Monitoring of inland surface water using multi-mission satellite radar altimetry

P.A.M. Berry

Earth and Planetary Remote Sensing Laboratory, De Montfort University, The Gateway, Leicester LE1 9BH, United Kingdom pamb@dmu.ac.uk

Abstract

Satellite altimetry has been used for many years to measure inland water heights of large lake targets. However, altimeters collect data over thousands of lake and river targets; the challenge is to interpret the echo shapes returned from these targets and hence derive time series of changing water levels. This paper presents the results of a comprehensive analysis of multi-mission altimeter echoes from the vast network of rivers in the Amazon basin, and uses comparisons with in-situ gauge data to demonstrate that river heights can be successfully retrieved from all altimeters considered if the echoes are properly retracked.

1. Introduction

The analysis and interpretation of satellite radar altimeter data obtained over inland water was pioneered using data from the Seasat and Geosat missions [e.g. Guzkowska et al., 1990]; this capability was extended as data from subsequent altimeter missions became available. The primary data source for much published work is still the long-running TOPEX mission; readily accessible data products give a range estimate derived from the onboard tracker, and the user friendly format of the MGDR [Benada & Digby, 1997] has facilitated use of these data. The TOPEX mission was succeeded by Jason-1 and Jason-2 [Zanife et al., 2004]. As these instruments were optimised for ocean operation they often fail to acquire echoes over rough terrain; however, where echoes are retrieved over a large ‘ocean-like’ lake target, good vertical precision can be obtained using the pre-processed datasets [Maheu et al, 2003; Birkett et al., 2002].

In contrast, the ESA altimeter missions were designed to recover data over topographically varying surfaces. ERS-2, with its 35 day orbit repeat pattern maintained over the mission lifetime, provides a long time-span of echoes over inland water, with the ‘ice mode’ utilised over land greatly facilitating the acquisition of inland water targets at the cost of some vertical precision. The user hostile format of the WAP product [Capp; 2001] has prevented these data being generally used. This is a great loss to the scientific community, as the altimeter performed very
well over both land and inland water surfaces; the potential of these data has not been realised to anything like the level which they merit. ERS2 was succeeded by the Envisat RA-2 [Benveniste et al., 2002], engineered to acquire data over most of the earth’s land surfaces using three modes of operation (though the 20Mhz mode is too coarse to obtain meaningful height changes over inland water).

This paper contains the results of a detailed analysis of retracked altimeter data from the Amazon river network, comparing the results with measurements from the in-situ network of gauges, to estimate the potential of satellite altimeters to retrieve inland water heights from more challenging targets. The first step is to retrack the individual waveforms to obtain range to surface estimates.

2. Waveform Retracking

Several groups have studied waveform retracking, generally by using the EnviSat dataset [e.g Frappart et al, 2006; Chu et al., 2008]. Uniquely, the EnviSat SGDR product contains up to four range estimates for each waveform, four retrackers being run over each waveform regardless of shape. This allows researchers to compare the outputs of various retrackers without actually reprocessing the waveform data. However, these retracker outputs should be utilised with caution: although the various algorithms may give a retracked range value, this does not imply that the output is always sensible. If inappropriate retracking algorithms are used, significant errors in the retracked range occur.

2.1. Expert System Approach

Using a rule-based expert system, which classifies each echo into one of eleven categories of waveform shape and picks an appropriate retracking algorithm, data from TOPEX (Ku band), ERS-2, Envisat (Ku band) and Jason-1 (Ku band) have been successfully reprocessed over inland water [Berry et al., 2005]. This technique has enabled retrieval of data from a huge number of lake and river systems [Berry & Benveniste, 2010]. The retracking of lake data is comparatively straightforward; for many large lake targets, the echoes are sufficiently similar to ocean returns to permit a Brown model fit [Brown, 1977] to be performed. However, the retracking of river data is far more complex because, other than over the largest targets, contamination from surrounding topography, interruptions to the water surface and off-ranging to bright targets are endemic.

3. Data processing and selection issues

3.1. Datasets

Retracked data from ERS-2, TOPEX, Envisat and Jason-1 have been used for
this work; Jason2 has been excluded because a sufficiently long timeseries has not yet accumulated.

The mission characteristics and data periods used for this study are summarized in Table 1. As the primary focus of the work, investigation of retracked heights over the Amazon river network, requires a dense spatial distribution of altimeter measurements, special emphasis has been placed on the ERS-2 and Envisat missions. All altimeter data used in this study have been retracked using an expert system approach.

**Table 1: Mission characteristics and datasets used in this work**

<table>
<thead>
<tr>
<th>Mission</th>
<th>Repeat period (days)</th>
<th>Orbits per cycle</th>
<th>Along-track sampling rate</th>
<th>Mode</th>
<th>Gate Width</th>
<th>Time span used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topex Ku Band</td>
<td>9.92</td>
<td>127</td>
<td>10Hz/594m</td>
<td>320Mhz</td>
<td>0.47m</td>
<td>Mar 1994-Aug 2002</td>
</tr>
<tr>
<td>ERS-2</td>
<td>35</td>
<td>501</td>
<td>20Hz/332m</td>
<td>320Mhz/80Mhz switching by mask</td>
<td>0.45m/1.82m</td>
<td>May 1995-Aug 2002</td>
</tr>
<tr>
<td>Envisat RA-2 Ku Band</td>
<td>35</td>
<td>501</td>
<td>18Hz/369m</td>
<td>320Mhz/80Mhz/20Mhz autonomous selection</td>
<td>0.47m/1.87m/7.5m</td>
<td>Aug 2002-Jul 2005</td>
</tr>
<tr>
<td>Jason-1 Ku Band</td>
<td>9.92</td>
<td>127</td>
<td>20Hz/297m</td>
<td>320Mhz</td>
<td>0.47m</td>
<td>Aug 2002-Mar 2004</td>
</tr>
</tbody>
</table>

For ERS-2, the best available orbits [Scharroo, 2002] were merged with the ALT.WAP dataset for this analysis. For TOPEX, the Sensor Data Record (SDR [Algiers J. Et al, 1993]) data were merged with the corrections from GDR and MGDR datasets. Only data obtained in ‘fine track’ mode were included as part of this study. Both the Envisat [Benveniste et al., 2002] and Jason-1 [Zanife et al., 2004] data are provided as Sensor Geophysical Data Record (SGDR) data. Also utilised is a global rivers mask.

### 3.2. Mask Development

Analysis of results obtained from prior work [Berry et al., 2005] has shown the existence of data from ERS-2 and TOPEX over hundreds of locations where the altimeters overflew river targets in the Amazon basin. Whilst this is significant as an indicator of the potential of satellite radar altimetry to acquire data over river systems, the mere presence of data over a crossing can only be used as a proxy indicator of the potential of an altimeter to retrieve information. With the lower along-track sampling rate of these altimeters (Table 1) the number of echoes obtained at each pass over a river is limited, and many echoes are returned from a composite surface (discussed later) making interpretation difficult. One key com-
ponent in successful retrieval of height information is therefore the initial data selection. To this end, a rivers mask was developed at 30" derived from the Global Land Cover Characterization (GLCC) database version 2.0. This dataset consists of a global 30" resolution classification of land cover type derived primarily from AVHRR data [Loveland et al., 2000].

4. Retracking and Height Retrieval

Initial results over the Amazon [Berry et al., 2005] showed that even over the principal rivers in this vast network, the majority of echo shapes returned from the water surface do not correspond to those obtained over the open ocean, but that they can be retracked using an expert system approach. The retracking methodology is summarized here for clarity. Before retracking waveforms from ERS-2, EnviSat, TOPEX and Jason-1 initial tests are performed on each waveform to ensure the following criteria are met: power in the waveform must be greater than the instrument-specific noise and the leading edge of the waveform must be successfully captured by the altimeter.

The accepted waveforms are then characterised according to the waveform shape using instrument specific values for leading edge width and waveform width together with additional anomaly checks. Figure 1 shows example waveforms from EnviSat illustrating both accepted echoes (with the retracking point bin number) and sample echoes that were rejected by the system, illustrating commonly occurring complex shapes. Figure 1 (a) shows a waveform excluded due to miscapture: the first part of the waveform is missing and there is therefore no leading edge. The second waveform, (b) shows a quasi-specular echo accepted by the system that can be retracked using the widely published methodology for such echoes over sea-ice [Laxon, 1994; Wingham et al., 1986]. A second category of accepted waveform is

![Figure 1: Waveform shapes from EnviSat Ku band adjacent to inland water](image-url)
shown in (c); this shows a much wider waveform typical of those returned from water in the presence of waves and appropriate for a Brown model fit [Brown, 1977]. The fourth waveform (d) shows a typical echo with minor anomalies that the system removes and then retracks to the dominant quasi-specular component as outlined previously. To illustrate complex waveforms, which were not included in this Amazon basin study, plots (e) and (f) show two waveforms that were rejected by the system. In (e), two quasi-specular peaks are seen and it is not possible to determine uniquely which of them, if either, comes from the surface directly below the altimeter. In (f), multiple broader components appear, probably from adjacent ruffled water / wet land.

The accuracy obtained when retracking non-Brown model waveforms is shape dependant. For a simple quasi-specular echo, extremely high accuracy may be obtained [Laxon, 1994]. However for more diffuse echoes [Berry & Benveniste, 2010] the expected accuracy is in the range 2-10cm. Land is a relatively poor reflector of Ku-band energy compared to inland water; the response from the bright water target therefore frequently dominates the altimeter return. It is emphasised that for effective retracking of echoes from inland water, it is essential that the re-tracker used for each waveform be configured to derive a mean range to surface for that waveform shape.

In order to derive height estimates from altimeter data a series of corrections must be applied to the retracked range to model the signal propagation through the Earth's atmosphere as well as instrument specific corrections, with a geoid model used to transform heights above the ellipsoid to heights above mean sea-level (e.g. Scharroo, 2002; Fu & Cazenave, 2001). The stated error in these corrections over the ocean is a few centimetres.

5. Analysis

Before proceeding to compare the time series against gauge data it is necessary to confirm that the along-track height estimates are consistent. The results for ERS-

<table>
<thead>
<tr>
<th>Mission</th>
<th>Alongtrack RMS (cm)</th>
<th>StdDev of Alongtrack RMS (cm)</th>
<th>Number of crossings</th>
<th>Cycle</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-2</td>
<td>3.96</td>
<td>9.04</td>
<td>408</td>
<td>30</td>
<td>March 1998</td>
</tr>
<tr>
<td>Envisat</td>
<td>2.52</td>
<td>5.23</td>
<td>230</td>
<td>34</td>
<td>March 2004</td>
</tr>
<tr>
<td>TOPEX</td>
<td>1.22</td>
<td>1.02</td>
<td>25</td>
<td>128</td>
<td>March 1996</td>
</tr>
<tr>
<td>Jason-1</td>
<td>1.03</td>
<td>0.90</td>
<td>29</td>
<td>43</td>
<td>March 2003</td>
</tr>
</tbody>
</table>
Monitoring of inland surface water using multi-mission satellite radar altimetry

2 cycle 30, TOPEX cycle 128, Envisat cycle 24 and Jason-1 cycle 43 over the Amazon Basin are shown in Table 2. These cycles were chosen because they correspond approximately to months of average river flow. The majority of crossings for all missions show an along-track RMS of less than 10cm for the subset of waveforms accepted by the system. Note that for Table 2 no crossings have been included when only one height estimate was made; for TOPEX and Jason-1 in particular this is a significant proportion of the total number of crossings.

5.1. Height Validation from Amazon ‘Natural Validation Zone’

The huge natural validation area of the Amazon basin provides both an extensive network of gauge data (http://hidroweb.ana.gov.br/) and a large number of targets for multi-mission altimetry. Because the orbits of ERS-2 and Envisat are almost identical, it was possible to use the same gauge data for both instruments; a similar approach was taken for data from Jason-1 and TOPEX.

Time series of height differences from a mean value were then calculated for the selected crossing points, and a comparison with adjacent gauge data was performed for ERS-2 and Envisat, TOPEX and Jason-1 data. The height differences rather than the orthometric heights were used because the vertical referencing of some gauge data is uncertain. The benefit of utilizing an altimeter configured to operate over rougher terrain is evident in the successful recovery of both ERS-2 and Envisat time series from the higher reaches of the Amazon River network. Both TOPEX and Jason-1 lose significant numbers of potential crossings where valid echoes were not returned. The dominant cause of this is the failure to recover the first part (leading edge) of the echo, which is required in order to obtain a range to surface. For ERS-2 and Envisat (Table 1), which have the capability to use a wider range window [Benveniste et al., 2002], both the nadir response and any off-nadir bright targets may be retrieved, which allows successful reprocessing of the echo to obtain a height estimate and, critically, prevents the altimeter from losing lock on the terrain when the off-nadir target moves out of the illuminated footprint [Berry, 2005].

5.2. Spatial Analysis

To investigate the distribution of data over the Amazon basin, an automated procedure was implemented to select crossing and gauge data. This resulted in 110 comparisons for TOPEX (Figure 2), 46 for Jason1, 275 comparisons for ERS-2 (Figure 3) and 278 for Envisat.

Prior results given by other researchers [e.g. Maheu et al., 2003; Birkett et al., 2002] indicate that on the main tributaries of this vast network where the rivers are extremely wide, unretracked TOPEX data can give valid results when extensive post-filtering is applied. Results generated from gauge comparisons with the retracted TOPEX data also show good results on the main tributaries. It was also
Figure 2: TOPEX gauge comparison results showing target location and cross-correlation coefficient

Figure 3: ERS2 gauge comparison results showing target location and cross-correlation coefficient
found in contrast to previously published work that very high cross-correlations are seen on a number of smaller tributaries where the terrain variation is greater; re-tracking these waveforms allows good height time series to be retrieved automatically.

Comparison of the spatial distribution of cross-correlation coefficient for ERS-2 (Figure 3), with the corresponding result for TOPEX (Figure 2), clearly demonstrates the advantages of an altimeter designed for use over non-ocean surfaces. Many of the smaller tributaries of the Amazon Basin show altimeter time series with extremely high cross-correlation coefficient with gauge measurements in the more rapidly varying terrain. Of particular note, the reported discrepancies between gauge data and altimeter heights at the minimum of the hydrological cycle [Maheu et al., 2003; Birkett et al., 2002] are not seen to any significant extent; this is attributed to the great improvement in height retrieval when data are properly retracted. In all cases the along-track RMS is less than 11cm throughout the annual cycle regardless of the echo shape processed.

To examine the altimeter height measurements at locations where gauge data are present the time series were screened using the cross-correlation coefficient. The results are shown in Table 4; the mean RMS between the altimeter and the gauge measurement for all time-series is given together with the number of time-series available. The results very clearly demonstrate the excellent performance of the Envisat RA-2, with the accurate height retrieval of the 320Mhz mode comple-

Table 3: Statistics for gauge comparisons in Amazon basin

<table>
<thead>
<tr>
<th>Cross-correlation coeff ≥ 0.925</th>
<th>ERS2</th>
<th>EnviSat</th>
<th>TOPEX</th>
<th>JASON1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS (m)</td>
<td>1.01</td>
<td>0.69</td>
<td>0.78</td>
<td>0.81</td>
</tr>
<tr>
<td>Std Dev of RMS (m)</td>
<td>0.42</td>
<td>0.35</td>
<td>0.24</td>
<td>0.36</td>
</tr>
<tr>
<td>No of time series</td>
<td>132</td>
<td>134</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>Cross-correlation coeff ≥ 0.950</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS (m)</td>
<td>0.92</td>
<td>0.60</td>
<td>0.70</td>
<td>0.71</td>
</tr>
<tr>
<td>Std Dev of RMS (m)</td>
<td>0.39</td>
<td>0.29</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>No of time series</td>
<td>96</td>
<td>108</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Cross-correlation coeff ≥ 0.975</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS (m)</td>
<td>0.76</td>
<td>0.48</td>
<td>0.48</td>
<td>0.44</td>
</tr>
<tr>
<td>Std Dev of RMS (m)</td>
<td>0.47</td>
<td>0.22</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>No of time series</td>
<td>32</td>
<td>68</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Cross-correlation coeff ≥ 0.990</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS (m)</td>
<td>0.51</td>
<td>0.42</td>
<td>0.50</td>
<td>0.44</td>
</tr>
<tr>
<td>Std Dev of RMS (m)</td>
<td>0.05</td>
<td>0.15</td>
<td>n/a</td>
<td>0.12</td>
</tr>
<tr>
<td>No of time series</td>
<td>8</td>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
mented by improved atmospheric corrections, when compared with those available for ERS-2. Both TOPEX and Jason-1 are disadvantaged by the comparatively small number of measurements obtained.

The results from TOPEX for the large tributaries of the Amazon Basin are in broad agreement with those obtain by other researchers [ibid] however only simple filtering has been applied to the results generated from the automated system discussed above. As the along-track RMS figures from Table 2 clearly show, retracking greatly improves the consistency of height retrieval and therefore reduces the requirement for extensive filtering to be applied to the output time series.

When compared with TOPEX the relatively poor performance of Jason-1 over the Amazon is clearly evident from these results, although no single cause for this has been determined.

6. Conclusions

Over the past decade the initial retrieval of timeseries of lake heights over a few selected targets from Seasat and Geosat data has evolved into a global monitoring capability which has the potential to derive timeseries of lake and river heights from thousands of targets worldwide. One of the key requirements for utilising this unique resource is, clearly, validation of the retracking methodology used to derive inland water heights. The results from analysis of the multi-mission altimeter heights derived over the vast natural validation area of the Amazon basin clearly demonstrate that accurate measurements of river heights can be obtained from satellite radar altimetry. The key to unlocking the information contained in waveform shapes from river systems is to reprocess the waveforms using multiple retrackers configured for the complex and widely varying echo shapes returned from these surfaces. The extensive analysis of along-track RMS confirms that the retracking is consistent and that no discernible biases in the heights are present between different algorithms. This is attributed to the use of an appropriate algorithm to obtain the retracted range for each waveform shape. The differences between the altimeter derived heights and adjacent gauge heights are primarily due to residual error in the corrections applied to the altimeter range measurements, with the results for Envisat showing a mean RMS against adjacent gauge data of 0.42m based on 29 time series.

Other vital ingredients for data recovery from smaller lakes and rivers include the derivation of an accurate inland water locations mask; this allows the short segments of data containing the water surface to be selected from the land response. Whilst many lakes present fairly straightforward surfaces for retrieval of good echoes by a satellite altimeter, significant numbers of complex echoes are generally returned from river surfaces; these are a combination of the nadir water response
with echoes from the surrounding topography. Accordingly, selection and filtering on echo shape are required to identify those echoes most likely to have resulted from a water surface at nadir. Filtering techniques must then be utilized to exclude the inevitable residual outliers from the height profiles for the crossings. The output from this system is able to retrieve time series that allow characterization of the seasonal, annual and inter-annual changes within river systems.

Of the altimeter derived datasets considered, the Envisat RA-2 offers the best signal retrieval over inland water surfaces in terms of number of crossings where data were acquired. The three modes of operation enable this instrument to retrieve most of the echo components from the underlying surface. Even when snagging on a bright off-nadir target, the wider range windows frequently allowed retrieval of the nadir echo component. It should be noted that in principle, many of the complex echoes excluded from this analysis can be retracked to isolate the nadir return from the numerous other signals; this is the subject of continuing research.

Acknowledgements

The author would like to thank the European Space Agency, NASA/Jet Propulsion Laboratory and Centre National d'Etudes Spatiales for generously providing satellite altimeter data; also Jennifer Freeman for supplying several of the figures.

References


