InSAR monitoring of surface displacements for a natural gas storage in salt caverns, case of the Tersanne and Hauterives operations (France)

Eric HENRION, Cécile DOUBRE, Frédéric MASSON - IPGS/EOST, University of Strasbourg and CNRS, FRANCE

e-mail : eric.henrion@unistra.fr

GENERAL CONTEXT

Operations of underground reservoirs such as hydrocarbon production, geothermal, or natural gas storage generally generate surface deformation. There is usually uplift around injection wells or Carbon Capture and Storage (CCS), and subsidence around production wells, oil reservoir or natural gas storage (Ferretti et al., 2011).

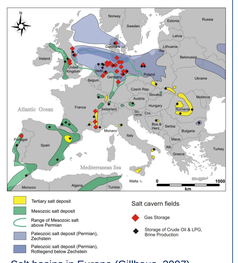
Surface deformation monitoring brings important information on the condition and evolution of the reservoir (pressure, volume changes) and the surrounding rock layers (flow migration, permeability, rheology).

Local authorities impose monitoring of surface displacements during to the operations. It is usually performed by leveling which is time consuming with a poor spatial resolution. The use of Radar Interferometry technics for monitoring allows high spatial and temporal resolutions without field intervention

1. GAS STORAGE

Natural gas can be stored in depleted oil fields, aquifers, lined mined cavities and **salt caverns**.
In Europe, because about 65% of natural gas is imported, it is necessary to store. Advantages:

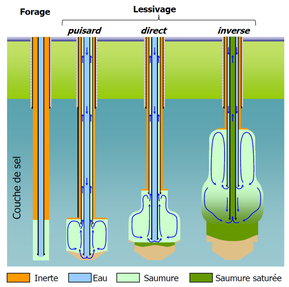
- Maintain a seasonal balance and face any consumption peak
- Be less dependent on pipelines
- Local storage implies less exchange costs, and thus economic optimization



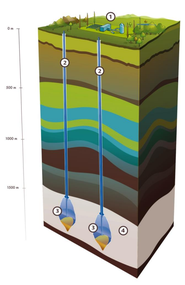
Salt basins in Europe (Gillhaus, 2007).

Why salt ?

- Geological abundance
- Highly soluble (~ 320 g/L)
- Porosity, permeability ~ 0
- Mechanical reaction (visco-plastic behavior), compression resistance



Steps of a cavern creation (www.storengy.com).



Operating caverns (www.storengy.com).

2. OPERATION SITE

The operation site belongs to **Storengy** (affiliate **ENGIE**), gas provider in France. It is settled in 2 villages (Drôme, France).

	Tersanne	Hauterives
Village:		
Surface of the operation:	~ 3.0 km²	~ 0.2 km²
Start of the operation:	1970	2012
Caverns:	13	2
Depth of caverns:	1500 m	1500 m
Storage volume:	262 M m³	200 M m³

In addition of reservoir controls such as pressure and volume of caverns, the vertical surface displacements are regularly measured using leveling every 3 years (obligation by local authorities):

First measurements:	1982	2004
Maximum amplitude:	-186.4 mm	-24.5 mm
Mean velocity:	-5.4 mm/yr	-2.0 mm/yr

Constraints:

- Time sparse data
- Logistics
- Financial

Location of Tersanne and Hauterives, black rectangle: zone of study.

MOTIVATIONS

Using spatial technics, we perform geodetic monitoring of the surface displacements associated with the natural gas storage in salt caverns of Tersanne and Hauterives (France). The challenge is to monitor displacements in an agricultural area (e.g. with strong temporal decorrelation), where the only information supports are well platforms and other man-made structures.

Aim of this study :

- Quantify small surface displacements by InSAR measurements and the associated uncertainties for the 1992 – 2019 period.
- Comparison to *in-situ* (leveling) and GNSS measurements.
- Analyze ground mechanical response with surface displacements (correlation with volume losses at depth).

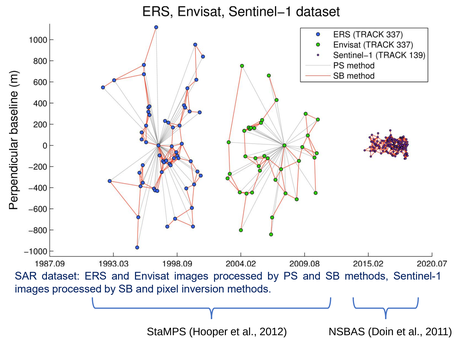
3. InSAR: DATA, PROCESSING AND RESULTS

C-band Image Dataset

ERS	Envisat	Sentinel-1
58 images	38 images	143 images
1992 - 2000	2003 - 2010	2014 - 2019
T = 35 days	T = 35 days	T = 6-12 days

Methods

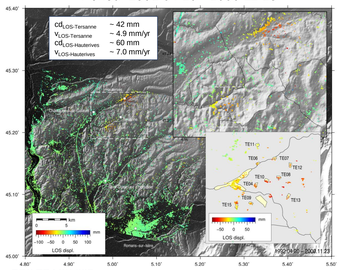
- Persistent Scatterer (StaMPS ; Hooper et al., 2012)
  - Identify phase stable pixels in the dataset
  - Urban areas
- Small Baseline subsets (NSBAS ; Doin et al., 2011)
  - Pixels with distributed scatterers
  - Reduce geometric and temporal decorrelation
- Pixel inversion
  - Inversion of each temporal pixel network by least squares method



SAR dataset: ERS and Envisat images processed by PS and SB methods, Sentinel-1 images processed by SB and pixel inversion methods.

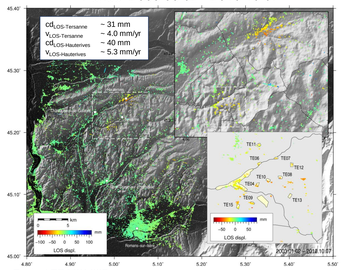
Cumulative LOS displacements over 3 periods

Period: 1992.04.20 - 2000.11.23



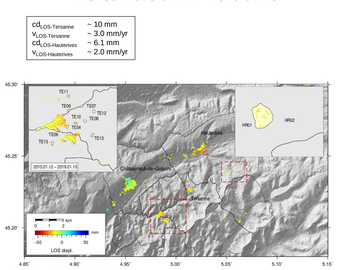
ERS TRACK 337.

Period: 2003.03.02 - 2010.10.07



Envisat TRACK 337.

Period: 2015.01.12 – 2019.01.15



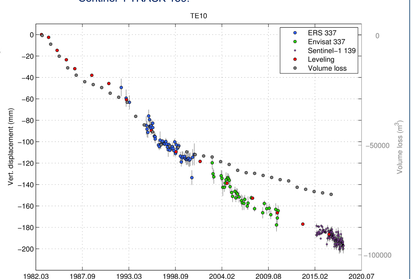
Sentinel-1 TRACK 139.

Spatial observations

- Pixels in high-coherence areas (e.g. man-made structures): villages, roads, operation site, **well platforms**
- Centered global depression in Tersanne operation as result of subsidence induced by each cavern
- Subsidence in Hauterives before the start of operation (2012)
  - Activity of Chloralp/Perstorp company (chemistry), Storengy's partner (brine)
  - Cavern creation

Time Series analysis

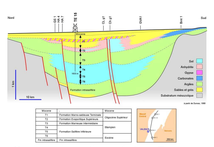
- Assumption: no horizontal displacements
- Decrease of subsidence rate from 1992 to 2018 in both operations
- Good fit with leveling data
- Temporal resolution of InSAR measurements allows to detect transient displacements (e.g. 1996)
- Correlation between volumes losses and surface displacements



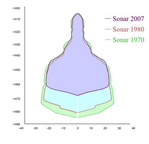
Vertical displacements by levelling and InSAR analysis (mm) and volume losses (m^3), period: 1982 – 2018 for the TE10 platform.

Analysis

- What information can be obtained from the subsurface behavior from InSAR measurements ?
  - Environmental response from balance disruption (e.g. cavern creation), long term response
    - Isostatic pressure > maximum operating pressure
  - Environmental response from operation activities (e.g. gas injection and withdrawal), short term response
    - Lateral pression from rock salt layer > operating pressure during withdrawal
    - Plastic flow and filling of the cavern from the bottom
    - Densification of the rock salt layer around the cavern (strain hardening)
  - Volume loss of 1 % per year to 0.5 % at depth during operation (consistent with the decrease of subsidence rate)



Geological section of the Tersanne operation (Storengy).

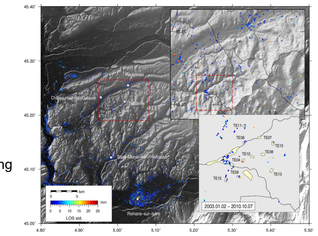


Cavern evolution during operation (Storengy).

4. CONTROLS AND UNCERTAINTIES

LOS displacement uncertainty estimate

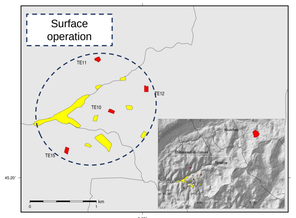
- Variance, use of Jackknife method (for n dates):
  - Normal distribution
  - $\sigma_{\varphi}^{2} = \frac{n-1}{n} \sum_{i=1}^{n} (\hat{\theta}_i - \hat{\theta}_.)^2$
  - $\hat{\theta}_i$: parameter estimator for i^{th} date
- Standard deviation of phase values of neighboring pixels
  - Consistence of adjacent pixels movements



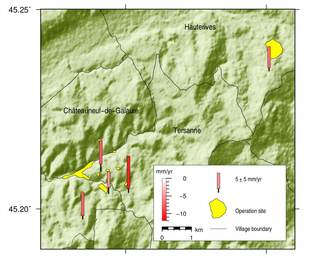
LOS standard deviation of each pixel (mm), ERS period.

Control by GNSS measurements

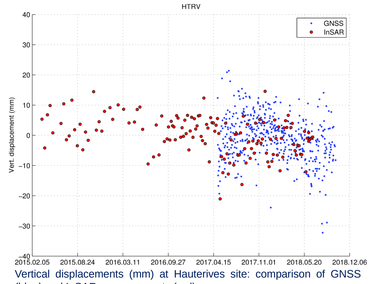
- Installation characteristics:
  - 5 cGNSS – 9 sGNSS
  - Installation : May 2017
  - T = 1 day
- GNSS subsidence rates:
  - $vU_{Tersanne}$ ~ -7.6 ± 7.1 mm/yr
  - $vU_{Hauterives}$ = -6.7 ± 4.6 mm/yr
- Timeseries of position comparison (HTRV site):
  - Assumption: no horizontal displacements
  - vU_{GNSS} = -3.6 ± 7.4 mm/yr
  - vU_{InSAR} = -2.6 ± 3.7 mm/yr



GNSS network.



Vertical GNSS velocities (mm/yr), period: 2017.05 – 2018.10.

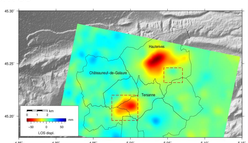


Vertical displacements (mm) at Hauterives site: comparison of GNSS (blue) and InSAR measurements (red).

5. CONCLUSIONS AND PERSPECTIVES

Conclusions

- Subsidence located at operation sites and the village of Hauterives
  - Decrease of the subsidence rate from 1992 to 2018
- Methodology
  - Validation of ERS and Envisat results by leveling
  - Validation of Sentinel-1 results by GNSS
- Estimate of InSAR LOS displacement uncertainties



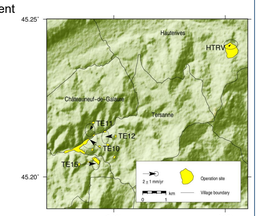
Geostatistical interpolation by Kriging method of LOS mean velocities (mm/yr), ERS TRACK 337.

Perspectives

- Understanding of subsurface behavior by…
  - Quantifying the relationship between surface displacements and volume losses at depth
  - And deduct the volume loss associated with a given displacement
- Hazard management, quantification of:
  - Subsidence duration
  - Maximum displacement amplitude

Additional information about the reservoir behavior by…

- Geostatistical interpolation of InSAR data (Kriging)
  - Weighted by uncertainty estimates
  - Define subsidence limits related to the operations
- Horizontal displacements analysis
  - Horizontal GNSS velocity field (more data required)
  - Resolve E-W displacements by InSAR (asc. / desc.Tracks)



Horizontal GNSS velocities (mm/yr), period: 2017.05 – 2018.10.

Acknowledgments: This work was carried out using ERS, Envisat and Sentinel-1 data provided by ESA processed by InSAR chains StaMPS (Hooper et al., 2012) and NSBAS (Doin et al., 2011), and GNSS processing chain GAMIT/GLOBK (Herring et al., 2018).