First results of geodetic deformation monitoring after commencement of CO2 injection at the Aquistore underground CO2 storage site

Natural Resources Canada / Ressources naturelles Canada

Canada

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1. INTRODUCTION

- Aquistore is a demonstration project for the underground storage of CO2
- Location: Estevan, Saskatchewan, Canada
- Storage depth: ~3350 m below surface

Project Objective

- Obtain quantitative estimates of change in subsurface fluid distributions, pressure changes and associated surface deformation
- Design, adapt and test non-seismic monitoring methods not systematically utilized to date for monitoring CO2 storage
- Integrate data from various monitoring tools
- Monitoring methods include satellite-, surface- and wellborne-based monitoring systems, such as:
  - Controlled-source electromagnetic systems
  - Absolute gravimetry
  - GPS
  - Synthetic aperture radar interferometry (InSAR)
  - Tiltmeter array analysis
  - Chemical tracer studies
- ***CO2 injection began on April 16, 2015 at a current rate of approximately 400 tonnes/day***

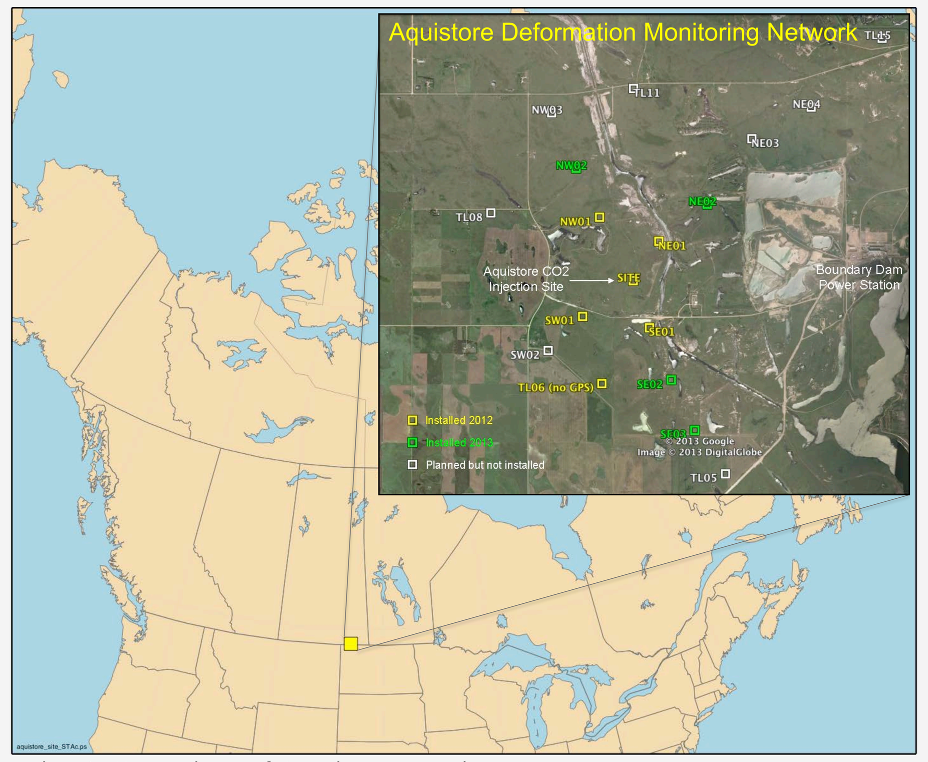


Fig. 1: Location of Aquistore project and deformation monitoring network (inset) at SaskPower Boundary Dam Power Station

Fig 2: CO2 injection well

2. DEFORMATON MONITORING NETWORK

- Covers a 1.7 x 3.8 sq. km area (see Fig. 1 inset map)
- NE area is an old open pit coal mine reclaimed to a depth of ~20-25 m
- 13 multi-technique sites were planned with additional 6 tiltmeter-only sites
- Only **9 multi-technique monitoring sites and 1 tiltmeter site installed**; 5 in 2012 & 4 in 2013 (see Fig. 1)
- Instruments mounted on or installed in 5-9/16" dia. well casings, most to a depth of 30 m to get below the reclaimed area
- 5 inner sites installed in Nov 2012 (SITE, NE01, NW01, SE01, SW01)
- 4 outer sites installed in Nov 2013 (NE02, NW02, SE02, SE03)
- **GPS Installations**
  - Trimble NetR9 receiver & Zephyr antenna
  - Autonomous operation (solar power, cell comms)
  - Monument depth: 30 m (24 m at NW01)
  - Monument height above ground: 2 m
- **InSAR Installations**
  - Retro-reflectors welded to side of well casing
  - Monument depth: 4 m
  - Monument height above ground: 2 m
  - GPS antennas also installed on 3 InSAR monuments (SITE, SE02 & SE03) to evaluate stability of shallow monuments w.r.t deep ones
- **Absolute Gravity Measurements**
  - Micro-g LaCoste A-10 absolute gravimeter
  - Gravity measured at all sites & a stable reference site "Area51" at Boundary Dam

Fig 3: Typical multi-technique monitoring site (NE01)

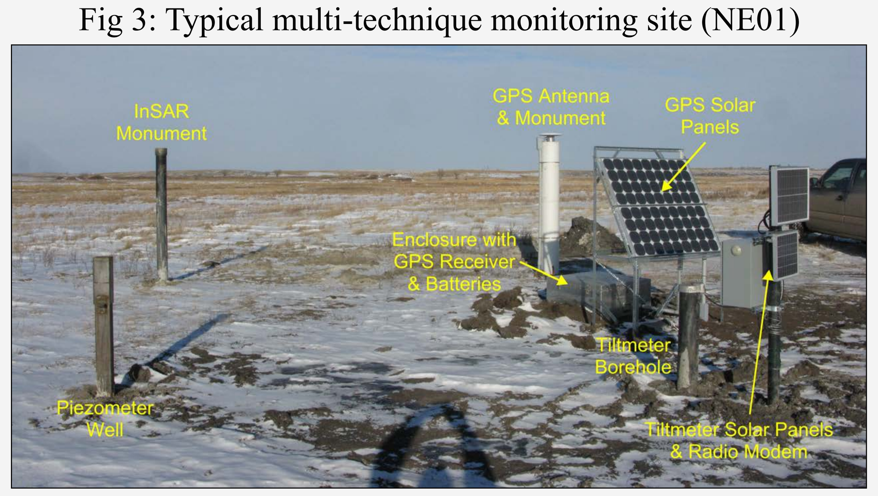


Fig 4: A-10 absolute gravimeter and observation tent

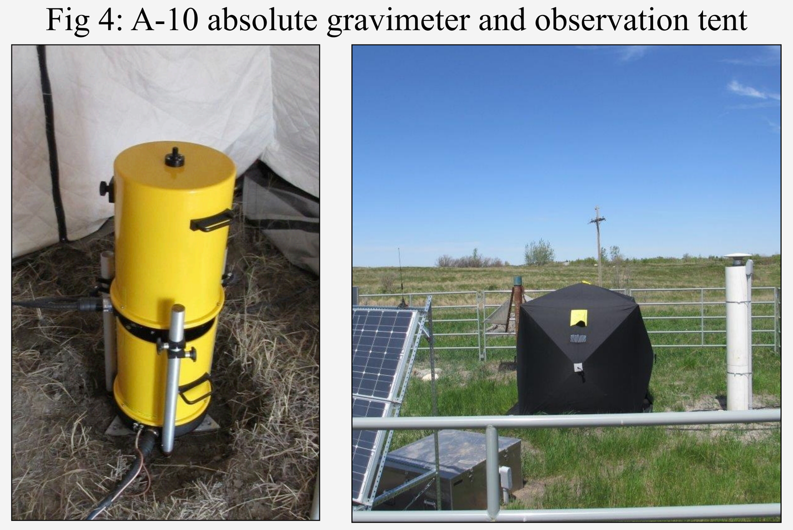


Fig. 5: GPS Pillar

Fig 6: InSAR Pillar w/ GPS

3. GPS Vertical Velocities

GPS Data Processing

- Daily solutions using Bernese GNSS Software v5.2
- IGS precise orbits & antenna calibrations in ITRF2008/IGb08
- 4 IGS stations define ITRF2008/IGb08 reference frame (DUBO, FLIN, PRDS, SASK)
- L1 baselines without tropo estimation for local baselines (< 2 km)
- Ionospheric-free L3 baselines with tropo estimation for long baselines to IGS reference frame stations

Absolute Vertical Velocities

- Estimated from time series of daily coordinate solutions (Table 1)
- No coloured noise models used => standard deviations overly optimistic
- Velocities for inner sites (3 years of data) more precise than outer sites (2 years of data)
- Vertical velocities estimated to be -2.0 mm/y on average
- Agrees very well with predicted background vertical velocity (-2.0 mm/y) derived from the surrounding regional velocity field from a Canada-wide velocity solution in ITRF2008/IGb08 (Craymer et al., 2011)

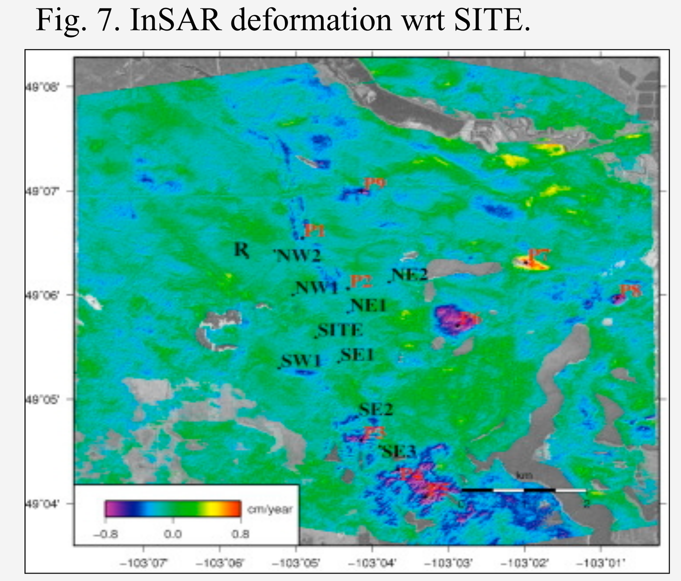
Table 1: Absolute vertical velocities

Station	Vert. Vel. (mm/y)	St. Dev. (mm/y)
Inner Sites		
SITE	-2.2	0.1
NE01	-2.2	0.1
NW01	-1.7	0.1
SE01	-2.1	0.1
SW01	-2.1	0.1
Outer Sites		
NE02	-1.8	0.4
NW02	-1.6	0.2
SE02	-2.3	0.3
SE03	-1.3	0.2

4. INSAR Vertical Velocities

- Using RADARSAT-2 data spanning 2012-06-15 to 2014-09-23 (prior to CO2 injection)
- Fig. 7 gives vertical deformation results computed using the Multidimensional Small Baseline (MSBAS) technique (Samsonov et al., 2015)
- Velocities relative to the selected stable reference area "R"
- Deformation estimated for a 5 x 5 m footprint around InSAR retro-reflector/monument at each site
- Represents surface motion rather than monument motion
- Points P1-P9 (red) are experiencing fast deformation; note the proximity of SE03 to P4 & P5
- Subsidence up to 1 cm/y with respect to "R" observed at former mining areas & heave in the north east
- InSAR time series agrees fairly well with GPS, following the same basic pattern except during initial monument settlement of new 2013 sites (right side of Fig. 8)

Fig. 7. InSAR deformation wrt SITE.



5. Absolute Gravity Monitoring

- A-10 abs-g measurements performed in 2013 (Fall), 2014 (Spring & Fall), 2015 (Fall)
- 2013 (Fall) & 2014 (Spring) were measurements of the entire network
- 2014 (Fall) & 2015 (Fall) were measurements of only part of the network
- Data processed with 'g' (v9) software using standard corrections for solid-earth tides, ocean loading, polar motion, and local atmospheric attraction & loading
- Secular (long-wavelength) rate of gravity change due to GIA is expected to be small with a regional gravity/uplift ratio of -0.17 ± 0.01 μGal/mm derived from 10-15 yr of GPS and absolute gravity data (Mazzotti et al., 2011)
- Based on GPS-observed subsidence rate (-2 mm/y), the gravity change is expected to be only 0.34 μGal/y (smaller than the measurement uncertainty)
- Absolute gravity results to date display a variability of 20-30 μGal at most Aquistore sites (formal manufacturer-reported uncertainty of A-10 is 10 μGal)
- Consistent seasonal and/or instrumental survey biases are not presently observed for all sites
- Gravity variability at Aquistore sites may result from temporally and spatially localized "transient" mass transfer signals associated with very near-field changes in total water storage, where 10 μGal would be equivalent to a 24 cm thick layer of water

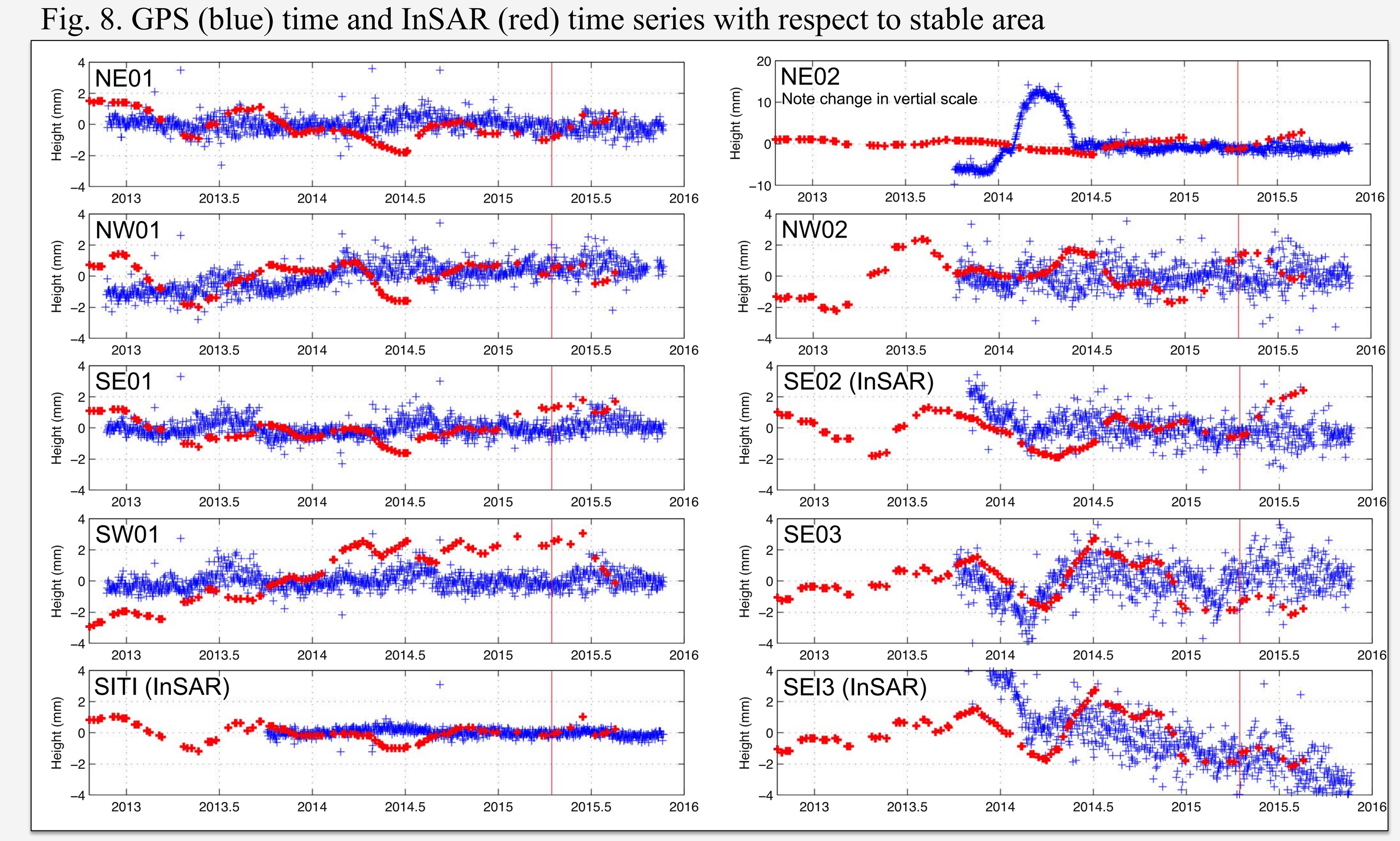
Table 2: Variability in absolute gravity measurements

Site	Number Epochs	Variability (μGal)
SITE	2	29
NE01	3	12
NE02	4	39
NW01	3	16
NW02	2	16
SE01	2	26
SE02	3	83
SE03	3	16
SW01	2	27
Area51	4	16

6. GPS & INSAR COMPARISON

- Compared relative time series of GPS and InSAR with respect to stable site (Fig. 8)
- Monument stability
  - GPS monuments installed in 2012 stable to ±1 mm (left side of Fig. 8)
  - GPS monuments installed in 2013 exhibit some anomalous behaviour after installation (especially NE02) then stable to ± 2 mm after one year => installers took less care in 2013
- Comparison of InSAR & GPS
  - GPS solutions represent relative motion at 30 m depth while InSAR solutions represent surface motion
  - Generally good agreement at the mm level after first year of installation, including some seasonal signals at some sites; differences likely due to the preceding point.
  - 4 m InSAR monument at SEI3 exhibits continued settlement while deeper SE03 in same location does not (InSAR results show surficial subsidence in this area as well)

Fig. 8. GPS (blue) time and InSAR (red) time series with respect to stable area



7. SUMMARY & FUTURE WORK

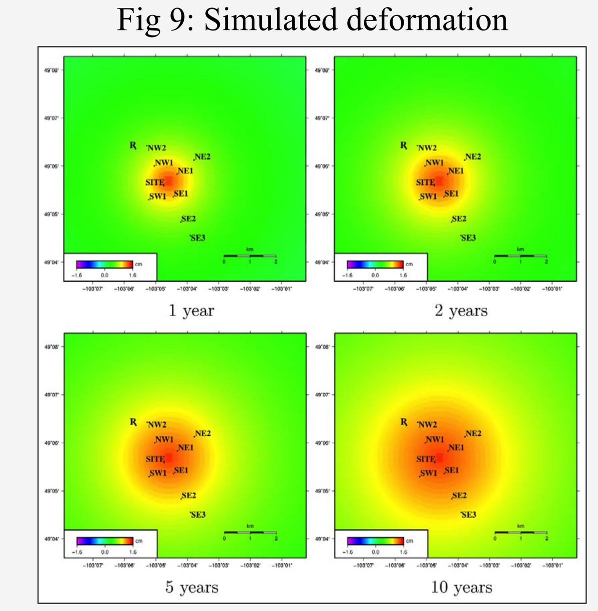
Current Results

- Can detect relative surface deformation to an accuracy of 1-2 mm/y with GPS & InSAR; no CO2-related deformation detected thus far
- GPS velocity results agree very well with regional velocity field
- InSAR & GPS agree well given different monument depths
- Absolute gravity variations can be detected at the 20-30 μGal level
- Some GPS & InSAR monuments took at least a year to stabilize
- SE03 site exhibits surficial background subsidence (low wet area)

Future Work

- Continue with GPS, InSAR for surface deformation and gravity monitoring for mass redistribution as CO2 injection continues
- Fig. 9 predicts deformation up to 1.6 cm over 10 years using a poroelastic model with a 1500 tonne/day CO2 injection rate at a depth of 3220-3280 m (Samsonov et al., 2015)
- Results indicate GPS and InSAR readily capable of detecting such motions

Fig 9: Simulated deformation



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