Global inland water monitoring from multi-mission altimetry

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[1] By "illuminating" the Earth's inland water surfaces with radar altimeter data from the ERS-1 Geodetic Mission, a global waveform analysis has shown that over 50% of echoes from even the largest lake targets are non-ocean-like in character. This paper shows that by retracking multi-mission altimeter data, height data can be obtained from the vast majority of lakes with surface area greater than 500 km^2. Results from the Amazon Basin also show the great improvement in both quantity and quality of data obtained. These results graphically demonstrate that by retracking all available echoes over inland water, the potential of altimetry to measure and monitor global land surface hydrology can be realized. **Citation:** Berry, P. A. M., J. D. Garlick, J. A. Freeman, and E. L. Mathers (2005), Global inland water monitoring from multi-mission altimetry, *Geophys. Res. Lett.*, *32*, L16401, doi:10.1029/2005GL022814.

1. Introduction

[2] Over the past few years, several research groups have published inland water heights derived from space-based satellite radar altimetry. Initial work with Seasat data over a small number of targets [*Rapley et al.*, 1987] has been followed by more recent extraction of decadal time series from the TOPEX mission [*Cazenave et al.*, 1997; *Birkett*, 1994; *Koblinsky et al.*, 1993]. These results have been extensively validated [*ibid*] and shown to be in generally good agreement with ground truth. However, the scope of this technique is constrained by the quantity of available data in the high-level products used in those studies.

[3] There are several reasons why non-ocean height data are not immediately available from existing high-level altimeter products (although this information is available in the engineering level products and can be accessed by more sophisticated processing of these data): firstly, altimeters were designed and optimized for operation over ocean, and their ability to maintain lock on the more rapidly varying land surface is limited. The second and, in fact, major limiting factor lies in the post-processing applied to the echo data returned by the satellite. For European Remote Sensing Satellites (ERS-1/2), only ocean data are processed through to height estimates. For TOPEX, some inland water data are available on the Merged Geophysical Data Record (MGDR) product [*Benada and Digby*, 1997]; however, the processing assumes that each echo is a true "ocean-like" return, which conforms to a Brown model [*Challenor and Srokosz*, 1989]. Consequently, the only valid heights are calculated from inland water bodies whose surface characteristics approximate to those of the open ocean. Clearly, then, large lake targets such as the Great Lakes [*Morris and Gill*, 1994] and the lower part of the largest rivers such as the Amazon [*Birkett et al.*, 2002; *Campos et al.*, 2001] have a good chance of returning echoes which are successfully "retracked" by the TOPEX processing, and from which valid heights can be determined. However, even over the Amazon main stream, significant loss of data occurs at and around the minimum of the large seasonal cycle [*Campos et al.*, 2001]. The reason for this is that the echo shapes returned are affected by interruptions to the water surface, such as the huge sandbars which break the surface at low water, and the effect of surrounding topography, which is greatest at minimum water extent. These cause distortions to the returned echo shapes, and cause them to be rejected by a Brown model fitting algorithm.

[4] There is a way to overcome this limitation, by "retracking" the individual echo shapes using a processing technique which does not assume conformance to the Brown model [*Berry*, 2002]. Over the past seven years, a rule-based expert system approach has been devised and used with great effect to retrack ERS-1, ERS-2 and TOPEX echo data over land [*Berry et al.*, 1997, 2000]. This approach has retrieved well over 400 million valid land height points per year from the ERS altimeter data, and is also successful at height retrieval from both TOPEX and Envisat. The technique works by analyzing the echo shape characteristics of each individual waveform, and then selecting one of eleven retracking algorithms depending on the echo shape. These algorithms have been refined and validated over several years using accurate terrain models [*Hilton et al.*, 2003] and the effects of slope components and bright targets within the illuminated surface footprint have been extensively studied [*Hilton et al.*, 2003; *Berry*, 2002; *Bramer et al.*, 2005]. This approach has now been used to extract river and lake heights on a global scale.

[5] This paper presents a global inter-comparison of retracked TOPEX, ERS-2 and Envisat data, and analyzes the extent to which these data sets can be used to obtain information over the Earth's land surface water.

2. Data Sets

[6] The data used in this study comprise the ERS-1 Geodetic Mission (April 1994 to March 1995), the ERS-2 35-day mission (1995 to 2003), selected Ku-band data from the TOPEX mission (February 1995 to November 1998), and sample Ku-band Envisat data (cycles 16 to 22). The ERS-1 and ERS-2 data are available as Waveform Altimeter Products (WAP) [*Capp*, 2001] and comprise about 160 Gigabytes of information per year. Data are available at 20 waveforms per second, corresponding to a ground spacing of approximately 350 m [*Scharroo*, 2002] and are collected primarily using the "ice-mode" tracker. This is an

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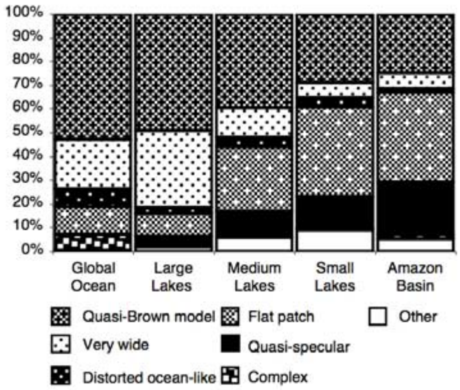

Figure 1. Echo shape distribution over the global ocean, lakes and the Amazon Basin obtained from the ERS-1 Geodetic Mission. Large lakes are defined as having a surface area >4000 km^2, medium lakes between 500 and 4000 km^2 and small lakes less than 500 km^2.

Table 1. Number of Lake Systems Acquired per Satellite Mission Based on the Best Available Cycle by Data Volume[a]

	Number of Lake Systems Acquired			
Mission	Large	Medium	Small	Total
ERS-2	40	230	2030	2300
TOPEX	37	110	415	562
Envisat	42	234	2240	2516
EAPRS lake database	43	248	6813	7104

[a]Also provided are the number of lake systems available in the EAPRS lake database. Large lakes are defined as having a surface area >4000 km^2, medium lakes between 500 and 4000 km^2 and small lakes less than 500 km^2.

additional mode of altimeter operation incorporated into the altimeters on ERS-1 and ERS-2, which enables the altimeters to maintain lock over more rapidly varying terrain, at the cost of a slight reduction in the vertical accuracy of measurement [*Benveniste and Greco*, 1997; *Scharroo*, 2002]. The modes are switched using an on-board static mask, which is set slightly inside the land boundaries, in order to ensure that all ocean data are retrieved using the most precise ‘‘ocean-mode’’ of tracking. Because of the presence of this ice-mode tracker, ERS-1/2 are found to obtain data usable for this application in significantly rougher terrain over land than TOPEX.

[7] The Envisat data are provided as Sensor Geophysical Data Record (SGDR) data [*Benveniste et al.*, 2002] containing 18 Hz waveforms. The Envisat radar altimeter (RA-2) uses a dynamic mode-switching algorithm which means that most data are collected over inland water in high-resolution mode. This improves the vertical precision obtained over lakes, but the current performance appears less optimized for height recovery over smaller rivers. For this study Envisat data were utilized regardless of acquisition mode. Whilst four ‘‘retrackers’’ are used in the Envisat processing schema, none are configured for retrieving heights from inland water. The TOPEX data in this study are obtained from two sources; the Sensor Data Record (SDR), which contain the individual waveforms, and the Geophysical Data Record (GDR), which contains higher level information [*Callahan*, 1993]. TOPEX data are available at Ku-band at ten waveforms per second, corresponding to a ground spacing of approximately 620 m. Only data in fine-tracking mode were used in this study.

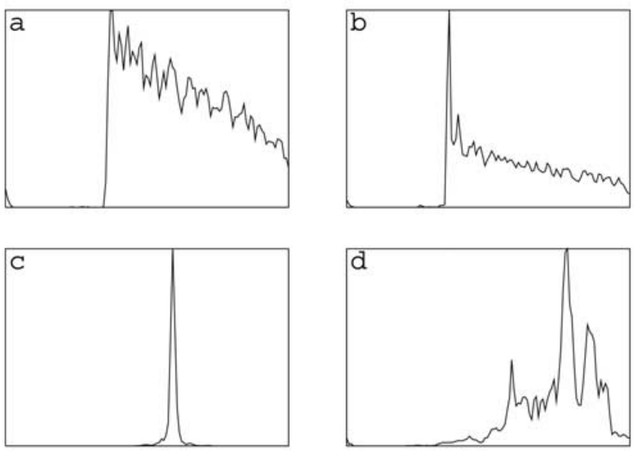

Figure 2. An example of quasi-Brown model (a), flat patch (b), quasi-specular (c) and complex (d) Envisat RA-2 waveform shapes acquired over various inland water targets. The waveform shapes are plotted as power in counts (y-axis) per tracker window bin (x-axis). Scales (not shown) are arbitrary.

[8] The waveform data have been retracked using the Earth and Planetary Remote Sensing Laboratory (EAPRS) expert system for ERS, TOPEX and Envisat. For TOPEX, these data have been merged with the corresponding GDR data set to obtain values for atmospheric and instrument corrections.

3. Echo Shape Analysis

[9] To assess the extent to which non-ocean echo shapes are returned from inland water targets, the ERS-1 Geodetic Mission (GM) was used to ‘‘illuminate’’ inland water surfaces. With an across-track spacing of a few kilometers, and a temporal extent of one year, this unique data set allowed statistical information to be gathered globally. Inland water data were selected using global masks, set slightly wider than maximum water extent, derived from the CIA World Databank 2 database; a detailed Amazon river mask was also derived.

[10] The waveform analysis results were classified by echo shape, and summarized for global lakes, banding by lake surface area. The results are shown in Figure 1, with descriptions of the echo classifications used. For comparison, using the same classification scheme, the distribution of echo shapes over the global ocean has also been included. An example of some of the echo shapes provided in Figure 1 are given in Figure 2, for clarity.

[11] Over the open ocean, significant numbers of ‘‘very wide’’ echoes are seen. These correspond to high sea states. Rain-affected echoes appear as distorted ocean shapes. Very low sea states give ‘‘flat patch’’ echoes too thin to fit the Brown model. For lakes, the distribution becomes increasingly different from that of the open ocean

Table 2. Average Number of Bank-to-Bank River Crossings Acquired for One Cycle of Each Satellite Mission Over the Amazon Basin

Mission	Number of River Crossings
ERS-2	737
TOPEX	125
Envisat	724

as the lake surface area decreases, with increasing amounts of quasi-specular and flat patch echoes.

[12] GM data were then selected over the Amazon Basin. The results of the echo analysis are also shown in Figure 1. As expected, even over this huge river basin, the majority of echoes are not "ocean-like" in character.

4. Global Lakes Comparison

[13] In order to perform a global analysis of the ability of these altimeter missions to retrieve data over lakes, successive cycles of retracked TOPEX Ku band, ERS-2 data and Envisat Ku band data were run through the mask selection procedure. The optimal statistics for global coverage (derived by selecting the cycle with the highest volume of successfully retracked land echoes) are shown in Table 1, banded by lake area.

[14] These results illustrate the advantage of the increased spatial sampling of ERS-2 on the number of systems acquired; this is of course offset by the decreased temporal sampling. A second, significant effect is the ability of the ERS and Envisat altimeters to maintain lock on the underlying terrain in areas of rough topography.

[15] The fact that altimeter data are present over such a high proportion of the Earth's major lake systems is of course significant: the second key question is whether the data are valid. The Merged Geophysical Data Record (MGDR) TOPEX data (ocean retracked) have been extensively validated with ground truth [*Campos et al.*, 2001; *Birkett et al.*, 2002] and the retracked land datsets from ERS-1, ERS-2 and TOPEX data have been validated over Australia [*Hilton et al.*, 2003] and in global intercomparisons with ground truth [*Berry et al.*, 2000; *Hilton et al.*, 2003]. However, further validation of heights obtained from these echoes is required since, for all but the largest lakes, significant amounts of non-ocean echo shapes are observed.

5. River Systems

[16] River systems present far more challenging targets for radar altimetry than lakes. Even the largest river systems are of limited width and, depending on the relative orientation of the river and satellite overpass, only a small series of echoes may be obtained. Since quasi-specular and complex echo shapes (Figure 1) are returned in much greater proportions over rivers, validation of the height retrieval has been performed over a river system.

5.1. Amazon Basin

[17] As demonstrated in Figure 1, the Amazon returns very high proportions of non-ocean echoes. Because the Amazon basin contains the largest river system, in which it is reasonable to expect the widest extents of open water, this region was used for the initial investigation of the effectiveness of retracking TOPEX, ERS-2 and Envisat data. Of particular interest was the fact that prior research using the MDGR TOPEX data set has reported difficulties in populating the time series at low water extent [*Campos et al.*, 2001; *Birkett et al.*, 2002]. Data were selected using the detailed Amazon river mask. The first analysis was carried out to determine how many crossing points of the Amazon river and its tributaries could be detected per cycle. Averaged crossing counts, including all crossings for which viable echo shapes (where the leading edge is present) could be retrieved, are tabulated in Table 2.

[18] The results show that TOPEX maintains lock over a significant number of river crossings in the Amazon basin. The statistics must be considered in the context of the different orbit repeat patterns: allowing for this, the improved ability of the ERS-2 altimeter to maintain lock over rough terrain is clearly illustrated, with echoes captured over far more crossings than can be accounted for purely on the basis of the longer repeat pattern. Spatial analysis confirms that the primary reason for this is the ability of the ERS altimeter to maintain lock over the rougher terrain of the higher reaches of the Amazon river system. This trend is also seen in the Envisat results. It should be emphasized that counting river crossings with valid echoes as a proxy indicator of those for which valid heights can be obtained represents an optimal outcome. Whilst data from many minor tributaries can be processed by the current system to yield good height estimates, there are some crossings where the returned shapes are all complex in character, requiring further enhancements to determine accurate heights. Research in this area is continuing.

5.2. Amazon Basin Validation

[19] Comparing the ERS-1/Envisat and TOPEX repeat patterns with the location of gauge stations in the Amazon basin (Data available from the Brazilian National Water Agency, ANA, Brazil at http://hidroweb.ana.gov.br/) a location was found where a gauge station (ID 15040000) was in close proximity to an ERS/Envisat river crossing

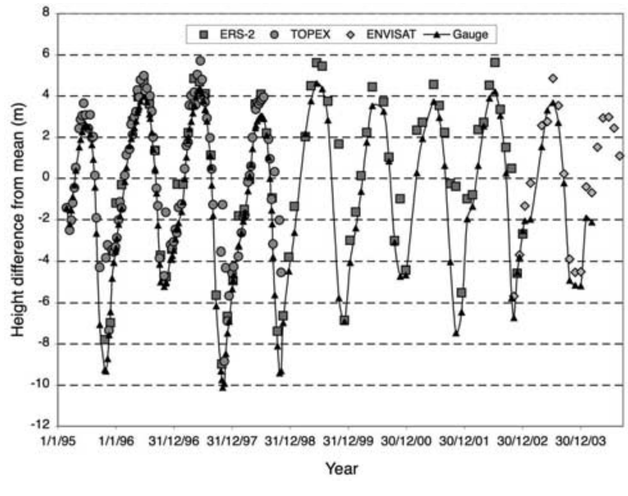

Figure 3. Time-series of height difference from mean at river crossing location, for TOPEX, ERS-2, Envisat and Gauge data (see text) over the Amazonas.

(0.3° downstream of the gauge), and to a TOPEX crossing (0.2° upstream of the gauge). The time series are shown in Figure 3, which shows extremely good agreement; the Pearson correlation coefficient for TOPEX and gauge data is 0.91, for ERS and gauge data is 0.93, and for Envisat and gauge data is 0.98. No temporal smoothing has been applied to the data, which show the filtered retracked altimeter heights against the gauge data for that day. Figure 3 clearly demonstrates that no difficulty is experienced in retrieving data from the lowest water levels, associated with the minimum of the annual hydrological cycle.

6. Discussion

[20] This analysis very clearly demonstrates that satellite radar altimetry has the potential to obtain valid height estimates over the majority of the Earth's lake systems and can also retrieve data from river systems at a far higher success rate and over much smaller targets than previously reported. The key to success in retrieving these data is to retrack the individual echo shapes. With a decadal time series available from TOPEX and ERS-1/ERS-2, and the continuing time series from Envisat and Jason-1, a wealth of surface hydrology information is potentially available. The ability to retrieve data from remote ungauged lakes and rivers on a global scale using retracked data offers a host of potential applications including climate signal detection, monitoring of river water usage, and inputs to hydrological models.

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