Characterization of Baseline Tiltmeter Readings in Aquistore Geologic CO2 Storage Project, Saskatchewan, Canada

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SUMMARY: A surface tiltmeter array was deployed in the Aquistore geologic CO_2 storage site in southeast Saskatchewan, Canada. The array serves as a part of the surface deformation monitoring system. Before the storage of CO_2 started, baseline readings from individual tiltmeters were recorded and analyzed, which revealed tilt patterns reflecting the natural movement of the earth surface. Prominent patterns, such as that induced by earth tides, surface meteorological conditions, temperature and seismic activities, could become significant noise signals in the monitoring system. To avoid the obscuration of storage-related signal, the baseline readings are characterized. Individual noise patterns are identified and reduced through empirical or modelling method. The characterized tiltmeter readings provide more accurate data towards the interpretation of the surface deformation from geological CO_2 storage.

KEYWORD: surface tiltmeter array, geologic CO_2 storage, baseline tiltmeter reading, noise reduction

1 INTRODUCTION

Aquistore is a dedicated carbon capture and storage project in demonstration the safety and workability of storing CO_2 in a deep saline formation. The storage site is located near the city of Estevan in southeastern Saskatchewan, Canada (Figure 1). The CO_2 is injected into a deep, highly saline sandstone reservoir at ~ 3.2 km depth in the Williston Basin. On April of 2015, the project started injecting CO_2 with average rates of 500 tons per day. By September 2016, 87 thousand tons of CO_2 were store into the reservoir. A network of InSAR reflectors, GPS stations, and surface tiltmeters are deployed as part of a comprehensive reservoir surveillance program to monitor surface deformation due to the storage activities.

The geological storage of CO_2 alters the strain field in the reservoir which could gradually radiates to ground surface (Samsonov et al., 2015). Surface deformation monitoring is a key component of the measurement, monitoring and verification process for CO_2 geological storage. It provides valuable information regarding the formation and development of CO_2 plume.

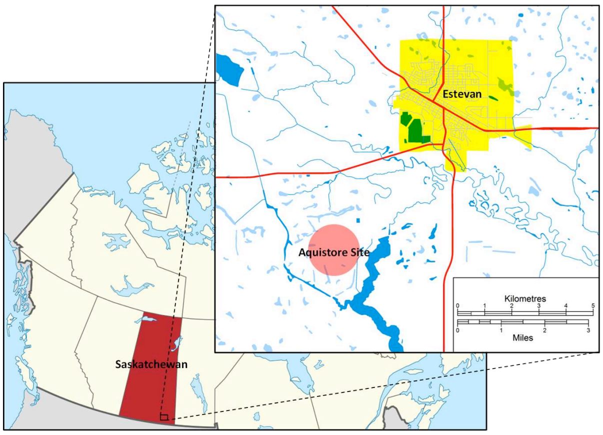

Figure 1: Location of Aquistore geologic CO_2 storage site

Tiltmeter array is a technology that helps establish an effective surface deformation monitoring system. IPCC (2005) listed the tiltmeters as an indirect technique that can be sued to monitor CO_2 storage projects. Each tiltmeter is built with two orthogonal, highly sensitive electrolytic levels that each measures the angle with local gravity vector. High-precision tiltmeters can resolve tilt to as little as one billionth of a radian. An array of tiltmeters provides a vector set over an area that can be integrated to obtain elevation changes (Figure 2). Compared to large-scale imagery technology such as InSAR, tiltmeter array has the advantage of continuous data output and a much finer resolution, especially over smaller areas.

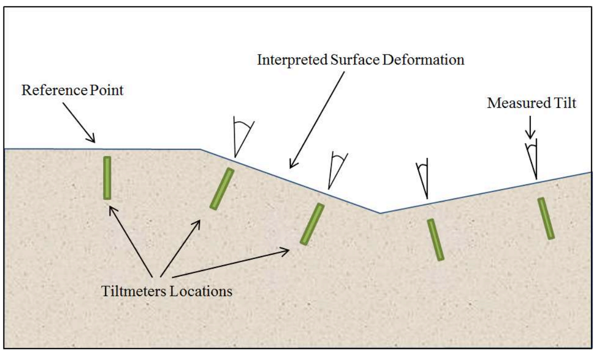

Figure 2: Conceptual diagram showing interpretation of surface deformation from cross section of tiltmeter array

One challenge in the application of tiltmeter array in geologic CO_2 storage is the possible obscuration of noise signals (Zambrano-Narváez, 2012). Noise signals refer to the tilt pattern induced by external factors other than the storage itself. High precision tiltmeters pick up noise signals down to nanoradian scale, which obscure valuable signals from CO_2 reservoir, leading to inaccurate or alternated interpretation. The issue of noise interference must be addressed when monitoring sensitive activities such as the geological storage of CO_2.

The tiltmeter array in Aquistore has been recording baseline data since late 2012. In this paper, instrumentation of the surface tiltmeter array and the characterization of noise signals are based on the work and data collected from Aquistore.

2 INSTRUMENTATION

The surface tiltmeter array in Aquistore includes a total of 15 tiltmeter stations that cover the estimated CO_2 plume. Tiltmeter model used in Aquistore is Series 5000 manufactured by Pinnacle. This model of tiltmeter has a minimal resolution of 30 nR. The tiltmeter has a built-in leveling motor that can extend its range to a maximum of ±3000μR. Figure 3 shows a photo the tiltmeter and a schematic of internal components.

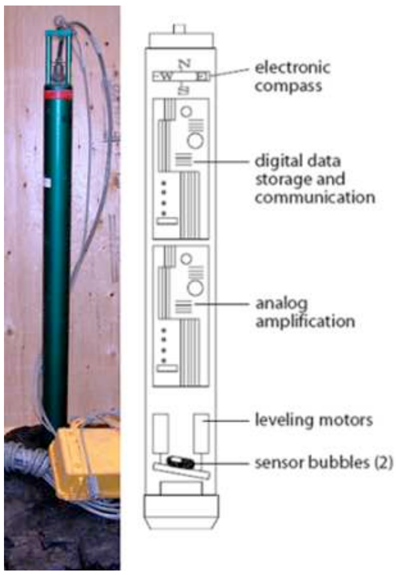

Figure 3: Pinnacle Series 5000 tiltmeter schematic

Figure 4 shows the spatial distribution of the Aquistore tiltmeter array. The aerial extent of the array covers the potential CO_2 plume. According to preliminary reservoir simulation

(Whittaker & Worth 2011), the CO_2 plume will have a diameter of 1 km after five years of injection and reach approximately 3 km after 25 years. The plume will also elongate towards the northeast. The distribution of tiltmeters is based on the simulated plume specification. Twelve tiltmeter sites are aligned in two axes centred at the injection site and covering an area of approximately 5 km by 5 km. Maximum spacing between the nearest instruments is less than 1 km.

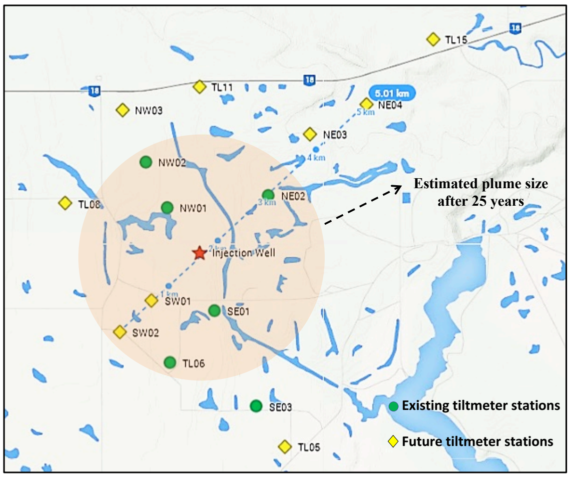

Figure 4: Aquistore tiltmeter array distribution map

The tiltmeters are installed at the bottom of 30-metre deep boreholes. Compared to conventional shallow burial depths (less than 10 m), this deep design helps avoid instability at the surface, as the site was reclaimed from surface mining activities. It also greatly minimizes the noise effect of surface and thermal phenomena. Figure 5 shows the design of the borehole, which consists of an outer steel casing and an inner PVC tubing. The steel casing with 12.85 cm of internal diameter is end-capped to isolate from groundwater at the installation depth. The annular space between the native soil and outside casing wall was filled with grout. The capped PVC tubing with 7.62 cm of internal diameter serves as a housing for the tiltmeter. The annular space between casing and tubing was filled with grout. To controls the vertical alignment of the PVC tubing during the grouting stage, multiple short sections of plastic houses were strapped on one quadrant to the tubing walls. The tiltmeter is locked inside the PVC casing with sand. This set ensures a fully coupled environment with native soil.

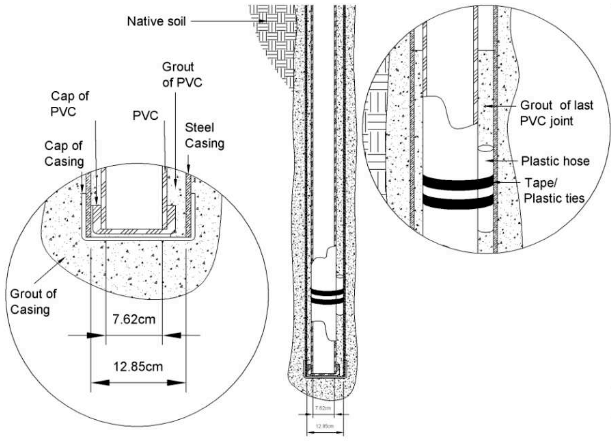

Figure 5: Tiltmeter borehole design in Aquistore

Tiltmeter data is collected and transmitted to the data acquisition system wirelessly using radio and satellite telemetry. A radio transmitting station (slave radio unit) is built alongside each tiltmeter station. The raw data are transmitted to a master radio unit via radio and to the remote data acquisition computer via cellular connection. Figure 6 shows the data transmission map.

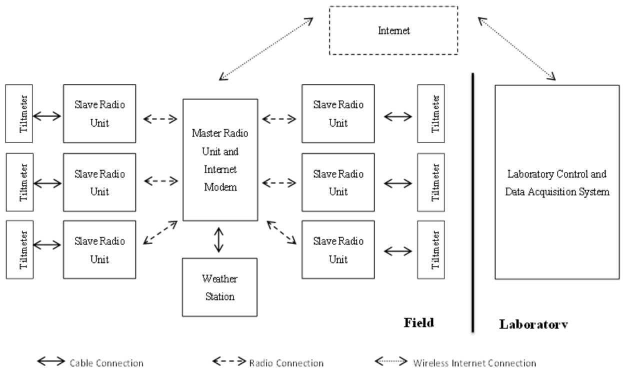

Figure 6: Aquistore tiltmeter data transmission map

In order to remove the noise effect of surface atmospheric conditions, a dedicated weather station is installed, which takes readings of temperature, precipitation, wind speed, and wind direction. Figure 7 shows the completed tiltmeter station with a nearby weather station and the master radio unit.

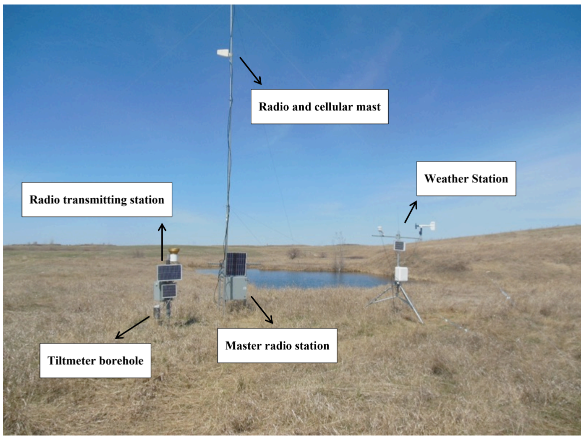

Figure 7: Photo of a completed tiltmeter station alongside a master radio station and weather station

3 BASELINE READING OVERVIEW

Baseline tiltmeter data were recorded prior to CO_2 storage. Baseline tiltmeter data reflect natural earth movement. different natural and anthropogenic processes, such as snow melting surface moisture fluctuations, ground and surface water level changes and post mining activities (Czarnogorska et al., 2014). Previous applications of tiltmeters show the impact by multiple external factors, including earth tides (e.g. Levine, Meertens, & Busby, 1989), rainfall, groundwater tables (e.g. Kümpel, Peters, & Bower, 1988), barometric pressure (e.g. Dal Moro & Zadro, 1998), thermoelastic deformation (e.g. Bonaccorso, Falzone, & Gambino, 1999), borehole cavity effects (e.g. Harrison, 1976), tectonic movements (e.g. Mentes, 2003), and human activities. Noise patterns from these sources are greatly determined by installation depth and environment. Tiltmeters installed at shallow depths are predominantly affected by surface disturbance and temperature fluctuations, which can create strong signals. Deeply buried tiltmeters can reveal less subtle signals such as earth tides, and are less sensitive to surface rainfall. Those installed in bedrock are more sensitive to subtle earth motion such as tectonic movements.

Figure 8 shows baseline differential tilt data collected from station TL06 between December 2012 and April 2014, revealing several patterns at different time scales. Figure 8a presents the typical long-term response of tiltmeters in Aquistore. The maximum differential tilt in 18 months was approximately 38 μR in the east-west direction. It is suspected that this initial response was related to ground disturbances due to installation as tilt measurements were more stable in the last 9 months. The long-term trend could also be related to ground thermal deformation or tectonic movement. Figure 8b presents weekly and monthly tilt patterns, which include large episodic fluctuations possibly related to rainfall and barometric conditions. Figure 8c presents tilt patterns on a

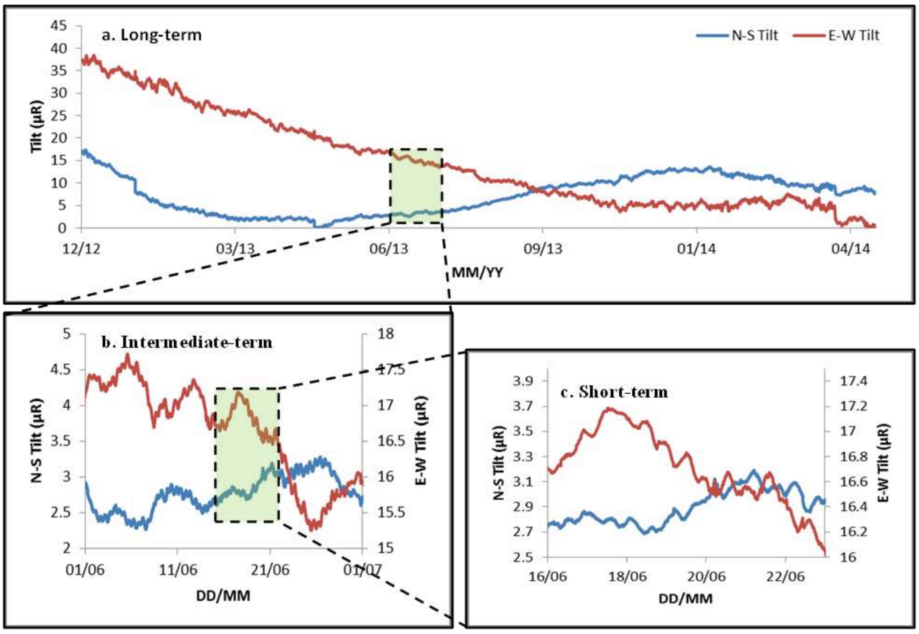

Figure 8: Baseline tiltmeter data from Station TL06, showing noise signals in different time scales

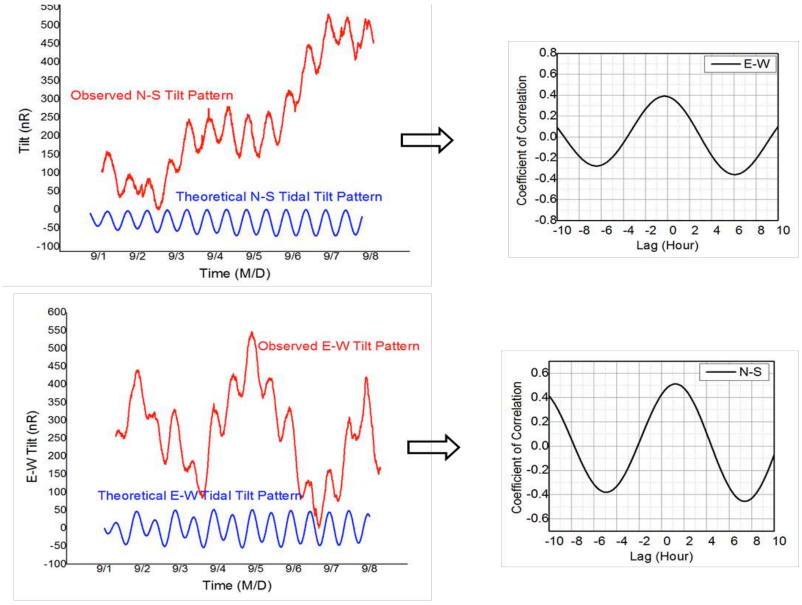

Figure 9: Theoretical and observed tidal tilt pattern from Site TL06 and their cross-correlation function

daily scale, which clearly shows the existence of semidiurnal earth tides.

Baseline tilt patterns are regarded as noise signals during injection monitoring program, as they could obscure or even alter the real signals from deep CO_2 geological storage process. The characterization and removal of noise signals become critical. Four types of noise signals are analyzed in the scope of this paper with baseline data from two tiltmeter stations: earth tide signals, atmospheric signals, thermal signals, and seismic signals. For each type of signal, either empirical or numerical modelling methods are proposed to quantitatively estimate the pattern.

4 EARTH TIDE NOISE SIGNALS

Short-term baseline readings in Aquistore exhibit clear semi-diurnal patterns, which reflect the periodic deformation and distortion of the earth by the gravitational pull of the Moon and the Sun, also known as earth tides. The largest constituent in tidal signals is semi-diurnal, which is produced by the orbiting Moon, followed by a diurnal contribution. Figure 10 shows baseline readings from Station TL06 between June 1st and November 1st, 2013, and the power spectrum analysis for this set of data. The frequency band clearly shows a large semidiurnal component and a smaller diurnal component. The capture of both tidal constituents indicates that tiltmeters are well coupled to the ground. In Aquistore, earth tide signals are the smallest noise signals captured by tiltmeters with an amplitude less than 100 nR. The amplitude of tidal noise essentially defines the minimum detection limit of injection signals from raw data.

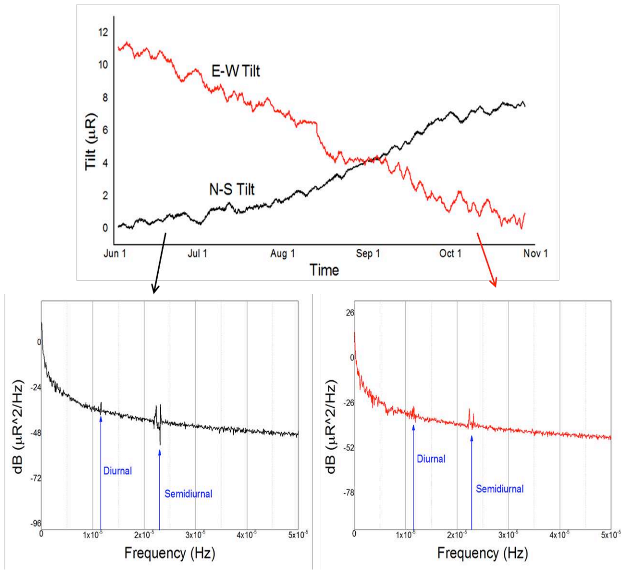

Figure 10: Baseline tilt data and power spectrum analysis of tidal signals

Baseline tidal signals can be estimated by fitting a theoretical solid earth model with existing data. Assuming an elastic, spherical, isotropic, non-rotating, and oceanless earth, tidal acceleration at a point in the earth's surface is determined by its relative position to the Moon and Sun. Tidal tilt is essentially the horizontal gradient of tidal acceleration. Earth tide data processing code SOLID (Milbert 2014) is used to calculate theoretical tidal tilt with the coordinates of Aquistore. Figure 9 shows the theoretical tidal tilt calculated in two orthogonal directions and the correlation function with observed tilt patterns from Site TL06.

Theoretical tilt patterns of both directions are in good agreement with observed tilt patterns. The observed amplitude in baseline readings is about 40% larger than the theoretical one, which can be explained by the non-rigidity of the earth (due to oceans, etc.) compared to the rigidity model. The differential factor in amplitude is determined for each direction using least square fitting. Table 1 shows a summary of the tidal amplitude in both observed and theoretical patterns. With the amplification factor, tidal signals can be subtracted from baseline data, as shown in Figure 11.

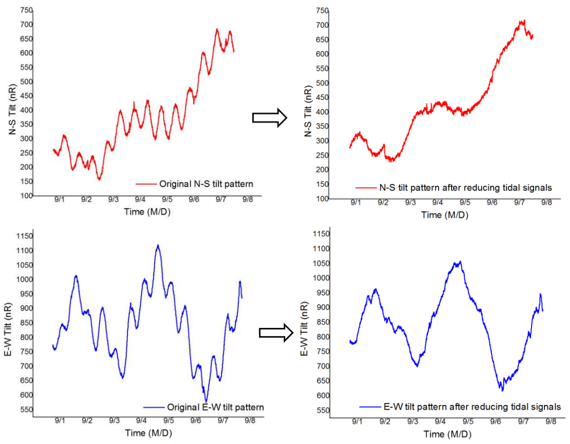

Figure 11: Baseline data before and after removing earth tide signals

Table 1: Summary of observed and theoretical tilt patterns

	Observed Amplitude (Average)	Theoretical Amplitude (Average)	Amplification factor
E-W	~110nR	~80nR	1.41
N-S	~110nR	~75nR	1.43

5 ATMOSPHERIC NOISE SIGNALS

Atmospheric noise refers to tilt signals induced by surface meteorological conditions in baseline readings. In Aquistore, major noise impacts from the surface include barometric pressure fluctuations and rainfalls, as tilt signals are created by the loading of newly distributed water and air mass. Observed signal amplitude can reach 1 μR. Atmospheric signal is a major baseline noise because of its large amplitude and episodic occurrence. A practical way to characterize atmospheric signals is to analyze baseline data with surface meteorological data.

The presence of strong signals from barometric pressure is statistically verified using the cross-correlation function. Baseline tilt data are processed through a band pass filter that removes both high (>1 cycle per day) and low (<0.05 cycles per day) frequency signals unrelated to atmospheric patterns. The filtered data are then organized in hourly

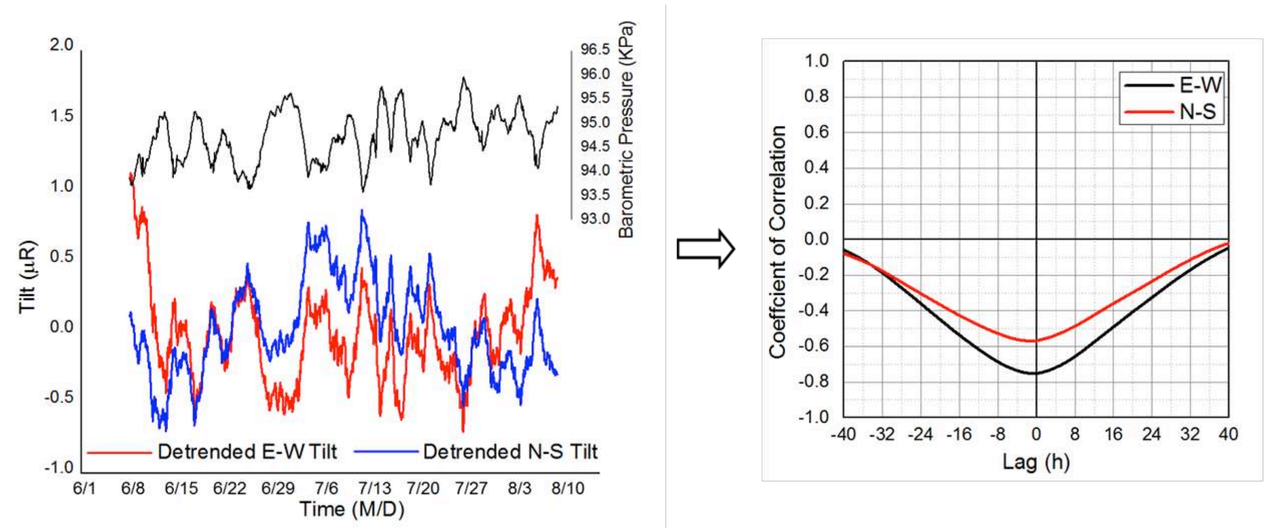

Figure 12: Cross correlation between tilt and barometric pressure

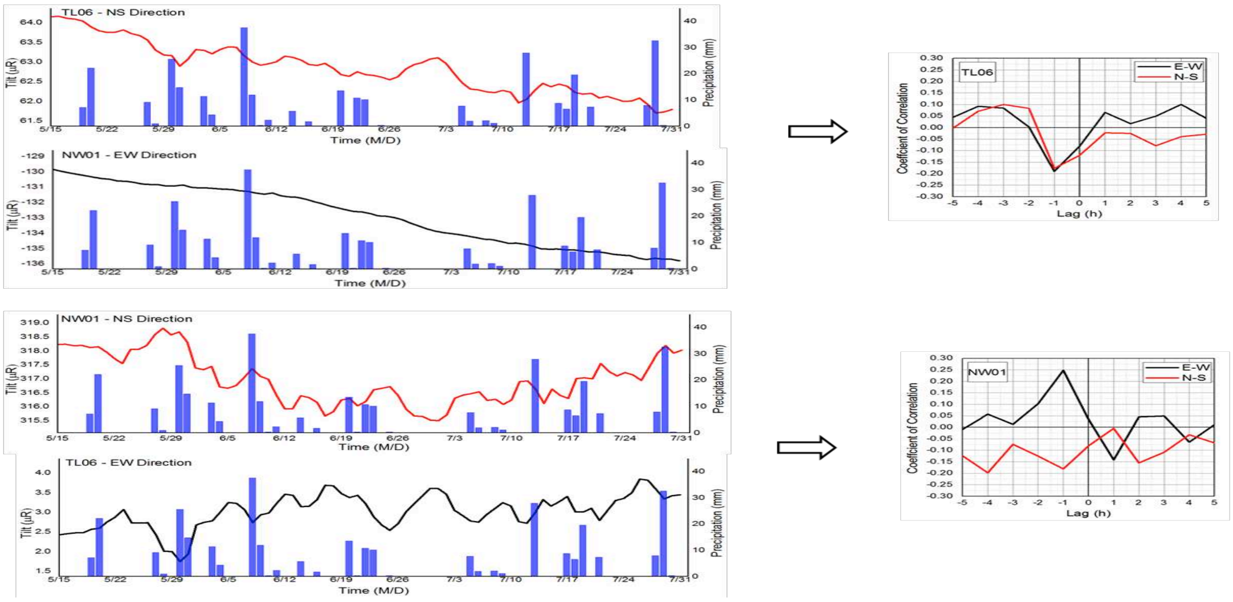

Figure 13: Cross correlation function between daily tilt derivatives and rainfall

averages and analyzed with barometric data from a weather station about 15 km from Aquistore. Figure 12 presents the cross-correlation function between tilt and barometric pressure data from site NW01. Data analysis reveals a high correlation factor of above 0.5 in both directions, and an almost linear relationship between barometric pressure and tilt.

Tilt signal from barometric pressure is induced by the loading effect of atmospheric mass. The back-regression method is used to quantify the barometric pattern in Aquistore. Constant regression coefficients are found for both directions, as shown in in Table 2. With additional barometric pressure data, barometric signals can be removed from the baseline pattern (Figure 14).

Table 2: Regression coefficient between barometric pressure and tilt

Tiltmeter site (direction)	**Plane Angle (° to N)**	**Regression Coefficient (μR/kPa)**
NW01 East-West	229°	-0.31
NW01 North-South		-0.42
TL06 East-West	114°	0.50
TL06 North-South		0.31

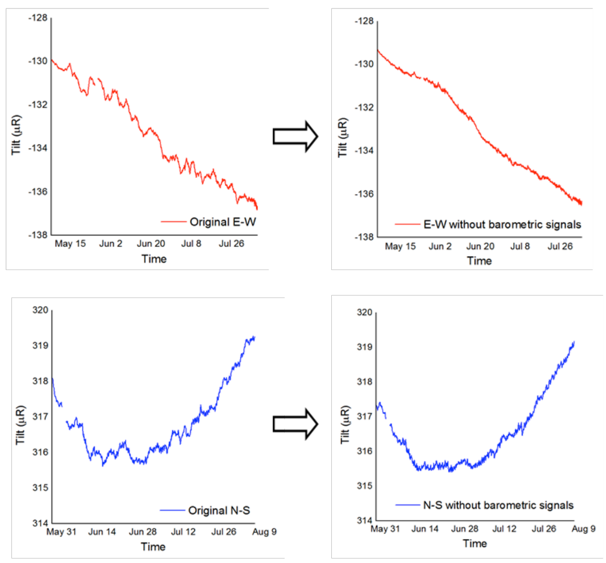

Figure 14: Baseline data before and after removing barometric signals

As barometric pressure and rainfall are negatively correlated, baseline rainfall patterns should be analyzed independently. After removing barometric signals, baseline data are resampled in daily steps. The residual intermediate fluctuations are only half the scale (up to 0.5 μR) of the barometric ones. Daily derivatives of the processed data are analyzed with daily precipitation for the cross-correlation function (Figure 13). Both negative coefficients in TL06 indicate that the tiltmeter is inclined towards the southwest after rainfall. The tiltmeter in NW01 is tilting

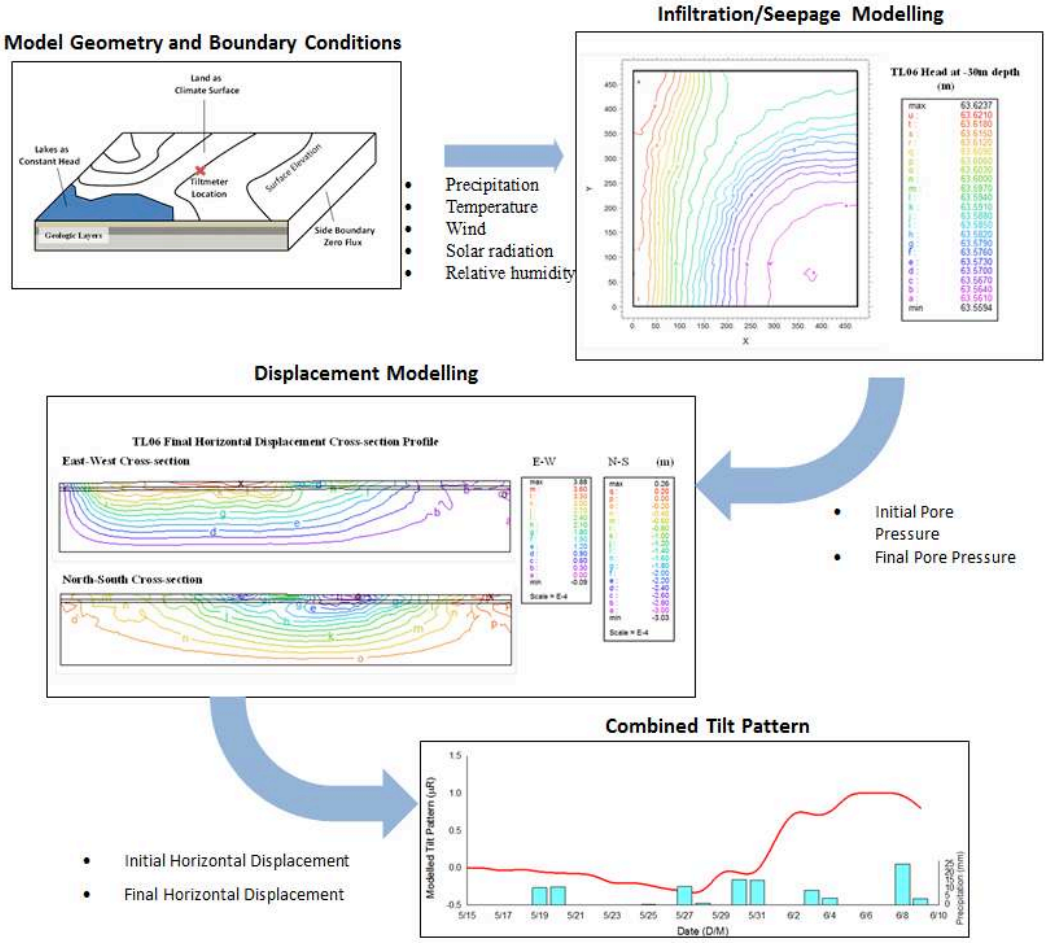

Figure 15: 3D Simulation flowchart used to estimate rainfall patterns

towards the east, and no correlation is found in the NS direction. With the low correlation coefficient and episodic nature of rainfall, a regression coefficient cannot be adequately determined, and a numerical model is built to simulate the physical tilting process due to rainfall.

Rainfall tilt pattern is the manifestation of the movement and distribution of rainwater in the subsurface. The mass of rainwater creates a loading effect, and the subsequent change in porewater pressure leads to pore-elastic deformation. In Aquistore, the installation geometry of tiltmeters is designed to prevent the direct ingress of water into the main borehole. Groundwater level outside the casing will fluctuate through the weather season. Surface rainfall leads to fluctuations in the phreatic water surface and creates volumetric deformation. Tilt signals are essentially a reflection of horizontal porewater pressure gradient, which may form due to surface topography, local hydrological conditions, anisotropic soil parameters, and spatial distribution of rainfall.

A 3D model is used to simulate the atmosphere-tilt phenomenon. It is built using commercial code SoilVision. The model stages and data interaction are presented in Figure 15. The model consists of three main stages: infiltration modelling, seepage modelling, and tilt modelling. Two tiltmeter sites (TL06 and NW01) are modelled separately. Each model is 475 m wide, 475 m long, and has a base height of 50 m. Surface elevation and boundary conditions are adjusted for each model based on digital elevation and satellite maps. For both models, initial groundwater table depth is assigned based on levels of surface lakes or local piezometer data. The level of surface water within the model is set to be static, and to act as a recharge/discharge source. Based on gamma ray logs from the tiltmeter boreholes, three parallel geological units are assigned for both models, consisting of 5 m of fissured clay at the surface, 3 m of silt, and 40 m of underlying till. Infiltration and seepage modelling simulates the movement of rainwater and subsequent porewater pressure change.

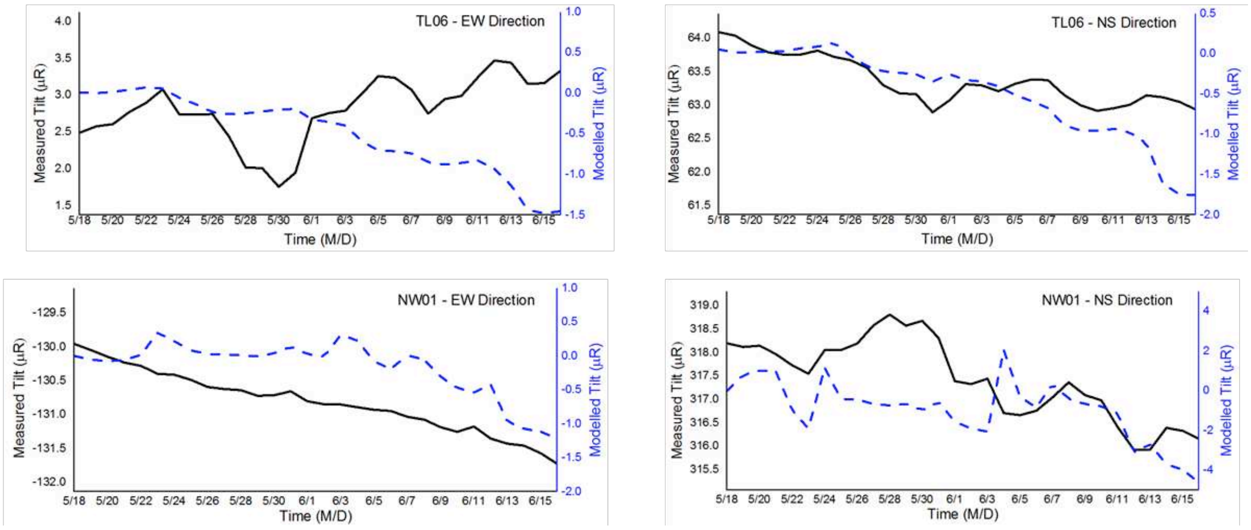

Figure 16: Modelled tilt pattern compared with filtered original data

Daily meteorological data (including precipitation, temperature, wind speed, relative humidity, and solar radiation) are applied to the surface to calculate net daily infiltration. The coupled seepage modelling then generates daily porewater pressure distributions, which are sequentially applied in deformation modelling. Porewater pressure and net mean stress are two variables involved in defining stress-state (Fredlund and Mogenstern, 1977), and deformation is determined from stress state through elasticity parameters. Deformation is obtained in daily steps between the initial and final conditions of porewater pressure distribution. In each step, tilts of two directions at a vertical subsurface location can be obtained from the deformation field. Then tilt vectors are calculated from each step and combined into a tilt pattern.

Figure 16 compares simulated and observed tilt patterns obtained between May 18th and June 15th, 2013. The modelling results show generally weak correlations. Higher correlations are only found in certain directions for partial time periods (e.g. N-S direction between June 5th and June 15th). The accuracy of this model is limited by the lack of consideration of the scale effect of rainfall, as precipitation intensity can vary and change constantly across the region. With spatial-limited meteorological data, high uncertainty can be expected. Mapping of regional precipitation intensity or groundwater level over time is recommended for best modelling outcomes, especially when rainfall is expected to have a large impact on tiltmeters. In Aquistore, the amplitude of rainfall tilt is small due to the great burial depth. The results from the physical simulation can be used as a reference for interpretation.

6 SEISMIC NOISE SIGNALS

Multiple seismic events were captured in baseline readings in Aquistore. Seismic signals consist of a large spike that can be induced by both far-off earthquakes and local seismic activities. The amplitude of seismic signals is proportional to the energy levels to which tiltmeters are exposed, which in turn are determined by the magnitude and relative distance of seismic events. Figure 17 shows the spike signal of a M7.7 earthquake centred 2269 km away in Alaska (55.368°N 134.621°W). Tiltmeters in Aquistore registered a signal of about 3 μR five minutes after the earthquake occurred on Jan. 5th, 2013. On Sept. 3rd, 2013 a series of three major (M6.2, M4.3, M5.6) earthquakes occurred in British Columbia, Canada (51.05°N, 130.62°W), about 1923 km away. Both tiltmeters registered the M6.2 and M5.6 events with spikes of about 0.025 μR. The seismic program in Aquistore was conducted with dynamite shooting investigations, and seismic signals were also captured. In this case, only nearby shootings created signals detected by tiltmeters, with spikes between 2-5 μR.

travelling temperature wave. Starting from Berger's model, Harrison and Herbst (1977) simplified the model by considering a uniform temperature field at surface and presented the solution of thermoelastic tilt at a depth (y) under a given slope (α):

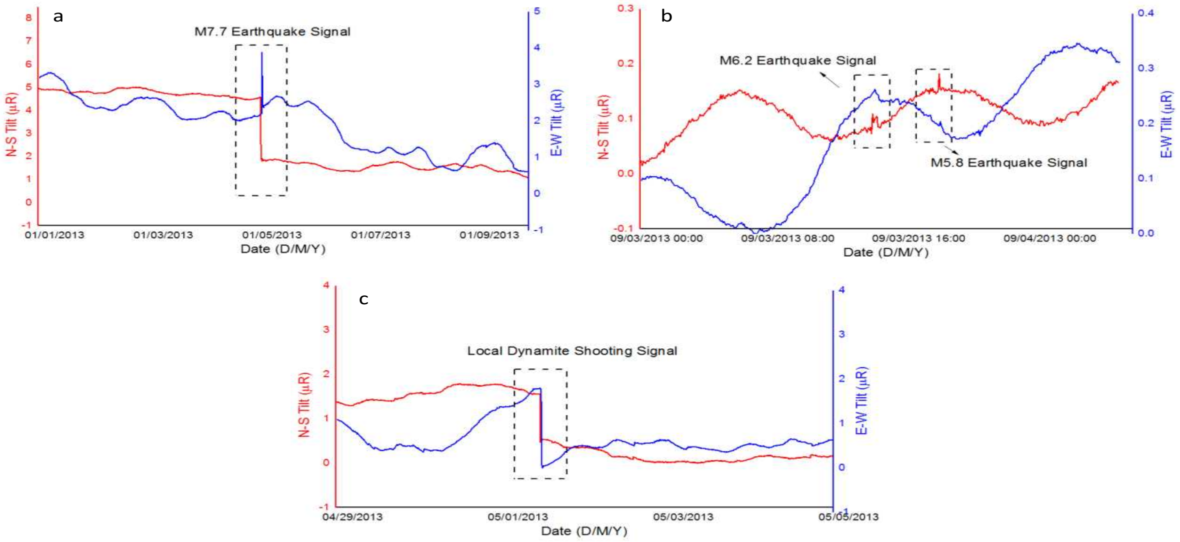

Figure 17: Tilt signals created by seismic activities

7 THERMAL NOISE SIGNALS

Thermal noise signals are created by surface temperature fluctuations. After the damping effect, the subsurface environment is in an attenuated temperature field sourced from both daily and seasonal temperature variations at the surface. Thermal expansion and contraction of the ground creates continuous deformation, known as thermoelastic deformation, and thermoelastic tilt is the manifestation of horizontal thermal gradients.

Thermal noise signals can be quite large for shallow tiltmeters and decrease exponentially with depth. With only 18 months of baseline data, the presence of annual thermal signals cannot be adequately observed. Berger (1975) proposed a general model simulating the thermoelastic deformation in an elastic infinite homogeneous half space under a

$$\text{Tilt}_y = \frac{1}{2}\frac{1+\sigma}{1-\sigma}\beta T_0\, e^{-y\sqrt{\omega/2\kappa}}\cos(\omega t - y\sqrt{\omega/2\kappa})\,\sin 2$$

Where σ is Poisson's ratio, β is thermal dilation coefficient, T_0 is amplitude of thermal fluctuation at the surface, ω is angular frequency, and κ is thermal diffusivity.

Theoretically, daily and seasonal temperature fluctuations from the surface can only reach 1 m and 20 m depth, respectively. Downhole temperature records from the TL06 thermal sensor (Figure 18) show a decrease of 0.3°C in the first five months before temperature stabilized around 10.15°C. The same trend is observed in NW01. The initial decline is probably due to the installation effect. The range of thermal noise in Aquistore is estimated using the solutions of

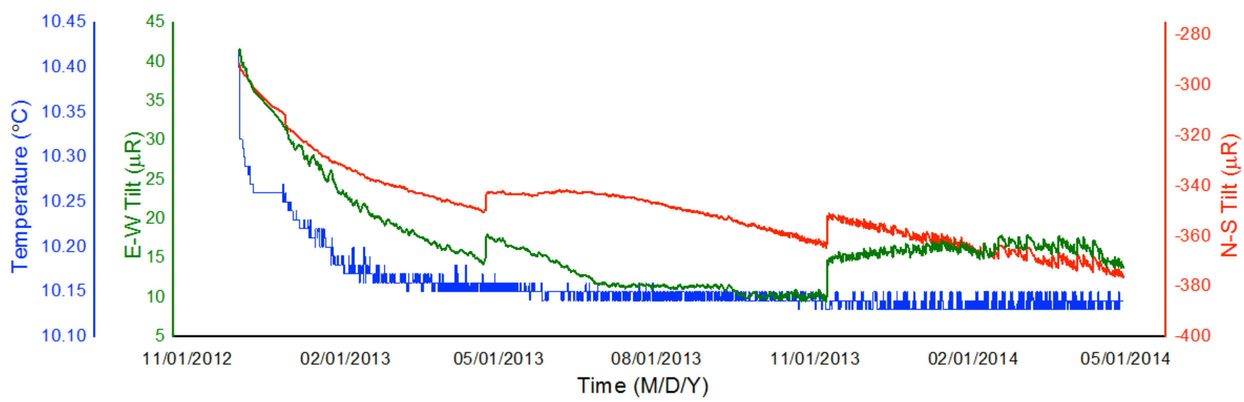

Figure 18: Long-term tilt pattern compared with downhole temperature record at Site TL06

Harrison and Herbst with the following assumptions: (1) A homogeneous subsurface environment, (2) thermal isotherms parallel with topography. The initial temperature fluctuations of 0.3°C create tilt amplitude of 170 nR at maximum and negligible thermoelastic signals after temperature stabilizes. Without additional data showing an annual sinusoidal trend, thermal signals are considered non-existent in Aquistore tilt data due to the great burial depth.

8 DISCUSSION AND CONCLUSIONS

A surface tiltmeter array was deployed in Aquistore to monitor induced surface deformation by CO_2 injection and storage. Surface deformation will be adequately interpreted by combining 15 tilt vectors covering the estimated CO_2 plume, within a 25 km^2 area. As tiltmeters are accommodated in 30 m boreholes in Aquistore, the noise effects of thermal and surface conditions on readings have been greatly minimized. The addition of a remote data acquisition system and a weather station enables real-time interpretation of tilt signals related to individual events, including injection and surface atmospheric activities.

Eighteen months of continuous tilt data are collected in two stations, representing baseline conditions without the influence of CO_2 injection. Baseline reading in Aquistore consists of tilt signals induced by earth tides, atmospheric activities, and seismic events. Table 3 summarizes the pattern of these noise signals.

Earth tide signals have the smallest amplitude (<0.1 µR) and a semidiurnal periodicity. Their scale barely changes with depth. The presence of smooth earth tide signals throughout baseline data indicates that the tiltmeter is fully coupled to the ground. Using a simplified earth model, theoretical tidal signals are estimated and compared with observed patterns. Besides a high correlation coefficient, observed amplitudes are about 40% larger. This factor arises because the earth is not purely rigid as the model assumes, but can be applied to future pattern estimates. Therefore, earth tide signals can be subtracted from tiltmeter data.

Table 3: Noise signals captured by tiltmeter in Aquistore

Type	Pattern	Scale in Aquistore
Earth tides	Sinusoidal wave	< 0.1 µR
Barometric pressure	Random fluctuations	< 1 µR
Rainfall	Random fluctuations	< 0.5 µR
Thermal deformation	Sinusoidal wave	Negligible
Seismic events	Spikes	< 3 µR

Atmospheric signals are induced by meteorological activities from the surface. The deep burial design in Aquistore has greatly reduced the scale of atmospheric signals. Two significant contributions found in Aquistore are barometric signal and rainfall signal, as both involve a mass redistribution effect. Barometric signals have twice the scale (up to 1 µR) of rainfall signals, and follow air pressure in a linear relationship with a coefficient of 0.5 µR/kPa. After subtracting barometric signals from baseline data, rainfall signals are revealed, with a generally weaker correlation to precipitation. The atmospheric-tilt model is used to estimate tilt patterns from discrete precipitation data. Boundary conditions and topography are the two factors used in defining the direction and amplitude of rainfall signals, as both determine local rainwater distribution. Soil properties, especially permeability and volume change index, affect patterns in the temporal and dimensional scales. This model gives a coarse prediction of tilt pattern due to a lack of full spatial characterization of the groundwater table or rainfall intensity. Its accuracy is greatly enhanced.

Tiltmeters can capture seismic signals from both local and distant activities. These signals are identifiable by rapid spikes that can reach 5 µR. The scale is directly proportional to the energy level, which is determined by the magnitude of the activity and its distance from the tiltmeter. Straightforward subtraction can be used to remove seismic signals, as they only affect baseline data for several hours.

Thermal signals come from thermoelastic deformation of the earth due to surface heat propagation. Assuming a homogeneous space under thermal isotherms with a constant slope, the amplitude of thermal signals is proportional to temperature variation on the slope. The impact of daily temperature fluctuations is only considered at shallow depth (less than 3 m) due to strong attenuation. Seasonal temperature variations can normally reach 20 m under the surface, but factors such as loose surface material and high thermal conductivity of borehole casings can increase this reach. The downhole thermal sensor of tiltmeter recorded a temperature drop of 0.03°C in the initial 6 months and no long-term trend in two-year period. Theoretical thermoelastic tilt created by this temperature pattern will not reflect in tiltmeter reading and therefore thermal signals do not exist in Aquistore tiltmeters with 30 m burial depth.

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