Joint Pixels InSAR for Health Assessment of Levees in New Orleans

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\textbf{ABSTRACT:} The integrity and reliability of levees, earthen dams and flood-control infrastructure are essential components of homeland safety. The development of a potentially affordable satellite-based interferometric synthetic aperture radar (InSAR) technique for use in a new health assessment framework to monitor, manage and ensure the safety of levees and other systems of flood-control infrastructure is presented in this paper. To estimate the yearly rate of deformation of both the concrete and grass-covered levee structures with sub-wavelength accuracy, a new InSAR technique referred to as joint pixels InSAR (JPInSAR) is proposed. The corresponding results of applying JPInSAR to TerraSAR-X Stripmap data from February 2009 to October 2011 for widespread settlement monitoring in the New Orleans area are presented herein. The presented data processing chain significantly increases the number of pixels where the deformation-rate can be estimated as compared to the number of pixels that can be processed by the classical persistent scatterer technique. Local measurements from GPS and ShapeAccelArrays (SAAs), which were installed in June 2012, will be integrated with the satellite-based InSAR measurements into a global-local network to monitor the response of flood-control levees.

\textbf{INTRODUCTION}

The United States has thousands of miles of levee systems and 43 percent of the U.S. population lives in counties with levees (CHC 2008). The continued functionality of these distributed systems is critical for the millions of people who live behind these structures and the further millions of people that depend on the clean drinking water supplies and hectares of agriculture protected by this flood-control infrastructure. Gradual land subsidence and relatively sudden flood events threaten these systems, and accordingly threaten the population, water supply, and vegetation that are
protected by these systems. Unfortunately, the risk of floods in these areas is steadily increasing as rising sea levels are resulting from climate change. Worse yet, some portions of this network are as old as 150 years (CHC 2008). The integrity and reliability of the flood-control infrastructure are essential components to homeland safety and sustainability of urban cities. However, the earthen dams and levees that comprise the national flood-control infrastructure are aging and its structural health is deteriorating. The American Society of Civil Engineers’ (ASCE) 2009 Report Card for America’s Infrastructure gives the condition of our nation’s dams and levees grades of D (ASCE 2009). The failure of such systems due to natural or man-made hazards, such as hurricanes, floods, earthquakes, deterioration, or terrorist attacks, may have monumental repercussions with dramatic and unanticipated consequences on human life and the country’s economy. The failure of levees during hurricane Katrina and subsequent catastrophic flooding of New Orleans is a highly illustrative example of the consequences of levee failure. Coastal and waterfront communities in the United States and countries worldwide are reinforcing their protective systems by building higher levees and dikes. But in many areas where communities are built immediately behind the system, simply increasing the size of the structure is not a sustainable solution. Presently, most levee health assessments are based on periodic field inspections. A remote sensing-based health assessment of this flood-control infrastructure that can identify weak sections and impending failures can be a key to the sustainability of flood-control systems.

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that offers the capability for recovering topographic profiles and measuring possible displacements of radar targets along the line of sight (LOS). Operating in the microwave domain, high spatial resolution, wide-area measurements can be obtained day or night, in all weather conditions using InSAR. In the past two decades, significant progress has been made in the use of InSAR measurement and monitoring of the deformation in the Earth’s surface including volcanic activity (Tomiyama et al. 2004; Sandwell et al. 2008) seismic-related events (Simons et al. 2002), landslides (Rotta and Naglerb 2006), glacier motion (Rosen et al. 2000) and urban subsidence (Dixon et al. 2006). The first successful InSAR technique applied in detecting various surface deformation is called differential InSAR (DInSAR; Rosen et al. 2000), (Gabriel et al. 1989) that subtracts topographic contribution from the differential phase values of two SAR scenes collected at different times over the same area of interest. However, DInSAR usually suffers from temporal and geometrical decorrelation due to reflectivity changes as well as atmospheric effect due to time-varying tropospheric and ionospheric conditions (Rosen et al. 2000). In order to overcome these DInSAR limitations, recent InSAR techniques including the persistent scatterer SAR interferometry (PSI) (Ferretti et al. 2001; Ferretti et al. 2000), multiple short-baseline (SBAS) technique (Berardino et al. 2002) and differential SAR tomography (D-TomoSAR; Fornaro et al. 2009) under the multi-interferogram (normally, more than 15) framework were developed. By taking advantage of a long time-series of SAR data, PSI allows the identification and exploitation of the stable phase scatterers to minimize the phase dispersions and the consequent loss of coherence. Because these persistent scatterers are unaffected by temporal and geometrical decorrelation, PSI has been proven to be very effective in
monitoring various natural hazards. Compared to traditional DInSAR, the major draw-back of PSI is the possible low spatial density of measurement points due to lack of dominant scatterers in the radar target of interest. In order to mitigate the limits of PSI, the latest time-series InSAR technique referred to as SqueeSAR™ was proposed by Ferretti et al. (2011) to extract deformation from persistent scatterers and statistically homogeneous distributed scatterers (DS).

The preliminary results of the aforementioned techniques seem very promising but have highlighted several challenges for this remote sensing technique to become a long-term solution for the needs of the health assessment framework. For example, grass-covered earthen levees lack the strong reflective surfaces necessary to return radar signals, resulting in poor spatial resolution of ground surface displacements. This is a significant shortcoming since the majority of levees in the US and in the world are grass-covered earthen levees.

SURFACE DISPLACEMENT-RATE MEASUREMENT USING JOINT PIXELS INSAR

Joint Pixel Concept

In order to increase the signal-to-noise ratio (SNR) of DS that cover the grass-covered levee area, a new technique referred to as joint pixels InSAR (JPInSAR) is proposed to retrieve time-series of displacement for health assessment of levees. PSI is a technique that is used to process stable SAR pixels in time dimension while SqueeSAR™ is used to jointly process statistically homogeneous pixels (including PS) in both the time and space dimensions (using the assumption that all of the single look complex images are accurately coregistered). Like SqueeSAR™, JPInSAR is also used to process SAR pixels in the time-space dimension. However, the essence of this technique is based on joint subspace projection (JSP), i.e., the projection of the joint signal subspace onto the corresponding joint noise subspace. JSP as proposed by Li et al. (2006) was successfully applied to image autocoregistration and interferogram estimation in the case of an interferometric image pair. In JPInSAR, JSP is extended to the time-series SAR case.

Given a stack of \(N\) single look complex (SLC) SAR images, the joint data vector \(\mathbf{ux}\) can be formulated using Equation 1,

\[
\mathbf{ux}(m) = \left[\mathbf{x}\left(m - \frac{k_1 \times k_2 - 1}{2}\right)^T,\ldots, \mathbf{x}(m)^T,\ldots, \mathbf{x}\left(m + \frac{k_1 \times k_2 - 1}{2}\right)^T\right]^T
\]

(1)

where superscript \(T\) denotes vector transpose, \(k_1\) and \(k_2\) are the sizes of a window, \(\mathbf{x}(i), i \in [m - \frac{k_1 \times k_2 - 1}{2}, m + \frac{k_1 \times k_2 - 1}{2}]\) is called a complex pixel stack (corresponding to the same ground resolution cell), i.e., \(\mathbf{x}(i) = [x_1(i),\ldots, x_N(i)]\) with \(x_j(i), 1 \leq j \leq N\), denoting the \(j^{th}\) pixel in \(j^{th}\) SLC, and \(\mathbf{x}(m)\) is the desired pixel stack whose phase vector is to be retrieved. An example to formulate the joint data vector with a window of \(3 \times 3\) is shown in Fig. 1. In Fig. 1, the circles represent SAR image pixels, a \(3 \times 3\) window centered at the shaded circle contains 9 pixels in each image and the shaded
circles constitute the desired pixel stack, which implies that the length of the joint pixel vector $\mathbf{u}_x(5)$ is a $9 \times N$.

Let $k' = (k_1 \times k_2 - 1)/2$. According to Lombardini et al. (2003), the joint data vector $\mathbf{u}_x$ can be expressed using equations 2 and 3

$$\mathbf{u}_x(m) = a(\phi_{m-k'}, \ldots, \phi_m, \ldots, \phi_{m+k'}) \odot \mathbf{u}_s(m) + \mathbf{u}_w(m),$$

and

$$a(\phi_{m-k'}, \ldots, \phi_m, \ldots, \phi_{m+k'}) = [a^T(\phi_{m-k'}), \ldots, a^T(\phi_m), \ldots, a^T(\phi_{m+k'})]^T,$$

where $\odot$ denotes the Hadamard product,

$$a(\phi_{m-k'}) = \cdots = a(\phi_m) = \cdots = a(\phi_{m+k'}) = \exp(j\phi_m)$$

with $\phi_m = [0, \vartheta_2, \ldots, \vartheta_N]$, is called the spatial steering vector of the pixel stack $m$, $\mathbf{v}_m$ is the vector of the phase values of the $N$ SAR images to be estimated, $\vartheta_i$ is the phase value of the $i$th SAR image, $\mathbf{u}_s(m)$ is the complex magnitude vector, and $\mathbf{u}_w(m)$ is the additive noise term. Denoting by $\mathbf{u}_a(\phi_m) = a(\phi_{m-k'}, \ldots, \phi_m, \ldots, \phi_{m+k'})$, the corresponding covariance matrix, $C_{\mathbf{u}_x}(m)$, is given by

$$C_{\mathbf{u}_x}(m) = E\{\mathbf{u}_x(m)\mathbf{u}_x^H(m)\} = \mathbf{u}_a(\phi_m)\mathbf{u}_a^H(\phi_m) \odot \mathbf{R}_{\mathbf{u}_w}(m) + \sigma_{\mathbf{u}_w}^2 \mathbf{I}.$$

Based on the concepts of joint pixel vector and the corresponding covariance matrix, an estimation technique used in JPInSAR will be introduced in next subsection.

**FIG. 1.** Formulation of Joint Data Vector with a Window of 3 x 3.

**Joint Subspace Projection**

A key objective in JPInSAR is the estimation of an optimal vector of $N$ phase values, $\phi_m = [0, \vartheta_2, \ldots, \vartheta_N]$, for the desired pixel stack to increase signal-to-noise ratio (SNR). The technique used here is called joint subspace projection (JSP) that was proposed in Li et al. (2006) to estimate the interferometric phase for a SAR pair. JPInSAR extends JSP to the case of time-series SLCs. The principle of JSP is based
on projection of the joint signal subspace onto the corresponding joint noise subspace. The joint signal subspace and the noise subspace are obtained by eigen-decomposition of the estimated joint covariance matrix of all the neighboring pixel stacks with a rectangular window. The joint noise subspace is spanned by the small eigenvectors of $\hat{C}_{ux}(m)$ and the joint signal subspace is spanned by the vectors that are equal to the Hadamard product of the principal eigenvectors of the estimated joint correlation function matrix $\hat{R}_{ux}(m)$ and the joint steering vector. The vector of $N$ phase values is then estimated by projection of the joint signal subspace onto the joint noise subspace and the optimal estimation corresponds to minimization of the projection, that is,

$$\hat{\phi}_m = \arg\min_k \sum_{k=1}^{K} \sum_{l=K+1}^{K+L} \left( u\left(\phi_m\right) \odot \hat{\beta}^{(k)}_{sur} \right)^H \hat{\beta}^{(l)}_{wic} \left( \hat{\beta}^{(l)}_{wic} \right)^H \left( u\left(\phi_m\right) \odot \hat{\beta}^{(k)}_{sur} \right)$$

where $\hat{\beta}^{(k)}_{sur}$, $k = 1, 2, ..., K$, are the principal eigenvectors of $\hat{R}_{ux}(m)$ and $\hat{\beta}^{(l)}_{wic}$, $l = K + 1, K + 2, ..., k_1 \times k_2 \times N$ are the corresponding noise eigenvectors of $\hat{C}_{ux}(m)$.

**Procedure of JPInSAR**

In order to estimate the joint covariance matrix, the samples from the neighboring pixel stacks are required to be independent and identically distributed. In other words, it is necessary to determine which of the surrounding pixels present a similar statistical behavior for each desired pixel prior to JSP. Such a pixel selection problem is usually referred to as a goodness-of-fit testing and four typical methods including the Kullback-Leibler divergence, the Kolmogorov-Smirnov test, the Anderson-Darling test, and the generalized likelihood ratio test were developed and analyzed by Parizzi and Brcic (2011). The following is the procedure of JPInSAR: 1) define an estimation window centered on each desired pixel $m$ and identify the corresponding homogeneous pixels by applying an appropriate goodness-of-fit testing; 2) construct the joint data vector with a certain length for each $m$; 3) apply JSP technique to retrieve an optimal phase vector $\hat{\phi}_m$; 4) update the original SLC SAR data using the estimated $\hat{\phi}_m$; 5) perform classical PSI analysis using the updated SLC SAR data.

**RESULTS**

To validate the effectiveness of JPInSAR applied for health assessment of levees, grass-covered levees at Sites 1 and 2 (subsamples of the 30 km by 50 km images) were selected as testing areas within New Orleans, which are shown in Fig. 2. Twenty-four TerraSAR-X Stripmap descending orbit images of this area were acquired between March 2009 and October 2011. TerraSAR-X is an X-band (9.6 GHz frequency) German Earth observation satellite launched on June 15, 2007 to acquire high-quality and high-resolution (up to 1 meter) SAR images. The data set used is presented in Table 1. All images were resampled and co-registered to the master acquisition, No. 6, and 24 interferograms were obtained. The co-registration
accuracy is on the order of 0.1 pixel. Image No. 6 was used as the master acquisition since its orbit is near the geometric center of the orbital tube spanned by the available SAR acquisitions and its Doppler centroid is close to the average Doppler centroid.

Table 1. TerraSAR-X Acquisition Dates, Time Intervals, and Perpendicular Baselines

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The data set was processed using both the standard PSI approach and the JPInSAR algorithm outlined in the previous section. The temporal coherence maps for the original and updated interferograms using four-looks are shown in Figure 3. Temporal coherence is a phase stability indicator that is used to evaluate whether the pixel is a PS. Compared to Fig. 3(a), the temporal coherence is improved significantly, up to 0.2 improvement, for the grass-covered levee indicated by the red ellipse after phase update. The subsidence-rate for the grass-covered levee using the standard PSI and the new algorithm are shown in Figure 4. Comparing Fig. 4 (a) and (b), it can be seen that the JPInSAR data processing chain significantly increases the number of pixels where the deformation-rate can be accurately estimated as compared to the pixels that can be processed by the classical PSI technique for the grass-covered levee area.

FIG. 2. Grass-covered Levees in New Orleans: (a) Site 1, (b) Site 2 (Source: Google Earth)
In order to better demonstrate the effectiveness of JPInSAR to process data scattered from grass-covered levees, a levee located at Site 2 was also processed and the corresponding results using PSI and JPInSAR are shown in Fig. 5 and Fig. 6, respectively. For the concrete top of levee, PSI is able to provide good estimates of displacement-rate as shown in Fig. 5. Unfortunately, for the two grass-covered sides of levee, the classical PS analysis techniques fail to estimate deformation due to low coherence and low SNR. However, using JPInSAR, deformation is obtained not only from the concrete top but also from two grass-covered sides as shown in Fig. 6. Due to the increase in the density of measurement points, JPInSAR is more suitable to be applied in health assessment.
FUTURE WORK & CONCLUSIONS

In-ground instrumentation (GPS and ShapeAccelArray with Pore Pressure (SAAP)) has just been installed at the London Ave Canal in New Orleans (2012) through the collaboration of Rensselaer and Geocomp Corp. in development of a multi-scale
monitoring and health assessment framework. The site will be monitored as part of future work and more installations will follow. Ultimately, data collected from the in-ground instrumentation will be combined with the surface displacement readings from the satellite-based InSAR analysis. The use of both types of monitoring enables the use of global-local health assessment of the distributed levee system. The combination of modeling and measurements will provide significantly more accurate information about the health state of levees than either modeling or measurements alone.

Application of radar remote sensing techniques to civil infrastructure monitoring is an exciting new research area. Traditional persistent scatterer interferometry is shown to be insufficient for providing dense deformation measurements on grass-covered levees. The use of joint pixels InSAR (JPInSAR) increases the signal-to-noise ratio of distributed scatterers on the levee surface. An increased number of available surface displacement data points are evident in the presented results from analysis of the German Space Agency’s TerraSAR-X imagery. This data must be validated through ground truth measurements, such as GPS measurements.

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