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THE EFFECT OF SUB-SURFACE VOLUME SCATTERING ON THE ACCURACY OF ICE-SHEET ALTIMETER RETRACKING ALGORITHMS

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The NASA and ESA retracking algorithms are compared with an algorithm based upon a combined surface and volume (S/V) scattering model. First, the S/V, NASA, and ESA algorithms were used to retrack over 400,000 altimeter return waveforms from the Greenland and Antarctic ice sheets. The surface elevations from the S/V algorithm were compared with the elevations produced by the NASA and ESA algorithms to determine the relative accuracy of these algorithms when sub-surface volume-scattering occurs. The results show that the NASA algorithm produced surface elevations within 35 to 50 cm of the S/V algorithm, while the performance of the ESA algorithm was slightly worse. Next, by analyzing several thousand satellite crossover points from the Antarctic dataset, we determined the retracking algorithm that produced the most repeatable surface elevations. The elevations derived from the S/V algorithm had the smallest RMS error for the region of the East Antarctic plateau examined here. The ESA algorithm produced erroneous estimates of elevation change when seasonal variations were present; it measured 0.7 to 1.6-m change in elevation over a 6-month period on the East Antarctic plateau where accumulation rates are only 10 cm/year.

INTRODUCTION

Early indications of a warmer climate in the polar regions are likely to show as increases in surface melting and ice-sheet thinning. Surface elevation data are used to delineate major drainage basins and to monitor changes in the mass balance (volume growth) of the ice sheets. Systematic monitoring of surface elevations requires accurate repetitive measurements over the millions of square miles that comprise the continental ice sheets. Over the last two decades, spaceborne radar altimeters have provided the only proven means for measuring surface elevations with the precision and spatial coverage required for meaningful ice-sheet studies.

Datasets provided by the Geos-3, Seasat, and Geosat satellite altimeters have been used to produce surface-elevations maps of large portions of Greenland and Antarctica with a 2-m accuracy. Volume changes in the polar ice sheets are directly related to global sea levels. During the past century, the sea level, as recorded from tide-gauge data around the world, has risen by 10 to 20 cm. Although both thermal expansion of the oceans and ice-sheet melting contribute to sea-level rise, no more than 25% of this increase can be attributed to thermal expansion [1]. By analyzing the time series of surface elevations from satellite altimeters, Zwally *et al.* [2] estimated that the southern portion of the Greenland ice sheet grew at an average rate of 23 cm/year from 1978-1986. Zwally [3] suggested an increase in precipitation rates caused by a warmer polar climate as a possible cause of the volume growth. Recently, Zwally *et al.* [4] reported preliminary results of volume changes in East Antarctica using Geosat altimeter data. These studies are the first to obtain mass balance estimates of the continental ice sheets and they demonstrate the ability of spaceborne altimeters to produce results of global significance.

ALTIMETER PROCESSING ALGORITHMS

Altimeter data over the ice sheets must be post-processed to produce accurate surface elevation measurements. The post-processing is called "retracking" and is required because the leading edge of ice-sheet return "waveforms" deviates from the altimeter tracking gate, causing errors in the telemetered surface elevations. A return "waveform" is the received power sampled at the satellite and is the result of the interaction of the altimeter's transmitted pulse with the scattering surface or volume directly beneath the altimeter. Retracking altimetry data consists of computing the departure of the waveform's leading-edge from the altimeter tracking gate and correcting the satellite range measurement accordingly. Martin *et al.* [5] developed the first retracking algorithm for processing altimeter return waveforms from the continental ice sheets. This algorithm, hereafter referred to as the NASA algorithm, processed all ice-sheet data from Seasat and Geosat to obtain corrected surface elevation estimates [6]. The European Space Agency is using an empirical method [7], hereafter referred to as the ESA algorithm, to process altimeter data from the ERS-1 satellite. The NASA and ESA algorithms differ significantly in their approach to retracking altimeter waveforms.

The NASA algorithm fits a 5- or 9-parameter function to the altimeter return waveform. This algorithm is based upon Brown's surface-scattering model [8], which was developed to describe the shape of altimeter return waveforms over the ocean. Each function contains a parameter that defines the location of the waveform's leading-edge position, which is used to correct the altimeter range measurement. The 5-parameter function is used to fit single-ramp returns, while the 9-parameter function is used to fit double-ramp returns. The double-ramp returns typically occur near the ice-sheet edge where two nearly equidistant surfaces within the altimeter's antenna beamwidth contribute to the received power at the satellite.

The ESA retracking algorithm computes a rectangular box from the waveform samples that has an area and center of gravity (COG) that is the same as the return waveform. The horizontal position of the center of gravity is calculated and then the amplitude of the rectangular box is taken to be twice the vertical center of gravity. The leading-edge position of the altimeter waveform is then determined by linearly interpolating between the bins adjacent to a threshold crossing. Currently, threshold values of 25%, 50%, and 75% of the rectangle's amplitude are used to determine the leading-edge position. The ESA algorithm is simpler computationally than the NASA algorithm. However, a disadvantage of the ESA algorithm is that it is not based on a physical model of the ice-sheet surface. The selection of one of the three threshold retracking locations is left to the individual user, and therefore is totally arbitrary.

Recent work has demonstrated that energy at altimeter frequencies can penetrate 5 to 10 m beneath the ice-sheet surface [9], [10]. This suggests that sub-surface volume scattering may affect the shape of altimeter return waveforms over the ice sheet. To account for the altimeter signal penetration, Davis and Moore [11] developed a closed-form analytical solution for the return power volume scattered from beneath the ice-sheet surface. The volume-scattering model was combined with a surface-scattering model and used to accurately characterize variations in the shape of ice-sheet return waveforms caused by differing contributions of surface and volume scattering. Davis [12] used the surface/volume-scattering model to develop an algorithm, hereafter referred to as the S/V algorithm, to process ice-sheet return waveforms. Davis and Zwally [13] used the S/V algorithm to measure geographic and seasonal variations in the surface properties of the Greenland and Antarctic ice sheets. This is the first altimeter processing algorithm to include volume scattering to describe ice-sheet return waveforms.

RETRACKING LOCATION COMPARISON

Because the NASA and ESA processing algorithms do not account for volume scattering, it is important to determine the accuracy and repeatability of surface elevations produced by these algorithms. The difference between elevation estimates derived from various retracking algorithms depends upon the difference between the leading-edge retracking locations. Ideally, the retracking point on the waveform's leading edge should correspond to the mean surface elevation within the altimeter's footprint. The NASA and S/V retracking algorithms use theoretical models to describe the shape of altimeter return waveforms. The thresholds used in the ESA algorithm arbitrarily assign the location of the mean surface to range gates associated with the different threshold values. For this comparison we denote the 25% and 50% threshold values in the ESA algorithm with E25 and E50, respectively. The 75% threshold value was not included in this comparison because it was found to produce very unrealistic estimates of the leading-edge position.

To compare the retracking locations, we selected over 400,000 Geosat altimeter waveforms from the Greenland and Antarctic ice sheets. Figure 1 shows the average location of the retracking points for the 1986 summer Antarctic data. The y-axis units are gates, which correspond to the sample locations (1-60) on the return waveform. The E25 retracking point is first, followed by S/V, NASA, and E50 retracking points, respectively. For the Greenland data we found that the NASA retracking point was closest to the S/V retracking point, while for the Antarctic data the E25 and NASA retracking points were comparable distances from the S/V retracking point, but were located on opposite sides of the S/V retracking point. The E50 retracking point was the furthest way from the S/V retracking point for both the Greenland and Antarctic datasets.

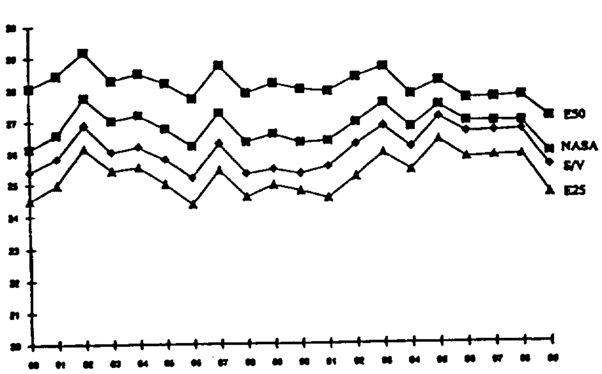

Figure 1. Average location of the ESA (E25 and E50), NASA, and S/V retracking points for the 1986 summer Antarctic dataset.

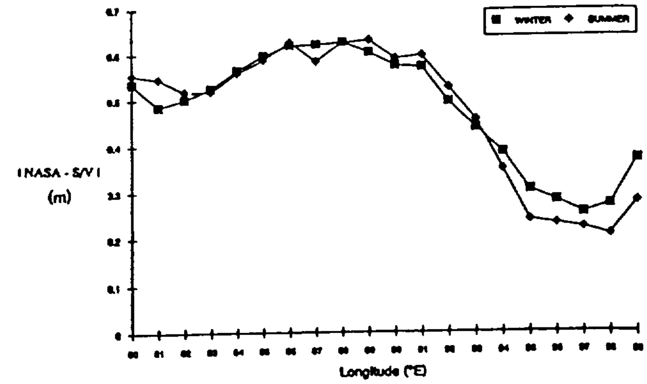

Figure 2. Absolute difference between NASA and S/V retracking locations for the summer (diamonds) and winter (boxes) 1986 Antarctic dataset.

The differences between the NASA, ESA, and S/V retracking E25 points can be converted to meters by subtracting the two gate locations and multiplying by the conversion factor G_{2m} = 0.468 gates/m. Figure 2 shows a comparison between the NASA and S/V retracking locations for the summer and winter 1986 Antarctic data. The absolute difference in the Antarctic data varies from 0.25 to 0.60 m. For both seasons the absolute difference decreases rapidly beyond 93° E. We found that the rapid decrease occurred because the 9-parameter NASA function fits volume-scattering waveforms accurately (which dominate this region of Antarctica), even though it was originally intended to fit double-ramp waveforms. Figure 3 shows a plot of the percentage of 9-parameter function fits for the Antarctic data. The percentage increases from approximately 55% to 75% as the difference between retracking locations decreases from 0.50 to 0.25 m for the longitudes from 93° to 99° E. Double-ramp waveforms occur near the ice-sheet periphery where complex topography is common. However, very few double-ramp waveforms occur over the ice-sheet plateau because of the flat surface. The 9-parameter function accurately fits volume-scattering waveforms because the combination of leading-edge and trailing-edge slopes for the two ramps form a piecewise linear type of fit to the volume-scattering return. The center location of the first "ramp" is near the beginning of the volume-scattering waveform, where the volume-scattering model predicts the mean-surface location to be. Thus, the large percentage of 9-parameter function fits

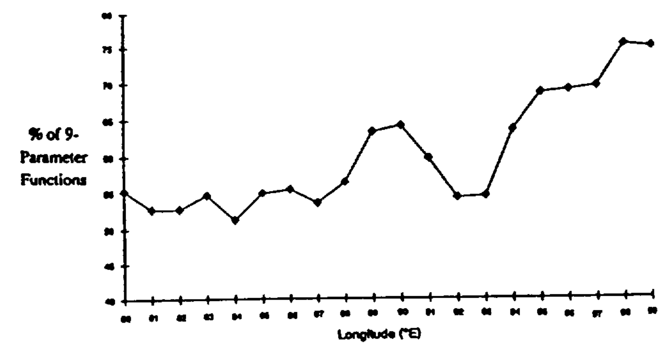

Figure 3. Percentage of the NASA 9-parameter functions for the Antarctic dataset. The percentage increases from 55% to 75% from 93° to 99° E where the difference between retracking locations (Figure 2) decreases from 0.50 to 0.25 m.

explains the close agreement between the S/V and NASA retracking locations when volume scattering occurs.

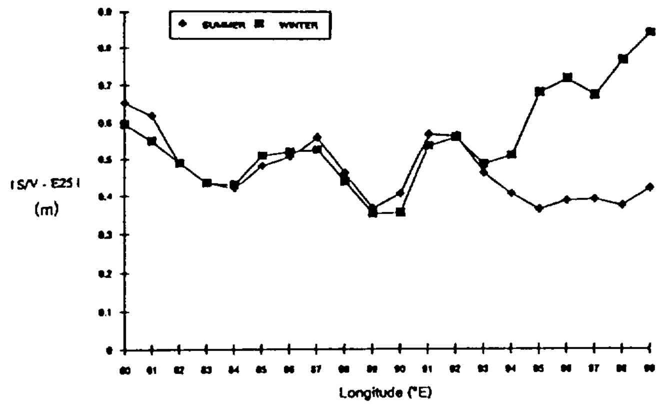

Figure 4. Absolute difference between E25 and S/V retracking locations for the 1986 summer (diamonds) and winter (boxes) Antarctic dataset. A large seasonal difference occurs from 94° to 99° E in the Antarctic data.

Figure 4 shows a comparison between the E25 and S/V retracking locations for the 1986 summer and winter Antarctic data. The absolute difference varies from 0.40 to 0.90 m. A large seasonal difference occurs in the data for the longitudes from 94° to 99° E. This difference was not present in the comparison between the NASA and S/V retracking locations. The difference occurs in the same location as seasonal differences in the surface properties of the ice sheet reported by Davis and Zwally [13]. Figure 5 shows a plot of the percentage of the pre-leading edge waveform DC bias to the maximum return waveform amplitude A_m. It is clear from the plot that a seasonal difference in the DC/A_m ratio occurs in the same location as the seasonal difference in the retracking locations. The ESA retracking algorithm uses all the waveform sample gates (n=1 to 60) to determine its retracking location. Thus, the pre-leading edge DC bias is included in the calculation of the threshold values. Because of this, the higher DC/A_m ratio in the winter season causes the threshold values to occur closer to the DC level on the leading edge of the return waveforms. This results in a larger winter difference between the E25 and S/V retracking points for the longitudes from 94° to 99° E. The NASA and S/V retracking points agree closely because both algorithms contain a pre-leading edge bias parameter, whereas the ESA algorithm does not. The seasonal difference present

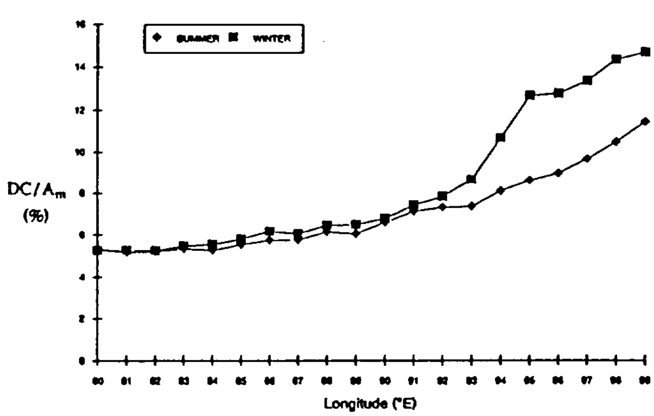

Figure 5. Percentage of the pre-leading edge DC bias to the maximum waveform amplitude A_m. A seasonal difference in the DC/A_m ratio occurs from 94° to 99° E.

in the E25 retracking location indicates that the ESA algorithm could make an erroneous estimate of ice-sheet elevation change.

Table I summarizes the average difference between the S/V retracking location and the NASA, E25, and E50 retracking locations for the entire Greenland and Antarctic data. The NASA retracking location is closest on average to the S/V retracking location for both the Greenland and Antarctic data, where the average differences are 0.33 m and 0.45 m, respectively. The E25 retracking location is the next closest to the S/V retracking location, where the average differences are 0.47 and 0.54 m for the Greenland and Antarctic data, respectively. The E50 retracking location is farthest from the S/V retracking location, where differences are on the order of 1 m or larger.

Table I. Average Difference in Retracking Locations

Dataset	|S/V - NASA|	|S/V - E25|	|S/V - E50|
Greenland	0.45 m	0.54 m	1.20 m
Antarctica	0.33 m	0.47 m	0.97 m

Bindschadler *et al.* [14] compared Seasat elevation measurements with elevations measured by geoceiver stations. They found that the Seasat elevations, derived from the NASA retracking algorithm, were lower by 2 to 3 meters on average than those derived by geoceiver. They suggested that a) orbit differences between the Seasat and geoceiver satellites or b) penetration of the radar pulse into the ice-sheet surface could cause the observed differences. Ridley and Partington [15] suggested that radar signal penetration could overestimate the satellite range (and underestimate the elevation) by as much as 3.3 meters, depending upon the retracking algorithm. The results here show that, on average, the NASA algorithm is within at least 0.5 m of the surface/volume-scattering retracking location. Thus, radar signal penetration into the ice-sheet surface cannot account for the magnitude of the elevation differences reported by Bindschadler *et al.* Therefore, orbital differences between the Seasat and geoceiver satellites are a more likely cause for the reported elevation differences.

SATELLITE CROSSOVER ANALYSIS

The technique for measuring changes in the surface elevation of the ice sheet consists of comparing elevations obtained as the satellite passes over the same point on the earth at two different times. Because elevation estimates are obtained by the satellite at discrete intervals, it is necessary to determine the location of the exact crossover point. Once a crossover point is determined, the elevation at the crossover is obtained by linear interpolation from adjacent elevation measurements. The measured elevation difference at a crossover point is

$$dH = H_2 - H_1 + E , \qquad (1)$$

where H_2 and H_1 are the surface elevations during successive orbits at times t_2 and t_1, and E is the random measurement error. Although E is usually larger than the actual elevation changes, average elevation changes can be obtained over areas of the ice sheet for time periods containing enough measurements [2].

We selected the Geosat Antarctic data to compare changes in the surface elevation of the ice sheet derived from the NASA, ESA, and S/V retracking algorithms. We chose the Antarctic data because it is located near the maximum latitude limit of the satellite, where the greatest number of sub-satellite crossover points occur. The 1986 winter data was crossed with the

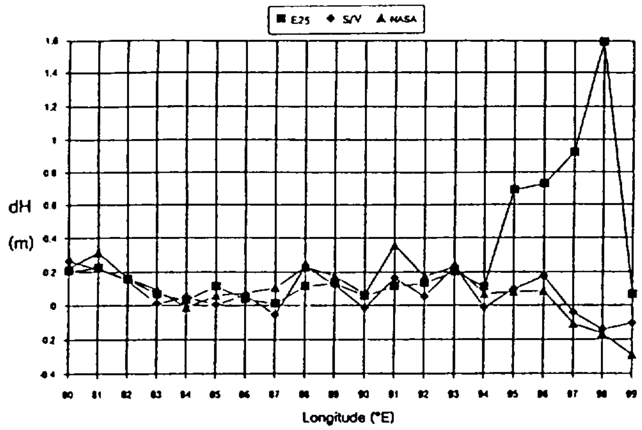

Figure 6. Average dH values from the NASA, ESA, and S/V retracking algorithms for the 1986 Antarctic dataset. The dH values from the ESA algorithm deviate substantially for the longitudes from 95° to 99° E.

1986 summer data to determine the average change in elevation over the 6-month period. Figure 6 shows the average dH values from the NASA, ESA, and S/V algorithms for the 1986 Antarctic data. The dH values from the S/V and NASA retracking algorithms follow the same trend, where the dH values range from 0.2 m at 80° E to -0.2 m at 99° E. The absolute magnitude of the dH values could be biased by satellite orbital differences between the two time periods. However, the relative change in the dH values agree with accumulation maps, where accumulation rates decrease with increasing elevation. The 0.2-m dH values in the lower elevations are consistent with accumulation rates of 0.10 to 0.15 m water equivalent reported for this region. The dH values from the ESA retracking algorithm follow the same trend as the NASA and S/V retracking algorithms for the longitudes from 80-94° E, but deviate substantially for longitudes > 94° E. Beyond 94° E, the ESA retracking algorithm predicts elevation changes from 0.7 m to 1.6 m. Maximum accumulation rates reported for this region would only yield a 0.2 to 0.35 m change in elevation over the 6-month period. The divergence of the ESA retracking algorithm coincides with the seasonal change in retracking location reported previously. Clearly, one should use caution when using the ESA algorithm to predict changes in the surface elevation of the ice sheet. While the large dH values from the ESA algorithm are clearly unreasonable, smaller elevation-change estimates could result from similar seasonal effects that would be within accepted bounds. The ESA retracking algorithm is more susceptible to seasonal differences in both ice-sheet conditions and satellite characteristics because it does not fit return waveforms with a theoretical model. Unlike the NASA and S/V algorithms, the ESA algorithm provides no information about the return waveforms with which to investigate seasonal effects.

The root-mean-square (RMS) value of elevation-change estimates provides an indication of the repeatability of these estimates [5], where lower values represent greater repeatability. The RMS value is determined from the elevation residuals, dH, using

$$\mathrm{RMS} = \sqrt{\frac{1}{N_c - 1} \sum_{i=0}^{N_c} (dH_i)^2} \qquad (2)$$

where N_c is the total number of crossovers for a given region. Table II summarizes the RMS values for the four regions in the Antarctic data from 80-85, 85-90, 90-95, and 95-100° E. The S/V retracking algorithm has the lowest RMS values for the four regions, while the NASA retracking algorithm has the second lowest RMS values. In the region where the ESA algorithm estimated large changes in elevation (95-100° E), the RMS value is four times greater than the S/V or NASA algorithm. This represents an average elevation error that is 3.3 m larger than the S/V or NASA algorithm. In the other three regions, the ESA retracking algorithm had the poorest performance.

Table II. RMS Values for the 1986 S/W Crossover Dataset

Region	Number of Crossovers	*RMS Values* S/V	NASA	ESA
80-85° E	464	0.95 m	1.00 m	1.08 m
85-90° E	403	0.93 m	0.99 m	1.07 m
90-95° E	309	0.80 m	0.94 m	0.96 m
95-100° E	336	0.72 m	0.81 m	3.41 m
Total	1512	0.87 m	0.94 m	1.85 m

The RMS values summarized in Table II reflect the repeatability of the different retracking algorithms. However, the 6-month period between the crossover points is large enough so that a real change in surface elevation may affect the RMS values. A better indication of the precision of the three algorithms can be obtained by calculating crossover residuals for a shorter time period, where significant changes in surface elevation are not likely. We crossed the 1986 summer data with itself and the 1986 winter data with itself and calculated the crossover residuals for the two-month periods spanned by the seasonal datasets. Table III summarizes these results. For both crossover datasets the S/V retracking algorithm had the lowest RMS values. The NASA retracking algorithm is second and the ESA algorithm is third. A likely reason that the ESA algorithm's RMS values are greater than either the NASA or S/V RMS values is due to the fact that the ESA algorithm does not fit the leading edge of the return waveform. By arbitrarily assigning the mean surface location to a threshold value, the ESA algorithm could be affected by variations in the waveform shape caused by local surface geometry or actual variations in the conditions of the ice sheet. The NASA and S/V algorithms are not affected by variations in the waveform shape as much because the theoretical models can adapt their fit to the changing shape of the return waveforms.

Table III. RMS Values for the 1986 S/S and 1986 S/W Crossover Datasets

Dataset	Number of Crossovers	*RMS Values* S/V	NASA	ESA
1986 S/S	803	0.99 m	1.06 m	1.11 m
1986 W/W	894	0.79 m	0.80 m	2.29 m

CONCLUSION

We compared surface elevations estimated from the surface/volume-scattering (S/V) retracking algorithm with elevations estimated from the NASA and ESA retracking algorithms. The NASA retracking algorithm surface elevations were, on average, within 0.33 to 0.45 m of the S/V algorithm elevations. The surface elevations from the ESA 25% threshold retracking algorithm were within approximately 0.5 m of the S/V elevation estimates, while the ESA 50% threshold elevation estimates differed by more than a meter. By analyzing several thousand satellite crossover points from the Antarctic data, we estimated the repeatability of the surface elevations from the three different retracking algorithms. The RMS values for the

1986 S/S crossover data in East Antarctica were 0.99, 1.06, 1.11 m for the S/V, NASA, and ESA retracking algorithms. This indicates that the S/V retracking algorithm produces the most accurate elevation estimates for the region of East Antarctica studied here. We found that the ESA retracking algorithm produced erroneous estimates of elevation change when seasonal variations occurred; it measured a 0.7 to 1.6 m change in elevation on the East Antarctic plateau over a 6-month period where accumulation rates are only 0.10 m/year. The RMS value of the ESA algorithm for this region was four times larger than the RMS values of either the NASA or S/V retracking algorithms. This type of analysis needs to be expanded to larger datasets from multiple satellites before any final conclusion can be made about the algorithm that should be used to provide the most accurate estimates of ice-sheet elevation change.

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