A Global 5 arc minute Digital Elevation Model derived from the geodetic phase of ERS-1

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Abstract

A five arc minute digital elevation model (DEM) of global land surfaces has been produced from the geodetic phase radar altimeter data from ERS-1. The across-track spacing of the complete 336 day cycle is about 8.3 km at the equator (or, alternatively, » 5 arc minutes of latitude) providing probably the most extensive global elevation data set, publicly available. The altimeter data were processed using a system developed for ice sheets with some minor modifications to the filtering and waveform retracking schemes. No slope correction was applied for two reasons: i) the difficulty in determining the appropriate local slope and ii) it was found that there was no correlation between any slope estimate and differences with validation data. A comparison with eight point data sets, from regional to global in scale, and several pre-existing DEMs was carried out. The preliminary results of this comparison suggest that the altimeter data have a relatively small bias (0.5 m for all the point data sets together) but a relatively large random error (79 m). It is apparent that a small number of erroneous radar altimeter points still exist in the filtered data and that a further filtering step is required. Further comparisons are being made and improvements in the radar altimeter data analysis procedures are being explored.
Keywords: DEM, global, altimetry

Introduction

Digital Elevation Models (DEMs) are an important boundary condition in a wide range of scientific and commercial applications. Large parts of south America, Africa and Eurasia have a paucity of publicly-available elevation data and existing DEMs of these regions have substantial errors and/or data gaps. The geodetic phase, radar altimeter (RA) data from ERS-1 provide a unique, consistent and comprehensive elevation data set for mapping global land and ocean topography. Until the launch of the Shuttle Radar Topography Mission and the Geosciences Laser Altimeter Satellite (scheduled for 2000 and 2001/2 respectively) the ERS-1 data set is the best available for many parts of the Earth's surface, despite the limitations of a pulse-limited RA over land surfaces. These include a footprint size of up to 20 km, uncertainty in the location on the surface of where the returned echo came from, poor tracking of rough terrain and relatively poor spatial resolution (compared to other satellite technology such as SAR interferometry and. Pulse-limited RAs were originally designed for ocean applications, where the surface gradients are low. The RA onboard ERS-1 has a new feature allowing it to switch between two range resolutions. The lower resolution is known as ice mode and was designed to provide more robust tracking over the polar ice sheets and land surfaces. The geodetic phase data have been used to derive DEMs for Antarctica and Greenland to accuracies of between 1 and 10 m (e.g. Bamber, *et al*, 1997). Ice sheets, however, tend to be relatively smooth on a 5-50 km wavelength with gradients only exceeding the half-power beamwidth of the RA antenna in a small fraction of the margins (Bamber, *et al*, 1997). Other land surfaces tend to be more complex, with variable radar reflection properties and much "rougher" topography on all scales. The interpretation of RA data over land surfaces is, therefore, more difficult and, in general, less accurate compared to the ice sheets. Nonetheless, the RA can produce good results over certain land surface types, such as marsh lands, rain forests, deserts and salt pans-generally relatively flat regions (e.g. Frey and Brenner, 1990).

The objective of this work was to produce a global DEM from a single, consistent, data source and to compare this DEM with other publicly-available DEMs and validation point data sets to assess the accuracy of the RA-derived DEM as a function of surface type and regional topography. The RA processing methodology is outlined, briefly, in the next section. Some preliminary results of the comparison with other data sets follows this. A discussion of the results and future directions of this research conclude the paper.

2. DATA REDUCTION & METHODOLOGY
2.1 Radar Data

To improve the accuracy of elevation estimates over land surfaces it is necessary to apply a range estimate refinement procedure (known as waveform retracking). The method adopted here was similar to that used for ice sheet applications and was carried out using the offset centre of gravity method of calculating the wave-form amplitude, with a power threshold of 10% (Bamber, 1994). This threshold was chosen to obtain the "first return" from the surface, as this is the only unambiguous point in the waveform. It does not, however, represent the mean surface for a Gaussian distribution of surface slopes. For this, the 50% power point should be used. A more sophisticated approach would involve the use of an adaptive threshold dependent upon terrain type and waveform characteristics.

Appropriate data filtering is required over non-ocean surfaces due to frequent occurrences of anomalous height returns. Fourteen different tests were applied to the return echo wave-form shape, backscatter coefficient, and retracking correction value for each altimeter height estimate. About 60 % of the total global data were removed during this filtering procedure. The majority of these bad data were associated with the altimeter having lost "lock" of the surface, in areas of rapid changes in slope. A further step was required to remove the occasional spurious orbit. These were identified by comparing one track with another at the point where they cross each other (known as cross-over analysis). The majority of poor orbits were found to be close, in time, to orbit manoeuvres of the satellite, even though the orbit manoeuvre flag in the data product was not set and had not been for one-two revolutions of the satellite.

The data were then interpolated onto a 5 arc minute grid. The spatial distribution of the altimeter data is highly anisotropic – height estimates are separated by 335 m along-track and by up to 8 km across-track. To prevent introducing biases on individual grid points (due to the spatial sampling pattern and grid spacing) a two-stage gridding procedure was employed. The first step involved producing local distance-weighted means of x, y and z in the region of a grid point, producing a quasi-regular array of average height estimates. A triangulation procedure was then used to interpolate to the exact grid point locations (Renka and Cline, 1984) and to extrapolate to grid points where no altimeter data were present. For validation purposes, however, the averaged x, y, z values were used rather than the interpolated DEM. For Antarctica, the region south of 81.5° latitude was obtained from terrestrial data sources (Bamber and Huybrechts, 1996).

2.2 Validation Data Sets and Methodology

Several different data sets were available for comparison with the RA elevations including 30 arc second DEMs derived from the GLOBE data set (GLOBE, 1997). Eight point data sets were also available, which had already been compared with GLOBE, and, from this analysis, an order of accuracy established. The six data sets were (in decreasing order of accuracy based on the analysis with GLOBE):

1) NOAA_AFD - a regional set of 18,796 spot heights of airport runway locations covering the USA and possessions supplied by NOAA-NGDC.

2) JEP_PORT - a proprietary (Jeppesen) global set of airport runways (12,515) used in current avionics systems by commercial airlines.

3) DMANET93 - a global set of 7,148 DMA (NIMA) gravity base stations supplied by NOAA-NGDC.

4) JEP_NAV - a proprietary (Jeppesen) global set of airline navigation beacons (4,309) used in current avionics systems by commercial airlines.

5) AFRICA - a regional set of 14,300 spot heights referring to South Africa and Namibia supplied by NOAA-NGDC.

6) ANDES - a regional set of 3,393 spot heights referring to Bolivia, N. Chile and N. Argentina.

At present, the most detailed comparisons have been carried out with these six data sets, and the results will be, therefore, related to these. Comparisons with the GLOBE data set have also been undertaken (Muller, 1997) but are not presented here. Elevation differences were calculated for any two points that were within 5 km of each other. No interpolation to exact "match-ups" was possible and this will increase the standard deviation of the results but should not, in principle, affect any bias.

3. Results
3.1 The DEM

Figure 1 is a colour-scaled image showing the global DEM. The height range displayed is from 0 to 3000 m a.s.l. to allow visualisation of the major topographic features. This results in the higher mountain ranges becoming "saturated".

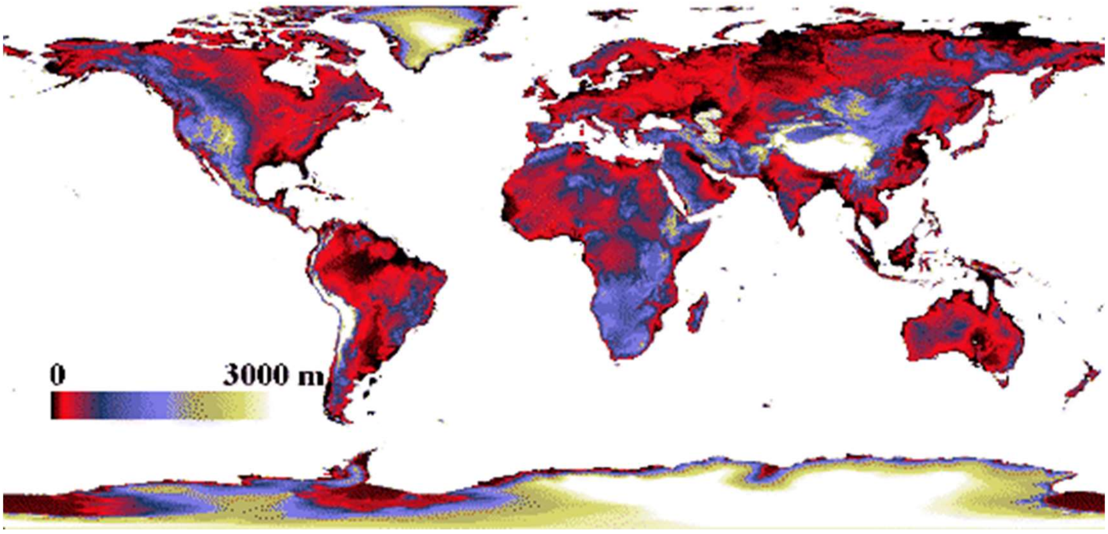

Figure 1. A colour scaled image of the global 5 arc-minute DEM. The elevation range shown is from 0-3000 m a.s.l.

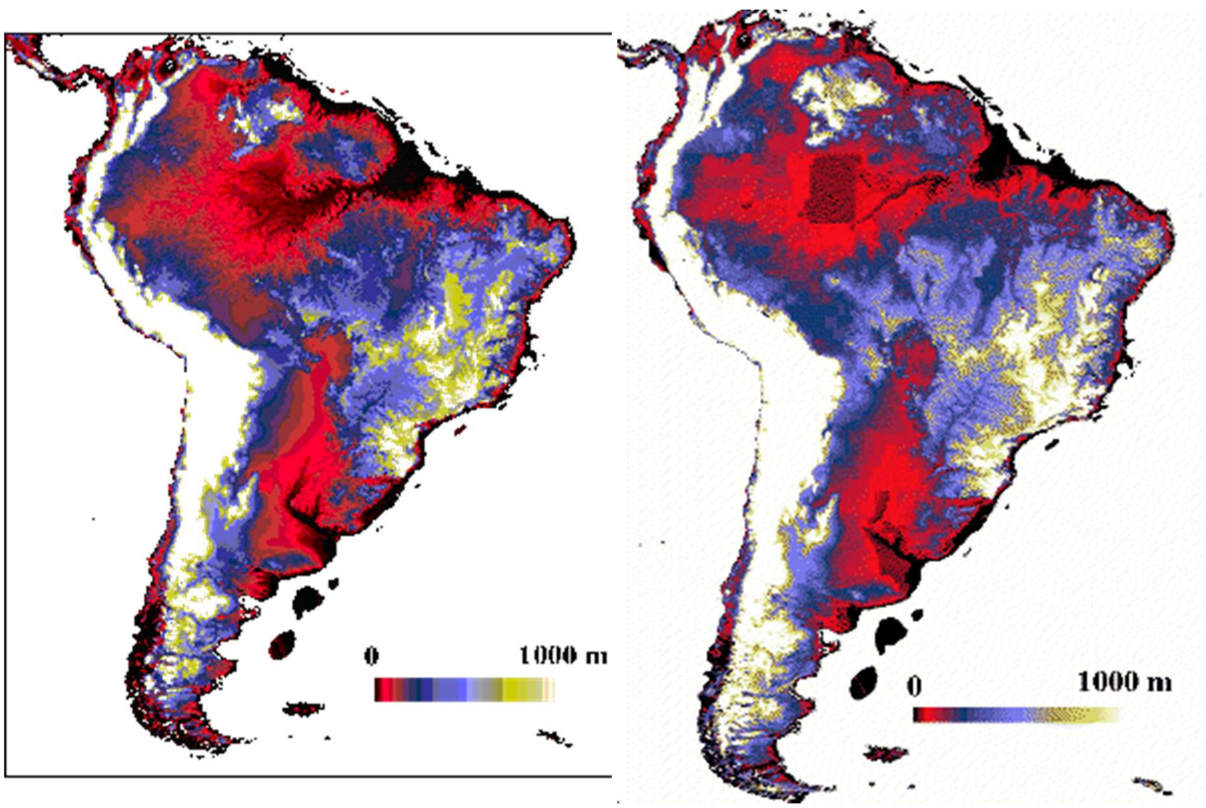

Figure 2. The RA-derived DEM of South America. Height range shown is 0-1000 m a.s.l.

Figure 3. The TerrainBase DEM of South America. Shown for comparison with the RA DEM.

Figure 1 is shown, primarily, to emphasise the global coverage of the data set. However, it does not adequately indicate the level of detail that is present in the DEM. To demonstrate this, an image for South America is shown in Figure 2. Individual tributaries of the Amazon and Paraná rivers are clearly visible and the topographic connection between the Orinoco and the Amazon can be seen.

To contrast with this, the 5 arc minute DEM distributed by the NGDC (on a CD-ROM titled TerrainBase: Row *et al*, 1995) is shown in Figure 3. Large data gaps can be seen around the Amazon and there is a general reduction in the spatial resolution of this data set over much of the continent. Other significant differences can be seen, for example, the shape and form of the Paran« flood-plain inland from Buenos Aires, which appears to be non-continuous in the TerrainBase DEM.

The first step in the interpolation of the RA data (the averaging procedure) allows the generation of standard deviations and number of points for the average height. The former provides an indication of the local height variability and acts as an additional simple quality control flag for the RA data. Large standard deviations (greater than, say, 100 m) indicate either very rough terrain and/or one or more erroneous altimeter measurements. A plot of the standard deviations for South America is shown in Figure 4 and the number of points used in Figure 5.

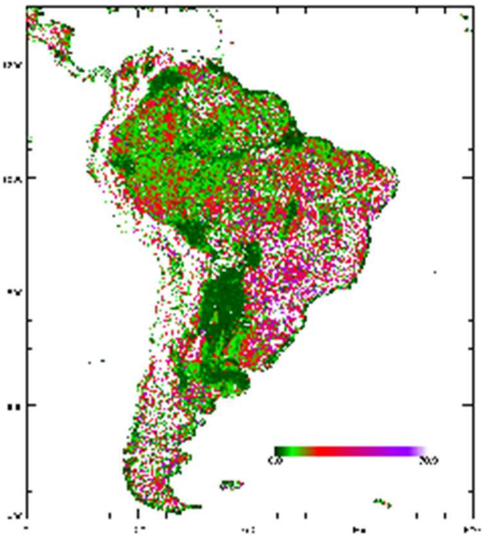

Figure 4 Standard deviations for average RA heights. Range 0-50 m.

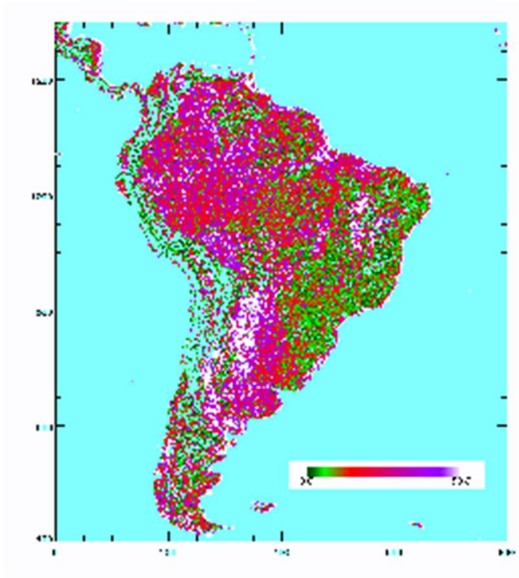

Figure 5. Number of points, N, used to produce the average heights. Range 0-50

The pattern in Figures 4 and 5 is expected. Higher standard deviations (and lower N) are associated with regions of high relief, the largest values being found in along the Andes and other mountainous regions. It can be seen that in some parts of these regions there are no valid altimeter data at all. In these regions the DEM consists of extrapolated elevations only. This problem is restricted almost exclusively to the Andes. The regions with the best coverage and lowest standard deviations are, primarily, Amazonia and the central region around Paraguay and the Paran« river.

3.2 Comparison with Point Data sets

A histogram of the differences between the RA and point data sets is shown in Figure 6.

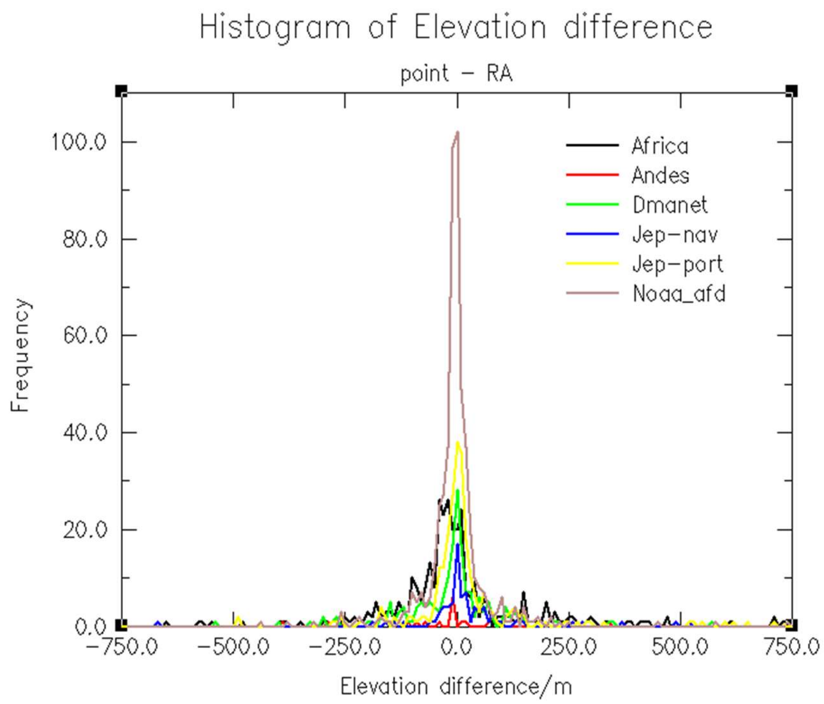

Figure 6. A histogram of the differences between the averaged RA heights and the six point data sets used in this study.

It can be seen from Figure 6 that, in all the comparisons, there a small number of large outliers. This is clearly visible in the most comprehensive data set (NOAA_AFD), that covers the USA. The distribution is not Gaussian and, in this situation, a more meaningful estimate of the accuracy of the data can be obtained from the full width at half maximum (FWHM) rather than from the standard deviation, which can be heavily influenced by the outliers. The FWHM for the NOAA_AFD data set is 32 m compared with the standard deviation of 93 m.

Table 1 provides some summary statistics for the six point data sets:

Data Set	***n***	***min***	***mean***	***max***	***RMS***	***sd***
AFRICA	345	-1159.87	3.96	1644.16	254.62	254.96
ANDES	28	-1156.74	89.57	1535.24	498.15	499.02
DMANET93	200	-1010.26	4.05	1304.72	163.22	163.57
JEP_NAV	98	-697.12	22.36	847.71	128.78	127.47
JEP_PORT	262	-255.58	10.76	749.70	83.59	83.05
NOAA_AFD	523	-1005.32	-3.77	585.20	93.24	93.26

Table 1. Statistics for the comparison between the point data sets and the RA elevations with no filtering applied.

As has already been mentioned, and as can be seen from the minimum and maximum differences in Table 1, a small number of large outliers are affecting both the standard deviation and means. In the following section, methods for removing the erroneous RA data are considered for future work as it is apparent that not all the erroneous RA data were eliminated by the filtering procedures. As a consequence, statistics were also calculated for all differences less than an absolute value of 300 m. These statistics are shown in Table 2.

Data Set	*n*	*min*	*mean*	*max*	*RMS*	*sd*
AFRICA	305	-290.40	-11.56	298.78	101.12	100.62
ANDES	21	-284.14	-30.99	103.30	109.11	107.20
DMANET93	191	-297.70	-3.14	285.19	81.89	82.05
JEP_NAV	94	-136.24	14.29	146.72	43.29	41.08
JEP_PORT	260	-255.58	5.88	256.50	61.22	61.05
NOAA_AFD	516	-255.58	0.00	256.50	58.38	58.44

Table 2. Statistics for the comparison between the point data sets and the RA elevations for differences < 300 m

4. Discussion

The mean difference, for all the point data sets was -0.488 ± 79 m for the filtered differences. The relatively large standard deviation is partly due to effects of the two points being compared not being at exactly the same location. For a regional surface slope of 0.5° the difference in elevation over 5 km is 43.6 m. It is also apparent, however, that "outliers" are still influencing the results. This is evident from the difference between the FWHM and standard deviation for the NOAA_AFD data set (32 m and 58 m respectively). This analysis has highlighted the need to apply a further stage of filtering to the RA data to reduce the number of erroneous height estimates and several approaches are being considered including reassessing the original filtering criteria and statistical analysis of the individual elevation estimates. A further step in improving the accuracy of the final DEM will be to include point data and elevations obtained from other DEMs in regions where no valid altimeter data exist such as in mountain ranges. The use of a different/multiple retrack threshold(s) will also be investigated.

One surprising result was the lack of correlation between height difference and surface slope (calculated from the RA DEM and the GLOBE data set over 20 km, which is close to the maximum footprint size). Over ice sheets the effect of slope induced error is very clear and not correcting for it introduces a bias in the data which amounts to about 30 m for a slope of 0.5° (Bamber *et al*, 1997). Ice sheets, however, have relatively small amplitude second-order slopes (or undulations) wheras land surfaces can have significant topographic variation at wavelengths of less than a kilometre. Consequently, it is difficult to determine the "appropriate" local surface slope for correcting the altimeter data with. Perhaps more important is the fact that a land surface will be made up of reflecting facets with a range of slopes with respect to the RA nadir angle and that those facets normal to the nadir will return a greater proportion of the EM radiation back to the instrument. As a result the altimeter may be effectively "viewing" the flatter regions within its footprint. These two effects could explain the lack of correlation.

5. Summary

A radar altimeter-derived global DEM has been presented and a comparison with several point data sets undertaken. The results presented here describe work that is in progress and are, therefore, of a preliminary nature. Various improvements to the RA data set are being considered and more accurate and reliable validation data sets are also being gathered for a more comprehensive validation exercise.

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