ASAR (all ESA format), Radarsat-1, Radarsat-2 (MDA format), ALOS PALSAR, Sentinel-1
  - Capabilities
    - Conversion of SAR data to Geotiff and JPG format and kmz format
    - Data Visualization
    - Geocoding (not for PALSAR)
    - Terrain Correction (Geometric and Radiometric) (not for PALSAR)
    - InSAR processing
    - Some Polarimetric tools

Get DEM Data

- For RTC and GTC, DEM information is required
- NEST is automatically downloading DEM data during processing
- For MapReady, DEM data needs to be provided by the user
- Free Access to DEM data is available through EarthExplorer (http://earthexplorer.usgs.gov/)

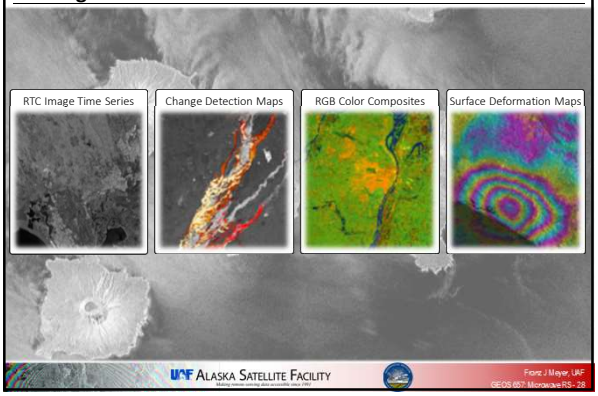
VALUE-ADDED PROCESSING SYSTEMS AT THE ASF DAAC - FREE-OF-CHARGE SOLUTIONS FOR GENERATING HIGHER-LEVEL SAR PRODUCTS

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

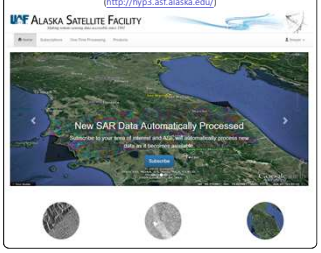
Current Value-Added Product Algorithms Available Through the ASF DAAC



HyP3 – ASF's Cloud-based Value-Added Processing System

- **HyP3 [Hybrid Pluggable Processing Pipeline]**: Cloud-based processing system for prototyping of value-added Sentinel products
- **Features:**
  - **Fully cloud-based processing and archiving**
  - Elastic scaling of compute resources
  - Easy integration of new algorithms
  - Create AOI-based subscription via API or map interface
  - Automatic production of SARVIEWS products for every incoming image
  - Distribution via pull or push
  - Email notification service

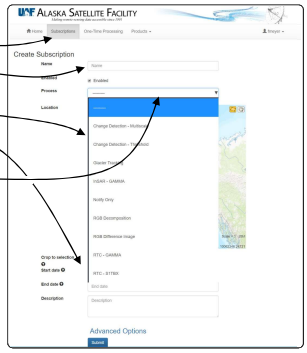
The Cloud-based **Hyp3** Data Processing Engine
(http://hyp3.asf.alaska.edu/)

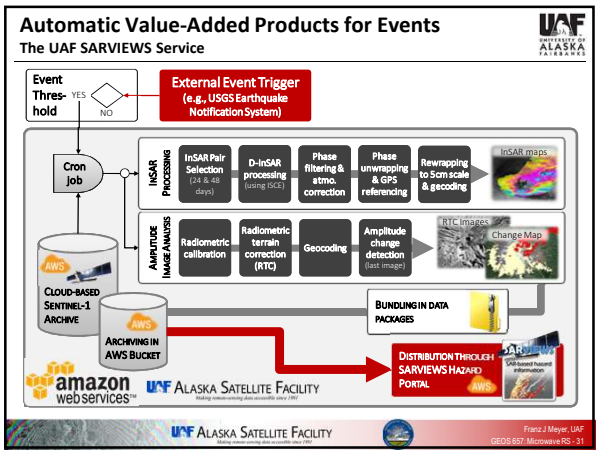


How Can YOU Use HyP3 Yourself?

- Once logged in, click on the **Subscription** Tab
- Provide a name for the subscription
- Select your area of interest
- Select a start date
- Select product type – most relevant for you:
  - RTC processing
  - Multiple Change Detection Methods
  - RGB Decomposition
  - RGB Difference Image
  - InSAR

http://hyp3.asf.alaska.edu/




Automatic Value-Added Products for Events
The UAF SARVIEWS Service
Event Thres-hold
YES
NO
External Event Trigger (e.g., USGS Earthquake Notification System)
Cron job
InSAR PROCESSING
InSAR Pair Selection (24 & 48 days)
D-InSAR processing (using ISCE)
Phase filtering & atmo. correction
Phase unwrapping & GPS referencing
Rewrapping to 5 cm scale & geocoding
InSAR maps
AMPLITUDE IMAGE ANALYSIS
Radiometric calibration
Radiometric terrain correction (RTC)
Geocoding
Amplitude change detection (last image)
RTC Images
Change Map
CLOUD-BASED SENTINEL-1 ARCHIVE
ARCHIVING IN AWS BUCKET
BUNDLING IN DATA PACKAGES
DISTRIBUTION THROUGH SARVIEWS HAZARD PORTAL
amazon web services
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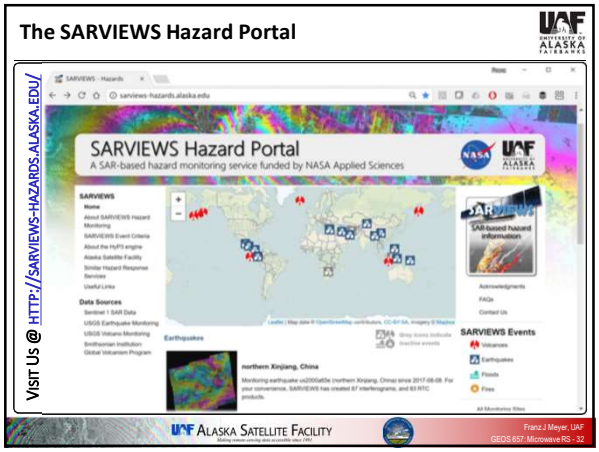
The SARVIEWS Hazard Portal
VISIT US @ HTTP://SARVIEWS-HAZARDS.ALASKA.EDU/
SARVIEWS Hazard Portal
A SAR-based hazard monitoring service funded by NASA Applied Sciences
SARVIEWS Events
northern Xinjiang, China
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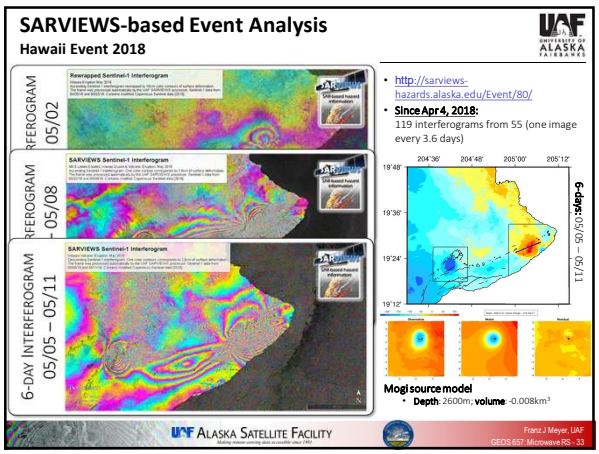
SARVIEWS-based Event Analysis
Hawaii Event 2018
6-DAY INTERFEROGRAM 05/05 – 05/11
INTERFEROGRAM 05/08
INTERFEROGRAM 05/02
http://sarviews-hazards.alaska.edu/Event/80/
Since Apr 4, 2018:
119 interferograms from 55 (one image every 3.6 days)
6-days: 05/05 – 05/11
Mogi source model
Depth: 2600m; volume: ~0.008km³
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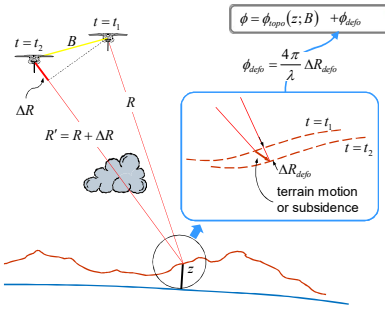
LIMITATIONS OF CONVENTIONAL INSAR

Recap of InSAR Acquisition Scenario

Interferometric Phase:

$$\phi = \phi_{topo}(z;B) + \phi_{defo} + \phi_{atmo} + \phi_{orbit} + \phi_{noise}$$

$$\phi_{defo} = \frac{4\pi}{\lambda}\Delta R_{defo}$$



Error Sources from:

- Variation of atmospheric signal delays ϕ_{atmo}
- Uncertainties of the orbit geometry ϕ_{orbit}
- Noise from signal decorrelation ϕ_{noise}

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 → ϕ: $[-\pi, \pi[$)

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

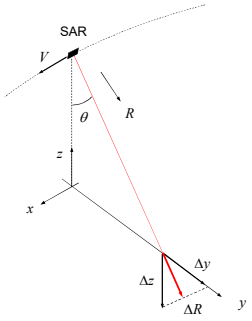
$$\Delta\phi = W\left\{\frac{4\pi}{\lambda}\frac{B_\perp}{R \cdot \sin(\theta)}h_{err} + \frac{4\pi}{\lambda}v \cdot \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\}$$

(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**
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 (2π) corresponds to

2.8 cm in R

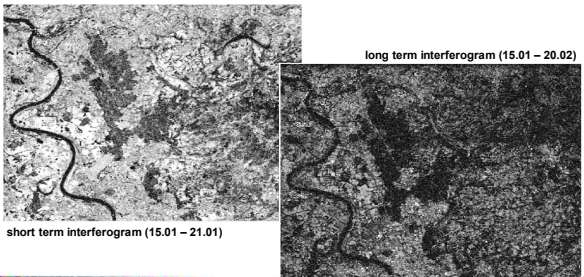
3.0 cm in z (e.g. subsidence)

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

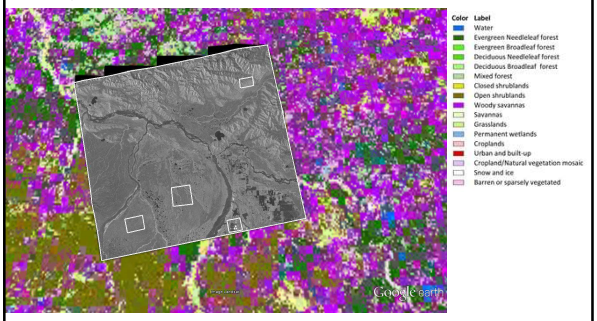


long term interferogram (15.01 – 20.02)

short term interferogram (15.01 – 21.01)

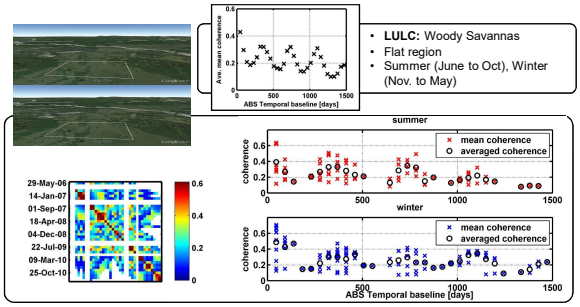
Examples of Coherence Change with Time
Boreal Dry Climate

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



Examples of Coherence Change with Time
Boreal Dry Climate

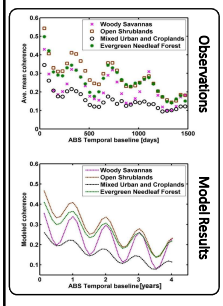
- **Delta Junction – Example for Subset-1**



- **LULC:** Woody Savannas
- Flat region
- Summer (June to Oct), Winter (Nov. to May)

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:**

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

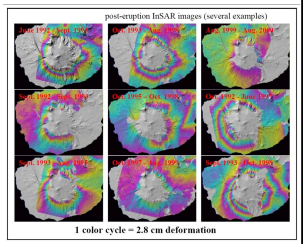
- Different exponential decay parameters (d & B)
- **Significant** & similar **periodic cycle** λ for analyzed land covers
- Differences in amplitude A of periodic signal
- Periodicity λ closely one year → near-seasonal signatures
- Good model fit (high R^2)

Limitations of InSAR:
2. Temporal Signal Decorrelation

Example: Volcano Monitoring

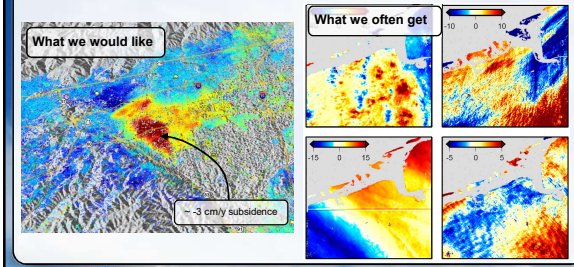
- Often, caldera of active volcanoes is decorrelated due to constant change (snow and ice melt; ash fall; lahars; lava flows; …).
- **Consequence**:
  - Area with strongest signals inaccessible
  - In modeling, shape of source model as well as horizontal location of source hard to define
  - combination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

Caldera of Westdahl Peak is decorrelated in all interferograms



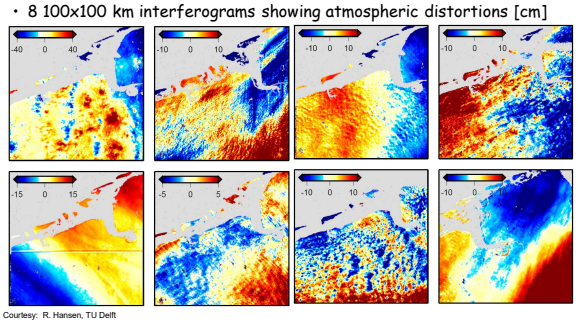
Limitations of InSAR:
4. Atmospheric Distortions

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



Examples of Atmospheric Phase Distortions in InSAR Data

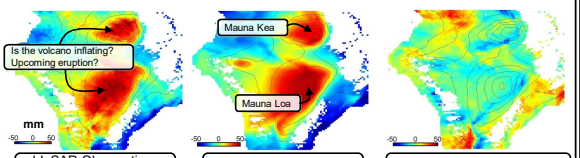
- 8 100x100 km interferograms showing atmospheric distortions [cm]



Courtesy: R. Hansen, TU Delft

Limitations of InSAR:
4. Atmospheric Distortions

Atmospheric Signals can lead to incorrect interpretation of observations:



d-InSAR Observations, Big Island, Hawaii | Atmospheric Model | d-InSAR – Atmospheric Model

What's Next?

- **This is what awaits next :**
  - **Thursday:** Project Concept Presentations
  - … and next week …