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.

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[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 $\lambda/2$ 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.

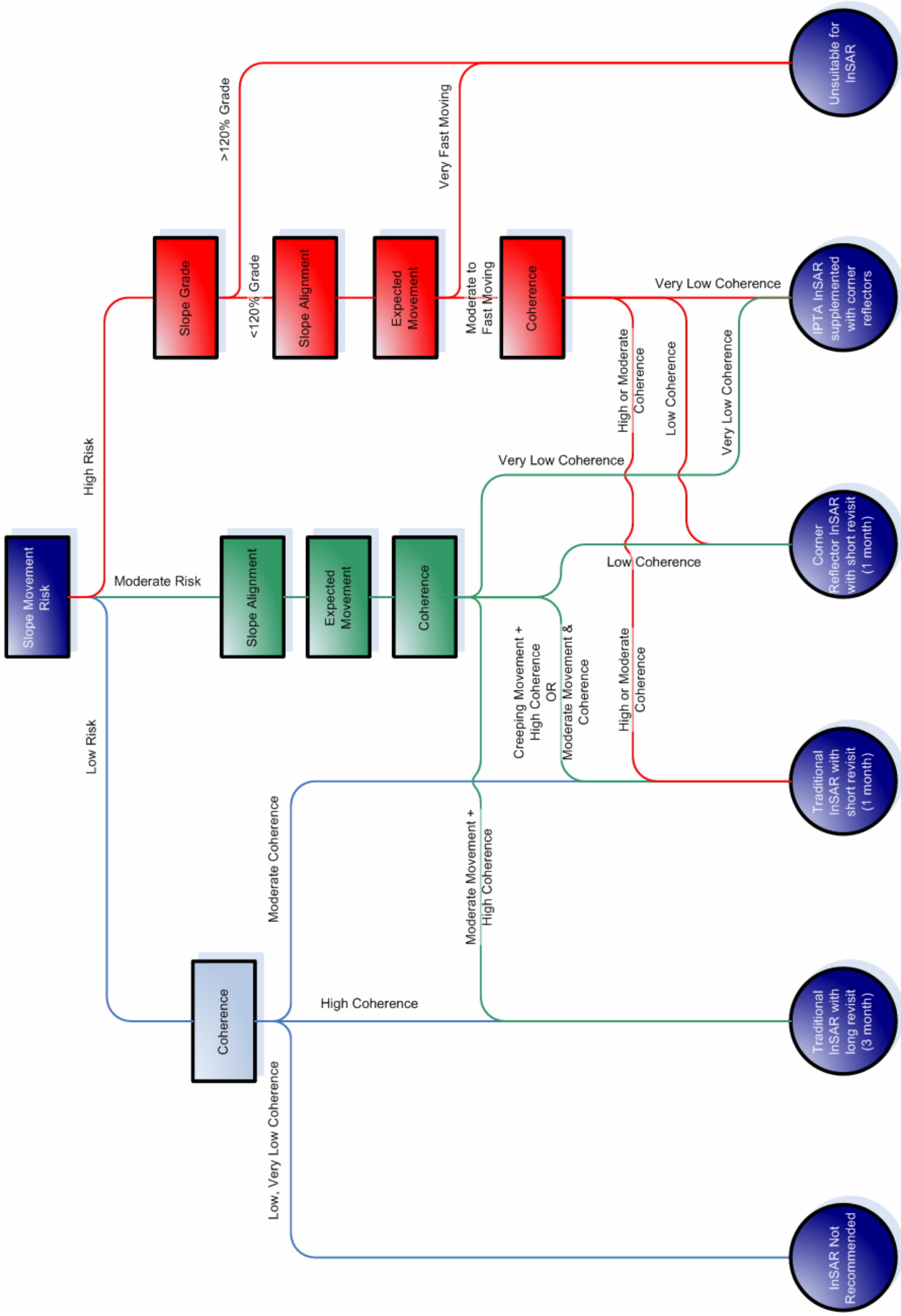

Figure 54. Schematic. Recommended decision tree methodology for application of InSAR to FLH projects.

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.

[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.

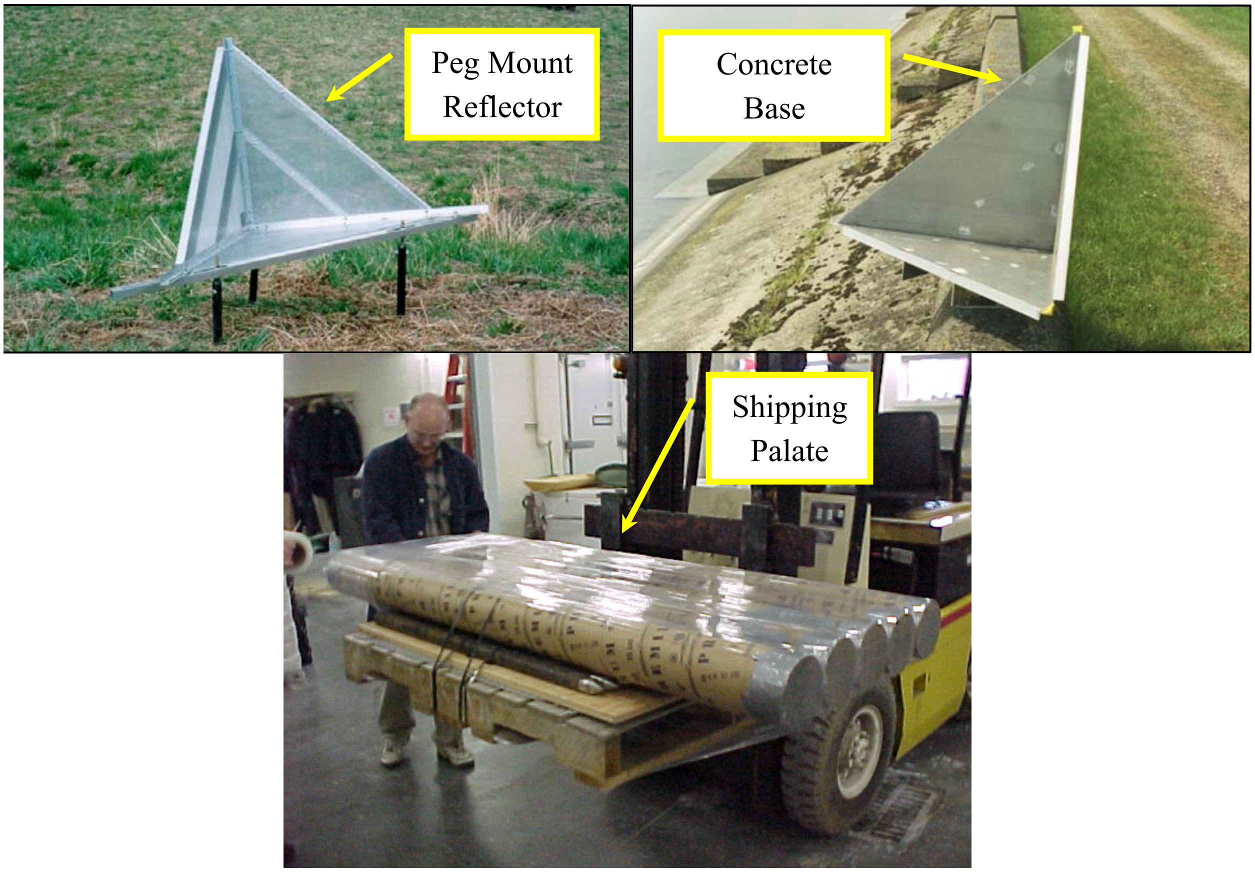

Figure 55. Photo. Radar reflectors using two different mounts (upper left and right), and packaged for shipping (lower centre).

- 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)

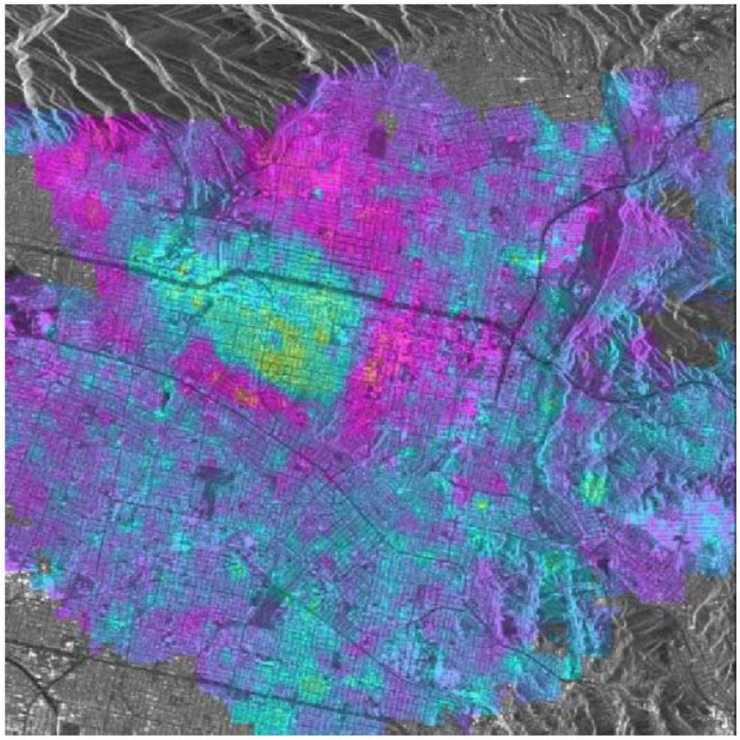

Figure 56. Graph. IPTA example (Colour Cycle = 4 mm (0.16 inch) /year).[(19)]

- 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.

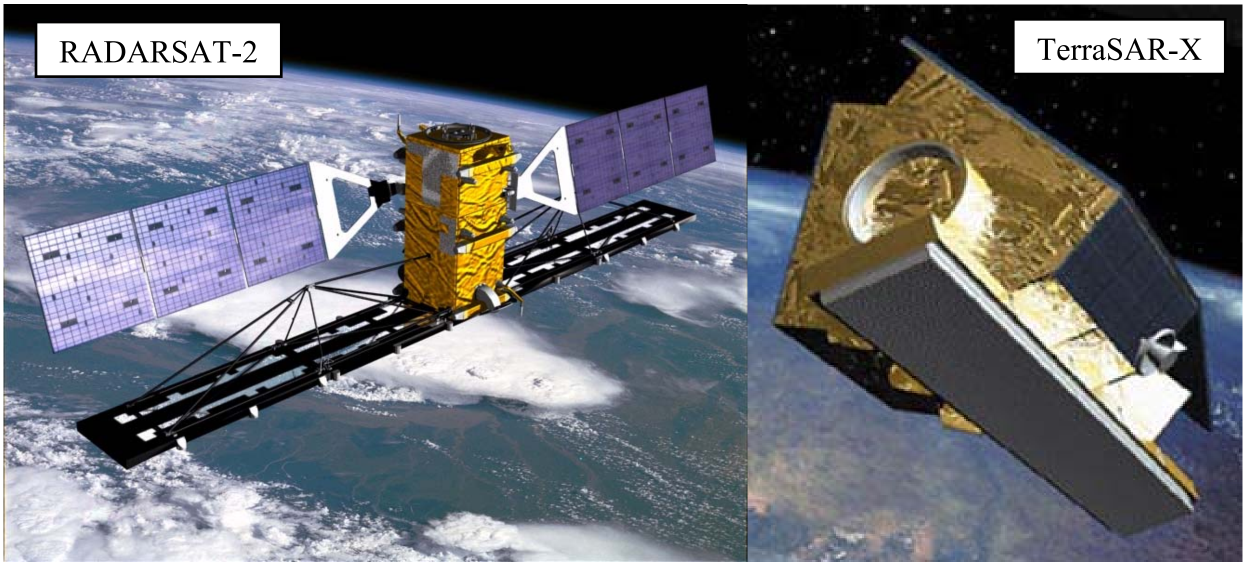

Figure 57. Drawing. The future SAR satellites RADARSAT-2 and TerraSAR-X.

- 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.