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

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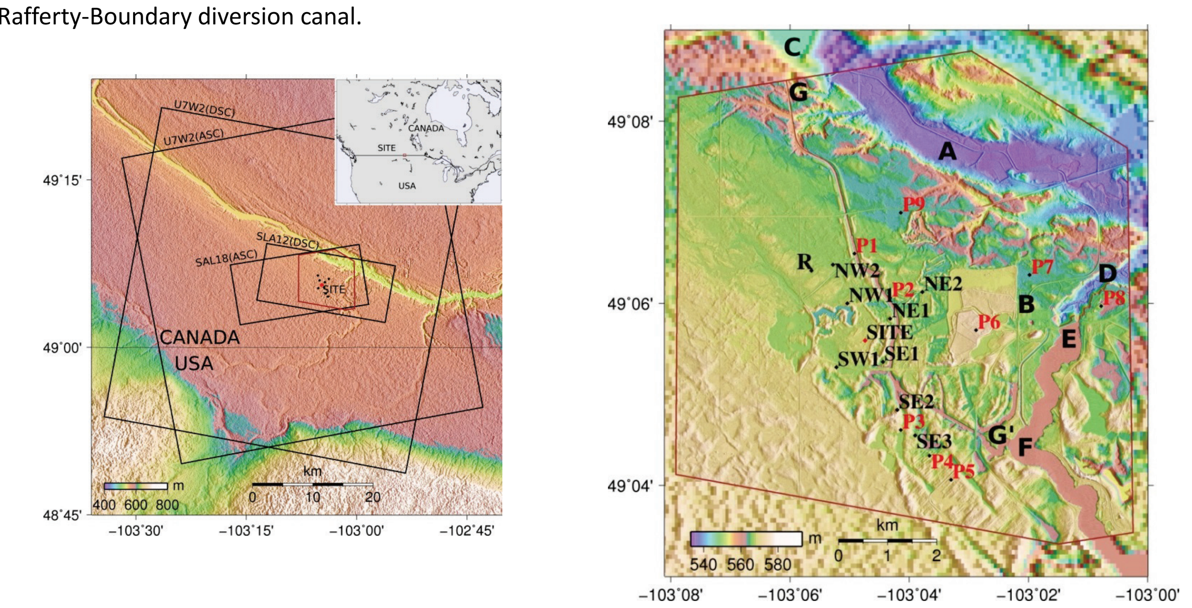
ABSTRACT: At the Aquistore CCS site, located in the south-eastern Saskatchewan, Canada, carbon dioxide (CO2) is to be injected at variable rates of up to 1500 tonnes/day. The storage reservoir comprises the brine-filled Deadwood and Winnipeg formations which reside at 3150-3350 m depth. Ground deformation at this site is being monitored to track pressure-induced uplift and potential upward migration of CO2 through faults and cracks. 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 CO2 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 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. Analytic elastic modeling was performed to estimate the ground deformation that will be produced when injection begins. It was determined that a maximum of vertical deformation of 1.0 cm/year will be located around the injection well, while the maximum of horizontal deformation of ± 0.4 cm/year will be located 2475 m away from the well. For proper validation of DInSAR results ground-based monitoring sites need to be installed near and also at the distance from the injection well. 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, especially now when SAR data is readily available.

LOCATION: Aquistore project study area, southeastern Saskatchewan: (left) ASTER 30 m resolution Digital Elevation Model (DEM) (from USGS/gdex, 2014). RADARSAT-2 frames are outlined in black. Region of interest is outlined in brown. (right) LIDAR 1 m resolution DEM plotted over ASTER DEM. Reference region "R" assumed to be as stable. Monitoring sites with corner reflectors installed 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.

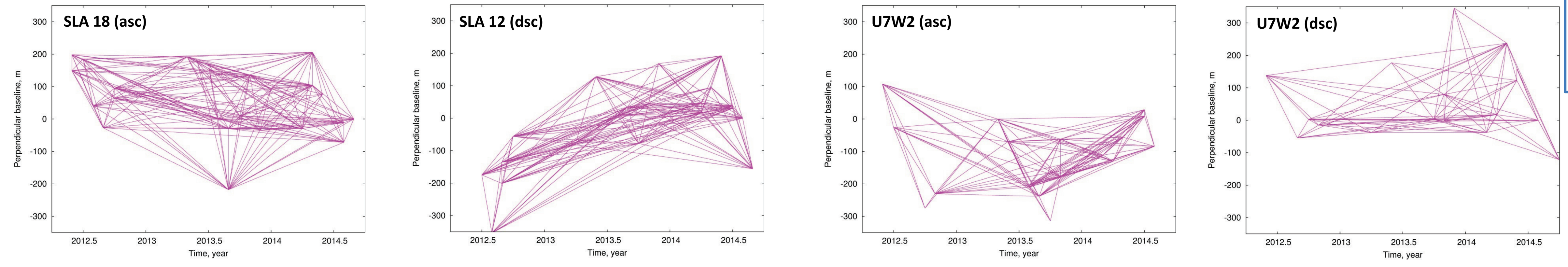


SATELLITE DATA AND PROCESSING METHODOLOGY: For monitoring ground deformation at the Aquistore storage site we used DInSAR (Differential Synthetic Aperture Radar Interferometry) advanced Multidimensional Small Baseline Subset (MSBAS) (Samsonov and d'Oreye, 2011; Samsonov et al. 2014) processing technique that computes the two dimensional (2D), vertical and horizontal, deformation time series by combing SAR data from various sensors and acquisition geometries, therefore significantly improving overall temporal resolution. To achieve high temporal and high spatial resolution of deformation measurements SAR data from four high resolution ascending and descending RADARSAT-2 beams, Spotlight and Wide Ultra-Fine, was acquired. By using four independent beams the temporal resolution was increased by a factor of four from 24 to six days, allowing detection of transient signals with minimal delay. High coherence is necessary for an accurate phase unwrapping. A single master for each beam was selected and remaining slave images were co-registered and re-sampled to the master geometry. Topographic phase was computed from the 1 m resolution air-borne LIDAR Digital Elevation Model (DEM) and removed from the interferograms. Adaptive filtering phase unwrapping and geocoding procedures were applied. The residual orbital ramps were computed and removed. The MSBAS technique was applied in order to produce vertical and horizontal East-West deformation rates and time series.

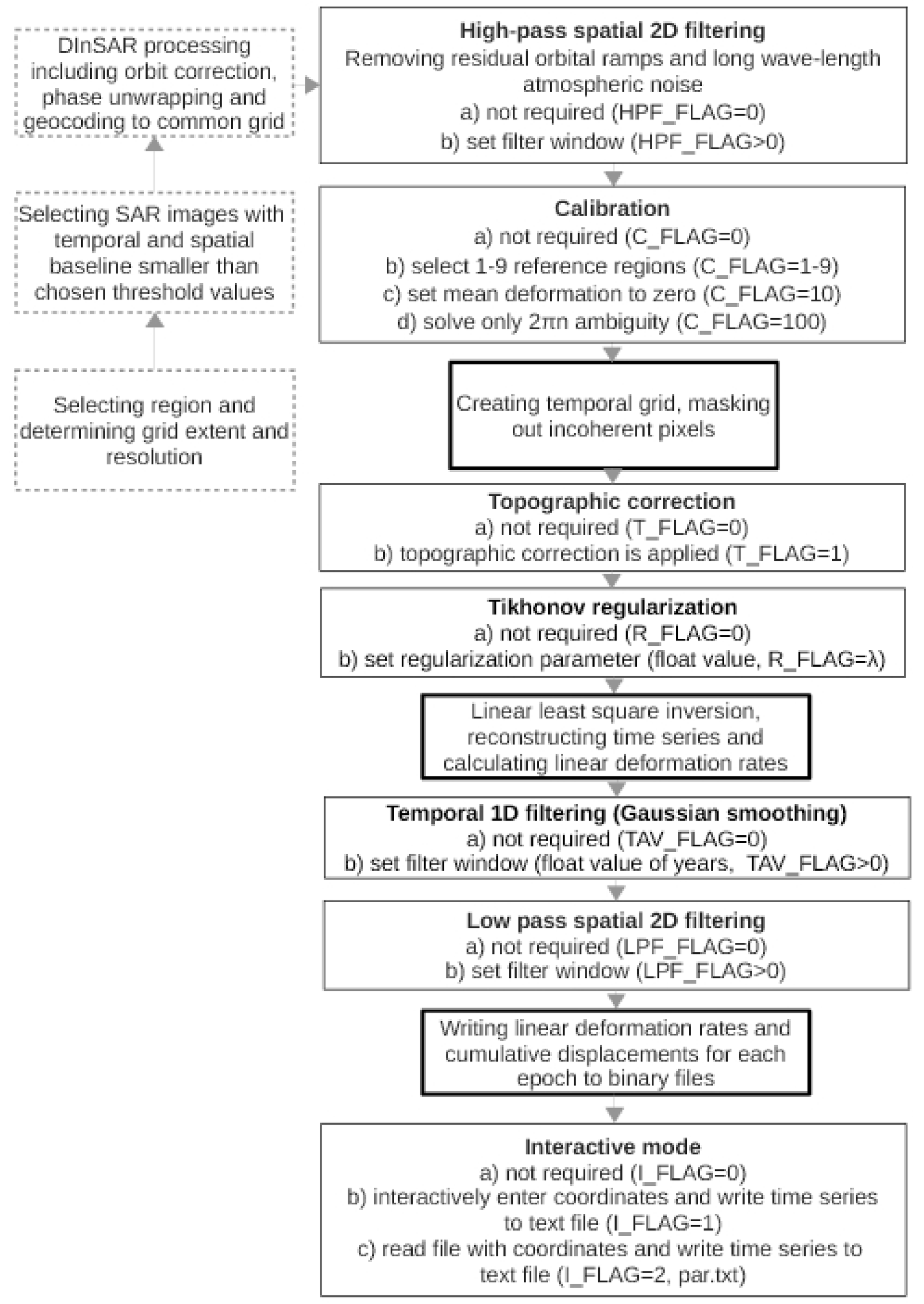
TABLE: SAR datasets used in this study. RADARSAT-2 Spotlight 18 (SLA18), Spotlight 12 (SLA12), Wide 2 Ultra-Fine 7 (U7W2); time span (in YYYYMMDD format), range-azimuth resolution, range-azimuth multi-looking, azimuth (Θ) and incidence (Φ) angles, number of available SAR images N, and number of calculated interferograms M for each data set.

InSAR data set	Time span	SLC resolution range-azimuth	Multi-looking range-azimuth	Θ [°]	Φ [°]	N	M
R2 SLA18 (asc)	20120605-20140923	1.6-0.8	3-12	351	44	25	184
					40		
R2 SLA12 (dsc)	20120716-20140916	1.6-0.8	3-12	-170		20	156
					37		
R2 U7W2 (asc)	20120619-20140820	1.6-2.8	4-3	349		18	110
					37		
R2 U7W2 (dsc)	20120615-20141003	1.6-2.8	4-3	-170		17	81
Total	**20120605-20141003**					**80**	**531**

Temporal and spatial baselines of RADARSAT-2 interferograms used in this study. Overall 80 SAR images spanning 20120605-20141003 produced 531 interferograms with perpendicular baselines less than 400 m.



MULTIDIMENSIONAL SMALL BASELINE SUBSET (MSBAS) ALGORITHM

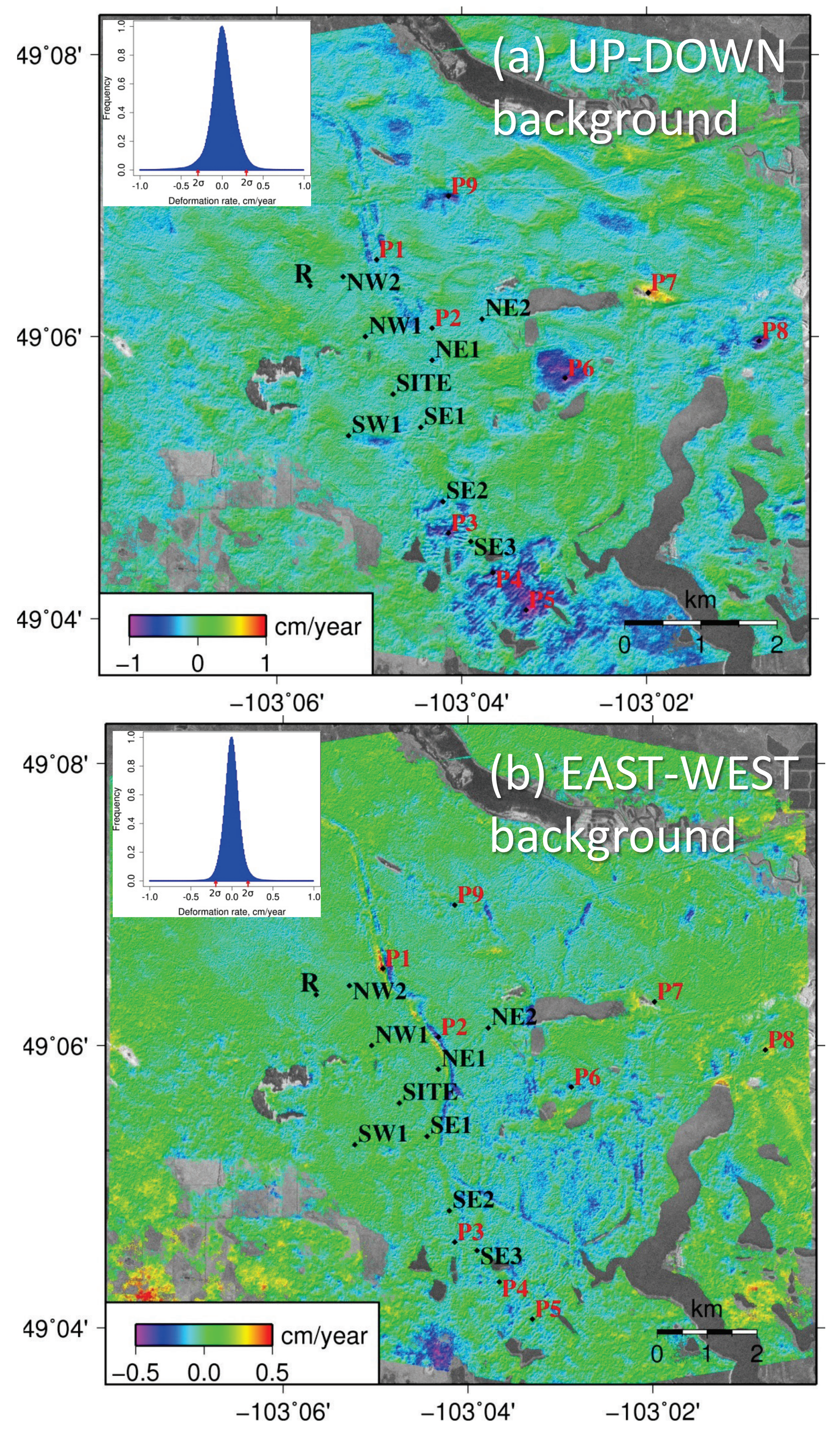


Multidimensional Small Baseline Subset (MSBAS, Samsonov and d'Oreye, 2011, Samsonov et al., 2014) methodology combines ascending and descending InSAR data and produces horizontal and vertical deformation time series and mean rates.

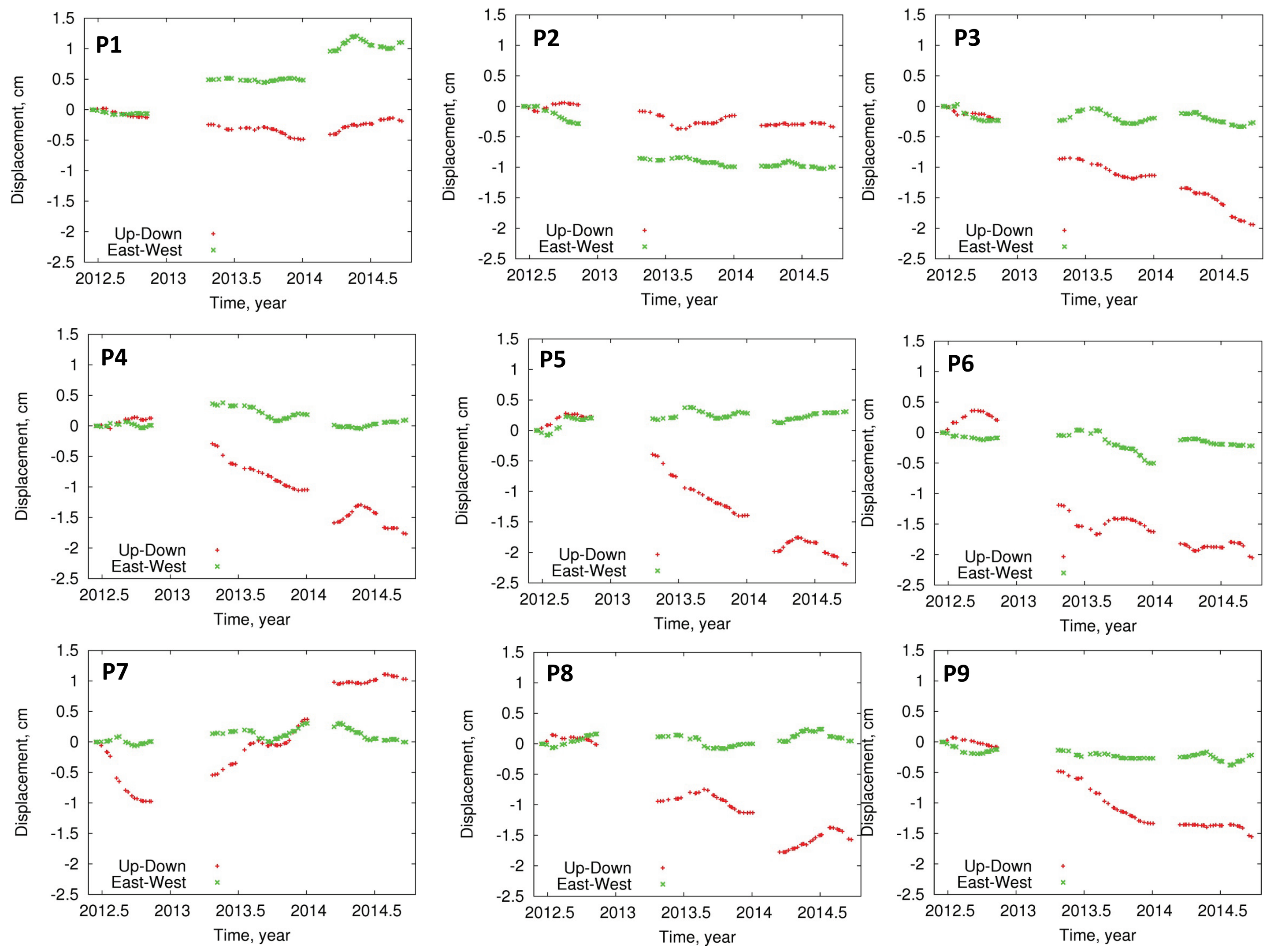
OBSERVED MSBAS GROUND DEFORMATION PRIOR TO CO_2 INJECTION

MEAN DEFORMATION RATES:

Vertical (a) and horizontal East-West (b)



TIME SERIES: Vertical (in red) and horizontal (in green) time series of ground deformation for selected regions P1-P9 experiencing fast motion computed by MSBAS method from RADARSAT-2 data



During 20120605-20141003 we observed vertical (a) and horizontal (b) ground deformation with rates up to ±1 and ±0.5 cm/year respectively. Monitoring sites and reference region "R" are plotted in black. Points P1-P9 experiencing fast ground deformation are plotted in red. SAR intensity image is exposed in background in regions of low coherence. Histograms of vertical (a) and horizontal E-W (b) distribution of deformation rates are added to the maps in blue. Red arrows mark 2σ 95% confidence interval equal to 0.3 cm/year and 0.2 cm/year respectively.

CONCLUSIONS

- Satellite interferometry or DInSAR can be successfully used for detecting ground deformation at the carbon sequestration studies, prior, during and after CO_2 injection.
- Synthetic Aperture Radar data from multiple satellites and acquisition geometries can be combined together to produce deformation time series with high temporal sampling. In this study we achieved 0.2-0.3 cm/year measurement precision and about 6 days sampling rate by combining four RADARSAT-2 beams with the individual repeat cycle of 24 days. We achieved five meter spatial resolution over about 8x8 km area.
- In order to accurately map deformation due to CO_2 injection the background deformation need to be estimated first. In this case we found that two years of observations are sufficient to map background processes with high-precision.
- Large number of SAR images acquired during June 2012-October 2014 allowed computing many highly coherent small-baseline interferograms achieving nearly uniform temporal coverage throughout the year, except during winter. Nine paired (i.e. ascending-descending) corner reflectors were installed at monitoring sites along with continuous GPS, tiltmeters, and gravimeters.
- The deformation rate maps for the Aquistore storage site showed active ground deformation prior to CO_2 injection. Vertical ground deformation with the maximum rate of ±1 cm/year are caused by natural and anthropogenic processed, such as, erosion, groundwater withdrawal and recharge, and post-mining activities. Horizontal motion with the maximum rate of ±0.5 cm/year is caused by erosion of the man-made structures.
- Forward modeling based on Mogi elastic pressurized point source model determined that extent of deformation due to injection is very broad. While the maximum of vertical component is located at the injection well, the maximum of horizontal component is located 2475 m away from the injection well. This means that the current location of the monitoring sites is sub-optimal.
- While vertical motion is accurately mapped at sites SITE, NE1, SE1, SW1, NW1. The horizontal motion at these sites is very small. The sites NE2, SE2, SE3, SW2, NW2 would capture signal better if they were removed from the injection well by 2475 m.
- In case of 2D MSBAS solution presented here the maximum East-West displacement would be observed along the East-West direction from the injection well, while in case of 3D continuous GPS North-South components will also be well resolved along the North-South direction from the injection well.

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Mogi, K. (1958). Relations between the eruptions of various volcanoes and the deformation of the ground surfaces above them. University of Tokyo, Earthquake Research Institute Bulletin, 36 , 99-134

Samsonov, S., and d'Oreye, N., (2012). Multidimensional time series analysis of ground deformation from multiple InSAR data sets applied to Virunga Volcanic Province, Geophysical Journal International, 191, pp. 1095-1108.

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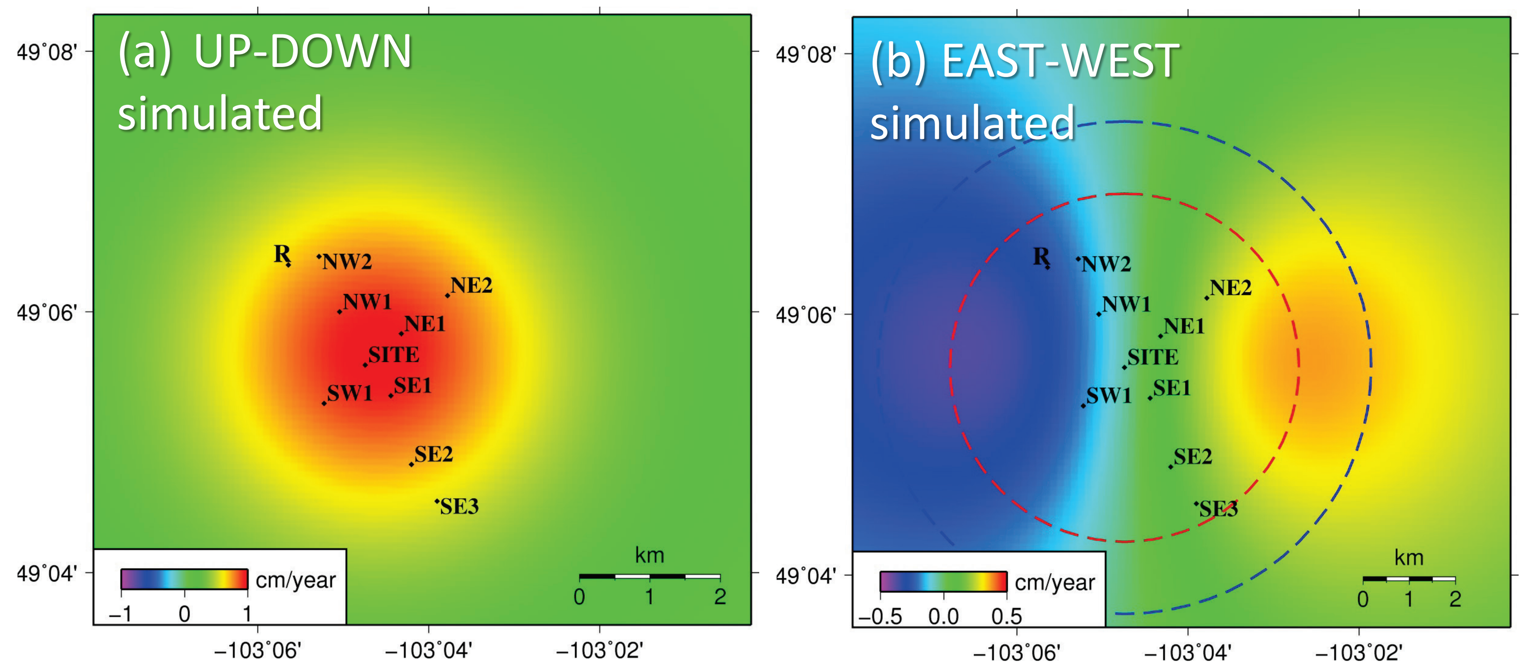
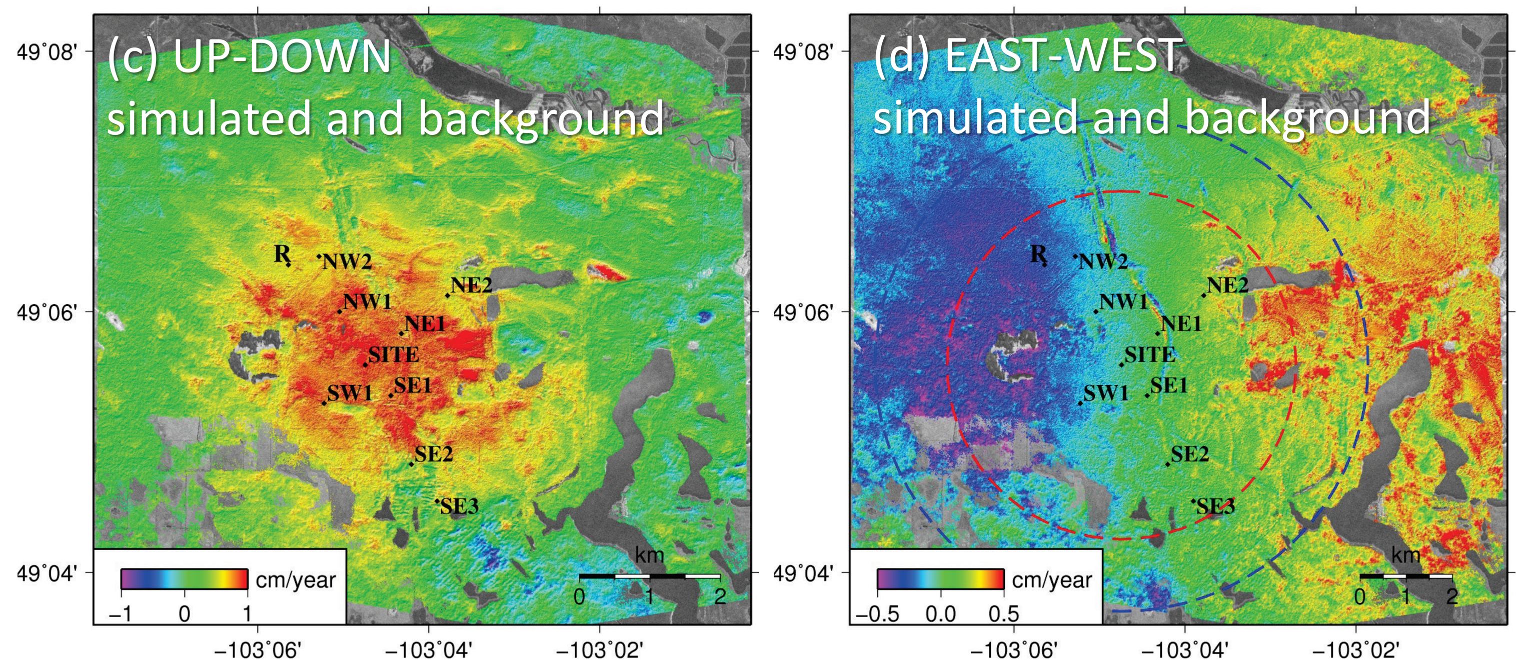
SIMULATED GROUND DEFORMATION DUE TO CO_2 INJECTION: Modelling was performed in order to simulate ground deformation that would be produced by CO_2 injection with the rate of 0.5 ML/year to the depth d of 3500 m. We assumed that the density of CO_2 is equal to 1000 kg/m3, therefore, 0.5 ML/year is equal to 0.5 MT/year. An elastic point pressure source (i.e. Mogi model) was assumed to be located at the injection depth (Mogi, 1958). The increase in pressure resulted in surface deformation shown in figures (a) and (b) below. The vertical component shows uplift or heave with the maximum magnitude of about 1 cm/year centered above the injection well. The horizontal component shows zero motion above the injection well that increases with a distance from the well and reaches its maximum of about 0.5 cm/year at $d/\sqrt{2}$ or about 2475 m away from the injection well. The location of the maximum horizontal deformation is marked with the red dashed circle in figure (b). Vertical deformation component is larger than horizontal within the blue circle with radius d. Horizontal signal displays linear symmetry, which may not be clear in figure (b) due to particular colour palette. Monitoring sites and reference region "R" are plotted in black.



Modeled vertical (c) and horizontal (East-West) (d) deformation rates superimposed on observed ground deformation rates. Presented here signal is expected in case of CO_2 injection. Monitoring sites and reference region "R" are plotted in black. In (d) red circle marks region where horizontal displacements produced by injection reach maximum. Blue circle marks region at which vertical and horizontal displacements produced by injection are equal.



TIME SERIES: Vertical (in red) and horizontal (in green) (East-West) MSBAS time series of ground deformation for monitoring sites NE1, NE2, SE1, SE2, SE3, SITE, SW1, NW1, NW2 computed by MSBAS method from RADARSAT-2 data. Simulated time series (marked as "SIM") due to continuous CO_2 injection and background processes are plotted in light red and light green