CHARACTERIZING COMPLEX DEEP SEATED LANDSLIDE DEFORMATION USING CORNER REFLECTOR INSAR (CR-INSAR): LITTLE SMOKY LANDSLIDE, ALBERTA

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RÉSUMÉ
Les glissements de terre rétrogressifs et profonds le long des parois de la vallée de la rivière Little Smoky, dans le nord-ouest de l'Alberta, ont mené à un entretien continu notable sur l'autoroute 49 au cours des 50 dernières années. Bien que les zones de vitesse plus élevées localisées aient résulté en une enquête et une surveillance spécifiques du site, les configurations de déformation générales des parois de la vallée restent difficiles à comprendre. Des études précédentes et une reconnaissance du champ ont mis l'accent sur une série de glissements plus actifs et plus récents, en superposition sur des glissements moins actifs et plus anciens, menant à la complexité des modèles de déformation et de vélocité. Puisque la végétation est importante sur ce site, une série de 18 réflecteurs à écho renforcé satellitaires ont été construits et installés sur les parois, le long des deux côtés de la vallée, à l'automne 2006 de sorte à fournir une série de sources ponctuelles où les déformations de niveau subcentimétrique peuvent être mesurées avec un niveau de confiance élevé au moyen de la technologie InSAR. La première année des données a démontré des tendances manifestes des réflecteurs à se déplacer dans la ligne de visée du satellite.

ABSTRACT
Deep seated retrogressive earth slides along the walls of the Little Smoky River valley, in northwestern Alberta, have lead to significant ongoing maintenance on Highway 49 for the past 50 years. While localized, higher velocity zones, have lead to site specific investigation and monitoring, the overall deformation patterns of the valley walls is not well understood. Previous studies and field reconnaissance have highlighted a series of younger, more active slides, superimposed on older, less active slides, lending to the complexity of the deformation and velocity patterns. As the site is heavily vegetated, a set of 18 corner reflectors designed to work with current space-borne SAR systems were built and installed over the walls along both sides of the valley during the fall of 2006. The corner reflectors can provide point measurements with subcentimetre accuracy with a high level of confidence using InSAR technology. The initial year of data exhibits clear trends for reflectors moving in the satellite line-of-sight.

1. INTRODUCTION

The study area encompasses the valley walls of the Little Smoky River adjacent to the Highway 49 river crossing, in the Peace River area of Northwestern Alberta (Figure 1). Both valley walls are undulating and slope gently, from the prairie uplands down to river level, about 120 m below. The slopes have been formed by large deep-seated, slowly moving landslides. At the site, the Little Smoky River occupies a broad pre-glacial valley eroded into interbedded marine shales and sandstones of the Cretaceous aged Smoky River group (Mollard and Associates, 1997). During glaciation the pre-glacial valley was filled with till produced by up to three separate glacier advances. Inter-till sand layers were deposited between the till units in some places. Following deglaciation and continuing to present day, the glacial deposits that infilled the pre-glacial valleys continued to be downcut and undermined. This results in ongoing oversteepening of the valley slopes and large scale land sliding that has produced the irregular, relatively flat slopes of the present valley walls.

The Little Smoky river bridge and approach roads were completed in 1957. Since that time there has been ongoing valley slope instability that has impacted the highway and west bridge abutment resulting in ongoing costly maintenance issues. In the late 1960's, studies were carried out by the University of Alberta, with the installation of the first slope indicators in Alberta, to characterize these movements.

In : J. Locat, D. Perret, D. Turmel, D. Demers et S. Leroueil, (2008).
Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

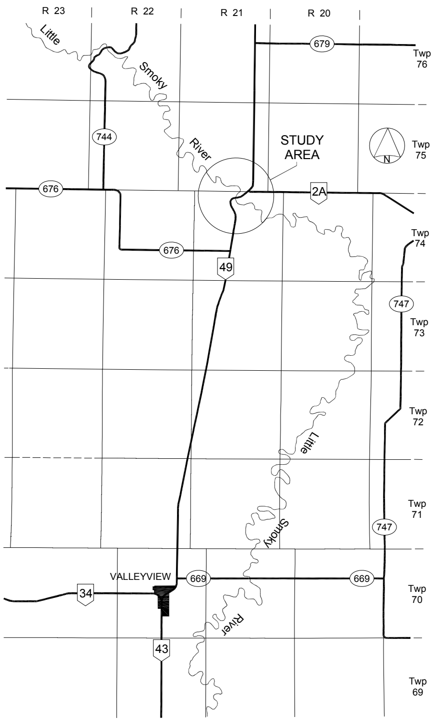

Figure 1. Site location

More recently, detailed studies with instrumentation have been undertaken in the area of a large, ongoing embankment failure on the northeast valley wall. This work was done in order to provide a viable long-term solution to mitigate the impacts of this slope movement on the highway. Options were considered for stabilization of the slide, and for a highway realignment away from the area of greatest instability. All options are costly and limited information is available to confirm the viability of each option, due to the very deep slide plane. As there is only sparse slope monitoring information available in the land-slide area, Alberta Infrastructure & Transportation (INFTRA) used differential InSAR (DInSAR) to gather information along both valley walls. This initial InSAR work was done in 2003 (Atlantis Scientific, 2003; Froese, 2003).

Both valley walls are heavily vegetated with deciduous, leafy tree cover. The slope was not considered as an ideal candidate for D-InSAR due to the potential for temporal decorrelation due to vegetation change. However the experience of the project team was that during early spring or late fall, when the trees were bare, landslide features could clearly be observed from the air. The time of year of the data acquisitions was carefully considered in the review of the available ERS, JERS and Radarsat-1 data in order to improve the chance of detecting landslide motion. Once a list of available data from the early spring/late fall was obtained, a review of the climatic conditions on and immediately prior to the date of the acquisition was completed using climate data from a local weather station. Data without snow cover or significant antecedent rainfall was chosen as the final list. Eight ERS scenes, two JERS scenes and four Radarsat-1 scenes were selected on this basis.

D-InSAR processing of the data from the three platforms only yielded one pair that had a level of coherence suitable for deformation mapping; a 24 days revisit period between October 4 to 28, 2002 using Radarsat-1 data. For this time period 30 zones of movement were detected on the northeast and southwest valley walls. These movements ranged from less than 3 mm up to 12 mm over a 24 days period on the descending Radarsat-1 data.

In order to differentiate between real movements and noise artifacts in the data only zones with movements greater than two times the statistical standard deviation level were considered to be reliable. The zones with significant movement were then compared to locations of known geotechnical instrumentation (slope inclinometers) to compare the rates of deformation observed using the D-InSAR. The overall range of movement correlated relatively well with the 24 day D-InSAR data, although it did not provide enough information to provide confidence in mitigative measures for the slope. A more thorough discussion of the D-InSAR results is provided by Froese et al (2004).Following the promising results from the D-InSAR assessment, the potential for the application of corner reflectors for the site was considered and a reflector array was designed.

2. CORNER REFLECTOR DESIGN AND INSTALLATION

To improve the signal return to the spaceborne SAR sensor, eighteen small areas were cleared of vegetation and corner reflectors were installed (Figure 2). The reflectors are trihedral shaped and made of perforated aluminum (Figure 3). The trihedral design ensures that the radar signal is returned exactly in the incident direction and with the same polarity. The perforations are made to minimize the reflector resistance to the wind and to drain water accumulation. As long as the diameter of the perforations is much smaller than the radar wavelength, the radar signal will not be affected by the loss of reflective surface.

The size of the corner reflector is proportional with the quality of the signal strength and implicitly with the quality of the measurement. The larger the reflectors, the better the precision of the measurement. The minimum size of the reflectors is a function of the SAR sensor wavelength and of the expected strength of the natural radar targets (rocks, houses, bridges). The corner reflector signal should dominate all the other reflections located in the immediate vicinity. The orientation of the corner reflectors is perpendicular to the radar line of sight. This is a very delicate operation because the Radarsat-1 line of sight (azimuth) angle varies with the latitude.

The corner reflectors used in this area were designed to properly work with radars at C-band or higher, meaning

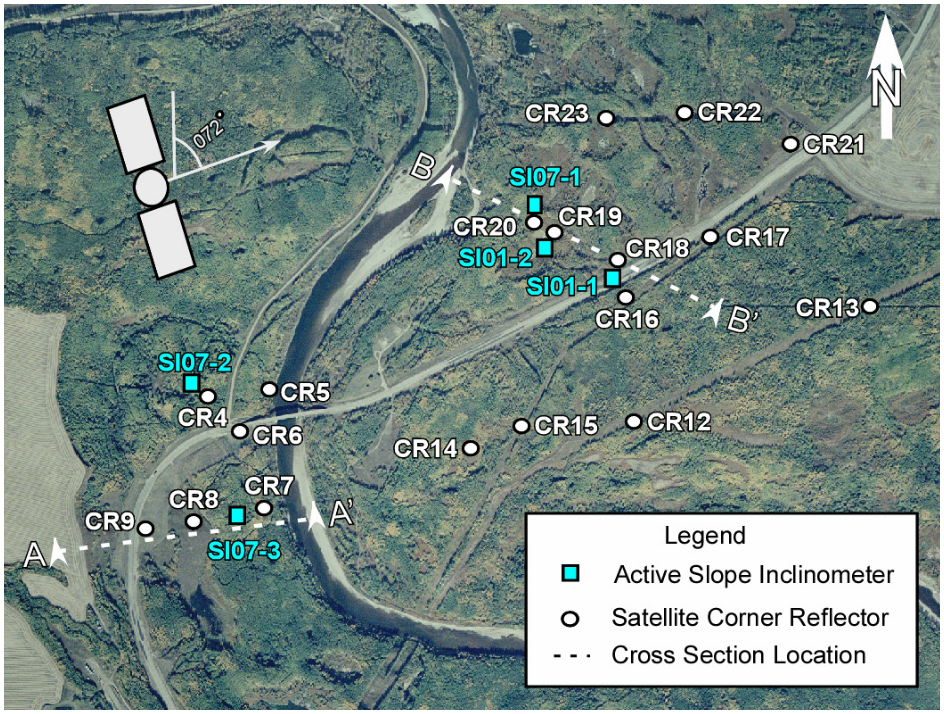

Figure 2. Layout of the corner reflector array in relation to recently installed instrumentation and profile locations**.**

that they could be used for Radarsat-1, Radarsat-2, Terra-SAR X and Cosmo-Skymed missions, given a proper orbit availability. SAR missions at lower frequency (JERS and ALOS at L band) may work too, but the phase error of the measurement will be theoretically a little bit higher.

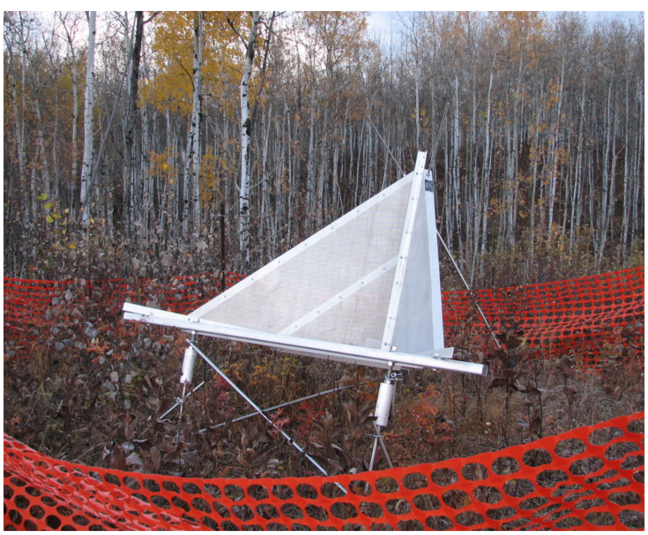

Figure 3. Photo of a corner reflector installed at the Little Smoky site

The acquired Radarsat-1 data confirms the proper installation of the corner reflectors. The reflectors can be easily identified on summer scenes where the abundant vegetation scatters the radar signal in all directions and the scenes are "darker", except the corner reflectors.

The reflectors are harder to identify in the winter scenes where the snow or the bare Earth are strong signal reflectors. Some of the reflectors installed on slopes oriented along the radar line of sight are still visible because the radar signal is reflected away by the slope, but corner reflectors installed on slopes perpendicular to the radar line of sight are buried into clutter noise because the radar signal is reflected by the slope back to the radar receiver. Figure 4 provides a radar image showing the relative strength of the returns from the reflectors against the natural surface.

3. GEOTECHNICAL DATA AND MOVEMENT TRENDS

Both valley slopes are examples of large scale, deep-seated retrogressive landslides. Based on the presence of at least one elevated depositional terrace and the varying orientations of head scarps on the northeastern side of the crossing, it appears that previous river courses/levels cut into the valley slopes during historic development of the river valley. The north valley slope has a somewhat more rugged and disjointed appearance then the south side, which may be partially due to the surface grading and drainage improvements undertaken on the south valley slope, which might mask irregularities.

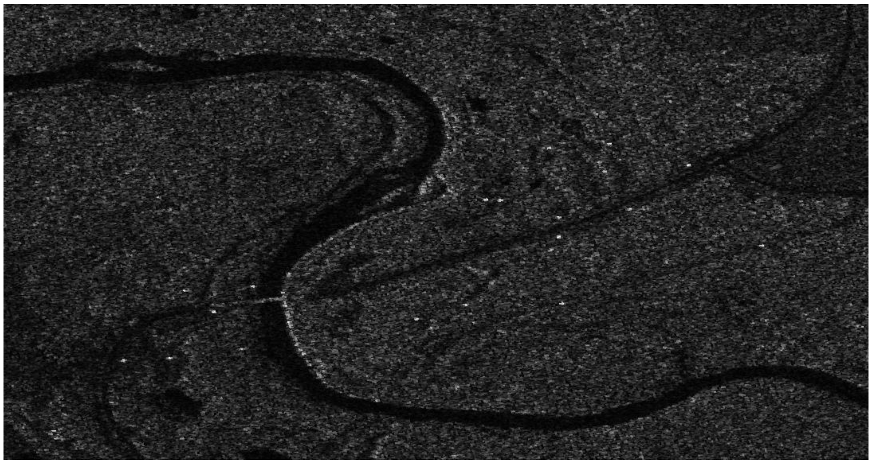

Figure 4. Radarsat-1 SAR image showing the location of the corner reflectors (white spots) in relation to the surroundings. Higher data quality is indicated by higher reflectance.

The geology and associated slope movement mechanisms on the southwest side of the valley are less complex than those on the northeast side of the crossing. The road and bridge on the south side are impacted by two adjoining slide zones; one on either side of the bridge. Borehole logs along profile A-A' (Figure 5) encountered clay and clay till derived colluvium overlying shale. The shale surface is approximately concave, dipping from a high point at about elevation 525 m and bottoming out at about elevation 485 m (about river level). The upper part of the valley is relatively steep, indicative of the thick upland till strata that is outside of the influence of the bedrock slide plane. Based on historical deformation data, previous geotechnical interpretations (Thomson and Haley, 1975; Bala and Proudfoot, 2007) and the slope morphology, the landslide at Profile A-A' would be described as a rotational retrogressive earth slide in the colluvium that comprises the landslide mass. Available deformation monitoring data (Thurber 2007b) for the past year indicates that movement rates of up to 26 mm/year have been observed on the lower rupture surface for installed slope inclinometers (SI07-3) at this section.

The stratigraphy and deformation patterns are more complex on the north side of the crossing where over 50 meters of colluvium encountered a variety of complex movement zones and directions. The northeast valley wall is comprised of a sequence of newer, more active landslides, superimposed on older and less active to dormant features.

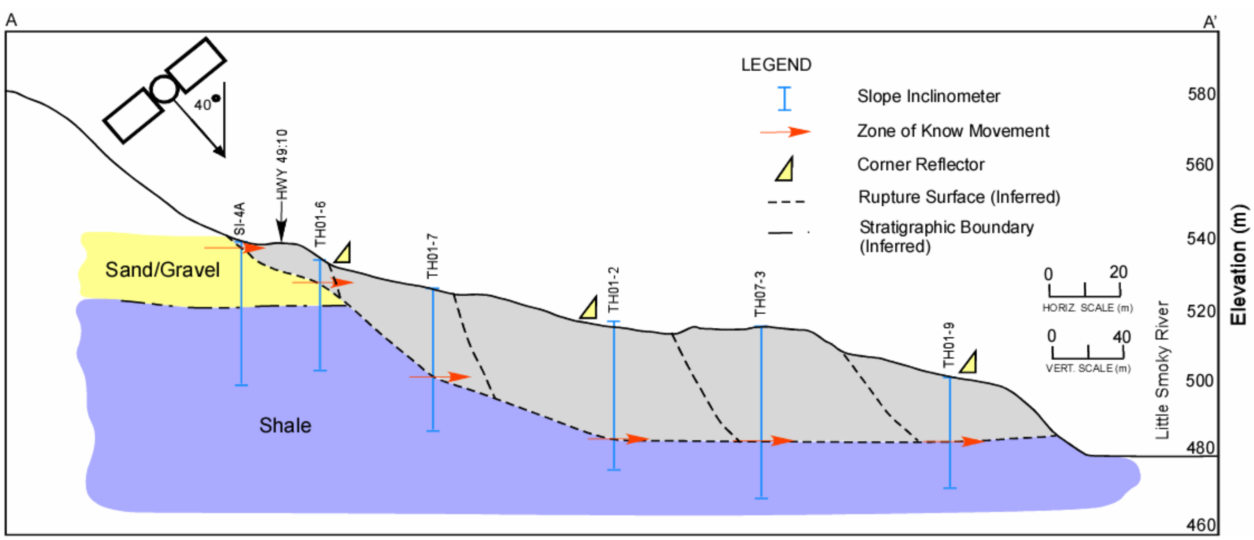

Figure 5. Profile A-A' shown on Figure 3.

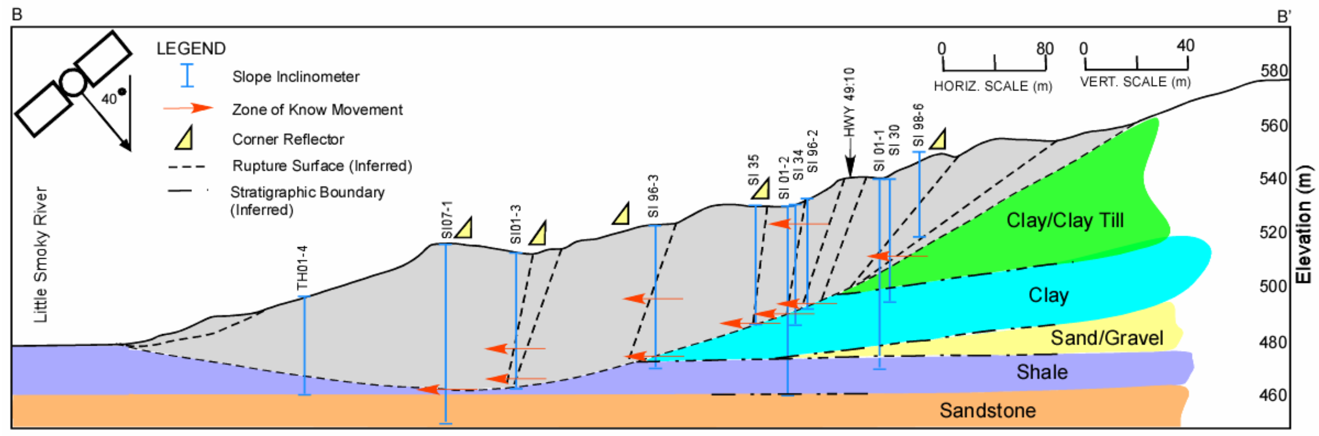

Figure 6. Profile B-B' shown on Figure 3.

In addition the different ages of landslides have been activated at different levels of river evolution where the paleo-river channel was meandering and cutting at different orientations than the existing channel morphology and thus the orientation of the older landslide scarps varies significantly. Therefore, when trying to characterize the directions and rates of movement for the entire valley slope, most of the previous investigations do not provide enough insight to provide a complete picture of the complexity of the overall slope movement patterns.

Since the 1970's, the majority of investigation has been focussed on areas of the highway that have been most significantly impacted upon by the landslides. In particular, the area in the proximity of SI07-2 and CR18 on Figure 3, there have been numerous investigations focussed around a very active headscarp that leads to annual maintenance (adding asphalt) of the highway surface.

Profile B-B' (Figure 6) provides cross-sectional representation of this area that shows the stratigraphy and movement zones identified over the past decade in investigations into this very active area of the northeast valley wall. As can be seen on profile B-B' the interpretation of deformation patterns and rate is complicated by the numerous blocks that comprise the slide and the fact that many of the previously installed slope inclinometers did not pierce the lower rupture surface, and therefore only provide information as to shear movement along the backscarp.

The true basal slide plane below the north valley slope remained elusive until a series of very deep slope indicators were installed in 2001 (refer to Figure 6). The boreholes, installed to 65 m depth, found the basal sliding plane mainly between elevations 465 to 485 m, approximately coincidental with that found on the south valley slope. Prior slope indicators, installed to shallower depths, intercepted intermediate back scarps of the translational block movement, giving a perception of a shallower based valley slope movement.
The north valley slope movement is significantly larger in size than the south side. Please note the 4x exaggeration of the horizontal scale between Figure 5 and 6. A broad arcuate failure mass, about 2200 m wide, 900 m long and 55 m deep exists. The highway traverses along the left flank of this very large movement. At the toe of the slide a small island exists within the Little Smoky River. The island may be a slide feature, or at the least presents an anomaly as a depositional river feature along the outside bend of the river.

The northeast valley slide continues to creep at a rate of 50 to 100 mm per year. A detailed back analysis of the north valley slope has also not been undertaken, although the slope is also considered to be meta-stable. The trigger mechanisms for the slope movements is still considered to be erosion of the toe of the slope, in combination with rainfall infiltration and a sliding plane at residual.

4. CR-INSAR DATA

The SAR data for this site was in the raw format; that means the data was a collection of radar signals that had to be focussed into a detected image. The reason to choose this format was that the Canadian Centre for Remote Sensing (CCRS) has multiple SAR processors available for focussing and the presence of corner reflectors in the images made it possible to estimate which SAR processor would performs best for the specific area. Some of the processors fail in the winter time due to a lack of contrast in the images, leading to a poor focussing of the corner reflectors.

The focussed (SLC) images were co-registered to a unique Master image. The Master image was chosen such as the baseline values between the Master and the slave images were kept at a minimum.

Using a unique Master would be a problem for regular interferograms because the decorrelation time for Little Smoky is less than a month. That means interferograms could be created with scenes separated by a 24 days interval but not for scenes separated by 48 days interval or more. Using corner reflectors eliminates this problem because the reflective quality of these aluminum devices does not change in time; therefore they maintain interferometric phase quality in time.

Once the Master image was chosen, the slave images were co-registered to the unique Master, such as the corner reflectors perfectly overlapped in the data stack with a precision up to 0.03 pixels. Using the co-registered data stack, an amplitude threshold was applied in order to detect the peak amplitude of each corner reflector. Processing was done on the data obtained at this peak amplitude. The processing steps consisted of:

- Removal of the flat Earth phase effect based on the SAR orbit estimation and orbit errors estimation from the co-registration polynomials.
- Removal of the topography contribution to the measurement. Since we were looking for deformation measurement, the height measurement component had to be eliminated. The precise height was measured with differential GPS at centimetre level and transformed into a SAR phase that was removed from the interferogram.
- Transformation of the differential phase into deformation values in line of sight. At this stage, the deformation values are wrapped, meaning that they are ambiguously determined within a 2.8 cm interval (characteristic to Radarsat). Any deformation larger than this limit would be wrapped back below this limit.
- The wrapped deformation values were unwrapped based on estimated trends and avoiding any apriori deformation models.
- The deformation trend (which are still in the line of sight) were estimated and projected to the most likely displacement direction, consistent with slope indicator monitoring results.

As the deformation profiles generated for the reflectors are relative, they must be references to a stable location. As most of the valley walls are moving to some extent, this was a challenge. On the northeast side of the valley reflector CR 13 was chosen as it was considered to be the most stable based on the valley morphology and the absence of signs of slope distress. On the southwest side of the valley there were no obviously stable reflectors so the east side of the bridge was used as the stable reference point. Using these stable reference reflectors, seventeen deformation profiles were generated

Once the profiles were generated, the quality of the measurements was assessed in relation to available meteorological data. As the reflectors would ideally be snow free for all of the readings, the snowfall records for the winter of 2006/2007 were reviewed to assess the potential time periods where there may be snow on the reflectors. As the crossing is in a remote location they were manually cleaned out only once during the winter months. Based on the review of the snowfall and temperature data it was expected that any readings from November 2006 to the end of March 2007 could be impacted by snow accumulation.

Using data from a local meteorological station, the snow accumulation on the ground was charted against all of the deformation profiles and a clear correlation was observed. Therefore, it is assumed that the periods when there is snow on the reflectors the results are not reliable; these periods can be clearly identified on Figures 7 and 8 .

5. DISCUSSION OF RESULTS

At the time of the preparation of this paper, a preliminary assessment of the entire array of the reflectors has been undertaken along with a more detailed review of selected reflectors, which will be the basis for this initial discussion.

As shown on the plan (Figure 2) the ascending F2N Radarsat-1 data was collected with a line-of-sight bearing of 072 degrees and a vertical angle of 50 degrees above horizontal (Figures 5 and 6). Therefore all of the CR-InSAR results show the component of the deformations at each reflector that occur along that bearing and dip angle. Under ideal situations where the line of sight and incidence angle are parallel to the direction of the slope movement, velocities close to real three dimensional slope movement velocities may be measured. Conversely on reflectors where the largest components of the deformation are near perpendicular to the satellite LOS or incidence angle, there is the possibility that no deformations may be detected in areas where significant movement may in fact be occurring. Both phenomenon are observed in the complex, rotational movements observed on the valley walls of the Little Smoky River and are discussed in the following section.

For illustration of the comparison of the results of the CR-InSAR with slope inclinometer readings over the same time period reflectors CR7 and CR20 are presented in relation to the proximal slope inclinometers that were read over the same time periods. Slope inclinometer readings for both of these locations indicate that the horizontal component of the deformations for both reflectors is very close to parallel to the satellite line-of-sight, making them good examples for discussion. The results are discussed below.

Southwest Side: Reflector CR7 is located along Profile A-A ‘ (Figure 5) on the southeast side of the bridge crossing. This reflector is situated on the lowermost block of a rotational retrogressive slide where deformations have been monitored since 2001.

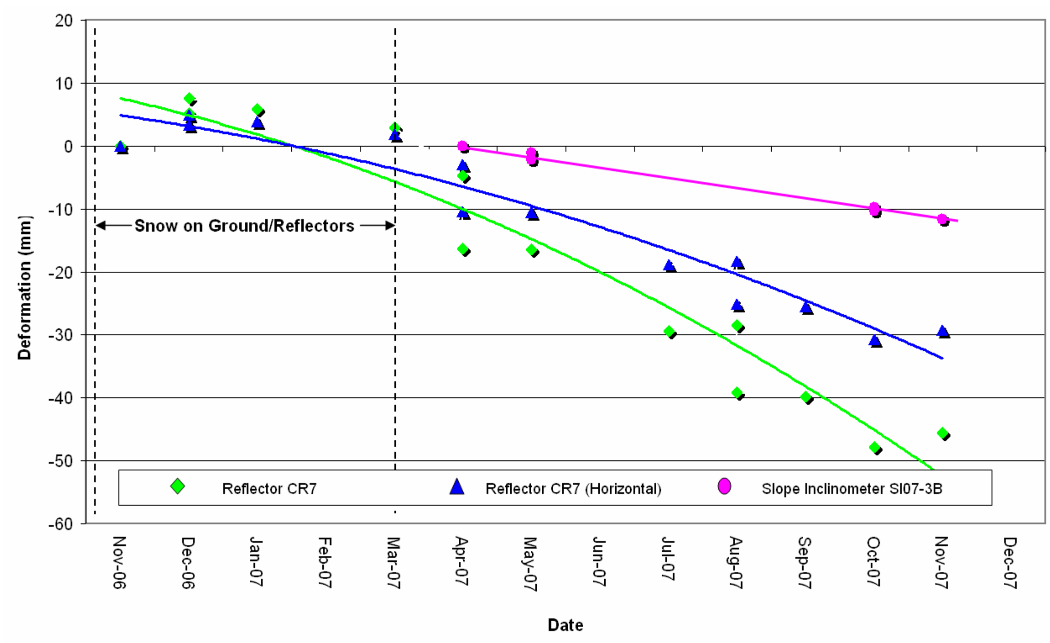

Figure 7. Deformations for CR7 vs. SI 07-3B (November 2006 to November 2007

The information derived from the 2001 slope inclinometer indicates that the resultant vector (horizontal component) is nearly parallel to the line-of-sight bearing from the Radarsat-1 F2N and therefore ideal for measuring slope deformations. In order to characterize the measured movement, the CR-InSAR results obtained between November 2006 and November 2007 were compared to a newly installed slope inclinometer (SI07-3B) where total movements between May 2007 and October 2007 over 7.8 mm (extrapolated to 22.3 mm/year) (Thurber, 2007b) have been recorded (Figure 7). Deformations of up to 50 mm have been obtained on CR7. There are two likely contributions to this discrepancy. First, as reflector CR-7 is located on the lowermost rotational block and is likely moving at a faster rate than the upslope block on through which SI 07-3B is drilled. For the inclinometer that was installed on the lower block in 2001, overall deformation rates of up to 50 mm/year were observed prior to the casing shearing off.

Another likely source of the difference is the fact that the line-of-sight for the satellite is likely more directly in line with the actual deformation vector for the lower rotational block. As the block is likely moving in a rotational manner, there would be expected to be a vertical component to the deformation that would not be detected on the slope inclinometer as it only projects the horizontal component of the deformation. Figure 7 also shows the results obtained from the CR-InSAR projected into the horizontal component to show the overall deformation of approximately 30 mm.

Northeast Side: On the northeast side of the valley, reflector CR20 (Figure 3) was chosen to illustrate the challenges in applying CR-InSAR. As seen on profile B-B', both CR20 and SI 07-01 are located at the head of a large rotational block in the lower portion of the slope. Readings were taken on the slope inclinometer between May and October 2007 (Thurber, 2007a) of up to 19 mm (47mm/year). The results obtained from the CR-InSAR analysis of target CR20 during this time period indicated negligible deformations (Figure 8). The reason for this is likely the opposite of what was discussed for CR7 on the southwest side of the crossing. As it is expected that the large block on which CR20 is located is moving in a rotational manner, it would be expected that there is a downward vertical component to the movement. If this component was significant enough, CR20 would then be moving nearly perpendicular to the line-of-sight of the satellite and deformations would not be quantified using CR-InSAR. A review of these trends in relation to the other reflectors on the northeast side of the valley is currently underway.

6. CONCLUSIONS

Based on the complexity of movements and the variation in movement rates, the Little Smoky Landslide site is an ideal test for the application of CR-InSAR for characterization and monitoring of large complex landslides in northern environments. Preliminary results available at this time have been compared with conventional slope inclinometer readings and slope morphology and have yielded both success and challenges in the application of the technique. This case history shows the potential for this application but also hopes to provide practical discussion to aid others when considering the use of this remote sensing tool. It is

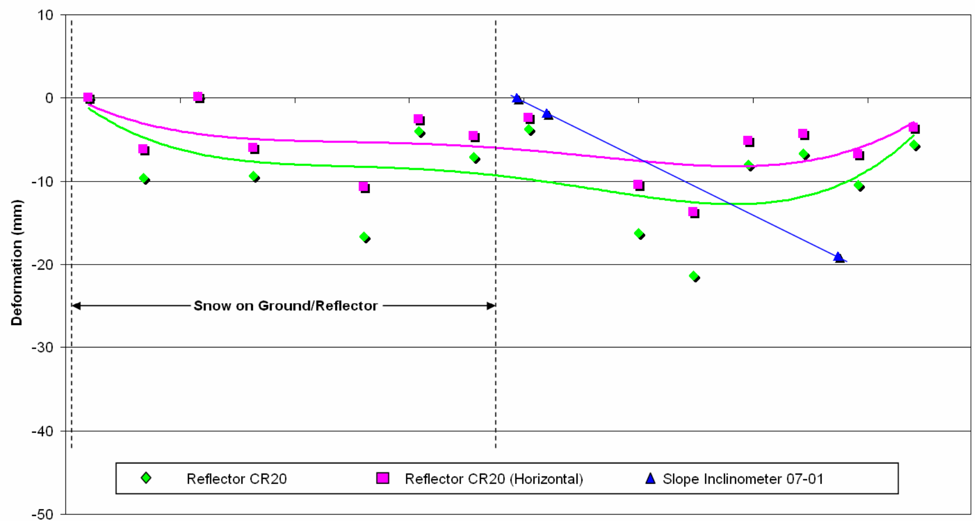

Figure 8. Deformations for CR20 vs. SI 07-1 (November 2006 to November 2007)

expected that a more detailed discussion of the complete results will follow in journal format in the near future.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Bala, G. and Proudfoot, D. 2007. 2007. Hwy 49:12 – Little Smoky River (SH3 and SH4) Geotechnical Investigation. Thurber Engineering. Report No. 15-85-62. Dated July 13, 2007.Prepared for Alberta Infrastructure and Transportation.

Froese, C.R., 2004. Little Smoky River InSAR Assessment of Slope Movement. AMEC Earth & Environmental. File No. EG09024. Prepared for Alberta Infrastructure and Transportation.

Froese, C.R., Kosar, K. and van der Kooij, M., 2004. Advances in the application of InSAR to complex, slowly moving landslides in dry and vegetated terrain; in Landslides: Evaluation and Stabilization, W. Lacerda, M. Erlich, S.A.B. Fontoura, A.S.F. Sayao (ed.), Proceedings of the 9th International Landslide Symposium, Rio de Janeiro, Brasil, A.A. Balkema, Leiden, Netherlands. p. 1255–1264.

J.D. Mollard & Associates Limited, May 1997, Office Airphoto and Map Study of the Little Smoky River Valley Upstream and Downstream From Highway 43 Bridge

Proudfoot, D., Froese, C.R., Skirrow, R, Thomson, S.. 2005. Update on the Little Smoky Landslide. 58th Canadian Geotechnical Conference. Saskatoon, SK

Thomson, S. and Hayley, D.W. 1975. The Little Smoky Landslide. Canadian Geotechnical Journal, Vol. 12, 279-392.

Thurber Engineering. 2007a. Instrumentation Monitoring Results, Fall 2007, Section C, Swan Hills Region, Site SH3: HWY49:12, Little Smoky River (North of Bridge). Prepared for Alberta Infrastructure and Transportation.

Thurber Engineering. 2007b. Instrumentation Monitoring Results, Fall 2007, Section C, Swan Hills Region, Site SH3: HWY49:12, Little Smoky River (South of Bridge). Prepared for Alberta Infrastructure and Transportation.

Vexcel Canada. 2004. InSAR Subsidence Monitoring: Deformation Monitoring of the Little Smoky Site: (October 4, 2002 to October 28, 2002 and October 9, 2001 to October 28, 2002). Prepared for A MEC Earth & Environmental Limited