INSAR Monitoring of Land Deformation
- Infrastructure Risk Assessment and Mitigation
GWF Hyderabad, January 2018

MDA Geospatial Services Inc. / DigitalGlobe
Background

• Space-borne INSAR as effective, reliable monitoring technology to detect ground movement
• Movement detected at cm / mm level at both horizontal and vertical directions
• Such land deformation poses risk to infrastructure assets, such roads, bridges, buildings
• Alert of movement allows organizations opportunity of early mitigation
Outline

• Intro to Land Deformation in Infrastructure Context
• Intro to INSAR
• Case#1: Seattle SR99 Bored Tunnel
• Case#2: High Speed Railway China
Infrastructures and Urban Land Deformation
Land Deformation – In Context of Infrastructure

Sinking or soaring?
by The China Watch on March 7, 2012

This hole appeared near Shanghai Railway Station to have been caused by subsidence because of moving underground water table. Photo: Cai Xianmin/GT

Kiruna: The Town That Moved
Winnipeg, New Residential Development

Extreme subsidence in a Winnipeg residential area, consistent with slumping of the riverbank.

Source: GoogleEarth Streetview

Linear rate
## Infrastructure Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| **Buildings** | • Vertical surfaces -> layover, cast radar shadows  
• Thermally active (vertical elongation of tall buildings, horizontal spreading of metal roofed industrial buildings) |
| **Bridges**   | • Multiple deformation sources (thermal expansion, vehicle loading, wind)  
• Complex radar return (e.g. double bounce off water) |
| **Roads**     | • Low radar backscatter from asphalt -> increases measurement noise -> requires filtering  
• May be cluttered by traffic parked cars, trees |
| **Tunnels**   | • Not directly observable  
• Overburden relaxation, groundwater removal may result in deformation of surface infrastructure within zone of influence |
| **Others**    | • Rail, dikes, airports, port facilities, ... |
## Deformation Drivers

<table>
<thead>
<tr>
<th>Deformation driver</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dewatering (underground water extraction)</td>
<td>Beijing, China</td>
</tr>
<tr>
<td>Dewatering (construction related)</td>
<td>Vancouver water filtration tunnel, Seattle SR99 tunnel</td>
</tr>
<tr>
<td>Sinkhole formation</td>
<td>Limestone karst region of Pennsylvania, USA</td>
</tr>
<tr>
<td>Excavation</td>
<td>Cut-and-cover sections of Vancouver ‘Canada Line’ project</td>
</tr>
<tr>
<td>Construction induced loading</td>
<td>New construction in alluvial areas</td>
</tr>
<tr>
<td>Unstable slopes</td>
<td>Urbanized hillsides – e.g. La Paz Bolivia</td>
</tr>
</tbody>
</table>
Introduction to InSAR
What does a SAR Sensor See?

- SAR is a side-looking sensor that receives a backscatter signal and movement (LOS) direction.
- SAR Geometry:
  - Flight path
  - LOS
  - Azimuth
  - Ground-range

Dark  Medium  Bright

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InSAR calculates the change in surface height between two imaging times, by using radar to measure the distance from the satellite to the surface.

InSAR can measure surface changes of a few millimeters using SAR phase information.
InSAR concept
Using SAR to Measure Surface Movement
Phase and amplitude change analysis

Phase Change Analysis (InSAR)

Analysis of the **phase change** of each pixel over time provides a time series of surface movement measurements with mm accuracy.

A series of SAR images collected with the same viewing geometry is used to perform either phase change or amplitude change analysis.

Amplitude Change Analysis

Analysis of the **amplitude change** of each pixel information about the appearance or disappearance of objects and features.

Changes at different times

New or missing objects
Demonstrate Absence of Deformation

- Analysis over a five year period using natural targets
- InSAR used to confirm absence of deformation over gas storage reservoir field
- Showed that technology worked by measuring ground movement in adjoining EOR field
- Ground movement at gas storage field very small and related to moisture variations during rainy/dry conditions
Monitoring Trends Over Time
Line-of-sight measurements

- Actual deformation is a 3D vector quantity
- InSAR measures projection of deformation along sensor line-of-sight → a 1D quantity
- 2 (or more) view geometries can be combined to measure other dimensions
Estimating 2D deformation with InSAR

1. Simple example of dewatering deformation

2. Line-of-sight InSAR measurements (apparent east/west shift)

3. Vector decomposition

1. Simple example of dewatering deformation

2. Line-of-sight InSAR measurements (apparent east/west shift)

3. Vector decomposition

Normalized deformation

+ 1.0

- 1.0

3D deformation

Ascending

Descending

East/West

North/South

Up/down

Error

Estimated

Actual
Case Study: Seattle Tunneling Project
SR99 Tunnel Project

- 3.2 km bored tunnel under downtown Seattle, U.S.A.
- 17.5 m diameter tunnel boring machine → ‘Big Bertha’
- TBM failed after 10% completion of tunnel
- Repair involves 24 m wide x 37 m deep rescue shaft with significant dewatering required → potential for surface displacement
SR99 Tunnel Project Timeline

Preparations for boring.

Boring

Inspection dewatering (1500 L/min.)

Cutter head failure

Access shaft dewatering (3000 L/min.)

RADARSAT-2 dataset: 79 Spotlight mode images (Ascending and Descending)

Ongoing RADARSAT-2 acquisitions

2012 2013 2014 2015
# RADARSAT-2 data

<table>
<thead>
<tr>
<th>Stack</th>
<th>Start Day</th>
<th>End Day</th>
<th>Number of Scenes</th>
<th>Incidence angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLA9 Ascending</td>
<td>2012/06/06</td>
<td>2015/02/15</td>
<td>41</td>
<td>37.0</td>
</tr>
<tr>
<td>SLA23 Descending</td>
<td>2012/06/06</td>
<td>2015/02/15</td>
<td>38</td>
<td>46.7</td>
</tr>
</tbody>
</table>

**Study Area**

- **SLA9Asc**
- **SLA23Des**

**Map**

- **Planned**
- **Completed**
- **Rescue shaft**
Line-of-sight deformation

Cumulative (2012/06/06 – 2015/02/15)

Same east/west pattern shift from example...

Normalized deformation

+ 1.0

- 1.0
2D deformation

Cumulative (2012/06/06 – 2015/02/15)

Same general patterns from example...

Normalized deformation

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>East/West</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.0</td>
<td>+1.0</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

1.5 cm/yr westward 1.5 cm/yr eastward

1.5 cm/yr eastward

1.5 cm/yr westward

Vertical

E-W Axis

N-S Axis

100 200 300 400 500

100

200

300

400

500

North Estimate

E-W Axis

N-S Axis

100 200 300 400 500

100

200

300

400

500

Up Estimate

E-W Axis

N-S Axis

100 200 300 400 500

100

200

300

400

500

West Estimate

E-W Axis

N-S Axis

100 200 300 400 500

100

200

300

400

500

1.5 cm/yr

-3.5 cm

+3.5 cm
Pre-dewatering linear deformation

(2012/06/06 – 2014/09/24)

Significant areas of long term (since June 2012) subsidence in area corresponding with infill of historic waterfront.
Pre-dewatering linear deformation

(2012/06/06 – 2014/09/24)

Westward deforming building shows external signs of damage and reinforcement.

0.5 cm/yr eastward

0.5 cm/yr westward
Dewatering correlated deformation

2012/06/06 – 2014/11/01: no deformation
2014/11/01 – 2015/02/15: linear deformation

Dewatering correlated deformation is spatially consistent with localized dewatering-induced deformation (both in vertical and east/west directions).

Pattern centered ~200 m south-east of rescue shaft.
Case Study: High Speed Railway Line Subsidence
Example: JingJin High Speed Rail (HSR) China

Water-pumping Subsidence Zone
Using RADARSAT-2 High Resolution Images Allows Detection of Stable Reflections from Rail Posts
Stable Reflections from the Rail Posts as Visible in the SAR Imagery

Green: stable reflection in 5 scenes, usable for InSAR (CTM)
Yizhuang Railway Station (at 21.3 km)
Significant Deformation Signal (~5 cm)
Subsidence Profile Along HSR
Maximum rates of approximately 10 cm per year
Conclusion
Benefits of INSAR-based Monitoring

- Interferometry is a proven technique which can measure mm of surface movement
- Surface movement measurements from InSAR can be readily integrated with other measurement programs used such as GPS, or in-situ survey etc.
- Satellites provide wide area routine monitoring
- Regular monitoring can be used as an alert for growing subsidence problems, and targeting engineering / maintenance resources
Organizations Benefiting from the Information

• Highway / Railway companies monitoring infrastructure assets
• State / Municipality governments monitoring its areas of responsibility
Thank You

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