1454

Pergamon

Phys. Chem. Earth, Vol. 21. No. 4, pp. 331–336, 1996

0079-1946/96 $15.00 + 0.00

PII: S0079-1946(97)00057-8

Comparison of Retracking Algorithms for ERS-1 Altimeter Data Over Greenland

O. Leeuwenburgh[1], C. C. Tscherning[1], P. Knudsen[2] and O. B. Andersen[2]

[1] University of Copenhagen, Department of Geophysics, Juliane Maries vej 30, DK-2100 København Ø, Denmark
[2] Kort- og Matrikelstyrelsen, Geodetic Division, Rentemestervej 8, DK-2400 København NV, Denmark

Received 10 May 1996; accepted 11 September 1996

Abstract.
Six months of processed ERS-1 full waveform altimetry data have been used to study the ERS-1 altimeter performance over the Greenland ice sheet. Surface profiles from repeated ground tracks have been studied to explain the character of the data and the performance of several waveform processing techniques. A cross-over analysis has been performed to assess the repeatability of retracked data. The RMS of ocean-mode cross-over differences is found to be around 0.5 m for most parts of the central ice sheet, with values larger than 2 m for areas with large variations in surface height. For these areas the ice mode cross-over differences are smaller. Average waveforms from the central part of the ice sheet show the presence of substantial sub-surface volume scattering. © 1997 Elsevier Science Ltd

1 Introduction

Ice sheet elevation data are required in determining ice sheet-climate interactions and the future of sea-level rise [Rapley et al., 1993]. The ice sheets of Greenland and Antarctica constitute 10% of the surface land area of the earth and the accumulated ice is equivalent to 70 m of sea level. Volume changes as small as 1% are therefore significant on the sea level [Thomas et al., 1985; Brooks et al. 1987] Satellite altimetry missions has for a decade been recognized as one of the most valuable source of elevation data of ice covered regions.

The combination of an inclination of 98.5°, 20 Hz measurement frequency and the incorporation of a special ice mode for the ERS-1 satellite, has enlarged the coverage of the ice covered regions considerably. Over the ice, the altimeter operates in "ocean mode" half of the time. The other half of the time, a special "ice mode" is used to improve the ability of the altimeter to keep track of the surface despite surface undulations, though be it at a four times lower resolution

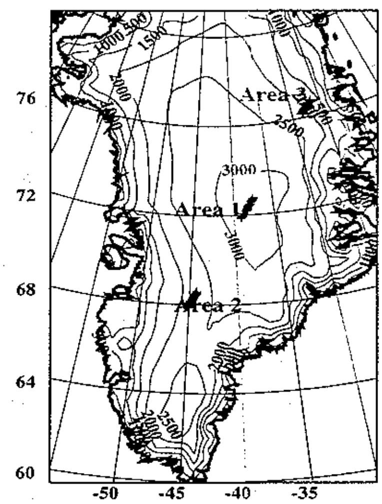

Fig. 1. The location of surface profile areas. Ice sheet elevations are contoured. The Greenland Digital Terrain Model is curtesy of S. Ekholm (KMS-Denmark).

Radar returns (waveforms) from land ice, unlike ocean returns, are considerably more complex and require special techniques of interpretation. On the ice, the waveforms are distorted by irregular surface height variations and by spatially and temporally changing scattering characteristics. Similarly the radar beam in not entirely returned by surface scattering as on the ocean, but the effects of both surface and volume scattering must be made on the waveform shape

Retracking is the process of correcting the range, transmitted by the satellite, for these effects. The range to the mean surface within the radar beam is normally associated with the half power position on the leading edge of the waveform. The waveform normally has

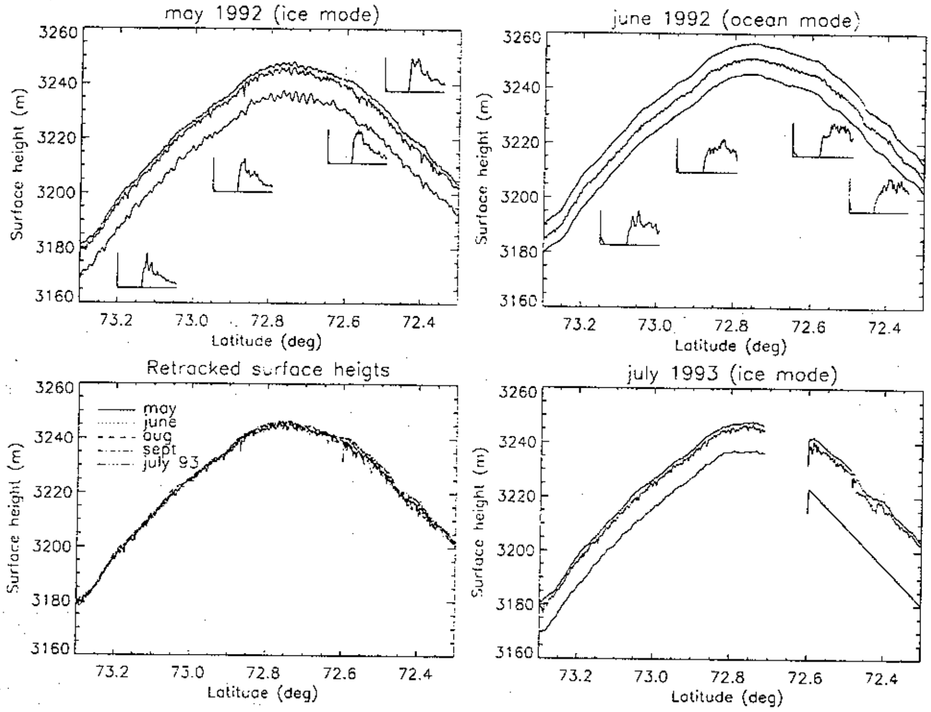

Fig. 2. Raw (lowest line), NASA retracked (middle), and ESA retracked (top) surfaces for May 1992, ice mode, june 1992, ocean mode (NASA offset by 5 m, ESA by 10 m), and July 1993, ice mode; NASA retracked surfaces for all available months are shown in lower left picture. The profiles are from Area 1 in Figure 1.

one leading edge and can be retracked using a single ramp altimetry waveform model. Occasionally, though, the waveform have two leading edges and the waveform must be retracked using a double ramp altimetry waveform model. One further complication on the use of ice or land measurements in the fact that sloping surfaces might introduce errors as large as tens of meters in areas with large surface slopes. However, by studying cross overs differences the slope-induced error will largely be cancelled, and temporal changes of the height of the ice sheet, important in mass balance and climate research, may be estimated.

2 Data

The data used in this investigation were obtained from NASA's ERS-1 data browser at Goddard Space Flight Center. These data are supplied with additionally post-processing information, such as retracking and slope corrections and include the ocean as well as ice mode full waveform data, obtained at a 20 Hz frequency. Since these processed waveform data are only slowly becoming available, only data obtained between May and October 1992 have been used here. The retracking corrections supplied with the data are the beta-retracking corrections used by NASA, and the Offset Center Of Gravity (OCOG) retracking corrections used by ESA [Martin et al., 1983; Bamber, 1994].

3 Surface profiles

Figure 2 shows surface profiles from raw (un-retracked) and retracked data from the central part of Greenland (Area 1 in Figure 1). This area is close to the summit of the ice sheet and lies within the dry snow zone. This zone is characterized by the absence of summer melting and a low snow density, enabling the radar pulse to penetrate the surface (see e.g. [Ferraro and Swift, 1995]). Surface heights were plotted only if a first ramp NASA retracking correction was available. This figure clearly shows the difference in ice mode and ocean mode data, as well as in retracking method and additionally shows some typical waveforms from this area. Retracked elevations for 5 available repeats of the same track can be seen to be consistent to the 2-5 m level where the larger differences occur on the downslope side. The repeat from July 1993 shows a distorted surface profile around 72.45°, due to the signal from a transponder which was operating at the GRIP site at that moment. The strong returns from that area cause small biases resulting from the retracking algorithms, especially where the transponder return signal approaches the normal return fronts (Figure 3).

The second area of interest is a section between 68°N

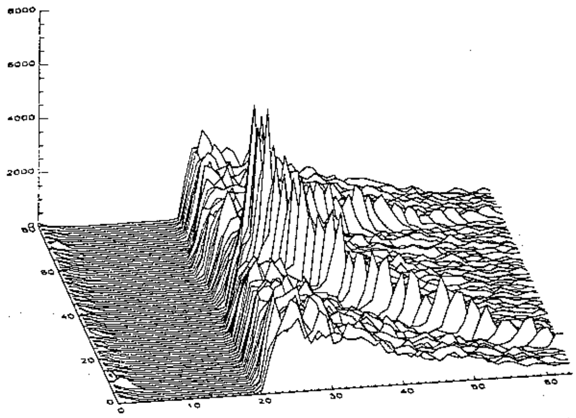

Fig. 3. Eighty waveforms representing 4 seconds of 20-Hz measurements are shown while the satellite passes the transponder at the GRIP site on the Greenland ice sheet. Each waveform is represented as a curve in the x-axis direction. The y-axis represents the waveform number, and the z-axis represents amplitude. The transponder return pulse is seen as the elliptic shape of maxima in the waveforms.

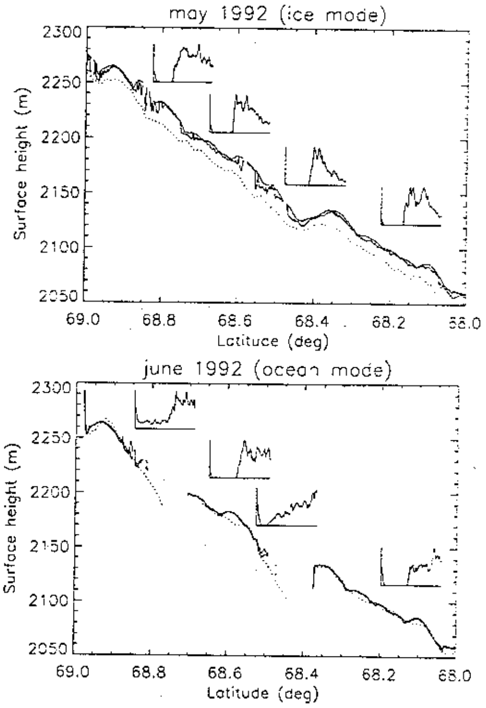

Fig. 4. Raw (dotted line) and NASA and ESA retracked surface heights (solid lines) for May and June 1992 from Area 2 in Figure 1.

and 69°N (Figure 4), about 1000 m lower in elevation (Area 2 in Figure 1). This area lies within the percolation zone where some summer melting occurs during which water percolates down into the sub-surface snow and refreezes into ice layers, ice pipes and ice lenses. The average slope of this particular section is about 0.1° which should be well within the capability of the satellite tracker. However, the combination of downhill slope and surface undulations apparently causes large problems to the tracking performance. (Figure 4 shows all NASA first and second ramp retracking corrections for a small section. The second ramp returns can be seen to represent true surface features since some general features are repeated every month.

The third area which was investigated is a section between 77° N and 78° N (Area 3 in Figure 1). This section lies another 1000 m lower in elevation and lies within the ablation or soaked zone, which is characterized by wet and dense upper layers of snow due to substantial summer melting. The average slope of this section is about 0.7° which is just more than half the beamwidth of the altimeter. Consequently, hardly any reliable height estimates have been obtained from the ocean mode data, as can be seen in Figure 6. At the beginning and end of this section, track is also lost in ice mode, indicating large surface undulations or very large slope. The plot of first and second return elevations does not suggest that the inter-monthly differences are solely due to tracking to different surface features, since there is hardly any correlation between the respective surface profiles.

4 Waveform averaging

Average waveforms will show a reduced influence of surface features on the waveform shape, thus allowing the separation of the effects of surface and volume scattering. This way it should be possible to extract physical parameters describing the surface snow condition. A method should be used which produces the best possibly average. Waveforms from 8 different areas, as shown in Figure 5, and covering most of the inland part of the ice sheet, were averaged according to 4 different methods: summing of the waveforms directly without re-alignment, alignment of the waveforms at the leading edge position as defined by the NASA algorithm, at the leading edge position as following from the ESA algorithm (the center of gravity minus half the box width), and at the position of the center of gravity itself. It was found that ocean mode waveforms are best averaged using the ESA leading edge definition, while in ice mode use of the NASA defined position will give the best average in terms of the lowest standard deviation. The ice mode waveforms resemble very well the classical surface scattering model used in the NASA algorithm and have

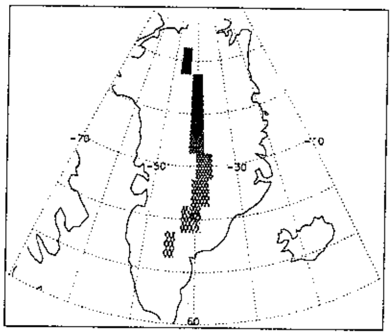

Fig. 5. The location of the data used for averaging.

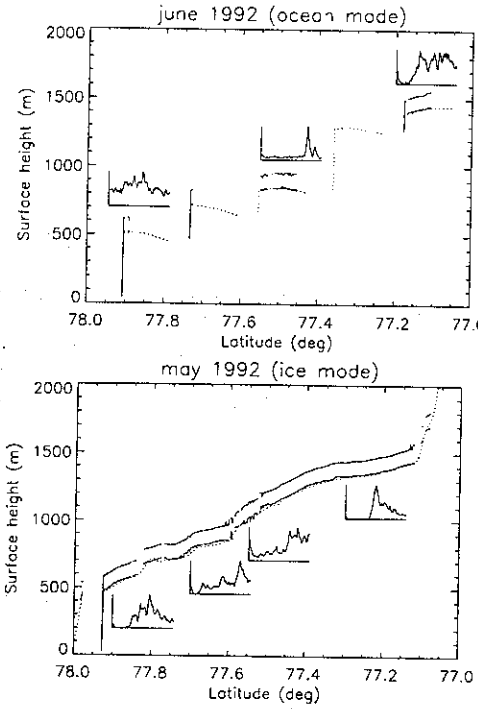

Fig. 6. Raw (dotted line) and NASA and ESA retracked surface heights for May and June 1992 (ESA retracked elevations are offset by 100 m) from Area 3 in Figure 1.

a well defined leading edge. Ocean mode returns on the other hand, might have a less well defined leading edge because of the more prominent influences of surface features and volume scattering.

Waveforms from the area around 66°N, 315°E show a dominant fraction of surface scattering during all three months (Figure 7). A large fraction of the return power in the waveforms from 70°N, 321°E is due to volume scattering. This agrees with the location of this area (in the dry snow zone). The returns from 74°N, 320°E show a significantly larger fraction of surface scattering present in August. This could be explained as being the result of melting of the upper layer of snow during the summer months, creating a wet surface.

5 Cross-over analysis

In order to evaluate the influence of the retracking algorithm on the repeatability of the altimeter, a cross-over analysis was carried out using the data from the 8 different areas, as shown in Figure 5. Ocean and ice mode data were treated separately. The two retracking methods which were compared, were the ESA low-track-point retracking method and the NASA retracking method. The S/V retracking algorithm, as described in [Davis, 1993], is not directly applicable to ERS-1 waveforms, which differ from the SEASAT and GEOSAT waveforms that the algorithm was developed for [Davis, pers. comm.]. In the following, only data were used for which a NASA first ramp correction was available, to enable a better and more fair comparison between the NASA and ESA corrected data.

For all areas RMS values of cross-over differences are smaller for the ESA retracked data (table 1). This seems to hold for ocean as well as for ice mode data. The mean values of the ocean mode cross-over differences are also the smallest for ESA retracked data, but in ice mode the NASA retracked mean values are slightly lower. The RMS values for areas with large height variations are lower for ice mode data than for ocean mode data, whereas for areas with little height variation the ocean mode values are lower. As was mentioned in [Davis, 1995], a problem with the NASA retracking is the mixture of single and double ramp fits. Table 2 therefore lists cross-over statistics for only those data which were retracked by a single ramp model.

This reduction of the data indeed improves the NASA retracking statistics. for ocean mode as well as for ice mode data. Especially for the areas for which large RMS values were listed, the improvement is substantial. On the other hand, it can also be seen that the results for the ESA retracking have improved as well. Even for this subset of the data, where the NASA retracking should perform optimally, the RMS values are significantly smaller for the ESA retracked data. This would suggest that the ESA retracking corrections are most reliable if it comes to the interpretation of cross-overs differences.

6 Conclusions

The ERS-1 and ERS-2 missions are currently the most important satellite missions for ice altimetry. The inclination of 98.5° and the availability of a special ice mode make them well suited for studies of the large ice covered regions of Greenland and Antarctica. The repeatability

area	NASA		ESA	
	ice (m)	ocean (m)	ice (m)	ocean (m)
66N 315E	1.108	1.082	0.664	0.702
68N 319E	1.967	4.261	0.959	1.998
70N 321E	1.291	0.861	0.528	0.564
72N 322E	1.062	0.831	0.563	0.542
74N 320E		0.831		0.690
76N 320E	0.736	0.505	0.456	0.405
78N 320E	0.901	0.569	0.533	0.436
80N 315E	1.896	2.811	0.748	2.207

Table 1. RMS of cross-over differences of beta-retracked (NASA) and OCOG-retracked (ESA) ice and ocean mode data.

area	NASA		ESA	
	ice (m)	ocean (m)	ice (m)	ocean (m)
66N 315E	1.024	0.814	0.679	0.673
68N 319E	1.188	0.799	0.941	0.468
70N 321E	1.396	0.783	0.534	0.566
72N 322E	1.062	0.800	0.564	0.445
74N 320E		0.643		0.380
76N 320E	0.736	0.499	0.456	0.377
78N 320E	0.871	0.554	0.532	0.404
80N 315E	1.159	0.556	0.729	0.416

Table 2. RMS of cross-over differences of single ramp beta-retracked (NASA) and OCOG-retracked (ESA) ice and ocean mode data.

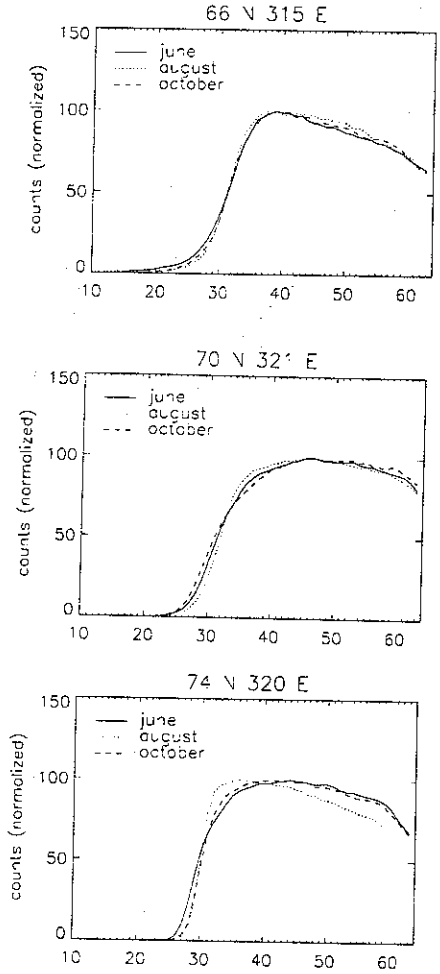

Fig. 7. Averaged ocean mode waveforms.

of ocean mode data, as computed from cross-over differences, is about 0.5 meter RMS for most areas of the inland part of the Greenland ice sheet, with values larger than 2 meters for areas with large topography variations. The ice mode measurements are more consistent in these areas, and have only slightly larger cross-over RMS values in the remaining areas. In this context, the OCOG retracking method, as used by ESA, performs significantly better than the beta-retracking method used by NASA, even for data with a single ramp character, and for ice mode data. The effects of volume scattering are clearly visible in the averaged waveforms from the top of the Greenland ice sheet. Waveforms from the southern tip of Greenland, on the other hand, are primarily the result of surface scattering. Of the averaging methods investigated here, the re-alignment according to the ESA leading edge position yields the lowest standard deviations for ocean mode data. Even though the results from most areas of the inland part of the Greenland ice sheet show cross-over discrepancies of about 0.5 meter RMS in this analysis, altimetry data are important for estimating elevation changes and by using new methods of cross-over analysis combined with improved atmospheric corrections substantial reduction in the cross-over RMS level can be obtained [Wingham et al., 1996] . A recent re-investigation by Zwally and others [Zwally, 1989] based on GEOSAT satellite altimetry data between 1978 and 1987 produced an average rate of growth of ± 10 cm/year for the same period, a value which seems to be supported by several ground-based studies [Davis, C. H., 1995]. Similarly results from numerical modelling usually yields results well below 5 cm /year [e.g., Huybrechts, 1994].

Acknowledgements. This is a contribution to the ESA AO project AFRICAR, sponsored by the Danish Space Board. The authors wish to thank A.C. Brenner and J. DiMarzio at Goddard Space Flight Center for preparing and supplying the waveform data.

References

Bamber, J.L., Ice sheet altimeter processing scheme, *Int. J. Remote Sensing*, *vol.15*, no.4, 925-938, 1994.

Brooks, R.L., W.J. Campbell, R.O. Ramseier, H. Ray Stanley and H. Jay Zwally. Ice sheet topography by satellite altimetry. *Nature*, *vol.274*, 539-543, 1978.

Davis, C.H., A surface and volume scattering retracking algorithm for ice sheet satellite altimetry, *IEEE Trans. Geoci. Remote Sensing, vol.31*, no.4, 811-818, 1993.

Davis, C.H., Growth of the Greenland ice sheet: a performance assessment of altimeter retracking algorithms, *IEEE Trans. Geosci. Remote Sensing, vol.33*, no.5, 1-9, 1995.

Ferraro, E.J. and C.T Swift, Measuring geophysical parameters of the Greenland ice sheet using airborne radar altimetry, *J. Glaciology, vol.41*, no.139, 607-618, 1995.

Huybrechts, P., The present evolution of the Greenland ice sheet: an assesment by modelling, *Global Planet. Change, 9*, 39-51, 1994.

Martin, T.V., H.J. Zwally, A.C. Brenner and R.A. Bindschadler, Analysis and retracking of continental ice sheet radar altimeter waveforms, *J. Geophys. Res., vol.88*, C3, 1608-1616, 1983.

Rapley, C.G., J.L. Bamber, J.G. Morley, J.K. Ridley, S.W. Laxon, D. Mantripp, J,A.D. Mansley and D.J. Wingham, Analysis of ERS-1 altimeter data over polar ice sheets, *Proc. First ERS-1 Symp.*, ESA SP-359, 235-240, 1993.

Thomas R.H., R.A. Bindschadler, R.L. Cameron, F.D. Carsey, B. Holt, T.J. Hughes, C.W.M. Swithinbank, I.M. Whillans and H.J. Zwally, Satellite Remote Sensing for ice sheet research, *NASA Techn. Mem. 86233*, 1985.

Wingham, D. J. and A. L. Ridout, Elevation changes of the Antarctic ice sheet 1993 - 1995 (abstract), *Annales Geophys., 58 (14)*, 272, 1996.

Zwally, H.J., Growth of Greenland ice sheet: interpretation, *Science, vol.246*, 1589-1591, 1989.