Challenges of deploying ground-based InSAR in remote areas in Canada – Trial study and preliminary results

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ABSTRACT
Ground-based, interferometric, synthetic aperture radar (GB-InSAR) has been extensively and successfully used in the last few years for monitoring natural and man-made slopes. This technology allows for remote monitoring of slope deformations in the line-of-sight (LOS) between the instrument and the slope, providing a map of displacements in the LOS. Successful and robust deployment of GB-InSAR requires some logistic details that can be challenging for some locations in Canada characterized by dense vegetation covers, lack of constant power and remote connectivity, and long winters associated with periods of snow coverage and short duration of daylight. This paper presents a pilot project at a location of easy access for assessing the logistical difficulties associated with deploying GB-InSAR for natural slopes in Canada. This paper further presents the installation, challenges and preliminary results of deployment of the GB-InSAR at the study site.

RÉSUMÉ
Le radar à ouverture synthétique interférométrique au sol (GB-InSAR) a été largement utilisé avec succès ces dernières années pour la surveillance des pentes naturelles et artificielles. Cette technologie permet la surveillance à distance des déformations de la pente dans la ligne de visée (LOS) entre l'instrument et la pente, fournissant une carte des déplacements dans la ligne de vue. Le déploiement réussi et robuste de GB-InSAR nécessite des détails logistiques qui peuvent être difficiles pour certains endroits au Canada caractérisés par des couvertures végétales denses, un manque de puissance constante et de connectivité à distance et de longs hivers associés à des périodes d'enneigement et de courte durée. Cet article présente un projet pilote dans un endroit facile d'accès pour évaluer les difficultés logistiques liées au déploiement de GB-InSAR pour les pentes naturelles au Canada. Cet article présente en outre l'installation, les défis et les résultats préliminaires du déploiement du GB-InSAR sur le site d'étude.

1 INTRODUCTION

Ground-based, interferometric, synthetic aperture radar (GB-InSAR) has been extensively and successfully used in the last few years for monitoring natural and man-made slopes (Corsini et al. 2006, Crosta et al. 2013, Severin et al. 2014, Matteo et al. 2016, Lombardi et al. 2017). This technology allows for remote monitoring of slope deformations in the line-of-sight (LOS) between the instrument and the slope, providing a map of displacements in the LOS. Highly accurate slope displacements are calculated through the change of phase in the reflected wave, as the distance between the radar and the slope changes. Details about the technology and processing methodologies can be found in Atzeni et al. (2014), Wasowski and Bovegna (2014), Colesanti and Wasowski (2006), Ferretti et al. (2007); and are out of the scope of this paper.

GB-InSAR has been used to complement ground instrumentation (monitoring prisms, inclinometers, etc.) and enhance understanding the mechanisms, patterns and extents of slope deformations (Crosta et al. 2013, Frodella et al. 2016, Matteo et al. 2016). Near real-time GB-InSAR monitoring (typically between one and 6 displacement measurements per hour) allows this technology to be used for safety management of slopes, providing early warning of potential slope collapse (Atzeni et al. 2014, Frodella et al. 2016 and 2017, Crosta et al. 2017).

Successful and robust deployment of GB-InSAR requires some logistic details, including: 1) continuous power source, 2) remote connectivity, 3) clear LOS between the instrument and the slope, 4) high and consistent ground reflectivity (bare ground or scarce vegetation, no to minimum snow cover), and 5) optimal orientation of the LOS such that most slope deformation is captured. An ideal setting for the technology is found in open pit mining, where pit geometries and the nature of operations allow for optimal orientations and adequate ground reflectivity, and continuous power and connectivity can be provided for a small fraction of operational costs (Atzeni et al. 2014, Severin et al. 2014).

In some natural settings, however, some logistic details are challenging to achieve or demand high operational and deployment costs. This is particularly the case for some areas in Canada characterized by dense vegetation covers, lack of constant power and remote connectivity, and long winters associated with periods of snow coverage and short duration of daylight.

The University of Alberta and BC Hydro have started a pilot project to assess and overcome the logistical difficulties associated with deploying GB-InSAR, including for remote, northern areas in Canada. A controlled, known environment was selected for the first stage of the project in order to allow for easy accessibility and troubleshooting, with the goal of deploying GB-InSAR at remote areas in future project stages. The site of this first stage is located north of Revelstoke, in British Columbia, within the Revelstoke Dam Reservoir. This stage of the project will also allow an assessment of the applicability of GB-InSAR at this site and potentially enhance the knowledge about the landslide deformation patterns.

This paper presents the location and characteristics of the study area, the GB-InSAR characteristics and installation details, logistic challenges and how these are being overcome, and some initial results.

2 CASE STUDY – CHECKERBOARD CREEK ROCK SLOPE

The landslide case study selected for this project is the Checkerboard Creek rock slope. This landslide was selected because of the amount of precipitation and overcast days in the year, the dense vegetation cover and the exposure of a rock face at its toe, and its proximity to Revelstoke and the Revelstoke Dam, allowing easy access to the site.

This section presents a summary of the landslide location, characteristics, geologic context and climate in the area.

2.1 Location

The Checkerboard Creek rock slope is located within the Revelstoke Dam reservoir in British Columbia, 1.5km upstream from the dam structure (Figure 1).

The Revelstoke Dam is part of a hydroelectric generation project in the Columbia River operated by BC Hydro. The dam, 5 km upstream of Revelstoke, British Columbia, comprises a 1,160-m-long earthfill dam that wraps around a 183-m-long concrete gravity dam and the concrete gravity spillway structure (Taylor and Lou 1983, Salmon 1988).

2.2 Landslide Characteristics and Geology

The Checkerboard Creek rock slope has an elevation of 260 m from Hwy 23 at an elevation of 590 m, to the middle reach of the Checkerboard Creek, at an average elevation of 850 m (Figure 2). It is 600 m wide and has an overall slope angle of 30°, steeper at the toe (45°) and flatter in the upper area (25°) (Watson et al. 2004). The extent of potential instability has been interpreted from the site geology, slope topography and deformation patterns (Macciotta et al. 2016). The upper boundary of the deformation area is defined by the uppermost tension cracks, but the lateral and toe boundaries are less clear. The active zone of deformation has an average slope angle of 45°, and deformations have been detected down to 50–60 m deep. The volume of this active zone is estimated between 2 and 3 million m^3.

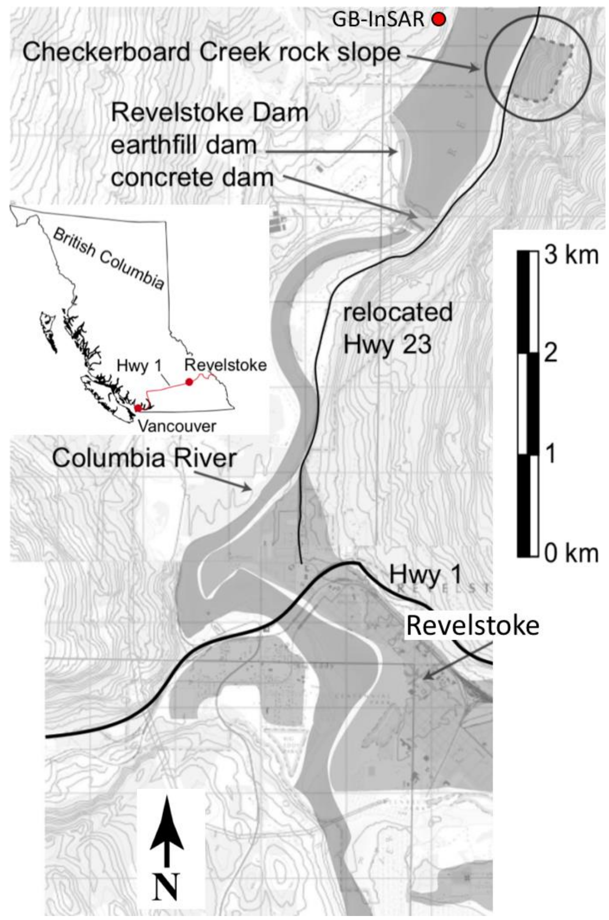

Figure 1. Location of the Checkerboard Creek Rock Slope (after Macciotta et al. 2016)

The slope lithology of the slope consists of massive to weakly foliated granodiorite. This unit overlies the easterly dipping gneiss and schist of Columbia River Fault. This fault has developed a broad, regional, brittle deformation zone of altered and mechanically deformed rock.

Shears and joints in the area dip steeply into and out of slope at angles of 60° to 90° from horizontal (Figure 2b). The primary joint set dips steeply (more than 80°) and generally parallel to the slope contours. The secondary joint set also dips steeply and strikes perpendicular to the slope.

Rock mass quality ranges from very strong, fresh, undisturbed and blocky rock to highly weathered and altered, weak and disturbed. The lower quality rock masses are typically found in the upper 60 m from the slope surface, coinciding with the observed active deformations. Rock masses beneath this depth are less sheared and present fewer structures (Stewart and Moore 2002, Watson et al. 2004 and 2006).

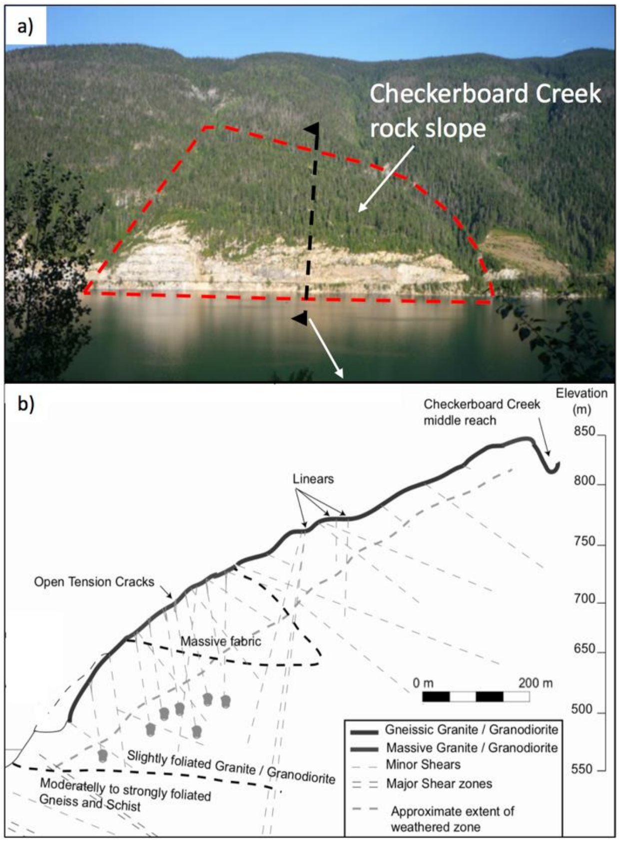

Figure 2. Front view of the Checkerboard Creek Rock Slope (a) and typical cross section (b). after Stewart and Moore (2002) and Macciotta et al. (2016)

The groundwater regime within the Checkerboard Creek slope is inferred from observations during drilling and site inspections, and monitoring of multiple-piezometers. These have revealed numerous, discrete, pore pressure differences of up to 40 m across short lengths indicating a compartmentalized groundwater regime. Continuously saturated conditions have been observed 50 to 80 m below the surface. These depths are deeper than the observed extent of the displacing rock mass. Seasonal variations in piezometric levels of up to 20 m occur, mainly at the top of the continuously saturated rock mass, and diminishing with depth (Stewart and Moore 2002).

2.3 Climate

The town of Revelstoke is located in interior British Columbia, and its climate is strongly influenced by moist air that tracks from the Pacific Ocean. Annual cumulative precipitation is typically between 1500 to 2000 mm at the Checkerboard Creek rock slope. Approximately 40% of precipitation occurs between October and January, usually as snow.

Air temperatures range between -25° and 35°C, with freezing temperatures typically prevailing from late November through March. Areas covered by snow keep ground surface temperatures usually above freezing throughout the winter. Because the slope is heavily treed, snow depths are variable. Typical snow depths are about 1 to 2 metres in mid-winter (Watson et al. 2004). Throughout the Fall and Winter months (October through March), days at the site are characterized by short periods of direct sun light, frequent overcast weather, and frequent snow falls between December and March.

2.4 Deformation Patterns

Instrumentation at the slope that measure landslide movement includes surface survey monuments, inclinometers with in-place probes, multipoint borehole extensometers, and surface cable extensometers (to measure opening of tension cracks).

Slope deformations are concentrated at the central part of the slope, near the crest of the cut required to accommodate Highway 23 (Figure 1). Some instruments near the exposed rock face have shown cyclic behavior, accelerating in the Fall and decelerating in the spring (Stewart and Moore 2002, Watson et al. 2004 and 2006). However, instrumentation located further back into the landslide and at depth have revealed a more steady displacement trend . Current interpretation is that displacement pattern is steady with an accelerated phase during spring snow melt, when piezometric pressures are at seasonal maximums. Investigations are ongoing regarding the causes of accelerating periods for some of these instrument measurements, and GB-InSAR is expected to provide some further insights into the deformation patterns at the slope surface.

The displacement rate of the Checkerboard Creek rock slope is 0.5 mm/year at the boundaries of the actively deforming mass, increasing to up to 15 mm/year within the most active area. These deformation rates are greatest at the surface and they decrease progressively with depth up to a point where no deformation is detected (about 50 to 60 m below surface). Deformations are generally widely distributed within the deforming mass with zones of concentrated deformations and zones with slower deformation rates. Deformations have been associated with dilation of the rock mass, where discrete block sliding and rotation occurs throughout the mass, rather than sliding as a block along a continuous failure plane or simple toppling mechanisms (Stewart and Moore 2002, Watson et al. 2004 and 2006).

3 GB-INSAR INSTALLATION

A GB-InSAR system (IBIS-L, IDS corporation) was installed in October 2016 on the west bank of the reservoir and aimed at the Checkerboard Creek slope, located on the east bank of the reservoir across from the location of the GB-InSAR (Figure 1). The instrument was installed inside a shed to protect it from weather and wildlife, and transmits its signal through a transparent protective window. The GB-InSAR installation is shown in Figure 3.

The GB-InSAR at Revelstoke is being powered by a solar power system that consists of a pair of 260 W panels in parallel with 3 parallel battery packs, 24V, 100A, each

(Figure 4). This system allows for 5 to 15 days of monitoring during the Fall and Winter months.

The challenges at the site include the limited availability of direct sunlight, the frequent snow falls in the winter months, which partially cover the rock face of the slope, and the variable weather conditions typical of large water bodies within mountainous terrain. In this regard, variable weather conditions influence the reflected wave characteristics and the calculated displacements require corrections (Colesanti et al. 2003, Ferretti et al. 2001). The method used here reduces this effect to some extent by selecting an assumed stable area and calculating deformations relative to this area. However, validation of calculated slope deformations at the Checkerboard Creek rock slope through merging monitoring campaigns requires validation against other instrumentation. Figure 5 shows a comparison of the weather variations for radar imaging and typical snow cover at the rock face after heavy snowfalls.

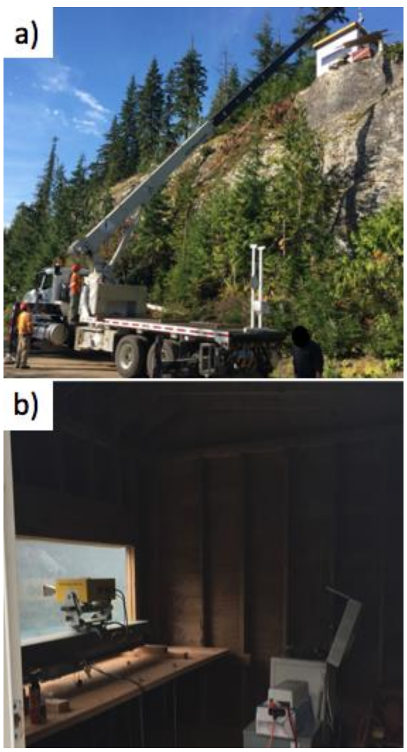

Figure 3. GB-InSAR installation (a) and location within the protective shed (b)

These challenges are translated into limited periods of continuous monitoring and the uncertainty regarding slope measurements during the winter months due to weather effects and transient snow covers. To overcome these issues and test the applicability of GB-InSAR at this location, 1 to 2-week monitoring campaigns are being conducted every 1 to 2 months, and the data is merged to calculate the overall displacement map of the rock face of the Checkerboard Creek slope. Slope displacement measurements will be compared against in-situ instruments to assess the validity of GB-InSAR measurements under these conditions.

4 PRELIMINARY RESULTS

The time of each monitoring campaign is characterized here as the mid-date between the first and last radar image acquired. The monitoring campaigns presented correspond to November 15th and December 15th, 2016; and February 5th, March 24th, and May 18th, 2017.

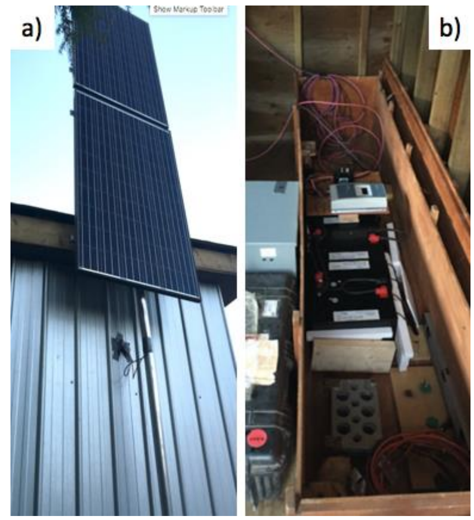

Figure 4. Solar panel installation (a) and battery pack (b) for the GB-InSAR

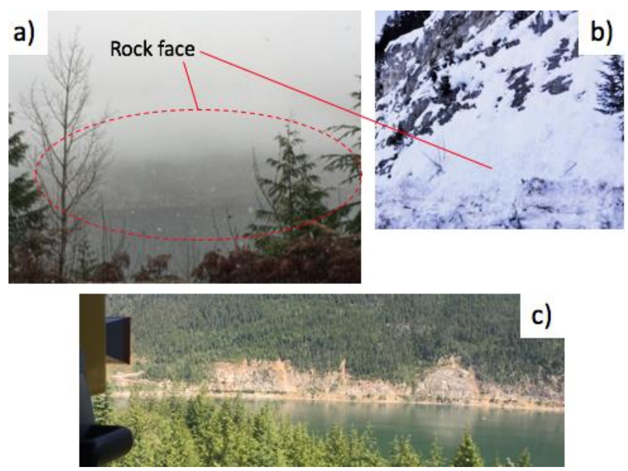

Figure 5. Radar visibility during periods of snow fall (a), snow cover at the rock face after a heavy snow fall (b), and radar visibility on a clear day (c)

The relative displacement between each consecutive pair of monitoring campaigns is calculated by assuming a stable section of the slope, and calculating the relative movement of the rest of the image. In this study, a rock face immediately north of the Checkerboard Creek rock slope was considered as stable. This is consistent with regular monitoring by BCHydro. The stable area is shown in Figure 6. Cumulative displacements are calculated by addition of the relative displacement between consecutive pairs of monitoring campaigns, and zeroing displacements for the image corresponding to November 15th, 2016.

Figure 6 shows the GB-InSAR LOS displacement map between November 15, 2016 and May 18, 2017. The radar image does not cover all of the rock face within the Checkerboard Creek rock slope. This corresponds to low reflection quality (low coherence between images) for this area. Displacement measurements are also constrained to non-vegetated sections of the slope, which corresponds to low coherence of the images of heavily vegetated areas.

Figure 6 shows the location of five points of interest. Point 1 is outside of the rock face at the Checkerboard Creek rock slope and points 2 through 5 are located within the exposed rock face of the landslide. Figure 6 also shows the location of extensometer CC10, oriented such that out of slope deformations can be measured. This instrument was selected for assessing the validity of the preliminary results presented in this paper due to the proximity to the exposed rock measured by the GB-InSAR. The displacements measured at CC10 correspond to the extensometer section most representative of displacements at the surface. Figure 6 also shows the location of inclinometer CC3. This inclinometer provides insight into the landslide displacements measured at depth (up to 100 m) and was selected as representative of the current understanding of the overall landslide displacement trends.

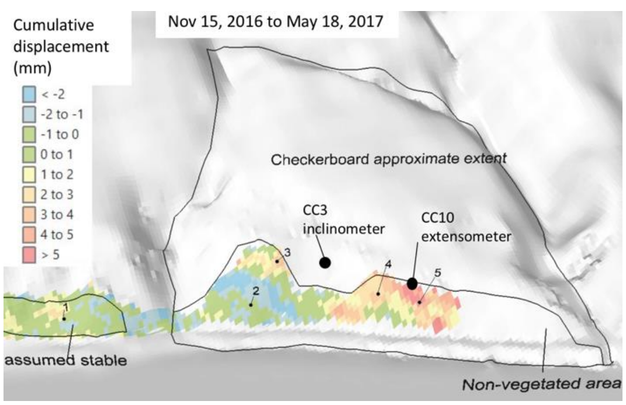

Figure 6 GB-InSAR LOS displacement map between November 15, 2016 and May 18, 2017. Locations of extensometer CC10 and inclinometer CC3 are also shown

Figure 7 shows the cumulative displacement in the LOS at the five locations shown in Figure 6. Table 1 presents the cumulative displacement magnitudes. Figure 7 also shows the displacements measured by extensometer CC10 and inclinometer CC3. Point 1, outside of the slope, shows no significant movement and an increase of less than 1 mm in January 2015 that later is recovered. This is likely due to atmospheric effects and snow cover.

The other four points within the Checkerboard Creek rock slope show different magnitudes of displacement. It is important to note that these four locations (surface displacements) started accelerating approximately at the same time as the measurements for CC10, however inclinometer CC3 maintained a sustained deformation with a shorter acceleration period between mid-February and mid-April, approximately. Further, the magnitude of displacement at Point 5, in close proximity to CC10, is consistent with measured displacements at CC10 and overall displacements at CC3. The higher displacement magnitudes observed at Points 5 and 4, and lower magnitudes for points 2 and 3 are also consistent with BCHydro's observations and experience at the site.

The cumulative displacements measured by the GB-InSAR show some recovery in the last monitoring campaign, coinciding with the slower deformations at CC10. However, further monitoring campaigns are being processed to evaluate if GB-InSAR surface displacement measurements show annual cyclic deformations or a sustained deformation trend similar to CC3. It is worth noting that the displacement at Point 2 fully recovers to near initial displacements as per the first monitoring campaign. Although Point 2 is also considered within an area of the landslide known to be less active, this and the behavior of point 1 at the stable area are potential quantitative indicators of the effects of weather for some surface deformation measurements.

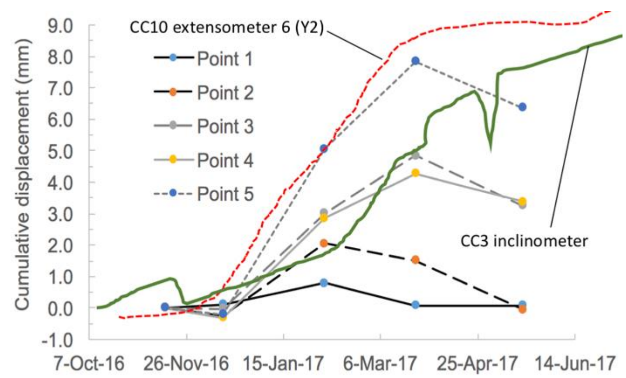

Figure 7 Cumulative displacement in the LOS at five locations (shown in Figure 6) and measured by extensometer CC10 and inclinometer CC3

5 CONCLUSIONS

This paper presented a study of the applicability of GB-InSAR at locations with challenging logistics, including heavily vegetated slopes with limited surface exposure, lack of remote connectivity, lack of constant power sources, short daylight duration limiting the use of solar-generated power, varying weather conditions, and snow accumulation on the slopes being monitored. Further, the GB-InSAR applicability is being assessed at the study area, the Checkerboard Creek rock slope in Revelstoke, BC; in order to enhance the understanding on its deformation patterns.

Subsequent pairs of short-term (1-2 weeks) monitoring campaigns starting in November 2016 are being used to calculate relative slope displacements between campaigns in order to overcome the lack of continuous power. This approach does not allow for continuous monitoring and early warning but can provide a map of displacements and increment the information about the rock face deformation patterns. Challenges associated to weather variability and snow accumulation are still present, however the preliminary calculations of slope displacements appear consistent with other instruments at the site.

Table 1. GB-InSAR LOS cumulative displacement (in mm) between November 15, 2016 and May 18, 2017

Point	Nov 15 2016	Dec 15 2016	Feb 5 2017	Mar 24 2017	May 18 2017
1	0	0.12	0.79	0.08	0.08
2	0	-0.23	2.06	1.51	-0.04
3	0	-0.03	3.02	4.84	3.25
4	0	-0.31	2.86	4.27	3.38
5	0	-0.21	5.06	7.83	6.37

Data acquisition is ongoing and efforts are underway to resolve power availability through a cost-effective and reliable solution that can be extrapolated to remote locations. One shortcoming of the installation is that the higher quality radar images do not cover all the area of the Checkerboard Creek rock face, however ongoing work to extract further information is showing promising results. Also, unlike other instruments at the site, the radar shows some substantial deformation recovery that could be associated with weather effects or snow accumulation. Further monitoring campaigns are being processed to investigate the extent of this recovery and if the behavior is repeated in the year and can be associated with snow loading on the slope.

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