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Ice Sheet Surface Features in Southwestern Greenland from Satellite Radar Altimetry

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National Aeronautics and Space Administration

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PREFACE

This study was sponsored by NASA's Wallops Flight Center under Contract NAS6-3232. We gratefully acknowledge the technical guidance provided by David W. Hancock III and William B. Krabill of Wallops Flight Center.

CONTENTS

INTRODUCTION

The radar altimeters onboard the Seasat and GEOS-3 satellites were designed for measuring ocean topography and monitoring ocean dynamics (Townsend, 1980). During both satellite altimeter missions, considerable data were also collected over the Greenland and Antarctica ice sheets.

The GeoScience Research Corporation (GSRC) has been evaluating the satellite radar altimeter performance over the ice sheets. The purpose of the evaluation is to provide design parameters for future altimeters with improved ice sheet measurement capability. To achieve this goal, GSRC is utilizing the existing satellite radar altimeter data base to determine typical ice sheet surface slopes as well as periodicity and amplitude of surface undulations. The geometric considerations for satellite radar altimeter measurements over ice sheets are discussed by Brooks, et al, (1978).

An area of the southwestern Greenland ice sheet was selected for detailed topographic analysis; all the available Seasat and GEOS-3 altimeter measurements for this area have been incorporated into this analysis.

STUDY AREA DESCRIPTION

The study area, shown in Figure 1, lies between latitudes 64.5°N and 65.5°N, and extends from 45.5°W to 48.0°W longitudes. This 13,000 km^2 area of southwestern Greenland is west of the north-south trending ice sheet crest line. The area's mid-latitude approximates the northernmost GEOS-3 coverage latitude (65.13°) so that the number of GEOS-3 altimeter groundtracks will be maximized. Fourteen Seasat and ten GEOS-3 groundtracks traversed the study area. Both satellites are in retrograde orbits and overflew the area in an east-to-west direction. Uemura's north-to-south traverse of Greenland by dogsled, in the Spring and Summer of 1978, passed just a few kilometers to the east of the study area. He reported percolation facies snow cover for the region (Fushimi, et al, 1979).

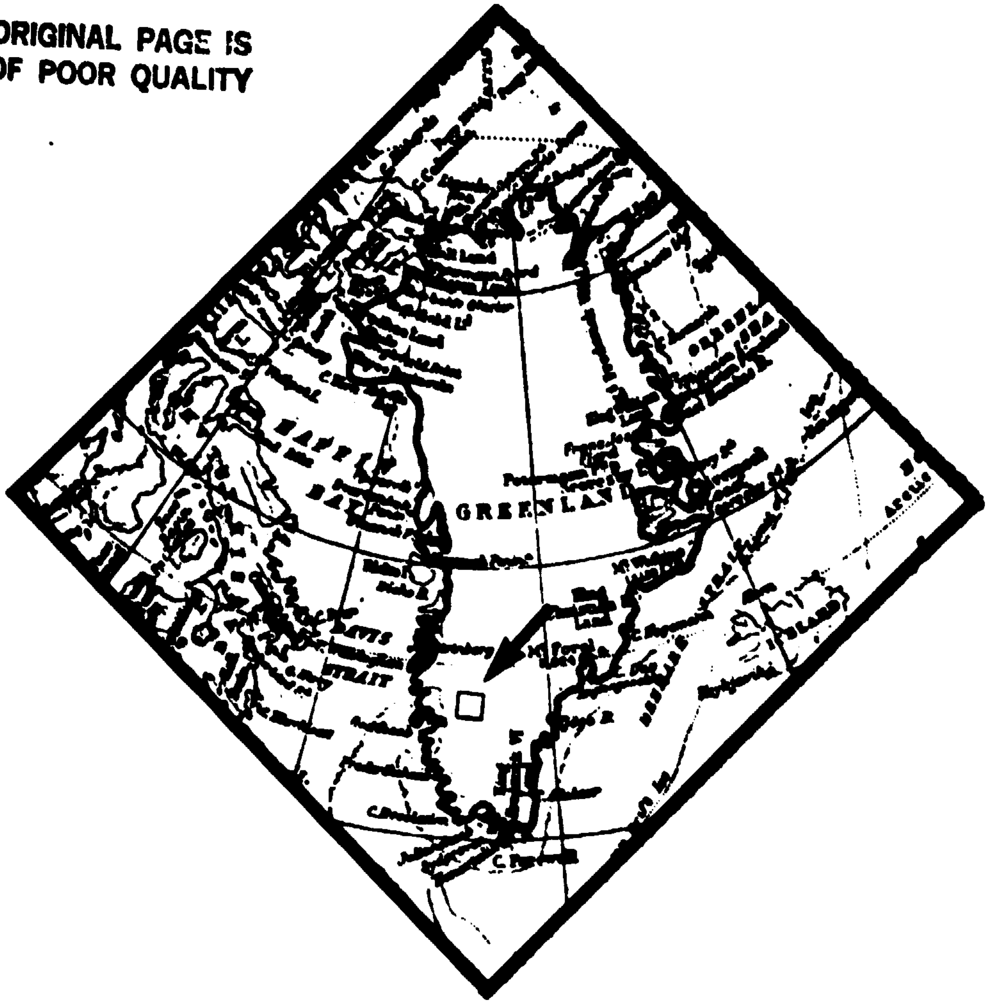

Figure 1. - Location of Study Area
in Southwestern Greenland.

ALTIMETER DATA PROCESSING

SURFACE ELEVATIONS

The data rate from both altimeter sensors was 10 per second, providing measurement spacing along each groundtrack at approximately 700 m intervals. The surface elevations (E) referenced to an ellipsoid of a = 6378.137 km and f = 1/298.257 were computed by

$$E = H - A + B$$

where H is the satellite height above the ellipsoid from orbital computations , A is the measured altitude, and B is the error in the computation of H.

The altitudes (A) were recomputed for all the Seasat measurements over the ice sheet. The recomputations were accomplished by repositioning the tracking gate at 50% of peak power on the surface return waveform ramp immediately preceding the peak power point. Previous experience with retracking the Seasat altimeter waveforms over terrain features in the United States has resulted in accuracies of ±1 m when compared with large-scale maps (Brooks, 1981a). The requirement for recomputing the Seasat altitudes over ice sheets are discussed by Brooks (1981b). The GEOS-3 radar altimeter measurements did not require recomputation as its tracking system was more responsive to the undulations of the ice sheet surface.

The orbital height error (B) is generally ±5 m. This error was computed over sea surfaces adjacent to Greenland on a pass-by-pass basis by algebraically subtracting the altimeter-derived surface elevations from the GEM10b geoid heights.

The subsequent contouring of the ice surface was done by hand. The contouring involved no averaging or smoothing; every altimeter-derived surface elevation was considered.

AUTOMATIC GAIN CONTROL (AGC) RENORMALIZATION

The Seasat AGC values are based on the average power in all 60 waveform samples. This calculation of AGC worked well over the open ocean, but the waveform mispositioning over terrain undulations resulted in erroneous AGC calculations. When the surface return waveform ramp was mispositioned towards the early gates, the calculated AGC was too high; conversely, when the waveform ramp occurred in the later gates of the waveform samples, the AGC value was too low.

For this study, the AGC values were renormalized involving the waveform samples in the vicinity of the repositioned tracking gates. Employing an algorithm developed by Hayne (1981, personal communication), the 60 waveform samples, S_i, for each 0.1 second measurement were rescaled by g where

$$g = 10.^{(D - D_r)/10.}$$

D = AGC value associated with the measurement from the onboard tracker

D_r = a reference AGC, assigned a value of 35 for this study

and $S_i = S_i g.$

Next, the 13 rescaled samples in the vicinity of the repositioned tracking gate (i.e., the tracking gate plus the 6 gates immediately prior to and the 6 gates immediately following the tracking gate) were averaged. This average value, A, was then used to compute the renormalized AGC as

$$AGC = 10. \log_{10} A + B_r$$

Where B_r is a bias, determined to be +18.5dB by comparing renormalized AGC values with onboard tracker AGC values over open-ocean areas.

RESULTS

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SURFACE ELEVATIONS

The resultant ice sheet surface features are depicted in Figure 2. The contour interval in the Figure is 20 m with all the elevations referenced to the ellipsoid.

The 24 altimeter groundtracks are shown by the thin lines; the line interruptions indicate areas over which the altimeters lost lock. In every instance of loss-of-lock, the altimeter waveforms showed evidence of a change in the surface slope. The altimeter did not lose lock at every surface undulation, however. These losses-of-lock due to surface undulations have also been observed over the Antarctic ice sheet and are described by Brooks (1981b).

The more highly-inclined groundtracks in Figure 2 are those of Seasat; the GEOS-3 groundtracks traversed the area in a more direct east-to-west pattern, extending northward only as far as 65.13°N latitude. The Seasat altimeter maintained lock over the area 82% of the time, while the more responsive GEOS-3 altimeter was locked-on 87% of the time over the area. Excluding the altimeter drop-outs, a total of 3,328 altimeter-derived surface elevations were computed for this study area.

It was observed during the analysis of the altimeter

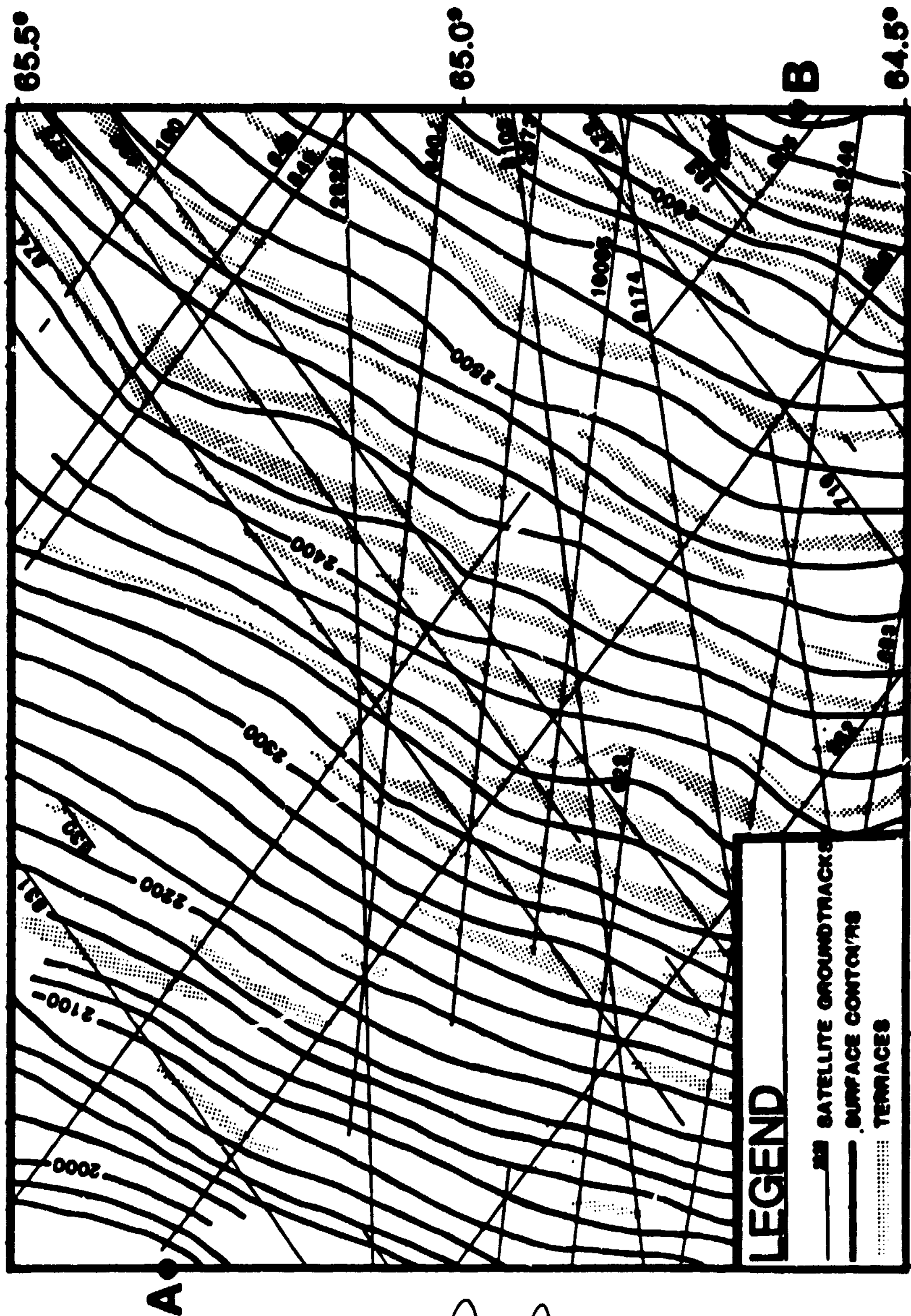

Figure 2. - Ice Sheet Surface Features in the Study Area.

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measurements that the ice surface slopes were not continuous; flattened areas or terraces appeared quite often along each groundtrack. Further, correlations with adjacent or crossing groundtracks frequently showed the presence of terraces at the same elevations. The terraces were traced from groundtrack to groundtrack; their extent (length and width) is shown by the stippled areas in Figure 2. Some of the terraces, e. g., the one at an elevation of 2,424 m, extend across the entire study area. An ice surface profile orthogonal to the surface contours between points A and B is shown in Figure 3. The average surface slope between points A and B is 4.8×10^{-3}.

The surface elevations of the eastern portion (64.5° - 65.5°N, 45.5° - 46.5°W) of the study area have been plotted in three dimensions, courtesy of W. Krabill of NASA; the three dimensional plot, shown as Figure 4, more vividly displays these terraces.

The existence of Greenland ice sheet terraces has been observed at certain sun angles by scientists on the ice sheet (C. Benson, 1981, personal communication), but their extent was not previously known. Certainly, it was not anticipated that the terraces would persist up to 100 km or more in length. It should be noted that the presence of these terraces probably would not have been discerned if conventional computer-contouring had been utilized; the averaging within each grid would have obscured the terraces.

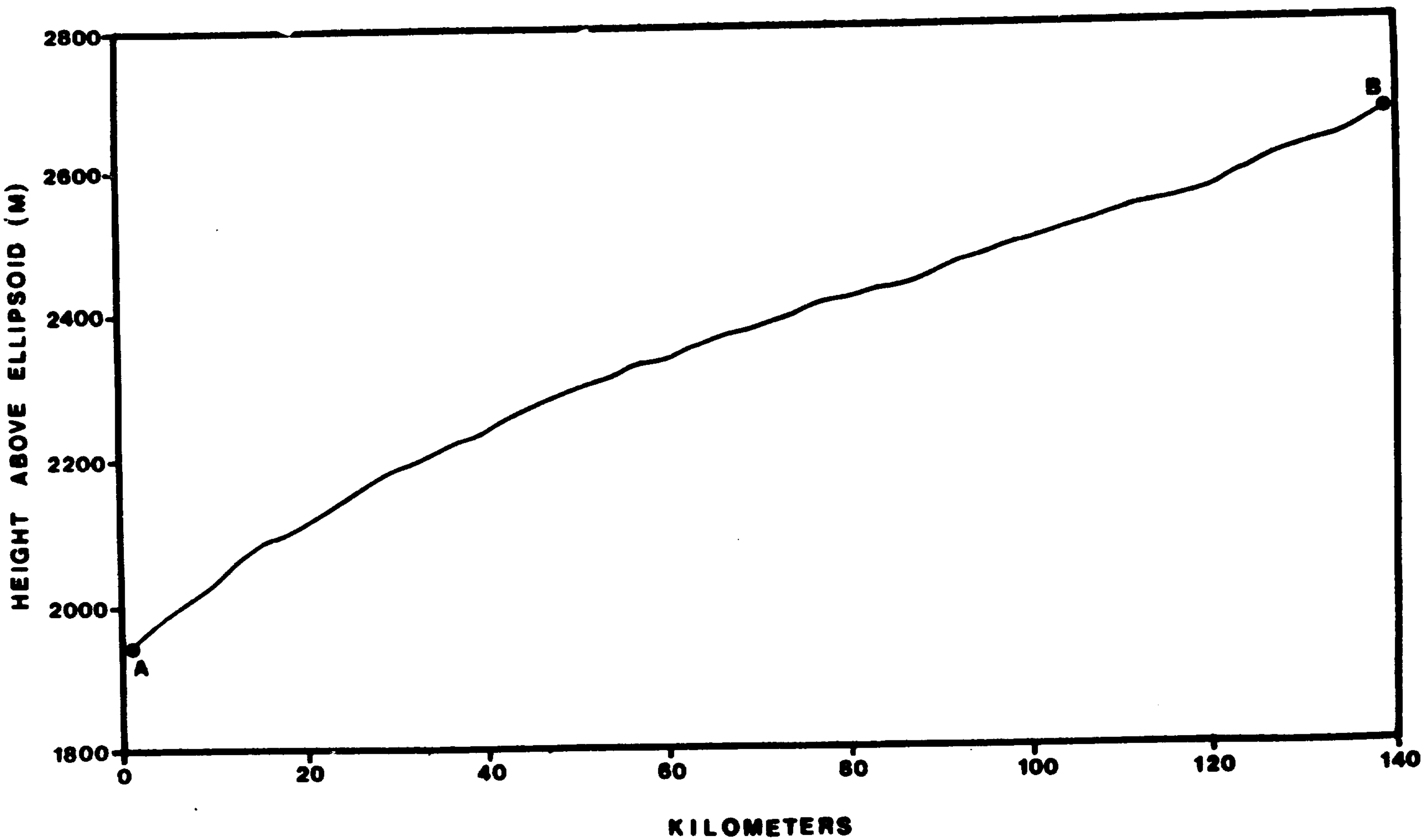

Figure 3. - Ice Surface Profile between Points A and B in Figure 2. Vertical Exaggeration is 81.4.

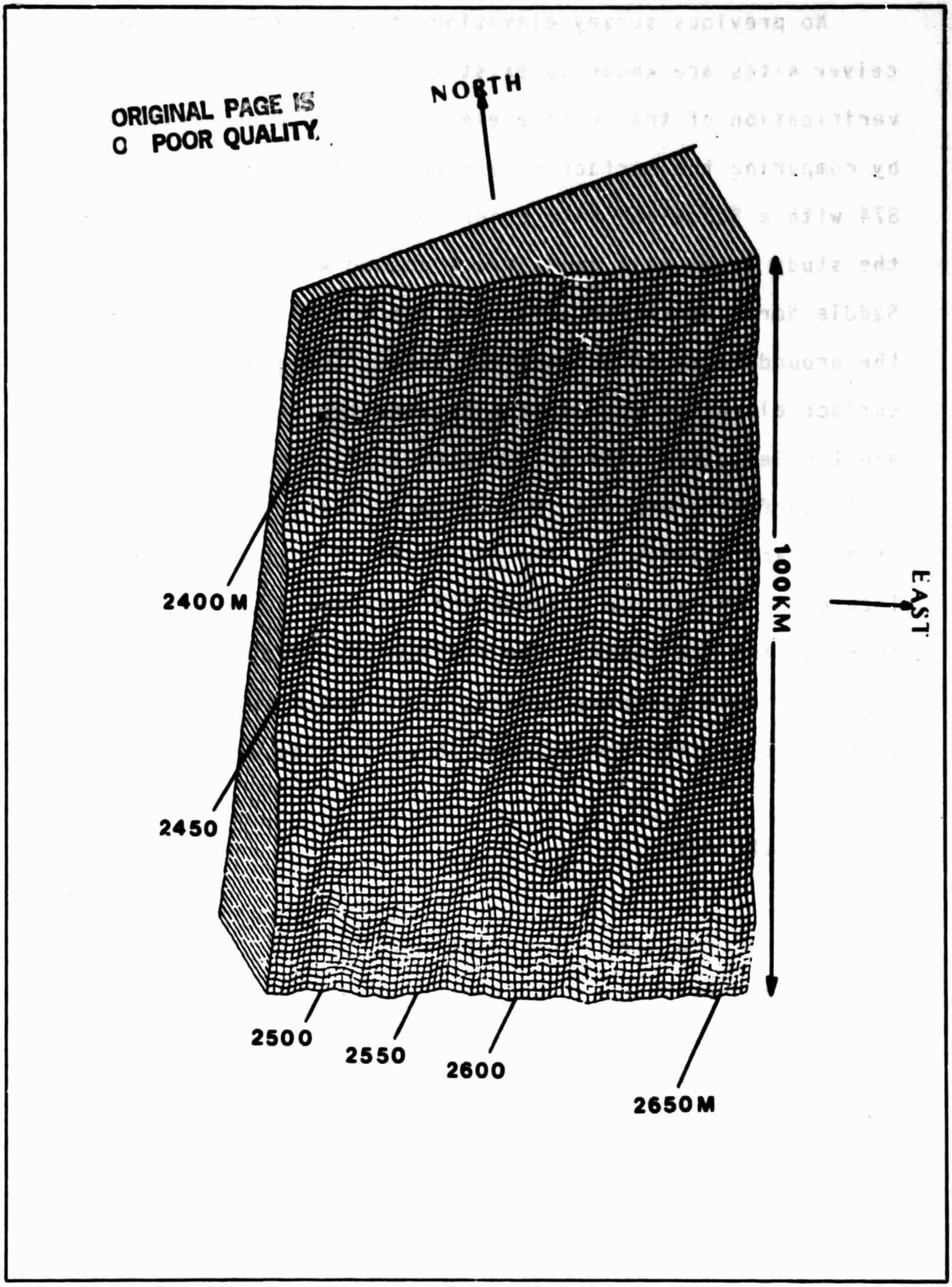

Figure 4. - Three Dimensional View of Surface Elevations in Eastern Portion (1°x1°) of the Greenland Study Area.

No previous survey elevations from traverses or Geoceiver sites are known to exist within the study area. The verification of the surface elevations has been performed by comparing the surface elevations from Seasat groundtrack 874 with a Geoceiver site prior to the groundtrack entering the study area; this groundtrack passed within 750 m of the Saddle North Geoceiver site, and was the closest of any of the groundtracks to a Geoceiver site. The geometry and surface elevation correlation between the Seasat groundtrack and the Geoceiver site is depicted in Figure 5. The Saddle North surface elevation is from Mock (1976), with no estimate of accuracy available. The Geoceiver site is described as located in the saddle between the northern and southern domes of the ice sheet. The maximum positive surface slope is to the west-northwest (Mock, 1976) which is consistent with the elevation comparisons shown in Figure 5.

RENORMALIZED AGC

The renormalized AGC values have been correlated with the surface elevations resulting from the waveform retracking. Generally, wherever the surface slope increased, the renormalized AGC values decreased; and wherever the surface slope decreased at one of the terraces, the AGC increased. As an example, Figure 6 contains a detailed portion of the surface elevations from Seasat orbit 806. This Figure also

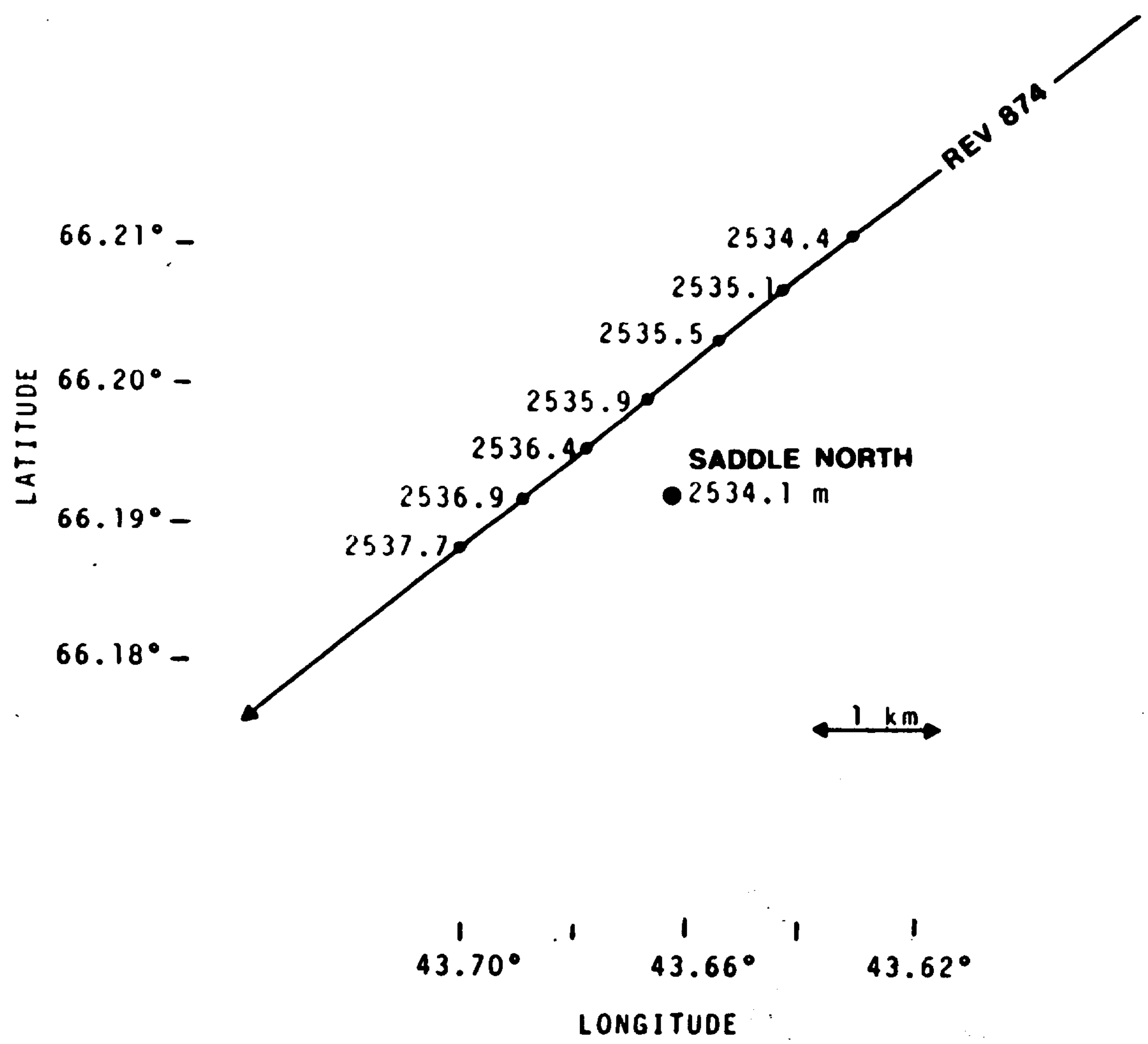

Figure 5. - Seasat Surface Elevation Comparison with Saddle North Geoceiver Station.

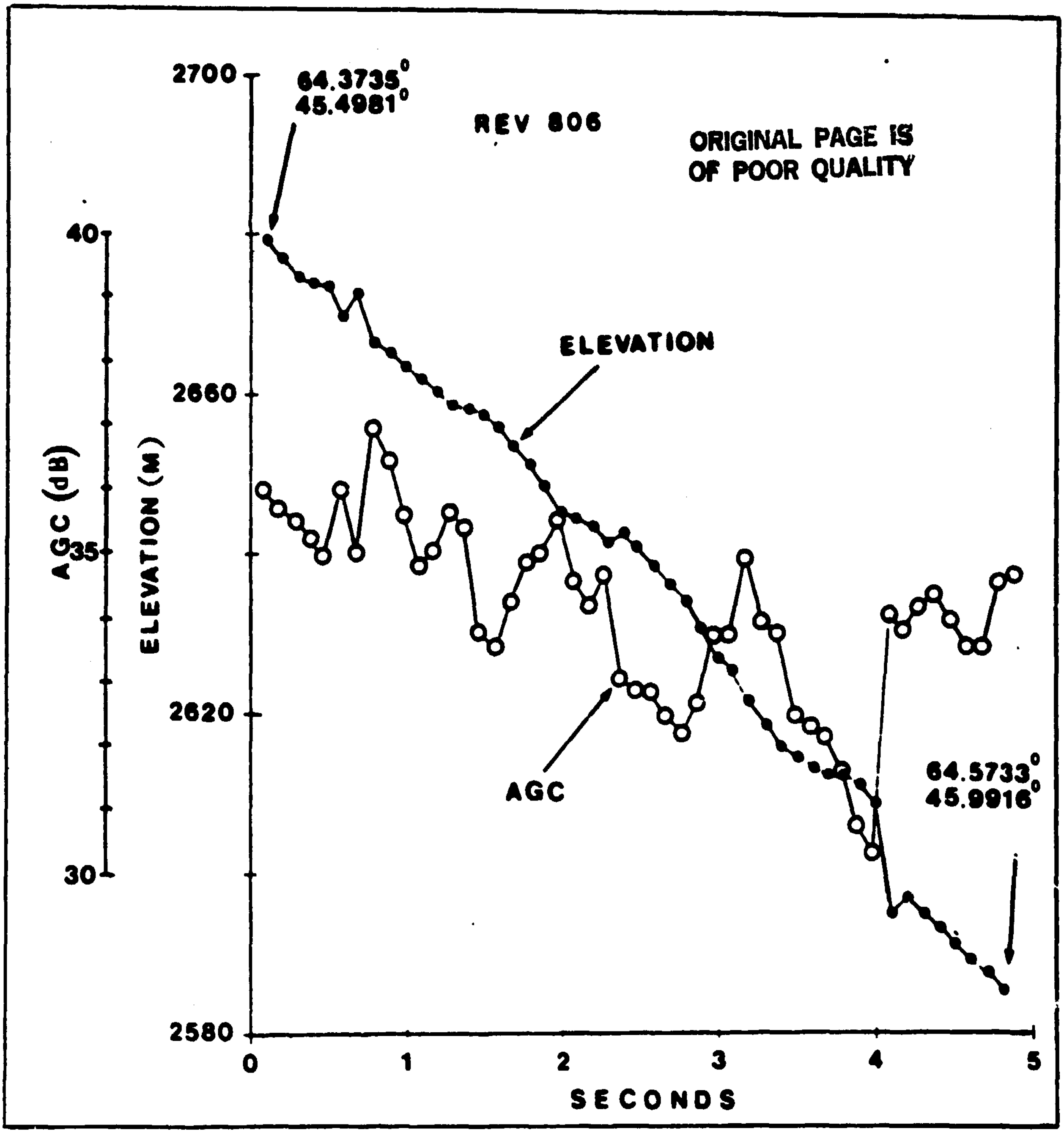

Figure 6. - Example of Correlation between Surface Slope and Renormalized AGC.

illustrates the corresponding renormalized AGC values and the excellent agreement between surface slope and signal level.

ALTIMETER PERFORMANCE

The Seasat and GEOS-3 altimeters performed quite well over this ice sheet area. Presuming that subsequent satellite altimeters to be launched in this decade will be of the Seasat-type, the analysis of performance has concentrated on the Seasat altimeter.

A typical waveform from the study area surface as recorded by Seasat is shown in Figure 7. The waveform rises abruptly and significant power levels are maintained for about 30 gates, indicating a highly reflective nadir target as well as numerous off-nadir surface facets oriented in the direction of the altimeter's receiving antenna. This waveform is typical, also, in that the waveform rise is mispositioned by the onboard tracker with respect to the tracking (or 0th) gate.

The average range velocities for the study area, based on the surface contours and the groundtrack orientation with respect to the contours, varied from 0-40m/sec with instantaneous velocities frequently exceeding 100m/sec. An example of calculated instantaneous range velocities is illustrated in Figure 8 where, for a portion of Seasat orbit 806, the average range velocity approximates +20m/sec. The corresponding surface elevations are in Figure 6.

The instantaneous range accelerations, again based on the surface elevations, frequently exceeded 100m/sec^2

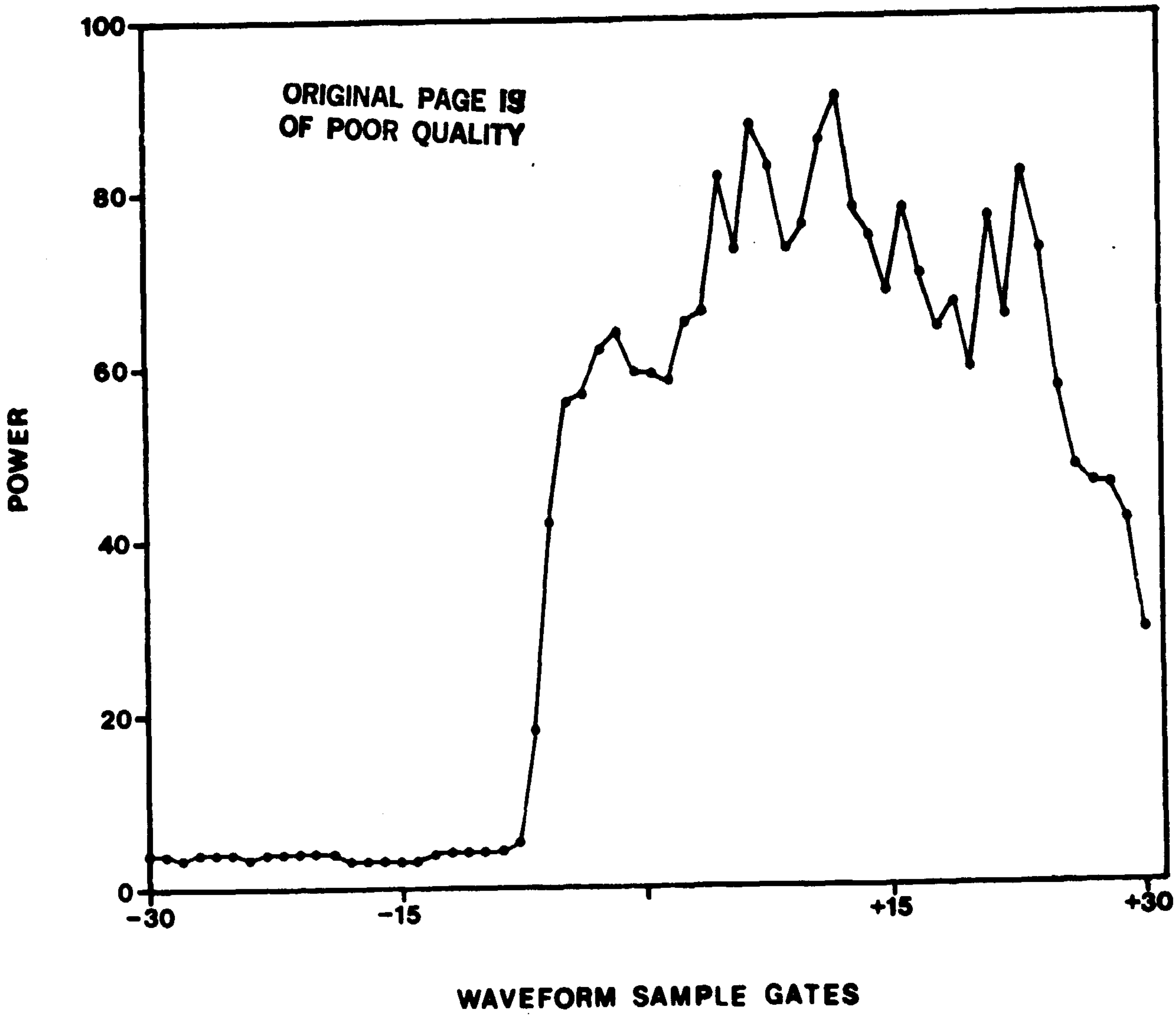

Figure 7. - Typical Seasat Altimeter Surface Return Waveform for Study Area.

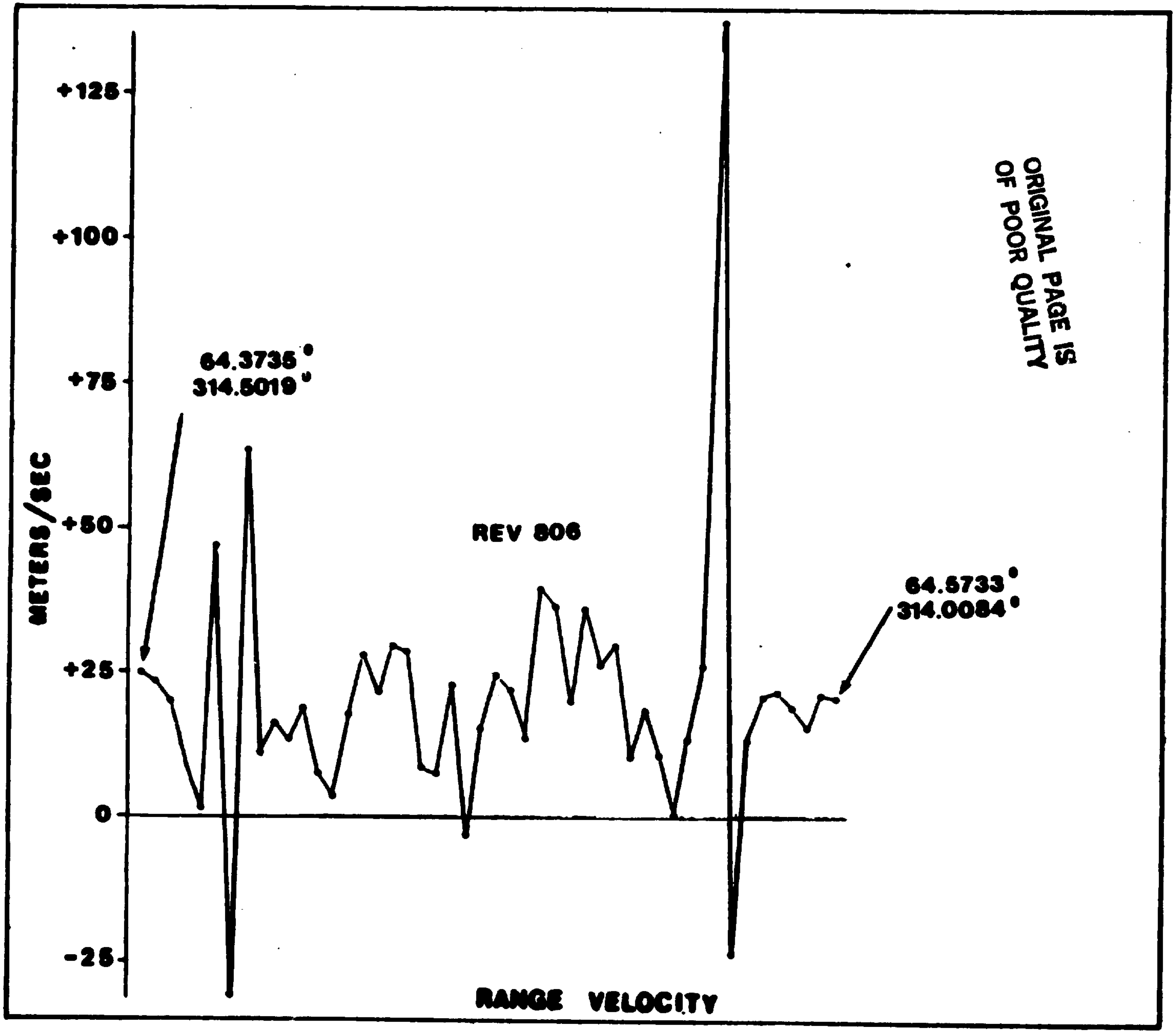

Figure 8. - Calculated Instantaneous Range Velocities for the Surface Elevations in Figure 6.

at the surface terraces. The range accelerations for the same portion of orbit 806 are depicted in Figure 9.

As discussed by Brooks (1981b), the altimeter losses-of-lock are not the result of high instantaneous surface accelerations, but are produced by a persistent surface change which causes the altimeter waveform to "walk-out" of the range gates. This "walking-out" occurs during 0.5 - 1.0 second time spans. A faster tracker update would solve this problem. As long as the waveform stays within the range gates, the waveform can be retracked to produce accurate surface elevations.

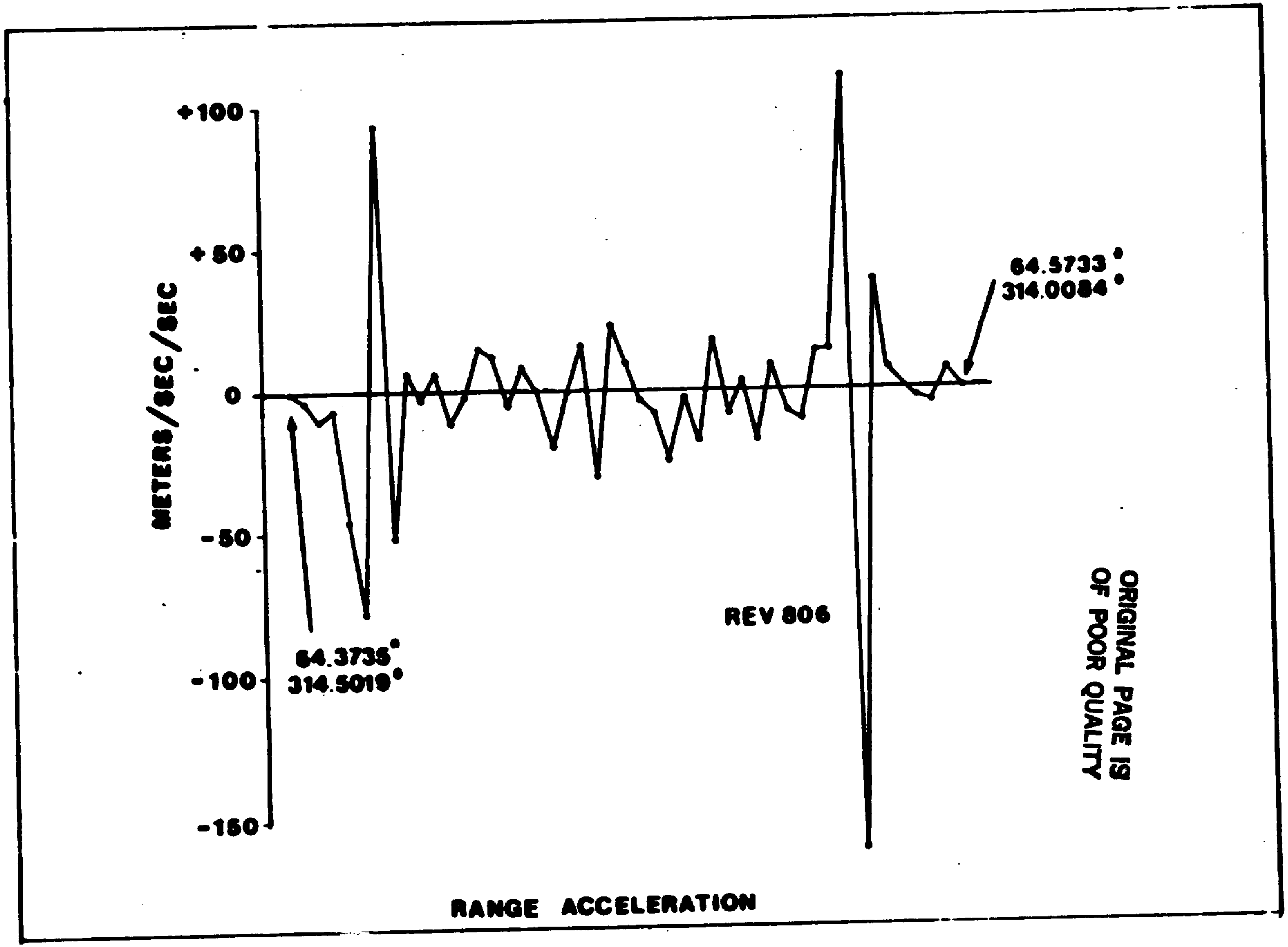

Figure 9. - Calculated Instantaneous Range Accelerations for the Surface Elevations in Figure 6.

SUMMARY

Fourteen Seasat and ten GEOS-3 satellite radar altimeter groundtracks across a 13,000 km^2 ice sheet area of southwestern Greenland yielded 3,328 surface elevations. The surface elevations derived from Seasat were recalculated based on a waveform retracking algorithm. Analysis of the elevations reveals the existence of surface terraces, some greater than 100 km in length. Renormalized Seasat AGC values were shown to be correlated with surface slopes.

The ice surface undulations caused frequent altimeter losses-of-lock. A faster servo response rate for future satellite altimeters would aid ice sheet mapping in the next decade; as long as the waveforms are retained in the range gates, the waveforms may be subsequently retracked to achieve accurate surface elevations.

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