International Journal of Greenhouse Gas Control 42 (2015) 188–199

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Satellite interferometry for high-precision detection of ground deformation at a carbon dioxide storage site

Sergey Samsonov[a,*], Magdalena Czarnogorska[a], Don White[b]

[a] Canada Centre for Mapping and Earth Observation, Natural Resources Canada, Ottawa, ON, Canada
[b] Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada

ARTICLE INFO

Article history:
Received 24 December 2014
Received in revised form 29 July 2015
Accepted 31 July 2015
Available online 24 August 2015

Keywords:
Aquistore
Carbon capture and storage
Satellite interferometry
DInSAR
MSBAS
RADARSAT-2
Ground deformation

ABSTRACT

At the Aquistore CCS site, located in the southeastern Saskatchewan, Canada, carbon dioxide (CO_2) is to be injected at variable rates of up to 1500 tonne/day. The storage reservoir consists of a dominantly clastic, brine-filled interval (Deadwood and Winnipeg formations) which reside at 3150–3350 m depth. Ground deformation at this site is being monitored to track pressure-induced uplift and potential upward migration of CO_2 through faults and fractures. Deformation monitoring is conducted using space-borne Differential Interferometric Synthetic Aperture Radar (DInSAR), capable of achieving millimeter precision and meter spatial resolution over the entire monitored area. During June 2012–October 2014, prior to CO_2 injection, two ascending and two descending high-resolution RADARSAT-2 data sets were acquired and simultaneously processed with the advanced Multidimensional Small Baseline (MSBAS) DInSAR producing vertical and horizontal East-West deformation time series with six days temporal sampling, four times more frequent than the repeat cycle of each individual data set. Two years of monitoring prior to the onset of (CO_2) injection allowed measurement of the deformation field of the background natural and anthropogenic processes. Vertical and horizontal ground deformation was detected with the rates of ±1.0 and ±0.5 cm/year and with precision of 0.3 and 0.2 cm/year (2σ) correspondingly. Background motion (shape and magnitude) may resemble deformation signals due to potential upward migration of CO_2 through faults and fractures. Analytic elastic and poroelastic modeling was performed to estimate the ground deformation that will be produced when injection begins. For this purpose, rock properties determined from geophysical well logs and in situ temperature and pressure were used. For the elastic model it was determined that a maximum of vertical deformation of 1.6 cm/year will be located around the injection well, whereas the maximum of horizontal deformation of 0.6 cm/year will be located about 3 km away from the injection well. For a more realistic poroelastic model, it was determined that maximum vertical deformation will not exceed 1.6 cm and maximum horizontal deformation will not exceed 0.1 cm/year during the entire 25 year injection cycle. According to this model, the established monitoring network cannot detect predicted horizontal motion since it is below its sensitivity, whereas for detection of vertical motion ground-based monitoring sites need to be installed near and also at distance from the injection well. Six day temporal sampling allows determination of the transient uplift phase. A proposed MSBAS strategy overcomes limitations of the classical DInSAR, such as sparse temporal resolution and the lack of ability to extract individual deformation components from the line-of-sight retrievals, and can be implemented at other onshore CCS sites for operational monitoring, using readily available SAR data.

1. Introduction

Carbon Capture and Storage (CCS) is one of a variety of means that are currently being implemented (IPCC, 2005) to reduce the amount of anthropogenic carbon dioxide that is released to the atmosphere. CCS refers to a broad range of technologies for the capture (e.g., from fossil fuel power plants), transport, and long term storage of CO_2 in geological formations (IPCC, 2005; Gibbins and Chalmers, 2008) including depleted oil and gas reservoirs, saline aquifers and deep coal beds. CO_2 storage also occurs in enhanced oil recovery operations (Bachu et al., 2007).

Site monitoring is a key component of any CCS project and is implemented based on the particular site characteristics and requirements. The main objective of monitoring is to

* Corresponding author.
E-mail address: sergey.samsonov@nrcan-rncan.gc.ca (S. Samsonov).

http://dx.doi.org/10.1016/j.ijggc.2015.07.034
1750-5836/

demonstrate that the storage site is safely and securely storing CO_2 and that it is not having detrimental effects on the surrounding area. An important component of monitoring is the measurement of geomechanical deformation due to increasing reservoir pressure and potentially CO_2 leakage through faults and fractures (Rackley, 2009). Shallow and surface monitoring used for ground deformation detection comprises tiltmeter and GPS measurements, and more recently satellite interferometry (Rutqvist et al., 2010; Vasco et al., 2010; Lubitz et al., 2013; Rinaldi and Rutqvist, 2013; Rucci et al., 2013; Ramirez and Foxall, 2014).

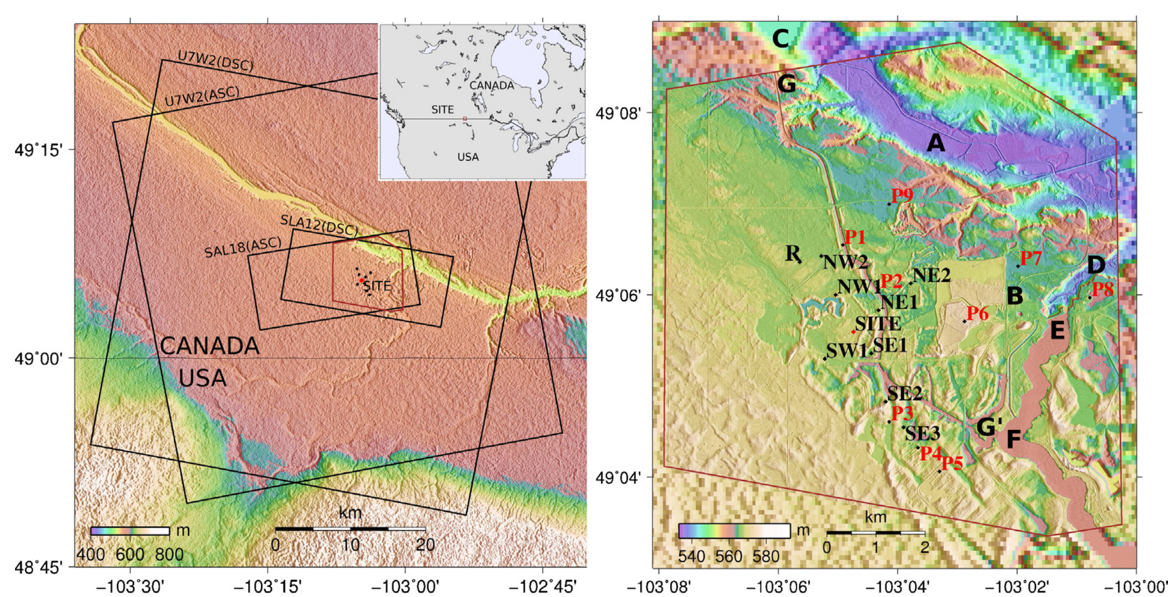
In this study, we report on baseline Differential Interferometric Synthetic Aperture Radar (DInSAR) monitoring conducted at the Aquistore CCS site in southeastern Saskatchewan, Canada, near Estevan township (Fig. 1). Eighty satellite images have been processed to image vertical and horizontal ground deformation for the period of June 2012–October 2014, prior to the start of CO_2 injection. The purpose of this pre-injection study is to characterize the vertical and horizontal ground deformation associated with background natural and anthropogenic processes. Specific objectives for the Aquistore site include: (1) establishing the level of measurement precision and temporal resolution that can be achieved, (2) constructing a baseline record of deformation that is demonstrably non-injection related, and (3) determining whether CO_2-injection related deformation will be discernable in the presence of other sources (natural or anthropogenic) of ground deformation. Toward the latter objective, simple analytic and poroelastic modeling has been conducted to estimate the magnitude and spatial extent of the expected deformation due to CO_2 injection. Furthermore, we demonstrate how vertical and horizontal deformation time series allow the detection of deformation trend changes with minimal delay (e.g. Samsonov et al., 2013a), which is not possible when only mean deformation (or deformation rate) is known (e.g. Rucci et al., 2013). These results are used to evaluate the Aquistore ground network design and the ongoing monitoring strategy.

2. The Aquistore CCS project

The Aquistore CCS project (Worth et al., 2014), started in 2012, focuses on research, development, testing and adaptation of monitoring methods for measurement and verification of CO_2 storage. A key objective is to integrate various data in order to determine subsurface fluid distribution, pressure change and associated ground deformation. The Aquistore site serves as buffer storage for the world's first commercial post-combustion CO_2 capture plant at the Boundary Dam coal-fired power station. At the Aquistore site CO_2 injection will occur within brine-filled clastic strata of the Deadwood and Winnipeg formations, which are the deepest sedimentary units in the Williston Basin, and are below any oil producing and potash-bearing formations (Norford et al., 1994). The Deadwood and Winnipeg formations are located at more than 3000 m depth. Similar deep saline formations are found elsewhere in western Canada, throughout North America and the world. The rocks in these formations are well-suited for the storage of CO_2 because they are porous and permeable, have huge volumes, and are overlain by effective barriers and geologic seals that will impede the upward migration of CO_2.

3. Satellite data and processing methodology

High-precision, high-resolution deformation maps are computed using DInSAR processing methodology (Massonnet and Feigl, 1998; Rosen et al., 2000; Hooper et al., 2012) from the Synthetic Aperture Radar (SAR) data repeatedly acquired by space-borne or occasionally air-borne sensors. A number of advanced techniques have been developed in order to mitigate temporal decorrelation and to remove orbital and atmospheric noise affecting DInSAR retrievals (Ferretti et al., 2001; Berardino et al., 2002; Hooper, 2008; Samsonov, 2010; Samsonov et al., 2011). In favorable conditions DInSAR achieves millimeter precision in measuring ground deformation at meter-scale areal resolution over a large area. Operational monitoring limitations of the early DInSAR included the



(a) 30 m ASTER DEM (b) 1 m LIDAR DEM

Fig. 1. Location of Aquistore CO_2 storage site in Saskatchewan, Canada. (a) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 30 m resolution Digital Elevation Model (DEM). RADARSAT-2 frames are outlined in black. Region of interest is outlined in brown. Extent in top-right corner shows location of study region in North America. (b) LIDAR 1 m resolution DEM plotted over ASTER DEM. Reference region "R" assumed to be stable. Monitoring sites NE1, NE2, SE1, SE2, SE3, SITE, SW1, NW1, NW2 are plotted in black. Points P1-P9 experiencing fast ground deformation are plotted in red. Location of injection site is plotted as red diamond. A – Souris river, B – Boundary Dam Power Station, C – Rafferty Dam, D – Long Creek River, E – Boundary Dam, F – Boundary Dam Reservoir, GG' – Rafferty-Boundary diversion canal.