Multi Sensor InSAR Analysis of a Large Deep-seated Gravitational Slope Deformation, Fels Glacier Slide, Alaska

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Outline

• Project background, goals and objectives
• Demodulation based phase unwrapping of historical InSAR data
  • Pre-processing of multi sensor InSAR data
  • Concept and sensitivity simulation of demodulation method
  • Near complete, near-final results
• Multivariate analysis of deformation and driver (meteorology, glacial retreat, seismic) time series
  • Started, preliminary results
• Comprehensive Geophysical Modeling (Discontinuous FEM) of Fels Glacier Slide
  • Not started, no results yet
• Conclusions
Project Background (Fels Slide Glacier Slide, Alaska)

* Very Large creep-type gravitational mass movement < 3km from Alaska Pipeline + Richardson Highway
* 2002 Denali Earthquake “feather ruptured” slope (main fault <2.5 km away)

Questions:
* Earthquake lead to “near critical” speedup?
* Role of meteorology, deglaciation drivers?
* How would a catastrophic failure unfold?
* Quantify risk scenario for Alaska Pipeline?

Slide faults (S. Newman, 2009)
Project Background (Previous and Ongoing/Planned Work)

Previous work:

Current project:
Comprehensive analysis of all existing/to be acquired remote sensing (SAR/InSAR, optical), ground based (fieldwork data, LIDAR, RAR), meteorological and other proxy data sets resulting in a predictive geophysical modeling of Fels Slide dynamics – first field visit July 2017

Project partners:
- B. Rabus, SFU SARlab: SAR/InSAR, Optical, Met Data Processing; Time Series Analysis
- J. Clague, SFU Centre for Natural Hazards Research: Geological Analysis
- D. Stead, SFU Resource Geoscience and Geotechnics: Geophysical Analysis + 4D FEM Modelling

Collaborators:
- F. Meyer, UAF Remote Sensing + ASF: Ground-based RAR interferometry
- F. Wuttig, Alyeska Pipelines, Risk Assessment: Exchange of Research Results, Logistics/field support

Expected publications (3-4), grouped into two areas:
- dedicated specifically to the Fels Slide temporal evolution and the underlying mechanisms and drivers
- comprehensive inventory of gravitational instabilities in the surrounding area of the Alaska Range
# SAR Datasets and Timeline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TSX STD</th>
<th>RSAT2 SLA19D</th>
<th>RSAT1 F4D</th>
<th>ERS 57D</th>
<th>ERS 329D</th>
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<tbody>
<tr>
<td>Direction</td>
<td>Des</td>
<td>Des</td>
<td>Des</td>
<td>Des</td>
<td>Des</td>
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<tr>
<td>Centre incidence angle [°]</td>
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<td>44.0</td>
<td>45.1</td>
<td>23.3</td>
<td>23.3</td>
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<td>Slant-range resolution [m]</td>
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<td>10</td>
<td>10</td>
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<tr>
<td>Azimuth resolution [m]</td>
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<td>0.8</td>
<td>9</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Number of scenes</td>
<td>19</td>
<td>23</td>
<td>23</td>
<td>16</td>
<td>6</td>
</tr>
</tbody>
</table>

ERS footprints cover entire area shown

7.9 $M_w$ Denali quake - November 3, 2002
Pre-processing of Multi Sensor InSAR Data: Common Geometry

LOS geometry difference:
for Descending passes:
* RSAT1 – RSAT2 ~1 deg
* TSX – RSAT ~3 deg
* TSX – ERS ~20 deg

Wavelength X/C + repeat interval difference:
* TSX – RSAT: 11d(X)-24d(C)
* TSX – ERS: 11d(X)-35d(C)

Combined (same motion):
compared to
TSX 11d-interferogram
* ~20 percent more fringes in
RSAT 24d-interferogram
* ~75 percent more fringes in
ERS 35d-interferogram
Pre-processing of Multi Sensor InSAR Data: Orbit/Atmospheric Model

r, a: range, azimuth location
h: topographic height (slant range DEM)

Parametric phase model:
\[ \Phi_{\text{orbit}} \approx \alpha_0 + \alpha_1 r + \alpha_2 a + \alpha_3 r^2 + \alpha_4 a^2 + \alpha_5 r a \]
\[ \Phi_{\text{static\_atmosphere}} \approx \beta \cdot h \]

Solve over non-moving areas ("white" in "Non-moving" mask):
\[
\begin{bmatrix}
\alpha_0 \\
\vdots \\
\alpha_5 \\
\beta
\end{bmatrix}
= \arg \min \sum \left( \Phi - \Phi_{\text{orbit}} \begin{bmatrix}
\alpha_0 \\
\vdots \\
\alpha_5 \\
\beta
\end{bmatrix} \right)^2
\]

Estimate motion component:
\[
\Phi_{\text{motion}} \approx \Phi - \Phi_{\text{orbit}} \begin{bmatrix}
\alpha_0 \\
\vdots \\
\alpha_5 \\
\beta
\end{bmatrix} - \Phi_{\text{stat\_atm}}(\beta)
\]
Motion Signal Estimation: Example

RS2: 20110709_20110802

"Non-moving" mask (region-labeled)

Challenge due to possible wrapping between discontinuous mask regions

Quality check: Static atmospheric phase vs. elevation (rest of model applied)
ERS (1993 – 1997)


RS2 (2011 – 2015)

TSX (2015 – )

Wrapped Motion Phase
All Sensors: Initial (Topo-flattened)

... weeks of blood, sweat, and tears ...

SARlab
ERS (1993 – 1997)

Wrapped Motion Phase (same geom.)
All Sensors: After Modeling


RS2 (2011 – 2015)

TSX (2015 – )
Demodulation Based Phase Unwrapping of Historical InSAR Data

Older SAR sensors (ERS/Envisat/RADARSAT-1/...)
- can be useful for retrospective/long-term analysis of landslide activity
- more difficult to analyze (more noise, lower resolution, less accurate + bigger baselines)
  • Landslides, add: deformation discontinuities + coherence loss from seasonal snow patches
=> significant phase unwrapping problems

Idea: (for landslides) demodulate older sensor data with data from newer highres. sensors
- Assumes long term stationary of spatial discontinuities

Fels slide faults (S. Newman, 2009)
Unwrapped phase template from newer sensor (ex. TSX spotlight)
Wrapped data from older sensor (ex. ERS)
Demodulation Morph — “Discontinuity Patch Match”

Goal: achieve spatially smooth phase residual

\[ \text{map} = \text{fac}(x,y) \ast \text{map}_{\text{ref}} + \text{res}(x,y) \]

1. Fit thin plate spline to \( n \) individual patch results \( \text{fac}_i \)

2. \( \text{fac}(), \text{res}() \): spatially smooth functions

\( \text{map}_{\text{ref}} \): reference igram (unwrapped)

\( \text{map} \): igram to be demodulated

\( \text{map}_{\text{ref}} \): TSX 20150803_20150814
Assessment of Demodulation Method with Simulated Data

- Template: elliptical nestable lobe(s)
- Simulate interferogram (tunable parameters):
  - Shifts in axes and center of the lobe(s)
  - Along- and across-lobes movement gradients (e.g. ramp)
  - Phase disturbances from image speckle, atmospheric remnants (spatially correlated random noise)
- Demodulation parameters (e.g. RBF type and stiffness, radius of demodulation patches)
- Many experiments done – observations:
  - method robust ✓
  - solution ambiguous if unwrapped template/interferogram differ by more than π across discontinuities
  - in-patch gradients can resolve ambiguity; ✓ alternatively: 1d unwrap along discontinuity

Radial basis function (RBF) type: multiquadric

$$\phi(r) = \sqrt{\left(\frac{r}{\varepsilon}\right)^2 + 1}$$
Early summer interferograms more challenging to unwrap:

• Snow patches + wet ground diminish coherence
• Landslide most active seasonally (water input)
Demodulation Example (RADARSAT-2): Demodulation Factor

Factor map:
- smooth continuous (thin plate spline)
- Spatial variation has no direct physical meaning
- Mean can be used as (robust but relative) measure of slide activity (if residual is small!)
RADARSAT-2: Demodulation Residual

Residual map:
- Smooth, continuous also (if method is applicable)
- Applicability condition: residual no longer wrapped on the “bending scale” of the thin plate spline

0 0.75 1.5 cm LOS
RADARSAT-2: Demodulation residual (smoothed)

Smoothed residual map; prepare for unwrapping:
• Basic multilooking used here
• Use more sophisticated spatially adaptive filter as needed
“Landslide Activity” Time Series

Demodulation factor is relative to reference map **20150803_20150814**:

\[ f = 1.0 \text{ corresponds to:} \]
\[ \sim 0.6 \text{ fringes, or} \]
\[ \sim 0.8 \text{ cm/d LOS displacement (center of Fels Slide East Lobe)} \]

Interesting fine structures/differences in the seasonal variations – to be studied further!
"Average Activity Factor" - Correlation with Total Water Input

**ERA Meteorological Re-Analysis Time Series (for the Fels Glacier Slide)**

* **Primary Time Series:**
  * Snow depth [m SWE]
  * Snow melt [m SWE]
  * Total snowfall [m SWE]
  * Total precipitation [m]

* **Derived Time Series:**
  * Annual cumulated snow melt
  * Annual cumulated rain
    (from Rain fall = Total precip – Total snowfall)
  * Total water input (spring+summer)
    (from Annual cumulated Rain fall + previous snow melt)

**Strange result!** Fitted factors suggest that RS1 period (2003-2006) had similar or lower slide activity but direct inspection of interferograms tells otherwise => patch demodulation method gives “wrong” answer - why?
Demodulation Residuals (Examples)

July-August (1995 to 2015)

ERS

map: 19950727_19950831

RS1

map: 20030715_20030808

Spatially smooth ...
but huge residual!

RS2

map: 20100807_20100831

RS2

map: 20150805_20100829
Original Wrapped Interferograms

July-August (1995 to 2015)

ERS
map: 19950727_19950831

RS1
map: 20030715_20030808

RS2
map: 20100807_20100831

RS2
map: 20150805_20100829

\( \pi \)
Seasonal Deformation Patterns

- **spring(snowmelt)**
  - 2003Jul15_Aug08
  - 2004Feb16_Mar11

- **summer/fall**
  - 2011Jun15_Jul09
  - 2011Aug02_Aug26
  - 2010Feb20_Mar16

- **winter**
  - 2015Jul01_Jul23
  - 2015Aug03_Aug14
Spring Residual Deformation Pattern (Dominant Mode Post Seismic)

Patter amplitud

=> Characteristic “deep” deformation pattern dominant for several years after Denali Earthquake!
Spring Residual Deformation Pattern Amplitude vs. ERA Snow Depth

Snowdepth
Spring residual deformation (pattern amplitude)
Spring Residual Deformation Pattern – Correlation with Max. Snow Depth

Max snow depth as proxy for water form cumulative snow pack melt (ignoring wind + sublimation losses)

=> Snow melt water suggested as linear driver for Spring Residual Deformation Pattern

=> Linear coefficient (slide sensitivity) strongly elevated after earthquake

Sensitivity slope of Fels Slide “spring” activity with max. size of preceding snowpack

"SPRING" LOS MOTION (Fels-East lobe) [cm/d] vs. MAX SNOW DEPTH [m swe]
Conclusions

• **Unique Multi-sensor InSAR data set** pre-processed to (Wrapped) Motion Phase

• **Demodulation Method** developed for re-analysis of Coarser Historic Data
  • robustly captures differential deformation across discontinuities
  • produces small, smooth unwrappable residuals outside multi-year period following Denali Earthquake

• **Deformation Pattern with “Shallow” Spatial Characteristics** (demodulation method)
  • mean annual amplitude linearly correlated with total water input into the slope
  • linear coefficient similar throughout observation coefficient

• **Deformation Pattern with “Deep” Spatial Characteristics** discovered (residual)
  • detectable throughout observation period
  • amplitude normally small except for immediate post-seismic period
  • short-term driver of pattern apparently is size of snow pack
  • linear coefficient (= slide sensitivity to snow pack size), increased >6-fold in immediate post-seismic period

• **Next:**
  • After Completion of Demodulation/Unwrapping => Unleash Full “Arsenal” of Spatio-temporal Analysis on Unwrapped Data Set (Multivariate, PCA, Wavelets, etc.)
  • Parameterization of Geophysical model (Driven by Spatio-temporal Analysis and Field Results)
  • Development of Predictive Hazard Model (together with Alyeska Pipelines Risk Assessment team)
  • Translate to other landslides in the area