What has 16 years of Satellite Radar Altimetry given us towards Global monitoring of the Earth’s inland water resources?

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ABSTRACT

The series of satellite radar altimeter missions has now given us more than 16 years of data gathered over the earth’s inland water. However, this incredibly rich database of unique hydrological information is only now beginning to be mined effectively, as researchers increasingly move from accepting the pre-processed range information to retracking the waveform data to optimise the range measurement and generate accurate heights. This paper presents the results of a global analysis of waveform data acquired by ERS-1/2, EnviSat, TOPEX and Jason-1 which demonstrates that only a tiny fraction, as low as 10%, of the potential hydrological information content has been utilised to date. A much greater fraction of overflown inland water targets do have viable waveform data: these results suggest that over perhaps 40% of the targets useable time series of heights could be derived by more sophisticated reprocessing of the data. Successful recovery of this information will give access to a huge decadal dataset of river and lake heights containing both climatological data and information on the anthropogenic use of inland water resources. Additionally, analysis of the target acquisition and echo characteristics from these missions gives a valuable and unique insight into the response of these complex surfaces to radar altimetry to aid future mission design.

INTRODUCTION

Satellite radar altimeters have been flying now for many years, primarily gathering data relevant to surface oceanography. However, these instruments have also gathered a vast amount of data over the earth’s land surfaces, including inland water. This application has advanced from the first tentative investigation of the possibility of inland water height retrieval over a few large lakes to the investigation of multi-mission, multi-year time series over many targets worldwide.

EXAMPLE TARGETS

Of the thousands of targets now successfully acquired by the series of satellite radar altimeter missions flown to date, a small selection are presented here to illustrate the potential and multi-mission retrieval of inland water heights.

Tonle Sapp

Ever since the beginning of inland water altimetry Tonle Sapp has been a popular target for scientists to measure, following on from the initial work utilizing SeaSat and Geosat data [1] which demonstrated the potential usefulness of these data in acquiring hydrological information where in-situ data were not available. The lake itself has a dramatic annual signature, and its extremely large spatial extent makes it an ideal target for altimeters to acquire. Fig. 1 shows a combined result over Tonle-Sapp obtained by the EAPRS lab. Data from three different satellites have been combined, with the more dense spatial sampling of ERS-2 and EnviSat resulting in two time series from each mission compared to the single time series over the target from TOPEX.
The good agreement between heights from these three independent altimeters is clear, with the annual cycle well represented. This target also illustrates the considerable inter-annual variations which can be assessed using the full temporal extent of altimeter measurements now available by merging different datasets, as is clear from the EnviSat continuation of this time series. Over large lakes the repeat period of the satellite becomes less of a constraint on the temporal sampling, since the denser spatial sampling of a 35 day repeat orbit results in several passes over the target for each cycle. When merged, therefore, the average temporal sampling approaches that of TOPEX 10 day measurements.

Merged timeseries over lakes
Over most major lakes, combined timeseries for 12 years worth of data can now be produced. As for Tonle Sapp, several timeseries from the 35 day repeat altimeters may be present where only one is available from TOPEX. One constraint on the multi-mission combined timeseries is that the contribution from Jason-1 is very significantly less than from TOPEX [2]. This places increased emphasis on the EnviSat RA-2, which fortunately performs extremely well overall in acquisition of inland water targets, and does permit derivation of good time series. However, the results which can be obtained from Jason-1 are very much better than has previously been reported; over many targets very good timeseries can be derived. A brief description of Jason-1 constraints is given here and reported more fully elsewhere [2]. For Jason-1, in addition to difficulties related to maintaining lock on the underlying terrain, a limitation common to altimeters optimized for ocean operation, a problem with the operation of the on-board compression algorithm means that part of the echoes may be absent from the waveforms when in the presence of a bright target. The affected bins contain zeros but the remainder of the waveform is unaffected. Since still water presents a mirror-like surface to a Ku band altimeter, this problem is more likely to arise when overflying lakes and rivers. Additionally, the location of the echoes within the ‘range window’ are extremely variable from Jason-1, far more so than for TOPEX. This in itself does not cause any problem; difficulties arise if these data are used without ‘retracking’ i.e. recalculating the range to the actual time of the echo arrival, rather than a reference location within the altimeter range window. For ocean operation, the tracker generally is able to keep the waveform well centred within the range window, because the ocean surface changes in elevation over spatial scales of many kilometers (except over strong geoid signals or ocean currents) and the correct range to surface is achieved by fitting a Brown model to the waveforms [3] and thus solving for the generally small residual corrections from the reference point to the actual retracking point. Because Jason-1 inland water waveforms move location rapidly within the range window for successive echoes, and are rarely at the theoretical tracking point, very large errors can result from the use of uncorrected range [2].

All data have been retracted using an Expert system approach [4,5], which isolates that part of the echo returned from a water surface directly below the satellite and recalculates the range to surface accordingly. Over these large targets the difference in temporal sampling of Envisat and TOPEX is less apparent as the closer spatial sampling of the 35 day Envisat orbit often obtains multiple profiles across the lake during each cycle.

An example over Lake Nasser is given in Fig. 2 from ERS-2, EnviSat and TOPEX, from 1994 to the end
of 2007. Here the merit of the long timeseries is seen. To illustrate the potential of this technique where the annual signature is smaller, Fig. 3 shows a combined timeseries over Lake Debo from ERS-2 and EnviSat. By correctly retracking the altimeter echoes, accurate range to surface can now be achieved over many thousands of targets globally. Some errors in the measurement remain. The signal must be corrected for time delays due to passage through the earth’s atmosphere [6]; of these corrections, for inland water, the most critical is the wet tropospheric range correction. This can change rapidly across a storm front, and has a maximum amplitude of about 40cms [6]. Research is ongoing to improve this correction. Overall, however, the retrieval of inland water heights is very effective despite these residual inaccuracies.

Figure 2  Lake Nasser temporal height variation using ERS2, EnviSat and TOPEX (only gross outlier removal applied)

Figure 3 Lake Debo from ERS2 and EnviSat showing good retrieval with smaller height variation (only gross outlier removal applied)
Merged timeseries over rivers
In general time-series over rivers cannot be combined. However with major river systems TOPEX crossings are occasionally spatially adjacent to those of ERS2 and Envisat. Two such examples are given here: the first on the Amazon in Fig. 4, the second, in Fig. 5, from the Congo. Good agreement is seen between the time-series which have all been retracked using an expert system approach.
In general, the crossing locations are not coincident; however, by combining data from different missions, many locations can be monitored. To illustrate this, Fig. 6 shows the river Ob, with a few of the many timseries obtained from this target.

![Figure 4 Combined timeseries over the Amazon from ERS2, TOPEX and EnviSat](image1)

![Figure 5 Combined timeseries over the Congo river from ERS2, TOPEX and EnviSat](image2)

To illustrate the river monitoring capability in spatial terms, Fig. 6 shows the River Ob, with example time series at different locations from multiple satellites.
Figure 6  Spatial locations of some timeseries over the river Ob from ERS2, EnviSat and Jason-1
ERS-2 shown in black, EnviSat in dark grey and TOPEX in light grey.

The image shows a 15 degree tile with South West corner 60N 60E. Due to the high latitude the water is susceptible to freezing in the winter making it more difficult to retrieve good data. These results show that there is a slight increase in the minimum water levels of the main stretch of the river but this increase is not present near to the river estuary.

DISCUSSION

Satellite radar altimeters have been overflying the earth’s inland water for more than a decade, collecting a vast database of echoes. Because these targets are complex, requiring ‘retracking’ of the echo data to retrieve good range to surface measurements, the application of this technique to inland water monitoring was initially restricted to a few large targets. For these targets the echo was well centred within the instrument range window or the ocean Brown model could be successfully applied to retrieve a range to surface (only possible in the very largest lakes where the echo shape approaches that seen over the open ocean). Retracking inland water echoes globally and retaining only those crossings for which good waveforms exist allows thousands of good time series of height variation to be retrieved from ERS-2, EnviSat and Topex targets. Whilst the contribution of Jason-1 is less than had been hoped due to the operation of the onboard processing, many good timeseries can also be obtained from this instrument: the key again is to retrack the echoes. The advantage of both ERS-2 and EnviSat is that these altimeters were configured for operation over multiple surfaces, and thus retain lock on the underlying terrain even in the presence of mountain ranges – Lake Titicaca and Lake Poopo are well represented in timeseries from these missions. However, the 35 day repeat sampling is a limitation on the applications of these data for many hydrological studies; this is mitigated by the closer spatial sampling, resulting in multiple timeseries over large targets and allows the aggregated timeseries to approach the temporal sampling of Topex. For retrieval of data over river systems, except in the very largest rivers such as the Amazon, the ESA altimeters perform significantly better due to their increased ability to maintain lock on the underlying surface when the surface is varying more quickly.
Whilst Envisat retrieves the highest proportion of inland water targets globally it should be noted that over mountainous terrain some of these time-series are obtained in 20MHz mode which renders the data unusable for hydrological purposes. Satellite radar altimetry has the ability to gather data over many thousands of river and lake targets worldwide. The key to deriving useful heights for the majority of these water crossings is to retrack the data to extract that part of the signal returning from a water surface at nadir.

REFERENCES