Pushing the accuracy limit for CO2 sequestration monitoring: Statistically optimal spatio-temporal removal of the atmospheric component from InSAR Networks

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Outline

• InSAR monitoring of CO2 sequestration
  - Complications

• Enhanced solution (novel spatio-temporal atmospheric filtering)

• Accuracy maps
InSAR solution for CO2 sequestration monitoring: previous results presented at Fringe 2009

- example Krechba/InSalah
- used ENVISAT data since injection start (2003)
- switched over to RADARSAT-2 data (2008)
InSAR solution for CO2 sequestration monitoring

: previous results presented at Fringe 2009

- Accuracy at 1-2 mm a^{-1} level
- Standard dual scale (long range) atmosphere removal (no static)
- Simple temporal filter (block average)
- Topo removal with SRTM 90 m DEM only

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Raw Interferogram → Baseline Correction → Long Range Atm Removal

Good!

… but …

not good enough …
CO2 sequestration - Diminishing SNR for InSAR...


Initial inflation: 15 mm
Reduced inflation: <2 mm

Envisat ~ 7 yrs
RADARSAT-2
Reduced inflation period => results differ between sensors and tracks (e.g. rms difference Tr65 vs. Tr 294 is 2.3 mm)
Factors Limiting SNR

SNR: Deformation is “Signal”; all other phase components are “Noise”

1. Atmospheric remnant error
   - static
   - dynamic
2. Topographic remnant error
3. Line-of-sight (LOS) projection loss (assuming deformation is mainly vertical)
4. Temporal decorrelation error (coherence)
Deformation Series Accuracy influenced by:

- Diminishing signal over time (yes: SNR worsens)

- Satellite parameters
  - Wavelength X/G (no: –far from optical limit)
  - High resolution (no: –multi-look reduces phase noise but can’t afford small footprint; need >50 km)
  - Incidence angle (yes: steeper angle improves SNR through shorter LOS + less atmosphere)

- Revisit time (yes: temporal decorrelation + inversion statistics improve with shorter revisit but: alternatively can interleave + coinvert stacks)
- Dawn dusk vs daytime/nighttime orbit (yes: atmospheric signal different)
Need to counter diminished SNR over time by improving processing accuracy

- scrutinize all steps
- optimally exploit spatio-temporal properties of:
  - deformation signal
  - atmospheric error
Improved Solution

Features:
- Robust Dual-scale-combined PSI and Network-DSI approach
- Dynamic atmosphere correction (dual scale concept)
- Network baseline + 2+1D phase unwrapping corrections
- Static atmosphere correction
- Robust, high performance height error correction
- Optimum post-inversion spatio-temporal filtering of atmospheric remnant error
- Highest possible spatial resolution (Wiener filter)
- Co-inversion of interleaving stacks => highest possible temporal resolution
- Fully integrated, tightly coupled InSAR + geophysical modeling solution
Topographic correction enhancement

with simple topographic removal (external DEM – SRTM)

with additional Stack-based topographic error removal

Example interferometric layer

Solve height error + linear rate for each pixel (as for PSI)
Topographic correction enhancement

By-product: accurate high resolution DEM
Post-Network Inversion Enhancements

#1: Temporal referencing

#2: Temporal filtering

#3: Spatial Filtering
Original Temporal Filter

Strategy:

• manually remove ‘bad’ layers
• interpolate over holes (green dots)
New Temporal filter (LOWESS-linear)

First order Lowess with 10 points
Optimized Spatial Filter
(remove short scale atmospheric error in spatial domain)

- Deformation areas are known
- Atmospheric modes are spatially slowly varying or const. throughout scene
- There is accuracy benefit in “relieving” the temporal filter

Concept: Spectrally estimate atmospheric modes (in non-deformation area)...then derive optimal per-layer spatial filter

Complication: How to estimate the spectra with holes in the image?
Spatio-Temporal Filtering overview

Wiener transfer function:

\[ G = \frac{S_{nr}}{S_{nr} + 1} \]

\( S_{nr} \): signal-to-noise power ratio
Example Power Spectrum

Prominent Atmospheric Mode

Estimated atmosphere (power spectrum)  Transfer function
Adaptive filter for advanced atmospheric phase component estimation and removal.

Total Signal = Water Vapor + Deformation
Adaptive filter for advanced atmospheric phase component estimation and removal.

Total Signal = Water Vapor + Deformation
Adaptive filter for advanced atmospheric phase component estimation and removal.

Total Signal = Water Vapor + Deformation
21-Sep-11

Envisat-Tr65

Envisat-Tr294


Radarsat-2 (F5N)

Original InSAR solution

Enhanced InSAR solution

+ KB-502 + KB-503
+ KB-14
+ KB-11
+ KB-12

+ KB-502 + KB-503
+ KB-14
+ KB-11
+ KB-12

+ KB-501 + KB-11
+ KB-12

+ KB-501 + KB-11
+ KB-12

+ KB-501 + KB-11
+ KB-12
Accuracy maps

2009 plan

<table>
<thead>
<tr>
<th>Correction</th>
<th>Signal (Motion)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline B</td>
<td>D (igrams)</td>
<td>T, ΔT, H, A</td>
</tr>
<tr>
<td>Topography H</td>
<td>D (igrams)</td>
<td>T, ΔT, ΔH, A</td>
</tr>
<tr>
<td>Spatial Filter = long scale Atmosphere $A_{long}$</td>
<td>D (igrams)</td>
<td>T, ΔB, ΔH, A</td>
</tr>
<tr>
<td>Network inversion SVD</td>
<td>D (SLC dates)</td>
<td>=&gt; Error propagation through network unnecessary (… is also unfeasible)</td>
</tr>
<tr>
<td>Temporal Filter = short scale Atmosphere $A_{short}$</td>
<td>D (SLC dates)</td>
<td></td>
</tr>
</tbody>
</table>

Now close to true thanks to (2+1)D correction

Phase unwrapping (assume: no errors)

Processing Flow

T: temporal decorrelation
A: original atmosphere

now: network fit => error negligible
Now: topographic correction => error negligible
Now: only used for phase unwrapping => no need to propagate

=> Error propagation through network unnecessary (… is also unfeasible)

Replaced by Wiener/ Lowess filters => sufficient to estimate post-inversion error map

+ temporal interpolation error $ΔI$ (for interpolated SLC dates only)
Accuracy Maps

Assume error ~ variance of residual phase (final vs. post SVD network inversion)

\[ e(x, y) = \kappa \sqrt{\frac{1}{N} \sum_{t=1}^{N} \left( \phi_{t}^{\text{final}} (x, y) - \phi_{t}^{\text{postSVD}} (x, y) \right)^2} \]

Accuracy map for mean deformation rate [rad]

- \( t \) : time index
- \( x, y \) : spatial indices
- \( \kappa \approx 0.04 \) estimated using retrieved atmospheric screens as a Monte Carlo dataset

\[ e(\tilde{x}, \tilde{y}, t) = \kappa \left( \left( \phi_{t}^{\text{final}} (x, y) - \phi_{t}^{\text{postSVD}} (x, y) \right)^2 \right)_{BxB} L(t) \gamma(x, y, t) \]

Accuracy maps for each date layer [rad] => time series error bars

- \( B \) : block filter width, choose corresponding to \( \approx 5 \) km
- \( L(t) \) : normalized response function of Lowess filter (temporal)
- \( \gamma(x, y, t) \) : SVD inverted (spatial) coherence of SLC data t
Accuracy Map Example (for mean deformation rate
Accuracy Map Example (error bars)
Multi-track comparison of vertical deformation

- Envisat Tr65 (Dsc)
- Envisat Tr294 (Dsc)
- RADARSAT-2 F5N (Dsc)
- RADARSAT-2 F4 (Asc)
Multi-track comparison of vertical deformation

1. Envisat Tr65 (Dsc)
2. Envisat Tr294 (Dsc)
3. RADARSAT-2 F5N (Dsc)
4. RADARSAT-2 F4 (Asc)
Envisat RMS difference maps
(Track 65 vs Track 294)

Original filter: std = 2.3 mm

Improved temporal referencing: std = 0.88 mm

Improved temporal filtering (lowess): std = 0.70 mm

Wiener filter and APS added: std = 0.58 mm
Homogenous Distributed Scatterer Interferometry: adaptive multi-look of phase, then process like PSI (=> precise deformation time series of both PS and DS)

Insignificant advantage of HDS vs. 2D for this application/area (high coherence, mostly DS)

.. but HDS superior to PS for semi-urban, temperate climate

=> see our poster on HDS InSAR
Conclusions

• MDA’s dual scale Network DSI solution was enhanced significantly over what I presented in 2009; added features include: topographic correction, 2+1D phase unwrapping, and adaptive spatio-temporal atmospheric filtering.

• Displacement maps produced with the enhanced solution from individual ENVISAT data stacks have accuracies of better than 0.4 mm at spatial and temporal resolution of 90 m (ca. 3 resolution cells) and 150 days (ca. 5 satellite repeat intervals), respectively.

• Comparison shows individually processed ENVISAT and RADARSAT-2 displacement series consistently agree to better than 0.6 mm per year for a several months temporal overlap of the image stack.

• The enhanced method captures signal after uplift magnitudes have been reduced due to reservoir maturation and also in the post-injection phase => we can conclude that (at the least for semi-arid areas) InSAR observation of surface uplift (in conjunction with deformation modeling based on geological and structural information) is method of choice for monitoring the volumetric spread of CO2 sequestered underground.