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OBSERVATIONS OF SEA ICE AND ICEBERGS FROM SATELLITE RADAR ALTIMETERS

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ABSTRACT

Satellite radar altimeters can make useful contributions to the study of sea ice both by enhancing observations from other instruments and by providing a unique probe of ocean-ice interaction in the Marginal Ice Zone (MIZ). The problems, results and future potential of such observations are discussed.

1. INTRODUCTION

Sea ice plays an important role in influencing high latitude weather and global climate through its effect on the ocean surface albedo and its modulation of exchanges of heat, moisture and momentum at the ocean-atmosphere interface. Systematic changes in sea ice extent may provide the first indications of climatic change. Indeed, the creation of an ice-free Arctic ocean may be one of the early dramatic consequences of even a modest atmospheric warming. Thus, global synoptic observations of the properties and behaviour of sea ice are of considerable importance to climatological research as well as being of direct interest to glaciologists and oceanographers. With growing activity in the exploitation of polar resources the applications value of the data is also significant.

However the geographic zones in which sea ice is to be found are extensive, remote and inhospitable. They experience long periods of darkness, and may often be cloud-covered. The advent of polar orbiting satellites carrying microwave instrumentation capable of making observations under any weather conditions and during the day or night thus represents a breakthrough in our ability to carry out global sea ice studies.

Until recently work has concentrated on the use of passive microwave radiometer systems to map the annual cycle and inter-annual variability of sea ice extent, concentration and type with rather coarse (30-100 km) spatial resolution (e.g. Svendsen et al., 1983). Studies of ice dynamics within certain selected areas have been carried out using high resolution (~25m) images from the Seasat Synthetic Aperture Radar (Leberl et al., 1983). However radar altimeter data gathered over sea ice by both GEOS-3 and Seasat have received comparatively little attention. This is surprising in view of the likelihood that the altimeter pulse waveforms contain useful, possibly unique, information on the nature of the ice pack. Also several studies based on airborne observations have indicated that improved discrimination of ice type under a wider variety of conditions of temperature and surface state (melting/freezing, snow cover etc.) can be obtained by combining both active and passive microwave data (e.g. Livingstone et al., 1981).

In this paper we review the problems, results and potential of sea ice observations using pulse-limited altimeters, and identify several areas in which further research effort is urgently needed. We consider the likely impact of observations to be made from ESA's first remote sensing satellite ERS-1 and other forthcoming or proposed missions. Finally, we speculate on long term possibilities including the development of advanced beam-limited, multi-satellite systems.

2. OBSERVATIONAL OBJECTIVES

A comprehensive account of current priorities in ice research has recently been published by the US National Research Council (Polar Research Board, 1983). Here we shall restrict ourselves to considering those observational properties of sea ice which might be measurable using satellite altimeters, either alone or in combination with data from other microwave sensors. These include:-

(i) Extent (defined as the zone with greater than 10-15% sea ice concentration)
(ii) Concentration
(iii) Floe size distribution
(iv) Presence of major leads, polynyas
(v) Type/Fraction
(vi) Average freeboard
(vii) Surface roughness (presence of pressure ridges)
(viii) Surface condition (presence of snow, melt ponds)
(ix) Sea state within pack
(x) Sea state and surface wind speed adjacent to pack
(xi) Iceberg concentrations, size distributions
(xii) Antarctic tabular iceberg locations

Currently only (x) may be considered a demonstrated capability, with (i), (iv), and (ix) showing considerable promise as discussed below in section (5). All the remaining possibilities are more speculative, requiring further research (cf. section (6)).

3. SAMPLING AND COVERAGE

Significant variations of all the parameters listed in section (2) may take place locally on short ($<$1day) timescales. Thus temporal and spatial sampling requirements are an important consideration.

Figure 1 shows the Seasat ground track pattern in the vicinity of Antarctica at a time when the orbit was adjusted to repeat with a three day cycle. The Seasat orbital period was 100 minutes, giving 14.3 revolutions each day and 43 contiguous ground tracks over the full 3-day repeat cycle. Ground tracks in the figure are numbered according to a scheme in which the ascending node of rev 1 lies just east of Borneo. Also shown are the Antarctic coastline and the approximate location of the sea ice boundary at maximum winter extent. If it is assumed that at an arbitrary time of the year the sea ice limit lies approximately along a circle of latitude, the average spatial sampling interval at the boundary is given by:-

$$\Delta \ell = \frac{2\pi R \cos \theta}{\alpha n} \qquad (1)$$

where θ is the latitude (>55), n is the number of revolutions in the cycle, R is the Earth's radius (~6360 km), and $1 < \alpha < 2$ depending on the disposition of the ice boundary with respect to the ground track pattern. Hence for the worst case, corresponding to the maximum winter extent and $\alpha = 1$, we have $\Delta \ell$ ~ 1700 km for 1 day's data and $\Delta \ell$ ~ 450km for the full three day cycle. With a beam limited footprint of ~20km and an ability to locate the ice boundary to much higher precision (cf. section 5) the altimeter spatial data is therefore severely undersampled.

Even so, the improved measurement precision relative to the passive microwave data is often referred to as a novel contribution of the altimeter to ice boundary monitoring. In practice it is difficult to take full advantage of this capability, since significant ice motion can take place on timescales short compared with the temporal sampling period. For example the average change in Antarctic ice boundary location at the time of maximum ice growth or decay may be ~10 km d^{-1} and localised variations of up to 50 km d^{-1} can take place at any time in response to storms. Thus for data collected on a 3-day repeat cycle spatial smoothing to ~30km resolution is necessary in order to achieve some degree of self consistency. Although experience shows that even then inconsistencies in the boundary location can still occur. Since the ice boundary motion in a given region is rarely monotonic on timescales of order three days, interpolation schemes dealing separately with each ground track over several repeat cycles do not help.

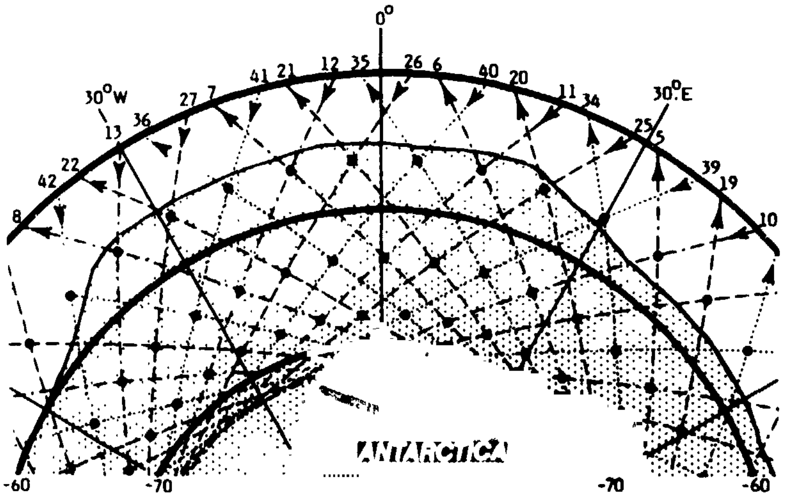

Figure 1: Seasat ground tracks in the vicinity of Antarctica for a 3-day orbit repeat cycle. Also shown are the Antarctic continent (dark dot) and the region covered by sea ice at the time of maximum winter extent (light dot).

Any attempt to overcome the temporal sampling problem by decreasing the period of the orbital repeat cycle merely worsens the degree of spatial undersampling. At the limit of a 1-day repeat cycle, smoothing to ~10 km resolution would be necessary to obtain reasonably self-consistent global sea ice maps (this may actually be quite acceptable since the ice edge is often difficult to define to better than ~10km) and sampling would be ~1700 km at the ice boundary. The inevitable conclusion is that a multi-satellite system is required if improved ice monitoring is to be achieved. For example a system of 5 satellites with orbits phased to provide the equivalent of five-day repeat cycle coverage each day would achieve usable ~10 km precision and 150-300 km spatial sampling (75 points) around the Antarctic ice boundary at maximum extent. (Note that for a single-satellite system a 3-day repeat cycle appears to be a near-optimum compromise.)

When considering the selection of orbital parameters the required latitude coverage must also be taken into account. For a nadir pointing, narrow swath instrument this is determined purely by the inclination of the satellite orbit. A low inclination is preferred for oceanographic missions in order to obtain approximately orthogonal ground track intersections over much of the globe since this is helpful in computing orbit error corrections. However an inclination of ~85° is necessary to achieve full coverage of Antarctic sea ice, and 90° is required if Arctic ice in the vicinity of the pole is not to be missed. (Note that for a 90° inclination orbit no ground track intersections occur except at the poles.) Once again it would appear that a multi-satellite system offers the only prospect of satisfying the conflicting requirements.

4. ALTIMETER OPERATION OVER SEA ICE

The action of a radar altimeter over a flat, horizontal, statistically homogeneous, rough surface such as the ocean surface is well understood. Two modes of operation are possible, the pulse limited mode and the beam limited mode (see Rapley et al., 1983). In the former case the use of a relatively broad beam results in an echo waveform with a time profile which corresponds to the height probability density function (pdf) of surface scatterers. Range estimates are made by timing to the 50% power point on the leading edge of the return pulse. For beam limited operation a narrow beam antenna is used and the echo waveform corresponds directly to the height pdf of scatterers. Range estimates are made to the 'centre of gravity' of the waveform. In both cases the use of an (effectively) short duration (~ nsec) transmitted pulse permits estimation of large (metre) scale surface roughness from detailed analysis of the waveform shape. Also the echo strength is related to the small scale (of order λ) surface roughness which for the ocean is determined by the surface wind.

Operation over a rough, flat surface which is not statistically homogeneous introduces certain fundamental difficulties. Firstly, the return waveform contains no information on the azimuthal direction of scatterers about the nadir. Also there exists an ambiguity between the height of a point scatterer relative to the mean surface and its radial distance from the nadir. Consequently it is impossible to unambiguously reconstruct surface details within the footprint from an analysis of individual waveforms. Furthermore, 'average' properties of the surface derived from individual echoes will be strongly biassed by any highly reflecting zones within the beam limited footprint (BLF), particularly those with slant ranges similar in value to the vertical range to the nadir point. Even the additional information provided by systematic changes in waveform shape as a surface feature is traversed permit reconstruction of only very simple geometries such as discrete height transition or a single highly reflective point located at a known height or distance off-nadir.

Under these circumstances the beam limited mode offers some advantage since the potential for confusion is reduced by limiting the area from which echo signals can be received. Also the surface area sampled remains fixed in size, in contrast to the pulse limited case where it varies with surface roughness. However beam limited operation requires a large (>10m) antenna and a high-precision spacecraft pointing system, both of which imply greater cost. For this reason and because pulse limited operation is satisfactory for ocean observations, past and planned missions have adopted the pulse limited mode of operation exclusively.

Other problems are encountered when sea ice waveforms are presented to an altimeter's on-board processor. This unit carries out a number of functions including the summation of many individual return pulses in phase to reduce noise fluctuations, the tracking of the surface as range values vary, and the adjustment of the receiver gain to compensate for signal strength variations. It may also generate estimates of geophysical parameters such as mean surface height, roughness and backscatter coefficient for rapid dissemination and analysis on the ground. In executing these tasks the algorithms employed generally assume a standard ocean form for the pulse shape and are set up to accommodate only relatively slow variations in time. Over sea ice we may identify three areas of difficulty as follows:-

(i) Shape induced errors: The non-standard shapes of the return waveforms introduce systematic offsets of the range tracking point. For a peaked time profile typical of sea ice returns, the tracking point is displaced early where it becomes more susceptible to statistical noise. Tracker jitter is thus increased.

(ii) Dynamic lags and pulse blurring: Rapid variations of the return pulse shapes and strengths occur on timescales too short for the altimeter to follow. Dynamic lags are introduced and may be exacerbated by interaction amongst the processing loops. Resulting errors in the superposition of summed pulses will introduce 'blurring' of intrinsic pulse shapes.

(iii) 'Snagging': When passing over a transition from high to low reflectivity, the range tracker may remain locked on to the receding bright feature. Generally, after a modest excursion, the tracker recovers since the reflectivity of the feature decays rapidly as it is viewed increasingly far from normal incidence. Sometimes, however, the excursion may be sufficiently large to cause loss of track. Loop interactions cause all computed outputs to be in error during excursions. Note that the shortening of time constants to reduce dynamic lags will increase susceptibility to 'snagging'.

From the preceding discussion we may draw three broad conclusions:-

(a) The performance of an altimeter over sea ice will be less stable than over the ocean.

(b) On-board computed parameters suffer increased systematic and random errors, making ground analysis of the waveforms mandatory if the full potential of the data is to be obtained. The waveform data will be partly corrupted by blurring.

(c) Even with analysis of the waveform data there exists a fundamental limit on the spatial resolution achievable for all but the simplest of surface features. In general this corresponds to the beam limited footprint (~20 km) although transitions in surface properties might be located to ~1/10 of this value.

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5. RESULTS FROM GEOS-3 AND SEASAT

Both GEOS-3 (inclination 65°) and Seasat (inclination 72°) carried pulse limited altimeters and obtained data over sea ice. Returns from first year ice were observed to be strongly peaked intense (peak power at least x10 that of ocean returns) and highly variable. Much deeper within the pack, possibly over multi-year ice or ice with a high concentration, return strengths could be as much as 8dB lower than for ocean returns. Brown (1982) has developed a model for near-normal incidence microwave scattering from first year ice which explains the main features observed in the GEOS-3 data. He suggests that the return waveform is dominated by power reflected from a population of smooth ice platelets all at the same height within the pack, corresponding to calm water or thin, smooth ice between the floes. The rapid fluctuations of the echo strength correspond to variations in the number of flat areas within the first few Fresnel zones as the footprint progresses across the pack. Robin, Drewry and Squire (1983), on the basis of a study of Seasat sea ice waveforms support Brown's general concept, pointing out that this may be described as a 'glistening' surface. They note that even if as little as 0.01% of the surface area contributes to the glistening component, it will dominate the diffuse echo from the tops of the floes.

Consequently we might expect the contrast in backscattering properties of first year ice and open water to provide a reliable means of locating the sea ice boundary. Dwyer and Godin (1980) exploited this technique using GEOS-3 data over the Bering sea, and carried out comparisons with cloud-free visible and infra-red images obtained from the DMSP satellites and TIROS-N. They were able to establish an 'ice index' which provided ice boundary discrimination in consistent agreement with the image data to an accuracy of a few km. They also noted qualitative correlations between their ice index and ice concentration and ice type, but did not pursue this result further.

Other uses of signal strength data have been as a means to eliminate 'ice-contaminated' results from ocean data (Marsh and Martin, 1982) and as a means to locate the Antarctic ice boundary and its variations over four of Seasat's 3-day repeat cycles in an analysis by Rapley (1984) described below (cf. Figure 2). However further intercomparisons of altimeter-deduced boundaries and estimates obtained independently by other means are certainly needed to validate properly the technique. For example, it is not at all clear that a criterion established for the location of first year ice boundaries will operate satisfactorily with multi-year ice or in regions where the ice concentration reaches a high value close to the ice edge.

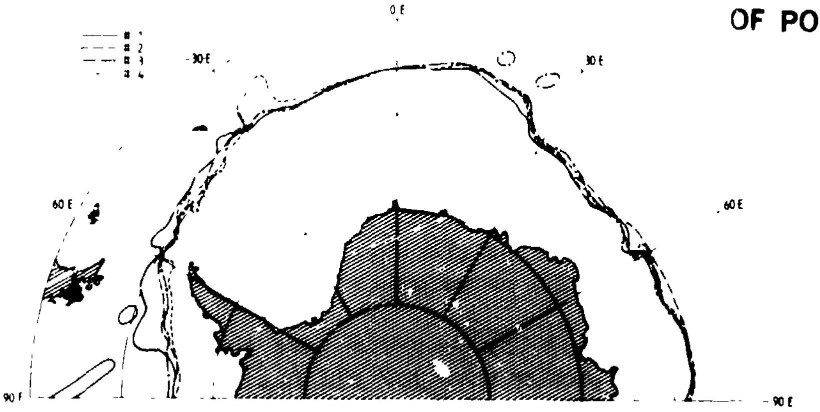

Figure 2: The Antarctic sea ice boundary and its variation over four of Seasat's 3-day repeat cycles as deduced from return echo strength (AGC) data (from Rapley, 1984).

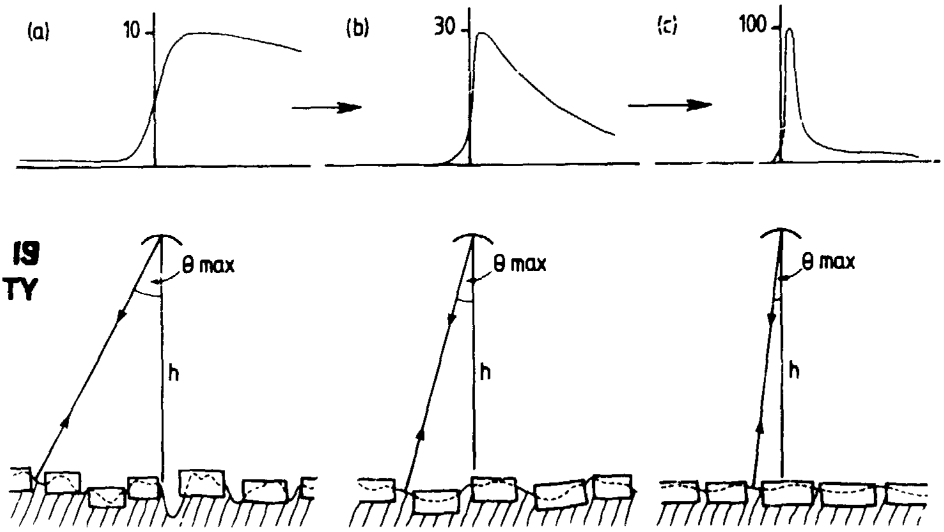

Figure 3: The evolution of waveform shape and strength as a function of increasing distance into the ice pack. Pulse falltimes are determined by the distribution of surface slopes as shown schematically in the lower panels. Pulse shape and strength change as ocean waves and swell are damped out by the action of ice floes within the pack.

Although ice boundary location is certainly a useful capability of the altimeter, the sampling problems discussed earlier make it clear that the altimeter data are unlikely to compete with the fully sampled global maps available from passive microwave imaging instruments such as the SMMR flown on NIMBUS-7. However a recent investigation by Rapley (1984) suggests that the altimeter can make a unique contribution to studies of the Marginal Ice Zone (MIZ) by monitoring the propagation of ocean swells within the ice. Figure 3 shows the typical evolution of return waveform shapes as the altimeter progresses from the ice edge into the pack. Initially the waveform is stronger but is of similar shape to nearby ocean returns. Subsequently the waveforms become increasingly peaked. Extending the concepts put forward by Brown and Robin, Drewry and Squire (as discussed above) Rapley suggests that the return pulse falltimes depend on the probability distribution of ocean surface slopes between the floes, as shown in the lower panels of Figure 3. The attenuation of ocean swell components by the floes is known to be exponential with an attenuation coefficient which depends strongly on the ice thickness and swell wavelength (e.g. see Squire and Moore, 1960). Thus an analysis of pulse falltimes using a modelled response could provide quantitative results from which estimates of ice and swell properties might be deduced. Such an analysis has not yet been completed. However the on-board computed values of Significant Wave Height (SWH) from the Seasat altimeter provide a crude measure of pulse peakiness and hence of ocean surface flatness amongst the floes. Figure 4 shows the behaviour of zones of apparent swell penetration within the Antarctic sea ice. The power of the altimeter to pursue this type of study is emphasised by its ability to monitor ocean swells in the vicinity of the ice using wind speed and sea state data and the method of Mognard (1983). Spatial and temporal correlations between the extent of the penetration zone and the presence of nearby ocean swell storms provide qualitative support for the suggestion that swell propagation is being monitored. Nevertheless, a more quantitative analysis modelling the Seasat waveform data is needed, as are comparisons of altimeter data with surface verification results, before the technique can be regarded as fully validated.

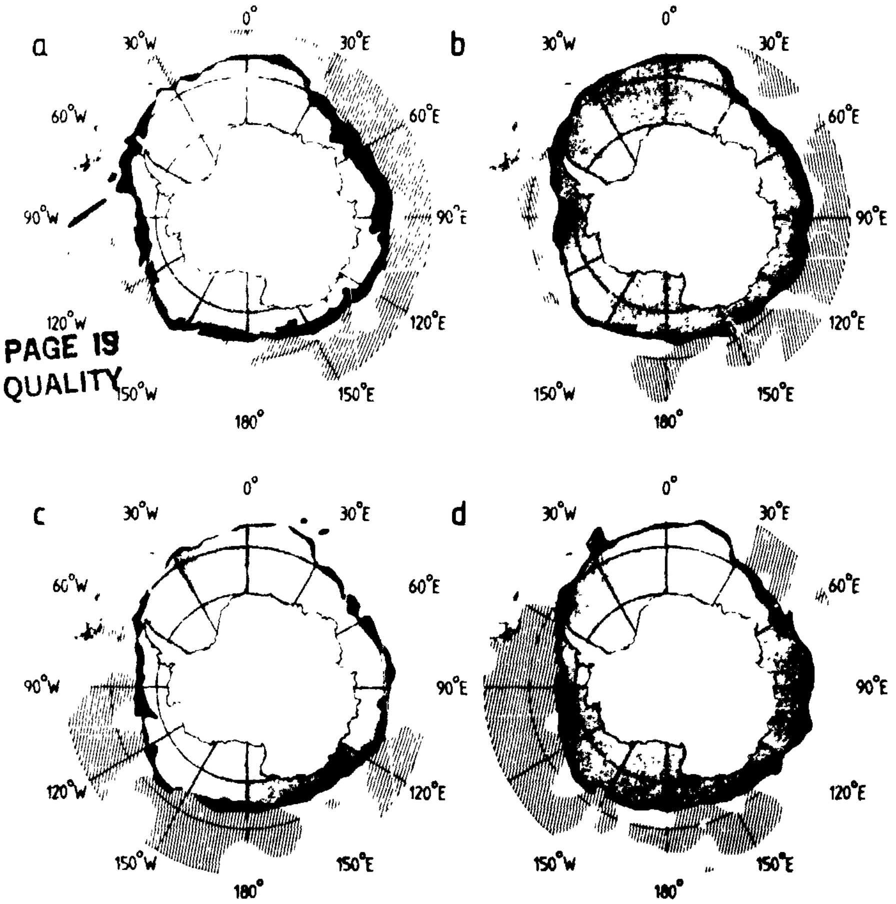

Figure 4: Four consecutive 3-day maps of Antarctic sea ice (shaded areas) and regions of ocean swell greater than 5m (cross-hatched areas) during September 1978. Zones of swell penetration into the ice (solid areas) derived from the Seasat SWH data contract and expand with the decline and subsequent growth of nearby ocean swell storms.

6. ADDITIONAL POSSIBILITIES

Of the observational objectives outlined in section (2) only the location of the ice boundary (and by analogy the presence of major leads and polynyas) and measurements of sea state adjacent to and within the MIZ have been addressed using actual satellite data. It has been stressed that even these capabilities require further validation. There is reason to believe that further studies of pulse strengths and shapes and the variability of both may permit others of the objectives to be achieved. However, the difficulty of obtaining adequate surface verification results for much of the GEOS-3 and Seasat data suggests that significant progress in these areas probably awaits future aircraft and satellite observations.

One area in which the usefulness of altimeter contributions seems dubious is that of providing locations of Antarctic tabular icebergs. Large icebergs may drift for many years in the Southern Ocean and have been monitored, albeit intermittently using visible and infrared images (e.g. McLain, 1978). In view of the small likelihood of such an iceberg passing through the altimeter footprint it seems unreasonable to consider iceberg location as a major altimeter task. Nevertheless if such an event did occur and the altimeter locked on to the upper surface it would be possible to provide an accurate value for the iceberg's freeboard.

7. FORTHCOMING MISSIONS

In spite of wide interest in the use of altimeter data by climatological, oceanographic and glaciological scientists worldwide, the first satellite to carry an altimeter for non-military purposes following the early demise of Seasat in 1978 will be the European Space Agency's ERS-1 to be launched in 1988. The instrument will be very similar to the Seasat altimeter but will provide coverage up to ±82° with a lifetime initially of 2 years, extendible to 3 or more depending on spacecraft and instrument status. Thus full coverage of Antarctic sea ice and much improved coverage over the Arctic will be obtained for the first time over two full seasonal cycles. Plans are currently being formulated to ensure that adequate surface validation data including aircraft altimeter underflights will be obtained during the mission.

Other altimeter carrying satellites include the US Navy's GEOSAT due for launch in 1984 but with the possibility of restrictions on data access, the proposed US-French TOPEX mission and the French Poseidon, both likely to fly at the end of the decade. However TOPEX is primarily an ocean mission and will most probably be restricted to ±62° coverage. It will therefore not observe sea ice. Possibilities for the next decade include the provision of a UK altimeter for the Canadian Radarsat satellite, and a Japanese national mission. As yet no serious attempts have been made to coordinate international interest to achieve either the multi-satellite coverage discussed earlier in section 3 or continuity of observations over an extended period of many years, although coordination of this type would clearly be very beneficial.

As a final comment, it is worth recalling that the interpretation of altimeter waveform data over sea ice should be more straightforward for the case of beam-limited operation than for the currently universal pulse-limited mode. Interest in building a multi-beam, beam-limited instrument arises primarily from a desire to achieve much improved performance over topographic surfaces such as the continental ice sheets and land. Thus it seems likely that in the long term the technical and financial challenges of building instruments of this type will be tackled. Whether or not the advantages of a beam limited system will make a substantial impact on sea ice studies is currently impossible to predict without the benefit of considerable further effort on the analysis and interpretation of current and anticipated pulse limited data.

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