Validation of Interferometric Synthetic Aperture Radar as a Tool for Identification of Geohazards and At-Risk Transportation Infrastructure

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ABSTRACT

As part of the USDOT-funded research program RITA-RS-11-H-UVA, “Sinkhole Detection and Bridge/Landslide Monitoring for Transportation Infrastructure by Automated Analysis of Interferometric Synthetic Aperture Radar [InSAR] Images,” the authors broadly validated the use of InSAR data as a tool for early detection of geological hazards and failing infrastructure, including sinkhole development, potentially dangerous rock slopes, distressed bridges, rock buttresses, and other geotechnical assets. By bringing the InSAR dataset into a GIS dataframe and correlating the data to published maps of sinkhole locations and karst terranes, the authors were able to correlate average displacement velocities of InSAR data points (scatterers) with respect to their proximity to mapped sinkholes. Additionally, the authors correlated the InSAR signal characteristics with kinematic analysis of rock slopes using point-cloud data generated using digital photogrammetry and LiDAR. Lastly, the displacement time-series of the InSAR scatterers were used to screen for compromised geotechnical assets and infrastructure, and the findings were strongly confirmed by field inspection of distressed bridges and a failing rock buttress. The validation of InSAR data for these purposes thus allows generation of GIS-based geohazard and at-risk infrastructure/asset maps and provides the opportunity to augment or eventually replace a periodic inspection-based infrastructure management system with continuous performance-based system.
INTRODUCTION

By combining several overlapping images of the ground using millimeter-scale wave radiation, Synthetic Aperture Radar (SAR) takes advantage of the motion of a satellite along its flightpath to create a long synthetic antenna, thus resulting in an image of much higher resolution than the one that would be created using a single image from the real aperture. The radar image contains both amplitude and phase information of the backscattered radiation from each pixel. When two images of the same location taken at different times are available, the phase information can be used to evaluate the local topography (InSAR – Interferometric SAR) and, if combined with already existing elevation information, it can be used to evaluate the changes in elevation of each pixel (DInSAR – Differential InSAR). A major limitation of these techniques is the phase distortion introduced by the changes in atmospheric water vapor content between acquisitions, resulting in erroneous evaluation of ground displacement. If several images of the same location are available, this error can be greatly reduced by identifying those pixel displaying stable scattering properties over the entire dataset. These pixels, called Permanent Scatterers (PS), can be used to remove the atmospheric interference thereby achieving a much higher resolution in detection of elevation changes. This technique is known as PSInSAR. PS are often due to man-made structures thus showing higher density in populated areas. To allow detection of changes in rural regions, the PSInSAR technique was extended to identify larger geographic areas exhibiting coherent spatiotemporal behavior. When these Effective Areas (EA) are referenced to Distributed Scatterers (DS) the resulting technique is called SqueeSAR; it is often coupled with PSInSAR to evaluate topographic changes over time. The authors use the term InSAR as a general term for all interferometric SAR applications related to topographic change and infrastructure evaluation. Under ideal conditions, changes in 0.1-in scale can be detected, and displacement and surface kinematics can be evaluated.

While SAR data has been available since the 1950s and airborne InSAR was first used in the early 1970s, it was not until the 1990s that InSAR was used to investigate topographic change over time. Most of those applications were for large-scale, slow-moving topographic changes, such as slowly-moving landslides or changes in rock-glacier mass. Applications to smaller-scale phenomena, such as formations of sinkholes, activity on rock slopes, or distortions to bridges or rock buttresses, have generally been targets of investigation for InSAR only more recently; furthermore, most investigations have been in relatively flat-lying topography and tectonically simple geology.

The authors evaluated the use of InSAR for such evaluations by bringing the InSAR dataset into a GIS dataframe and correlating the data to sets of control data. For karst geohazards, these correlative datasets included published maps of sinkhole locations and karst terranes, as well as field validation. For rock slopes, the authors correlated the InSAR signal characteristics with kinematic analysis using point-cloud data generated using digital photogrammetry and terrestrial LiDAR. Lastly, the displacement time series of the InSAR data were used to identify potentially compromised geotechnical assets and infrastructure, and the findings were evaluated by field inspection of distressed bridges and photogrammetric time-series analysis of a failing rock buttress. The validation of InSAR data for these purposes thus

1 A pixel is the smallest ground resolution element. For our data one pixel is 3x3m (10x10ft).
allows generation of GIS-based geohazard and geotechnical/asset database and provides the opportunity to augment or eventually replace a periodic inspection-based infrastructure management system with continuous, performance-based system.

**UD DOT PROJECT “RITA-RS-11-H-UVA”**

The authors are cooperative investigators in RITA-RS-11-H-UVA, a USDOT-funded project titled “Detection & Bridge/Landslide Monitoring for transportation Infrastructure by Automated Analysis of Interferometric SAR Images.” The Research and Innovative Technology Administration (RITA) coordinates the U.S. Department of Transportation's (DOT) research programs. The purpose of RITA is to advance innovative and interdisciplinary technologies leading to improvements in the US transportation system. In order to evaluate whether InSAR data should be further subjected to algorithms intended to detect and quantify surface change and to evaluate infrastructure condition, it was determined that the data should first be broadly validated with regard to control or ground-truth datasets. The authors selected an Area of Interest (AOI) corresponding to one full Cosmo-SkyMed image tile of 617.8 square miles (40 by 40 km, or 1,600 square km) for data acquisition. The environment of the AOI is fairly mixed. Dense vegetation covers nearly half of the satellite tile, while active agriculture, fallow fields, infrastructure and towns (including Staunton, Stuarts Draft, Vesuvius, and Middlebrook) comprise the remainder of the area.

![Figure 1 - Area of Interest](image-url)
The AOI is a tectonically complex area spanning the Valley and Ridge and Blue Ridge physiographic provinces (10). Geological ages ranging from Holocene sediments to Precambrian granulite gneiss (11), with frequent unconformities, are represented within the AOI. The predominant tectonic framework consists of eastward-dipping thrust faults and decollements related to repeated orogenic cycles (12). The AOI contains carbonate, non-carbonate clastic, and metamorphic terrains, resulting in both rock slope stability and karst geohazards. The karst areas range in age from Cambrian to Devonian and formed during the Taconic and Acadian Orogenies and their associated divergent and inter-orogenic periods. Karst lithologies consist mainly of limestone and dolostone, while non-carbonate clastic lithologies consist of occasionally interbedded shales, siltstones, conglomerates and sandstones, and the metamorphic lithologies consist of charnockite, granulite gneiss, quartzite, and greenschist and blueschist-grade metabasalt. Figures 2 and 3 represent areas of karst and rock-slope geohazards, respectively.

Several control datasets exist for existing sinkholes; Figure 4 is an aggregate dataset of known sinkhole locations compiled from Virginia Department of Transportation records of repaired sinkholes and limited-release data from the Virginia Department of Mines, Minerals, and Resources. Figure 5 represents locations of bridges and box culverts within the AOI.
The authors selected COSMO-SkyMed, a constellation of four identical satellites built and operated by the Italian Space Agency, for data acquisition. Each satellite is equipped with an X-band SAR operating at 9.6 GHz. Between August 29, 2011 and October 25, 2012, 32 SAR scenes were acquired and were processed by TRE-Canada, Inc. The resulting dataset consisted of 298,954 PS and DS scatterers. The size of the AOI and a densely vegetated swath running through the AOI necessitated data processing in two clusters. Figure 6 represents the processed InSAR scatterers. Heavily vegetated areas proved to be an obstacle to InSAR data collection; however, such areas tend to have limited human population and infrastructure, and are therefore of lesser value in terms of surface analysis.
Each scatterer is associated with an identifier and a location consisting of latitude, longitude, and elevation, for each acquisition date. Each scatter is also associated with an effective area (EA), with PS having an effective area equal to zero, and DS having an effective area greater than zero. Additionally, each point is associated with a value for coherence (C), which is a representation of the stability of the point through time and with respect to its nearest neighbors. C values generally are considered to be reliable in the range of 0.8 to 1. Scatterers which have a motion greater than one-half a wavelength lose coherence entirely and are generally lost from the dataset. The data allow generation of a time-series of movement at each scatterer, with the time series of a PS indicating consistent and coherent movement at a very small geographic area, and the time series of a DS indicating movement over a larger area. Figure 7 represents such a time series. The negative slope of the time series indicates that the point is undergoing sinkhole-like subsidence.

![Figure 7 - Time Series of InSAR Point A8UOL](image)

*Figure 7 – Time Series of InSAR Point A8UOL*

Time series for each, or a set, of InSAR points can therefore be evaluated for absolute motion – subsidence or rebound – as well as the velocity of that motion relative to surrounding points or with respect to their proximity to other features.

*InSAR Validation: Karst Geohazards*

The relative motion of the points is highly variable across the AOI. Areas of anthropomorphic activity, such as agriculture, quarrying, or construction may show a positive
velocity, suggesting rebound due to stockpiling or staging activities, negative velocity, suggesting subsidence or settlement, or some combination of patterns. Isolating scatterers with respect to proximity to mapped sinkholes yields the data in Table 1.

<table>
<thead>
<tr>
<th>Cluster Number</th>
<th>Proximity to Mapped Sinkhole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Within 100 ft</td>
</tr>
<tr>
<td>Cluster 1</td>
<td>-0.21</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>None</td>
</tr>
</tbody>
</table>

Evaluation of the InSAR scatterers yielded several phenomena proving to be developing sinkholes. Figure 8 shows the growth of a sinkhole, represented by InSAR points AO96K and AO96J, which developed during the data collection period.

Figure 8 – Sinkhole Identified by InSAR Points AO96K and AO96J

The average velocity of all scatterers in Cluster 1 was 0.22 mm/yr, reflecting a slight rebound running southwest to northeast across the AOI, possibly correlating to fault activity. The increasingly-negative velocity with increasing proximity to mapped sinkholes suggests very strongly that the InSAR data is reflecting true sinkhole activity, rather than a false-positive result. The velocity inverts at approximately 300 feet from the center of the mapped sinkholes, suggesting that this may represent the maximum average area of influence of sinkholes or sinkhole clusters in the Valley and Ridge Physiographic Province of Virginia. That there are no scatterers intersecting with mapped sinkholes in the region of Cluster 2 reflects the fact that Cluster 2 is largely outside of the area susceptible to karst geohazards (see Figures 2 and 6).
InSAR Validation: Rock Slopes

One large rock slope within the AOI had a geometry and radar reflectance characteristics suitable for InSAR data analysis. Field observations of the slope, Site Number RS-600-001 (Virginia State Route 600, River Road in Augusta County, Virginia) indicate dip slopes of dark blue-gray, fine- to medium-grained, cherty limestone belonging to the Licking Creek Limestone (Silurian-Devonian). The slope height and angle are approximately 120 feet and 40 degrees, respectively. A joint set meets the slope at a steep angle, resulting in slab failure where these joints intersect bedding planes, which range from 4 to 12 inches in thickness (13). The lithotectonic conditions result in small-scale, continuous, very wide-angle wedge failure along the entire length of the rock slope. The clasts resulting from the wedge failures are small, generally in the gravel- to cobble-size range. The slope behavior was characterized by digital photogrammetry and terrestrial LiDAR, which allowed the behavior of the slope as characterized by InSAR to be evaluated against the activity characterized by site-specific data collection. Figure 9 is a site image. The red circle is a figure for scale.

Digital photogrammetry and LiDAR are both point-cloud data collection methods, which yield an XYZ file that can be brought into a GIS (or other geospatial) dataframe. This allows three-dimensional analysis of the rock slope. The authors used Sirovision® (version 4.1, 2011), a geology / geotechnical mapping and analysis system, to generate scaled 3D images of rock faces from stereo photographs. A second module, Sirojoint®, was used for limited geotechnical and structural analysis of the 3D images. The data resulting from Sirovision® was then brought into ArcMap® 10.0, and surface analysis was used to interpret the kinematics and geomechanics. Figure 10 is an aggregate of the digital photogrammetry data and interpretation brought into an ArcMap® dataframe, and relates the field conditions to the GIS analysis. The surface analysis highlights portions of the slope of different azimuthal aspect. The yellow wedges are surfaces formed by the intersection of the joints and the bedding. The purple colors represent incoherent slope aspect along the entire toe of the slope, indicating a broad failure mode along its entire length.
Figure 11 is an aggregate of the digital photogrammetry data and interpretation brought into an ArcMap® dataframe, and the stereonet represents site kinematics.
Both the digital photogrammetry and the GIS interpretations agree well with the field conditions: Sirojoint® reveals a systematic set of wedge failures formed by the intersection of moderately-dipping bedding and high-angle joints. The GIS surface aspect analysis reveals the wedge failures to be pervasive along the rock slope surface. The data yielded by the LiDAR consist of a set of point cloud data overlapping the digital photogrammetry data and yielded similar results and interpretations.

The InSAR data agrees with the field conditions as characterized by GIS and digital photogrammetry. Figure 12 illustrates data of selected InSAR scatterers falling on RS-0600-001.

The scatterers falling on RS-0699-001 are all DS, i.e., they represent movement over a large area. This agrees well with the field observations and the surface analysis rendered by GIS and digital photogrammetry, in that the failure is occurring over the entire slope in small individual areas. Were the slope absolutely stable and undergoing no weathering whatsoever, there would have been no phase changes detected, and therefore a lack of data. Were the slope undergoing severe weathering, losing very large clasts (on the order of boulder-size) the
individual scatterers would have lost coherence entirely. Furthermore, InSAR points A002Z and A003F, both DS, yielded vertical settlement of 0.6 and 0.7 in, respectively (i.e., rock face unloading), which agrees well with field observations of activity at this slope.

While only one rock slope within the AOI had characteristics conducive to analysis by InSAR, LiDAR, and digital photogrammetry, and neither digital photogrammetry nor GIS analysis yielded results in terms of quantifiable volumetric loss that the authors considered reliable, the general agreement between the observed behavior of the slope and the InSAR data suggests that the method may be useful for remote monitoring of slope activity and discrimination of rock slope hazards based on C and EA values.

**InSAR Validation: Geotechnical Infrastructure**

The AOI contains 408 bridges and 224 box culverts, 94 rail crossings, and 1 active municipal landfill, as well as an unknown number of rock buttresses and soil slopes. Each bridge and box culvert is associated with a location and quantifiable inspection data. While the bridges and box culverts are inspected on a frequency of no less than 24 months, rock buttresses and soil slopes are not inventoried, nor are they associated with any performance metrics or specifications, nor are they subject to an inspection program. Rock buttresses are considered to be an inherently reliable design and are considered to require no post-construction inspection.

A systematic evaluation of bridge sufficiency data and inspection reports with respect to InSAR data is underway as of the date of this article; for the purposes of the preliminary validation of InSAR data, various InSAR points showing motion near or on infrastructure were selected for field inspection. Where possible, areas of two bridges in close proximity or sistered bridges of different ages, one with InSAR scatterers and the other lacking scatters, were chosen in order to minimize the potential for confirmation bias. InSAR scatterers were validated according the rubric in Table 2.

<table>
<thead>
<tr>
<th>Validation</th>
<th>Typical Validation Evidence</th>
<th>Validation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute</td>
<td>Cracks, settlement, recent unvegetated scarps</td>
<td>1.0</td>
</tr>
<tr>
<td>Strong</td>
<td>Distortions or cracks, overgrown scarps</td>
<td>0.75</td>
</tr>
<tr>
<td>Weak</td>
<td>Repairs or cracks, geomorphology indicates activity</td>
<td>0.5</td>
</tr>
<tr>
<td>Possible</td>
<td>Near existing active region In correct terrain, presence of pinnacles</td>
<td>0.25</td>
</tr>
<tr>
<td>None</td>
<td>No or negative confirmation</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

Figure 13 is an example of a field verification site. The location is a sistered bridge, with a modern structure to the right in the photograph, and an older structure to the left. The InSAR data includes scatterers indicating settlement at the older structure, but no scatterers located on
the modern structure. This data is validated by field observations, which include evidence of
damage and deterioration over the older, but not the modern structure.

![Figure 12 – Field Validation Site](image)

Table 3 contains a partial set of data relating selected infrastructure, InSAR points, and
notes on validation or refutation of the InSAR data related to actual asset condition. Because
bridge condition data is not public information, location data is not included.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Validation Value</th>
<th>Validation Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>001SL</td>
<td>1.00</td>
<td>Distortions to rock buttress</td>
</tr>
<tr>
<td>002RA</td>
<td>0.75</td>
<td>Recent addition to farm waste pile</td>
</tr>
<tr>
<td>003RA</td>
<td>1.00</td>
<td>Quarry spoils pile</td>
</tr>
<tr>
<td>004RA</td>
<td>1.00</td>
<td>Active auto junkyard</td>
</tr>
<tr>
<td>005SH</td>
<td>1.00</td>
<td>Recently decommissioned landfill cell</td>
</tr>
<tr>
<td>006RA</td>
<td>0.75</td>
<td>Recent addition farm waste pile</td>
</tr>
<tr>
<td>007NC</td>
<td>-1.00</td>
<td>No confirmation</td>
</tr>
<tr>
<td>008SL</td>
<td>1.00</td>
<td>Bent trees, slope sloughing near creek, and settlement in drainage basin</td>
</tr>
<tr>
<td>009SL</td>
<td>1.00</td>
<td>Distortions to rock buttress</td>
</tr>
<tr>
<td>010SL</td>
<td>1.00</td>
<td>Distortions to rock buttress</td>
</tr>
<tr>
<td>011SL</td>
<td>1.00</td>
<td>Bent trees, slope sloughing near creek, and settlement in drainage basin</td>
</tr>
<tr>
<td>012SL</td>
<td>0.75</td>
<td>Noted wetlands at toe of slope</td>
</tr>
<tr>
<td>013SL</td>
<td>1.00</td>
<td>slope drainage pipe had broken</td>
</tr>
<tr>
<td>016SL</td>
<td>0.50</td>
<td>Noted spring/wetlands/drainage at toe of slope</td>
</tr>
<tr>
<td>017SL</td>
<td>1.00</td>
<td>Recent Burn Area</td>
</tr>
<tr>
<td>021SL</td>
<td>0.50</td>
<td>Noted shallow failure on slope</td>
</tr>
<tr>
<td>022SL</td>
<td>1.00</td>
<td>Noted leaning signal pole</td>
</tr>
<tr>
<td>023PV</td>
<td>0.50</td>
<td>Distortion and Cracking in Pavement</td>
</tr>
<tr>
<td>024BR</td>
<td>0.50</td>
<td>Distortion on Erosion and Scour Protection</td>
</tr>
</tbody>
</table>
Validation is ongoing; as of the date of this article, the overall validation value is 0.6, strongly suggesting a positive correlation between displacement activity identified by InSAR scatterers and distortion or damage to infrastructure.

One area of InSAR scatterer data was noted early in the investigation; this area corresponded to a rock buttress within the AOI. Figure 14 represents the motion of the scatterers located on the surface of the rock buttress.

![Displacement, INSAR Scatterers At Rock Buttress](image)

**Figure 14 InSAR Scatterer Data at Rock Buttress**

The AOI contains a number of rock buttresses. Because the locality represented in Figure 14 was the only rock buttress which demonstrated consistent negative-trending displacement, the authors decided to further investigate its behavior. Several site visits, as well as two episodes of digital photogrammetry data collection, were conducted. Figure 15 is an image of the digital photogrammetry data rendered by Sirovision® along with a site image.
The red lines show area of maximum calculated displacement at the rock buttress slope between September and November 2012. While the digital photogrammetry was able to image the rock buttress, the results were not deemed by the authors to be sufficiently reliable to create a time-series of movement along the slope; however, because of the minimal cost, ease of use, and compatibility of the dataset with other types of software, the authors consider digital photogrammetry to be an attractive method of rock buttress characterization for future research.
Field instigations of the site suggested that a combination of internal settlement and blocked drainage is causing the surface of the rock buttress to distort, and may indicate future failure risk. While the InSAR signal cannot be used to quantify motion along the rock buttress, field investigations strongly suggest that the InSAR scatterer data did reveal previously-unidentified motion along the face of the rock buttress.

DISCUSSION

The authors evaluated the value of InSAR scatterer data applied to evaluation of geohazards and infrastructure condition. The authors determined that velocity measurements of InSAR scatterers were most strongly negative nearest to mapped sinkholes, whereas the overall average velocity of all scatterers in the karst-prone areas was slightly positive. While the AOI allowed analysis of only one rock slope by InSAR and ground-based methods, the coherence and effective area data yielded by the InSAR agreed with field observations and measurements made by digital photogrammetry and terrestrial LiDAR. Lastly, the InSAR scatterer data was positively correlated with field evidence of infrastructure damage or distortion on a range of geotechnical assets including soil slopes, bridges, pavement, and rail crossings. Additionally, a rock buttress displaying motion was identified by InSAR scatterers, and degraded performance of the rock buttress face was confirmed by field investigation.

Validation data collection is ongoing as of the date of this article. Next steps include a systematic evaluation of geotechnical assets which lack InSAR scatterer data in order to evaluate the potential of false negatives, and inclusion of the scatterer data in the bridge inspection program. This may prove to be the best implementation of the InSAR data collection, in that it may reveal damage or distress to bridges between scheduled inspections, and may allow better allocation of staff hours for bridge inspections and include an element of performance-based bridge inspection. Plans are underway to include condition data derived from the InSAR into a new, GIS-based geotechnical asset management system, which will be delivered to field inspection personnel via handheld devices.

Major challenges to the full implementation of InSAR data collection remain. Among the greatest of the challenges is the loss of coherence in areas of sudden ground or infrastructure motion. New methods of identifying scatterers which have coherence for a period of time and then suddenly lose coherence, suggesting a break in the rate-of-change of the motion, are being developed. Regardless of the challenges, the authors view the application of InSAR to remote detection and early warning methods for geohazards and infrastructure failures as highly promising. The InSAR data collection and interpretation lends itself to wide-scale scanning and monitoring at the transportation-corridor level, particularly in areas of very dense transportation infrastructure such as roads, bridges, rail lines, and embankments. Wide implementation of InSAR monitoring may yield more comprehensive and integrative asset management and inspection programs, and, by revealing early signs of failure on critical assets, may be a source of considerable return on investment and mitigation of liability.
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