Comparison of ERS altimeter and GPS heights on the Amery Ice Shelf, East Antarctica

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Abstract

A Global Positioning System (GPS) survey has been carried out on the Amery Ice Shelf, providing "ground-truth" measurements of ellipsoidal height for the ERS-1 and ERS-2 satellite altimeters. A 120 km by 20 km grid made up of 10 km squares was established on the ice shelf using kinematic GPS techniques. A local tidal signal was subtracted from the GPS data, producing profiles relative to a tide-free surface. Contemporaneous ERS altimeter waveform data over the survey region were retracked and tide-corrected, producing altimetric height profiles. Two approaches were used for comparison. Firstly, GPS and altimeter heights were compared at intersecting points of the two types of surface profiles. Secondly, a gridded surface was generated from the GPS data and resulting surface heights compared with altimeter heights along the satellite ground tracks. In both cases the combined mean and RMS of the height differences over the region were 0.2 m and 1.7 m respectively. Along individual profiles, the RMS difference was 0.5 m where the surface was relatively flat, and 2.9 m where it was more topographically variable. The survey has provided an excellent "ground truthing" reference surface for ERS altimeter data, which are being used within the Antarctic CRC to generate a precise, high resolution digital elevation model for the Lambert Glacier - Amery Ice Shelf system.

Keywords: altimeter, Amery, GPS

1. Introduction

The periodic monitoring of the ice sheets and ice shelves of Antarctica and Greenland using satellite radar altimeters has long been proposed by the climate change and glaciological communities. Processing of altimeter data collected over ice-covered surfaces requires different treatment to those collected over ocean surfaces, for which the instrument was originally designed: ice-covered regions have sloping surfaces with undulations of a wavelength comparable to the diameter of the altimeter pulse-limited footprint, making the response of the altimeter over this type of surface considerably more complex than over an ocean. Table 1 outlines the major sources of possible height biases inherent in satellite radar altimeter data collected over ice shelves, and where possible the approximate magnitude is given.

Error/bias	Magnitude
Radial orbit error	10-30 cm
Tracking error	+/- 20 m
Surface penetration	< 2 m (Ref. 1)
Seasonal variation	< 30 cm (Ref. 2)
Terrain variation	unknown
Tide	1-2 m
Propagation delays	~2.3 m total

Table 1. Major sources of height biases, and their approximate magnitudes, in satellite radar altimeter data collected over ice shelves.

After all corrections have been applied, the internal consistency of the altimeter data can be determined by comparing surface heights along repeating tracks, and at exact crossover locations. However, in order to assess the quality of the absolute measurement and to determine how well the altimeter profile represents the true surface, an independently surveyed reference surface is required. This paper presents preliminary results of a kinematic GPS survey designed to provide "ground truthing" for the ERS-1 and ERS-2 altimeters, carried out on the Amery Ice Shelf, East Antarctica during the Austral spring of 1995.

2. The GPS field survey and data processing

The field program took place on the Amery Ice Shelf between 25th October and 14th November 1995. A 120 km by 20 km grid made up of twenty four 10 km squares was surveyed using kinematic GPS techniques. The orientation of the survey grid on the ice shelf is shown in Figure 1, together with the ground tracks of the ERS orbits which cross it. Six base camps were established along the centre line of the grid at 20 km spacing, which served both as reference stations for the kinematic GPS measurements and also enabled horizontal and tidal signals to be computed. The survey used two Leica 299 geodetic GPS receivers, one serving as a local reference station at the base camps, and one mounted on a ski-doo which was driven around each of the four 10 km squares surrounding the base camps, at approximately 10 km/h using a sampling interval of 5 seconds. A fixed reference station for the survey was located on rock at Beaver Lake (a small tidal lake adjacent to the western edge of the ice shelf), using a third Leica 299 geodetic receiver observing at the same sampling interval.

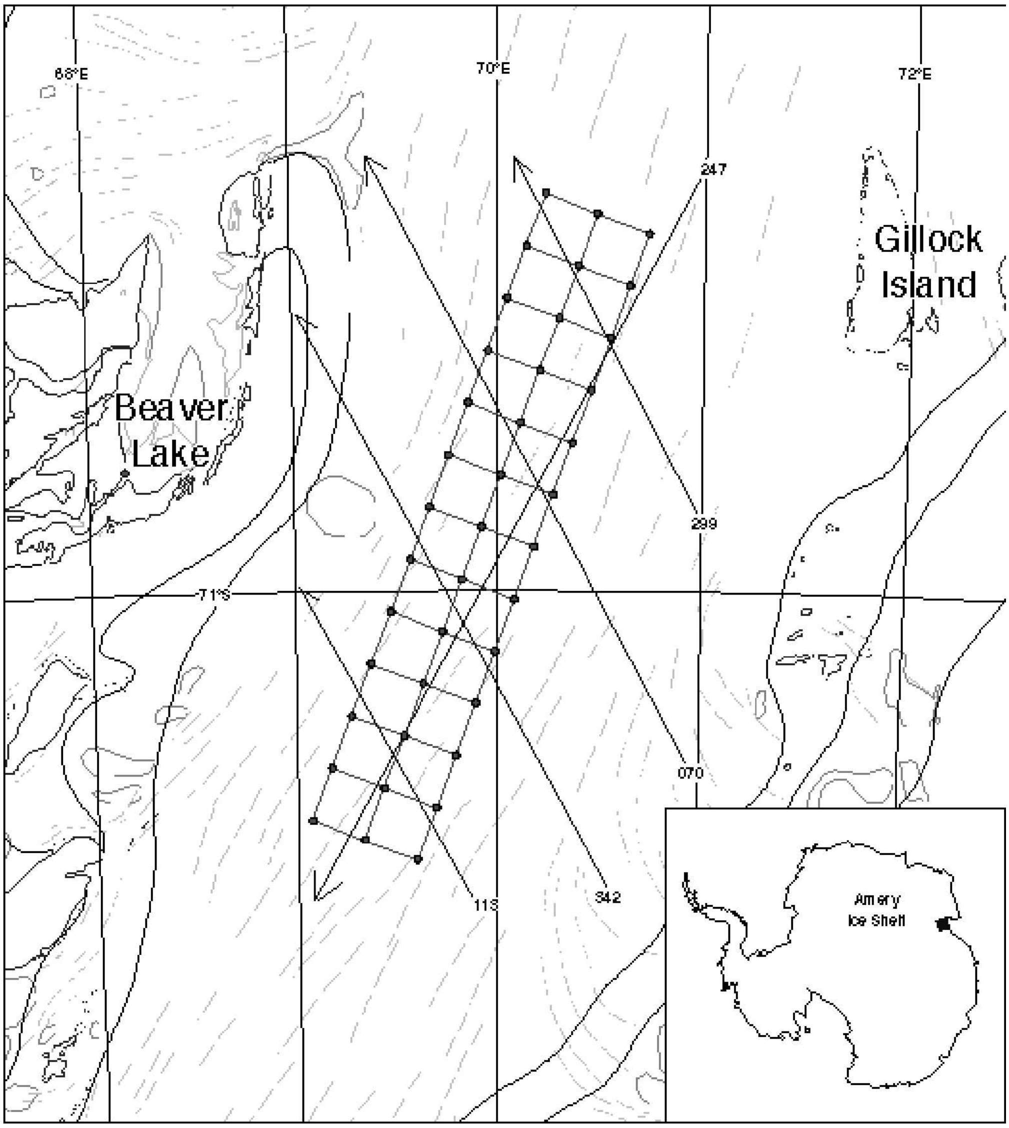


Figure 1. Location of survey grid and ERS altimeter ground tracks on the Amery Ice Shelf. The grid dimensions are 120 km x 20 km (adjacent grid nodes are 10 km apart). Base camps were established at every second grid node along the centre line. Arrows on ERS tracks indicate the direction of satellite travel.

The reduction of GPS kinematic data relies on having at least one known stationary point. There were two options for this survey: the Beaver Lake rock site or an Amery base camp. The first option provides the most stable station but has the disadvantage of having longer baselines (60-100 km), and hence uncertainties in resolving ambiguities. The base camps are in constant horizontal and vertical motion due to ice flow and tides, and differential processing with the rover unit on the ski-doo is problematical with conventional GPS processing software. To minimise these effects the data were processed using both options, and the results combined. GAMIT was used for the static GPS processing and Leica's Static KInematic (SKI) software for the kinematic data.

With the base camps as the stationary point, only 2 out of 24 squares of kinematic data processed completely, others could only be processed part-way round a square. Using the Beaver Lake site, 21 out of 24 squares processed completely, although ambiguities were not resolved. The GPS closure, ie. the RMS differences in the base camp station coordinates between the start and finish of the survey, was approximately 0.4 m in all three components (latitude, longitude and height).

3. Altimeter data processing

As seen in Figure 1, there are five ERS satellite ground tracks which cross the survey grid. There are two repeat cycles of ERS-2 and one cycle of ERS-1 currently available from October and November 1995, all in ice mode. The dates and times of the different passes are listed in Table 2. By using altimeter data from the same time period as the field survey we hope to have minimised any temporal height bias.

Track	Direction	Dates
070	ascending	6, 7 Oct, 11 Nov
113	ascending	9, 10 Oct, 14 Nov
247	descending	19, 20 Oct, 24 Nov
299	ascending	22, 23 Oct, 27 Nov
342	ascending	25, 26 Oct, 30 Nov

Table 2. Track number, direction and date of each repeat, for ERS tracks over the survey grid, from the same time period as the GPS survey.

There are several stages to the altimeter data processing:

3.1 Merging of precise orbits

Highly precise ERS orbits (relative to the WGS-84 ellipsoid) produced with the Delft Gravity Model DGM-E04, based on satellite laser ranging, altimeter residuals and altimeter crossovers, have recently been made available from the Delft University of Technology (Ref. 3). These orbits were used to update the spacecraft position, therefore minimising the radial orbit error.

3.2 Retracking

The power received from each return altimeter echo is recorded as a waveform within a finite width range window, quantised into 64 range bins of equal width (1.82 m in ice mode) with the leading edge corresponding to the initial interaction with the surface. The range measurement is made to the mid-point of the range window and therefore to obtain the true range, the distance to the leading edge needs to be determined. The technique used to do this is the simple Offset Centre of Gravity (OCOG) algorithm described in Ref. 4. A percentage threshold value, determined by the total power under the waveform, is used to locate the retrack point on the leading edge. This is converted into a range correction which is then subtracted from the range. Retracking corrections in this analysis have been made using the 10%, 25% and 50% threshold values.

3.3 Tidal correction

Ice shelves undergo vertical motion as a result of ocean tide interaction. Each surface height profile can be thought of as a "snap-shot" of the instantaneous ice shelf surface at the observing epoch. For any point on the ice shelf surface, to a first approximation, the height ht above the ellipsoid is made up of the tide-free height component (h0) and the temporal tidal height component (Δ htide) ie. ht = h0 + Δhtide. To compare heights measured at different epochs it is necessary to remove the tidal height component and use the mean height component.

The ocean tide values supplied in the altimeter records are not valid over ice shelves. A tide model, constructed from tide observations collected over a 22 day period during 1990-91, is available for Beaver Lake from the National Tidal Facility. Our GPS static processing results show that the Amery Ice Shelf responds hydrostatically, with little or no damping effects, to tidal forcing at 5 of the 6 base camps and that the tidal signal mimics the tide values predicted by the Beaver Lake tide model to within 1-5 cm (Ref. 5). The Beaver Lake tidal model has therefore been used to correct both the kinematic GPS data and the ERS altimeter data for this analysis. All altimeter and GPS heights collected on the Amery Ice Shelf were referenced to the same datum (epoch fixed), using the predicted tidal value for the observing epoch.

3.4 Atmospheric and ionospheric corrections

Mean atmospheric and ionospheric corrections calculated from in situ data were subtracted from the altimeter range value, in place of those provided with the altimeter records. A dry tropospheric correction of 2.23 m was used, based on a mean value of measured daily air pressures for the Amery Ice Shelf survey period of 983 hPa. Data from atmospheric balloons launched at Davis and Mawson were used to calculate the total integrated water vapour values for the survey period. The average value was 3.7 kg/sq. m, corresponding to a wet tropospheric correction of 2.6 cm. For the ionospheric correction, a simple total electron content (TEC) shell was constructed for the Amery region from GPS data collected at Mawson, and the TEC calculated along the ERS propagation path. The delay due to the ionosphere for the survey period ranged from 0.5 - 16 mm, thus an average correction value of 9 mm was used.

4. Inter-comparison of GPS and ERS altimeter data

There is a fundamental difference between the height measurement returned by the two systems under consideration. For ERS, it is a mean height for the whole altimeter pulse-limited footprint (approximately 2 km in diameter), whilst for GPS it is a height of a single point in space.

Two methods for inter-comparison were used in this study, as outlined below.

4.1 Direct comparison at intersecting points.

There are 87 intersecting points (3 cycles with 29 crossovers per cycle) between the ERS tracks and the GPS survey, as shown in Figure 1. Each of the ascending ERS tracks had four or five points of intersection along their length while the descending track had ten. Linear interpolation was used to obtain the two height values at the exact point of intersection.

Figure 2 shows histograms of the height differences between the GPS profiles and the altimeter profiles, at the three retracking thresholds, and Figure 3 illustrates the spatial distribution of these differences over the region, at the 25% threshold level. The means and RMS differences in metres are shown in Table 3.

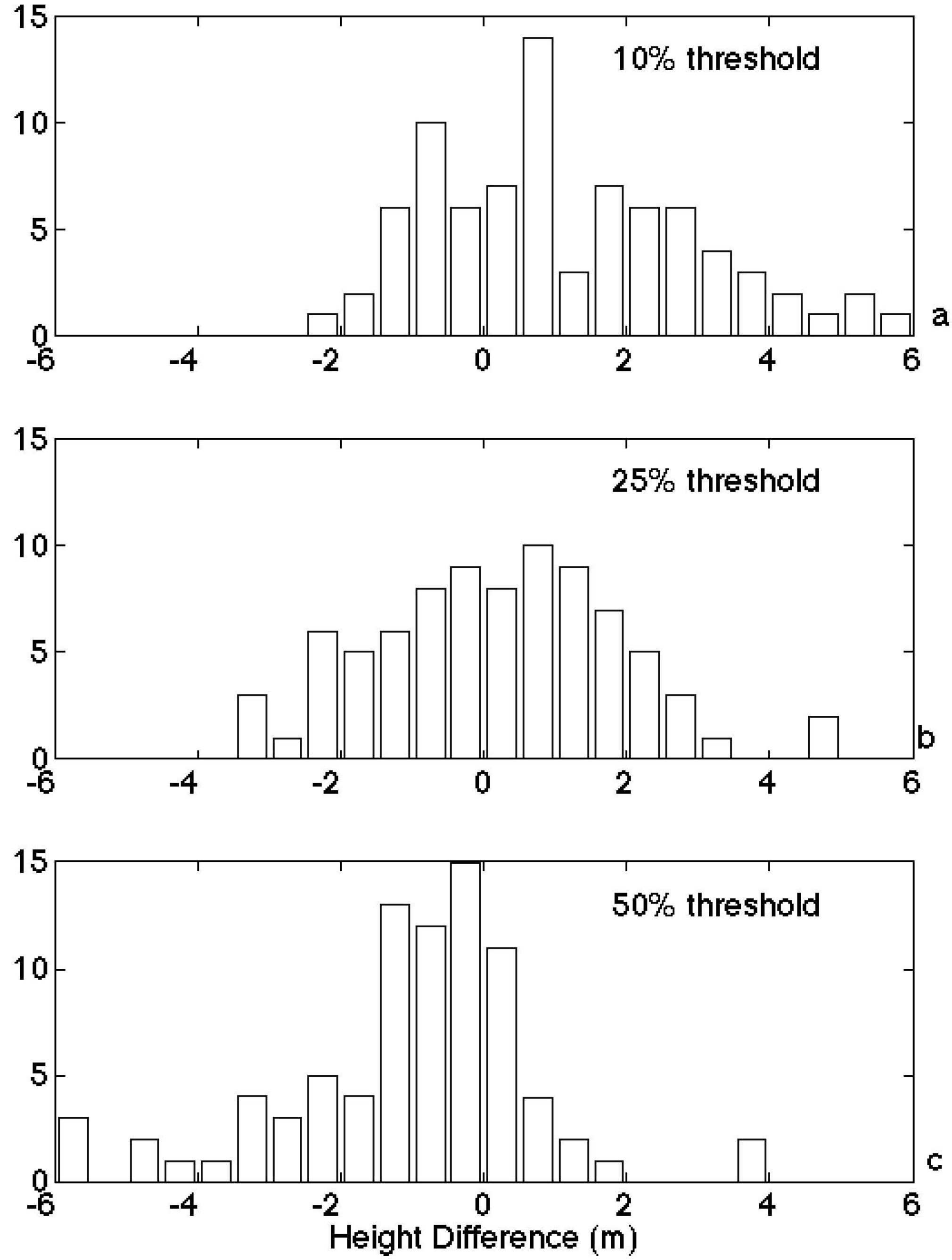


Figure 2. Histograms of height differences, for the 87 intersecting points of the ERS tracks and GPS grid (3 cycles and 29 per cycle); bin width used is 0.5 m.

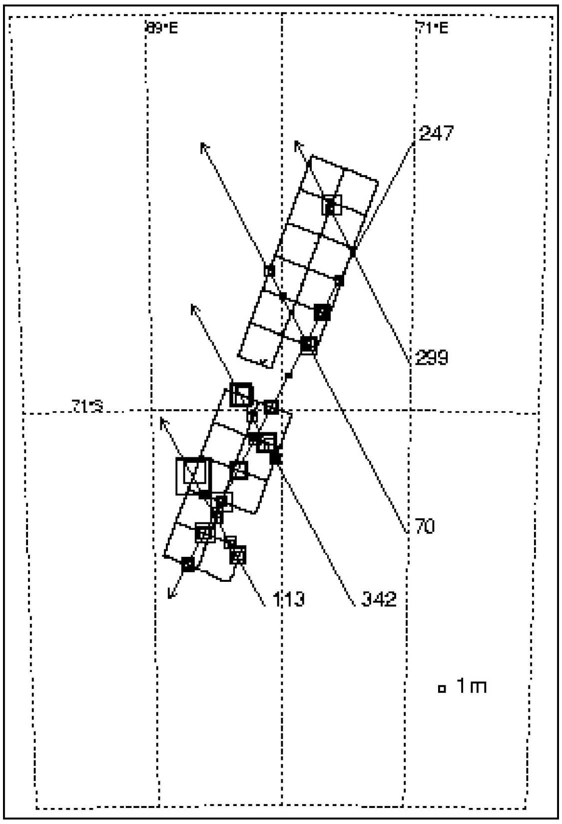


Figure 3. Spatial distribution of height differences at intersecting points of ERS tracks and the GPS survey grid. The sides of the squares are scaled according to the magnitude of the RMS height difference; the inset square represents an RMS of 1 m.

Threshold	Mean (m)	RMS (m)
10%	1.2	2.0
25%	0.2	1.7
50%	-1.0	1.8

Table 3. Mean and RMS of the height differences at the 87 intersecting points of the ERS tracks and the GPS grid.

It can be seen from these results that the 25% threshold produces the best agreement with the GPS data, and that the height differences are greater in the south-western region of the survey. Indeed, when considering just the intersecting points which lie in the northern part of the survey region, the RMS height difference at the 25% threshold reduces to 1.2 m.

4.2 Comparison of surface height profiles

To compare the altimeter height profiles with the GPS data, a gridded reference surface over the surveyed region was created from the tide corrected kinematic GPS profiles. The technique chosen for the gridding was "kriging", a geostatistical technique which produces an optimal prediction of the surface at unobserved points (Ref. 6).

The resulting gridded surface is illustrated in Figure 4. It can be seen from this plot that the survey covered a wide variety of topographic features, with some relatively large height changes. Towards the northern end of the surface, the topography is relatively smooth, whereas in the southern end two longitudinal depressions are revealed, approximately 2 km wide and about 5 m lower than surronding surface. These features are refrozen meltstreams, which at the time of the survey were still frozen from the previous winter. For the comparison with altimeter heights, the grid resolution of the GPS height surface was increased to 2 km, the approximate diameter of the altimeter pulse limited footprint.

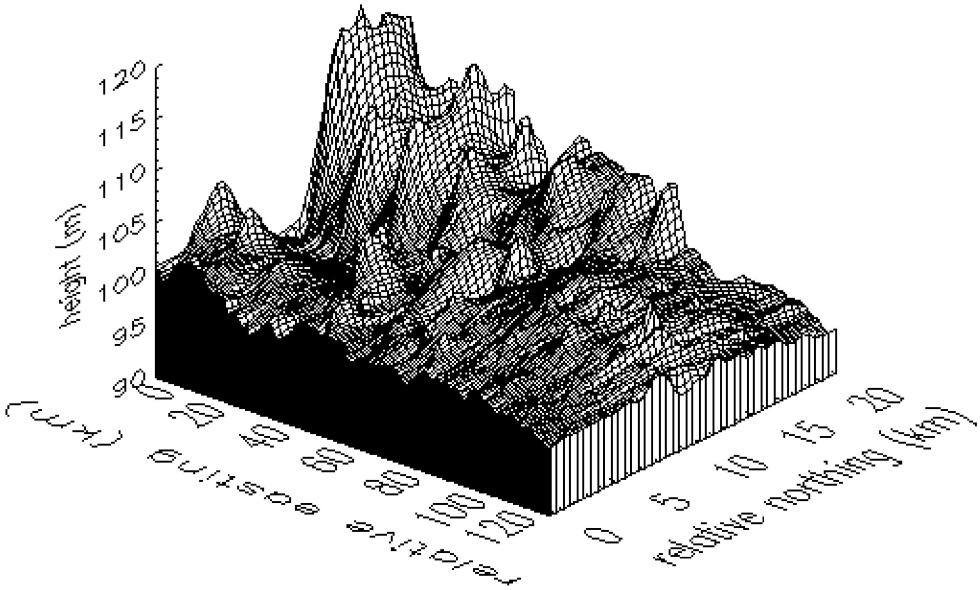
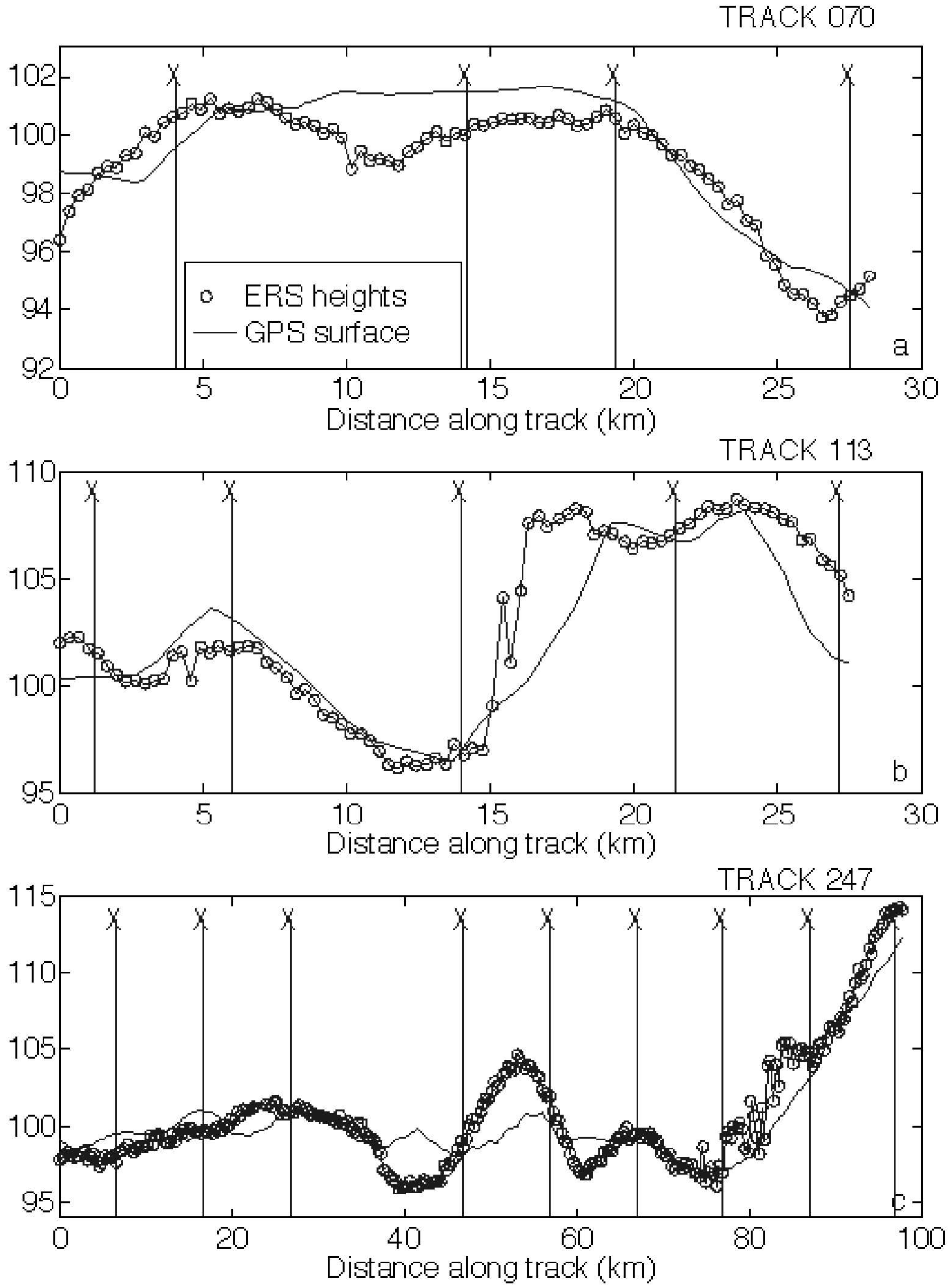


Figure 4. GPS surface generated on a 0.5 km grid using kriging, with a spherical semivariogram model (range = 7865.784 m and sill = 8.475 sq. m). Units of the X and Y axis are local eastings and northings (km) with the origin in the south-east corner, latitude 71.43°S, longitude 69.60°E. Note that the units of the Z axis are metres, therefore the plot is greatly exaggerated in this direction.

The resulting height profiles along three of the five ERS tracks are shown in Figure 5. The profiles, using the 25% threshold, are plotted against distance in kilometres along the ground track, making the direction of satellite travel from left to right. Only one repeat of each ERS track has been shown, as the tracks repeat very closely. Track 70 is shown in Figure 5a; this track has the least topographic variation and it can be seen that the altimeter follows the surface reasonably well. The profiles along track 113 shown in Figure 5b, however, clearly illustrate the problems in using an altimeter to realistically reproduce rougher surfaces. For example, the small 3 m surface bump at 5 km is under-estimated using the 25% threshold, and the 10 m rise at 20 km is detected early by the altimeter, as soon as it comes into the pulse-limited footprint. The long descending track (247), shows a good agreement over the majority of the surface (Figure 5c). The surface bump in the altimeter profile at 50 km is a real feature, but located to one side of the ground track and therefore not present in the sampled GPS profile.



Figures 5. Height profiles along three of the five ERS tracks. The interpolated GPS surface, sampled along each track., is shown as a solid line. Each intersecting point between ERS tracks and the GPS survey grid is marked with a cross.

The mean and RMS of the differences between the ERS altimeter heights, h(ERS) and the interpolated GPS heights, h(GPS) along the tracks gives an estimation of accuracy for that track. For each track the mean and RMS errors using the 25% threshold value (all three repeats combined) are given in Table 4a, and the combined mean and RMS errors for all tracks at the three thresholds in Table 4b.

Track	Mean (m)	RMS (m)
070	-0.4	0.5
113	1.5	2.9
247	1.0	2.7
299	-0.7	1.2
342	0.7	1.9

Table 4a. Mean and RMS height differences, h(ERS)- h(GPS) at the 25% retrack threshold for each ERS ground track (all three repeats combined).

Threshold	Mean (m)	RMS (m)
10%	1.2	2.0
25%	0.2	1.7
50%	-1.0	1.8

Table 4b. Combined mean and RMS height differences at different thresholds, for all three repeats of all five tracks.

5. Contributions to observed height differences

The observed height differences, h(ERS - h(GPS) between the ERS altimeter heights and the GPS heights may consist of a number of components, as outlined below:

Radial orbit error: the radial precision of the Delft orbits is approximately 9 cm.

Propagation delays: after applying mean values for the atmospheric and ionospheric corrections based on in situ parameters, the maximum height bias remaining is approximately 6 cm.

Tide: The estimated error in the Beaver Lake tide model is 1 cm. The error in using the Beaver Lake tide model for the Amery Ice Shelf is approximately 5 cm. There will however be a greater discrepancy in any regions of the ice shelf which are partially sticking.

Retracking error: the RMS error introduced by the OCOG retracking method is 49 cm per waveform in ice mode (Ref. 7). This amounts to ~5 cm for the ascending tracks (86 waveforms) and ~3 cm for the descending track (296 waveforms).

The total combined RMS error remaining after correcting for the orbit error, propagation delays, tidal motion and tracking error is approximately 13 cm. The potential remaining sources of bias are:

Terrain bias: the shape of the altimeter waveform received by a radar altimeter is dependent on the properties of the surface with which the pulse interacts, and will be distorted to a varying degree, depending on inhomogeneities on the surface. No simple retracker can account for these non-uniform waveforms, and techniques such as waveform migration (Ref. 8) are being developed to cope with this problem.

Surface penetration: this problem has been approached by Davis (Ref. 9) in his surface and volume retracking program, but has not been fully tested for ice mode waveforms, which have a wider range window and are more coarsely sampled.

Interpolation method: kriging, like any interpolation scheme, has limitations when attempting to produce a gridded surface from data sampled at high density along profiles that are relatively widely spaced. The resolution of the GPS gridded surface will be at a minimum in the centre of the survey squares, and therefore some topographic features seen in the altimeter profiles will most likely be missing or smoothed in the GPS surface.

Conclusions

It has been shown that the ERS altimeters are providing accurate ellipsoidal height measurements over the survey region, especially when surface topography is smooth. At the 25% threshold in the OCOG algorithm, the mean and RMS height differences along track are -0.4 m and 0.5 m respectively, which increases to 1.5 m and 2.9 m when there is varying topography. The combined mean and RMS height differences for all tracks across our survey region at the 25% threshold are 0.2 m and 1.7 m, both by the direct comparison of intersecting points and by comparing GPS heights along altimeter surface profiles. The spatial distribution of height differences is highly correlated with the surface topography evident in the gridded surface.

The total combined RMS error remaining after correcting for the orbit error, propagation delays, tidal motion and tracking error is 12 cm which, when considering the GPS closure error of 40 cm, does not fully account for the range of RMS values of height differences being obtained along individual ERS tracks. The only remaining sources of discrepancy are the biases arising from terrain effects and, to a lesser extent, surface layer penetration.

A combination of retrackers or an a priori knowledge of the surface topography would be required to extract the best possible height information from satellite altimetry over ice regions. This survey has provided an excellent "ground truthing" reference surface for ERS and future altimeter satellite missions due to the wide DEM swath and the high precision of the GPS coordinates.

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