# Mapping and monitoring coal mine subsidence using LiDAR and InSAR



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# ABSTRACT

In the early 1900s, the booming coal mining industry removed millions of tonnes of coal from underground workings spread around the Crowsnest Pass in southeastern Alberta. Since the abandonment of those workings in the early 20th century, the crowns of these workings have been subject to ongoing strain that is reflected at the surface. In some cases, where there was poor documentation, the exact locations of these workings are not known. In areas where the locations are known, the rate at which the strain is progressing in advance of collapse is not well understood. As part of the work on Turtle Mountain, in the Crowsnest Pass, both airborne LiDAR and spaceborne InSAR technologies have provided valuable new information on the distribution of abandoned underground coal mine workings and quantitative information on the patterns and rates of subsidence.

# RÉSUMÉ

Au début des années 1900, l'industrie prospère de l'extraction de la houille a permis de retirer des milliers de tonnes de charbon des chantiers souterrains répartis autour du pas du Nid-de-Corbeau, dans le sud-ouest de l'Alberta. Depuis l'abandon de ces chantiers au début du 20<sup>e</sup> siècle, les voussures de ces chantiers ont été exposées à une tension continue, laquelle se reflète à la surface. Dans certains cas, où l'on retrouvait peu de documentation, les emplacements exacts de ces chantiers demeurent inconnus. Dans les secteurs où les chantiers sont connus, le taux auquel la tension progresse avant unneffondrement demeure incompris. Dans le cadre du travaille sur les collines Turtle, dans le pas du Nid-de-Corbeau, les technologies LiDAR aéroportée et InSAR spatiale ont fournies de nouvelles informations utiles quant à la distribution des chantiers de charbonnage souterrains abandonnés et des informations quantitatives sur les modèles et le taux de subsistance.

## 1 INTRODUCTION

In the late 1800's and early 1900's, the discovery of surface accessible coal deposits in southwestern Alberta led to the establishment of both surface and underground coal mines. As there was little in the way of mechanized equipment for the coal extraction, much of this work was done manually.

For underground mines, the most common method of extraction was a conventional roof and pillar method by which pillars of intact coal were left in place to support the crown of the openings. In some cases, at the end of mining these pillars were robbed to maximize the extraction of the coal. In other cases, the pillars were left in place to theoretically continue to support to crown of As the abandonment of coal mine the openings. workings was not regulated during the early 1900's and closure documentation was very poor, the condition of the remaining pillars was not known. As well, while the general locations of mine footprints are known, the asbuilt locations of the specific adits and shafts have often been lost or available in a format that cannot be easily utilized in planning. In many cases in Southwestern Alberta there is existing infrastructure built on top of the old coal mine workings with no detailed record of the locations of the abandoned openings or monitoring of displacements.

### 2 DOCUMENTATION OF COAL MINE SUBSIDENCE AND COLLAPSE

Coal mines that were operated and closed prior to 1975, jurisdiction for addressing ongoing issues associated with abandoned workings lies with Alberta Environment. For operated/operating coal mines post-1975. the jurisdication for the regulation of these workings lies with the Energy Resources Conservation Board (ERCB) under the Coal Conservation Act and Regulation. When talking to local municipalities regarding the locations of old mine workings and jurisdiction to address subsidence hazards, the linkage is often not clear and in general the response to subsidence issues are addressed on a very ad hoc basis

With this confusion it is also often difficult to obtain detailed information as to the location of existing abandoned underground mine workings and understand the associated ground movements. In the Crowsnest Pass in southwestern Alberta, verbal reports from both the Municipality of Crowsnest Pass (MCNP) and Alberta Transportation (AT) have indicated that the occurrence of surface collapse associated with abandoned coal mine workings is a common occurrence in developed areas with the frequency of the collapses increasing in the spring (R. Mahieux, Municipality of Crowsnest Pass, personal communication, 2008). In most cases the mitigation of these collapse events is site specific and reactive.



Figure 1. Location of coal mine workings in the vicinity of the Frank Slide

As part of recent studies at Turtle Mountain, in the Crowsnest Pass, new remote sensing techniques have been utilized in order to better understand the landslide mechanisms and rates of movement for the eastern face of the mountain (Figure 1). Although these techniques have been successful for the initial purpose, they have also been an effective tool to better understand the extent and nature of the coal mine subsidence hazard in the Turtle Mountain area by both allowing for mapping of the location of the surface collapse, thus better delineating the location of the workings (e.g., Figure 2), and monitoring the rates of subsidence. The two technologies used are airborne Light Detection and Ranging (LiDAR) and spaceborne Interferometric Synthetic Aperture Radar (InSAR). The following sections provide brief detail of these technologies and their application to mine subsidence hazards in the Turtle Mountain area.

## 3 MAPPING WITH LIDAR

The use of airborne LiDAR sensors is becoming an increasingly common and effective tool essential for many projects requiring characterization of ground movement in relatively large areas.

Airborne LiDAR systems consist of a laser mounted beneath an airplane or helicopter that follows a predefined path. The ground is then scanned by means of tens of thousands of pulses per second emitted from the laser. In order to obtain measurements for the horizontal coordinates (x, y) and elevation (z) of the objects scanned, the position of the aircraft is determined using accurate differential GPS measurements and the distance from the aircraft to the ground calculated (Zang et al. 2002).

These measurements generate a 3-dimensional cloud of points with irregular spacing. Left unfiltered, the model includes treetops, buildings and vehicles. Many of these non-ground features can be removed to produce a bare earth digital elevation model (DEM). Several algorithms to eliminate non-ground objects have been proposed (Kraus & Pfeifer 1997; Pfeifer et al. 2001; Vosselman 2000).



Figure 2. Typical scanned mine as-built drawing.

However, erroneous elevation data can be obtained by removing non-ground points from LiDAR data sets. A detailed description of the sources of error when classifying LiDAR data by any filtering method can be found in Zang et al. (2002).

Airborne Imaging Inc. acquired LiDAR data near the town of Frank, Alberta, Canada in the summer of 2005. The Alberta Geological Survey purchased the license for an area covering Turtle Mountain and the "Frank Slide" areas. The project covers an area of 33 sq. km.

An extensive geodetic network was established in the area including existing government control and newly established points. The network was held fixed in three dimensions to Geodetic Survey station 55A105 on the Nad83 CSRS datum. The aircraft positions were derived from a base station WAT4 located at the Pincher Creek airport. The Airborne LIDAR survey was conducted using an OPTECH 3100 system. Flight line spacing was designed to provide an overlap of 50% between flight lines. These strips had a full scan angle of 50°. The lines were flown in a North-South direction, with adjacent lines typically flown in opposing direction. One mission was required to cover the project area, and was flown on July 24, 2005.

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Figure 3. (top) Aerial oblique photo of the east face of Turtle Mountain, (bottom) Oblique view of the east face of Turtle Mountain using the sunshade relief image of the bare earth LiDAR DEM. Note the clearly visible coal mine collapse pits that can be clearly seen on the bare earth model but not on the aerial photo.

The raw airborne kinematic data measurements were then blended with the post-processed aircraft trajectory to compute an optimally accurate, best estimate navigation solution (position and attitude). The aircraft position, attitude, mirror angles and ranges were combined to produce X, Y, Z coordinates with intensity values.

As a means to virtually remove the vegetation above the ground, a series of algorithms were run to classify LiDAR points into ground (second return) and non-ground points (first return).

In order to create a digital terrain model (DTM), a surface was interpolated by applying natural neighbour interpolation technique to the LiDAR three-dimensional points for the ground. The mesh size of the grid is 0.5 meters based on a raw point collection distribution of approximately 1 point per metre. The natural neighbour interpolation was used due to its efficiency to handle large number of input points and produce a smooth surface.

The three dimensional DTM (or bare earth model) was then used to generate sunshade relief images with various sun angles and at different orientations in order to highlight different ground features. One of the prominent features that stands out using this technique is a line of subsidence pits associated with the Frank Mine that was mined between 1901 and 1918 at the foot of Turtle Mountain (Figure 3). Figure 3 shows an aerial view of the mountain and a view generated using the LiDAR data. As is evident, the line of subsidence pits is not visible visually from the air as they are obscured by vegetation but they are clearly visible on the image generated from the bare earth model.

Figure 4 shows another series of subsidence pits across the valley and provides both the full feature (with trees) LiDAR view and the bare earth model view, clearly showing the power of utilizing LiDAR to map and locate these features. Figure 5 shows what a typical collapse pit looks like in the Crowsnest Pass and the types of features that are able to be mapped using the LiDAR.

## 4 MONITORING WITH INSAR

Radar, an acronym for Radio Detection and Ranging, is an active imaging technology that operates in the microwave portion of the electromagnetic spectrum. A radar sensor or antenna emits a series of electromagnetic pulses to the Earth's surface in the form of a sine wave, and detects the reflections of these pulses from the imaged ground targets. It records the strength of the signal, the time delay and the arrival phase of the pulse. Radar images are made up of pixels; the strength of the signal (defined as the amplitude) detected by a radar antenna defines the pixel brightness and is what we usually associate with a remotely sensed image. The time delay enables us to determine the distance from the radar antenna to the ground target, which is called "the range" in Radar terminology. The arrival phase makes it possible for Radar to detect millimetre-scale changes in the range.







Figure 5. A typical collapse pit observed on the ground in the area shown on Figure 4. A typical feature is only a few metres across and cannot be observed from the air.

A satellite with an active microwave sensor allows us to image the Earth's surface along its pass; such a satellite typically orbits the Earth at an altitude of approximately 800 km. Each pixel in the acquired image has a specific size influenced by the radar sensor resolution on the ground imaged: the higher the resolution, the smaller the pixel size. To increase the image resolution, Synthetic Aperture Radar (SAR) technology has been developed to take advantage of the spacecraft movement and advanced signal processing techniques (called SAR focusing) to simulate a large antenna size.

The reflection of the electromagnetic pulses from an area on the ground, covered by the pixel in a SAR image, is recorded as both the intensity and arrival phase of the electromagnetic pulse. Accurate measurement of the arrival phase is possible because the radar signal is coherent. This coherence means the transmitted signal is generated from a stable local oscillator and the received signal has a precisely measurable phase difference in relation to the local reference phase (the transmitted oscillator phase). This gives SAR the capability to measure the change in the distance between the radar sensor on the satellite and the target on the ground-in phase or fractional wavelength-in addition to measuring the time delay of the electromagnetic pulse. Phase is a measure of how far the wave has traveled in units of wavelength. For example, if the signal has traveled by a wavelength then the phase has changed by  $2\pi$ . Usually the phase can be accurately measured to about 10 % of the wavelength. This allows a much more accurate distance measurement than that using time delay. For example, for Radarsat-1 (C-band) with a wavelength of 56 mm, the change in the distance between the radar sensor on the satellite and the target on the ground can be measured to an accuracy in the order of millimetres (for example, (56/2) mm\*10%=2.8 mm). Compared with an 8.4 m resolution of the Fine Beam mode from the standard time delay measurement, this is about 3000 times more accurate.

However, there are millions of wavelengths between the radar sensor and the reflector on the ground, and the total number of wavelengths is not determined. Thus, the phase measurement is a relative measurement, and can be used only to tell the change in range from one measurement to the next. If two separate radar acquisitions are obtained with the same viewing geometry, or with a small distance between the two locations of the SAR platform over the same area, then, the phase difference between the two image acquisitions is related to the change in the range occurred between the two acquisitions. In turn, the change in the range between the two acquisitions is related to the change on the ground surface, or ground deformation. This forms the foundation on which Interferometric fundamental Synthetic Aperture Radar (InSAR) technology has been developed to extract information on ground deformation: by subtracting the phase of the second acquisition from that of the first acquisition. InSAR is capable of measuring the line of sight distance changes to a fraction of the wavelength of the radar sensor, and the magnitude of ground movement between two satellite passes can be measured to millimetre-scale accuracy.

To measure ground changes, images from multiple acquisitions are combined together. By calculating the phase change over the acquisition period, the ground movement in the radar line of sight can be measured within a few millimetres on a very broad area. With respect to mapping of ground subsidence using InSAR technology there have been many successful case histories published over recent years on the application of InSAR for mapping coal mine subsidence in Asia (Gao et al, (2005), Jung et al, (2007)) and Europe (Devleeschouwer et al, 2007).

Initially the area of interest for the application of InSAR for Turtle Mountain was the rugged, unstable upper portion of the mountain. Due the limitations in the orientation of the available radar satellites, the technique was not considered to be ideal for application for mapping movements in the upper portion of the mountain but was found to be very well suited for mapping deformations on the lower slopes of the mountain. As the lower slopes and valley bottom are covered with bare rock debris from the Frank Slide and recent rock fall events there were thousands of points identified that provided very good quality data for deformation monitoring.

By using data acquired by the Canadian Radarsat-1 over the time frame from April 2004 to October 2006, deformations were monitored over the lower slopes of Turtle Mountain and across the Frank Slide debris. The processing steps and findings are described in detail in Mei et al (2008). Over this time frame two active processes were observed: slow movement of the loose rock deposited on the lower slope and subsidence over abandoned underground coal mine workings.

Perhaps of most interest are the ground movements associated with the abandoned coal mines. Below the Frank Slide debris there are two coal mines that were active in the early 1900's: Frank Mine and Bellevue Mine (Figure 6). These mines consisted of large shafts that were mined with pillars of coal being left in place in order to support of the roof of the shafts. Over time these pillars may no longer support the roof, leading to slow downward movement of the roof until the point that it collapses, often creating a hole that extends to the surface. In the Crowsnest Pass there are many documented collapse pits that exist as the results of mine working collapse.

The InSAR results have showed that the ground surface above Frank Mine has been settling at an annual rate of up to 3.15 mm, relative to the reference area (Figure 6). Average changes of up to 3.2 mm per year, relative to the reference area (Figure 6), were also observed overlying the footprint of the abandoned Bellevue underground mine to the east. For both of these mines, the municipality does not currently have ground monitoring in place but acknowledges that surface collapse associated with mine subsidence is a regular occurrence that is identified and mitigated on a case-bycase basis.

#### 5 CONCLUSIONS

Over the past decade, airborne and spaceborne remote sensing techniques have slowly been incorporated into geo-engineering practice. Light and radar technologies have been demonstrated worldwide as techniques with promise for the detection and monitoring of ground hazards. In the Crowsnest Pass, airborne LiDAR data has proven important in the mapping of coal mine subsidence locations that were not previously documented. The spaceborne InSAR data over the same area has provided the first quantitative information as to the rate of subsidence over these workings.

In the future is it expected that these technologies will become more readily available and incorporated into geoengineering practice for the application to ground hazard detection, monitoring and management.

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Figure 6. Results of the PSI analysis using Radarsat-1 data from April 2004 to October 2006 showing the subsidence observed over the Frank and Bellevue Mines. Blue tones indicate downward movement in the line of sight of the radar sensor. Movements are relative to the stable reference area (black square) within the Frank Slide debris (From Mei et al, 2008).

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