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Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 63 (2014) 4019 – 4026
Energy Procedia

GHGT-12

Improving Persistent Scatterers Interferometry (PSI) analysis in highly vegetal / agricultural areas for long term CO2 storage monitoring

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Abstract

In the present study, we applied two strategies for improving the use of InSAR/PSI techniques for long-term monitoring ground surface deformation induced by CO_2 injection areas presenting a large cover of vegetation (agricultural fields, forests, etc.). The first approach relies on advanced processing techniques using the Diffuse-Scatterers-like (DS) technique. Our test case is a potential French test site presenting a vegetated cover not very adapted for the application of InSAR techniques. Though our algorithm remains under development, its application to the test-case revealed the limitations of DS-like techniques in areas presenting extended forest cover (i.e. of very low coherence). A second strategy relies on the optimization of the number and positions of Corner Reflectors (CR) regarding risk-oriented monitoring objectives: regional-scale surveillance, local anomaly (e.g. abandoned well) with known or unknown spatial locations. Using the deformation rate at KB-501 well at In-Salah as a reference solution, we showed that a network of moderate number of CR (density of 0.5 CR/km²) was sufficient to reveal the deformation information for both the regional-scale surveillance and the local anomaly with known location. Yet, detecting an anomaly with unknown location remains very difficult unless installing a very dense CR network (100 CR over an area defined by a radius of 4 km).

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Surface deformation; space-borne Synthetic Aperture Radar (SAR) interferometry; CO_2 injection; Vegetation; Corner Reflector; Diffuse Scatterer.

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.432

1. Introduction

Persistent scatterers Synthetic Aperture Radar Interferometry (PSI, e.g. [1-2]) analysis is viewed as a promising monitoring technique for multiyear detection of ground surface displacements during long term CO_2 injection into deep aquifers of the order of 25 to 50 years ([3]).

This technique was successfully implemented at the CO_2 storage site of In Salah Gas Project in Algeria, where 0.5–1 million tons of CO_2 per year have been injected (e.g. see site context described by Mathieson et al., 2009). Fig. 1 provides the map of deformation rate derived from our processing of 31 Envisat/ASAR Descending mode images at In-Salah in the area of the KB-501 well over the injection period from 2004 to 2009.

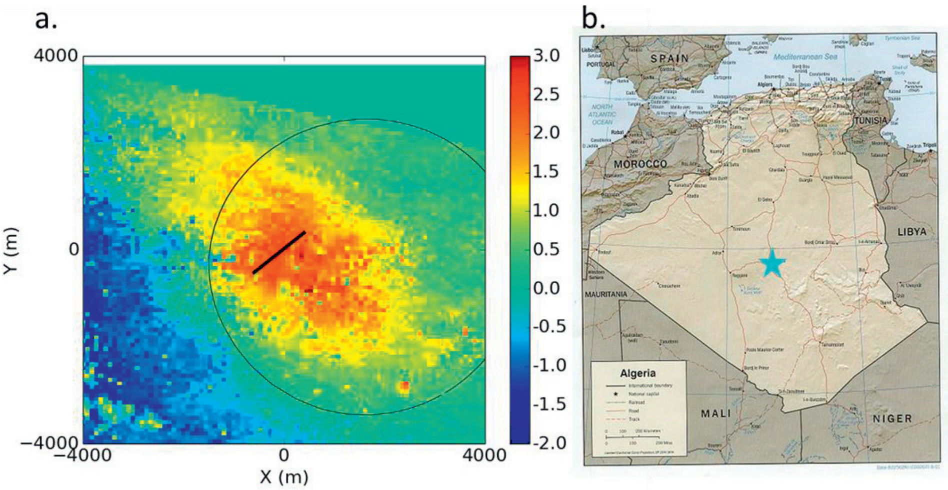

Fig. 1. Left: Deformation rate map (in line of sight) for 5 years of CO_2 injection at In-Salah (mm/year). The location of the middle of the KB501 horizontal well is indicated. Right: location of the In-Salah site in Algeria (blue star); Adapted from [11].

Yet, the success of In-Salah may not be generalized to future onshore industrial-scale CO_2 storage sites, which are planned in far more complex contexts mostly presenting natural terrains variation either agricultural or vegetal areas. An example is the Aquistore CO_2 storage site, where advanced monitoring techniques were deployed (see e.g., [5]). These areas are generally characterized by poor Persistent Scatterers (PS) density, which might locally drop to zero, hence hampering the deployment of the PSI technique. For illustration purpose, a sector (of 3,455 km²) in the Paris basin, where the potential implementation of CO_2 storage sites was investigated, is characterized by a land use composed of less than 5 % of artificial or urban areas and more than 95 % of natural (mainly forests) and agricultural areas ([6]). In such natural terrains, the absence of bright man-made structures (or bare rocks) might lead to sparse PS network (with density ~10 PS/km² to less than 1 PS/km²). This constitutes a major obstacle to the phase unwrapping stage, for which the solutions are directly dependent on the PS density and makes reliable estimation of deformation using PS techniques a challenging task.

The present study aims at exploring the applicability of two approaches to enhance the performance of the PSI technique in such constraining conditions for long term monitoring of CO_2 storage sites.

1. The first approach relies on the use of an advanced PSI processing technique adapted from the Diffuse Scatterers analysis, referred to as DS (based on [7]), which can improve considerably the density of usable “natural” scatterers on certain non-urban area;
2. The second approach relies on the implementation of a network of corner reflectors (CR) corresponding to artificial devices installed on ground to complement the existing “natural” PS network. A strategy for optimization (number and position) of the CR network is proposed based on the position of the existing

PS and on hydro-mechanical large-scale simulations constrained by the observations (through history-matching) as proposed by [6].

2. Application of Diffuse Scaterrers-like Interfererometry

The test of the DS-like technique should ideally be carried out on an industrial-scale (injection of more than ~0.5 Mt/y) on-shore CO_2 storage site characterized by surface conditions difficult for the application of InSAR/PSI techniques (with few urbanized areas and large cover of natural terrains, either agricultural or vegetated areas). Therefore, we propose to assess the potential of InSAR on an area under consideration for a potential injection site (on the basis of the underground material characteristics) in France.

Based on a supervised classification of a SPOT 5 image of the area, Fig. 2 provides the spatial distribution of the land cover, which reveals that the area is mainly composed of fields (~49%) and forests (~50%). We believe that this land-cover is representative of most on-shore potential CO_2 injection sites in Europe.

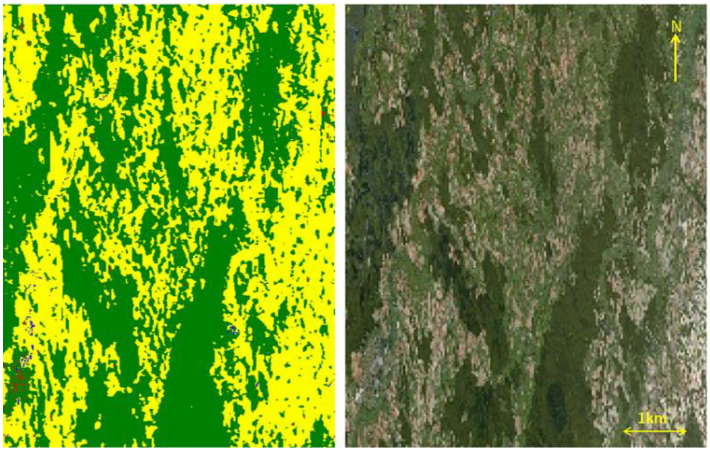

Fig. 2. Left: classification: in yellow: fields, in green: forests, in red: build up areas; Adapted from Raucoules et al. (2014).

In Fig. 3, we reported the PS spatial distributions in the area in the vicinity of KB-501 well at In-Salah (considering the time period 2004-2009) and on our potential injection site. PSI processing was carried out with the GAMMA software ([2]). A clear difference is obvious: except for a few small urbanized areas, the density of PS remains very low.

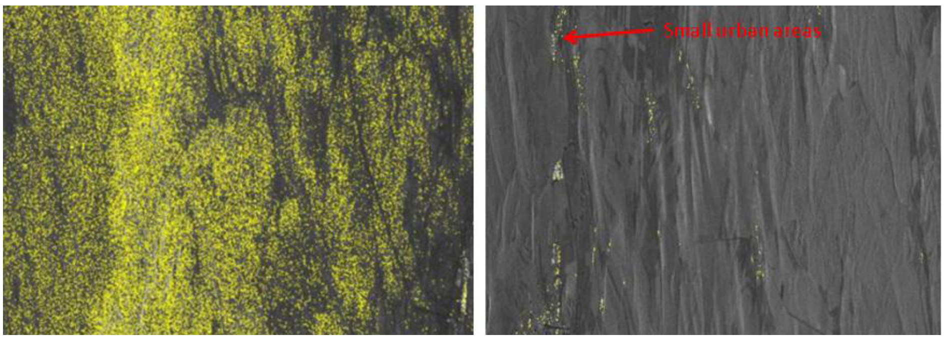

Fig. 3. Left: PS density at In Salah (area in the vicinity of KB-501); Right: a potential injection site in France; Adapted from [10].

In order to increase the PS density, we applied an algorithm based on the concept of Diffuse Scatterer (adapted from [7]). To test the efficiency of such an approach, a synthetic case was constructed as follows:

1. we use as a “reference case”, the deformation field observed at In-Salah during CO_2 injection into the KB-501 well between 2004 and 2009 (based on EnviSAT/ASAR data);
2. the surface characteristics of this reference case are then modified by “artificially” applying the surface conditions (urban areas, natural terrains, either agricultural or vegetated areas) of an on-shore site in France, which can be considered representative of future industrial-scale storage sites in Europe. In practices, we added the deformation phase component estimated on In Salah to the SLC (Single Look Complex) images covering our French test site.

Fig. 4 shows the application of the algorithm to the synthetic test case. Though future improvements are still possible, Fig. 4 shows that the densification only occurs on the urban areas and few agricultural fields. The extended forest cover of the area seems to be the major limitation for the algorithm, requiring probably installation of Corner Reflectors (CR) to complement the network (see next section).

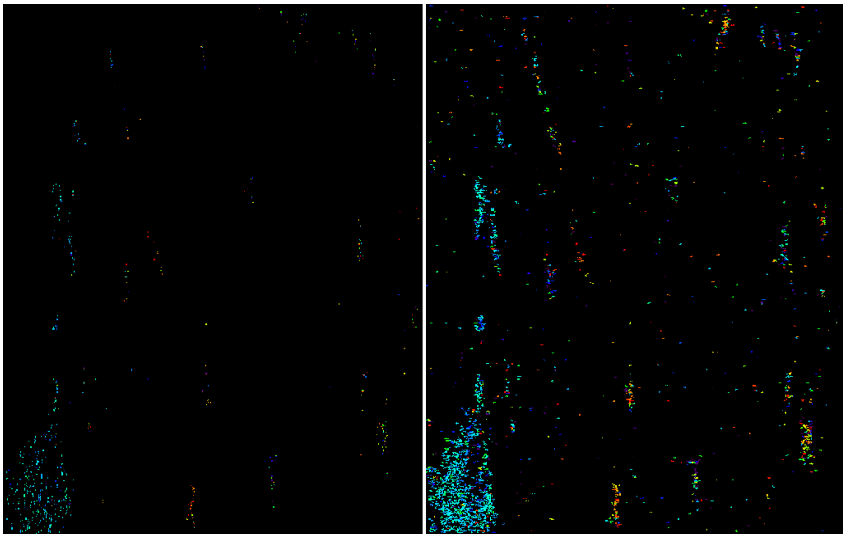

Fig. 4. densification of the measurement point density on the French test site. Left: PS ; Right: PS+DS (1 fringe blue-red = 4.5 mm/yr); Adapted from [10].

3. Optimizing the installation of corner-reflectors

In order to optimize the number and spatial location of CR for a CO_2 storage site, we propose an *a posteriori* method based on results from the In-Salah site where information is available for all spatial points (see Fig. 1). The main steps of the methodology are described in Fig. 5. The novelty of the approach resides in the optimization regarding the monitoring objectives: regional-scale surveillance, local anomaly with known and unknown spatial locations.

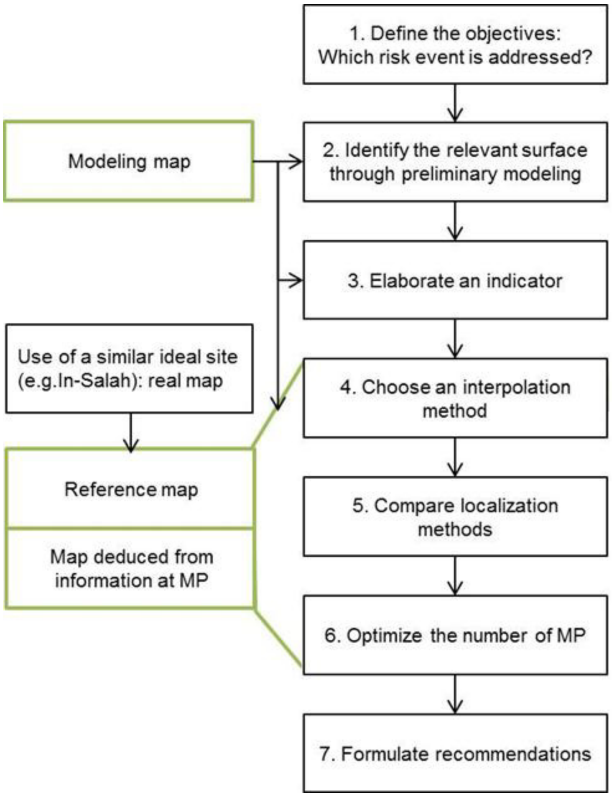

Fig. 5. Main steps of the optimization strategy of the measurement points MP (here the corner reflectors) for monitoring the deformation induced by CO_2 injection depending on the risk objective. Adapted from Loschetter et al. (2014).

We assumed that all information visible on Fig. 1 (Left) is unavailable, except for data at the pixels corresponding to the CR over an area defined by a 4-km radius. This area was chosen based on preliminary coupled hydro-mechanical 3D simulations of the CO_2 injection at KB-501 using the modeling approach of [8] and based on the site conditions (initial stress state, rock properties, etc.) reported by [9]. By comparing the reference map and the map deduced from data only at the CR, it is possible to assess to optimize the number of CR necessary for efficient monitoring.

Several configurations of CR distributions were tested (random, on a regular grid, on a circle, on a series of circles, etc.) for the global deformation and local anomalies. Fig. 6 provides an example of maps deduced from radial basis spatial interpolation with data from 21 CR using different positioning strategies. In the context of In-Salah, the different tests showed that a limited number of CR in the order of ~20 (density of <0.5 CR per km²) enabled to accurately capture the regional deformation pattern using the “2 circles” strategy.

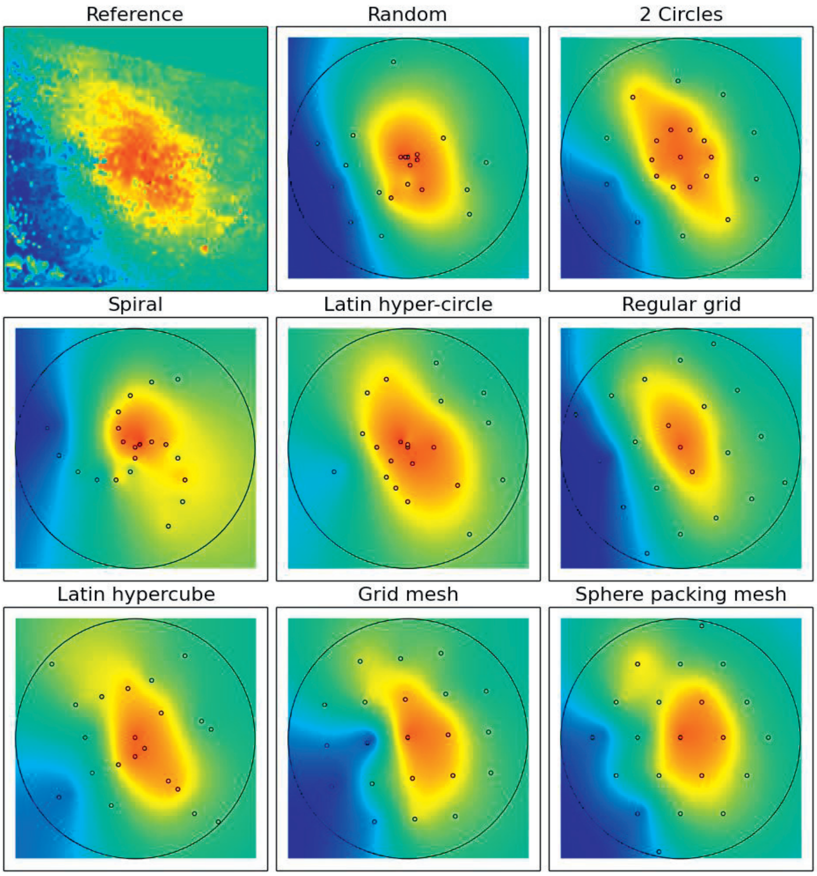

Fig. 6 Maps deduced from radial basis interpolation with data from 21 CR, for 8 different localization methods. The radius of the circle is 4 km. Adapted from Loschetter et al. (2014)

For a local anomaly, we distinguished the cases of an expected (e.g. abandoned wells, or fault zones) anomaly and of an unexpected one. In the first case, the network density can a priori be locally increased during the network design, whereas in the second case, there is no such a possibility. Fig. 7 provides an example of how an anomaly with a known location was added to the deformation field at In-Salah.

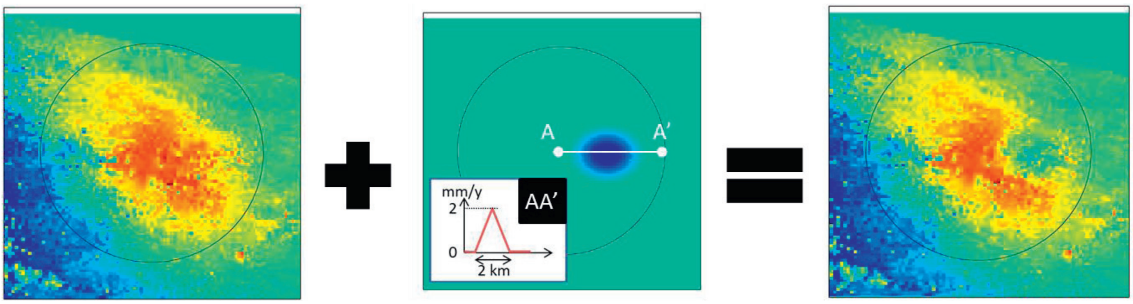

Fig. 7. Generation of an anomaly (radius: 1 km, maximal magnitude: 2 mm/y). Left: reference map. Middle: anomaly pattern only, with a profile view following AA'. Right: In Salah surface deformation map with addition of the anomaly. Adapted from [11].

Our tests showed that the addition of less than 5 supplementary measurement point CRs brings useful information to detect punctual anomalies of small-to-moderate size for a known position (See an example in Fig. 8). On the other hand, for detecting an unpredicted anomaly, the measurements network density needs to be significantly increased, making the method more expensive (at least 100 CR in a 4-km radius from the injection was required).

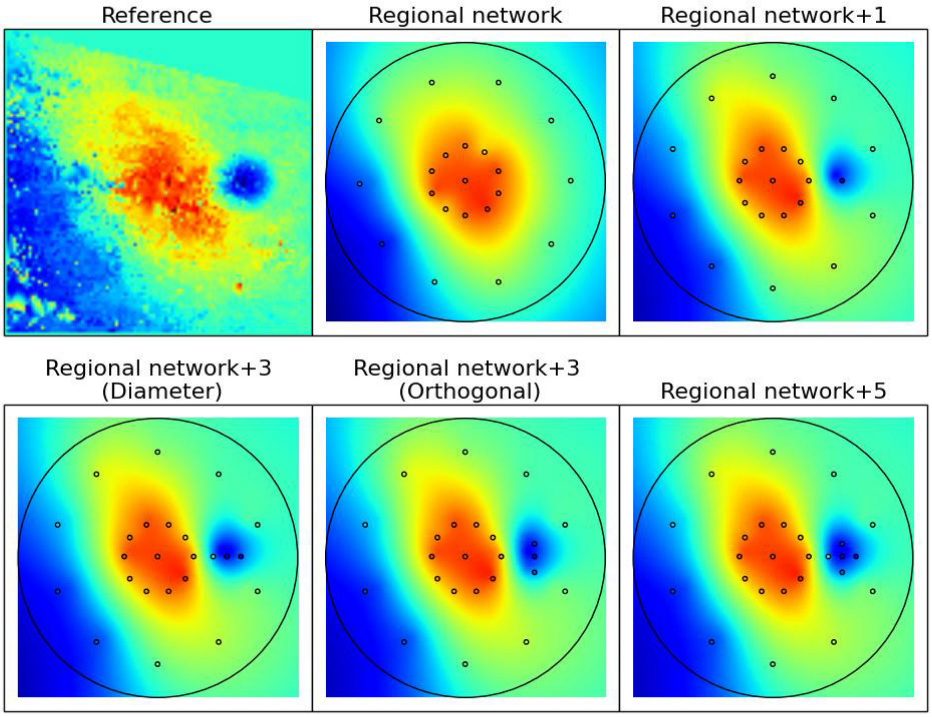

Fig. 8. Different setting options of CR for monitoring a local anomaly with known spatial location. Adapted from [11].

Concluding remarks and further work

In the present study, we applied two strategies for improving the use of InSAR/PSI techniques for long-term monitoring ground surface deformation induced by CO_2 injection in highly vegetated areas. The first approach relied on advanced processing techniques using Diffuse-Scatterers-like techniques (based on [7]). Our test case is a potential test site (considered representative of a typical European CO_2 injection site) with a vegetation cover not suitable for the application of InSAR techniques. Though our algorithm is still under development (further details in [10]), its application to the test-case revealed the limitations of DS-like techniques in areas presenting extended forest cover (i.e. low coherence). This justified investigating a second option based on the installation of Corner Reflectors (CR) to complement the network of PS.

A strategy for optimizing the number and positions of CR was proposed regarding different monitoring objectives: regional-scale surveillance, local anomaly (e.g. abandoned well) with known and unknown spatial locations. Using the deformation rate at KB-501 well at In-Salah, we showed, using in-depth parametric studies (full details in [11]), that a network of moderate number of CR (density of 0.5 CR/km^2) was sufficient to capture the necessary information for both the regional-scale surveillance and the local anomaly with known location. Yet, monitoring of an anomaly with unknown location remains very difficult unless installing a very dense CR network (100 CR over an area defined by a 4-km radius). The implications in terms of cost were not considered. Further developments should focus on the integration of the existing PS network (though of low density) in a similar fashion as [12].

Finally, it should be underlined that we focused on the limitations due to the presence of a vegetated cover. To design a surveillance plan integrating InSAR techniques, two additional limitations should also be accounted for:

1. The expected deformation induced by CO_2 injection is expected to be at the limit of detectability of the method (in certain cases much less than 1 mm/yr on more than 20 km width, i.e. below the detectability limit of current application of InSAR, e.g. [13], and most of ground based operational geodetic techniques). Besides, natural and other anthropogenic causes of surface deformation are expected to be major sources of noise ([5]);
2. CO_2 storage sites will be active for at least 30-40 years. Availability and continuity of SAR missions on a very long period are therefore required for such an application: the uncertainty on the future of such missions could be in fact the major limitation. This is further discussed in [6].

Acknowledgements

This work was supported in part by ADEME (the French Environment and Energy Management Agency) through the AMIRAL project. Envisat SAR data were obtained within a European Space Agency CAT-1 research proposal.

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