# LANDSLIDE CHARACTERISATION IN CANADA USING INTERFEROMETRIC SAR AND COMBINED SAR AND TM IMAGES.

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ABSTRACT

In Canada and the United States the direct and indirect cost of the damages caused by landslides is about US 2.2 billion dollars a year. These slides are mainly the result of excessive precipitation or ground shaking from earthquakes. Developing new remote sensing techniques to identify and characterise landslides will assist in the current national landslide inventory and hazard mapping programs. This paper reports on the use of interferometric SAR, RADARSAT, and airborne SAR combined with Landsat TM images to identify diagnostic features of landslides and their slope characteristics.

The landslide types in Canada are found in different physiographic regions and are associated with certain kinds of soil and rock materials, geologic structures and topographic settings. Interferometric SAR images provided information on detail slope profiles of the large rock slides occurring on steep slopes and along faults in the Canadian Cordillera. From this image, faults, rock slumps, block slides, slide scars and debris slopes were identified. RADARSAT images with incidence angles varying from 40- 59 degrees, particularly the fine mode images, are the most useful to identify landslide features, in mountainous areas. An interpretation of retrogressive slope failures on the shale banks of the Saskatchewan river was conducted using a combined Landsat TM and SAR images. Flow slides on sensitive marine clays were identified on airborne SAR images in the Ottawa valley. These examples show that several remote sensing techniques can assist in producing landslide inventory and risk assessment maps by providing the information on the morphological features of landslides.

Keywords. Landslides, Interferometric SAR, SAR/TM integration, RADARSAT Canada

## INTRODUCTION

Landslides have significant bearing on economic, engineering, environmental and land use projects. In Canada and the United States the direct and indirect cost of the damages caused by landslides is about US 2.2 billion dollars a year. Developing new remote sensing techniques to identify and characterise landslides will assist in the current national landslide inventory and hazard mapping programs. The significance of identifying landslide features is that they provide clues on the nature of motion and therefore indicate potential hazards along transportation routes and where protective measures are necessary. The landslide types in Canada are found in different physiographic regions and are associated with certain kinds of soil and rock materials, geologic structures and topographic settings. In this study three different topographic and geologic regions were selected. These are the Fraser valley in the Canadian Cordillera, and the Saskatchewan river valley in the prairies and Ottawa river valley in eastern Canada (Figure 1). All these areas are important transportation and economic corridors in Canada.

Landslides are abrupt shortlived geomorphic events that constitute the rapid downward motion of soil and rock materials occurring in sloping terrains. The triggering mechanism may include excessive precipitation, earthquakes, or deforestation which upset the natural stability of the slope, resulting in falling, sliding or flowing of landmass under gravity. Aerial photography has been used extensively to characterize landslides and to produce landslide inventory maps, particularly because of their stereo viewing capability and high spatial resolution. Airphotos were used to identify steep slopes underlain by weak soils, slopes undercut by rivers and waves, tension cracks, steep hummocky topography, failed surface scarps, anomalous bulges and lumps, terraced slopes, discontinuous bedding planes, drainage-vegetation patterns and elongated ponds on hillslopes (Mollard & Janes, 1983; Mollard, 1977; Alfoldi, 1973; Cruden and Lu, 1992; Savigny, 1993; Nilsen and Brabb, 1977).

The spatial resolution of satellite data TM and SPOT are generally too coarse for landslide characterization unless the image data is resampled and merged with other higher resolution airborne images. This synergistic use of satellite images for landslide hazard assessment is demonstrated by Singhroy 1995, Leroi et al.,1992; McKean et.al 1991; Rengers et al.,1992; Koopmans and Forero, 1993. This paper provides examples of the capability of combining airborne SAR and TM images, and interferometric techniques for identifying the morphological characteristics of landslides.

## METHODOLOGY

To develop new remote sensing techniques for landslide inventory, the Canada Centre for Remote Sensing (CCRS) acquired C-HH airborne SAR over several landslide prone areas along in the Fraser Saskatchewan and the Ottawa rivers. At the Fraser valley site, airborne interferometric techniques and three RADARSAT images with different incidence angles were interpreted for the identification of landslide features. At both the Saskatchewan and Ottawa river valley sites the combined airborne SAR and TM images was interpreted. An IHS technique (Singhroy 1994, 1995) was used to combine the SAR and TM images.

SAR image processing follows the procedures described by Singhroy et al.(1994). Preprocessing reduces the radiometric and geometric distortions of the SAR image thereby facilitating subsequent data integration and image interpretation. The correction of antenna pattern, and the conversion of slant to ground range was carried out by image processing tasks included in radar software packages of PCI. Georeferencing involves geometric rectification and registration to a topographic base map, and was conducted using procedures described by Guindon and Adair (1992).The airborne SAR data was geometrically corrected using 1:20,000 topographic maps. Following preprocessing the image enhancement procedure include the use of a lee filter which reduce the radar speckle, and a simple contrast stretch which improves the visual interpretability of landslide features on the image.

Radar interferometry is another technique used to characterise landslide features in mountainous areas. This technique takes advantage of the phase difference between images of two scenes. The scenes may be collected either by a single antenna from repeat passes of the platform (multipass interferometry) or by two separate antennas on a single platform (singlepass interferometry). Gray & Farris-Manning (1993) demonstrated in the early 1990's that multipass airborne interferometry could be used to measure the movement of a radar reflector to an accuracy of a few millimeters. Single pass airborne interferometry, pioneered by Graham (Graham, 1974) demonstrated its use to accurately derive terrain elevation, and thereby removal of terrain elevation induced distortions from SAR imagery.

The CCRS C-band airborne interferometry was developed the early 90's (Gray et al, 1992), An across-track InSAR data was acquired in the Fraser Valley on March 27, 1995. Two passes were flown, one from north to south looking west and the other south to north looking east. During data acquisition the ground based component of the GPS system was located at a site in Hope BC, which was also surveyed by differential P-code GPS with reference to a known site in Victoria BC maintained by the Canadian Active Control System Network. At the same time a radar calibration arc was placed by the GPS receiver to aid in subsequent phase calibration of the data.

In the following sections, some of the theoretical and practical considerations of airborne single-pass interferometry is described, and the advantages of interferometry for identification and characterisation of landslides is discussed.

## InSAR System Description

The CCRS CV-580 airborne SAR has been described elsewhere [Livingston et al, 1995]. The radar was upgraded with a C-band interferometric mode in 1991. A second, receive-only, C-band, H-polarisation, antenna was mounted at window level on the right-hand side of the Convair to complete the interferometric pair. In the interferometric mode the radar pulses are transmitted by the main antenna, and subsequently received by both antennas having nominally identical channels.

A cross-track profile of the basic InSAR imaging geometry is shown in Figure 2. A1 & A2 represent the phase centers of the main and secondary antennas, with A1 at an elevation Z above the ellipsoid; B, the baseline between the phase centers; R1 & R2, the ranges to the footprint on the ground P, located at a certain elevation above the ellipsoid h; and Θ, the incidence angle to the footprint P.

Traditional SAR systems can measure the range, R1 & R2, very accurately by precise timing the transmission and reception of the radar pulse. In these systems the transmission angle, $\Theta$, and consequently the location of footprint on the ground, remains unknown. With the two antenna system, InSAR overcomes this limitation. By measuring the phase difference of the images obtained from A1 and A2, $\rho$ (where $\rho = |R1-R2|$) can be determined to an accuracy of a fraction of a wavelength, $\lambda$ (at C-band $\lambda$ = 5.656 cm). Knowing $\rho$ and the baseline vector it is a simple matter of geometry to calculate the incidence angle, $\Theta$. Knowing $\Theta$, R1, and the location of R1, one can then calculate the position of the footprint, P, in three dimensional space. Unlike the derivation of DEMs from stereo photography or stereo radar, InSAR data processing does not include any correlation techniques to derive the DEMs. Each and every pixel in the pair of images are automatically correlated.

The CCRS Convair-580 flies at a maximum altitude of 22,000 feet above sea level. At this altitude the ground-range swath width usable for derivation of DEMs is approximately 17 km for fairly flat terrain, less for very mountainous terrain. Data is acquired from nadir. The usable incidence angles are from 30° to 75°.

As in all airborne imaging systems, a good motion compensation system is necessary. In the CCRS system, an inertial navigation unit (INU: Litton LTN-92), acquiring data at up to 64Hz, is mounted immediately above the main antenna pedestal, providing for SAR motion compensation as well as navigation. Data is also acquired from two P-code GPS (Global Positioning System) receivers, one mounted on the aircraft and the other at a known survey point on the ground. The GPS data is processed differentially post-flight and integrated into the rest of the motion compensation data. The GPS information is used post flight to compensate for vertical and horizontal drifts in the INU, and for geocoding. Together with SAR parameters, antenna drive and position data, and UNS (Universal Navigation System) flight management data, these form the basis for post-flight motion compensation. Analysis of the InSAR motion compensation system is given by Stevens et al (1995). All signal processing, which includes data resampling, motion compensation, image focusing, interferogram generation, phase unwrapping, phase calibration, phase to height conversion and geocoding, is accomplished in post-flight processing. The elevation can be mapped to a 5m or 10m grid in UTM, and is referenced to the WGS-84 ellipsoidal model. Typically the accuracy of DEMs are 1-5 m RMS error, and a height bias dependent of the use of ground control points, but normally is less than 10 m. Details of the processing and validation are discussed in Mattar et al (1994).

## Terrain Feature Extraction.

Slope features have been used for the study and prediction of terrain susceptibility to landslides (Gao & Lo, 1995). The combination of good resolution, wide swath, and direct registration of the scenes on the pixel level gives InSAR derived DEMs an advantage as a tool for the derivation of terrain features. The InSAR image and superimposed DEM is shown in Figure 6  The DEM has a grid spacing of 10 m x 10 m and covers an area 7.9 km x12.2 km. Each colour cycle represents a 50 m change in elevation.  The elevation varies from an average of 65 m in the valley to over 1300 m in the surrounding mountains.  The black regions are areas where no data was available due to either radar shadow, layover, or low return (as in the river itself). Most (but no necessarily all) of the shadow or layover regions could have been filled in had an opposite looking pass been available.

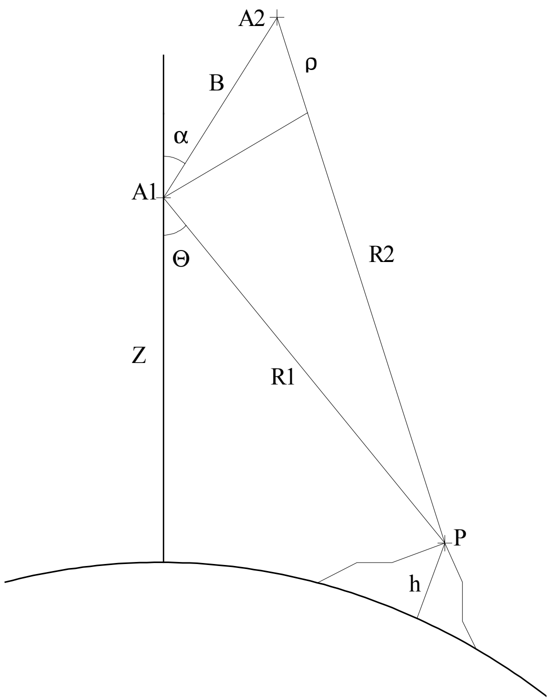


Fig.  2. Basic cross-track profile of the InSAR imaging geometry with two antenna phase centers, A1 & A2 and ranges, R1 & R2, to a footprint on the ground, P, at an elevation, z, above the ellipsoid.

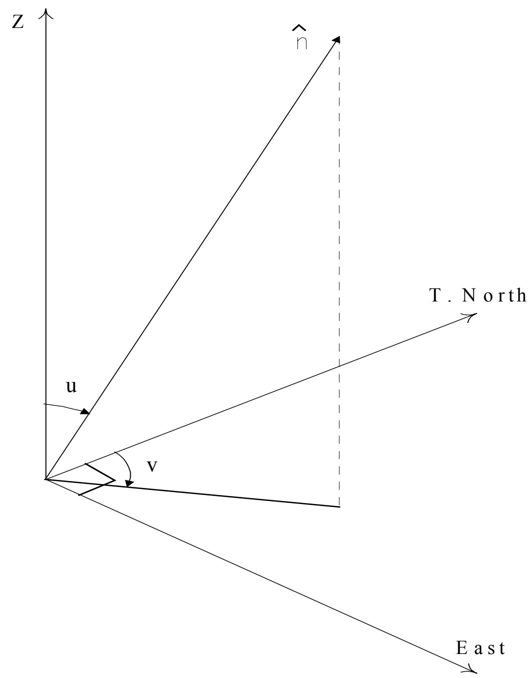


Fig.  3. Schematic of slope parameters.  u varies between 0° and 90°, and v between -180° and +180°

The InSAR DEM is in UTM coordinates, referenced to Grid North.  For this region, to convert to True North:

$$DEM_{TN} = DEM_{GN} + 1.33°$$

To derive the slope magnitude, u and direction, v, (see Figure. 3) the plane of best fit in the least square sense over a 5 x 5 window is first determined. The slope magnitude, u, can then be determined from:

$$u = \cos^{-1}\left(\frac{1}{\sqrt{1+\left(\frac{\partial h}{\partial n}\right)^2+\left(\frac{\partial h}{\partial e}\right)^2}}\right)$$

The slope magnitude, u, for this region is shown in Figure 6. It is presented in UTM coordinates forming essentially a slope map of the region. The most typical slopes are near zero (black) in the valley, and light to mid gray tones, approximately 37°. The radar signal is typically reflected by the top of the canopy. So highways and railroad tracks cut into the trees show up as a slightly different elevation. They also show up clearly as a sudden change in elevation as shown in Figure 6.

## DISCUSSION

Fraser Valley.

The Fraser valley in the Canadian Cordillera, is one of the most strategically important transportation corridors in Canada. Almost all the transportation lifelines that link the resource rich prairie provinces with metropolitan Vancouver utilize this corridor. Recently, these landslides have caused serious damage to the major transportation links. In the spring of 1997, landslides have caused the derailment of the CN railway resulting in two deaths and 20 million dollars of damage. In 1965, a large rock avalanche ($48 \times 10^6$) known as the Hope slide, occurred 160 km east of Vancouver. The slide probably triggered by two small earthquakes (M) 3.2 and 3.1, buried three vehicles and claimed four lives.

Thirty-five large landslides ranging in size from at least 1 million to more than 500 million cubic metres have been identified in the lower Fraser Valley. The causes of landslides in the area include the weakening of failure planes in carbonate rocks, solution erosion, seismic shaking, the presence of clay infilling along discontinuities, steep slopes, excessive precipitation and deforestation. Savigny (1993) identified three types of slides in the lower Fraser Valley. These include (1) slump and earth flow of surficial materials, mainly glacial drift; (2) rock slide with slide scars and multiple scarps and (3) rock slumps with several arcuate scarps. These slides mainly occur along the contact between plutons and metamorphic pendants and are associated with regional north trending thrust and strike slip faults and lineaments.

.A number of RADARSAT images with different viewing geometry were evaluated to determine which beam mode is suitable for landslide characterisation. Figure 4 shows a comparison of Standard beam mode, S1 (20-27 degrees), and an Extended high beam mode, EH6 (57- 59 degrees). It is clear that the landslide features on the steep slopes of the Fraser valley are more easily recognized on the EH6 images than from the S1 image.The S1 image with its steep viewing geometry resulted in considerable layover, which restricts interpretation of landslide features. The eastern slopes where most of the slides are occurring has a local slope which vary from 40-65 degrees, and as such are suitable for RADARSAT viewing at the higher angles between 40 and 60 degrees. From the EH6 image, block slide scarps and transverse ridges, associated with rock slumps and faults were identified. In Figure 4, block slides (1) are characterized by a number of parallel fault blocks, and steps. The rock slumps are characterized by numerous closely spaced arcuate and transverse ridges (2) with considerable rock exposure and sparse vegetation. Slide scarp (3) appear as light tone areas on steep convex slopes. Faults associated with slides appear as linear depressions are shown by arrows on the the image.

An interpretation of the landslide site in the Fraser valley using RADARSAT fine mode image (F2) is also shown in Figure 5. This image is particularly useful to identify several landslide features, such as faults, rock slump, block slides, and scars.

Figure 6 shows an airborne InSAR DEM and derived slope image, similiar to the landslide areas shown in Figures 4 and 5. A comparison of Figure 4 and 6 shows that InSAR image technique provides a better representation of landslide features than normal enhanced RADARSAT image. More lineaments (probably faults) are recognized from the InSAR image than the enhanced RADARSAT image. Since the slides occurs along fault zones, these linears, not shown on current geological maps, will provide additional information on the occurrence of future slides. In addition, slide scarp, transverse ridges and block slides are more easily identified on the InSAR image than on the RADARSAT data.The interferometric technique provides a is better representation of changes in elevation and slope and as such landslide features on the valley slopes are easily recoginzed.

Saskatchewan Valley

Along the south Saskatchewan river, landslides occur mainly in upper Cretaceous highly plastic bentonitic marine clay ,shale and silty shale. Retrogressive slope failures are flattened out as a result of slow creep movements to gradients ranging from 4-10 degrees. Such landslides are easily identified on both the SAR and combined SAR and TM images, because of their large dimensions, poorly vegetated failure surfaces, ponds, swamps and closed depressions, characteristic locations along valley walls and arcuate ,elongate ridge and depression topography (Figure 7). Faintly expressed fracture traces, developed at the high head scarp, and accentuated by surface runoff are recognized on both images shown in Figure-. Translated slide blocks produced the characteristic muntiple, subparallel elongated ridges. These translational movements are usually accompanied by some rotational and sinking movements on blocks next to the valley walls (Mollard 1977).

Landslide locations generally corrispond to areas of active lateral river erosion and to deeply incised tributaries, in which active downcutting is ongoing. Features indicative of viscious flow, described below, are not associated with these movements. Mollard (1977) noted that the slow retrogressive movements are associated with shale rebound following glacial melting and rapid downward and lateral erosion.

Ottawa Valley

The Ottawa valley, lies in a northwest trending graben, between uplifted Precambrian rocks to the north, and is underlain by Paleozoic sedimentary rocks. The valley is filled by late Quaternary sediments which consist of thick marine clays, underlain by a thin till sheet and glaciofluvial deposits. The landslides occurred in the massive to weakly stratified gray marine clay and silt with average thickness of 30-50 meters.(Gadd 1986). These slides vary from relatively small slumps to large deep seated rotational failures. When these sediments fail, they are transformed into a viscous mud, producing large retroggressive flow slides. Within the Ottawa valley, landslides have caused thirty three deaths, serious damage to homes and property, disrupted transportation and dammed rivers.In a 60 km radius of Ottawa, over 250 landslides have been mapped, on marine clays, (Aylsworth et .al 1997, Gadd et al 1978).

Figure 8 shows the CCRS airborne SAR and the combined SAR and Landsat TM images of the landslide areas along the South Nation river. Field slides show the nature of the flow slides and the engineering structures constructed on the slide zones. From the airborne SAR image, all the major slide zones were identified along the South Nation river.The slides are identified by the presence of arcuate scarps and ridges. These ridges represent the blocks of intact sediments that were broken off and carried downflow of the scarp by the underlying liquified mud. The SAR/TM colour composite image (Figure 8) is more useful from a landuse planning standpoint since both landuse and areas of landslides can easily be interpreted more easily from this image.

## CONCLUSION

It is clear that the integrated SAR/TM images and SAR interferometric techniques are useful to characterize landslides in both high and low relief areas.These techniques will supplement the current airphoto methods that are currently being used for landslide characterization and inventories. These examples have shown the following:

- In mountainous terrain's, RADARSAT incidence angles varying from 40-59 degrees, are the most the suitable to map landslide features.The high resolution fine mode image is recommended.
- The interferometric SAR technique provides a is better representation of changes in elevation and slope, and as such landslide features on the steep valley slopes are easily recognised.
- A combination of airborne SAR and TM image is suitable to characterise retrogressive slope failures and flow features in low relief areas.

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