Study of movement and seepage along levees using DINSAR and the airborne UAVSAR instrument

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ABSTRACT

We have studied the utility of high resolution SAR for levee monitoring using UAVSAR data collected along the dikes and levees in California's Sacramento-San Joaquin Delta and along the lower Mississippi River. Our study has focused on detecting and tracking changes that are indicative of potential problem spots, namely deformation of the levees, subsidence along the levee toe, and seepage through the levees, making use of polarimetric and interferometric SAR techniques. Here was present some results of those studies, which show that high resolution, low noise SAR imaging could supplement more traditional ground-based monitoring methods by providing early indicators of seepage and deformation.

Keywords: levee and dike health, synthetic aperture radar (SAR) remote sensing, seepage detection, UAVSAR, Sacramento Delta

1. INTRODUCTION

Remote sensing offers the potential to augment current dike or levee monitoring programs by providing rapid and consistent data collection over large areas irrespective of the ground accessibility of the sites of interest, at repeat intervals that are difficult or costly to maintain with ground-based surveys, and in rapid response to emergency situations. While synthetic aperture radar (SAR) has long been used to measure large-scale subsidence[1], applying this technique directly to levee monitoring is a new endeavor, mainly because it requires both a wide imaging swath and fine spatial resolution to resolve individual levees within the scene, a combination that has not historically been available. Application of SAR remote sensing directly to levee monitoring has only been done in a few pilot studies[2,3]. Here we describe how synthetic aperture radar remote sensing can be used to determine levee conditions, drawing from the results of two levee studies we have undertaken, one of the levees in the Sacramento-San Joaquin Delta, California, USA, and another that imaged levees along the lower Mississippi River during the Spring 2011 floods. The studies seek to develop new techniques that employ SAR polarimetry (POLSAR) and differential interferometry (DINSAR) to successfully assess levee health through the quantitative measurement of deformation on and near levees and through detection of areas experiencing seepage.

Both studies use data acquired with NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), which has the spatial resolution needed for this application (1.7 m single-look), sufficiently wide imaging swath (22 km), and the longer wavelength (L-band, 0.238 m) required to maintain phase coherence between repeat collections over levees, an essential requirement for applying DInSAR techniques to a time series of repeated collections for levee deformation measurement. For example, because land in the Sacramento-San Joaquin Delta is primarily used for agriculture, temporal decorrelation is a major problem for DInSAR studies of the area, with temporal decorrelation more severe for shorter wavelength radars. Unlike the L-band UAVSAR, today's operational satellite-based imaging radars that have resolutions in the one to ten meter range, namely TerraSAR-X and COSMO-Skymed, operate in the X-band, where frequent repeat cycles or sparse point analysis are needed to derive subsidence rates from the rapidly decorrelating scenes. Although asphalt surfaces along levees crowns and toes in urban areas can maintain coherence for long times, extended levee systems typically include earthen levees, infrequently paved, located in agricultural and riverine settings, and often with vegetation growing along the embankments.

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2. LEVEE STUDIES USING UAVSAR

2.1 Sacramento-San Joaquin Delta, California, USA

The Sacramento-San Joaquin Delta, located to the east of San Francisco Bay, is the primary water source for the state of California and represents a complex geographical area comprised of tidal marshland, levee rimmed islands that are used primarily for agriculture, and urban communities built on the flood plain. The Delta currently contains more than 60 unflooded reclaimed islands and tracts within a 2800 km^2 area. Since the islands' formation in the 1800s, subsidence has decreased the land elevation to as much as 8 meters below mean sea level, currently requiring nearly 1700 km of levees to maintain the integrity of the islands and flow of water through the Delta.[4] The current average subsidence rates for each island varies, with 1.23 cm/yr on Sherman Island in the western Delta and 2.2 cm/yr for Bacon Island in the central Delta, as determined by ground-based instruments located at isolated points in the Delta.[5] The Delta's status as the most critical water resource for the state, an endangered ecosystem, and an area continuously threatened with levee breakage from hydrostatic pressure and the danger of earthquakes on several major faults in the San Francisco area make it a focus of efforts by both the state and national government.[6] This activity is now almost entirely done by ground-based efforts undertaken by a mix of private, state, and federal personnel, with the result that levee monitoring, maintenance, and repair are implemented using a wide variety of methods of different efficacy.

Since July 2009 we have collected UAVSAR data over California's Sacramento - San Joaquin Delta near monthly to evaluate the suitability of high resolution L-band DInSAR for measuring changes on and near earthen levees and to collect a comprehensive historical repeat-pass data set for estimating subsidence rates on a spatial scale small enough to resolve localized subsidence within individual islands. Nine flight lines are collected to image all levees in the Delta from at least three near-orthogonal directions (Figure 1), which is needed to detect movement along the levee embankments irrespective of the levee orientation. This project is studying the potential of SAR DINSAR for consistent monitoring of Delta levees with widescale spatial and frequent temporal coverage.

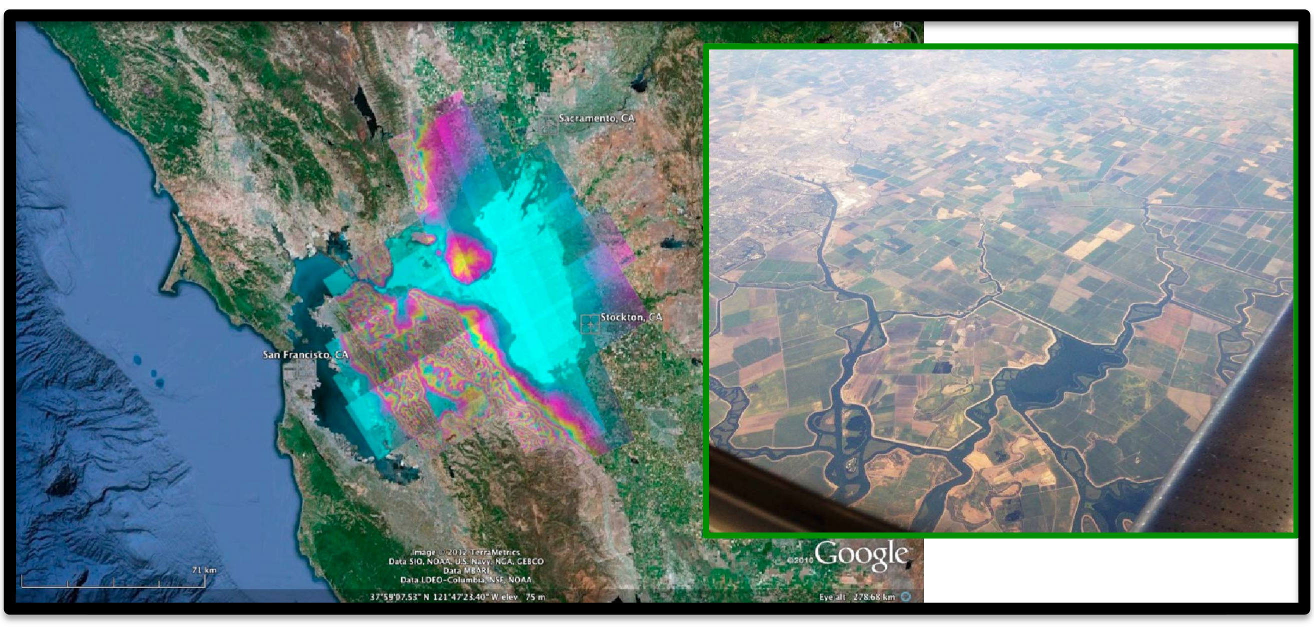

Figure 1. (Left) Overlay in Google Earth of the terrain digital elevation model (DEM) along the nine UAVSAR flight lines that cover the Sacramento-San Joaquin Delta. (Inset right) Photo of the central Delta (foreground) looking eastward, taken from the UAVSAR G-3 platform. (photo credit C. E. Jones)

The UAVSAR data are acquired in quad-polarization mode from an altitude of 13.5 km. For our study, we use products that are multilooked by a factor of 3 (12) in the slant-range (along-track or "azimuth") direction, which reduces the speckle noise in the images while maintaining a sufficiently high resolution (~7 m) to well resolve the levees. Differential interferograms constructed from the HH-polarization returns (transmit and receive horizontally polarized radiation) are typically used, although some analysis of the polarization-dependent difference between the interferograms formed with different polarizations has been made.

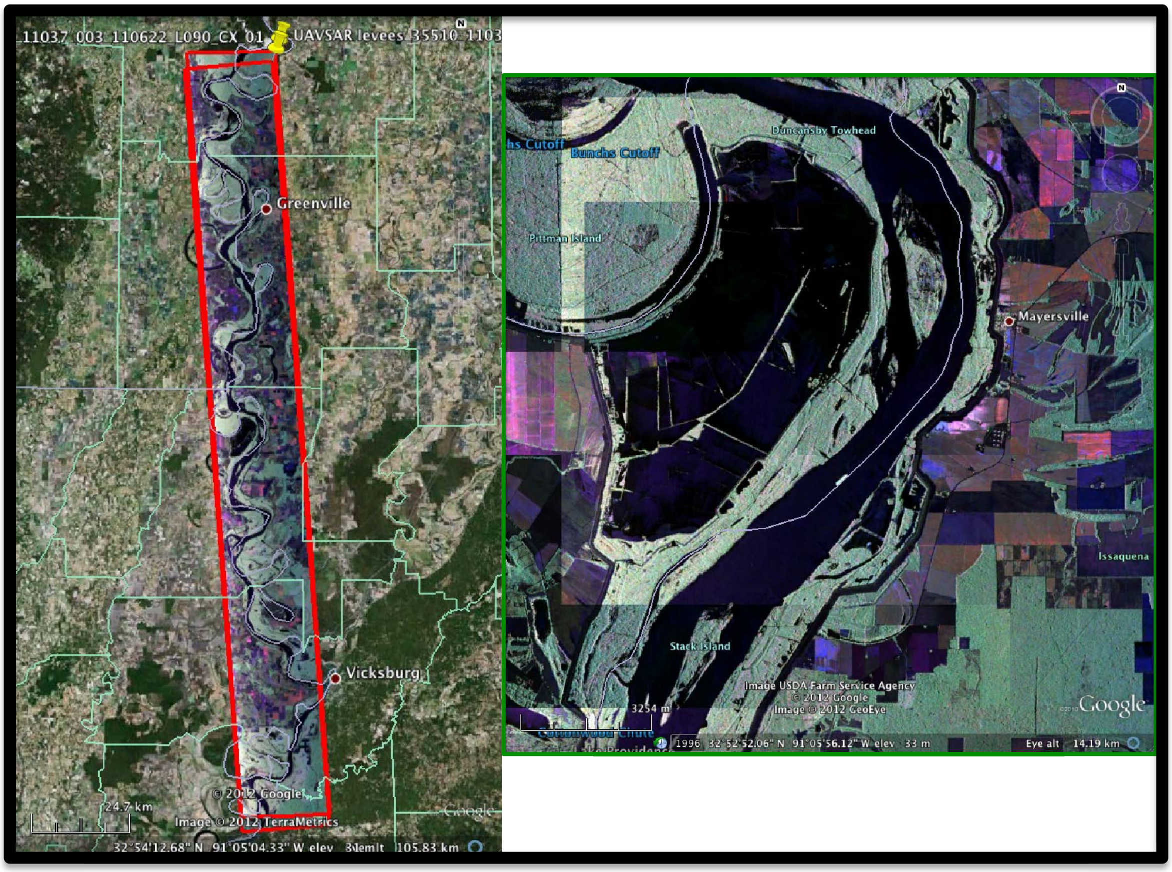

Figure 2. (Left) Overlay in Google Earth of the UAVSAR flight line acquired along the lower Mississippi River during the record-breaking floods of Spring 2011. (Inset right) Zoomed multi-polarization image of the Mississippi River near Mayersville, MS, and an area where agricultural fields were flooded following a levee break (red = HH, blue = VV, green = HV).

2.2 Lower Mississippi River, USA

In the spring of 2011, snow melt originating in Minnesota and Wisconsin combined with run-off from heavy precipitation across Arkansas, Missouri, and the Ohio River Valley to produce record water levels in the lower Mississippi River. During this time, UAVSAR was deployed to collect data along the section of the river between Mississippi and northern Louisiana/southern Arkansas, in the area around Greenville and Vicksburg, Mississippi. The data were collected in June 2011, at a time when this section of the river was still in flood stage. Figure 2 shows the flight line we have used for this study and the multi-polarization false color image zoomed to an area flooded by a levee break. For the study reported here, we used the data acquired on 6/7/2011. Both of the flight lines used were repeats of acquisitions made earlier and we used the June 16, 2009 acquisitions for baseline, non-flood condition data to which the June 2011 data could be compared.

Because of the long temporal baseline and rapid decorrelation in this wet, vegetated, and cultivated area, we cannot use DINSAR techniques to look for levee deformation under the increased hydrostatic pressure with these data sets. Instead, we focused on applying simple algorithms to identify areas with increased soil moisture between June 2009 and June 2011 to determine whether we could identify quickly and accurately areas with significant levee seepage and or piping through sand boils. In this case, we could validate our results using the known locations of relief wells along this section of the Mississippi River to determine the accuracy and limitations in identification of seepage through the levees.

As for the Sacramento-San Joaquin study, the UAVSAR data was acquired in quad-polarization mode from an altitude of 13.5 km. In this case, because of the sustained high water conditions, seeps through the levees extended a significant distance into the fields adjacent to the levees, usually many tens of meters. Therefore, the fine spatial resolution of UAVSAR was not critical to project success. However, radar returns from water are very low, so the low noise floor of the UAVSAR instrument[7] was an important factor in discriminating deeper ponded water from saturated soil.

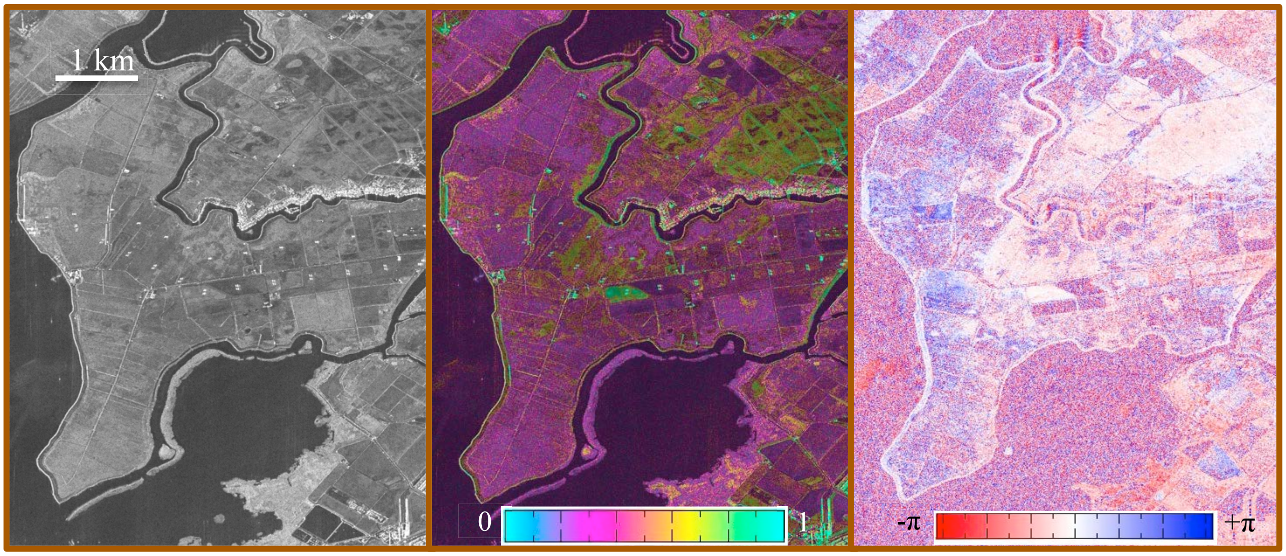

Figure 3. (Left) HH-polarization amplitude image of Jersey Island, in the western part of the Sacramento-San Joaquin Delta; (Center) Overlay of amplitude and interferometric coherence formed from images collected on 10-Aug-2010 and 25-Sep-2010 (46 day temporal baseline). The levees along the island boundaries generally maintain coherence in the month-to-month interferograms even when fields within the islands decorrelate; (Right) Interferometric phase, with blue corresponding to relative subsidence and red to relative uplift. In this image the phase is normalized so that the major power lines footings (bright features at regular linear spacing in amplitude image), which extend deep underground, are near zero.

3. TEMPORAL DECORRELATION

Because the land in the Sacramento-San Joaquin Delta is owned by many different people, the levees' conditions vary greatly across the region, for example, some are bare earth while others have vegetation grown on them, possibly including large trees, and even in some cases with buildings placed directly on the levees. Furthermore, different maintenance procedures are followed on each island, leading to different amounts and causes of decorrelation on and in the vicinity of the levees. This challenges quantitative assessments that rely on repeat pass SAR remote sensing but also provides the opportunity to test the robustness of different methods for detecting change along levees within a fairly small geographical region.

The land in the Delta is primarily used for agriculture so temporal decorrelation is potentially a major problem for DInSAR studies of the area. We find that the levees do not usually decorrelate at L-band over the 1-month repeat interval, particularly along the crown. This is seen in Figure 3 which shows the amplitude, interferometric coherence, and interferometric phase of a repeat-pass interferogram formed from images over Jersey Island in the western Delta collected on 8/10/2010 and 9/25/2010, a 46-day temporal baseline, which is near the longest separation between the flights that we've had. We observe total loss of coherence in fields that are in active use, but see sufficient coherence to make deformation estimates for most levees from at least one of the flight lines imaging the location and along many roads and some land areas within the islands. The interferometric phase shows our sensitivity to variations in subsidence within the island, although these are preliminary, uncalibrated results so we do not have a quantitative measurement of the subsidence rates yet. Figure 4 shows the interferometric coherence over islands in the western Delta, where current subsidence rates are highest, for 30-, 65-, and 100-day temporal baselines, all relative to an initial track collected on 29-Aug-2011. The figure shows the loss of coherence as the interval between flights increases. Within the islands, decorrelation is severe for the 3-month interval, but at L-band the phase coherence is still maintained along some of the levees. We find that even for 1-year temporal baselines coherence is often maintained along the levees for acquisitions during the summer months when there is little rainfall in the area.

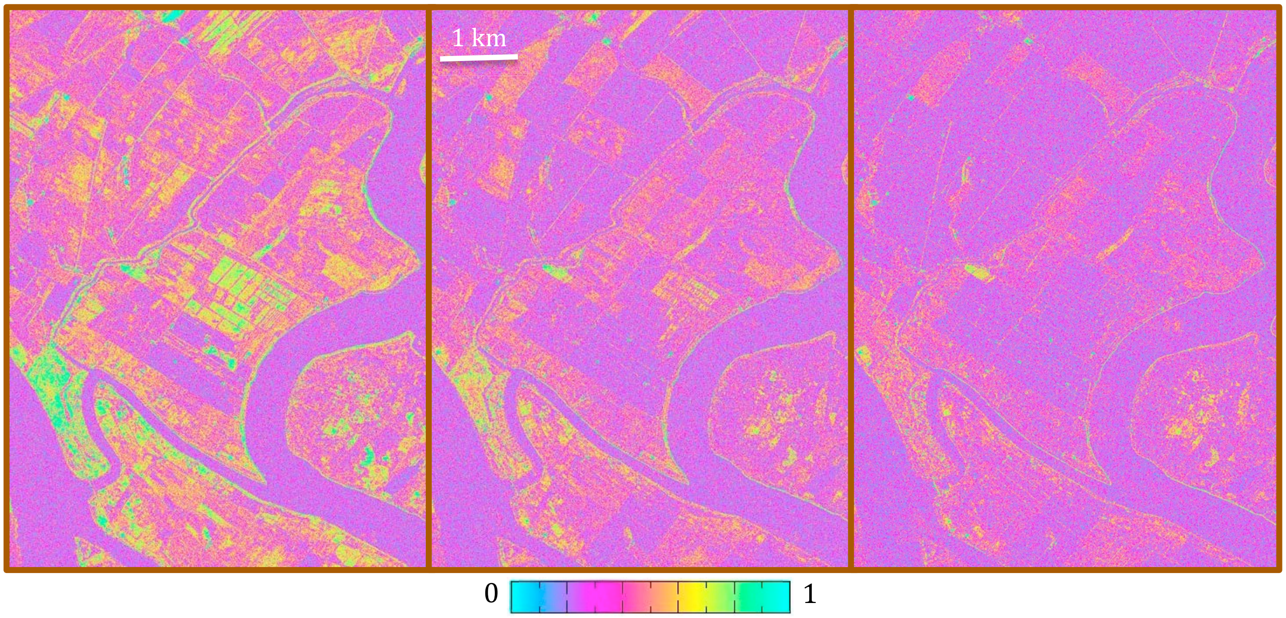

Figure 4. Interferometric coherence of islands in the western Sacramento-San Joaquin Delta for different temporal baselines, formed relative to an initial track collected on 29-Aug-2011: (left) 35 days; (center) 65 days; (right) 100 days.

4. CHANGE DETECTION ALONG LEVEES

4.1 DINSAR

Differential interferometry uses coherent processing of radar signals collected over the same scene at two different times to derive surface deformation from the change in the relative phase of the two returns. In this way, deformation along the line-of-sight on the scale of a fraction of the radar wavelength can be resolved as long as the phase coherence between the signals is maintained, i.e., where there are no disruptions to the target between the two collections. In most scenes there are targets that maintain coherence even when the general scene does not, so sparse point algorithms can be used to estimate the deformation using the coherent points or weighting the measurements by the coherence. At this point, we have not completed that type of analysis of the Sacramento-San Joaquin Delta data. However, we have observed several instances of surface deformation on levees or in the area along the levee toe that is detectible in the 1-month interferograms and, in some cases, interferograms of much longer temporal baseline. An example of this is shown in Figures 5 and 6. Figure 5 shows an interferogram of Bradford Island, formed from data collected on 17-July-2009 and 8-Sept-2009. In the time between the two collections, a barge rammed the levee on the north side of the island causing substantial cracks to open in the levee and requiring extensive repair (see photos, Figure 5). The impact point is clearly seen in the 1-month timescale image, which captured the pre-image to post-repair levee change. Figure 6 shows a 1-year interferogram spanning the time between 17-July-2009 and 12-July-2010 for which coherence is maintained along this section of the levee. In this case, deformation is observed to extend all along the repaired section, a process that is expected as the new fill material settles.

Figure 5. Map formed from an overlay of the signal amplitude, interferometric phase, and interferometric coherence showing the location when the Bradford Island levee was damage by ship impact in August 2009. Photos to the right show the levee before and after repair (photo credit J. Dudas).

Figure 6. (left) Google Earth map image of the north Bradford Island levees and (right) interferometric phase from a 1-year temporal baseline interferogram formed from data collected in July 2009 and 2010 along the stretch of levee shown in Figure 5.

4.2 POLSAR

Because of the sustained high water levels along the lower Mississippi River in May and June 2011, by the time of the UAVSAR deployment on 7-June-2011 significant amounts of water had seeped through the levees. We find that areas with significant water coming under or through the levees are visible in the UAVSAR data as areas of anomalously bright VV return. The left image in Figure 7, which is a multi-polarization composite (HH in red, VV in blue, and HV in green), shows an area where relief wells facilitate water flow below the levees; the relief wells are just visible as bright red dots along the levee toe. Similar features are seen throughout the line, with an example of these seeps in locations where there are no relief wells shown on the right in Figure 7. We are examining different algorithms for detecting soil moisture with SAR to automate identification of seepage locations for emergency response. We note that these seeps are so prominent in the image because of the size and duration of the flood, so further study would be needed to see if this could identify nascent seeps. Also, the ground conditions at the time of the UAVSAR acquisition were generally dry in the area because there had not been rain recently. Soil moisture from recent precipitation would interfere with this method of identifying seeps.

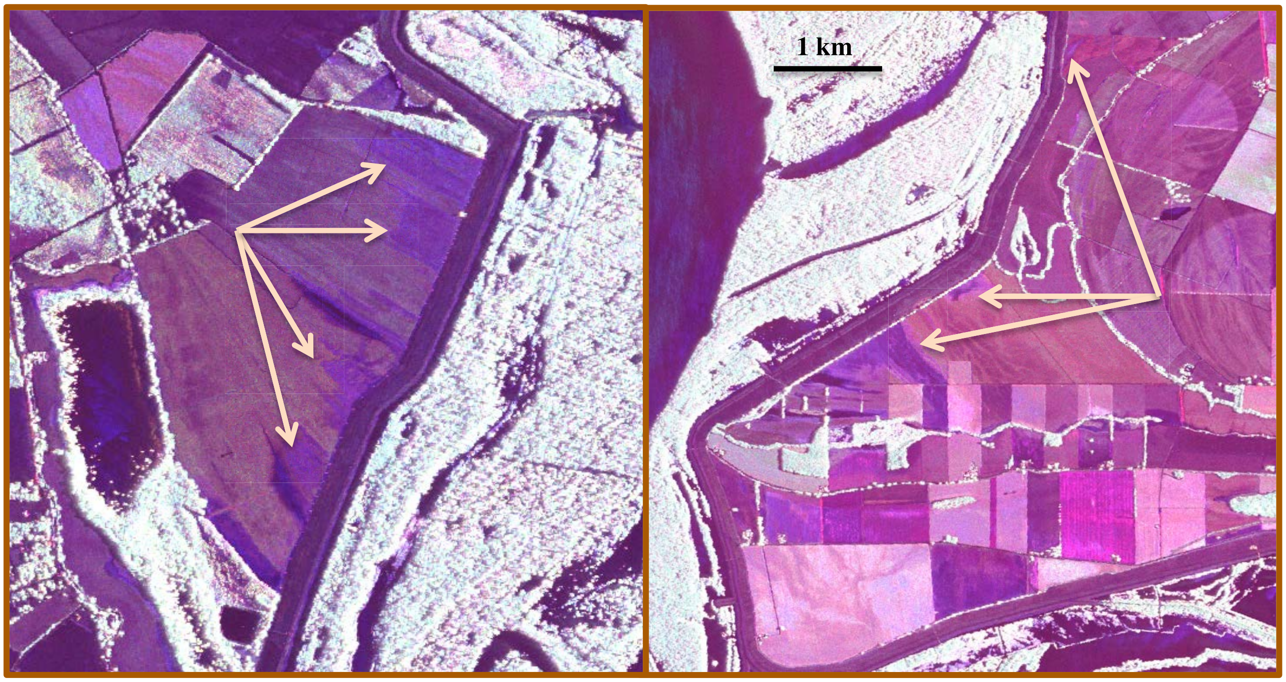

Figure 7. Multi-polarization images of areas along the lower Mississippi River acquired with UAVSAR in June 2011 during the historic high water event of that year. (left) Area where relief wells along the base of the levee allow water to pass under the levee. Saturated soil is seen as anomalously bright in the VV returns. (right) Similar features seen in a different area where there are no relief wells, indicating unregulated seepage through the levee. (red = HH, blue = VV, green = HV)

5. CONCLUSIONS

Through our study using differential interferometry and L-band UAVSAR data to detect changes along levees in the Sacramento-San Joaquin Delta, we find that the levees and much of the land within the islands do not usually decorrelate over the 1-month repeat interval and that we can successfully measure consistent deformation along the levee crown and toe in areas of recent repair. Analysis of the POLSAR UAVSAR data collected along the lower Mississippi River show promising results for detecting levee seepage using multi-polarization, single pass SAR. Analysis of the data from both of these studies is continuing, with the focus on deriving products usable by levee engineers and emergency responders to identify at-risk sections and prioritize repairs and mitigation measures. This type of levee health status information acquired with radar remote sensing could provide a cost-effective method to significantly improve the spatial and temporal coverage of levee systems and inform targeted levee maintenance, repair, and emergency response in the future. Our results show, for example, that during an emergency, when time is of the essence, SAR remote sensing offers the potential of rapidly providing levee status information that is effectively impossible to obtain over large areas using conventional monitoring, e.g., through high precision measurements of subcentimeter-scale levee movement prior to failure and identification of high seepage areas.

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