L- and C-band SAR Interferometry analysis of the Wieliczka Salt Mine’s area (UNESCO Heritage Site, Poland)

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Summary

✓ Test site
✓ PSI analysis of ERS-1/2 dataset
✓ InSAR processing of ALOS data
✓ Results analysis
✓ Conclusions and future works
Test site: Wieliczka
Why Wieliczka

- Unique salt mine, over 700 years old, tourist attractions in Poland (since 1978 is in the UNESCO International List of the World Cultural and Natural Heritage).
- Subsidence documented by ground topographic measurements with rate up to 3 cm/yr.
ERS / ALOS satellite images were provided by ESA under the ALOS ADEN 3595 project.

ERS-1/2:
- descending acquisitions
- Track = 179, Frame = 2601
- 39 images $\in [1992, 2000]$

ALOS PALSAR:
- ascending acquisitions
- FBS mode
- Path = 622, Frame = 990
- 4 images $\in [2007, 2008]$
SAR data coverage
## ALOS vs ERS

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>POL.</th>
<th>CHIRP BW</th>
<th>$\theta_{inc}(beamID)$</th>
<th>$B_{\perp,c}$</th>
<th>$R_{gr}$</th>
<th>$R_{az}$</th>
<th>$H_M$</th>
<th>SWATH</th>
</tr>
</thead>
<tbody>
<tr>
<td>L (1.27 GHz)</td>
<td>HH</td>
<td>28 MHz</td>
<td>$\sim 38.7^\circ$ (#8)</td>
<td>$\sim 15.38$ km</td>
<td>$\sim 8.6$ m</td>
<td>$\sim 5.0$ m</td>
<td>$\sim 700$ km</td>
<td>$\sim 70$ km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>POL.</th>
<th>CHIRP BW</th>
<th>$\theta_{inc}(beamID)$</th>
<th>$B_{\perp,c}$</th>
<th>$R_{gr}$</th>
<th>$R_{az}$</th>
<th>$H_M$</th>
<th>SWATH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (5.3 GHz)</td>
<td>VV</td>
<td>15.55 MHz</td>
<td>$\sim 23.2^\circ$</td>
<td>$\sim 1.10$ km</td>
<td>$\sim 24.5$ m</td>
<td>$\sim 5.0$ m</td>
<td>$\sim 789$ km</td>
<td>$\sim 100$ km</td>
</tr>
</tbody>
</table>

### Advantages:
- Less temporal decorrelation thanks to longer wavelength (23.6 cm vs 5.6 cm)
- Longer critical baseline (15.4 km vs 1.1 km): InSAR possible for every pair of acquisitions (but topographic error can dominate for high $B_{\perp}$)
- More chances to detect high velocity deformation:
  \[
  V_{max} = \frac{\lambda}{4 \cdot dt} = 46.8 \text{ cm/y (ERS: 14.6 cm/y)}
  \]

### Disadvantages:
- Longer baselines require more care in coregistration on steep topography and are more sensible to topographic errors
- Inospheric effect is expected to be 20.5 times stronger
- LOS range precision of L-band InSAR is 1.5 times worse than ERS [Sandwell et al. TGRS, 2007].
Objectives

1. Cross compare the deformation fields.

2. Cover rural or vegetated area where C-band decorrelate and PS-like targets are very few.

3. Provide measurements where deformation have high rate (complementarity wrt C-band).
SPINUA processing chain
PS results

PS distribution over a GE image.
PS results

Danilowicz shaft: main mine entrance.
PS results

Geological map of the Wieliczka area draped over a DEM (background image) and PS distribution.
PS results


- The ground topographic measurements documented subsidence up to 1m in the period 1970-2000 (i.e. 3 cm/yr or 2.7 cm/y ERS LOS).

- The detected width of the subsiding zone corresponds very well to the extent of the underground salt mine, whereas its length (around 4.5 km) is somewhat shorter with respect to that of the mining works and of the known salt deposit. This discrepancy results in part from the lack of suitable radar targets in the rural areas east and west of the town of Wieliczka. (ALOS)
L-band potentiality

✓ Cover rural or vegetated area where C-band decorrelate and PS-like targets are very few.

✓ Provide measurements where deformation have high rate (complementarity wrt C-band).
## ALOS Dataset

<table>
<thead>
<tr>
<th>No</th>
<th>Scene Date</th>
<th>Off-nadir angle</th>
<th>Orbit</th>
<th>Scene ID</th>
<th>Cycle</th>
<th>PRF(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2007/01/02</td>
<td>34,3</td>
<td>5015</td>
<td>ALPSRP050150990</td>
<td>8</td>
<td>2155172,414</td>
</tr>
<tr>
<td>2</td>
<td>2007/02/17</td>
<td>34,3</td>
<td>5686</td>
<td>ALPSRP056860990</td>
<td>9</td>
<td>2132196,162</td>
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<tr>
<td>3</td>
<td>2008/01/05</td>
<td>34,3</td>
<td>10383</td>
<td>ALPSRP103830990</td>
<td>16</td>
<td>2155172,414</td>
</tr>
<tr>
<td>4</td>
<td>2008/02/20</td>
<td>34,3</td>
<td>11054</td>
<td>ALPSRP110540990</td>
<td>17</td>
<td>2132196,162</td>
</tr>
</tbody>
</table>
ALOS InSAR pre-processing

✓ Resampling of the images in azimuth direction were required in order to uniform the PRF of PALSAR FBS acquisitions Level 1.1 (differences even more than 20 Hz were observed).

✓ Doppler centroid frequency results stable for all the images $df_{DC} < 10$ Hz: azimuth common band filtering not required.
ALOS InSAR processing

2/3 pass InSAR

1. Differential InSAR phase starting from either 2 images + SRTM DEM or 3 images
2. Spatial convolution 11x21
3. PU (SNAPHU)
4. Repeat steps 2-3 by using 6x11 spatial convolution window
5. Compare the resultant unwrapped phase field and generate a mask M1 which filters out pixels where $\Delta \Phi > \pi$
6. Generate a mask M2 which filters out pixels where $\gamma < 0.3$
7. The final mask to apply to the InSAR Phase is $M = (M1) \cup (M2)$
8. Phase detrending: estimate and remove a bilinear phase trend on the interferogram (orbital error, …)
InSAR results: 2 pass

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>$B_1$ [m]</th>
<th>$B_1$ [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR_20070102_PSR_20070217</td>
<td>1705.3</td>
<td>46</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20080105</td>
<td>3671.7</td>
<td>368</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20080220</td>
<td>4568</td>
<td>414</td>
</tr>
</tbody>
</table>
InSAR results: 3 pass
InSAR results: 3 pass

PSR_20070102_PS0_20080105

PSR_20070102_PS0_20082020

[Map images showing InSAR results]
ALOS DInSAR and ERS PS
ALOS Coherence and ERS PS
 ✓ The InSAR phase can be explained in terms of:
   – residual topography
   – atmospheric contribution (due to both troposphere and ionosphere)
   – deformation
   – system noise
Phase due to topographic residues depends on the $B_\perp$: so the difference between normalized phase should be close to zero.
Tropospheric contribution

- **ALOS** - Variograms don’t show any power law since data were acquired during **night time (20h 57m) in winter season** (January / February).

- **ERS** - Tandem pair ($B_t = 1$ day, $B_\perp = 74$ m) has been selected in order to ensure high coherence. Data acquired during **daytime (09h 32m) in summer / autumn** seasons when tropospheric turbulences can strongly affect the InSAR signal.

$$V_\phi(d) = \left[ \Phi(p + d) - \Phi(p) \right]^2$$

$d \in [200 \text{ m}, 22 \text{ km}]$
**Inonospheric contribution**

✓ Contribution due to ionosphere for L-band it is expected to be stronger than in C band:

\[
\Delta l_{Iono atm} = - \frac{40.28}{f_i^2 \cos(\theta_i)} \cdot TEC
\]

\[
\frac{\Delta l_{Iono, L}}{\Delta l_{Iono, C}} = \left(\frac{f_C}{f_L}\right)^2 \cdot \frac{\cos(\theta_C)}{\cos(\theta_L)} = 20.5
\]

✓ Since night time acquisition TEC \(\approx 0\) and consequently also the ionospheric effect:

\[
TEC \approx \begin{cases} 
0 & \text{at night;} \\
20 \cdot 10^{16} \text{ m}^{-2} & \text{at min of solar cycle} \\
100 \cdot 10^{16} \text{ m}^{-2} & \text{at max}
\end{cases}
\]

\[
\Delta l_{Iono atm} \approx 0
\]
Deformation

✓ Deformation field: L-band vs C-band

\[ V_{ERS} = 2.4 \text{ cm/y} \rightarrow V_{ALOS} = 2 \text{ cm/y} \]

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>( B_t ) [d]</th>
<th>( dR ) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR_20070102_PSR_20080105</td>
<td>368</td>
<td>2</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20080220</td>
<td>414</td>
<td>2.3</td>
</tr>
</tbody>
</table>

[Sandwell et al 2007]:
ALOS def_rms = 1.4 cm
The slant range L-band precision can be estimated by computing the rms of the residual InSAR phase after removing all the other signals (topography, atmosphere, deformation):

$$\sigma_R = \frac{\lambda}{4\pi} \sigma_\varphi$$

### Radar noise

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>$B_t$ [d]</th>
<th>$B_\perp$ [m]</th>
<th>Phase rms [rad]</th>
<th>Slant range rms [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR_20070102_PSR_20080105</td>
<td>368</td>
<td>3671.7</td>
<td>1.07</td>
<td>20.09</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20080220</td>
<td>414</td>
<td>4568</td>
<td>1.05</td>
<td>19.82</td>
</tr>
</tbody>
</table>

Sandwell et al 2007 reported ALOS range rms $\in [3.3, 5.8]$ mm with $B_\perp=690$ m $B_t = 46$ d.
Conclusions

✓ C-band PSI was able to infer deformation field related to the Wieliczka subsidence.

✓ The use of L-band ALOS DInSAR data resulted unfeasible to measure the low deformation rate (< 2.4 cm/y).

✓ No higher rate deformation seems to be present in the same area.

✓ L-band and C-band InSAR can play a complementary role in deformation monitoring:
  – high vs low deformation rate
  – low coherent area vs single persistent target
Coherence: ALOS vs ERS

An estimation of the coherence distribution of L-band and C-band interferograms has been performed. A simple model can be applied to describe the temporal decorrelation behaviour:

$$\gamma_t = \exp\left(-\frac{|B_t|}{T}\right) \rightarrow \ln(\gamma_t) = -\frac{|B_t|}{T}$$

where $$\gamma_t = \frac{\gamma_{tot}}{\gamma_g}$$, $$\gamma_g = 1 - \frac{B_t}{B_c}$$

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>B_x [m]</th>
<th>B_t [d]</th>
<th>(\gamma_{tot})</th>
<th>(\gamma_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR_20070102_PSR_20070217</td>
<td>1705.3</td>
<td>46</td>
<td>0.41</td>
<td>0.46</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20080105</td>
<td>3671.7</td>
<td>368</td>
<td>0.14</td>
<td>0.18</td>
</tr>
<tr>
<td>PSR_20070102_PSR_20082020</td>
<td>4568</td>
<td>414</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>PSR_20070217_PSR_2008105</td>
<td>1967.4</td>
<td>322</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>PSR_20070217_PSR_20080220</td>
<td>2864</td>
<td>368</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>PSR_20080105_PSR_20080220</td>
<td>896.6</td>
<td>46</td>
<td>0.36</td>
<td>0.38</td>
</tr>
<tr>
<td>E1_19950805_E2_19950806</td>
<td>74</td>
<td>1</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>E2_19990919_E2_19991024</td>
<td>20.6</td>
<td>35</td>
<td>0.14</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Coherence: ALOS vs ERS

- **PSR_20070102_PSR_20070217**
  - $B_\perp = 1705$ m
  - $B_t = 46$ d
  - $\gamma_g = 0.89$
  - $\langle \gamma \rangle = 0.41$
  - $\sigma_\gamma = 0.18$

- **PSR_20070102_PSR_20080220**
  - $B_\perp = 4568$ m
  - $B_t = 414$ d
  - $\gamma_g = 0.7$
  - $\langle \gamma \rangle = 0.15$
  - $\sigma_\gamma = 0.12$

- **E1_19950805_E2_19950805**
  - $B_\perp = 74$ m
  - $B_t = 1$ d
  - $\gamma_g = 0.93$
  - $\langle \gamma \rangle = 0.31$
  - $\sigma_\gamma = 0.14$

- **E2_19990919_E2_19991024**
  - $B_\perp = 20.6$ m
  - $B_t = 35$ d
  - $\gamma_g = 0.98$
  - $\langle \gamma \rangle = 0.14$
  - $\sigma_\gamma = 0.08$
Future works

✓ Further ALSO PALSAR data processing
✓ More investigation on coherence
✓ X-band data for further comparison