GEOPHYSICAL INVESTIGATION OF ICEBERGS IN ANTARCTICA

by

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A thesis submitted in partial fulfilment of the requirements for the Diploma in Polar Studies

Scott Polar Research Institute
Cambridge

May 1980

DECLARATION

I declare that this thesis is between 10 000 and 20 000 words in length and is a result of my own work, and includes nothing which is the outcome of work done in collaboration.

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15 May 1980

ACKNOWLEDGEMENTS

I wish to thank the organization Iceberg Transport International Limited for providing the data for this thesis. I also wish to thank Dr G de Q Robin, Dr David Drewry, Dr Peter Wadhams, Dr Olav Orheim and Mr Stuart Moore for help and advice. And to Dr Terence Armstrong my thanks for inspiring me to come to Scott Polar Research Institute, Margaret Androu for sparing me the agony of typing, and my fellow students of the Diploma in Polar Studies course for good company during the year.

ABSTRACT

One of the most important technical questions relating to iceberg transport are the causes of disintegration of the iceberg at sea. In order to obtain a better understanding of the factors involved in the response of icebergs to the environment, an automatic data collection platform was placed on a tabular iceberg in the Antarctic in February 1979. This experiment, and an analysis of some of the collected data, form the basis of this thesis.

The background for the experiment, details of the instruments, the mounting of the platform and the data collection are outlined.

Some relevant research in glaciology, physics and mechanics of ice, oceanography and other related topics is summarised.

The collected data (over a period of one year) are divided in three sets:- the dynamical behaviour of the iceberg; thermodynamical data; and mechanical data.

Preliminary results of research on the dynamical data have been obtained at other scientific institutes and a summary is given. No analysis of the thermodynamical data has been made.

The mechanical data, including surface strain measurements and tilting of the iceberg, have been analysed at Scott Polar Research Institute by the author. Results from the analysis are given.

It is found that the 'instantaneous' surface strain caused by the iceberg's bending in the ocean waves, together with the existence of cracks and crevasses in the iceberg's surface, may be large enough to produce fracture. Other conclusions from the analysis are summarised. Comparisons with other relevant papers on iceberg tilting and bending have been made.

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CHAPTER 1

INTRODUCTION

Projects for towing icebergs are being considered both in the Northern and Southern Hemisphere; in the north to protect the ship lanes and off shore oil drilling equipment, and in the south to provide fresh water to arid areas such as the south-west coast of Australia, California and Saudi Arabia.

Icebergs have been studied since the eighteenth century, but most of the early work consisted of occasional reports on iceberg sightings, observations on unusually large icebergs, and some statistics on iceberg numbers and sizes along expedition routes.

The interests of researchers on icebergs in the north are still concentrated on drift patterns and size and shape distributions, as well as detection of icebergs and protection measures (Russell, 1979).

In the Antarctic the research on icebergs was greatly increased when Saudi Arabian interests invested large sums of money from 1973 on to sponsor investigations and experiments directly related to an iceberg utilization scheme. In June 1977 and April 1980 a First and Second International Conference on Iceberg Utilization were held in Iowa and Cambridge respectively.

An iceberg utilization project could in short be described as follows:

CHAPTER 1

INTRODUCTION

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An iceberg utilization project could in short be described as follows:

- To locate a suitable tabular iceberg in a suitable position off the Antarctic continent.
- To transport the iceberg with minimum costs and losses of fresh water as close as possible to the final destination.
- To process the iceberg into fresh water with minimum costs and losses, and to transport the fresh water from the site of the iceberg to the final destination.

The world's major iceberg production sites are from ice shelves off the Antarctic continent, primarily the Amery, Filchner and Ross ice shelves.

Iceberg deterioration was early defined as a major problem in iceberg towing. The mass of the iceberg is reduced both by melting and fracturing, of which fracturing may be the more serious problem (Weeks, 1980).
In a summary of major papers up to 1977, at the First Conference on Iceberg Utilization, Dr Henri Bader described the research done as follows:

(1) Much attention has been given to the dynamics of towing of immense rectangular solid bodies floating on a calm sea.

(2) Some attention has been given to the thermodynamics of ice melting in contact with moving water.

(3) Little attention has been given to the problem of converting large masses of ice, floating in salt water at destination, into fresh water delivered to land.

(4) Almost no attention has been given to the glaciology of icebergs.

(Bader, 1978)

Even if the emphasis on topics has changed, very few papers on the glaciology of icebergs have been published to date, and much work is still left to be done before satisfactory conclusions can be reached as to how and why icebergs break up.

One of the very few geophysical experiments done on tabular icebergs in the Antarctic was designed in 1978 by a French company, Iceberg Transport International Limited, (ITI), sponsored by Saudi Arabian financial interests. The experiment was designed to collect data on the dynamical behaviour of an iceberg, as well as thermo-dynamical and mechanical properties. An automatic data collection platform was deployed on a tabular iceberg in the Weddell Sea by the Norwegian Antarctic Expedition in February 1979. The data are broadcast to low orbiting satellites and despatched through the Argos system. Four groups of scientists are working on an analysis of various parts of the data. Research on the mechanical behaviour of the iceberg and its response to the environment have been done at Scott Polar Research Institute, Cambridge, by the author, and results from this analysis are presented in this thesis.

CHAPTER 2

GLACIOLOGY OF ICEBERGS

A SUMMARY OF SOME RELEVANT RESEARCH

2.1 General

As was mentioned, few papers relevant to the problem of iceberg fracture have been published in connection with the First and Second Conference on Iceberg Utilization. This has also been the case at other conferences, such as the International Conferences on Port and Ocean Engineering under Arctic Conditions, 1971, 1973, 1975, 1977 and 1979, and the Iceberg Dynamics Symposium in 1980. There is, however, literature to be found which contains information on the subject, but it is often located under such topics as 'general glaciology' or 'physics of ice'.

More important is the fact that review articles on the subject do not exist, and few attempts to reach general conclusions on iceberg mechanics have been made.

The review articles published at the Iceberg Utilization Conferences and elsewhere are mostly concerned with the feasibility of iceberg towing, and contain little actual information as to why and how icebergs disintegrate. (Weeks and Campbell, 1973; Hult and Ostrander, 1973; Weeks and Mellor, 1977; Schwerdtfeger, 1980).

The following subsections include results from some research that will be used later in this paper.

2.2 Mechanics of ice

Ice as a material is investigated in several books and monographs (Fletcher, 1970; Michel, 1978; Hobbs, 1974; Glen, 1974, 1975).
There are, however, difficulties in adapting theories of ice mechanics directly to floating, tabular icebergs, as the calculations involved are both complex and tedious and many simplifying assumptions have to be made. Theory and experiements on creep and fracture toughness of ice have been done by Goodman (1977), Goodman and Tabor,(1978) and Smith (1977).

In this paper critical conditions for the breaking of the icebergs are of interest.
Two factors are of importance in the iceberg's response to the environment; the instantaneous strain and a critical strain-rate.

When iceberg fractures rapidly it usually does so in a brittle manner, that is, a crack develops somewhere and spreads rapidly to produce failure (Glen, 1975). If cracks are already present in the ice, the possibility of failure is enhanced.
When an iceberg is exposed to a wave field, the period of application of the oscillating stress (a few seconds) is so small that the plastic strain forms a negligible part of the total strain response. The flexural behaviour of the iceberg is therefore almost elastic, and a critical value of strain could occur depending on the ocean wave

spectrum. Goodman, Wadhams and Squire (1980) have estimated a critical instantaneous surface strain to be 8.4×10^{-5} for the failure of a perfect ice body at $0^{o}C$. This is assumed to be an upper limit, as the existence of cracks in the iceberg will tend to multiply the stress at the crack tip.

Ice reacts to a constant stress with plastic deformation, creep. As the internal temperature decreases, the ice is harder to deform, and the critical strain rate at which the ice fractures is expected to be lower. Holdsworth (1969) found a critical strain rate of $3.5 \pm 0.5 \times 10^{-5}$ per day on a temperate glacier in a region of initial transverse fracturing. Corresponding measurements on a polar glacier (with a temperature of $-27.9^{o}C$ at 10 metres depth) indicated that the critical strain rate is about $0.6 \pm 0.5 \times 10^{-5}$ per day.

As the internal temperature of the Antarctic icebergs at approximately 10 metres depth ranges from $-10^{o}C$ to $-27^{o}C$, the latter value of critical strain rate will be taken as a basis of comparison in this thesis.

2.3 Distribution of icebergs in the South Polar Sea

Distributions of iceberg numbers, size and shape could indicate possible mechanisms for disintegration of icebergs.

In general there are large numbers of icebergs located near the Antarctic continent, and a gradual decrease further north. Some data show a gradual increase in the mean distance between icebergs with distance from the coast, off East Antarctica and in the Weddell Sea. (Weeks and Mellor, 1978).

Iceberg size distributions have been obtained by Gordienko (1960), Nazarov (1962), Dmitrash (1965) and Weeks, Mellor (1978). The distributions are listed and compared in a review article by Neshyba (1980).

Most of the size distributions show a high probability in the occurrence of middle-sized icebergs, around 0.7 km in width for icebergs protected by the pack ice and 0.4 km width for icebergs in open waters at the edge of the pack (Figure 2.3.1).

Two conclusions have often been drawn from these features; first that the pack ice protects the icebergs from breaking up, and second that with the icebergs of less than a certain size, the fracture mechanisms are not as important as for larger bergs. The first assumption will be more closely examined in section 2.4.

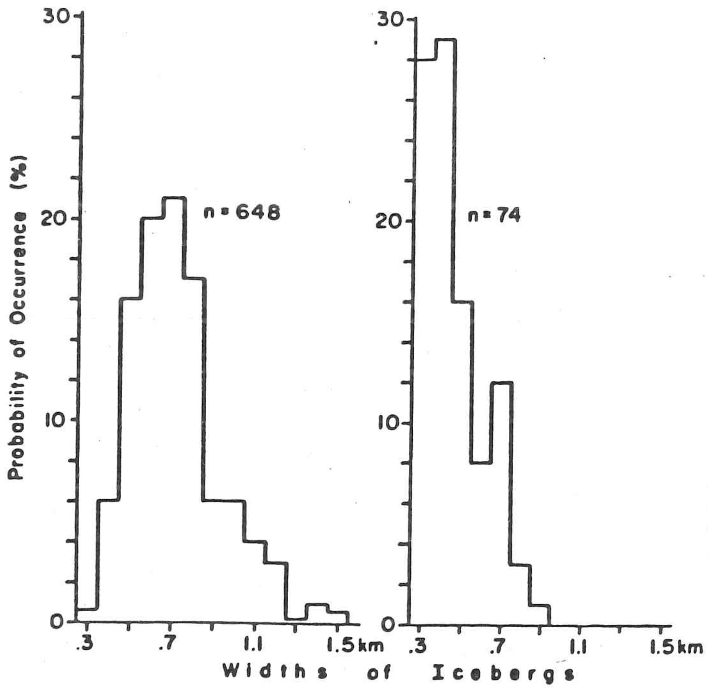

FIGURE 2.3.1 Probability of occurrence of icebergs in the Antarctic plotted against the estimated width. The distribution to the left is for icebergs in the pack ice. (Weeks and Mellor, 1978)

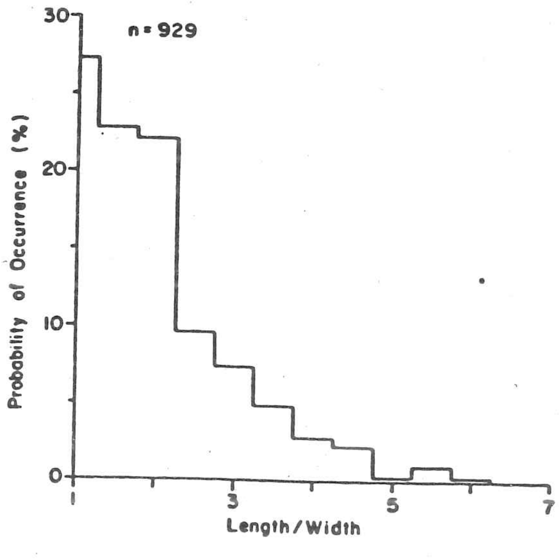

FIGURE 2.3.2 Probability of occurrence of length/width ratio of icebergs in the Antarctic. (Weeks and Mellor, 1978)

Recent iceberg counts from a ship have been made by Norwegian Polar Institute's expedition to the Antarctic in 1978-1979 and statistics on these data are presented by Orheim (1980). Orheim reports a larger percentage of small icebergs than previously observed, concluding that small icebergs break up as frequently as larger icebergs. The reason for this discrepancy between new and older data could be that very small icebergs were simply not counted and defined as icebergs. The LANDSAT data discriminate clearly in favour of larger iceberg dimensions because of the observation technique (Neshyba, 1980).

The observations made by Orheim do not dispute the general distribution of the length/width ratio of icebergs in the Antarctic (Figure 2.3.2). Most icebergs are believed to have a length/width ratio of between 1:1 and 2:1, and that length/width ratios of 5:1 or greater are not common. This indicates that icebergs frequently fracture across the middle (transverse to the main axis).

2.4 Attenuation of ocean waves by the pack ice

Both theory and field experiments have been done to investigate ocean wave propagation through fields of ice floes. Investigations by Evans and Davies (1968) and Robin (1963) suggest that attenuation of the wave field is dependent on ice thickness, diameter of the ice floes and periods of the incoming waves.

Observations by Robin show that for waves of 4 seconds period (wave length of about 22 metres), almost all the wave energy was absorbed by the ice cover. For waves of 8 seconds period (wave length of about 100 metres), ice floes of 10 metres in diameter and a thickness of 3 metres caused a decrease in the wave energy to a third of the initial value. No wave energy of 8 seconds period was detected when estimated floe diameters were 40 meters or more. Swell of 16 seconds period (wave length of about 400 metres) was heavily attenuated by ice floes with a diameter of 1000 metres or more. When floes were 40 metres or less in diameter, no appreciable loss of energy in this band was evident. (Robin, 1963). These observations are confirmed by Evans and Davies who demonstrate the existence of two critical wave lengths, one below which all the wave energy is attenuated and one above which little of the wave energy is attenuated.

A recent paper by Squire and Moore (1980) gives the attenuation coefficient for energy decay at various wave

periods. For a period of 5.5 seconds it is 1.2×10^{-4} per metre compared to a value of 0.3×10^{-4} per metre for a period of 12.2 seconds.
Attenuation coefficients measured by Wadhams (1978) in the much thicker pack ice near Greenland were 1.2×10^{-4} per metre for a 9 second swell and 0.7×10^{-4} per metre for a 12 second swell.

If bending of the iceberg in the ocean wave field is one of the main factors for disintegration, it can be concluded that the pack ice does not entirely protect icebergs from breaking up. Very large period swell penetrates pack ice, and this is the swell to which an iceberg can respond by bending. This swell is still attenuated to some extent, therefore there is some degree of protection.

2.5 Iceberg shape and cracks

The shape of icebergs and presence of cracks and crevasses have been investigated by several different methods, such as remote sensing with a pulsed radar system (Swithinbank, 1977; Kovacs, 1977), underwater photography (Girard, 1977) and thermal radiation instruments (Foldvik, Gammelsrød and Gjessing, 1980).

Three conditions have previously been stated as important for the 'integrity' of an iceberg; that it is relatively free from crevasses, that it does not have cliffs overhanging the sea or an otherwise too irregular shape, and that it is not dome shaped.

There is not enough data available from direct observations on icebergs to reach any conclusion as to whether cracks in icebergs are common or not. Recent geophysical and glaciological investigations on the Ross ice shelf, one of the major sources of tabular icebergs, indicate that rift zones, surface and bottom crevasses, freeze-on zones and other fault features are more commonly occurring than previously thought. (Shabtaie and Bentley, 1980). Observations reported by Orheim suggest that crevasses are usually aligned with one of the sides of the iceberg (Orheim, 1980).

Melting takes place along the sides and the bottom of the iceberg, where the ice is in contact with water. Enhanced melting takes place near the water line due to wave action. Wave-induced undercuttings generate unsupported ice cliffs which eventually collapse (Martin, Josberger and Kauffman, 1978). The enhanced melting caused by wave action will also enlarge existing cracks and crevasses in the iceberg. Studies of ice melting and iceberg deterioration have been reported in several papers at the First and Second International Conferences on Iceberg Utilization (published in Proceedings, 1978 and 1980).

Domed icebergs have been thought to be less suitable for towing since they probably are under a constant stress and therefore are more likely to break up than rectangular icebergs. Orheim (1980) has reported that all the icebergs investigated at the Norwegian Polar Institute's expedition to the Antarctic were dome-shaped.

It is therefore probable that dome-shaped icebergs are the rule and not the exception.

Two possible explanations have been suggested for the dome shape. A 'wavy pattern' on the surface of glaciers has been observed, and icebergs may calve from the ice shelves along the weak, low surface lines (Orheim, 1980), thus making the iceberg dome-shaped from the beginning. Another explanation could be that the iceberg deforms plastically into a dome shape, and that this slow deformation eventually reaches a critical value of strain rate at the iceberg's surface and causes fracture. A statistical count of shapes of icebergs northwards from the site of calving of an ice shelf should reveal whether icebergs are dome-shaped from the beginning or not.

Some results of the analysis of strain-data made later indicate that a continuous surface strain gradient is present on the observed iceberg.

2.6 The ocean wave field in the Southern Hemisphere

Since breaking up of icebergs caused by wave action will be strongly dependent on the wave periods, it is of interest to examine in detail recordings of sea waves in the Southern Hemisphere.

The Oceanographic Atlas of the Polar Seas (1957) contain several maps of the Antarctic with isolines showing per cent frequency of high sea (wave-height over 5 feet) and high swell (wave-height over 12 feet). There are no recordings of wave periods. Insufficient data have been collected in several areas, among which is the Weddell Sea. In the Southern Ocean around 60°S, 40°W the percentage of high swell in summer and autumn is between 20 and 30. In winter and spring it is somewhat lower, between 10 and 20.

The percentage of high sea in the same position is about 40 in summer and autumn, and between 10 and 20 in winter and spring.

Mean wave-height and mean wave period isolines are given in Atlas of Antarctica (1966), as well as maximum recorded wave height and period and frequency of occurrence of mean wave heights of 3 and 6 metres.

During December - March the mean wave height at above 60°S, 40°W is between 1.0 and 1.5 metres, and the mean wave period is about 5.5 seconds. The same figures for the winter season (April - August) are between 1.5 and 2 metres for the mean wave height and about 6 seconds for the mean wave period.

The frequency of occurrence of waves higher than 3 metres is less than 5 percent, and for waves higher than 6 metres, it is less than 0.1 percent. The maximum wave height and mean wave period during a year (0.3 percent of occurrence) is less than 15 metres and about 11 seconds, respectively. Finally, Draper (1966) has measured sea waves outside Sekondi, Ghana, in the direction of 156^{o}. Results of these measurements are given in Figure 2.6.1. The recordings show that a substantial part of the wave energy is present in the form of swell of a period of between 8 to 16 seconds.

In view of the scarcity of direct data on wave heights and periods of long swell in the Southern Ocean, it appears to be more useful to draw conclusions from meteorological data as wind speeds and storm frequencies. Darbyshire and Draper (1963) have shown how significant wave height and period are related to wind speed, fetch and duration of storms in oceanic waters. Figure 2.6.2 shows a graph relating significant (mean of longest 1/3) wave period to wind speed duration and fetch.

A significant wave period of about 10 seconds would correspond to an ocean wave field with a presence of long swell (longer than 20 seconds). As the fetch in the oceanic waters around Antarctica is larger than 600 nautical miles, it follows from Figure 2.6.2 that winds of about 35 to 50 knots lasting from 2 to 12 hours would generate such long period waves.

Again, the information available is insufficient, but charts of wind observations at sea level in Oceanographic Atlas of the Polar Seas (1957) suggest that windspeeds of 28 knots

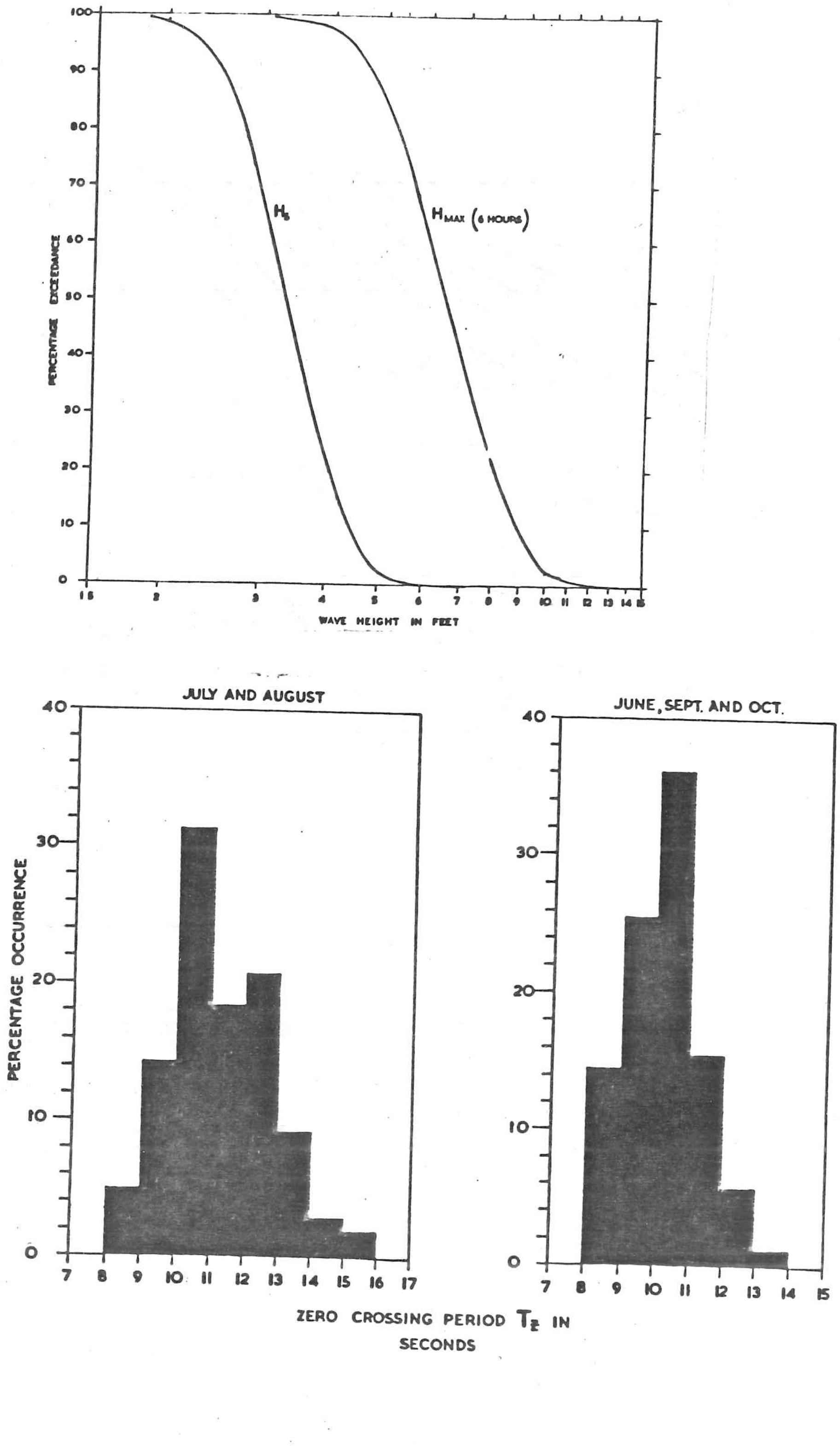

FIGURE 2.6.1 Some characteristics of ocean wave spectra measured by Draper (1966) off Sekondi, Ghana.

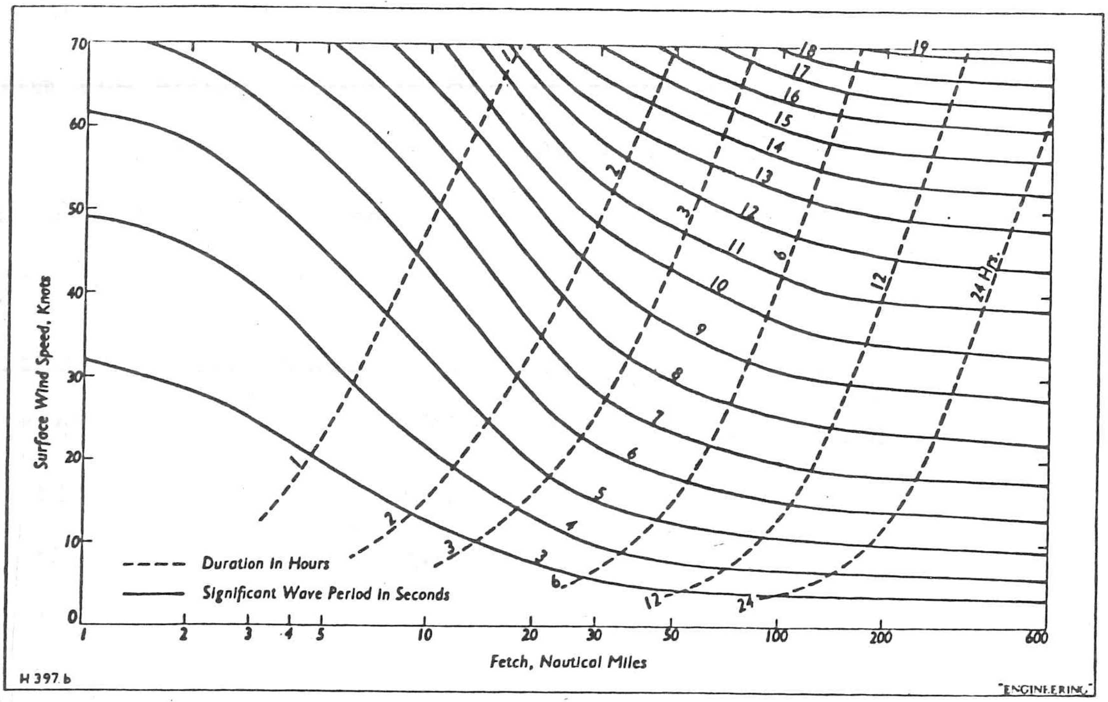

FIGURE 2.6.2 Estimated significant wave periods as a function of fetch, wind speed and duration of wind. (Darbyshire and Draper, 1963)

and larger (7 - 12 Beaufort) are measured 20 - 40% of the time at some positions. The difference between summer and winter conditions does not appear significant.

From the above observations it seems likely that the wave periods most critical for iceberg fracture, those around 20 seconds, are present in the wave energy spectrum and detectable most of the time.

Although there could be a difference between the summer and the winter wave energy spectrum, this difference could be insignificant in the long period end of the spectrum. If this is the case, the icebergs are as likely to break up during summer as during winter.

CHAPTER 3

AUTOMATIC DATA COLLECTION ON AN INSTRUMENTED ICEBERG

3.1 The automatic data collection platform

An automatic data collection platform was placed on a tabular iceberg in the Weddell Sea on 4 February 1979 by the Norwegian Antarctic Research Expedition (NARE) 1978-1979, an expedition organized by Norsk Polarinstitutt, Oslo. The station was ordered by Iceberg Transport International Limited (ITI), from the Chr. Michelsen Institute, Bergen.

The platform was deployed on an iceberg 1030 metres by 890 metres and 35 metres above sea level, corresponding to an approximate iceberg thickness of 210 metres. A photograph of the iceberg is shown on the front page of this thesis.

The sensors of the data collection platform measure the dynamical behaviour as well as themodynamical and geophysical parameters.
The following parameters are collected by the platform:

- position (latitude, longitude)
- heading of the main axis of the iceberg (against the north)
- wind speed and direction against the main axis
- air temperatures and snow temperatures
- internal temperature of the beacon
- barometric pressure
- surface strain
- tilt in two directions

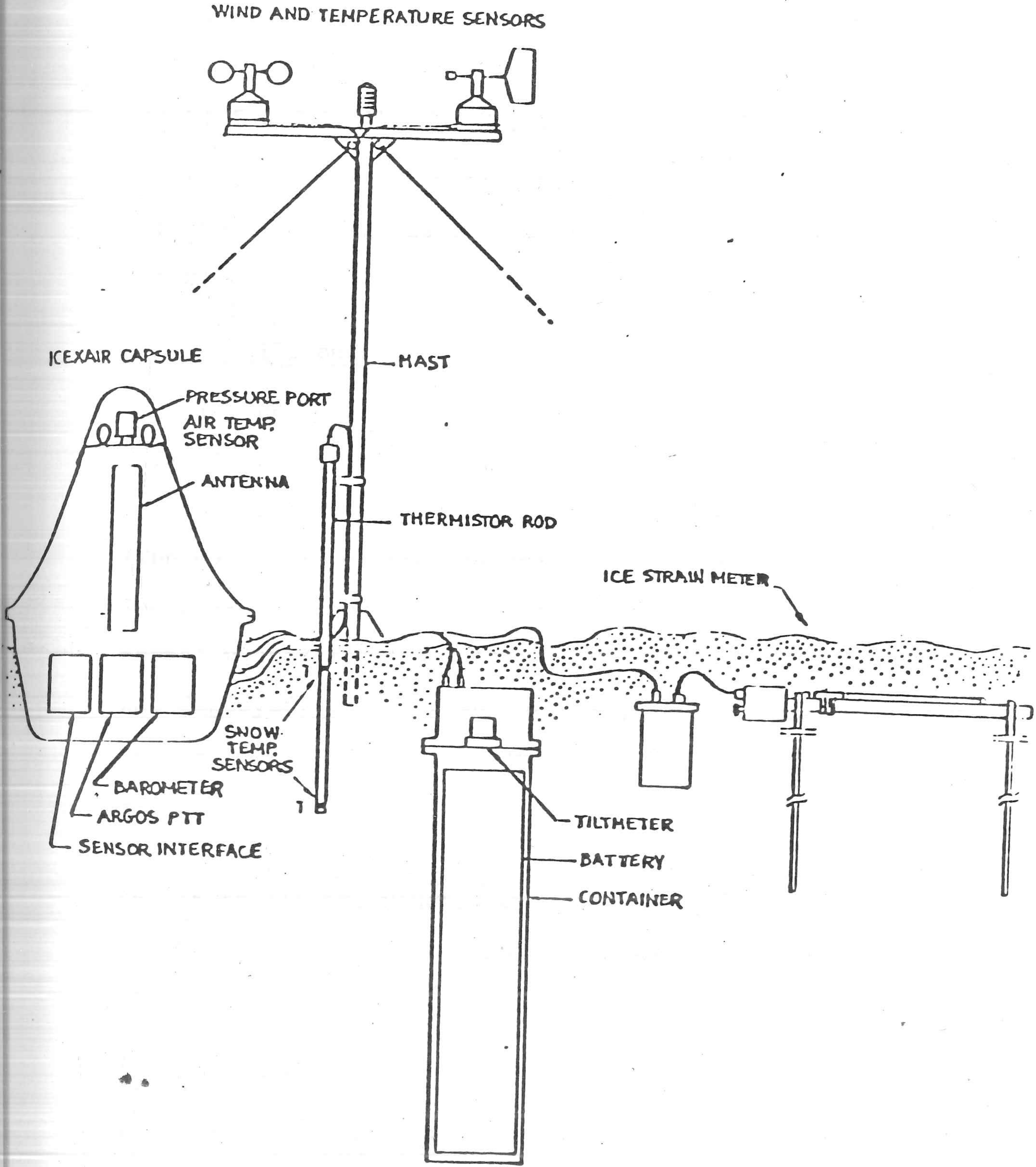

FIGURE 3.1.1 The Iceberg Data Collection Station consists of 5 main components; the ICEXAIR capsule, the wind sensor mast, the battery container, the ice strainmeter and the temperature sensor rod. The components are interconnected by waterproof cables and connectors. (CMI Report, 1979)

The power supply was designed for 24 months capacity. Figure 3.1.1 shows a layout of the station. A detailed description of the various components of the platform can be found in the CMI Report (1979).

Since the construction and setting up of the strainmeter and the tilt meter is of interest in this paper, a description is given in the following subsections.

3.2 The tilt sensor

The tilt sensor is a Singer-Kearfott 'bubble type' two-axis electrolytic vertical sensing element detecting angular displacement about two orthogonal horizontal axes. (The main axis of the iceberg and an axis transverse to it). The sensor is mounted on a levelling platform of the type normally used for theodolites. When the automatic station was deployed, the tilt sensor was placed on top of the two metres long battery container (see Figure 3.1.1), which was placed in a hole drilled in the snow. The tilt sensor was level with the surface. The range of the tilt meter is -15 to +15 arc-minutes with a resolution of 0.12 arc-minutes. The tilt meter has no re-zeroing device. (CMI Report, 1979).

3.3 The strainmeter

The strainmeter consists of a 1 metre INVAR rod fixed at the passive end of the instrument to a mounting block and plate, and at the active end to a Linear Variable Differential Transformer (LVDT). The core is suspended

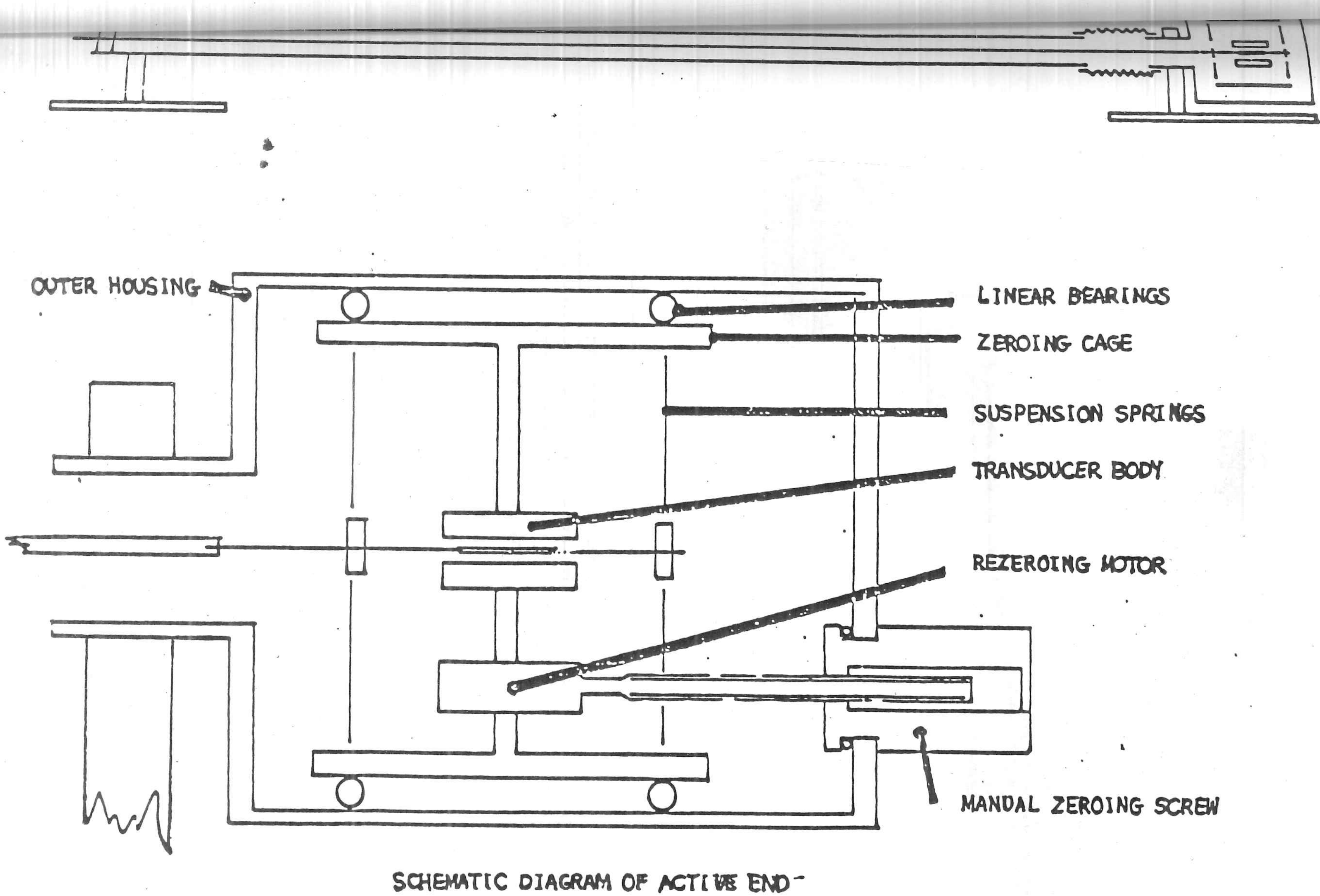

FIGURE 3.3.1 A schematic diagram of the ice strainmeter deployed on the iceberg surface. (CMI Report, 1979)

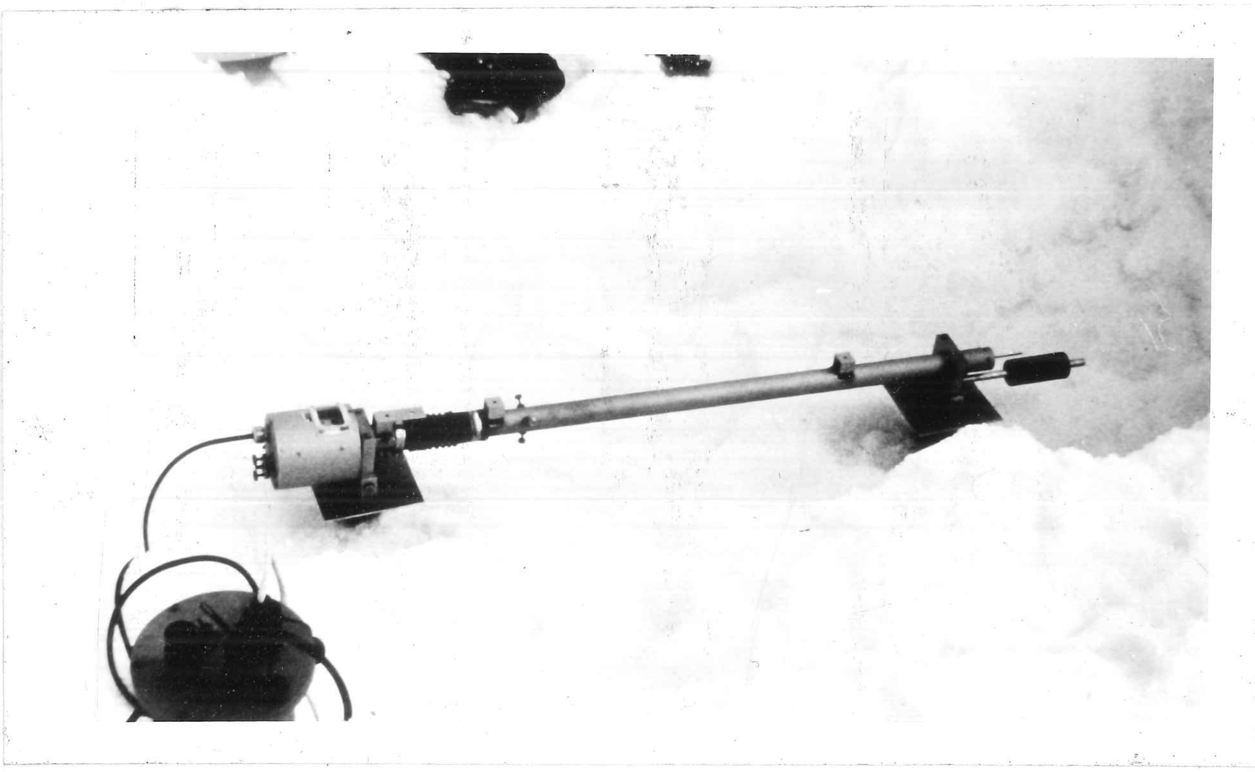

FIGURE 3.3.2 The ice strainmeter being deployed on the iceberg. A trench, about 1 metre deep, was dug in the snow, and holes about 1 metre deep were drilled. The strainmeter was anchored to the ice by snow and freezing water.

on a six point spring suspension to constrain its motion to an axial direction. The strainmeter has a re-zeroing device attached. A schematic diagram of the strainmeter is shown on Figure 3.3.1. The range of the strainmeter is 1.2×10^{-2} metres, and the resolution is 10^{-7} metres. The strainmeter was manufactured for Scott Polar Research Institute, Cambridge, by the company Delta-T Devices.

The strainmeter was mounted in a trench approximately one metre deep. Holes were drilled for mounting tubes which were fixed with snow and freezing water. The trench was then filled with snow. A picture of the strainmeter in the trench is shown in Figure 3.3.2.

3.4 Data collection

A measuring sequence is repeated every third hour. During this sequence both tilt and strain-signals are sampled twenty times with a sample interval of 6 seconds. The signals are digitized and stored in memory banks before being transmitted to the satellite.

3.5 Data transmission

The data are transmitted to the TIROS-N low orbitting satellite and despatched through the ARGOS system. Before 30 June 1979 only one satellite was operating, corresponding to an average of eight significant daily passages (providing a location for the iceberg). After 30 June 1979, two satellites have been operating, and the number of passages are doubled. The times for passages are not however, regularly spaced. Some of the passages are quasi-instantaneous, reducing the number of significant locations to approximately eleven per day.

A satellite passage provides ten minutes of information.

3.6 Data processing

The sensor signals are converted to coded records which are stored on magnetic tape. An example of the output is shown in Figure 3.6.1. The iceberg has ID code 1080. The data are decoded and calibrated through a Fortran programme. Since repeated sequences, as well as unmeaningful data occur, the data have to be edited before further processing is done.

Approximately one year of information, from 4 February to 31 December, is available.

The data is divided into three sets corresponding to a hydrodynamical set, a geophysical set and thermodynamical set. The hydrodynamical data concern the motion of the centre of the iceberg and the orientation of the iceberg compared to relevant parameters such as wind speed and direction. Analysis of these data are made in Bergen, Oslo and Paris, but so far only some preliminary results are obtainable. These are summarised in Chapter 4. No work has up to now been done on the thermodynamical set of data, which includes air and snow temperatures and correlations between temperature gradients and wind speed.

```
28   58   1080 32 10665 79   74   4 14 31 1   -1 1              0 401649783
28        -1       -71.681  339.665   -64.486   300.437          0 401649783
28 10665   5 51  10   1    +.98964E+3    41            -.99900E+2 ? 125
28                          010          018            135           119
28                          123          118            120           002
28                          220          220            220           219
28                          219          219            219           220
28                          219          219            219           222
28                          221          221            221           221
28                          220          220            220           220
28 10665   5 52  12   1    +.98964E+3    41            -.99900E+2 ? 125
28                          010          022            135           119
28                          123          118            120           004
28                          138          135            139           131
28                          125          137            125           137
28                          131          131            137           139
28                          133          134            141           129
28                          131          139            133           142
28 10665   5 55  17   1    +.98964E+3    41            -.99900E+2 ? 125
28                          006          003            135           119
28                          123          118            120           004
28                          138          135            139           131
28                          125          137            125           137
28                          131          131            137           139
28                          133          134            141           129
28                          131          139            133           142
28 10665   5 56  19   1    +.98964E+3    41            -.99900E+2 ? 125
28                          006          011            134           119
28                          123          118            120           001
28                          067          066            067           067
28                          068          069            067           067
28                          067          067            068           067
28                          067          066            066           066
28                          067          067            067           067
28 10665   5 57  20   1    +.98964E+3    41            -.99900E+2 ? 125
28                          004          019            134           119
28                          123          118            120           002
28                          220          220            220           219
28                          219          219            219           220
28                          219          219            219           222
28                          221          221            221           221
28                          220          220            220           220
28 10665   5 58  22   1    +.98964E+3    41            -.99900E+2 ? 125
28                          007          018            134           119
28                          123          119            120           004
28                          138          135            139           131
28                          125          137            125           137
28                          131          131            137           139
28                          133          134            141           129
28                          131          139            133           142
28 10665   5 59  24   1    +.98964E+3    41            -.99900E+2 ? 125
28                          005          025            134           119
28                          123          119            120           001
28                          067          066            067           067
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FIGURE 3.6.1 Unprocessed data from magnetic tape. The data are in code, and has to be decoded and calibrated.

The geophysical set, which contains the tilt and strainmeter data, is analysed in detail in Chapters 5, 6, 7 and 8. The work has been done at the Scott Polar Research Institute utilizing the Cambridge University IBM 370 computer.

CHAPTER 4

DYNAMICAL BEHAVIOUR OF THE ICEBERG

4.1 Drift track of the iceberg

The circulation in the Southern Ocean is characterized by the Antarctic Circumpolar Current north of 60°S, the westward flowing Antarctic Coastal Current, and a series of eddies and gyrations between these two current regimes (Vinje, 1979).

The largest of these gyres is the Weddell Sea Gyre, bounded in the west by the Antarctic Peninsula and turning in the east near 30°W towards the south. Scientists from the Norwegian Polar Institute, Oslo, have been studying these cyclonic circulations by observing drift tracks of icebergs.

When the automatic station ID 1080 was deployed on a tabular iceberg in the Weddell Sea, the iceberg was in the position of approximately 70.5°S, 20.3°W. The drift track of the iceberg from 4 February to 31 December 1979 is shown in Figure 4.1.1. The speed of the iceberg was on the average 27 km per day.

Pack ice surrounded the iceberg from about 10 March and throughout the period for which data have been analysed (Figure 4.1.2).

4.2 Iceberg heading

A preliminary four day manual analysis of the iceberg heading data and wind speed and direction data have been made by scientists at Iceberg Transport International Limited (ITI Report, 1980).

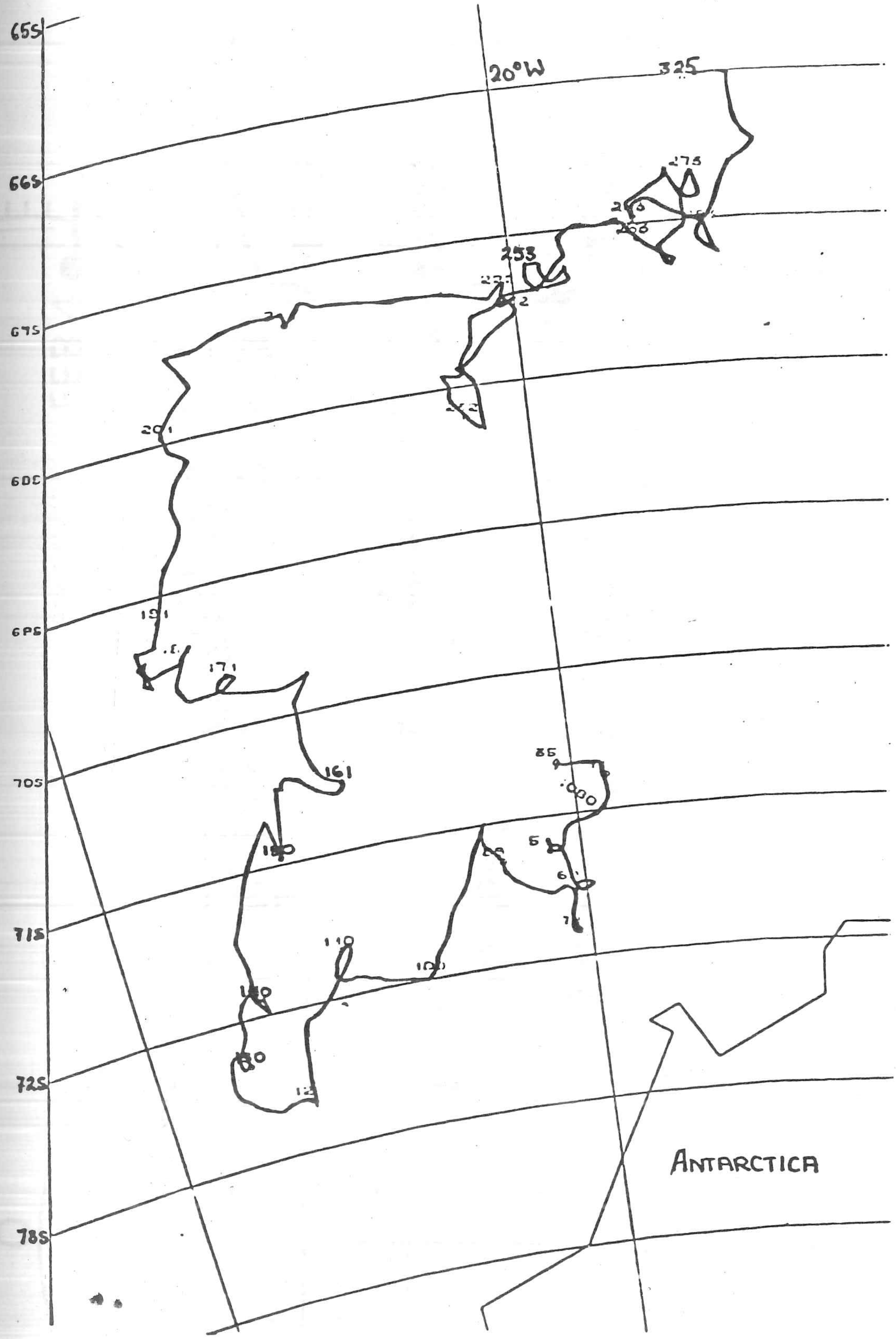


FIGURE 4.1.1 The drift of the iceberg from 4/2/79 - 31/12/79 (Vinje, 1979)

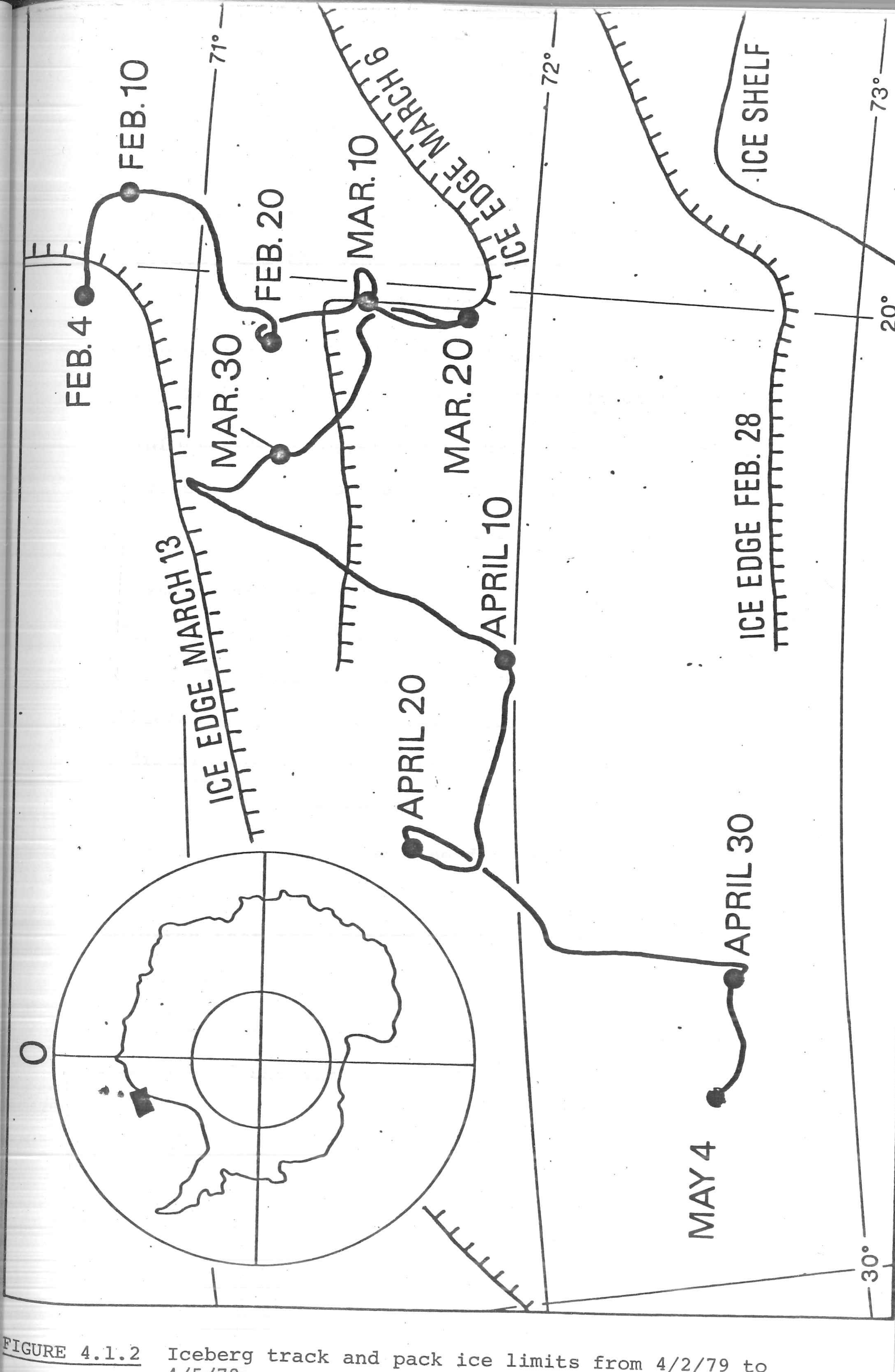


FIGURE 4.1.2 Iceberg track and pack ice limits from 4/2/79 to 4/5/79.

The analysis of hydrodynamical data could yield information on various problems:

- the angle between the speed of the centre of the iceberg and the wind speed could show the coriolis deflections of the water mass and the iceberg itself
- the variation of this current effect could make apparent the influence of the tide (lunar period)
- information on other components of the drift of the iceberg (currents, waves and swell)

(Icebergs for the future, 1979)

The amount of data analysed by ITI was, however, not a sufficient basis for reaching any conclusions on these points. The analysis did not give any information on the influence of pack ice on the drift of the iceberg and lack of direct information on the current around the iceberg left the analysis incomplete.

Figure 4.2.1 shows iceberg heading and windspeed and direction plotted for a four day period. The plot indicates that the iceberg rotates around its centre frequently.

Much work is still left to be done on the dynamical behaviour of the iceberg.

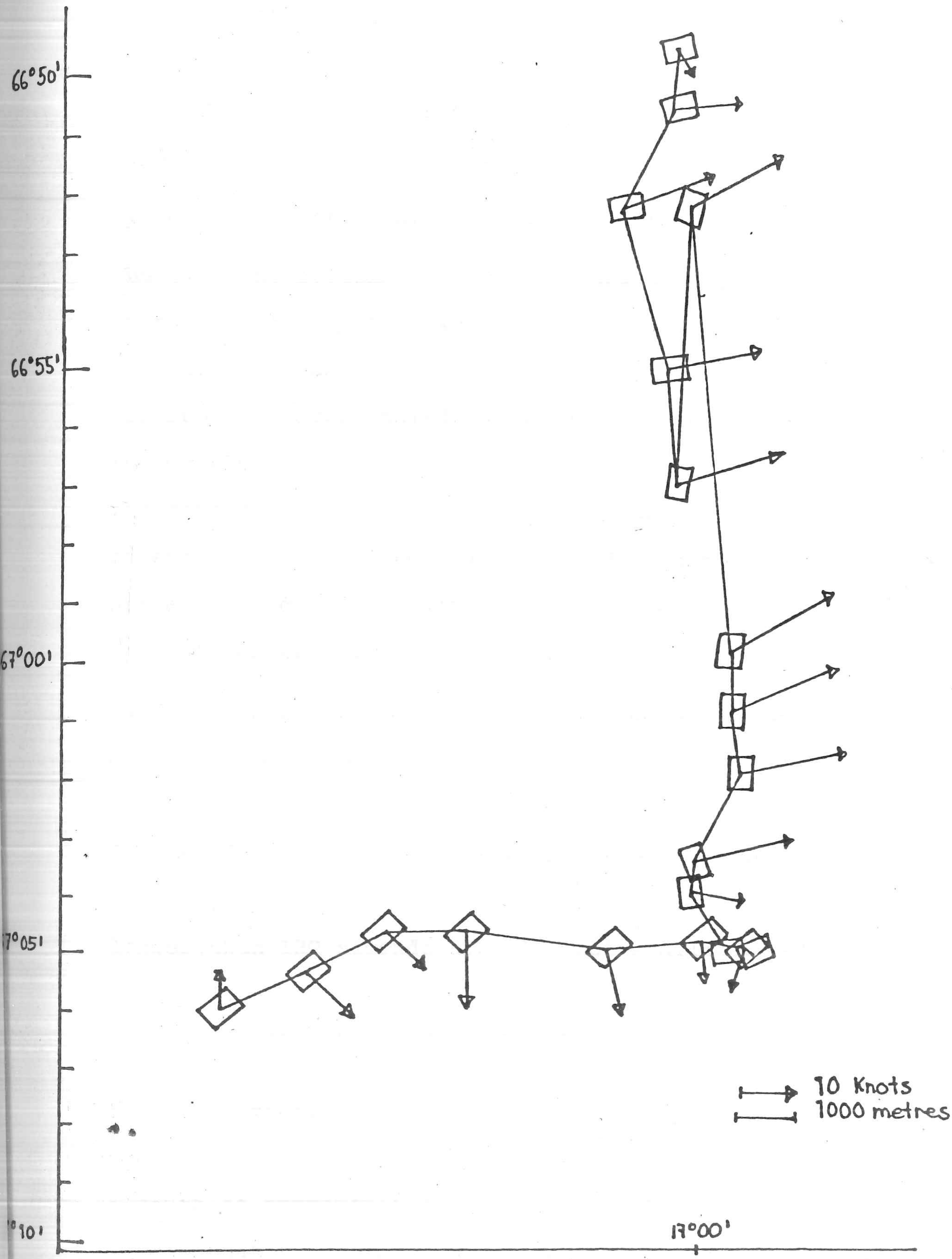


FIGURE 4.2.1 Iceberg drift, wind speed and direction for the days 26/9/79 to 30/9/79. (ITI Report, 1980)

CHAPTER 5

STATISTICAL ANALYSIS OF THE STRAINMETER AND TILT SENSOR DATA

5.1 Characteristics of the data samples

The tilt and strainmeter sensor signals are sampled every six seconds for two minutes. Hence the samples consist of 20 data points. These measuring sequences are repeated every third hour, but only occasionally are the complete set of 8 sequences for one day available in the data files. As mentioned in Chapter 3, the passages of satellites are irregularly spaced over the day, and not all the data are successfully transmitted without 'noise' occurring.

The fact that the sensor signals are sampled every 6th second places a 6 second filter on the data, and possible components of the data spectra, with periods less than 12 seconds (the Nyquist frequency) are therefore lost. Similarly, components of the data spectra with periods longer than 120 seconds are also not available. Ocean waves with periods of 12 seconds have wavelengths of somewhat over 200 metres (Groen, 1967).

This is similar to the draught of the iceberg, but since the effects of the wave action are not noticeable below a depth of approximately half the wavelength, it is unlikely that the iceberg would respond to waves with shorter periods than 12 seconds. Wavelengths corresponding to periods of 120 seconds are approximately 14 miles,

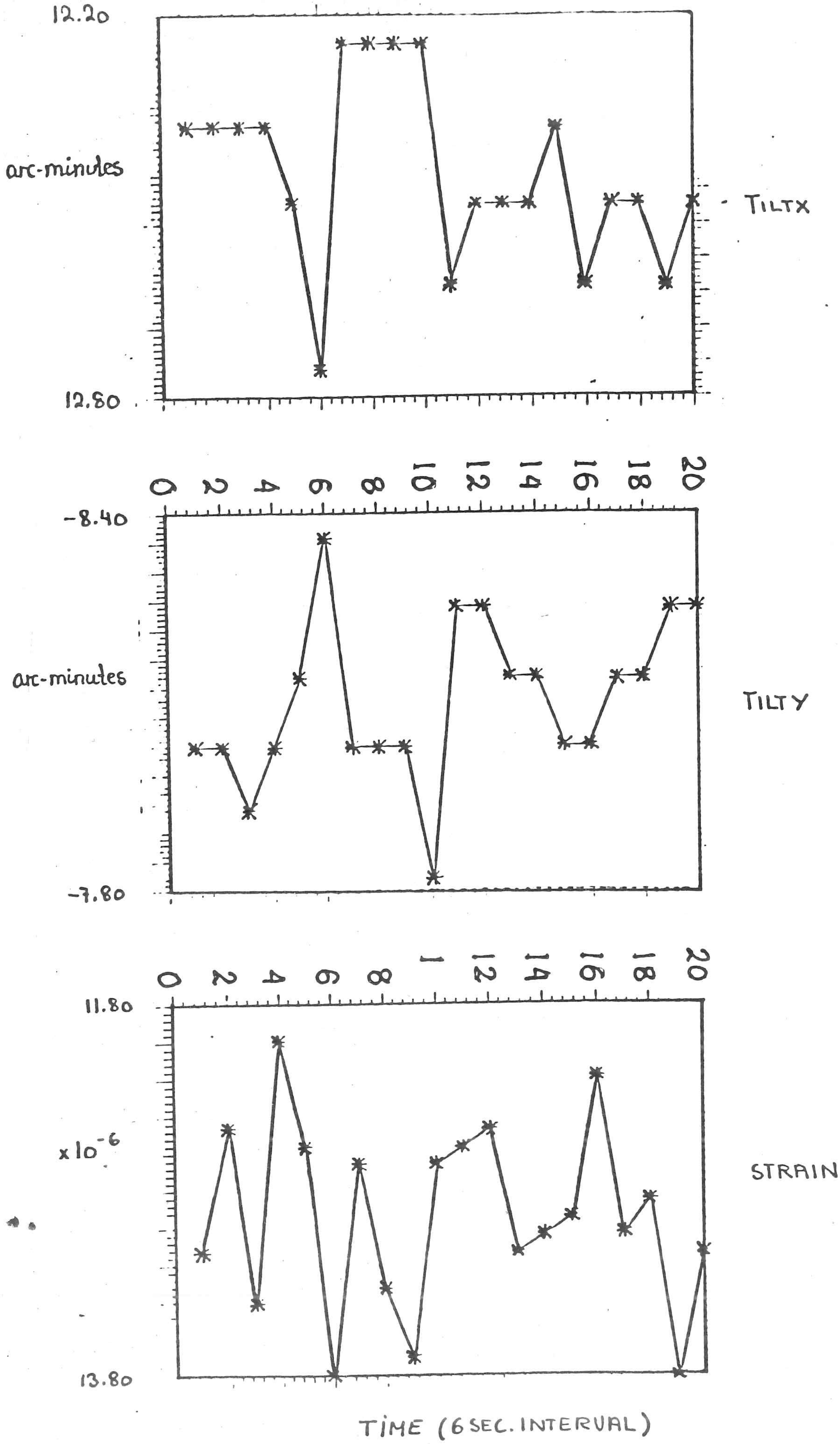


FIGURE 5.1.1 Typical plots of tilt and strain data samples

and it is not expected that these will make the iceberg bend or tilt noticeably.

It is therefore concluded that although the data samples do not include response periods lower than 12 seconds and higher than 120 seconds, the tilting and bending periods of the iceberg is likely to be within these limits.

An example of 2 minute data samples of tilt in two directions and strain is shown in Figure 5.1.1.

5.2 Choice of a statistical method

As the data samples contain only 20 data-points, and as joining of several data samples will lead to inclusion of discontinuities, it is very difficult to use a Fast Fourier Transform Analysis and obtain reliable results. A statistical 'hand' method developed at the National Institute of Oceanography (now Institute of Oceanographic Sciences), is therefore employed for the analysis of each of the data samples.

A number of conditions must apply to the data if this method is to be used. The processes generating the tilt and strain sensor signals must be linear and random. This means that the signal amplitudes are functions of time only (Tann, 1978). The sample graph is considered as a resultant of sinusoidal components of random phase leading to a distribution of statistical symmetry about the mean line. It is further assumed that the data samples are representative for the processes that initiate the data. As was argued in section 5.1, there is a basis for assuming this when the production of the tilt and strain data are taken to originate as a response to the ocean wave field.

The statistical method chosen also offers a procedure to calculate maximum expected amplitudes between data samples and in a specified time interval along the lines of analysis used to compute 'design waves' in ocean structure engineering (Pitt, Driver and Ewing, 1978).

The basic assumption for these calculations is that the data samples are representative for the 3 hour period between samples.

As there seems little justification in assuming that two minutes of data is typical for the conditions of the environment and the response of the iceberg for several hours on both sides of the data sample, these calculations have been omitted in this thesis.

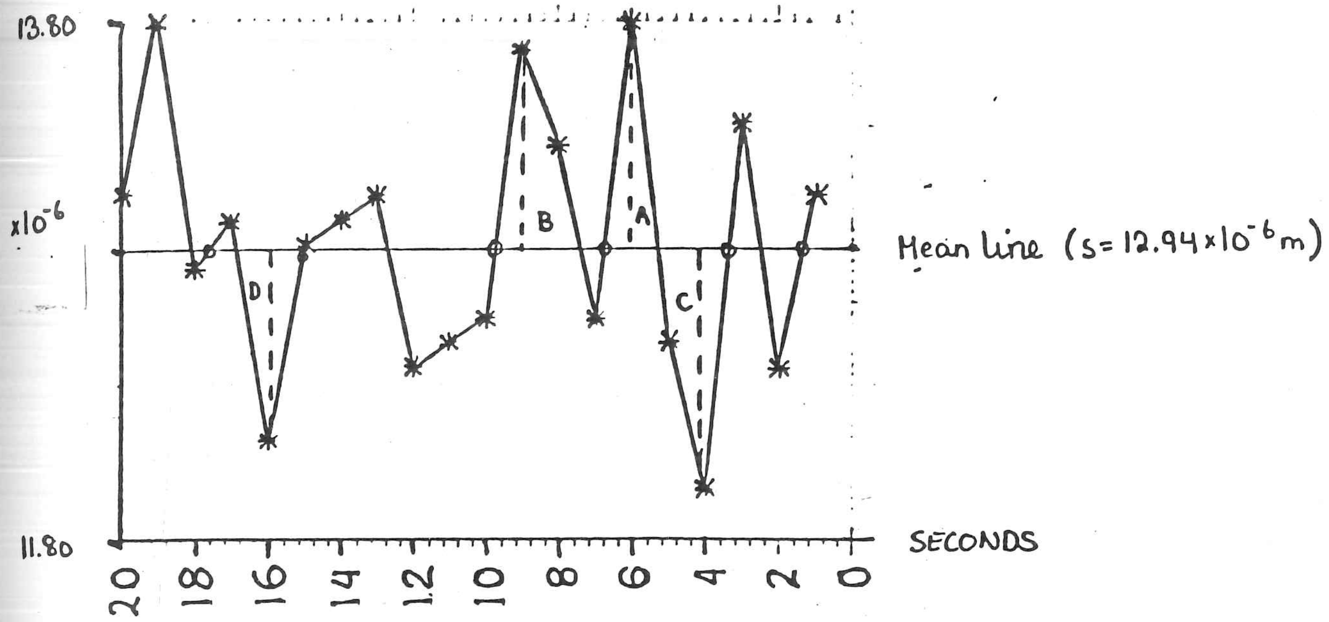
5.3 Short term analysis. A description of the statistical method used

An outline of the main points in the statistical method used will be made, following the description given by Tann (1976). A more detailed account is given in Appendix B with some references to the theory and practical use of the method. For each data sample the zero up-crossings are counted. A zero up-crossing is defined when the graph of the record passes through the mean line (defined as the mean value of the sample) in an upward direction.

The period of a zero up-cross wave is defined as the time interval between the two zero up-crossings which bound it. Given a record of duration t minutes, the mean zero up-crossing period is then:

$$T_z = \frac{t \times 60}{\text{number of zero up-cross waves}} \quad \text{seconds}$$

A trough is defined as a local minimum on the graph, and a crest as a local maximum. For every data sample the largest and second largest crest, as well as the smallest and second smallest trough, is measured from the mean line.
The root mean square amplitude is then calculated as a function of these numbers. The significant amplitude, defined as the mean of the largest third of the amplitudes, can be found from the root mean square amplitude.



Day 74 , Time 162638 - Strain

$A = 0.87 \times 10^{-6}$ m

$B = 0.77 \times 10^{-6}$ m

$C = 0.94 \times 10^{-6}$ m

$D = 0.75 \times 10^{-6}$ m

$N_c = 6$

$N_z = 6$

RESULTS :

$T_z = 20$ SECONDS

$E^{1/2} = 0.27 \times 10^{-6}$ METERS

$H_s^* = 1.08 \times 10^{-6}$ METERS

FIGURE 5.3.1 The statistical method demonstrated on one strain data sample.

The following parameters are noted for each 2 minute sample:

A = height of largest crest

B = height of second largest crest

C = depth of largest trough

D = depth of second largest trough

N_z = number of zero up-crossings

and the following parameters are calculated for each 2 minute sample:

Mean zero up-cross period, T_z:

$$T_z = \frac{120 \text{ sec}}{N_z}$$

Root mean square amplitude, $E^{\frac{1}{2}}$:

$$E_1^{\frac{1}{2}} = \frac{A + C}{2\sqrt{2\theta}} (1 + 0.289\theta^{-1} - 0.247\theta^{-2})^{-1}$$

$$E_2^{\frac{1}{2}} = \frac{B + D}{2\sqrt{2\theta}} (1 - 0.211\theta^{-1} - 0.103\theta^{-2})^{-1}$$

where $\theta = \ln N_z$

$$E^{\frac{1}{2}} = \frac{E_1^{\frac{1}{2}} + E_2^{\frac{1}{2}}}{2}$$

Significant amplitude, H_s:

$$H_s \simeq 4E^{\frac{1}{2}}$$

A worked example of the method is shown in Figure 5.3.1.

5.4 Statistical treatment of data collected over long periods of time

One year of continuous recordings of data is available for analysis. With such a large amount of data, it is important to separate significant features of the long term development of the data, without losing important information. Some conclusions can be reached from studying single sensor samples, while other results are obtained by investigating changes over a period of time, and correlations to other parameters.

Data from a period of approximately three months are analysed in this thesis from 4 February to 4 May 1979.

A Fortran program has been developed to count and calculate the necessary statistical parameters from each sample. Mean values of the parameters for the three month period have been calculated, and absolute maxima and minima in the values of amplitudes have been noted. The results from the long term analysis are given in Chapter 6. Part of the results from the short term analysis are listed in Appendix A but lack of space made it necessary to reduce the total amount of results presented, to about $^{1}/_{10}$ of the results obtained from the analysis.

CHAPTER 6

RESULTS OF ANALYSIS

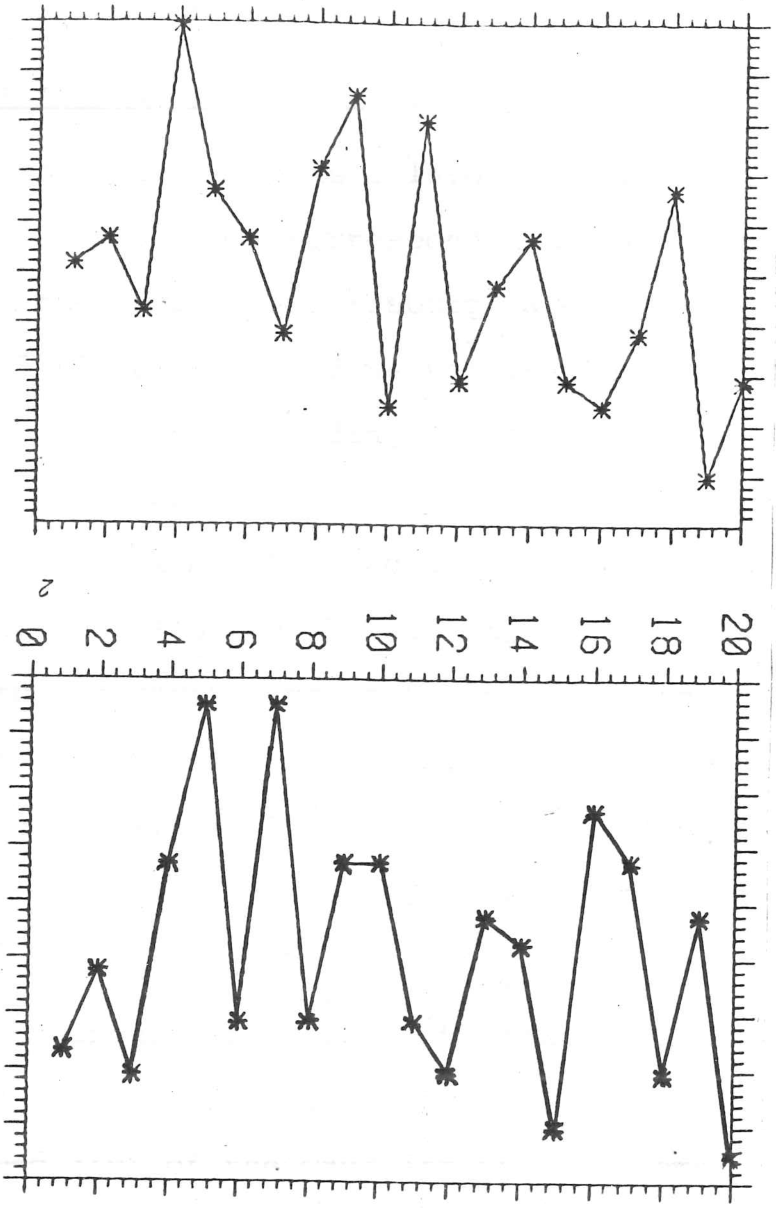
6.1 General

The data collection platform deployed on the tabular iceberg in the Antarctic is the first experiment of its kind to be attempted. Although data is available for all the sensors listed in Chapter 3 for one year, only the strainmeter and tilt data for a period of three months have been analysed in this thesis. Examples of listed and plotted data are given in Figure 6.1.1 and in Appendix A.

As a first approach to the collected data, it is necessary to assess whether the instruments are functioning correctly and whether the measured values are physical representations of the iceberg's response to the environment.

Mean response periods of tilt and strain are calculated from the statistical method described in Chapter 5. The change in values of the periods and correlations between periods and tilt periods (in both directions) may indicate something about the response of the iceberg to the direction of swell, as well as the general ocean wave field. Correlations between wind speed and direction and tilt and strain periods are looked for.

Other calculated parameters are presented. Changes in mean and significant amplitudes may yield information as to how close the surface strain amplitudes are to critical values.



YEAR 1979 DAY 73 TIME OF LOCATION :0 HOUR 59 MIN 9 SEC
STRAIN X-AXIS (IN CM,MEASURELENGTH 94 CM) 20 MEASUREMENTS EACH 6 SECS

12.563	12.468	12.754	11.612	12.278
12.468	12.849	12.183	11.897	13.134
11.992	13.039	12.658	12.468	13.039
13.134	12.849	12.278	13.420	13.039

YEAR 1979 DAY 74 TIME OF LOCATION : 4 HOUR 14 MIN 31 SEC
STRAIN X-AXIS (IN CM,MEASURELENGTH 94 CM) 20 MEASUREMENTS EACH 6 SECS

13.134	12.849	13.230	12.468	11.897
13.039	11.897	13.039	12.468	12.468
13.039	13.230	12.658	12.754	13.420
12.278	12.468	13.230	12.658	13.515

FIGURE 6.1.1 Strainmeter data samples for two locations, presented as graphs and listed. (Numbers are to be read horizontally)

6.2 Values of tilt response

The range of the tilt meter is ± 15.0 arc minutes in both x- and y- direction. This corresponds to a variation of the height of the edge of the iceberg (above and below the horizontal plane) of ± 2.3 metres in the direction of the main axis. The corresponding values in the transverse direction are ± 1.9 metres. Thus a maximum steepness factor of about 0.004 may be recorded by the tilt meter. Theoretical calculations on the tilting response of the iceberg due to the variations in the pressure under the iceberg corresponding to waves of different periods, are not simple. An analysis of this problem, including the bending response, has been made by Goodman, Wadhams and Squire (1980).

A very simple approach is to look at some basic upper limit data on ocean waves in general. Wave heights are found never to exceed 1/10 of the wave length. The amplitude of the wave at about half the wave length from the surface is about 4%.

If the iceberg behaved like a rigid body with zero mass, it would tilt with a maximum steepness of 0.004 in response to a wave with a period of about 16 seconds. Since the percentage of waves that exceed 4-5 metres in wave height is very small (see subsection 2.6), and assuming that the tilt variations are about the horizontal plane, the range of the tilt meter is adequate.

However, it is evident from the data that the mean plane of variation of the tilt, that is, the plane defined by the mean values of tilt in x and y direction, is not the same as the horizontal plane (defined as parallel to the surface of the ocean when there are no waves). Furthermore, the mean plane of variation of the tilt is changing, often over a very short period of time.

An example of this is shown in Figure 6.2.1 where the mean value of tilt along the main axis of the iceberg is changed from -0.9' to +10.9', and the mean value of tilt transverse to the main axis is changed from +9.6' to -7.5'. Such events are recorded frequently in the data.

There are several possible explanations for the sudden variations in the mean tilt of the iceberg.

The tilt meter was placed on a levelling platform on the same level as the iceberg's surface. Since the upper layer of the iceberg consists of snow down to a depth of 1 to 2 metres, irregular melting around the platform could cause listing of the tilt meter rather than the iceberg itself tilting. The approximate melt-rate is thought to be 0.5 metres a year in the Antarctic, and it is unlikely that this effect is the reason for sudden changes in the mean tilt values during the first three months of data recording. It is therefore assumed that the event shown in Figure 6.2.1 was due to a real change in the average tilt of the iceberg. The explanation must be a real change in the mass distribution or the form of the iceberg, either caused by small scale fracture, or by opening of surface crevasses which may be filled and emptied by sea water and change the balance of the iceberg.

DAY 55 (20/2) 1979 TIME : 0 HOUR 44 MIN. 46 SEC.

TILT X-AXIS (IN ARC-MINUTES),20 MEASUREMENTS EACH 6 SECS :,

-1.000	-0.882	-0.882	-0.882	-0.765
-0.765	-0.882	-0.882	-0.882	-0.882
-0.882	-0.765	-0.882	-0.882	-1.000
-0.882	-0.882	-0.882	-0.765	-0.882

TILT Y-AXIS (IN ARC-MINUTES),20 MEASUREMENTS EACH 6 SECS :,

9.706	9.706	9.706	9.588	9.588
9.588	9.588	9.588	9.588	9.588
9.588	9.471	9.471	9.588	9.588
9.588	9.588	9.471	9.471	9.471

DAY 55 (20/2) 1979 TIME : 7 HOUR 25 MIN. 49 SEC.

TILT X-AXIS (IN ARC-MINUTES),20 MEASUREMENTS EACH 6 SECS :,

10.882	10.882	11.000	11.000	10.882
10.882	10.882	10.882	10.882	10.882
10.882	10.882	10.882	10.882	10.882
10.882	10.882	10.765	10.765	10.765

TILT Y-AXIS (IN ARC-MINUTES),20 MEASUREMENTS EACH 6 SECS :,

-7.588	-7.471	-7.588	-7.588	-7.588
-7.588	-7.471	-7.471	-7.471	-7.588
-7.353	-7.353	-7.471	-7.471	-7.588
-7.353	-7.353	-7.353	-7.471	-7.471

FIGURE 6.2.1 On day 55 (20/2/79), the iceberg suddenly listed, and significant changes in tilt in both directions (along and transverse to the main axis) were recorded.

As the mean values of tilt in both directions are not zero, the values of the possible range of amplitudes may be substantially smaller than ± 15.0 arc minutes. This may eventually cause the tilt meter to go off scale permanently, since the tilt meter does not have a re-zeroing device. However, this did not happen during the first three months of recorded data.

6.3 Values of strain response

The range of the strainmeter before rezeroing occurs, is dependent on the sensitivity chosen for the recording of the strain.

Generally the mean value of the strain is not zero, but the value is both a function of how the instrument was set up, variations of instrument characteristics, variations due to possible temperature change as well as long term changes in the strain due to a possible plastic deformation of the iceberg. Typical values of the amplitudes of the strain variations are between 10^{-7} and 10^{-5}. Since so few measurements of surface strain with strainmeters on icebergs have been done, and none in the Antarctic, it is difficult to establish whether these values are respresentative of the actual bending of the iceberg.

Goodman, Wadhams and Squire (1980) have measured the bending response of a 35 metres thick iceberg with a size of 431 by 179 metres to the ocean swell off the coast of East Greenland. Although the paper does not give typical figures of the strain variations, it is indicated that they are generally smaller than 10^{-5}.

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Another experiment during the same field operation measured fracture of multi-year ice floes at a surface strain of 3×10^{-5}. As the bending response of a 200 metres thick iceberg is expected to be much smaller, the recorded values of strain of 10^{-7} to 10^{-5} seem reasonable. A further comparison of the results obtained in this thesis and those given in the paper by Goodman, Wadhams and Squire, is given in Chapter 7, as well as in some of the following subsections.

6.4 Mean up-cross periods of strain

Mean response periods of the surface strain was found to have values between 15 seconds and 120 seconds. Frequencies of occurrence in percentages are listed in Figure 6.4.1 and plotted in Figure 6.4.2. As is evident from the plot, the iceberg mostly responds to ocean swell of periods between 20 to 30 seconds, but swell of shorter periods down to 15 seconds and up to 120 seconds will also make the iceberg bend. Because of the statistical method used in obtaining the mean up-cross period, only the large amplitude part of the graph will contribute to the number of up-crossings.

Smaller amplitudes with higher or lower periods will not be counted if they do not cross the mean value line.

Periods below 20 seconds and above 30 seconds are therefore obtained only if the 20 to 30 second swell is not present or if waves of the former periods have much larger amplitudes than the latter. Again, it is not a simple relationship between the bending response of the iceberg and the periods and amplitudes of the ocean wave field, as is shown in the paper by Goodman, Wadhams and Squire (1980).

PERIODS (SECONDS)

	15	17.14	20	24	30	40	60	120
ILT X	0	0	1.8	8.2	35.5	39.1	11.8	3.6
ILTY	0	0	2.9	2.9	16.1	48.9	14.6	14.6
TRAIN	0.7	3.7	27.6	32.2	25.0	7.2	2.9	0.7

FREQ. OF OCCURRENCE

FIGURE 6.4.1 Percentage of tilt and strain up-cross periods. The data are from the period 4/2/79 to 4/5/79. Figure 6.4.2 shows a plot of the same results.

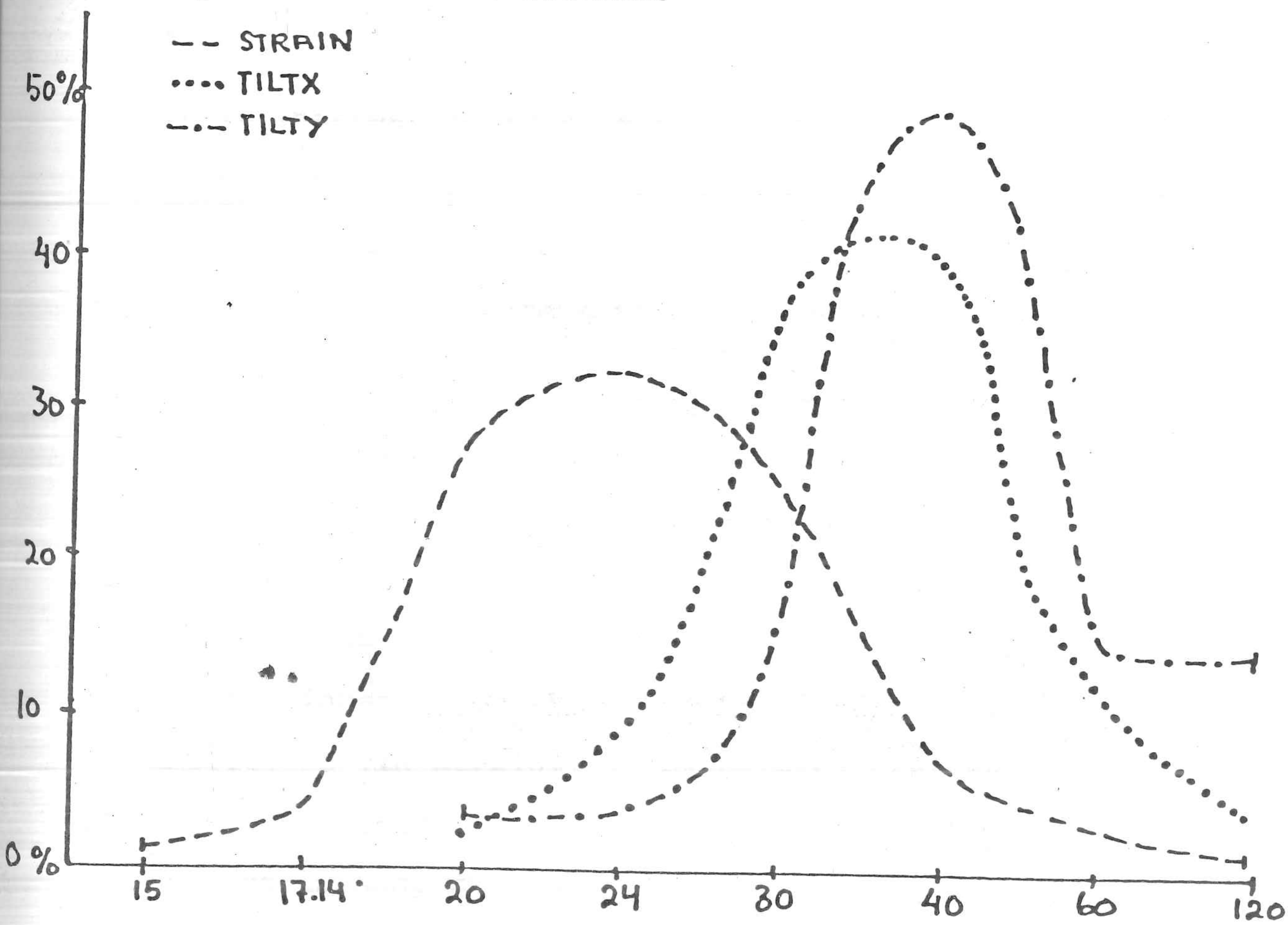

FIGURE 6.4.2 Percentage of occurrence of tilt and strain up-cross periods. The tilt is measured in two directions, tilt along the main axis of the iceberg (tilt x) and transverse to the main axis (tilt y). Strain is measured along the main axis.

However, it is not expected that the iceberg is bending in response to waves with a shorter wave length than the double value of the iceberg thickness, that is, waves with a period less than about 15 seconds. This is in accordance with the obtained results.

6.5 Mean up-cross periods of tilt

Frequencies of occurrence in percentages of mean up-cross periods of tilt in the direction of the main axis of the iceberg (x-axis) and transverse to it (y-axis), are listed and plotted in Table 6.4.1 and Figure 6.4.2. Typical response periods for tilt in the x-direction are around 35 seconds, and for tilt in the y-direction are around 40 seconds.

It is interesting to note that the average response period of tilt in the y-direction is longer than the average response period in the x-direction, and that both are longer than the average strain response period.

If the explanation of this is a feature of the iceberg's response to the ocean wave field, rather than being an instrumental effect, it must be assumed that the tilt meter records larger amplitudes in waves with long periods (larger than 35 seconds) than in waves with shorter periods. The strainmeter, on the other hand, records the largest amplitudes (in strain!) in waves with periods between 20 to 30 seconds. If the ocean waves with periods larger than 35 seconds do have larger amplitudes than waves with shorter periods, the graphs of the tilt data would show crossings of the mean value lines following the long periods, but the superimposed short period, small amplitude waves would not result in a crossing of the mean line and would not count in the calculations of the mean up-cross period of the tilt. An explanation as to the difference in average mean up-cross periods between tilt in the two directions, could be that the iceberg tends to align with its long side parallel to the long period, large amplitude swell.

Subsection 2.6 summarised some existing data on ocean swell in the Southern Hemisphere, and it is clear that the information available is insufficient for concluding anything about the correlations between amplitudes and periods of the swell.

6.6 Correlations between the tilt and strain response periods

Strain is measured along the main axis of the iceberg, and it is therefore expected that changes in the strain response periods should correlate with changes in the response periods of tilt in the x-direction.

Correspondence between the tilt in x and y directions should also be present. If the mean up-cross period of the tilt in the x-direction is small, it can be assumed that the iceberg is lying with the main axis transverse to the direction of the swell, and the mean up-cross period of the tilt in the y-directions should be expected to be longer. Similarly short mean up-cross periods of tilt in the y-direction should correspond to long mean up-cross periods of the tilt in the x-direction.

In Figure 6.6.1 are listed some mean up-cross periods of strain and tilt during a time period of three days. There seems to be a general correspondence between short periods of tilt in the x-direction and long periods of the tilt in the y-direction and vice versa.

Since the iceberg frequently rotates around the centre in a period of days, the swell will be coming from all directions during this period, and there will also be periods of time when tilt periods in both directions have similar values.

A lack of knowledge of the direction of swell relative to the main axis of the iceberg, makes it difficult to draw other than these general conclusions.

There is no clear correspondence between tilt in the x-direction and the measured surface strain variations. The reasons for this seem to be that the iceberg tilts and bends in a complex manner in response to the ocean wave field, and that neither the method of data sampling not the statistical method of analysing are sophisticated enough to describe this complex response.

6.7 Correlations between wind speed and direction and tilt and strain response periods.

The orientation of the iceberg's main axis is a function of the winds, waves and currents acting on the iceberg, and the iceberg's geometrical shape. Preliminary results from analysing main axis heading compared to wind speed and direction for a few days, do not show a correlation between

		STRAIN (SECONDS)	TILTX (SECONDS)	TILTY (SECONDS)
		MEAN UP-CROSS PERIOD	MEAN UP-CROSS PERIOD	MEAN UP-CROSS PERIOD
4/2	143640	30.00	40.00	120.00
		40.00	40.00	60.00
		40.00	30.00	30.00
		20.00	30.00	40.00
5/2	142559	40.00	40.00	40.00
		24.00	30.00	40.00
		20.00	30.00	40.00
		20.00	60.00	40.00
		20.00	20.00	120.00
		20.00	20.00	120.00
		30.00	24.00	60.00
6/2	141612	40.00	40.00	120.00
		24.00	40.00	120.00
		30.00	120.00	40.00
		30.00	120.00	40.00
		24.00	24.00	120.00
		20.00	24.00	40.00
		20.00	40.00	40.00
		30.00	40.00	60.00
		30.00	40.00	120.00
		30.00	40.00	120.00
		30.00	60.00	60.00
7/2	140547	24.00	60.00	60.00

FIGURE 6.6.1 Mean up-cross periods for the days 4/2/79 (143640) to 7/2/79 (140547). Tilt is measured in two directions; tilt along the main axis of the iceberg (tilt x) and transverse to the main axis (tilt y)

these parameters. Banke (1971) has estimated the response of a very small iceberg (2 x 3 x 4 metres above water) to wind. He observes that equilibrium drift relative to the water current occurs when the wind force is balanced by current drag, and concludes that the small iceberg will respond twice as fast as an ice sheet, and 5000 times faster than a 10 metre water layer to the wind. It can safely be presumed that these simple calculations do not apply to icebergs several orders of magnitude larger in volume. Another theory will therefore be investigated:
Whether the iceberg will tend to align with waves generated by a steady wind in a prevailing direction in the vicinity of the iceberg.

Wind speed and direction have been plotted for a three day period in Figure 6.7.1. It may be deduced from the plot that during the first part of the period 4-7 February 1979 the wind was about 15 knots and coming from a small angle to the main axis. After the waves around the icebergs have reached a certain amplitude and period, the iceberg is turned around so that the wind is coming from approximately the direction transverse to the main axis. If the tilting was in response to the wind-generated waves, it would be expected that in the middle part of the period, 4-7 February 1979, the tilt in the y-direction would have shorter periods than the tilt in the x-direction. By consulting Table 6.6.1 it is found that this is not the case, and that the situation is the reverse.

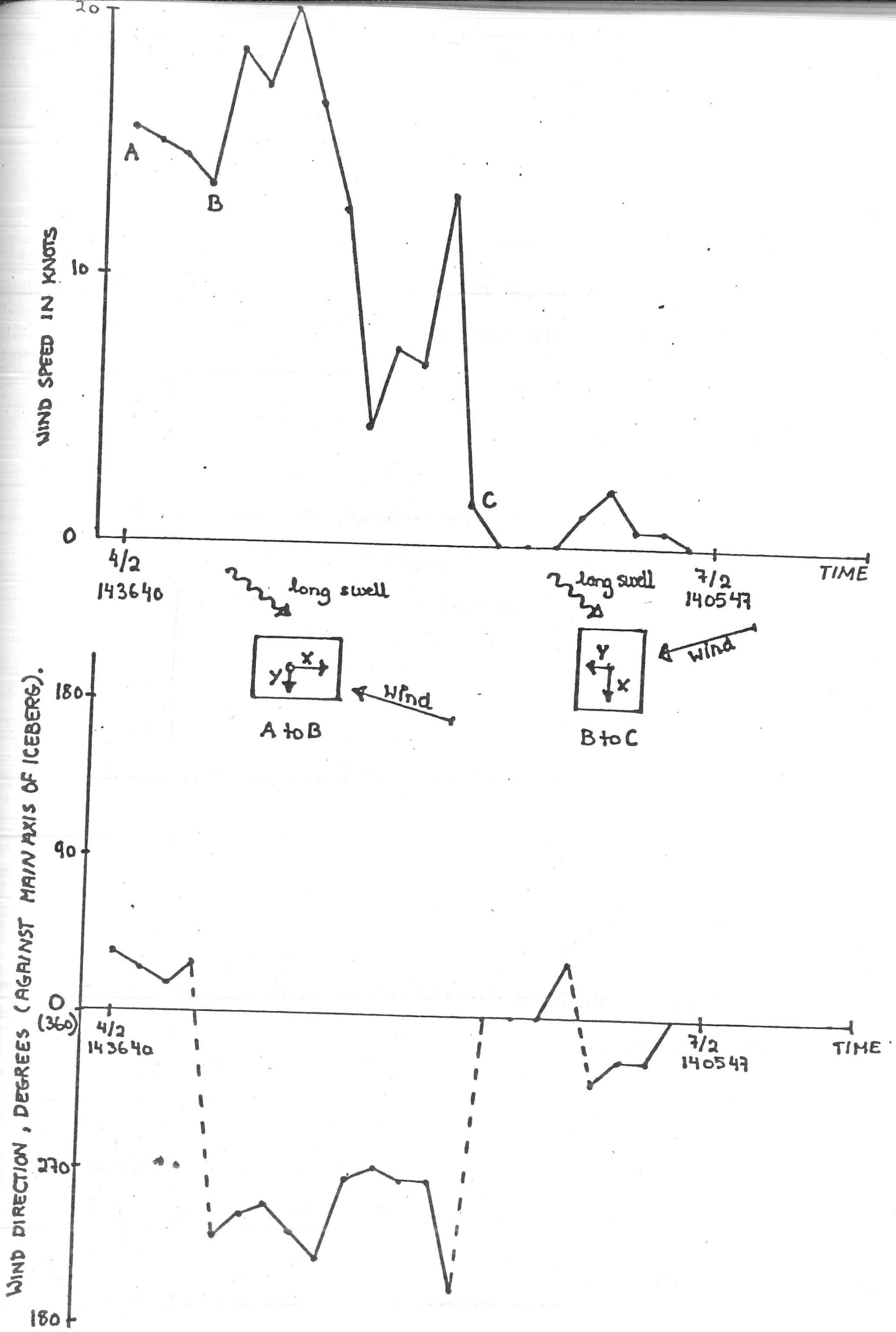

FIGURE 6.7.1 Wind speed and direction plotted for the period 4/2/79 to 7/2/79. The small drawings of the iceberg, show the change in orientation of the iceberg relative to the wind direction during this period.

It therefore seems likely that there may be a correlation between the direction of waves generated by a prevailing wind in the vicinity of the iceberg and the heading of the iceberg, but that the tilt meter records much longer period swell generated at storm centres far from the position of the iceberg.

Longuet-Higgins (1977) has estimated the force exerted by high amplitude waves. For a 200 metre thick iceberg it is assumed that approximately all the wave energy is reflected from the wall of the iceberg. The equation for force per unit length is then

$$F = \tfrac{1}{2}\rho g \alpha^2$$

where ρ is the density of sea water, g is the constant of gravity and α is the amplitude of the incident wave.

6.8 Amplitudes of strain and tilt variations

A mean value, mean amplitude and significant amplitude are calculated for each data sample for the tilt and strain data. Averages for a three month period of these parameters are presented in Figure 6.8.1, as well as minima and maxima over the whole period. For tilt in both directions the average values are given up to the event which caused the surface of the iceberg to drastically change its permanent tilt.

SENSOR	UP-CROSS PERIODS* (SECONDS)			MEAN VALUE (LINE) (M/M OR ARC-MIN.)			MEAN AMPLITUDE (M/M OR ARC-MIN.)			SIGN. AMPLITUDE (M/M OR ARC-MIN.)			MAX. AMPLITUDE (M/M OR ARC-MIN)
	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	MIN.	MEAN	MAX.	
TILTX*	20	40.0	120 ∞	-1.76	0.32	1.42	0.01	0.28	4.48	0.04	1.12	17.93	12.26
TILTY*	20	51.9	120 ∞	3.69	6.09	9.92	0.15	0.43	4.29	0.61	1.72	17.18	17.96
STRAIN	15	26.9	120	11.70×10^{-6}	13.50×10^{-6}	21.81×10^{-6}	0.11×10^{-6}	0.21×10^{-6}	0.31×10^{-6}	0.43×10^{-6}	0.82×10^{-6}	1.23×10^{-6}	7.48×10^{-6}

* UP TO DAY 55 TIME 072949

FIGURE 6.8.1 Results from processing of a three month period of data, from 4/2/79 to 4/5/79. The average tilt in both directions (along and transverse to the main axis of the iceberg) is given up to 24/2/79 in this table, when the average tilt changed significantly.

The average of the mean amplitude of tilt in the y-direction is about twice as large as that for tilt in the x-direction. This confirms the previously mentioned theory that the iceberg tends to align with the long side parallel to large amplitude swell.

Other features of the tilt data have already been commented on.

The strain parameters of interest in Table 6.8.1 are the average of the mean amplitude, and the maximum amplitude occurring during the three month period. These amplitudes correspond to an instantaneous strain, as explained in subsection 2.2. The average mean amplitude is 0.2×10^{-6} and the maximum amplitude recorded in three months is 7.5×10^{-6}. This is substantially smaller than the value quoted in subsection 2.2 from the paper of Goodman, Wadhams and Squire of 8.7×10^{-5}.

6.9 Drift of the mean strain values

It has already been mentioned that the mean strain value is an arbitrary product of characteristics of the strain-meter and the setting up of the instrument. What contains information on the bending response of the iceberg, is the strain amplitude as measured from the mean value of each sample. There is, however, a long term variation of the mean value of the strain, which possibly relates to a plastic deformation of the iceberg.

Rezeroing of the strainmeter occurred frequently, as often as several times a day. Since the rezeroing takes a short time (a few seconds) it usually occurs in between data samples, but if the mean values of the strain for a period of a few days are plotted, the rezeroing is easily seen, and the drift in the mean strain values can be calculated. Before it is concluded that this drift corresponds to a plastic deformation, other explanations should be examined.

The INVAR metal in the wire (rod) strainmeter has a very low expansion coefficient dependent on the temperature variations in the instrument, but if the variations are large enough this would result in a drift in the mean value of the recorded strain.

The mean values of strain (for each data sample) have been plotted for a period of three days (Figure 6.9.1), and the snow temperatures 0.2 metres from the snow surface have been plotted for the same period of time in Figure 6.9.2. A drift in the mean value of the strain can be calculated by summing the 'jumps' in the curve obviously caused by rezeroing of the strainmeter, and averaging over the time period. A result of 0.3×10^{-5} per day is obtained. Since Figure 6.9.2 shows that the temperature in the snow is decreasing during the time period, and since the temperature inside the strainmeter is assumed to follow the snow temperature around the instrument, the expected drift caused by changes in the temperature would be decreasing rather than increasing.

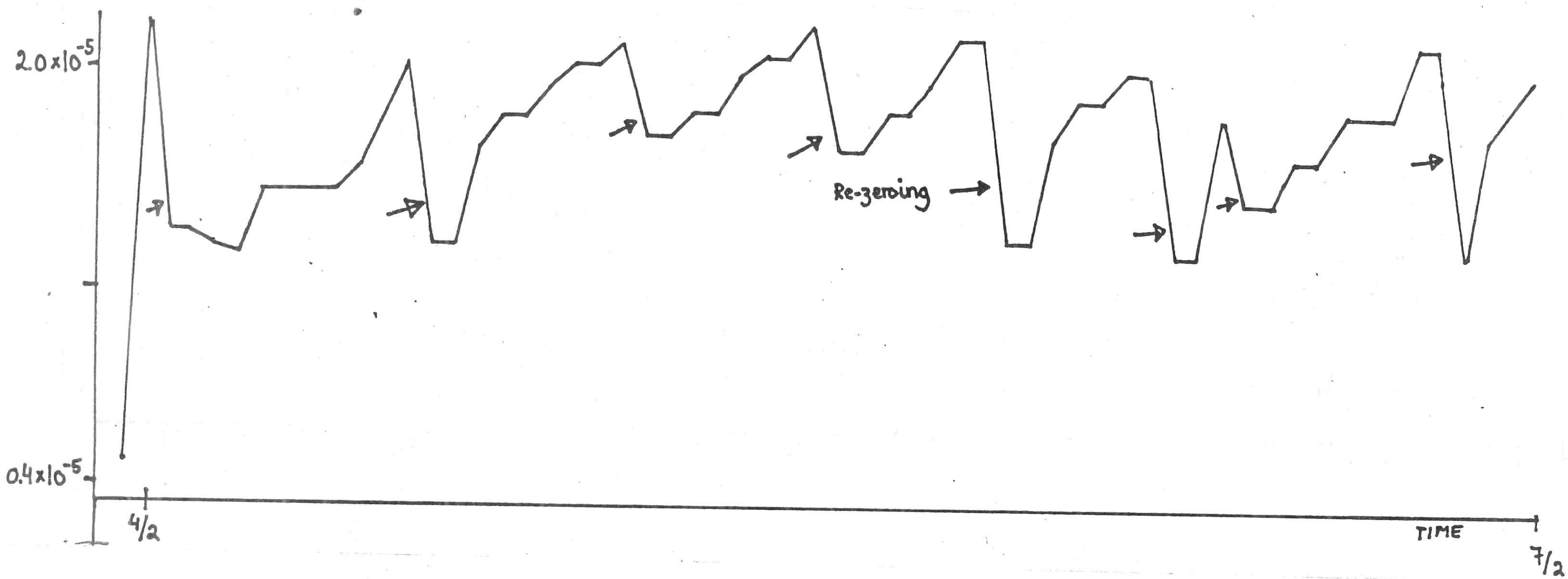

FIGURE 6.9.1 (above) Drift in the mean strain value in the period 4/2//79 to 7/2/79. Rezeroing of the strainmeter shows clearly.

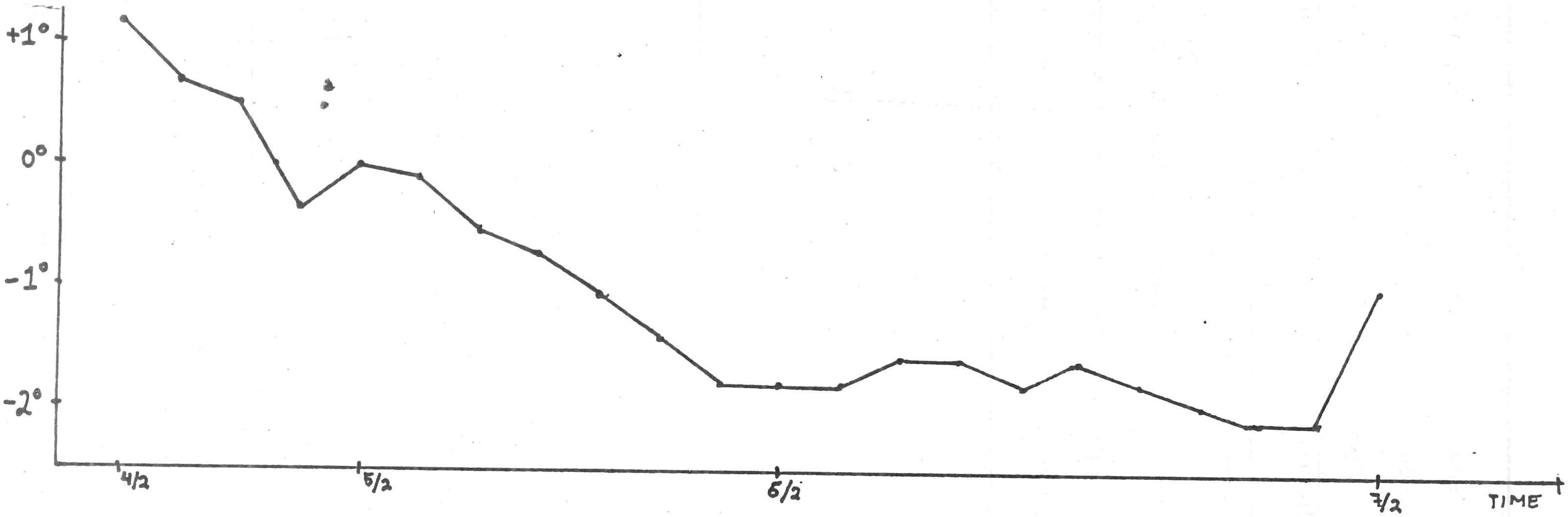

FIGURE 6.9.2 The temperature variations at a depth of 0.2 metres into the snow during the period 4/2/79 to 7/2/79.

Another explanation for the observed drift of the mean value of the strain, could be that the INVAR rod gradually stretched because of its own weight, but it is not expected that this effect is large enough to cause any observed drift in the strain. If, on the other hand, the drift in the mean value of the strain is caused by plastic deformation of the iceberg, the value obtained is close to the critical value quoted in Chapter 2.

Such a large strain rate, which is also calculated for plots from other time periods, could be almost sufficient to cause crevasses to open on the surface of the iceberg.

CHAPTER 7

DISCUSSION

7.1 Comparison with some relevant papers

To evaluate the results obtained in this thesis, it is of interest to compare them with some conclusions reached in other papers. Very few measurements have actually been done on icebergs, but at the Conference on the Use of Icebergs held in Cambridge this year, two other investigations were reported. One additional paper with some theoretical considerations on iceberg equilibrium will also be of interest.

A paper by Goodman, Wadhams and Squire (1980), previously referred to in this thesis, contains results from strain measurements on a tabular iceberg off the East Greenland coast, as well as theoretical calculations on the heaving and bending response of an iceberg to ocean waves. The ice island on which the measurements were made, was 431 by 179 metres in size and 35 metres thick, and a wire strainmeter was used. Vertical heave was measured with an accelerometer and the ambient wave field was measured with a wave buoy. Twenty minute recordings were made, and a Fast Fourier Transform program was used to separate the components of the wave energy spectrum. The results of the analysis showed that the ocean wave field consisted of swell with a peak of 17 seconds, a secondary swell with a peak at 12 seconds and a slight but detectable sea with periods down to 7 seconds. The heave response of the ice island was found to be in response to the longest swell periods, with almost no energy below a period of 14 seconds.

This effect is qualitatively explained in the paper by Goodman, Wadhams and Squire (1980) as follows:

> When a body undergoes oscillating motion in a fluid, hydrodynamic effects on the body will behave as an additional mass for bodily motions (surge, heave and sway) and like an additional moment of inertia for rotations (pitch, roll and yaw). This is known as added mass and is frequency dependent. The body, in responding to the incident wave also used some of the energy to generate out-going waves. This loss is equivalent to a damping of the body's motion, expressed as a damping coefficient. A third effect is that incoming waves are diffracted by the body. A proper approach requires a numerical integration scheme.

It is expected that on a much larger iceberg these effects will be even more important in determining the heave response of the iceberg to the ocean waves. This seems to be in correspondence with the large mean value of the tilt periods found in this thesis.

It is beyond the scope of this discussion to go into the theory of bending response of an iceberg to an ocean wave field as it is described in the paper of Goodman, Wadhams and Squire (1980). The end result is, however, an equation which describes the relationship between surface strain, dimension (length and thickness) of the iceberg and the amplitude and period of an incoming ocean wave. The equation is of such a complexity that it has to be solved numerically. An attempt to solve it for the instrumented iceberg has therefore not been made.

A solution for a 100 metres thick iceberg flexing in response to a 24 second period wave is included in the paper, Assuming a critical surface strain of 8.7×10^{-5} gives a critical amplitude of 2.6 metres which is easily achieved in the Southern Ocean. It should be noted that the theory presented in the paper of Goodman, Wadhams and Squire (1980) does not include effects caused by the large vertical walls of the iceberg, and this introduced an unknown error. The maximum amplitudes of strain found in Chapter 6 is an order of magnitude smaller, but this may indicate that for an iceberg of thickness over 200 metres, the effect of the large vertical walls is important and should be included in the calculations.

It should again be pointed out that the critical strain of 8.7×10^{-5} used in the paper of Goodman, Wadhams and Squire (1980) was obtained by assuming a perfect ice body, and that the existence of surface cracks and crevasses will lower the value of critical strain substantially.

The other experiment which measured surface strain on an iceberg in the Antarctic, was reported by Foldvik, Gammelsrød and Gjessing (1980). Flexural movement was measured by using a theodolite and the mutual displacement of stakes which were driven into the snow over a distance of 1 kilometer. Tilting movement was also measured and the maximum reported displacement of the edge of the iceberg was ± 0.40 metres. Unfortunately few details of the dimensions of the iceberg (a thickness of 120 metres is reported) or the manner of execution of the measurements are given. If it is assumed that the iceberg is 1000 metres in length, an amplitude of oscillation of ± 0.40 metres corresponds to an angular displacement of 2.75 arc-minutes as measured from the centre of the iceberg. This is in accordance with the measured mean amplitudes on the instrumented iceberg, which range from 0.15 to 4.29 arc-minutes. (Table 6.8.1). Foldvik, Gammelsrød and Gjessing report that no detectable strain was measured over 1000 metres and that the accuracy of the system was 1 millimetre over 1000 metres. This corresponds to an accuracy of the strain of 10^{-9}.

An explanation as to why strain was not measured could be that the stakes were not driven into the ice (approximately 2 metres below the surface of the iceberg), but were fastened in the snow-ice transition layer, and that the strain experienced by the iceberg was not transferred to this layer.

Finally it will be of interest to compare some of the general results in the paper presented by Nye and Potter (1980)** on iceberg stability, with the sudden changes in mean values of tilt previously described in this paper. (Subsection 6.2).

As an iceberg melts, the resulting change of shape can cause it to list gradually or to become unstable and suddenly topple over. Catastophe theory is used in the analysis of stability of various shapes of icebergs, and the main point of the paper is to demonstrate the usefulness of catastrophe theory when analysing equilibrium positions of an iceberg.

The paper concludes that icebergs with certain near-square cross-sections can readily topple over, and that icebergs with trapezoidal shapes, larger below the water line, are significantly less stable than those with a rectangular shape.

Thus the analysis made by Nye and Porter could explain the frequent changes in the mean tilt of the instrumented iceberg, and it can be concluded that substantial melting at the bottom and the sides of the iceberg constantly changes its equilibrium position in the ocean water.

7.2 Future research

During the analysis of the data from the instrumented iceberg in the Weddell Sea, lack of information on certain topics, and some unfortunate characteristics of the data sampling have been the most serious obstacles to overcome.

A survey of some of the existing literature on ocean waves in the Southern Hemisphere shows that little information is available on long period swell in the waters around Antarctica.

If reliable results are to be obtained from iceberg research it is important to measure periods, wave heights and frequency of occurrence of long swell in this area. It would also be interesting to obtain wave spectra in different seasons to see if any changes in the ocean wave field would be of importance to the breaking up of icebergs.

More exact information on wave spectra would also be of interest in solving such problems as the breaking up of the fast ice around Antarctica in spring.

The data obtained from the instrumented iceberg are recorded digitally with a 6 second filter and a record length of 2 minutes. This prevents the use of a Fast Fourier Transform method of analysis, and limits the use of the statistical hand method which is utilized. However, since the satellite passages only provide approximately 10 minutes of receiving time, the designers of the experiment had the choice between enough parameters measured to cover the three important aspects of the iceberg's behaviour in the environment (dynamical, thermodynamical and mechanical), or fewer parameters and longer data samples of the strain and tilt.

For several reasons the former alternative was chosen.

As an addition to the considerable amount of data present from the instrumented iceberg, it would be of interest to perform another investigation of icebergs in the Antarctic, where strain would be measured in several directions over a much longer period of time (twenty minutes is suggested) along with tilt and the ocean wave spectrum. This experiment would be a valuable way of controlling the accuracy of the overall picture obtained from the data measured on the instrumented iceberg.

CHAPTER 8

CONCLUSION

The previous chapters have given the background for and the results obtained from an experiment measuring the mechanical behaviour of a tabular iceberg in the Antarctic. The experiment was constructed to yield definite answers to the questions of when, how and why icebergs break up. The success of the experiment could be judged by the success in answering these questions.

As to the problem of when icebergs fracture, it is first necessary to establish the causes of fracture. It has been argued in this thesis that the iceberg's flexure response to long period waves is one of the causes of iceberg deterioration, and that long term plastic deformation of the iceberg may be another important factor. Little is known about how icebergs break up on a large scale, that is, apart from small scale breaking at the edges due to melting. It is probable that the iceberg fractures along already existing crevasses. So far, the analysis of the data from the experiment has confirmed the existing theories of iceberg fracture.

What is not clear, however, is how long an iceberg is expected to survive in the waters around Antarctica. From the statistical method of analysis, it is possible to calculate a 'design amplitude', that is, the largest expected strain amplitude within a specified time interval. Using this method and comparing with statistical counts on iceberg sizes, it might be possible to predict the duration or the 'life expectancy' of the iceberg. Unfortunately the method of data sampling and the shortness of the data sampled (2 minutes every 3 hours) make it difficult to assume that the data samples are representative for the time interval between them, and the method can therefore not be used to predict 'design amplitudes'.

However, a number of important conclusions can be reached on the basis of the analysis of the data from the instrumented iceberg:

(1) The strainmeter is functioning satisfactorily over a long period of time, and gives a good estimate of variations of surface strain with the bending of the iceberg in the ocean wave field.

(2) The performance of the tilt meter is somewhat more doubtful over a long period of time, since only a slight listing of the iceberg may cause it to go off scale. It would have been advantageous to have a rezeroing device on the tiltmeter.

(3) Although the strain and tilt sensor sampling are limited by the sampling of other parameters, these are important to form an overall picture of the response of the iceberg. As an experiment that is designed to run for a long period of time it is not necessary to sample the tilt and strain response in detail. However, it is important that short term investigations are made, and the total energy spectra of the ocean wave field, the tilt response and the surface strain are obtained.

(4) The amplitudes of surface strain were about an order of magnitude less than the critical strain value adopted by Goodman, Wadhams and Squire (1980), but this value was obtained for a flawless ice body, and the existence of cracks in the surface of the iceberg may decrease the critical 'instantaneous' surface strain to near the observed amplitudes of strain.

(5) If the observed drift in mean strain values is due to a plastic deformation of the iceberg, then this creep is very close to observed critical values of strain rate necessary to fracture ice at that temperature (Holdsworth, 1969).

If a general mechanism for iceberg fracture were to be outlined, it is tempting to suggest that cracks and crevasses appear in the iceberg surface caused by plastic deformation reaching a critical limit, and that the flexure of the iceberg in the ocean wave field further fracture the iceberg caused by a high value of the 'instantaneous' elastic strain.

APPENDIX A

Results from statistical analysis of tilt and strain data samples from the period 4/2/79 to 27/2/79.

TILT ALONG MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
40.00	1.87	7.50
40.00	1.87	7.50
30.00	1.02	4.08
30.00	1.02	4.08
40.00	6.98	27.93
30.00	3.41	13.66
30.00	3.41	13.66
60.00	137.72	550.90
20.00	63.61	254.43
20.00	63.61	254.43
24.00	63.61	254.43
40.00	57.32	229.28
40.00	57.32	229.28
120.00	57.23	228.94
120.00	57.23	228.94
24.00	57.41	229.62
24.00	57.41	229.62
40.00	56.47	225.89
40.00	56.47	225.89
40.00	56.47	225.89
40.00	56.47	225.89
60.00	57.15	228.59
60.00	2.12	8.50
60.00	2.12	8.50
120.00	133.42	533.69
40.00	103.93	415.70
30.00	103.07	412.28
30.00	103.07	412.28
30.00	3.75	15.01
30.00	3.75	15.01
24.00	1.96	7.86
40.00	2.12	8.50
40.00	2.12	8.50
40.00	2.21	8.84

TILT ALONG MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE (x10⁻² ARC-M.)	SIGNIFICANT AMPLITUDE (x10⁻² ARC-M.)
40.00	2.04	8.15
40.00	2.04	8.15
40.00	152.12	608.48
60.00	9.48	37.94
30.00	3.75	15.01
30.00	3.75	15.01
30.00	2.55	10.22
30.00	2.55	10.22
30.00	60.33	241.32
30.00	2.04	8.15
30.00	2.04	8.15
60.00	1.96	7.84
30.00	1.87	7.50
30.00	0.94	3.77
30.00	2.13	8.53
24.00	1.28	5.11
24.00	1.29	5.11
30.00	1.28	5.11
24.00	1.28	5.11
30.00	1.28	5.11
40.00	1.28	5.11
30.00	2.64	10.56
30.00	2.64	10.56
40.00	1.71	6.83
40.00	1.71	6.83
40.00	2.64	10.56
30.00	85.01	340.05
30.00	85.01	340.05
30.00	84.08	336.31
40.00	84.16	336.63
60.00	84.16	336.63
40.00	84.16	336.63
40.00	84.16	336.63
40.00	3.68	14.70

TILT ALONG MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
40.00	3.68	14.70
40.00	7.60	30.39
40.00	7.60	30.39
40.00	3.86	15.46
40.00	3.86	15.46
60.00	3.86	15.46
60.00	3.86	15.46
60.00	3.86	15.46
40.00	3.25	13.00
40.00	3.25	13.00
30.00	2.32	9.27
60.00	3.34	13.35
60.00	3.34	13.35
40.00	2.40	9.61
40.00	2.40	9.61
40.00	3.34	13.35
30.00	3.50	14.00
30.00	3.50	14.00
30.00	2.47	9.87
30.00	2.47	9.87
40.00	2.30	9.19
30.00	2.30	9.19
30.00	2.30	9.19
30.00	2.30	9.19
40.00	2.30	9.19
60.00	2.30	9.19
30.00	1.29	5.14
30.00	1.29	5.14
40.00	2.30	9.19
40.00	2.30	9.19
30.00	1.36	5.45
40.00	3.83	15.33
40.00	3.83	15.33
30.00	2.81	11.25
30.00	2.81	11.25

TILT ALONG MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
30.00	1.80	7.20
24.00	2.23	8.91
24.00	2.23	8.91
40.00	19.59	78.36
40.00	19.59	78.36
120.00	448.33	1793.32
40.00	96.52	386.10

TILT TRANSVERSE TO MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
120.00	7.60	30.39
60.00	167.85	671.38
30.00	429.65	1718.61
40.00	6.57	26.26
40.00	5.63	22.53
40.00	5.63	22.53
40.00	3.50	14.00
40.00	3.50	14.00
120.00	3.67	14.67
120.00	3.67	14.67
60.00	10.42	41.67
120.00	9.56	38.25
120.00	11.45	45.80
40.00	5.72	22.87
40.00	5.72	22.87
120.00	332.13	1328.51
40.00	5.63	22.53
40.00	5.63	22.53
60.00	5.72	22.87
120.00	7.60	30.39
120.00	7.60	30.39
60.00	19.22	76.89
60.00	19.22	76.89
40.00	7.68	30.73
40.00	9.56	38.25
40.00	9.56	38.25
40.00	3.75	15.01
40.00	14.26	57.05
40.00	14.26	57.05
60.00	7.60	30.39
40.00	14.35	57.39
40.00	14.35	57.39
40.00	6.57	26.26
120.00	65.30	261.21

TILT TRANSVERSE TO MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE (x10⁻² ARC-M.)	SIGNIFICANT AMPLITUDE (x10⁻² ARC-M.)
30.00	7.60	30.39
120.00	8.54	34.16
120.00	8.54	34.16
40.00	7.60	30.39
40.00	358.66	1434.65
24.00	7.60	30.39
40.00	13.33	53.31
120.00	323.16	1292.65
30.00	9.48	37.94
30.00	7.61	30.42
40.00	6.57	26.26
40.00	6.57	26.26
120.00	76.95	307.79
20.00	5.63	22.53
20.00	5.63	22.53
40.00	17.08	68.33
40.00	17.08	68.33
40.00	7.61	30.42
40.00	7.61	30.42
30.00	3.67	14.67
40.00	9.48	37.94
40.00	9.48	37.94
40.00	5.63	22.53
30.00	7.60	30.39
30.00	5.72	22.87
40.00	13.33	53.31
40.00	13.33	53.31
40.00	277.36	1111.42
30.00	8.53	34.12
30.00	7.60	30.39
30.00	7.60	30.39
60.00	12.38	49.53
60.00	12.38	49.53

TILT TRANSVERSE TO MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
30.00	5.72	22.87
30.00	5.72	22.87
30.00	5.63	22.53
30.00	7.60	30.39
40.00	10.50	41.98
40.00	5.63	22.53
40.00	5.63	22.53
40.00	5.72	22.87
60.00	3.75	15.01
60.00	2.38	9.53
40.00	5.80	23.19
40.00	3.33	13.31
40.00	3.33	13.31
40.00	2.38	9.53
40.00	2.38	9.53
120.00	5.63	22.53
40.00	5.72	22.87
40.00	5.72	22.87
40.00	7.60	30.39
40.00	8.53	34.12
60.00	4.10	16.41
60.00	4.10	16.41
40.00	3.83	15.33
40.00	3.83	15.33
60.00	5.80	23.19
60.00	5.72	22.87
60.00	5.72	22.87
30.00	5.63	22.53
20.00	2.65	10.59
20.00	2.65	10.59
40.00	7.60	30.39
40.00	7.60	30.30
60.00	33.17	132.69
40.00	3.75	15.01

TILT TRANSVERSE TO MAIN AXIS.

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-2}$ ARC-M.)	SIGNIFICANT AMPLITUDE ($\times 10^{-2}$ ARC-M.)
40.00	5.72	22.87
30.00	2.73	10.94
30.00	2.73	10.94
30.00	2.73	10.94
30.00	5.72	22.87
40.00	8.53	34.12
40.00	5.63	22.53

STRAIN (ALONG MAIN AXIS)

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-8}$ m/m)	SIGNIFICANT AMPLITUDE ($\times 10^{-8}$ m/m)
30.00	23.26	93.04
40.00	17.73	70.92
40.00	17.73	70.92
20.00	17.11	68.45
40.00	278.09	1112.35
24.00	20.85	83.41
20.00	12.36	49.45
20.00	12.36	49.45
20.00	25.36	101.42
20.00	25.36	101.42
30.00	16.96	67.85
40.00	15.48	61.91
24.00	24.50	97.98
30.00	15.56	62.24
30.00	15.56	62.24
24.00	16.95	67.81
20.00	20.06	80.25
20.00	20.06	80.25
30.00	22.56	90.24
30.00	20.92	83.69
30.00	20.92	83.69
30.00	15.48	61.91
24.00	22.24	88.96
24.00	22.24	88.96
30.00	19.91	79.63
30.00	19.91	79.63
30.00	21.70	86.79
30.00	19.37	77.48
30.00	19.37	77.48
24.00	28.78	115.14
30.00	23.18	92.71
30.00	23.18	92.71
20.00	26.44	105.78
20.00	26.44	105.78

STRAIN (ALONG MAIN AXIS)

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-8}$ m/m)	SIGNIFICANT AMPLITUDE ($\times 10^{-8}$ m/m)
24.00	15.48	61.93
20.00	15.47	61.90
20.00	15.47	61.90
24.00	20.15	80.59
24.00	20.15	80.59
17.14	19.28	77.14
20.00	18.52	74.06
20.00	18.52	74.06
30.00	10.81	43.24
30.00	10.81	43.24
24.00	18.67	74.68
24.00	18.67	74.68
30.00	25.51	102.05
20.00	21.62	86.49
20.00	21.62	86.49
20.00	18.52	74.66
20.00	18.52	74.66
24.00	21.01	84.03
24.00	21.01	84.03
24.00	21.01	84.03
24.00	15.40	61.60
24.00	15.40	61.60
24.00	30.89	123.54
30.00	16.26	65.04
30.00	16.88	67.53
20.00	20.07	80.28
20.00	20.07	80.28
24.00	17.12	68.48
24.00	17.12	68.48
24.00	18.51	74.04
30.00	72.57	290.28
30.00	21.71	86.83
30.00	21.71	86.83

STRAIN (ALONG MAIN AXIS).

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-8}$ m/m)	SIGNIFICANT AMPLITUDE ($\times 10^{-8}$ m/m)
24.00	17.66	70.62
24.00	17.66	70.62
30.00	14.79	59.14
30.00	22.32	89.29
30.00	20.93	83.71
24.00	23.87	95.50
24.00	23.87	95.50
20.00	21.62	86.49
40.00	17.03	68.13
20.00	20.15	80.59
24.00	19.37	77.48
40.00	21.62	86.49
40.00	21.62	86.49
20.00	24.73	98.93
20.00	24.73	98.93
24.00	17.81	71.24
20.00	16.17	64.70
120.00	110.23	440.93
40.00	18.59	74.37
40.00	339.69	1358.77
20.00	21.70	86.78
20.00	20.92	83.69
20.00	20.92	83.69
20.00	292.48	1169.91
17.14	24.89	99.57
17.14	24.89	99.57
24.00	22.24	88.98
24.00	22.24	88.98
20.00	19.29	77.16
20.00	25.67	102.68
20.00	25.67	102.68
30.00	19.37	77.48
30.00	19.37	77.48

STRAIN (ALONG MAIN AXIS).

MEAN UP-CROSS PERIOD (SECONDS)	MEAN AMPLITUDE ($\times 10^{-8}$ m/m)	SIGNIFICANT AMPLITUDE ($\times 10^{-8}$ m/m)
24.00	18.67	74.68
24.00	18.67	74.68
40.00	20.15	80.59
30.00	22.79	91.15
30.00	22.79	91.15
24.00	256.77	1027.07
24.00	14.54	58.18
20.00	15.40	61.60

APPENDIX B

A STANDARD METHOD OF STATISTICAL ANALYSIS OF SHORT DATA SAMPLES

This appendix contains a more detailed description of the statistical method of analysis used in this thesis. An outline of the method is also given in Chapter 5.

The graph trace of one data sample is considered as a part of a random function, f, given by the sum

$$f(t) = \Sigma C_n \cos(\omega_n t + \delta_n)$$

where the frequencies ω_n are densely distributed in the interval (O,) and the phases δ_n are random and uniformly distributed in (O, 2π). The amplitudes C_n are such that in any small interval of frequency $d\omega$

$$\sum_{\omega_n = \omega}^{\omega + d\omega} \tfrac{1}{2} C_n^{\,2} = S(\omega)d\omega$$

where $S(\omega)$ is the energy spectrum of f(t), and continuous. The nth moment of the energy spectrum is defined by

$$m_n = \int_0^{\infty} \omega^n S(\omega)d\omega$$

and the mean square amplitude is

$$E = m_o$$

utilizing that the functions f(t), f'(t) and f"(t) may be considered random variables, and that they therefore have a joint normal distribution, a probability function Z for a maximum of f(t), is derived by integrating over regions of negative f" and zero f'

The probability density function is

$$p(\eta) = \frac{1}{\sqrt{2\pi}} \quad \varepsilon e^{-\frac{1}{2}\left(\frac{\eta}{\varepsilon}\right)^2} + \sqrt{1+\varepsilon^2} \; \eta e^{-\eta^2/2} \int_{-\infty}^{\eta/\varepsilon\sqrt{1-\varepsilon^2}} e^{-\frac{1}{2} x^2} dx$$

where $\eta = {}^{z}/E^{\frac{1}{2}}$ and ε, the band width parameter is a measure of the range of frequencies present, given by

$$\varepsilon = \frac{m_o m_4 - m_2^2}{m_o m_4}$$

The probability density function reduces to the Rayleigh distribution as ε tends to zero.

The probability that a given maximum shall exceed $xE^{\frac{1}{2}}$, is

$$q(x) = \int_x^\infty p(z)dz$$

The largest of N_c crests (N_c = number of crests) is less than x if and only if each of the N_c crests is less than x.

If the crests may be considered independent, the cumulative distribution function of the height Z_1 of the largest of N_c crests, is

$$P_{N_c}(x) = (1 - q(x))^{N_c}$$

The mean of this distribution, is

$$\overline{Z}_1 = E^{\frac{1}{2}} \sqrt{2\theta} \quad (1 + \tfrac{1}{2} A_1 \theta^{-1} - \tfrac{1}{8} A_2 \theta^{-2} + \tfrac{1}{16} A_3 \theta^{-3} + \ldots)$$

where

$$\theta = \ln (N_c \sqrt{1 - \varepsilon^2})$$

$$A_1 = 0.5772$$

$$A_2 = 1.9781$$

$$A_3 = 5.4449$$

The distribution function of Z_2, the height of the second highest of N_c crests, is derived similarly, and the mean value of Z_2 is obtained as

$$\bar{Z}_2=E^{\frac{1}{2}}\sqrt{2\theta}\ (1-\tfrac{1}{2}(1-A_1)\theta^{-1}+\tfrac{1}{8}(2A_1-A_2)\theta^{-2}-\tfrac{1}{16}(3A_2-A_3)\theta^{-3}+\ \ldots)$$

$E^{\frac{1}{2}}$ can now be estimated, provided ε, Z_1 and Z_2 are known.

To find Z_1 and Z_2, the trace is assumed to be statistically symmetrical about its mean value. Therefore A and C (highest crest and lowest trough) are both samples of the random variable Z_1 and the sample mean $\frac{1}{2}(A + C)$ is the best estimator of Z_1. Similarly $\frac{1}{2}(B + D)$ is the best estimator of Z_2 (B and D is the second highest crest and lowest trough respectively). It should be noted that these sums are not dependent on the position of the zero line drawn in by the analyst, so long as it is parallel to the true mean line.

It may be shown that the bandwidth is

$$\varepsilon^2 = 1 - (1 - 2r)^2$$

where r is the proportion of negative maxima in the record.

Any difference between N_c and N_z (where N_z equals number of zero up-crossings) must be due to either positive minima or negative maxima (relative to the mean line).

$N_c - N_z$ = number of positive minima and negative maxima

= 2 (number of negative maxima)

since the amplitudes are assumed statistically symmetrical.

Proportion of negative maxima

$$r = \tfrac{1}{2}\,(1 - {}^{N_z}/_{N_c})$$

$$\varepsilon^2 = 1 - ({}^{N_z}/_{N_c})^2$$

$$\theta = \ln N_z$$

The root mean square amplitude is obtained by omitting all terms after the second term

$$E_1^{\frac{1}{2}} = \frac{A+C}{2\sqrt{2\theta}}\,(1 + \tfrac{1}{2}A_2\,\theta^{-1} - \frac{1}{8}\,A_2\,\theta^{-2})^{-1}$$

$$E^{\frac{1}{2}} = \frac{B+D}{2\sqrt{2\theta}}\,(1 + \tfrac{1}{2}(1-A\ )\theta^{-1} + \frac{1}{8}(2A_1 - A_2)\theta^{-2})^{-1}$$

and

$$E^{\frac{1}{2}} = \frac{E_1^{\frac{1}{2}} + E_2^{\frac{1}{2}}}{2}$$

A detailed description of this statistical method, including the deriving of a significant amplitude of the sample, and maximum expected amplitudes for a given period of time, is given by Tann (1976). The paper by Tann is a summary of earlier works by Cartwright and Longuet-Higgins (1956), Draper (1963) and Tucker (1961).

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