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Evaluation of Synthetic Aperture Radar Satellite Remote Sensing for Pavement and Infrastructure Monitoring

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Abstract

This study aims to carry out investigation of the capability of Synthetic Aperture Radar (SAR) satellite data and interferometric synthetic aperture radar (InSAR) for use in advanced infrastructure monitoring, which is a tangible breakthrough allowing to assess pavement deformations and deformation velocities with millimetric accuracy. Recent developments in satellite remote sensing and availability of high-resolution SAR products have created an opportunity for SAR-based monitoring in pavement and infrastructure management. Therefore, SAR-based monitoring has become valuable for monitoring and rehabilitating the nation's deteriorating roadway infrastructure elements such as bridge settlements and displacements, roadway surface deformations, geohazards and sinkhole detection, historical analysis of problematic sites, etc. In this research study, the feasibility, and effectiveness of use of satellite remote sensing technology for pavement and infrastructure monitoring were evaluated. A cost benefit analysis for a possible SAR-based monitoring system was performed. It was found that SAR-based methods are useful as a complementary tool rather than a replacement for current technologies and practices, specifically in the sense of state of good repair.

Keywords: Synthetic Aperture Radar; InSAR; Pavement Monitoring; Satellite Remote Sensing

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1. Introduction

As a vital part of the system, adequate infrastructure is an essential precondition for complex and dynamic transportation systems. Aging transportation infrastructures in the U.S. emphasizes the importance of preserving the existing assets and maintaining the transportation system in sustainable level. Researches indicate that 65% of the roadways are rated as “less than good condition” and 25% of bridges require “significant repair” in the U.S. [1]. The Federal Highway Administration (FHWA) has estimated the necessary annual investment of $77 billion for federal-aid highway system compared to federal highway receipts of $34 billion as of 2014 [2]. Budget limitations and decreased revenues have made extremely difficult for many states to maintain the state of good repair on roadways.

Traditional pavement inspection techniques offer a method of determining the pavement condition through observing and recording, which causes this pavement survey work to be cumbersome and inefficient. In fact, some of these periodic inspection-based monitoring efforts are redundant and some of them cause late-detection of the problems which cause money and energy loss. Therefore, any contribution towards network-scale monitoring tools that facilitate the early detection of the problems and reduce the vehicle-based inspection trips to the sites will help building more robust and effective monitoring programs. Such tools will benefit state and federal agencies to prioritize their investment strategies that will yield economic and other benefits.

In the last two decades, SAR technology and Interferometric Synthetic Aperture Radar (InSAR) applications have been widely investigated for large-scale monitoring studies and mature fields for SAR applications have been summarized by Ouchi [3]. Recently, availability of high-resolution SAR images and developed advance data processing methodologies has taken the attention of transportation research community. With these developments, extracting the information about the identity and extent of the problems at the targeted scene became possible for relatively small areas, which makes the technique useful for pavement and infrastructure monitoring.

In the light of current infrastructure and pavement monitoring practices, this study aims to investigate the capability of satellite remote sensing technologies, specifically SAR satellite data for use in advance infrastructure monitoring, which is tangible breakthrough in sensing technology allowing to assess deformations with millimetric accuracy. Scope of this research is limited to the evaluation of the possibility of using SAR-based systems, data sources and SAR image analysis tools for pavement and infrastructure monitoring in general and does not include the effectiveness of such systems for detecting different type and severity of pavement surface distresses and infrastructure problems which require further exploration.

2. Current Pavement and Infrastructure Monitoring Technologies

Pavement condition surveys provide an indication of the physical condition of the pavements and consist of data collection, pavement condition rating and quality management elements. Both manual (human observations) and automated (line and area scanners, ground penetrating radars, acoustic sensors, optical imagery, LIDAR, etc.) data collection techniques are widely used based on agencies’ priorities, available resources and geographic limitations. The condition ratings are then used for estimating and managing the rehabilitation and maintenance works, long-term economic planning and historical pavement performance records. Pavement condition data has been collected in variety forms, however, most common data types could be categorized as distress data, structural capacity data, ride quality data and skid resistance data as suggested by Attoh-Okine and Adarkwa [4]. Distress data and ride quality data were found relevant for considering the potential contribution of SAR based monitoring.

Two critical challenges in pavement management are the timely detection of problems and frequency data collection. Many studies and experiences of agencies show that early detection of problems treated with preventive measures increase the service life of the assets and reduce the total maintenance cost while maintaining the safety and quality [5]. Haider et al. [6] stated that “longer monitoring intervals may underpredict the expected roughness and overpredict the expected life on the basis of roughness” and highlighted the importance of early detection of problems for the prediction of propagation. Therefore, a SAR-based continuous monitoring system might help building more robust pavement and infrastructure monitoring and reduces/prioritizes routine vehicle-based inspection trips and associated monitoring cost. Considering most agencies perform routine inspections on pavement and infrastructure elements such as bridges in different cycles (1-3 years), monthly monitoring with satellite imagery is expected to contribute to the routine monitoring efforts by providing more frequent data in network-level [7].

3. Overview Of Satellite Remote Sensing and InSAR

SAR imagery is produced by measuring the distance and transmitted/backscattered radiation of the target scene, and contains both amplitude and phase in each pixel. Amplitude is the measure of the radiation backscattered by the objects in each pixel and phase measures distance between radar and scene proportional to wavelength (λ) for the detection of surface deformations. Cloud-penetrating capability, day and/or night operating flexibility and all-weather working ability give SAR superiority over other imaging techniques especially on tough climate locations [8,9]. SAR Interferometry (InSAR) uses two or more SAR images acquired at different times to derive more information about the scene by co-registering them in an appropriate order[8]. InSAR analysis requires determination of phase difference as presented in equation 1. Among these five components, $\Delta\varphi_{\text{displacement}}$ is expected to be accurately calculated by removing or minimizing other effects.

$$\Delta\varphi=\Delta\varphi_{\text{displacement}}+\Delta\varphi_{\text{elevation}}+\Delta\varphi_{\text{flat}}+\Delta\varphi_{\text{atmosphere}}+\Delta\varphi_{\text{noise}} \tag{1}$$

Differential InSAR method (DInSAR) has long been used for the detection of surface deformations such as detection of slow-moving landslides; observation of volcanic and tectonic activities, etc. Later, Ferretti et al., [10] introduced Permanent Scatterers (PS) method (PSInSAR) to effectively remove the atmospheric interference by using stable neutral reflectors such as buildings, transmission towers and similar man made objects that are consistent in terms of radiation reflectivity in each SAR image over a series of images taken from same scene and calculated the surface deformations with millimetric accuracy [10,11]. On the other hand, low density of PSs in nonurban areas encouraged researchers to use Distributed Scatterers (DS) to extract more information on the scene where PSInSAR is not applicable or not sufficient enough [12-14]. Although DSs do not produce high backscattered radiation as PSs, they are still statistically consistent in a homogenous area to reduce the noise.

Since the InSAR and developed advanced deformation detection techniques upon InSAR are able to measure the millimetric surface deformations [9,10], and high-resolution satellite images can significantly increase the number of detected points [15,16]; satellite based infrastructure monitoring could be possible for deteriorating roadway infrastructure such as bridge settlements and displacements, surface deformations and sinkhole detection [17-19] or detailed analysis of targeted areas that are already known problematic by previous studies [20]. The promising satellite remote sensing technology is expected to play a crucial role for reducing the cost of network-scale pavement and infrastructure monitoring for state and federal agencies in near future as the high-resolution satellite imaging become more available and less costly, and analysis methods and algorithms become more mature [16,17].

4. Current Transportation Infrastructure Practices of SAR Remote Sensing

Recent studies highlight the effectiveness of InSAR methods in pavement and infrastructure monitoring. Cascini et al. [16] compared medium- and high-resolution SAR images with PSInSAR method on a high-speed railway and a close by highway section, and concluded that availability of high-resolution SAR images can significantly increase the accuracy of the results and level of detail for detection of deformations. Hoppe et al. [19] used both DS and Temporary Scatterer (TS) approach (a by-product of DS) and found that PSs and DSs are densely populated along highways, railways and infrastructure elements. They also found that both methods are very useful for detection of sinkhole formations, progressive settlements on bridges and dangerous rock slopes [18,19]. In the same study, they evaluated the pavement surface distress with TS raster data and highlighted the possible use of such technique and recommended further exploration as presented in Figure 1.

In another study, Hoppe et al. [20] used InSAR analysis technique for evaluating an ongoing water intrusion problem at both approaches of Monitor-Merrimac Memorial Bridge-Tunnel in Virginia by using 46 medium- and high-resolution SAR images in 10 years time frame, and provided a good example for the use of historical satellite imagery for long-term evaluation. Suanpaga and Yoshikazu [21] predicted the pavement roughness with SAR imagery and found single polarization backscatter values are correlated with the condition of the pavement.

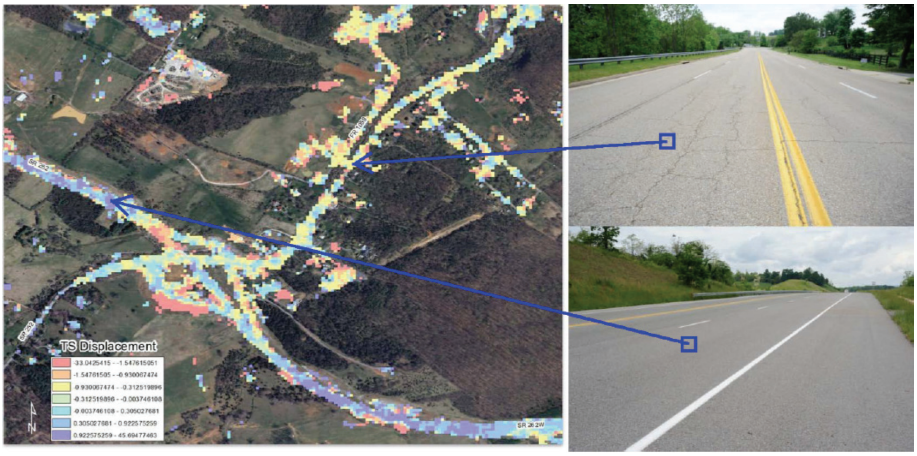

Fig. 1. Pavement surface deformation detection with TS. Source: [19]

One common result in previously mentioned studies is that researchers were not able to identify the type of pavement surface distress or settlement problem without further investigation on site. This is mainly the result of limited research and available methods in the field of transportation and infrastructure monitoring. InSAR has recently gained attention by transportation and infrastructure research community. However, many of these studies did not specifically focused on the detection of pavement deformations but presented the results as a contribution of SAR-based monitoring. Therefore, further research investigating the possible use of SAR-based applications, specifically for pavement monitoring, might reveal more reliable information regarding the use of technology in pavement management.

5. Data Sources and Data Analysis Tools for SAR Imagery

Space agencies and governmental organizations such as ESA, CSA, NASA, and USCS have long been providing and are the main source of satellite imagery. Additionally, some other regional organizations and consortiums such as Alaska Satellite facility (ASF), UNAVCO, and WinSAR might provide raw or processed SAR satellite imagery that could be useful for SAR-based monitoring. Although most high-resolution satellite images are costly, some could be freely available to research community upon proposal submission and approval. Early generation satellites that provide medium-resolution satellite imagery contributes the historical analysis of sites, where currently operating satellites that provide high-resolution SAR imagery could be used for continuous monitoring of pavement and infrastructure elements. Table 1 provides a list of SAR capable satellites for a SAR-based monitoring.

Table 1. Details of satellites for InSAR analysis.

Satellite	Agency- Country	Year of Launch	Band	Resolution (m)	Polarization	Revisit Time (days)
ERS-1	ESA/Europe	1991	C	5, 25	VV	35
ERS-2	ESA/Europe	1995	C	5, 25	VV	35
JERS-1 SAR	NASDA/Japan	1992	L	6, 18	HH	44
ENVISAT-ASAR	ESA	2002	C	10, 30	dual	3
RADARSAT-1	CSA/Canada	1995	C	8, 8	HH	5
RARDASAT-2	CSA/Canada	2007	C	3, 3	quad	24
ALOS-PALSAR	JAXA/Japan	2006	L	5, 10	quad	7
ALOS-PALSAR-2	JAXA/Japan	2013	C	10, 100	quad	14
Cosmo-SkyMed (4)	ASI/Italy	2007	X	1, 1	dual	5
TerraSAR-X	DLR/Germany	2007	X	1, 1	quad	11
TanDEM-X	DLR/Germany	2009	X	1, 1	quad	11
RISAT-1	ISRO/India	2012	C	3, 3	quad	25
HJ-1-C	China	2012	S	5, 20	VV	31
Sentinel-1A	ESA/Europe	2014	C	9, 50	dual	12

There are many open source and commercially developed software packages available for SAR data analysis. Due to broad range of data types and different level of data products, selection of data processing tool requires serious attention specifically for non-experts. It is important to note that this selection is vastly related to the goal of the research and needed outputs as well as the prior knowledge of data analysis personnel. Some code-based SAR data processing applications might provide a simple and quick solution if the objectives and data output needs overlap with what the application offers. Additionally, most open-source and code-based software packages are developed by the researchers who are working in the field of SAR Interferometry and require basic knowledge on compiling and running the program in a suitable environment.

6. Monitoring Seasonal Changes and Urban Growth with SAR Time Series

Initial investigation in this case study evaluated the seasonal changes in the area of interest. Due to excessive cost of high-resolution satellite imagery within limited budget, the research team used freely available historical data sources and data analysis tools. Dataset contains 10 Envisat ASAR images of Rome, Italy and acquired between 2004 and 2010, and processed in Bilko software.

First, radiometric calibration applied to individual SAR images to assign backscattering coefficient to each pixel. SAR imagery is expressed as Digital Numbers in general and converted into backscattering coefficient values, decibel (dB) in most cases. Then, the set of images could be co-registered by selecting master and slave images and using Ground Control Points (GCP) that are clearly identifiable in all images such as buildings, bridges, etc. In the next step, speckle reduction is performed to remove the noise from images, where Lee speckle filtering method is used.

The SAR image stack, then, can be evaluated by using changing backscattering intensity. Considering different surface types provide different backscattering intensity, this analysis could provide comparison of different pixels, or time series analysis of specific pixels. In Figure 2, time series analysis of two different pixels presented where Figure 2a represents a pixel from a vegetated area and 2b represents a pixel from an asphalt pavement. It is clearly visible that the pixel in 2a shows variation over time possibly due to seasonal changes, while asphalt pavement corresponding pixel backscattering is relatively constant except towards the end of the monitoring period, which is possibly caused by pavement defects.

Additionally, urbanization growth is investigated in Leonardo da Vinci International Airport to present the detection of new buildings between 2004 and 2010 in the Area of Interest (AOI) in Figure 3. For this investigation, “blue” has been assigned to pavement, “red” has been assigned to buildings and “green” has been assigned to vegetation/green area. Then, distribution of surface characteristics investigated in the AOI both in 2004 and 2010. Results show that distribution of buildings (red) changed from 29.3% to 57.1% and pavement (blue) increased from 15.1% to 21.4% between 2004 and 2010. Exploration of optical images visually presents the added buildings to the airport facility and increased paved surfaces in the area.

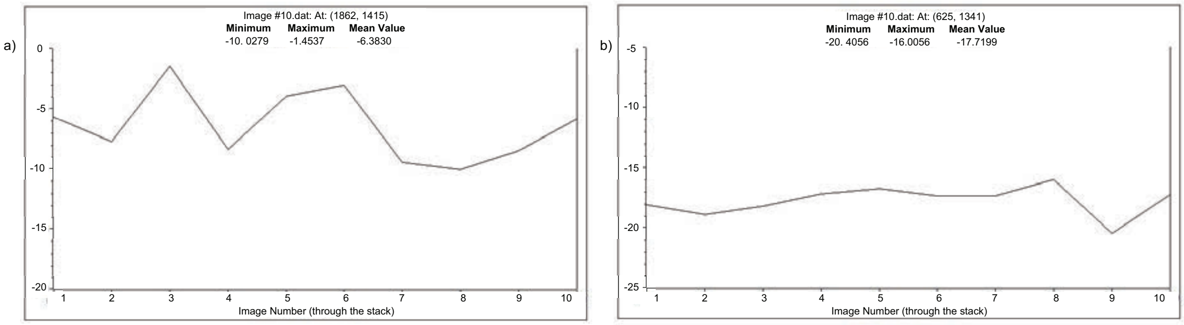

Fig. 2. Time series of a pixel with different variation in backscattered signal intensity (a: vegetation, b: asphalt pavement)

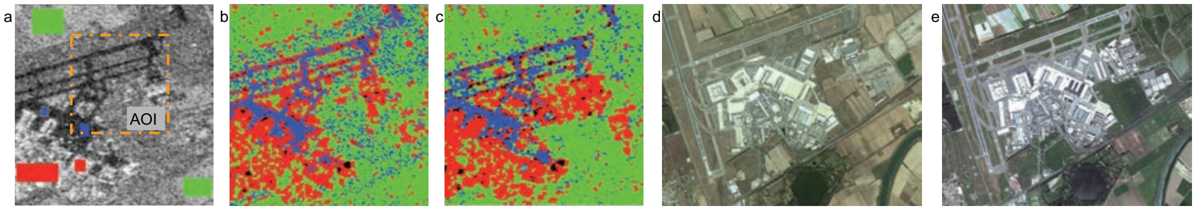

Fig. 3. Urban growth tracking by using surface changes (a: assigning colors to surface characteristics, AOI presented with dashed line; b: 2004 surface distribution; c: 2010 surface distribution; d: October-2004 optical imagery of area; e: April-2011 optical imagery of area)

7. Cost-Benefit Analysis

In many cost-benefit analyses that investigate monetary effects of a possible new technology or method, it is common to evaluate the cost in two parts: capital costs and maintenance/operating costs[22]. Capital costs include one-time expenses such as adaptation of system and associated technical infrastructure, computer and software costs, new personnel, etc. On the other hand, maintenance/operating cost includes ongoing or scheduled expenses during the time where system is in use such as continuous SAR imagery acquisition, data processing cost, etc. It is also considered that there are direct and indirect benefits and costs to both responsible agency such as DOTs and society.

In the case study, applicability of SAR-based monitoring is evaluated for all bridges and federal-aid highways in the New Castle County (NCC) in the State of Delaware to understand the costs and benefits associated with it. It is assumed that SAR-based monitoring will reduce routine vehicle-based monitoring efforts for pavement surface distress monitoring and bridge health monitoring. Although it is difficult to quantify the reduction percentage in conventional methods, it is assumed that even small changes might affect the overall cost of monitoring efforts. In the case study, only direct benefits to agency, which is reduction in routine vehicle-based inspections accounted in calculations as benefits. The cost estimates were developed by calculating rough quantities and applying unit costs. Costs were then translated into per mile or per category costs. All adjusted cost values were normalized to a base year of 2016. Inflation factors were developed based on Producer Price Index for Highway and Street Construction from the 1986–2010 data to convert unit costs from 2016 levels to the build year. 5% discount rate is used with a 20-year time horizon (2016-2035) for the calculation of discounted paybacks and cash flows.

In this study, cost alternatives are investigated based on three options and three resolution levels, and satellite imagery purchasing cost calculated based on Cosmo-SkyMed's SAR price list provided by e-geos[23] as follows:

- Option 1: Purchasing data & in-house data processing
- Option 2: Purchasing data & outsourcing data processing
- Option 3: Outsourcing data collection & data processing

• H: 7x7 km coverage, 1m resolution (per image)	€ 9,450 (new)	€ 4,725 (archive)
• M: 10x10 km coverage, 1m resolution (per image)	€ 6,150 (new)	€ 3,075 (archive)
• L: 40x40 km coverage, 5m resolution (per image)	€ 3,600 (new)	€ 1,800 (archive)

Table 2. Summary of B/C ratio.

			Option 1	Option 2	Option 3
	Size	**Resolution**	**Purchasing data & in-house data processing**	**Purchasing data & outsourcing data processing**	**Outsourcing data collection and data processing**
H	**7x7 km**	1m	0.43	0.39	0.41
M	**10x10 km**	1m	**1.34**	1.24	1.31
L*	**40x40 km**	5m	18.53	23.25	25.76

* Despite the fact that low-resolution (40x40 km, 5m resolution) has highest B/C ratio, it is only useful for detection of sinkhole formations. Low-resolution images cannot be used to clearly identify the distress type in pavement surface).

Investigation of B/C ratios in Table 2 presents that SAR-based monitoring systems could be cost-effective and quickly pays back for 10*10 km and 40*40 km sized products. Considering the spatial resolution and high B/C ratio, purchasing the SAR imagery and in-house processing option would be a good option for SAR-based pavement and infrastructure monitoring. Fig. 4 shows the discounted cash flow in different periods and the estimated discounted payback period. This option pays back in five years considering 20-year time horizon. As shown in Table 3, B/C ratio equals to 1.34, which means that this scenario leads to appealing results for investments.

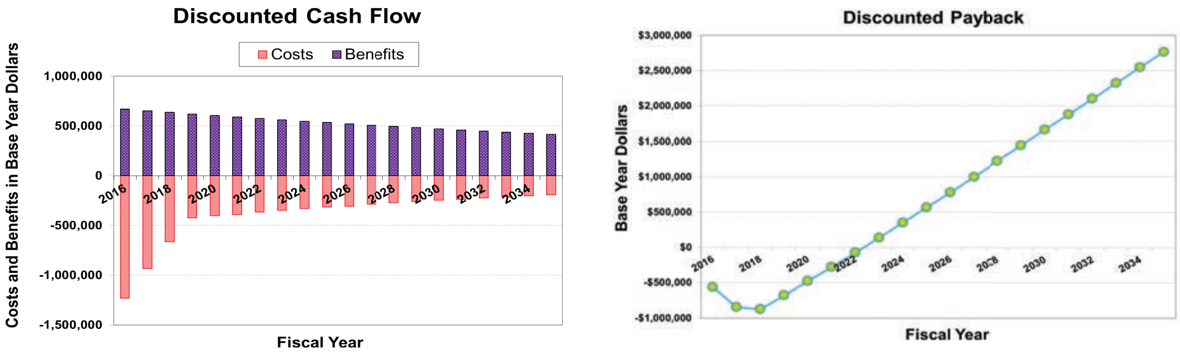

Fig. 4. a. Discounted cash flow (Discount rate=5%); b. Estimated discounted payback period.

Table 3. Benefit and cost components of investments 1M (2016-2035)

Benefit (present value)	**Value ($)**
Reduced costs	16,891,509
TOTAL BENEFIT	16,891,509
Costs (present value)	
Computer and software purchase	40,000
Data storage cost	60,000
Training personnel	200,000
Image purchase	10,205,618
Image processing	0
Total budget costs	10,505,618
Tax-cost factor, 20% of budget costs	2,101,124
TOTAL COST	12,606,741
Benefit/cost ratio	1.34

8. Conclusions

Considering the limitations in economic resources, importance of cost-effective and reliable methods to support the monitoring and management of transportation infrastructure systems cannot be over-emphasized. This research has investigated the possible use and contribution of satellite remote sensing technology, specifically SAR, for pavement and infrastructure monitoring. Recent studies indicated the usefulness of such technology to determine the location and severity of pavement and infrastructure problems at certain level however; they do not yet differentiate the problems among different types. Pavement and infrastructure monitoring related methods are still in its development stage and further research needed.

SAR-based methods are highly effective for detection of surface deformations and determining deformation velocities with millimetric accuracy. This highly sensitive deformation detection ability may specifically be very useful for bridge health monitoring. SAR-based monitoring for pavement and infrastructure management found useful as a complimentary tool to improve the effectiveness of overall monitoring system and reduce the total cost, rather than replacing conventional methods at this point, which may change with the advancement in the technology.

Moreover, this approach will directly contribute to the US DOT strategic goals of "state of good repair" and "economic competitiveness".

Complexity of SAR image types and features require extra attention for evaluating the available and appropriate data sources for pavement and infrastructure monitoring. Besides the data selection, image processing should also be carried out carefully for accurate calculation of deformation and deformation velocities. SAR-based monitoring and data analysis end products might also be very helpful and cost saving for many other departments and agencies in the region. Therefore, cooperation and collaboration within and between departments/agencies will reduce the total cost of monitoring and SAR data analysis efforts while increasing the overall benefits.

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