Global digital elevation

Philippa A M Berry applies satellite altimetry to dry land and finds errors in the elevation models.

Satellite altimetry has been used for many years to monitor the dynamic sea-surface topography. Results from this work have led to major advances both in geodesy and in physical oceanography over the past couple of decades, with data from a series of satellites including Seasat, Geosat, Topex/Poseidon and ERS-1 and -2 making major contributions to our understanding in these fields.

The advent of ERS-1, launched in 1991 into an orbit at high inclination (~98°) produced the first coverage of parts of Antarctica, with its “ice tracker” mode allowing the altimeter to maintain contact with the surface over varying terrain far more successfully than with previous missions. Research into cryospheric mapping, fuelled by the Antarctic mass balance question, has thus advanced rapidly over the past few years, pushing the limits of applicability of altimetry in this domain (e.g. Bamber et al. 1997). However, land altimetry has received comparatively little attention, despite the fact that ERS-1 and ERS-2 have collected a huge volume of data from the Earth’s land surfaces. In particular, the ERS-1 satellite collected a unique dataset, sampling much of the Earth’s land surface whilst in ice mode during its geodetic mission.

During this one-year period, the satellite orbit was configured such that instead of maintaining a short “repeat cycle”, overflying the same ground tracks periodically, it built up a closely spaced network of tracks with no repeat passes at all, giving a unique opportunity for land topographic studies.

In this paper, one application of these data is explored; the use of altimeter-derived topographic information to validate the ground-based height datasets contained within Global Digital Elevation Models (GDEMs).

Altimetry

Pulse-limited altimeters such as those carried by ERS-1 and ERS-2 send series of chirped microwave signals to the Earth’s surface, and recover the returned echoes. In ideal circumstances over the ocean, an echo or “waveform” response is observed as in figure 1. The two-way time delay is then used to obtain a range to surface. Corrected for delays as the signal propagates through the atmosphere, and with the addition of accurate orbit information and a tidal correction, the height of the underlying surface above some reference shape (usually an ellipsoid) can be determined to an accuracy of a few centimetres (figure 2). Over land, the rapidly varying topography gives rise to complex echo shapes (figure 3), and the onboard processor is unable to calculate an accurate range to surface. In order to use these data, each individual waveform must be reprocessed, in a procedure known as retracking, analysing the echo shape to try to determine which time point in the returned waveform corresponds to the mean range to surface. This is a complex problem. One way of proceeding is to sort the echoes according to shape, and attempt to determine relationships between different waveform characteristics and underlying topography that will allow the mean range to surface to be deduced.

This approach has been used to analyse the returns from ERS-1 and ERS-2 obtained over land, using a rule-based expert system (Berry et al. 1997a). Within this processing scheme, each waveform is analysed individually, and the system decides which one of a number of retrackers is most appropriate to reprocess the echo to obtain an orthometric height estimate. The principle limiting factor is the inability of the altimeter, which was designed primarily for ocean monitoring, to keep tracking over the surface – “maintain lock” – over very rough terrain, even when in ice mode. Thus, over the
models – fact or fiction?

Ground truth datasets

Over the last few years, a succession of Global Digital Elevation Models (GDEMs) has been produced, with spatial resolution between 10 arc minutes and 30 arc seconds. These GDEMs are a compendium of ground truth datasets of varying resolution and accuracy. Information about the origin and precision of input data is often sketchy or non-existent. However, different GDEMs can show good agreement over significant proportions of the continental land masses (e.g. Arabelos and Tscherning 1999). This paper presents results from a near-global evaluation with altimeter-derived heights of two typical recently generated GDEMs: GLOBE, and JGP95E.

The GLOBE GDEM, produced by the National Geophysical Data Center, exists both in early beta release, containing data for about 60% of the Earth’s land surface, and with full coverage at version 1. The spatial resolution of this GDEM is 30″, corresponding to about 1 km at the equator.

JGP95E is a GDEM with a spatial resolution of 5′ and complete coverage of land surfaces, with additional bathymetric data over the oceans (Lemoine 1998). This dataset was produced as part of a collaboration between NASA/GSFC and the US Defence Mapping Agency as part of the development of the global gravity model EGM96.

Altimeter-derived dataset (RAR)

Altimeter Waveform Product data (ALT.WAP), which contain information on the altimeter echoes from the surface, are distributed as orbit-based products on exabyte tapes by the European Space Agency. With about three days’ worth of orbits on each tape, and about 120 tapes containing 160 Gbyte of WAP data produced by the ERS-1 geodetic mission alone, processing these data is a significant task. In order to utilize them for land-based studies, each orbit of data is first preprocessed using a suite of algorithms which re-implement key components of the WAP processing scheme, discard error-flagged and ocean data, and segment the data by geographic region into 15° areas (for ease of handling). The data are then piped through the current version of the expert system, which recalculates a range to surface from each waveform for which the first part of the echo – the leading edge – has been received. This process transforms upwards of 80% of the echoes into orthometric heights (heights above mean sea level), using a system with ten discrete classes of waveform shape. Most of these return shapes have a known relationship with the underlying terrain type, and returns are processed differently according to the way in which the terrain is found to affect the waveform shape. The output of this system is an ellipsoidal height, referenced to the ellipsoid model WGS 84. This is then transformed into an estimate of orthometric height by using a global geoid model to predict where sea level would be, relative to the ellipsoid, if the land did not exist, and subtracting. From the ERS-1 Geodetic Mission, this approach has yielded over 100 million height estimates with near global distribution spaced along tracks a few kilometres apart at the Equator: the RAR dataset (Berry 1999).

Altimeter data verification

Before using these altimeter-derived heights to assess existing GDEMs, the accuracy of the altimeter data must be confirmed. To this end, global crossover analyses have been performed, comparing heights obtained from data on ascending and descending arcs near crossover points. The global statistics of crossover differences, for every land crossover from the ERS-1 geodetic mission, are given in figure 4; details are presented elsewhere (e.g.
Dowson and Berry 1997). The results show that over 40% of the heights of crossover pairs (comprising datapoints on ascending and descending arcs that lie within a nominal 300 m ground separation) agree to within 1 m vertically. Further comparisons with detailed ground truth have also confirmed the accuracy of the altimeter-derived height dataset (e.g. Berry and Thornton 1998), indicating that for specific classes of waveform shape, the effective footprint (the part of the ground contributing significantly to the returned echo) can be as small as a few hundred metres across. This observation is attributed to the relatively poor performance of land as a reflector of radar altimeter signals, as compared to the response over water and ice.

**GDEM comparison**

For every pixel of the GLOBE GDEM for which RAR heights were available, the two datasets were compared, and difference maps and statistics were calculated over each 1° square. Analysis of these results revealed a “patchwork quilt” effect, with relatively small areas, generally 1° squares, showing relative vertical displacements from a few metres to a few tens of metres. This result was not unexpected, since some of these effects had previously been observed in the GLOBE beta release (Berry et al. 1997). There is no mechanism whereby the altimeter data can produce this type of error; false illumination or “shadow mapping” of affected areas confirmed that these discontinuities reside in the GLOBE dataset.

To facilitate intercomparison with JGP95E, both the GLOBE and the RAR datasets were averaged to 5°, and the comparison with averaged RAR data repeated for both GLOBE and JGP95E. This resulted in the generation of thousands of bitmaps and statistics files. Some-what unexpectedly, examination of the JGP95E difference maps revealed similar tile effects peppered over the JGP95E land surface representation. This initiated an examination of both datasets for commonality, looking for similar geometric patterns of differences. Such patterns were found to exist in many of the difference plots, generally indicating the presence of systematic errors in the ground truth, common to both GDEMs. Such errors are well illustrated in the picture on the cover, which shows a mosaiced difference file over South America of (RAR – JGP95E) with differences plotted from –80 m (dark blue) to > 80 m (dark red). (Yellow and green indicate low differences.) It is worth noting that a significant proportion of these effects persist at difference scales in excess of 100 m in both JGP95E and GLOBE.

The overall analysis of both global difference sets, together with an examination of the coverage and performance of the early GLOBE beta release, has revealed several distinct categories of differences. These characteristic effects are summarized here, together with illustrative examples drawn from the very large archive of difference files. The effects fall into two primary categories of confirmed DEM error, artefacts, and geographically related differences.

**Artefacts**

Two classes of common “artefact errors” have been identified in the difference maps generated: tile effects and regional artefacts.

Tile effects are evident as “tile” offsets, typically running along the 1° boundaries of a single 1° × 1° tile, or across a group of adjacent tiles. These effects, typically a few tens of metres in vertical offset, are seen over most of the world, even across Europe and North America. A typical example of a common tile error dataset is given in figure 5. Two sets of differences are presented: figures 5a and 5c show the RAR–JP and RAR–GLOBE results at ± 40 m, and figures 5d and 5f show the corresponding images at ± 120 m. Comparison with the early GLOBE beta release (figure 5b, at ± 40 m) shows that the pattern of these tile effects often corresponds to the availability of GLOBE-beta information, suggesting that missing data have been infilled from some less accurate model. Unexpectedly, however, the same patterns of differences may also be seen in JGP95E (as illustrated in figure 5). Note that some of these errors are still very apparent at excess of 120 m. Figure 5e shows the JGP–GLOBE image of the same region, at ± 120 m, to illustrate the much smaller expression of the common error signature in the GDEM difference dataset, as expected.

Regional artefacts are much larger, more significant both in spatial extent and, typically, in vertical offset, showing clear boundaries which do not necessarily run along degree edges, but do sometimes match political map divisions.

One of the worst common offsets found, the central part of the “Siberian red” offset, was first identified in the GLOBE beta release (Berry et al. 1998) and has now been found to be common to both GLOBE version 1 and JGP95E. This error runs above 250 m, in striking horizontal lineations, in total across 25° of longitude and between 5° and 10° of latitude.

**Topographic features**

These differences group in a way closely related to terrain, and are widely observed. Figure 6 shows topographic offsets observed in GLOBE and JGP95E across a region including the Amazon river delta. The Amazon river is clearly visible, running across the upper part of the images, the yellow and green colouration in these difference plots confirming that the GDEM data are reasonably accurate over the Amazon river and immediate surroundings, but far from accurate elsewhere! These difference patterns are observed in areas where the terrain variation is actually very gentle, and altimeter loss of lock is not observed. In such areas, the altimeter data are found to be highly accurate; in fact, over the Amazon basin, the altimeter heights from the RAR dataset are so consistent it is possible to map to better than 1 m vertically over much of the region. The difference signatures, which even in this example can exceed 80 m, and in many cases run to hundreds of metres, are attributed to lack of high frequency information in the DEM representation of terrain, with adjacent pixel values...
of metres, where topographic variation has been insufficiently sampled by existing models.

Wider implications

GDEMs are used in various applications, ranging from global climate models to terrain correction of remotely sensed imagery. The effect of errors in the terrain representation varies with the application; for some, the effect will be considerable. It is inevitable, for example, that the error signatures contaminating JGP95E will have had a significant effect on the global gravity model EGM96, especially over South America, Africa and parts of Asia. In general it is the model users who are best placed to assess the impact of these GDEM errors on their research results. It is therefore essential that users of GDEM data appreciate the scope and location of the defective datasets residing in the current generation of GDEMs.

Altimeter data have a vital contribution to make, both in detection of these errors and in correction of them. This research is already producing quantitative assessments of these large common error datasets, and work is continuing to determine the best way to derive and apply corrections to GDEM data. In areas where the entire ground truth dataset appears to be corrupted, and the spatial sampling of the altimeter data prohibits accurate direct mapping, this work will enable future mapping effort to be prioritized to those regions where reasonable topographic representation is non-existent in the public domain.

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References

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