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).

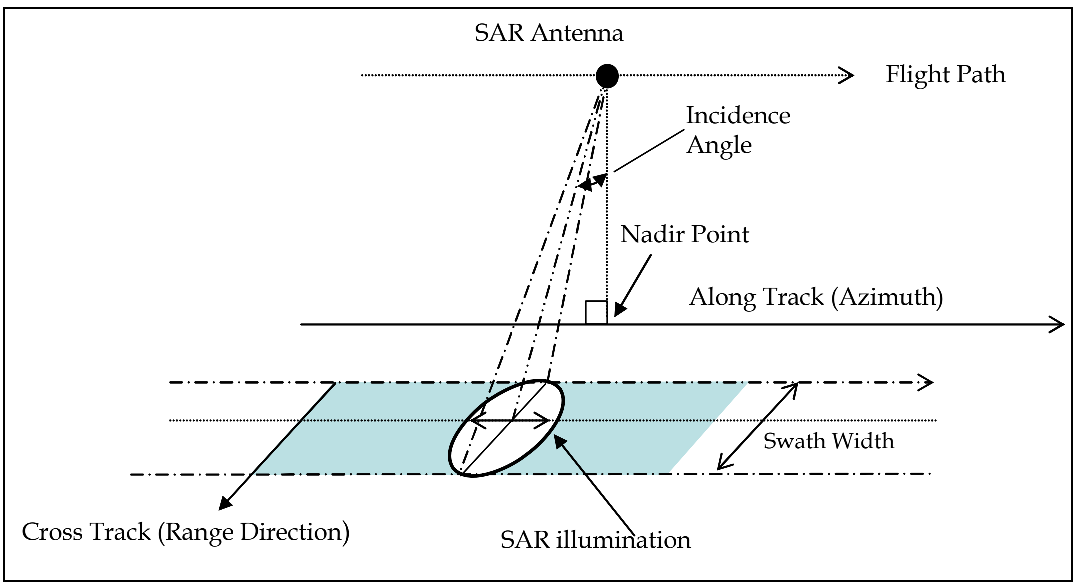

Figure 1. Schematic. Geometry of synthetic aperture radar.

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.

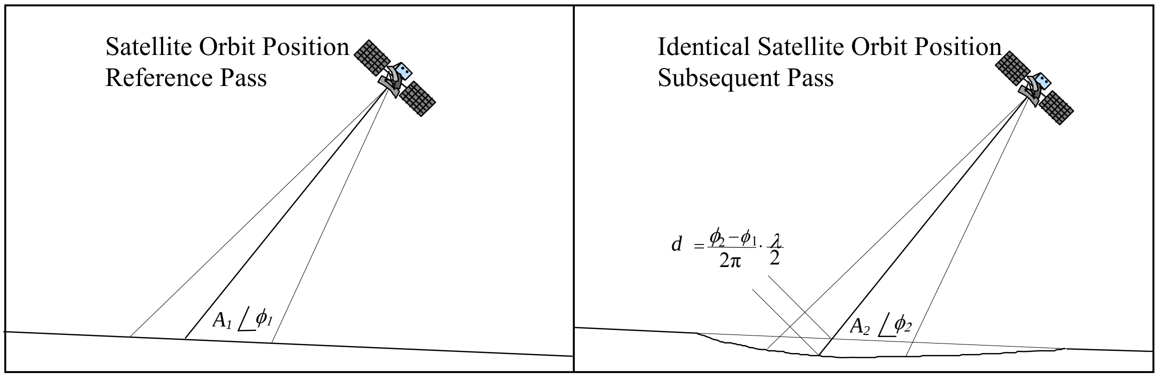

Figure 2. Schematic. InSAR measurement of ground movement.

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.

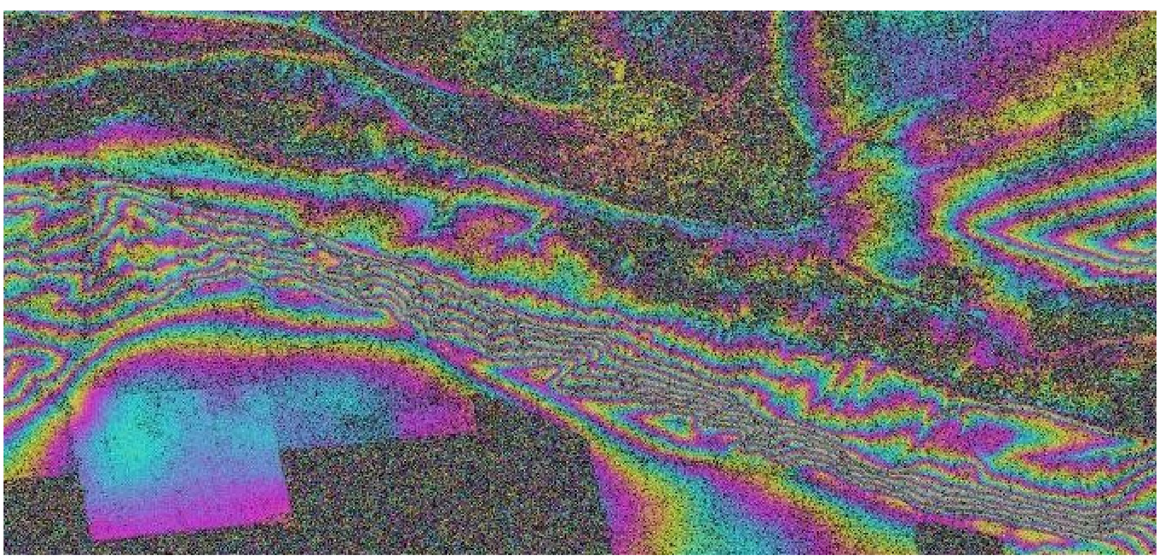

Figure 3. Graph. InSAR interferogram (location – near Benton City, Washington). Each complete color cycle, i.e. red to red, represents 360º (2π radians) of phase shift.

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]

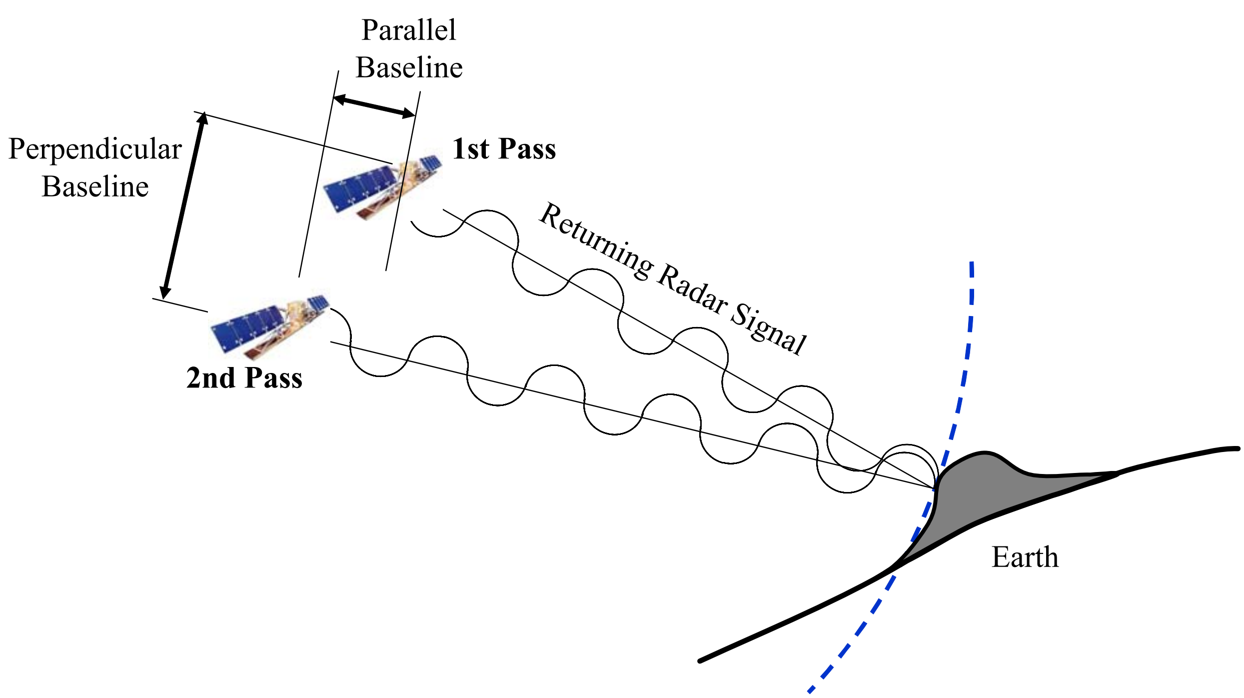

Figure 5. Schematic. Orbit baseline changes can produce varying phase shifts.

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.

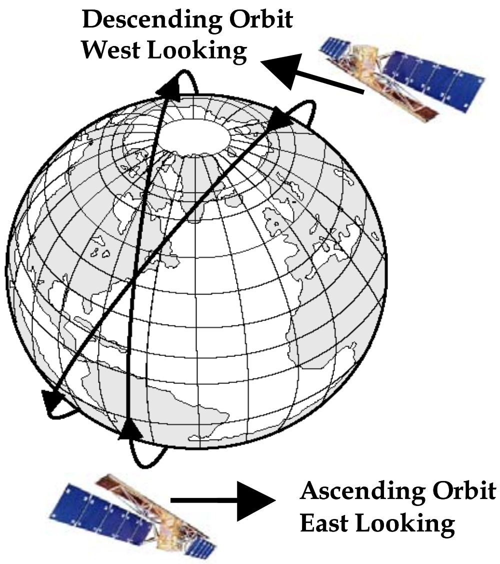

Figure 6. Schematic. Polar orbiting satellites have an east looking and west looking perspective.[12]

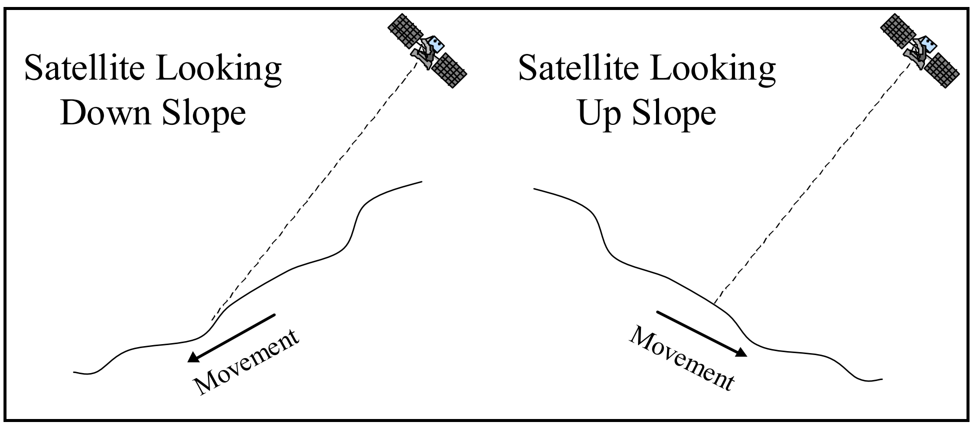

Figure 7. Schematic. Example of satellite looking up-slope and down-slope.

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.

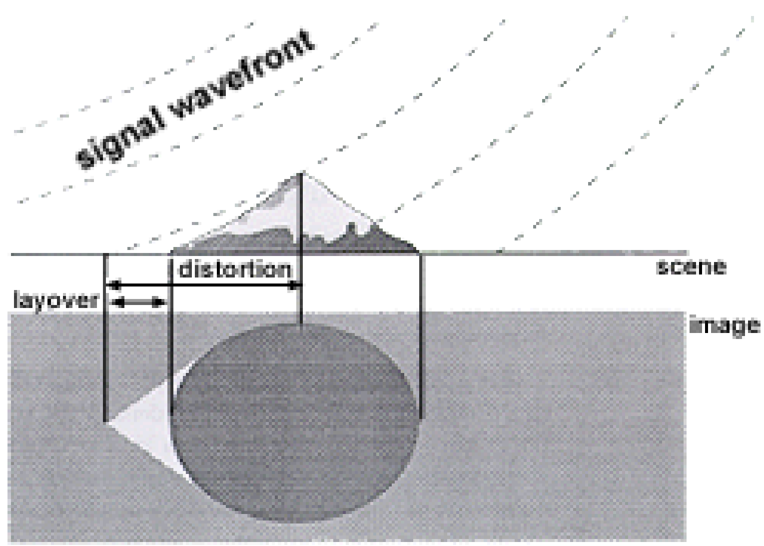

Figure 8. Schematic. The concept of layover in SAR image acquisition.

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.

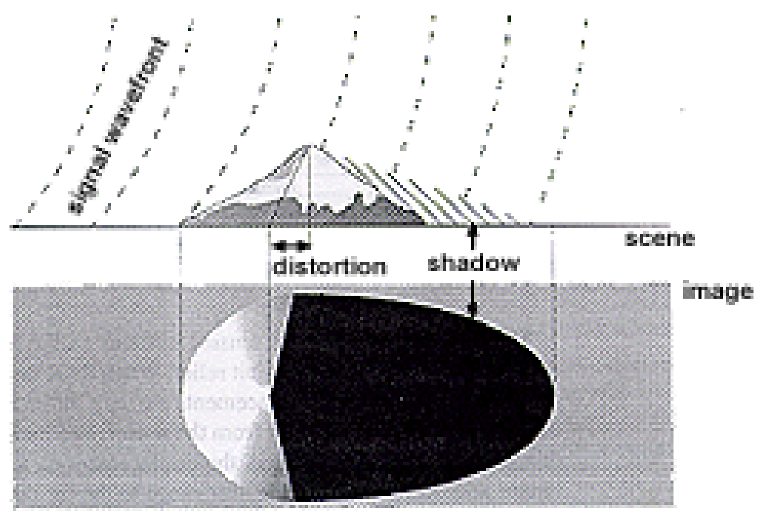

Figure 9. Schematic. The concept of shadow in SAR image acquisition.

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.