First results of continuous GPS monitoring of surface deformation at the Aquistore underground CO2 storage site

M.R. Craymer[1], R. Ferland[1], M. Piraszewksi[1], S. Samsonov[2], M. Czarnogorska[2]
[1]Canadian Geodetic Survey, Natural Resources Canada
[2]Canada Centre for Remote Sensing, Natural Resources Canada

Natural Resources Canada / Ressources naturelles Canada
Canada
AGU
AGU Fall Meeting
San Francisco, December 15-19, 2014
Paper G41A-0466

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
- ***This is the first analysis with one year or more of GPS data to determine the natural rates of surface deformation before CO2 injection begins in 2015***

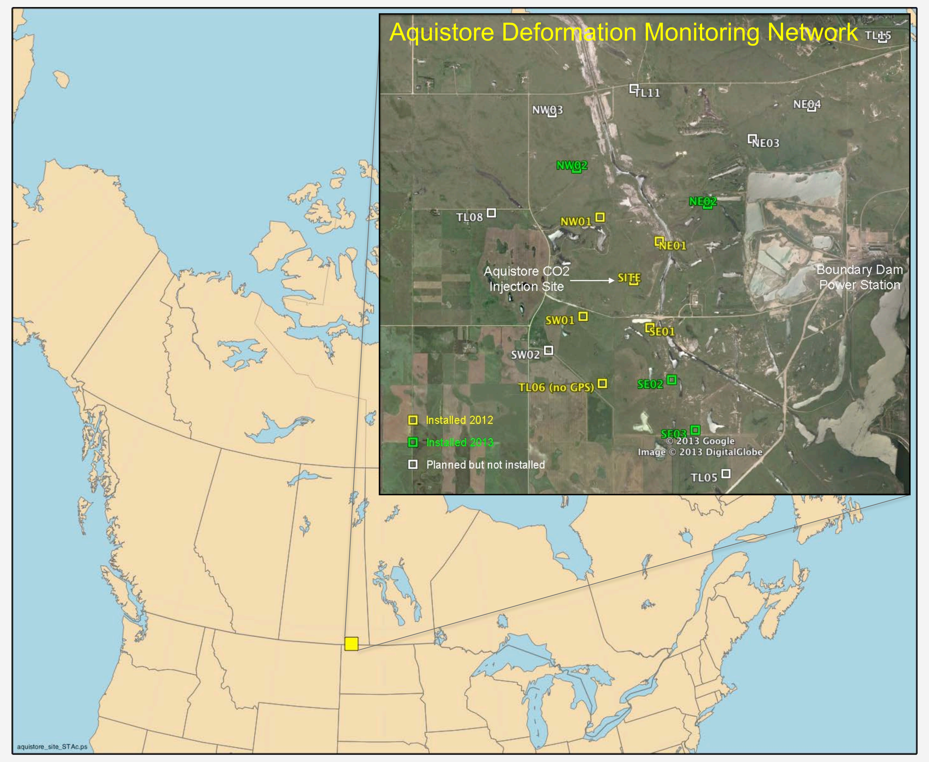


Fig. 1: Location of Aquistore project and deformation monitoring network (inset) at SaskPower Boundary Dam Power Station

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
- Drilling in well casings very difficult and expensive at some sites
- ***This analysis focuses only on the GPS monitoring using 2 years of data at 5 sites and 1 year at 4 sites***

GPS & InSAR Installations

- GPS
  - Trimble NetR9 receiver + Trimble Zephyr antenna
  - Automonous operation (solar power, cell comms)
  - Antenna monument depth: 30 m (24 m at NW01)
  - Monument height above ground: 2 m
- InSAR
  - Retro-reflectors welded to side of well casing
  - Monuments depth: 4 m
  - Monument height above ground: 2 m
- GPS antennas also installed on 2 InSAR monuments (SITE & SE03) to evaluate relative stability of shallow monuments with respect to deep ones

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

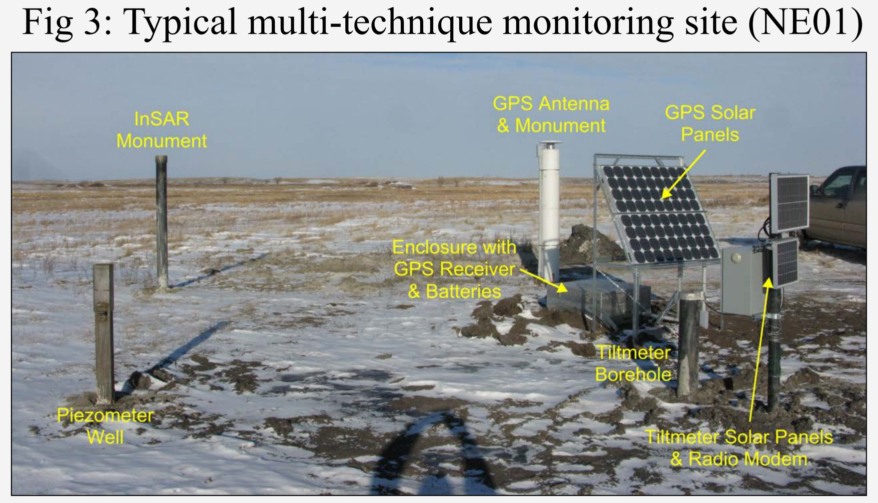


Fig 4: GPS Installation

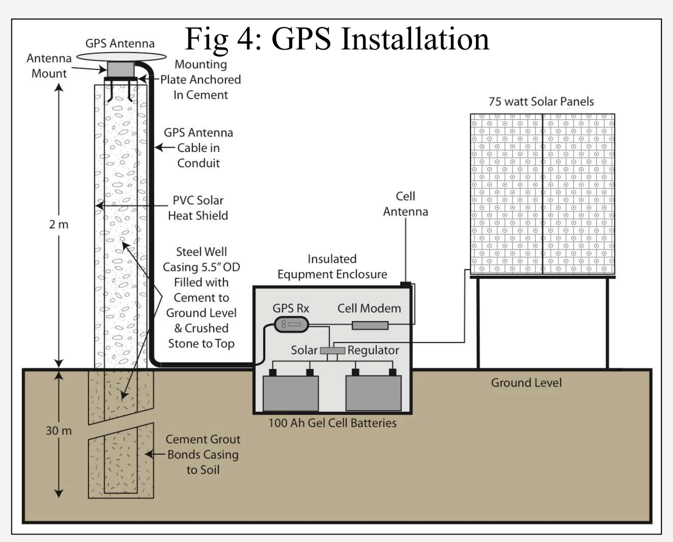


Fig. 5: GPS Pillar

Fig 6: InSAR Pillar

3. GPS DATA PROCESSING

Data Used

- 5 inner sites (SITE, NE01, NW01, SE01, SW01) with 2 years of data
- 4 outer sites (NE02, NW02, SE02, SE03, SW01) with 1 year of data
- 4 IGS stations (DUBO, FLIN, PRDS, SASK) define reference frame

Daily Solutions

- Bernese GPS Software v5.2 & current IGS processing guidelines using:
  - IGS precise orbits & antenna calibrations
  - Ionospheric-free L3 baselines to IGS stations with tropo estimation
  - L1 for local short baselines (< 2.5 km) without tropo estimation

Multi-Day (Velocity) Solution

- Simultaneously aligned and combined daily solutions into a 4D solution for coordinates and velocities using new SINEX combination software
- Daily and combined solutions aligned to IGb08 (ITRF2008)
- Variance factors estimated for each daily solution and outliers removed
- NEU RMS of fit of daily & combined solutions: 1.5, 1.4, 4.0 mm
- NEU RMS of fit of combined solution to IGb08: position 3, 3, 5 mm, velocity 0.5, 0.7, 0.4 mm/y

4. GPS & INSAR MONUMENT STABILITY

- Examined time series of short GPS baselines from SITE to other Aquistore monuments
- SITE selected as reference due to best stability of absolute coordinate time series
- GPS antennas also installed on InSAR monuments at SITE (2012) & SE03 (2013) to assess stability of shallow 4 m deep InSAR monuments versus deep 30 m GPS monuments (Fig. 7)

2012 Monuments (left side of Fig 8)

- Currently stable to ±1 mm with exception of NW01 (small uplift with respect to site)

2013 Monuments (right side of Fig 8)

- Most show significant vertical settlement until spring 2014
- Likely a result of large horizontal motions (well casings had to be braced into vertical => may be drifting back)
- NE02 exhibited a strange systematic pattern of motion Horizontal exhibited the same pattern (the cause)
- All monuments appear to have stabilized except for shallow InSAR at SEI3 – but larger noise than 2012 ones

Fig. 7: SE03 GPS on SEI3 InSAR

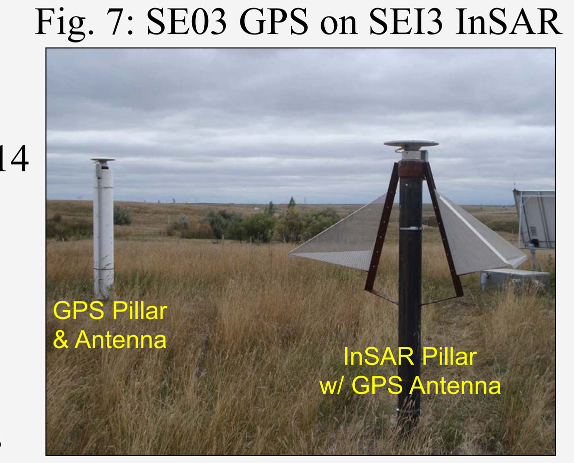
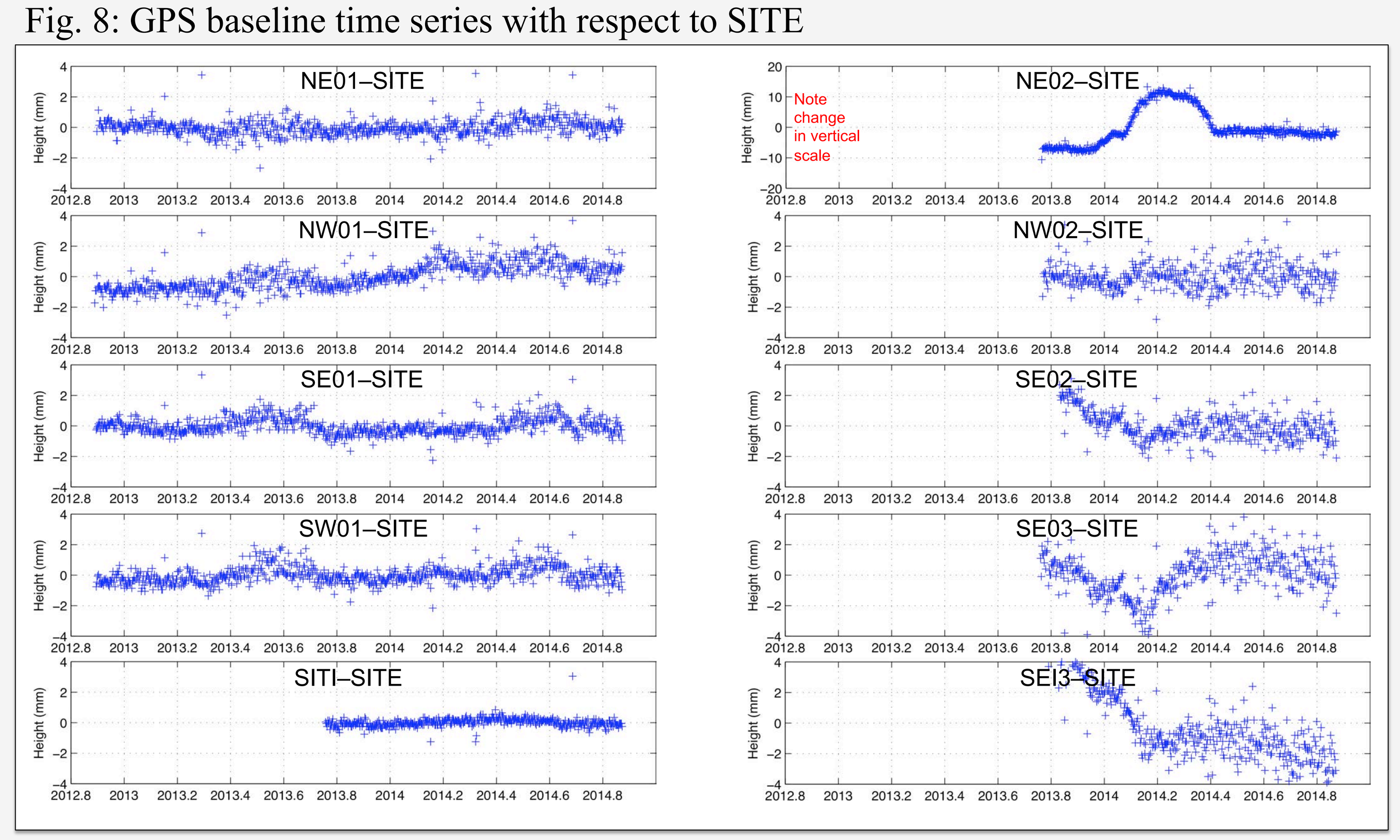


Fig. 8: GPS baseline time series with respect to SITE



5. GPS VERTICAL VELOCITIES

- Surrounding regional velocity field estimated from Canada-wide solution in IGb08 (ITRF2008)
- Estimated Aquistore subsidence (-5.5 mm/y) larger than that predicted from regional velocity field (-2 to -3 mm/y) but not statistically significant difference due to high uncertainty from short time series
- Velocities at 2012 (inner) Aquistore sites exhibit very consistent subsidence of -5.5 mm/y except at NE01 (Table 1)
- Some of the new 2013 (outer) sites exhibit large differences from others due to monument instability immediately after installation (red entries in Table 2)

Fig. 9: Regional & Aquistore velocities.

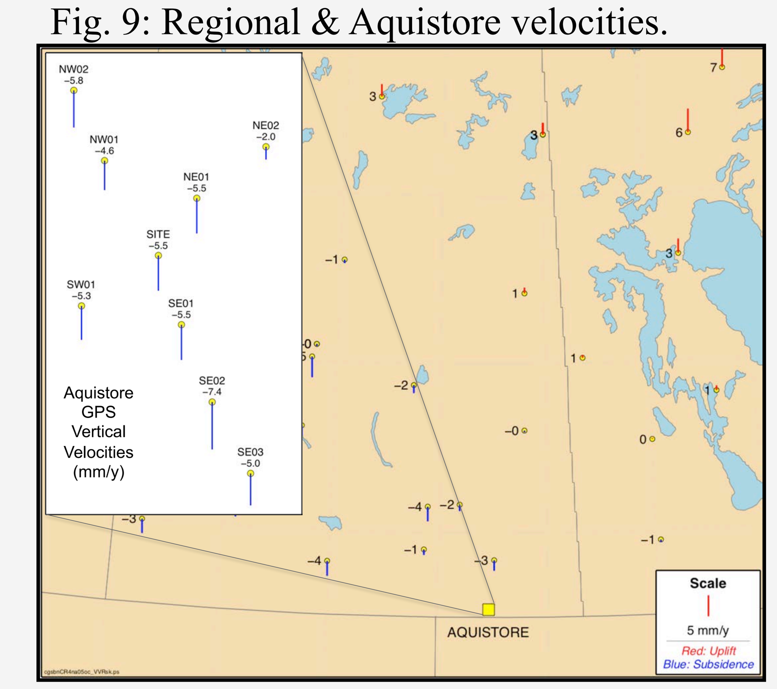


Table 1: Absolute velocities of 2012 sites

Station	Vert. Vel. (mm/y)	St. Dev. (mm/y)
SITE	-5.5	2.3
NE01	-5.5	2.3
NW01	-4.6	2.3
SE01	-5.5	2.3
SW01	-5.3	2.3

Table 2: Absolute velocities of 2013 sites

Station	Vert. Vel. (mm/y)	St. Dev. (mm/y)
NE02	-2.0	4.5
NW02	-5.8	2.5
SE02	-7.4	2.5
SE03	-5.0	2.4
SEI3	-9.4	2.6

6. COMPARISON WITH INSAR

- InSAR results in Fig. 10 based on RADARSAT-2 using the methodology of Samsonov et al. (see G41A-0467)
- Linear deformation relative to the selected stable reference area "R" in Fig. 10
- Deformation estimated for a 5 x 5 m footprint at each site
- Represents surface motion rather than monument motion
- 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. 11)

Fig. 10. InSAR deformation wrt SITE.

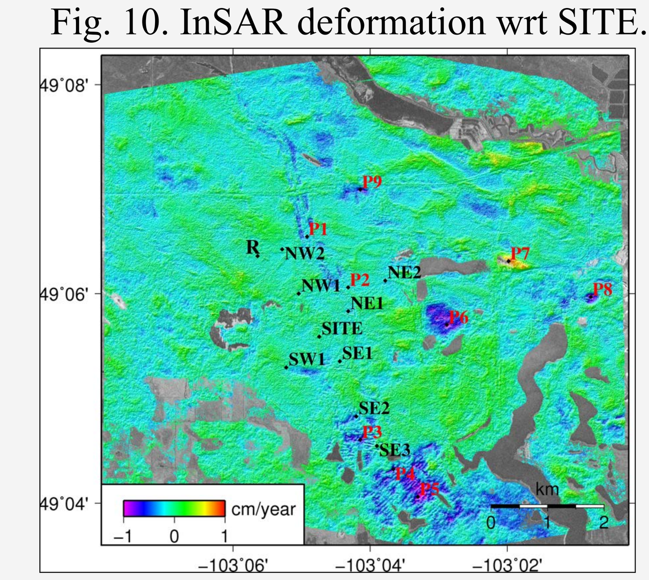
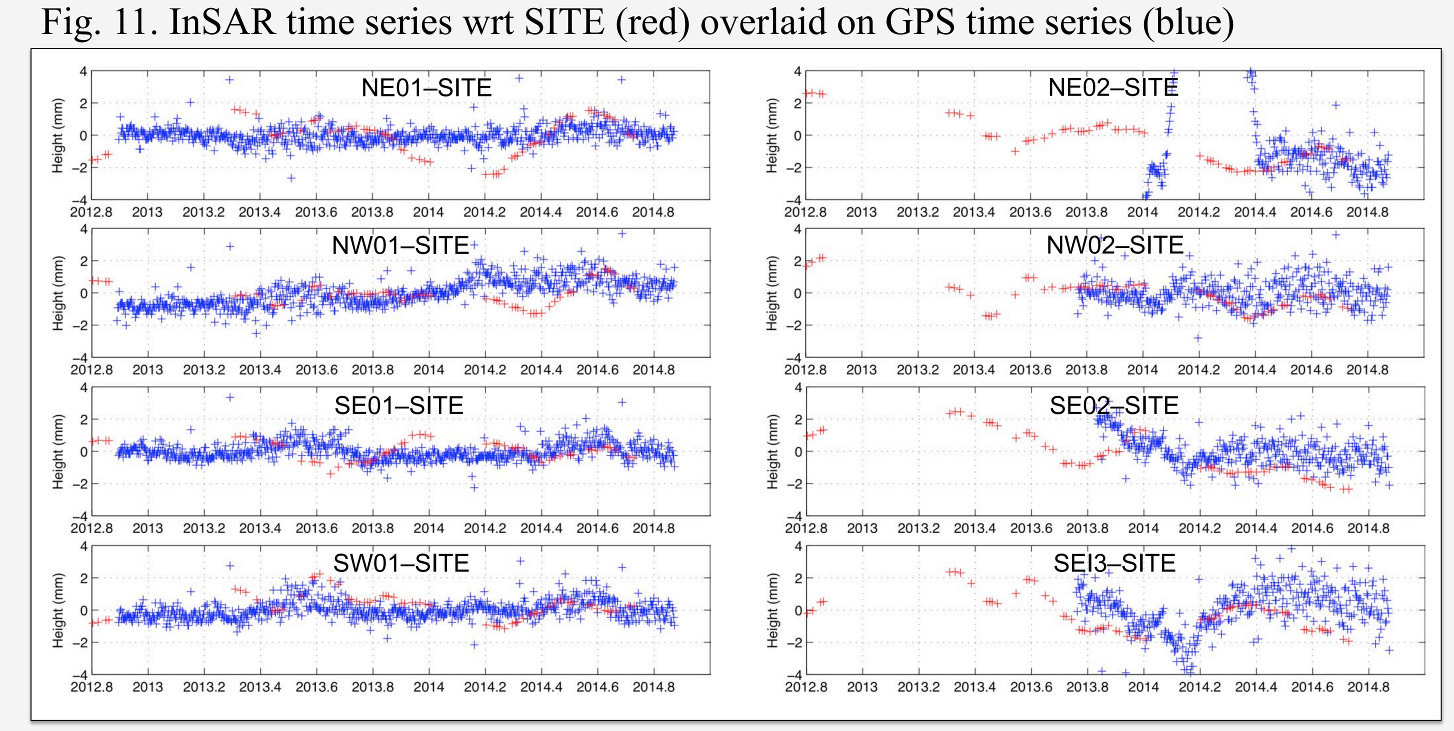


Fig. 11. InSAR time series wrt SITE (red) overlaid on GPS time series (blue)



7. SUMMARY & FUTURE WORK

- Fairly good agreement of GPS with regional velocity field and InSAR
- Need longer time series (first year not really useable because of monument settlement at new sites)
- Need to use more IGS stations to define reference frame more reliably

8. ACKNOWLEDGEMENTS

Funding and support for this work has been provided by NRCan's ecoEII program, the Petroleum Technology Research Centre, and Prof. Ben Rostron of the University of Alberta