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

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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, including:
  - Controlled-source electromagnetic systems
  - Absolute gravimetry
  - GPS
  - Synthetic aperture radar interferometry (InSAR)
  - Tiltmeter array analysis
  - Chemical tracer studies
- ***This study focuses on the analysis of the first year of continuous GPS data for monitoring surface deformation in order to determine the natural rates of deformation before CO2 injection begins***

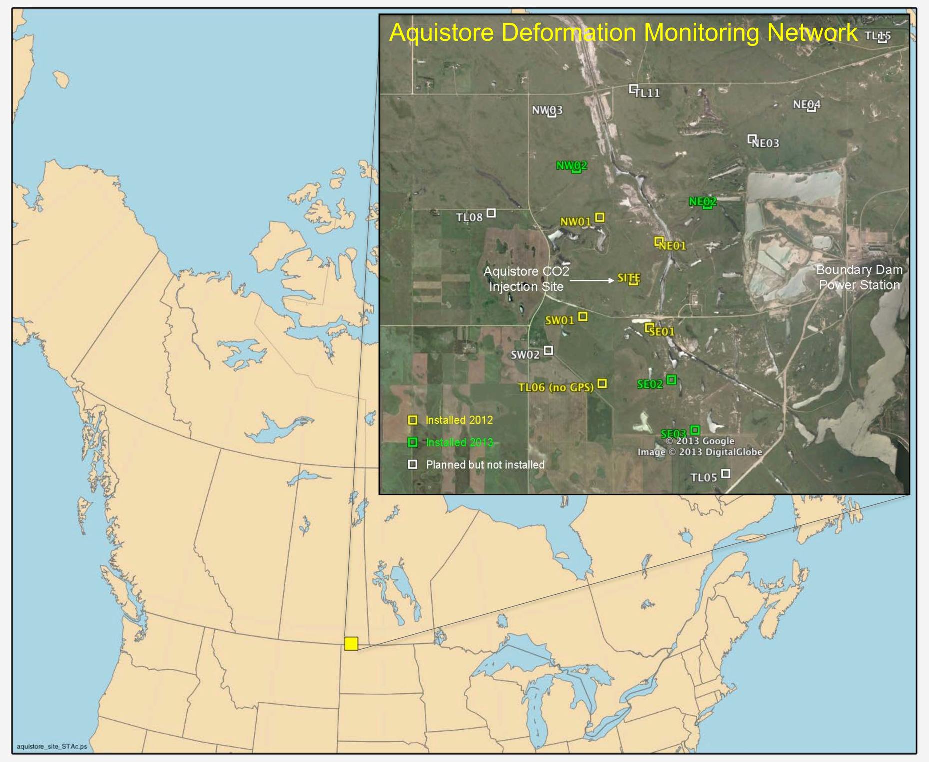


Fig. 1: Location of Aquistore project and deformation monitoring network (inset) at SaskPower Boundary Dam Power Station

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 5 sites with 1 year of GPS data***

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)

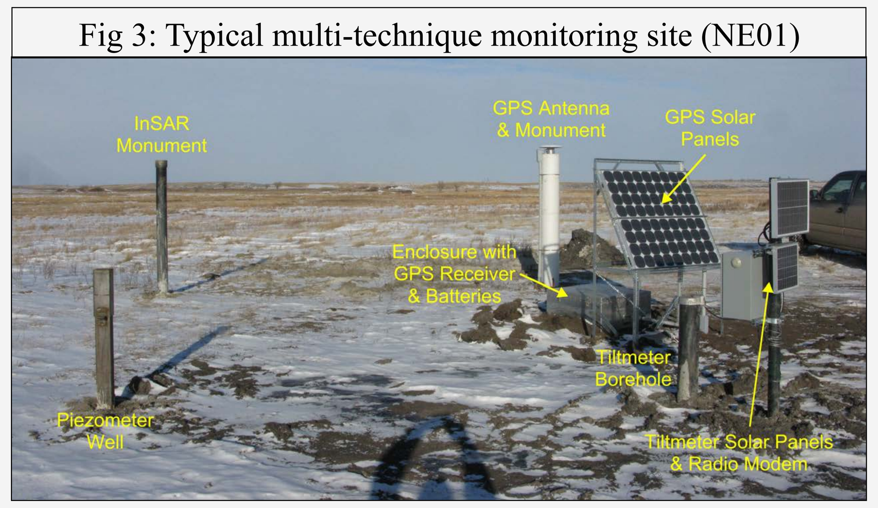


Fig 4: GPS Installation

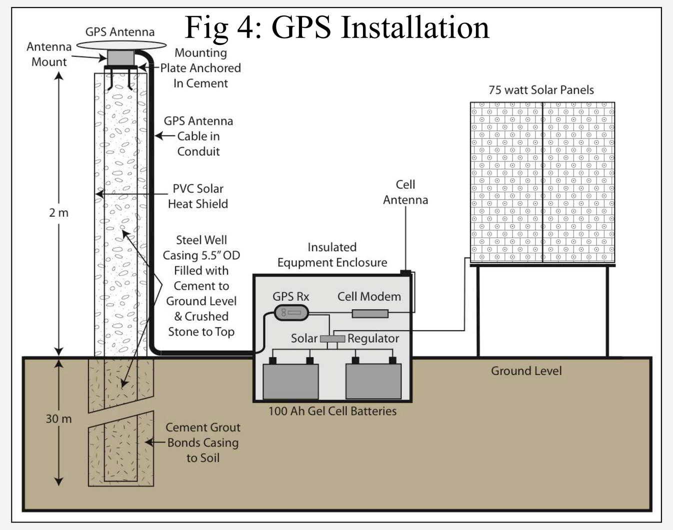


Fig. 5: GPS Pillar

Fig 6: InSAR Pillar

3. GPS DATA PROCESSING

Data Used

- One year of data for 5 sites installed in 2012 (2012-11-22 – 2013-11-16)
- 3 IGS stations (DRAO, DUBO, FLIN) used to define reference frame

Daily Processing

- New Bernese GPS Software v5.2 used
- Current IGS processing guidelines used
- Baselines defined radially from central station SITE to other local and IGS sites (except for baseline between GPS & InSAR pillars at SE03)
- Processed observables
  - Ionospheric-free L3 for long baselines to IGS stations with tropo est.
  - L1 for local short baselines (< 2.5 km) without tropo estimation

Reference Frame Definition

- IGb08 (nominally ITRF2008)
  - IGS “Final” precise orbits used
  - Current IGS absolute antenna calibrations used
- Aligned to frame using the 3 IGS stations minimally constrained to IGS weekly coordinate solutions (inner constraints)

4. GPS VERTICAL VELOCITIES

- Estimated velocities (Fig. 7) agree well with surrounding regional velocity field estimated independently by Craymer et al. (2011)
- Velocity differences between Aquistore sites statistically insignificant (Table 1)
- Position time series exhibit very strong coherence and season signal (Fig. 8 & 9)

Table 1: Absolute vertical velocities from linear trend of time series.

Station	Vert. Vel. (mm/y)	St. Dev. (mm/y)
SITE	-3.8	0.8
NE01	-4.1	0.8
NW01	-3.1	0.8
SE01	-3.7	0.8
SW01	-3.2	0.8

Fig. 7: Comparison with absolute regional GPS vertical velocities from Craymer et al. (2011).

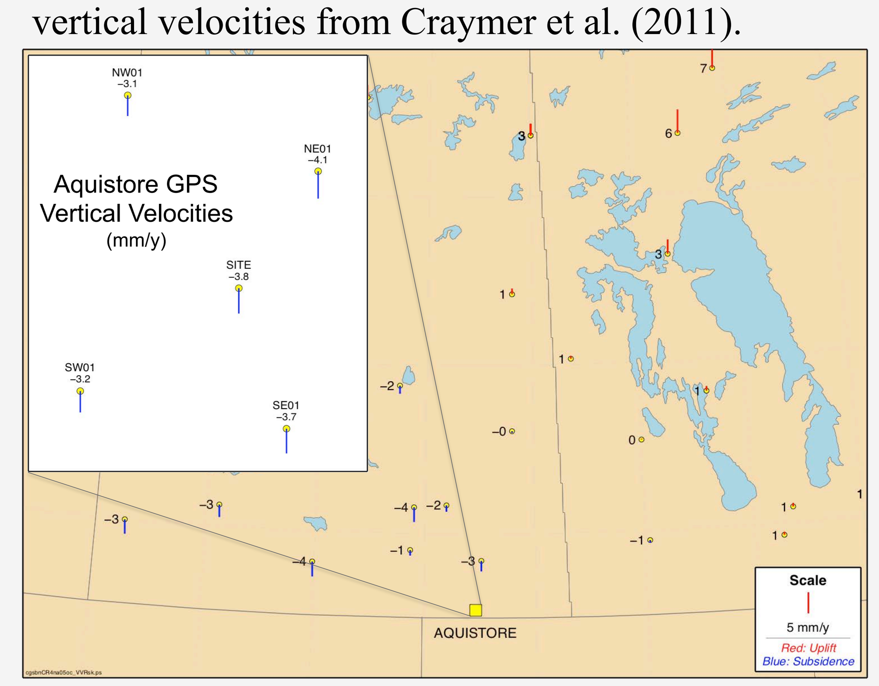


Fig. 8. Absolute vertical time series.

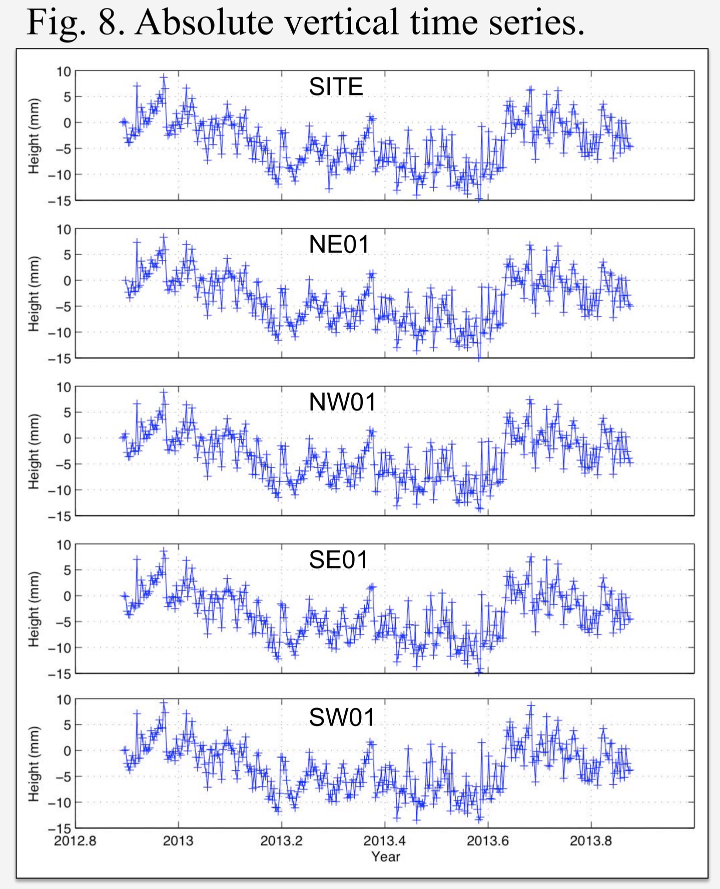
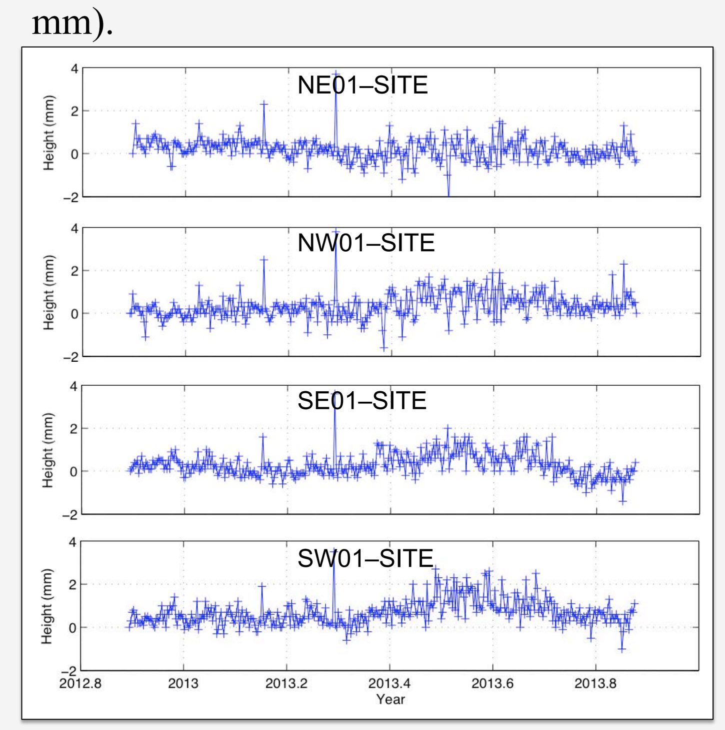


Fig. 9. Relative vertical time series with respect to SITE. Noise level is only ±0.5-1 mm).



5. COMPARISON WITH INSAR

- InSAR results (Fig. 10) from RADARSAT-2 Spotlight 12 using methodology in Samsonov et al. (2013)
- Using > 1.5 years of data: 2012-06-22 – 2013-11-08
- Linear deformation relative to a selected stable reference area
- Gives deformation for a 150 x 150 m footprint centered on each site
- Represents surface motion rather than monument motion
- Very good agreement with GPS vertical velocities except at NE01
- Will process results for InSAR retro-reflectors next

Fig. 10. InSAR relative vertical deformation with respect to SITE.

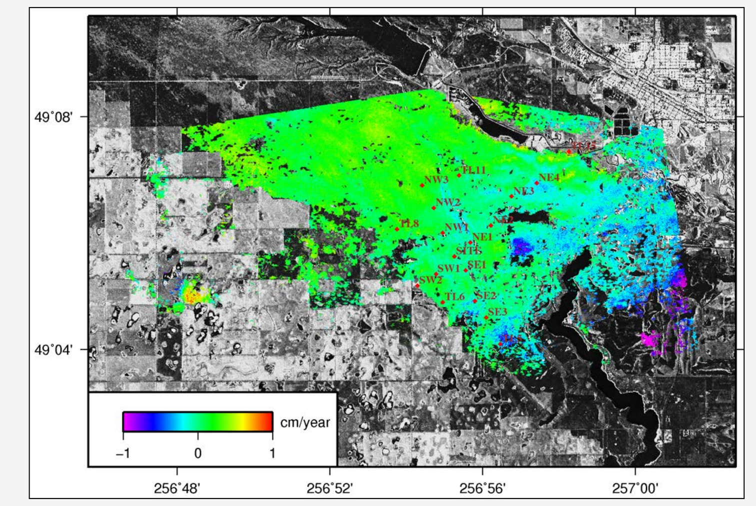
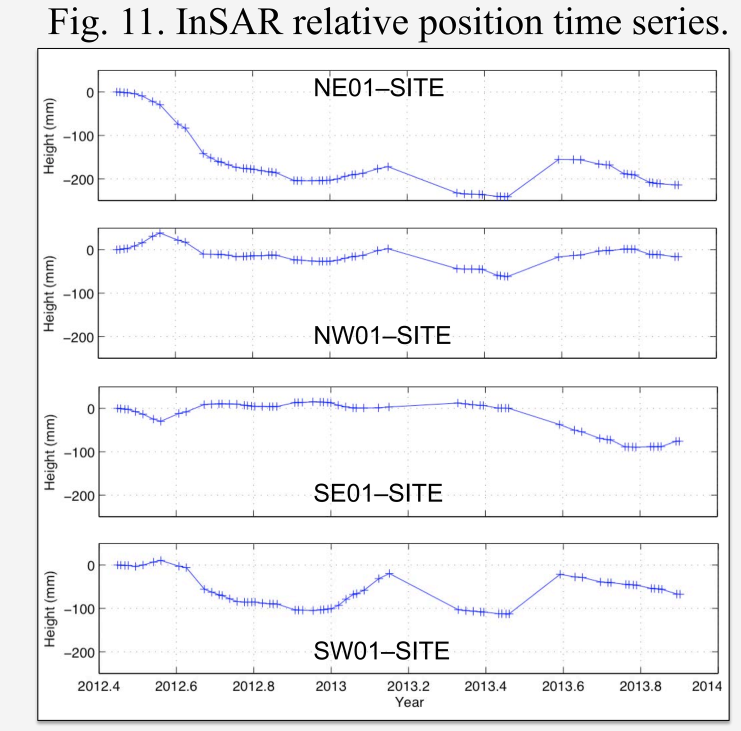


Table 2: Relative vertical velocities.

Station	InSAR (mm/y)	GPS (mm/y)
SITE	0.0	0.0
NE01	0.8	-0.3
NW01	0.5	0.7
SE01	-0.2	0.1
SW01	0.8	0.6

Fig. 11. InSAR relative position time series.



6. GPS & INSAR MONUMENT STABILITY

- GPS antenna installed on InSAR monuments at SITE (1 yr old site) & SE03 (new site)
- SITE’s monuments have been installed since Nov 2012
- SE03’s monuments have been installed since Oct 2013 (only 44 days available)
- Relative time series between GPS & InSAR (Fig 13) indicate:
  - SITE monuments currently stable within 1 mm
  - SE03 InSAR monument drifting ~6 mm south
  - InSAR well casing had to be braced into vertical position => drifting back?
  - Appears to be stabilizing in last few days

Fig. 12: SE03 GPS on InSAR

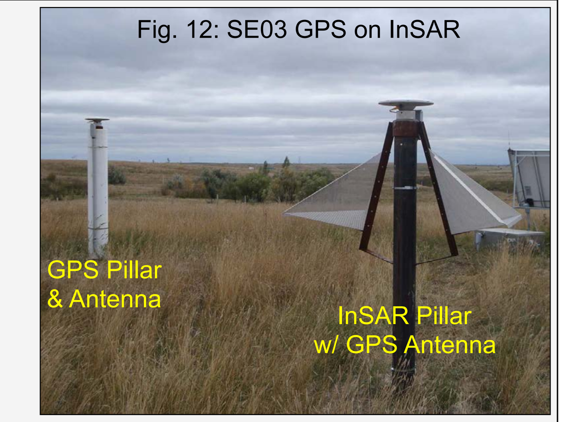
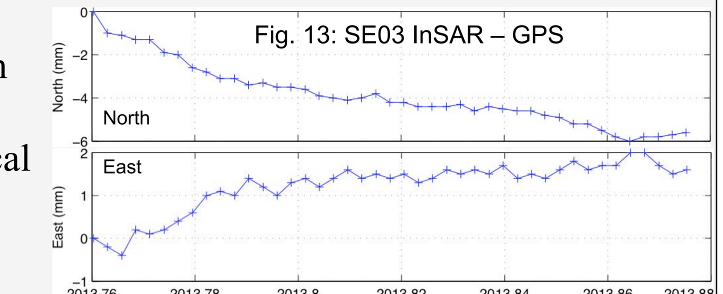


Fig. 13: SE03 InSAR – GPS



7. SUMMARY & FUTURE WORK

- Absolute vertical velocities agree well with independently determine regional velocities
- Very high degree of coherence in position time series among the GPS monitoring sites
- Some monumentation needs time to stabilize – may monitor more InSAR with GPS
- Good agreement with InSAR relative velocities in spite of large ground footprint
- Will soon estimate InSAR motion at retro-reflectors for direct comparison to GPS

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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