Guidelines for InSAR Monitoring of Landslides in Canada.

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ABSTRACT
Satellite radar interferometry (InSAR) techniques are increasingly being used for slope stability assessment and monitoring rates of movement. In this paper we provide a summary of published case studies in Canada that assisted in producing guidelines for InSAR monitoring of gradual landslide motion. With the exception of the Frank rock avalanche all the landslides are in vegetated areas and as such installed trihedral corner reflectors were used as permanent scatters. This is very typical of most Canadian landslides. Differential InSAR technique, using two or three scenes, provide a more general and simple snap shot of slope motion. PSInSARTM/ CTM TM and Squeeze SAR TM processing techniques are more complex using more than twenty repeat pass scenes. They show the spatial and temporal heterogeneities of the terrain movements and can assist in defining the parameters controlling the dynamics of low-velocity landslides.

RÉSUMÉ
Les progrès réalisés sur l'application des techniques d'interférométrie radar (InSAR) satellitaire permettent la détermination de la stabilité des pentes et le suivi des taux de déplacement de celles-ci. Le présent compte-rendu résume les études de sites canadiens épaulant l'établissement de lignes directrices pour le suivi interférométrique de glissements de terrain graduels. À l'exception du site d'avalanche rocheux Frank, l'ensemble des sites présente un couvert végétal faisant en sorte que l'installation de réflecteurs en coin fut nécessaire pour instaurer des diffuseurs persistants locaux. Ce contexte environnemental est typique des zones de glissement de terrain au Canada. La technique InSAR différentielle, utilisant deux ou trois scènes, permet un cliché général et simplifié du déplacement de pentes. Les traitements plus complexes tels que PSInSAR$^{TM/}$ CTM ^{TM} et Squeeze SAR ^{TM} demandent plus de vingt scènes SAR de même orbite relative. Ces techniques caractérisent spatialement et temporellement les mouvements hétérogènes du terrain. Elles peuvent soutenir le processus d'élaboration des paramètres servant à contrôler la dynamique des glissements de terrain de faible vélocité.

1 INTRODUCTION

Over the past ten years, satellite radar interferometry (InSAR) techniques are increasingly being used in slope stability assessment and monitoring rates of movement. Other non-contact well-documented tools include GPS, Terrestrial Laser Scanner (TLS) and Terrestrial SAR Interferometry (TInSAR). There is an increasing interest in these innovative monitoring technologies by the geotechnical community. The InSAR monitoring techniques are becoming more widespread and reliable with rapid improvements in image processing, the availability of coherent ground targets and the more frequent revisits of radar satellites. There is therefore a need to provide InSAR guidelines for best practice. This paper will provide some simple guidelines based on published Canadian case studies of different landslides, aimed at the understanding different triggering mechanisms and rates of movement

There are several radar satellites that are being used for InSAR monitoring. Currently in orbit are RADARSAT1&2 from the Canadian Space Agency (CSA), the TerraSAR-X and TanDEM X from the German Space Agency (DLR), ERS1&2 and EnviSAT from the European Space Agency (ESA), ALOS from the Japanese Space Agency (JAXA) and COSMO-SkyMed from the Italian Space Agency (ASI). ERS -1(Cband) and both the Japanese JERS and ALOS- L band satellites are out of commission but archival InSAR images are still being used. All these satellites have different repeat cycles, radar frequencies, resolutions and viewing geometries. In the next few years, the Canadian RADARSAT Constellation (RCM) and the (ESA) Sentinel program will provide more frequent revisits (4-6 days) in support of InSAR monitoring. Table 1 summarizes the characteristics of these current and future radar satellites.

2 LANDSLIDE MONITORING USING InSAR

Current state-of-the-art in real-time monitoring of active slopes developed for early warning of landslides is very expensive. Satellite radar interferometry is used to complement real time monitoring such as GPS, TLS, and TInSAR and in-situ field measurements (Singhroy 2008) and others.

Interferometric Synthetic Aperture Radar (InSAR) techniques are being used to measure small millimetre displacement on slow moving landslides. An interferometric phase image (interferogram) represents the phase differences between the backscatter signals in two or more SAR images obtained from similar positions in space. In case of spaceborne SAR the images are acquired from repeat pass orbits. Once the topographic phase is removed, the phase differences between two repeat-pass images are the result of changes in topography, changes in the line-of-sight distance (range) to the radar due to displacement of the surface and change in the atmospheric conditions between scenes. On non-moving target, the phase differences can be converted into a digital elevation model.

InSAR techniques are being used to monitor gradual landslide motion under specific conditions, provided coherence is maintained over the respective orbit cycle. Landslide movements are measured in millimetres to centimetres per orbit cycle of the radar satellite. This orbit cycles can range from 44 days for ALOS, 24 days for RADARSAT 2, 11days for TerraSAR X 2.5 days Cosmo-SkyMed (Table1).

Reliable measurements of surface displacement can be achieved under specific conditions. These include using radar image pairs or numerous scenes (more than 25), with similar viewing geometries, short perpendicular baselines (less than 100m), short time intervals between acquisitions, and correcting for the effect of topography and atmospheric conditions. The InSAR deformation maps or profiles provide linear motion along the line of sight. However, under some geotechnical assumptions assessments can be refined to vertical and horizontal components. Recent research in the early stages is producing 3D-motion using ascending and descending orbits and additional viewing geometries.

3 InSAR PROCESSING

The common starting point of all InSAR processing is the use of the relative phase difference between two or several radar acquisitions.

Digital elevation model of the Earth surface (DEM) is the first operational success story of InSAR. Using two SAR scenes acquired on the same relative orbit, the phase difference estimation (e.g. interferogram) can be estimated. This interferogram is a function of the local topographic elevation of the surface and the baseline distance between the satellite radar antennas. As this relative phase, value is cycling over a two times PI circle, which appears as fringes on the interferogram. Phase unwrapping techniques need to be applied in order to estimate a relative surface elevation model.

Another InSAR application is the precise measurement of surface deformations. Surface deformation is estimated the result of subtracting the radar topographic phase from the SAR interferogram. The remaining phase variation on the interferogram refers to a slight geometric change of the surface. This differential InSAR technique uses a pair of SAR images. (Differential refers to the subtraction of topographic phase contribution from the SAR interferogram).The relative phase can be unwrapped and converted to a surface displacement map at centimetre scale accuracy.

InSAR DEM and differential InSAR are sensitive to atmospheric effect, incoherent temporal change of the surface and system noise. These effects can be reduced by exploiting the temporal stability of the electromagnetic properties of the surface of some area and the availability of a large amount of InSAR scenes.

PS-InSAR^{TM}(persistent scattering-PS) processes strong signals reflected from relatively small objects, which stay coherent over the time. These objects can include targets such as outcrops, buildings and other corner reflectors etc... MacDonald Detwilder and Associates, a Canadian company that commercially distributes RADARSAT images uses the term CTM ^{TM} (Coherent Target Monitoring Technique) instead PS-InSAR^{TM}. From a user perspective, both techniques are similar (Coco Cola/ Pepsi). By analysing the temporal evolution of the radar phase over a series of scenes, a deformation profile of each persistent target can be assessed at an accuracy of mm for each orbit cycle. This accuracy can be reached because of the high level of signal purity of the selected target and using more than twenty InSAR scenes which help in reducing any atmospheric effects. PS-InSAR^{TM} /CTM^{TM} are used to monitor subsidence/ deformation using man-made infrastructure or installed trihedral/dihedral corner reflectors.

SBAS (Small Baseline Subset) algorithm and its subcomponent, the “stacking” technique, are complementary methodology to PS-InSAR^{TM}, which also uses a large number of SAR scenes and short orbital baseline between acquisitions. This allows the estimation of average deformation over extended natural areas by assuming linear deformation and by reducing non-linear feature like atmospheric phase delay.

Squeeze SAR^{TM} is a new processing technique recently introduced by TRE Inc in 2011. This InSAR processing technique takes advantage of both PS and distributed scatters (DS) of homogeneous areas where the backscatters are less strong as PS. These distributed areas can include for example bare earth debris field and poorly vegetated rangeland. These additional distributed targets provide more data points thereby improving the quality of the displacement time series. This is achieved by averaging the time series of the pixels with the DS thereby reducing noise in the data.

Most of these processing techniques are available in commercial packages. However, each processing step needs to be cautiously analysed and processing parameters needs to be adapted to each site by trained operators. As part of the InSAR processing chain, phase unwrapping is still challenging under steep slope condition or discontinued areas and further improvements is needed. Additional research is also needed for non-linear deformation assessment, atmospheric effect, vegetation decorrelation and 3D deformation modeling.

4 CORNER REFLECTOR DESIGN AND INSTALLATION

Vegetation decorrelates the radar signals. Therefore, stable coherent targets such as installed trihedral or dihedral corner reflectors or buildings, roads and bridges are used to calculate the landslide motion. The uses of installed field corner reflectors are increasing on remote vegetated sites. Reflectors in Canada are generally trihedral shaped and made of perforated aluminum. 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 phase measurement. Large reflectors produce the more precise measurements. In order to maximize the target phase purity and reduce the surrounding clutter phase, the corner reflector signal has to dominate all the other scatters located in the immediate vicinity. The minimum size of the reflectors is a function of the SAR sensor wavelength of the spatial resolution and of the expected strength of the natural radar targets (rocks, houses, bridges). The corner reflector signal normally dominates 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&2 line of sight (azimuth) angle vary with the latitude. The corner reflectors used on most Canadian sites were designed to be used for Radarsat-1, Radarsat 2, and Terra-SAR X and Cosmo-Skymed missions (Forese et al 2008). During winter season, when the reflectors are filled with snow, they could become difficult to identify because their attenuated reflected signal and the snow clutter return are similar.

5 SUMMARY

Table 2 provides a summary of InSAR monitoring techniques of landslide motion under different slope, moisture, lithological/structural and vegetation conditions. The triggering mechanisms are all varied and complex ranging from permafrost melt to coastal erosion etc. The landslide types are also different.

InSAR processing techniques used include differential InSAR, PSInSAR^{TM} /CTM $^{TM\ and}$ more recently Squeeze SAR ^{TM}. The differential InSAR uses only two or three scenes or orbit cycles and provide a more general and simplified snapshot of the deformation activity of the landslide. It is a powerful tool to measure displacements because it offers a synoptic view of the landslide. The more detailed point targets or corner reflector data using PSInSAR$^{TM/}$ CTM ^{TM} or Squeeze SAR ^{TM} processing techniques are more complex. The InSAR deformation profiles for both point and distributed targets show the spatial and temporal heterogeneities of terrain movements and assist in defining the parameters controlling the dynamics of low-velocity landslides. This simple guideline on InSAR monitoring of Canadian landslides should be revised as more case studies are documented. The uses of InSAR monitoring is rapidly increasing with the availability of more frequent satellite revisits from our future RADARSAT Constellation Mission (RCM), combined with improved InSAR processing techniques taking advantage of several viewing geometries, distributed targets and smaller corner reflectors.

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Table 1. Current and future radar satellite missions

Satellite	ERS-1	ERS2	Radarsat-1	JERS-1	Envisat	Radarsat-2	AlOS	Terra SAR-X	Cosmo/ SkyMed	TanDEM X (TDX)	Sentinel	RADARSAT Constellation Mission (RCM)
Space agency	ESA	ESA	CSA	JAXA	ESA	CSA/MDA	JAXA	DLR/Infoterra GmbH	ASI	DLR / Astrium	ESA	CSA
Launch	1991	1995	1995	1992	2002	2005	2004	2006	2005	2010	2013	2015
Out of service since	2000			1998			2011					
Band	C	C	C	L	C	C	L	X	X	X	C	C
Wavelength (cm)	5.7	5.7	5.7	23.5	5.7	5.7	23.5	3	3	3	5.4	5.4
Polarization	VV	VV	HH	HH	HH/VV	QUAD-Pol	All	All	HH/VV	All	Dual (VV VH, HH HV)	HH, VV, HV, VH, Compact Polarimetry
Incidence angle (°)	23	23	20-50	35	15-45	10-60	8-60	15-60	Variable	20-55	20-45	10-60
Resolution range (m)	26	26	10-100	18	30-150	3-100	7-100	1-16	1-100	1-16	5-40	1-100
Resolution azimuth (m)	28	28	9-100	18	30-150	3-100	7-100	1-16	1-100	1-16	5-40	3-100
Scene width (km)	100	100	45-500	75	56-400	50-500	40-350	5-100 (up to 350)	10-200 (up to 1300)	5-100	20-400	5-500
Repeat pass cycle (days)	35	35 (3)	24	44	35	24	44	2-11	5-16	2-11	12	5-14
Orbital elevation (km)	785	785	798	568	800	798	660	514	619	514	693	592

Table 2. Summary of InSAR applications for Monitoring Landslides in Canada (2004-11)

Diagnostic feature/ causative factors	Sensors/ Incidence angles.	Methods	Location	Authors	Comments
InSAR monitoring of rock Avalanche: Post-slide motion Debris size and distribution Triggers: Coal mining subsidence and blast induced seismicity, geological structure and freeze thaw cycles	Radarsat SAR (fine mode-5.4m) and InSAR ERS (10m) 41 deg	D-InSAR and PS InSAR. Classification of debris apron from SAR textural analysis. .	Frank Slide, Alberta (Canada)	Singhroy & Molch(2004) Mei et al 2008	Landslide surface structures and roughness provide information on flow emplacement parameters (e.g.,emplacement, velocity and rheology) useful to characterise landslide debris. InSAR motion maps are integrated with other insitu measurement to understand post failure mechanism and mobility.
InSAR monitoring of Permafrost triggered landslides retrogressive motion	Radarsat-2 Ultra Fine Mode 3m and Spotlight (1m) 41 deg	D-InSAR and CR (corner reflector) InSAR	Thunder river, along the Mackenzie Valley Pipeline route	Singhroy 2004. Singhroy at al 2010. Singhroy et al 2008	D-InSAR techniques used to monitor seasonal motion related to spring snow melt and fall rain storms, as debris flow triggering factors.
InSAR monitoring of rock slump , toppling retrogressive failure: Post slide downslope debris flow triggered by rainfall and snowmelt	Radarsat1 (25m) 41 deg	D-InSAR	East Gate Landslide along Trans Canada highway	Singhroy et al 2006	Low SAR coherence resulted from wet slide material makes monitoring difficult without corner reflectors.
InSAR monitoring of large complex deep seated densely vegetated landslide on. dipping concave shale beds- overlain by clay and clay till.	RADARSAT-1 and ERS 25m and 41 deg	D-InSAR and CR InSAR using corner reflectors and comparison with slope inclinometer data	Little Smoky, Alberta	Froese et al 2008	With complex deformation and velocity patterns InSAR processing of corner reflectors provide point measurements with subcentimetre accuracy with a high level of confidence
InSAR monitoring landslides triggered by coastal erosion and ground water seeps	Radarsat 2 fine mode 5.6 m Terra SAR X (3m) 41 deg	D-InSAR and PS InSAR	Daniels Harbour, NF	Singhroy et al 2011 (in press)	InSAR monitors current landslides and identifies new areas of potential failures.
InSAR monitoring of Coastal Landslides Complex network of open fishers along the coastline	Fine quad mode (5m) 41 deg and Spotlight (1m) ascending 32 deg, Descending 27, and 44 degrees.	PT (Point Target) InSAR	Gascons, Gaspé, Que	Couture et al 2010	InSAR is used to monitor displacement of rock blocks and open fishers affecting the main railway line.
InSAR monitoring of Earthquake triggered landslides	Radarsat2 fine mode 5.4m (41 deg)	D-InSAR	Port-au Prince Haiti	Singhroy et al 2011	Earthquake landslides are still unstable and can be easily triggered by heavy rainfall and additional shaking. InSAR ultrafine results o show that slope stability has significantly reduced one year after the earthquake.
InSAR monitoring of deep seated rotational failures	Radarsat2 fine mode 5.4m (41 deg)	CR InSAR	Alaska Highway	Singhroy et 2011	InSAR is used to monitor gradual movement of rotational failures affecting the Alaska highway and gas pipeline.
InSAR monitoring of a slow moving earthflow	Radarsat2 fine mode (5.4m) Ascending and descending 43 and 45 deg	SqueezeSAR TM	Thomson Canyon, BC	TRE, Canada Inv 2011	Vertical and Horizontal ground motion were determined from ascending and descending LOS images