SAR Calibration Requirements for Interferometry Applications: inching towards sub millimeter measurements

Alessandro Ferretti (**)
Andrea Monti Guarnieri (*)
Fabio Rocca (*)
Alessio Rucci (*)

(*) POLIMI - DEI
(**) TRE, TeleRilevamento Europa
WHY?

Requisites for CO2 storage and oil reservoirs monitoring
(30% of the energy right away, 10000 years sequestration ???)

Reservoir kinematics
From Volume Changes to Surface Deformation
A one line theory
From elasticity theory

In the case of an elastic model, starting from Segall (1985), it’s possible to get the relation between surface deformation and percentage volume change. The vertical deformation is:

\[ u_z(x, y, z) = \int V \Delta(\bar{\xi}) g_z(x, y, z, \bar{\xi}) dV \]

where \( \bar{\xi} = (\xi_1, \xi_2, \xi_3) \) ranges over \( V \)

\[ g_z(x, y, z, \bar{\xi}) = \frac{(1 + \nu)}{3\pi} \frac{z - \xi_3}{\left(\sqrt{(x - \xi_1)^2 + (y - \xi_2)^2 + (z - \xi_3)^2}\right)^3} \]

\( \nu \) is the Poisson Ratio \((0 < \nu < 0.5)\)
In case of CO$_2$ injection

- What’s the minimum amount of injected CO$_2$ we can detect using PSInSAR™?

Assuming:
- a reservoir 2Km depth
- a single layer overburden

Assuming an accuracy of 1mm, we can detect 30,000 m$^3$ of injected CO$_2$.
InSalah Case study (Algeria)

The InSalah Gas storage project is the first $CO_2$ sequestration effort in an active reservoir.

1 million $CO_2$ tons are reinjected into the subsurface each year.

PSInSAR estimated volume and pressure changes, and finally the permeability within the reservoir. A fault had been reactivated.
CO2 Sequestration - North Africa

Pattern anisotropy $\rightarrow$ Fault reactivation?
Algeria - PSInSAR™ analysis - Track 65

Envisat Data

12/07/2003

Displacement rate along LOS direction
Arrival time and Trajectories

Pressure changes $\rightarrow$ propagating fronts
We use the time derivative of the pressure
From the time arrivals $\rightarrow$ permeability

A. Rucci, D. W. Vasco, Fluid pressure arrival time tomography, SEG 2009, Houston
Steam Assisted Gravity Drainage

Heavy crudes

Tiltmeters (GPS, InSAR)

Passive Seismic
Microseismics precede subsidence
The periods of significant seismic release precede periods of uplift by a few days. The microseismic data shows the creation of a fracture network to be later filled with steam causing the surface uplift.
We can map surface deformations into permeability changes and fault patterns; the InSalah story is condensed in 1 cm surface motion

1 mm sensitivity is achieved today with reduced resolution, but can improve with numerical atmospheric models.

The revisit time is paramount
HOW?

What we can do today with good atmospheric control i.e. with a dense and long set of PS
The CESI experiment

Ground Based Radars: The XX dam
The CESI experiment
Estimated displacement (Radarsat 1 data)

Rmse = 0.58mm (h!); 0.75mm (v)
A Ground Based SAR at the XX dam
Contribution by D. Giudici, Aresys

The future: UAV, geosynchronous, both?
Permanent Scatterers displacement analysis: close view

Displacement Map

+3 mm

-3 mm
Permanent Scatterers analysis : displacement series
Permanent Scatterers analysis: displacement series
Permanent Scatterers analysis: displacement series
Conclusions for the Ground Based SAR 
(15 h. observation)

The data show coherence > 0.8

The atmospheric effect is very low for the 
good meteorological conditions

The rms noise is of the order of 0.1mm
Controlling the Atmospheric Phase Screen from the satellite with a dense and long set of PS
We are close to the objective; the revisit time of Sentinel 1A/B is 6 days.
Controlling the Atmospheric Phase Screen without a dense and long set of PS

<table>
<thead>
<tr>
<th></th>
<th>Density</th>
<th>Dense</th>
<th>Sparse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>series</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td></td>
<td>OK</td>
<td>Distrib. Scatt. NWP</td>
</tr>
<tr>
<td>Short</td>
<td></td>
<td>NWP</td>
<td>UAV, Geo synchronous?</td>
</tr>
</tbody>
</table>

Today, Numerical Weather Predictions yield useful Water Vapor topographic gradients but not the turbulent component. This may improve with a better description of the Boundary Layer (towns, forest, etc). Besides, InSAR is instantaneous, NWP time smooth. TIGIR, 2009.
Statistics of atmospheric data

rms delay ≈ 10mm two way
Dense and **short** data sets

Using the APS estimates from NWP

Estimate the master of the $N_i$ interferometric takes using the $N_\psi$ estimates (GPS, MM5 etc.) and then remove it. The m.s. errors are:

$$\sigma_{\varepsilon,i}^2 = \frac{\sigma_a^2}{N_i}; \quad \sigma_{\varepsilon,NWP}^2 = \frac{\sigma_\psi^2}{N_\psi}; \quad k = \frac{\sigma_\psi^2}{\sigma_a^2}$$

The gain $G$ (as if we had $N_i'$ interferometric images) can be large if the NWP are good ($k < 0.3$):

$$\frac{1}{\sigma_{\varepsilon,t}^2} = \frac{N_i'}{\sigma_a^2} = \frac{N_i}{\sigma_a^2} + \frac{N_\psi}{\sigma_\psi^2}$$

$$G = \frac{N_i'}{N_i} = 1 + \frac{N_\psi}{N_i} \frac{\sigma_a^2}{\sigma_\psi^2}$$
Long and **sparse** data sets

If the revisit time is short, we can use distributed scatterers, that slowly decorrelate. For C band the decorrelation time constant is $\tau \approx 40$ days. For 1 month, 1 looks, N=5 revisits, the dispersion of the subsidence estimate due to decorrelation is

$$\sigma_{m,1mo} = \frac{\lambda}{4\pi} \sqrt{\frac{1 - \gamma^2}{2LN\gamma^2}}$$

$$\gamma = \gamma_0 \exp\left(-\frac{T}{\tau}\right) = 0.6e^{-6/40} = 0.51$$

$$\sigma_{m,1mo} = 5.4 \sqrt{\frac{1}{NL}} \text{ mm / mo} = 0.24 \text{ mm / mo in 100x100m}^2$$

Now, we have to consider the APS
Interferogram stacking and subsidence

When the targets decorrelate, interferogram stacking is optimal. The resulting subsidence velocity dispersion is (C band, L looks):

$$\sigma_{s,\text{decor},\text{Tobs}} = \frac{\lambda}{4\pi} \frac{T_{\text{obs}}}{T} \sqrt{\frac{T}{T_{\text{obs}}}} \sqrt{\frac{1 - \gamma^2}{2\gamma^2}} = 42\sqrt{\frac{1}{L}} \text{ mm/year}$$

An atmospheric bubble, $\varnothing = .8\text{km}$, contains 5000 looks. Then, $\sigma_{s,\text{decor}} \sim .6\text{mm/year}$, lower than the effect of the APS $\sim 1.3\text{mm/}\sqrt{\text{M years}}$.

We either need NWP or multiannual time series.
Conclusions

For the oil and CO$_2$ applications, spatial resolution is not essential, but short revisit time and good vertical precision are paramount.

With a dense and long set of PS (desert areas), we are already below the millimeter error.

In the case of short or sparse data sets, we need improved Numerical Weather Predictions.

... Les nez ont été faits pour porter des lunettes
Noses were made to hold glasses
Voltaire, Candide
The competition:
Optical and GPS levelling:
Approximate results
A recent survey comparison for an accelerator design in Japan

The 10th International Workshop on Accelerator Alignment, KEK, Tsukuba, 11-15 February 2008

SURVEY COMPARISON USING GNSS AND ME5000 FOR ONE KILOMETER RANGE

S. Matsui, H. Kimura, RIKEN, Kouto, Sayo-cho, Sayo-gun, Hyogo, 679-5148 JAPAN
Fig. 22. Shifts of survey monuments for sixteen years.
Fig. 19. Survey network and error ellipses.
Fig. 6. Two GNSS antenna on the stage.

Fig. 7. Fluctuation of the GNSS position result for 2 days.

Fig. 11. Mekometer, thermometer and barometer.

Fig. 13. One kilometer baseline and GNSS receivers in the SPring-8 site.
Fig. 14. Distance comparison of one kilometer baseline between ME5000 and GNSS.

Fig. 15. Distance and the influence of rain.
The future: Photon counting devices

![Graph showing photon counts over time](image)

**Fig. 3.** Histogram of photon-count data. The target peak is on the left and the reference peak is on the right.

**Photon-counting detector with an accuracy of 20 ps (3.3 mm two way)**

*Max point rate ~ 1000 pts/sec*

*Low atmospheric effects*
Cosmo SkyMed and variable revisit times.

Uniform: 16d; checkerboard 8d; stripes 4d.

A constellation of N satellites with revisit time T, may dedicate N-1 passages to one location, and the N-th passage to the entire strip, with a 1/N azimuth resolution. trading revisit time and resolution,
Seafloor geodesy

Sonardyne - Shell deployed two 10 sensors sonar networks to measure to the cm underwater displacements at 1km (depth or horizontal motion). The main problem are water velocity changes.
periodic model

June - Sept.

Terrasar X Berlin