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The use of airborne laser data to calibrate satellite radar altimetry data over ice sheets

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Abstract

Satellite radar altimetry is the most important data source for ice sheet elevation modeling but it is well established that the accuracy of such data from satellite borne radar altimeters degrade seriously with increasing surface slope and level of roughness. A significant fraction of the slope-correlated noise can be effectively removed by the so-called relocation error correction method. The adjustment, however, produces a different spatial sampling of the data, which introduces a non-negligible slope related bias to the computation of digital elevation models. In this paper we incorporate high-precision airborne laser profiling data from the so-called Arctic Ice Mapping project as a tool to determine that bias and to calibrate the satellite altimetry. This is achieved by a simple statistical analysis of the airborne laser profiles, which defines the mean amplitude of the local surface undulations as a linear function of surface slope. This linear correspondence is in turn tested as a model for adjusting the satellite altimetry data for the observed slope correlated bias. The adjustment is shown to have a significant effect in terms of reducing the bias, thus improving the modeling accuracy of the data. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Ice sheet surface topography is an essential boundary condition for modeling their dynamics and a range of other glaciological applications such as estimating surface mass balance. Satellite radar altimeters (SRA) have been the primary source of data for producing ice sheet digital elevation models (DEMs). This is due to the fact that these instruments are the only sensor to date that have provided elevation data of sufficient coverage, accuracy and density over large regions of the ice sheet.

The first DEM, covering the southern tip of Greenland, was published in the aftermath of the first geodetic satellite, GEOS-3, (Brooks et al., 1978) and subsequently a number of others, primarily

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focusing on the large ice sheets of Antarctica and Greenland, were produced with altimetry from Seasat (Zwally et al., 1983), Geosat (Zwally et al., 1987), and ERS-1 (e.g. Bamber, 1994b; Ekholm, 1996). ERS-1, which was launched in 1991, is of special importance in this context as it extended the coverage from 72.1 to 81.5° thus covering the Greenland ice sheet in its entirety as well as 80% of the Antarctic ice sheet. Furthermore, the satellite in April 1994 was placed in what was known as the geodetic phase orbit consisting of two offset 168 day repeat cycles providing across track spacing of approximately 8 km at the equator, reducing to approximately 4 km at 60°. The predecessor of ERS-1, Geosat, operated in a similar geodetic phase for 18 months but as the area of coverage was limited by the 72.1° latitude bands, it supplements ERS-1 excellently on the lower latitudes. Hence, the combination of Geosat and ERS-1 enabled for the first time development of full-coverage, high-resolution models of the Greenland ice sheet and four fifths of Antarctica.

However, a substantial problem associated with satellite altimetry over non-ocean surfaces is that the accuracy of the measurements degrades with increasing surface slope and level of roughness. This is a result of the combination of the large footprint of the radar altimeter and the sloping and undulating nature of the ice surface. It is possible to reduce errors related to this problem by careful processing and editing of the data but even after the most meticulous treatment, a significant drop in accuracy in the more sloping marginal areas is found compared to the flatter, smoother, central regions (see e.g. Bamber et al., 1998). For addressing this problem, airborne laser altimetry has proven to be particularly useful as a consequence of the higher, and more uniform, accuracy of the data. Here, we show how high-accuracy airborne laser altimetry can be used to adjust SRA data, thus reducing the long and medium wavelength errors (generally with wavelengths of 10 km or more) in sloping or strongly undulating parts of ice sheet DEMs.

2. Satellite radar altimetry

Details of the SRA data used here have been presented elsewhere (Bamber et al., 1998). However, some characteristics of satellite-derived elevations are critical to the analysis presented here and they are, therefore, discussed briefly in this section.

As mentioned in the introduction, SRAs have the key advantage over any other instrument in that they provide an extensive, and densely distributed, all-weather dataset of elevations defined in an Earth-based reference system. For this reason the data are highly suitable for modeling the topography of remote, inaccessible regions like the Greenland and Antarctic ice sheets. However, the current suite of SRAs were designed primarily for oceanography and an irregular surface, like an ice sheet, presents various technical problems which must be addressed before the data can be useful for topography modeling.

On a flat surface like the ocean, the onboard waveform tracker is practically always able to keep the leading edge of the waveform centred at the tracking point. On a topographic surface like an ice sheet, however, the tracking device in general cannot keep pace with the relatively rapid changes in range to the surface. As a result, it is necessary to apply a range refinement procedure, known as waveform retracking, to the raw data. (Martin et al., 1983; Bamber, 1994a). More serious is the problem that the radar primarily ranges to the point within the footprint, which is closest to the satellite and over a sloping surface, this range does not correspond to the nadir point. As the nadir point coordinates are being recorded as the horizontal position, a slope-correlated error is introduced which can in principle be dealt with in three different ways (Brenner et al., 1983; Remy et al., 1989; Bamber, 1994a):

1. The direct approach where a bias is calculated from a simple geometric argument, assuming a constantly sloping surface, and added to the range,
2. The relocation approach where the true position of the nearest point is determined and the range is adjusted for the fact that it is a slant (as opposed to nadir) measurement and associated with the new position.
3. The intermediate approach, where the point (in between the nadir and the true position), which actually corresponds to the measured range, is determined and associated with the measurement.

For a regional slope of 1°, for example, the vertical offset is about 120 m. For relatively low slopes, less than 0.2–0.3°, these standard adjustment schemes provide an adequate correction. For steeper slopes, however, closer to the ice sheet margins, a significant amount of slope-dependent bias and/or noise cannot be removed by any of the methods described above. It is primarily in these areas where the presence of an additional, densely sampled, elevation data set with a considerably higher data quality can be used to model a significant fraction of the remaining error.

3. Airborne laser altimetry

The Arctic Ice Mapping (AIM) project is presented in detail elsewhere in this issue (Martin et al., this issue) so only a brief outline is given here for completion. The project was an airborne campaign over Greenland, which was initiated in 1993/1994 and repeated in 1998/1999 (Krabill et al., 2000) but only data from the two first years of the project are considered for this analysis. The onboard altimeter was a conical, circular scanning system known as the Airborne Topographic Mapper (ATM) (Krabill et al., 1995). The ATM collected extremely dense, 200 m wide, swaths of points along a fairly irregularly distributed pattern of flight tracks over the Greenland ice sheet (see Fig. 1). The data were averaged by the manufacturers to approximately 1/6 Hz but in the context of topography modeling, even this sampling frequency is too high. We, therefore, brought the large volume of points further down by a subsequent averaging to 1 Hz, corresponding to an along-track resolution of 150 m. The averaged data are generally of outstanding quality with a rms error on the order of 10 cm (Martin et al., this issue). There is, however, a non-negligible quantity of grossly erroneous data points. These are primarily due to reflections by the laser from low clouds, diamond dust etc. or effects from manoeuvring the aircraft and the data must be carefully examined and edited before they can be used for determining correction factors to the satellite altimetry.

4. Comparisons of airborne ATM laser profiling and satellite radar altimetry

The complete ERS-1 Geodetic Phase data, combined with the Geosat geodetic mission data, provided, for the first time, complete coverage of the Greenland ice sheet with a sampling rate of

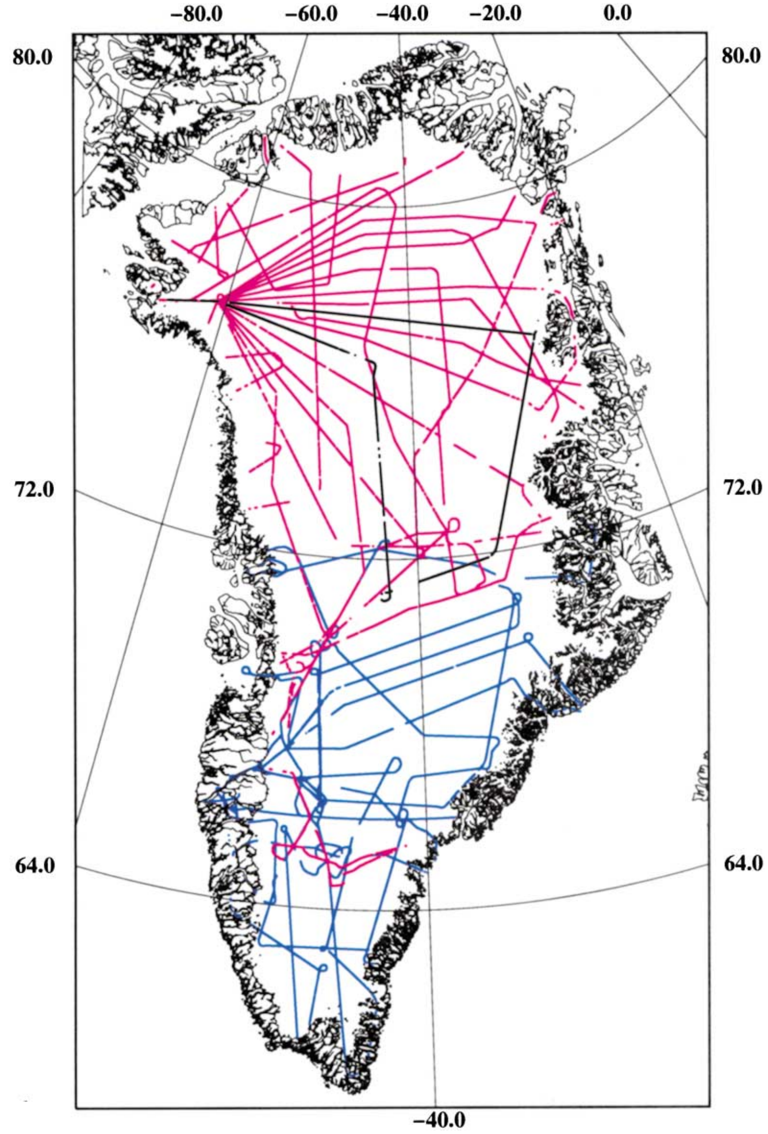

Fig. 1. Distribution of 1993 (blue) and 1994 (red and black) ATM laser altimetry tracks. The black track is signifying a special test track.

better than 1 point per km^2. Hence, we had excellent range rate information, along-track as well as across-track, and could compute a reliable two-dimensional range rate surface necessary for applying the relocation method for slope correction (Bamber, 1994a). Using this approach, which is considerably more advanced than the traditional direct method, proved to have a significant impact on removing the slope related noise and comparison with AIM data over the southern ice sheet. Bamber et al. (1998) showed that the random error was reduced from a level of 10–50 m to between 3 and 10 m on surfaces with slopes ranging from 0.3 to 0.8°. In fact, even on steeper slopes, significantly beyond the half power beam width of the altimeter (which is normally regarded as the upper limit from which useful returns can be expected), noise levels of less than 15 m were found, far better than in any previous analysis.

However, a SRA has a beam-limited footprint with a radius of typically 10–15 km over a rough ice sheet and from undulations at wavelengths of this scale or less, more of the signal is reflected from the peaks of the undulations and less from the troughs. Hence, a consequence of applying the relocation method is that the data points tend to be relocated towards higher elevations (see Bamber, 1994a, Fig. 10, p. 936) and a positive sampling-induced elevation bias is introduced. This observation is illustrated in Fig. 2, showing elevation profiles obtained from ATM data and interpolated from ERS-1 radar altimetry along a section of a ATM-track in an undulating region in mideast Greenland (southern part of black track in Fig. 1). It is clearly seen that the satellite altimeter, although picking up the majority of undulations remarkably well, is unable to monitor many of the more pronounced troughs in the surface. The magnitude of the positive bias between the altimetry height and the true surface is crudely related to the wavelength and amplitude of the sub-30 km undulations and we have thus applied a standard gaussian high-pass filter, with a cut-off wavelength of 30 km (approximately corresponding to the diameter of the radar footprint), to the ATM-profiles. Fig. 3 shows the distribution of the magnitude of the high-pass filtered elevations, and is a clear illustration of how the amplitude of the undulations increases from the interior of the ice sheet towards the margins where the ice sheet is thinner. This is because the surface expression of sub-ice bedrock undulations are increasingly ‘‘damped’’ towards the interior by the overlying ice masses. The relationship between surface slope and ice thickness, on the other hand, is shown in Fig. 4. It can be seen that, although there is substantial scatter for ice thickness less than about 1000 m there is a distinct inverse relationship between slope and thickness. Hence, higher slope areas (where the ice is thinner) will have more pronounced undulations, and we will use surface slope as an indirect measure of the amplitude of sub-30 km wavelength undulations.

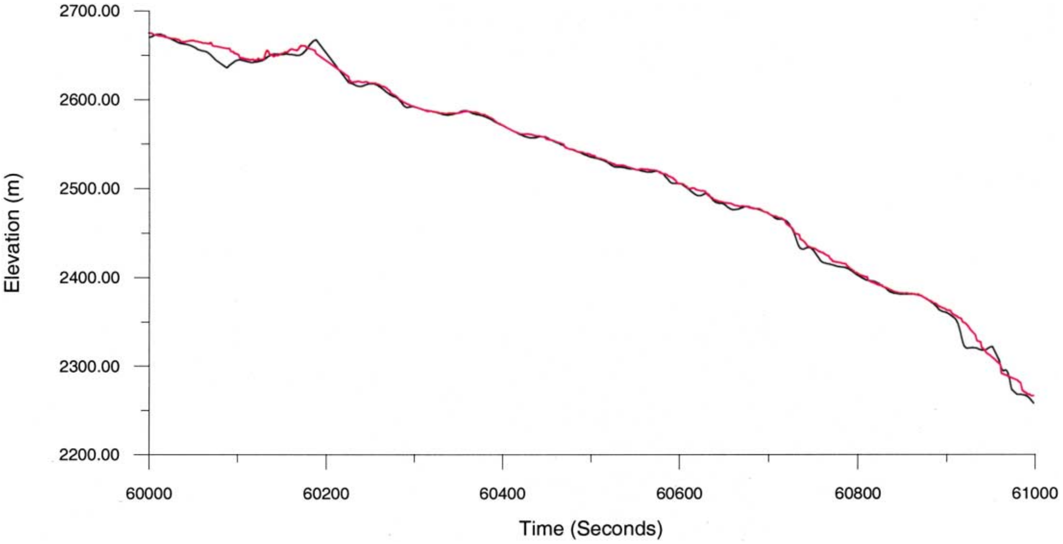

Fig. 2. ATM-profile, approximately 150 km long (1 second is corresponding to approximately 150 m flying distance). Black: observed ATM elevation, red: interpolated satellite altimetry elevation.

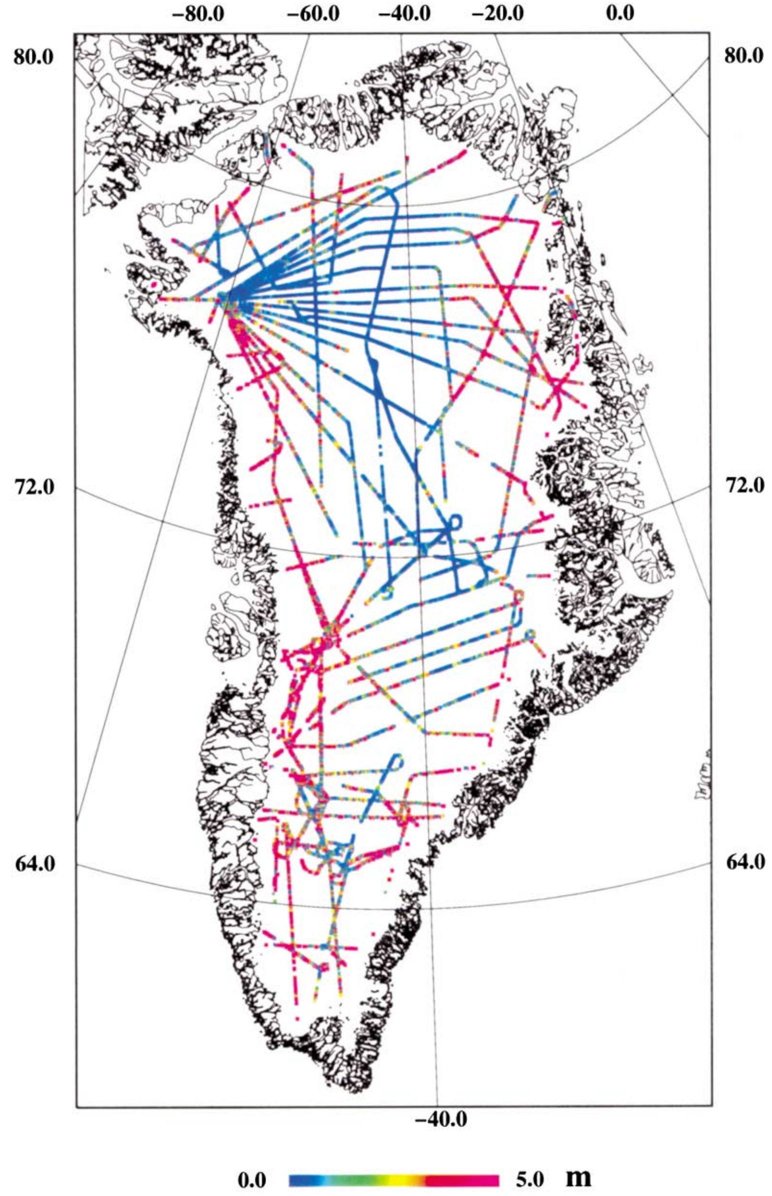

Fig. 3. Distributions of magnitudes of short wavelength undulations as determined from filtering the ATM laser altimetry tracks.

In order to investigate the relationship between surface slope and the discrepancy between satellite and airborne altimetry, we have compared all the averaged ATM points from the 1994 season (covering the northern half of the ice sheet, cf. Fig. 1) with those interpolated from the ERS-1/Geosat SRA data set. In order to avoid introduction of additional errors, a simple inverse distance interpolation scheme was used, taking only the four closest SRA points around each ATM-observation (in a distributed fashion so that one point from each of the NW, NE, SW, and

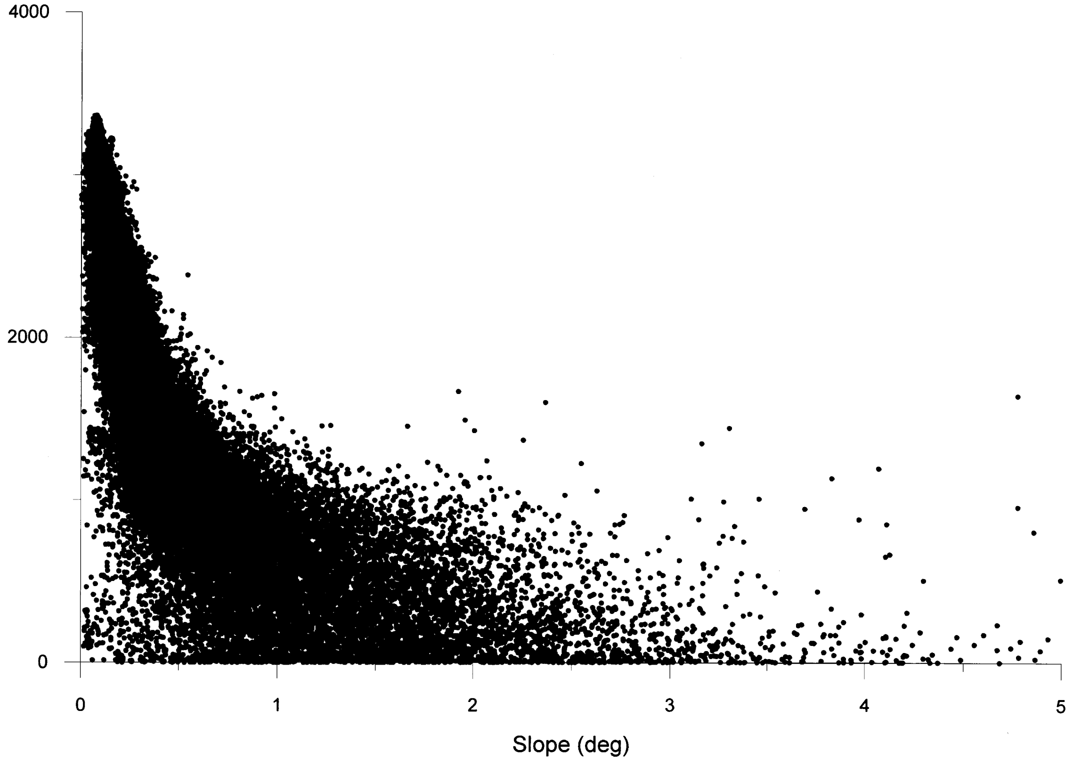

Fig. 4. Ice sheet thickness plotted versus surface slope.

SE quadrants surrounding each point is selected, see also Ekholm et al., 1995). The overall bias between the satellite and the airborne data is approximately 2.5 m. We are aiming at determining this bias as a function of slope but a plot of the residuals between interpolated satellite minus observed airborne laser elevations versus slope (computed from a 2 km resolution slope model derived from the ice sheet DEM) is, however, not very informative as the scatter at almost all slopes masks any clear pattern although a tendency towards positive values is quite obvious (see Fig. 5). If, however, all the residuals are plotted consecutively (Fig. 6), the positive tendency is much clearer. Furthermore, comparison with the corresponding profile of local slopes, computed from the above-mentioned model, in Fig. 6 reveals a distinct positive correlation between the average magnitudes of the slope and residuals, respectively. This relationship is clearly seen when examining individual tracks too. In Fig. 7, elevations, slopes and residuals are plotted along a 3000 km long track segment covering different types of surfaces varying from the smooth interior to the highly sloping and undulating margins (black track in Fig. 1). Fig. 7b shows that there is excellent agreement between the two data sets over the low slopes with little relief and pronounced differences, with a clear tendency towards positive values, over the sloping and undulating parts. These visual observations are corroborated by a correlation coefficient, computed from the full set, of approximately 0.4 between the point residuals and slopes. The reason that the correlation is not more than this is probably due to the facts that (i) the SRA elevations are affected in a complex way by

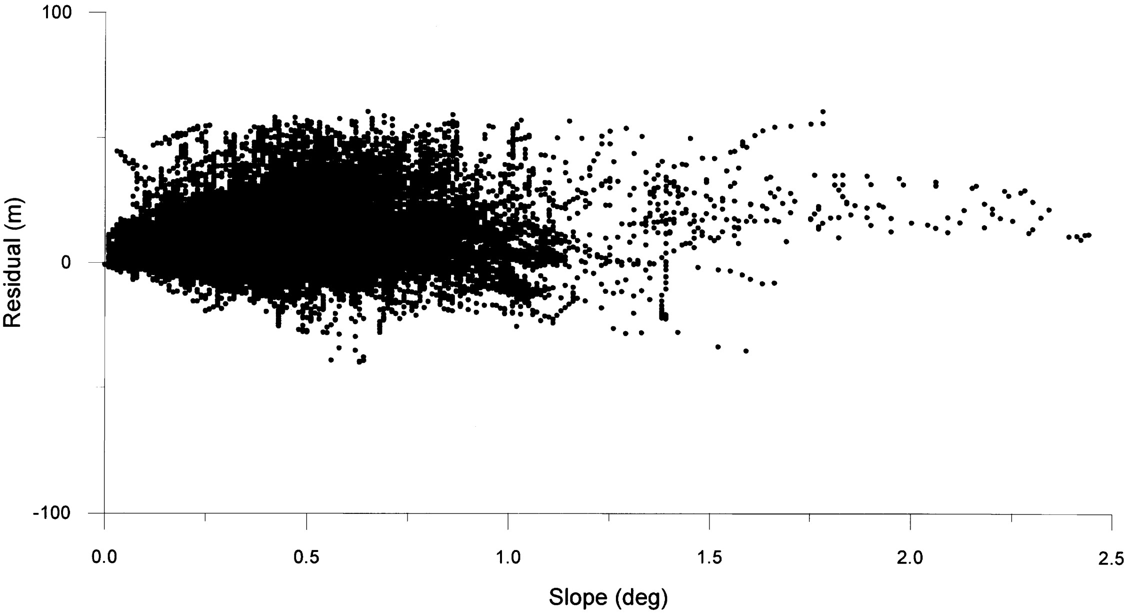

Fig. 5. Residuals between interpolated satellite and observed ATM elevations as a function of surface slope.

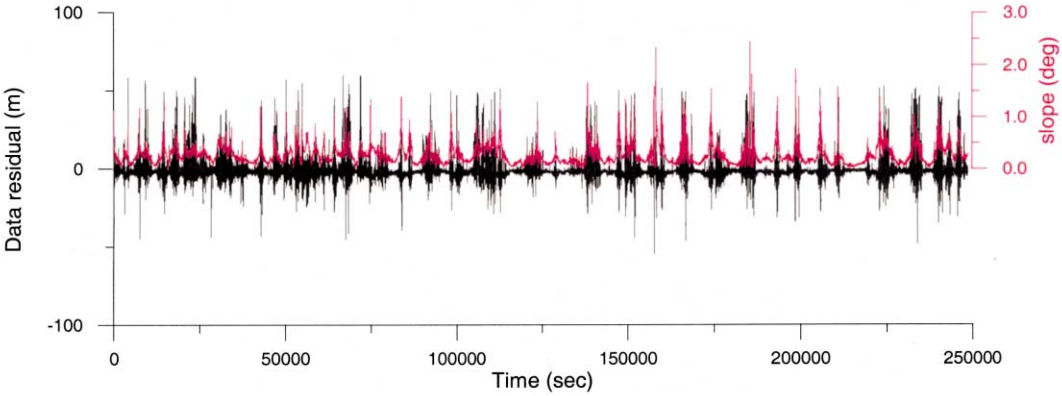

Fig. 6. Residuals between interpolated satellite and observed ATM elevations (black) and surface slope (red) as a function of time.

the local surface undulations, and (ii) the ice sheet surface undulations is related to bedrock undulations, which is unlikely to be statistically stationary across the whole of Greenland.

It is important to note that the observed tendency towards higher elevations in the relocated altimetry cannot be considered as a data error. It is simply a consequence of the way the SRA samples an undulated surface, nevertheless, it introduces a significant slope correlated bias when the data are applied as input to interpolation of DEM's. Thus, our objective is not so much to enhance the principal data quality but rather to optimise the data as a source for computation of elevation models.

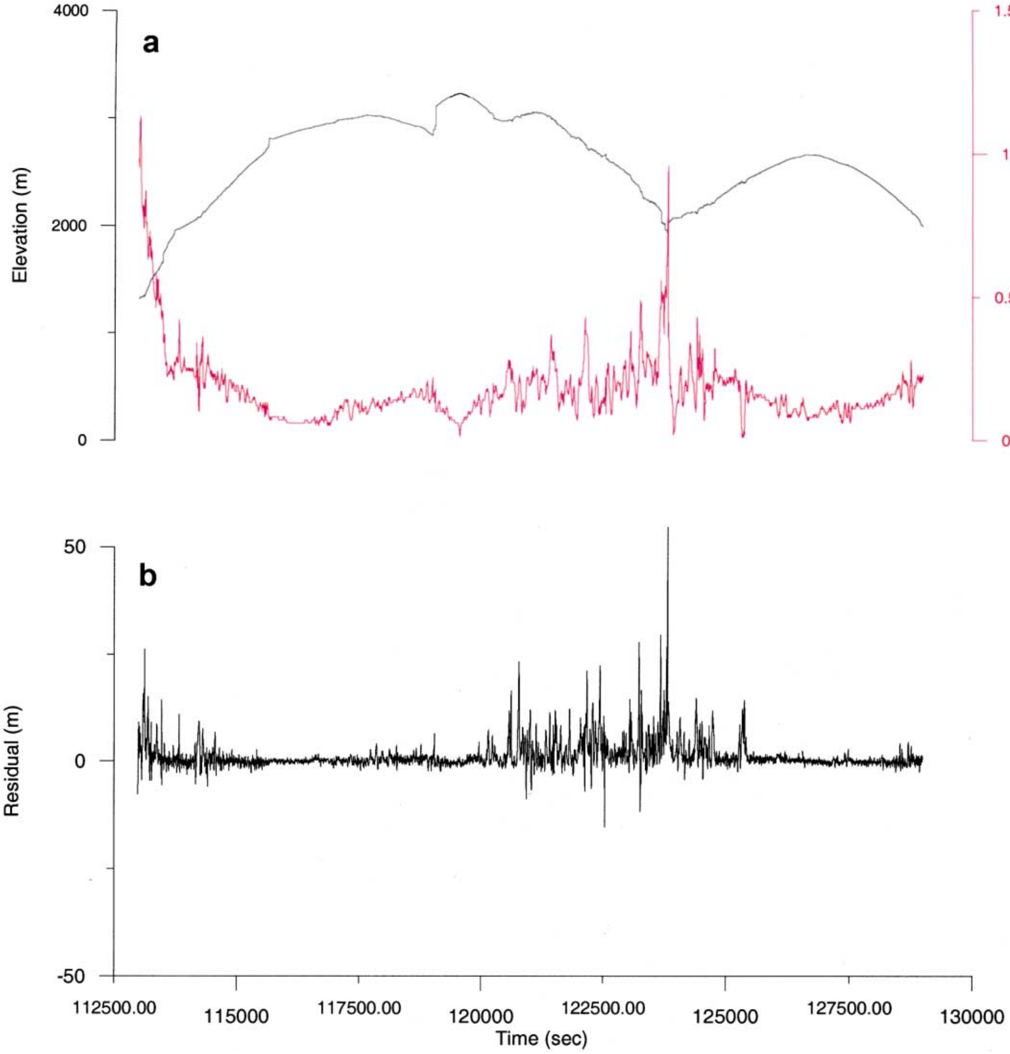

Fig. 7. (a) Observed elevations (black) and interpolated slopes (red) and (b) residuals between interpolated satellite- and observed ATM elevations along a 3000 km long ATM track segment.

5. Estimation of adjustment parameters from ATM altimetry

In Ekholm (1996) airborne radar and laser altimetry was applied in an adjustment routine for SRA data, using a standard draping technique. The adjustment was very successful but the method has two drawbacks. First, it requires a well distributed set of airborne data with a track separation of less than 10–20 km and this is not met everywhere by the ATM data set. Second, draping is a fitting procedure based on a local comparison between two types of data and, hence, the estimated adjustment model applies purely to the two data sets in question and cannot be used in other circumstances. This also implies that the involved ATM data cannot be used anymore as control data and in order to get the optimal result from the draping it is necessary to include all airborne data in the analysis. Therefore, it would not be possible to examine the effect of the adjustment without a third independent, well-distributed set of high-accuracy elevation data and this is presently not available. Finally, the draping was applied to a set of satellite derived elevations which were corrected for slope induced errors using the direct method (Section 2) which does nothing in terms of reducing the very significant amount of slope correlated noise, present in the data and therefore a more "heavy-handed" procedure was required to bring the data to an acceptable level of quality. As it is mentioned above and shown in Bamber et al. (1998), the relocation technique is a much more effective method of removing the slope induced error if an adequate slope or range-rate model is available.

Here, we suggest a more global and somewhat subtler approach and use the airborne altimetry from AIM as a source for estimation of adjustment parameters to the satellite altimetry, primarily in order to try to reduce the slope correlated bias, which, as shown above, is a consequence of the spatial sampling of the relocated satellite data. We have established that the magnitude of the short wavelength undulations (see Fig. 3) is correlated with the magnitude of the surface slope. In order to obtain a clearer picture of the behaviour of the undulation profiles, we have made use of an approach first introduced by Ekholm et al. (1995) and distributed the full set of undulations with respect to slope. The data were divided in a number of sub-intervals of slope, each of length 0.02°, and statistics (mean and standard deviation) were calculated within each interval. We interpret the standard deviations associated with each interval as a measure of the mean amplitude of the undulations corresponding to that particular slope level. Hence, in reference to the discussion in the previous section, we expect a relationship between these standard deviations and the bias between satellite altimetry and ATM profiling data. In Fig. 8 the individual standard deviations are depicted as a function of surface slope and it is evident from the graph that there is a very well defined linear correspondence between the two on surfaces with slopes less than 0.8–

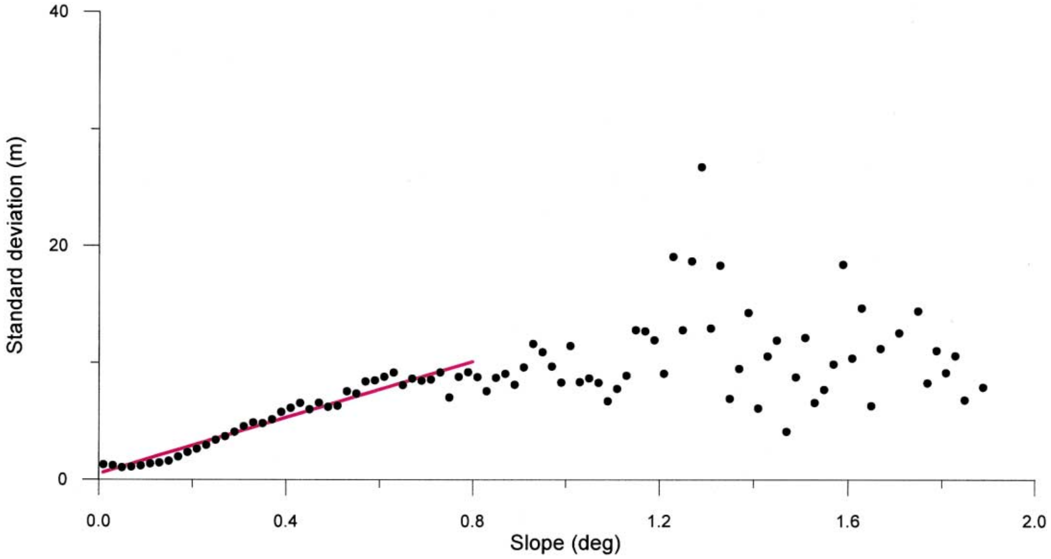

Fig. 8. Standard deviations of high-pass filtered ATM elevation profiles, calculated within slope intervals with length 0.02°, as a function of mean slope. Superimposed in red is the least squares line best fitting all points with slope less than 0.8°.

0.9°. On steeper slopes the assumption apparently breaks down but it is important to emphasize that the ATM data collected on the high slope areas of the ice sheet are few and highly clustered. Thus, both the mean value and the standard deviation are much more randomly determined compared to the lower slope intervals where the number of observations is much larger. Furthermore, as the part of the ice sheet where the surface is sloping 0.8° or less is corresponding to more than 90% of the full area, we have chosen to restrict the linear estimation to entries with up

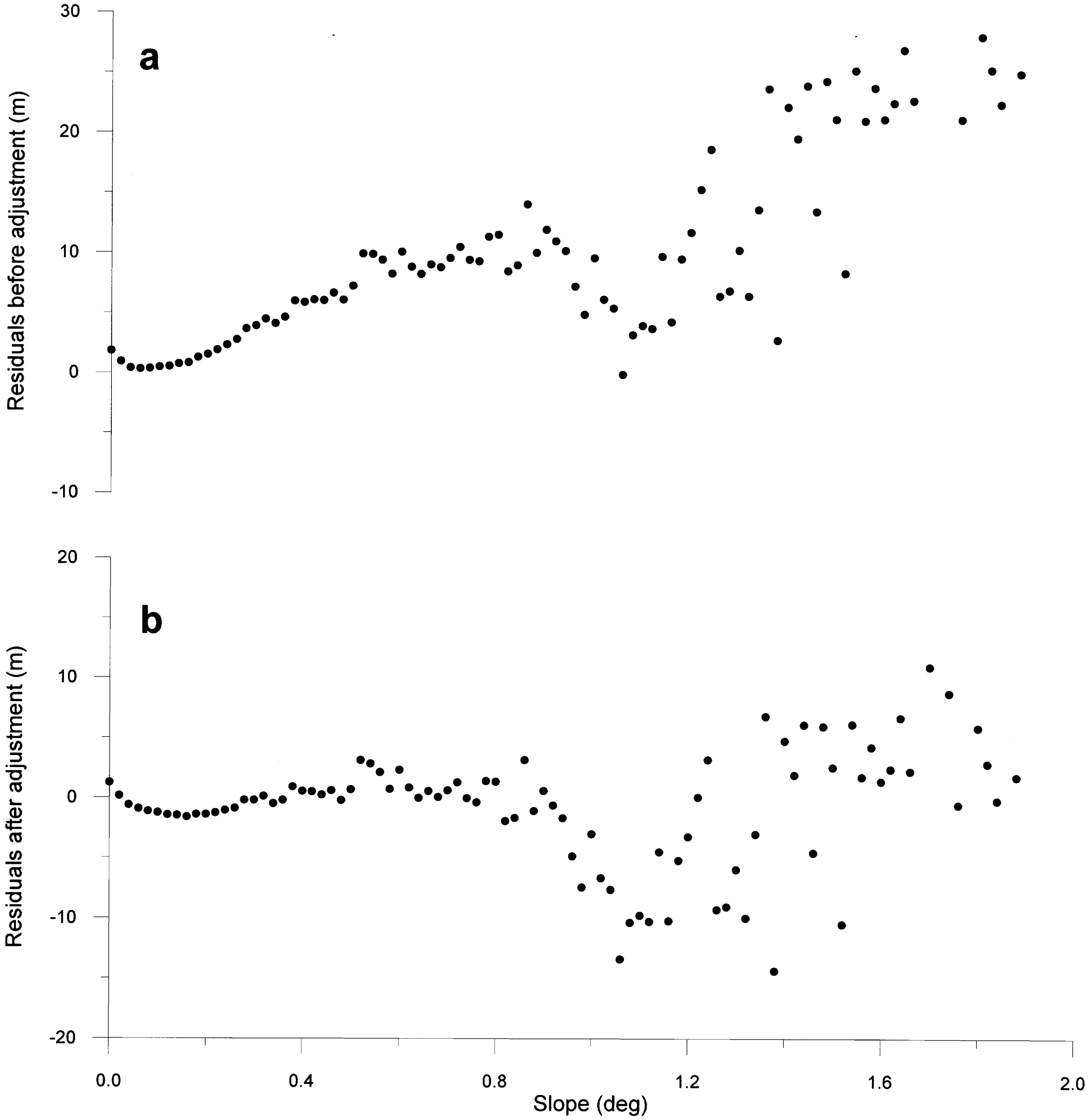

Fig. 9. Mean residuals between interpolated satellite- and observed ATM elevations, calculated within slope intervals with length 0.02°, as a function of mean slope, (a) before and (b) after linear adjustment of satellite altimetry.

to 0.8° slope. Under these considerations, the linear regression produced a least squares line defined by

$$f(\text{slope}) = 12.0 \cdot \text{slope} + 0.5 \tag{1}$$

The sigma of the fit was as low as 0.1 which (particularly when it is taken into account that the estimation was done without introducing error bars as allowance for the fit) indicates that the assumption is statistically sound and, indeed, supporting the hypothesis of a linearly defined relation between the ATM standard deviations, corresponding to each sub-interval, and the average interval slope.

We have previously demonstrated a positive correlation between slope on one hand and the residuals between satellite- and airborne data on the other hand and, therefore, it appears as a reasonable assumption that (1) can well apply as a tool for reducing the slope correlated bias in satellite radar altimetry. In order to test our theory, we have calculated the term defined by (1) for every satellite derived observation, reduced the corresponding elevation by subtracting this term from the measured elevation, and re-interpolated the elevation in all ATM-points. The result is illustrated in Fig. 9a and b where we have distributed the residuals with respect to slope, the same way as described above, and plotted the mean residual of each slope group both before and after the linear adjustment. It is clear that the linear trend from Fig. 8 is also found in Fig. 9 and we see that the adjustment of the SRA data with (1) effectively reduces the bias on almost all slope levels (the mean discrepancies corresponding to slopes between 1.0 and 1.2° look rather strange but, again, all values relating to the higher slope groups are determined from a sparse and clustered material and it is very difficult to quantify why the fit is peculiarly poor in those regions but apparently works very well on much steeper slopes). Our observations are fully supported by the correlations: the coefficient between the entries of mean slope and mean residual in Fig. 9 decreases from 0.80 to 0.15 and the correlation computed from the data itself dropped from 0.4 (as mentioned in the previous paragraph) to less than 0.1 as a result of the adjustment.

Overall, the linear reduction has provided a reduction of the residual between the interpolated satellite- and observed ATM elevations from 3.2 to −0.6 m and at the same time the general rms discrepancy between the two data sources has dropped approximately 15% from 7.8 to 6.7 m.

6. Conclusions

We have established through practice that a significant fraction of slope-correlated bias, remaining in satellite radar altimetry after applying standard adjustment procedures, can be removed by introducing high-precision laser airborne altimetry. The proposed idea is to examine high-pass filtered ATM profiles statistically, in a very simple fashion, and define a linear function, relating the surface slope to the magnitude of surface undulations. Subsequently, the linear term is subtracted from the satellite radar elevations. This adjustment approach has the significant advantage that the correction factors are determined exclusively from the airborne profiles and, consequently, are completely independent of the data they are applied to.

We conclude that the linear adjustment is effective in decreasing the bias on all surfaces of slopes less than about 0.9° (corresponding to well over 90% of the ice sheet). As a result, the residuals between observed airborne and adjusted, interpolated satellite elevation has a mathematical expectation of close to zero and the correlation between slope and residuals are reduced from 0.4 to virtually zero. Finally, the general rms uncertainty of the relocated satellite data is reduced by approximately 15% as a consequence of the data reduction. In conclusion, we suggest that the modeling accuracy of all satellite altimetry, slope adjusted with the relocation method, can in principle be improved accordingly by subtracting a linear term, defined by (1), from all elevations. In all fairness, it should be added that in this analysis we have only established that the proposed adjustment principle works well along the flight lines of the AIM project. We obviously assume that the determined adjustment line (1) applies for all other ice sheet surfaces (with a slope of less than 0.8–0.9°). We believe this to be a very reasonable assumption given the volume and good distribution of the AIM data and the fact that the line is a function only of the surface slope and not in any way of the positions or distribution of the individual data points. However, we would off course have preferred to have a completely independent data set of equally good quality to test our adjustment approach against, but such a set is unfortunately not available at this time.

In this way, we have attempted to combine data from the two sources in a way, which takes advantage of the high and uniform accuracy of the airborne laser data as well as the unprecedented data density and coverage of the satellite information. The reduced satellite altimetry was applied in a modeling effort which resulted in a DEM of the ice sheet with a overall mean accuracy of approximately 6 m, ranging from 1 m on the almost flat, central part to 10–12 m on strongly sloping sides in the ablation zone bordering the coastal regions (Bamber et al., 2001). We firmly believe that by combining the technique of relocation of the satellite altimetry and the high precision associated with laser profiling data, in the proposed manner, we have brought ice sheet satellite radar data to a current “state of the art” in terms of digital elevation modeling. A higher level of modeling accuracy in ice related radar altimetry can probably only be achieved in connection with a much deeper understanding of the altimeter return waveform including detection of multiple returns in the signal and analysis of penetration of the pulse into the ice.

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