INSAR APPLICATIONS
For Highway Transportation Projects

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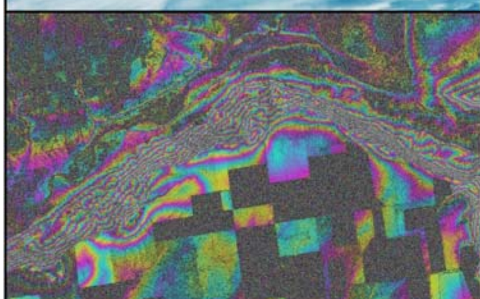

U.S. Department of Transportation
Federal Highway Administration

CTIP

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

Interferometric Synthetic Aperture Radar (InSAR) technology provides the ability to detect ground movement from satellites. Wherever vertical differential movement occurs due to subsidence, slides, settling, or creep, InSAR can estimate the differential movement to sub-centimeter resolution. Several radar satellites are commercially available to collect InSAR data on corridors of interest. For some locations, historical data dating back to 1992 is also available.

The FHWA is interested in evaluating this technology to monitor slide movements that may impact roads. To this end, the pilot project described herein was undertaken to evaluate InSAR technology at three sites using historical and recently acquired satellite data. This is the final report for this project, which establishes the relative effectiveness of InSAR in monitoring ground movement, and includes a comparison to conventional survey techniques. In addition, the described guidelines for the coordinated use of InSAR with other FHWA data collections, including photogrammetry, field surveys, boreholes and slope inclinometers.

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16. Abstract

Satellite Synthetic aperture radar (SAR) technology, in combination with interferometry (InSAR), has the ability to measure topography or ground movement to sub-centimeter accuracy. Many factors affect the ability to apply InSAR for the detection of slope movement. If these factors are considered, InSAR can often be successfully used to monitor slope movement. The Federal Lands Highway Program (FLH) of the Federal Highway Administration (FHWA) has initiated the project described within this report to evaluate the utility of InSAR technology to monitor slide movements that impact road networks. The project objective was to establish and demonstrate reliable, cost effective procedures to measure ground movement using InSAR in support of federal highways projects. This report describes the effectiveness of InSAR in monitoring ground movement, and recommends guidelines for the coordinated use of InSAR with other FLH data collections, including photogrammetry, field surveys, boreholes and slope inclinometers. InSAR has the unique ability to measure both present and prior (based on the data archives accumulated over the last 12 years) ground movement and consequently, the present study involved collection and analysis of InSAR data from both the past and present at three sites. The first site, the Prosser slide in Benton County WA, provided a site with excellent InSAR coherence and gradual creeping movement that demonstrated the limits of InSAR movement measurement. The combination of a set of InSAR movement maps over a two-year period produced movement on the order of several centimeters that qualitatively correlated well with site observations and slope inclinometer measurements. The second slope, the Cimarron slide in Owl Creek CO, exhibited moderate coherence and highly visible InSAR movement signatures were produced over periods of only several months. The third site, in Mesa Verde National Park near Cortez, CO, is a region of significant topographic relief, which made the use of satellite-based InSAR a challenge.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS AND SYMBOLS

ALOS	- Advanced Land Observing Satellite
DEM	- Digital Elevation Model
DInSAR	- Differential Interferometric Synthetic Aperture Radar
DTED	- Digital Terrain Elevation Data
EROS	- Earth Remote Observation Satellite
ERS	- European Remote-Sensing Satellite
FHWA	- Federal Highway Administration
FLH	- Federal Lands Highways
GCPs	- Ground Control Points
GIS	- Geographic Information System
GPS	- Global Positioning System
InSAR	- Interferometric Synthetic Aperture Radar
IPTA	- Interferometric Point Target Analysis
JERS	- Japanese Earth Resources Satellite
LIDAR	- Light Detection and Ranging
MP	- Milepost
NAD	- North American Datum
NMAS	- National Map Accuracy Standards
PALSAR	- Pulsed Array type L-band SAR
PS	- Point Scatterer
PS InSAR	- Point Scatterer InSAR
SAR	- Synthetic Aperture Radar
SI	- Slope Inclinometer
SRTM	- Shuttle Radar Topography Mission
USGS	- United States Geological Survey
UTM	- Universal Transverse Mercator
WGS	- World Geodetic System
WS-DOT	- Washington State Department of Transportation

CHAPTER 1 – INTRODUCTION

BACKGROUND

Synthetic aperture radar (SAR) technology, in combination with interferometry, has the ability to measure topography or ground movement. The technique is called Interferometric Synthetic Aperture Radar (InSAR), and in the context of its use in measuring relative ground movement, it is often referred to as Differential InSAR, or DInSAR. When SAR is mounted on a satellite, InSAR provides a convenient means of measuring ground movement, often without the deployment of field personnel or the expense of aircraft. Wherever vertical differential movement occurs due to subsidence, slides, settling, or creep, InSAR can often estimate the differential movement to sub-centimeter accuracy. Several radar satellites are commercially available to collect InSAR data on corridors of interest. For some locations, historical data dating back to 1992 is also available which provides a unique ability to perform historical reviews of ground movement when other data sources do not exist.

OBJECTIVES

The Federal Lands Highways (FLH) of the Federal Highway Administration (FHWA) is interested in evaluating InSAR technology to monitor slide movements that may impact road networks. A previous study by the FLH used InSAR to evaluate two landslide areas in Badlands National Park in South Dakota.(1) The FLH has initiated the current project to establish and demonstrate reliable, cost effective procedures to measure ground movement using InSAR in support of federal highways projects. This project demonstrates the effectiveness of InSAR in monitoring ground movement, and includes a comparison to conventional survey techniques. In addition, this project recommends guidelines for the coordinated use of InSAR with other FLH data collections, including photogrammetry, field surveys, boreholes and slope inclinometers.

STUDY METHODOLOGY

To execute the objectives of this project, three sites with a known history of slope instability were chosen for piloting the application of InSAR, including the Cimarron slide at Owl Creek (CO), the Prosser slide near Benton City (WA) and several unstable slopes in Mesa Verde National Park (CO). InSAR has the unique ability to measure both present and prior ground movement and consequently, the study involved collection and analysis of InSAR data from both the past and present. As stated in the original FLH solicitation, InSAR analysis was to be conducted over the following time periods, referenced to the start of the project in September 2003.

1. For a period beginning from the previous one to five years and ending within the previous year (to demonstrate the use of historical data),
2. Then for a period of time beginning at the end of the previous period and ending at a point in time following the award of this contract (to demonstrate the use of combining historical data with newly collected data),
3. Then for a period of time beginning at the end of the previous period and ending at a later point within the contract time where both InSAR and geotechnical data would be

collected simultaneously (to demonstrate the correlation of the InSAR and geotechnical data.)

The study methodology could be followed as outlined above to the extent that SAR data were available at the sites chosen for the project, and geotechnical data were collected for the correlation. However, as outlined in this document, there were several deviations made to the original study methodology to accommodate the availability of SAR images, the limited coherence of the SAR data over the desired monitoring intervals, the coordination of SAR imagery with slide events, and the availability of geotechnical data.

The collection of geotechnical data at the sites was not within the scope of this project. Instead, it was required to coordinate and direct the collection of these data, which would be funded by the participating transportation agencies if funding became available.

There are several sources of SAR data available for this study, including ERS-1/2, JERS, ENVISAT and RADARSAT-1. There are limited useful datasets available from ENVISAT and RADARSAT-1 prior to 2003 at the sites chosen for this study, and thus the main source of historical SAR data is ERS-1 and ERS-2. For all newly acquired data collected during the timeframe of this study, RADARSAT-1 was chosen as the main source of SAR data; this satellite has data which is generally more expensive than ERS-1/2 and ENVISAT however, the satellite has higher resolution imaging capabilities that are more conducive to imaging slopes.

The general methodology of the InSAR analysis was;

- Select and procure SAR data based on meteorological data and satellite baseline (see further the sections on the Factors Affecting InSAR Results and Slope Movement Monitoring in Chapter 2).
- Extract/acquire digital elevation model (DEM) for use with the analysis.
- Perform InSAR analysis, which includes:
    - SAR image processing;
    - Image geo-referencing (to DEM and other site data);
    - Image pair registration;
    - Coherence measurement;
    - Interferogram production;
    - Phase unwrapping;
    - Phase conversion to deformation; and
    - Map product generation.
- Perform deformation analysis.
- Perform geotechnical analysis and correlation of InSAR deformation movement to in-situ data collections.

REPORT ORGANIZATION

This report is organized as follows:

- Chapter 2 presents an overview of SAR and InSAR, including their application to slope monitoring and issues that must be considered when performing the monitoring.

- Chapter 3 presents an overview of the three sites selected for this study and provides background on the slope stability problems being experienced at the sites.
- Chapter 4 describes the InSAR processing that was conducted for each site, including the scenes selected, the processing and analysis performed and the interpretation of the data.
- Chapter 5 presents overall recommendations for the application of InSAR with federal highways projects and the coordinated use of the data with other data collections (surveys, photogrammetry, slope inclinometers, etc.).

CHAPTER 2 – OVERVIEW OF SAR AND INSAR

INTERFEROMETRY FROM SPACE

In recent years, space borne repeat-pass InSAR has received much attention for its ability to generate deformation maps with unprecedented accuracy (centimeter or millimeter level). SAR is an active sensor that was developed as a means of overcoming the limitations of real aperture radars.(2) SAR achieves relatively good resolution using a small radar antenna, which is an important consideration when dealing with satellites that are limited in size and are typically launched into orbits that are hundreds of miles above the Earth. To achieve this high resolution, SAR uses the motion of the radar along a flight path (or orbit) to form a 'synthetic antenna' that is much larger than its real aperture. This improves the resolution of the radar in the direction parallel to the satellite track, namely, the azimuth direction, as shown in Figure 1. To achieve a high resolution in the across track or range direction, the radar uses a frequency modulated waveform and pulse compression to simulate a very short pulse, hence a high-resolution echo. The typical horizontal, spatial resolution obtained via current satellite SAR ranges from 8-150 m (25-500 ft), and resolutions typically used for InSAR are 8-30 m (25-100 ft).

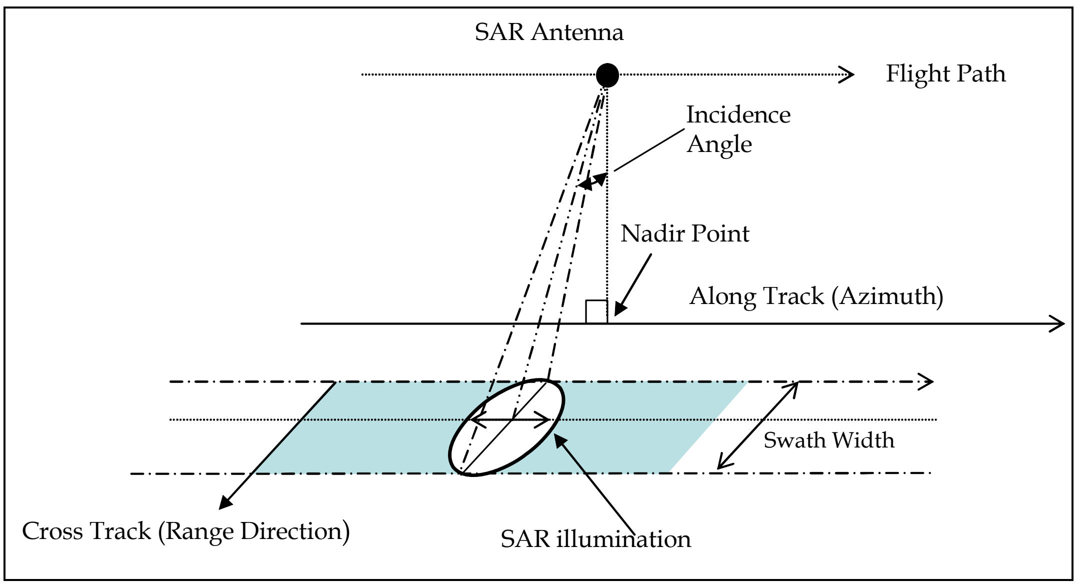

Figure 1. Schematic. Geometry of synthetic aperture radar.

Since the radar image contains the phase (ϕ) as well as the magnitude (*A*) of the backscattered radiation, topographic information can be derived from the difference in the phase, that is, the interferogram, between two images.(3) In particular, Figure 2 is a simplified illustration of the variation in phase due to ground movement. The change in the distance (*d*) between the satellite and any point on the ground (change along the look direction of the SAR) is simply the fraction, as determined from the interferogram phase ($\phi_2 - \phi_1$) for the two images, of half the radar wavelength (λ). The conversion from measured change along the look direction to the actual ground movement relies on an understanding of the ground dynamics in order to interpret the direction, and hence magnitude, of movement. When possible, measurements from another look direction may also be used to help decipher the actual ground movement.

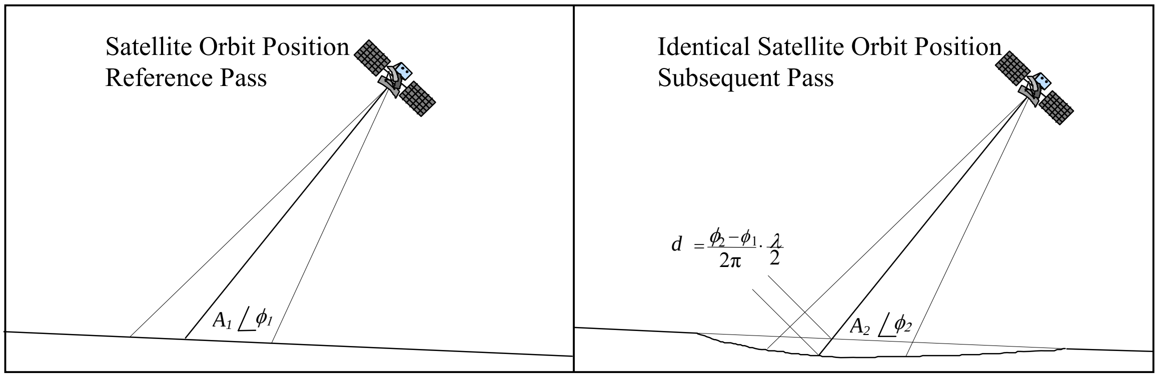

Figure 2. Schematic. InSAR measurement of ground movement.

InSAR is thus based on the combination of two complex (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 between the scatterer (the ground) and the SAR antenna as shown in Figure 3. If the observation points for the two images composing the interferogram are slightly different, a digital elevation model (DEM) can be derived from the interferogram phase, assuming that no large-scale deformation has occurred between the recordings.[(4)] On the other hand, deformation information can be derived if the SAR observation points are the same for the two images composing the interferogram, or if a DEM of the area is available. The latter is achieved by modeling the topographic phase contributions based on an input DEM and the geometry of the imaging. The phase contributions arising from the topography are then subtracted from the overall interferogram. This technique allows generation of very high accuracy (centimeter or millimeter level) deformation maps.

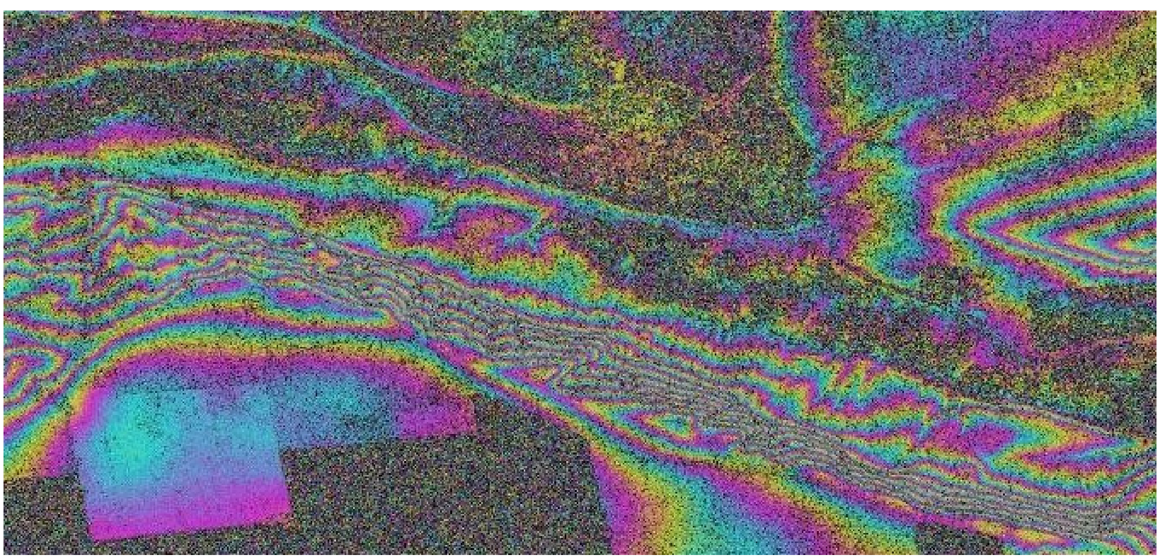

Figure 3. Graph. InSAR interferogram (location – near Benton City, Washington). Each complete color cycle, i.e. red to red, represents 360º (2π radians) of phase shift.

InSAR is unique and hardly comparable to any conventional technique of deformation measurement. Although it is becoming more accepted, the technique has to date been used in a limited number of operational applications, such as volcano and earthquake monitoring as well as subsidence monitoring. Two European satellites (ENVISAT and ERS-2) and one Canadian satellite (RADARSAT-1), as well as data from previous European (ERS-1/2) and Japanese (JERS) satellites exist that are suitable for interferometric work. The spatial resolution for the SAR sensors on these satellites ranges from 30 m (100 ft) to 8 m (25 ft – RADARSAT Fine Mode), and the orbit repeat cycles are 24 days (RADARSAT), 35 days (ENVISAT and ERS-1/2 for the majority of the mission time), and 44 days (JERS). The ERS-1/2 satellites were also operated in a tandem mode, with a 24-hour difference between the orbits of ERS-1 and ERS-2. Since there is only 24 hours between these tandem mode image acquisitions, there is generally good coherence, and hence the tandem mode is an excellent source of data for creating DEMs. The Shuttle Radar Topography Mission (SRTM) has generated DEMs at 30 m (100 ft) spatial resolution for areas of the Earth below 60° latitude (only 90 m (300 ft) resolution data have been released for areas outside the U.S.). The RADARSAT, ENVISAT, and ERS-1/2 SAR systems all use a radar wavelength of 56 mm (2.2 inch) corresponding to a frequency of 5.3 GHz, which is within the C-band radio spectrum. The JERS SAR used a wavelength of 235 mm (9.25 inch) corresponding to a frequency of 1.3 GHz, which lies within the L-band radio spectrum.

The use of satellite imagery for InSAR is convenient in that one can monitor almost any region, or as many regions, in the world as desired with equal ease. InSAR has also been successfully demonstrated from SAR equipped aircraft. This is usually more expensive but it offers the advantages of providing higher spatial resolution and the ability to control the time of data acquisitions.

FACTORS AFFECTING INSAR RESULTS

Because InSAR measures relative changes in phase, accuracy is on the order of fractions of a wavelength. For RADARSAT, ENVISAT and ERS satellites, one wavelength is 56 mm (2.2 inch) and measurements of ground subsidence on the millimeter scale have been demonstrated. However, the use of InSAR in the measurement of ground movement relies on accounting for any changes in the radar phase over the monitoring interval due to factors other than the change in the slant range distance. In particular, the radar phase will be affected by changes in the reflectivity (and the relative location) of the ground (temporal decorrelation), by changes in the viewing perspective (baseline decorrelation), and by changes in the atmosphere. In the worst cases, these factors will prevent the determination of ground movement from the interferogram phase. However, there are many cases where sub-centimeter and, indeed, millimeter accuracy can be achieved.

Temporal Decorrelation

Probably the most important limiting factor in the application of InSAR is temporal decorrelation of the ground between the interferometric acquisitions, and hence a loss of meaningful phase relation between corresponding pixels in an image pair. Temporal decorrelation usually results from changes in the complex reflection coefficient of the imaged surface.(5) Changes in the reflection coefficient are generally due to variation in the moisture content or the vegetation. Thus, decorrelation times can be as long as months to years for arid terrain and as short as several hours to several days for rainy and / or forested areas. Sparsely vegetated terrain can have decorrelation times between several days to several months. Snow-covered and frozen terrains are generally coherent over short-terms, but are sensitive to melting and snowfall. Since each pixel in a SAR image is formed by the coherent sum of the backscatter from thousands of cells on the scale of the radar wavelength, temporal decorrelation can also result from the relative movement of the scattering cells within the SAR resolution. This is particularly relevant to slope movement, since in some instances relative motion of the ground on a scale smaller than the SAR resolution may occur.

Since C-band radar has a wavelength similar to the size of small-scale vegetation characteristics — such as crop structure, foliage, and tree canopy structure — SAR images at C-band are dependent on the variations of these features, which often occur on a daily or weekly timeframe. In contrast, longer wavelength L-band radar has a wavelength on the scale of tree trunk and branch structures, which generally change over a much longer timeframe. Thus, in vegetated areas, the longer wavelength SAR provides the possibility of obtaining useable interferometric pairs over longer timeframes than provided by C-band SAR.

The problem of temporal decorrelation due to changes in the complex reflectivity of the ground or the vegetation can be mitigated through the use of phase-stable targets, such as buildings, other anthropogenic infrastructure, rock or gravel outcroppings, or radar reflectors — as shown in Figure 4 — that are installed specifically for this purpose. In these cases, however, the ground movement is measured at isolated points, and only if the spatial density of such points is high, can a continuous spatial estimate be made of the ground movement.

Figure 4. Photo. Reflectors can be used to mitigate the problem of temporal decorrelation.

Radar reflectors may be either passive or active — the former most often being constructed from metal panels as shown in Figure 4, and the latter being constructed with receive and transmit antennas linked through an amplifier. Active reflectors are smaller but they require a power source and are generally more expensive. Passive reflectors come in several variations, including dielectric lens, flat panels (mirror-type), dihedrals (two perpendicular panels), and trihedrals (three-panel corner, as in Figure 4).

In recent years, interest has been increasing in the use of permanent scatterers for SAR interferometry.(6,7,8) It is based on identifying point targets that are coherent over an extended timeframe. By measuring the interferometric phase at such points over multiple timeframes, the topographic, atmospheric, and decorrelation noise contributions can be isolated, thereby permitting an accurate assessment of the differential phase due to ground movement. Specifically, the technique relies on using the characteristic temporal and spatial scales of these contributions to aid in their identification. Accuracies approaching a millimeter have been obtained based on interferogram stacks of 40 to 60 ERS-1/2 scenes.

Baseline Decorrelation

Variation in the phase occurs with different viewing geometries, since the relative locations of the scattering cells depend on the viewing position.(4) The different viewing geometries are denoted by the satellite baseline, or the difference in orbit position from one satellite pass to the next. Satellite baseline position (both parallel and perpendicular) is illustrated in Figure 5. The variation in phase due to baseline is beyond the simple distance and phase relationship that is the basis of DEM and deformation measurements. The variation of phase with viewing geometry leads to a maximum separation between two observation locations that can be used for InSAR analysis. This maximum separation is called the critical baseline, and is dependent on the radar wavelength, the sensor-target distance, the range resolution and the incidence angle (the angle of the satellite look direction from nadir, i.e., perpendicular to the ground). Further, the coherence of an interferometric pair depends on the spectral correlation between the two observations at different viewing geometries.(9)

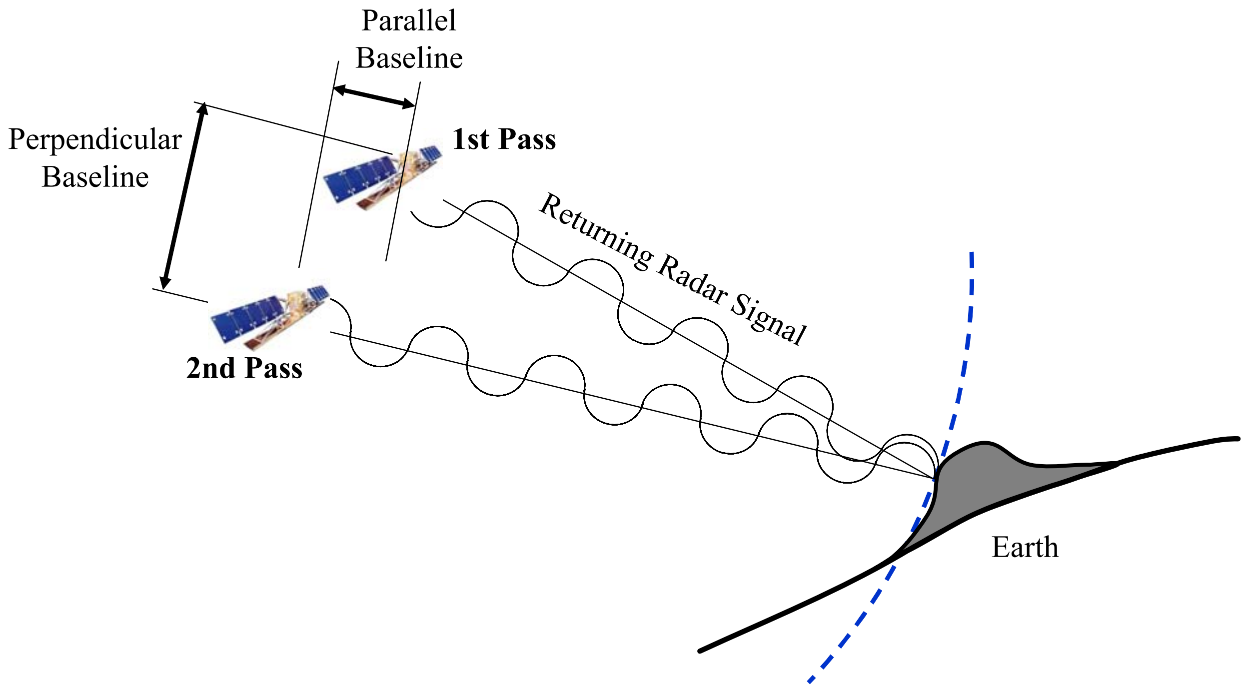

Figure 5. Schematic. Orbit baseline changes can produce varying phase shifts.

One should note that when a point target dominates the radar return within a SAR resolution cell, there is no baseline decorrelation. This, of course, assumes that the radar response from the point target is isotropic, at least within the variation of the SAR viewing geometries. The use of point targets, therefore, has the advantage that it is not sensitive to orbit baseline separation, so that it permits the use of available SAR images with larger baselines, often enabling more frequent monitoring.

Atmospheric Effects

There are numerous studies of the influence on InSAR of atmospheric effects, ranging from homogeneous effects to heterogeneities in both the troposphere and the ionosphere.(10) Phase shifts due to homogeneous atmospheres produce additional interferometric fringes and can be accounted for by adjusting the satellite baseline. Given sufficient coherence, heterogeneities can often be recognized on the interferogram. Alternatively, the variation due to atmospheric effects can be isolated from multiple interferograms.(11) This is also the approach in using interferometric stacks and in permanent scatterers analysis. In particular, for large numbers of interferograms, the atmospheric effects can be identified as a random process over time and thereby separated from other contributions to the interferometric phase.

SLOPE MOVEMENT MONITORING

The use of InSAR to measure ground movement along slopes is not as common as other applications, such as measuring crustal deformation due to earthquakes and volcanoes, and measuring subsidence, especially in urban areas. There are issues associated with using InSAR that are accentuated when it is applied to measuring slope movement. This includes the sensitivity of the SAR system to the actual slope movement, based on its look-direction and spatial and temporal resolutions.

SAR Look Direction

For the current polar-orbiting SAR satellites, the look direction (except at high latitudes) is generally either east or west, for either ascending or descending orbits respectively, as shown in Figure 6. These SAR systems are, therefore, sensitive to movement along slopes facing either east or west, and insensitive to movements in either a north or south direction. Furthermore, if the SAR look direction faces the slope, then once again the SAR is not very sensitive to movement along the slope, and, in addition, the slope face may be imaged at close to the same SAR slant range, as seen in Figure 7. This effect is worst when the slope inclination is equal to the SAR incidence angle. For steeper slopes, the SAR image suffers from layover, since the upper section of the slope is closer to the sensor and therefore it appears to be laid over the lower section.

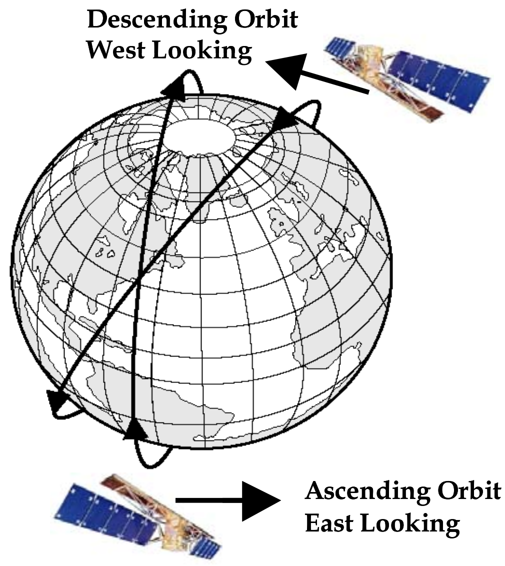

Figure 6. Schematic. Polar orbiting satellites have an east looking and west looking perspective.(12)

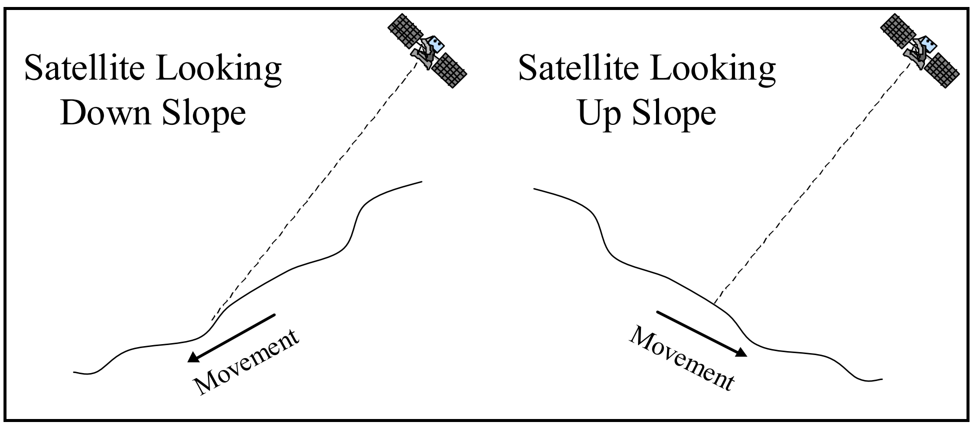

Figure 7. Schematic. Example of satellite looking up-slope and down-slope.

Movement along specific slopes is usually defined by characteristic spatial and temporal scales. These may or may not be congruous with the SAR spatial and temporal scales. In particular, small and / or fast moving slopes are difficult to measure using space borne InSAR, since the spatial resolutions of the available sensors at present are 8 m (25 ft) to 30 m (100 ft), while the orbit repeat cycles are 24 days for RADARSAT and 35 days for ENVISAT and ERS-2. If movement along larger slopes is composed of different mechanisms acting on smaller blocks, then once again the spatial resolution of the SAR may be a limiting factor in identifying these mechanisms.

In instances where a slope has to be monitored at high spatial and temporal scales, ground-based SAR systems have been used. Such systems have been used, for example, to monitor landslides in Valdarno, Italy(13) and in Schwaz, Austria.(14) An additional advantage of employing this system for high frequency monitoring is that the temporal decorrelation is minimal over the short timeframe between acquisitions.

SAR Layover and Shadow

In addition to considering issues of coherence, baseline and atmosphere, slope monitoring with SAR must also consider the slope direction and steepness along with the SAR incident angle and look direction. During the SAR acquisition, radar shadow will occur whenever the radar is looking downslope and the radar incidence angle is greater than the slope angle. In this case, the area obscured by the top of the slope will obviously not be imaged. Conversely, if the radar is looking at the slope and the radar incidence angle is less than the slope angle, then the top of the slope will be imaged before, or laid over, the lower part. In areas of either layover or shadow, the particular SAR acquisition geometry cannot provide information on slope movement. ERS-1/2 has a fixed incidence angle of approximately 23°, which is considered to be steep. RADARSAT on the other hand has variable incidence angles. For the highest resolution imagery from RADARSAT (i.e. Fine Mode), the incidence angles vary from 36° - 48°. Further explanation of this effect is provided below.

When a space borne SAR looks down and to the side toward a steep mountain, many objects on the mountain's facing slope may appear to be located at the same distance from the satellite. Since those many objects are located at nearly the same distance from the SAR, their backscattered signals will return to the spacecraft at about the same time. The SAR sensor will interpret this as a single object located at that distance; consequently, the SAR image will be very bright at that location, in which all those responses from the separate objects are mapped into one location. This is called foreshortening in the case with the objects' distances are closely spaced, or layover in the extreme case where responses from, say, a mountain's peak are positioned before surrounding locations. Figure 8 below shows an illustrative example of this for one particular incidence angle. In this case, the entire left side of the mountain cannot be imaged properly by the SAR.

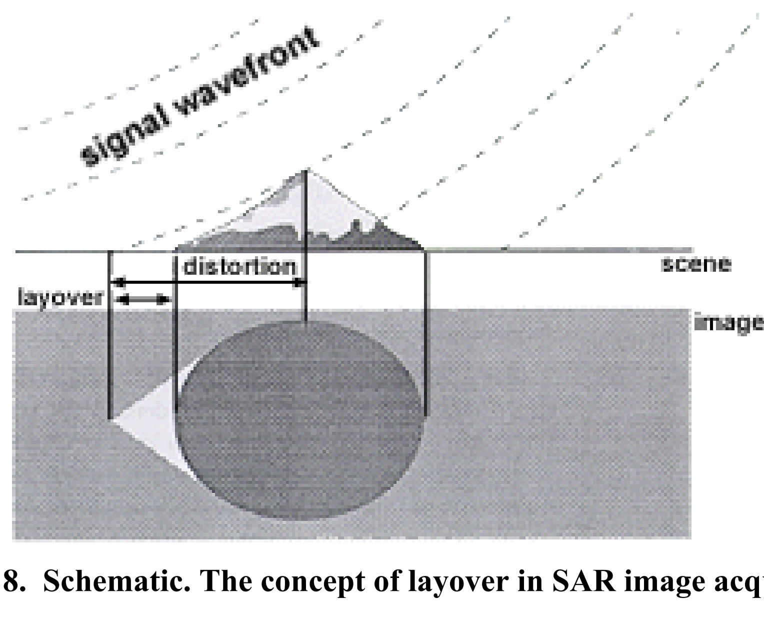

Figure 8. Schematic. The concept of layover in SAR image acquisition.

SAR illumination is much like solar illumination, and thus shadowing will also occur in cases where the front side of a slope or mountain creates a shade effect on the back side of the slope or mountain. An example of this is shown in Figure 9, except in this case, a much shallower incidence angle is used. After obtaining the very response from the front side of the slope, the SAR will suddenly sense very little or no response from the mountain's opposing face. Note that the mountain's back facing slope may be nearly parallel to the incoming radar, making it seem to the SAR that there are few responses for a significant distance.

As you can see in Figure 9, shadow is much worse for shallow incidence angles than for steep ones. In Figure 8, there was almost no shadow on the right side of the slope, but in Figure 9, the entire left side of the slope is shadowed. So, for example, ERS will have less shadow problems than RADARSAT-1. However, as Figure 9 shows, the satellite does not have a problem imaging the left side of the slope, as did the satellite in Figure 8. This implies that there is a trade off; satellites with shallow incidence angles will have a more difficult time imaging all slopes of an area of high relief if there are regions of shadow. However, shallow incidence angles may be more suitable for imaging certain portions of some steep slopes, depending on the geometry of the slope.

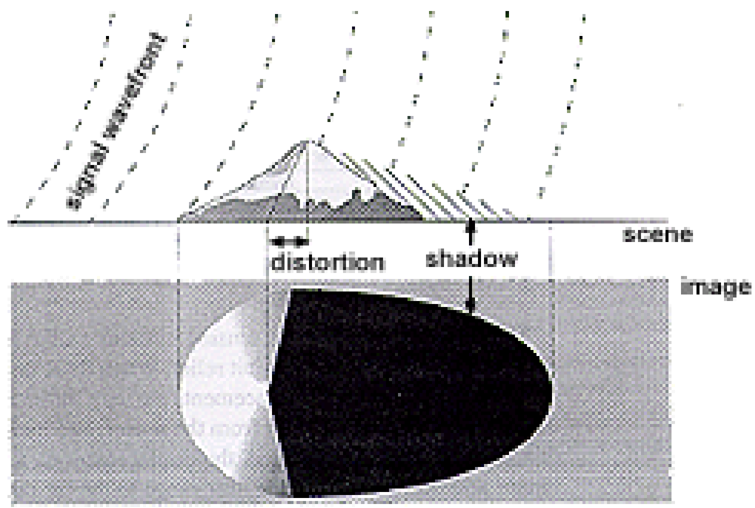

Figure 9. Schematic. The concept of shadow in SAR image acquisition.

GEO-REFERENCING AND CONTROL OF SAR IMAGES

The native format of a SAR image and the resulting movement data derived by InSAR is a raster image of data points on a uniform grid pattern. These data are not unlike that of aerial photographs, however, points on the ground are representative of microwave radiation echoes (or interpreted ground movement) rather than solar illumination. As a consequence, SAR data can be placed on a ground coordinate system (i.e., geo-referenced) using methodologies already established for use in aerial or satellite photogrammetry. These methodologies usually involve the use of surveyed ground control points (GCPs) located in the region of interest that can fix a point in the image to a location on the ground.

Collection of GCPs for Geo-referencing of SAR Images

For aerial photography, usable GCPs are objects or monuments that can be easily identified and surveyed in the air photo such as the corners of buildings or road intersections. In the absence of easily identifiable GCPs (e.g., in a rural area), control points can be placed throughout a region of interest prior to image acquisition. For example, a large white cross or square placed on bare ground can serve as a convenient and inexpensive benchmark; this artificial monument can be surveyed and subsequently removed after the air photo is captured. A suitable number of these GCPs located (or placed) throughout the air photo will allow the image to be tied to ground coordinates (e.g., state plane) and subsequently projected to a particular map projection (e.g., Universal Transverse Mercator, (UTM)).

Since SAR images are comprised of microwave echoes, the method of collecting GCPs is slightly different than that performed for air photos. Many objects that are highly visible in air photos are not visible to the SAR instrument. For example, painted white lines on a road are highly visible in an air photo but are invisible to the SAR. Therefore, GCPs must be selected that are highly visible to the radar and are easily geo-located or surveyed. For example, roadways are generally visible in SAR images and road intersections can be used as GCPs. Suitable natural GCPs include lakes and river edges (that generally are dark in SAR images) and ridgelines (that generally are bright in SAR images). Corner reflectors as shown previously in Figure 4 are most commonly used as artificial GCPs in SAR because they show up very brightly as point targets in the SAR image. They can also be pegged in place permanently if necessary and are easily surveyed with traditional equipment.

Rigorous geo-referencing of SAR images is particularly important for the application of InSAR. Raw SAR data received from image vendors is typically poorly geo-referenced with geo-referencing errors on the order of hundreds or thousands of metres. New generation satellites such as ENVISAT and RADARSAT-2 have much better base geo-referencing due to the availability of onboard Global Positioning System (GPS) for precision orbit estimation. This does not eliminate the importance of a rigorous manual geo-referencing procedure using GCPs from the most accurate source available. Manual geo-referencing allows a more accurate placement of the SAR image (and the interpreted InSAR derived movement data) in a coordinate system that is common with other forms of data, such as GIS layers (road networks, infrastructure, etc.), elevation models and topographic maps. This will facilitate a more accurate assessment of the implications of movement measurements with InSAR. In addition, InSAR requires the alignment of the SAR images with a digital elevation model to remove topographic phase; thus the precise alignment of SAR images to a reference coordinate system common with the elevation model is important. Otherwise, residual topographic phase might remain in the InSAR derived movement image, and in the extreme case, might mask actual movement data, which would lead to incorrect movement interpretations.

Sources of SAR GCPs

As mentioned above, surveyed corner reflectors are one of the best sources of GCPs for SAR data. While this is the case, it is not always possible or even necessary to place corner reflectors in the region of interest. Cost of procurement and placement of reflectors may preclude their use in a project and a new SAR image must be acquired after reflector placement to reference previously acquired SAR images in data archives. Often, there are other equally suitable data available for geo-referencing purposes, which involve other raster or vector data that have been previously referenced using survey and control methods. These data include USGS quadrangles, orthophotography, and photogrammetry, and are described in the following subsections.

Quadrangles

USGS quadrangles (topographic maps) provide the most comprehensive coverage as a control source. Thus, this is the most readily available source of SAR GCPs. These are available for all 50 U.S. states with a highest scale of 1:24,000. These can be used to geo-reference SAR data to within 20 metres (66 ft) horizontal accuracy. Features such as road intersections, water body edges and ridgelines are easily identified on these maps and their corresponding geo-locations can be used as GCPs for the SAR image. For many InSAR projects, the geo-spatial accuracy obtainable using USGS topographic maps is often more than suitable. Stated accuracies are National Map Accuracy Standards (NMAS), which are 12.2 m (± 40 ft) horizontally and one-half of the contour interval vertically (for example, contours are typically 1.5 m (5 ft) to 12.2 m (40 ft) depending on the relief.

While these topographical maps are readily available, they are limited by the geo-spatial accuracy of the base map and the limited quantity of natural or manmade GCPs that may be available throughout the image. In the case of flat rural terrain with few roads or other infrastructure, it can sometimes be challenging to find more than a couple of suitable GCPs. The use of topographic maps might also result in inaccurate geo-referencing of the SAR images if the information on the topographic map is not up-to-date. For instance, recent road re-alignments may not be reflected in the topographic map, and this could lead to incorrect placement of the SAR image if the new road alignment was used as a source of GCPs. This is particularly relevant in this project; two of the three sites used in this project have had extensive roadwork performed within the last eight years.

Another convenient source of SAR GCPs is aerial photography that has been properly geo-referenced to a standard datum and orthorectified to a suitable map projection. These include orthophotography and site specific photogrammetry.

High Resolution Orthophotography

Existing digital orthophotography can provide highly accurate horizontal control, assuming availability in the study areas. Many counties or local consortiums maintain high-resolution orthophotography as part of their electronic Geographic Information System (GIS). Pixel resolutions typically range from 15 – 60 cm (0.5 – 2.0 ft). Since this is a 2-dimensional product, only horizontal control can be obtained. Vertical control could conceivably be obtained (interpolated) from the underlying Digital Elevation Model (DEM). Although these are not as accurate as a contour DTM, elevations obtained are certainly suitable for the desired application. Elevation inaccuracies could range up to 3 m (10 ft).

For example, Benton County has 60 cm (2.0 ft) resolution color orthophotography that was acquired in 1998. These data are referenced to North American Datum 1983 (NAD-83) in Washington State Plane (South) coordinates.

Photogrammetry

Existing photogrammetry projects are another source of controlled SAR GCPs. The accuracy of photo identifiable control is relative to the flying height of the photography, which can vary widely depending on the mapping requirements (i.e. map scale and contour interval). Typical photogrammetry mapping projects will range from 1:600 to 1:2400 in map scale and will yield horizontal accuracies ranging from 30 – 150 cm (1 – 5 ft). Vertical accuracies of the underlying elevation model, assuming contour intervals from 30 – 150 cm (1 – 5 ft), will range from ± 15 – 75 cm (0.5 – 2.5 ft).

In the case of the Cimarron site, 1 m (3.3 ft) aerial photography was captured in support of the 1998 realignment of Forest Highway 78 (see further the specific section on the Cimarron slide in Chapter 3). The coverage of the air photo is 4.7 × 3.3 km (2.9 × 2.0 mi), and includes the main region of interest, i.e., the Cimarron slide and the surrounding region. The photogrammetry work conducted in 1998 included the generation of 5 m (16 ft) contours over a small section of the captured air photo. Both of the examples provided above are excellent sources of GCPs, and provide the convenient benefit of geo-referencing to control data that have already been established to CFLHD standards.

Summary of GCP Collection

In the case of the examples provided above, GCPs are only available within the extent of the established air-photo and associated control. In cases where the high-resolution air photo coverage is much smaller than that of the SAR image (as in the case of the Cimarron imagery), additional GCPs must be collected from other sources. For the U.S., 1:24,000 topographic maps can be considered the default fallback source of GCPs.

It is important to note that the presence of comprehensive site survey and control data will not alone facilitate the geo-referencing of SAR images unless the benchmarks used in the survey can be visualized in the SAR image. This is most often not the case, since the monuments used for surveying (i.e., pegs or rebar rods) are not visible in a SAR image. The site survey and control information is only useful if it is tied in with a source of usable GCPs, which is most often an orthorectified air photo.

Survey Standards for InSAR

The discussion above confirms the utility of aerial photography in combination with site control in the application of InSAR to FLH projects. Appropriate standards of these data types will now be discussed to assist in the future planning of projects that are coordinated with InSAR.

As mentioned in previous sections, the relative vertical accuracy of InSAR derived movement can be on the order of centimeters or millimeters. However, these data are placed on a raster grid with a horizontal resolution that is typically much lower than standard aerial photography. For example, RADARSAT-1 Fine mode resolution is 8 – 9 m (26 – 30 ft), which is almost an order of magnitude coarser than standard 1 m (3.3 ft) orthophotography. Even coarser are the European satellites (ERS1/2, ENVISAT) and RADARSAT-1 Standard mode, at 25 – 30 m (80 –

100 ft) resolution. SAR data can typically be geo-referenced to a maximum accuracy of half of a resolution cell, which implies that the accuracy of GCP sources should be better than 4 m (13 ft), corresponding to RADARSAT-1 Fine mode. These required accuracies imply fairly relaxed control standards for SAR-GCPs. However, it should be noted that future satellites planned for launch in 2006 (TerraSAR-X and RADARSAT-2) will have resolutions approaching 1 m (3.3 ft). Therefore to meet the highest GCP standard for existing and future satellites, GCP data sources should be referenced to sub-meter accuracy.

Recommended Survey Specification

In summary, to accurately survey monuments to support the geo-referencing of the InSAR data for the present and in the near future, a minimum of 0.5 m (1.6 ft) accuracy must be used. All of the conventional surveying techniques listed in the previous sub-sections will meet these standards. Therefore, it is recommended that, at a minimum, resource grade surveys with differential correction be used to support InSAR projects requiring accurate placement of movement data. However, it is recognized that there may be times when accurate placement of InSAR derived movement data may not be required. These cases may include, for example, projects requiring a generalized picture of movement information, rather than movement data used to assess potential impact to road infrastructure. Therefore, the following guidelines are presented to guide future InSAR projects.

1. Generalized InSAR Analysis: To obtain a generalized picture of movement over a region of interest, USGS Topographic maps can be used as the basis for InSAR control. If these data reveal potential impact to road infrastructure, control should be reverted to resource grade surveys at a minimum using the guidelines presented in points (2) to (5) below.
2. InSAR for Highway Infrastructure Analysis – Archived Data: Should post geo-referencing of the InSAR data be necessary at a slide site, identifiable features in the SAR data should be collected as GCPs and surveyed per the direction of the InSAR Specialist. Post geo-referencing refers to SAR data that have already been collected.
3. InSAR for Highway Infrastructure Analysis – Newly Acquired Data: Should geo-referencing of the InSAR data be necessary for future satellite data capture, the site and available aerial photography should be reviewed to determine the possible existence of suitable SAR GCPs. If suitable orthorectified aerial photography is not available or if a large quantity (20 or more) of suitable GCPs cannot be identified in the existing air-photos, then corner reflectors should be installed on site at the direction of the survey engineer and InSAR specialist. A minimum of six reflectors should be placed throughout the region of interest, with an additional reflector added for every 10 km^2 (4 mi^2) of monitoring interest. Using this rule of thumb, a hypothetical 5 x 5 km (3 x 3 mi) site should have nine corner reflectors installed. The corner reflectors should be surveyed to better than 0.5 m (1.6 ft) accuracy using differentially corrected resource based surveys at a minimum.
4. Final Coordinate Systems and Datum: The surveyor should coordinate with the Central Federal Lands Highway Division prior to commencement on the site to resolve any datum issues before the commencement of the fieldwork. It is recommended that the survey report the horizontal position of the geo-referencing point in the NAD 83 datum. The data should be post processed and the differential correction applied to achieve the sub-meter accuracies. It is recommended, prior to the survey, that a resource grade

position be surveyed on a known geodetic published point to provide a calibration or accuracy check.

5. Survey Report: Upon completing the geo-referencing of point positions, a Final Survey Report should comment on the accuracies of the surveyed points, meta data and procedures used. At a minimum, the report should:
   - Include an executive summary of the survey and its results;
   - Provide the metadata commenting on the point positional accuracies and post processing techniques;
   - State a narrative description of all aspects of the surveys;
   - List equipment and software details;
   - Comment on final coordinate listings;
   - Include station sketches for the ground control points.

SUMMARY OF INSAR SUITABILITY

To summarize the details presented above, there are several factors to be considered when determining a site's suitability for InSAR monitoring. These include:

- Slope Alignment:

  Slopes that are ideal for InSAR monitoring are those facing in a general East or West direction. This maximizes sensitivity of the SAR instrument, because it is pointed in the direction of the assumed slope movement. Slopes that are facing in a North or South direction may be effectively monitored with InSAR; however, the minimum detectable movement is higher for these slopes. This minimum detectable movement is determined by the slope geometry.

- Slope Grade:

  Steep slopes are often difficult to monitor with InSAR due to layover, foreshortening and shadow effects. In addition, complicated topography creates a challenge in eliminating residual topographic phase, especially when an accurate DEM is not available. Slope grades that are much less than the SAR incidence angle are preferable.

- Image Coherence:

  The InSAR coherence is one of the main factors in determining suitability. Slopes with heavy brush, fast growing vegetation and deciduous forests are generally not suitable for InSAR monitoring unless natural or artificial (e.g., structures, corner reflectors) point targets are present.

- Existing Site Data:

  The availability of site survey and control data, coupled with orthophotography, is very useful for maximizing the accuracy of the horizontal positioning of the InSAR data. In addition, these data help to provide a means to interpret the InSAR-derived movement information to determine the overall impact of any significant movement. The availability of a recent DEM is also important to the application of InSAR. Usable DEMs have the following specifications: 25 – 30 m (80 – 100 ft) spacing with vertical accuracies of 5 – 20 m (16 – 65 ft). Ideally, the DEM should cover the entire region SAR image (50 × 50 km or

100 × 100 km), and minimally should cover about 5% (~125 km^2 or ~50 mi^2) of the SAR image.

- Data availability:
  New data can always be captured on sites of interest; however, the availability of a large quantity of SAR data in the historical archive will also facilitate a review of the movement history if the data are closely spaced in time and have reasonable coherence. This is particularly relevant in this project, where it is required to perform an historical analysis of the movement at the three sites using data available in the SAR archive.

CHAPTER 3 – OVERVIEW OF SLOPES

SLOPES IDENTIFIED FOR STUDY

To execute the objectives of this project, three sites with a known history of slope instability have been chosen for piloting the application of InSAR, including the Prosser slide near Benton City (WA), the Cimarron slide at Owl Creek (CO) and several slides within Mesa Verde National Park (CO). Descriptions of these sites are described below in further detail.

PROSSER

This section is a summary from a Washington State Department of Transportation (WS-DOT) memorandum, dated November 2002.(15) WS-DOT has documented several problematic regions of ground movement along Interstate-82 near Benton City, at mileposts (MP) 90.6 and 91.9 as indicated in Figure 10 and shown in the accompanying photograph in Figure 11. The MP 90.6 site became a problem in 2002, while the MP 91.9 section (Prosser Landslide) has been a problem area since construction of the highway in the mid to late 1980's.

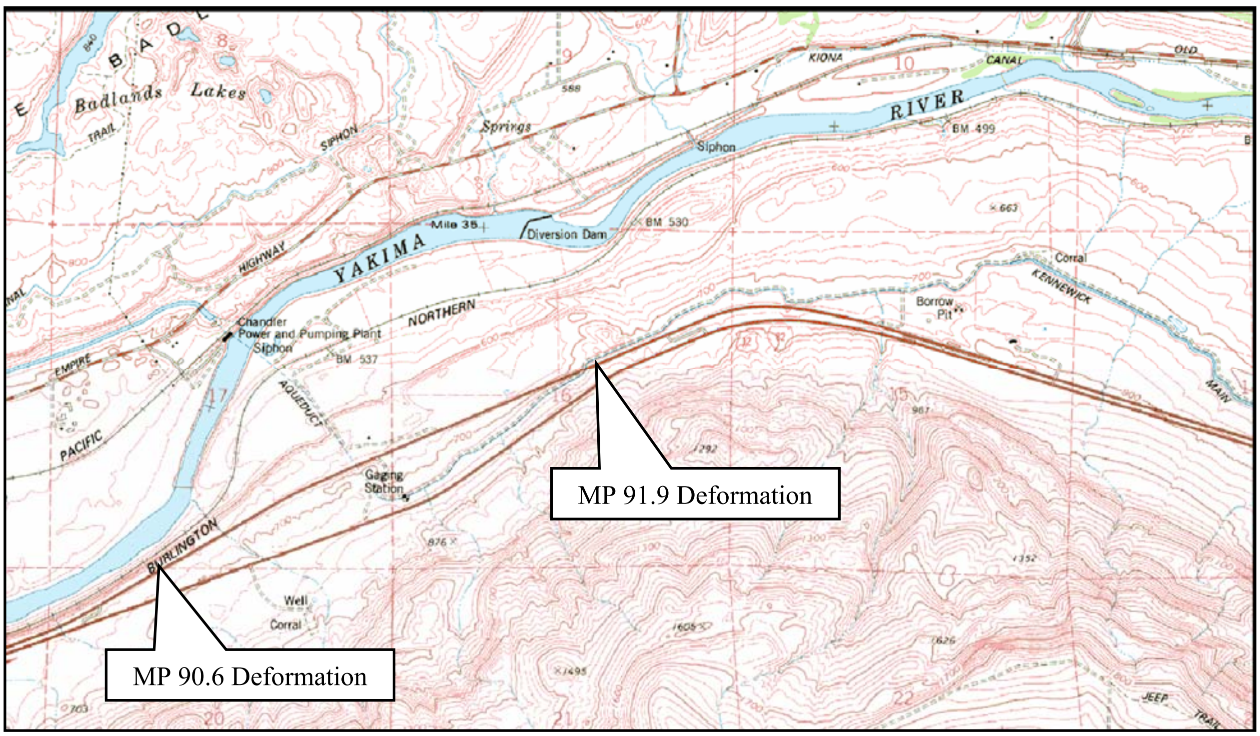

Figure 10. Map. Topographic map showing Interstate-82 and the unstable slopes to the south of the Interstate.

Figure 11. Photo. Site of historical road deformation along Interstate-82 near Benton City.

Geotechnical Background

There has been no long-term history of deformation at the MP 90.6 site. The 2002 report was the first to note the vertical uplift and deformation of the concrete panels in the eastbound lanes. Two boreholes were drilled and SIs installed as part of the 2002/03 geotechnical investigation. Large landslides exist upslope of this road deformation site as well, but to-date this upslope area has not been visibly active.

In the mid- to late-1980's, during excavation around MP 91.9 for the realignment of Interstate-82 near Benton City, WA, an approximately 1000-foot section of the eastbound lanes and the slope above began to deform. Construction was halted and a geotechnical investigation ensued. A number of borings with instrumentation were installed. The conclusion of this investigation was that the excavation had undercut a large, prehistoric landslide and reactivated it. A shear-key rock buttress was constructed to mitigate the upslope landslide movement.

In the early 1990's, tension cracks in the upslope county road and significant vertical movement of the road surface were observed. As a result of these observations, WS-DOT investigated the nature of this new distress and four additional borings were installed in 1993 and 1994. Three were placed upslope of the buttress section and one was located in front of the buttress section at its east end. The three upslope borings experienced significant lateral movement while the boring located in front of the buttress lacked any conclusive evidence of landslide-related movement. A geotechnical summary memorandum was submitted in 1995, concluding that the landslide movement continues upslope of the buttress, but no significant movement was identified in the slope inclinometer (SI) between the buttress face and the deforming eastbound lanes. It was noted that vertical movement of the highway pavement slabs may be due to the presence of a layer of expansive clays in this vicinity.

Vertical displacement continued to be observed in the concrete panels in the eastbound lanes. Since 1992, WS-DOT has removed some of the concrete panels in the MP 91.9 section to reduce the traffic hazard and improve maintenance of this problematic section. Maintenance alternates between grinding and paving to re-level this section of highway.

To reassess the extent of the movement problems at MP 91.9, further work was conducted from 2002 to 2003. The work included borings and SI measurements at several times over approximately one year.

Suitability for InSAR

To determine the suitability of this site for InSAR monitoring, the five characteristics for site selection, listed previously in the section on the Summary of InSAR Suitability of Chapter 2, were reviewed.

- Slope Alignment: The Prosser slope generally dips to the North, although it is thought that the movement is in a northwesterly direction. Therefore, the alignment of this slope can be considered fair to poor for InSAR monitoring.

- Slope Grade: The overall grade of the Prosser slide and surrounding slopes are well within recommended limit for InSAR monitoring. Shadow and layover are not a problem in the main region of interest and in the surrounding regions.

- Image Coherence: The Prosser slide and surrounding hills are characterized by dry grasses and sparse shrubs. The region is considered semi-arid, with slow growing vegetation on the slopes to be monitored. There are a number of agricultural regions in the area, in particular to the south and northwest of the Prosser slide. This may introduce some challenges to phase unwrapping. In spite of this, the site is considered to be an ideal candidate for producing high InSAR coherence over the regions of interest. This was confirmed by examining a test InSAR pair, which, as shown in Figure 12, produced relatively high coherence over the entire region of interest for the 24-day revisit time. Note that in Figure 12 the landslide area of immediate concern is outlined by the black polygon, with the two larger prehistoric landslide areas given by the red and orange polygons, and the roads denoted by the white lines.

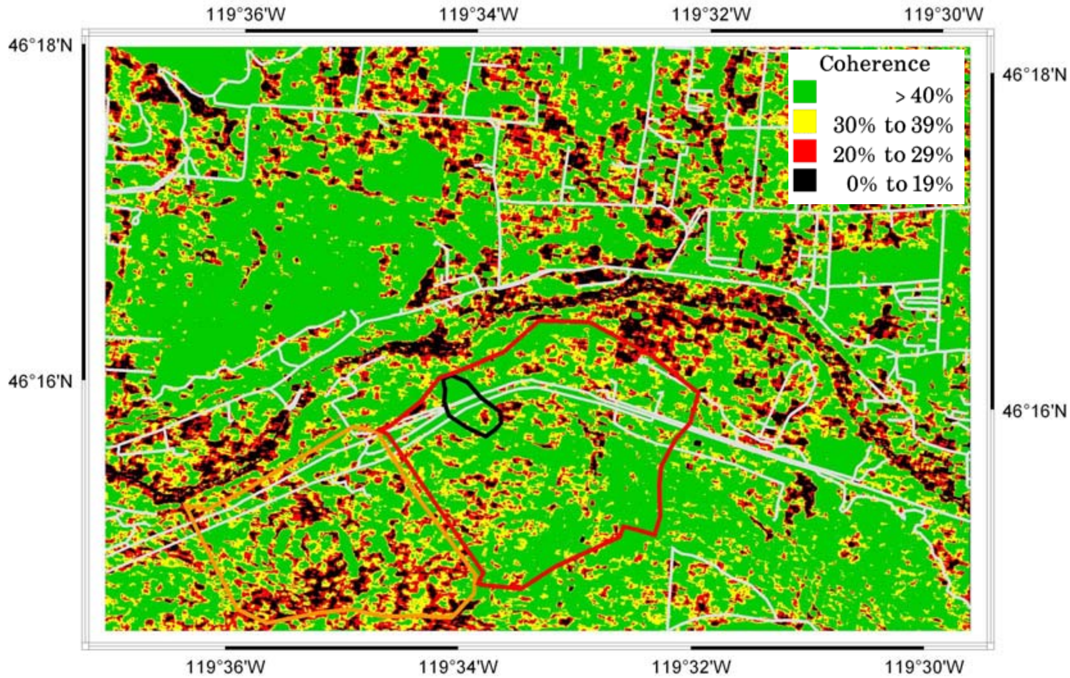

Figure 12. Graph. Coherence of Prosser site for January 15 – February 8, 2003.

- Existing Site Data: Benton County has 61 cm (2.0 ft) resolution color orthophotography that was acquired in 1998. These data are referenced to NAD-83 in a Washington State Plane (South) coordinates. Although there was no site survey meta data available at WS-DOT, survey control is believed to be well established for the site. An evaluation of the digital orthophotography revealed that it lined up well with other sources of data for the region, which confirms the accuracy of the established control in the absence of the survey meta data.

- Data availability: There is a large quantity of ERS data available over the site, comprising 20 scenes from 1998 to 2000. In addition, there is a quantity of RADARSAT-1 data starting in November 2002.

The slope alignment for this site is poor; however, the other site factors are excellent. There is generally good InSAR coherence and the orthophotography will be an excellent source of SAR GCPs to establish good geo-referencing of the SAR data. Therefore, the suitability of this site to InSAR monitoring is considered good in spite of the poor slope alignment.

CIMARRON

The following section is a summary from a paper presented at Geo-Denver 2000.[16] The Cimarron Valley is south of U.S. route 50 and east of U.S. route 550, near the town of Montrose, in southwest Colorado. A topographic map of the Cimarron Valley is given in Figure 13. There are numerous historic and prehistoric landslides in the valley. A pre-existing earth flow had been exhibiting slow creep for years. The earth flow has had an unlined irrigation ditch crossing its upper half since the early 1900's and, prior to 1996, maintenance efforts of this ditch and the nearby highway (Forest Highway 78) were minor. By 1996, however, the ditch width had reached about 50m (164 ft), probably through gradual movement and erosion. In 1996, the ditch was reconstructed to its narrower section and a depression that had developed in Forest Highway 78 was filled where it crossed the earth flow below the ditch. No other actions were taken in 1996 and no unusual movement was observed.

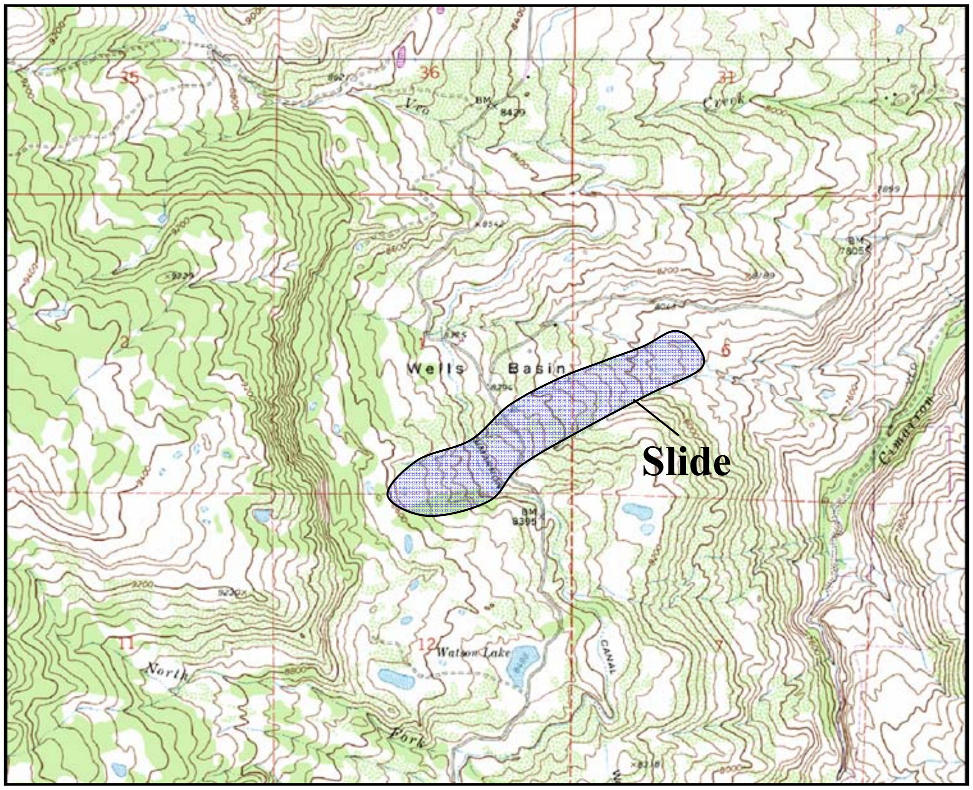

Figure 13. Map. Topographic map showing a portion of Cimarron Valley and the Cimarron Slide.

The spring of 1997 was wetter than average and in June 1997 part of the earth flow started to move rapidly, reaching rates of up to a few meters per day. More than 150 m (490 ft) of horizontal movement accumulated during the summer and the rapid movement stopped by November.

Geotechnical Background

A geotechnical investigation conducted by FLH on this problem indicated that failure occurred by sliding along a basal clay layer just above the shale bedrock and that shear failure in this clay layer was triggered by excessive pore fluid pressures most likely resulting from the unusually high precipitation. Available geotechnical data includes surface site inspections throughout the period of major sliding from June to November 1997, subsurface soil profiles from a borehole program from November 1997 to February 1998, and SI measurements from November 1997 to May 1998. Descriptive reports of similar land sliding in the valley more than 100 years previous were discovered during the investigation of this slide, which aided in the understanding of slope failures generally within the valley.

The Cimarron River valley elevation is between about 2,100 m (6,930 ft) and 2,800 m (9,240 ft) above sea level. The lower valley slopes are vegetated with grass and sagebrush, and other limited woody vegetation. The upper slopes contain aspen and conifer trees. The lower valley slopes are gently sloped and undulating, and the upper slopes are notably steeper, in many places consisting of bedrock outcrop. A recent photo of the slide is provided in Figure 14, with the slide location indicated by the yellow arrow.

Figure 14. Photo. Cimarron Slide, Owl Creek, CO.

Suitability for InSAR

To determine the suitability of this site for InSAR monitoring, the five characteristics for site selection, listed previously in the section on the Summary of InSAR Suitability of Chapter 2, were reviewed.

- Slope Alignment: The Cimarron slide is generally facing towards the East-Northeast direction, which is generally favourable for InSAR.

- Slope Grade: The overall grade of the Cimarron slide and surrounding slopes are well within the recommended limit for InSAR monitoring. Shadow and layover are not a problem in the main region of interest, however there is some layover and shadow present along the river valley to the east of Cimarron. This will not present a problem for monitoring the Cimarron slide.

- Image Coherence: The Cimarron slide is similar to Prosser in that the slope face is characterized by dry grasses and sparse shrubs. Unlike Prosser however, the Cimarron area also contains some stands of conifers and deciduous trees (mostly aspen and scrub oak as seen in the upper left of Figure 14). These forested regions will make phase unwrapping challenging for summer SAR acquisitions because it will create patches of low coherence. This problem should be reduced in the fall and spring when leaves are absent from the deciduous trees. Based on the above, the site is considered a reasonable candidate for producing good coherence of large portions of the SAR image from spring to summer to fall. However, due to snow cover in the winter, monitoring during these months will not be possible. A test InSAR pair captured at a 24-day interval early in this monitoring program revealed good coherence over much of the image, with low coherence patches, as shown in Figure 15. The slide area of interest is outlined by the black polygon in the figure, with the roads shown as red lines. Since this pair was captured in the fall, this coherence represents the best-case scenario, and lower coherence should be expected for summer intervals.

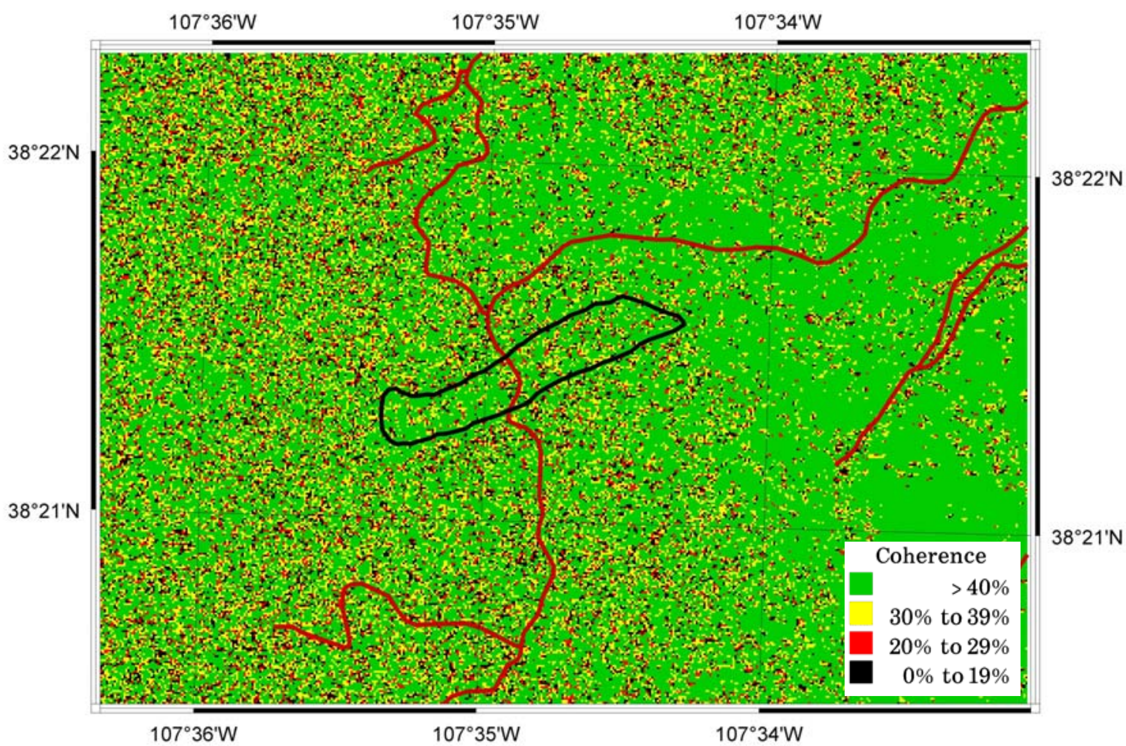

Figure 15. Graph. Coherence of Cimarron site (slide outlined) for September 3-27, 2003.

- Existing Site Data: Of the three sites, the Cimarron site has the most survey control information available. Aerial photography, digitized to 1 m (3.3 ft) resolution, was captured in support of the 1998 realignment of Forest Highway 78. The coverage of the air photo is 4.7 × 3.3 km (2.9 × 2 mi), and includes the main region of interest, i.e., the Cimarron slide, and surrounding region. The photogrammetry work conducted in 1998 included the generation of 5 m (16 ft) contours over a small section of the captured air photo. Wilson & Company performed the primary control network in 1997 for the

ground control supporting the aerial mapping. The final coordinates for the primary control and panel points were published in:
  - NAD 83 Geodetic, Meter
  - State plane Lambert, Colorado Central, Meter
  - Ground Coordinate System by modified state plane, Meter

  The positional accuracies of the published points are within centimeters.

- Data availability: In the timeframe from 1993 to 2003, there is a quantity of ERS SAR data that was available in the summer of 1997 during the time of the main slide event. In addition, there is a quantity of SAR data captured over the region during the summer of 2000.

Given the above favorable site characteristics, this area is considered to be a good candidate for InSAR monitoring.

MESA VERDE

Public access to Mesa Verde National Park and the cliff dwellings it contains is only from the north on the Main Access Road, as shown in the topographic map of Figure 16. This road crosses slopes comprised of the Mancos shale and other problematic sedimentary formations to reach the cliff forming Mesa Verde sandstone and the historic sites. The road has been continuously impacted by landslides and has been realigned several times in an effort to find more stable ground, safer and more dependable access, and lower maintenance requirements.

Geotechnical Background

Major realignments to the Main Access Road started in 1927 when the road was removed from the slope northwest of Lone Cone and located on the east-facing slope east of Point Lookout, which is its current location. Figure 17 shows a topographical map circa 1926 with the original alignment of this road. Once in Morfield Canyon however, the road continued back to the northwest and around the north and west of the Knife Edge to the Montezuma Valley Overlook. This continued to be the alignment until approximately 1950, when the existing tunnel was built to connect Morfield and Prater Canyons. Several years later, another realignment was made between Montezuma Valley Overlook and Moccasin Overlook, to the south. This alignment reduced the grade on the road and added several new cuts and fills. Subsequent to these realignments, slope stability has been an ongoing issue, especially in the Point Lookout area (Point Lookout Slide), north of the Mancos Valley Overlook and in the cuts and fills in the vicinity of Moccasin Overlook (for example, MP 8.3, MP 8.6, MP 8.9, and MP 9.3 slides as indicated in Figure 16). Further details of this are provided below.

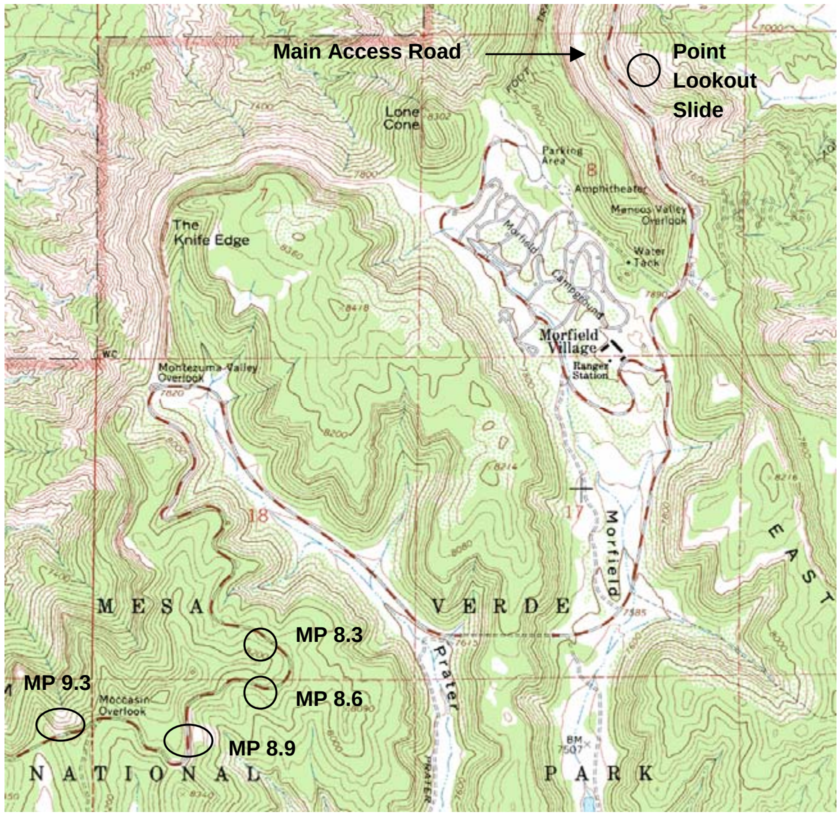

Figure 16. Map. Topographic map showing locations of unstable slopes in Mesa Verde National Park.

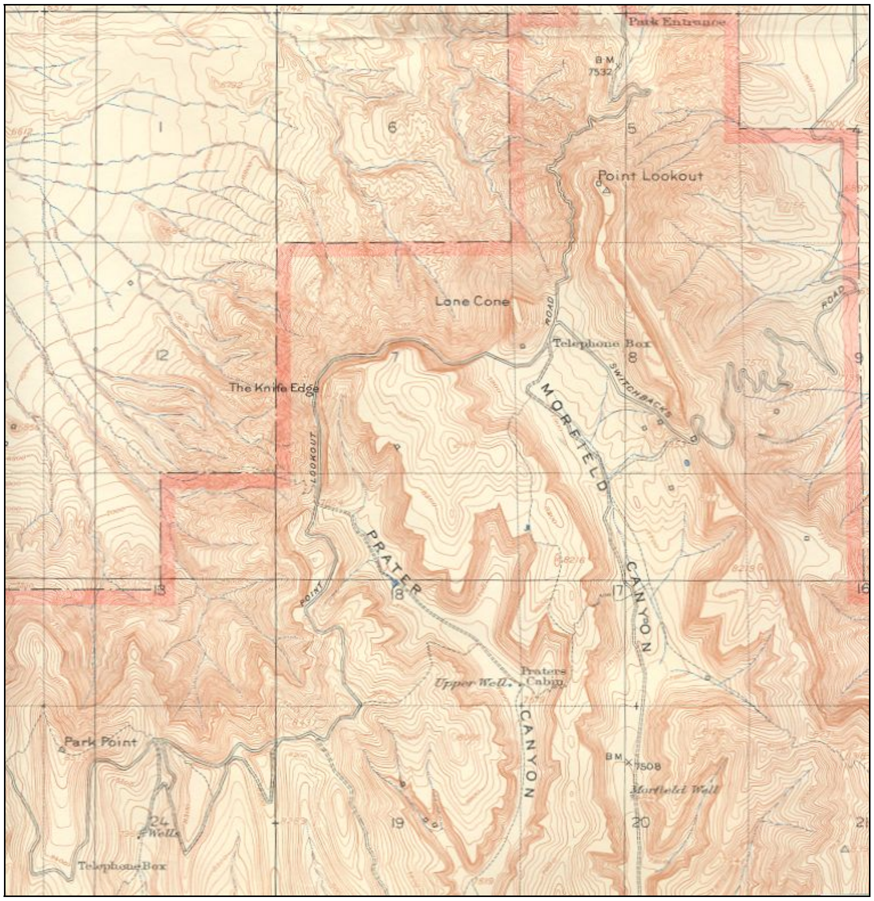

Figure 17. Map. Topographic map circa 1926 showing original alignment of Main Access Road to the park.

Figure 18. Photo. Unstable slope near Mile Post 9.3 in Mesa Verde National Park, CO.

Figure 18 shows the MP 9.3 site, where a rock fall is occurring in the cut above the road and slumping is occurring below the road. This area was reconstructed in 1985 and there has been movement since; pavement cracking, a settling shoulder, and visible distress in the slope well below the road are evidence of this.

MP 8.9 was reconstructed in 1985; some indication of movement was apparently evident prior to November 1996, when a slope indicator (SI) was installed. The SI was read once on April 30, 1997, and indicated movement. A small failure occurred in the spring of 1997, followed by a major failure in the spring of 1998; this happened again in January 2000, where more of the toe slope moved and more of the road was lost. In 2000, the site was repaired with a flatter slope and additional drainage.

MP 8.6 was reconstructed in 1985 and slope failure began in the spring of 1989. SIs were installed in September 1994 and were monitored occasionally through April 1997; at the time they were monitored, the SIs showed movement. Initial mitigation was through small fill wall construction and finally by realignment away from the slope in 2001.

MP 8.3 was reconstructed in 1985 and slope failure began in the spring of 1989. SIs were installed in November 1996 and they show no movement through 1997. Movement has not been evident since 1989.

The Point Lookout Slide failed so significantly in 1959 that the Park was closed for an extended period, the slope was re-graded and the road was reconstructed. Movement continued through the 1980's and 1990's, a period where lightweight fill, tieback walls, ground anchors, re-grading, horizontal drains and drainage galleries were all installed to stabilize the slope and slow movement.

Suitability for InSAR

To determine the suitability of this site for InSAR monitoring, the five characteristics for site selection, listed previously in the section on the Summary of InSAR Suitability of Chapter 2, were reviewed.

- Slope Alignment: Of particular interest for the current evaluation were the slopes along the east side of Point Lookout, as indicated Figure 16. Since these slopes generally face an easterly direction, the slope alignment is good for satellite-based InSAR. Other slopes of interest are at MP 8.3, 8.6, 8.9 and 9.3, as also indicated in Figure 16. The slope at MP 8.9 is east facing. The other slopes have less favourable alignment: at MP 8.3 the slope faces northeast, at MP 8.6 the slope faces south, and at MP 9.3 the slope faces north.

- Slope Grade: Many of the slopes within Mesa Verde are extremely steep, with vertical sections. Thus, layover and shadow are significant problems in this area.

- Image Coherence: The relatively dry climate and sparse vegetation in the Mesa Verde area are both beneficial in yielding good temporal coherence for InSAR analysis. However, within the mountainous region the coherence is variable, with significant areas of moderate to poor coherence. There are numerous areas of layover and shadow that preclude the use of InSAR for measuring ground movement. In particular, the slopes to the east of Point Lookout (encircled in blue in Figure 19) are within the layover regions and cannot be monitored by InSAR. As shown in Figure 19, the areas of more gentle relief generally have quite good coherence, especially outside the mountainous area. The poor coherence within the mountainous areas generally mirrors the topographic relief.

- Existing Site Data: Digital orthophotography with 1 m (3.3 ft) resolution is available for the Mesa Verde area. The photography was acquired in 1993 and orthorectified to a DEM from1995.

- Data availability: There are ERS acquisitions available from 1992 to 2004. In particular, for the descending satellite pass along track 413 there are 16 ERS-1 acquisitions spanning 1992 to 1996, and 15 ERS-2 acquisitions from 1995 to 2002. Fine mode RADARSAT acquisitions were programmed specifically for this project, starting in August 2004 and continuing until August 2005.

Many of the slope alignments are good, and in particular, the slopes to the east of Point Lookout are aligned favorably for InSAR. However, layover and shadow are significant, and certainly restrict the areas in which InSAR may be applied. The suitability of the various sites in this region varies depending on the specific site topography.

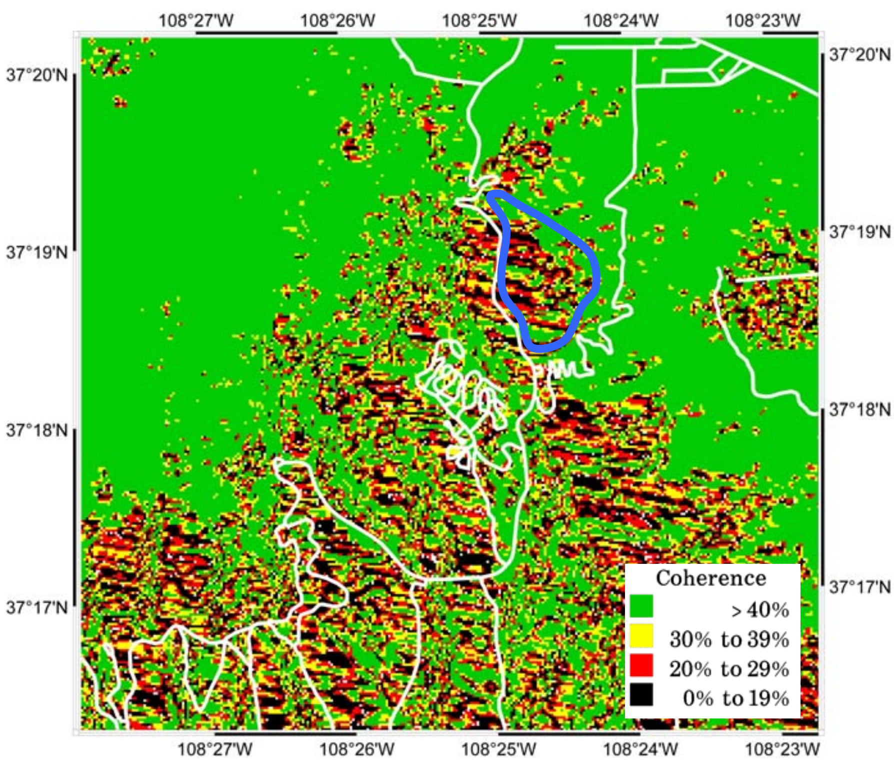

Figure 19. Graph. Coherence of Mesa Verde sites for May 28 – September 10, 1996.

CHAPTER 4 – INSAR MONITORING OF SLOPES

PROSSER

Acquisitions

For the Prosser slide, most acquisitions in the ERS-1/2 archive are along Ascending Track 20, Frame 2673[1]. In this location, there are 13 ERS-1 images from 1992 to 1996, and a further 36 ERS-2 images between 1995 and 2000. Within the scope of this project, four ERS images, as listed in Table 1, having suitable satellite baselines and acquired during favorable weather conditions, were procured in the 1998-2000 timeframe to establish limits on the ability to apply InSAR to long timeframe acquisitions from the archive. The high coherence experienced in this area was speculated to facilitate the longer-term analysis. However, there are sufficient acquisitions in the archive to perform traditional interferometry over much shorter time intervals, or to perform Interferometric Point Target Analysis (IPTA). The IPTA technique, which is sometimes referred to as PS or Point Scatterer InSAR, requires a large stack of images (15 minimum, 25-35 preferred), which was beyond the scope of this project. However, this technique may be considered at some future date, since the technique holds promise for long timescale analysis over this region.

A tandem mode pair was also selected in the 1995 timeframe to facilitate the generation of a DEM for the InSAR analysis. A DEM was generated using this pair; however, a more recent Shuttle Radar Topography Mission (SRTM) DEM from 2000 was used in its place.

Table 1. Prosser ERS images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Pasco Weather Station
November 10, 1995*	~6°	clear
November 11, 1995*	~5°	clear
July 18, 1998	27°	cloudy
January 9, 1999	4°	clear
September 11, 1999	22°	clear
December 9, 2000	3°	overcast

*Tandem Pair for DEM

In the case of RADARSAT-1, acquisition planning began for this area in September 2003, with an Ascending Fine Mode F3F chosen for acquisition. There were also additional acquisitions captured with this mode prior to September 2003. In total, 35 acquisitions were captured over the site with this beam mode between November 2002 and June 2005.

[1] The Track and Frame of the ERS satellites fix the position of the SAR image on the Earth. Often times, there are multiple choices of track and frame combination for an area, due to multiple overlapping tracks.

Within the scope of this project, scene selection was made on roughly a quarterly basis over the duration of the contract from September 2003 to June 2005. An additional four scenes prior to this period were also procured to maximize the overall timeframe of the RADARSAT data. The rationale for this was to ensure the likelihood that sufficient movement would occur over the site to be measurable by the satellite SAR. The scenes were chosen with particular emphasis on minimizing the baseline (to less than 500 meters (1600 ft)) and choosing scenes acquired on days without precipitation. The list of RADARSAT-1 scenes procured is given in Table 2.

Table 2. Prosser RADARSAT images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Pasco Weather Station
January 15, 2003	4°	mist
February 8, 2003	2°	mist
June 8, 2003	18°	clear
August 19, 2003	17°	clear
October 6, 2003	10°	clear
October 30, 2003	4°	clear
December 17, 2003	-1°	clear
April 15, 2004	14°	cloudy
June 2, 2004	28°	clear
August 13, 2004	39°	clear
October 24, 2004	14°	clear
February 21, 2005	-6°	clear
May 28, 2005	14°	clear
June 21, 2005	19°	clear

Analysis

Differential interferograms were computed for ERS and RADARSAT image pairs with perpendicular baselines around 500 m (1600 ft) or less, and with timeframes no longer than four months for RADARSAT, but up to fifteen months for ERS. Three ERS and eleven RADARSAT interferograms, as listed in Table 3, were generated.

The generation of the SAR interferograms was performed mainly through the use of the Gamma and Atlantis SAR processing software. The SAR signal data were first processed to yield image data, which were then co-registered so that all images were aligned in the SAR acquisition geometry. An external DEM was obtained for the study area from the 30 m (100 ft) SRTM DEM data available from the USGS. This DEM was co-registered to the SAR data as well, and then used to determine the topographic phase contribution for each interferogram. Both the curved-Earth and topographic phase were calculated based on the SAR acquisition geometry, and initially relied on the intrinsic satellite orbit information. The orbit baseline information was then refined by using the curved-Earth fringe rate evident in the differential interferogram, and/or by using ground control points with accurate horizontal and vertical information. The differential interferogram is generally spatially filtered to reduce phase noise. The phase of the differential interferogram is unwrapped to remove the 2π discontinuities inherent in the measured values. The unwrapped phase is directly proportional to the change in distance along the look vector of the radar and can be converted to ground movement assuming either vertical displacement or a principal direction of motion. The conversion of the measured movements to an absolute scale, that is, removing any offsets or simple trends in the data, relied on identifying known stable areas that could be used to define the zero displacement level.

Table 3. Prosser SAR interferometric image pairs.

Figure	Acquisition Dates	SAR Sensor	Perpendicular Baseline (m)	Δ Time (days)	Mean Coherence	Standard Deviation
20	Jul 18, 1998–Jan 09, 1999	ERS-2	-163	175	29%	17%
21	Jan 09, 1999–Sep 11, 1999	ERS-2	228	245	15%	8%
22	Sep 11, 1999–Dec 09, 2000	ERS-2	127	455	22%	13%
23	Jan 15, 2003–Feb 08, 2003	RSAT	235	24	53%	19%
24	Feb 08, 2003–Jun 08, 2003	RSAT	-414	120	27%	22%
25	Jun 08, 2003–Aug 19, 2003	RSAT	173	72	40%	27%
26	Aug 19, 2003–Oct 06, 2003	RSAT	-486	48	47%	31%
27	Oct 06, 2003–Oct 30, 2003	RSAT	258	24	59%	28%
28	Oct 30, 2003–Apr 15, 2004	RSAT	66	168	35%	25%
29	Jun 26, 2004–Aug 13, 2004	RSAT	89	48	28%	23%
30	Aug 13, 2004–Oct 24, 2004	RSAT	-36	72	28%	22%
31	Oct 24, 2004–Feb 21, 2005	RSAT	26	120	54%	21%
32	Feb 21, 2005–May 28, 2005	RSAT	-55	96	36%	26%

Results

The resulting ground movement maps as derived from the ERS and RADARSAT SAR interferograms are shown in Figure 20 to 22 and 23 to 33, respectively (negative values denote subsidence). In these figures, the background is an orthophoto and the landslide area of immediate concern is outlined by the green polygon, with the two larger prehistoric landslide areas given by the red and orange polygons. For individual interferograms, displacements that are less than 10 mm (0.4 inch) are considered to be within uncertainty levels and therefore are transparent in the above figures. Movement greater than 10 mm (0.4 inch) should be interpreted within the constraints associated with the phase variations and systematic uncertainties. Since areas of low temporal coherence stem from changes in the radar-scattering characteristics of the ground, such areas produce noisy interferometric phase. Further, systematic uncertainties may arise due to residual inaccuracies in the orbit modeling, atmospheric variations between the two acquisition times, and inaccuracies in the DEM and / or its co-registration to the SAR images. Except for small-scale atmospheric effects, these systematic variations will generally be aligned with the topography and can therefore be identified.

From Table 3, it is evident that the ERS interferograms have only limited coherence, with mean values ranging from 15% to 29%. It should be noted that these interferograms are over relatively long timeframes, from 6 to 15 months. From Figure 34, it is seen that there are no extended areas of consistently good coherence. Thus, the displacement derived from these interferograms appears to contain many small areas of noise that fluctuates by around 20 mm (0.8 inch). Given the limited coherence and the absence of any consistent displacement signatures in these ERS interferograms, it appears that no movement has been detected along the slopes of interest.

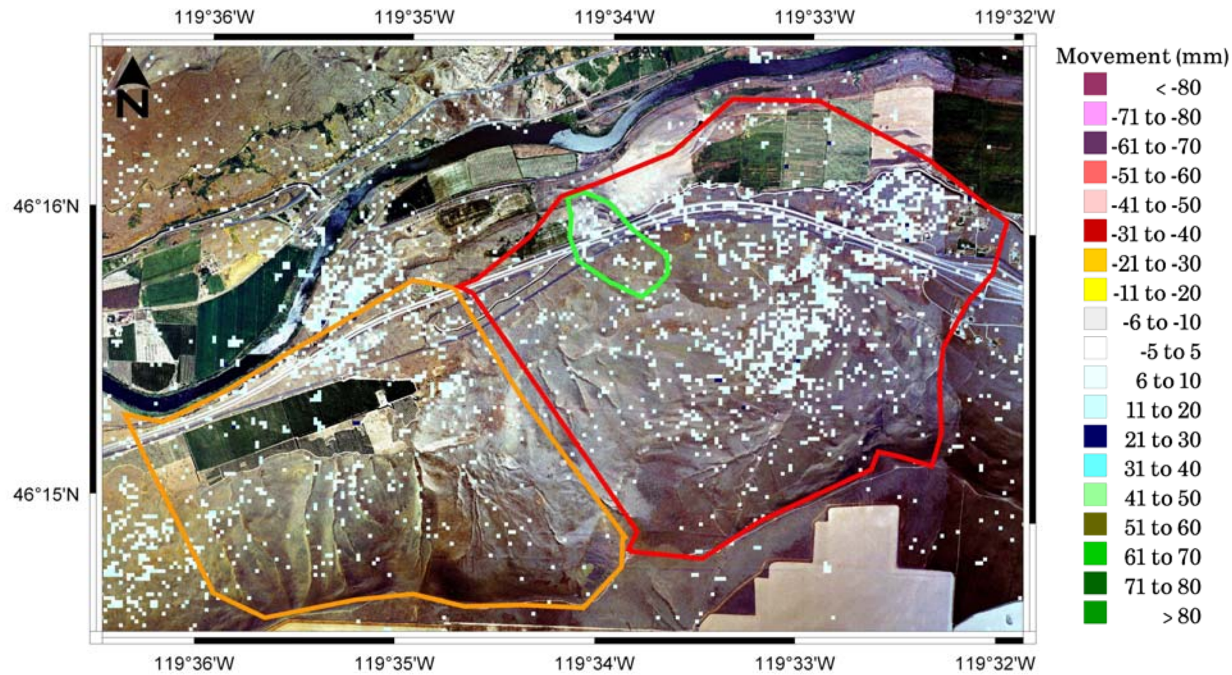

Figure 20. Graph. ERS InSAR derived height change for July 18, 1998 to January 9, 1999.

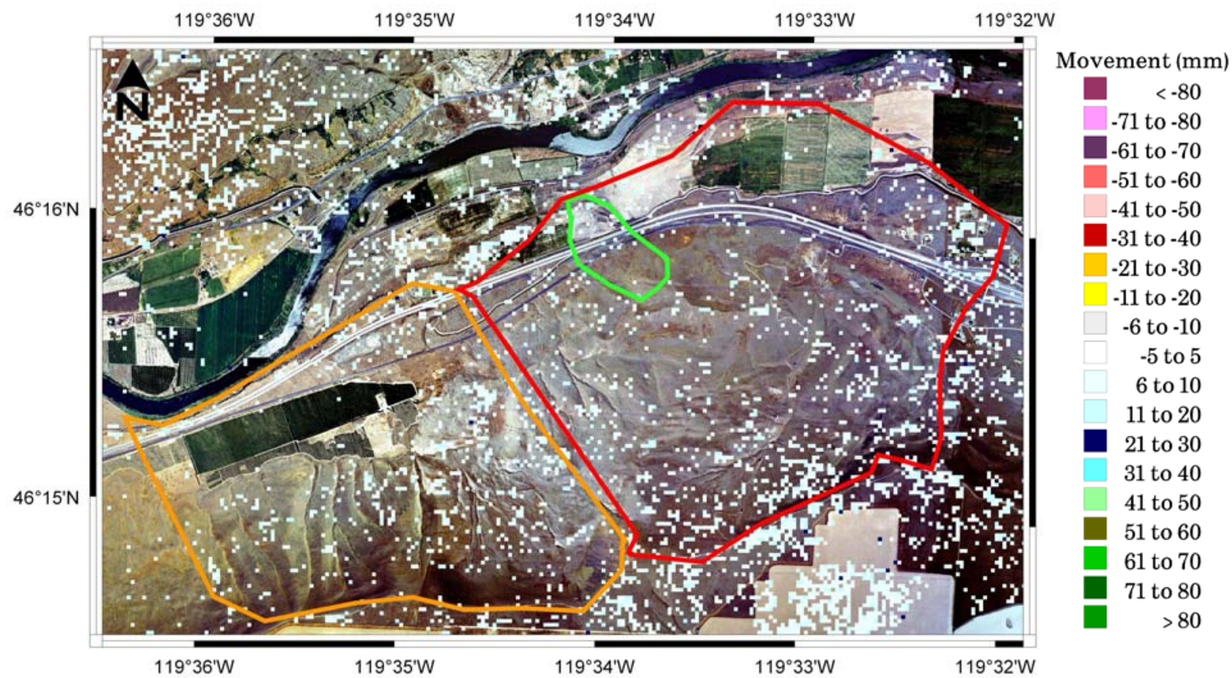

Figure 21. Graph. ERS InSAR derived height change for January 9 to September 11, 1999.

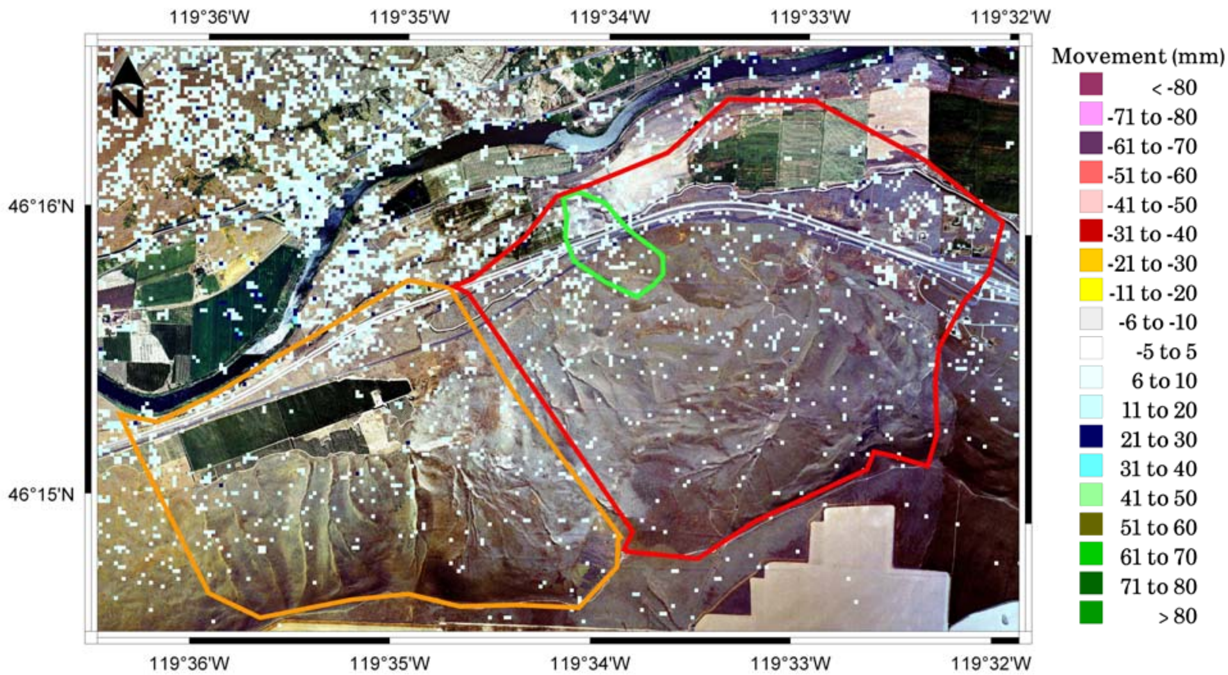

Figure 22. Graph. ERS InSAR derived height change for September 11, 1999 to December 9, 2000.

The RADARSAT image pairs in general have good coherence, with mean values in the range of 30% to 60%. Indeed, the average scene coherence along the slope of interest is consistently higher than elsewhere in the image, as seen in the coherence maps of Figure 35 and 36, where, for example, on the north side of the river the agricultural fields obviously reduce the temporal coherence. The precipitation in this area is relatively low, which contributes to the generally good coherence. From Figure 37 it is seen that the monthly precipitation values generally range between 1 mm (0.05 inch) to 8 mm (0.3 inch) with maximum monthly values less than 20 mm (0.8 inch).

For the ten RADARSAT interferograms shown in Figure 23 to Figure 32, there is no obvious movement detected along the slope of interest — at least to the 10 mm (0.4 inch) level of uncertainty. However, the notable feature within all the displacement maps is the residual values aligned with the ridges that are to both the east and the west of the area of interest. Since this residual interferometric phase is strongly correlated with topography, it may arise from errors in the orbit baseline modeling, from errors in either the magnitude or co-registration of the DEM, or from homogeneous atmospheric effects.

Since any movement along the slope of interest is within the measurement uncertainty of the individual interferograms, all ten displacement maps were combined to attempt to reduce the random errors. The associated level of uncertainty is roughly estimated as the square root of 10 times 10 mm (0.4 inch), or about 30 mm (1.2 inch). The resulting total displacement is shown in Figure 33. There appears to be some displacement on the slope of interest, just above the rock buttress adjacent to the canal and highway, which is consistent with the location and the magnitude of the expected movement. However, the magnitude of the movement is also within the above noted uncertainty level. Any indication of movement from this composite would imply slight heave at the base of the slope above the rock buttress.

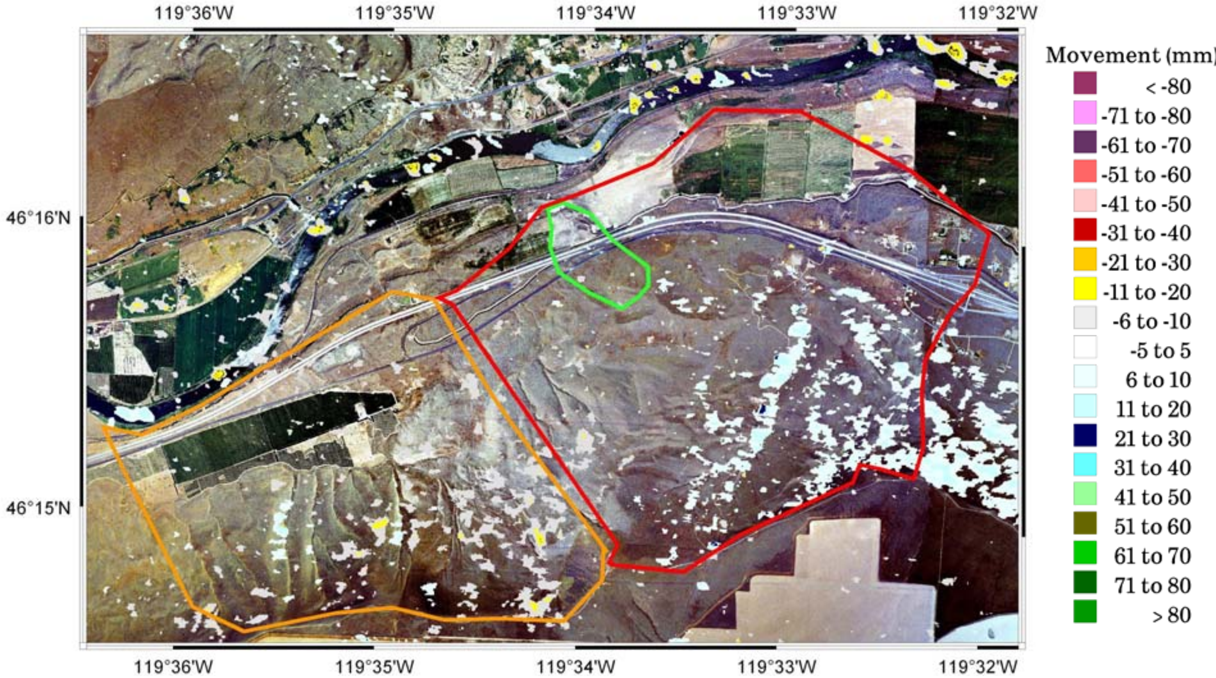

Figure 23. Graph. InSAR derived height change for January 15 to February 8, 2003.

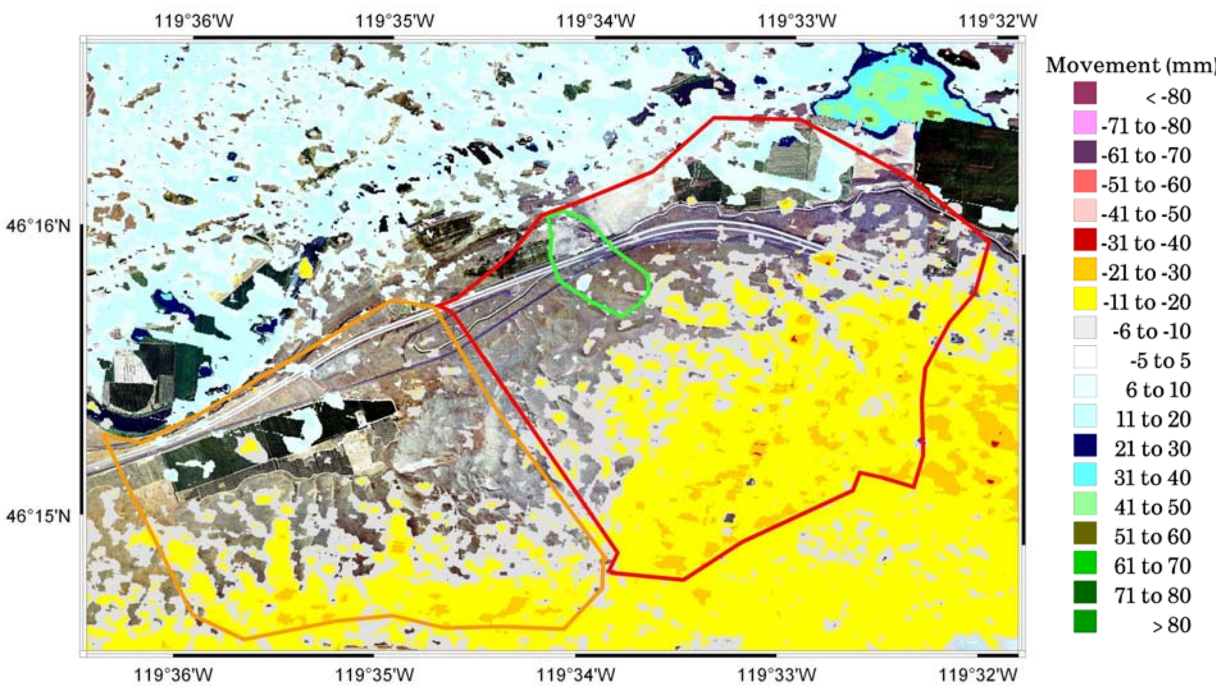

Figure 24. Graph. InSAR derived height change for February 8 to June 8, 2003.

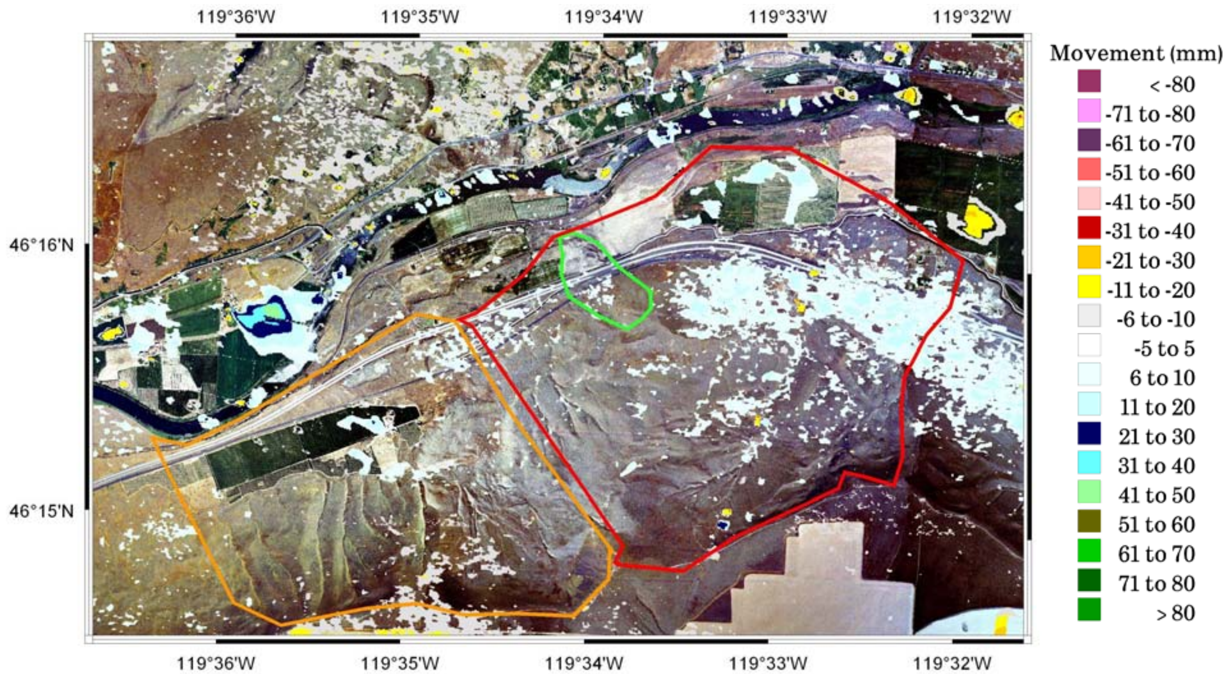

Figure 25. Graph. InSAR derived height change for June 8 to August 19, 2003.

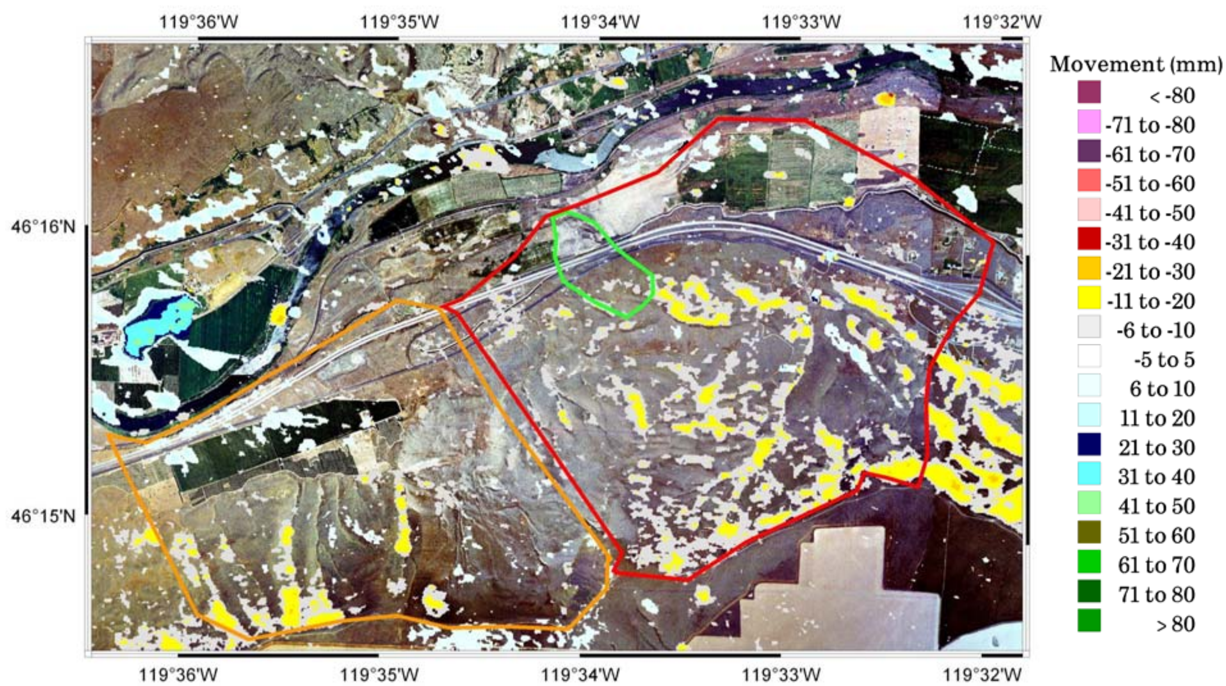

Figure 26. Graph. InSAR derived height change for August 19 to October 6, 2003.

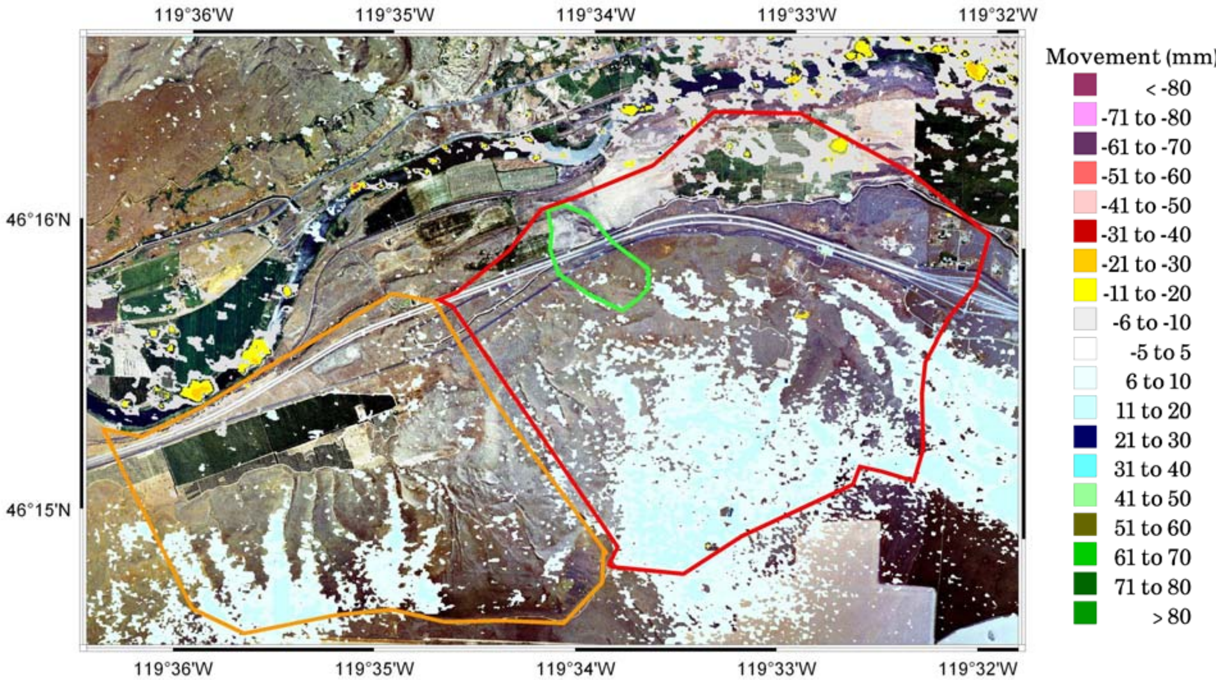

Figure 27. Graph. InSAR derived height change for October 6 to October 30, 2003.

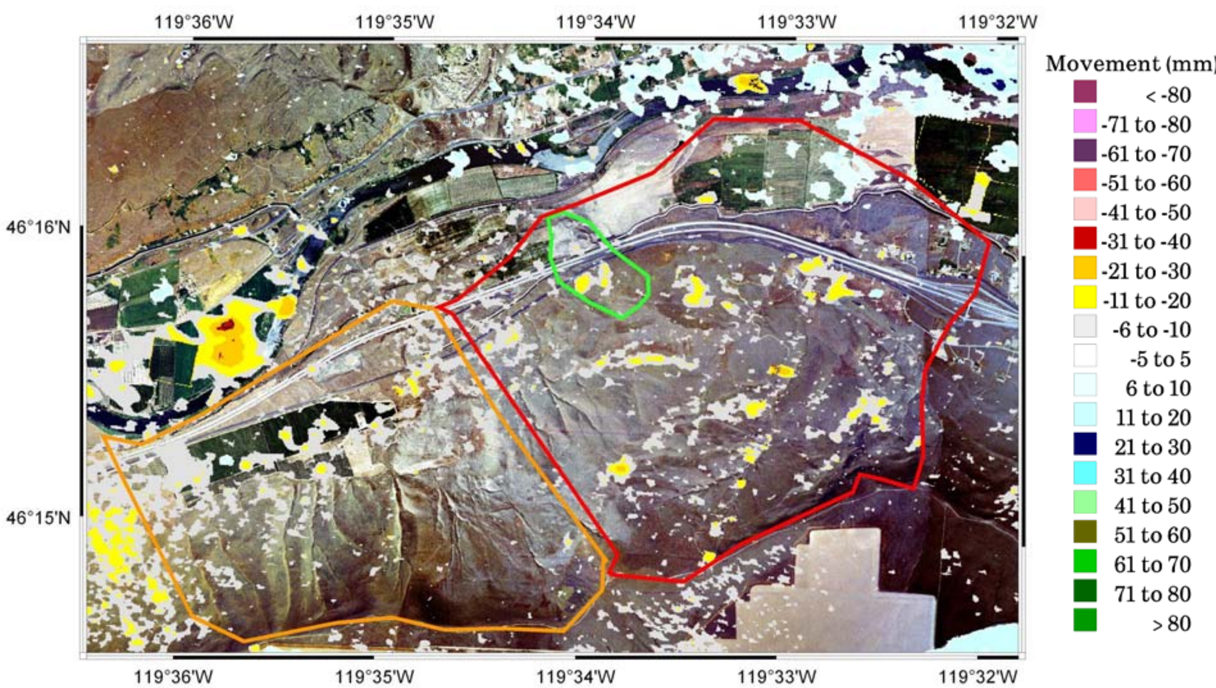

Figure 28. Graph. InSAR derived height change for October 30, 2003 to April 15, 2004.

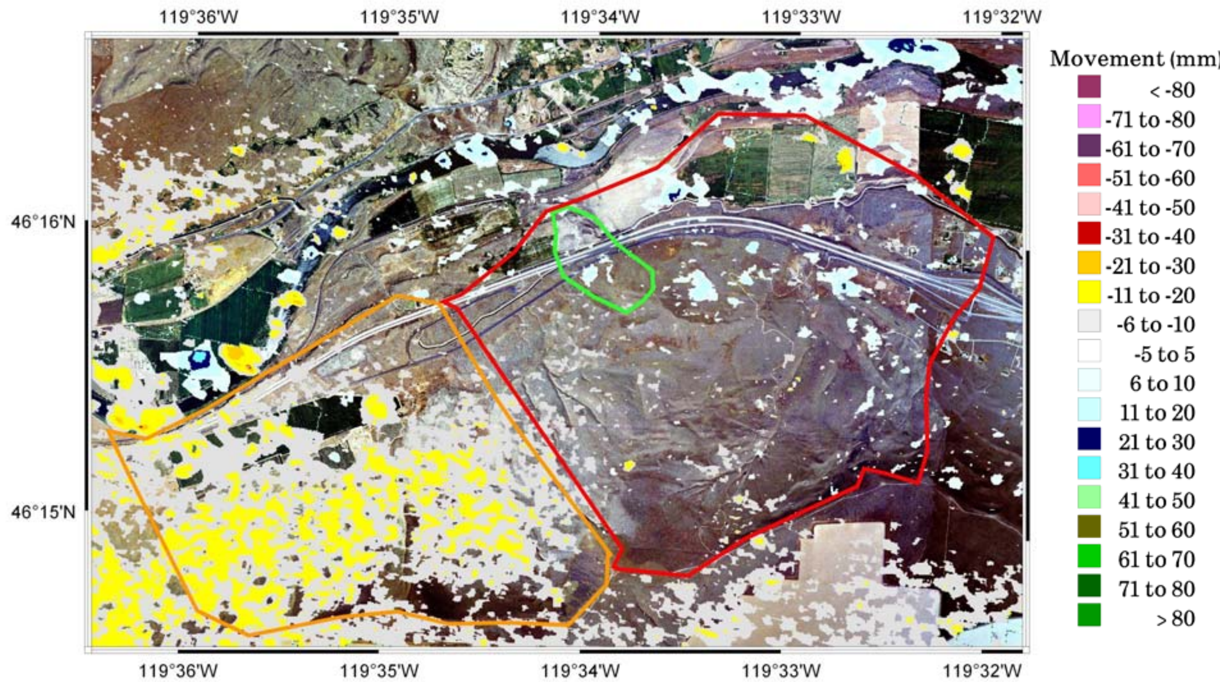

Figure 29. Graph. InSAR derived height change for June 26 to August 13, 2004.

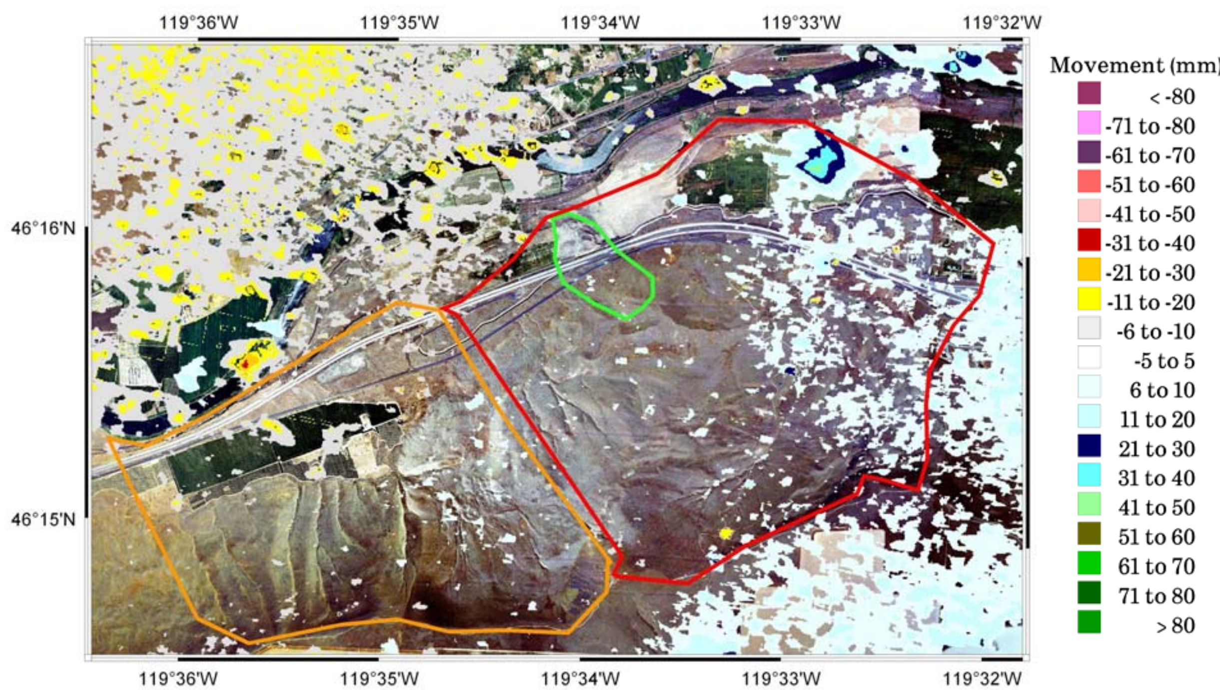

Figure 30. Graph. InSAR derived height change for August 13 to October 24, 2004.

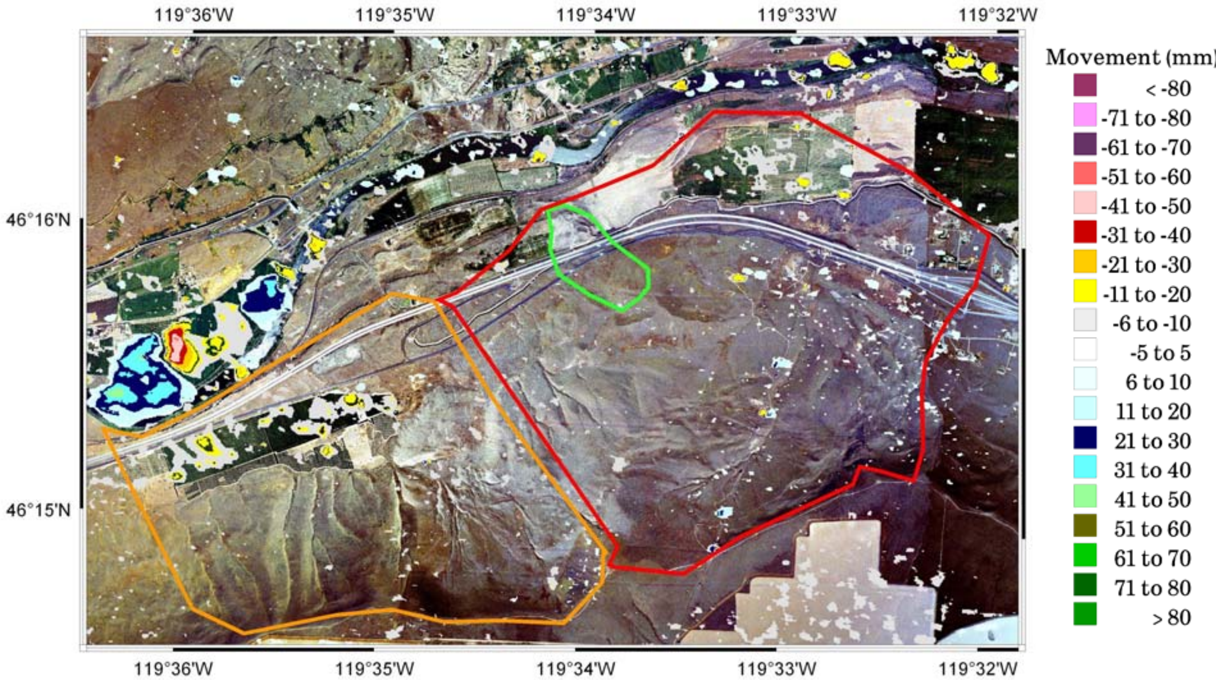

Figure 31. Graph. InSAR derived height change for October 24, 2004 to February 21, 2005.

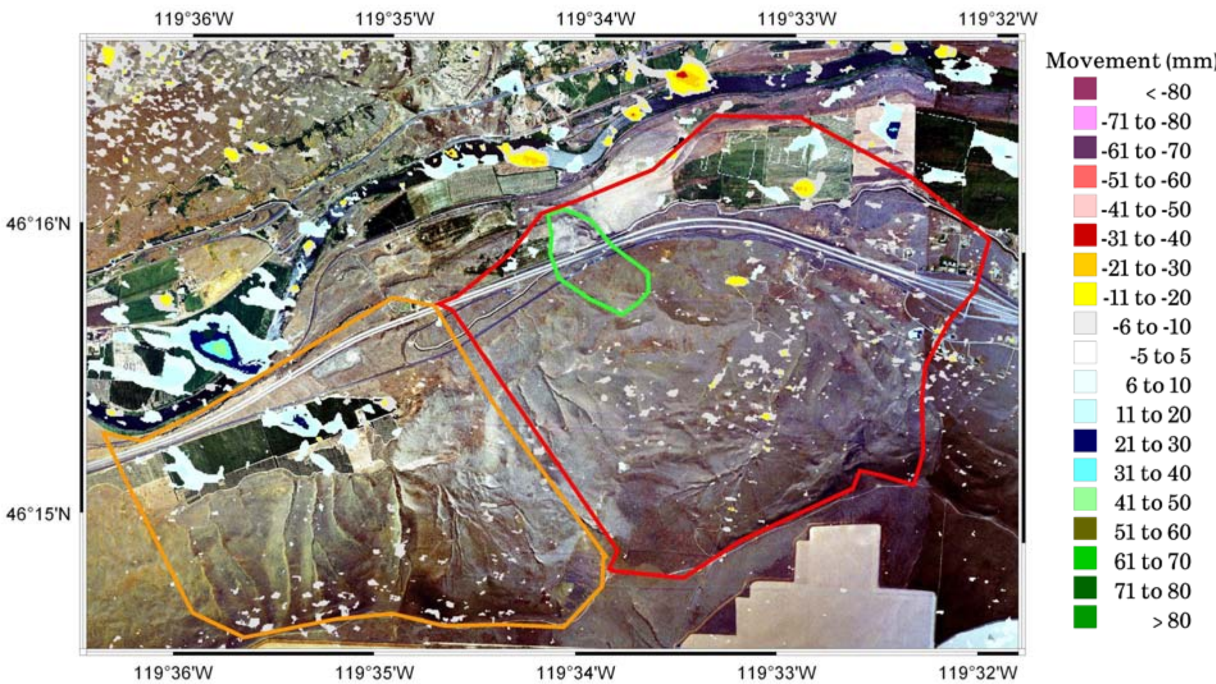

Figure 32. Graph. InSAR derived height change for February 21 to May 28, 2005.

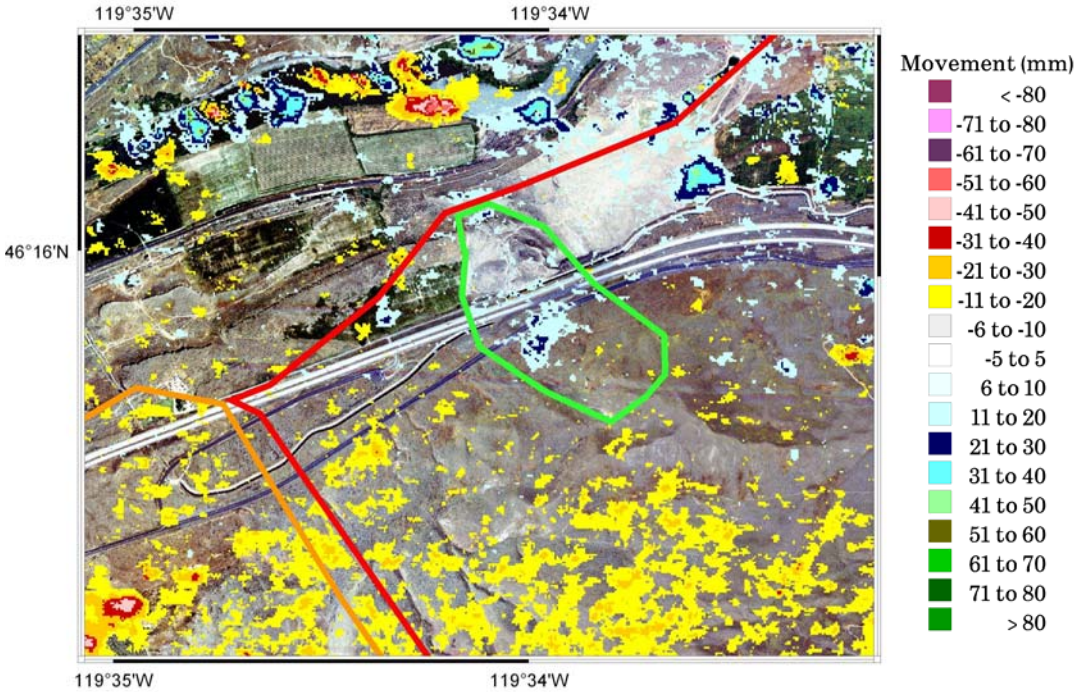

Figure 33. Graph. InSAR derived cumulative height change for January 15, 2003 to May 28, 2005.

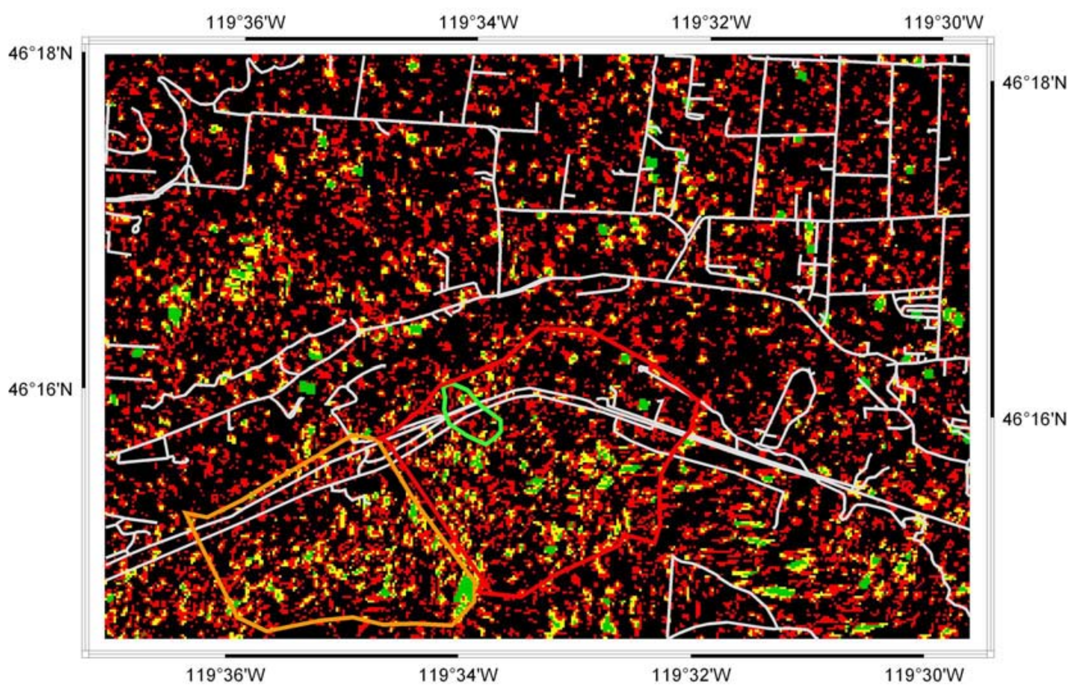

Figure 34. Graph. ERS SAR coherence for acquisitions on January 9 and September 11, 1999.

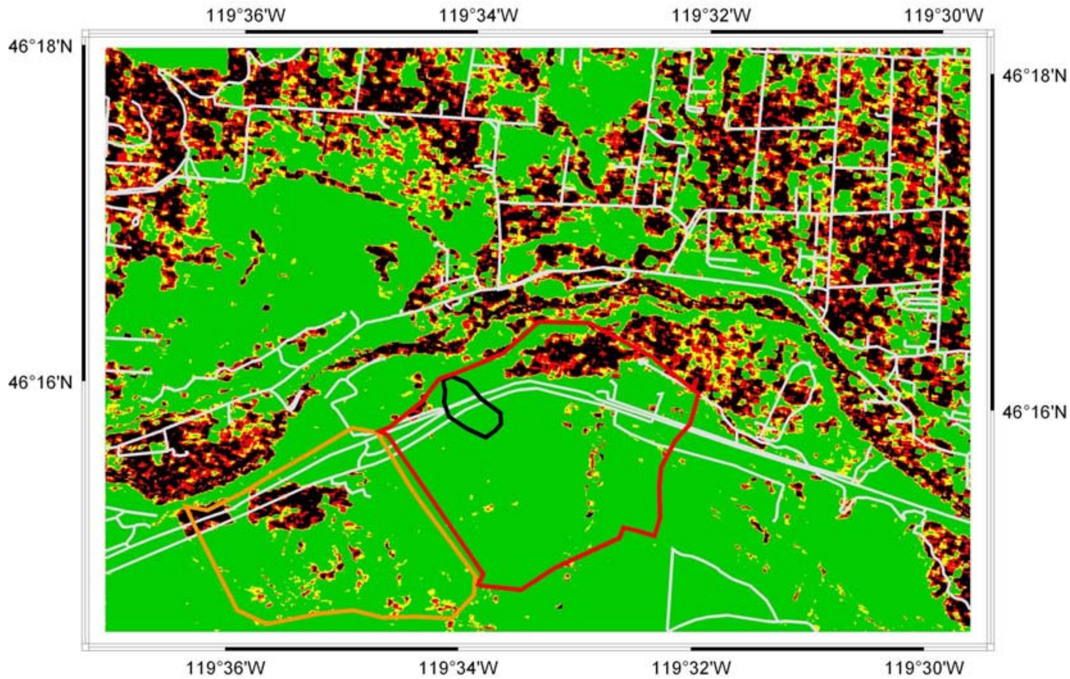

Figure 35. Graph. RADARSAT SAR coherence for acquisitions on October 6 and October 30, 2003.

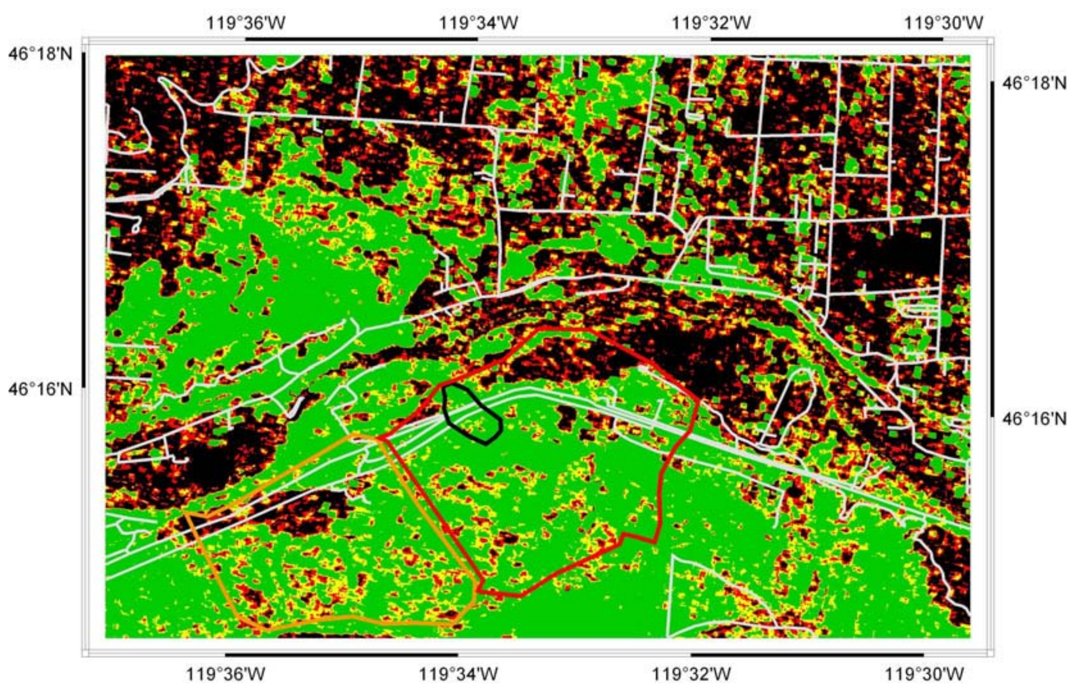

Figure 36. Graph. RADARSAT SAR coherence for acquisitions on October 30, 2003 and April 15, 2004.

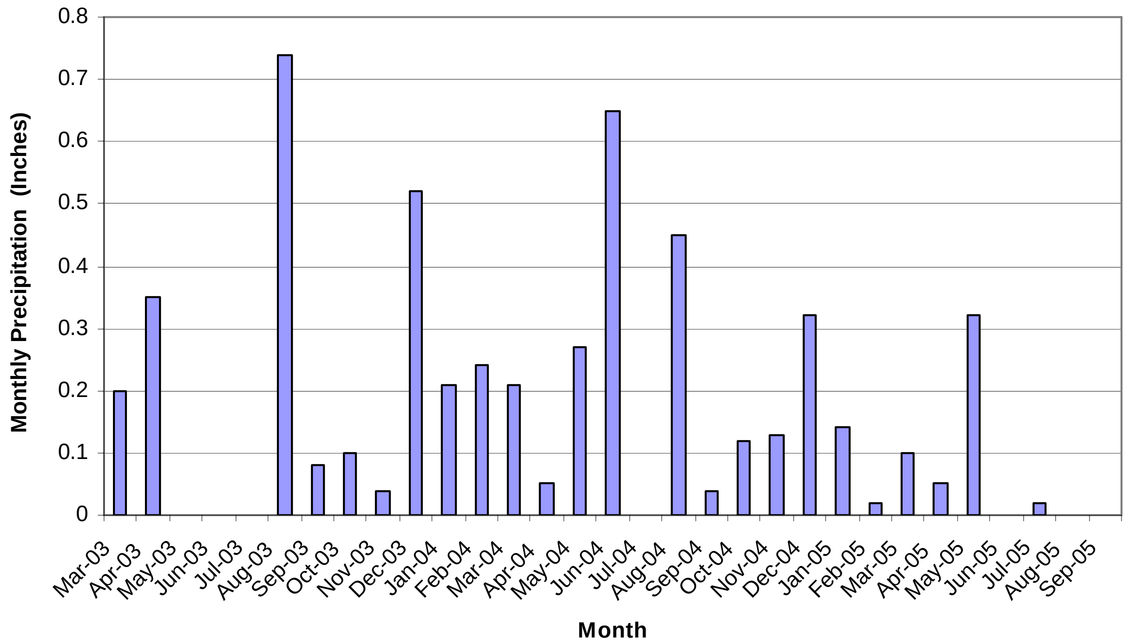

Figure 37. Graph. Monthly precipitation from March 2003 to September 2005 for the Prosser site.

Interpretation

Within the uncertainty associated with the InSAR analysis of the Prosser slide area, no obvious movement was measured. The most recent slope inclinometer data from H5-02 located at the base of the rock buttress indicated that the lateral movement was around 25 mm (1 inch) at 7° west of north over the timeframe from November 2002 to August 2004. The direction of the slope movement shifted from a generally westerly direction as measured further up the slope in 1987. For the current slope movement direction of slightly west of north, the SAR look-direction is poor, being about 10° north of east, at this latitude, for the ascending satellite pass. To further understand the InSAR results, a geotechnical analysis was undertaken to determine the potential movement mechanisms and the likely magnitude of any potential slope movement.(17)

Geotechnical data supplied by WSDOT was reviewed to develop a suitable geometric and material model for the analysis. The data consisted of borehole logs from a number of site investigations, readings from slope inclinometers installed within the slope area and reports prepared over a period of time that discuss the potential movement regime. The soil conditions consist of interlayered, silty clay and gravel, overlying conglomerate or basalt bedrock. It was established that the lower gravel layer could potentially act as a confined aquifer, and a likely mode of slope instability could be attributed to groundwater level variations acting to reduce the soil strength directly above the confined gravel layer. Movement records obtained from slope inclinometers indicated a seasonal correlation between observed movement and rainfall data for the area.

Two methods were employed to perform the geotechnical analysis; limit equilibrium techniques that allow a factor of safety to be calculated for a slope under particular conditions, and finite element analysis, which determines soil stresses and potential strain effects, and indicate the development of tensile and shear forces within the soil matrix. The analyses were performed with essentially the same soil models, with a range of soil strengths and groundwater conditions being considered to reflect the uncertainty in these parameters and provide some understanding of the sensitivity of the various parameters. The issue of the use of residual strength parameters was also considered in some detail.

The results of the geotechnical analyses suggest that the slope is essentially stable using both analysis techniques. Slope instability could be simulated by considering particularly low residual shear strength, or high (above-artesian) water levels within the lower gravel layer. The large movements initiated during highway construction works in the 1980s were attributed to toe excavation and were simulated using the finite element analysis. Thus, the InSAR and geotechnical analysis results both imply that the slope is essentially stable. The slight cumulative movement indicated by the InSAR results for January 2003 to May 2005 should be confirmed. Given that there is ongoing deformation of the highway in this area, it is recommended that InSAR and in-situ monitoring be continued to determine the actual movement.

CIMARRON

Acquisitions

For the Cimarron slide, ERS-1/2 acquisitions are most plentiful along Ascending Track 141, Frame 2835. In this location, there are 11 ERS-1 images from 1992 to 1996, and a further 37 ERS-2 images between 1995 and 2001. Within the scope of this project, six ERS images, as listed in Table 4, having suitable satellite baseline were procured in the 1995-1997 timeframe to coincide with the timeframe of "just prior to" and "during" the active slide of 1997. A tandem mode pair was also selected in the 1996 timeframe to facilitate the generation of a DEM for the InSAR analysis. A DEM was generated using this pair, however, a more recent SRTM DEM from 2000 was used in its place.

As part of the image selection process, precipitation and temperature information were gathered to allow the selection of scenes acquired outside of precipitation periods or when snow was present on the ground. The weather data for the acquired SAR scenes are presented in Table 4. Unfortunately, the closest weather station to Cimarron, which readily provided historical data, is approximately 50 miles (80 km) away in the city of Gunnison. Cimarron's elevation is also higher than that of Gunnison, and consequently the weather conditions (in particular the temperature) may be different at the slide site from that at the weather station. As shown in Table 4, precipitation occurred during the time of each ERS acquisition in 1997. However, given the importance of this data set to the study according to the slide movement that is known to have occurred, the satellite baseline data were judged to be sufficient to justify the data procurement even though precipitation was recorded on the day of each acquisition.

Like the Prosser site, there are sufficient data for Cimarron in the archive to perform interferometric point target analysis (IPTA). The IPTA technique requires a large stack of images (15 minimum, 25-35 preferred), which was beyond the scope of this project. The IPTA technique is used to isolate ground movement from atmospheric and topographic effects, and to mitigate phase unwrapping issues associated with spotty coherence. Therefore, this technique may be considered for application to this site at some future date.

Table 4. Cimarron ERS images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Gunnison Weather Station
November 11, 1995	No Data	No Data
May 8, 1996	~11°	(clear) Tandem Pair for DEM
May 9, 1996	~11°	(clear) Tandem Pair for DEM
September 26, 1996	7°	Precipitation
April 24, 1997	8°	Precipitation
July 03, 1997	15°	Precipitation
August 07, 1997	16°	Precipitation
September 11, 1997	21°	Precipitation

In the case of RADARSAT-1, acquisition planning began for this area in August 2003, with an Ascending Fine Mode F2F scene chosen for acquisition. In total, 26 acquisitions were captured over the site on this beam mode between August 2002 and June 2005.

Within the scope of this project, scene selection was made on roughly a quarterly basis over the duration of the contract from September 2003 to June 2005. The scenes were collected with particular emphasis on minimizing the baseline (to less than 500 meters (1600 ft)) and choosing scenes on days without precipitation. The list of RADARSAT-1 scenes that were procured is given in Table 5.

Table 5. Cimarron RADARSAT images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Gunnison Weather Station
September 03, 2003	21°	cloudy
September 27, 2003	19°	clear
November 14, 2003	1°	clear
March 13, 2004	2°	clear
April 06, 2004	9°	clear
June 17, 2004	20°	clear
July 11, 2004	24°	cloudy
September 21, 2004	16°	cloudy
October 15, 2004	12°	clear
December 02, 2004	-23°	clear
April 25, 2005	8°	cloudy
June 12, 2005	13°	cloudy

Analysis

Differential interferograms were computed for ERS and RADARSAT image pairs with perpendicular baselines around 600 m (1,980 ft) or less, and with timeframes no longer than seven months. Five ERS and eleven RADARSAT interferograms, as listed in Table 6, were generated.

The generation of the SAR interferograms was performed mainly through the use of the Gamma SAR processing software. The SAR signal data were first processed to yield image data, which were then co-registered so that all images were aligned in the SAR acquisition geometry. An external DEM was obtained for the study area from the 30 m (100 ft) SRTM DEM data available from the USGS. This DEM was co-registered to the SAR data as well, and then used to determine the topographic phase contribution for each interferogram. Both the curved-Earth and topographic phase were calculated based on the SAR acquisition geometry, and initially relied on the intrinsic satellite orbit information. The orbit baseline information was then refined by using the curved-Earth fringe rate evident in the differential interferogram, and/or by using ground control points with accurate horizontal and vertical information. The differential interferogram is generally spatially filtered to reduce phase noise. The phase of the differential interferogram is unwrapped to remove the 2π discontinuities inherent in the measured values. The unwrapped phase is directly proportional to the change in distance along the look vector of the radar and can be converted to ground movement assuming either vertical displacement or a principal direction of motion. The conversion of the measured movements to an absolute scale, that is, removing any offsets or simple trends in the data, relied on identifying known stable areas that can be used to define the zero displacement level.

Table 6. Cimarron SAR interferometric image pairs.

Figure	Acquisition Dates	SAR Sensor	Perpen-dicular Baseline (m)	Δ Time (days)	Mean Coherence	Standard Deviation
38	Sep 26, 1996–Apr 24, 1997	ERS-2	-339	210	12%	6%
39	Apr 24, 1997–Jul 03, 1997	ERS-2	188	70	15%	8%
40	Jul 03, 1997–Aug 07, 1997	ERS-2	304	35	15%	8%
41	Aug 07, 1997–Sep 11, 1997	ERS-2	232	35	20%	12%
42	Jul 27, 2000–Oct 05, 2000	ERS-2	320	70	8%	4%
43	Sep 03, 2003–Sep 27, 2003	RSAT	-143	24	39%	19%
44	Jun 17, 2004–Jul 11, 2004	RSAT	611	24	29%	15%
45	Jul 11, 2004–Sep 21, 2004	RSAT	-364	72	31%	15%
46	Sep 21, 2004–Oct 15, 2004	RSAT	193	24	45%	21%
47	Apr 25, 2005–Jun 12, 2005	RSAT	-128	48	28%	14%

Results

The resulting ground movement maps as derived from the ERS and RADARSAT SAR interferograms are shown in Figure 38 to Figure 42 and Figure 43 to Figure 47, respectively (negative values denote subsidence). For individual interferograms, displacements that are less than 10 mm (0.4 inch) are considered to be within uncertainty levels and therefore are transparent in the above figures. Movement greater than 10 mm (0.4 inch) should be interpreted within the constraints associated with the phase variations and systematic uncertainties. Since areas of low temporal coherence stem from changes in the radar-scattering characteristics of the ground, such areas produce noisy interferometric phase. Further, systematic uncertainties may arise due to residual inaccuracies in the orbit modeling, atmospheric variations between the two acquisition times, and inaccuracies in the DEM and / or its co-registration to the SAR images. Except for small-scale atmospheric effects, these systematic variations will generally be aligned with the topography and can therefore be identified.

From Table 6, it is evident that all the ERS interferograms suffer from poor coherence, with mean values ranging from 8% to 20%, as illustrated by the example shown in Figure 48. The displacement derived from these interferograms appears to contain mostly small areas of noise that fluctuates by up to 20 to 30 mm (0.8 – 1.2 inch). Given the poor coherence and the absence of any consistent displacement signatures, one can only conclude that no movement has been detected.

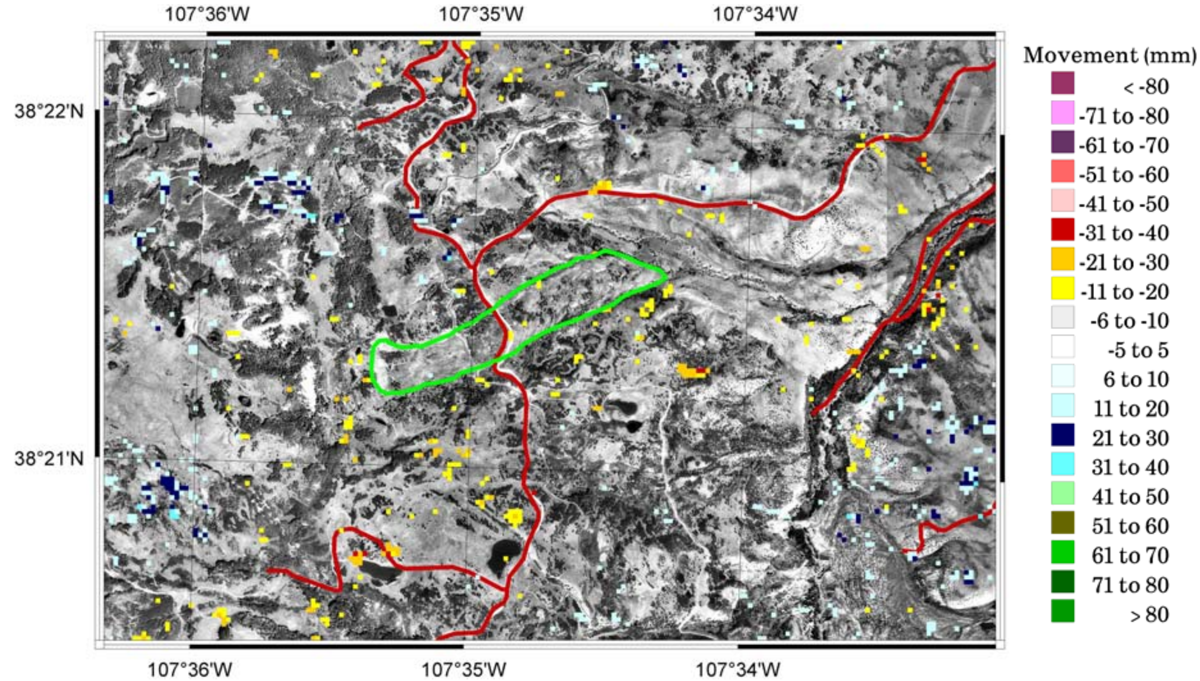

Figure 38. Graph. ERS InSAR derived height change for September 26, 1996 to April 24, 1997.

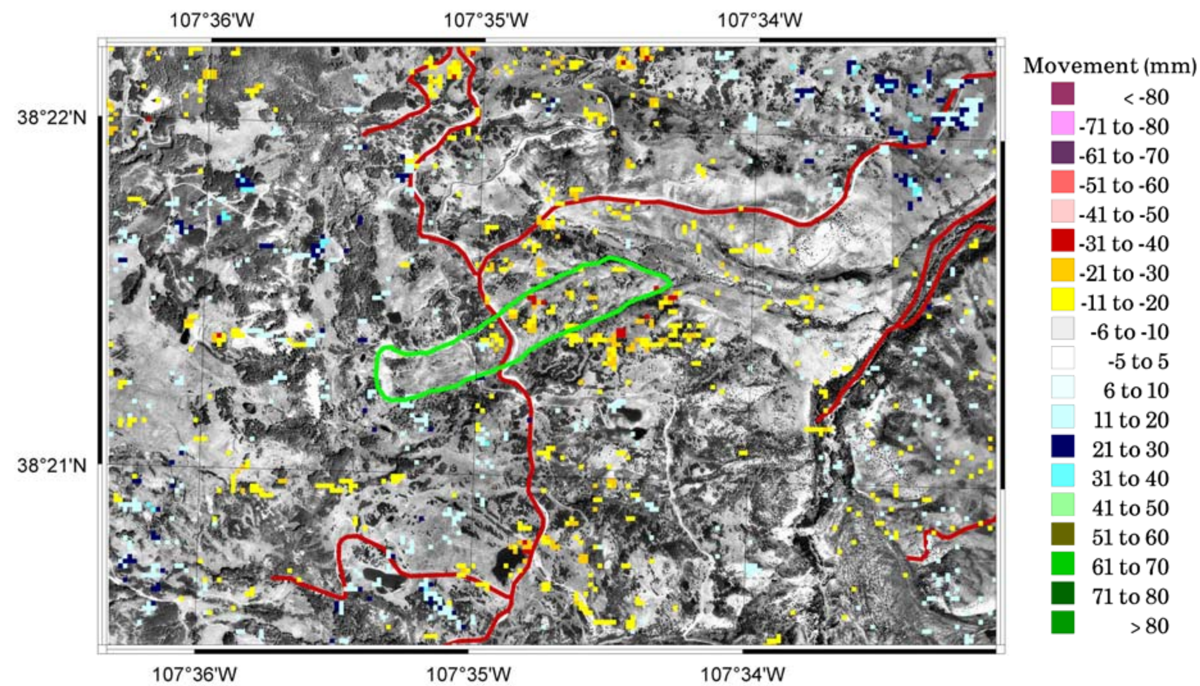

Figure 39. Graph. ERS InSAR derived height change for April 24 to July 3, 1997.

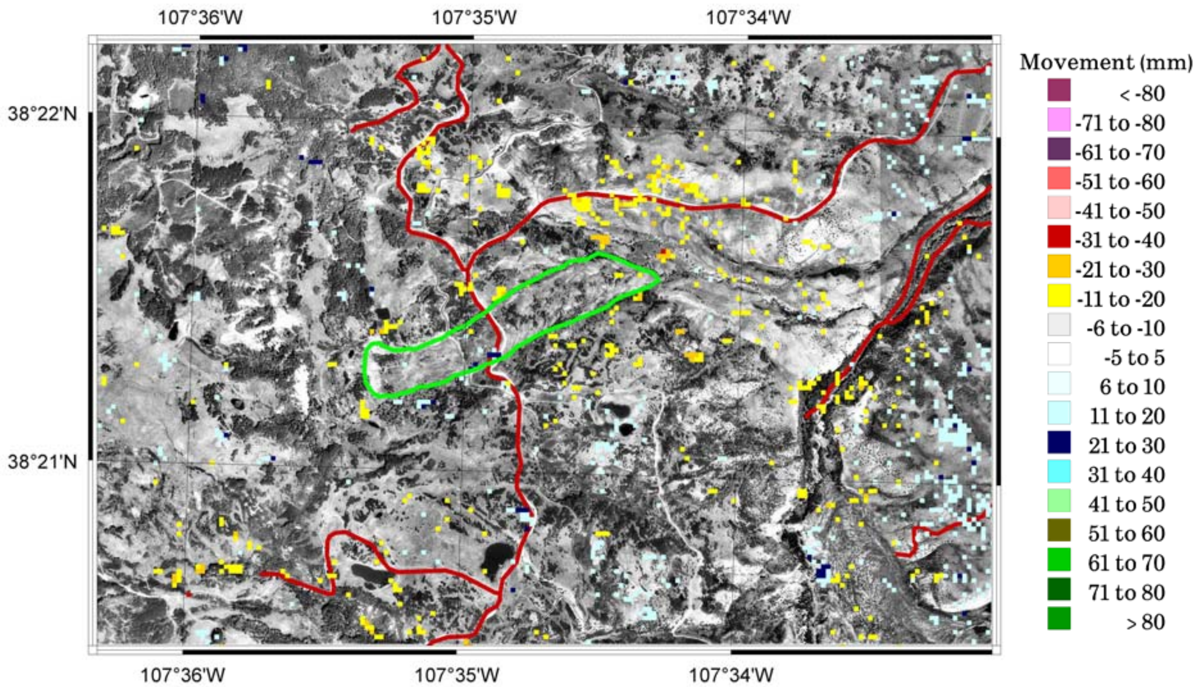

Figure 40. Graph. ERS InSAR derived height change for July 3 to August 7, 1997.

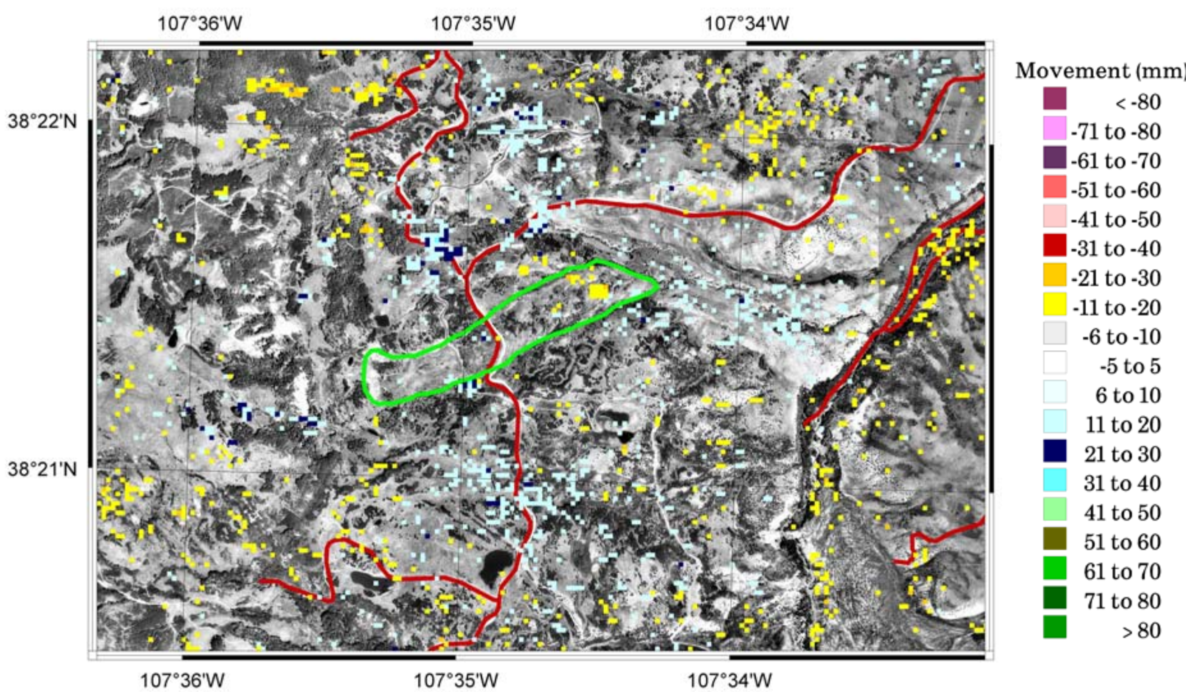

Figure 41. Graph. ERS InSAR derived height change for August 7 to September 11, 1997.

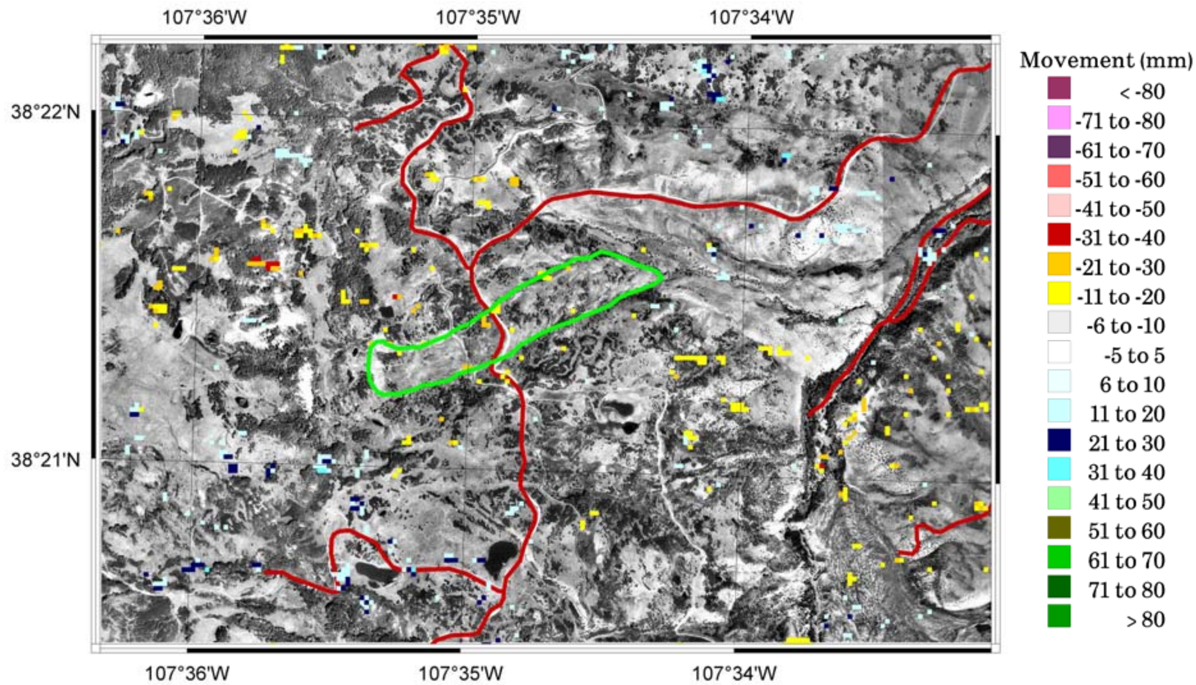

Figure 42. Graph. ERS InSAR derived height change for July 27 to October 5, 1997.

In contrast to the poor coherence of the ERS interferograms, the RADARSAT image pairs at least have reasonable coherence with mean values in the range of 28% to 45%. The quality of the InSAR estimates for movement will depend on the local coherence in the area of interest. For the eleven interferograms considered during the timeframe from late summer 2003 to late spring 2005, well-developed movement signatures are seen along the slide area during the autumn of both 2003 and 2004, as shown in Figure 43 and Figure 46. Specifically, movement of 10 to 20 mm (0.4 - 0.8 inch) near the top of the slide was observed over the 24-day cycles from September 3 to 27, 2003 and September 21 to October 15, 2004. It should be noted that these two interferograms have the highest coherence of the eleven pairs considered, so that the resulting movement estimates are influenced the least from phase noise. Further, given that the coherence is consistently higher at the top of the slope, as seen in Figure 49, the movement signature in this region is particularly visible. Slight movement may be evident in some of the other interferograms, such as June to July and July to September 2004, as shown in Figure 44 and Figure 45, although in these cases the lower coherence results in a less consistent movement signature.

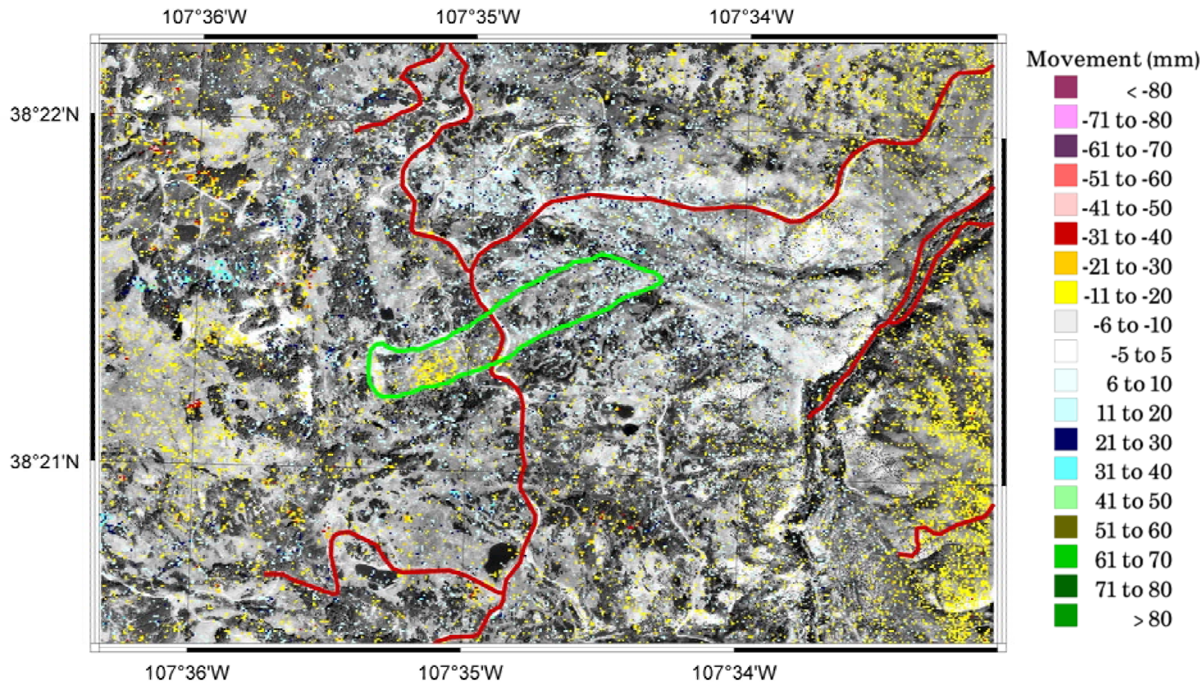

Figure 43. Graph. InSAR derived height change for September 3 to 27, 2003.

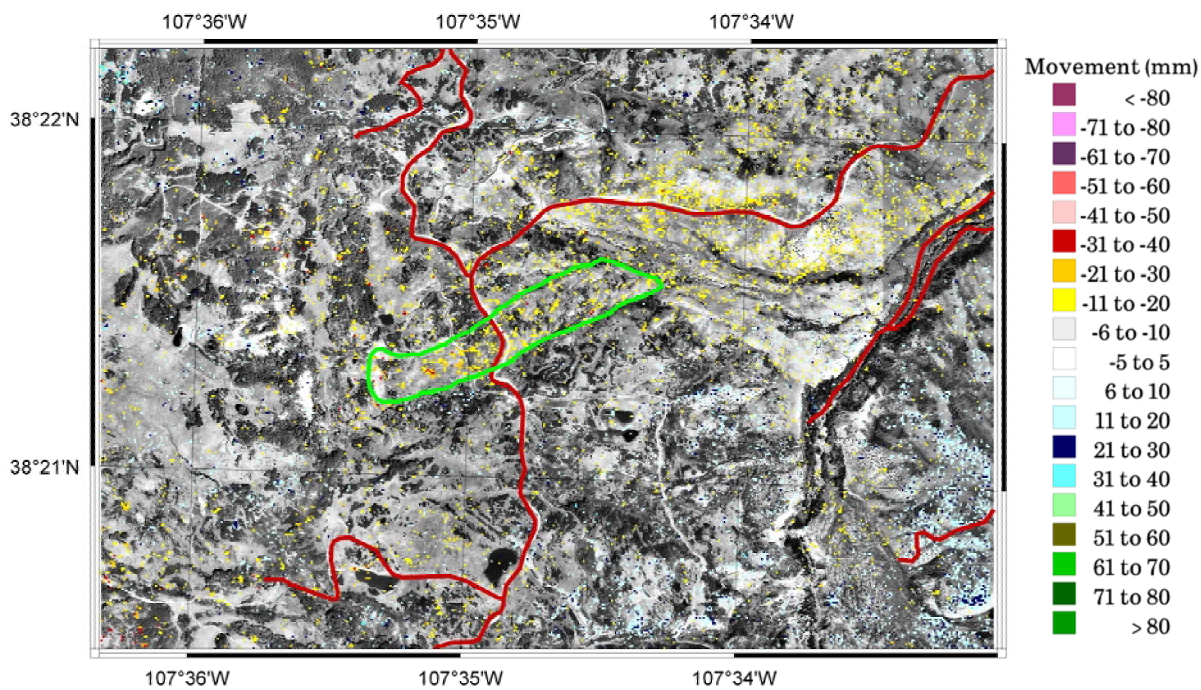

Figure 44. Graph. InSAR derived height change for June 17 to July 11, 2004.

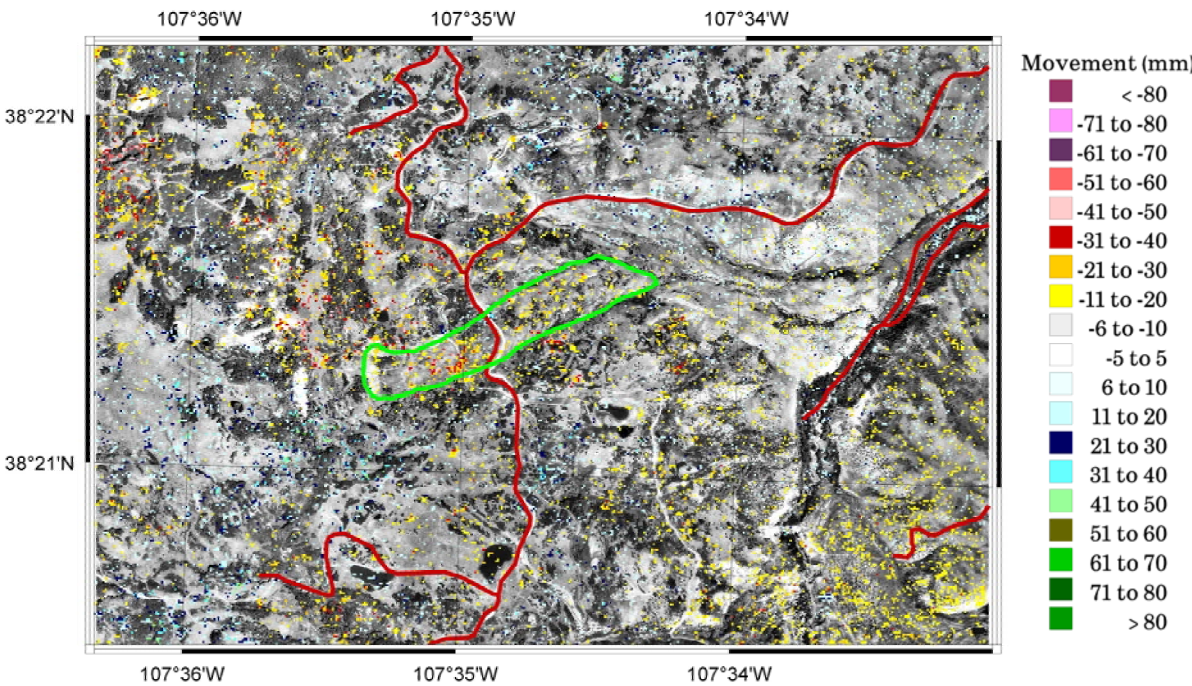

Figure 45. Graph. InSAR derived height change for July 11 to September 21, 2004.

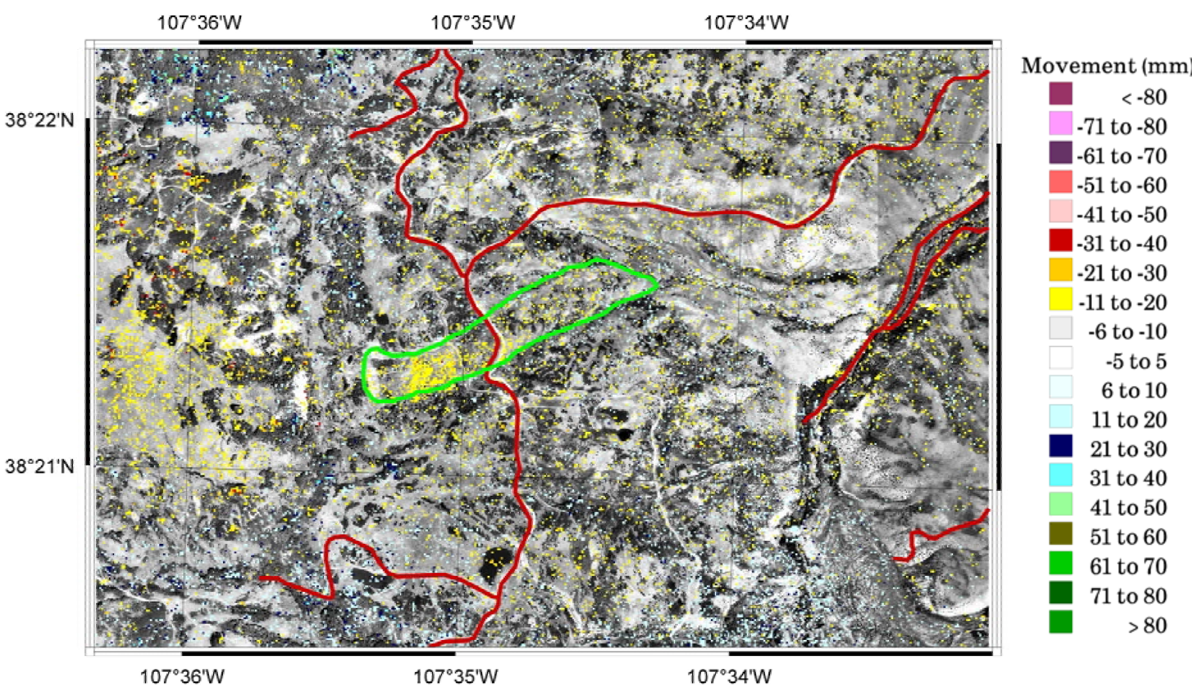

Figure 46. Graph. InSAR derived height change for September 21 to October 15, 2004.

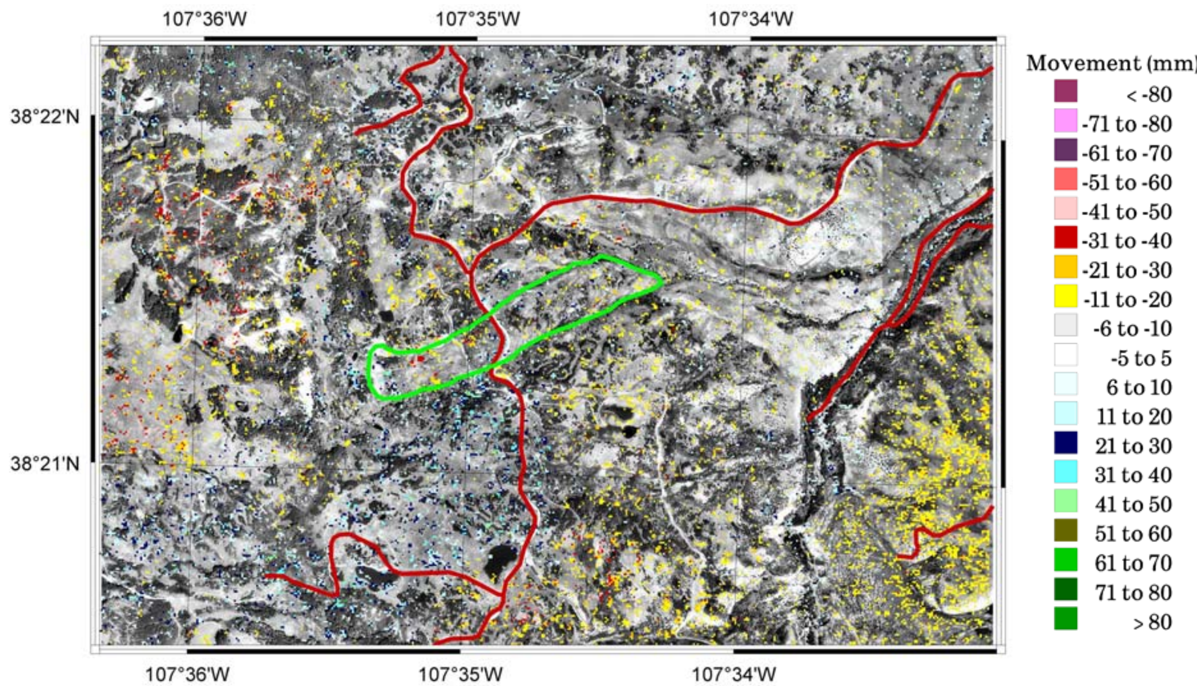

Figure 47. Graph. InSAR derived height change for April 25 to June 12, 2005.

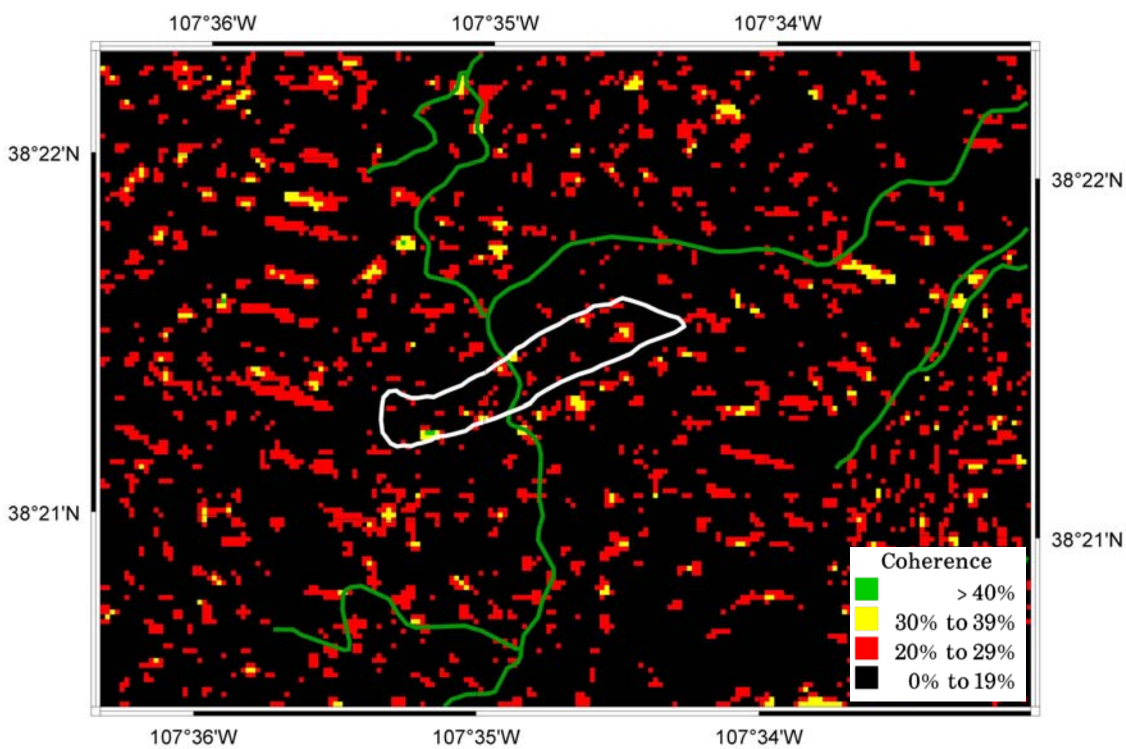

Figure 48. Graph. ERS SAR coherence for acquisitions on July 27 and October 5, 1997.

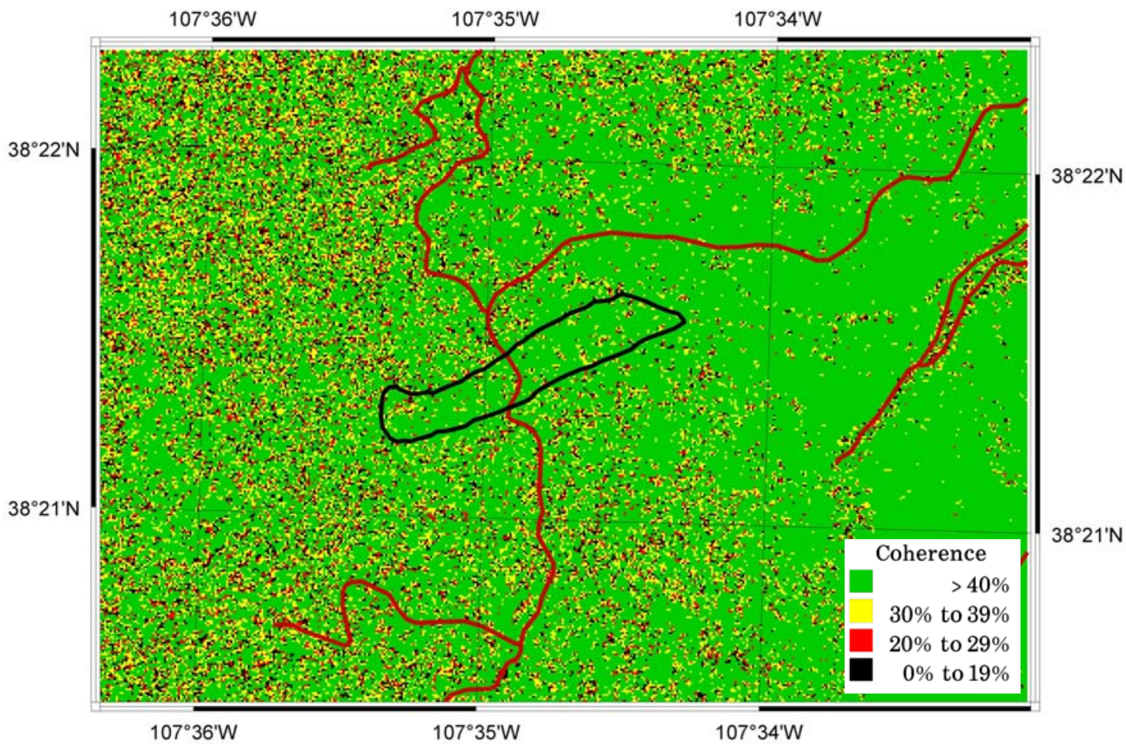

Figure 49. Graph. RADARSAT SAR coherence for acquisitions on September 21 and October 15, 2004.

Interpretation

The only evidence of movement observed over the monitoring period was during the autumn of 2003 and 2004, for the upper, reactivated section of the Wells Basin Landslide. During each of these two timeframes, subsidence or downslope movement of roughly 10 mm (0.4 inch) to 20 mm (0.8 inch) was measured along a 300 m (1000 ft) section near the top of the 1997 reactivated slide. Any detection of movement during the other monitoring intervals was limited due to the generally poor temporal coherence of the area. Good coherence would obviously help to determine limits on the amount of movement occurring at the site, as well as the exact area experiencing movement.

The reason for the observed movement signatures during the autumn is unclear. It is assumed that the slide activity depends on the amount of ground water, and since snowmelt is the principal source, the major movement would be expected to occur during the spring. The monthly precipitation from January 2003 to August 2005 is shown in Figure 50, from which it is evident that the autumn of 2003 and 2004, as well as the spring of 2004, received precipitation amounts well above the other months. However, the relative influence of direct precipitation compared to accumulated snowmelt is unknown at this time.

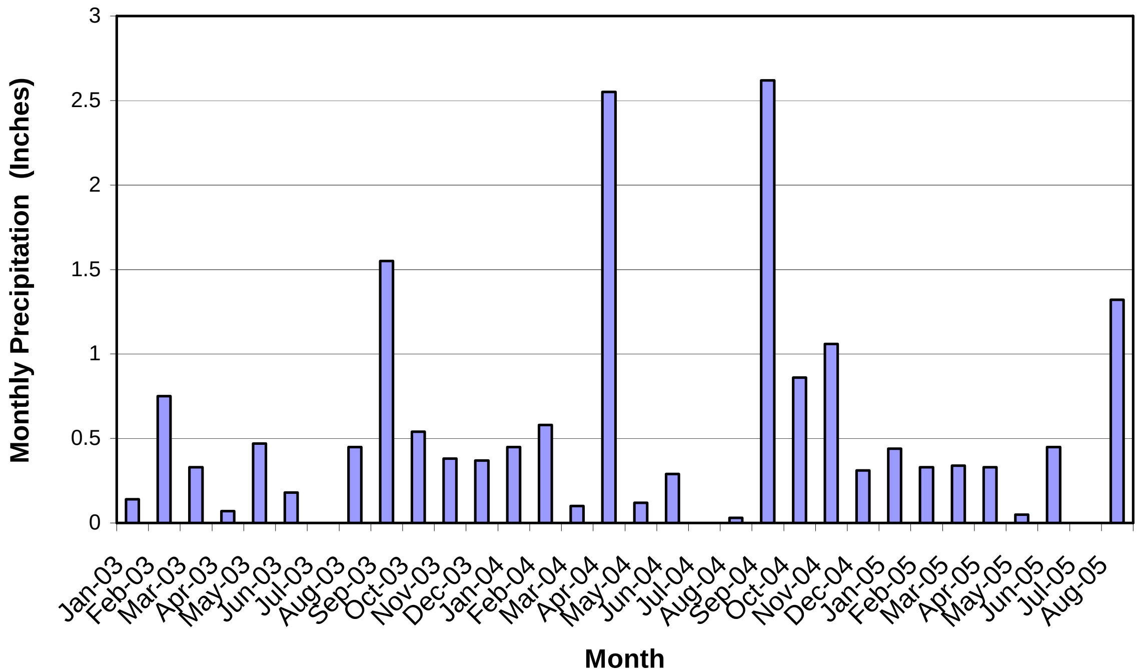

Figure 50. Graph. Monthly precipitation from January 2003 to August 2005 for Montrose, Colorado.

MESA VERDE

Acquisitions

For the slide areas along the access highway in the vicinity of Point Lookout, the best available ERS archive data were acquired during the descending satellite pass along track 413, for which there are 16 ERS-1 acquisitions spanning 1992 to 1996, and 12 ERS-2 acquisitions from 1995 to 1999, with three additional acquisitions in 2002. Three ERS images, as listed in Table 7, were procured initially. The ERS-1/2 tandem pair from May 27 and 28, 1996 was obtained as an option for generating a DEM of the Mesa Verde area. The standard DEM used in the InSAR processing was obtained from the SRTM data available through the USGS. The third scene from September 10, 1996 was obtained to generate a differential pair spanning May to September 1996, thereby enabling the general coherence in the area to be evaluated.

Table 7. Mesa Verde ERS images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Cortez Weather Station
May 27, 1996*	N/A	N/A
May 28, 1996*	N/A	N/A
September 10, 1996	18°	precipitation

*Tandem Pair for DEM

Fine mode F2 RADARSAT acquisitions along the descending satellite pass were programmed specifically for this project, starting in August 2004 and continuing until August 2005. A total of thirteen acquisitions were made during this two-year timeframe, with seven being used in the InSAR analysis, as indicated in Table 8. These scenes were chosen to obtain maximum coherence, according to the weather during the acquisitions, the short time intervals for image pairs, and the small perpendicular baselines.

Table 8. Mesa Verde RADARSAT images procured for analysis.

Date	Temperature ° Celsius	Meteorological Conditions, Cortez Weather Station
August 1, 2004	11°	clear
August 25, 2004	7°	clear
October 12, 2004	3°	overcast
March 5, 2005	6°	overcast
May 16, 2005	24°	clear
July 3, 2005	33°	clear
August 20, 2005	23°	clear

Analysis

Differential interferograms were computed for ERS and RADARSAT image pairs with perpendicular baselines less than 500 m (1600 ft), and with maximum timeframes of around three months. One ERS and five RADARSAT interferograms, as listed in Table 9, were generated.

The generation of the SAR interferograms was performed through the Gamma processing software. The SAR signal data were first processed to yield image data, which were then co-registered so that all images were aligned in the SAR acquisition geometry. An external DEM was obtained for the study area from the 30 m (100 ft) SRTM DEM data available from the USGS. This DEM was co-registered to the SAR data as well, and then used to determine the topographic phase contribution for each interferogram. Both the curved-Earth and topographic phase were calculated based on the SAR acquisition geometry, and initially relied on the intrinsic satellite orbit information. The orbit baseline information was then refined by using the curved-Earth fringe rate evident in the differential interferogram. Further issues relating to residual phase were dealt with at the interferogram stage.

Table 9. Mesa Verde SAR interferometric image pairs.

Figure	Acquisition Dates	SAR Sensor	Perpen-dicular Baseline (m)	Δ Time (days)	Mean Coherence	Standard Deviation
	May 28, 1996–Sep 10, 1996	ERS-2	98	105	33	17
	Aug 1, 2004–Aug 25, 2004	RSAT	12	24	74	18
	Aug 25, 2004–Oct 12, 2004	RSAT	250	48	38	18
	Mar 5, 2005–May 16, 2005	RSAT	299	72	30	15
	May 16, 2005–Jul 3, 2005	RSAT	196	48	36	17
	Jul 3, 2005–Aug 20, 2005	RSAT	389	48	35	17

Results

The InSAR interferograms for the intervals given in Table 9 were computed. As noted previously, the coherence in the areas of interest along the mountain slopes was generally poor, with regions of radar layover and shadow. The mean coherence values for the InSAR interferograms are included in Table 9, and are seen to generally be in the 30% range. However, as previously seen in Figure 19, the Mesa Verde area is characterized by quite good coherence in the low relief regions, and poorer coherence in the more rugged regions.

The ERS InSAR pair from May to September 1996 was used to evaluate the longer-term coherence, and estimate the likelihood of obtaining movement measurements in the specific areas of interest. No useful movement results were obtained from this interferogram, and further attempts concentrated on short timeframe InSAR pairs, as well as the higher resolution Fine mode of RADARSAT in order to help isolate specific slopes of interest.

The short timeframe interferograms generated from the RADARSAT Fine mode data provided the best coherence, and, in particular, the 24-day InSAR pair from August 2004 yielded average coherence of roughly twice the typical value. The precipitation for Cortez, which is 15 km (10 mi) to the west of Point Lookout, is given in Figure 51, from which it is seen that the amount of precipitation varied substantially from month to month.

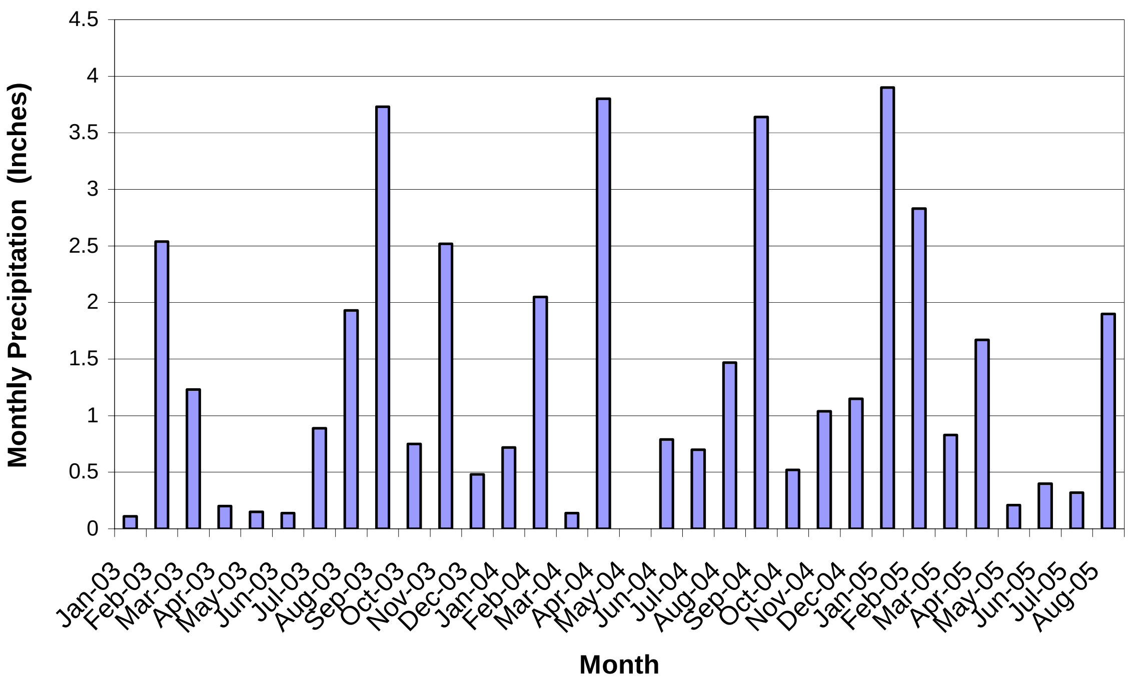

Figure 51. Graph. Monthly precipitation from January 2003 to August 2005 for Durango, Colorado.

All InSAR interferograms showed significant residual phase that was correlated to the topography. To date, this has not been eliminated, and therefore it is a major source of uncertainty in these datasets. This combined with the radar layover and shadow and the poor coherence associated with the mountain slopes, has prevented useful movement maps from being obtained.

The InSAR pair from August 2004 has the advantage of a short timeframe, of only moderate precipitation, and of, especially, an exceptionally good baseline of only 12 m (40 ft). The residual phase, interpreted as differential height, is shown in Figure 52, with the SAR intensity image in the background and the road network given by the red lines. It is seen that the residual phase is correlated with topography. Further, areas of radar shadow are seen as extremely dark regions in the SAR intensity image, while areas of radar foreshortening and layover are seen as extremely bright areas in the image, both of which are aligned with the large ridges and slopes. Regardless, within these obvious artifacts, no movement signatures are visible.

A more typical representation of the residual phase in the Mesa Verde region is given for the July to August InSAR pair as given in Figure 53. This pair has a more typical baseline value of near 400 m (1300 ft), as well as a longer timeframe of 48 days. Here, the correlation of residual phase and topography is still visible, but interpretation is further hampered by the increase in phase noise associated with the lower coherence.

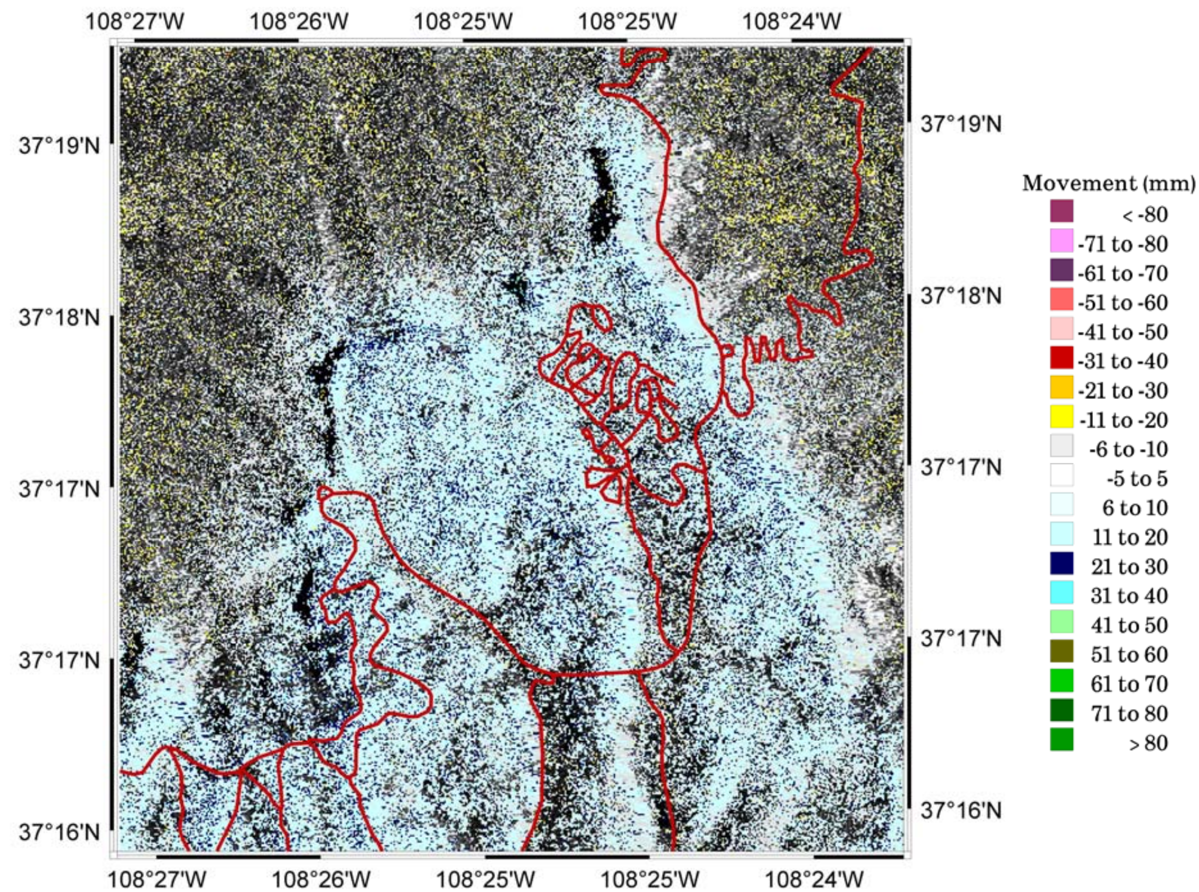

Figure 52. Graph. Residual phase, displayed as height change, for the August 1 to 25, 2004 InSAR pair.

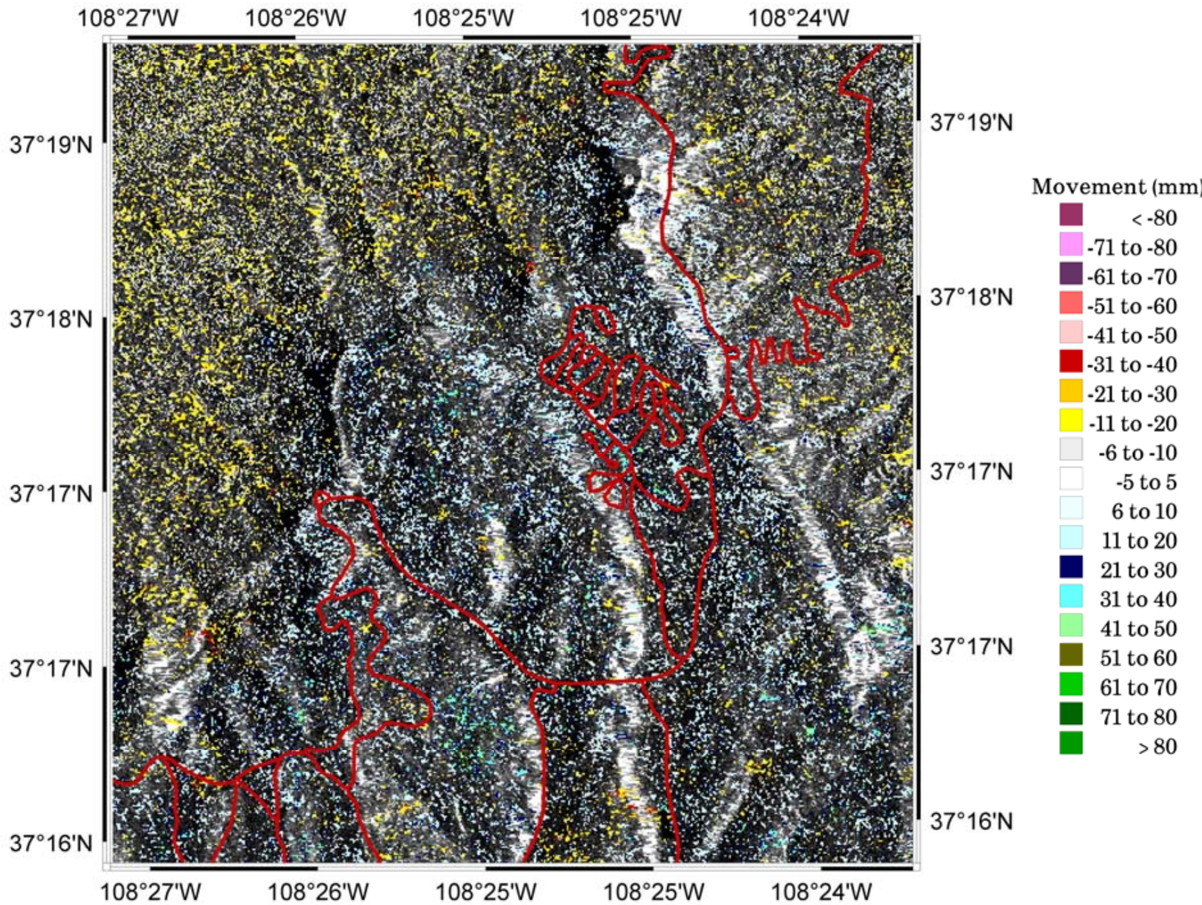

Figure 53. Graph. Residual phase, displayed as height change, for the July 3 to August 20, 2005 InSAR pair.

Interpretation

The Mesa Verde area, and in particular, the slide areas located on the slopes of Point Lookout, have rugged topography that has prevented InSAR determination of the movement. In some instances, the slopes are simply obscured by radar shadow or layover, and no movement information can be obtained. In the remaining mountain areas, there are generally poor InSAR coherence and residual topographic phase that preclude meaningful interpretation of the InSAR data.

CHAPTER 5 – RECOMMENDATIONS ON INSAR USE WITHIN FLH

IMPLEMENTATION OF INSAR

When implemented and interpreted correctly, InSAR can often be used to measure slope movement as an input to slope stability determination. This study has demonstrated that there are many factors that affect reliable movement detection. A summary of these has been provided below as recommendations for the future application of InSAR. In addition, guidelines have been determined for the coordinated use of InSAR with other FLH data collections, including photogrammetry, field surveys, boreholes and slope inclinometers. These are also listed below.

Geotechnical Suitability

A series of risk evaluation criteria has been developed to aid future evaluation of slope stability, and are given in Table 7. Three risk categories have been developed that provide details of proactive monitoring programs that could be undertaken to evaluate the likelihood of slope instability. The suggested monitoring actions have been selected to minimize cost and make use of InSAR techniques that have been the focus of this project. The criteria are based on slope angle, rainfall (groundwater) and previous evidence of slope movements.

Table 10. Slope movement risk analysis and monitoring recommendations.

Slope Movement Risk		
High Risk	***Intermediate Risk***	***Low Risk***
• Active displacements of roadways observed. • Tension cracks observed on slope faces. • Heave or subsidence of slopes observed. • Evidence of slope creep e.g. rotating fence posts, poles. • Any further evidence of increase in rates of observed displacements.	• Slope grades of 15% or higher. • History of slope movement in vicinity. • Evidence of high or periodically high ground water levels e.g. springs on surface, fluctuating pond levels, etc. • New road construction or similar infrastructure involving slope excavation. • Seasonal or otherwise periodic high rain/runoff periods or flooding observed.	• Slope grades less than 15%. • No evidence of high groundwater levels. • No history of instability.
InSAR Recommendation		
• InSAR and ground–based monitoring if any of the above factors is present.	• InSAR monitoring if two or more of the above factors are present.	• Periodic InSAR monitoring is optional.

Site and InSAR Suitability

Sites should be thoroughly reviewed before proceeding with the application of InSAR. There are six primary site characteristics and SAR data issues that should be considered. The six issues have been ranked in order of importance, and are discussed below.

1. Image Coherence: The InSAR coherence is one of the main factors in determining suitability. Slopes with heavy brush, fast growing vegetation and/or forests are generally not suitable for InSAR monitoring unless corner reflectors are used to provide high coherence points. There are several ways to evaluate image coherence, including an on-site evaluation of vegetation, the analysis of a recent multispectral image (colour air photo or satellite image) and the acquisition of a 'test pair' of SAR images over a single orbit cycle (24 days for RADARSAT-1 and 35 days for ERS/ENVISAT). In practice, both the on-site evaluation and a 'test pair' coherence evaluation should be performed. Their evaluation should place the site in the following categories for C-Band satellites[2]:

    Category 1: Greater than 30% coherence over greater than 80% of the region of interest – this site will typically be a semi arid or arid region of slow growing vegetation, dry grasses and no tree canopies.

    Recommendation – Use traditional InSAR with 3-cycle SAR image revisit (i.e., quarterly)

    Category 2: Greater than 30% coherence over greater than 60% of the region of interest – this site will typically have mixed vegetation including dry grasses, low brush and sparse deciduous/coniferous tree canopies. Dry, slow growing vegetation will cover most of the region.

    Recommendation – Use traditional InSAR with 1 cycle SAR image revisit (i.e., monthly).

    Category 3: Greater than 30% coherence over greater than 40% of the region of interest – this site may have an even mixture of grasses and fast growing vegetation and/or deciduous tree canopies.

    Recommendation – Use traditional or Corner Reflector InSAR with 1 cycle SAR image revisit (i.e., monthly) supplemented with corner reflectors on low coherence regions of interest.

[2] The categories have been derived based on experience with C-Band satellites (RADARSAT, ERS, ENVISAT). L-Band SAR, such as PALSAR and JERS, use longer wavelength radar of 235 mm that is sensitive to the larger tree structure on this scale rather than the leaf, branch and stalk structure that influences C-band scattering. Since the larger structure changes less over moderate time intervals, the L-band SAR coherence is usually better.

Category 4: Less than 30% coherence of greater than 60% of the region of interest – this site may have a combination of fast growing vegetation and/or tree canopies over most of the region.

Recommendation – Use corner reflector or Interferometric Point Target Analysis InSAR with 1 cycle SAR image revisit (i.e., monthly) with corner reflectors installed on locations or benches of interest at 50 – 80 m (164 – 262 ft) spacing.

2. Slope Alignment: Slopes that are ideal for InSAR monitoring are those facing in a general East or West direction. This maximizes sensitivity of the SAR instrument measurement since the SAR look-direction is along the direction of the assumed slope movement. Slopes that are facing in a North or South direction may be effectively monitored with InSAR, however the minimum detectable movement and the uncertainty in the estimated slope movement are higher for these slopes. This minimum detectable movement is determined by slope geometry.

   Recommendation – Using the slope geometry and satellite acquisition, the minimum measurable movement based on the noise limit sensitivity should be estimated. Traditional InSAR should not be applied if the expected movement over the InSAR monitoring interval is much less than the measurement error due to noise. When this happens, corner reflectors used in conjunction with Interferometric Point Target Analysis should be applied. The revisit frequency should be minimized (1 cycle – 24 to 35 days). Corner reflectors should be installed on locations or benches of interest at 50 – 80 m (164 – 262 ft) spacing.

3. Slope Angle (or Grade): Steep slopes are often difficult to monitor with InSAR due to layover, foreshortening and shadow effects. In addition, complicated topography creates a challenge in eliminating residual topographic phase, especially when an accurate DEM is not available. Slope angles that are much less than the SAR incidence angle are preferable. Although layover and shadow effects may not be present in some SAR satellites with angles approaching 70° [3], these slopes are too steep to monitor in practice. A more reasonable monitoring limit can be set by considering the “local incidence angle,” or the angle between the SAR look direction and the slope. Since most SAR satellites and aircraft have incidence angles between 20° and 70°, this can be considered a good *rule of thumb* limit for the local incidence angle. For looking downslope, this sets the slope limit at approximately 50° or a grade of 120%.

   Recommendation –The recommended maximum grade for InSAR is 120%. For grades between 100% and 120% ERS and ENVISAT should be used. For slopes with grades less than 100%, all available satellites can be used. To maximize the InSAR measurement sensitivity, it is recommended that the radar look direction be oriented ***downslope****. Upslope look directions should only be used for gentle slopes with grades less than 20%.*

[3] ENVISAT’s steepest incidence angle is nominally 14° to 22°, corresponding to a slope of around 90°-18°= 72°.

4. Expected Movement: InSAR is applicable to slopes whose movement along the look direction of the SAR satellite exceeds the measurement noise level of the satellite, or 0.5 – 1.0 cm (0.2 – 0.4 inch) per revisit interval. However, InSAR is not suitable if the expected movement is sufficiently high to result in reduced coherence or skipped phase intervals on the InSAR interferogram. This was demonstrated at the Cimarron site, in which the slide movement during 1997 could not be measured using InSAR even over short time intervals. The practical upper limit of this movement was not determined by this study; however to avoid skipping of phase intervals in the interferogram, the upper limit of the movement ***gradient*** should be less than 28 mm (1.1 inch) (the satellite's λ/2 at C-Band) per resolution cell, or 8 m (26 ft) for RADARSAT Fine and 30 m (100 ft) for ERS/ENVISAT. To use the movement gradient criteria, consider the distance from the point of maximum movement to the outer perimeter of the sliding region and divide that by the resolution cell size to get the number of resolution cells between the point of maximum movement and stable ground. Multiplying this by 28 mm (1.1 inch) gives the maximum movement within the InSAR monitoring interval. Creeping slopes may require short revisit intervals coupled with an extended series of satellite images (10–15) to improve movement measurement relative to noise limits.

   Recommendation for fast moving slopes – InSAR is not recommended for use on slopes whose monthly movement exceeds 0.0035d for RADARSAT Fine mode and 0.00112d for ERS / ENVISAT, where d is the distance from the point of maximum movement to the edge of the slide.

   Recommendation for creeping slopes – For sites in which the movement is expected to be at or below the InSAR measurement noise level (i.e. < 1.0 cm (0.4 inch)) in monitoring interval, it is recommended that InSAR be applied with a 1-cycle SAR image revisit (i.e. monthly) over a minimum timeframe in which the overall expected movement in the satellite look direction exceeds 5 cm (2 inch). The use of corner reflectors with Interferometric Point Target Analysis is highly recommended to increase measurement sensitivity to the millimetre scale.

5. Data availability: New data can always be captured on sites of interest, however, the availability of a large quantity of SAR data in the historical archive will also facilitate a review of the movement history if the data are sufficiently spaced in time to have reasonable coherence. This is particularly relevant in this project, where it was required to perform an historical analysis of the movement at the three sites using data available in the SAR archive.

   Recommendation – For historical studies, InSAR should be applied with the same repeat cycles as is recommended under Point (1) Image Coherence. For sites with moderate coherence, Interferometric Point Target Analysis may also be used if the number of available images exceeds 15 over several years. Long time interval revisits used in combination with traditional InSAR have, at times, been used successfully to extract movement, however this procedure is not always reliable due to the possibility of low coherence pairs. Therefore, the use of extended monitoring intervals for (historical) InSAR (i.e. 6 months to 1 year revisit) is not generally recommended.

6. Existing Site Data: The availability of site survey and control data, coupled with orthophotography, is very useful for maximizing the accuracy of the horizontal positioning of the InSAR data. In addition, these data help to provide a means to interpret the InSAR-derived movement information to determine the overall impact of any significant movement. The availability of a recent DEM is also important to the application of InSAR. The DEM should cover the entire region of interest, which for a SAR scene is nominally 50 × 50 km or 100 × 100 km; sub areas of interest should minimally cover 5% of the imaged scene.

   Recommendation – Refer to the next two subsections on Elevation Models and Survey and Control for recommendations on the coordinated use of InSAR and other FLH site data.

Elevation Models

To measure ground movement using InSAR, an elevation model is required for removal of topographic phase. The minimum standard of this elevation model for moderate relief is as follows:

- Data Format: Raster grid of absolute elevations, equivalent to Digital Terrain Elevation Data (DTED®), or be grid format that preserves the accuracy of the elevation model points.
- Accuracy: Horizontal positioning – ±20 m (65 ft) minimum, Vertical – ±16 m (50 ft) minimum.
- Coverage: Region of interest with a minimum area of ~5% (~125 km^2 or ~50 mi^2) of the SAR images.

The specifications given above may not be suitable for regions of significant relief, such as the slopes of interest in Mesa Verde National Park. Higher resolution and accuracy DEMs may be required and consequently this should be evaluated on a site-specific basis.

The standard given above is for InSAR topographic phase removal only and thus should not be applied for other analytical aspects of a project. DEMs with closer grid spacing and higher vertical and horizontal accuracies may be required, for example in the subsequent analysis of ground movement derived from InSAR. The standard described above is equivalent to DTED Level 2 (30m (100 ft)), similar to a 1:50,000-scale map.

With the standard given above, DEMs could be derived for InSAR using the ERS-1/2 tandem mode mission, captured in 1995 to 1996. In this case, InSAR is used to derive the DEM from the SAR tandem mode pair. A more recent source of DEM data is the Shuttle Radar Topography Mission (SRTM) available from the USGS EROS Data Center. These data were captured in 2000 and are available in several formats, including DTED Level 1 (100 m (330 ft) raster) and DTED Level 2 (30 m (100 ft) raster). SRTM data at the DTED-2 specification are currently available for the United States, its territories and possessions.[18] It is recommended that SRTM data be used by default because it is currently the most recent data available with complete U.S. coverage. In some cases, DTED Level 1 data can be used successfully with InSAR. However, the use of these data should be avoided if possible, especially in regions of complex topography such as in Mesa Verde National Mark. In these regions, the DTED-1 100 m (330 ft) spacing might under-sample complex topography leading to residual topographic phase in the output InSAR product.

As mentioned above, higher resolution DEMs may be available for specific projects. These data may be captured, for example, by airborne LIDAR or InSAR instruments. It is recommended that these data be used, if available in a raster format suitable for InSAR.

It should be noted that contours extracted by optical photogrammetry are not a suitable DEM format for InSAR due to their incompatibility with existing commercial InSAR software. Consequently, contours must be translated to a raster grid before being suitable for use in the InSAR software. In addition, short interval contours often cover small areas (i.e. only the region of interest) due to the expense in deriving contour information outside the region of interest. An example of this is the 5 m (16 ft) contours derived for Cimarron in 1998. In this example, these data only covered a small portion of the region of interest and were thus unsuitable for topographic phase removal of wide coverage SAR scenes. Therefore, the expense to convert these contour data back to a raster DEM is not worthwhile. This does not preclude the expansion of photogrammetry for **new** projects to a larger region to facilitate InSAR, especially in areas of high or complex relief where a higher scale DEM would be beneficial to InSAR.

Survey and Control

There are several recommendations on the coordinated use of survey and control data with InSAR projects. To support accurate geo-referencing of the SAR data for present and near future satellites, a minimum of 0.5 m (1.6 ft) accuracy survey monuments must be used. It is recommended that at a minimum, resource grade surveys with differential correction be used to support InSAR projects requiring accurate placement of movement data. However, it is recognized that there may be times when accurate placement of InSAR derived movement data may not be required. Therefore, the following guidelines are presented for future InSAR projects.

- Generalized InSAR Analysis: To obtain a generalized picture of movement over a region of interest, USGS Topographic maps (1:24,000) can be used as the basis for InSAR control. If these data reveal potential impact to road infrastructure, control should be reverted to resource grade surveys at a minimum using the guidelines presented in points (2) to (5) below.

- InSAR for Highway Infrastructure Analysis – Archived Data: Should post geo-referencing of the InSAR data be necessary at a slide site, identifiable features in the SAR data should be collected as GCPs and surveyed per the direction of an InSAR Specialist. Post geo-referencing refers to SAR data that have already been collected.

- InSAR for Highway Infrastructure Analysis – Newly Acquired Data: Should geo-referencing of the InSAR data be necessary for future satellite data capture, the site and available aerial photography should be reviewed to determine the possible existence of suitable SAR GCPs. If suitable orthorectified aerial photography, tied into local survey and control, is not available or if a large quantity (20 or more) of suitable GCPs cannot be identified in the existing air-photos, then corner reflectors should be installed on site at the direction of a survey engineer and InSAR specialist. A minimum of six reflectors should be placed throughout the region of interest, with an additional reflector added for every 10 km^2 (4 mi^2) of monitoring area. Using this rule of thumb, a hypothetical 5 × 5 km (3 × 3 mi) site should have nine corner reflectors installed. The corner reflectors should be surveyed to better than 0.5 m (1.6 ft) accuracy using differentially corrected resource based surveys at a minimum.

- Final Coordinate Systems and Datum: The surveyor should coordinate with the Central Federal Lands Highway Division prior to commencement of the on-site field work to resolve any datum issues. It is recommended that monument positions be reported with horizontal positioning geo-referenced to the NAD 83 datum (FLH specification). The data should be post processed and the differential correction applied to achieve the sub-meter accuracies. It is recommended, prior to the survey, that a resource grade position be surveyed on a known geodetic published point to provide a calibration or accuracy check.

- Survey Report: Upon completing the geo-referencing of point positions, a Final Survey Report should comment on the accuracies of the surveyed points, meta data and procedures used. At a minimum, the report should:
    - Include an executive summary of the survey and its results;
    - Provide the metadata commenting on the point positional accuracies and post processing techniques;
    - State a narrative description of all aspects of the surveys;
    - List equipment and software details;
    - Comment on final coordinate listings;
    - Include station sketches for the ground control points.

IMPLEMENTATION DECISION TREE

Many of the InSAR recommendations listed in the previous subsections have involved a decision-making methodology that should be employed to determine the suitability of InSAR for a particular region. Therefore, it was deemed appropriate to formulate this methodology into a decision tree framework that would guide FLH personnel in the future use of the technology. This methodology is somewhat complex and difficult to distil into a simple decision tree process because many of the decision factors are interrelated to some extent. However, the decision tree provided in Figure 54 is certainly representative of the most important decisions that have to be made in the process of determining InSAR suitability to a particular slope or project. The major factors that have been included in this tree include both geotechnical and site suitability factors including:

- Slope movement risk as defined by Table 10;
- Image coherence as defined by the four categories listed in the previous section;
- Slope alignment, whether facing east, west, north or south;
- Slope grade, which defines the maximum grade that can be reliably monitored by InSAR;
- Expected movement, which defines the movement that would be seen by the satellite.

These factors, as they relate to the decision tree, will now be summarized (and in some cases simplified) to ease the understanding of the decision tree. The slope movement risk decision box, as it is defined in Table 10, provides a means to categorize a slope into low, moderate and high risk.

The slope grade decision box provides a means to eliminate those slopes that are too steep to monitor with InSAR. The overall geometry of the slope (including grade and alignment), together with the expected or anticipated slope movement will determine the amount of movement that will occur in the satellite look direction. In other words, there are three parameters (grade, orientation and expected movement) that collectively define a single parameter (expected movement in the satellite look direction). In the decision tree, these three parameters are shown in separate boxes, but in practice, they are considered together. For the purposes of the decision tree, the parameter *expected movement in the satellite look direction* is subdivided into three categories, including:

- Creeping movement, which is much less than 28 mm (1.1 inch) in one month;
- Moderate movement, which is approximately 28 mm (1.1 inch) in one month;
- Significant movement, which is greater than 28 mm (1.1 in) in one month.

As a reminder, 28 mm (1.1 in) is one cycle of movement in phase for RADARSAT, ERS and ENVISAT.

The coherence categories are defined by categories 1 through 4 as listed in the previous subsection. For the purposes of the decision tree, these categories have been 'described' as High, Moderate, Low and Very Low for categories 1 through 4 respectively. In evaluating the coherence for the purposes of the decision tree methodology, one would first 'estimate' the coherence based on the vegetation cover, as listed previously in the category guide. This would give a first indication as to the InSAR category that could be applied to the project. It would also provide the first means of eliminating unsuitable slopes without collecting any satellite data. If the slope was deemed appropriate for InSAR based on the coherence estimate, the coherence could then be measured cost effectively with the purchase of a single InSAR pair[4]. Note that the final decision on the type of InSAR to apply to a given project should only be made once the coherence has been measured quantitatively with a pair of SAR images.

Note that not all of the decision boxes have been placed throughout the decision tree; many of the boxes have been eliminated to simplify the tree structure. For example, moderate risk slopes are likely not of a steep grade and therefore the Slope Grade decision box has been removed from that path. In the case of low risk slopes, it is expected that the total movement will be a creeping type of movement, as it is defined here. In addition, low risk slopes are not high grade slopes (as defined by Table 10). Therefore, the grade, alignment and expected movement boxes have been eliminated from this path. Since there is a cost associated with installing reflectors, in the case of low or very low coherence, low risk slopes are deemed to be unsuitable for InSAR on the basis of cost versus overall benefit of monitoring.

[4] Many InSAR contractors provide this service free of charge.

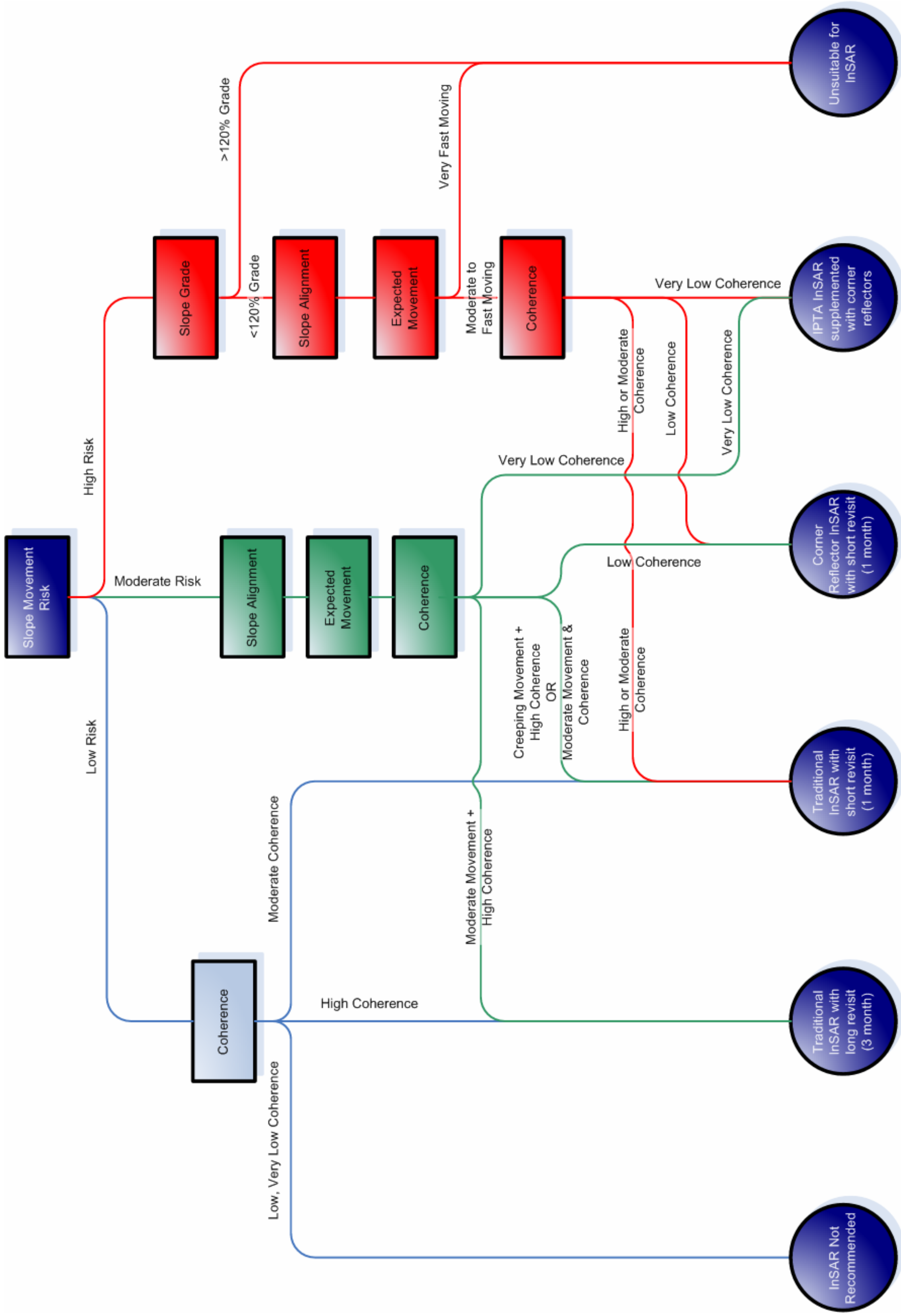

Figure 54. Schematic. Recommended decision tree methodology for application of InSAR to FLH projects.

PROCUREMENT OF INSAR

Presently, InSAR is an emerging technology in many operational sectors. This is particularly true for slope stability monitoring due to the number of issues that must be addressed for effective and accurate monitoring. Consequently, a few guidelines and recommendations concerning InSAR application and costs are presented here as a reference to future procurement.

InSAR and Slope Monitoring Experience

The InSAR industry is growing and many remote sensing companies are adding InSAR to their slate of services. Throughout this report, it has been emphasized that slope stability assessments with InSAR are typically more challenging than simple InSAR DEM extraction or InSAR movement monitoring over relatively flat regions. Therefore, prospective InSAR contractors should be requested to include a list of experience and references for previous projects involving slope stability assessment and interpretation. It is also beneficial for contractors to provide their expert opinions on slope movement mechanisms rather than to just provide a deformation map. Therefore, it is recommended for contractors to offer the services of a resident geotechnical engineer or geologist who has experience in interpreting InSAR derived ground movement.

Given that InSAR is a fledgling industry, it may be challenging for FLH personnel to find qualified contractors. Domestically, there are a number of InSAR service providers whose primary focus is digital terrain models. In the case of movement monitoring, the current majority of companies providing commercial InSAR services reside in Canada and Europe. Consequently, the best source of InSAR contractor information can be found on company directories of the various Space Agency websites.[5]

Given the challenge of locating qualified contractors, it is highly recommended that FLH go through a pre-qualification process to compile an official list of InSAR contractors. To maximize the number of respondents, an international distribution of the pre-qualification solicitation is recommended.

Standards

Currently there are no standards available that specifically govern InSAR monitoring. The Earth Observation Industry is moving towards the development of standards[6] and consequently this situation may be rectified by 2010. In the meantime, care should be taken to ensure that companies adhere to US state mapping standards and that all InSAR derived movement data be georeferenced according to the guidelines presented here.

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[5] See for example the Canadian Space Agency's *Canadian Space Directory* at http://www.space.gc.ca/asc/eng/Industry/default.asp or the European Space Agency's list of service suppliers at http://www.eomd.esa.int/compendium/companies.asp. If these links change after publication of this report, please refer to the main Space Agency web pages at www.space.gc.ca or www.eomd.esa.int.

[6] The European Space Agency has initiated a feasibility study on EO standards in the fall of 2005. This ESA study was ongoing at the completion of this FHA project and consequently no publications were available at press time.

InSAR Suitability

The report has suggested guidelines for the implementation of InSAR on federal highways projects. Depending on how these rules are implemented in practice, FLH personnel may choose to either become highly involved in the Implementation Decision Tree or they may choose to rely on contractors to make informed decisions on their behalf. If the latter approach is taken, it is recommended that InSAR contractors go through a similar decision process to rule out sites that are unsuitable for InSAR. The industry is in a relatively early stage of development and it is not uncommon for certain contractors to over promise and under deliver, particularly since InSAR cannot be applied to all situations. It is recommended therefore that procurement contracts include go/no-go stage gates after the initial coherence evaluation has been completed, and annually thereafter for multiyear projects. It is also recommended that initial coherence evaluations include InSAR pairs during wet and dry seasons so that FLH personnel can get a better appreciation for InSAR seasonal suitability. The above recommendations are most easily achieved by including a Feasibility Study as the first phase of any InSAR contract and including annual performance stage gates for long term monitoring. Some InSAR contractors offer initial Feasibility Study services for free, but these services may not include a comprehensive analysis of the seasonal coherence. The analysis and recommendations of the Feasibility Study should be documented in a report to facilitate a thorough review by FLH personnel. Annual reports should also include the same level of detail and analysis on site coherence to facilitate go/no-go reviews.

Corner Reflectors and IPTA Analysis

Future FLH projects involving point target analysis or corner reflector analysis should only be conducted by those contractors who have experience in applying this technique. There are issues specific to those techniques that have not been fully explored within this project. These issues include, for example, the proper sizing, placement and positioning of reflectors, the resolution of phase ambiguities in the interferograms with spatially discontinuous phase information, and the removal of artifacts such as atmospheric effects.[6,7,8] Consequently, when corner reflectors are to be used, it is recommended that FLH only use those InSAR contractors who can demonstrate several prior projects in this area. If a pre-qualification solicitation is undertaken by FLH, corner reflector and IPTA expertise could be included as an optional requirement by prospective contractors.

Final Products

Final products of an InSAR contract for slope monitoring can vary in the amount of geotechnical interpretation that is provided. As suggested above, it is recommended that some level of interpretation be included in InSAR monitoring contracts, however, this may not be necessary if available FLH personnel have prior experience in InSAR work. If no interpretation is requested, the final product of the contract should be a deformation map(s) with the following information included in the transmittal report: satellite used, dates of images, quantification of coherence over regions of interest, georeferencing process used, precipitation over the monitoring interval and precipitation during the day of the image acquisitions. This product is essentially a factual representation of the satellite imagery with data presented to allow the user to georeference the movement information in the image and to assess the uncertainty in the measurements. The user would then be responsible for interpreting the map and reconciling it with other observations in the process of evaluating slope stability. Alternatively, the final product may consist of this factual report plus a separate interpretation report prepared by a professional (geotechnical engineer, geologist or other) experienced in the interpretation of InSAR and reconciliation with other geotechnical observations.

Operational Costs

The following section on InSAR operational costs is included as a budgetary guide. Since operational costs vary significantly between contractors, it is recommended that budgetary estimates from qualified contractors be solicited before fixing project budgets. In addition, operational costs are expected to increase somewhat over time from the publication of this report.

Costs of performing ground movement analysis using InSAR may be subdivided into four different areas:

- Generation of DEM.
- Installation of radar reflectors (if required).
- Generation of ground movement measurements.
- Interpretation of the movement data.

For the US, SRTM DEMs are generally available at the appropriate scale, and consequently the cost of generating a DEM may not be a factor. However, as suggested previously, in certain cases it useful to have a higher scale DEM, which could be produced by higher resolution SAR, stereo optical or LIDAR.

As suggested earlier, some InSAR projects will require the use of radar reflectors. Reflectors are generally fabricated out of aluminum angle and sheet metal and can be fabricated at most machine shops for about $700-$900 per unit. Due to the costs of shipping reflectors, it is recommended that they be manufactured at a machine shop in the vicinity of the InSAR project. Many InSAR contractors can access design drawings specifically for this purpose, while some contractors have their own in-house designs. The reflectors themselves are not complicated to manufacture and most machine shops experienced in sheet metal fabrication and machining are suitable for this task. If the monitoring region is accessible by vehicle (which would be the case for most highways projects), then the cost of reflector installation is generally the cost of the vehicle and labor expenses. For a two-person installation, it takes about 1 day to mobilize to the site and about 1 day to install 4-5 reflectors. If the monitoring region is remote and accessible only by helicopter (which might be the case for a new highway project or realignment), then the cost of helicopter time should also be considered, along with additional time to mobilize equipment to the sites. However, it is noteworthy that once the installation is completed, the site need not be visited on a regular basis for monitoring, and consequently, the reflector installations are an upfront cost only.

The cost of generating a ground movement pair is composed of the cost of the SAR image pair and the cost of the labor to perform the processing. The amount of labor required to perform processing is generally dictated by the size of the area being considered for ground movement and the amount of relief. For areas of low relief, small regions (about 2.6 – 5.2 km^2 (1 – 2 mi^2)) may be processed in 1-2 days, while larger areas (26 km^2 (10 mi^2)) may require five or more days to process. For moderate and high relief regions, longer processing time should be anticipated. Processing times that are double or triple that of low relief regions are to be expected. Most reputable InSAR contractors will perform a preliminary site analysis, evaluating coherence and topography before providing a quotation on costs. In some cases, contractors have established a fixed base-price for doing InSAR movement maps (including the SAR data) that do not vary with the complexity of the project.

Based on the above analysis, a table of costs has been derived (Table 11) to provide a guide to determining the actual costs. Several assumptions have been made to devise this table including the following:

- Labor cost: $1000/day
- Per diems and hotels to laborers (for reflector installation, includes approximate hotels costs): $300/day
- Reflectors: $900 each in small quantities
- SAR data costs
  1. ERS/ENVISAT: $1,000 per image (100 x 100 km (60 × 60 mi))
  2. RADARSAT-1: $2,500 per image (50 x 50 km (30 × 30 mi))

It should be noted that the cost provided for SAR data above is at the upper end for typical SAR data costs. Substantial discounts ranging to as high as 50% to 75% can be realized on data purchases in quantity. Many InSAR contracts are able to access such volume discounts for provision of their services. The labor rates used are also considered somewhat conservative. For example, it is known that several companies can provide a complete InSAR monitoring service at a more competitive rate than that quoted in Table 11. In addition, the installation of radar reflectors may be accomplished using internal FLH labor.

With these costs in mind, Table 11 has been compiled under the assumption that an initial feasibility may be required for any InSAR project. The initial feasibility study is envisaged as an examination of several InSAR pairs over a season for coherence, and the generation of a report on the coherence analysis. Ongoing operational costs will vary depending on the frequency of InSAR monitoring (quarterly, monthly) and the level of expert interpretation requested from the contractor. For example, if no interpretation is required, the costs of quarterly monitoring could vary between $16,000 and $48,000 depending on the topographic complexity of the region.

Table 11. Costs of InSAR Monitoring.

Item	**Cost Item Amount**	**Total Cost**
Up front cost		
Feasibility Study:		
SAR imagery (ERS or ENVISAT)	4 × $1,000	$4,000
Generation of coherence images	2 person-days	$2,000
Generation of Feasibility Study Report	2 person-days	$2,000
Radar reflector installation (if required):		
Radar reflectors (5 reflectors per site)	5 × $900	$4,500
Field installation labor	3 days	$3,000
Field installation expenses	3 days	$1,800
Mobilization expenses (vehicle rental, helicopter, etc.)	Variable	
Ongoing cost per monitoring interval		
Ground movement maps generated using RADARSAT-1		
SAR imagery	2 × $2,500	$5,000
InSAR deformation map generation	2-10 person-days	$2,000 to $10,000
Ground movement maps generated using ERS/ENVISAT		
SAR imagery	2 × $1,000	$2,000
InSAR deformation map generation	2-10 person-days	$2,000 to $10,000
Expert interpretation of InSAR derived deformation map	*Variable*	

IMPROVEMENTS FOR INSAR MONITORING

There are several improvements that could be made to the application of InSAR, but which were outside the scope of the project presented here. In addition, there are several new satellites that will be launched in the near future, and which will provide enhancements over current capabilities. For example, corner reflectors, Interferometric Point Target Analysis, higher resolution satellites, and L-Band SAR are discussed below.

- Corner reflectors: Phase stable reflectors can serve the dual purpose of facilitating geo-referencing to site control and improving coherence in regions that are not suitable for traditional InSAR. They were not used in this program due to the relatively good single-cycle coherence of the Prosser and Cimarron sites. Reflectors made from sheet and angle aluminum are robust and not generally susceptible to wind, rain or snow damage. Tests conducted in Alberta and Newfoundland, Canada, have demonstrated their ability to weather harsh environments over many years. As shown in Figure 55, several designs are available, including those mounted with steel pegs and on concrete base foundations. The steel peg design can be field assembled and installed in about 90 minutes.

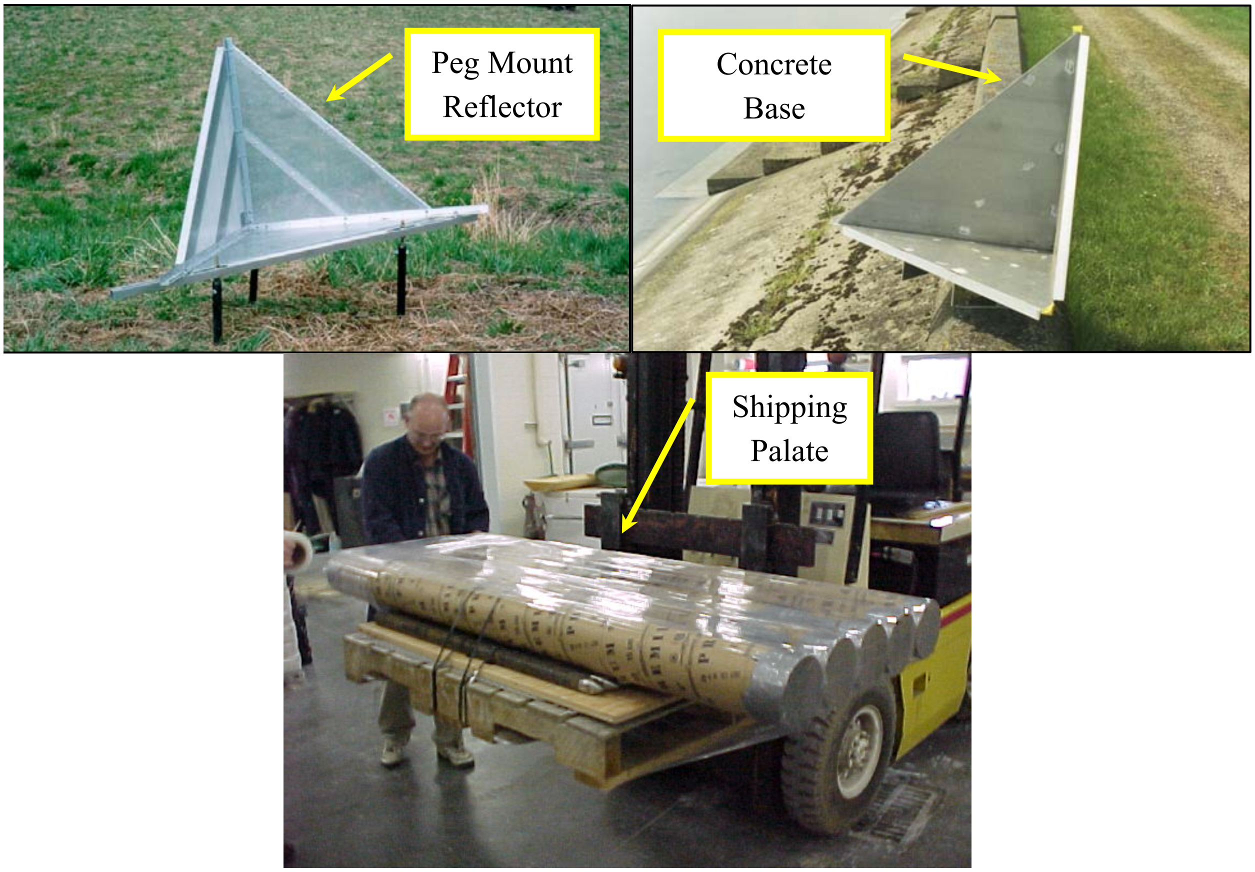

Figure 55. Photo. Radar reflectors using two different mounts (upper left and right), and packaged for shipping (lower centre).

- Interferometric Point Target Analysis (IPTA): IPTA and PS InSAR is finding greater use due to lower costs of European ERS and ENVISAT data and the relative success that monitoring programs have seen in producing high accuracy results (on the order of millimeters). They are typically used with historically archived data and require stacks of images of minimum 15 scenes and more typically between 25 – 35 images covering 3 – 5 year timeframes. When used in conjunction with corner reflectors, success in the application of InSAR is virtually guaranteed regardless of the site. If the ground movement behavior can be described by a mathematical model, the technique can also be used to correct for atmospheric effects and topographic errors. Both the Cimarron and Prosser sites are good candidates for an IPTA program and have large volumes of ERS-2 data dating from 1995-2001. Figure 56 shows an example of subsidence within an urban area as determined using the IPTA technique.(19)

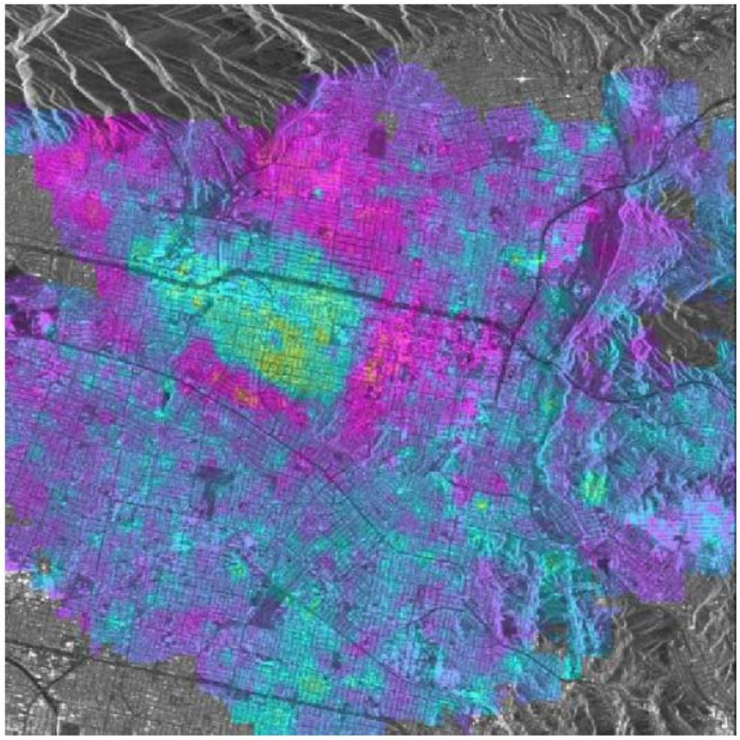

Figure 56. Graph. IPTA example (Colour Cycle = 4 mm (0.16 inch) /year).(19)

- Higher resolution satellites: Within the next 12-18 months, two new high resolution SAR satellites will be launched, including RADARSAT-2 and TerraSAR-X, as shown in the illustrations of Figure 57. RADARSAT-2 is a C-band satellite (similar to RADARSAT-1, ERS and ENVISAT) and will have a maximum resolution of 3 m (10 ft), with the possibility of being increased to 1 m (3.3 ft) after launch. This platform will have much better orbit control than its predecessor RADARSAT-1, and consequently more of the scenes acquired for monitoring programs should be suitable for InSAR. The increased C-Band (5.4 GHz) resolution should, in theory, improve coherence due to reduced clutter levels in higher resolution cells and consequently regions that are presently not suitable for InSAR may be suitable with RADARSAT-2. TerraSAR-X will have a maximum resolution of 1 m (3.3 ft), although it operates at X-Band (9.65 GHz) and may be less suitable for InSAR in vegetated regions compared with RADARSAT-2. The relatively high resolutions from these two satellites imply that slope stability monitoring will increase significantly due to the ability to image smaller features on the ground and thus measure greater movement details. This will be particularly relavant for monitoring smaller slopes or slopes with smaller or more complex moving features.

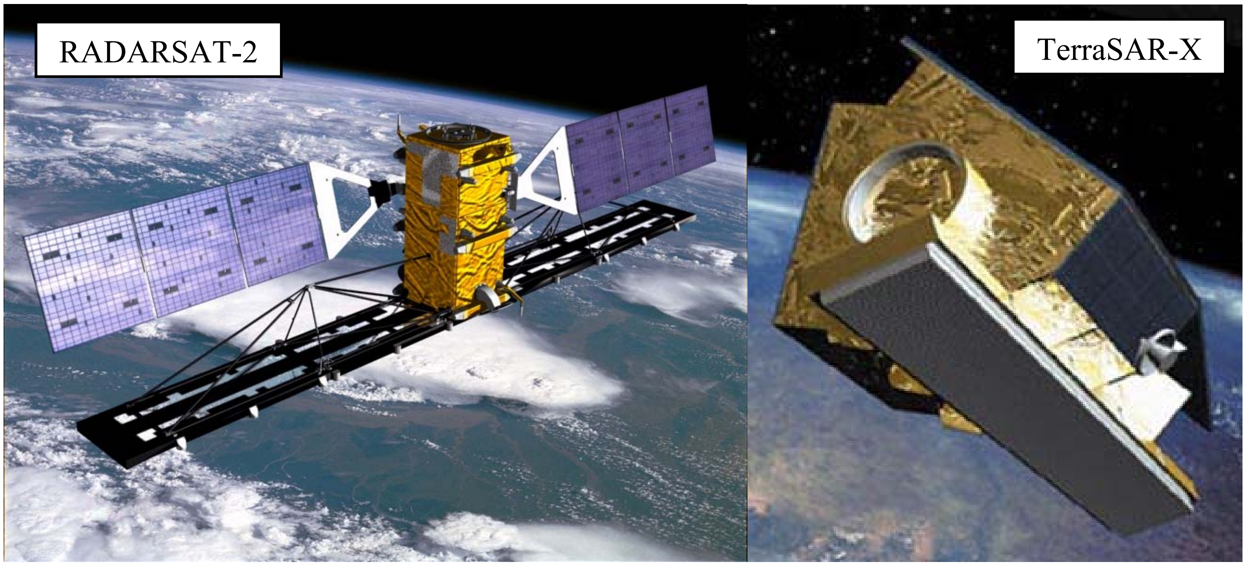

Figure 57. Drawing. The future SAR satellites RADARSAT-2 and TerraSAR-X.

- L-Band SAR: Advanced Land Observing Satellite (ALOS) will carry an L-Band (1.27 GHz) sensor called PALSAR. It is the successor of the Japanese satellite JERS and with imaging resolutions between 7 – 44 m (23 – 144 ft) in Fine Mode, it will be similar in resolution to RADARSAT-1 and ERS/ENVISAT. L-Band is known to be less susceptible to problems of temporal decorralation due to vegetation. Compared with C-Band (approximately 56 mm (2.2 inch)), the longer L-Band wavelength (approximately 246 mm (9.7 inch)) does no interact as much with tree canopies because the wavelength is much larger than a typical tree leaf, needle or branch structure. Consequently, certain vegetation types are transparent to the L-Band sensor, thus the SAR receives more echoes from the ground compared to the vegetation. Although there is improved overall coherence, L-Band is more susceptible to ionsphere effects than C-Band. ALOS currently does not have a firm launch date, but it is expected to be launched in 2006.

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18. Source - http://edc.usgs.gov/

19. Source - Gamma Remote Sensing, http://www.gamma-rs.ch/

GLOSSARY

ALOS: Planned for launch in 2006, ALOS is a follow-on satellite to JERS-1. The main purposes of ALOS are to produce more accurate maps of Japan and the Asia-Pacific region, to monitor natural disasters, to survey resources and to develop new technology for Earth observation from Space. ALOS has three remote-sensing instruments, the most relevant to this report being a Phased-Array type L-band (1270 MHz) Synthetic Aperture Radar (PALSAR) for day and night and all-weather land observation. The lower frequency of PALSAR relative to RADARSAT, ENVISAT and ERS provides for increased InSAR coherence in vegetated regions, but a higher susceptibility to atmospheric phenomenon.

C-Band: The electromagnetic spectrum has been categorized into several bands for reference convenience. There are a number of different band designations defined, and in particular at radar frequencies the Letter Band designation used by the Institute of Electrical and Electronic Engineers (IEEE) includes L, S, C, X, Ku, K, Ka, V, W and mm. C-Band is defined as 4–8 GHz by the IEEE.

Coherent (or phase stable) Reflector: A coherent reflector is a simple or complex surface (such as a corner reflector) from which reflected wave components are coherent with respect to each other, and thus combine to yield larger effective power than would be observed from a diffuse scattering surface of the same area. A coherent reflector will provide phase stable returns that are useful in InSAR applications.

Corner Reflector: A corner reflector is a combination of two or more intersecting specular surfaces that combine to enhance the signal reflected back in the direction of the radar. The strongest reflection is obtained when the materials are good conductors. Corner reflectors serve several purposes; in the context of InSAR they can serve as a ground control point for georeferencing and co-registration purposes and can serve as a phase stable point target to improve InSAR coherence and act as a Point Scatterer. There are several types of corner reflectors, including (but not limited to) trihedral, dihedral and active reflectors. A trihedral reflector is a passive radar calibration device made of 3 flat surfaces arranged to form a corner with the sides intersecting at 90° – hence the term "corner reflector". A dihedral reflector is a corner reflector formed by two intersecting flat surfaces that are perpendicular to each other. An active reflector (also referred to as a transponder) is a transmitter-receiver device, the function of which is to transmit signals automatically when the proper interrogation is received. Therefore, a transponder can serve the same purpose as a corner reflector.

DEM: A Digital Elevation Model is a representation of the topography of the Earth in digital format, that is, by coordinates and numerical descriptions of altitude.

DTM: A Digital Terrain Model is a representation of a surface's topography stored in a numerical format. Each pixel is has been assigned coordinates and an altitude. Digital Elevation Model (DEM) is the preferred term.

DInSAR: Differential Interferometric Synthetic Aperture Radar is an InSAR technique used to produce a ground deformation map. DInSAR is a specific application of InSAR in which topographic phase is removed using a DEM to leave only phase contributions due to ground deformation.

DTED: Digital Terrain Elevation Data is a standard for representing raster elevation data or DEM.

Coregister: Coregistration is a process of aligning two images such that coincident pixels in the image pair are produced from the same source. In the context of satellite or aerial photography, coincident pixels would represent the exact same point on the earth. The coregistration process usually involves the selection of a finite number of GCP pixels in an image and then mathematically fitting the remainder of the pixels using a least squares technique.

EROS: Besides its meaning in Greek mythology, EROS (Earth Remote Observation Satellite) also refers to a satellite constellation owned by ImageSat International N.V. As of early 2006, the first satellite in the series, EROS-A1 is in orbit operating at an altitude of 480 kilometers, and is capable of taking high-resolution pan-chromatic (black and white) pictures of an area of 12.5 x12.5 kilometers, at a resolution of 1.8 meters.

ERS: The first and second European Remote-Sensing Satellites (ERS-1 and ERS-2) were developed by the European Space Agency as a family of multi-disciplinary Earth Observation Satellites. Respectively launched in 1991 and 1995, the ERS-1/2 satellites operate in a sun synchronous polar orbit at a height of 782–785 km. They have a number of onboard sensors, the most relevant to this report being the SAR, which operates at C-Band (5.3 GHz) and nominally offers 100 by 100 km scenes at 30-metre resolution. Shortly after ERS-2's launch in 1995, ERS-1/2 were operated in tandem to provide image pairs of nominally 1 day apart to provide good coherence for InSAR topographic measurement. The ERS-1 mission ended on March 10, 2000 by a failure of the onboard attitude control system. ERS-2 has been operating without gyroscopes since February 2001, resulting in some degradation of the data provided by the instruments. InSAR applications have been especially challenging since the ERS-2 gyroscope failure although it is possible to use scenes acquired since February 2001 by a careful selection of image acquisition parameters.

ENVISAT: The Envisat (ENVIronmental SATellite) satellite is an Earth-observing satellite built by the European Space Agency. It was launched on March 1, 2002 into a Sun synchronous polar orbit at a height of 790 km. It orbits the Earth in about 101 minutes with a repeat cycle of 35 days. Envisat carries an array of nine Earth-observation instruments that gather information about the earth (land, water, ice, and atmosphere) using a variety of measurement principles. One of ENVISAT's main instruments is the advanced SAR called ASAR. The ASAR specifications are similar to ERS-1/2, with the addition of a number of new beam modes, including an alternating polarization (AP) mode and a global monitoring mode.

Flattening: In the context of an InSAR derived movement map, flattening is the process by which an interferogram is processed after phase unwrapping to remove trends in the data that are not due to ground movement. The process generally involves the a priori identification of regions or monumentation that have zero or measured movement (either through regional knowledge or site surveys) movement. Sometime trends through an image can be visually identified and removed without a priori regional knowledge.

GCPs: Ground Control Points are geographical features of known location that are recognizable on images and can be used to determine geometrical correction.

Geocoding or Georegistration: Geocoding is a geographic correction of image data to conform to a map projection. Ground control points are often used to increase the accuracy of the geocoding process. The finished product is resampled to a standard square pixel size.

GIS: Geographic Information System is a computer-based system designed to input, store, manipulate, and output geographically referenced data.

Interferogram: An interferogram is a phase image or signal produced by combining two complex and co-registered images or signals. For InSAR, two SAR images that include both magnitude and phase information are used as the basis of an interferogram.

InSAR: Interferometric Synthetic Aperture Radar is a technique involving phase measurements from successive SAR images to infer differential range and range changes for the purpose of detecting very subtle changes on or of the earth's surface with unprecedented scale, accuracy and reliability. The InSAR technique combines two complex SAR images to produce an interferogram. The phase fringes in the interferogram can be interpreted as topography or alternately as ground deformation if the topographic phase is removed from the interferogram.

Interferometric Point Target Analysis: See PS-InSAR. Point target and point scatterer can be used interchangeably in the context of InSAR.

JERS: Japanese Earth Resources Satellite is an Earth Observation Satellite used to image the global land area for national land survey, agriculture, forestry, and fishery, environmental protection, disaster protection, and coastal monitoring, etc. focusing on observation around the world and resource exploitation. It was launched into a sun-synchronous orbit in 1992 at an altitude of 568 km with a repeat cycle of 44 days. The SAR instrument on board operated at L-Band (1.275 GHz). The lower frequency of JERS relative to RADARSAT, ENVISAT and ERS provides for increased InSAR coherence in vegetated regions, but a higher susceptibility to atmospheric phenomenon. This satellite operated until 1998, and re-entered the Earth's atmosphere in 2000.

L-Band: The electromagnetic spectrum has been categorized into several bands for reference convenience. There are a number of different band designations defined, and in particular at radar frequencies the Letter Band designation used by the Institute of Electrical and Electronic Engineers (IEEE) includes L, S, C, X, Ku, K, Ka, V, W and mm. L-Band is defined as 1–2 GHz by the IEEE.

LIDAR: Light Detection and Ranging (LIDAR) is an active remote sensing system that uses a LASER light beam (instead of a microwave beam as used in RADAR) to measure vertical distance.

LCCP: The Lambert Conformal Conical Projection is a commonly used projection for large countries in the mid-latitudes having an east-west orientation. It was presented by Lambert in 1772. The Earth's surface is visualized as being a cone that has been unfolded.

Map Projection: A map projection is a systematic representation of a round body such as the Earth on a flat (plane) surface. Map projections are usually defined by a set of mathematical equations that specify for each point on the globe, one and only one corresponding point on a flat map.

NAD: There are two North American Datums (NAD) – North American Datum of 1927 (NAD 27) and North American Datum of 1983 (NAD 83). Both are geodetic reference systems, but each is based on different measurements. NAD 27 incorporated all horizontal geodetic surveys completed up to 1927. NAD 83 updated NAD 27 with current measurements using radio astronomy and satellite observations. NAD 83 positions are consistent with satellite location systems.

PALSAR: PALSAR is the SAR instrument on board the ALOS satellite. It is a Phased-Array type L-band (1270 MHz) SAR for day and night and all-weather land observation. The lower frequency of PALSAR relative to RADARSAT, ENVISAT and ERS provides for increased InSAR coherence in vegetated regions, but a higher susceptibility to atmospheric phenomenon.

Phase Ambiguity: In interferometry, phase ambiguities arise from the fact that phase is a cyclic measure that is only described from 0° to 360° and the true phase may in fact be ±*n*360°, where *n* is an integer. The movement or topography that produces the phase information in an interferogram is not cyclic, and therefore a single-phase value may describe an infinite number of different movement measurements or elevation changes. For example, in the context of C-Band SAR (5.3 GHz), 0 degrees in phase may refer to ±2.7*n* cm of movement (i.e., the movement could be 0 cm or 2.7cm or 5.4cm, etc.). Phase ambiguities are resolved using a number of strategies depending on the application. For general InSAR, interferograms are spatially 'unwrapped' in phase to resolve the ambiguities by examining where the phase changes from 0 to 360 degrees or vice versa. For Point Scattering InSAR or Interferometric Point Target Analysis, phase ambiguities are 'unwrapped' for each point target by applying a movement model (for example, linear progression of movement over time) to the phase measured at each target over the series of satellite images.

Phase Unwrapping: Phase unwrapping is the process of spatially or temporally removing phase ambiguities by examining locations of phase discontinuities. If the phase information is changing too quickly to resolve the phase ambiguities (e.g., in the case of IPTA where movement jumps by more than ±*n*360° in phase from one sample to the next), then a phase model (e.g., linear progression) must be applied to the phase samples to properly resolve the ambiguities.

Point Scatterer: In the context of satellite interferometry, a point scatterer is an object or collection of tightly packed objects on the ground that produces consistent microwave echoes back to the SAR instrument. The echoes of a point scatterer are defined to be relatively strong and statistically consistent (i.e., having a low variance of intensity) from one SAR image to the next. Point scatterers are also defined as being point targets whereby the source of the echoes originate from one distinct point in space rather than from multiple points such as in the case of a tree canopy or ocean surface where scattering is complex and spatially distributed in nature.

PS InSAR: Point Scatterer InSAR is an interferometric technique that identifies point scatterers in a series of SAR images and calculates movement from the phase variation of each point scatterer. The identification of point scatterers requires the use of a large number of SAR images in order to identify consistent scatterers.

RADARSAT-1: RADARSAT-1 is an advanced Earth observation satellite project developed by Canada to monitor environmental change and to support resource sustainability. With a planned lifetime of five years, RADARSAT-1 is equipped with a Synthetic Aperture Radar (SAR). The

SAR is a powerful microwave instrument that can transmit and receive signals to "see" through clouds, haze, smoke, and darkness, and obtain high quality images of the Earth in all weather at any time. This provides significant advantages in viewing under conditions that preclude observation by aircraft and optical satellites. Using a single frequency, C-Band, the RADARSAT-1 SAR has the unique ability to shape and steer its radar beam over a 500-km range. Users have access to a variety of beam selections that can image a swath from 50 km to 500 km with resolutions from 10 metres to 100 metres respectively. Incidence angles range from 10 degrees to 60 degrees.

RADARSAT-2: RADARSAT-2 is a Canadian C-Band (5.405 GHz) satellite SAR currently being built to provide data continuity to RADARSAT-1. In addition to providing data continuity with RADARSAT-1 by including the same modes of operation, RADARSAT-2 will include a number of improved capabilities compared to its predecessor. Some of the enhancements include:

- a resolution as fine as 3 m;
- a rotating capability so that the antenna points either right or left, providing more versatile and timely coverage;
- a variety of polarization options, including dual polarization and full quadrature polarization;
- GPS positioning for better orbit knowledge and control, which will improve InSAR applications; and
- provision for possible future tandem operation with RADARSAT-3.

The system is jointly funded by the Canadian Government and MacDonald Dettwiler Associates (MDA). The launch is planned for 2006 for operation by mid 2007. The RADARSAT orbit has a nominal altitude of 798 km, with a period of 100.7 minutes and an inclination of 98.6°. The orbit is sun-synchronous to maximize the power intake of the solar panels.

SAR: A synthetic aperture radar, or SAR, is a coherent radar system that generates high-resolution remote sensing imagery. Typically, SARs operate at microwave frequencies, typically C-Band at 5.3 GHz (for comparison, a microwave oven operates at 2.4 GHz); however, there are L-Band (JERS and PALSAR) and X-Band SARs (TerraSAR-X). The image produced by a SAR is composed of the intensity of the echoes from objects on the ground, thus producing a ‘black and white’ image. SAR data also includes phase information that is a result of the complex reflectivity of the ‘scattering objects’ on the ground. The phase information is also used by InSAR to produce topography or ground movement.

SRTM: The Shuttle Radar Topography Mission Shuttle was a C-Band interferometric SAR mission performed by a US Space Shuttle in 2000. SRTM data are available as raster elevation data rather than the raw SAR/InSAR pairs.

Topographic Phase: Topographic phase is phase information present in an interferogram that is due to topography or elevation differences on the earth. For the DInSAR process, topographic phase is removed from the interferogram using an elevation model. If that elevation model is inaccurate or has not been properly co-registered with a SAR image pair, the left over phase in an interferogram that is not attributed to ground movement or atmospheric effects is usually referred to as residual topographic phase. Residual topographic phase generally correlates well with elevation.

UTM: Universal Transverse Mercator Projection is a projection of the Earth's ellipsoid upon a surface of transversal cylinders (axes on the equatorial plane) enveloping the Earth at 6-degree intervals of longitude.

WGS-84: The World Geodetic System (WGS-84) Ellipsoid is a mathematical model representing the shape of the Earth. It is a very simple model, just an ellipsoid of revolution, so it is often the preferred model for satellite positioning systems. The standard units for WGS-84 are in degrees latitude and longitude. Other geodic models exist that more accurately describe the earth, but which are quite complex.

X-Band: The electromagnetic spectrum has been categorized into several bands for reference convenience. There are a number of different band designations defined, and in particular at radar frequencies the Letter Band designation used by the Institute of Electrical and Electronic Engineers (IEEE) includes L, S, C, X, Ku, K, Ka, V, W and mm. X-Band is defined as 8–12 GHz by the IEEE.