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Final Report

Utilizing Remote Sensing Technology in Post-Disaster Management of Transportation Networks

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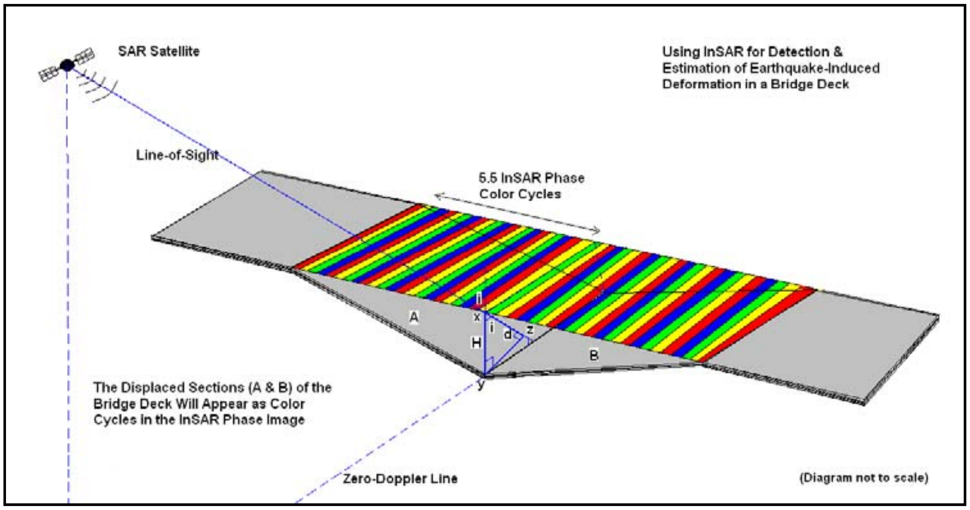

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16. Abstract

Infrastructure system components such as bridges, highways, tunnels, traffic systems, road pavements, and other systems are considered assets that should be protected and properly managed. Yet, the degree of deterioration and the risk of exposure to natural (e.g., earthquakes, floods, etc.) as well as malicious disasters are dangerously high. Major decisions must be made to allocate the available but limited funds for maintaining and safeguarding our national infrastructure. Additionally, transportation services play an important role in post-disaster recovery and are an integral part of most response functions. These services are vital for initial rescue operations and disaster assistance. Traffic delays that occur during the reconstruction period can be greatly minimized through effective traffic management strategies. The need for vulnerability assessment and disaster mitigation in densely populated areas, such as the NY/NJ metropolitan area, is obvious.

In this project, we propose the use of novel remote sensing technologies to quickly assess damage to the transportation infrastructure. Some of the latest remote sensing technologies can detect very small displacements of infrastructure elements, such as roads and bridges, up to centimeter accuracy. Thus, this information along with historic information about transportation infrastructure components combined with simple yet accurate structural engineering models can be used to determine individual components of a given network that are susceptible to failure under various loading conditions. This probabilistic failure mapping of the infrastructure can then be used to develop robust transportation and emergency response plans that minimize the risk of disruptions.

Based on the preliminary findings of this research project, it is shown that the information obtained from remote sensing technology is important in providing reliable support for the decision-making system for preparedness and mitigation. However, the availability of high-resolution images is key to the future success of the research initiative described in this report.

In the absence of such high-resolution satellite images, the proposed post-disaster management approach cannot be realistically tested unless simulated images are employed. Even though using simulated images is beyond the scope of this project, the authors hope to be able to access high-resolution satellite SAR data of earthquake-prone urban areas in the near-future. This option will allow to further study the appearance of bridges and highways in SAR and InSAR images, and extract as much information as possible on their conditions. Once the feasibility of damage assessment is verified using real satellite images, the next step will be to use this information in conjunction with probabilistic routing and dynamic traffic assignment algorithms that can generate low risk routes for evacuation and other post-disaster operations in dense urban areas.

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Transportation Infrastructure, Deterioration, Post-Disaster Recovery, Remote Sensing, Mitigation, Satellite Images.

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EXECUTIVE SUMMARY

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INTRODUCTION

Infrastructure systems constitute a major part of the national investment and are critical for the mobility of our society as well as its economic growth and prosperity. The U.S. has an estimated $25 trillion investment in civil infrastructure systems, including all installations that house, transport, transmit, and distribute people, goods, energy, resources, services and information. The infrastructure system components such as bridges, highways, tunnels, traffic systems, road pavements, and other systems are considered assets that should be protected and properly managed. Yet, the degree of deterioration and the risk of exposure to natural as well malicious disasters are dangerously high. Major decisions must be made to allocate the available but limited funds for maintaining and safeguarding of our national infrastructure network. The need for vulnerability assessment and disaster mitigation in densely populated areas such as in the NY/NJ metropolitan area is obvious.

Additionally, transportation services play an important role in post-earthquake recovery and are an integral part of most response functions. These services are vital for the initial rescue operations and disaster assistance. In addition, traffic delays that occur during the reconstruction period can be greatly minimized through effective traffic management strategies. The key issues in post-earthquake (or disaster) transportation response include:

- Advanced planning and preparation
- Immediate response strategies
- Intermediate traffic management
- long term recovery strategies

Most studies on emergency management identify pre-planning, coordination and communications as vital components of any response process. Ulman et al. (1991) in their study on traffic management for major emergencies point out that, while predictable emergencies such as nuclear plant disasters and hurricanes have received a considerable planning emphasis, pre-planning for unpredictable emergencies like earthquakes has often been ignored. It is important to note that, though it is impossible to develop specific response plans for emergencies like earthquakes, generic plans can be developed to facilitate appropriate response operations when such an emergency does occur. The study on Southern California's transportation response capabilities (1990) recommends the development of a comprehensive regional transportation emergency plan (after a major earthquake) which will require coordination of transportation services over a number of jurisdictions.

However, immediate response strategies that are the response procedures employed in the immediate aftermath of an emergency are very important in terms of saving lives and reducing impact of disasters. These include operations like damage assessment, disaster assistance and post-disaster planning. In their study on the Mexico City earthquake Hobeika et al. (1987) strongly recommend the development of a computer based support system to manage information and provide decision support for these operations. Kruger (1990), in his report on the immediate response operations after the Loma Prieta earthquake, identifies communications and information management as the most critical area.

The implementation of immediate response strategies would require a collaborative effort between disciplines in diverse engineering and innovative use of technology. There is a need for new generation of efficient damage assessment techniques that can respond rapidly and would cover large areas and transportation networks affected by earthquake damage.

RESEARCH OBJECTIVES

The main objective of this project is to study the feasibility of utilizing remote sensing technology that can be used for damage prediction and probabilistic routing algorithms as a tool for the post-disaster management and planning of transportation networks in densely populated areas such as the NY/NJ metropolitan region. The report will first focus on the identification, review, and evaluation of applicable remote sensing technologies. Then, a detailed evaluation of the most applicable remote sensing approach will be studied in detail in the context of post-disaster damage assessment. Finally, detailed recommendations about the real-world application of these technologies to post-disaster management as well as future research needs will be made.

REVIEW OF REMOTE SENSING TECHNOLOGIES: MAIN FOCUS ON SAR & INSAR

The satellite and airborne remote sensing systems, currently available for disaster response, utilize optical and SAR (Synthetic Aperture Radar) imaging technologies. Optical systems image the Earth's surface by collecting sunlight that reflects off the surface. On the other hand SAR systems image the earth surface by collecting the electromagnetic signals which they emit and are backscattered from the surface.

The main advantages of optical systems are:

- They can provide very high-resolution imagery of roads and bridges (with < 1 meter spatial resolution).
- They can also provide detailed information on the type of road and bridge surface materials.

The main disadvantages of optical systems are:

- They can only operate in daytime since they rely on sunlight, which makes them un-usable for night time disaster response.
- They are hindered by cloud or smoke cover, because sun light does penetrate either, which could be a serious problem for disaster response.

The main advantages of SAR systems:

- They can provide very high-resolution imagery of roads and bridges using the new SAR satellites TerraSAR-X and Radarsat-2 (with 1 & 3 meter spatial resolutions), or airborne SAR systems (with sub-meter resolution). Older SAR satellites (e.g. Envisat) provide only medium resolution imagery (with 20-30 meter resolution).
- They can operate day or night and in any weather conditions, which make them ideal for disaster response at any time.

In this report we focus on the use of SAR systems and the advanced InSAR technique due to their significant advantages, especially, their ability to be used at any time.

Spaceborne and airborne synthetic aperture radar (SAR) systems transmit electromagnetic waves at a wavelength that can range from a few millimeters to tens of centimeters. The radar wave propagates through the atmosphere and interacts with the Earth's surface. Part of the energy is reflected back to the SAR system and recorded. Using a sophisticated image processing technique called SAR processing, both the intensity and phase of the reflected (or backscattered) signal of each ground resolution element or pixel (1-25 meters wide) can be calculated in the form of a complex-valued SAR image. This image represents the reflectivity of the ground surface. The amplitude or intensity of the SAR image is determined primarily by terrain slope, surface roughness, and dielectric constants. Whereas the phase of the SAR image is determined primarily by the distance between the satellite antenna and the ground targets, slowing of the signal by the atmosphere, and the interaction of electromagnetic waves with the ground surface (Zhong Lu, NASA/ASF News & Notes).

Interferometric SAR (InSAR) imaging, a recently developed remote sensing technique, utilizes the interaction of electromagnetic waves, referred to as interference, to measure precise distances to ground targets The InSAR technique uses the phase of the return SAR signal in addition to its amplitude. The phase of the return signal depends on the distance to the ground, since the path length to the ground and back will consist of a number of whole wavelengths plus some fraction of a wavelength. Having two SAR acquisitions of the same area (pixels) on the ground from two separate orbits causes a phase difference or phase shift in the returning signals between both acquisitions, and this difference is called interferometric phase. This difference in phase values in corresponding pixels of pre- and post-disaster SAR images of an area can be partly due to changes or deformation (e.g. due to an earthquake) that occurred in these pixels in-between the dates of acquisition of the SAR images. Below are two diagrams that illustrate the satellite imaging geometry necessary for InSAR.

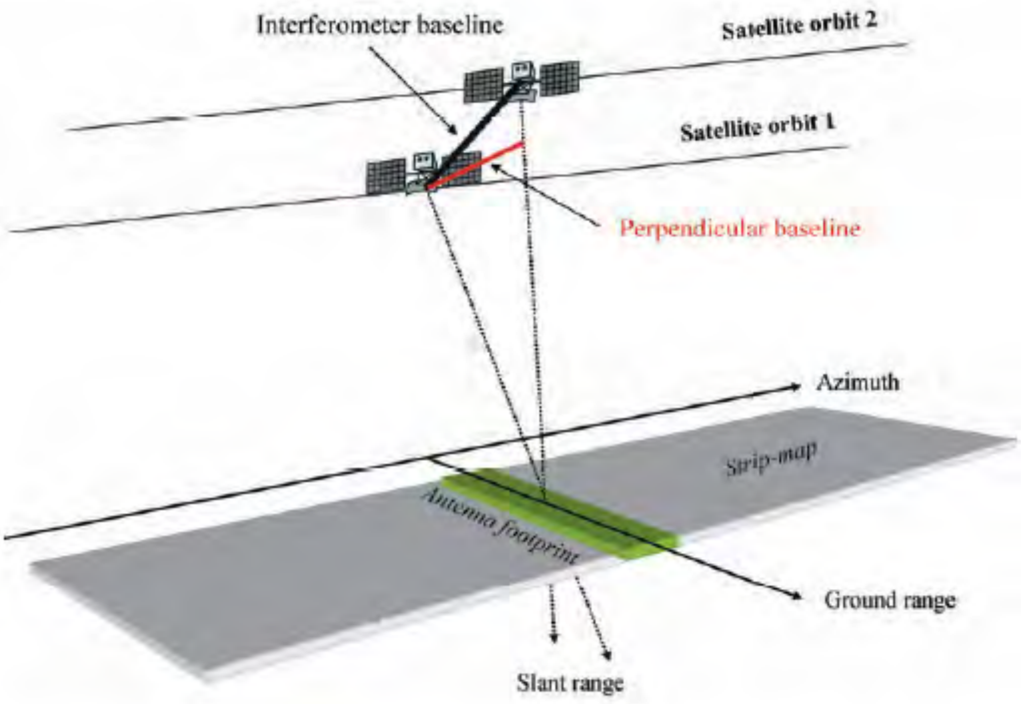

Figure 1: A 3-D diagram of InSAR imaging geometry (European Space Agency, 2007)

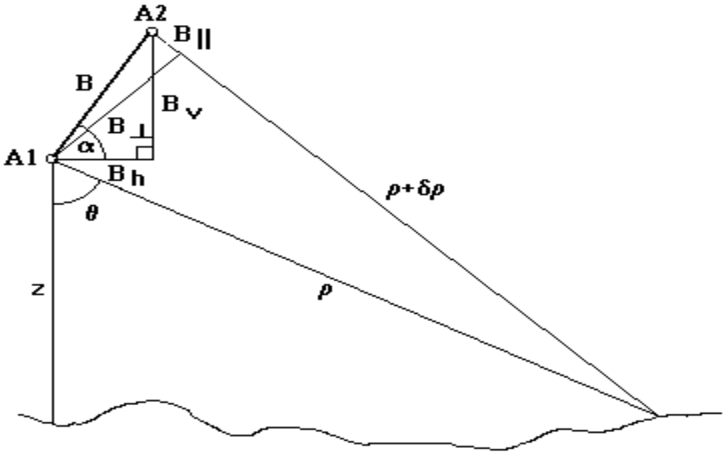

Figure 2: A 2-D diagram of InSAR imaging geometry. (Zebker et al, 1997)

In the diagram above, A1 and A2 are the satellite orbits, separated by baseline B, from which the SAR images are acquired of the same area on the ground at different points in time. The distances between the satellite orbit positions A1 and A2 and the same pixel on the ground differ by “delta p”, and this distance difference is related to the interferometric phase “phi” as expressed in the following equation:

$$\phi = \frac{4\pi\delta\rho}{\lambda}$$

Where lambda is the SAR signal wavelength. Then using the interferometric phase and the SAR imaging geometry, two types of data products can be computed. First, a digital elevation model (DEM) for the imaged area can be computed, giving the elevation value for every pixel in the area. Second, the displacement in corresponding pixels in-between SAR image acquisitions can be computed, if pixel displacement did occur, using the following equation:

$$\Delta\phi_d = \frac{4\pi}{\lambda} d$$

Where d is the pixel displacement in the line-of-sight of the SAR system (ESA 2007)

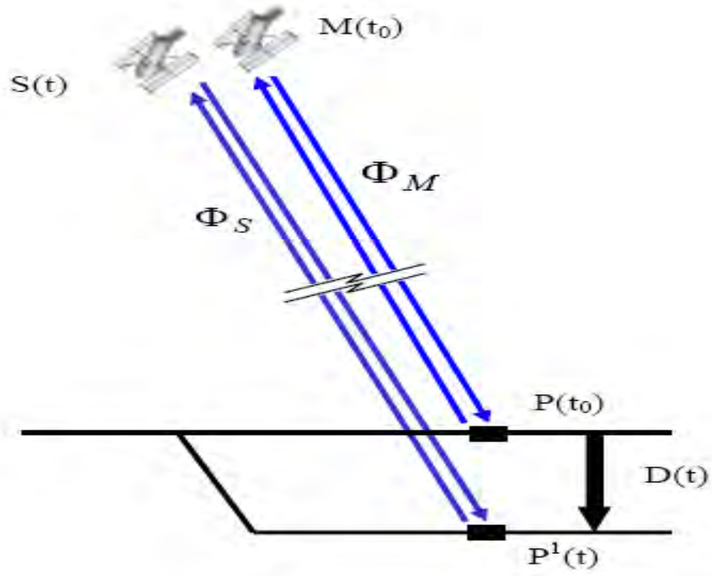

Figure 3: A 2-D diagram of InSAR imaging geometry showing a pixel P that displaced a vertical distance D between satellite acquisitions M & S (Crosetto et al, 2005)

The displacement or deformation on the ground due to an earthquake for example, can be estimated by InSAR only in the line-of-sight (LOS) of the SAR satellite. Knowing the LOS displacement and the SAR look or incident angles, the vertical displacement (D in Figure 3) can be computed by using simple triangle geometry.

The pixel deformation pattern is represented in the InSAR image product, phase interferogram, as a series of color fringes (contour lines), where each color cycle (red-to-red) represents half a wavelength of displacement in the line-of-sight of the satellite. Below is an example of the phase interferogram showing a ground surface deformation pattern caused by an earthquake, where the color fringes radiate away from the epicenter of the earthquake.

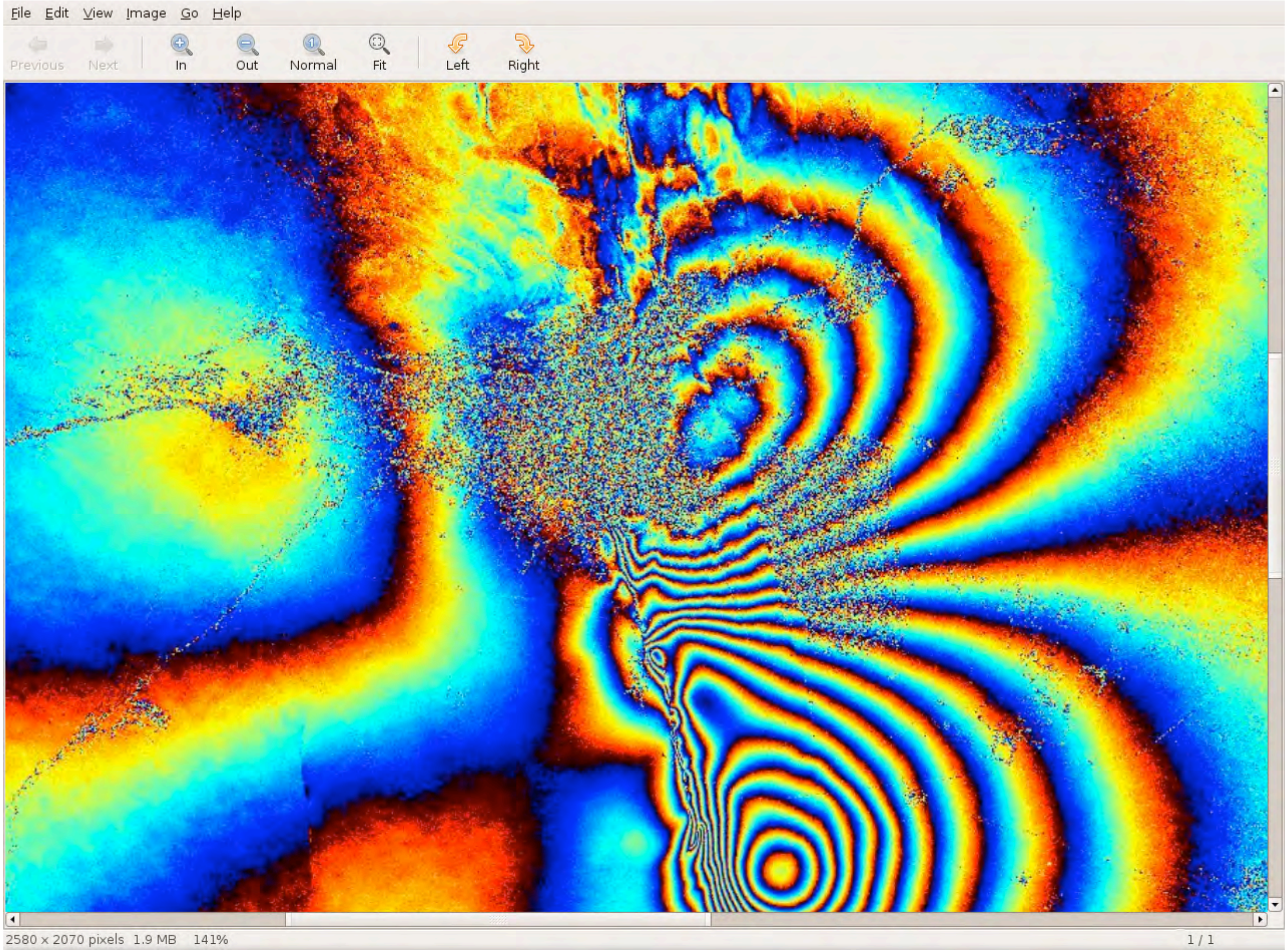

Figure 4: InSAR Phase Image of Ground Surface Displacement from Bam, Iran Earthquake

Figure 4 illustrates the use of InSAR processing of Envisat satellite SAR images to map earth surface deformation. This is an InSAR phase image or interferogram, generated by our team, showing concentric color fringes (contours) which represent part of the ground surface displacement caused by the 26 December 2003 earthquake at the city of Bam, Iran.

The InSAR processing chain used to generate the image products, or interferograms, varies according to the software used and the precise application, but will usually include some combination of the following steps. Two SAR images are used to produce an interferogram. The two images must first be co-registered using an amplitude correlation procedure to find the offset and difference in geometry between the two SAR images. One SAR image is then re-sampled to match the geometry of the other, meaning each pixel represents the same ground area in both images. The interferograms are then formed by complex-multiplication of corresponding pixels in the two SAR images. This means that the signal amplitude values of the corresponding pixels are multiplied to generate an image called “Magnitude Interferogram”, and the phase values of the corresponding pixels are subtracted to generate another image called “Phase Interferogram”. The pixels in the Magnitude Interferogram have signal magnitude values, while the pixels in the Phase Interferogram have phase difference (i.e. interferometric phase) values. InSAR also generates a third image called the Coherence image whose pixels’ values are the correlation of the two SAR images’ pixel-to-pixel phase values (see next page for additional details on image products).

Then, a component of the interferometric phase value which is due to the reference ellipsoid is removed from the phase interferogram, a process referred to as flattening. Then and for deformation applications, a Digital Elevation Model can be used in conjunction with the images baseline data to simulate the contribution of the topography to the interferometric phase. This can then be subtracted from the phase interferogram to generate a new phase interferogram that shows only the deformation pattern on the ground. Once the basic phase interferogram has been produced, it is commonly filtered using an adaptive power-spectrum filter to amplify the phase signal. For most quantitative applications the consecutive fringes present in the phase interferogram will then have to be “unwrapped”, which involves interpolating over the 0 to 2π phase jumps to produce a continuous deformation field, where each pixel will contain an absolute deformation value in the line-of-sight of the SAR satellite. At some point, before or after unwrapping, incoherent areas of the image may be masked out. The final processing stage involves geocoding the image, which involves resampling the phase interferogram from the acquisition geometry (related to direction of satellite path) into the desired geographic projection.

The following is additional description of the three InSAR image products. The Magnitude Interferogram is a gray-scale image, where pixels with high amplitude values would show up as bright or light-gray indicating strong SAR signal backscatter from those pixels. On the other hand, pixels with low amplitude values would show up as dark-gray indicating weak SAR signal backscatter from those pixels. The Phase Interferogram, after removing the topographic effect, shows the distribution of the displaced/damaged pixels in the target area by representing them as a series of color-coded fringes. Each fringe or color cycle represents a surface displacement of half a wavelength in the line-of-sight of the SAR satellite. This means that potential displacement/deformation of infrastructural components of the transportation network can be numerically estimated at least in one dimension down to centimeters level, if certain conditions are met. The Coherence image displays the phase correlation values of corresponding pixels in the pre- and post-disaster SAR images. The coherence image is displayed in grey scale where brighter colored pixels represent high correlation values which indicates pixels did not experience any change or displacement, and darker pixels represent low correlation values which indicates pixels experienced change or displacement (e.g. due to an earthquake).

We selected the SAR and InSAR remote sensing technology as the main tool and source of data for our on-going research on rapid post-disaster response mainly due to their ability to operate at any time and in all weather conditions. As previously discussed, InSAR has the potential to estimate cm-level surface deformation/displacement in infrastructures impacted by earthquakes or other disasters. Having both pre- and post-earthquake high-resolution SAR images of an area, would allow the performing of InSAR analysis to detect roads, bridges and airport runways, and to extract deformation (damage) information in the immediate aftermath of the disaster. Acquiring this information rapidly would be crucial for post-disaster evacuation, rescue, logistical support, and traffic management operations.

REVIEW OF PREVIOUS RESEARCH ON SAR & INSAR INFRASTRUCTURE APPLICATIONS

The following is a summary of the most relevant studies that has been conducted on the application of SAR and InSAR for the detection and assessment of urban and transportation infrastructure.

A. SAR & InSAR for Detection of Bridge Structures

In a recent study, Wegner and Soergel (2008) discussed bridge height estimation from combined high-resolution SAR and optical imagery. They noted that recently deployed airborne and spaceborne SAR sensors provide very high-resolution imagery in addition to being independent of daylight and cloud cover. Spaceborne systems achieve spatial resolutions of down to 1 meter, while airborne sensors are capable of acquiring images with sub-metric resolution. In this kind of data, urban objects like buildings and bridges become visible in much detail. However, due to the side-looking SAR sensor principle, layover and occlusion hampers the interpretation particularly in urban scenes. One possibility to overcome this drawback is the use of additional information from high-resolution optical imagery.

In this paper, first findings of using both SAR and optical imagery for the modeling and extraction of bridges were presented. The focus was on bridges because they play a key role as connecting parts of man-made infrastructure and are of high importance in case of rapid natural hazard response. Differences between bridges over water and bridges over land were explained, and concepts for estimating bridge heights from a single SAR image and by means of combined optical and SAR imagery were derived. The authors' comparison of bridges over water and bridges over land showed that the appearance of bridges in SAR imagery strongly depends on their environment. Due to multi-path signal propagation at bridges over water, a height value can be determined directly from a single image. Such multiple bounces usually do not occur at bridges over land. In summary, they showed that three-dimensional modeling of elevated man-made objects is possible from a single SAR image and from combined optical and SAR data.

According to a study by Soergel et al. (2006), modern airborne SAR sensors provide spatial resolution of less than half a meter. In such data many features of urban structures, such as bridges, are visible, which were beyond the scope of radar remote sensing only a few years ago. In high spatial-resolution InSAR data even small bridges are mapped to extended data regions covering large numbers of pixels. Therefore, in data of this quality the identification of bridge structure details is possible at least by visual interpretation. Soergel et al. discussed the special appearance of bridges over water in high-resolution InSAR data, and the geometric constraints for the mapping of certain bridge elements in InSAR imagery. They proposed an approach for detection of such bridges, and Information about the bridge structure was extracted in subsequent fine analysis. First results of their approach were demonstrated using orthogonal InSAR single-pass data sets of ground spatial resolution better than 40cm.

The authors concluded that InSAR processing of high-resolution airborne SAR data supported bridge extraction. However, the constraints arising from the sometimes multiple appearance of bridge structures in the data have to be considered carefully. Height estimate based on InSAR elevation data seemed to be more robust compared to analysis of amplitude SAR data alone. First results of the proposed approach for bridge detection and geometry extraction were promising. The authors indicated that as their focus was on bridges over water, the morphological water segmentation might fail in the case of narrow rivers or creeks. Therefore, in order to detect such thin water bodies they recommend that a line-based approach be developed. Moreover, different types of bridges (e.g. spanning roads, railway tracks, or valleys) should also be investigated by high-resolution InSAR.

A paper by Thiele et al. (2007) studied the InSAR signal phase profiles at building locations, which can also be applied to bridge structures. They noted that building recognition suffers from the consequences of the inherent side-looking viewing geometry of SAR systems, in particular, occlusion and layover hinder the analysis. Usually extracted layover regions are not considered further in the recognition workflow. However, since layover regions contain information mixture of the building and its surrounding area, it is worthwhile to make efforts to understand such signal in order to tell different contributions of building façade and roof apart from those of other objects aiming at improvement of recognition. Considering InSAR data phase distributions at building locations are observable. The concerned area begins always at the building parts facing the sensor, in extreme cases even the entire data of the building area is inferred by layover. The characteristics of the phase profile in range direction depend on sensor and illumination properties as well as on geometric attributes of buildings. The processed InSAR phase information of a single range cell may result from superposition of several signal contributions of backscatters with same range distance to the sensor.

The authors presented a model to calculate the expected InSAR phase values based on a given surface profile. The process takes into account that a mixture of several contributions defines the InSAR phase of a single range cell. Based on this model, simulations were included in an iterative analysis-by-synthesis approach for building recognition from multi-aspect InSAR data. The focus of the proposed model is to understand the impact of the building's geometry on the phase profiles, material properties were not considered in the present state. The assessment process of the simulated phase profiles was performed by comparison with real InSAR data, based on phase values of single range lines.

Roth et al. (2005) discussed in their paper the high potential of the new German SAR satellite TerraSAR-X, especially its SAR and InSAR urban applications. Beside the typical advantages of a SAR system like all weather as well as day and night observation capability, TerraSAR-X provides high resolution data (1-5 meters ground spatial resolution) which will enable very detailed studies of urban infrastructure such as roads and bridges. It also offers short revisit times, which will be very useful for monitoring and assessing post-disaster areas. Additionally, it offers polarimetric SAR data that can be used to distinguish between different backscatter mechanisms on the ground. This can certainly be applied to bridges and roads, which might enhance the assessment of their conditions, especially in a post-disaster situation.

B. SAR Simulation & 3-D Urban Structure Models

SAR simulation of urban structures is a very useful tool in studying the interaction of SAR signals with various structures and their backscattering mechanisms, and therefore in improving the interpretation of SAR imagery. A paper by Balz and Haala (2007) notes the difficulty in interpreting SAR data due to a number of reasons such as the side-looking property of SAR systems, the speckling effect and the relatively large wavelength as compared to optical sensors. These problems not only hamper the visual interpretation, but they also result in difficulties for processes like automatic classification as compared to optical images. The authors emphasized that the availability of a SAR simulator is very important in order to enable the reconstruction of buildings (or bridges) from single intensity SAR images. The combination of 3D models, simulator and real images allows a huge improvement in the interpretation of SAR images and enables semi-automatic reconstruction approaches. The quality of the building reconstruction can be further improved by using additional data, such as SAR images from different locations and angles, which can solve the problems of image occlusions and ambiguities.

To improve the reconstruction process, the application of InSAR data may be very useful, by generating a Digital Elevation Model (DEM) which can be can used for 3D object reconstruction. Another possibility is using a fully-polarimetric SAR system, where an additional range of information about the imaged structures will be available. The polarimetric response can be used to discriminate between odd-bounce and even-bounce signal reflections by target decomposition. This differentiation is very useful for further refining the reconstruction of buildings. Signal double-bounces occur often in built-up areas and are quite typical for those regions. Looking at a single house (or bridge), the double bounce area is related to vertical walls and therefore this information can be used to discern between vertical walls and horizontal roofs (or bridge decks) that may look very similar using just one polarization. Having a look-angle larger than 30° and a small terrain roughness surrounding the building the returned radar signal is very sensitive to the orientation of the building (or bridge). Polarimetric SAR data also provides information about the slope and the surface roughness that may also be useful. So, despite all limitations of SAR data for 3D object reconstruction, there is a huge potential of applying this data source for this type of application.

Stilla et al. (2002) discussed the geometric constraints that limit the reconstruction of buildings from InSAR data of dense urban areas. They proposed a segmentation approach for building reconstruction, taking into account InSAR's side-looking illumination effects and the signal noise estimation. The approach exploits the image elevation and intensity information to detect building areas. Their results show that building reconstruction is possible from InSAR, but the achievable level of detail cannot be compared with results from LIDAR.

C. SAR & InSAR for Post-Disaster Assessment of Transportation Infrastructure

A study by Arciniegas et al. (2006), although conducted mainly for the assessment of urban structures after an earthquake, offers useful InSAR methods that may be applicable to the assessment of bridges in the aftermath of an earthquake, provided high resolution SAR data are available. The study involved the use of Envisat satellite SAR images (20 meters ground resolution) to assess the capacity of InSAR data for detecting urban damage caused by the 6.6 magnitude earthquake in Bam, Iran, on December 26, 2003. They analyzed InSAR properties, such as complex coherence and signal amplitude and their sensitivity to changes in ground surface and urban damage, both induced by the earthquake event. These changes lead to quantifiable decorrelation in the InSAR image pixels corresponding to impacted areas on the ground.

The authors analyzed the methods of pre/post-event pixel-by-pixel comparison of SAR amplitude images and change detection of InSAR properties to compare and evaluate both methods for their actual potentials and limitations through validation. They found that coherence works relatively better than amplitude in extracting damaged areas as it discriminates total destruction better. SAR data have an important sensitivity for measuring surface changes at the range of microwaves. Based on earlier studies, it was assumed that collapsed buildings or heavily damaged areas have different backscattering properties than undamaged areas. But empty spaces, vegetated areas or rubble/debris can also have different backscattering properties, which may be similar to those of collapsed buildings. SAR datasets have been previously used to classify urban damage into several levels. In the authors' study, such classification was not achieved. Earthquake destruction lead to high decorrelation on SAR data, but several other factors might as well have posed influences that may be wrongly attributed to the event, such as changes in vegetation, atmospheric and seasonal changes, and long temporal baseline.

The authors concluded that it appeared to be a very difficult task to separate earthquake-induced changes from those related to other causes. Moreover, it seemed to be even more difficult to separate damage classes with SAR data. They recommended that further studies should be conducted on how to differentiate earthquake-related decorrelation of SAR data quantitatively and qualitatively, from other sources of decorrelation of these types of data in urban areas. In addition, they recommended the studying of how the use of SAR data can complement current methods that use optical images, stressing on features that stand out above those of optical images. The SAR backscattering behavior of urban areas with heterogeneous building stock or uniformity in building height should be studied as well. They also noted that it is important to choose pairs of SAR data which are suitable in terms of baseline and time gap, although there is not a definite rule about the optimal values of spatial baselines for the urban domain. Spatial baseline values can be studied with the purpose to define optimal values for studies related to urban-domain applications, for different SAR sensors.

A study by Loh and Shinozuka (2004) researched the capabilities of bridge damage and change detection schemes based on simulated complex SAR images of pre- and post-events. They noted that a SAR image, obtained from a coherent and complex imagery system, can be described in three dimensions, whereby two dimensions represent the image and the third dimension represents the phase information which is relevant to the detection of the finer details in the image. The authors' main goal is to compile a library of SAR images related to damage states experienced by common structures such as buildings or bridges.

In this study, simulated SAR images were obtained for two different sets of model bridges. The model bridges were created such that the deck width and length were equal. However, the height and support conditions were varied, and a parapet was added on one of the model bridges. Without any material property differences or other changes to geometry, the SAR simulations captured differences in signal response from these geometrical changes on the bridge models.

One of the most obvious observations from the SAR images was seen from the difference between the pre- and post-damage effects. In the damaged bridge models, SAR signal responses were complicated, and the EM signature did not represent what a damaged bridge would look like. Since the SAR system measures the reflected EM waves, these EM waves are affected by the planes of material they come in contact with. When these surfaces are shaped and directed at odd directions, such as in a damaged bridge, reflected waves are measured far beyond the bridge model itself.

A study by Eguchi et al. (2004) investigated the use of SAR and optical imagery for structural damage detection following the 1999 Marmara earthquake in Turkey. Their visual comparison of SAR and optical images obtained 'before' and 'after' the earthquake, revealed distinct changes in signal return. They noted that following the earthquake event, surface reflectance on the SPOT satellite optical image increased within the urban center, where numerous buildings collapsed. This suggested that debris piles associated with collapsed structures exhibited a higher signal return than the original standing structure. Trends were more difficult to discern from simple inspection of the ERS satellite SAR image, with temporal changes dominated by scene-wide variations in signal return. However, from examining derived SAR correlation images, low correlation, indicative of change due to building collapse, was evident throughout central areas of Golcuk city. The preliminary SAR and optical change detection algorithms successfully distinguished between spatial variations in the extent of catastrophic building damage observed in Golcuk. For the optical data, simple subtraction and correlation profiles varied with observed damage. While SAR correlation indices also distinguished trends in the density of collapsed buildings, the subtraction profile was instead dominated by a large radiometric offset between the 'before' and 'after' scenes. The change detection techniques presented in this paper successfully employed remote sensing technologies to detect and determine the extent of urban building damage.

In summary, several studies have focused on the use of SAR technology in post-disaster urban damage assessment. The main method employed was the generation of change detection maps based on changes in the SAR signal amplitude in corresponding pixels between pre- and post-disaster images. This technique although useful for providing rough estimates of damaged areas, it cannot measure surface deformation and is not as accurate as the more advanced InSAR technique. On the other hand, in most studies involving the use of satellite InSAR for post-disaster urban damage assessment, the method most employed was the use of the coherence image (as described in section 4) to detect and estimate extent of urban structural damage. Variations of this method were employed by Gamba et al. (2003) in their study on the 2007 Peru earthquake, and Gustavo Arciniegas Lopez (2005), in their study on the 2003 Bam earthquake.

It is important to note that the focus of most of those studies has been on trying to detect, estimate and map the extent of damage in built urban areas in general, with no special emphasis on damage assessment in the transportation infrastructure. Moreover, since the SAR imagery utilized in those studies were acquired by SAR satellites that offer medium spatial resolution (around 20-30 meters), therefore the resulting damage assessments were at the city bloc level which included groups of structures rather than individual structures.

However, in a very recent study by Balz et al. (2009), the authors showed a number of high-resolution satellite SAR images of damaged bridges in Sichuan province, China, following the 12 May 2008 earthquake. The study shows only post-earthquake SAR amplitude images of the bridges because pre-earthquake SAR images were not acquired by the high-resolution satellites. This prevented the authors from performing a change detection analysis on the damaged bridges to estimate the damage or deformation.

REVIEW OF RESEARCH ON INSAR FOR POST-DISASTER DAMAGE ASSESSMENT

So far, most studies on SAR applications in post-disaster damage assessment make use of the amplitude of the return signal (reflected from the ground back to the satellite) and ignore the signal phase data. In this on-going research project, we will study the feasibility of using the SAR phase information by applying the InSAR technique to detect and assess the conditions of post-disaster transportation infrastructures.

Software & Hardware

For the purposes of our research work, we have acquired the remote sensing software package ERDAS IMAGINE V.9.3, with an InSAR Module, from Leica Geosystems company, to allow for the processing of satellite optical and SAR data, and generate InSAR data products. The software package was installed on a new high-speed computer (acquired for this project) that was networked with another Unix computer (SUN Station) to allow for data processing using different software tools on different platforms. Moreover, the open-source DORIS InSAR software, developed by DEOS Institute of Delft University in the Netherlands, was also installed on the Unix computer, and used to process the same SAR image data sets to generate InSAR data products.

Data Selection & Acquisition

Having a strong interest in studying the impact of major earthquakes on urban transportation infrastructure, we decided to start our research by attempting to study the impacts of two recent earthquakes using available remote sensing technology and data. Our first case study was on the 6.6 magnitude earthquake that severely damaged the city of Bam in Iran on 26 December 2003. For this study, we selected two Envisat satellite SAR images of the impacted area that were highly suitable for InSAR deformation analysis, with dates of acquisition as 3 December 2003 (pre-earthquake) and 18 February 2004 (post-earthquake), respectively. The images were freely available from the European Space Agency (ESA).

Our second case study was on the 7.9 magnitude earthquake that severely impacted parts of Sichuan province in China on 12 May 2008, including several urban centers. For this study, we selected two Envisat satellite SAR images of the impacted area, which were among only a very few pre/post-earthquake SAR image pairs available and potentially suitable for InSAR deformation analysis. The images' dates of acquisition were 6 February 2006 (pre-earthquake) and 28 May 2008 (post-earthquake), respectively, and were purchased from Eurimage company, a data distributor for the European Space Agency (ESA).

BAM-IRAN 2003 EARTHQUAKE CASE STUDY

In this study, we performed InSAR processing on two Envisat satellite SAR images of the city of Bam, Iran, which was severely damaged by a 6.6 magnitude earthquake on 26 December 2003. One of the images was acquired before the earthquake (3 December 2003) and the other image acquired after the earthquake (18 February 2004). The open-source and advanced software DORIS, developed by Delft University in the Netherlands, was used to perform the InSAR processing. The image products generated were generally of high quality due to the facts that the selected image acquisitions had a relatively short spatial baseline of 2 meters and temporal baseline of around 10 weeks, to maximize the capability for detection of ground deformation patterns.

While Arciniegas et al. (2006) applied the InSAR technique on similar 20-meter resolution Envisat SAR imagery to try to assess the building damage distribution at the city block level, we on the other hand focused our study on trying to detect and assess the conditions of the city's transportation infrastructure. But the 20 meter ground resolution limitation made most roads and bridges narrower than 20-30 meters wide undetectable. However, we were able to detect damage on part of the city's airport runway, located a few kilometers east of the city and the earthquake's epicenter, by visually inspecting the InSAR coherence image (Figure 5). This was confirmed by a World Bank report, which stated that the airport runway, with its relatively thin asphalt surface, suffered moderate damage due to the earthquake and the numerous flight landings and take-offs in the weeks following the earthquake. Due to the spatial resolution limitation, it was not possible to quantify the damage from the generated InSAR images.

The following optical and InSAR images show various types of information about the city of Bam airport runway and the surrounding area.

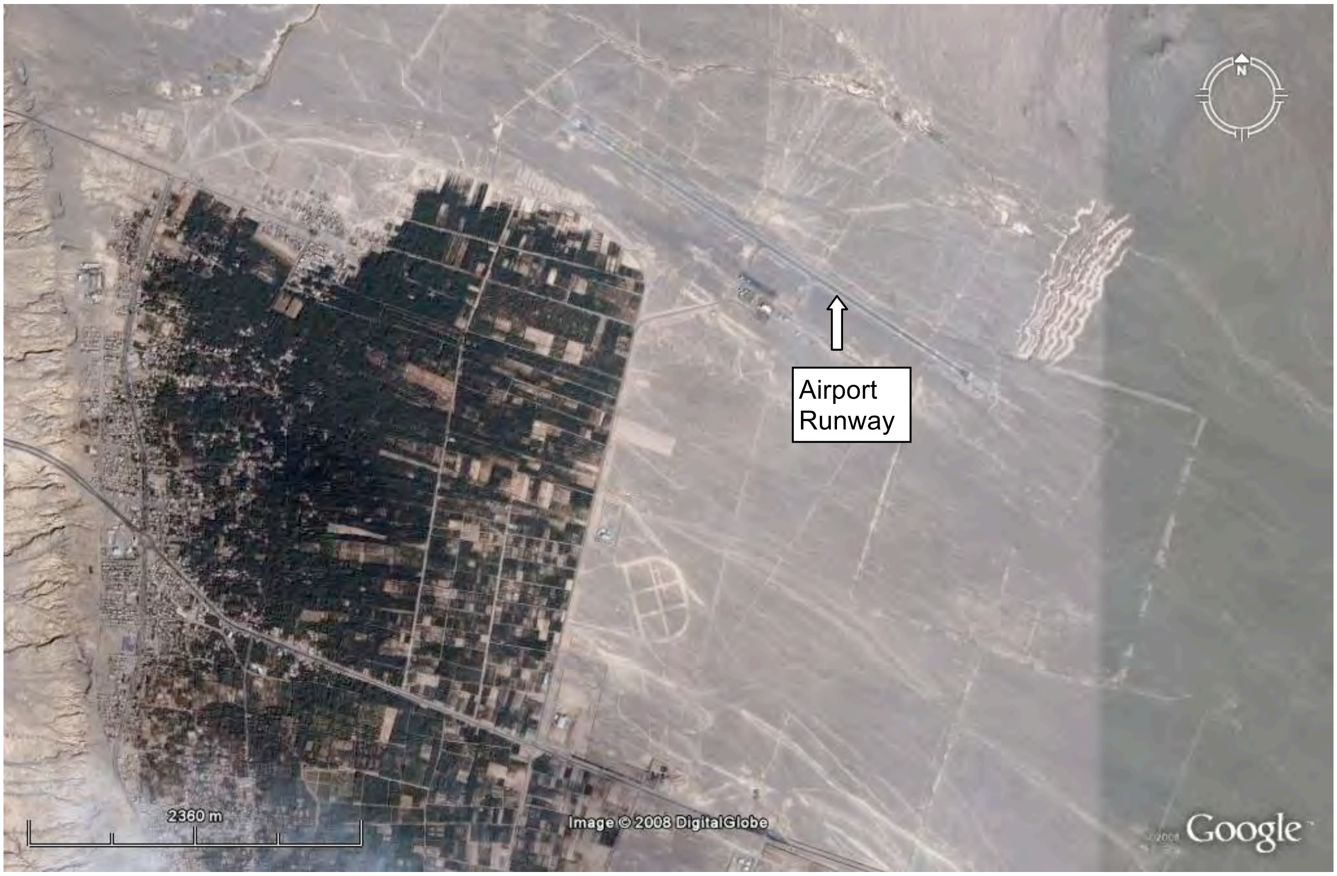

*Figure 5: **S**atellite Optical Image of Bam, Iran, showing the city's airport runway as oriented from north-west to south-east (Source: Google Inc., 2008).*

A number of features in the optical image above, including the airport runway, can be seen in the following InSAR images that we generated for this study area.

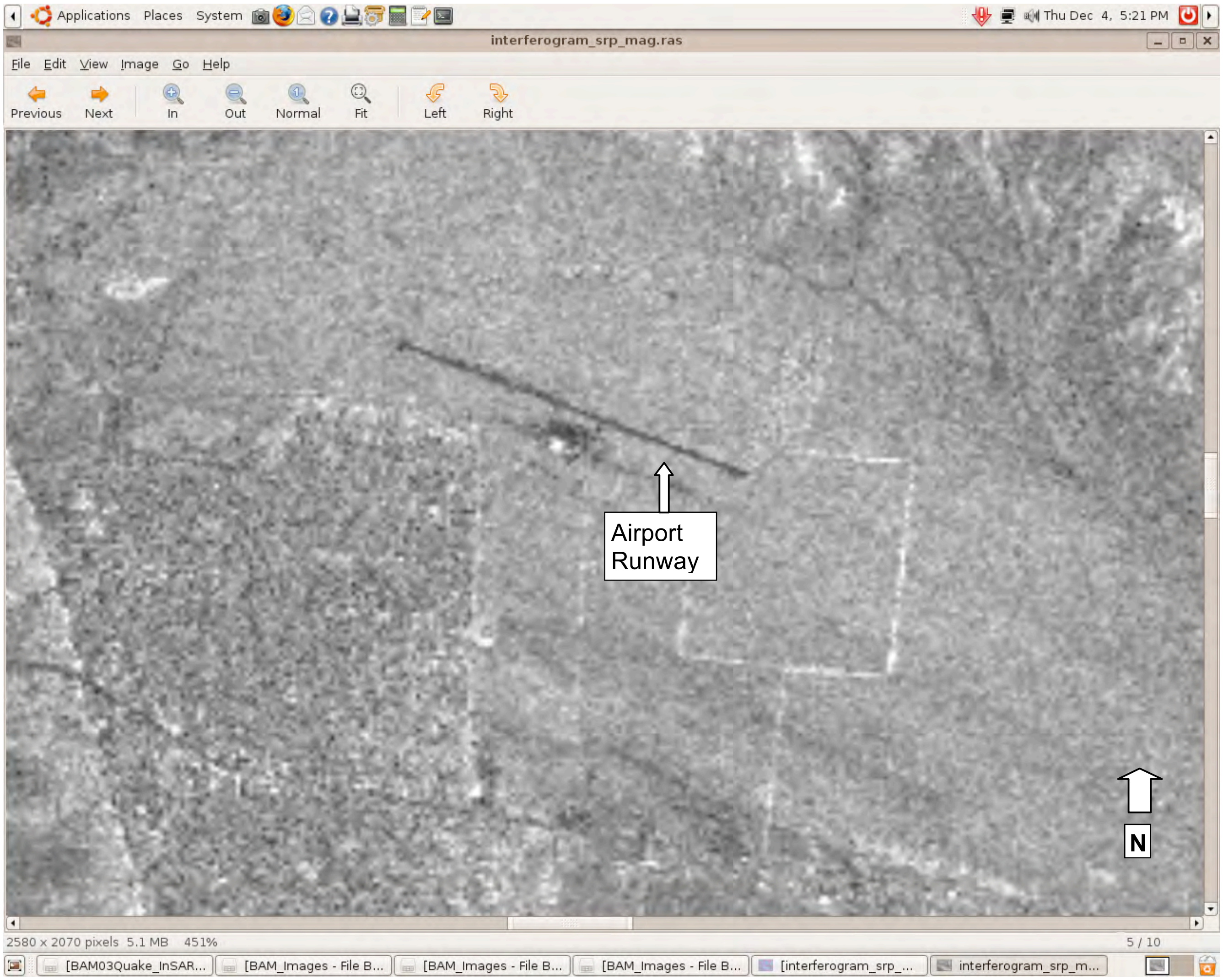

Figure 6: InSAR magnitude image generated with DORIS software

Figure 6 is the result of pixel-to-pixel multiplication of pre- and post-earthquake SAR amplitude images of the study area, with bright pixels representing strong SAR signal backscatter to the imaging satellite and dark pixels representing weak signal backscatter.

The InSAR magnitude image above clearly shows the Bam airport runway as a linear feature that is much darker than its surrounding area, an indication that the imaging satellite received very little signal backscatter from the runway. This is due to the fact that the SAR signals from Envisat satellite hit the flat and horizontal runway and reflected away from the satellite, as it imaged the area from east to west while on its north to south flight orbit.

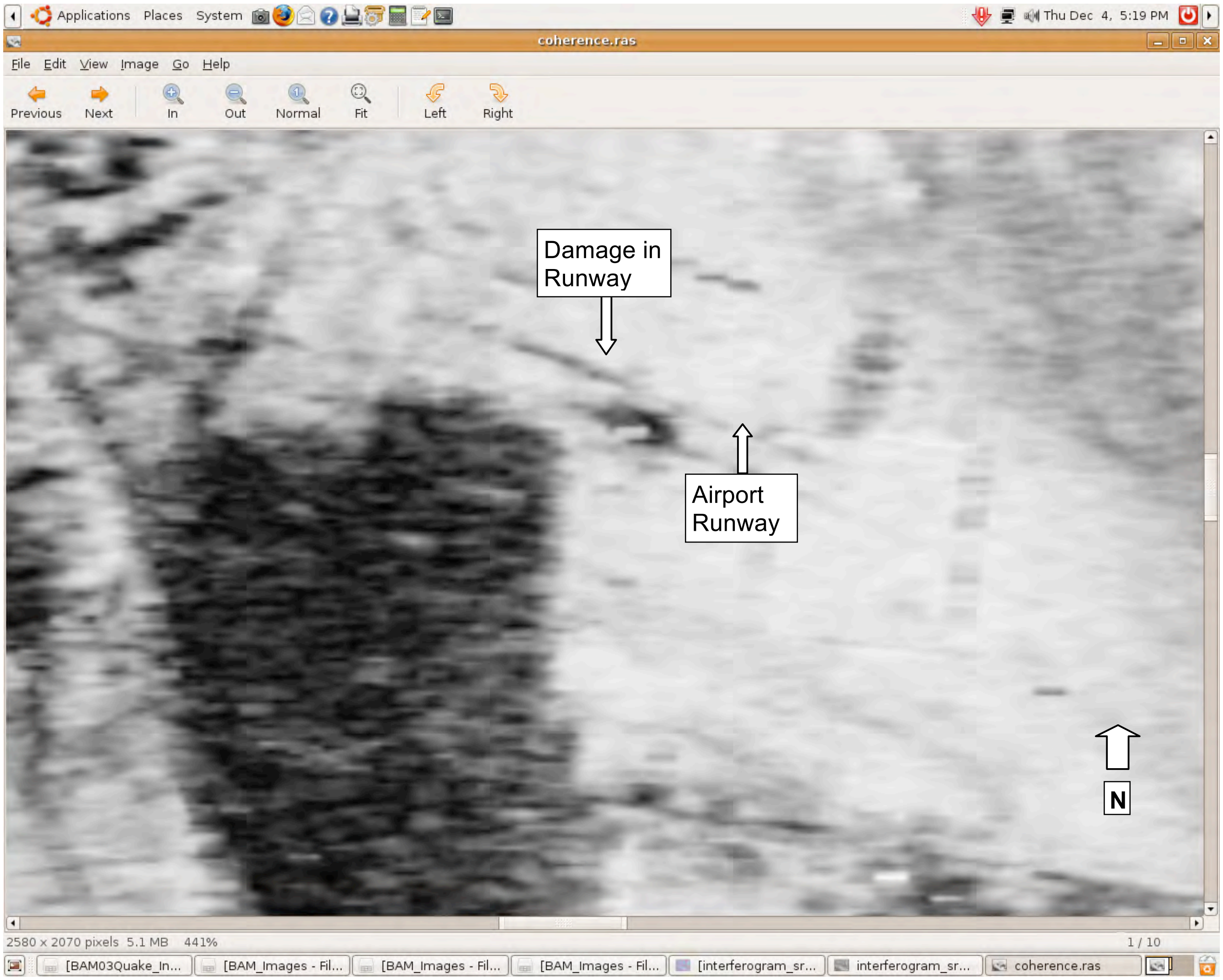

Figure 7: InSAR coherence image generated with DORIS software

Figure 7 is the result of pixel-to pixel phase correlation between pre- and post-earthquake SAR images, where bright pixels indicate high correlation and dark pixels indicate low correlation.

The InSAR coherence image above clearly shows the western part of the Bam airport runway as significantly darker than its surrounding area. This means that those pixels on the runway suffered significant amount of deformation (or damage) due to the earthquake or other effects, which caused significant changes in their backscattered SAR signal phase values as compared to pre-earthquake signal phase values. These significant differences in the runway pixel phase values, between pre- and post-earthquake SAR images, led to low correlation values for those pixels which therefore made them appear as dark in the InSAR coherence image. Even though the detected deformation on the airport runway appears to be significant, it is difficult however to give a more detailed assessment of the runway's operational conditions based on this image alone due to the 20 meter spatial resolution limitation.

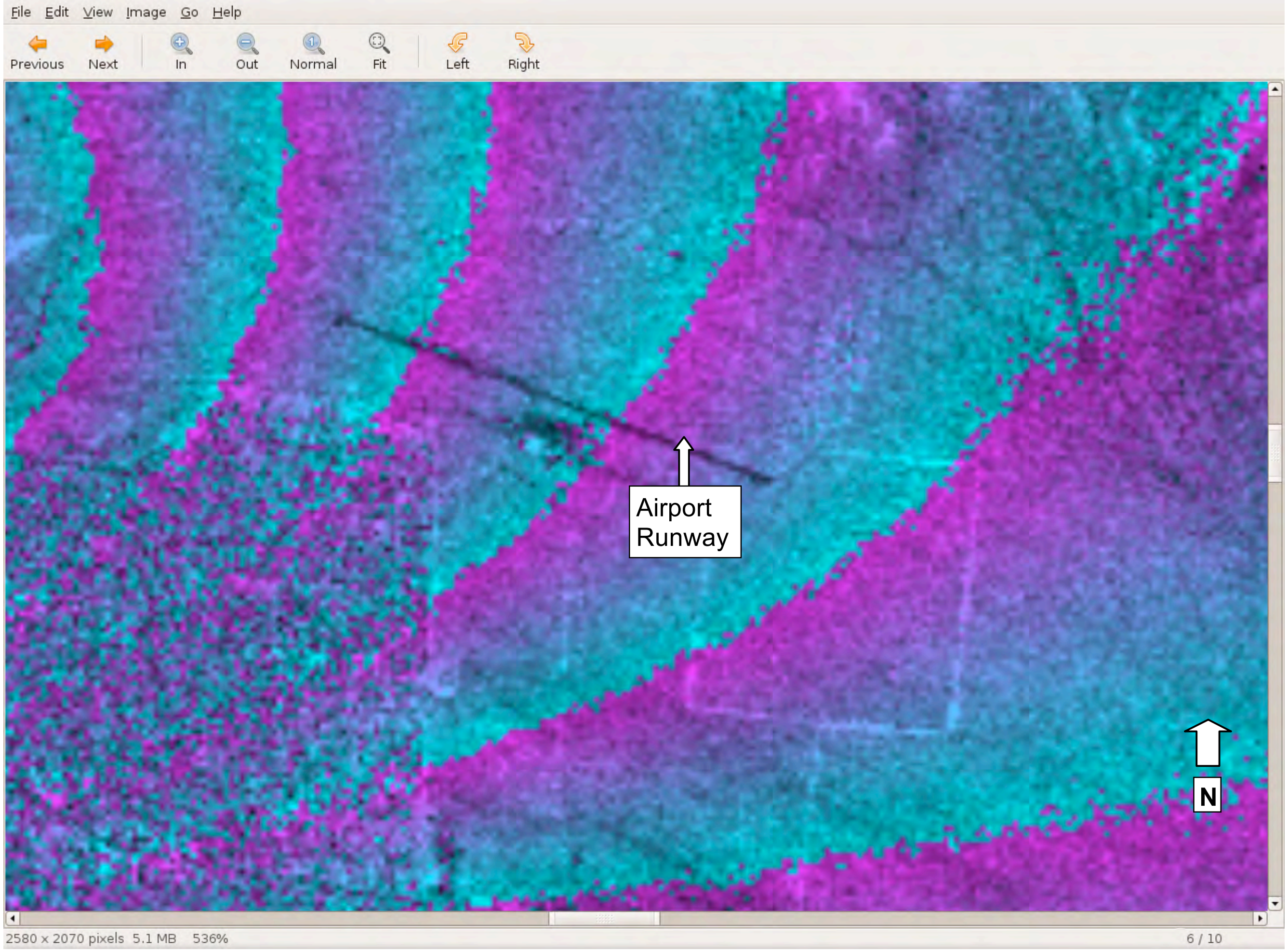

Figure 8: Composite InSAR image generated with DORIS software, consisting of an InSAR phase-difference image superimposed on an InSAR magnitude image.

The InSAR phase-difference image, showing the earthquake-induced ground deformation pattern as color fringes, is superimposed on an InSAR magnitude image showing the Bam airport runway as dark in color. Note that the deformation pattern (color fringes) caused by the traveling earthquake shock wave, traverse the length of the airport runway from west to east. We also note from Figure-6 that the western part of the runway, which is closer to the earthquake epicenter, shows the most noticeable damage.

SICHUAN-CHINA 2008 EARTHQUAKE CASE STUDY

In this study, we performed InSAR processing on two Envisat satellite SAR images of a selected area of Sichuan province in China, which was impacted by a strong earthquake on 12 May 2008. One of the images was acquired before the earthquake (6 February 2006) and the other image acquired after the earthquake (28 May 2008). The open-source and advanced software DORIS, developed by Delft University in the Netherlands, was used to perform the InSAR processing. The InSAR image products generated varied in their quality from high quality for the magnitude image to low quality for the phase and coherence images. This low quality was mainly due to the facts that the selected image acquisitions had a relatively long spatial baseline of 600 meters and temporal baseline of around 2.25 years, which significantly increased the level of decorrelation between the images and thus severely reduced the capability for detection of ground deformation patterns. However, we used this image data set because it was among very few datasets that were available for the impacted area and the same time was suitable for InSAR processing. The generated InSAR magnitude image was the only image that we were able to utilize in our attempt to detect and assess the conditions of the transportation infrastructure in the earthquake-impacted area. The following images are first results showing information about the study area.

Figure 9: Satellite optical image of the city of Mianyang in Sichuan province, China, which was impacted by the 2008 earthquake.

Figure 9 shows a road-dam structure spanning a river channel (Source: Google Earth, 2008).

A number of features in the optical image above, including the road-dam structure, can be seen in the following InSAR image that we generated for this study area.

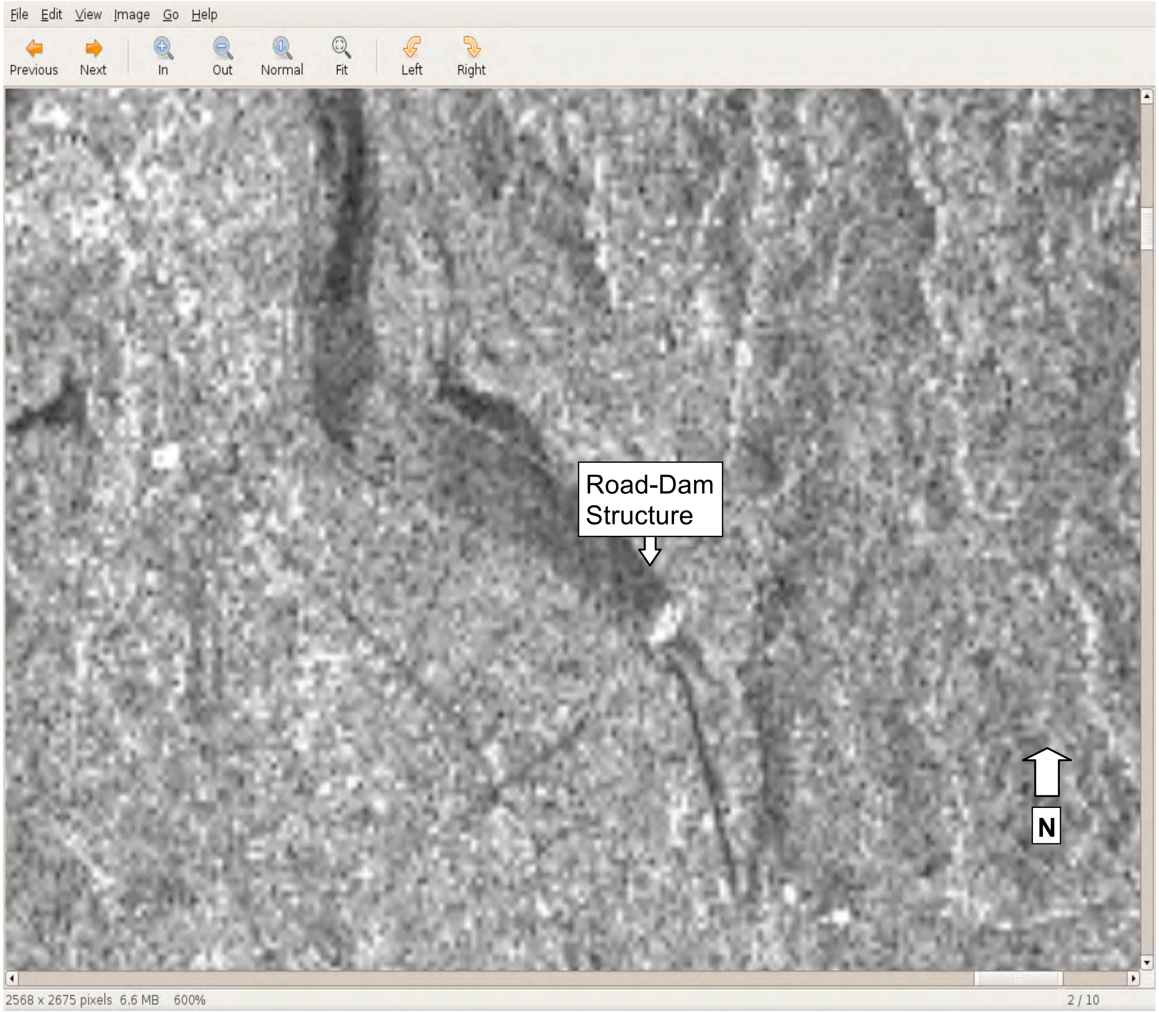

Figure 10: InSAR magnitude image generated with DORIS software

Figure 10 is the result of pixel-to-pixel multiplication of pre- and post-earthquake SAR amplitude images of the study area, with bright pixels representing strong SAR signal backscatter to the imaging satellite and dark pixels representing weak signal backscatter.

Note in the image above that the road-dam structure spanning the river channel shows as bright pixels. This means that the SAR signals backscattered from the road-dam structure with high amplitudes due to the fact that the structure is oriented at almost 45 degrees angle with the north-south flight path of the imaging satellite. The other reason for the structure's bright signals is that the width of the structure was estimated at around 50 meters (using a Google Earth tool) that is more than 2 SAR pixels wide, and thus makes it detectable by the SAR system. Therefore, based on the brightness of the return signals from the road-dam structure, we can say that the structure appears to be intact following the earthquake. However, we cannot determine from this image alone if the structure has suffered moderate or minor damage, due to the image's 20-meter spatial resolution limitation

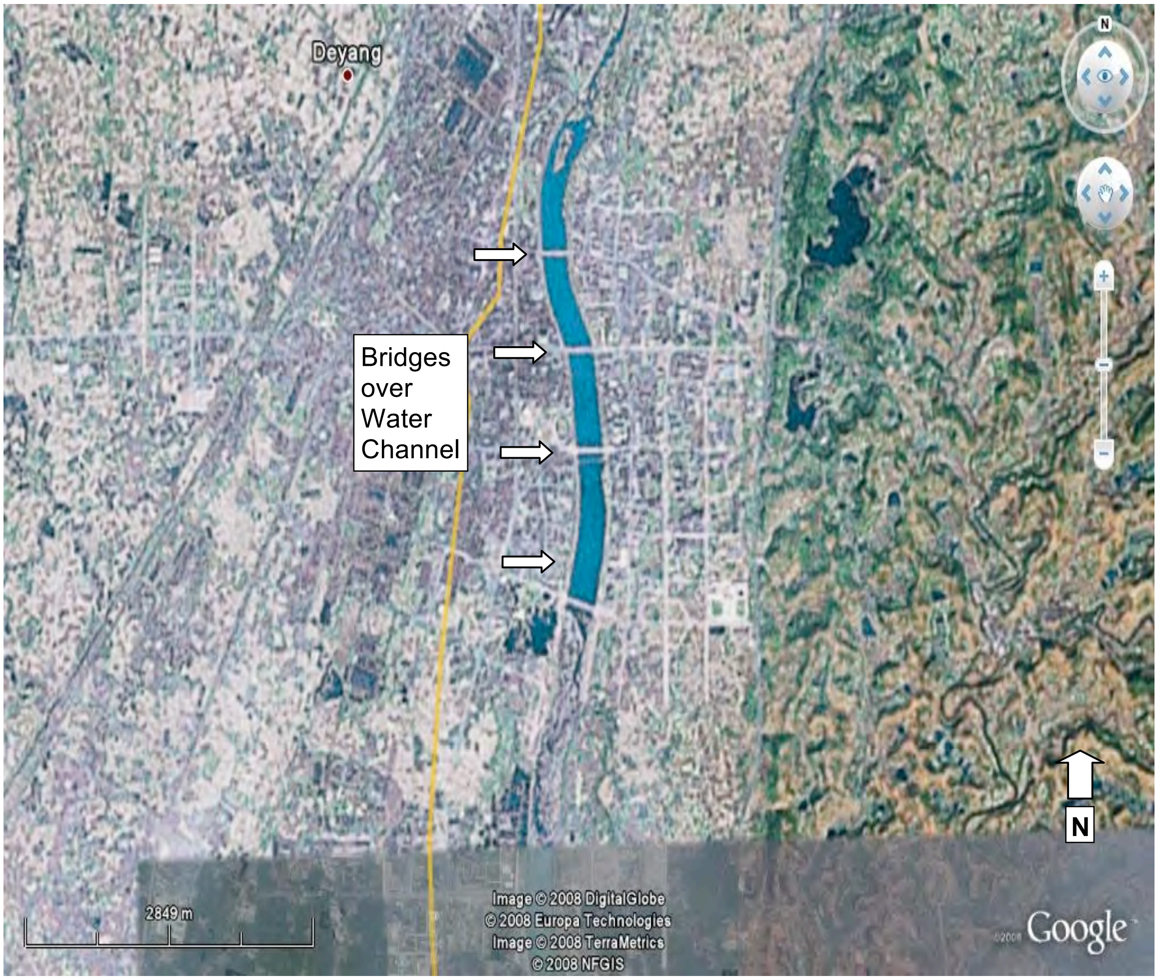

Figure 11: ***S****atellite optical image of the city of Deyang in Sichuan province, China, which was impacted by the 2008 earthquake.*

Figure 11 shows a number of bridges spanning a river channel (Source: Google Earth, 2008).

A number of features in the optical image above, including the bridges, can be seen in the following InSAR image that we generated for this study area.

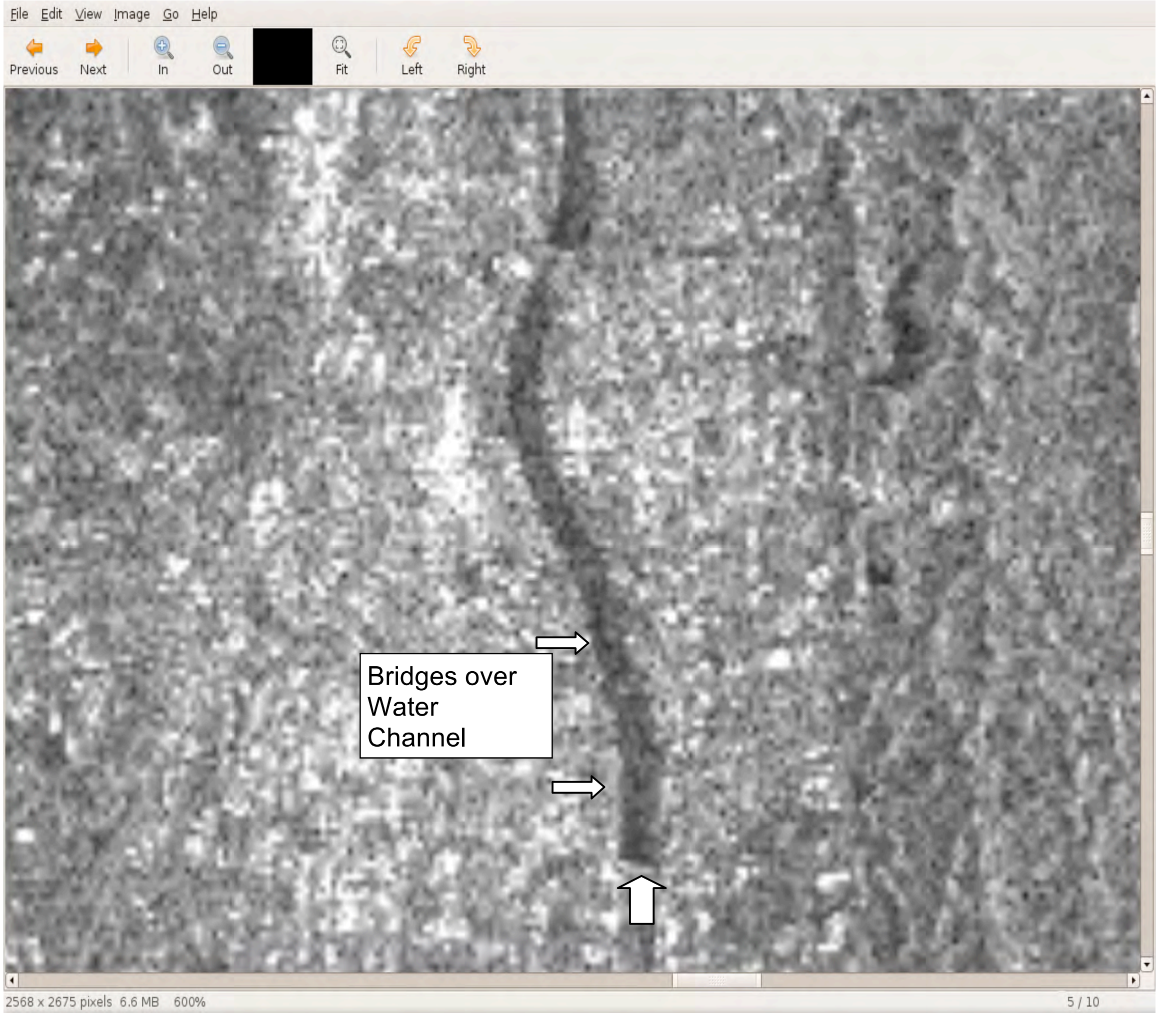

Figure 12: InSAR magnitude image, generated with DORIS software

Figure 12 is the result of pixel-to-pixel multiplication of pre- and post-earthquake SAR amplitude images of the study area, with bright pixels representing strong SAR signal backscatter to the imaging satellite and dark pixels representing weak signal backscatter.

Note that the bridges showing in the optical image are barely detected in the InSAR image above. One reason for that could be the 20-meter spatial resolution limitation of the SAR system, which means that only structures of width significantly larger than 20 meters can be detected. In this case, the estimated width of those bridges was around 35 meters (using a Google Earth tool) which is less than two SAR pixels wide. The other and most likely reason could be the fact that the bridges are oriented east-west which is almost perpendicular to the north-south flight path of the imaging satellite. In this case, most of the satellite SAR signals would have hit the flat and horizontal bridge decks and reflected away from the satellite. Therefore, only few low amplitude signals would have backscattered to the satellite, which made the bridges appear much darker on the InSAR magnitude image and therefore barely detectable over the dark water channel.

Hence, in this case, we can say that the following combination of factors: the image spatial resolution limitation, the bridges' perpendicular orientation to the imaging satellite and the bridges being over a water channel, prevented us from clearly detecting the bridges and determining if the bridges remained intact following the earthquake.

CONCLUSIONS

Based on visual inspection of the generated InSAR images in the case studies discussed earlier, we can conclude the following:

1) The Envisat satellite's 20-meter spatial resolution only allows for the detection of bridge structures, roads, and airport runways that are at least 20 to 30 meters wide, by using the InSAR magnitude image. However, bridge structures over water channels can only be detected if they are oriented in a non-perpendicular direction with respect to the imaging satellite. Moreover, only significant level of deformation or damage in these structures can be detected by using the InSAR coherence image. Therefore, the extraction of detailed and quantifiable post-disaster damage information about the transportation infrastructure is not feasible while using the 20-meter spatial resolution SAR imagery. Hence, the need for much higher spatial resolution SAR data that allows for detailed post-disaster damage assessment becomes very obvious.

2) The recent deployment of the German SAR satellite TerraSAR-X (with spatial resolution of 1-5 meters) and the Canadian SAR satellite Radarsat-2 (with spatial resolution of 3+ meters) makes them highly suitable for the detection and detailed assessment of roads and bridges in post-disaster situations. Below is an example that illustrates the spatial resolution of a TerraSAR-X image as compared to that of an ERS image of the same area in Germany. In relation to our study, we note that both ERS and Envisat satellite imagery have the same spatial resolution of 20

meters.

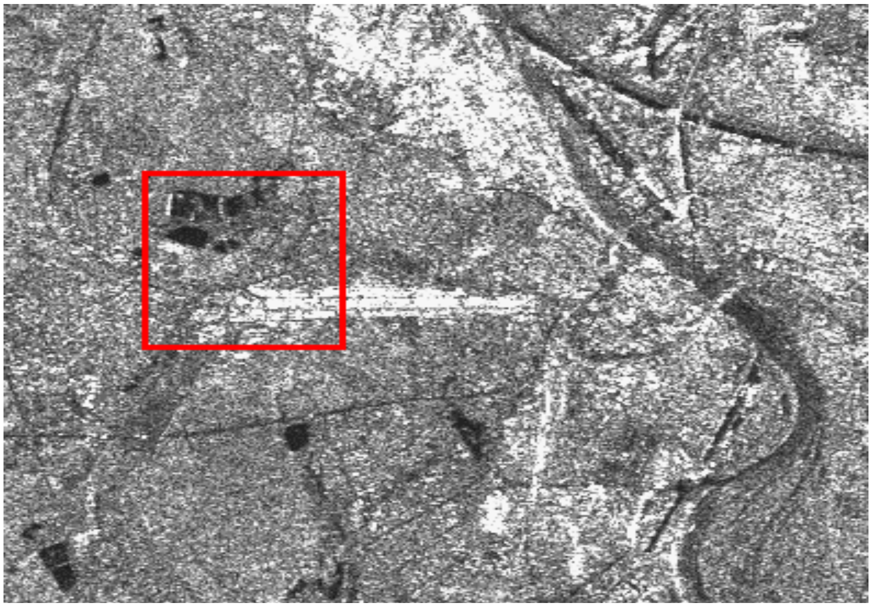

Figure 13: SAR image of Ludwigshafen, Germany, acquired by ERS satellite with 20 meter spatial resolution, which is similar to that of Envisat satellite (Source: Roth et al, 2005)

Figure 14: This is a very high resolution SAR image, of the same area in Figure-11, acquired with airborne ESAR that has the same (1-5 meter) resolution as the TerraSAR-X satellite.

Note in Figure 14 the vast improvement in spatial resolution in this image in relation to roads and bridges as compared to the 20 meter resolution SAR image in Figure-9 (Source: Roth et al, 2005).

The availability of high-resolution images is key to the future success of the research initiative described in this report. In the absence of such high-resolution satellite images, the proposed post-disaster management approach cannot be realistically tested unless simulated images are employed. However, the authors are proposing a future research project as a second phase for this research based on the approach described below.

RECOMMENDATIONS AND FUTURE RESEARCH

Given the limited amount of funding for this pilot study and the lack of availability of high-resolution images, the authors are proposing future research recommendations. In the next phase of our on-going research, we plan to study the effects of various combinations of bridge deformation geometries and SAR satellite imaging geometries on the backscattered SAR signals. In this study, we will utilize real and simulated high-resolution SAR imagery to estimate the SAR image signature of as many potential bridge deformation geometries as possible. These SAR image "deformation signatures" will be compiled into a database for a selected number of bridges that are considered as crucial transportation links in a major urban area. Having this information readily available in the immediate aftermath of a severe earthquake will significantly aid in the interpretation of the post-earthquake SAR imagery and in estimating the type and level of deformation/damage in impacted bridges.

We are proposing a three-step methodology for rapid post-disaster damage assessment and management of transportation networks using satellite SAR and InSAR remote sensing, a predictive bridge structural model, and a transportation network model.

Step 1: The main purpose of the **first step** is to assess the conditions of critical transportation links, such as bridges and road sections, in the immediate aftermath of a major disaster such as a severe earthquake. The assessment may include the detection and estimation of possible deformation in these structures. The rapid determination of which of these transportation links are available for various modes of traffic, shortly after the disaster, is very crucial for evacuation and rescue operations and thus for saving as many lives as possible. Post-disaster high-resolution SAR amplitude images of the impacted area can be used, first, to determine which critical bridges and roads are still intact and which are severely damaged or destroyed. Then InSAR phase and coherence images can be used to further evaluate the seemingly intact bridges to try to detect any potential slight to moderate deformation in those structures. As a result, a good preliminary assessment can be made which may include any of the following:

(a) Bridges and roads that are sill intact with no visible deformation.
(b) Bridges and roads that are sill intact but show slight to moderate deformation.
(c) Bridges and roads that are severely damaged or destroyed.

In category (a) all modes of traffic will be possible, in category (c) no traffic will be possible, while in category (b) further evaluation will be needed, using the second step in the methodology, to determine what modes of traffic these structures can support.

Step 2: The second step in this methodology involves the input of the bridges' estimated deformation values into a bridge predictive structural model, to predict the post-disaster structural integrity of each deformed bridge, and thus its ability to support vehicle and/or pedestrian traffic.

Step 3: The third step in this methodology involves the input of the information from steps 1 & 2 into a transportation network model to generate a near-optimal routing map for evacuation, rescue and logistics operations in the disaster impacted area.

To illustrate our proposed methodology, we use two hypothetical scenarios/examples of deformed bridges being imaged by a high-resolution SAR satellite, to show what information can be obtained and what technical issues/considerations are involved.

Figure 15 illustrates the first example where a high resolution SAR satellite (e.g. TerraSAR-X) images a bridge deck that is partially deformed due to an earthquake. In this scenario, section "A" of the bridge deck suffers no deformation and remains horizontal, sections B1 and B2 partially collapse downward, and section "C" tilts moderately to one side (facing the satellite). From the diagram, we can see that the behavior of the SAR signals (red arrows) is mainly determined by the satellite imaging geometry, and the bridge's orientation and deformation geometry. Therefore, these factors determine how much of the SAR signals are backscattered to the imaging satellite.

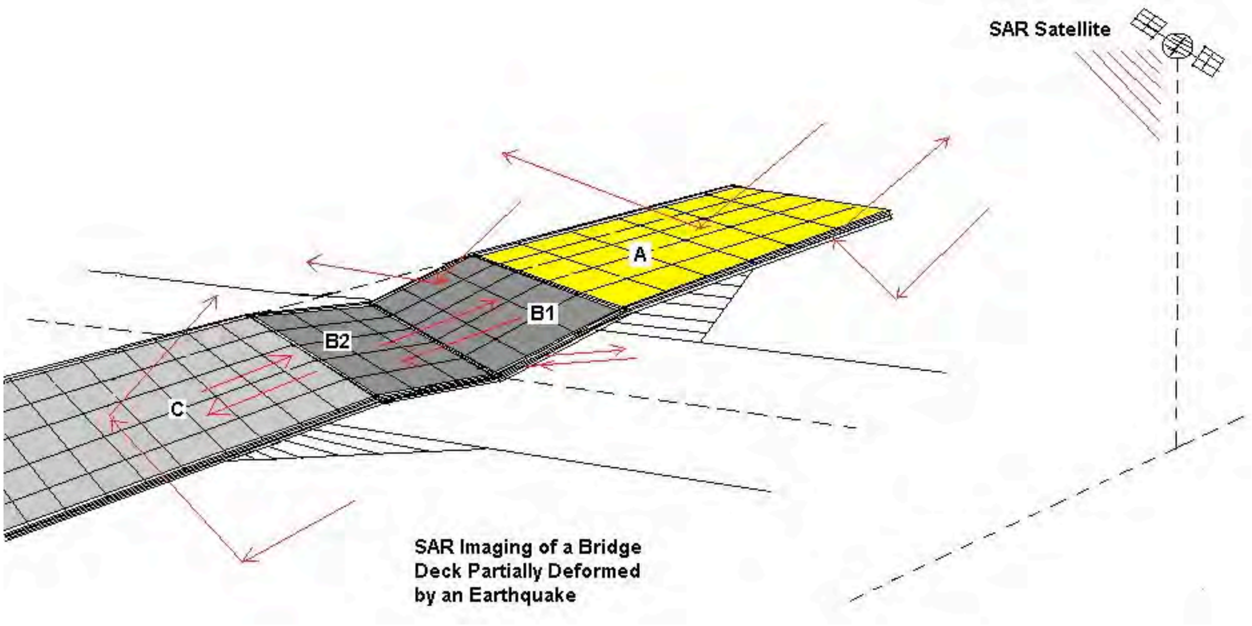

Figure 15: Expected effects of SAR signal backscattering with parallel orientation

Figure 15 (example-1) illustrates the expected effects of the imaging and deformation geometry on the SAR signal backscattering, when the SAR satellite track is parallel to the orientation of an earthquake-deformed bridge.

Expected appearance of the deformed bridge deck in post-disaster SAR image (example-1)

At section “A”, in Figure 15, the SAR signals are expected to hit the horizontal deck and reflect away from the satellite (specular reflection), which means that this section would appear as dark in the SAR amplitude image. At section B1, partially facing away from the satellite, the SAR signals are expected to hit the deck and reflect away from the satellite, which means that this section would also appear as dark in the SAR amplitude image. At section B2, partially facing the satellite, some of the SAR signals are expected to hit the deck and reflect back toward the satellite, which means that this section would appear as brighter than section “B1” in the SAR amplitude image. At section “C”, tilted moderately toward the satellite, some of the SAR signals are expected to hit the deck and reflect back toward the satellite, which means that this section would appear as brighter than section “A” in the SAR amplitude image. Also as illustrated in the diagram, some of the SAR signals are expected to undergo “double-bounce”, where they hit the ground first, then reflect onto the bridge deck at section “C” and onto the vertical side of section “A”, then reflect back toward the satellite. This effect would also contribute to the brighter appearance of section “C” and almost all the vertical sides of the deck sections in the SAR amplitude image.

Expected appearance of the deformed bridge deck in InSAR images (example-1)

In the InSAR magnitude image, the same results are generally expected as with the SAR amplitude image (see previous paragraph). In the InSAR phase image, only the deck sections that suffered any kind of deformation or displacement would contribute to this image, such as sections “B1”, “B2” and “C”. The deck's deformation or displacement causes a difference in the phase values of corresponding pre/post-earthquake SAR image pixels. These pixel phase differences would appear as color cycles (or contours) on the affected deck sections in the InSAR phase image, where each color cycle (red-to-red) is equivalent to half a wavelength of displacement in the line-of-sight of the SAR satellite. We note here, for example, that the TerraSAR-X satellite emits a SAR signal of 3 cm wavelength. Therefore, by using the InSAR phase image we expect to be able to estimate the amount of displacement on the affected bridge decks at least in one dimension. In the InSAR coherence image, the non-deformed section “A” of the bridge deck is expected to appear as bright pixels, due to high phase correlation in the pre/post-earthquake SAR image pixels. On the other hand, the deformed/displaced deck sections “B1”, “B2” and “C” are expected to appear as various shades of dark pixels, due to low phase correlations in the pre/post-earthquake SAR image pixels as a result of earthquake-induced deformation or displacement. Therefore, by using the InSAR coherence image we expect to be able to roughly detect and delineate parts of the bridge deck that suffered any kind of deformation, displacement or changes in its surface materials.

Estimation of bridge deformation using the InSAR phase image (example-2)

In Figure 16 shown below, the displaced sections (A & B) of the bridge deck are expected to appear as a series of color fringes or cycles in the InSAR phase image (or interferogram). Pixels that suffered deformation will experience changes in their phase values from pre- to post-earthquake, where those phase differences will appear as color cycles in the InSAR phase image. Each color cycle (Red-to-Red) will represent half a wavelength of displacement in the line-of-sight of the satellite. As we can see from Figure 16, the displaced (collapsed) section “A” of the bridge deck is expected to show up as 5.5 color cycles in the InSAR phase image.

If we assume that the imaging satellite is TerraSAR-X, which emits SAR signals of 3 cm in wavelength, then the maximum displacement "d" of sections "A" and "B" in the line-of-sight of the satellite would be as follows: d = (5.5 color cycles)(1.5 cm) = 8.25 cm. Once "d" has been estimated then, from the right-angle triangle xyz in Figure 3, we can estimate the vertical displacement "H" of section "A" of the bridge deck, as follows: cos (i) = d / H, or H = d / cos (i), where 'i' is the known incidence angle of the SAR satellite. It is important to note that in this example, and for the sake of simplicity, we assumed that the direction of displacement or deformation of bridge decks "A" and "B" to be vertically downward, which is not always the case after an earthquake. The geometry of the bridge's non-vertical displacement would certainly add more complexity to this analysis, which we plan to address in our future research.

The estimated vertical displacement "H" of the bridge deck can then be input into the bridge structural model to try to predict the deformed bridge's ability to support various modes of traffic.

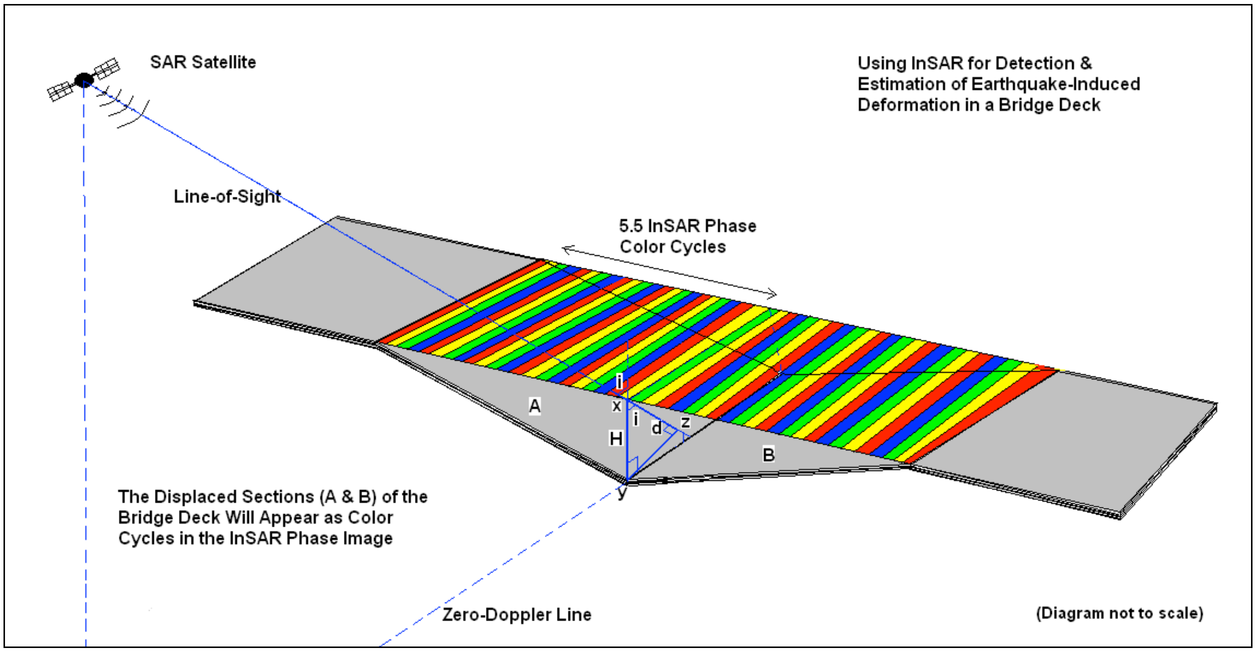

Figure 16: Potential of InSAR technique for detecting deformation

Figure 16 (example-2) illustrates the potential of the InSAR technique, using high-resolution satellite SAR, for detecting and estimating earthquake-induced moderate deformation in a bridge deck.

Short-term response needs a quick assessment of damage top the infrastructure and the use of this information to decide best transportation and emergency response strategies. Unfortunately, this kind of quick yet reasonably reliable post-disaster information is not usually available. Imagine a major earthquake after which some important bridges and roadways are expected to be damaged. It is almost impossible to predict and make real-time decisions about the extent of the damage as a result of an earthquake. Especially, other than major damages such as partial or full collapse of a bridge that is not visually easy to identify and report back to the decision makers can in fact create major problems when designing post-disaster response strategies. For example, a bridge can be seriously impacted but still be intact until heavy trucks start using it. If the decision makers are not aware of this situation, they can route fully loaded response truck through such bridges causing further loss of life and valuable resources needed by the victims of disasters. Given the geographical extent and shear size of regional transportation networks, even a preliminary assessment of the transportation infrastructure can take days if not weeks. The experience of recent earthquakes, tsunamis, and hurricanes showed us that we do not have the luxury of time in the presence of such calamities. We have to act fast and decisively to save innocent lives.

In this report, we present a methodology using hypothetical scenarios as an example to illustrate the potential capabilities of high-resolution SAR and InSAR remote sensing technologies for post-disaster damage detection and assessment of bridges and highways. Here we would like to emphasize that these technologies may be the <u>only</u> ones applicable if a severe earthquake or disaster strikes a highly-populated urban area at night-time or under total cloud cover, resulting in widespread damage to the transportation infrastructure.

As mentioned earlier, the availability of high-resolution images is key to the future success of the research initiative described in this report. In the absence of such high-resolution satellite images, the proposed post-disaster management approach cannot be realistically tested unless simulated images are employed. However, using simulated images is beyond the scope of this project. In the near-future, we hope to be able to access high-resolution satellite SAR data of earthquake-prone urban areas, to further study the appearance of bridges and highways in SAR and InSAR images, and extract as much information as possible on their conditions. Once the feasibility of damage assessment is verified using real satellite images, the next step will be to use this information in conjunction with probabilistic routing and dynamic traffic assignment algorithms that can generate low risk routes for evacuation and other post-disaster operations in dense urban areas.

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