Annals of Glaciology 8 1986

ANALYSIS AND SIMULATION OF ALTIMETER PERFORMANCE FOR THE PRODUCTION OF ICE SHEET TOPOGRAPHIC MAPS

by

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ABSTRACT

Satellite-borne, radar altimeters have already demonstrated an ability to produce high-precision, topographic maps of the ice sheets. Seasat operated in a tracking mode, designed for use over oceans, but successfully tracked much of the flatter regions of the ice sheet to ± 72° latitude. ERS-1 will extend coverage to ± 82° latitude and will be equipped with an ocean mode similar to that of Seasat and an ice mode designed to permit tracking of the steeper, peripheral regions. The ocean mode will be used over the flatter regions, because of its greater precision.

Altimeter performance over the ice sheets has been investigated through a study of Seasat tracking behaviour and the use of an altimeter performance simulator, with a view to assessing the likely performance of ERS-1 and the design of improved tracking systems. Analysis of Seasat data shows that lock was frequently lost, as a result of possessing a non-linear height error signal over the width of the range window. Having lost lock, the tracker frequently failed to transfer rapidly and effectively to track mode. Use of the altimeter performance simulator confirms many of the findings from Seasat data and it is being used to facilitate data interpretation and mapping, through the modelling of waveform sequence.

1. INTRODUCTION

Satellite-borne, radar altimeters have the potential to revolutionise the production of topographic maps of the polar ice sheets. In contrast with surface campaigns and observations from balloons and aircraft, they can provide a regular sequence of elevation measurements, unaffected by the hazardous, polar environment, or, indeed, by the time of day or night, or prevailing meteorological conditions. The time-scales for completing a large area survey are short, compared with the times over which significant elevation changes are likely to take place and the areas accessible are restricted only by the maximum latitude over which the satellite platform passes. With a slowly precessing orbit, very dense spatial sampling could be obtained.

Accurate, topographic maps are of value for studies of ice-sheet dynamics, for the assessment of ice-sheet mass balance, and for the modelling of katabatic wind flows. More specifically, it may prove possible to use altimetric maps to locate surface inflections associated with transitions in ice-sheet basal conditions. These transitions are expected to be sensitive to changes in world climate. Thus, altimetric measurements could play a key role in future investigations of the interactions of ice sheets and climate.

Results from the Seasat altimeter have shown that, over the relatively flat central plateau regions, elevation accuracies better than a few metres can be achieved (Zwally and others, 1983), compared with a best performance of approximately thirty metres by other methods. Elsewhere, over more steeply-sloping and undulating terrain, the Seasat instrument experienced difficulties in maintaining track and provided only intermittent coverage. Data obtained from regions with severe slopes, or extreme topographic relief, are difficult to interpret in terms of an average elevation.

The ERS-1 mission, to be launched by the European Space Agency at the end of the decade, includes altimetric mapping of the polar ice sheets as one of its major goals. With a latitude range of ± 82°, it will provide the first-ever coverage of the northern half of the Greenland ice sheet and the major part of Antarctica, including the climatically sensitive West Antarctic ice sheet. Over the flatter, ice-sheet areas, the instrument will operate in its ocean tracking mode, to achieve high-precision measurements directly comparable with those from Seasat. Over more difficult terrain, it will switch to a lower-resolution "ice mode", designed to ensure continuous tracking. Assuming successful operation over the planned three-year lifetime, we may anticipate a substantial increase in the ice-sheet altimetric data available by 1992.

In order to evaluate the likely performance of the ERS-1 altimeter, it is necessary to understand the origins of the tracking difficulties experienced by the Seasat instrument. Additional information can be obtained from computer simulations, which are especially important for ice sheet regions, over which the Seasat instrument obtained little or no data. Results from the simulations may also be used in the development of new techniques for the interpretation of the data.

In this paper, we briefly review the operation of altimeters over ice sheet surfaces and show how the analysis of Seasat data and the use of computer simulations are providing the foundations for the production of accurate and extensive topographic maps from ERS-1.

2. THE ALTIMETER WAVEFORM

Altimeters may be designed to operate in either a beam-limited, or pulse-limited, mode. In the former case, the polar response of the antenna would be made sufficiently narrow to define the area of the surface to which range estimates are made. At satellite altitudes, this would necessitate the use of a large (>10 m) antenna, with attendant difficulties in construction, deployment, and pointing. As a result, the altimeters flown on previous missions and those planned for the immediate future all operate in the less technically-demanding and less costly, pulse-limited mode.

In the pulse-limited mode, the combination of a broad antenna beam and short pulse duration ensures that range measurements are made to a restricted region, within the overall beam-limited footprint. Over a flat, uniform, diffuse surface, viewed at normal incidence, the leading edge of the waveform corresponds to the integral of the height distribution of scatterers and, if the distribution is symmetrical, the half-power point corresponds to the mean surface elevation. The shape of the leading edge provides information on the surface roughness and the maximum amplitude of the waveform is related to the surface reflectivity. The important point is that only a small part of the return echo need be recorded and analysed, to derive the geophysical parameters of interest.

Over topographic surfaces, the situation is more complex. The return waveform corresponds to the convolution of the transmitted pulse, with the range distribution of scatterers within the entire, beam-limited footprint of the instrument. Information on surface elevation is contained throughout the entire waveform. Since all azimuthal information is lost, individual profiles are highly ambiguous. However, provided the full profile is recorded and sufficiently dense surface sampling is carried out, it should be possible, in principle, to reconstruct the dominant features of the surface, using corrections of the form used by Brenner et al (1983), or migration techniques similar to those used in the analysis of sonar data.

A further difficulty arises from the rapid variations of pulse shape and delay time, which occur over steeply-sloping regions with significant topographic relief. These can defeat the range tracking system, causing loss of lock and reduced coverage. Subsequent attempts to re-acquire the surface may also be disrupted.

Fortunately, vast areas of the central Greenland and Antarctic ice sheets are characterised by mean gradients of less than 1°, with surface relief less than ± 10 m (Squire and others, 1984). Altimeter waveforms from these areas correspond closely in shape to those observed over the open ocean, permitting the use of ocean mode tracking and allowing estimates of the surface elevation to be based on the half-power point of the leading edge. Elsewhere, it is necessary to record as much as possible of the waveform for subsequent analysis. Improved techniques for surface tracking are also required.

3. THE SEASAT ALTIMETER

The Seasat altimeter was designed for use over the open ocean and operated at 13.5 GHz in the pulse-limited mode, with an effective, transmitted, pulse duration of 3 ns (MacArthur, 1976, 1978). Seasat's ± 72° latitude range provided coverage of the southern half of the Greenland ice sheet, the Antarctic peninsula, and the periphery of East Antarctica, including the Amery ice shelf. Despite some intermittent coverage and an unexpectedly short operating lifetime of only three months, 600 000 usable range measurements were obtained, representing the most comprehensive and accurate set of ice-sheet, topographic data yet collected. These data have been used by various workers to produce topographic maps with contour intervals as small as 2 m (Zwally and others, 1983; Brooks and Norcross, 1982, 1984; Brooks and others, 1982).

Figure 1, taken from Zwally and others (1983), shows the distribution of usable altimetry from the two ice sheets. The data density increases towards the polar limits of the orbit as the ground tracks converge and also varies systematically across the ice sheet, as a function of tracking success. Over the more central regions, the combination of a high density of ground tracks and continuous sampling, with an along-track spacing of 662 m, allows the production of reliable maps. Elsewhere, only intermittent measurements are available. Clearly, it is important to understand the origins of the intermittency.

4. SEASAT ALTIMETER PERFORMANCE OVER THE ICE SHEET PERIPHERIES

The Seasat altimeter range tracker aimed to predict the delay time of successive waveforms, based on estimates of the range, range error, and range rate, calculated on board in real time. The purpose was to maintain the leading edge of each waveform centred within the 60 samplers of its range window. Specifically, an alpha-beta tracking filter was employed, using the following set of recursion equations:

$$h_{n+1} = h_n + \alpha\Delta h_{n-1} + \dot{h}_n \tag{1}$$

$$\dot{h}_n = \dot{h}_{n-1} + \beta(\Delta h_{n-1}/\Delta t) \tag{2}$$

where h_n , $\dot{h}_n$ are the range and range rate values at sample n, Δh_n is the corresponding range error and Δt is the sampling interval. The ratio of α to β was chosen to critically damp the tracker response and β was chosen to limit tracker lag to a maximum of 10 cm for a range acceleration of 0.6 ms^{-2}, the maximum value likely to be encountered over the open ocean (Martin et al, 1983). The values adopted were thus α = 1/4 and β = 1/64, resulting in a tracker response time of 0.4 s, or 8 sample intervals. When the instrument was in its acquisition mode, the loop

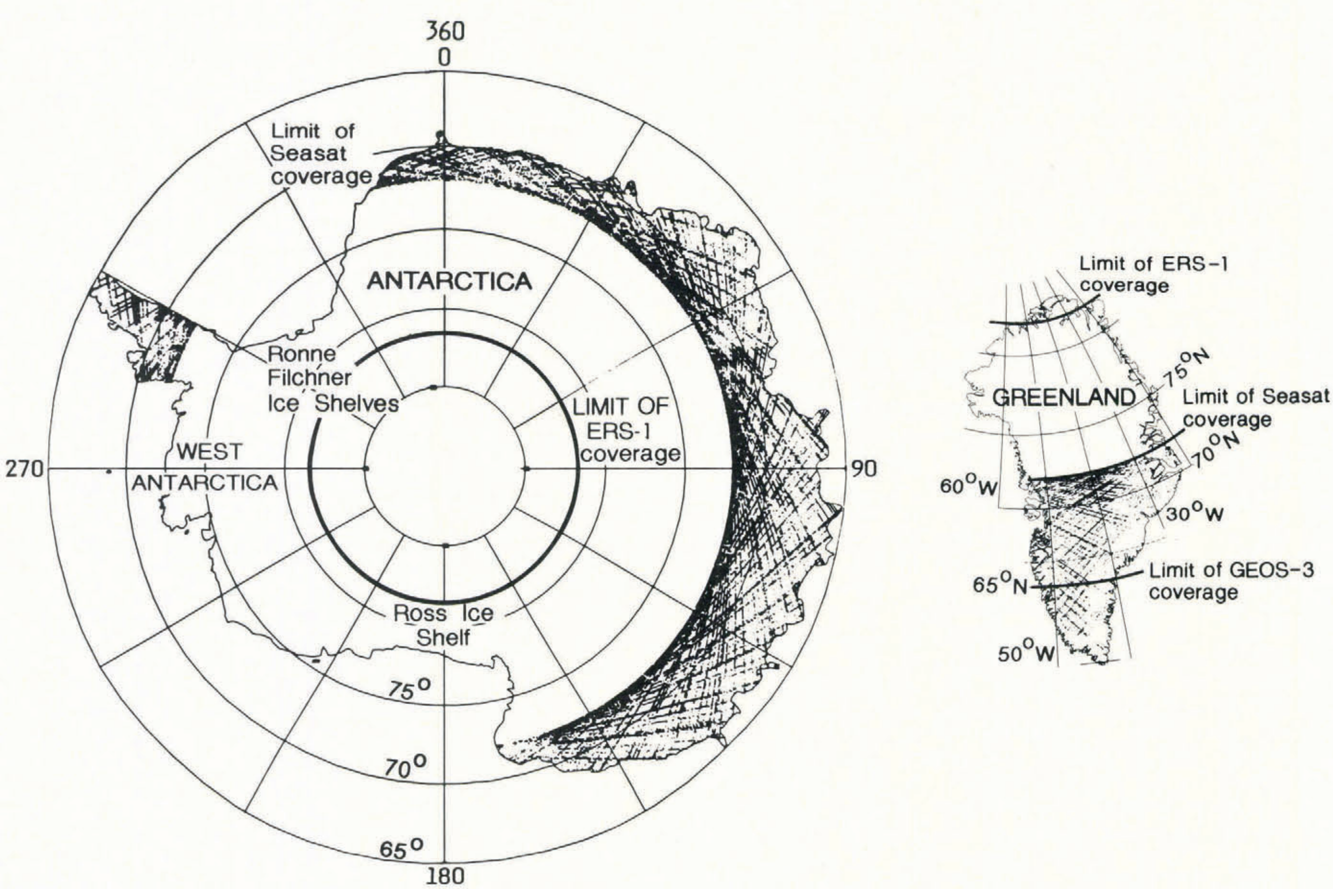

Fig.1. Seasat ground tracks of usable altimetry data over Greenland and Antarctica (only 50% of passes plotted over Antarctica). (After Zwally and others, 1983).

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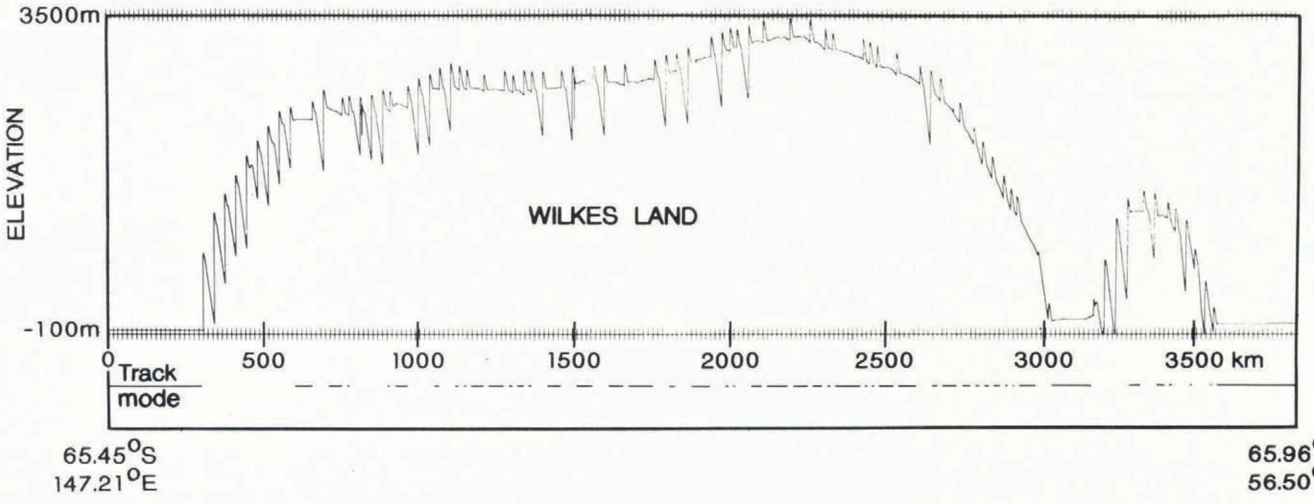

Fig.2. Transect across Antarctica along orbit 1074, showing satellite range corrected for orbit and an acquisition/track mode flag.

constants were $\alpha = 1/2$ and $\beta = 1/16$, giving a faster response time.

The generation of the range error signal in the Seasat instrument was achieved, using a split gate algorithm. Six gate triplets, of various widths, were formed symmetrically about the central range bin. A particular triplet was selected to span the leading edge of the waveform with its middle gate. The range error was formed by comparing the selected middle gate with the average power returned in the overall range window, after applying a correction for the leading-edge slope. For zero error, the tracking point was aligned with the point on the leading edge corresponding to the mean surface. The formation of the range error in this fashion produced a linear error signal provided:

(i) the leading edge crossed the central range bin.
(ii) the return was "ocean-like" in shape.

Over the ice sheet peripheries, these conditions were often violated. The effect of not satisfying (i) was significantly to reduce the error signal gain.

During acquisition, the range error was calculated from the offset of the earliest threshold crossing from the central bin, producing a completely linear error signal.

The gate triplets were also used to test for loss of tracker lock. The instrument calculated running averages of the difference between the late gate and early gate of each triplet. Track was maintained, provided that at least one of these running averages exceeded a fixed threshold.

Following any occasion when the tracker lock condition was not satisfied, the instrument entered its acquisition sequence. This commenced with the transmission of a series of 3.2μs pulses, to provide a coarse estimate of surface range. The tracking point was then set 150 m above the estimated location of the surface and the range window was stepped down 7.5 m every 0.05 s until a threshold signal crossing was detected. Estimates of range and range rate were then generated, using fast tracker constants until 2 s after the start of the stepping-down sequence. Following this, the tracker transferred to track mode, provided any running, average, late-early gate difference exceeded a threshold. If the threshold condition failed, acquisition was recommenced after 5 s.

A transect of Seasat data from each of the Greenland and Antarctic ice sheets has been studied to identify the limitations of the Seasat tracker performance. The profile across Antarctica is shown in figure 2, along with an acquisition/track mode flag. The more consistent tracking over the central plateau regions is immediately apparent.

Table I shows the results of an analysis of the sources of data intermittency. The causes are split into four categories, as follows:

<u>Failure of the acquisition sequence to declare track mode within the 5 s time limit:</u>

This accounted for 40% of the "loss of track" events and 90% of these were over upslopes. Over the steeper

TABLE I. LOSS OF LOCK OVER THE ICE SHEETS (orbit 1074)

Total number of acquisition attempts:	147	upslopes:	90
Failure of acquisition to declare track mode:	59	upslopes:	53
Loss of lock within I second of transfer to track mode:	38	upslopes:	14
Successful transfer to established track mode:	50	upslopes:	23

Causes of loss of lock after transfer to track mode (orbit 1359, Greenland and Antarctica)

Discrete change in surface elevation	2
Overshoot of leading edge from acquisition	25
Overshoot and locking onto false leading edge	2
Overshoot and indistinct leading edge	7
Change in gradient and/or double ramp	18
Total	54

slopes, the tracker overshot the leading edge of the return, partly because it was extremely attenuated. Otherwise, the tracker failed to transfer to track mode because the leading edge of the waveform had already disappeared from the range window by the time the transfer test was executed (after 2 seconds chirp acquisition). Over downslopes, the surface was often detected after 2 s, so the transfer test was executed and passed whilst the leading edge was still within the range window.

<u>Acquisition sequence overshoot:</u>

This was also an important source of acquisition failure, accounting for a further 26% of data losses. After transfer to track mode, the tracker would lose lock within 1 s. This is attributed not so much to the slower response times of track mode as to the collapse of the height error signal for large displacements of the waveform leading edge from the tracking point. The problem also resulted, in part, from inadequate estimation of range rate prior to the transfer.

Loss of lock due to change in gradient:

This was the most common cause of loss of lock, once tracking had been firmly established. It is important to appreciate that very few of these events can be unambiguously attributed to the slow response time of the tracker. In several events, the range variations were well within the capability of the tracking loop to follow, but loss of lock resulted once again, as a result of the non-linearity of the range error signal.

"False" feature tracking:

In some 9% of the total number of events, the tracker locked on to features that migrated to the rear of the waveform, causing violation of the late-early gate criteria. Often, a feature would develop at the top of an established leading edge and would grow to form a new leading edge at reduced range, leaving the tracking point "stranded" on the rear of the waveform. This behaviour is typical of surfaces exhibiting discontinuous changes in elevation or slope.

We may therefore summarise the limitations of the Seasat tracker over ice sheets as follows:

(i) The sensitivity of the altimeter to extended leading edge slopes was responsible for many failures of acquisition. This problem may be solved by increasing the range window width and bin width to sharpen the leading edge.

(ii) Loss of lock, occurring immediately after transfer to track mode, resulted from the non-linearity of the range error signal and from poor estimation of range rate, during the acquisition sequence.

(iii) The poor linearity of the range error signal was the major cause of lost lock, once tracking was declared.

(iv) Although there is evidence for occasional losses of lock due to a sluggish tracker response, this is not a major problem area. Indeed, it is possible that any reduction in tracker time constants would increase the tendency to track features into the rear of the waveform, thereby increasing the number of lost-lock events from this cause.

5. THE ALTIMETER PERFORMANCE SIMULATOR (APS)

Independent confirmation of several of the conclusions drawn in the previous section has been obtained from computer simulations of the response of altimeter trackers to model waveform sequences. As part of an ESA supported study, Rapley and others (1983) demonstrated the importance of the linearity of the range error signal in maintaining track and the need to derive an accurate value for range rate, prior to transferring from acquisition mode to track mode.

The computer code used in the early study has subsequently been upgraded and extended to include a mathematically rigorous waveform synthesiser, an improved, ice-sheet surface model, and a model of the ERS-1 altimeter ocean mode tracker. Descriptions of the program, known as the Altimeter Performance Simulator (APS), have been given by Rapley and others, (1985a, 1985b) and Novotny and others (1984).

The objectives of the APS include assessment of the performance of specific altimeter designs over a variety of different types of surface, the development and evaluation of instrument design improvements, and the development of techniques to interpret altimeter waveforms over complex surfaces.

The current version of the ice-sheet surface model has been described by McIntyre and Drewry (1984). It consists of a circular surface, near-parabolic in cross section, upon which are superimposed bell-shaped undulations, with realistic spatial scales and amplitudes, representing local roughness. Ice streams and outlet glaciers are modelled in the coastal perimeter by cosine indentations in the cross-slope direction, with increasing width towards the coast. At present, small scale roughness (snow dunes and sastrugi) are not modelled, for want of reliable, in situ data. However, these could be added readily, as could variability of the surface backscatter coefficient. The latter is currently assumed to be constant and Lambertian, on the basis of preliminary studies of the Seasat altimeter ice sheets data.

Figure 3 shows a sequence of four waveforms,

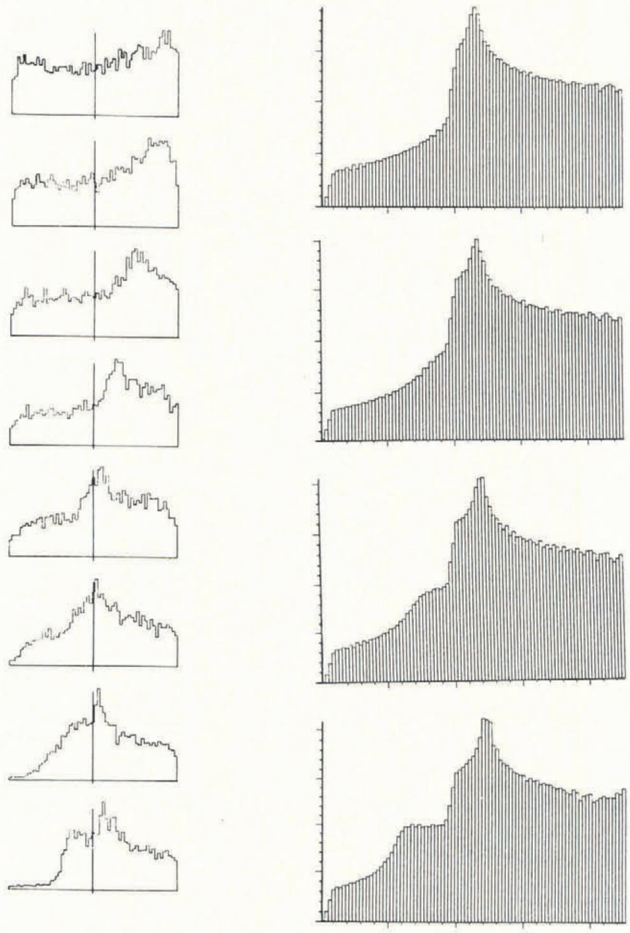

Fig.3. Sequence of four waveforms, generated using the waveform synthesiser and the ice sheet surface model of the APS (right) with Seasat altimeter data over Greenland (left).

generated using the waveform synthesiser and the ice-sheet surface model. Comparison with waveforms recorded by the Seasat altimeter (also shown) suggests that the model provides realistic outputs, since the waveform shapes and evolution are qualitatively very similar.

Studies are currently in progress, which relate features in the waveforms generated over the ice-sheet surface model to topographic features within the modelled footprint, in order to obtain insights into techniques for data interpretation (to be reported elsewhere). The same waveform sequences are being used to evaluate ERS-1 tracker performance.

Since the evolution of waveform shapes can be very complex, sequences of waveforms, corresponding to simple surface transitions, are being studied. Figure 4 shows the response of the ERS-1 ocean mode tracker to a passage over a positive step in an otherwise planar surface. The tongue, which appears at the base of the waveform, corresponds to power returned from the more elevated part of the surface. The range tracker does not respond to this feature and, as the return from the upper surface becomes increasingly dominant, the tracking point is left stranded on the rear of the waveform and track is lost. The case shown corresponds to a 30 m step, but similar results are observed for steps >15 m and for significant, discrete increases in surface slope. The tracker behaviour is identical to that observed in the Seasat data, and indicates that the ERS-1 ocean mode will be inappropriate for ice-sheet regions, where transitions of this type are likely to be encountered.

6. THE ERS-1 ALTIMETER

The ERS-1 altimeter has been described by Francis, 1984. It will operate in the pulse-limited mode, at a frequency of 13.6 GHz. In many respects, it will be similar to the Seasat instrument. For example, in its ocean tracking

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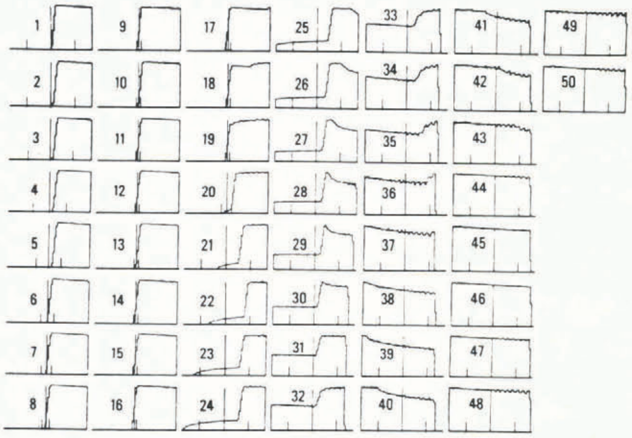

Fig.4. Response of the ERS-1 ocean mode tracker to passage over a 30 m positive step in an otherwise planar surface. The waveforms read down the columns. The range window width is 28 m, the altimeter beamwidth 1.6°, pulsewidth 3 ns, measurement rate 20 Hz and groundspeed 6.7 kms. The sensor is initially 10 km from the step (at the upper left of the diagram) and is directly over the step in the 31st frame.

mode, it will transmit a pulse of 3 ns effective duration and it will record the leading edge of the return waveform, using 60 samplers, covering a range window of 28 m. Thus, the ocean-mode data, from ice sheet areas already covered by Seasat, should be directly comparable with the 1978 data, allowing searches for topographic changes that may have taken place during the period between the two missions.

A consequence of the similarity to the Seasat design is that the ERS-1 ocean mode will be susceptible to several of the tracking problems discussed earlier. For this reason, the instrument will be provided with an alternative operating mode, the ice mode, for use over steeper topographic terrain. In the ice mode, the effective pulse duration and range-window width will be increased by a factor of four, reducing range resolution, but 'sharpening' the waveform leading edge and extending the percentage of the return waveform recorded. A centre-of-gravity range tracker will be employed, giving a linear error signal over the full range-window width. As a result, the instrument will provide much greater coverage of the peripheral ice sheet areas, where the Seasat instrument had difficulty maintaining track. Furthermore, the increased percentage of the waveform recorded will assist greatly in the interpretation of the data. Studies of the ice-mode performance and the development and testing of an algorithm to permit autonomous switching between the ocean and ice modes are about to commence, using the APS. Any autonomous, switching algorithm must be sufficiently rigorous to ensure that data quality is not compromised through the use of an inappropriate algorithm, which employs the ice mode where it is not necessary.

7. CONCLUSIONS

We have shown that the Seasat altimeter, ice-sheet data, in combination with computer models and simulations, provide an invaluable source of information for the improvement of the mapping capabilities of future altimeter instruments. On the basis of experience with the Seasat data, we may anticipate a major advance in the knowledge of the topography of the Earth's ice sheets, as a result of the improved performance and greatly increased, geographic coverage to be achieved by ERS-1.

ACKNOWLEDGEMENTS

The work reported here was supported in part by ESA contracts 5182/82/F/CG(SC) and 5684/83/NL/BI. The authors acknowledge the work of Dr Eva Novotny and Mr Paul Cooper of the Scott Polar Research Institute in the production of the waveform synthesiser for the APS and thank Dr Duncan Wingham and Mr Hugh Griffiths of University College London for valuable discussions.

REFERENCES

Brenner A C, Bindschadler R A, Thomas R H, Zwally H J 1983 Slope-induced errors in radar altimetry over continental ice sheets. *Journal of Geophysical Research* 88(C3): 1617–1623

Brooks R L, Norcross G A 1984 Ice sheet surface features from satellite radar altimetry. *Marine Geodesy* 8: 211–220

Brooks R L, Williams R S Jr, Ferrigno J G, Krabill W B 1983 Amery Ice Shelf: topography from satellite radar altimetry. *In* Oliver R L, James P R, Jago J B (*eds*) *Antarctic earth science*. Cambridge etc, Cambridge University Press: 441–445

MacArthur J L 1978 Seasat-A radar altimeter design description. *John Hopkins University. Applied Physics Laboratory Publication* SDO-5232

McIntyre N F, Drewry D J 1984 Modelling ice-sheet surfaces for the ERS-1's radar altimeter. *ESA* (European Space Agency) *Journal* 8(3): 261–274

Martin T V, Zwally H J, Brenner A C, Bindschadler R A 1983 Analysis and retracking of continental ice sheet radar altimeter wave forms. *Journal of Geophysical Research* 88(C3): 1608–1616

Rapley C G *and 16 others* 1985 *Applications and scientific uses of ERS-1 radar altimeter data. Final report.* Noordwijk, European Space Agency (Contract Report 5684/83/NL/BI)

Rapley C G *and 6 others* In press *ERS-1 altimeter tracker performance simulation. Presented at EARSEL/ESA Symposium on European Remote Sensing Opportunities: Systems, Sensors and Applications, 31 March – 3 April, 1985, Strasbourg, France*

Squire V A, Drewry D J, Cowan A M, McIntyre N F 1984 Cryospheric data products available through satellite altimetry. *In* Guyenne T D, Hunt J J (*eds*) *ERS-1 radar altimeter data products; proceedings of an ESA workshop held at Frascati, Italy on 8-11 May 1984*. Noordwijk, ESTEC: 51–57 (ESA SP–221)

Zwally H J, Bindschadler R A, Brenner A C, Martin T V, Thomas R H 1983 Surface elevation contours of Greenland and Antarctic ice sheets. *Journal of Geophysical Research* 88(C3): 1589–1596