Synthetic Aperture Radar Interferometry (InSAR)

Adapted from the ESA Interferometric SAR overview by Rocca et al.  
[http://earth.esa.int/workshops/ers97/program-details/speeches/rocca-et-al/](http://earth.esa.int/workshops/ers97/program-details/speeches/rocca-et-al/)


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- Synthetic Aperture Radar (SAR) systems record the time delay, amplitude, frequency and phase of the backscattered signal.
- The phase of each pixel of a focused SAR image is the sum of three distinct contributions:
  1. the two-way travel path that, divided by the used wavelength, corresponds to millions of cycles;
  2. the interaction between the incident EM waves and the scatterers within the ground resolution cell;
  3. the phase shift induced by the processing system used to focus the image.
- The phase of a single SAR image is of no practical use.
- Two SAR images from slightly different viewing angles form an interferometric pair.
- Their phase difference (interferometric fringes) can be usefully exploited
  - to generate Digital Elevation Maps (DEMs),
  - to monitor terrain changes and
  - to improve the range resolution.
- The interferometric fringes image is derived as the phase of the SAR interferogram, that is the complex image formed by cross-multiplying the two SAR images.
- The relation between the interferometric fringes and ground elevation is usually explained by means of the monochromatic approach, i.e., one assumes that the RF bandwidth is so small that it is considered to be negligible. (This is the case of most satellite systems including SEASAT, ERS-1, JERS-1, ERS-2 and RADARSAT)

For a perfectly flat surface the entire wave front would arrive at the same time.

The components of the return pulse would be in phase.

In fact, the wave front from a single pulse is spread over a range of distances and there will be a range of phases for a single return. Nonetheless there is a coherence to the return.
For a rough surface the components of the wave front would arrive at the slightly different times.

The components of the return pulse would then be out of phase, or incoherent (even for a vanishingly small time interval).

Phase of Scatterers

Assumptions:

- Many discrete scatterers per cell
- Pixels are large compared to $\lambda$ so that phases from randomly distributed scatterers are uniformly distributed (phase speckle).

The complete description of a SAR image includes an amplitude and a phase for each pixel.

While the phase of a single image may be of no practical use, the change in phase between two images of the same scene contains a great deal of useful information.
Phase Differencing

- Although phase is randomly distributed, it is causally connected to physical features.
- Hence, the phase of a given area should be the same if viewed from the same position.
- Taking the difference in phase of two scenes yields an interference pattern representing topography and time-dependent changes.
- The phase shift represents a relative distance that is much finer than the range measurement. For example, if $\tau = 6 \times 10^{-8}$ s and $\lambda = 10$ cm, then
  1. Time delay: resolution = $c \tau / 2 = 9$ m
  2. Phase: resolution = $\lambda / 100 = 1$ mm

Components of a SAR Image

Interferometric phase depends on:
1. **Satellite geometry (baseline)**
2. Topography
3. Surface changes
4. Atmospheric propagation delay
Given: Two SAR receivers at an elevation $H$ and separated by a baseline $B$ oriented at an angle $\alpha_0$ with respect to local horizontal. The ranges, $r_0$ and $r_0 + \delta$, to the same target, $P$, at height $z = h$ above the reference plane and ground range, $r_g$, are measured independently at the two antenna apertures. The phase difference, $\delta$, is given by:

$$\Delta \phi = \frac{4\pi}{\lambda} h \sin(\psi)$$


### Topography from Interferometric phase

Knowing phase ($\phi$), wavelength ($\lambda$), and the geometry below,

$$\theta = \sin^{-1}(-\lambda \phi / 4\pi B)$$

$$\&$$

$$h = H - r_0 \cos \theta$$

- The sensitivity of an interferogram to topography depends upon the baseline.
- **Ambiguity Height** ($h_a$) is the elevation change resulting in $2\pi$ phase change:

$$h_a = \frac{\lambda r_0}{2B \cos(\theta - \alpha)} \quad \text{for} \quad r_0 \gg B$$

<table>
<thead>
<tr>
<th>$B$ cos ($\theta - \alpha$)</th>
<th>$h_a$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>$\infty$</td>
</tr>
<tr>
<td>100.0</td>
<td>187.5</td>
</tr>
<tr>
<td>200.0</td>
<td>93.8</td>
</tr>
<tr>
<td>300.0</td>
<td>62.5</td>
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<tr>
<td>400.0</td>
<td>46.9</td>
</tr>
<tr>
<td>500.0</td>
<td>37.5</td>
</tr>
<tr>
<td>1000.0</td>
<td>18.8</td>
</tr>
</tbody>
</table>

ERS 1/2, $\lambda = 5.56$ cm, $H = 780$ km
Interferometric phase also depends on Surface changes

Effects of a surface change (in the range direction): \( \phi = \frac{4\pi}{\lambda} \left[ B \sin(\theta - \alpha) - D \cos(\gamma) \right] \)

Hence, \( D_\parallel = D \cos(\gamma) = \frac{\lambda}{2} \) \( \Rightarrow \) changes \( \phi \) by \( 2\pi \) for a given baseline

Interferometric phase depends on Atmospheric propagation delay

Change in atmospheric moisture producing apparent shift in topography. (modified from Fujiwara et al., 1998)

Coherence
- Coherence must always be measured to assess the suitability of the data set for InSAR processing.
- Coherence magnitude is closely related to the local standard deviation of differential phase.
- High coherence magnitude tells us:
  - images have good SNR
  - phase centers of scatterers are stable
  - any motion is spatially “organized”
Interferometric SAR Performance

Comparative performance numbers for repeat-pass interferometric SARs:

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>TOPS AR</th>
<th>JERS-1</th>
<th>ERS-1/2</th>
<th>Radarsat</th>
<th>SIR-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>L-C Band</td>
<td>L-Band</td>
<td>C-Band</td>
<td>C-Band</td>
<td>L-C-X-Band</td>
</tr>
<tr>
<td>2.5, 5 m</td>
<td>300-700 m</td>
<td>100-250 m</td>
<td>100-400 m</td>
<td>50-150 m</td>
<td></td>
</tr>
<tr>
<td>Airborne/Space born</td>
<td>Air</td>
<td>Space</td>
<td>Space</td>
<td>Space</td>
<td>Space</td>
</tr>
<tr>
<td>Height accuracy</td>
<td>1-5 m</td>
<td>10-15 m</td>
<td>8-15 m</td>
<td>10-15 m</td>
<td>8-15 m</td>
</tr>
<tr>
<td>Ht. change accuracy</td>
<td>N/A</td>
<td>&lt; 1 cm</td>
<td>&lt; 1 cm</td>
<td>TBD</td>
<td>&lt; 1 cm</td>
</tr>
<tr>
<td>time b/w data takes</td>
<td>0 sec</td>
<td>44 days</td>
<td>1 day, 35 days</td>
<td>24 days</td>
<td>1-3 days, 6 months</td>
</tr>
</tbody>
</table>

Producing an interferogram:

**Processing**

1. **Image Registration**
2. **Resample 2nd Image**
3. **Generate Interferogram**
4. **Unwrap Phase**
5. **Baseline Estimation**
6. **Final Product**

Image co-registration

- sub-pixel co-registration required for correlation in phase
- relative offsets determined for many small (e.g., 128 x 128) image chips
- one image resampled relative to the other

Interferogram calculation

- The interferogram is calculated by multiplying one image by the complex conjugate of the other.
- Result includes the *phase difference* plus the product of the two image amplitudes.

\[
\text{INT} = c_1^*c_2 = A_1e^{i\phi_1} * A_2e^{i\phi_2} = A_1A_2e^{i(\phi_1-\phi_2)} \\
= A_1A_2 \left[\cos(\phi_1) + i\sin(\phi_1)\right]\left[\cos(\phi_2) + i\sin(\phi_2)\right]
\]
Removal of Flat-Earth Fringes
Interferograms for flat terrain and a Gaussian-shaped hill.
After removal of the flat-earth fringes, the residual fringes form a “contour map”

Interferogram
- Strong influence of curved earth
- High fringe density in places -- difficult to trace bands of continuous phase (i.e., “unwrapping”)
- Water and steep valleys show no coherent phase

Elevation and Range Difference
From the Law of Cosines
\[ B \sin(\theta - \alpha) = -\delta - \frac{\delta^2}{2r_0} + \frac{B^2}{2r_0} \]
which is solved for the look angle
\[ \theta = \arcsin \left( -\frac{\delta}{B} - \frac{\delta^2}{2Br_0} + \frac{B}{2r_0} \right) + \alpha \]
For a spherical earth with radius, Re, elevation and ground range are related to look angle by:
\[ z = -R_e + \sqrt{R_e^2 - 2\left( R_e + H \right) r_0 \cos \theta + r_0^2 + 2HR_e + H^2} \]
And
\[ y = R_e \arccos \left( \frac{2HR_e + H^2 + z^2 - r_0^2 + 2R_e(R_e+z)}{2(R_e+z)(R_e+H)} \right) \]
"Flattening" -- removal of curved earth signal

Phase ramp in the range direction

Fewer fringes for easier unwrapping

Unwrapping

- Following continuous bands of constant phase
- Successive bands differ by integer values of $2\pi$ relative to an arbitrary starting point

Determine Precise Baseline

- Satellite orbits are usually known to the meter level
- Need better for precise baseline estimation
- "Geocoding" of the unwrapped interferogram using ground control points

Interferometric Correlation

- Estimation of the degree of similarity between the two images
- Subject to surface changes as well as changes in material properties (e.g., dielectric constant)
**Sources of Decorrelation**
- Independent thermal noise sources
- Viewing geometry and terrain gaps
- Baseline
- Temporal changes

**Single-pass and Repeat-Pass INSAR**
- **Repeat-Pass** - Uses two observations acquired at different times from nearly repeating orbits or flight paths.
  
  In repeat-pass interferometry, the range difference is also sensitive to surface displacement between passes in the radar line of sight.
- **Single-Pass** - Uses two observations acquired at the same time using separate antennas.

**Applications of Interferometry:**
- Topography
- Seismic motion
- Glacial movement

**InSAR for Topography**

No terrain correction
(Apparent fault bend is artificial)

Terrain correction
Topography from Interferogram

Chitina River Valley, S.E. Alaska

- \( B_\perp = 40 \text{ m} \)
- Flat-earth fringes were removed.
- Phase is still wrapped.
- Each revolution of the color wheel represents an increase of 200 m in altitude.

Vesuvius, the Volcano

Source:
Ferretti, A., C. Prati, F. Rocca and A. Monti Guarnieri, POLIMI, 1997
Differential Interferometry

- A differential interferogram shows only motion. There are two methods for isolating displacement:
  - DEM Elimination (DEME): \( \text{Interferogram} - \text{DEM} \)
  - Double Differencing: \( \text{Interferogram}_A - \text{Interferogram}_B \)

Satellite InSAR – Measuring Motion

To measure motion:
  - The time delay must be appropriate to the scale of motion to be measured.
  - The spatial cohesiveness of the motion must be adequate given the coherence of the image.
  - One of 3 conditions must apply in order to remove the topographic component:
    - The baseline must be small enough for the topographic component to be neglected.
    - An accurate DEM must be used to remove the topographic component.
    - Three separate observations must be used to remove the topographic component

1992 Landers Earthquake Displacement
Timeline of Events

Antofagasta Earthquake
7/30/95

Mw = 8.0
July 30, 1995

USGS NEIC 48 km
Harvard CMT 28 km

Subsidence
Lost Hills and Belridge, CA

Fielding et al., 1998 GRL Plate 1
Mt. Etna, Italy

Topography: 1 fringe ~ 100 m
Deformation: 1 fringe ~ 2.8 cm

Glacial Velocities

Digital Elevation Map of San Rafael Glacier

Patagonia
Examples of other applications

- Interferometry to monitor changes in flood height in the Amazon basin (Alsdorf et al., Nature, 2000)
- Coherence to monitor soil moisture changes (e.g., Wegmueller et al., 1997)
- Coherence and Backscatter for forest mapping in Europe

GeoSAR – from EARTHDATA

*GeoSAR aircraft at Van Nuys,*  
*Camp Lejeune, October 7, 2001*
A new satellite mission called TanDEM-X is currently scheduled for launch in December 2009. Together with the almost identical TerraSAR-X which is to be launched in autumn this year, it will form a high-precision radar interferometer.

With the aid of the tandem formation TerraSAR-X/TanDEM-X it will be possible to completely measure the Earth's land surface, that is 150 million square kilometres, within a period of only 2.5 years. For a 12m grid (street width), height information can be determined with an accuracy of < 2 meters.

The decisive advantage of a satellite-based Earth measurement is the generation of a world-wide, consistent and homogeneous terrain model with no discontinuity at regional or national borders and no inhomogeneities resulting from different measurement procedures and measurement campaigns staggered in time (mosaics). The radar plays a decisive role here, since it can be operated completely independent of weather and light conditions.