Monitoring and Assessing Geohazards in Permafrost Terrain using Spaceborne Synthetic Aperture Radar (SAR)

Pierre-Jean Alasset & Joseph Chamberland
C-CORE, Ottawa, Ontario, Canada
Jerry English, Des Power & Nikolay Volkov
C-CORE, St. John's, Newfoundland, Canada

ABSTRACT
The objective of this article is to demonstrate the capability of Interferometric Synthetic Aperture Radar (InSAR) to identify, monitor and assess geohazards in permafrost terrain. InSAR was investigated as a complementary tool to enhance the current mapping, surveying and geotechnical analyses. From interferometric techniques, deformation maps and Digital Surface Models have been derived in two northern locations with different permafrost types. Using both remote sensing monitoring and traditional geotechnical engineering provides two independent sources of ground surface displacement information which increases the forecast accuracy of the geotechnical conditions.

RÉSUMÉ
L'objectif de cet article est de démontrer la capacité de l'Interférométrie Radar à Synthèse d'Ouverture (InRSO) dans les applications géoscientifiques pour identifier, contrôler et évaluer les aléas géologiques dans le pergélisol. L'InRSO a été étudiée comme un outil complémentaire pour améliorer les analyses actuelles en cartographie, en surveillance et en génie géotechnique. A partir des techniques interférométriques, des cartes de déformation, des modèles numériques de surface ont été dérivés dans deux sites septentrionaux avec différents types de pergélisol. L'utilisation combinée de la surveillance par télédétection et du génie géotechnique traditionnel fournit deux sources indépendantes d'information sur les déplacements de la surface du sol, augmentant ainsi la précision des prévisions des conditions géotechniques.

1 INTRODUCTION

Earth Observation (EO) was investigated as a complementary analysis tool to existing practice, such as terrain analysis, permafrost science and geotechnical engineering. Interferometric Synthetic Aperture Radar (InSAR) using European and Canadian radar satellites is presented and used since it has been demonstrated as effective for subsidence and slope stability monitoring in non-permafrost environments. In this paper, InSAR products such as preliminary Digital Surface Model (DSM), point target ground motion analyses, and deformation maps have been derived and applied to permafrost environments.

The objectives of the paper are to validate advanced InSAR techniques in geosciences applications, and specify the accuracy to be expected from these products. The long-term goal is to develop the framework and conditions through which they can be developed into a year-round service to assist the client. In many cases, monitoring permafrost instability with satellite interferometry provides an additional tool that could reduce the cost and increase the effectiveness of geohazard monitoring.

Permafrost is a thermally sensitive geo-material where the thermal conditions define the mechanical strength and behaviour of the soil. The trend of global warming has a significant destabilizing effect on the mechanical behaviour of permafrost terrain. For thaw-susceptible soils, permafrost degradation has the potential to significantly reduce the geotechnical load carrying capacity. This may trigger process-related geohazards such as slope instability, slides, debris flows and settlement.

Two sites in North-western Canada were selected and studied. One site in the Mackenzie Delta Region and the second is in the Yukon Territory. The Mackenzie Delta region is a unique continuous permafrost environment in the Canadian North that is rich in hydrocarbons and supports a fragile ecosystem. Here, a need exists to define nominal remote coastal conditions prior to hydrocarbon extraction and to assist in monitoring conditions once the extraction is underway. The second area is located in the Yukon Territory near the southern boundary of the extensive discontinuous permafrost zone in North America. This area was studied to monitor the seasonal motion of the ground near the highway infrastructure. In both cases, traditional surveying methods were used to corroborate the InSAR analyses.

Geotechnical engineering studies can use Earth Observation results as input data to calibrate geotechnical models and to evaluate foundation behaviour for structures constructed in permafrost regions. InSAR products can be complementary and in some cases replace GPS, or LIDAR datasets. Indeed, monitoring becomes an important aspect of any development in the permafrost regions particularly where a site is not easily accessible for routine measurements. In this regard, the use of satellite monitoring has a great potential to address issues like degradation of ice-rich permafrost, observations of the active layer behaviour and slope stability. These displacements challenge the design and safe operation of structure and infrastructure facilities such as buildings, dams and pipelines.

2 PRINCIPLES OF SYNTHETIC APERTURE RADAR

2.1 SAR Basics

Unlike optical satellite sensors the spaceborne SAR sensor has day/night, all weather, all season capability that enables monitoring features of interest reliably on a routine basis. This is due to the fact that SAR sensors are active devices; the sensor illuminates its target by emitting a directional microwave frequency pulse. The radiation reflected from that target is detected and measured by the sensor. This radiation is characterized by its wavelength and frequency and this affects how the radiation interacts with the ground targets. Wavelength (λ in metres) and frequency (f in Hz) are related by Equation 1:

$$C = \lambda * f \quad [1]$$

C is the speed of light ($3x10^8$ m/s).

The electromagnetic spectrum range used by SAR is longer wavelength (cm) and lower frequency than the optical sensors such as SPOT or IKONOS. SAR sensors can operate on different bands. These bands are labelled according their wavelengths: the most commons are X- (~3cm), C- (~5.5cm) and L- (~20cm) bands. In this study three sensors were used: ASAR on the ENVISAT satellite, launched by the European Space Agency, and RADARSAT-1 and -2 from the Canadian Space Agency. These are all C-band.

The signal reflecting back from the earth surface constitutes the radar image which contains the magnitude (A) as well as the phase (φ) of the backscattered radiation. Topographic information can be derived from the difference in the phase, that is, the interferogram, between two images (see, for example, Massonnet and Feigl, 1998). Reviews of the InSAR technique and applications are wide and varied; early and best known examples include Prati and Rocca (1990), Hartl and Xia (1993), Massonnet and Feigl (1998) and Rosen et al. (2000).

Spaceborne InSAR has received much attention for its ability to generate deformation maps with unprecedented accuracy (centimetre or millimetre level).

2.2 Introduction to Interferometry

InSAR can be performed on either a single-pass or repeat-pass basis, depending on whether the analysis is performed using two separated antennas flying past the area at the same time, or from one (or more) antennas flying past at different times. In the case of spaceborne SARs with a single antenna, as in this study, repeat-pass InSAR is generally the only choice. This implies that the time interval between two consecutive acquisitions is determined by the orbit cycle of the spacecraft: 24 days for RADARSAT-1/-2 and 35 days for ENVISAT. New and future SAR satellite missions will have a time span of 4 to 6 days between acquisitions with identical target observation parameters. This will increase the performance of interferometry and the temporal resolution.

The variation in phase due to ground movement between two acquisitions is the principle of interferometry. The change in the distance (d) between the satellite and any point on the ground is simply the fraction of half the radar wavelength (λ, Figure 1), where the fraction is determined from the interferogram phase ($\varphi2$-$\varphi1$, in radians) for the two images. In single dimension analysis, the conversion from measured change along the slant range measurement to the actual ground movement relies on an understanding of the ground dynamics in order to interpret the direction of movement based on the projected magnitude.

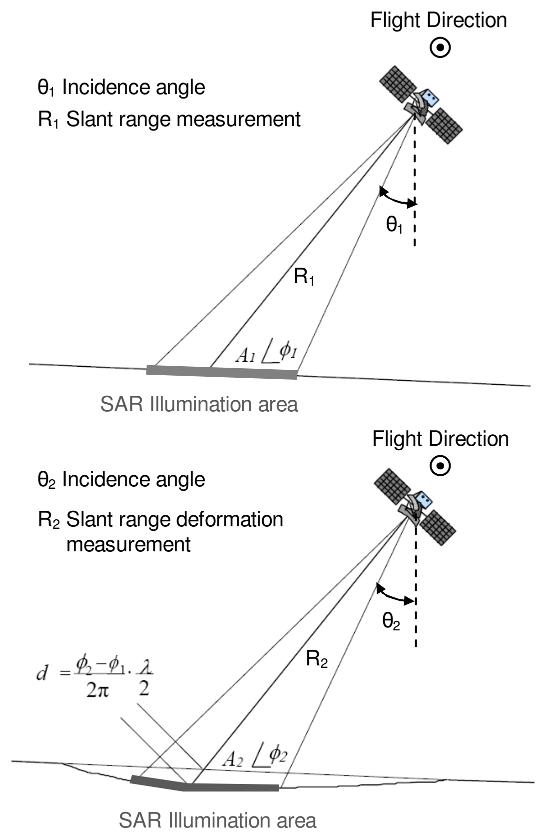

Figure 1. InSAR measurement of ground movement for two different acquisitions.

InSAR is based on the combination of two complex wave components (magnitude and phase) and co-registered (aligned) radar images of the same area from an almost identical perspective. The phase difference for each pixel in the resulting interferogram is a measure of the relative change in distance (d) between the target (scatterer) and the SAR antenna. A coherence image can also be extracted from the phase. The coherence is a measure of the correlation in signal return between the two images. This measure provides information on the reliability of the data (high coherence level means a high confidence in interferometric values).

The baseline, noted B in Figure 2, representing the distance between the two satellite positions. This baseline could be broken down into a parallel component ($B_{\parallel}$, along the line-of-sight of the satellite) and a perpendicular baseline ($B_{\perp}$). The perpendicular baseline is a key parameter in interferometry, and will give the stereo effect which enables extraction of the 3D information. A 0m baseline means the satellite is imaging the area with exactly the same angle/position as first acquisition; consequently no information on topographic relief can be extracted from such an imaging geometry. On the other hand, a very large baseline (1km+) could affect the quality of the interferogram due to a baseline de-correlation. Variations in baseline are a natural result of variations in the satellite orbit.

In the case of active deformation area, the change of scattering within a resolution cell or their electrical properties between consecutive acquisitions can create a temporal de-correlation (Zebker & Villasenor, 1992, Strozzi et al., 2003). Indeed, deformation mapping (e.g. settlement) over large areas relies on the ground surface stability of the region. Low noise in the repeated coherence measurements are necessary since this mapping is done over extended periods of time and large noise related variations in ground coherence can become an issue which affects the quality of the final product.

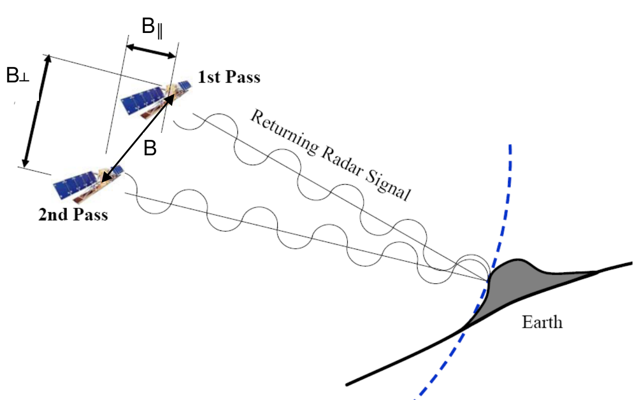

Figure 2. Orbit baseline changes can produce varying phase shifts.

The accuracy of the DSM derived from InSAR depends on the radar image resolution, the coherence of the image pair and the geometry between the acquisitions. For example, RADARSAT-2 Ultrafine mode (3m resolution) can be used to produce a 10m resolution DSM.

Note that the InSAR technique measures only the surficial layer deformation. Thus, in a permafrost environment only the active layer will be monitored. If any more in-depth movement is added (uplift, settlement) the measured deformation will reflect the combination of both deformations. However, using man-made reflectors, anchored down to several meters and isolated from any direct contact with surficial layer, should provide isolated in-depth monitoring.

2.3 Interferometric Derived Products

InSAR products can be obtained from the collection of radar images over a region of interest. The InSAR technique can be used to generate sub-centimetre accuracy deformation maps, or the Persistent Scatterer Interferometry (PSI) technique can be used to make point measurements of similar accuracy.

2.3.1 D-InSAR Products

For each SAR pair a master and slave image are defined. It is convention that the first image in time is called the master and the second, the slave. The two images are co-registered to match an identical perspective and alignment. From this co-registration a coherence image and an interferogram are derived from the difference of the two images (thus the name of D-InSAR). The measured phase difference (interferometric phase) is the key element in the process and represents the sum of the phase values due to topography, land deformation, orbit uncertainties, atmosphere effects and other noise. The orbit uncertainties and atmosphere can be estimated and removed almost entirely. Thus the enhanced interferogram is obtained and contains essentially topographic and deformation interferometric phase. In Figure 3 an example interferogram is shown with one 2 pi cycle of phase defined by the colors blue to red to yellow. Note that no interferometric phase information from the water can be derived as the water is returning a random phase between the two acquisitions.

If no significant deformation is expected on the area of interested a DSM can be extracted.

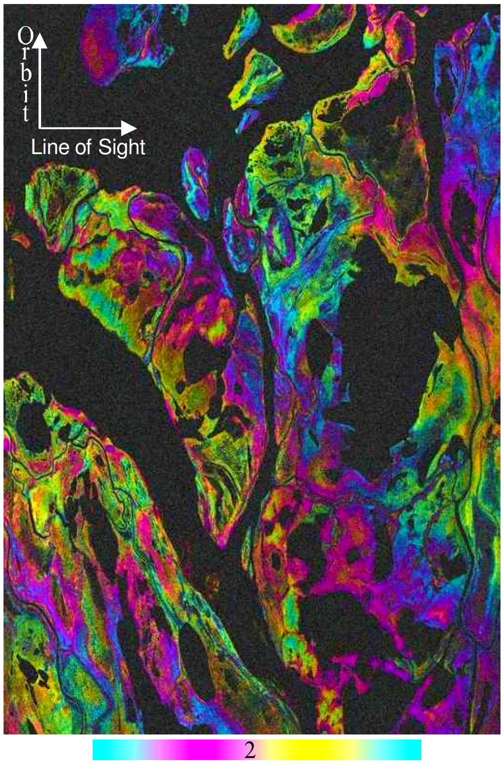

Figure 3. Interferogram from RADARSAT-2 2009-07-08—2009-08-01 Ultrafine image pair (3m resolution) over the Mackenzie Delta. The interferometric phase range is 2π. This image represents the total length of the acquisition of ~25km.

If a deformation map is the desired final product, a high resolution Digital Surface Model (DSM) can be used to subtract the phase contribution arising from the topography from the overall interferogram.

2.3.2 PSI products

In regions where multi-year monitoring is required the Persistent Scatterer Interferometry (PSI) technique can be applied. The main difference between the D-InSAR and PSI techniques is the number of images needed to be acquired and processed. In practice, with 24-day time interval for RADARSAT-1/-2 satellites, 16 images could be acquired per year. By stacking all the images together, an accumulated deformation image can be generated.

If long-term surface coherence changes due to vegetation and moisture (temporal de-correlation) are significant, it will be impossible to obtain a cumulative deformation map through D-InSAR. Therefore, PS Interferometry can be performed by relying on fixed targets, often called coherent scatterers or point scatterers (PS). Common point scatterers could be buildings, outcrops, vehicles, or other man-made structures. If insufficient PSs are present in the area of interest, man-made reflectors can be installed. These are typically aluminum trihedral 'corner' reflectors (CR). For areas with winter snow accumulation, the Installation of a Plexiglas snow cover coupled with an installed height above the average snow accumulation height can allow for year round monitoring.

These aluminum CRs can have a rod on the back end to receive a GPS dish antenna – for collaborative ground truthing measurements. In this case (Figure 4) there is only one CR, but when 3D analysis is desired two CRs can be installed with a suitable formation.

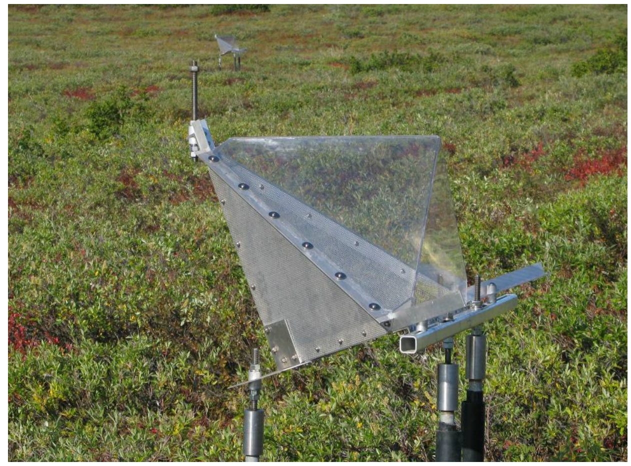

Figure 4. Example of corner reflectors installed along the Mackenzie Delta. A Plexiglas cover is installed on top to avoid any snow accumulation during the winter season. A rod is installed on the back end of the CR to mount a GPS dish antenna (Photo courtesy of JC Lavergne, Geological Survey of Canada, 2009).

The interferometric output product consists of a phase history for each point scatterer compared to a reference corner reflector. The annual deformation rate can be extracted either in line-of-sight direction or any projected vertical and/or horizontal direction. A subcentimeric creeping deformation can be observed with a millimetric standard deviation. In remote areas these interferometric outputs can be compared with in-situ measurements (GPS, levelling, inclinometers) and used as initial input for any geotechnical modelling.

3 INTERFEROMETRIC PRODUCTS

The Mackenzie delta and Yukon Territory sites have been selected for their geohazards impact on infrastructure and environment.

The Mackenzie delta site, along the delta's Middle Channel, faces a variation in deformation rate on each side of the channel. This is a natural phenomenon due to sediment compaction. There is a need to know this natural deformation rate prior to any gas extraction and infrastructure installation (pipeline, platform). This is an on-going project and preliminary Digital Surface Model and Point Scatterer analysis are presented here.

The Yukon Territory presents discontinuous permafrost along the Alaska Highway; the largest and most heavily- traveled highway in the Yukon Territory. It is a critical infrastructure route for both Canada and the USA, being the primary land-based connection between Alaska and the rest of the United States. More than 80% of the 315 000 tonnes of goods shipped into the Yukon each year are transported on the Alaska Highway. In addition, 85% of Yukon's population resides along the highway corridor and 70% of tourists visiting the Yukon travel the highway (Huscroft et al., 2004). Thermokarst and subsidence are currently an ongoing geotechnical problem along much of the highway in SW Yukon. Analysis for this project completed in 2006 and the final deformation map is presented below.

Three types of products that can be used by geoscientists and geotechnical engineers are described in the following sections.

3.1 Interferometric Digital Surface Model

For the Mackenzie Delta, a DSM was desired to provide a baseline map elevation model of the delta. DSM generation is based on the D-InSAR technique. With no RADARSAT-2 archive imagery over the region of interest to provide InSAR DSM pairs, a data acquisition plan was developed by focusing acquisitions on the fall season. From past experience, this season corresponds to a period of the year permafrost is the least active (Alasset et al. 2008). Utilizing a period of lower activity reduces the risk of temporal de-correlation for DSM generation, which is one of the main obstacles to using InSAR processing in the Mackenzie Delta. In order to detect small vertical variations, the acquisition is based on UltraFine resolution combined with a high incidence angle (θ, Figure 1). The greater the incidence angle, the more sensitive the process is to vertical variations.

As the baseline is an artefact of the control of the spacecraft flight, it cannot be determined prior to acquisition. Hence, it is unknown until after acquisition as to whether the image pairs are suitable for DSM generation. Thus, several images are typically ordered in order to increase the likelihood that an interferometric pair is acquired which is suitable for DSM generation. In this case, the 24-day interferometric pairs show a perpendicular baseline range from 50m to 370m. The largest baseline (370m) provides the best topographic signature. From the interferogram presented in Figure 3, with a perpendicular baseline of 370m, the final SAR product before height conversion is shown in Figure 5. Figure 5 shows detailed relief along the drainage channels and lakes. The final Digital Surface Model would present height variation of 20m-30m once processing and calibration performed.

For this test site, the coherence is excellent in the late fall or late summer. During these times the change in surface conditions were not significant over a 24 day satellite re-visit timeframe. An incidence angle close to 45 degrees provided the best InSAR DSM potential in the region with low topographic relief. The choice of a large perpendicular baseline (300 meters and more) is the final key element to consider for performing this kind of process.

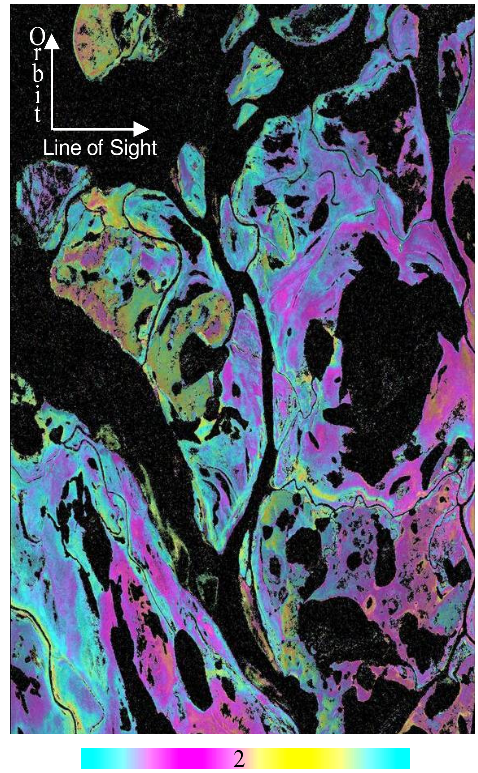

Figure 5. Final D-InSAR product (unwrapped phase) just before height conversion.

3.2 Point Scatterer Analysis

The Persistent Scatterers Interferometry (PSI) technique is being used to measure subsidence in the delta over a large time period. In this case, there are areas of old and new delta sediment along the Middle Channel in the Mackenzie delta which have different thickness of permafrost: 500m vs. 100m. Since this site spans two different types of permafrost, subsidence trends can be examined in both areas once sufficient data has been collected over the site. The PSI technique can be used with a minimum of 15 RADARSAT-2 images, to get a good statistical representation of the phase variation that overcomes the uncertainties due to noise and atmosphere effects. Three reflectors have been installed to provide a 1.5km transect across the two different thickness of permafrost. One of the three reflectors is used as a reference point (installed in an area which is not experiencing movement) and the other two reflectors are measured with respect to this control point. Figure 6 presents a radar image acquired in late December 2009 using the RADARSAT-2 UltraFine mode (3m cell resolution). The water is characterized by low signal return value (dark area), however the presence of ice is visible as a weak (light grey) signal return. The corner reflectors can be located thanks to their high radar signal return, appearing as white dots next to the red arrows in Figure 6.

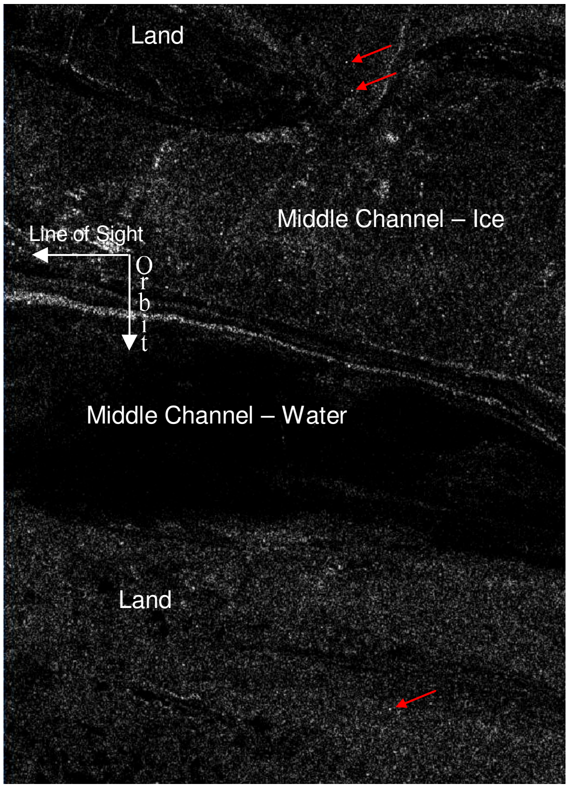

Figure 6. RADARSAT-2 UltraFine image acquired on 2009/12/24. The three corner reflectors are visible to the left of the arrows. The total length on ground is approximately 2km. RADARSAT-2 Data and Products © MacDONALD, DETTWILER AND ASSOCIATES LTD, 2009.

This project began during the summer of 2009 and is expected to last until summer 2010. This will provide a year round dataset showing the difference in settlement over the year and between young and old delta permafrost areas.

3.3 Interferometric Deformation Map

Interferometric deformation maps provide a wider-area view of deformation in a region of interest. In the Yukon Territory, InSAR techniques have been applied in 2004 and 2006 for the assessment of geohazards in permafrost degradation areas and interferometric deformation maps were a product of this analysis. These results compared favourably with conventional monitoring methods including GPS and levelling surveys.

Thawing of ice within the permafrost or within the active layer leads to various types of terrain hazards in the southern Yukon, including thermokarst, landslides (retrogressive thaw failures and active-layer detachments) and thaw settlement (subsidence). When frozen ground thaws, the soil also loses structural strength because soil particles are no longer bonded together. In permafrost with high ice-contents, thawing releases excess water that cannot be absorbed by the soil pores. In addition, the base of the permafrost can confine high groundwater pressures below the base of the permafrost. This can raise pore pressures and can create highly unstable conditions on slopes. Finally, thawed soil will settle to fill the volume formerly occupied by ice and the ground surface will subside.

The maximum amount of subsidence was on the order of 3cm, and was detected by InSAR using ENVISAT in a location west of the highway from late June to late July 2006. This is shown as the dark red area in Figure 7, and is indicative of seasonal thaw settlement in the active-layer of the undisturbed muskeg.

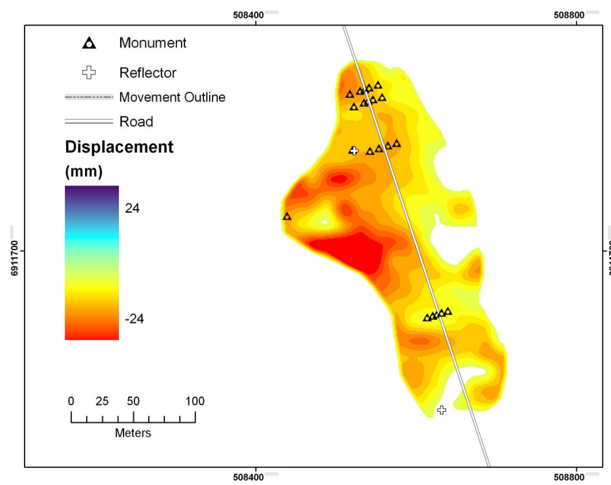

Figure 7. Movement map derived from ENVISAT data (June 21 to July 26, 2006) along the Alaska Highway, YT.

The survey monuments across the highway are showing similar results to those obtained from InSAR. The high coherence combined with the good agreement between InSAR and in-situ measurements provides high confidence in the results.

The other findings of this study were that gradual movement over relatively flat terrain was qualitatively shown to be measurable with InSAR. The technique is also suitable for slope stability monitoring if movement is either creeping or moderate movement (on the order of <10cm/year). On the other hand, this study demonstrated that significant ground motion along steep slopes, particularly if most of the movement occurred over a short time period, can cause the movement to be under sampled by the SAR sensor, leading to an underestimation of ground movement. With the recent and future launches of additional high resolution radar satellites, revisit times are decreasing to the 4-6 day range, and this under sampling anomaly is being addressed.

This study allowed end users to obtain geohazard mapping tools that define the spatial extent, temporal variation, amplitude and rate of ground movement.

4 GEOTECHNICAL APPLICATIONS, PERMAFROST

Satellite based InSAR monitoring is applicable to several specific permafrost conditions. In the northern regions unique geocryological processes such as frost heave, settlement caused by permafrost thawing, thermokarst, solifluction, and slope processes commonly occur. These processes cause vertical and/or horizontal ground displacements which in turn pose significant challenges for design and safe operation of structure and infrastructure facilities such as buildings, dams, roads and pipelines. These vertical and/or horizontal ground displacements can be monitored and verified through satellite based InSAR monitoring. Such processes can start during the construction phase and continue into the service phase. Geosystems in polar conditions can be very sensitive to even very small changes in geological conditions, because of its metastable balance. Aberration of natural geosystem balance can trigger these negative geocryological processes.

In many cases the development of settlement with time may be quite substantial. In engineering practice one has to consider the long-term effects of loading on frozen grounds as the strength characteristics of permafrost can change over time. The ultimate long-term strength of permafrost foundation may be considerably less (4 to 10 times) than its instantaneous (temporary resistance) strength. Decrease in strength takes place over a relatively long period of time, ranging from a month to a year. The long-term strength and rheological properties of frozen soils depend on temperature, grain size composition, state of compaction and consistency, total moisture or ice content of soil, and unfrozen water content. As such, monitoring becomes an important aspect of any development in the permafrost regions. In this regard, the use of satellite monitoring has a great potential to address the following issues:

1) *Degradation of ice-rich permafrost due to human activities.* For example, exploration and extraction of oil and gas resources in permafrost areas may cause thawing of frozen soil and ground subsidence. The settlement of ice-rich melting permafrost may also cause inflow of water into the well system, development of void space along the conductor and casings, and finally bending of the well tubing. Another example is construction of earth embankments (roads or dams) over permafrost ground settlement can compromise the integrity of the structure. For such cases, a satellite monitoring program with frequency of one measurement every 24 days could provide sufficient information in terms of geotechnical modeling of the site and deformation forecasts.

2) *Observations of the active layer behaviour and areas where frost heave may be an issue.* Installation of reflectors at different depths of the active layer provides the capability to monitor displacements of the freezing-thawing layer in full-year cycle; the enables measurement of the differential frost heave during the cold season, and thaw settlement during the warm period. Using both meteorological data and frost heave data with the help of modeling, one can estimate the maximum frost heave values which can occur in the case of the worst natural conditions such as a wet, rainy autumn followed by a cold winter without lack of snow. Measurement frequencies of one time every 4-6 days would provide sufficient information for appropriate model development. The area of monitoring is defined based on an engineering object – each point on the surface includes at least 3 base points at different depths in the active layer.

3) *Slope stability*. In areas of continuous permafrost, instability may occur on slopes as flat as a few degrees. Solifluction develops on low gradient slopes in summer period and vertical displacement can reach significant values starting from tens of centimetres per year. In relatively warm summers the process becomes significantly intense. The process is usually accelerated by the destruction of vegetation cover, which tends to increase thawing depth and to decrease cohesion of the active layer soils, and by small changes in hydrological regime of the active layer in summer. Measurement frequencies of once every 24 days during the year, and every 4-6 days at the end of the summer period typically provide sufficient information for appropriate model development. The area of monitoring is defined depending on the size of unstable area.

Geothermal-mechanical analysis is usually based on the physical properties of soils which can be divided into water-physical (water content, density, pure ice content), thermo-dynamical (freezing point temperature, unfrozen water content), thermo-physical (thermal conductivity, heat capacity, specific latent heat), and thermo-mechanical properties (temperature and time dependency of mechanical properties). Knowledge of the temperature regime of the ground site is also necessary which includes temperature at zero annual fluctuation depth, average annual temperature of air and ground surface, and temperature amplitude. For each specific problem additional data is needed, for instance: 1) thaw settlement – for forecast of permafrost degradation, 2) segregation potential – for frost heave prediction, 3) cohesion and strength of vegetation cover – for solifluction problem. The results of geotechnical modeling for the above mentioned cases are the following: 1) vertical settlements of ground surface for permafrost degradation related problems, 2) annual cyclic vertical displacements for frost heave problem, 3) horizontal displacements for solifluction slope stability. Using both satellite monitoring and geotechnical models provides two independent sources of information about displacements of ground surface which increases the forecast accuracy of geotechnical conditions.

4) *Construction in Arctic conditions*. This can be classified into two types of soil foundation: 1) frozen condition, and 2) unfrozen condition. Problems related to construction and operation of engineering objects in Arctic conditions are caused by the change of soil

foundation conditions such as from frozen to unfrozen or vice versa. In other words, an engineering object originally designed for the first type cannot be operated on the second type. In order to control the condition of the soil foundation the geotechnical forecast based on condition modeling is usually provided and temperature monitoring is carried out. Since the transition from frozen to unfrozen condition and vice versa is accompanied by displacements of the soil surface, the satellite monitoring of ground surface provides the necessary information in order to take timely actions to prevent negative geocryological process development.

The application of satellite monitoring will aid to prevent and to control development of negative geocryological (permafrost) processes, to minimize the impact on the environment and to improve the operation reliability of engineering objects.

5 CONCLUSION AND PERSPECTIVES

The InSAR techniques applied to measure ground deformations in two permafrost test sites have demonstrated and proven the capability of Earth Observation products to identify, monitor and assess geohazards in permafrost terrain.

The three interferometric derived products - Digital Surface Models, Persistent Scatterers, and deformation mapping - have effectively supported the applications.

A short time revisit combined with a large baseline (300m+) can lead to a high resolution interferometric Digital Surface Model. The example presented here, along the Mackenzie Delta, demonstrates the ability to predict the location of potential flooding, monitor relative height variations, and keep a historical record of coastal erosion.

The Persistent Scatterers Interferometry has the capability to measure ground deformations with a millimetric resolution, and to overcome the effects of natural decorrelation and atmosphere.

Deformation mapping provides a subsidence and heave view of an entire area that can help to identify specific phenomena which may be overlooked by singular point measurements collect by tradition survey means.

The spatial resolution capability of EO sensors could potentially provide the necessary high resolution products for developing and calibrating geotechnical models. These models can then be used for predicting ground deformation and for monitoring purposes at specific sites, and particularly those located in remote areas.

The geotechnical models for predicting the ground deformation are based on the data obtained during site investigations and laboratory tests. These are often times unavailable or very limited for development sites in northern and permafrost regions, and site investigation data may be too localized. InSAR could potentially provide a wider coverage helping to better characterize the site conditions and to monitor the infrastructures installed or constructed.

The applications of InSAR techniques in the North have a large potential. Natural gas exploitation is expected to create deformation of the land in the vertical direction due to its extraction. Establishing solid nominal values for environment variation in this vertical motion combined with geotechnical engineering will help to meet a mandate to ensure environmentally safe and sustainable development and exploitation of Canada's North.

Other potential applications for InSAR in permafrost areas include the analysis of infrastructure construction, installation of reflectors at-depth for active layer monitoring, and slope stability. As well, the availability of archival data which has been collected and stored in the past by these and other sensors provides the opportunity for back-analysis to increase the timeframe over which results can be generated.

The number of applications and quality of results continues to increase as the number of satellites and their capabilities increase providing shorter revisit-periods and higher resolution data.

ACKNOWLEDGEMENTS

The writers would like to acknowledge the support of the European Space Agency and the Canadian Space Agency and the contribution of JC Lavergne (Geological Survey of Canada) to the paper.

REFERENCES

Alasset, P.-J., Couture, R., Poncos, V., Singhroy, V. 2008. InSAR monitoring of permafrost activity in the lower Mackenzie Valley, Canada, *Proceedings of International Geoscience and Remote Sensing Symposium (IGARSS)*, Boston, USA, 4p.

Hartl, P. and Xia, Y. 1993. Besonderheiten der Datenverarbeitung bei der SAR-Interferometrie. *Zeitschrift für Photogrammetrie und Fernerkundung,* 61 (6): 214–222.

Huscroft, C.A., Lipovsky, P.S. and Bond, J.D., 2004. A regional characterization of landslides in the Alaska Highway corridor, Yukon. *Yukon Geological Survey, Open File* 2004-18, 65 p., report and CD-ROM.

Massonnet, D. and Feigl, K.L. 1998. Radar interferometry and its application to changes in the earth's surface. *Reviews of Geophysics*, 36(4): 441-500.

Prati, C., Rocca, F., Monti Guarnieri, A. and Damonti, E., 1990. Seismic migration for SAR focussing: interferometrical applications. *IEEE Transcations on Geoscience and Remote Sensing,* 28(4): 627–639.

Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodríguez, E. and Goldstein, R.M. 2000. Synthetic Aperture Radar Interferometry, *Proceedings of IEEE,* 88 (3): 333-382.

Strozzi, T., Wegmüller, U., Werner, C.L., Wiesmann, A., Spreckels, V. 2003. JERS SAR interferometry for land subsidence monitoring, *IEEE Transactions on Geoscience and Remote Sensing,* 41 (7 PART I): 1702-1708.

Zebker, H., Villasenor, J. 1992. Decorrelation in interferometric radar echoes, *IEEE Transactions on Geoscience and Remote Sensing*, 30 (5): 950-959.