Wetland InSAR: A new space-based hydrological monitoring tool of wetlands surface water level changes

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ABSTRACT

Wetland Interferometric Synthetic Aperture Radar (InSAR) is a relatively new application of the InSAR technique, which detects water level changes in aquatic environments with emergent vegetation. It provides high spatial resolution hydrological observations of wetland and floodplains that cannot be obtained by any terrestrial-based method. However, InSAR observations are relative both in space and time and, hence, depend on terrestrial (stage) observations for calibration and validation. In this study we explore which SAR data type is most suitable for the wetland application, as well as explore the usage of InSAR for detecting water level changes in various wetland environments around the world. Our analyses indicate that longer wavelength SAR systems (L-band), horizontal (HH) polarization of the radar pulse, and short repeat orbits provide best results. Wetland InSAR applications include high spatial resolution water level monitoring, detection of flow patterns and flow discontinuities, and constraining high resolution flow models.

1 INTRODUCTION

Wetlands are transition zones where the flow of water, nutrient cycling, and the sun's energy meet to produce a unique and very productive ecosystem. They provide critical habitat for a wide variety of plant and animal species, including the larval stages of many ocean fish. Wetlands also have a valuable economical importance, as they filter nutrients and pollutants from fresh water used by humans and provide aquatic habitats for outdoor recreation, tourism, and fishing. Globally, many such regions are under severe environmental stress, mainly from urban development, pollution, and rising sea level. However, there is increasing recognition of the importance of these habitats, and mitigation and restoration activities have begun in a few regions. A key element in wetlands conservation, management, and restoration involves monitoring its hydrologic system, as the entire ecosystem depends on its water supply. Heretofore, hydrologic monitoring of wetlands are conducted by stage (water level) stations, which provide good temporal resolution, but suffer from poor spatial resolution, as stage stations are typically distributed several, or even tens of kilometers, from one another. Wetland InSAR provides the needed high spatial resolution hydrological observations, complementing the high temporal resolution terrestrial observations. Recent studies showed that InSAR observation can provide high resolution maps of water level changes in floodplains and wetland environments. Alsdorf et al. [1] were the first to use this method to study water-level variation in the Amazon floodplain. Wdowinski et al. [2] applied a similar method to detect water level changes in the Everglades, south Florida. Their study shows that InSAR observations can capture dynamic water level topography, providing the first three-dimensional regional-scale picture of wetland sheet flow. Lu et al. [3] applied the same technique to wooded wetlands in Louisiana demonstrating that the method works with various SAR data types.

In this study we explore the usage of InSAR for detecting water level changes in various wetland environments around the world, including the Everglades (south Florida), Louisiana Coast (southern US), Chesapeake Bay (eastern US), Pantanal (Brazil), Okavango Delta (Botswana), and Lena Delta (Siberia). Our main study area is the Everglades wetland (south Florida), which is covered by probably the densest stage network in the world (more than 200 stations), located 5-10 km from one another. The stage data is very important in evaluating the uncertainty of the InSAR observations. Stage data also allow us to tie the relative InSAR observations (water level changes) to absolute reference frame and to produce high spatial-resolution (10-100 m resolution) maps of absolute water levels. We also examine the various applications of wetland InSAR, which provides direct observations of flow patterns and flow discontinuities and serve as excellent constraints for high resolution flow models.

2 INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)

Space-based Synthetic Aperture Radar (SAR) is a very reliable technique for monitoring changes of both the solid and aquatic surfaces of the Earth. SAR measures two independent observables, backscatter amplitude and phase, over a wide swath (50-400 km) with pixel resolution of 10-100 m depending on the satellite acquisition parameters. Backscatter amplitude, which is often presented as gray-scale images of the surface (Figure 1a), is very sensitive to the surface dielectric

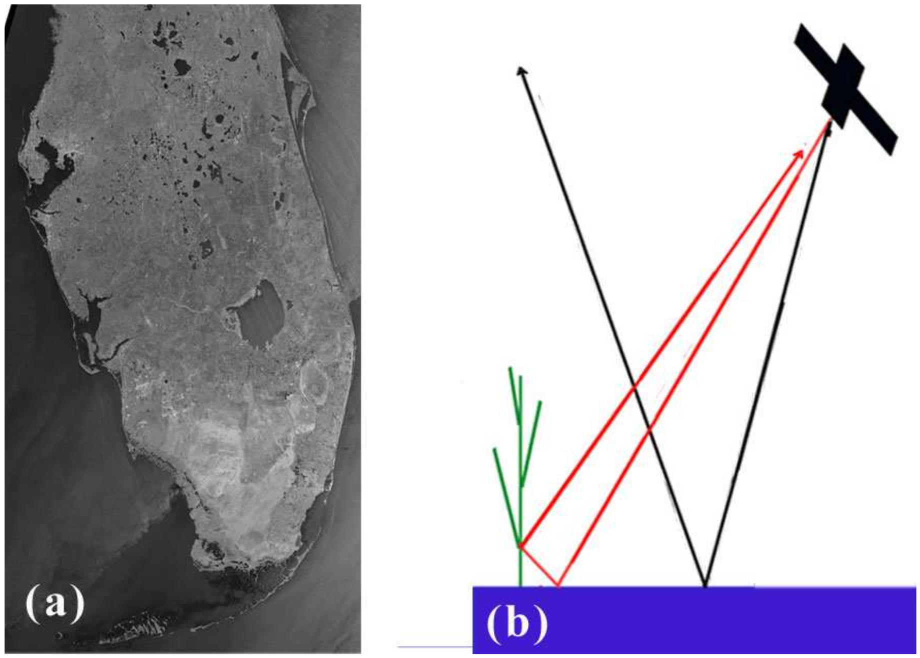

Figure 1. *(a) RADARSAT-1 ScanSAR image of Florida showing location of study area (RADARSAT data © Canadian Space Agency / Agence spatiale canadienne 2002. Processed by CSTARS and distributed by RADARSAT International). (b) Cartoon illustrating the double-bounce radar signal return in vegetated aquatic environments. The red ray bounces twice and returns to the satellite, whereas the black ray bounces once and scattered away.*

properties, surface inclination towards the satellite, and wave direction in oceans. Amplitude images are widely used for studying surface classification, soil moisture content, ocean waves, and many other applications. The second observable, backscatter phase, measures the fraction of the radar wavelength that returns to the satellite's antenna. It is mainly sensitive to the range between the surface and the satellite, but also to atmospheric conditions and changes in the surface dielectric properties. Phase data are mainly used in interferometric calculations (InSAR) for detecting cm-level displacements of the surface (Figure 2). The method compares pixel-by-pixel SAR phase observations of the same area acquired at different times from roughly the same location in space to produce high spatial-resolution displacement maps. Such maps, termed interferograms, are widely used in studies of earthquake induced crustal deformation, magmatic activity (volcanos), water-table fluctuations, and glacier movements.

Space-borne SAR data have been acquired since the 1970's by several satellites using various systems and acquisition parameters. The first civilian space-based SAR system was NASA's SEASAT, which operated an L-band (24 cm wavelength) system for less than 2 years. The satellite focused on ocean observations and didn't have sufficient repeat orbit data for interferometric calculations. Another L-band satellite is the Japanese Earth Resources Satellite (JERS-1), which operated during the years 1992-1998. Archived JERS-1 data are very useful source for wetland InSAR. In January 2006 the Japanese space agency (JAXA) launched a new L-band SAR satellite, ALOS, which is currently in a validation/calibration period. ALOS data will provide useful current data for wetland InSAR. Most SAR data, however, have been acquired by four C-band (5.6 cm wavelength) satellites ERS-1, ERS-2, ENVISAT, and RADARSAT-1. The first three satellites were launched and operated by the European Space Agency, whereas the fourth one by the Canadian Space agency. Another important acquisition parameter is the radar polarization, which can be horizontal, vertical, or both. The JERS-1 and RADARSAT-1 operate an HH system (sending and receiving horizontal pulses), ERS-1 and ERS-2 operated VV systems, ENVISAT can acquire data in either HH or VV, and the new ALOS satellite is capable of acquiring HH, VV, and quadruple observations.

Wetland InSAR is a relatively new application of the InSAR technique that detects water level changes in aquatic environments with emergent vegetation. Although conventional wisdom suggests that interferometry does not work in vegetated areas, several studies have shown that both L- and C-band interferograms with short acquisition intervals (1-105 days) can maintain excellent coherence over wetlands

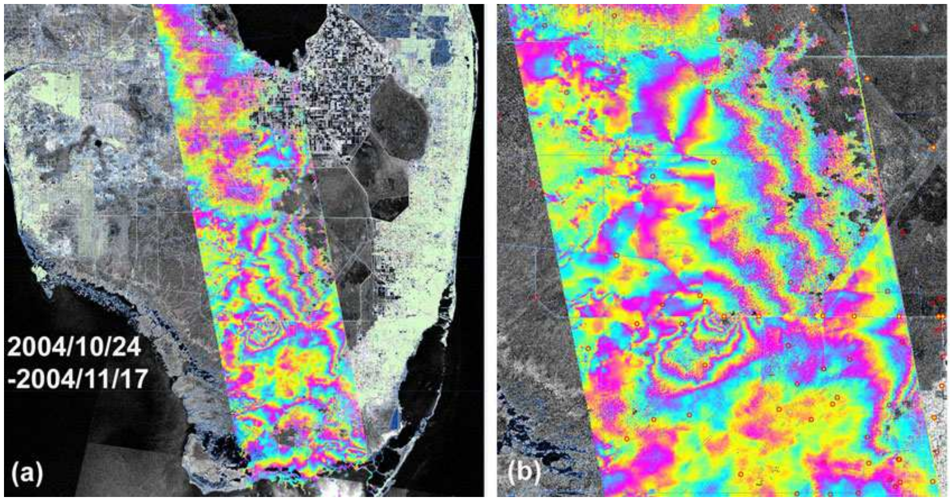

Figure 2. *(a) RADARSAT-1 interferogram of central south Florid (2004/10/24-2004/11/17), overlying a Landsat ETM band8 and vectors maps showing the geographic location of the data. The interferogram shows backscatter phase changes between the two RADARSAT-1 Synthetic Aperture Radar (SAR) acquisitions. The observed phase changes measure cm-level changes in the wetland surface water level. (b) Enlarged section of the same interferogram showing phase discontinuities mainly along man-made structures (roads, levies) indicating uneven water level changes across the structures. Red circles mark the location of stage (water level) stations in the study area.*

[1, 2, 3, 4, 5] (Figure 2). Interferometric coherence is a measurement of how much the complex phase signal of two SAR images is coherent; it reflects a quality measure of an interferogram. In specific cases of wooded wetlands, coherence can be maintained over several years. The method works, because the radar pulse is backscattered twice ("double-bounce" [6]), from the water surface and vegetation (Figure 1b). Interferometric phase is maintained over both woody and herbaceous vegetations, suggesting that double-bounce is the dominant backscatter mechanism in both wetland environments.

3 INTERFEROMETRIC COHERENCE ANALYSIS OF WETLANDS

In order to evaluate which data type and acquisition parameters are most suitable for wetland application of InSAR , we ordered, acquired and processed a variety of data collected by the ERS-1/2, JERS-1, RADARSAT-1, and ENVISAT satellites. Our main study area is the Everglades wetland because (1) it contains various wetlands types (woody - cypress, herbaceous - sawgrass, saltwater mangrove, graminoid, and mixed shrubs), (2) it contains both natural and managed flow areas, and (3) it is hydrologically monitored by a dense network of stage (water level) stations. The most robust method for evaluating the quality of the InSAR observation is calculating coherence maps for the study area and comparing the coherence values of the various data types. As coherence strongly depends on the vegetation type, we subdivided the study area into five wetland vegetation types (Figure 3).

Our results indicate that woody wetlands like cypress and mixed shrubs marsh have better coherence than herbaceous wetlands like sawgrass and cattail in all satellite systems. JERS InSAR pairs as much as 3 years apart still maintained adequate coherence in wetlands, especially in woody wetlands, while ERS-1/2 required short temporal baselines (<70-day) to maintain coherence in herbaceous wetland. The backscatter from JERS-1 and RADARSAT-1 is closely linked with coherence in four wetland vegetations (sawgrass, cypress, mixed shrubs and mangrove), but ERS backscatters has no relation to coherence except sawgrass marsh. Our study also clearly indicates that HH polarization with high resolution and small incidence angle is more suitable to wetland InSAR application in terms of decorrelation.

4 InSAR studies of various worldwide wetland environments

As part of our evaluation study of the wetland InSAR technique, we analyzed SAR data from various wetland environments around the world. This part of the study includes usage of some archived data, but mostly of current acquired data. Because most SAR and InSAR applications do not require short time span between observations, most archived data has a sparse temporal coverage of wetland regions. However, ordering

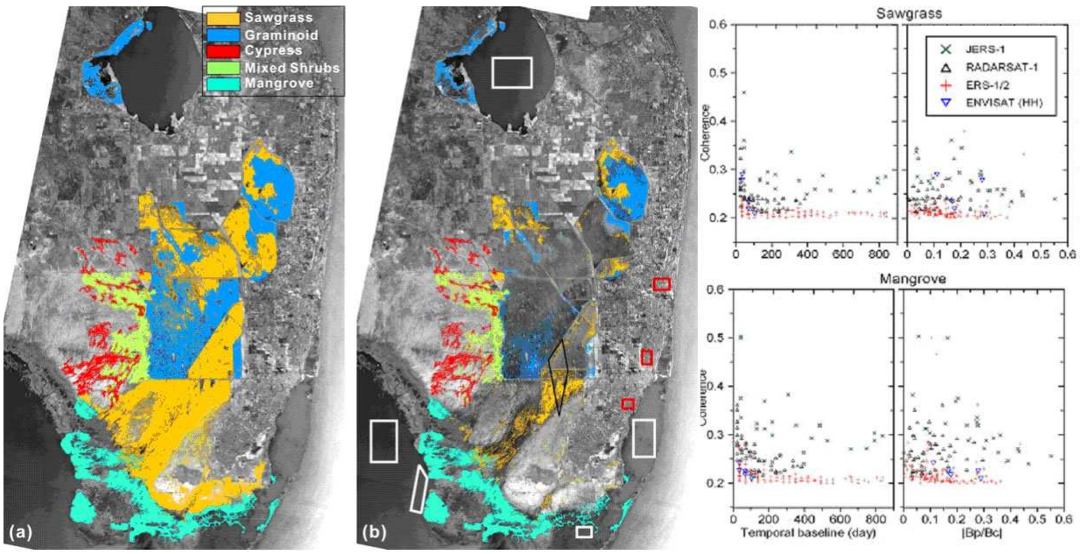

Figure 3. *Characteristic wetland environments in the Everglades superimposed on ERS multi-reflectivity SAR image. (a) Selected five wetland types based on 1999 land cover map distributed from SFWMD (South Florida Water Management District) and NLCD 2001 land cover map. (b) Five typical marshes with low backscattering variation selected for statistic analysis of coherence and backscatter using ERS-1/2, JERS-1 and RADARSAT backscatter variation map. White polygons and red polygons indicate open water surface and urban area, respectively. Backscatter and coherence is used to estimate background noisy coherence and evaluate radar backscatter calibration accuracy. Black polygon represents sawgrass marsh covered by all of four different RARARSAT observations. (c) Comparison between the coherence obtained with the JERS-1, RADARSAT, ERS, and ENVISAT SAR dataf as a function of time interval between acquisitions and baseline normalized by the critical baseline of each SAR system.*

current data enables us to request data of every repeat cycle, which is most suitable for wetland InSAR.

We chose to test the InSAR wetland applicability in seven wetland regions, five included in the Ramsar convention signed in 1971, and two additional interesting wetlands regions in Siberia and Mauritania (Figure 4a). The test regions include the Everglades (south Florida), Louisiana Coast (southern US), Chesapeake Bay (eastern US), Pantanal (Brazil), Okavango Delta (Botswana), Mâle (Mauritania), and Lena Delta (Siberia). Our study reveals various success levels of wetland InSAR. The analysis of ENVISAT VV data from the Okavango Delta (Figures 4b) and Pantanal shows that most of the wetland area does not maintain phase over a single repeat orbit (35 days). Nevertheless, several fringes where identified in both wetlands (Figure 4c). L-band observations generally produce good results and can maintain phase over a single repeat orbit (44 days) or even several cycles. We analyzed JERS-1 data from the Everglades, Louisiana, Lena Delta, and Okavango Delta. In the first three areas, phase was maintained throughout the wetland areas, as can be seen in Figures 4d and 4e. The limited archived JERS-1 data from Okavango with 18-20 month span between observations produced partially good results, where most of the vegetated area is decorrolated; however, some patches of coherent interferometric phase were still maintained over this long time span between acquisitions. Our analyses of various data types revealed that RADARSAT-1 observations are very suitable for wetland InSAR (Section 3). So far, we obtained and analyzed data from the Everglades (Figure 2) and the Louisiana Coast (Figure 4f). We are now in a process of obtaining RADARSAT-1 data from other wetlands in Africa (Okavango and Mâle), the Bahamas, and other wetland regions. We also were approved to acquire SAR data with the next generation of satellites (ALOS, RADARSAT-2, and TerraSAR-X) over several important wetland regions worldwide.

5 Wetland InSAR Applications

Wetland InSAR observations provide high special resolution maps of water level changes of the dynamic wetland environment. Because InSAR observations are relative in both space and time, it is important to tie the space-based observations with ground observations of water level (stage monitoring). In the Everglades, there is a dense stage monitoring network, which allows us to calibrate and validate the InSAR observations and tie them to an absolute reference frame.

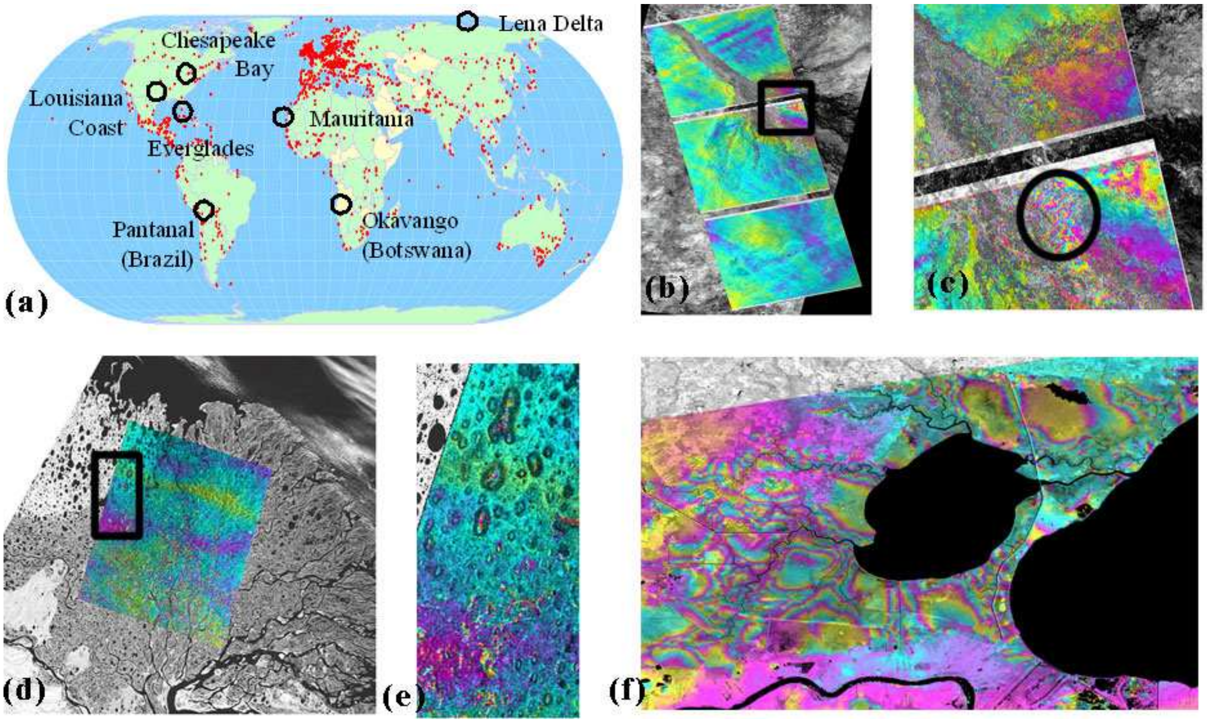

Figure 4. *(a) Map of the global distribution of the 1469 Ramsar wetlands sites (red dots) and the seven wetlands used for our InSAR detection study (black circles). (source) (b) ENVISAT interferogram (VV polarization) of the Okavango delta showing good coherence in the arid area and mostly decorrelation in the vegetated area. (c) Close of vegetated area in (b) where some fringes are detected. (d) JERS-1 interferogram (HH) of the Lena Delta showing good coherence of the wetland area, but with limited phase changes. The long-wavelength variations are most likely atmospheric effect. (e) Close up of the marked area in (d) showing some phase variations in several islands. (f) RADARSAT-1 interferogram (HH) of wetlands in Louisiana showing phase changes due to water level changes.*

Our calibration studies suggest an accuracy level of 5-10 cm [2, 4]. The man-made structures in the Everglades create many flow discontinuities, which require such dense network for accurate and reliable monitoring. However, in natural undisruptive wetland area, such as in the Everglades National Park in the southern part of the Everglades eco-system, the flow is continuous and can be monitored by a less dense network. Thus, sparsely distributed stage stations in natural wetland areas may be sufficient for calibrating the InSAR observations. In remote wetland areas, where no stage monitoring exists, one can use altimetry data for InSAR calibration, as used by Alsdorf et al. [7]. However, altimeter observations are also characterized by low temporal resolution, which may acquire at a different time than the SAR acquisitions. Nevertheless, altimeter observations will be useful for calibration, if no other accurate measurement can be obtained.

One very useful and important observation can be derived directly from the raw interferogram, without the need of stage data for calibration. The high resolution wetland interferograms provide direct observations of flow patterns and flow discontinuities, as shown in the figure 2b. As water level and water level changes tend to be different across barriers, these differences will be shown in the interferogram as phase discontinuities. This observation is important for wetland restoration efforts that aim to restore a managed or degraded wetland, such as the Everglades, to its natural undisturbed condition.

Another very important application of wetland InSAR is constraining high resolution flow models, which are important tools for wetland management and restoration. This application also does not require stage calibration, as the model results are converted into the interferogram phase domain, as shown in Figure 5. The stage data are typically used as boundary conditions of the flow model. We conducted such preliminary study by comparing the InSAR observations with the the TIME model (Tides and Inflows in the Marshes of the Everglades), which was developed by US Geological Survey and University of Miami. Our study indicates that the models predict well longer wavelength water levels, which are constrained by the stage data, but miss many of the shorter wavelength features (figure 5).

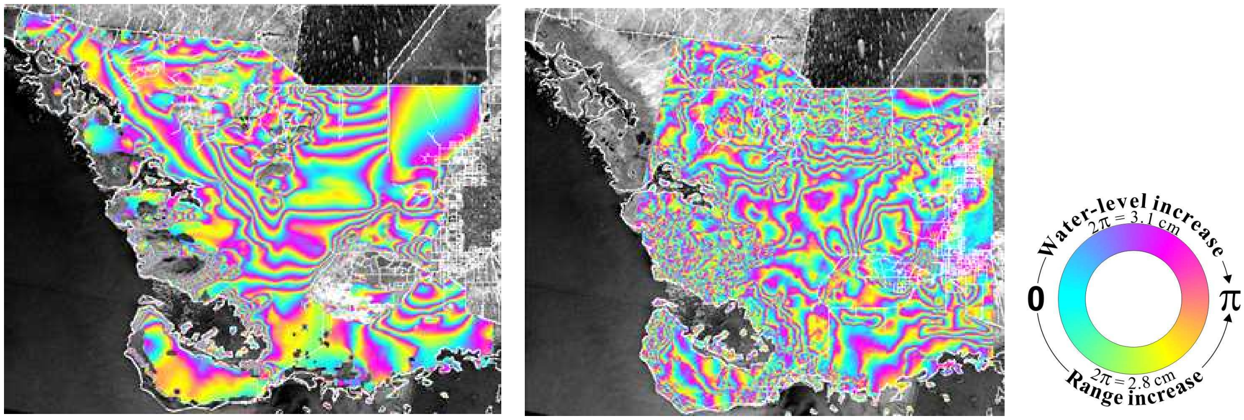

Figure 5. *Comparison between synthetic (TIME model) and observed (InSAR) interferograms describing water level changes occurring between the two RADARSAT-1 acquisition dates on 1997/07/13 and 1997/08/06. The comparison shows similarities in the orientation and shape of the longer wavelength fringes, but many differences in the shorter wavelength features.*

6 CONCLUSIONS

The new wetland application if the InSAR technique provides high spatial resolution observations of surface water level changes in aquatic environments with emergent vegetation, such as wetlands and floodplains. The technique works because of the “double-bounce” effect, in which the radar pulse is backscattered twice, from the water surface and the vegetation. Interferometric coherence analysis of various SAR data types indicates that longer wavelength (L-band), short repeat orbits, HH polarization, high acquisition resolution and small incidence angle are more suitable to wetland InSAR application in terms of decorrelation. Best results have been obtained with the L-band JERS-1 data and fine beam (7 meter resolution) C-band RADARSAT-1 data with 24 days repeat orbits. Analysis of SAR data from seven wetland environments around the world reveals various success levels. In all seven wetlands we found some areas with coherent phase, but also areas with decorrelated signal. Best results were obtained with JERS-1 and RADARSAT-1 data. Wetland InSAR applications include high spatial resolution water level monitoring, detection of flow patterns and flow discontinuities, and constraining high resolution flow models.

Acknowledgements. We acknowledge the support and collaboration of the Department of the Interior, U.S. Geological Survey and the Florida Water Resources Research Center, University of Florida, under Grant No. 04HQGR0160, as well as, for NASA and ONR. We also thank JAXA, ESA, CSA, NASA and ASF for access to the various SAR data.

7 REFERNCES

1. Alsdorf D. E. et al. Interferometric radar measurements of water level changes on the Amazon flood plain. Nature, 404, 174-177, 2000.
2. Wdowinski, S., F. Amelung, F. Miralles-Wilhelm, T. Dixon, and R. Carande, Space-based measurements of sheet-flow characteristics in the Everglades wetland, Florida, Geophys. Res. Lett., 31, L15503, 10.1029/2004GL020383, 2004a.
3. Lu, Z., M. Crane, O.I. Kwoun, C. Wells, C. Swarzenski, and R. Rykhus, “C-band radar observes water level change in swamp forests,” EOS, vol.86(14), 2005.
4. Wdowinski, S., F. Amelung, T. Dixon, F. Miralles-Wilhelm, and R. Sonenshein, Space-based detection of surface water level changes in South Florida, submitted to Remote Sensing for Environment, 2006.
5. Kim, S., S. Wdowinski, F. Amelung, and T. Dixon, C-Band Interferometric SAR Measurements of Water Level Change in the Wetlands: Examples from Florida and Louisiana, IGARSS meeting proceedings, 2005.
6. Richards, L. A., P. W. Woodgate, and A. K. Skidmore. An explanation of enhanced radar backscattering from flooded forests, Inter. J. Remote Sensing, 8, 1093, 1987.
7. Alsdorf, D., Birkett, C., Dunne, T., Melack, J. & Hess, L., (2001). Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry. Geophysical Research Letters, 28(14): 2671-2674.