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Water Level Changes in a Large Amazon Lake Measured with Spaceborne Radar Interferometry and Altimetry

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Abstract. We demonstrate that interferometric processing of JERS-1 SAR data over an Amazon lake containing ~1500 islands yields centimeter-scale changes in the height of the water surface from February 14 to March 30, 1997. For the method to work, we qualitatively find that inundation of about one or two leafless trees per 25 m^2 multi-look SAR pixel is sufficient to return the radar pulse to the side-looking antenna. Validation is provided by multi-temporal TOPEX-POSEIDON altimetry profiles, which directly measure surface heights relative to a fixed datum. Because SAR provides an image, the water height changes (~12 cm) can be converted to a net volume measurement (280 million m^3) over the 44 days separating the JERS-1 acquisitions. Compared to historical gauge records, removal of this volume from the lake required a ~50% greater flow.

Introduction

Storage within and outflow from large surface water bodies, including wetlands, constitute important components of water balances in river basins. Unfortunately, the costs associated with installing and maintaining numerous stage recording devices throughout a basin, especially in remote regions, is prohibitive. To alleviate this limitation, hydrologists seek methods of remotely measuring components of discharge including water surface elevation, inundation area, and flow velocity. One method uses image-based observations to measure the area of inundation, which is then regressed against measurements of discharge at downstream gauging stations (see references in *Smith* [1997]). However, surface area-discharge relationships do not work well in environments where small changes in water heights yield little change in surface area yet significant changes in discharge. An intriguing new contribution uses ground penetrating radar to define the channel cross-section and pulsed doppler radar to measure surface velocity: combined, the observations yield discharge [*Costa et al.*, 2000]. However, this local approach lacks the broad-scale view necessary for defining discharge in complex lowland terrain with water bodies and wetlands.

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Satellite radar altimetry measures the elevation of the water surface with results comparable to stage measurements at gauging stations [e.g., *Birkett*, 1998]. More recently, interferometric processing of synthetic aperture radar (SAR) data has been used to measure water level changes as well as the surface area [*Alsdorf et al.*, 2000; 2001]. However, both methods have weaknesses. Altimetry is a profiling tool, not an imaging tool, whereas the interferometric observations, which cover an area, require a "double-bounce" travel path that typically occurs only in flooded vegetation. In this paper, we demonstrate that combining both methods can yield viable measurements of water surface height change spatially distributed across a large water body with only sparse, flooded vegetation.

Lake Balbina

Lake Balbina is a man-made reservoir created to supply hydroelectric power to the city of Manaus, located 125 km to the south. The reservoir is located on the Uatumã River and drains a 19100 km^2 basin of mostly upland topography where the relief extends from 30 m to 200 m in elevation (Figure 1) [*Fearnside*, 1989]. The lake includes a cluster of ~1500 islands separated by submerged, shallow valleys within a flooded water-surface area of 2400 km^2 [*Melack and Wang*, 1998]. Prior to dam closure on October 1, 1987, the annually

Figure 1. Location of Lake Balbina within the Amazon Basin. Grey scale image represents the basin topography. The Amazon, Negro, and Uatumã Rivers, are marked on the stream network.

averaged flow on the river was about 450 m^3/s. Water depths in the full reservoir average 7.4 m. Because the vegetation was not cleared before filling, the lake consists mostly of forest and inundated trunks of dead, leafless trees (Figure 2).

Interferometric SAR Coherence and Vegetation Density

Over open water, the transmitted radar pulse specularly reflects away from a side-looking SAR antenna, yielding low returns, poor interferometric coherence, and unreliable interferometric phase values. Over inundated vegetation, an L-HH radar pulse follows a path that penetrates the vegetation canopy, reflects from the underlying water surface, backscatters from the vegetation trunks, and returns to the antenna (i.e., "double-bounce", *Richards et al.* [1987]; *Hess et al.* [1995]). Our previous effort used L-HH band SIR-C SAR data collected over the Amazon floodplain on October 9 and 10 in 1994 during recessional mainstem flow [*Alsdorf et al.*, 2000; 2001]. For the one-day temporal baseline of the SIR-C observations, the resulting coherence is stronger than locations with non-inundated vegetation. New interferometric observations were acquired over Lake Balbina by the L-HH band JERS-1 satellite on February 14 and March 30 of 1997. This 44-day temporal baseline contrasts sharply with the one-day time separation of the SIR-C observations. Nevertheless, the interferometric coherence throughout the flooded vegetation of the lake is strong (Figure 3).

In both the SIR-C and JERS-1 cases, random changes in the dielectric properties and positions of the scattering centers between SAR acquisitions result in poor coherence [*Zebker and Villasenor,* 1992]. Unlike C-band radar, which scatters from centers located within the canopy, L-band scattering centers are composed of vegetation trunks and the underlying water or land surface. Compared to the trunks of forest trees and woody vegetation, scattering from the water surface has a greater potential for random change over time (e.g., wave action). The possibility exists that during the 24 hours separating the two SIR-C acquisitions, the dense Amazon floodplain vegetation prevented wind and wave roughening of the water surface, thus preserving temporal coherence. Yet given the low vegetation density and large water surface of the lake, it is doubtful that wind and wave action would be similarly subdued across the entire JERS-1 image (Figure 3). Qualitatively, it appears that only one or two inundated dead tree trunks within an area the size of a SAR multi-looked pixel (see 25 m by 25 m square in Figure 2) are necessary to provide the "double-bounce" travel path and thus to maintain coherence over the 44-day time period.

Interferometric Phase and Altimetry Derived Heights

The interferometric phase over the lake surface measured both the topography and the net accumulation of water surface displacements during the 44 days between JERS-1 acquisitions. As with the SIR-C observations across the Amazon floodplain, the lack of a high-resolution digital elevation model (DEM) prohibits a direct subtraction of the synthesized topographic phase (e.g., the "two-pass" method, *Massonnet et al.* [1993]). Because the elevation of the lake water surface is constantly changing, the topographic phase cannot be easily extracted from additional JERS-1 images (e.g., the "multi-pass" method, *Zebker et al.* [1994]). However, the short perpendicular baseline (-118 m, measured at the image center) and orientation combined with the low topographic relief can be used to separate components of the phase related to valley topography from phase related to changes in water levels.

As expected from the baseline orientation, phase values are peaked over topographic ridges and form troughs over valleys. The short perpendicular baseline yields 71.3 m of topographic relief for each 1.0 radian of phase whereas using the 38° incidence angle and L-band wavelength (23.5 cm) of JERS-1, the same radian is equivalent to 2.40 cm of vertical change in water level. Thus, although the interferogram has been unwrapped [*Goldstein et al.*, 1988], the topographic phase component should not exceed about three radians. For example, interpretation of the amplitude data suggests that a topographic high exists in the location of phase profile 1 in Figure 3. Although the coherence is poor, the phase values increase from -1 to +2 radians across this topographic high. Yet, unexpectedly, phase values across obvious topographic valleys are also peaked (e.g., profiles 2-5, Figure 3): these phase values can only be related to increases in water levels from February 14 to March 30 [*Alsdorf et al.*, 2000; 2001]. Assuming the topographic phase of the water surface is equivalent to the immediately surrounding land surface, the increases in phase values range from 3.25 (profile 2) to 6.5 radians (profile 5) equivalent to 7.8 and 15.6 cm of water level increases, respectively.

The accuracy of the interferometric measurement of water level change is related to local coherence and the delineation of the topographic phase component in the total observed phase. Coherence values across the inundated vegetation throughout the lake average about 0.63 which is equivalent to a ~0.3 radian error (given the 14 looks used in the processing, *Zebker and Villasenor* [1992]). The topographic phase component of the surrounding land surface has an average coherence of 0.30, equivalent to about a 0.8 radian error. Thus, combining these error sources produces a ±2.4 cm measurement accuracy.

The TOPEX/POSEIDON radar altimeter has measured water surface heights every ~10 days from 1992 to 2000 along a satellite track that crosses Lake Balbina ("A" Figure 3). Because the radar pulse acquisition is not optimized for land surface hydrology, the derived water surface heights are averages within the footprint of the instrument and are given every ~580 m along the profile. To further improve on accuracy, a large number of such values across the lake are additionally averaged to provide the final height variations observed in Figure 4 (at best the accuracy is ~10 cm rms, *Birkett* [1998]). Linear interpolation of the altimeter derived height values surrounding the JERS-1 acquisition dates yields a 21 cm rise in water level. Given the accuracies of the two radar-derived measurements, we consider them to be in agreement (i.e., altimeter values of 21 ±10 cm compared to interferometric values of 12 ±2.4 cm).

Interpretation

Based on a simple classification scheme that uses the strong coherence and radar backscatter values to separate inundated vegetation and open water from non-flooded upland areas, the water area within the JERS-1 frame is 1440 km^2. The remaining 960 km^2 water surface area is located entirely west of the interferogram with flow delivered mostly to the drowned tributary marked in Figure 3. Profile 5 crosses

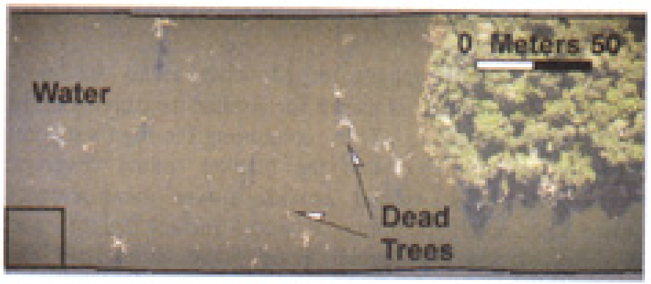

Figure 2. Airborne digital videography of Lake Balbina. An island of trees is located in the upper right whereas the trunks of dead trees are sparsely distributed throughout the water. Box in lower left measures 25 m by 25 m, about the size of a multi-looked SAR pixel.

a drowned tributary that is supplied with runoff from uplands north of the interferogram yet still within the Balbina basin. Profile 2 is closest to the dam, and lacking high-resolution digital topography for Balbina, we infer from stream morphology that the altimetry footprint and profiles 3 and 4 are located within a sub-basin measuring 360 km^2 (note the narrowing of the coherence area downstream of profiles 3 and 5). In agreement with this sub-division, water levels around profiles 3 and 4 have increased 11-12 cm, which are slightly less than upstream values (profile 5, 16 cm) and slightly more than downstream values, nearest the dam (profile 2, 8 cm). Because of its height resolution, footprint, and large between-profile distance (~300 km), these intra-basin variations cannot be measured by existing radar altimetry.

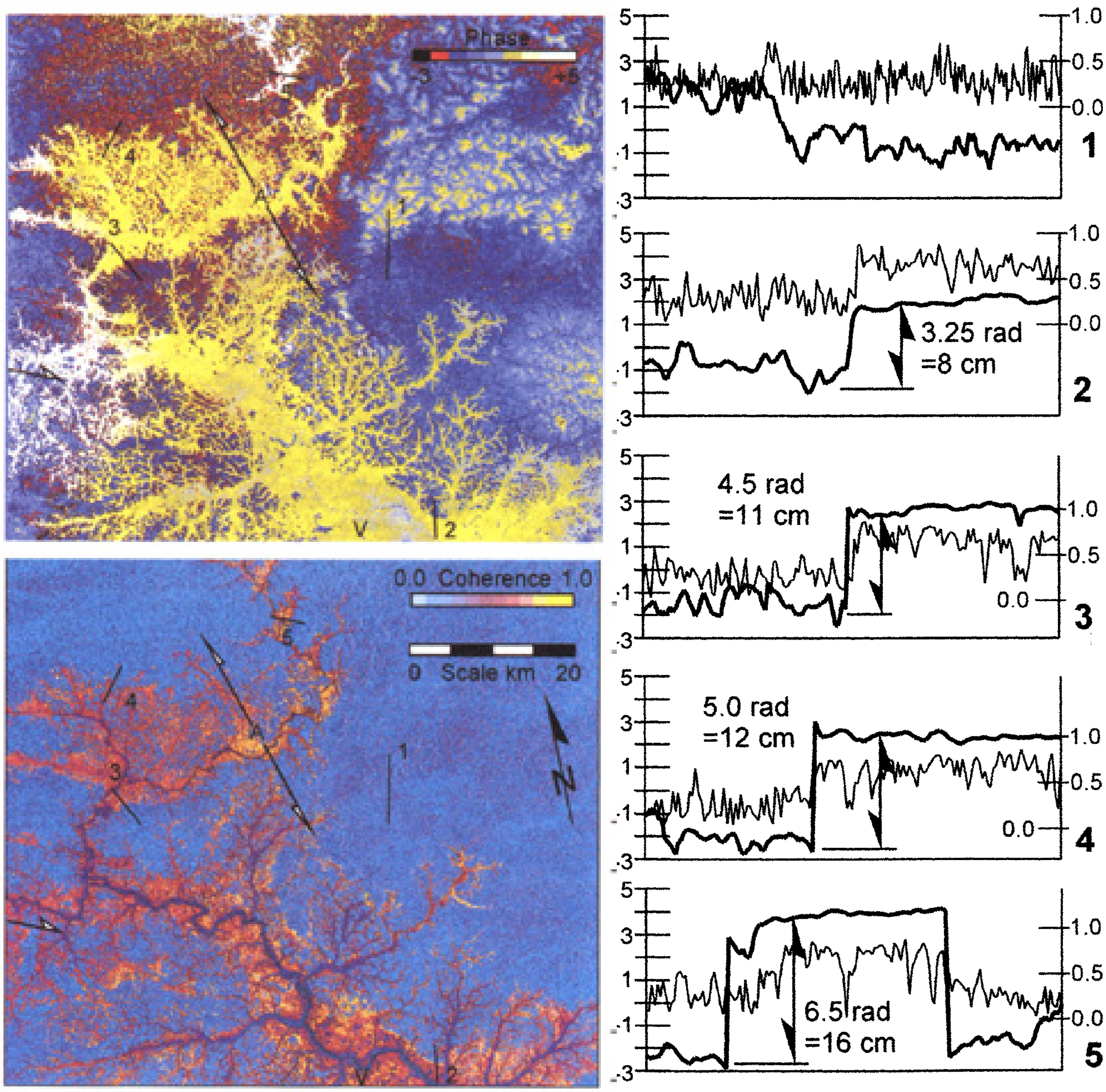

Figure 3. JERS-1 flattened and unwrapped interferometric phase (top image) and coherence (bottom image) calculated from data collected on February 14 and March 30, 1997. Coherence image brightness is a function of backscatter intensity. Images are in SAR coordinates, thus the scale bar is approximate. Profiles of phase (bold black line, associated with radian values on left ordinate) and coherence (thin green line, associated with right ordinate) are plotted on right side of figure. "A" in images marks the location of the altimetry-derived heights of Figure 4, "V" marks the location of the digital video image of Figure 2, and the arrow next to the tributary along the western side of the images indicates flow delivered from the remaining lake area.

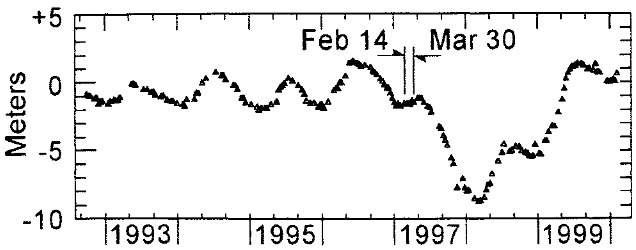

Figure 4. Water surface heights, relative to a common datum, derived from radar altimetry. Accuracy of each height is about the size of the symbol.

The interferometrically measured net changes in water surface heights, Δh, represent a volumetric net gain in water, ΔV, throughout Lake Balbina of 280 ±58 million m^3. At the pre-dam average annual discharge rate ($Q = 450\ m^3/s$) it would take about seven days to remove ΔV from the lake. The area weighted average increase in surface water height throughout the lake is 12 cm, giving an average height change rate of 1.6 cm/day to remove ΔV. From May 1997 to March 1998 the altimetry profile shows an average water surface drop rate of 2.5 cm/day thus, assuming post-dam annual baseflow is the same as pre-dam, the average discharge from the dam at this time exceeded the pre-dam average Q by 230 m^3/s. From March 1998 to July 1999 the average rise rate is 2.0 cm/day (Figure 4), yielding a negative average discharge from the dam of -110 m^3/s compared to the pre-dam Q. Effectively, during the reservoir emptying period, Q from the dam was maintained for 300 days at a rate ~50% greater than the annual pre-dam average rate whereas during the filling period, Q from the dam slowed to a trickle for 500 days. Unfortunately, we lack 1997-1999 rainfall and dam gauge data to check for any compensating gains from increased rainfall or to verify our flow calculations. The downstream ecological impact of these flow variations is unknown, however, historical flows are known to be both limited (e.g., 18 m^3/s were found in February 1983 [*Fearnside*, 1989]) and excessive (1400 m^3/s, early May 1979) for brief periods.

Conclusions

Compared to interferometry, the advantage of altimetry is its ability to directly measure surface heights relative to a fixed datum every ~10 days. Given either a geographic or temporal distribution of altimeter profiles with a common datum, the water surface slope ($\partial h/\partial x$) or its temporal change ($\partial h/\partial t$), respectively, can be measured. Interferometry measures only temporal change, not slope or height of the water surface. Furthermore, when height changes exceed 2π radians (e.g., 15.1 cm for JERS-1), interferometry requires phase unwrapping to sum the total number of phase cycles indicative of the height change. If the phase change occurs over just a few pixels (e.g., when traversing from dry land to the water surface, a sharp phase change often occurs at the shoreline, Figure 4), this summing process can miss-count cycles leaving measurement errors of ±15.1 cm, ±30.2 cm, etc. [*Alsdorf et al.*, 2001]. Altimetry shows these large changes in water surface height (e.g., note the –9 to +2 m changes in 1997-1999, Figure 3) while interferometry gives the spatial variations.

Although on-site gauges record water levels for most reservoirs, our method is useful for similar measurements in remote, ungauged lakes. Thus, combining the high temporal resolution of altimetry with the blanket spatial coverage provided by SAR, should provide future measurements toward a complete mapping of water surface heights and variations during the annual flood wave throughout the Amazon Basin.

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