Eos, Vol. 86, No. 14, 5 April 2005

C-band Radar Observes Water Level Change in Swamp Forests

PAGES 141, 144

C-band radar pulses backscatter from the upper canopy of swamp forests, and consequently interferometric synthetic aperture radar (InSAR) analysis of C-band imagery has not been exploited to study water level changes in swamp forests. This article explores C-band ERS-1 (European Remote Sensing Satellite) and ERS-2 InSAR data over swamp forests composed of moderately dense trees with a medium-low canopy closure in southeastern Louisiana to measure water level changes beneath tree cover.

Wetlands cover more than 4% of the Earth's land surface and interact with hydrologic, biogeochemical, and sediment transport processes that are fundamental in understanding ecological and climatic changes [*Alsdorf et al.*, 2003; *Prigent et al.*, 2001; *Melack and Forsberg*, 2000; *Dunne et al.*, 1998]. Measurement of water level changes in wetlands, and consequently of changes in water storage capacity, provides a required input for hydrologic models, and is required to comprehensively assess flood hazards [e.g., *Coe*, 1998].

Inaccurate knowledge of floodplain storage capacity in wetlands can lead to significant errors in hydrologic simulation and modeling. In situ measurement of water levels in wetlands is cost prohibitive, and insufficient coverage of gauge stations results in poorly constrained estimates of the water storage capacity of wetlands.

Recent applications of interferometric synthetic aperture radar (SAR) to image both land surface topography and subtle changes in its surface elevation have made substantial contributions to our understanding of natural events such as volcanic eruptions and earthquake faulting [*Massonnet and Feigl*, 1998; *Rosen et al.*, 2000]. However, InSAR has generally been considered an inappropriate tool for studying water level changes of open water.

As an imaging radar, SAR transmits radar pulses at oblique look angles, causing most of the radar energy over open water to be reflected away from the radar sensor, and resulting in little energy being returned back to the SAR receiver. This explains why open-water surfaces generally appear dark in SAR imagery. When an open water surface is rough and turbulent, part of the radar energy can be scattered back to the sensor; however, the SAR signals lose coherence (a parameter quantifying the degree of changes in backscattering characteristics) over open water if two radar images are acquired at different times.

Over flooded vegetation, longer-wavelength, L-band radar pulses (24-cm wavelength) typically follow a double-bounce path—bouncing off of the water surface and trunks of vegetation—enabling part of the transmitted radar energy to return to the sensor [*Richards et al.*, 1987; *Hess et al.*, 1995; *Wang et al.*, 1995]. This explains why inundated vegetation appears bright in SAR imagery.

Alsdorf et al. [2000, 2001], who discovered that interferometric analysis of L-band SAR imagery can yield centimeter-scale measurements of water level changes throughout inundated floodplain vegetation, confirmed that scattering elements for L-band radar consist primarily of the water surface and vegetation trunks. Their finding relies on a common understanding: Flooded forests permit double-bounce returns for L-band radar pulses, thus allowing InSAR coherence to be maintained for monitoring changes in the height of the water surface.

The shorter-wavelength radar, such as C-band (wavelength of 5.7 cm), backscatters from the upper canopy of swamp forests rather than the underlying water surface, and a double-bounce travel path from that band can only occur over short aquatic plants and small shrubs [*Richards et al.*, 1987; *Beaudoin et al.*, 1994; *Hess et al.*, 1995; *Wang et al.*, 1995]. As a consequence, C-band radar images have not been exploited to study water level changes beneath swamp forests.

In this article, C-band InSAR data in swamp forests are used to demonstrate the feasibility of measuring changes in water level beneath tree cover. If C-band radar can maintain coherence in swamp forests, it will measure water level changes at a higher accuracy than L-band radar due to the difference in radar wavelength.

InSAR Analysis

Using C-band SAR images from European ERS-1 and ERS-2 satellites, it was unexpectedly discovered that the InSAR images maintained adequate coherence to allow for useful phase change measurements over swamp forests in southeastern Louisiana.

The land cover images (Figures 1a and 1b) indicate the study area consists of two primary land cover classes: sugar cane fields occurring throughout the northeastern portion of the image and swamp forests elsewhere. The swamp forests are composed of moderately dense trees ranging from 10 to 25 m in height with a medium-low canopy closure (i.e., 20–50% tree cover) (Figure 1c).

The 70-day interferogram (the phase difference between two SAR images) (Figure 2a) was generated from two C-band SAR images acquired on 5 January and 16 March 1997 during the dormant season when the majority of tree species were in the leaf-off condition. Interferograms acquired during the leaf-on season (about May-October) have lower coherence than those obtained during the leaf-off season. A full cycle of colors (called a fringe), ranging from red, yellow, green, and blue, to purple, represents a 2.8-cm change in the distance from the satellite to the ground or a 3.1-cm vertical displacement.

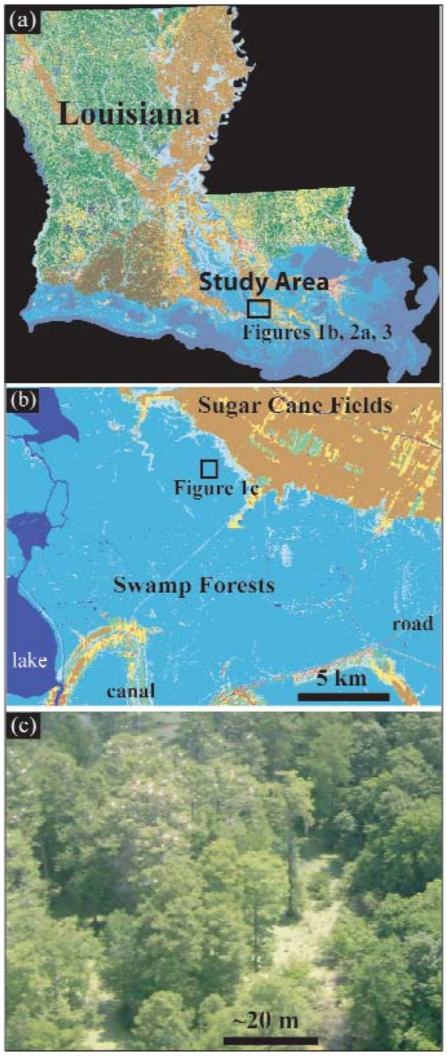

Fig. 1. (a) Map of Louisiana and location of swamp forests in this study. (b) Land cover map of the study area from the U.S. Geological Survey National Land Cover Database (http://landcover.usgs.gov). (c) An oblique aerial photo showing the swamp forests. The tree size is about 20 m, and aquatic vegetation atop water is visible between trees.

Maintaining coherence over the swamp forests indicates that the majority of the returned C-band SAR signal must be from the interaction with tree trunks and the water surface beneath. If the scattering elements came primarily from the top of the forest canopy, it is unlikely the SAR signal would be coherent over the 70-day separation [*Zebker and Villasenor*, 1992; *Hagberg et al.*, 1995], because leaves and small branches composing the forest canopy change due to weather conditions.

The observed fringes exhibit control by structures such as levees, canals, and roads, and therefore are not likely due to changes in atmosphere (water vapor) or vegetation conditions. The authors conclude that the observed fringes are caused by changes in water level

---

By Z. Lu, M. Crane, O.-I. Kwoun, C. Wells, C. Swarzenski, and R. Rykhus

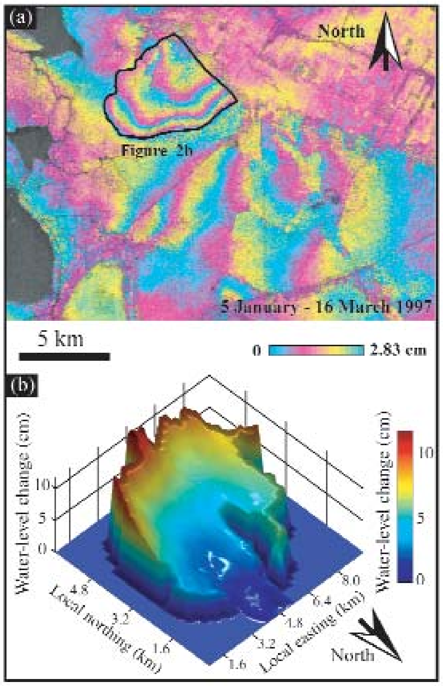

Fig. 2. (a) C-band (wavelength of 5.7 cm) interferogram showing water level changes over swamp forests between 5 January and 16 March 1997. The interferogram was produced from radar images from the European ERS-2 satellite. The interferometric phase image is draped over the radar intensity image. Each fringe (full color cycle) represents a 2.8-cm change in range distance or a 3.1-cm change in water level. (b) A three-dimensional perspective view of water level changes. The approximate coverage of Figure 2b is outlined in Figure 2a.

between the two observation dates. The SAR images used in this study have VV polarization (i.e., vertically transmitted and vertically received signal). Because SAR signals with HH polarization (horizontal transmission and horizontal reception) penetrate vegetation more than VV polarized signals, the authors speculate that HH-polarization SAR images such as RADARSAT-1 may be better suited to detect water level changes beneath tree cover.

Another remarkable observation is that the water level changes are not homogeneous (Figure 2b). For example, the water level change varies by more than 10 cm over a distance of less than 10 km (Figure 2b). Such heterogeneity in water level change reflects local differences in flood depth and topographic constrictions.

Flooding throughout this area is primarily controlled by sheet flow after the rivers and bayous leave their banks. Under ideal circumstances, water should flow placidly and smoothly over a symmetrically smooth surface devoid of obstructions. However, the topography of the study area is dissected by roads, canals, and other man-made structures, and swamp forests are the dominant land cover. Thus, the sheet flow should not be symmetric throughout the study area. It would not be a smooth, even surface of constant elevation from one edge of the swamp to the other (Figure 2b). Instead, there should be bulges and depressions in the water surface due to topographic constrictions in sheet flow.

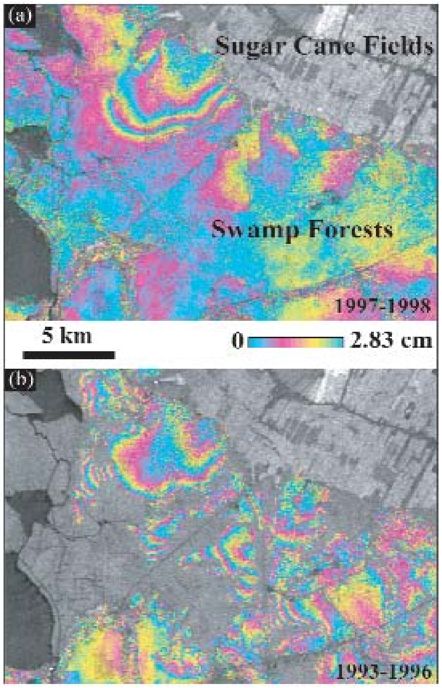

Fig. 3. C-band ERS-1 and ERS-2 interferograms over swamp forests spanning (a) one year, from 5 January 1997 to 25 January 1998, and (b) three years, from 7 January 1993 to 20 January 1996. The interferometric phase image is draped over the radar intensity image. Each fringe (full color cycle) represents a 2.8-cm change in range distance or a 3.1-cm change in water level. Areas that lack interferometric coherence are uncolored.

Heterogeneous changes in water level such as these make it impossible to accurately characterize water storage capacity based on measurements from a network of sparsely distributed gauging stations.

The generation of interferograms with time separations of one and three years provided another unexpected discovery (Figure 3). The resultant InSAR images over the swamp forests maintained full coherence over one year (Figure 3a) and partial coherence over three years (Figure 3b). As anticipated, interferometric coherence was lost over the sugar cane fields. However, the coherence of C-band radar images for as much as three years over swamp forests characterized by a medium-low canopy closure was surprising.

Scientific Advances

Using C-band ERS-1 and ERS-2 SAR images, it is shown that InSAR images maintained adequate coherence over swamp forests composed of moderately dense trees over a time window of a few months. The results of this research are important because they demonstrate that (1) moderately dense swamp forests with a medium-low canopy closure permit double-bounce returns for C-band radar, and (2) C-band InSAR images can measure water level change beneath moderately dense tree cover at a greater vertical accuracy. For InSAR to become an effective tool for monitoring dynamic water level changes beneath wetlands, a SAR system with shorter imaging repeat times is required. InSAR imagery will then be capable of characterizing the temporal evolution of water level changes to improve hydrological modeling predictions and enhance the assessment of future flood events over wetlands.

Acknowledgments

ERS-1/ERS-2 SAR images are copyright 1993, 1997, and 1998 European Space Agency (ESA), and were provided by the Eurimage and ESA. This research was supported by funding from the U.S. Geological Survey (USGS) Director Venture Capital Fund, USGS Eastern Region Venture Capital Fund, USGS Land Remote Sensing Program, NASA Solid Earth and Natural Hazards Program (SENH-0000-0229), and USGS contract O3CRCN0001. Comments and suggestions by C. K. Shum, D. Alsdorf, G. Senay, and B. Wylie are greatly appreciated.

References

Alsdorf, D., J. Melack, T. Dunne, L. Mertes, L. Hess, and L. Smith (2000), Interferometric radar measurements of water level changes on the Amazon floodplain, *Nature, 404*, 174–177.

Alsdorf, D., C. Birkett, T. Dunne, J. Melack, and L. Hess (2001), Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry, *Geophys. Res. Lett., 28*(14), 2671–2674.

Alsdorf, D., et al. (2003), The need for global, satellite-based observations of terrestrial surface waters, *Eos Trans. AGU, 84*(20), 269, 275–276.

Beaudoin, X., et al. (1994), Retrieval of forest biomass from SAR data, *Int. J. Remote Sens., 15*(14), 2777–2796.

Coe, M. (1998), A linked global model of terrestrial hydrologic processes: Simulation of modern rivers, lakes, and wetlands, *J. Geophys. Res., 103*, 8885–8899.

Dunne, T., L. Mertes, R. Meade, J. Richey, and B. Forsberg (1998), Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil, *GSA Bull., 110*, 450–467.

Hagberg, J., L. Ulander, and J. Askne (1995), Repeat-pass SAR interferometry over forested terrain, *IEEE Trans. Geosci. Remote Sens., 33*, 331–340.

Hess, L., J. Melack, S. Filoso, and Y. Wang (1995), Delineation of inundated area and vegetation along the Amazon floodplain with SIR-C synthetic aperture radar, *IEEE Trans. Geosci. Remote Sens., 33*, 896–904.

Massonnet, D., and K. Feigl (1998), Radar interferometry and its application to changes in the Earth's surface, *Rev. Geophys., 36*(4), 441–500.

Melack, J., and B. Forsberg (2000), Biogeochemistry of Amazon floodplain lakes and associated wetlands, in *The Biogeochemistry of the Amazon Basin and Its Role in a Changing World*, edited by M. McClain et al., Oxford Univ. Press, New York.

Prigent, C., E. Matthews, F. Aires, and W. Rossow (2001), Remote sensing of global wetland dynamics with multiple satellite data sets, *Geophys. Res. Lett., 28*(24), 4631–4634.

Richards, J., P. Woodgate, and A. Skidmore (1987), An explanation of enhanced radar backscattering from flooded forests, *Int. J. Remote Sens., 8*, 1093– 1100.

Rosen, P., S. Hensley, I. R. Joughin, F. K. Li, S. N. Madsen, E. Rodriguez, and R. M. Goldstein (2000), Synthetic aperture radar interferometry, *Proc. IEEE, 88*, 333–380.

Wang, Y., L. Hess, S. Filoso, and J. Melack (1995), Understanding the radar backscattering from flooded and nonflooded Amazon forests: Results from canopy backscatter modeling, *Remote Sens. Environ., 54*, 324–332.

Zebker, H., and J. Villasenor (1992), Decorrelation in interferometric radar echoes, *IEEE Trans. Geosci. Remote Sens., 30*, 950–959.

Author Information

Zhong Lu, Science Applications International Corporation, U.S. Geological Survey National Center for Earth Resources Observation and Science, Sioux Falls, S.D.; Mike Crane, U.S. Geological Survey National Center for Earth Resources Observation and Science, Sioux Falls, S.D.; Oh-Ig Kwoun, Science Applications International Corporation, U.S. Geological Survey National Center for Earth Resources Observation and Science, Sioux Falls, S.D.; Chris Wells, National Wetlands Research Center, U.S. Geological Survey, Lafayette, La.; Chris Swarzenski, Water Resources District Office, U.S. Geological Survey, Baton Rouge, La.; and Russ Rykhus, Science Applications International Corporation, U.S. Geological Survey National Center for Earth Resources Observation and Science, Sioux Falls, S.D.

For additional information, contact Z. Lu; E-mail: lu@usgs.gov.