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PROCEEDINGS
OF THE
UK DATA BUOY (DB1) SYMPOSIUM

A Compendium of the papers presented at the symposium, organised jointly by the Institute of Oceanographic Sciences and the Society for Underwater Technology, held at Wormley on the 23rd November 1976

IOS REPORT NO 44

1977

INSTITUTE OF
OCEANOGRAPHIC
SCIENCES

NATURAL ENVIRONMENT RESEARCH COUNCIL

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INSTITUTE OF OCEANOGRAPHIC SCIENCES

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Institute of Oceanographic Sciences
Wormley,
Godalming,
Surrey GU8 5UB

PREFACE

These proceedings were issued originally as preprints for use by the participants at the UK Data Buoy (DB1) Symposium held at the Institute of Oceanographic Sciences, Wormley, in conjunction with the Society for Underwater Technology, on the 23rd November 1976 . . It was thought that selected papers would be published separately at a later date, but as this now appears unlikely, and considerable interest has been shown in the meeting, it has been decided to issue the proceedings in this form to give them a wider distribution.

Proceedings of the

UK DATA BUOY (DB1) SYMPOSIUM

Held at the Institute of Oceanographic Sciences
Wormley, Surrey

on the 23rd November 1976

Sponsored by the Society for Underwater Technology
and the Institute of Oceanographic Sciences

Background to the DB1 data buoy project J.S.M. RUSBY
(Institute of Oceanographic Sciences)

UK National data buoy DB1 project review 1974/76 R.F. KELLEY
(Hawker Siddeley Dynamics Limited)

DB1 on-board data handling commissioning and in-service experience J. WALL
(Hawker Siddeley Dynamics Limited)

Shore station hardware and software design and operation J. BUTCHER
(E.M.I. Electronics Limited)

The Piccolo telemetry system on DB1 J.D. RALPHS
(Communications Engineering Dept. Foreign and Commonwealth Office)
and D. BILLINGS
(Racal Limited)

Experience with the thermo-mechanical generator as a marine electrical power source E.H. COOKE-YARBOROUGH
(Atomic Energy Research Establishment)

Motions and mooring forces of the buoy R.M. CARSON
(Institute of Oceanographic Sciences)

The buoy as a directional wave sensor J.A. EWING and C.H. CLAYSON
(Institute of Oceanographic Sciences)

An assessment of the meteorological sensors on DB1 H.A. DOUGLAS
(Meteorological Office) and M. BADER

An intercomparison of the data buoy current meters and near-surface drifting floats P.G. COLLAR
(Institute of Oceanographic Sciences)
(MAFF. Fisheries Laboratory, Lowestoft) J.W. RAMSTER

Data Buoy DB1 - Harwell Acoustic Current Meter type 3244 W.R. LOOSEMORE
and F.H. WELLS
(Atomic Energy Research Establishment)

UK DATA BUOY (DB1) SYMPOSIUM - 23rd NOVEMBER 1976

BACKGROUND TO THE DB1 DATA BUOY PROJECT

by

J.S.M. RUSBY

Institute of Oceanographic Sciences

1. THE FEASIBILITY AND DESIGN STUDY

Early in 1971 the Standing Committee on Ocean Data Stations (SCODS) of the Natural Environment Research Council (NERC) identified the likely UK future need for data buoys. and proposed that NERC should support a feasibility and design study for a prototype UK buoy. However, NERC felt that it would be more appropriate if the then Committee on Marine Technology (CMT) of the Department of Trade and Industry should handle the project. This was agreed and in June 1971 CMT asked its Marine Technology Support Unit (MATSU) at Harwell to make a quick study of the requirements and report back on what action should be taken. This report was issued two months later. Its main recommendation was that a buoy should be built to act as a vehicle for the development of suitable unattended sensing instruments, telemetering facilities and power supplies, and should also be, in effect, a prototype for any further buoy developments. CMT asked the Institute of Oceanographic Sciences (IOS) to undertake the feasibility and design study for this buoy, this was agreed, and the study commenced in January 1972.

An informal Advisory Group representing potential users and other interested bodies was set up, and this group met three times during the period of the study. It consisted of members from the:

Department of Trade and Industry,
Meteorological Office,
Ministry of Agriculture, Fisheries and Food - Fisheries Division
- Land Drainage Division
Ministry of Defence (Navy)
Trinity House Lighthouse Service.

and the

Institute of Coastal Oceanography and Tides (now part of IOS).

The study was completed by Dr. Collar, Mr. Tucker and their team towards the end of 1972. Their report, entitled 'Data buoy (DB1) project feasibility and design study', is a comprehensive document covering every aspect of such a project, from details of the preferred data handling and timing schemes to ensure the necessary flexibility for the buoy's initial role as a test platform, through to the need for continuing commercial involvement in this new field. The bulk of the report was concerned with the proposed layout of the buoy hull, its sensors, power supplies and data handling system, and also with the unmanned shore station which would include the necessary software to control the data checks, data storage and the local and remote retrieval systems. In addition to the report a draft specification was written for use by the Department of Trade and Industry when tenders were requested.

After a careful analysis of the relative merits and costs of different buoy hulls, including model trials, the report proposed that a steel discus hull should be used, big enough to allow straightforward access to a two-ton payload. The Americans had shown that a large discus hull could be boarded in moderate weather, and frequent boarding would be necessary during the test phase. It was also hoped that it would be possible to collect directional wave data using the wave following characteristics of such a design. The hull would be held by a three-point chain mooring to limit rotation and to allow cables to be connected to additional underwater sensors. The study also identified the sensor, power supply and radio telemetry needs, some of which would be satisfied by proven equipment and others by recent developments. Three of the new developments highlighted by the report were the Harwell gas-fired Stirling cycle generator and acoustic flow meter, and the multi-tone HF Piccolo telemetry system developed by the Diplomatic Wireless Service for long range communication to UK embassies. Certainly the most important development has been the advent of COS/MOS (Complimentary-Symmetry Metal-oxide Semiconductor) circuit technology, providing data handling circuits with very low current consumption and high reliability. The report proposed that all data handling circuits should use this technology, so that coupled with sensor power switching it should be possible to service the sensors, with 50 or more data channels,and the transmitter from a power source of only 20 watts.

The report emphasised the importance of choosing a main contractor who would be responsible for the development and production of the hull, data handling system, power supplies, certain standard sensors and the shore station, and who would also be responsible for the long term maintenance and further development of these systems. It was hoped in this way to establish a UK commercial capability in this field by using the project initially as a development 'bench'.

2. CONSTRUCTION

In January 1974 the main contract was awarded by the Ship and Marine Technology Requirements Board (SMTRB) of the Department of Industry to Hawker Siddeley Dynamics Limited on behalf of the successful consortium Seatek Limited, formed to reply to the above specification. In this consortium Hawker Siddeley Dynamics Limited managed the project and were also responsible for the buoy data handling system and power supplies, EMI Electronics Limited were responsible for the radio telemetry link and shore station and R and H Green and Silley Weir Limited were to design and build the buoy hull and mast with all fittings and wiring. Additional contracts were awarded by SMTRB to Racal Limited to design and build the Piccolo telemetry equipment under the guidance of the Diplomatic Wireless Service and EMI Limited, and to the Atomic Energy Research Establishment (AERE) at Harwell to provide a 'marinised' thermo-mechanical generator (TMG) and acoustic flow meter. The Meteorological Office agreed to provide the meteorological sensors, and the MAFF Fisheries Laboratory, Lowestoft, the site for the shore station as well as a contribution towards the development of oceanographic sensors by IOS. The value of the main contract awarded in January 1974 by SMTRB was for some £250K and the subsidiary contracts totalled approximately £150K. In addition, as part of the newly constituted Rosthchild customer/contractor relationship IOS was commissioned by the Department of Industry to oversee the technical side of the construction and test phases, as well as being asked to develop and provide certain sensors for the project.

From the contributions to this Symposium you will be able to glean the main mechanical, electronic and software considerations which went into the design and construction of the buoy and its shore station. Mr. Kelley of Hawker Siddeley Dynamics, was project manager and quarterly progress meetings were held during the construction phase with Dr. Lusher of the Department of Industry and the many different Government and commercial bodies involved. These were effective and enjoyable meetings with a minimum of bureaucracy and a maximum of creativity.

The buoy hull, in a partially fitted out state, was launched in June 1975 from the Blackwall yard of R and H Green and Silley Weir Limited and towed by a Trinity House vessel to Lowestoft. At Lowestoft the buoy was completed and commissioned in conjunction with the shore station at the nearby Fisheries Laboratory. Commissioning the systems took longer than expected, and this reflected the problems of integrating the electrical supply, sensor timing and data conversion needs of the Meteorological Office, AERE, EMI/Racal and IOS with the heart of the buoy - the power supply, timing and data handling systems provided by HSD. Considerable effort was also expended in the shore station, aligning the identification and synchronising circuits in the Piccolo demodulators, and completing and checking some 40 control programmes for the PDP11 computer and its peripheral equipment.

3. TEST PHASE

The buoy was towed out by Trinity House at the end of November 1975 and moored to a three-point chain mooring 3 miles off the Suffolk coast in position 52° 23.8'N, 1° 48.2'E (see Figure 1). During 1976 it has remained at this site so that we can check the performance of its equipment and make any necessary modifications, carry out sensor evaluation trials and develop underwater data retrieval techniques.

During the course of this Symposium you will be hearing about some of the work carried out during this period. It has been a very valuable phase when each contributor has been able to take a long hard look at his contribution to a prototype system, without being too circumscribed by immediate operational considerations. Due to its present role as a development platform it is considerably more sophisticated than a purely operational buoy would need to be, for example it can accommodate 90 data channels with the option of accepting analogue, frequency-modulated or parallel binary sensor signals to a resolution of 1 part in 10^3. It has two power supplies so that in the event of a failure of the prototype thermo-mechanical generator, air-depolarized batteries come on load. Apart from monitoring many housekeeping and event channels it telemeters seven meteorological and seven oceanographic and buoy motion parameters routinely, and during particular trials many more channels may be in use. Something of this sophistication can be seen in Figure 2 which shows the main features of the buoy design and lists those responsible for its various components.

It may be useful to summarise the main lessons learnt on reliability from this test phase. Since the telemetry was fully commissioned in February 1976, 155 days of data have been recorded on the completed magnetic tapes from a possible 250 days. That is a 62% recovery of data. A major part of this loss occurred during July and August when long periods of easterly winds made it difficult to complete the servicing of a faulty transmitter on the buoy. Part of the loss is also attributable to shore station debugging problems and component failures, either in the computer software or hardware, or in the receiving Piccolo demodulators. During this period we have also had two primary sensor failures: an encoding compass had to be replaced in April and the anemometer unit in September. From these and other more minor events we can learn the following lessons:

1. That it is important to include more redundancy in the primary equipment on an operational buoy (the compass was duplicated but not the transmitter and anemometer).
2. If an operational shore station is to be 'unmanned' then comparable reliability standards to that of the buoy system must be included in the initial design and build standards.

Both of these requirements will increase the system cost significantly but such costs will be negligible in the long term compared with the value of lost data and the cost of service ship time. In an operational shore station there should also be some limited capacity raw data recording facility as far 'upstream' as possible, so that in the event of a 'downstream' computer or storage failure data is not lost while repairs are being effected. Again in an operational system it is self evident that servicing contracts must be very carefully drawn-up with the main sub-contractors so that the failure of any piece of equipment in the chain ensures a fast servicing response from that supplier. In this project we have lost many days of data through inadequate servicing agreements with certain sub-contractors. This is in spite of the fact that many items of essential equipment were duplicated.

A number of components on the buoy have an impressive record for reliability during the 1976 test period. Notable amongst these is the timing and data handling system, servicing 90 channels every hour and a 20 minute-log subroutine every 3 hours for directional wave analysis. Since commissioning there has been only one central component failure in this system which includes over 100 circuit boards, due to the care taken in the design and construction of the circuit boards, electronic cases, connectors and harnesses. Another component which has worked outstandingly well is the acoustic current meter, providing hourly vector-averaged values continuously for the past year through all sea conditions. This likewise reflects the standard of care and thought in the original study and in the design and construction of the individual parts: the transducers, spars and processing circuits. The heave, pitch and roll sensors built by Datawell have also worked faultlessly, providing raw data every 3 hours for subsequent directional wave spectral analyses. We have also obtained a great deal of information on mooring loads from the specially built underwater load cells which continue to provide data after a year in the sea.

We hope that the work reported in this Symposium has shown the value of this trial period in developing and testing new equipment and new concepts in a working marine environment. We are all very conscious of the fact that to place an unmanned data station far from land, subject to storm stress and the slow ravages of sea water and salt-laden air, requires the greatest care in detailed design and in the choice of materials and construction techniques in every part. The name of the game is 'reliability', and at sea that is only achieved by taking infinite trouble.

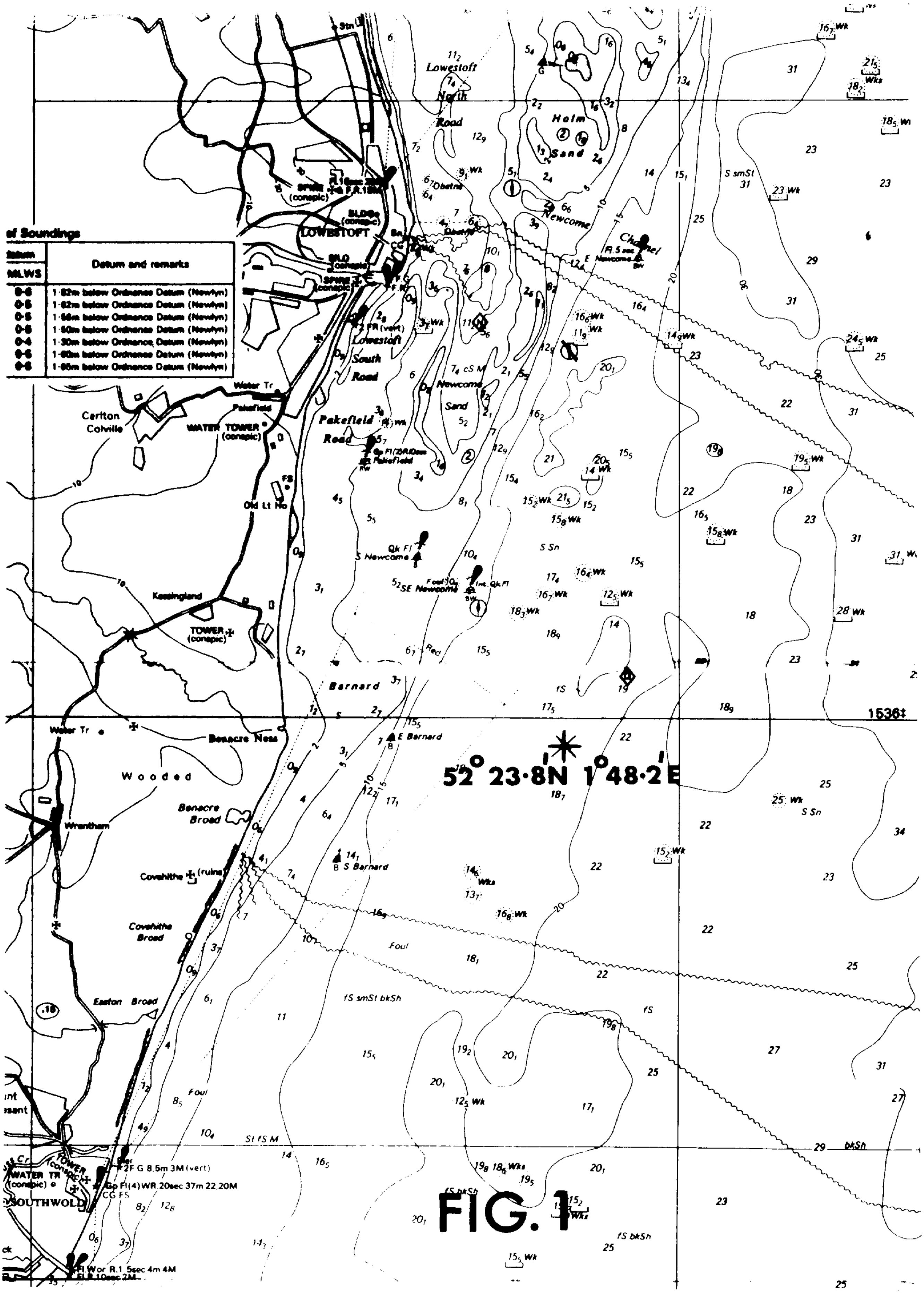
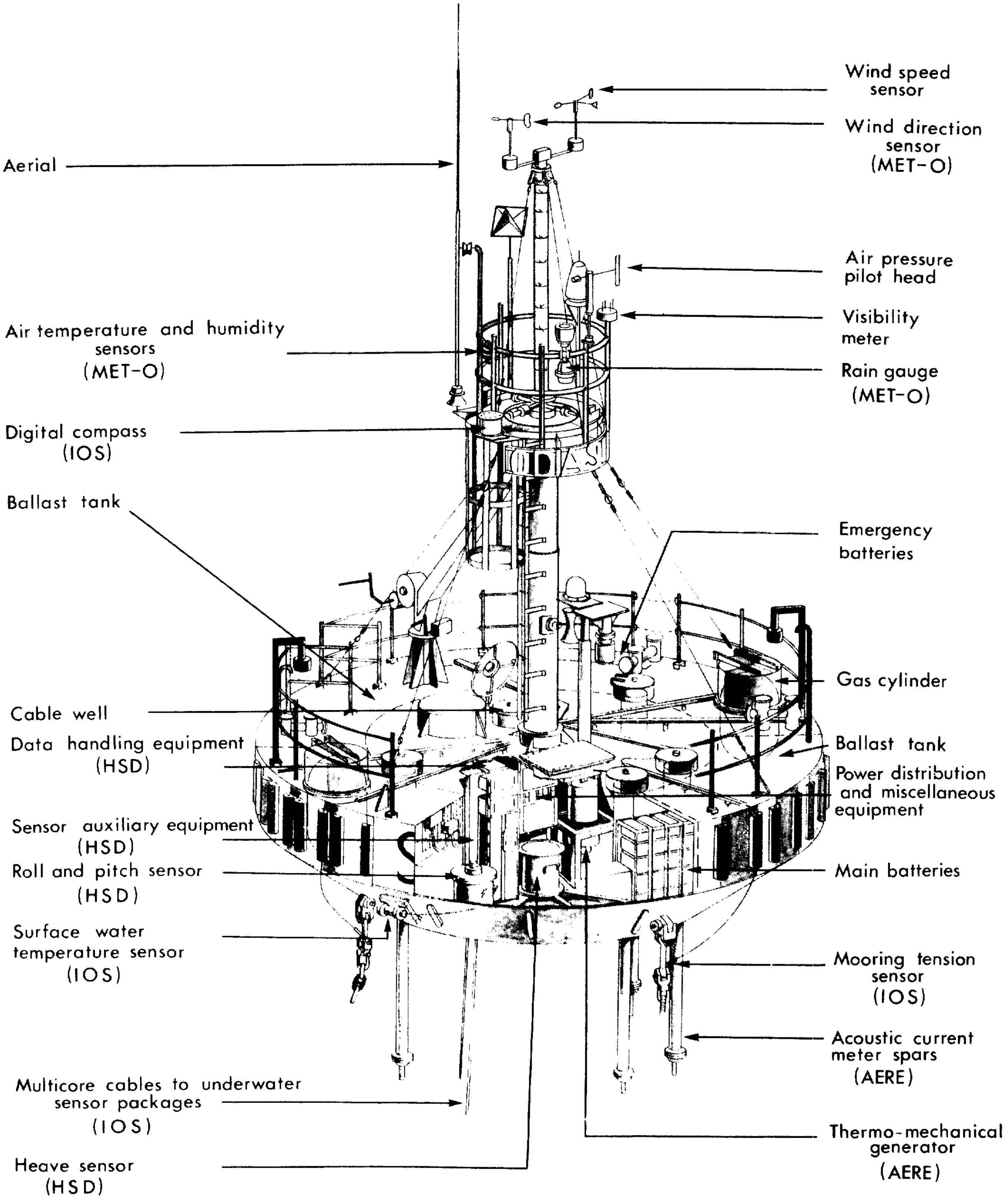

of Soundings
Datum and remarks
1·62m below Ordnance Datum (Newlyn)
1·50m below Ordnance Datum (Newlyn)
1·30m below Ordnance Datum (Newlyn)
1·60m below Ordnance Datum (Newlyn)
Lowestoft North Road
Holm Sand
Newcome Channel
LOWESTOFT
SPIRE (conspic)
Lowestoft South Road
Newcome Sand
Pakefield Road
Carlton Colville
WATER TOWER (conspic)
Water Tr
Pakefield
Old Lt Ho
Kessingland
TOWER (conspic)
Qk Fl S Newcome
SE Newcome
Barnard
E Barnard
S Barnard
Benacre Ness
Wooded
Benacre Broad
Wrentham
Covehithe (ruins)
Covehithe Broad
Easton Broad
SOUTHWOLD
2F G 8.5m 3M (vert)
Gp Fl(4) WR 20sec 37m 22,20M
CG FS
Fl.Wor R.1 5sec 4m 4M
Fl.R.10sec 2M
52° 23·8N 1° 48·2E
1536

FIG. 1

Acknowledgements

May I take this opportunity to thank all those who have contributed to this project, in the drawing offices, in the laboratories, in the yards and at sea. Many 'unsocial' hours were worked by many people, and we hope that the results of their labours may be seen through the contributions given at this Symposium.

FIG. 2


Wind speed sensor
Wind direction sensor (MET-O)
Aerial
Air pressure pilot head
Visibility meter
Air temperature and humidity sensors (MET-O)
Rain gauge (MET-O)
Digital compass (IOS)
Ballast tank
Emergency batteries
Gas cylinder
Cable well
Ballast tank
Data handling equipment (HSD)
Power distribution and miscellaneous equipment
Sensor auxiliary equipment (HSD)
Main batteries
Roll and pitch sensor (HSD)
Surface water temperature sensor (IOS)
Mooring tension sensor (IOS)
Acoustic current meter spars (AERE)
Multicore cables to underwater sensor packages (IOS)
Thermo-mechanical generator (AERE)
Heave sensor (HSD)

U.K. NATIONAL DATA BUOY - D.B.1.

PROJECT REVIEW 1974/1976

R.F. KELLEY C.ENG. F.I.MAR.E.

PROJECT MANAGER.

HAWKER SIDDELEY DYNAMICS LTD.,
MANOR ROAD,
HATFIELD,
HERTS.

A feasibility and design study for the U.K. National Data Buoy (D.B.1.) was started early in 1972 at the Institute of Oceanographic Sciences, following the identification of the need by the Standing Committee for Ocean Data Stations set up by the National Environment Research Council and some preliminary work by M.A.T.S.U. The study recommended a design for a large buoy capable of acting mainly as a vehicle for the development of sensors, data handling systems, telemetering facilities and power supplies, as well as providing data for a number of different bodies such as M.A.F.F., Meteorological Office and I.O.S.

On conclusion of the study, a number of industrial companies were invited to tender for the detailed design, manufacture and maintenance of the buoy and after due consideration, a contract was awarded by the Department of Industry to the "SEATEK" group in February 1974.

"SEATEK" was formed by Hawker Siddeley Dynamics Ltd., E.M.I. Electronics Ltd. and R. & H. Green and Silley Weir Ltd., in order to bring the maximum amount of knowledge and expertise to this project and to prepare the ground for more extensive activity in this and associated fields. Seatek were subsequently awarded the contract for the highly successful 80 foot long, 120 ton Tower Placement Control Module for Burmah Oil's Thistle A platform and are currently working on an Offshore Research Structure for the National Maritime Institute and a Structural Monitoring System for the Department of Energy. Since the initial formation of Seatek, W.S. Atkins & Partners have been appointed as Consulting Engineers to yet further strengthen the off-shore capability.

For the D.B.1. project, Hawker Siddeley Dynamics acted as prime contractor and were thus responsible for the overall co-ordination of the work to Dr. G.V.G. Lusher, Project Director from the Department of Industry. H.S.D. were also responsible for the design and supply of the buoy data handling equipment, E.M.I. were responsible for the complete shore station, whilst the design and

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manufacture of the buoy itself was undertaken by R. & H. Green and Silley Weir.

The buoy is a wave-riding discus 7.62 metres diameter carrying a combined main and sensor mast 7.5 metres high. The hull is of fabricated mild steel construction and is divided into seven compartments, one central circular hold surrounded by six wing compartments. The data handling equipment and main power source are housed in the central hold, the wing spaces containing the main and emergency batteries together with gas tanks, ballast and buoyancy tanks.

Access to the central hold is gained through a 1 metre diameter spring assisted hatchway and a main bolted deckhatch is provided for removal of equipment. The six wing spaces are each fitted with watertight doors opening into the central hold. Two separate pumping systems are installed, one for bilge, the other for ballast, each with its own semi-rotary handpump. The bilge suction is taken from a strum box fitted in each compartment, a non-return valve being combined with each box as a protection against reverse flow. The pump and associated compartment control valves are conveniently situated inside the main entrance hatch and a float switch is provided in each compartment to detect and alert the shore station of any high level bilge condition. A higher capacity hand pump is fitted in the ballast system with control valves suitably arranged to allow each tank to be separately pumped, flooded, or filled from the sea.

In addition to natural ventilation, an exhaust fan is fitted to take air from the battery compartments, whilst a supply fan, operated on a time switch, can provide purge air to all compartments.

A 1 metre high handrail is provided around the periphery of the deck, this rail being stopped and chains attached in way of the four lifting and towing bollards. A 10 cwt. hand operated Davit with controlled movement of swing and lowering is provided for lifting equipment in and out of the buoy, the buoy side being protected by "D" shaped vertical rubber fenders attached to the hull by external bars and bolts.

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The mast assembly is fabricated from aluminium and is suitably insulated from the steel deck. The main mast is in the form of a 0.46 metre diameter tube which houses the main ventilation trunking and the winding gear for the retractable sensor mast. A maintenance platform is constructed at the top of the main mast some 3.58 metres above deck level. When fully extended the sensor mast stands a further 3.58 metres above the maintenance platform level and can be retracted some threequarters of its length into the main mast. A navigation warning light, controlled by a daylight switch, is mounted off the maintenance platform and a continuously sounding swept tone fog signal is also carried.

1974 started with a national fuel crisis which, as far as the D.B.1. contract was concerned, presented us with an immediate problem regarding the supply of steel plate. At the same time it was agreed that D.B.1. should be fitted with some unique equipment, including the Harwell Thermo-Mechanical Generator and Acoustic Current Meter, together with the Piccolo telemetry system developed by the Diplomatic Wireless Service. Couple this to all the necessary start of project meetings and discussions - with the Meteorological Office regarding Met. sensors, with I.O.S. regarding oceanographic sensors, with M.A.F.F. regarding the shore station facilities, with Trinity House regarding the mooring of the buoy - and you have all the ingredients for making a project manager's life interesting.

The design, however, progressed at a very satisfactory rate, Lloyds Register of Shipping approved the hull steelwork and mast structure drawings in April 1974, the steel plate was finally delivered in August/September 1974 and we started cutting metal. In February 1975 we were able to report that the steel shell was complete and on Friday 20th June 1975 the whole team assembled at Green and Silley Weir's Blackwall Yard to drink the health of the buoy as Trinity House towed it away to Lowestoft for final fitting out and test.

This phase of the contract was carried out in Brooke Marine's yard at Lowestoft and tribute must be paid to the excellent facilities and co-operation afforded us during our stay.

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With E.M.I. having installed the shore station equipment in the M.A.F.F. Lowestoft Laboratory and H.S.D. their data handling system in the buoy, there now followed some long days and nights establishing the radio link and finally proving that given sensor outputs checked right through the system to the shore station recorder. Even "Barney" the buoy's dog became confused as to when he should be sleeping and when he should be barking his warning of strangers.

Gradually, however, the problems were solved and following an abortive attempt due to gales, the Trinity House vessel appeared out of the early gloom of a foggy Sunday morning, and, with the Project Manager riding on its deck the buoy was towed out to sea on 30th November 1975.

The buoy is stationed some 3 miles off Benacre Ness in position 52^{o} 23' 48" N, 1^{o} 48' 12" E. It is moored on a three point system using $1\frac{5}{8}$" stud link chain to 3 ton cast iron sinkers and 3 ton AM12 anchors and thanks to a highly professional job by Trinity House, the three arms are within 2^{o} of their true bearing.

As previously mentioned, one of the objectives of the contract was to produce a platform for the further development of sensors etc., and the present buoy station is well suited to this purpose, being close enough inshore to allow reasonable access and yet demonstrably able to record fairly severe sea states.

Other papers written for this symposium describe the main items of D.B.1. equipment and the experiments completed so far, but in concluding this overall Seatek review I would end on an optimistic note for future joint projects. A real spirit of help and co-operation has existed throughout the project, not only in the three companies brought together as Seatek, but in every organisation involved, a spirit which has made my job as project manager one of comparative ease and pleasure.

RFK/RMI
29th October 1976.

DB1 ON-BOARD DATA HANDLING

COMMISSIONING AND IN-SERVICE EXPERIENCE

J. Wall,
Chief Electronics Engineer,
M.E. & S. Division,
Hawker Siddeley Dynamics Limited,
Hatfield.

DB1 ON-BOARD DATA HANDLING

COMMISSIONING AND IN-SERVICE EXPERIENCE

Introduction

A fairly comprehensive technical description of the data handling system design was included in a paper published in the Proceedings of the Symposium on Oceanography held at Bangor, North Wales, in September 1975. The present paper attempts to analyse the performance of the equipment during the period while it was being installed in the buoy and mated with the user equipments, and also for the first 11 months of service at sea.

System Design Principles

The data handling and power distribution systems trace their pedigree to experience gained over many years in the design of guided weapon instrumentation and telemetry installations, spacecraft operating systems and scientific experiments, and general radio and line communication systems. This experience existed not only as back-up in the Company, but within the design team actually employed, which also included some special experience of marine instrumentation systems and their inherent problems.

One of the principal lessons which this sometimes bitter experience had taught was the need to design the equipment from the "total system concept"; the effects of power supply characteristics, earth loops, signal levels, data rates and interactions between sub-systems all being considered at each stage of the circuit and packaging design. It is a measure of our success that only one problem occurred which was traceable to an earth loop, and none to cross-coupling in wiring, RF pick-up or noise emission.

The avoidance of earth loops was tackled by a series of informal meetings at engineer level between HSD, EMI and Racal. One of the first decisions made was that the RF transmitter should have its own completely separate battery which would be fully floating except for a single point connection to the buoy hull from within the transmitter, which would also act as the RF ground connection. This immediately raised the problem of how to bring logic signals into the transmitter from a system using a different battery, without coupling the signal common to the transmitter earth. Luckily some genius in a remote semiconductor design laboratory had combined one of the newfangled light emitting diodes with a rather more ancient beast called a phototransistor to produce the answer to our prayers - the opto-isolator. All data and control pulses into the screened boxes housing the modulator and RF transmitter pass through such devices, giving complete isolation. Unfortunately the maker's claim that they could handle signals up to 2MHz proved unfounded and the IMHz master clock signal had to be isolated by a pulse transformer.

All data signal and control pulse circuits use 2 wire systems to avoid cross coupling, the common line being connected to the battery return only in the main junction box, at which point it has its sole connection with the buoy hull. All connections between data handling system and users, and between the power system and data handling pass through the main junction box and this forms a very useful test point for sub-systems interconnections. To help this, all terminations in the junction box are made via waterproof connection blocks and each of these has a third position to accommodate a test probe without disturbing the functional connections.

The buoy was originally designed to run solely from air-depolarised batteries, and even when the decision was made to use the buoy as a field trial installation for the Harwell Thermo-Mechanical Generator, a smaller number of these primary batteries were retained as a back-up supply.

Because of the weight of batteries (to say nothing of cost) maximum efficiency in the power distribution system was essential. The batteries had wide voltage swings, (48V to 26V for the primary banks and 31V to 24V for the TMG) and most users needed very stable supplies to achieve the 0.1% accuracy of measurement they were seeking. It was therefore decided (to the accompaniment of quiet chuckles from various sources) to use switching mode regulators throughout, as being constant power devices their internal losses are very low and almost constant. Once again lessons learnt the hard way on Blue Streak and Sea Dart telemetry were brought to bear from the start and all such regulators are totally enclosed in screened boxes and all leads into and out of the boxes pass through RF suppression filters which have a guaranteed attenuation of 50dB at the nominal switching frequency. Again the measure of our success is the fact that the system includes 30 switching regulators with ratings from 5A to 150mA, and even with analogue signals down to 10mV passing round the system and a data clock rate of 1MHz, no part of the system has malfunctioned due to interference from these regulators.

Setting to Work and Commissioning

Mr. Kelley has already mentioned the effects of the 3 day working week during early 1974 on the construction of the buoy hull. This also had a significant effect on the electronic equipment. Not only did it cause delays in our own design and manufacturing effort, but suppliers of components and other equipment also found themselves unable to maintain their earlier delivery promises. Consequently the 3 month period planned for system test and integration in the laboratory was gradually whittled away until we were faced with the situation where the buoy was at Lowestoft ready for fitting out and only 2 of the 6 equipment cases were fully tested, and no real integration work was complete.

In an attempt to maintain the original schedule, and against all my natural instincts, it was decided that the equipment would be shipped to Lowestoft as each case became available and that integration, both as a system and with the buoy facilities, would be done simultaneously on an ad-hoc and continuously up-dated programme. It was of course impossible at this stage to carry out the planned interfacing with user equipments, and all users were reluctantly asked to stay away until the buoy was ready to receive them. Some of the problems involved at this stage can be imagined if you think of the buoy on the quayside, in an ambient temperature approaching 25°C, with a couple of welders working in the wing compartments, 2 caulkers chipping metal on deck, 3 wiremen trying to terminate cables in the junction boxes, painters covering every possible place with glossy white but very wet paint, and amongst all that lot 3 electronics engineers trying to get their bits working for the first time. After a few hectic visits, a very patient Project Manager accepted that his most effective place was somewhere else, trying to ensure that we got all we needed when we needed it!

In spite of some very long and often depressing weeks, during which Dr. Rusby became really adept at incorporating wire wrapped modifications into our equipment (he owned the only hand operated tool), very few significant design problems were experienced. The most serious, and at times puzzling, of these was eventually traced to lack of line driving power in the Common Equipment. The inter-wiring capacitance in the cable looms proved to be about 3 times the predicted value and this, combined with the current limiting circuitry on each printed circuit card, meant that logic levels to other equipments were badly distorted and at times dropped into the "no man's land" between 6V and 4V at which not only are logic levels indeterminate, but over dissipation in the CMOS gates can occur. A large number of mystifying symptoms occurred apparently at random, until the solution was eventually shown to be a reduction in the series limiting resistor value on all Common Equipment cards.

Another serious problem which caused a number of integrated circuit failures was found to be due to the system of switching off sensors when not actually in use. Many equipments had incorporated large decoupling capacitors on each circuit card (shades of TTL practice!) and when the power was switched off, the very low current demand of the CMOS logic caused these capacitors to discharge only very slowly. As a result, a situation again existed where the input logic levels drifted slowly downwards until they spent a considerable time in the vulnerable region between 6V and 4V. We now believe that even where actual failure did not occur, cumulative over stressing of the gate insulation occurred and was a contributary cause of some later faults. The solution was derived in the cooperative manner so typical of this project, with users reducing their decoupling to the minimum practical value, while HSD shunted all inputs to ground through 1M resistors to discharge the capacitors more rapidly.

Another small, but typical, puzzling problem was associated with the internal fault alarms in the Acoustic Current Meter, which were fed into Event Channel inputs. Although the equipment consistently went through its self check routine successfully, the data handling system equally consistently showed an alarm condition. Eventually it was realised that during the self check routine these alarm signals were briefly but deliberately generated and the Event Channel latches were holding these levels until the following transmission. Complex circuit modifications to inhibit these pulses were being discussed when it was realised that if they were transferred to a Parallel Binary channel, they would not be entered until data was sampled, and this proved a simple but complete solution.

Some of the problems sound very simple now, but picture if you can, its 2 a.m. on Sunday after a day which started at 9 a.m. Four assorted engineers, the Project Manager and the Project Scientist are grouped round a small oscilloscope hanging precariously from a bent wire "sky hook". They are debating whether a pulse, which lasts only 80 mSec and occurs only once per hour, actually exists at all and if so, was it 10V, 7V or even 6V high. This is what development is all about!

Eventually, towards the end of November 1975, it was generally agreed that all users were getting data which they believed and, although there were still a number of minor question marks in non essential areas, the Project Manager would get his way and Trinity House would tow the buoy out to meet the elements. As has already been said, this was done on 30th November.

Reliability

It was realised right from the receipt of the invitation to tender that the equipment would be complex and achievement of a suitably high order of reliability would be difficult. An initial assessment using an estimate of the numbers of integrated circuits, soldered connections and connector pins through the system gave an MTBF of 50 hours - not really good enough to meet a requirement for service visits at 6 monthly intervals!

The equipment was therefore divided into 2 classes, Class A being that which carries information from all channels or which controls such circuits, while Class B equipment was that in which a single failure would affect only 1 or at most very few channels. Class A was to have an overall MTBF of 6 months, but while Class B equipment would be made as reliable as possible, our tender made it clear that in any 6 month service interval, some of these circuits could be expected to fail. A fault in Class A equipment would require an unscheduled service visit, but Class B would be attended to on an "as available" basis.

Throughout the design, reliability requirements have featured high in our thinking. The use of high reliability connectors such as MIL-C-38999 and Smith's Hypertac types, wire wrap PCB inter-connections and crimped connections wherever possible are just some examples. Bought in sub-assemblies were burnt in and tested before assembly to the boards, and all boards were put through 100 hours of functioning burn in as part of a test sequence which involved 3 cycles through a fully automatic logic tester. As past experience had shown that potentiometers were a regular source of trouble these were eliminated and test selected resistors used for setting up.

At the time of going to sea, 54 of the 100 channels were required and channel circuit cards are fitted only to these. Even so, the HSD produced equipment contains 134 printed circuit boards on the buoy, each having an average of 20 integrated circuits and these total up to an estimated 2 million active devices or "transistors". There are also some 40000 connector pins of various types throughout the system and some 60000 soldered joints.

Although ceramic packaged industrial grade integrated circuits were used rather than the very much more expensive HI-REL series, careful use of antistatic precautions throughout assembly and test produced the remarkably low IC failure rates of:-

On initial assembly	2.2%
During burn-in temperature cycling	0.5%
During conformal coating	0.2%

These results are being repeated on the second set of equipment intended as a back-up station and for testing.

In the 11 months from 1st December 75 to 1st November 76 the buoy has been on station at sea, and only 1 Class A fault has occurred, due to a counter failure in the clock decoder. This has since been attributed to the test set having been left connected while the main equipment was switched off. A modification has now been incorporated which should prevent a reoccurence. 10 days data were lost due to this fault, but this was almost entirely due to bad weather preventing access. During the same period, 5 channel circuit cards have failed and one existing fault remains to be isolated. No systematic faults have shown up, the only fault occurring twice being a failure of the channel store to recirculate correctly.

In addition to these data handling faults, some problems have occurred in proprietry equipment, including 2 failures of the fog signal diaphragm, a faulty daylight switch in the navigation light and 2 intermittent faults in the over temperature sensor. It is now believed that this last fault may in fact be in the wiring, as it has not been possible to reproduce the faults in the laboratory, and a similar fault was seen before going to sea.

For reasons on which Mr. Cooke-Yarborough will expound later, the back-up batteries have been called into service on a number of occasions. The no-break changeover system has worked perfectly each time and no data has been lost, nor have there been any errors directly attributable to this. Battery performance has been well up to expectation, although it was found necessary to readjust the number of cells in the 2 main banks due to assymetric loading, the positive supply now having 32 cells to the negative's 26. On the basis of their present performance, it is expected that the original bank of cells installed in May 75 at the start of commissioning should remain operational until the spring of 1977.

A particularly gratifying feature has been the performance of the master clock oscillator. This is a Vectron modular device with internal temperature compensation rather than the usual temperature controlled oven. Extensive laboratory tests were carried out on a prototype and these confirmed that in the range -10°C to +70°C the 1MHz signal remained within

1 part in 10^7 through 1000 hours of temperature cycling. All production units have been similarly pre-aged before incorporation. Just before the buoy was put to sea the frequency was checked and found to be still within 1 part in 10^7 of its original setting, after 6 months continuous use during commissioning. It has not been possible to check to this order of accuracy at sea, but there is no reason to believe that is is not still performing equally well.

Maintainability

The design concept was that little or no fault investigation and certainly no repairs would be practical on the buoy, except in a very calm sea. It was, and still is, the intention to have a complete duplicate equipment at the shore station which would be used to replace any faulty or modified equipment case. Sufficient diagnostic test facilities were built into each case to allow a fault to be diagnosed and localised into 1 case.

Unfortuately, the after effects of the 3 day week and the subsequent upsurge in demand which followed produced severe shortages of some of the more exotic components, such as ultra low power linear amplifiers, hot carrier diodes and even some of the MSI CMOS devices. As a result this duplicate equipment is not yet fully operational.

However, necessity is the mother of invention and our stalwart Service Department engineers have achieved performances on the buoy which confound belief, although one would hope that it will not be necessary to continue in this way for much longer as it must put the equipment at risk, with a consequent degradation of long term reliability. Fault investigations and repairs have regularly been carried out in sea state 4, when boarding the buoy is itself an athletic exercise, and on one occasion a printed circuit board was successfully replaced in a sea state 6.

Future Work

It would be an exceptional design team which could get its prototype equipment working exactly right first time. We at HSD have put forward proposals for improvements to the present system to ease testing and ensure even higher reliability. These are mainly small additions to the built in test facilities and some redesign of the system for retaining the cases in the racks, where although no actual failures have occured, some commercial fasteners have proved to be inadequate and the accessibility of some of them falls short of the ideal.

Conclusion

I would like to take this opportunity to thank those people associated with the project at all levels for their help, cooperation and forebearance.

JW/MRR
31.10.76

SHORE STATION HARDWARE AND SOFTWARE DESIGN AND OPERATION

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Summary

This paper describes the basic system design of the shore based receiving station developed for National Data Buoy DB1. Layout of the hardware is first discussed and this is followed by a review of the software including data checks and ordering of the data for Magnetic storage and accessing facilities.

1. Introduction

The Data Buoy has been designed and developed by the SEATEK Consortium for the Department of Industry, following a feasibility study by the Institute of Oceanographic Sciences, Wormley.

The Buoy is designed to provide a platform for the automatic collection and transmission of oceanographic and meteorological data, and to provide a base for the further development of sensors and telemetry systems, under operational conditions.

The shore station collects the hourly data, where possible reduces it to engineering units, stores the data on Magnetic Tape and makes the data available on request either, locally to a teletypewriter or, remotely via a modem and telephone line.

2. System Hardware

Fig.1 indicates the system as developed for the shore station at Lowestoft.

2.1 Aerials

Briefly, the two aerials are 24ft fibreglass 'marine whips' manufactured by Bantex. It was hoped to use them in a space diversity mode but the space to allow the recommended separation of at least 5 wavelengths (400 metres) to be achieved, was not available. The system in fact functions with either or both aerials in circuit each connected through a receiver into the demodulator.

2.2 Radio Receiving System

The telemetry system employed is a ten tone 'Piccolo' system based on the original work of the Diplomatic Wireless Service and designed by Racal Ltd. (See contribution by

Ralphs and Billing). The hourly transmission by 'Piccolo' from the Buoy consists of the following sequence:-

(i) 20 secs. slow morse, call sign 2NI02, sent twice by switching on and off the '0' line output.

(ii) 30 secs. synchronisation, 2 tones (10 and 11 lines) alternated every 100 milliseconds to give a reference frame for the following data.

(iii) 108 secs. data, 1 decimal character (0 to 9 lines) every 100 milliseconds, 3 characters per channel, 90 channels in all, sent 4 times.

(iv) Every third hour after the data in (iii) above, the subroutine data is sent for 20 minutes. At present the subroutine consists of heave, pitch, roll and compass readings each sampled once every 1.2 secs. This information is sent at the same data rate, one character per 100 milliseconds, 3 characters per channel.

(v) 10 secs. slow morse, call sign 2NI02 sent once.

In order to input the incoming signal into the computer 6 data lines are provided from the demodulator into the special interface unit:-

SYNC. On line

DATA 4 BCD lines

DATA RATE line 100msec strobe pulse

Opto-isolators are used at the demodulator/computer interface.

2.3 Frequency Standard

A sophisticated frequency standard was selected before the radio equipment was defined. The selection was made on the grounds of short term stability for the demodulator, and long term stability for the computer clock. The Hewlett Packard 105A has a stability quoted in the region of 1 part in 10^{10} depending upon load, temperature and supply voltage and an ageing rate after three months of continuous use is typically $\pm 1 \times 10^{-10}$ per 24 hours.

Operating experience has shown that whilst the 105A is quite suited to the tasks of providing 1MHz for the Receivers, Demodulator and computer, it could well be dispensed with. Each receiver has an internal source of 1MHz which is capable of driving the receiver as well as the demodulator. The computer itself adequately maintains 'time now' by using the mains frequency. (The local mains is in fact shut off twice every two weeks in order to allow testing of a standby generator, 'time-now' being reset after these breaks). The only important aspects of the time keeping are that: a) the computer 'time-now' clock should be between Buoy time (GMT) and GMT+30 mins, ensuring that the shore station and the Buoy agree as to when Wave Data will be transmitted, and b) the computer 'time-now' clock should be set accurately to GMT whenever the test set is to be used to feed in a new Buoy time.

2.4 Computer

A PDP11/05 computer from Digital Equipment Company Ltd., is the system controller and Fig.2 shows the basic system configuration. As can be seen the UNIBUS provides the communication between devices.

Information from the Buoy is passed from the demodulator to the memory via the Input/Output Interface. The interface circuit contains an opto-isolator to isolate the computer from the 'outside world'.

After processing, the data is stored on the Magnetic Tape and a print-out is given on the ASR33 Teletypewriter. At present, a print-out of any faults due to transmission errors or range errors is given prior to the main data and then any housekeeping faults are printed after the main data. The EMI Warning Display Unit (WDU) gives an immediate indication of the more serious faults such as Buoy Adrift or Navigation Aid Failed. In addition the WDU provides a 'Time of Day' Clock and TOD output in order that the Buoy Test Set may be loaded with the accurate time. All outputs from the WDU are fed via relay contacts to ensure isolation.

Locally, information may be called from magnetic tape using the teletypewriter. The same facility exists via a telephone line and modem. In each case data is retrieved from the magnetic tape and then passed serially through the DL11-E to the Datel facility.

A second Datel service is provided exclusively for the output of current meteorological data. This information is updated by each hourly input from the Buoy and does not utilise the magnetic tape storage system.

Wave data may be accessed by the teletypewriter locally as for ordinary sensor data but a facility has also been provided for a simple graph to be drawn of any one of the four outputs. (Heave, pitch, roll or compass). This has no scientific value, but in engineering terms, provides a 'quick look' assessment of the sensors performance and to some extent, that of the radio link. As for Met. data, this is not accessed from Mag. Tape storage but directly from stored values.

3. System Software

3.1 Overall Concept

As with the hardware on the Buoy the software reflects the role of the Buoy in developing new sensors. The Buoy message format is handled in a standard manner regardless of how many of the 90 channels are allocated. A software mathematics package is used to compute engineering units for each channel in turn, provided they fall within the scope of the system. If a new sensor is fitted, the user merely types in the constants and limits for the particular sensor, indexed by its allocated channel number. The channel status flag should be reset and then after the next complete hourly cycle of the Buoy the data would be printed out at the shore station.

Fig.3 indicates the Shore Station Data Flow and in particular one should note the differing conversions from one numbering system to another. Some of the features of the system are given below.

3.2 Data Read-In

The routine which reads data in from the demodulator is continually searching for a 'SYNC PRESENT' signal, once acquired it must remain for at least one second or the timer resets and starts again. After 1 second the system waits for the 'not present' indication before reading data into store. The first nine characters received are checked against the buoy identification code, shifted if necessary, and provided at least 7 out of 9 of those characters agree, the rest of the message is read in.

This may seem a lengthy and complicated procedure but it has been evolved to suit the hardware and to overcome some of the problems experienced. As originally designed, 'sync.' had to be present for 20 seconds and a 9 out of 9 agreement achieved on the identification code. This was far too stringent, especially in view of the fact that the following data could be reconstituted from the four sends with a high level of confidence given even a 20% error rate.

The read-in routine will give an indication if the Buoy fails to transmit one hour from the last transmission and if two or more transmissions fail a 'Communication Lost' signal is given. Once all the sensor data transmission has been received the Data Check Routine is triggered. The routine will then 'time share' with the reception of wave data if any is sent.

3.3 Data Check

This routine performs all the essential steps in sorting the data and storing it on Mag. Tape.

It is worth repeating the reasons for choosing four sends of the data set each hour. One constraint imposed was power consumption and four sends would be the maximum allowable for this reason. Changing from 4 sends to 3 sends each hour would in fact save less than 5% of power in any three hour period.

For assumed error rates we used probability theory to calculate.

a) Probability of a correct code being decoded.

b) Probability of a false code being accepted.

c) Probability of a correct code being rejected.

for 3 from 4, 2 from 4 and 2 from 3 criteria. As was to be expected, an extremely low probability of a false code being accepted was shown for a 3 from 4 criterion but the chances of rejecting good data were high compared with 2 from 4. On both these parameters 2 from 3 fared badly. It was decided that the software should look for 3 from 4 agreement on data values, but where data failed to meet this, a 2 out of 4 agreement would be accepted and flagged to indicate a lower confidence level. The system has worked extremely well, the incidence of lower confidence level results has been extremely small, and have at times indicated faults in the system rather than results due to transmitting conditions.

Once the data has been correlated into one set a quadratic equation is applied to each on-line channel. The equation is $V = aX^2 + bX + c$ and provides for scaling and offset to transform the received value X to engineering units. a and b are scaling factors and c is the offset. Negative values are catered for but the values are constrained within certain limits to avoid overflow of the calculation. By using the channel number as an index a subroutine brings out the received value, finds the constants, does the calculation and stores away the result, logging any lowering status by channel number where necessary. Naturally there were some sensors where this particular equation could not be applied, in these cases a and c were put to zero and b unity. Any calculations required are then completed after the main routine.

Fig.4 gives an example of an hourly print out showing the Sensor Data and the associated fault messages. As one can see it is made up of 7 groups, each group labelled with the Day No. and time of Day when the record was taken and there are 13 channels per group. The letters against each channel denote the level of confidence of either the user or the system itself as per the following list

A.	Believed good	Set by user and not modified to a lower status by system.
B.	Subject	Set by user doubting information or as in the case of channel 29 (pressure), where the accuracy of the readout capability would overrun the maths package.
C.	Poor transmission	Set by system software if only 2 of 4 received values agree.
D.	Probably Invalid	Preset by user.
E.	Data Out of Limits	Set by software; in this example channel 34 is flagged E because the received value has to be 5 or more before the subsidiary calculation can be meaningful.
F.	Sensor off line	Preset.
G.	No transmission correlation	Set by software.

The fault numbers immediately following the data are set by another routine which checks the housekeeping data within groups 1 and 2. The numbers given here would be checked against the fault list sheet and appropriate action taken on the first occurrence. Some numbers make regular appearances on the print out and it would be quite useful to be able to cancel them until action has been taken to remedy the significant faults. Thus attention would be drawn to those numbers that do not appear regularly rather than the case at present where they tend to be hidden by well known items.

The Data Check routine also controls the writing of data onto magnetic tape. The data is structured as follows:-

<u>Volume Header:</u> ↓	Written on by an 'Open Tape' routine controlled from the local teletypewriter and containing information as to the start date and time of this volume.
<u>EOF:</u>	End of File mark.

File Header:		Denotes the start of days data.
Record 1	Sensor Data for 1 hour:	Written on by Data Check.
Record 2	Sensor Data:	each record contains either groups 1 to 7 of sensor data or 40 sets of Wave Data. If there is wave data in the hour the data will be contained within 25 separate records, each containing 40 sets.
Record n	Sensor Data:	
File Trailer:		Denotes the end of days data.
EOF		
File Header:		
Record 1		
until Record x:		corresponding to day m
File Trailer: EOF EOF		Written on by a 'Close Tape' routine controlled from the local teletypewriter.

Approximately 56 days' data are held on each reel, on day's data being contained in a file.

3.4 Local Teletypewriter Control

A number of control features were written into the main programme to allow users to exercise control over the computer locality. Some of the routines originally written have never been used in 'anger' and due to other changes some are no longer required. Below is a list of those routines which are regularly used:-

1. Setting of the computer clock.
2. Opening the Magnetic Tape Volume.
3. Closing the Magnetic Tape Volume.

4. Setting of Sensor correction constants.
5. Setting of Sensor readout limits.
6. Setting of Sensor status.
7. Cancel Alarms.
8. Test Alarms.
9. Request for data from Mag. Tape.
10. Request for plot of Wave Data.

3.5 Remote Requests

The system allows the user to request data from Mag. Tape in the same way as it is done locally. Subroutines have been written to allow this and data may be requested either by record number or by identification listing groups hour and day. Examples of this latter type of request (made remotely) are shown in Figures 6 and 7.

All data on the Current Magnetic Tape is available for accessing at any time either remotely or locally.

The Meteorological data is obtained merely by establishing contact and there are no 'handshaking' routines required, information is 'streamed' down the telephone line until completed and then the computer automatically breaks the connection. The information is updated by each hourly transmission from the Buoy.

3.6 Memory Size

For those concerned in minicomputer structure the following information may be of interest. Designation of the 20K core size (All figures in octal) is:-

0	-	320	Vector Area	- Interrupt pointers
320	-	776	Stack	- used as required by programme
1000	-	6602	IOXMTA	- DEC Input - Output Executive modified by EMIE
6620	-	6752		- Executive reference table
6754	-	22530		- Main Data Buoy Storage Area
22532	-	64144		- Main Data Buoy Programme
64146	-	104200		- Storage area for Binary Wave Data
74000	-	117500		DEC Mag. Tape System Monitor and on-line debugging routine which are used to load and test

	the programme but use of these is limited by the first input of wave data.
117500 - 117776	DEC Absolute loader and System 'Bootstrap'

4. Day to Day Running

Given briefly above is an idea of how the shore station functions and some of its features. IOS, HSD and in particular MAFF have all assisted in the day to day running of the system. Due to the large distance between EMI and the Lowestoft site it has been convenient for a preliminary investigation of any reported fault to be made by telephone, using as 'hands and eyes' MAFF personnel. This has proved extremely useful in enabling an estimate to be made as to where the problem lies prior to a site visit.

The main problems encountered have been twofold

4.1 Hardware

Several component failures in the radio system have proved particularly difficult to find because of their occurrence simultaneously on the Buoy and the shore station equipment. At one point four unrelated faults occurred in the computer hardware coincident with a local lightning strike.

4.2 Software

It has been fairly obvious that some software errors have been masked by circumstances, in particular those concerned with the modem handling routines. Some modifications to the system have been forced by other events. For example, the Buoy Adrift Alarm is now obtained from compass conditions rather than the mooring tension sensors.

5. Conclusion

The experience gained in keeping the shore station running over the last year has been valuable and many useful lessons have been learnt for the future on how to improve reliability and to reduce data loss in a sophisticated 'unmanned' shore station of this type. Since any failure at present is likely to lead to data loss it would be particularly valuable to have some emergency audio storage capacity available for recording 'Piccolo' transmissions whilst faults are corrected. In a largely 'unmanned' station like this it is also important to ensure that the initial design philosophy calls for the highest reliability standards in all the hardware components.

FIG 1. DB1 SHORE STATION HARDWARE

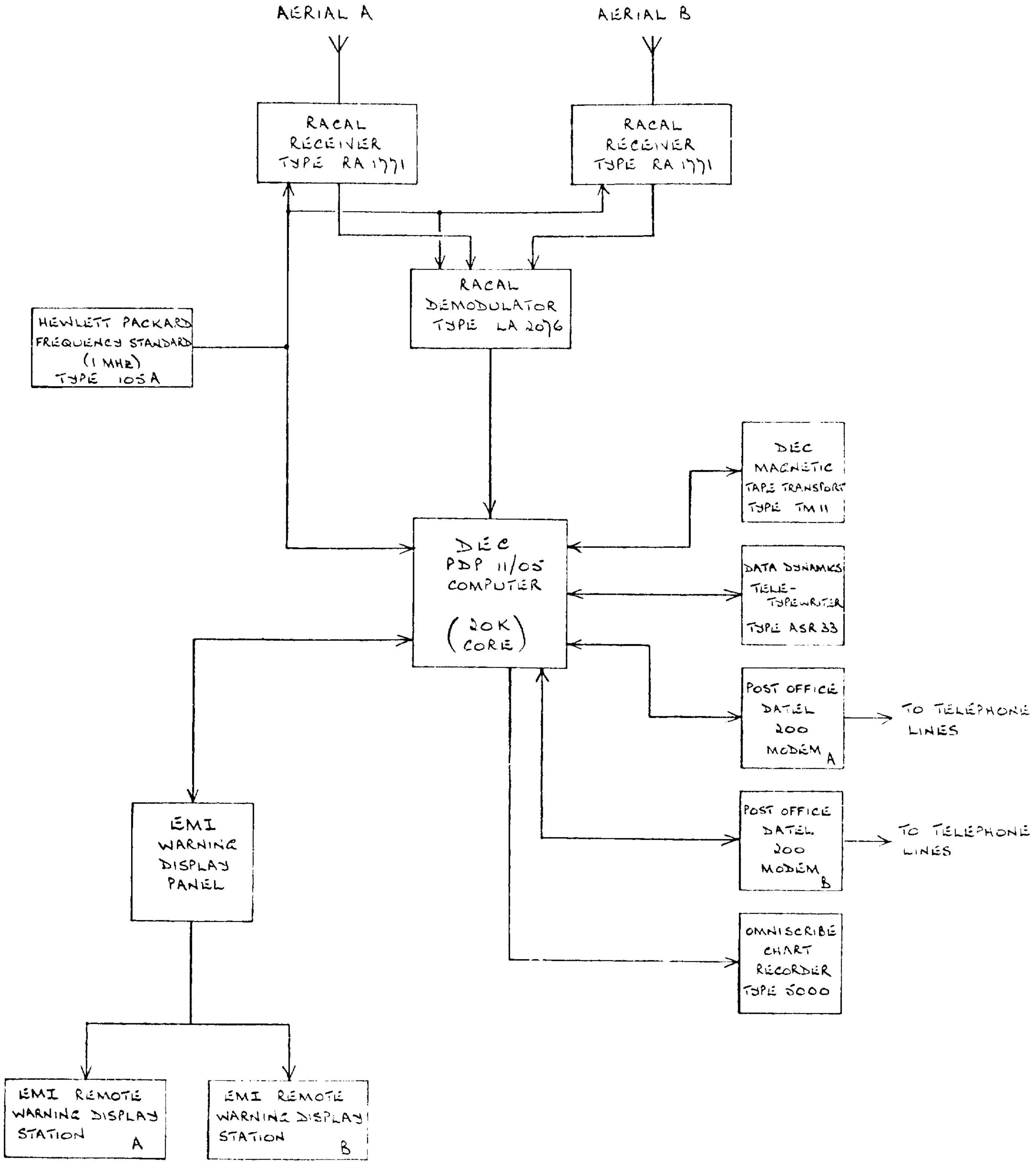

FIG 2.

DB1 SHORE STATION COMPUTER ARCHITECTURE

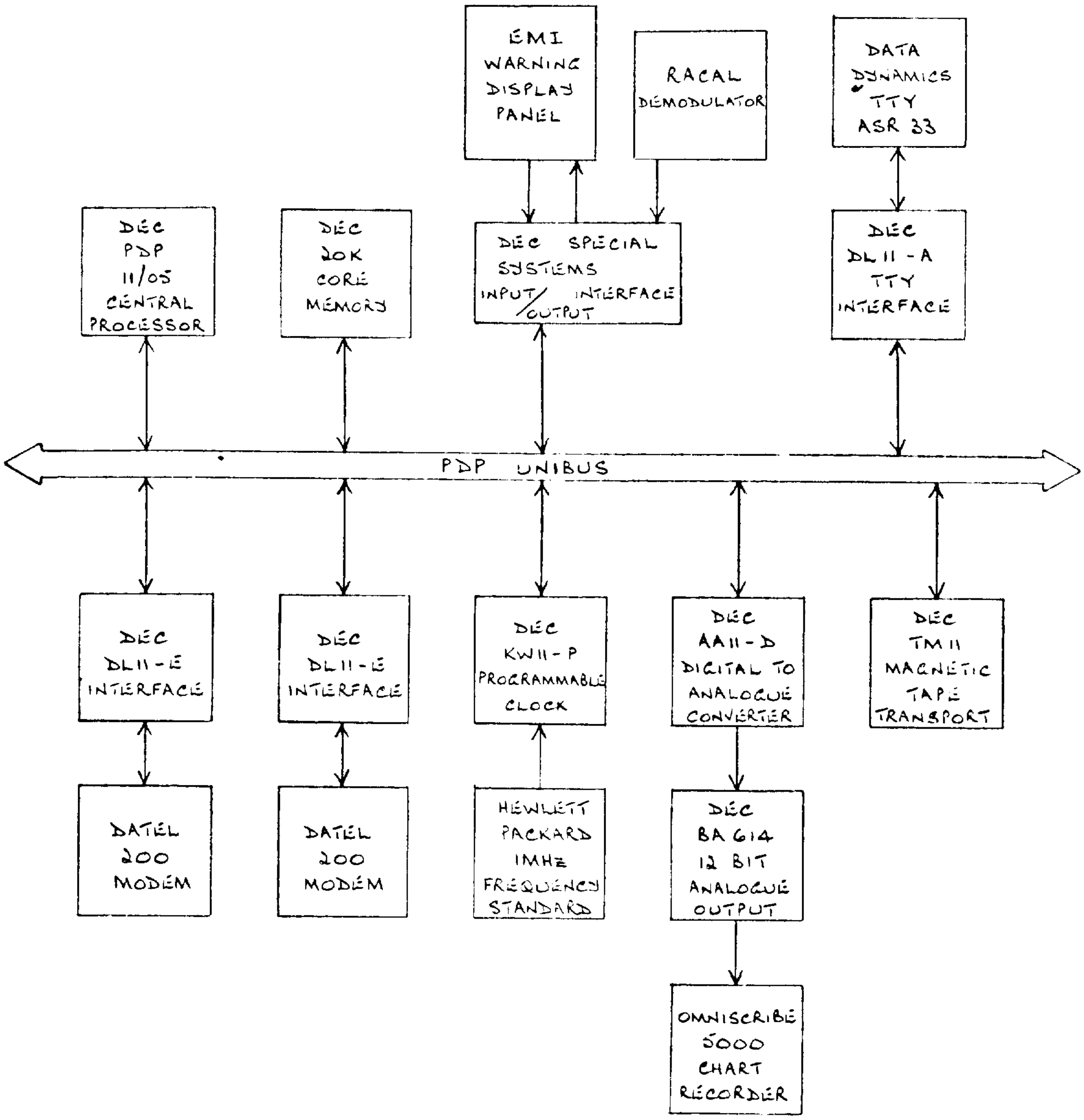

FIG. 3 SHORE STATION DATA FLOW

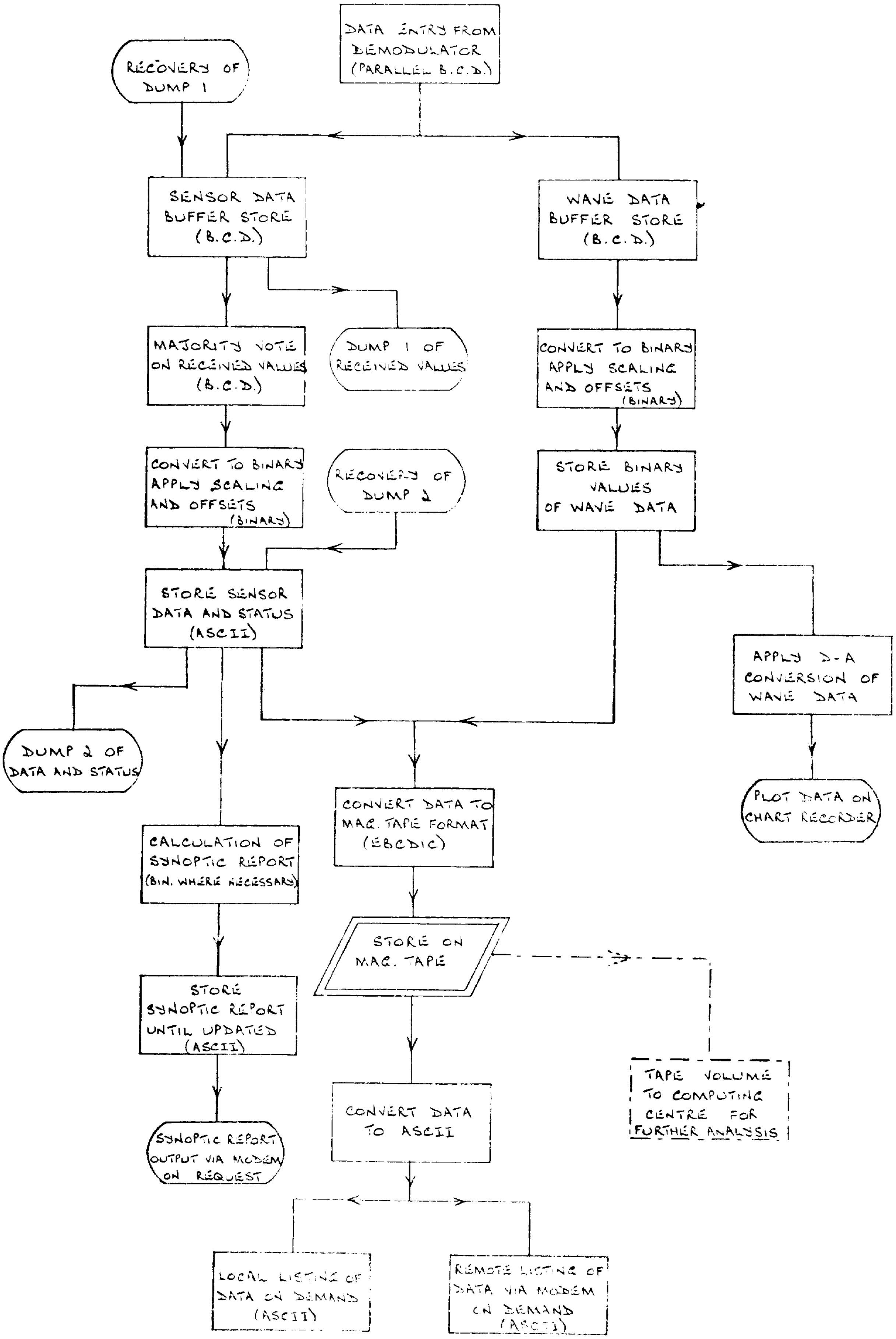

FIG. 4

SAMPLE OF DATA BUOY HOURLY PRINT OUT

```
289:13:13   FAULT  50:34
01 289 1313      23A    790A    241A     13A       F       F      0A
                   F      8A      0A       F       F       F
02 289 1313       9A      3A       F    466A    556A    740A    784A
                244A    790A    143A    547A    350A    952A
03 289 1313 -    22A    125A    457B    119A    257A    184A    610A
                  0E       E   6696A       F       F       F
04 289 1313      82A     27A     14A      0A       F       F      0A
                  0A     12A     18A      0A      0A      0A
05 289 1313       7A    339A    486A      0A      0A      0A       F
                   F       F   1543A       F       F       F
06 289 1313       0A      0A      0A       F      0A      0A      0A
                   F      0A     23A     23A       F       F
07 289 1313        F       F       F       F       F       F       F
                   F       F       F       F       F       F

289:13:14    FAULT 70

289:13:14    FAULT 60

289:13:14    FAULT 20

289:13:15    FAULT 19

289:13:15    FAULT 13

289:13:15    FAULT 11
```

FIG. 5

SAMPLE OF DATA BUOY WAVE DATA

```
PD 3 289
         DONE
09 289 1215
      A       A        A        A
-   32     516      517       18
-   24     453      501       18
    20     456      475       37
    12     491      510       14
-   16     484      528       35
-   32     473      500       16
-   12     483      494       19
    10     478      515       33
    16     482      499       19
    28     436      490       19
    10     492      520       16
-   38     493      517       35
-   50     490      499       21
     0     446      496       35
    48     456      510       36
    16     519      499       35
-   26     476      513       19
-   18     461      506       37
    14     462      497       18
     6     487      503       36
-   14     491      509       19
-   12     462      502       33
-   12     477      517       21
-    8     495      495       37
     4     458      501       35
    28     452      496       36
-    6     513      517       13
-   24     477      511       35
     6     451      489       21
     6     473      501       16
-    4     484      525       33
-   22     497      496       33
-   16     466      506       18
    18     451      506       37
    24     495      498       19
     4     484      498       36
-   12     475      509       14
-   18     470      532       39
-    8     463      471       15
-    2     490      518       40
```

```
REQ:PD 4 4 255 17


04 255 1713   376A   306A     6A     0A      F      F     0A
                0A    26A    25A     0A     0A     0A
REQ:PD 7 7 257 21

ERROR 5
REQ:PD 1 1 259 12

01 259 1215   135A   790A   241A    12A      F      F   264A
                 F     8A     0A      F      F      F

REQ:PD 1 1 259 11

01 259 1115   135A   790A   241A    11A      F      F   264A
                 F     8A     0A      F      F      F

REQ:PD 1 1 259 10

01 259 1015   135A   790A   241A    10A      F      F   264A
                 F     8A     0A      F      F      F

REQ:PD 1 1 259 9

01 259 0915   135A   790A   241A     9A      F      F   264A
                 F     8A     0A      F      F      F

REQ:PD 1 1 259 8

01 259 0815   135A   790A   241A     8A      F      F   264A
                 F     8A     0A      F      F      F

REQ:PD 1 1 259 7

01 259 0715   135A   790A   241A     7A      F      F   268A
                 F     8A     0A      F      F      F

REQ:END

GOODBYE
```

FIG. 6

EXAMPLE OF REMOTE REQUESTS BY MODEM

```
REQ:PD 1 1 246 5

01 246 0513     135A    790A    241A      5A       F       F    332A
                   F      0A      0A       F       F       F

REQ:PD 3 3 248 4

03 248 0413 -    58A    113A    589B      1A    285A    133A    420A
                  5A   5992A   7322A       F       F       F

REQ:PD 2 2 250 2


02 250 0213       1A      2A       F    469A    553A      1A    160A
                272A    368A    159A    570A    367A    947A
REQ:PD 30 30 253 0

30 253 0032
      A      A      A      A
-   24    497    511     33
    10    470    490     19
     2    508    517     39
-   10    485    486     21
-    2    477    511     43
     6    494    496     14
-   14    496    509     33
     4    472    494     21
-    2    504    500     11
     4    480    509     36
-   12    491    497     18
-   14    479    502     21
     0    494    502     35
     4    483    505     21
     4    508    491     19
-   18    476    519     21
    18    475    483     19
     4    516    506     19
-   20    468    508     18
-   12    490    502     21
-    6    491    494     21
-    8    485    508     36
     0    501    506     19
    18    486    489     33
    10    487    505     19
     0    483    509     40
-   20    491    494     15
-   16    485    514     40
-    6    486    483     14
    10    480    516     33
-   20    516    501     12
    12    468    491     39
    18    492    508     35
     4    494    498     40
-   22    490    510     15
-   10    470    503     36
     0    499    489     18
-   20    498    521     43
-    6    475    480     19
    32    496    513     40
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FIG. 7

EXAMPLE OF REMOTE REQUESTS BY MODEM INCLUDING WAVE DATA

THE PICCOLO TELEMETRY SYSTEM ON DB 1

by J D Ralphs (Foreign & Commonwealth Office, Communications Engineering Dept)

1. INTRODUCTION

A major problem in any unmanned marine Data Acquisition system is that of telemetering the measured data from the measurement station to a shore station. There are several communication media which may be considered, eg Cable, Acoustic link, Satellite, HF radio and Radio at higher frequencies than HF, but for longer ranges (exceeding line of sight) the choice is very restricted. An economically viable satellite system for a network of small low power stations has yet to be engineered and in the opinion of the author of this paper is unlikely to be so within the next ten or fifteen years. Therefore despite the known difficulties of signalling over HF this remains the first choice.

In the early days of HF signalling, machine telegraphy (as distinct from manually received Morse) earned for itself an unenviable reputation for unreliability due to the inability of the modulation systems to operate accurately through the time varying and frequency varying characteristics of an ionospherically reflected signal, and high levels of noise and interference. The "Piccolo" HF Telegraphy system (Ref 1) was designed and developed by the Foreign and Commonwealth Office for its own network to overseas Embassies, and first installed in the early 60s. The aim was quite specifically to obtain the highest possible reliability from an HF telegraphy link by the full application of the best of modern theory and electronic techniques. This has proved extremely effective and a second generation of the equipment has been designed and is now commercially available. A variant of the Piccolo systen, based on the same techniques, is in use as the telemetry system from the DB1.

2. PICCOLO PRINCIPLES

In a conventional FSK system, data is sent by transmitting each bit on one of two available tone frequencies. In an MFSK (Multiple Frequency Shift Keying) system each transmitted element represents H bits of data, and is sent by selecting one of $M = 2^H$ available tones. The Piccolo telegraphy system transmits the teleprinter alphabet, and so H = 5 and M = 32. The DB1 telemetry system uses data 'words' of 3 decimal digits, or 10 bits total, conveniently transmitted as three elements selected from M = 10 tones. The techniques of 'matched filtering' and 'orthogonal frequency spacing' are well described in the literature but may be illustrated simply as in Fig 1. A single pole bandpass filter with zero bandwidth will produce a linear rising response to an input at its resonant frequency, but any other frequency will produce zero response at intervals equal to the inverse of the frequency "error". Thus, in the DB1, the elements are 100 mS duration and the tone frequencies are spaced at 10 Hz intervals. In the receiving system the signal is applied in parallel to ten such filters, which are 'quenched' to zero and released at the beginning of each signal element, and 100 mS later the outputs of the ten filters are compared and the highest identified as the transmitted tone. The filters are then immediately quenched again for the next element.

In fact, the system operates in dual space diversity. Two receiving aerials feed two radio receivers, and the audio outputs drive two identical banks of filters. The comparison circuit then selects the highest of twenty filters, thus giving 'channel selection diversity' over each element interval.

The above description ignores the synchronising system, which requires two additional tone frequencies (making a total of 12). The two synchronising tones are transmitted on alternate elements for a minimum of 10 seconds at the beginning of each buoy transmission and the receiving synchronising system operates on the resulting phase modulation and adjusts its timing accordingly. The relative timing is maintained throughout the transmission because the sending element rate and the receiving element rate are each controlled from the same accurate sources that determine the radio frequencies.

/3.

3. THEORETICAL PERFORMANCE

The theoretical performance of an 'ideal' MFSK system can be calculated and Fig 2 shows the theoretical word error rate (for a 10-bit word) against normalised Sig/Noise ratio for a non-fading signal in Gaussian noise and it can be seen that in general the performance improves as M increases. The curve for M = 2 (binary) system is identical with that of an "ideal non-coherent reference system" quoted by CCIR. The measured performance of a practical MFSK system is usually within 1-1½ dB of theory, giving 7-12 dB improvement over a conventional FSK system.

The normalised bandwidth (Fig 3) can be shown to be a minimum for M = 6 to 12, and therefore the DB1 system, in which M = 10, is a very good compromise between performance and bandwidth.

The long element duration of an MFSK system gives it a high immunity to multipath effects and it can be shown that path time delays of up to 10 mS cause a relatively small deterioration in performance.

4. MEASURED PERFORMANCE

The performance of the 32-tone Piccolo system has been measured on fading simulators and also compared to conventional systems in radio trials (Ref 2).

In 1975 the Foreign and Commonwealth Office Development Section, working in close co-operation with the Christien Michelsen Institute of the University of Bergen carried out direct comparison trials between a 10-tone MFSK modulation system very similar to that used on the DB1, and a conventional binary FSK system designed by the CMI. A test signal consisting of 670 10-bit words was transmitted by each system in turn from a 25 watt transmitter on the Norwegian coast near Bergen and received at the FCO receiving station in Bucks, UK. More than 300 test transmissions were made over a period of about 2 months. Detailed results of these trials are available to interested organisations but the results may be summarised in the table below, expressed in terms of the 'availability' (the average number of successful transmissions) at a given level of accuracy (the maximum acceptable word error rate).

Maximum Acceptable Word-Error Rate	1%	10%
Availability of Binary System	9.7%	31%
Availability of 10-tone System	32.3%	60%

The received signal was weak, and optimum aerials were not available, but the superiority of the 10-tone system is obvious. Laboratory measurements on the two systems indicated a superiority of between 7 and 14 dB in signal-to-noise ratio depending on the conditions of the tests and the mode of synchronising of the binary system.

5. ERROR CODING

The above discussion does not include the use of error-coding, and while a multi-tone system on a reasonably clean signal will give an accuracy which is more than adequate for continuous data (eg real-time wave analysis), data consisting of single measurements of high significance require a higher degree of accuracy than can be obtained without the use of some form of error detection or correction. It can be shown that it is extremely ineffective to apply an orthodox binary code to an MFSK system, and in general a code for use on an M-level system must employ Modulo-M arithmetic. At present the DB1 system uses an experimental "majority vote" code.

/Each block

Each block of data is repeated a total of 4 times and the decoding is carried out by stages, first on a "three out of four" basis, and where this fails on a "two out of four" basis, and the data is marked with a "confidence grade" accordingly. This certainly gives a very high degree of accuracy but is probably unnecessarily complex and uneconomic in time for some applications. Where an ARQ (Automatic Request for Repeats) system is to be used a simple parity check may be carried out analogous to the usual binary parity check. In the binary case a single parity bit is added at the end of a block of (say) nine data bits, so as to make the modulo-2 sum of the 10 bits equal to zero. Similarly in a decimal case an additional decimal digit can be added to a block of nine data digits so as to make the modulo-10 sum equal to zero. This is an extremely powerful error detecting code with a much smaller probability of undetected error blocks than the equivalent binary, particularly at high error densities (see Fig 4).

Error-correcting codes equivalent to some of the standard binary codes (eg BCH or Hamming codes) may be made in Modulo-M arithmetic by expressing the decoding algorithm as a series of parity checks as above. Such codes are extremely efficient but may lead to relatively complex electronics. This is a field in which more theoretical work is required in order to realise its full potential.

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File Ref 9980. NLL No P186242.

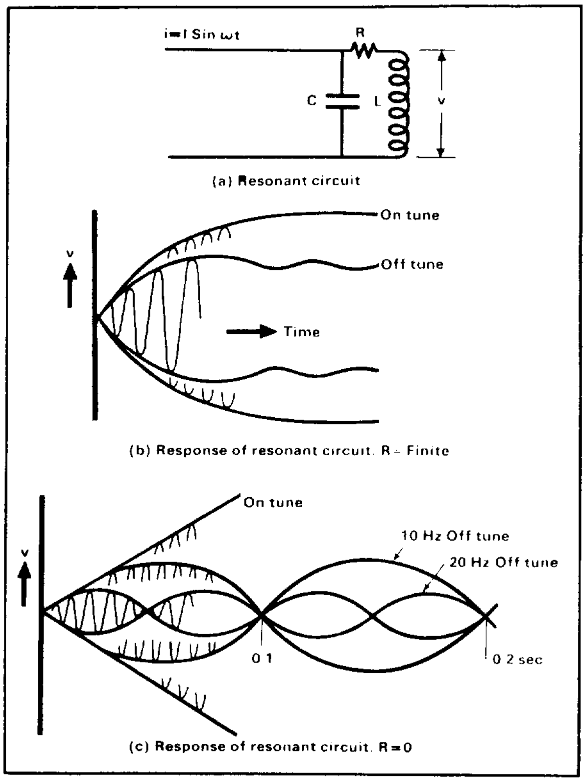

FIG. 1. TRANSIENT RESPONSES OF A RESONANT CIRCUIT.

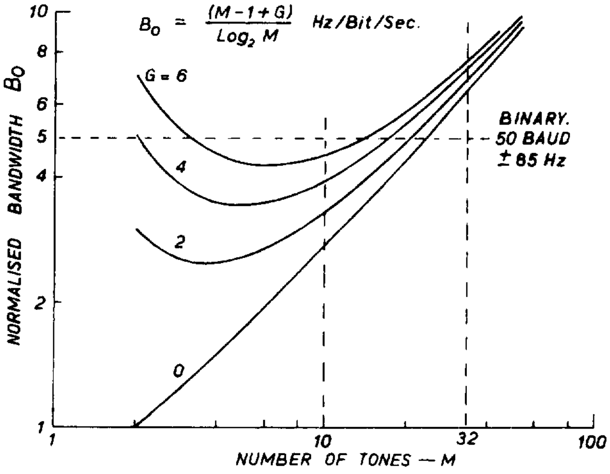

Fig.3 NORMALISED BANDWIDTH OF MFSK

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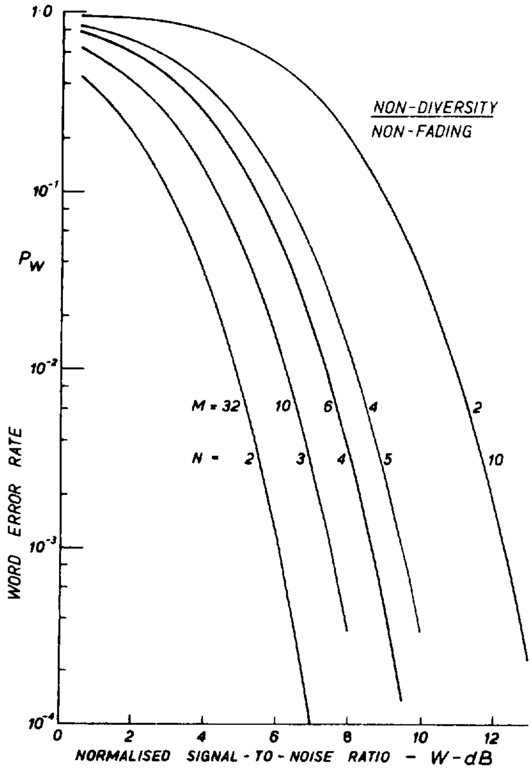

Fig. 2 WORD ERROR RATE FOR VARIOUS SYSTEMS

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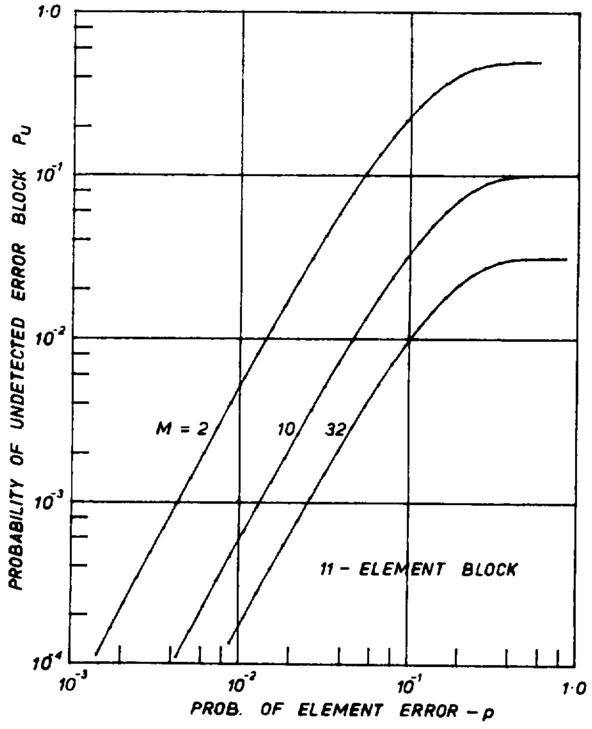

Fig. 4 MULTILEVEL PARITY CHECK

LAB 122/4

EXPERIENCE WITH THE THERMO-MECHANICAL GENERATOR AS A MARINE ELECTRICAL POWER SOURCE - BY EH COOKE-YARBOROUGH (AERE, HARWELL)

1 Introduction

The Thermo-Mechanical Generator was originally developed at Harwell to provide a way of converting the heat from a radioisotope heat source into electricity more efficiently than was possible by thermoelectric means, and thus to reduce the amount of radioisotope required to provide a given amount of electrical power. The resultant R&D programme showed that at power levels of a few tens of watts the Thermo-Mechanical Generator was capable of converting heat into electricity with efficiencies three or four times greater than those obtainable with thermoelectric conversion at comparable temperatures. Although this made radioisotope-powered generators more attractive, it produced an equally great improvement in the fuel consumption of electrical power sources using hydrocarbon fuel. For example, a 25-watt TMG consumes about 200kg of propane a year, whereas a proprietary thermoelectric one will require about 750kg. Alternatively, about 1000kg of primary air-depolarized batteries are required to provide the same amount of electrical energy.

While development was proceeding at Harwell, IOS became aware of the possibilities of using the TMG as a source of electrical power for the National Data Buoy. In particular it appeared that the low fuel consumption would make it possible to accommodate on the Buoy more than enough fuel for a two-year mission, thus avoiding the refuelling at sea which is required by a thermoelectric system or air-depolarised batteries.

As a result of this, the Ship and Marine Technology Requirement Board of DoI funded a development programme which took the propane-heated TMG design from the laboratory model illustrated in Fig 1 to the field-trial design illustrated in Fig 2. This is the machine which is installed in the National Data Buoy.

The principles of the machine have been described elsewhere[1,2,3], but may be briefly summarised as follows:-

Fig 3 shows the basic configuration. A cylindrical displacer piston mounted on a stiff spring (not shown) oscillates up and down inside a cylinder containing helium. The lower end of the cylinder is heated, and the upper end cooled, so as the helium is displaced from one end to the other, the pressure changes cyclically. This deflects the metal diaphragm at the top of the cylinder, which oscillates a magnet between magnetic pole pieces which carry windings to deliver an alternating current. The vibrations of the masses of diaphragm hub and alternator magnet induce smaller vibrations in the body of the machine, which is spring-mounted. Since the displacer spring is mounted on this vibrating body, this maintains the displacer in oscillation at its natural frequency. With this design there are no sliding surfaces in contact, so there is no sliding friction, no requirement for lubrication and no wear. Because of the absence of rotation and sliding friction, the TMG is self-starting when heated.

2 Development

The most important difference between the laboratory machine and the one developed for the Data Buoy is that the former had the upper side of the diaphragm exposed to the atmosphere, whereas the latter has a sealed cover over the whole of the upper side of the machine and this contains helium at the working pressure. This helium is able to pass through a slow leak in the diaphragm hub to or from the working volume. This change was necessary in order to cope with the specified variations of ambient temperature and pressure without significant differencesdeveloping in the average pressures on the two sides of the diaphragm. It also greatly increased the amount of helium in the machine and so made slight losses through diffusion or leakage much less important. This change had a great many repercussions elsewhere in the machine's design, which, while involving a great deal of work, were beneficial in their total effect.

The laboratory machine had carbon foam thermal insulation inside the displacer piston, but it was found at a late stage of the development programme that the manufacturer of plastic foam which was the starting material had altered his process and that as a result the carbon foam fitted to the displacers of the field-trial machines was much weaker than the original material and was breaking up under the acceleration of about 60g to which it was subjected. The immediate solution to this problem was to discard the carbon foam and to fill the displacer with low-pressure xenon to discourage heat conduction and convection, and to aluminize the opposing ends of the displacer internally to reduce radiative heat loss. This solution was adopted for the first two field-trial machines. However, we were concerned that should helium leak into the displacer some thermal insulation will be lost, so to avoid this danger the method now adopted is to fit a number of thin stainless steel heat baffles inside the displacer to suppress convection and radiation, and to allow helium in the spaces between them.

3 Commissioning in the Data Buoy

Because of the delay resulting from this problem, the TMG for the Data Buoy was completed and operating only two days before it had to be shipped for installation at Blackwall.

After installation it was taken in the Data Buoy to Lowestoft, where it was started up using propane in small bottles, since the main buoy tanks had not yet been filled. At this point it was found that the static heat loss in the machine was about double that measured in the laboratory. This is believed to be due to helium having entered the displacer piston, but it will not be possible to verify this for certain until the TMG can be returned to the laboratory.

It was also found that the burner could not raise the hot end of the TMG to its normal temperature without lighting-back, and as a result the machine is operating with a hot-end temperature about 60 degrees C lower than the other field-trial machines. This may be partly due to the increased heat load imposed on the burner by the added heat leakage, but it is possible that an unusually poor thermal contact between the burner and the hot end of the machine may also be contributing by reducing the heat flow from the burner.

The effect of this was that the output available from the machine was some 25% less than expected. Since no one at the time knew with any certainty the total power drain imposed by the equipment on the Buoy, we could not know whether this reduced power output would be adequate to meet the average load.

When eventually the main Buoy tanks were filled with propane and the TMG was supplied from these tanks, we found the power output falling steadily. This was eventually traced to partial obstruction of the burner jet by a liquid coming down the gas pipeline, which analysis showed to be a mixture of mineral oil and plasticiser. The origin of this liquid was not very apparent, but thorough cleaning of all the Buoy gas pipe-work eventually eliminated this trouble. As a precaution a liquid trap and filter were fitted to the gas-handling system on the TMG, and, since the plasticiser might have come from the flexible PVC tube supplying low pressure propane to the burner, this tube was replaced with a flexible steel tube.

The electrical system of the TMG includes an electronic stabilizer stabilizing the amplitude of the mechanical oscillation, temperature sensors connected to a cut-off circuit to turn off the gas supply if the hot-end temperature goes above or below predetermined limits, an ignition circuit to produce sparks in the burner continuously at the rate of one per second and battery charge controllers for all four secondary batteries.

The electrical power system of the Buoy is quite complex, because it feeds a wide variety of instrumentation requiring different voltages, and drawing current at different times. This was rationalized into two 28V(nominal) supplies, positive and negative with respect to earth and a third similar supply floating with respect to earth (which powers the radio transmitter). Each of these supplies has a secondary nickel-cadmium battery floated across it, and an air-depolarized back-up battery which comes into operation if the voltage falls below about [illegible] V. A fourth secondary battery supplies the Buoy lighting and ventilation. The first three supplies have priority and all are charged effectively in parallel through separate rectifiers. When the voltages on all these three batteries are above a predetermined level of about 1.45V/cell, the charging current delivered by the TMG is transferred to the fourth battery, and when this in turn is fully charged, the ventilation fans are turned on.

When the TMG began to be operated while the Buoy was at the dock side it soon became apparent that transients on the various power lines, due to work being done on other equipment, which included frequent short-circuits, were affecting the sensitive d.c. amplifier associated with the thermocouple temperature sensors at the TMG hot end and was causing the gas supply to shut down several times a day. Whenever work was being done on the Buoy, it was therefore necessary to operate a manual switch which de-activates the gas cut-off. It also became apparent that the secondary batteries were not behaving as expected. Even though the battery terminal voltages were stabilized to the correct value, voltages measured across individual cells fell sharply into two groups, one well above the correct voltage and the other well below. We came to the conclusion that the charge/discharge efficiencies of different individual cells varied widely and, with identical charges being alternately drawn out of, and fed into, the cells in series, the more efficient cells were becoming over-charged and the less efficient ones under-charged. The effect of this was to reduce the charge/discharge efficiency of the complete battery to that of the worst cells. Some of the worst cells were, therefore, replaced with cells from the spare battery and were returned to the manufacturer, who reported that some were beyond repair. Some tests on other cells at Harwell showed charge/discharge efficiencies as low as 40%. Clearly, much of the electrical output of the TMG may be being wasted in the secondary nickel-cadmium batteries used at present.

Towards the end of the period at Lowestoft almost all the instrumentation and other equipment was installed and running continuously. The TMG seemed to be just keeping pace with this load, the voltage to the main batteries varying between 25V and 27V, but it was clear that there was no power to spare to charge the fourth battery.

4 Performance since commissioning

(a) Gas supply

The Data Buoy was commissioned on December 6, 1975 though after December 11 there was no telemetered data available about the performance of the TMG, and it was still running on 18 January 1976. By 27 January, however, it had stopped, the gas cut-off valve having operated. The cut-off valve was reset and the TMG re-started on 8 February, but the cut-off valve had operated again by 18 February. The gas cut-off valve was reset on 19 February and the TMG re-started, but it had stopped again on 22 February because the main fuel tanks had become exhausted, due to a leak in a blanking plate associated with one of the Buoy tanks. This time we got a good telemetered record of the shut-down, showing all the TMG parameters normal until the hot-end temperature fell gradually over a few hours, eventually causing the gas low-temperature cut-off to trip, whereupon the machine cooled, as would be expected, within the next two hours.

The reason for the shutdown on this occasion is clear, but one can only surmise the reasons for the two earlier shut-downs. These may have been due to electrical interference; on the other hand the gas supply was within only a few days' running time of exhaustion, and this may have caused the hot-end temperature to go outside the predetermined temperature limits, causing the cut-off valve to operate. We do know that the characteristics of the gas coming from a cylinder of propane tend to alter as the cylinder approaches exhaustion. It may well be that the same thing was happening on a much longer time scale with the two 100 gallon tanks installed in the Buoy.

For the next four months the TMG had to be run from 13kg cylinders carried out to the Buoy. On several occasions a cylinder became exhausted before the Buoy could be visited to connect a replacement cylinder, and on these occasions, of course, the TMG shut down and the primary batteries took over. Running cylinders of a known capacity to exhaustion at least enabled us to obtain a check on the fuel consumption, which came out at 183kg/year.

The fourth cylinder was not used because the connector to it had become damaged and could not be sealed properly. Consequently, the TMG was shut down for a month until June 24, when one of the main Buoy propane tanks was re-filled, and the TMG was re-started by Hawker Siddeley staff.

Our experience with using propane in the Buoy has not yet resolved one important question. The Clyde Port Authority, who have been using propane marine lights for 30 years, report that their propane jets may clog progressively unless a small percentage of methylated spirit is added to the propane in the tank. This was not done with the fuel in the Data Buoy, so we have been concerned to see whether there has been any tendency for the jets in the TMG burner to clog progressively during normal operation. When the TMG has shut down we usually do a flow test to see whether the jet is obstructed, and it nearly always needs to be cleared. On the other hand we have no evidence of a progressive fall in burner temperature while the machine is running, though the telemetered temperature recordings are very incomplete. However, we do have one piece of evidence to show that a jet can become partially obstructed after the burner has been shut off. On one such occasion in the laboratory we were able to remove the jet without dislodging the obstruction, and put it under the scanning electron microscope. The picture we obtained showed an obstruction which clearly must have dropped in from the outside. Since the propane leaves the jet at supersonic velocity, this can hardly happen while the burner is operating. We concluded that it is prudent always to test the flow rate through the jet after the machine has been shut down, and to clear the jet, if necessary. We have no evidence that regular cleaning of the jet is necessary, if the machine is running continuously. Nevertheless, we think it would be prudent in future to follow the Clyde Port Authority's recommendation to add methylated spirits (or methanol) to the fuel.

(b) Cooling system

At the beginning of April we noticed from the telemetery records that the mechanical amplitude of the TMG was fluctuating between its normal value (determined by the amplitude controller) and a lower value, outside the range of the controller. The output current was fluctuating similarly. Both then fell steadily and had reached a level about 23% below normal by early July.

At this point it should be explained that the reject heat is taken away from the TMG by a pentane cooling circuit, in which pentane evaporates inside tubes attached to the hub of the diaphragm, the vapour is carried along a flexible nylon tube outside the TMG to an external radiator, and the condensed liquid is returned via another similar tube. A visit to the Buoy on July 28 showed that all this pentane had disappeared, and that as a result there was no cooling and the machine body was running very hot. It is quite surprising to note that despite the absence of cooling, the machine was giving more than 75% of its previous output current. Since an immediate repair to the cooling system could not be effected, the machine was left operating in this condition.

Leaks in the pentane cooling system had already occurred in the two machines purchased by AGA, one now at Dungeness and one at Harwell. All these leaks were found to have resulted from one minor error in the design of one of the flexible cooling pipe connections between the TMG body and the radiator, which became over-stressed when the TMG was subjected to vertical acceleration. A simple modification was devised to overcome this problem. A modified radiator and piping system was taken out and fitted to the Buoy on August 30, and the cooling system was filled with fresh pentane. This was a rather difficult operation, since the machine was still hot, and it was essential to get the pentane into the system and sealed off before the radiator became hot enough to boil the pentane at atmospheric pressure. Successful completion of this operation, which we had never envisaged doing in the field, was a great credit to all concerned. The machine was re-started,&after a partially-blocked burner jet had been cleared,its operating parameters returned to normal, and remain so up to the time of writing.

(c) Secondary batteries

Telemetered records recently obtained of the voltages of the three main secondary batteries, supplemented by measurements carried out on the Buoy, have shown all three battery voltages to be fluctuating widely as the load varies. We believe this may have been happening for some months and may be due to a loss of battery capacity. It is to be noted that the batteries are cycled eight times a day, so they have been cycled more than 2,000 times since the Buoy was commissioned. We have now been informed that these secondary batteries cannot be expected to withstand more than about 1,000 deep cycles, and are consulting the manufacturers again to see whether more suitable batteries are now obtainable. It is possible that we may be able to dispense with the secondary batteries on two of the main power lines, if we can be sure that the load on these lines never exceeds the power available from the TMG.

5 Performance of other machines

Our experience with other thermo-mechanical generators has been good. The propane-heated laboratory machine shown in Fig 1 ran for 7,000 hours and is still in good condition (though it did suffer damage to piping when being taken by road from England to Iran). The radioisotope-heated laboratory machine was fuelled with Strontium-90 in November 1974 so has now been running continuously for two years. This is so far the machine with the longest running record.

One of the field-trial machines supplied to Messrs AGA was flown to Ottawa in the Summer of 1975 and was run in the marine light exhibition there. It was subsequently used for demonstrations at AGA and when it was eventually returned to Harwell a year later its operating parameters were re-checked and found to be identical to those measured before it was sent to Ottawa. On behalf of AGA this machine is now being up-rated at Harwell, and nearly 70W output has already been obtained with electrical heating. To deliver this power with propane will require a new burner design and some other modifications.

The machine supplied through AGA for Trinity House is being evaluated at Dungeness. As already mentioned, this machine also suffered a pentane leak, and modifications, similar to those described above have been carried out, to avoid a recurrence.

The spare machine for the National Data Buoy has been running extremely well in the laboratory. For reasons of which we are not sure at present, this burner is able to heat the machine to about 550° C so that the a.c. power output is well over 30W, and some 26W d.c. are being delivered into the three batteries. We plan to substitute this machine for the one in the Buoy in the Spring of 1977.

6 Conclusions

The TMG has been supplying power to the Buoy for 75% to 80% of the total time since commissioning. However, for 16% of this time the TMG was prevented from functioning by the absence of a propane supply, because of a single leak in the Buoy gas installation. The TMG has provided power to the Buoy for 90% to 95% of the time that propane has been available.

Virtually all of the 5% to 10% of down-time occurred while the TMG was waiting to have its gas cut-off valve reset. After manual re-setting of this valve the TMG never failed to re-start.

This field trial has revealed a few weaknesses, but these are mostly of a peripheral nature, and have resulted in modifications which should prevent recurrence. Clearly great care is needed in the design and assembly of the gas plumbing all the way from the Buoy tanks to the TMG burner, and also with the plumbing of the cooling system. We need to look at the electronic temperature sensing system to make it less susceptible to electrical disturbances from outside. Whether we shall suffer from progressive clogging of the gas jet, once we achieve really continuous operation, is still an open question, but experience with propane marine lights on the Clyde suggests that the problem is soluble if it exists.

The TMG on the Data Buoy is the first one to operate outside the laboratory on a continuous basis and the first to be put into service anywhere. To obtain better than 90% availability at this stage of development indicates the fundamental reliability of the TMG concept. This field trial has so far provided information about operation which could be obtained in no other way, and if we profit from the lessons learned we ought to be able to meet all the Buoy power needs with a margin in hand, and with a high probability of 100% availability.

Finally, I would like to express our appreciation to numerous members of the SEATEK staff and to our own John MacDonald, who have worked on the Buoy to supplement information provided by the telemetery and to do the work on the TMG which I have already described. I am told that conditions on the Buoy at sea are often hard to bear, and all concerned are to be congratulated for working in these conditions with resourcefulness, with care and, most important, with success.

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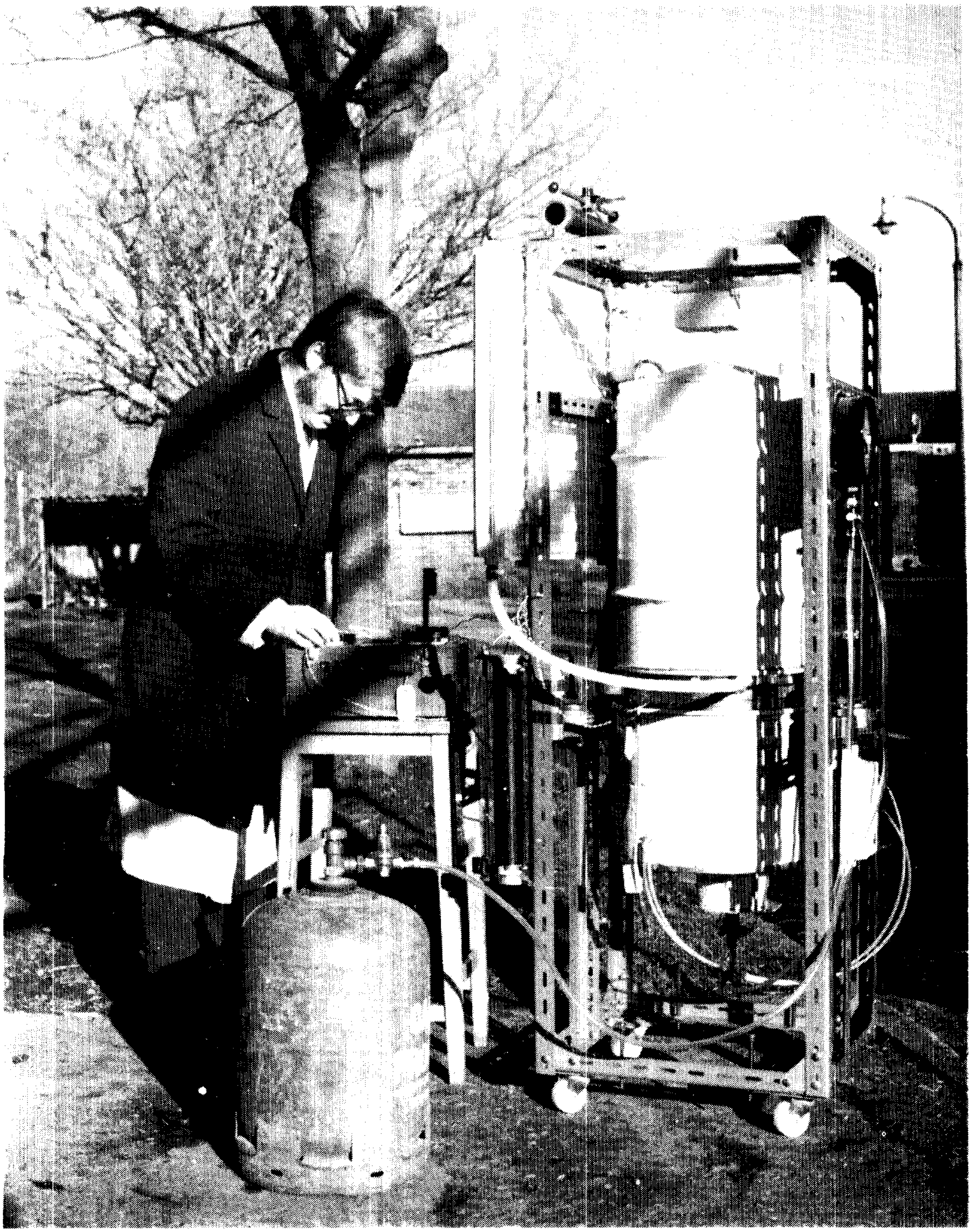

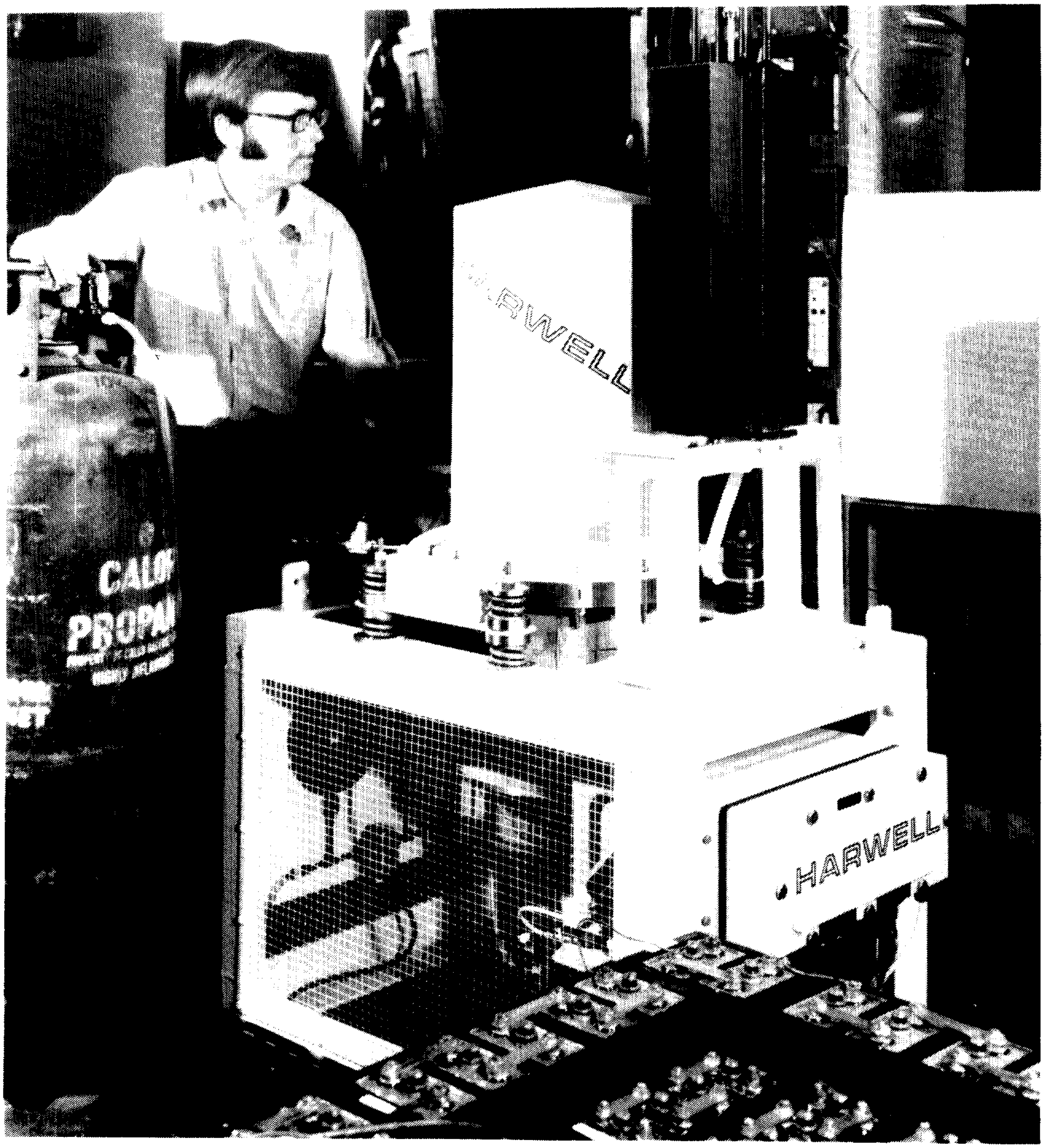

The Harwell Thermo-Mechanical Generator undergoing final test in the laboratory before installation in the National Data Buoy. The nickel-cadmium batteries in the foreground are charged by the TMG and provide power for the Buoy instrumentation and telemetery. The propane in the cylinder shown would be sufficient to fuel the TMG for four months. Tanks in the Buoy carry enough propane for two years continuous operation.

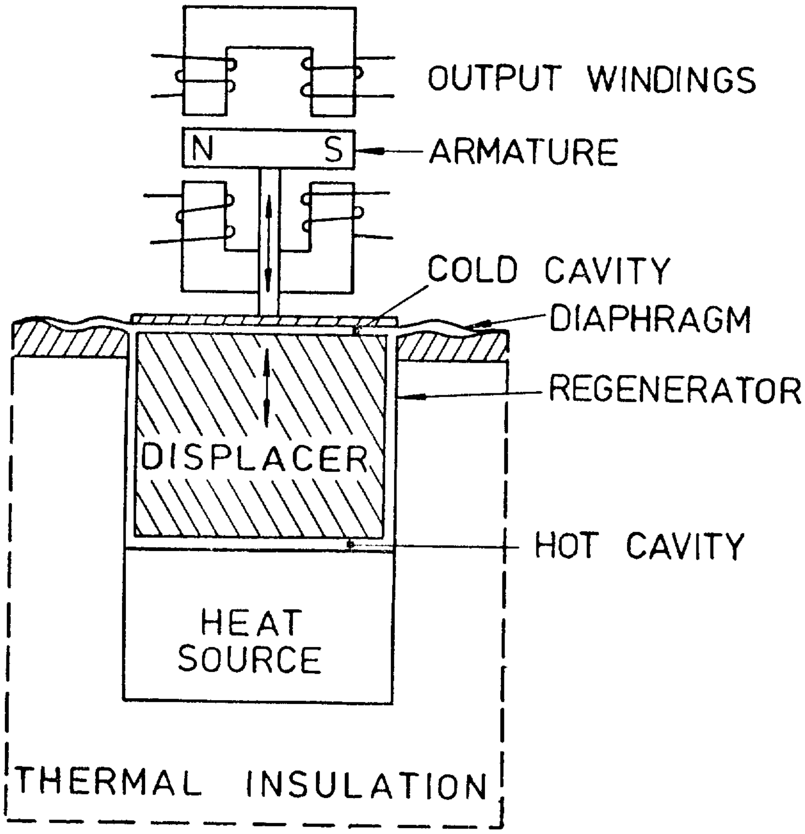

FIG. 3. DIAGRAM OF THIRD RESEARCH MACHINE.

MOTIONS AND MOORING FORCES OF THE DATA BUOY

R.M. Carson

Institute of Oceanographic Sciences

Introduction

From the beginning of the Data Buoy project, we have been very aware that the most critical and conspicuous failure would be a broken mooring. We found that no comprehensive theory existed for calculating buoy motions and mooring tensions in the sort of shallow water mooring which the prototype buoy would require, nor were there any relevant data from similar buoys. The experience of Trinity House, with LANBY navigation buoys, is of course comparable, and we were grateful for their co-operation and advice: however, they had not actually measured mooring tension on their buoys.

In this paper I will describe the steps we took, using model tests, to predict the mooring loads and to establish whether the motion of the buoy would allow it to be used as a measure of the directional wave spectrum. I will also give results from the buoy itself: the peak loads experienced have been larger than anticipated for the prevailing conditions. This I conceive to be a consequence of the shallow depth in which the buoy is currently moored, which reduces the mooring compliance.

1 : 24 model tests

The first model tests were done in 1972 in the IOS wave tank at Wormley; they are fully reported in Carson (1972). Operational requirements had determined us in the choice of a discus hull, and a three-point mooring was essential to allow cable connections to the sea-bottom instruments. Furthermore, we felt that in the interests of reliability and long-life a chain cable should be used throughout. The general lay out that was eventually adopted by Seatek under the guidance of Trinity House is shown, in true scale, in Figure 1.

The model motion was filmed and the wave-following ability of the hull estimated by a frame-by-frame analysis of a single wave cycle. We found that the pitch/roll motion was modified by the three-point mooring: if the chains were taken to the centre point, the buoy was underdamped and showed a pitch resonance. If the chains were made to the deck or to the upper break of the chine, the hull was restrained and failed to follow the wave surface. Attachment at the chine bottom was the most satisfactory, giving something approximating to critical damping. We noticed a tendency of the buoy to clip the crests of sharp waves; this is the inevitable averaging effect of the finite buoy diameter, which becomes less significant in longer waves.

We also measured peak mooring tension, using a miniature spring balance in the leading chain.

We were unable to study extreme wave conditions at a sensible scale; in practice, we were able to simulate waves up to 6 m in height, and having periods in the range 1.5 - 8.5 S. Beyond this we were forced to extrapolate in both height and period, obtaining an estimated peak mooring force of 28 - 30 t in 18 m waves of 15 S period; the current being 2.5 m/s (5 kts) (Fig. 2). This value was used in the actual mooring design. Note that this work was all done in a scale depth of 40 m, appropriate to the original Smith's Knoll site.

1 : 10 model trials

We were naturally unhappy with the extrapolations in Fig. 2, and determined to extend our tests by using a larger model in a real seaway. The model was 1 : 10 scale, and contained a pendulum-stabilised heave accelerometer (Clayson and Smith 1974) and three strain gauge load cells measuring tension in the mooring legs. Data was recorded internally on a 2 channel FM tape recorder: the tension channel was switched alternately to each leg, once in 20 minutes. The mooring was correctly modelled using light boat chain, clumps, and Danforth anchors. It was laid by divers to a high geometric accuracy (Lawford 1975).

The chosen site for the experiment was the West Pole bank off the entrance to Chichester Harbour. This site offered the correct depth at mean tide, a range of currents, and a suitable range of wave heights. We were also able, by courtesy of the Chichester Harbour Authorities, to use the West Pole Tower itself as a base for filming the model buoy and for mounting observations of current speed and direction.

We found that these tests were more difficult to perform than we had anticipated. It was barely possible to work in the wave heights (>1 m) which we required, and the Chichester Harbour bar offered an additional hazard en route to the site. Finally, the simultaneous occurrence of the right conditions of tide, waveheight, and lack of fog was surprisingly rare.

The analysis of our best 20 minute record shown in Fig. 3 as spectra of heave displacement and mooring tension. The scales have been converted to hull size values; the main wave energy was at 5 S period in the actual experiment. The peak load obtained during the run was equivalent to 7.5 t full size in a peak wave height of 7 m: the scale current was 0.6 m/s (1.2 kts).

In Fig. 4 I have plotted the transfer function, mooring tension/wave height, as a function of wave period. Despite a large scatter, there is a definite trend to higher values at short wavelengths. When we combine this with the maximum probable wave height at each frequency, derived from North Sea Wave data (Carson 1972), we obtain a near flat response, with maximum loads in the range $5\frac{1}{2}$ - 7 t. Extrapolating to 3.72 S period, the transfer function is 1.2 t/m. i.e., a 2.5 m wave gives 1.2 x 2.5 = 3 t tension in 0.6 m/s current. In a current of 1.0 m/s the 1 : 24 scale trials predict 5.2 t in the same wave conditions - this difference seems quite reasonable.

The filmed model motion was compared with the 1 : 24 tests. We found that the character of the motion was similar; the buoy followed well with no obvious resonance, but clipped the shorter wave crests.

Full size measurements

The Data Buoy offers a unique opportunity for a controlled mooring experiment, since the environmental parameters, including surface current, wind and waves, are being regularly sampled. We determined to sample and hold peak tension during each hour; and we have also recorded mean tension averaged over 15 minutes in each hour.

The load cells were made by the British Hovercraft Corporation Ltd., with the collaboration of IOS and Seatek. Each cell is machined from Inconel alloy, and the signal is converted to frequency by circuitry mounted on the cell before feeding to the buoy hull. Two of these cells have given satisfactory service throughout the buoy's deployment: the cable of the third was damaged on installation and it has not been available.

A southerly gale in September 1976 has produced the highest loads observed to date. (An initial load of 30 tons immediately after lay probably indicated excessive preload in the mooring, relaxed by anchor dragging). The record (Fig. 5) shows a peak load at 1200 hrs of 25 t, with mean loads of 3 - 4 t. These loads occurred in the southerly leg. The conditions at the time were all combining to load this leg, viz.

a) Current, 1.5 m/s (3 kts) N (E-W component negligible)

b) Wind, 20-25 kts, SSW (direction steady)

c) Waves, from the south, significant height 1.4 m
probable max. height 2.5 m
Mean period 4.7 s

Several features of Fig. 5 are of interest:

1) From 0200 onwards the southerly wind rose steadily (and consequently the sea state also); the southerly tension only rose at 0900, when the current reversed. This indicates the dominant role of current in determining both mean and peak loads.

2. After 1200 the mean loads drop steadily away, apparently with the fall in current. However, the peak loads drop quite dramatically. It is particularly interesting that the waveheight and period at 1500 are the same as at 1200, yet the peak load registered is 6 t instead of 25 t. In the same period the Northerly current drops from 1.3 m/s to 0.8 m/s.

3. Tidal height appears to be much less important than current.

4. For comparison, Fig. 6 shows a record in which an easterly gale is blowing across the N-S tidal current. The southerly leg shows mean and peak tensions very close to the no-wind values.

Discussion

The peak load observed in Fig. 5 is, of course, much greater than the model tests had predicted. The 1 : 24 scale tests suggest somewhat less than 5.3 t at 2 kts, or about 7.5 t at 5 kts. The 1 : 10 scale tests are at 1 kt; Fig. 4 gives a transfer function of 0.94 at 4.7 S period, or a peak load of 2.3 t in 2.5 m waves. The model tests are, it seems, mutually consistent, but fail to predict the observed behaviour.

I believe that the excessive peak tension, and its abnormal dependence on current, both arise from the reduced compliance of the mooring in 20 m depth, as compared with 40 m. In Fig. 7 I show calculated force/displacement curves for horizontal motion of the buoy;

a) for a single mooring leg acting alone,

b) for a three-point mooring with two values of preload, 1 t and 2 t.

The effect of preload is to reduce the mooring compliance and to diminish the horizontal surge available to cope with wave motion. The effect, however, is far more severe in the shallower depth; with 2 t preload the buoy can only move 3 m before coming up hard on the mooring.

The effect of the mean load, due to current, wind and mean wave forces, is to displace the mean position of the buoy further along this curve. Taking this mean load as 4 t (from Fig. 5), we see that the mean displacement is 2 m; and the remaining displacement available is only 1 m. By contrast, under the same conditions, in 40 m depth, we have about 4 m at our disposal. Curiously, the comparison is very similar with a 1 t preload.

This extreme non-linearity of the mooring compliance gives a qualitative explanation of the observed peak loads. Firstly, a small increase in mean force due to current, plus a displacement of the buoy proportional for example to wave amplitude, gives a gross increase in peak load. Secondly, the model tests performed in 40 m scale depth have a much greater compliance than the present 20 m mooring, and this may account for the very different peak loads.

To make quantitative deductions of peak load from the force/deflection curve alone is not possible, and one would ideally go to a full numerical simulation of the buoy/mooring dynamics. However, one can learn something by considering the energy absorbed by the mooring catenary.

Suppose the preload on the mooring is 1 t; taking the mean load as 4 t the available deflection S is 1 m. The energy absorbed in reaching a peak load of 25 t is equal to the buoy kinetic energy - i.e.,

$$\bar{F}s = \frac{1}{2}mv^2$$

from which we may deduce that the buoy velocity v is approximately 2.4 m/s. The wave particle velocity in 2.5 m, 4.7 s waves is 1.7 m/s; however, it is colinear with the current velocity of 1.3 m/s giving a total of 3.0 m/s., so that a buoy velocity of 2.4 m/s, though large, is not impossible.

If we assume the same buoy energy to act on the same mooring in 40 m of water, we find the buoy moves $\sim$ 2 m, with a peak load of $\sim$ 10 t; this is still large, but is more nearly comparable with the model tests.

Conclusions

The mooring performance in waves depends primarily on its available compliance. This is reduced by preload and by current, and these need to be carefully controlled and measured in any model trials. A limitation of model trials at sea, such as our Chichester Harbour work, is that current is an uncontrollable variable: in our case we needed higher currents than were available, and we can only make crude estimates of the effect of a change of current.

The mooring compliance is also drastically reduced in shallower depths. At its present site the buoy mooring is far less resilient than it would be in 40 m of water. This is resulting in high peak loads, not predicted by the deeper water model tests. Although the wave conditions are depth-limited in 20 m of water, there must be a possibility of overload which will drag the leading anchor and gradually relax the mooring. Future moorings in this depth might be improved by (a) clumps near to the buoy or (b) springs of nylon warp in the moorings themselves. The problem becomes less severe in deeper water.

Acknowledgements

The model tests were supported by many people at IOS, notably C. Hunter, C. Clayson, J. Ewing, A. Madgwick, V.A. Lawford, S. Willis and members of the IOS diving team.

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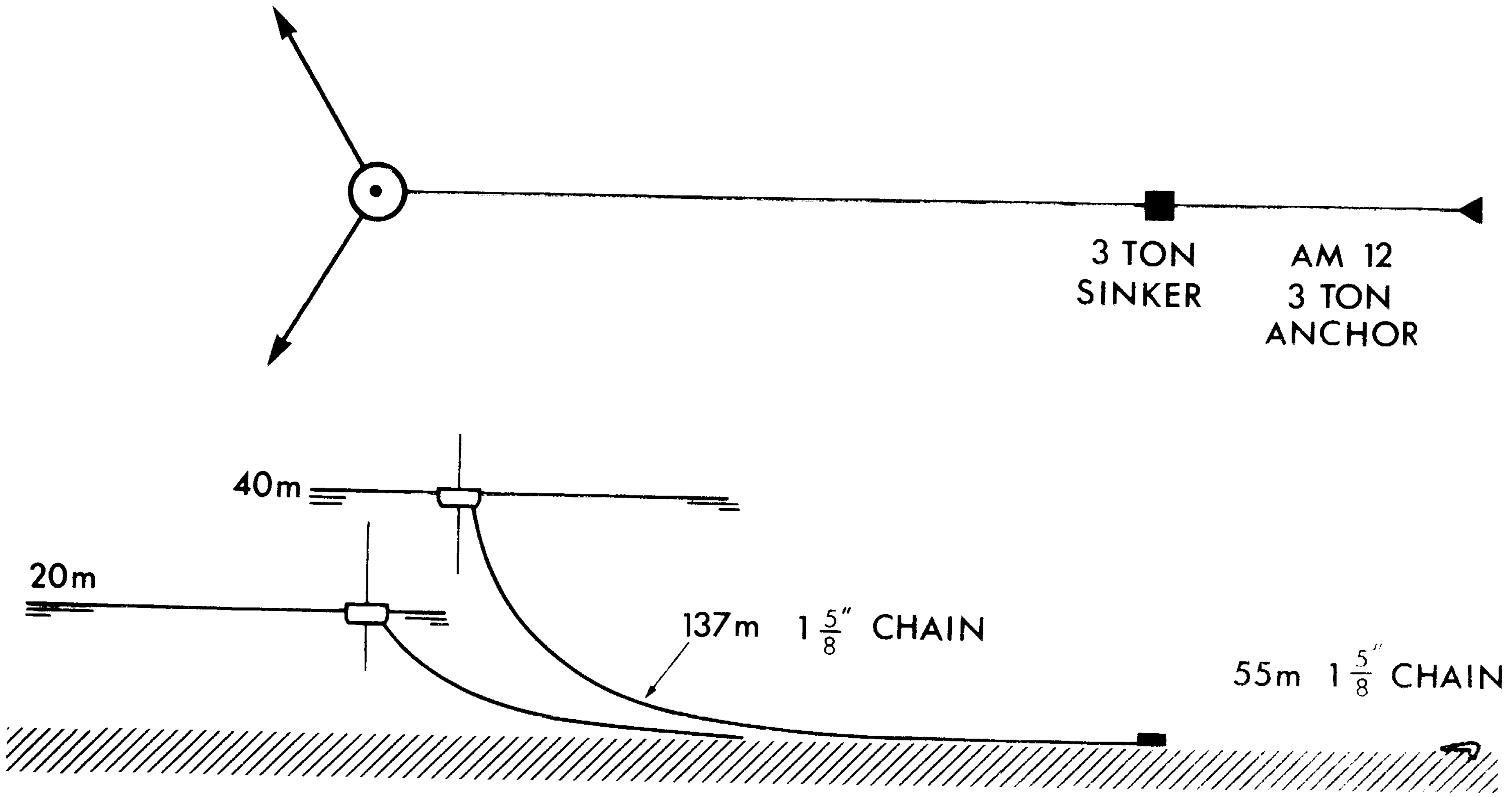

Fig. 1 General arrangement of DBI three point mooring, showing geometry at two depths, 20 m and 40 m.

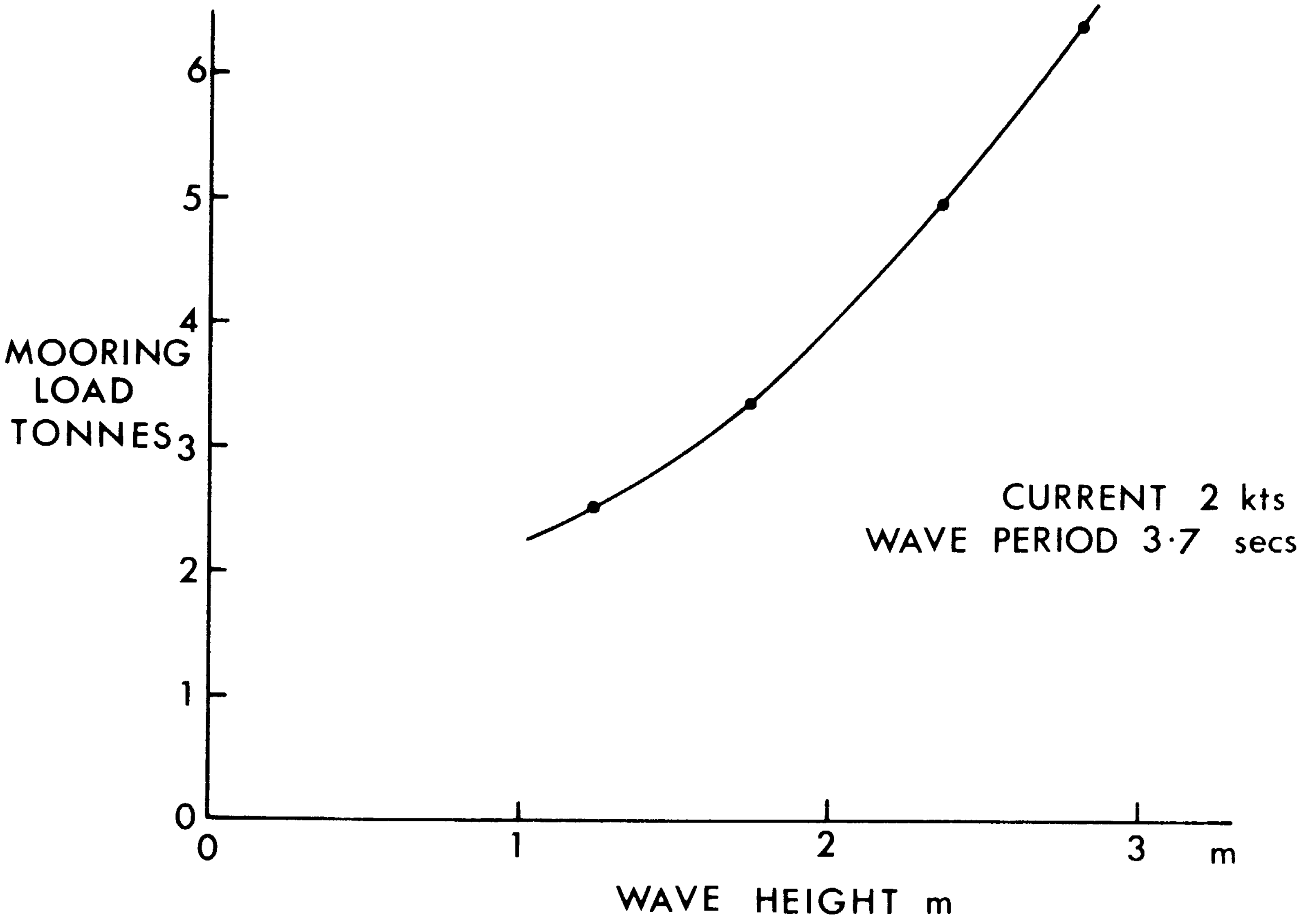

Fig. 2(a) Maximum mooring loads derived from 1 : 24 scale model tests.

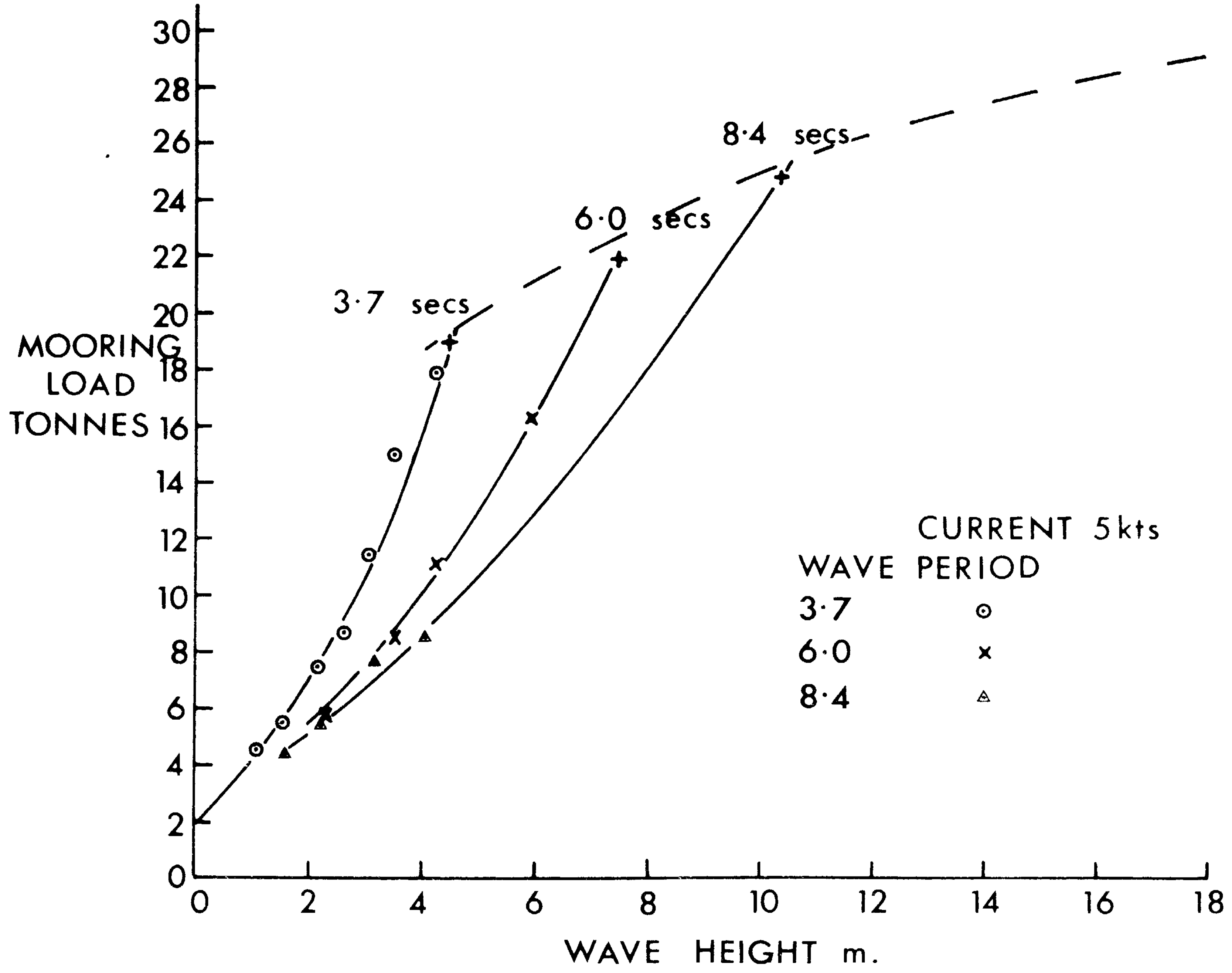

Fig. 2(b) Maximum mooring loads derived from 1 : 24 scale model tests.

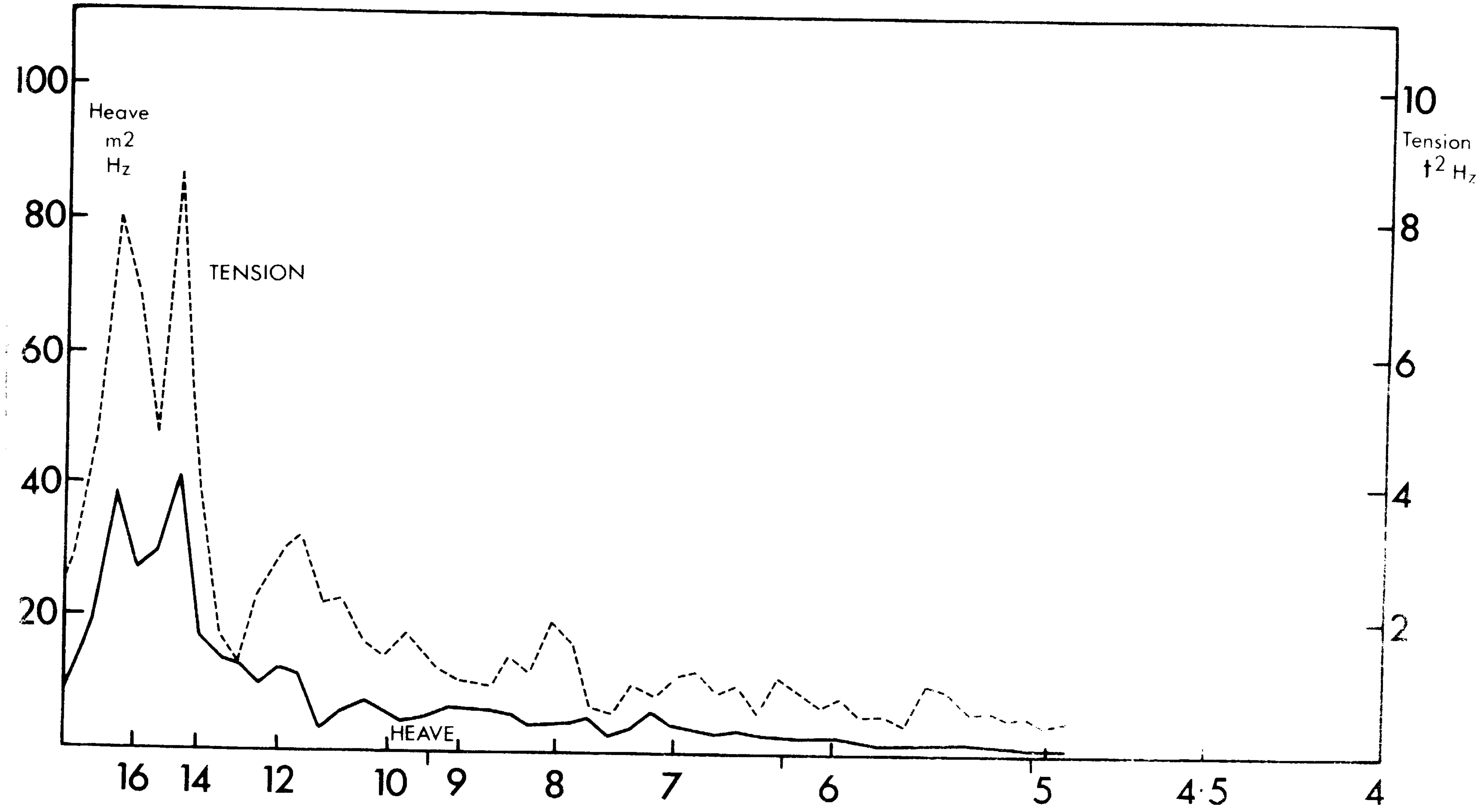

Fig. 3 Mooring tension and heave spectra derived from 1 : [illegible]
scale model tests.

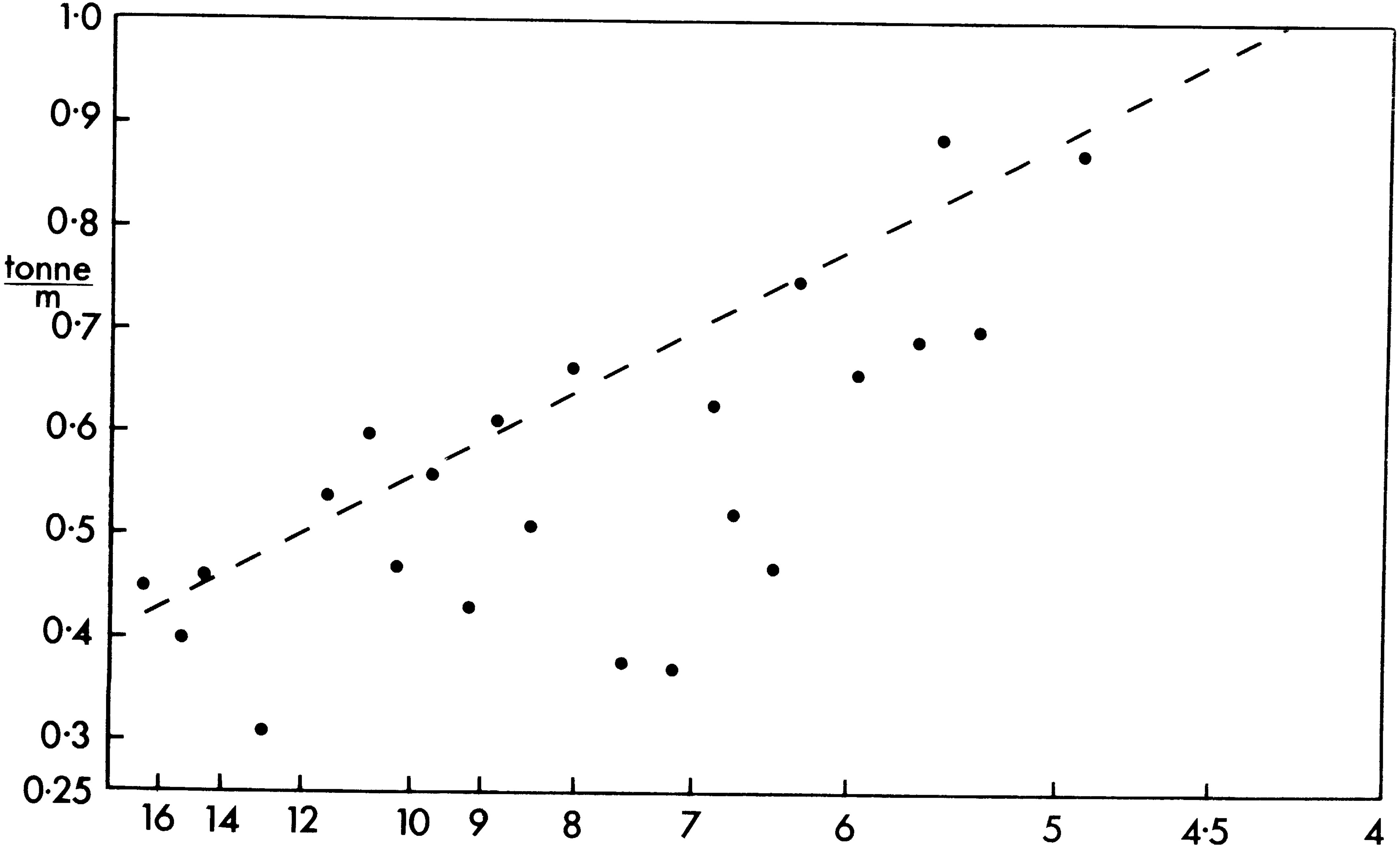

Fig. 4 Buoy transfer function (tension/heave) derived from spectra.

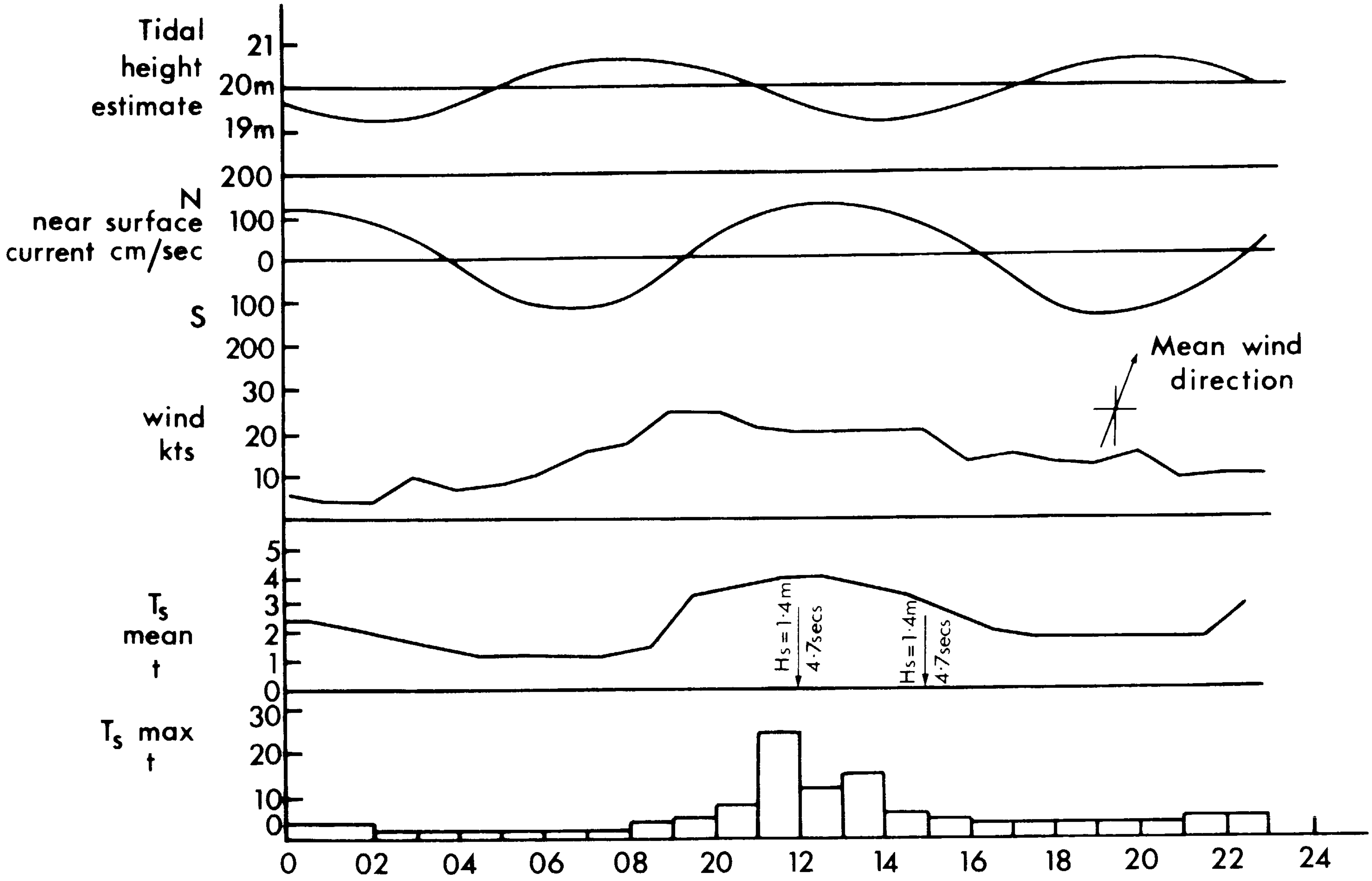

Fig. 5 Data from DBI showing high peak load 1200 Day 295 Wind SSW

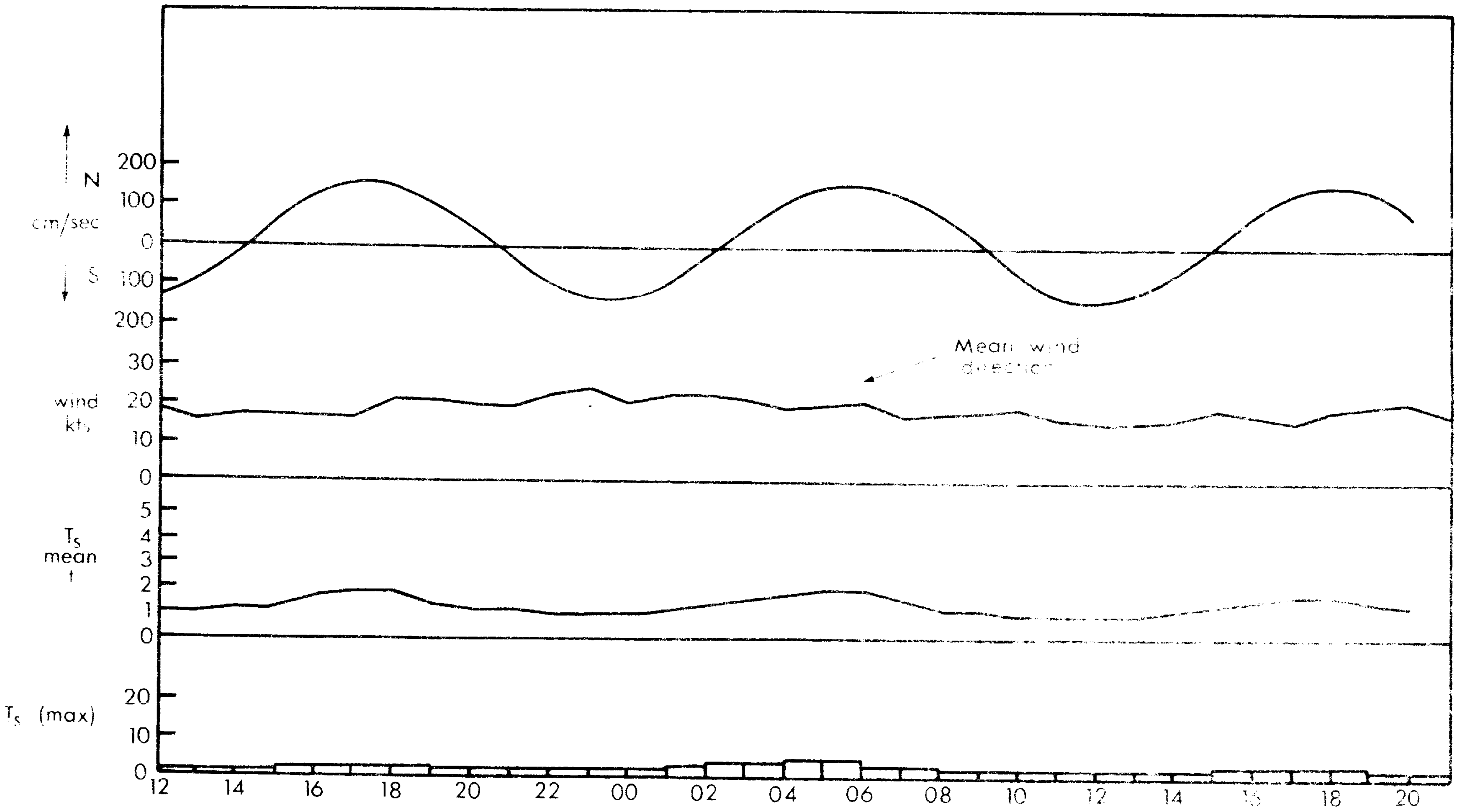

Fig. 6 Data from DBI showing low loads Day 65 on wind [illegible]

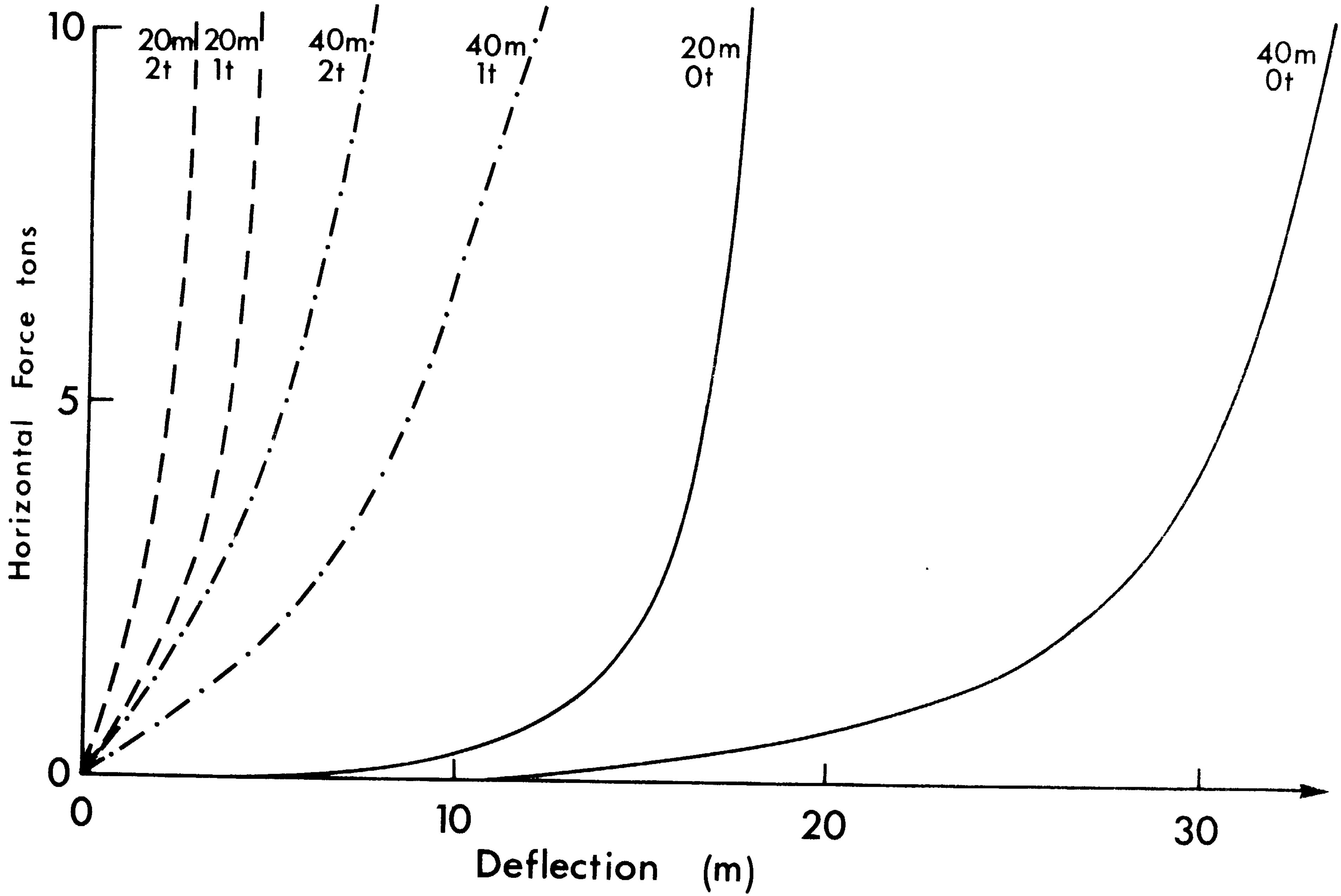

Fig. 7 Mooring catenary stiffness in 20 m and 40 m depth, showing effect of preload.

UK Data Buoy (DB1) Symposium: 23 November 1976

The buoy as a directional wave sensor

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Estimates of the integrated statistics of the vertical and angular motions of the data buoy are compared with results obtained using a pitch-roll buoy. Wave directional characteristics obtained from the two systems are also compared.

Introduction

Data on wave height spectra are often used by engineers in the design of ships and ocean structures. There is however an increasing requirement for wave directional information especially in the design of platforms and wave energy devices which are sensitive to changes in wave direction. Routine directional wave spectra measurements are not yet generally available and almost all such measurements have been made during research programmes such as JONSWAP (Hasselmann et al., 1973). One of the most successful methods for obtaining directional wave spectra information in the open ocean is by measuring the vertical acceleration and slopes of the sea surface using a surface following pitch-roll buoy. The UK data buoy has been designed to follow the sea surface so that in principle it should also be possible to obtain wave directional information in a similar way to that employed when using a pitch-roll buoy. This paper shows the extent to which this intention has been realized.

Measurements

The intercomparisons between the data buoy and an IOS pitch-roll buoy (Clayson and Smith, 1970) were made during a cruise of the M.A.F.F. Research Vessel 'Clione' in March 1976. The test site of the data buoy at 52°23.8'N, 1°48.2'E lies about 6 km off the Suffolk coast in a water depth of 20 m. The heave, pitch and roll sensors used in the data buoy were developed by Datawell, N.V. The cruise was devoted primarily to float tracking described in the paper by P.G. Collar and J.W. Ramster (to be presented at this meeting) and pitch-roll buoy recordings were made when convenient.

Conditions for the three intercomparison measurements are shown in Table 1. The wave conditions were those generated by off-shore winds over short fetches and therefore consisted of steep waves with lengths less than about 40 m. Measurements with an acoustic current meter on the data buoy confirmed the presence of strong tidal currents.

Table 1

	Record date and time (data buoy)	Average wind speed and direction*	Current speed and direction*
Comparison 1	28 March 1976, 0900 hrs	7.5 m/s, 060°	0.55 m/s, 203°
Comparison 2	29 March 1976, 0900 hrs	10 m/s, 030°	0.85 m/s, 199°
Comparison 3	31 March 1976, 1500 hrs	13 m/s, 060°	1.38 m/s, 019°

The pitch-roll buoy recordings were made at times coincident with the data buoy's wave data sampling routine and were carried out within about 2 km range of the data buoy. The records started with the pitch-roll buoy upstream of the data buoy so that the pitch-roll buoy drifted past within about $\frac{2}{3}$ km of the data buoy. This minimum separation was necessary to allow safe room when manoeuvring the R.V. 'Clione' to keep the pitch-roll buoy cable slack. During the comparisons, Decca fixes, wind speed and direction were recorded on R.V. 'Clione'.

Principle of the analysis

The principle of the pitch-roll buoy in its earliest instrumental form has been described by Longuet-Higgins et al. (1963). The buoy measures the two components of surface slope (after correction of the pitch and roll signals with the compass reading) with respect to true North-East axes and vertical acceleration. The one dimensional wave height spectrum is then obtained from the spectrum of vertical acceleration by division by $(\text{frequency})^4$. Various approximate forms for the directional distribution of wave energy have been proposed in terms of the first four angular harmonics a_n, b_n $(n = 1, 2)$ of the directional distribution (a_n and b_n depend on the co- and quadrature spectra of appropriate pairs of signals selected from acceleration and slope records). However two simple directional parameters which are often used are

(i) the mean wave direction $\theta_1 = \arctan(b_1/a_1)$

and (ii) a directional spread parameter $\theta_2 = \sqrt{\left[2 - 2\sqrt{(a_1^2 + b_1^2)}\right]}$.

For a wave spectrum with a narrow directional beam θ_2 is equal to the r.m.s. directional spread about the mean direction θ_1.

If we assume the data buoy follows the wave surface we may also use the above method with the exception of wave elevation which has already been obtained by electronic integration of the acceleration.

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*Wave, wind and current directions are referred to as the directions towards which the appropriate variable was travelling with respect to true North.

Method of analysis

The co- and quadrature spectra of the three series (after correction for buoy heading) were computed using the Fast Fourier Transform (FFT) algorithm. The total record length was divided into a number of non-overlapping sections each of length T sec and the spectra evaluated by taking the FFT of each section and averaging over the M sections. This process yields spectral estimates at $^1/T$ Hz intervals with 2 M degrees of freedom.

Measurements from the pitch-roll buoy were recorded at 0.5 sec intervals for 25 mins. while the measurements from the data buoy were obtained at 1.2 sec intervals for 20 mins. For comparative purposes it was decided to evaluate the spectra by choosing the number of data points used in the FFT method to give almost identical spectral resolution. Table 2 sets out the details of the values used in the analysis.

Table 2

	Length of section T (sec)	Spectral resolution (Hz)	Total no. of sections (M)	Degrees of freedom	95% confidence limits
Data buoy	129.6	0.00772	7	14	0.55, 2.4
Pitch-roll buoy	128	0.00781	11	22	0.59, 2.1

Results

Comparisons between results from the pitch-roll buoy and the data buoy were made difficult because of the short wavelengths generated by winds blowing over a short fetch and also because of strong tidal currents. Most of the wave energy was observed to be concentrated in the range of wavelengths from about 25 m to 40 m which is comparable to the 7.6 m diameter of the data buoy but much larger than that of the 1.2 m diameter pitch-roll buoy. The comparisons that have been made therefore represent a severe test of the data buoy in conditions which would not normally be observed in more exposed locations or in the open ocean.

The influence of tidal currents results in a Doppler shift of waves observed by the pitch-roll buoy compared to the moored data buoy. Methods for transforming wave spectra from a fixed to a moving frame of reference are well known in ship motions studies (St Denis and Pierson, 1953). The transformations are always much easier to make when going from the fixed to the moving frame of reference especially in the case of comparison 3 where the waves and tidal current are travelling in almost the same direction. For this reason all data buoy wave spectra have been transformed to those in a frame of reference moving with the current.

The heave resonance of the data buoy, estimated at 0.6 Hz, does not appear within the measured spectral range and there is no evidence of increased heaving motion at the highest frequencies obtained in the analysis. Model tests and full-scale observations confirm that the heave motion is well damped. For the pitch and roll motions the estimated resonances at 0.45 Hz are again outside the measured spectral range and there is no evidence for increased energy in these motions at high frequencies confirming that the angular motions are well damped by the three-point mooring.

Table 3 compares the significant values of the wave height and the two angular motions. (The significant value was obtained from $4 \times \sqrt{(\text{area under the spectrum})}$. This value is the same in a fixed or moving frame of reference). Table 3 shows that in all cases the data buoy motions are less than those of the pitch-roll buoy, the average difference being about 15%.

Table 3

Significant value	Comparison 1		Comparison 2		Comparison 3	
	P-r buoy	Data buoy	P-r buoy	Data buoy	P-r buoy	Data buoy
Wave height (m)	0.50	0.43	0.88	0.68	0.99	0.84
Slope: N-S (deg)	6.7	6.4	11.3	8.1	7.8	7.6
Slope: E-W (deg)	5.0	4.2	7.4	5.9	5.2	4.6

Comparisons of wave spectra and directional parameters are shown in Figs. 1-3. The upper diagram in each figure shows the data buoy and pitch-roll buoy wave spectra together with the data buoy spectra transformed to axes moving with the observed current. This transformation has been made over the main energy containing region assuming that the waves are travelling in the mean wave direction θ_1 (at each frequency) and also that the angular spread, θ_2, is small. The transformed data buoy wave spectra are lower than those of the pitch-roll buoy in accord with the differences in significant wave height given in Table 3. In the case of comparison 2 the spectral differences between the two systems lie outside the 95% confidence limits for the computations.

The mean wave direction θ_1 is compared at each frequency in Figs. 1-3. The Doppler shift due to tidal currents results in a shift in the data buoy values to higher frequencies in comparisons 1 and 2 and to lower frequencies in comparison 3 as indicated by the broad arrows at the peaks of the wave spectra. (The magnitude of θ_1 is not altered by the transformation). This shift is rather small in the case of comparisons 1 and 2 and is therefore not shown in Figs. 1 and 2 and there is clearly close agreement between the two systems. However for comparison 3 the shift is much larger and when taken into account gives good agreement between the two recording systems. At high frequencies θ_1 from both data buoy and pitch-roll buoy agree with the observed wind direction.

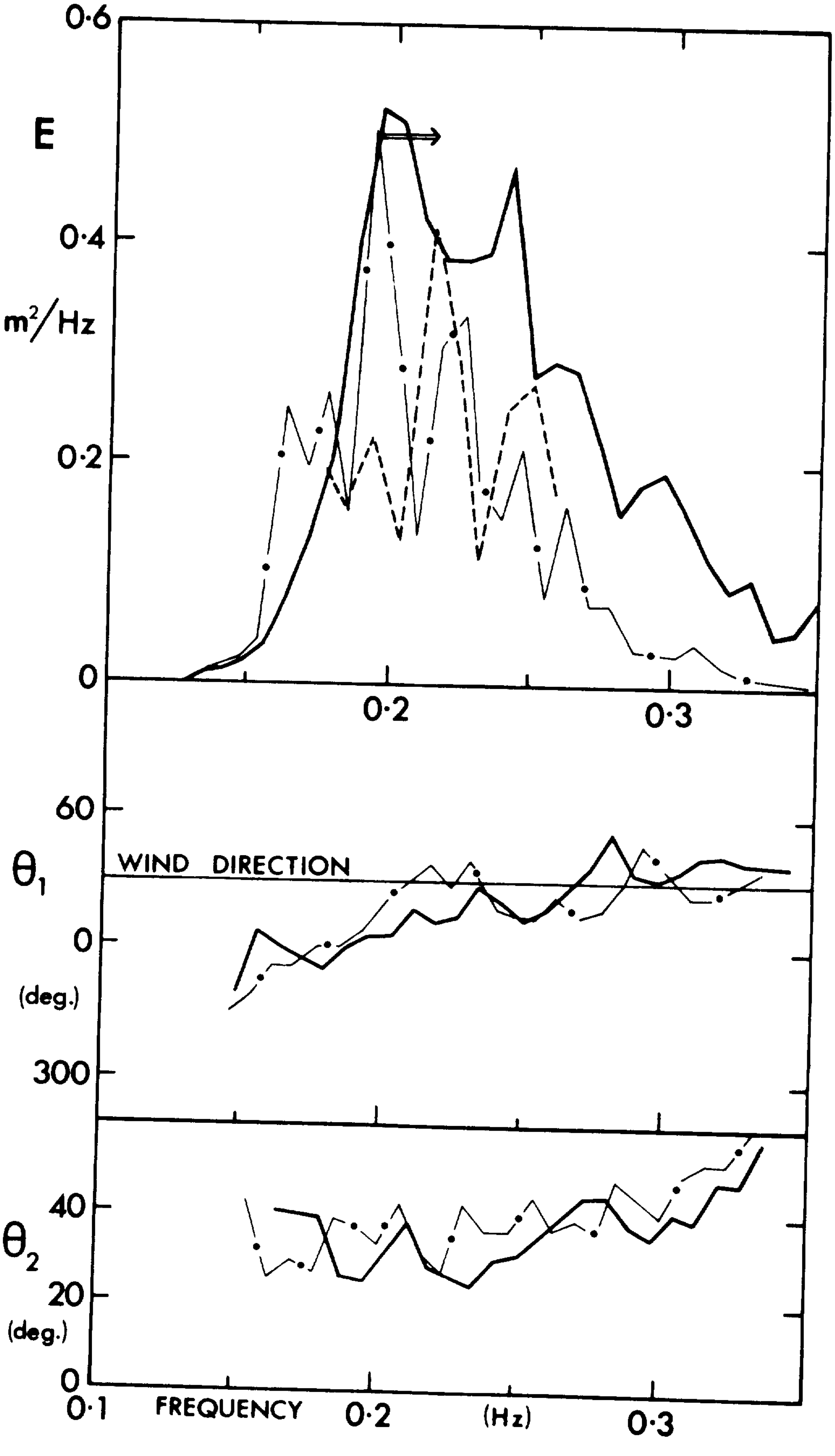

Fig. 2. Comparison 2 of wave spectra, E, and directional parameters θ_1 and θ_2. The arrow indicates the shift of the data buoy spectral peak to the frame of reference moving with the current.

Pitch-roll buoy ▬▬▬▬▬▬▬▬

Data buoy ——— • ——— • ——— • ———

Data buoy transformed to moving reference — — — — — —

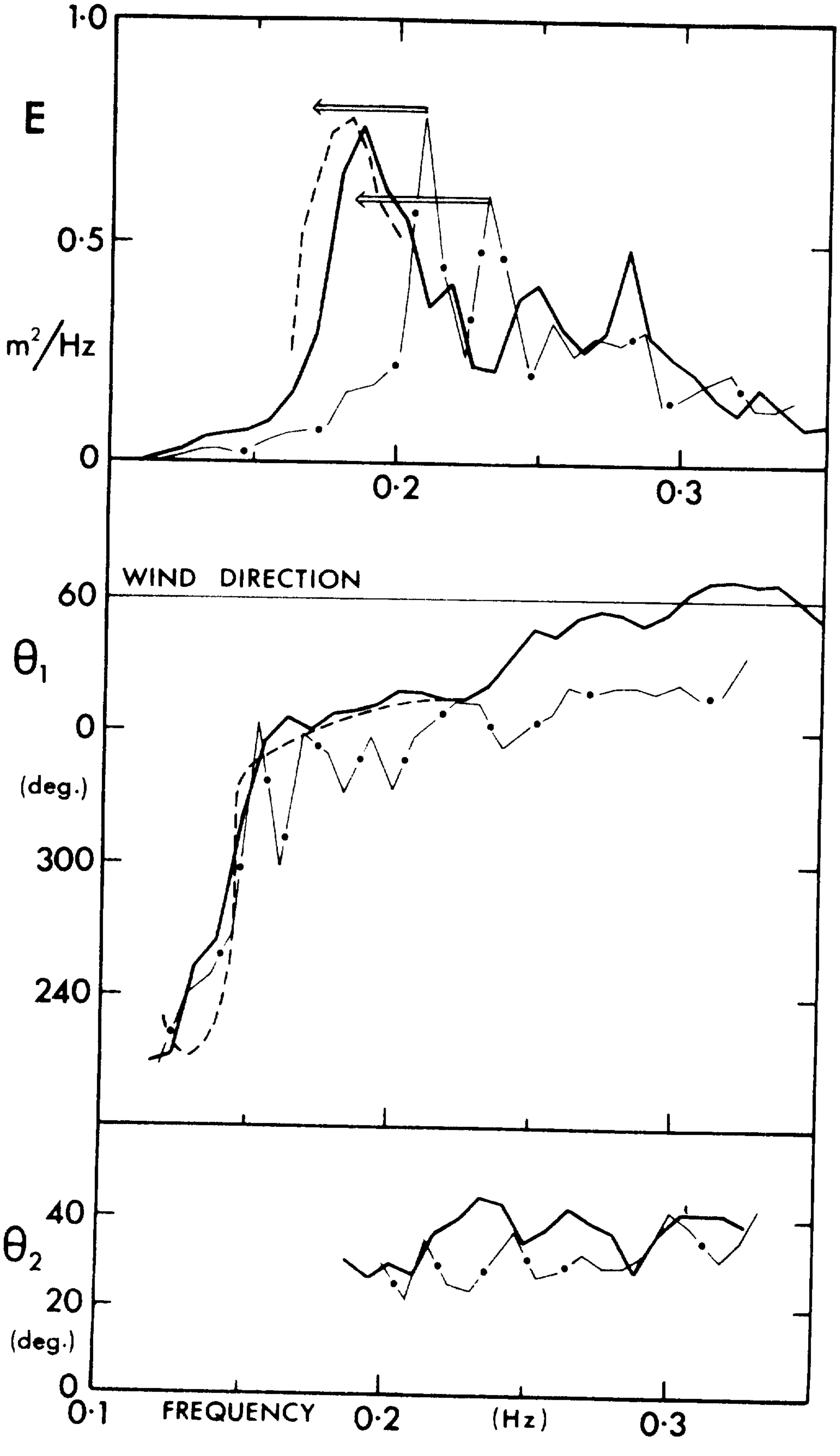

Fig. 3. Comparison 3 of wave spectra, E, and directional parameters θ_1 and θ_2. The arrows indicate the shift of the data buoy spectral peak to the frame of reference moving with the current.

Pitch-roll buoy ————————

Data buoy —— • —— • —— • ——

Data buoy transformed to moving reference – – – – – –

Comparisons of the directional spread θ_2 are made in the lower diagram of Figs. 1-3. Values of θ_2 exhibit a large degree of scatter from both systems but the trend of variation of θ_2 with frequency is in general agreement.

Conclusions

The significant wave heights measured by the data buoy at this coastal site were about 15% lower than those obtained by the pitch-roll buoy. Most of the wave energy during the comparison measurements was in the range of wavelengths from 25 m to 40 m, that is, about three to five times the data buoy diameter. From experimental and theoretical studies it is known that a discus-shaped buoy will closely follow the wave surface for wavelengths greater than five buoy-diameters; in shorter wavelengths the buoy tends to cut through the sharper wave crests with a reduction in vertical displacement. This effect can well explain the measured reduction of about 15 cm in displacement in these short, steep waves. In a deeper and more exposed site where the waves are higher and longer this difference is unlikely to be significant.

Measurements of significant wave slopes from the data buoy were about 15% lower than those obtained by the pitch-roll buoy. In this case the reduction of the pitch and roll motions is likely to be due to restraints caused by the three-point mooring. This effect will not be important for a mooring in deep water.

The mean direction of the waves from the data buoy agrees closely with that obtained from the pitch-roll buoy and, at higher frequencies, with the wind direction. There was a large degree of scatter in the directional spread parameter from both systems but the general trend of variation is in agreement.

Acknowledgements

The authors wish to thank the officers and crew of R.V. 'Clione' for their capable assistance and Mr K.G. Birch of I.O.S. for making the measurements.

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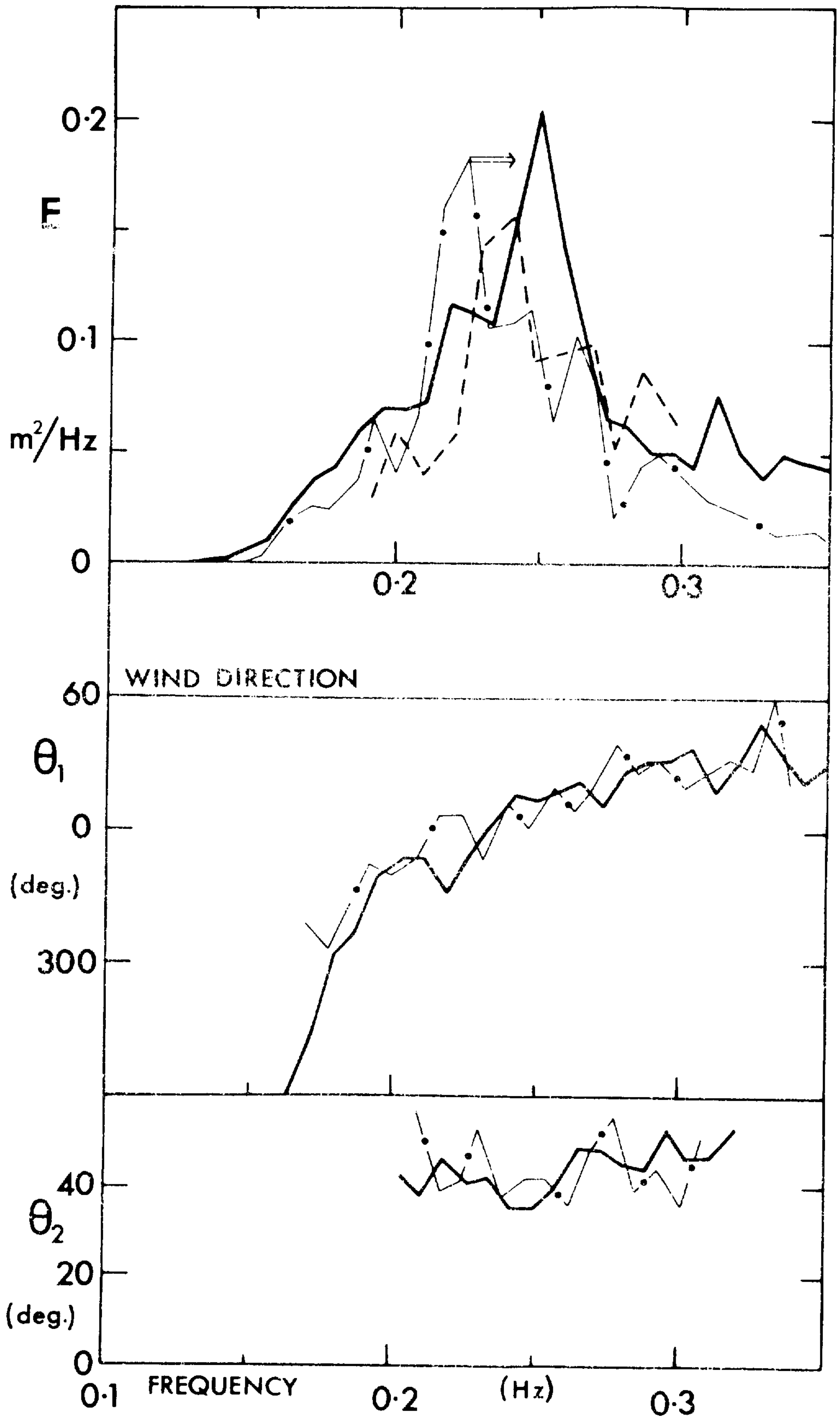

Fig. 1. Comparison 1 of wave spectra, E, and directional parameters θ_1 and θ_2. The arrow indicates the shift of the data buoy spectral peak to the frame of reference moving with the current.

Pitch-roll buoy ————————————

Data buoy ——— ● ——— ● ——— ● ———

Data buoy transformed to moving reference — — — — — —

AN ASSESSMENT OF THE METEOROLOGICAL SENSORS ON DB1

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Introduction

The increase in offshore activities, particularly in oil and gas field exploration and exploitation, has led to an increase in the requirements for weather and sea state forecasts, and climatological data for design purposes. The areas principally concerned are "data sparse" and it is likely that the data from traditional sources such as lightships and coastguard stations will decline as automated systems replace manned units. This is only one aspect of a general situation in which a variety of factors, mainly economic, are leading to a steady decrease in the flow of data from ocean areas.

The Meteorological Office is therefore looking for ways of supporting automatic weather stations (AWS) in a marine environment, and valuable experience is being gained through its participation in the DB1 project. In particular the buoy has provided a suitable platform on which sensors can be evaluated.

The paper briefly describes the sensors used on DB1, the reliability both from technical and operational standpoints and the accuracy of the sensors. In the final section, the conclusions which have been reached at this stage are presented.

Description of Sensors

The meteorological variables measured are temperature, pressure, humidity, wind speed and direction, visibility, rainfall and sea-surface temperature. Details of these instruments are given in Table 1, but some additional details are given below.

Humidity is measured by a hygrometer (Folland 1973) in which the electrical resistance is a function of the relative humidity. The element, with a protective cellulose sleeve, is mounted in a special holder (see figure 1(a)). Both the humidity and temperature elements are housed in a specially designed glass-fibre screen (see figure 1(b)) mounted on the upper rail.

Air pressure is measured by an aneroid barometer with a differential transformer transducer. In strong winds, the error due to the wind's dynamic pressure can be significant and a moving vane static pressure head (similar to that used at land AWS), designed to reduce this effect to an acceptable level, is fitted.

Wind speed and direction were averaged over 5 minute periods. This is particularly important in respect of wind direction since the basic resolution of the Graycode shaft encoder is only $22\frac{1}{2}^{\circ}$. This output is sampled continuously, and the results are averaged exponentially to produce an output resolution of 1.41°.

Visibility is measured using a Plessey Point Visibility Meter (PVM) (Winstanley and Adams 1975) which utilises the forward scatter of light by the atmospheric aerosols at a fixed angle ($\sim 34^{\circ}$) (see figure 2(a)). Aerosol concentration is related to atmospheric attenuation co-efficient (σ_V) and hence visibility (V) by the relationship $V = 2.996/\sigma_v$ Km, where $\sigma_v = 11.0686D - 0.1013$, and D is the output of the instrument in the range 0-5V. Assumptions on particle sizes, etc, are implicit in these equations, and thus the instrument will not necessarily give valid readings for all meteorological conditions. Four spikes were mounted on the instrument to try and discourage sea-birds resting on it and fouling the optics (see figure 2(b)).

The raingauge, based on an RAE design was specially built for this project. The funnel leads to the main chamber which fills with liquid, electrical contact with a probe is made, and a peristaltic pump removes a fixed quantity (equivalent to 0.1mm rainfall) of liquid. A count of the number of pump operations gives a cumulative total.

For all sensors, waterproof plugs and sockets are used, and Elasomer applied where possible, to protect parts liable to corrosion. The Meteorological Office has also provided the interface boards, which power the sensors and convert the sensor outputs into digital or voltage signals. These are mounted in a single 19" rack-mounted waterproof case.

Reliability

a. Of the Sensors : Table 2 lists the number and types of faults experienced by each sensor since installation. Both sensor and interface faults are included in the table. During the period under consideration, from 30 November 1975 to 1 October 1976, the buoy has been subjected to winds of up to about 70 kn without physical damage to the sensors or their mountings. In the period, the temperature sensors have not be changed and only the raingauge has required more than one service call. The visibility, humidity and wind direction faults have been in the sensor element (the first two of these were results of faulty installation procedure) whilst the barometer failure was in the power supply. The reason for the anemometer failure has not been established.

As mentioned above, the raingauge is under development and experience on DB1 has led to small modifications in the liquid detection circuit and in the method of protecting the electronics from damp. No fault has been detected since 18 May.

b. In Operational terms : the data recovery rate which is required from an operational buoy depends on several considerations including cost effectiveness and varies with the application and location. In general, data from "data sparse" areas is valued highly and a relatively low recovery rate can be accepted.

During the periods of DB1 transmission (starting from 22 March) the data recovery has been 78%, but overall the rate has only been 47%, due to failures outside the control of the Meteorological Office.

Sensor Performance

a. Method of Assessment : It was originally intended to evaluate the meteorological sensors on DB1 by making comparison observations from a nearby lightship. This comparison has not yet been possible since the position of DB1 was changed for this stage of the trial. Further it has only been possible to monitor the outputs of the sensors when the transmission link to the shore has been fully operational. This has generally precluded comparisons during service visits. Thus an alternative method has been used.

The measurements on the buoy have been compared with other observations made in the vicinity of DB1, namely :-

1. measurements, approximately twice daily, from the east coast auxiliary observing station at Gorleston, approximately 13 miles NNW of DB1. This was during the period 20 February to 5 March,

2. measurements, every three hours, from RV Clione, moored close to the buoy from 27 March to 2 April,

3. estimates made every three hours by London Weather Centre (LWC) using operational weather charts, for the period from 22 March to date.

The LWC estimate was made with hindsight and with full access to all reports except those from DB1. These reports were in SYNOP and SHIP codes and result in limited resolution (temperatures to nearest degree, humidity in the form of dewpoint and wind direction to nearest 10°).

The most accurate comparison is probably obtained using (2). The data from (1) must be treated with caution because Gorleston is too far away for good comparisons. Further more as it is situated on the coast it will be representative of a different regime from DB1, particularly when the wind is offshore. The comparisons from (3) are better than (1) because they approximate the conditions in the DB1 area itself, giving weight to neighbouring observations appropriate to the prevailing weather situation.

The differences between the values of each variable measured on DB1 and the appropriate comparison ((1)-(3) above) were obtained and from these, the mean weekly differences and standard deviations were calculated (see figure 3). Differences were not obtained for rainfall or visibility because of the large spatial variations commonly observed for these variables. Comparisons were made whenever a variable was reported from both DB1 and the reference station at the same observation time. However, when the measured wind speed at DB1 was less than 5kn, the corresponding wind directions were not included in the analysis because the wind vane becomes insensitive at such low wind speeds.

b. Results : The largest group of comparisons is from source(3) with the data falling into three distinct periods (I, II and III), each separated by transmission failures lasting several weeks. The comparisons from (2) cover part of Period I, and those from (1) are for the time just prior to this Period. The results show that the corresponding magnitudes of the mean weekly differences (d) and standard deviations (σ) were not different (those from (2) were, in general, smaller) from those calculated using the LWC data. However, both d and σ did fluctuate with time and there are some points worth noting concerning each variable.

1. Wind direction : Both d and σ fluctuate considerably during Periods I, II and III. The fluctuations in II were partly due to a sensor fault which developed during this period and was rectified by the week beginning 13 September. However, due to a fault with the mast raising system, the wind sensors are not as well exposed as they were during Periods I and II.

2. Wind Speed : The values of d and σ were higher in Period I than in Periods II or III. The exposure problem may have affected the data in Period III.

3. Air Temperature : The values of d were generally negative and never exceeded 1°C, and σ only exceeded 1°C on two occasions (both in May).

4. Relative Humidity : Both d and σ varied by a few percent from week to week with the DB1 value generally the lower. It is possible that the hygrometer on DB1 was reading systematically low. However the lack of a good standard of comparison must be borne in mind and is particularly important for this variable.

5. Sea Temperature : The values of d (and to a certain extent σ_{0}) are different in all three Periods with d reaching a maximum of about 2°C in June. An independent comparison with the Institute of Oceanographic Sciences (IOS) sea temperature sensor, for the period 15-23 June gave a mean difference (Met. Office - I.O.S.) of -0.5°C with a standard deviation of 0.1°C. This highlights the problems in accurately estimating the sea surface temperature. LWC put considerable weight on the sea temperature reported by Smiths Knoll lightship (27 miles distant), and this may not always be representative of the sea temperature in the DB1 area because gradients of sea temperature near the coast may be quite large. Furthermore, it is not possible to account for other features which influence the temperature, such as tidal direction and local upwelling. The comparisons based on Clione and IOS sensor are clearly the more accurate - both give a negative difference of less than 1°C.

6. Pressure : The values of d and σ remained nearly constant at about 0.5 mb throughout Periods I, II and III.

The results of this trial so far show that the mean differences (with their standard deviations) for pressure, windspeed and air temperature fall within the WMO accuracy requirements for synoptic AWS over the sea (WMO, 1971). For the other variables, the accuracy requirements are apparently not generally met. It should be emphasised however that most of the comparisons are based on estimates of the values at the position of DB1 and these estimates cannot accurately reflect the local effects of meteorological phenomena such as sea breezes and thunderstorms, in the DB1 area. These phenomena would affect particularly wind direction and humidity, which, in fact, have given large values of d and σ. Thus it is possible, given direct local comparisons, that these sensors may have fallen within the WMO limits. Indeed, taken alone, the comparisons with the Clione data, would bring the wind direction within the WMO limits. If the sea temperature comparisons are made with those from Clione and the IOS sensor, and not with the LWC comparisons, then again the values are within WMO limits.

Conclusions

The trial has established that the Meteorological Office has a set of sensors which can be mounted on a buoy, such as DB1, and provide measurements of pressure, air and sea temperatures and wind speed, which lie close to if not within the operational requirements of accuracy and reliability. The trial has also shown that sensors designed to measure precipitation and visibility can operate under such conditions, but an assessment of their accuracy has not been possible. The lack of suitable data from the wind direction and humidity sensors has led to an inconclusive result for these variables. A more detailed and useful trial would have been possible if the data had been recorded on the buoy so that transmission breaks did not interrupt the trial.

A secondary aspect is that since a comparison was possible, there can be only limited operational benefit from having a buoy in the present position.

The future need of the Meteorological Office is for this type of meteorological information from data sparse areas. The data recovery rate must be high enough to justify the costs of upkeep, and the reliability of the sensors and the overall system (and thus the cost of maintenance) is a major factor in deciding whether the Meteorological Office should use buoys such as DB1. In the absence of extensive operational experience, a system MTBF of 6 months is presently considered to be a minimum (failure being defined as 2 faulty sensors or a transmission failure). Ignoring installation and development-caused faults, the meteorological sub-system has a MTBF of 152 days (∼ 5 months) and this is expected to improve.

References

Folland, C K	1973	"Low-power humidity sensor for unattended use on buoys" Geneva, W.M.O. Reports on Marine Science Affairs. No 7, pp 186-198
Winstanley J V and Adams M J	1975	"Point Visibility Meter ; a forward scatter instrument for the measurement of aerosol extinction co-efficient". Applied Optics, Vol. 14, No 9, pp 2151-2157
W.M.O.	1971	"Guide to Meteorological Instrument and Observing Practices" W.M.O. No 8, Tech. Pub. No 3, I-33.

Table 1 METEOROLOGICAL SENSORS DEPLOYED ON DB1

Meteorological Variable	Type of Instrument	Manufacturers type and number	Range	Interface and Output details	Calibration accuracy
Pressure	Aneroid capsule	KDG Ltd. Type ACT 30B with series 400 transmitter	900–1050 mb	Direct output 0–3.667V d.c.	$\pm$0.2 mb
Air Temperature	Platinum resistance thermometer	Rosemount Ltd Type E13418	-10 – 40°C	Met. Office designed Kelvin Bridge with output 0 – 1.955V d.c.	$\pm$0.1°C
Wind Speed	Cup anemometer	Vector Instruments Type A100SR	0–100 kn	Contact closure rate of 24 min^{-1} kn^{-1}. Frequency to voltage converter and 5 min. exponentially smoothed mean output. 0–4.899V. Met. Office Design.	$\pm$0.5 kn
Wind Direction	Wind Vane	Vector Instruments Type W200G4	0–360°	Graycode to binary converter. Met. Office designed 5 min. exponentially smoothed output. Resolution of output 1.41°. Resolution of shaft encoder 22.5°.	$\pm$2°
Humidity	Chemical hygrometer	Phys-Chemical Research Corps. Type PCRC 11	0–100%	Non-linear output 4–0V	$\pm$3%
Precipitation	Peristaltic Pump	Meteorological Office design.	0–120 mm h^{-1}	1 pump rotation $\equiv$ 0.1mm. Output given as a running total of counts.	$\pm$2%
Sea-surface temperature	Platinum resistance thermometer (hull mounted)	Meteorological Office design manufactured by Market Engineering	-10 – 10°C	Met. Office designed air-sea difference Kelvin Bridge. Output 0 – 0.978 V d.c.	$\pm$0.1°C
Visibility	Forward scatter	Plessey Radar PVM	50m – 5 km	Analogue voltage related to extinction co-efficient, and visibility	$\pm$12%

Table 2 LIST OF SENSOR FAULTS DURING THE FIRST 10 MONTHS ON DB1

Meteorological Variable	No of faults	Type of fault	Period of operation (days)
Pressure	1	Fuse blown on power supply board - reason unknown	305
Air Temperature	Nil	-	305
Wind Speed	1	Sensor and connecting cable found to be satisfactory on return. Reason for failure unknown. Possibly a faulty connection in the plug.	305
Wind Direction	1	Faulty diode in sensor.	305
Humidity	1	Contamination of sensor - protective sleeve not applied on installation.	305
Precipitation	2	Design fault on liquid-detection circuit. No fault since 18 May.	305
Sea-Surface Temperature	Nil	-	305
Visibility	1	Faulty emitter diode on installation, not identified at the time. Replaced 18 May. Satisfactory since then.	135
		Mean sensor system MTBF	51 days

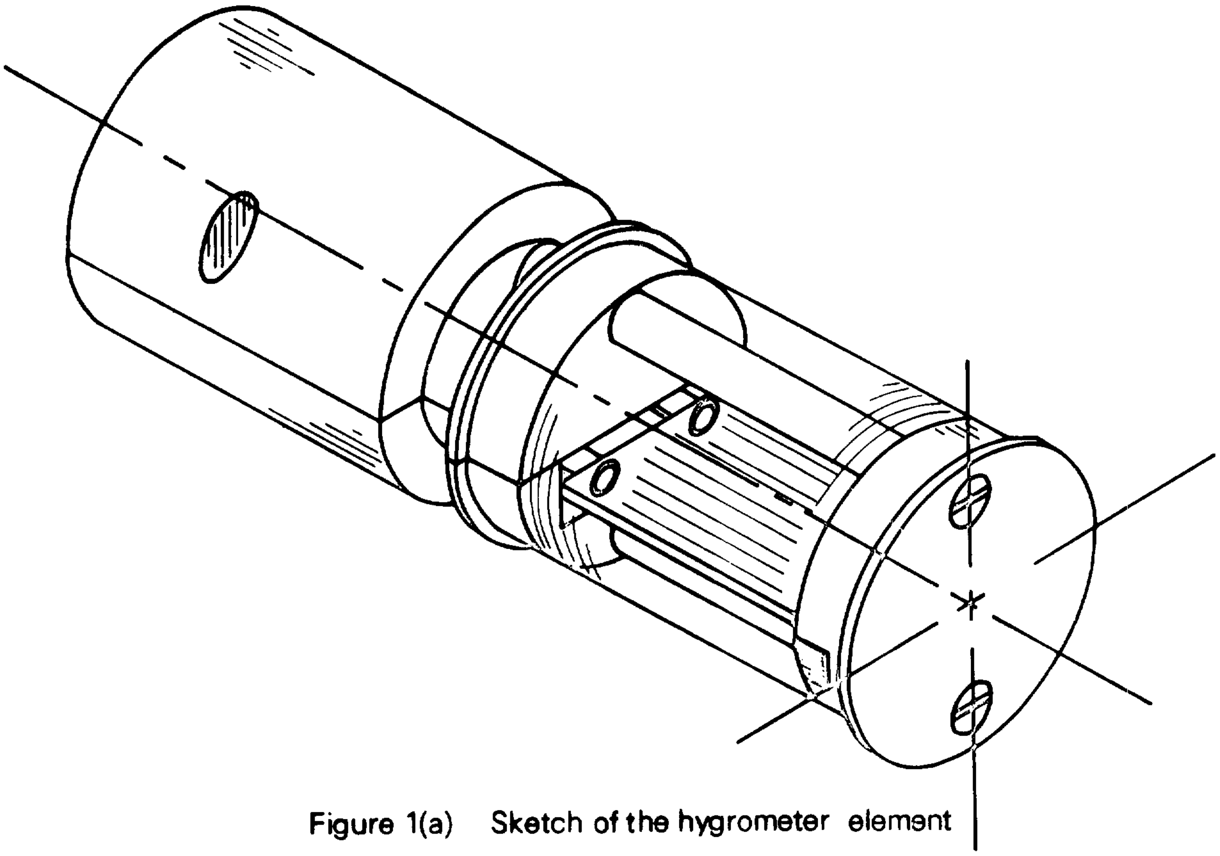

Figure 1(a) Sketch of the hygrometer element

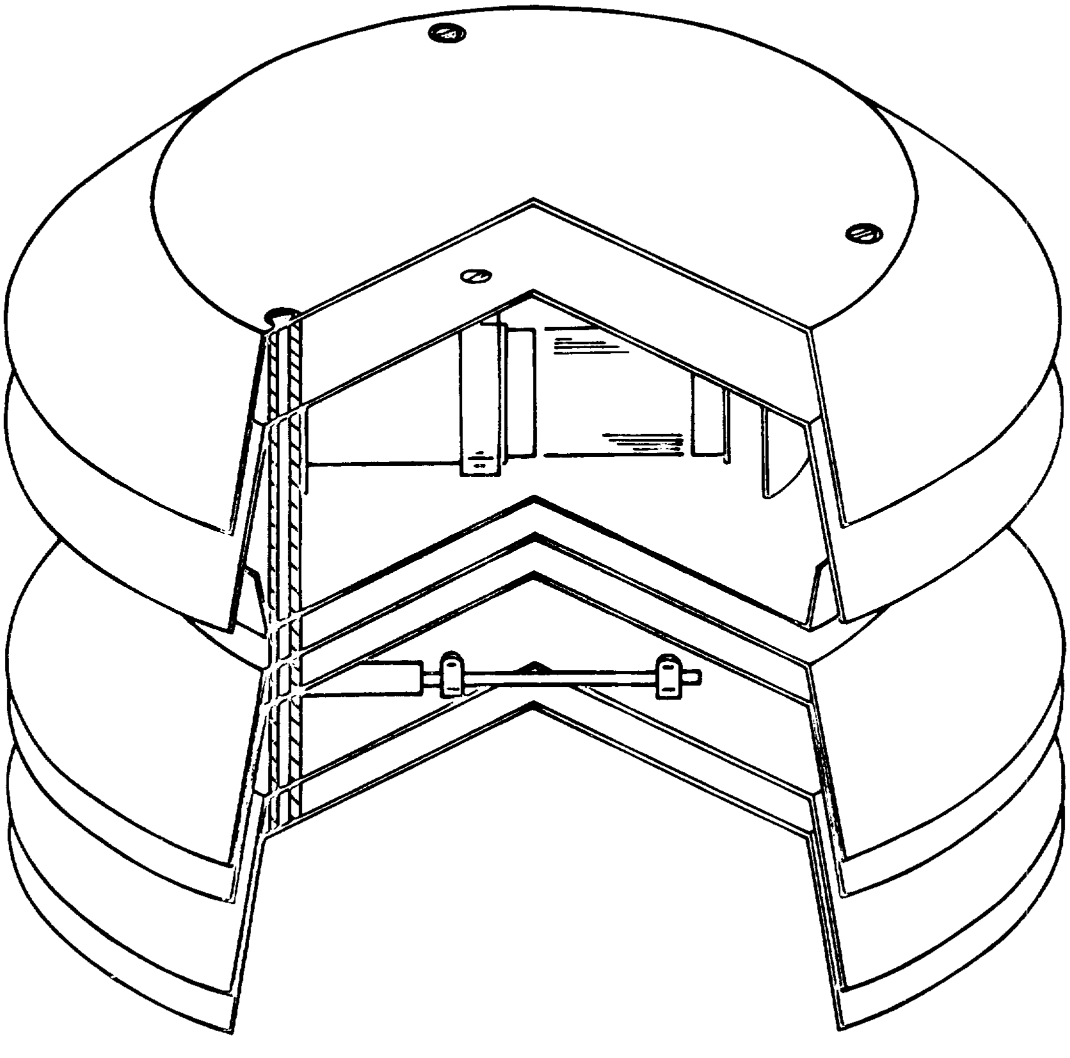

Figure 1(b) Cut away view of the glass-fibre screen showing position of the temperature and humidity elements

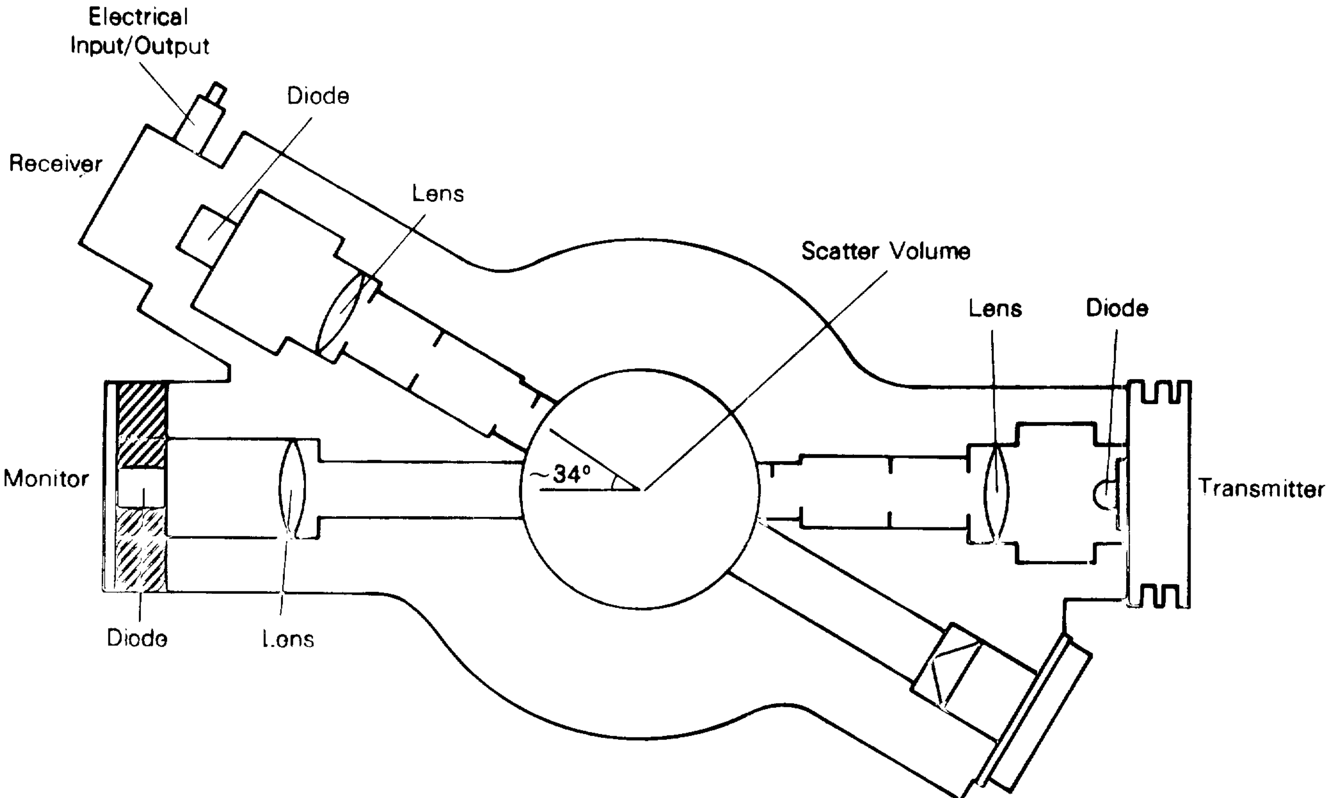

Figure 2(a) Schematic diagram of the Point Visibility Meter (PVM)

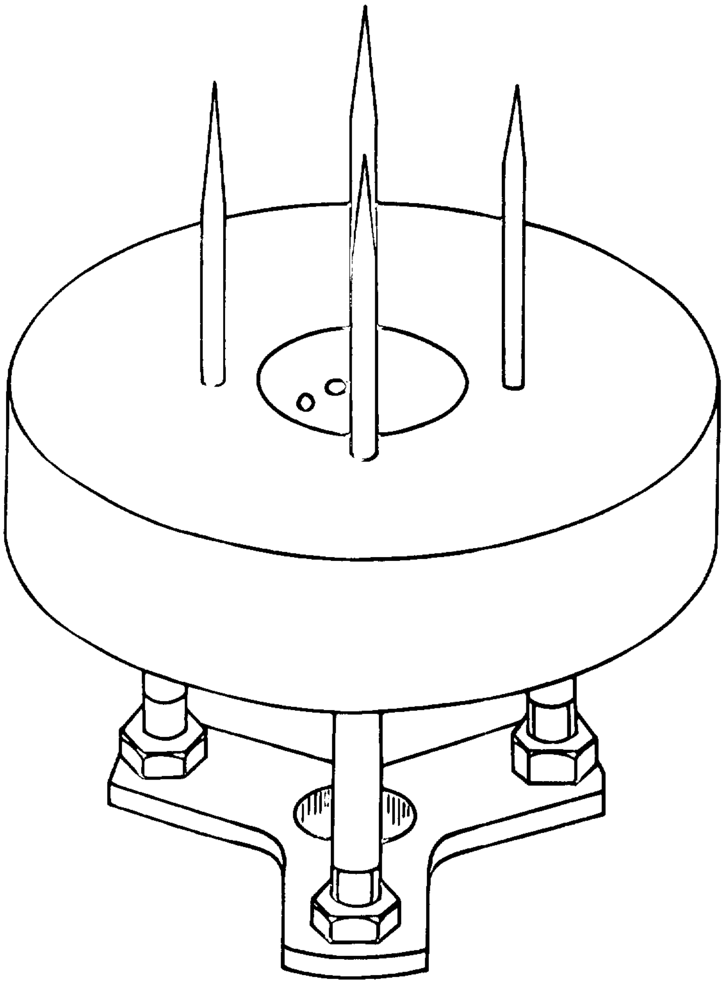

Figure 2(b) Sketch of the PVM showing the spikes attached

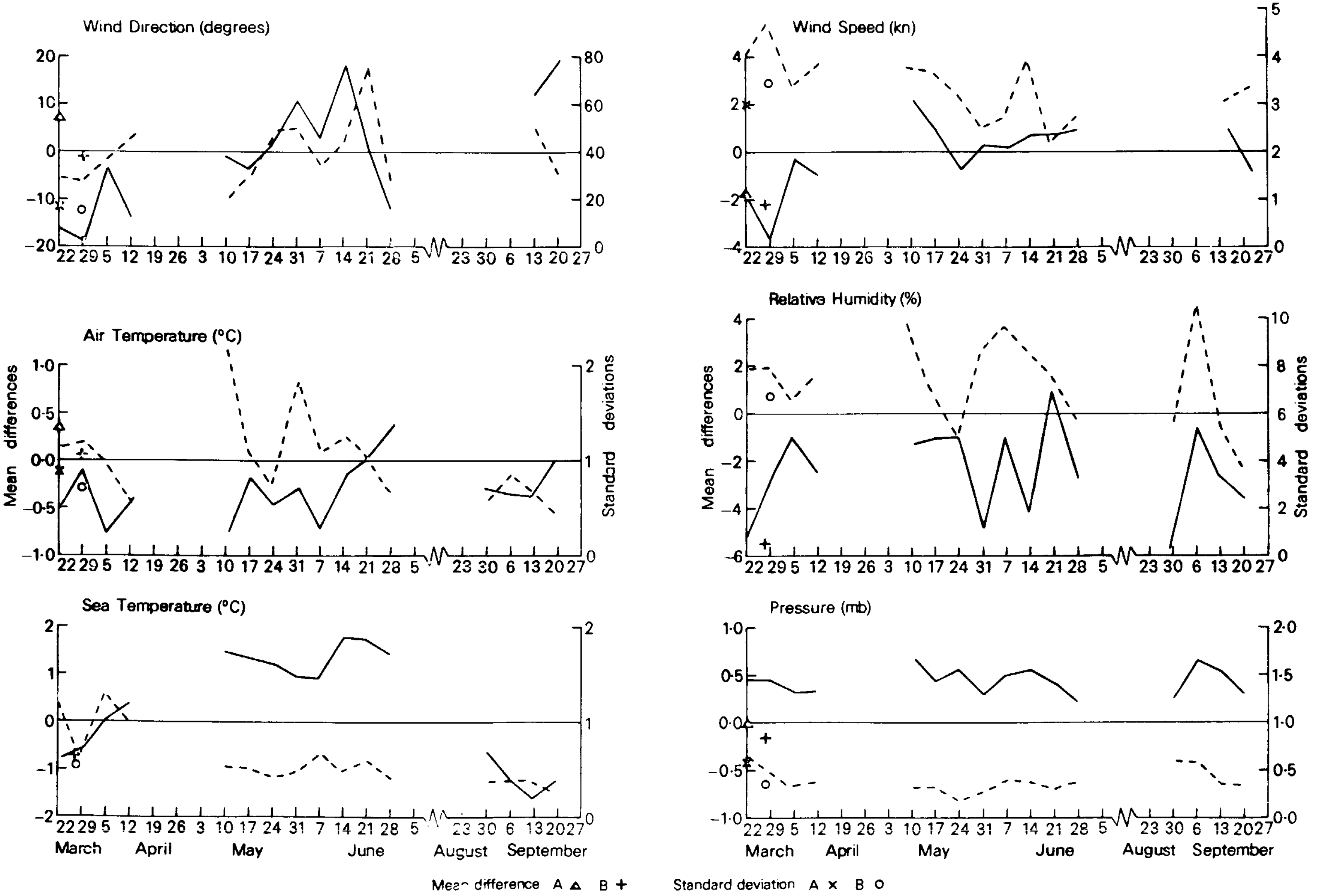

Figure 3 Plots of mean differences (DBI-LWC) —— and standard deviations – – – for each variable and for (DBI-Gorleston) for 20 Feb–5 Mar (A) and (DBI-Ship) for 27 Mar-2 Apr (B)

AN INTERCOMPARISON OF THE DATA BUOY CURRENT METERS AND NEAR-SURFACE DRIFTING FLOATS

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SUMMARY

The measurement of current in the near surface region in the open sea presents a difficult problem. However, a knowledge of such currents is of considerable importance in research, dispersal problems, and offshore engineering, and a possible means of accomplishing the measurement at 3 metres depth was therefore included in the design of DB1. In this paper, a brief description is given of the acoustic current meter, designed and built by AERE, Harwell and installed under the direction of Seatek/IOS, and of a joint IOS/MAFF intercomparison of current measurement techniques which took place between 26th March and 2nd April 1976. In the experiment the displacements of drifting floats, tracked acoustically. were compared with the integrated output from the AERE current meter; a comparison was also made between the AERE meter and an electromagnetic current meter temporarily installed on the buoy. The extent of agreement between these different techniques is examined.

Introduction

In making measurements of currents there are fundamentally two approaches possible. The first is to measure the displacement vectors of drifting floats between known times (Lagrangian method); in the second, or Eulerian approach, observations are made at fixed points using current sensors. The two approaches are essentially complementary, (Longuet-Higgins, 1969) and some care is required in attempting to relate the one set of information to the other. In practice the choice of method rather depends on the use to which the data are to be put. However, in measuring near surface currents, the existence of wave orbital velocities which can be large compared with the mean flow presents severe problems for either method (see for example Saunders 1976 and McCullough 1974). In the case of the Eulerian approach, flow is incident on the sensor at all angles: ideally the sensor should not obstruct the flow at all. At the same time, if (as is assumed throughout this paper) the sensor is measuring horizontal mean flow, it should be completely insensitive to any vertical components of flow, while responding linearly to horizontal components. Moreover linearity and stability in response are required over a wide range of frequencies: basically from the highest frequencies encountered in the relative motion of the water past the sensor to, perhaps, a few cycles per year if long term residual currents are of interest. Taken with other requirements of the sensor, and those of associated sampling and data storage or telemetry systems, these represent a difficult, though not insoluble design problem. However, the situation is very greatly complicated by the absence of a fixed reference for the measurement; the structure or platform supporting the sensor has, in general, a complex motion in response to wave action, and, in such circumstances, contamination of the output of even a perfect instrument can be severe (Pollard 1973). The use of a large structure to reduce wave induced motion reduces the problem, but then introduces some additional uncertainty because it modifies the flow around it.

The need for near-surface current measurement was recognised at an early stage of the data buoy feasibility study and it was believed that in the very near surface region it might be possible to make a measurement from a surface following buoy. This should greatly reduce the oscillatory part of the flow, including, somewhat paradoxically, 'noise' induced by sensor motion. The choice of a discus hull was thus advantageous, although there were, of course, a number of other considerations leading to it.

In specifying the type of current meter required, particular emphasis was placed on minimizing the effects of marine fouling and corrosion in view of the necessity for long service with minimum maintenance. This effectively excluded all rotor and vane meters, leaving essentially a choice between electromagnetic and acoustic types. Of these, it was thought that the acoustic type might prove the more suitable for long term use, particularly if a relatively long path length were to be used. This would have the added advantage of minimizing interference with flow. At that time, many of the necessary techniques had been developed by AERE, Harwell, for an acoustic river flowmeter. The method (Loosemore 1969) lent itself well to vector averaging techniques, and, following a design study, an approach similar in principle was developed for the data buoy current meter, a brief description of which is given in the accompanying document by Loosemore.

Assessment of Data Quality

The records obtained from the current meter have apparently been of excellent quality (fig.3) without gaps or 'glitches' attributable to sensor malfunction (although there has been data loss through other causes). This in fact is still true, almost twelve months after deployment, and suggests that aeration and fouling under the hull do not pose serious problems. Assessment of the accuracy of the measurement is not simple, however, for the reasons discussed previously. One possible approach is that of comparative measurement, preferably employing different methods or techniques. In this way it may be possible to identify any systematic errors inherent in one system. Time dependent errors (for example, those caused by accretion of marine organisms) may, in addition, be detected by suitable comparison of data from two different periods of time. A third approach is to examine the data for consistency with oceanographic and meteorological conditions prevailing in the area. The experiment described in the following sections - a comparison of the data buoy measurement with Lagrangian drift velocities of floats - is essentially the first method, although it is hoped to apply the other two methods also.

Drifting Float Experiment - Method

For this experiment we used acoustic transponding floats which had originally been developed for tracking water movements in the deep ocean (Swallow, McCartney and Millard 1974). The floats are cylindrical tubes, 4 metres long and 0.12m in diameter and, in this application, floated with only 10cm or so, an identification flag and a grappling line above the surface. In shape and size the floats were not ideal: ideal dimensions are small compared with wave amplitude and the floats would be neutrally buoyant at the exact depth of the buoy current meter, 3 metres.

Furthermore a spar has a complex motion when subjected to wave action and the effect of this on drift velocity is not readily calculable, although for reasons given below we believe this can be neglected in the present circumstances. The over-riding advantage of using the spars was their immediate availability.

The position of a transponding float at a given time was determined by simultaneous pulse travel time measurements from the MAFF research ship RV CLIONE to the float, and remotely from DB1 to the float. The ship position relative to three bottom-moored transponding beacons, operating acoustically in a similar manner to the free surface floats, was determined at the same time. The disposition of the beacons with respect to the shore and DB1 is shown in fig.1. In principle the positions of the beacons relative to each other can be ascertained by acoustic ranging, but, since the experiment was carried out within (at times) visual range of the shore, the opportunity was taken to make sextant observations based on prominent landmarks. From these the beacon positions at the time of laying, and a number of ship positions during float tracking, were computed in terms of Ordnance Survey Grid coordinates with an uncertainty of less than 30 metres. The position of DB1 was regarded as fixed; later comparisons of acoustic range from known ship positions showed that its displacement with tide was no greater than the uncertainty in the measurements generally.

The measurement of float range from DB1 was achieved by mounting an interrogating transponder below the buoy waterline. This was triggered acoustically from RV CLIONE in the manner shown schematically in fig.2. In fixing a float position the sequence of events was a 2.5 minute direct transmission in mode (a) at 5.1kHz followed by retransmission via DB1 (mode (b)) for a similar period. In both modes the pulse length was 30 milliseconds and repetition frequency 15 pulses/minute. The shipboard display is so designed that both sets of pulse replies from a float can be referred by eye to a single point in time halfway through the fix period, and this made the measurement independent of ship motion relative to floats, beacons or the data buoy. The value of sound velocity used in calculating ranges from pulse travel times was established by direct measurement before the experiment, and was checked immediately after. There was an insignificant variation of sound velocity with either depth or time, and direct propagation paths were assured. Received signals were generally satisfactory within a range of about 10km.

Although the most useful measurements for direct comparison are those made close to the buoy, a tactical approach comprising float launch, position fixing and recovery close to the buoy did not represent an efficient use of time. Furthermore it was important to get some idea of the spatial homogeneity of the flow. Floats were therefore generally launched a kilometre or so North or South of the buoy, depending on tide phase, and, after passing close to the buoy, were allowed to execute one or more tidal oscillations (see fig.1 for example). Generally between one and five floats were tracked at any given time, this being the maximum number which could be comfortably handled at a position fixing rate of two or three fixes per hour. Float tracking was carried out for the major part of five days, during which time other current measurements were made; also a wave following comparison experiment, reported on by Ewing and Clayson in an accompanying paper at this meeting.

Other Current Measurements

In order to make the comparison against as wide a background of information as possible, a number of additional measurements were undertaken. On the buoy itself a two component electromagnetic current meter had been temporarily installed in the week prior to the experiment. This was mounted at the end of a spar to measure flow at the same depth as the acoustic current meter (3 metres), and the two systems were powered and sampled simultaneously by the buoy data handling system. A vector averaging package does not yet exist for the electromagnetic instrument and so simple averages over five minutes were taken each hour, relying on the three point buoy mooring to maintain adequate stability in heading. The taking of five minute means of the compass readings at different times in a tidal cycle revealed a maximum change in buoy heading of 2.5°.

To provide some idea of the current-depth profile, a separate mooring was laid 400m East of DB1, attached to which were a Plessey type MO 21 and an AMF-Sea-Link vector averaging current meter at distances of 6 metres and 3.5 metres above the bottom respectively. These measurements were supplemented by two 12 hour series of direct observations made with a Kelvin Hughes Direct Reading Current Meter deployed from the ship at anchor.

Results

A record from the acoustic current meter covering the period of the experiment, 26th March - 2nd April, is shown in fig.3. The wind conditions measured on DB1 are shown in fig.4. The wave conditions discussed by Ewing and Clayson were typical of the period: a hoped-for change in wind and waves - to assist in correlating current measurements with sea state - unfortunately did not materialize.

Comparison of Acoustic and Electromagnetic Current Meters

In order to show more clearly any systematic differences, the magnitudes and directions of current vectors as measured by each system during the 5 days of the experiment have been plotted against each other (figs.5 and 6). The comparison of the magnitudes shows two clear trends. First, there is a general tendency for the acoustic meter to record slightly higher values than the electromagnetic sensor. At speeds above about 60cm/sec this amounts to no more than 2%, which is of the same order as the calibration inaccuracy for the electromagnetic sensor (in principle, the acoustic meter makes an absolute measurement.).

At lower speeds a much more noticeable discrepancy exists between the two systems, and, in addition, differences exist between North and South bound flow conditions which tend to reverse at speeds above about 70cm/sec.

The comparison of current directions ($\tan^{-1} V_{EW}/V_{NS}$) shows the two principal directions of flow very clearly. The differences at full flood and ebb tides evidently do not exceed a degree or so. this is, of course, a measure of the rotational stability (over the 5 minute averaging time) of the three point buoy mooring since the electromagnetic sensor package had no inbuilt compass sampling. At intermediate points, at which current magnitudes are very much lower, the electromagnetic sensor yields larger angles for North going flow than the acoustic meter, while the reverse occurs for the South bound stream. Both this effect, and the discrepancy in magnitudes at low currents are explicable by the presence of an offset in the N-S axis of one of the instruments, and, possibly, to a lesser extent in the E-W axis. (Offset is defined here as non zero output at zero flow.). Resolving the current vectors along, and orthogonally to, the major flow axes shows an absence of offset for higher currents, however. We can think of at least two explanations for this. First, without a compass reference, the electromagnetic sensor output is sensitive to any rotation of the buoy as tensions in anchor chains change near slack water. The angular discrepancies are quite large, however, and a more probable cause is the phenomenon of stalling of the electromagnetic head (Tucker 1972). Ideally a sensor mounted immediately below a perfect surface following buoy should not experience a vertical velocity component which causes stall. However, in this instance the head was, of necessity, mounted at the buoy periphery, where it would be much more sensitive to deviations from perfect surface following in the short seas present. Unfortunately the relative motions are too complicated to allow straightforward calculation, but we do know that vertical velocity components of a few cm/sec will produce errors at the lower horizontal velocities experienced by the buoy.

In conclusion, we feel that the agreement between the two systems is good in view of the known limitations of the electromagnetic sensor package.

Intercomparison of Float Tracks and Acoustic Current Meter

The mean velocity between each position fix for a given float, resolved into two orthogonal components (N-S, E-W) has been compared with the corresponding DB1 current meter outputs averaged over the corresponding period. Interpolation between the hourly current meter samples was made by the method of cubic splines. To obtain some idea of the spatial homogeneity of the flow, the differences between the current meter outputs and the mean float velocities have been plotted as a function of distance from DB1. The axes chosen for this are not in fact N-S, E-W, but have been rotated through 18° to lie directly along and across the principle flow directions, to try to make any gradient in flow arising from bottom topography (fig.1) more easily identifiable. Northward and southward flow are treated separately in figs.7(a-d) and 8(a-d). All float velocities have been included in the figures regardless of averaging time or tidal phase at which positions were fixed. The great majority were in fact made at times of strong flow. The exclusion of measurements based on long averaging times (> 1 hour) and relatively weaker flow (< 110cm/sec) makes little difference to all distribution except that in fig.8(d). In this case points relating to low N-S velocities (< 70cm/sec) fall mainly above the distance axis: those relating to higher velocities, below it. On this evidence floats moving slowly southwards tend to move faster than the current measured at the buoy. We are uncertain of the cause of this, since the reverse is undoubtedly true at all speeds going North.

Apart from this exception the scatter in values of $(V_{ac} - V_f)$ is generally between ±5 and ±10 cm/sec, once allowance has been made for any systematic trends present. A 30 metre radius of uncertainty in fixing position of a float, when the time between fixes is 2000 seconds, yields an uncertainty of ±3cm/sec in current. This, of course, becomes worse for fixes at shorter intervals: a number of fixes were made at 800 second intervals. To this source of scatter must also be added the error, estimated as ~ 2cm/sec, in interpolating between hourly samples in the current meter record. We feel that these two sources account for almost all the observed scatter, although some bad position fixes are undoubtedly present in spite of careful processing of the records. These may generally be expected to occur at positions at which a float was almost in line with DB1 and RV CLIONE.

The amount of scatter, and the concentration of float paths, effectively masks any offshore (East-West) gradient in the flow, (figs.7,8(a),(b)), although rather more definite evidence exists for a gradient in the North-South direction (figs.7(d) and 8(d)). For the northward flow floats seem to move more slowly when south of DB1, typically 10-20cm/sec below the buoy value, at 10km distance. To the north, the trend is for constant velocity over the first 2km or so, then a steady decrease, followed by a final increase at around 10km North. However, behaviour in these areas to the north is almost certainly complicated by the extensive shoaling at the approaches to Lowestoft harbour (fig.1). At first sight the differences measured during southward flow appear to be greatly scattered with no particular trend evident. However, as we remarked above, at peak velocities the behaviour agrees rather more closely with that of the northward flow, although the scatter is still rather greater. A possible reason for this lack of uniformity in velocities is the influence of the channels and shoals during flow southward. Fig.7(c) and 9(c) show a rather puzzling correlation between East-West components of velocity and North-South distance: for southward flow floats moved faster East to West and West to East than the current at DB1 would suggest, while for flow North, the reverse seems to be true, though less obviously.

Hoever, all gradients are sufficiently small to justify neglect within a kilometre or so of DB1. True N-S, E-W comparisons based on the closest passes are tabulated below and it is clear that the degree of agreement between floats and current meters is in fact remarkably good.

TABLE I

COMPARISON OF INTEGRATED OUTPUT OF ACOUSTIC CURRENT METER AND MEAN CURRENT MEASURED BY FLOAT DRIFT FOR FLOATS PASSING CLOSEST TO DB1

Time between adjacent float fixes	Mean Distance(m) from buoy	Float Velocity cm/sec		Current Meter Output cm/sec	
		N-S	E-W	N-S	E-W
1620	70	137	34	137	41
2760	240	118	44	118	41
2040	470	126	44	130	44
1680	480	119	39	112	37
* 2460	1000	39	18	41	15
3000	380	-102	-36	-101	-33
1800	500	-118	-32	-122	-30
2100	540	-128	-24	-125	-31
2940	600	-12	3	-15	2

* Included because it affords a comparison shortly before slack water, although this was not one of the floats closest to DB1.

Investigation of Possible Systematic Errors in the Comparison

There were initially three factors contributing some uncertainty to the float motions: wind forces on the small area above the water, dynamic response of the float in waves, and possible changes in the velocity profile (shear) in the upper 4 metres. In conditions of constant shear, but absence of waves, the 4m float would be expected to respond to the current at a 2m depth: the data buoy current meter is situated at 3m, and hence would detect a lower velocity. If shear were not constant with depth, errors could be increased. During the experiment shear was undoubtedly present in the water column below 3 metres depth. The differences between the moored current meter records and the DB1 record give an average of ~4cm/sec/metre between 3 and 14 metres depth at maximum flow. The Kelvin Hughes direct reading instrument, sampling between these depths at times yielded ~ 7cm/sec/metre. However, we had no means of ascertaining velocity profile very close to the surface.

To try to detect differences in behaviour arising from these effects three floats which had the characteristics summarized in Table 2, were deployed together.

TABLE 2

	Float 1	Float 2	Float 3
Length	4m	4m	2m
$\frac{\text{Area in air}}{\text{Area in sea}}$	0.05	0.05	0.1
$\frac{\text{Pitch frequency}}{\text{Heave frequency}}$	0.7	3	1.2

The first two parameters should enable differences due to shear, and wind, to be detected; the third parameter governs the response to waves.

The three floats were tracked twice, over 1 and 2 tidal cycles, respectively. The experiment revealed no large systematic differences between floats in N-S velocity (Table 3). The short float at times moved more rapidly southwards but its final position was slightly north of the longer floats. On both occasions the short float was recovered well to the east of the 4m floats, whose final separations were only 500m and 200m respectively. Most of this eastward movement, however, took place north of DB1 at a turn of the tide and the effects of the channels may have been important.

The results are, then, a little inconclusive. The lack of much separation between floats 1 and 2 suggests that the effect of wave induced motions may safely be neglected. However, in attempting to account for the velocity differences in Table 3 we cannot really distinguish between possible shear effects and horizontal velocity gradients, (compare floats 1,4 for example), although it seems certain that any systematic errors arising from vertical shear are less than a few cm/sec.

A fourth uncertainty in the comparison lay in the possible modification to the flow at the level of the acoustic current meter due to the presence of the buoy hull. During the DB1 design study phase, measurements were made on a 1/24 scale model, but not without difficulty, and the answers, apart from suggesting some degree of over-reading, were not reliable. The close correspondence of the float and current meter values in this experiment suggests that the extent of any modification to the flow is small.

TABLE 3

SUCCESSIVE MEASUREMENTS OF AVERAGE N-S CURRENT BY DRIFTING FLOATS AND DB1 CURRENT METER

Time between fixes (sec.)	Float 1 (cm/sec)	Float 2 (cm/sec)	Float 3 (cm/sec)	Float 4 (cm/sec)	DB1 Current Meter
1560	124	118	118	-	133
2040	129	127	127	-	137
1920	128	128	130	-	134
2640	117	117	119	-	121
13440	-13	-13	-12	-	-2
1920	-126	-126	-112	-	-128
3720	-117	-117	-140	-	-128
1800 2400 } 4200	-97 -84 } $\overline{90}$	-97 -82 } $-\overline{88}$	$-\overline{95}$	-122 -104 } $-\overline{112}$	-126 -98 } $-\overline{110}$
5040	-42	-43	-53	-49	-33
3960 2400 } 10560 4200	38 106 } $\overline{91}$ 131	38 104 } $\overline{90}$ 131	$\overline{85}$	17 87 } $\overline{81}$ 139	55 115 } $\overline{104}$ 143
1920	146	138	150	129	147
4080	120	119	111		136
9120	37	40	58		50
5160	-90	-85	-77		-93

Typical separation of floats 1 and 2 was ~ 100 metres
Typical separation of float 3 from 1 and 2 was ~ 1 km
Typical separation of float 4 from 1,2,3 was ~ 5 km

(Float 4 had characteristics identical to those of float 2 in Table 2. It was deployed much later than 3,5,8 and at several kilometres distance from them.)

Conclusion

A close measure of agreement is obtained between currents measured by drifting surface floats and values obtained from the data buoy acoustic current meter, in sea conditions not generally conducive to good surface following. This, and the satisfactory general performance of the acoustic meter encourages us to believe that the instrument and technique may prove satisfactory in providing long time series of very near surface currents in the open sea.

Acknowledgements

The authors wish to acknowledge the contributions of their colleagues in IOS and MAFF to this experiment, and in particular the help of Dr. B.S. McCartney with the float tracking, and Mr. R. Clements with help in installing the temporary spars on DB1. The assistance received from the officers and crew of RV CLIONE - and especially some sterling work with the sextant - contributed greatly to the success of the measurements. We are grateful to Dr. R.M.Carson for advising on float dynamics

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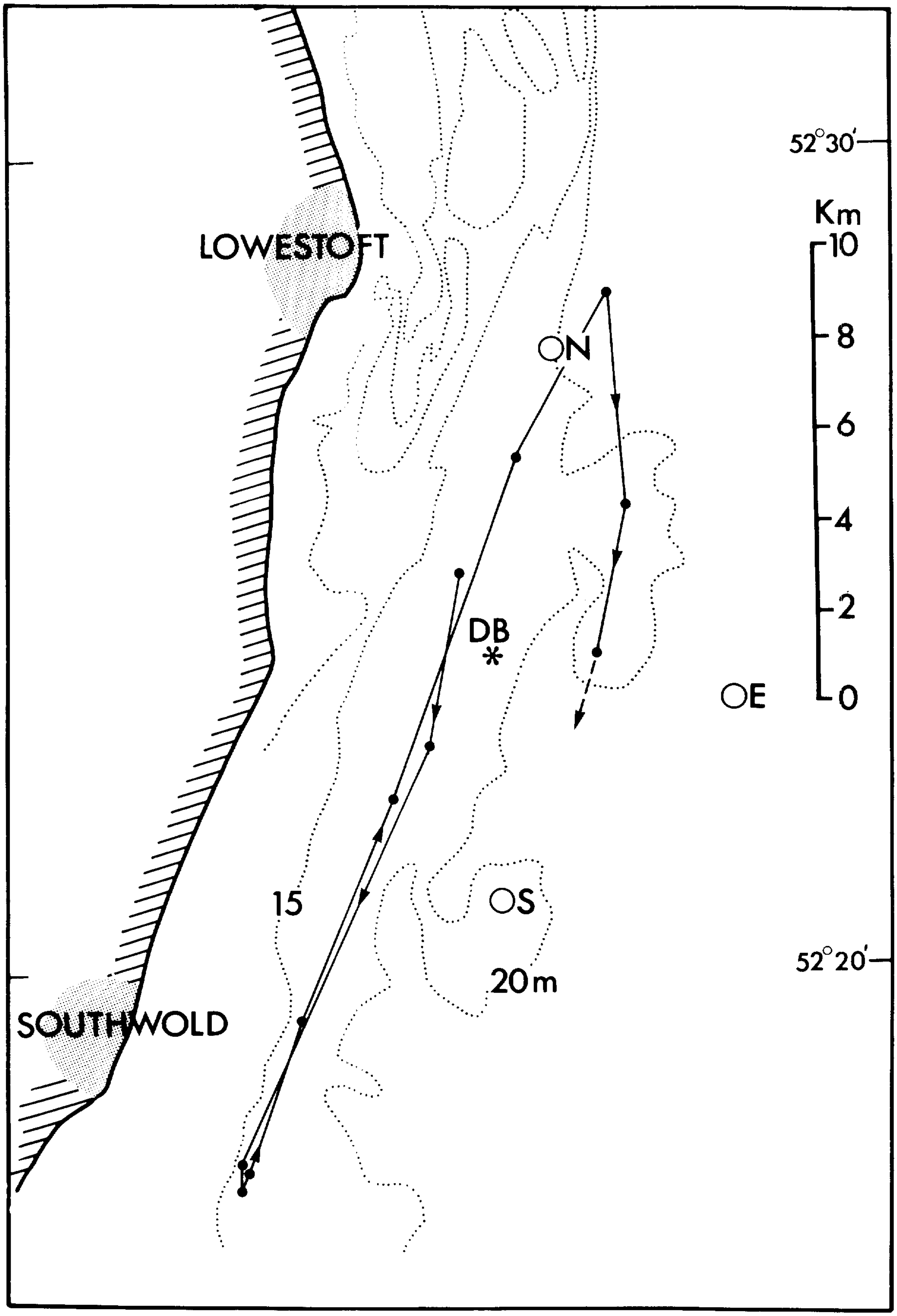

Fig. 1 Area covered by float tracking experiment

A typical series of float positions during one tidal cycle is shown (black dots). Beacon positions are marked by open circles.

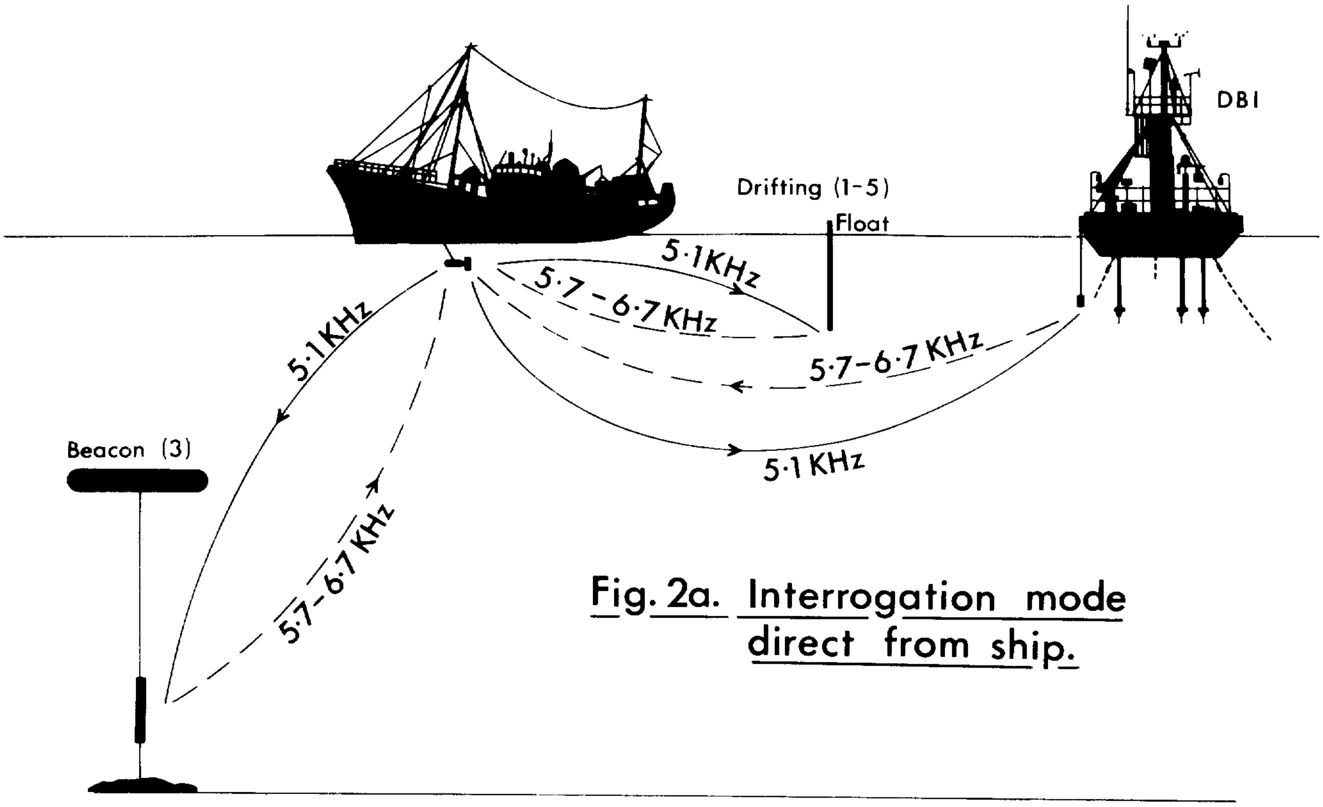

Fig. 2a. Interrogation mode direct from ship.

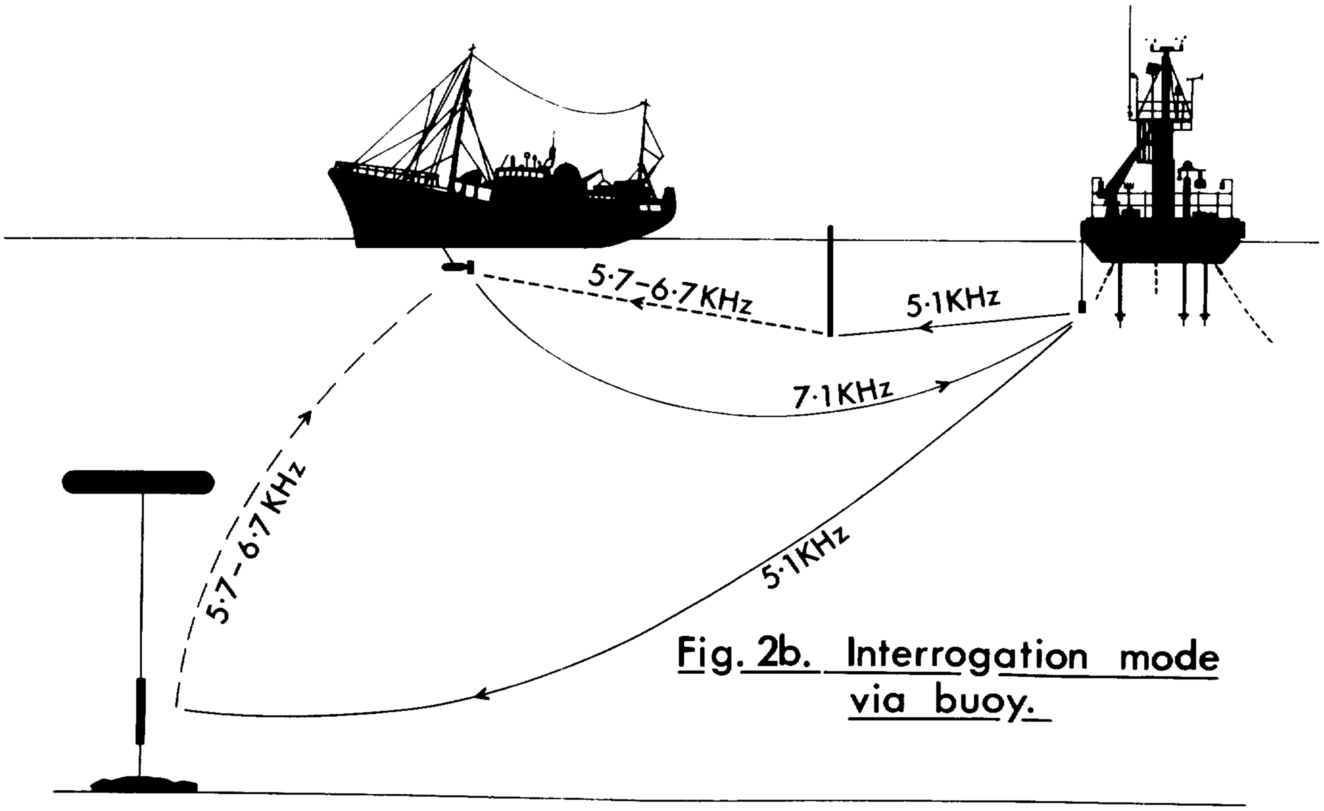

Fig. 2b. Interrogation mode via buoy.

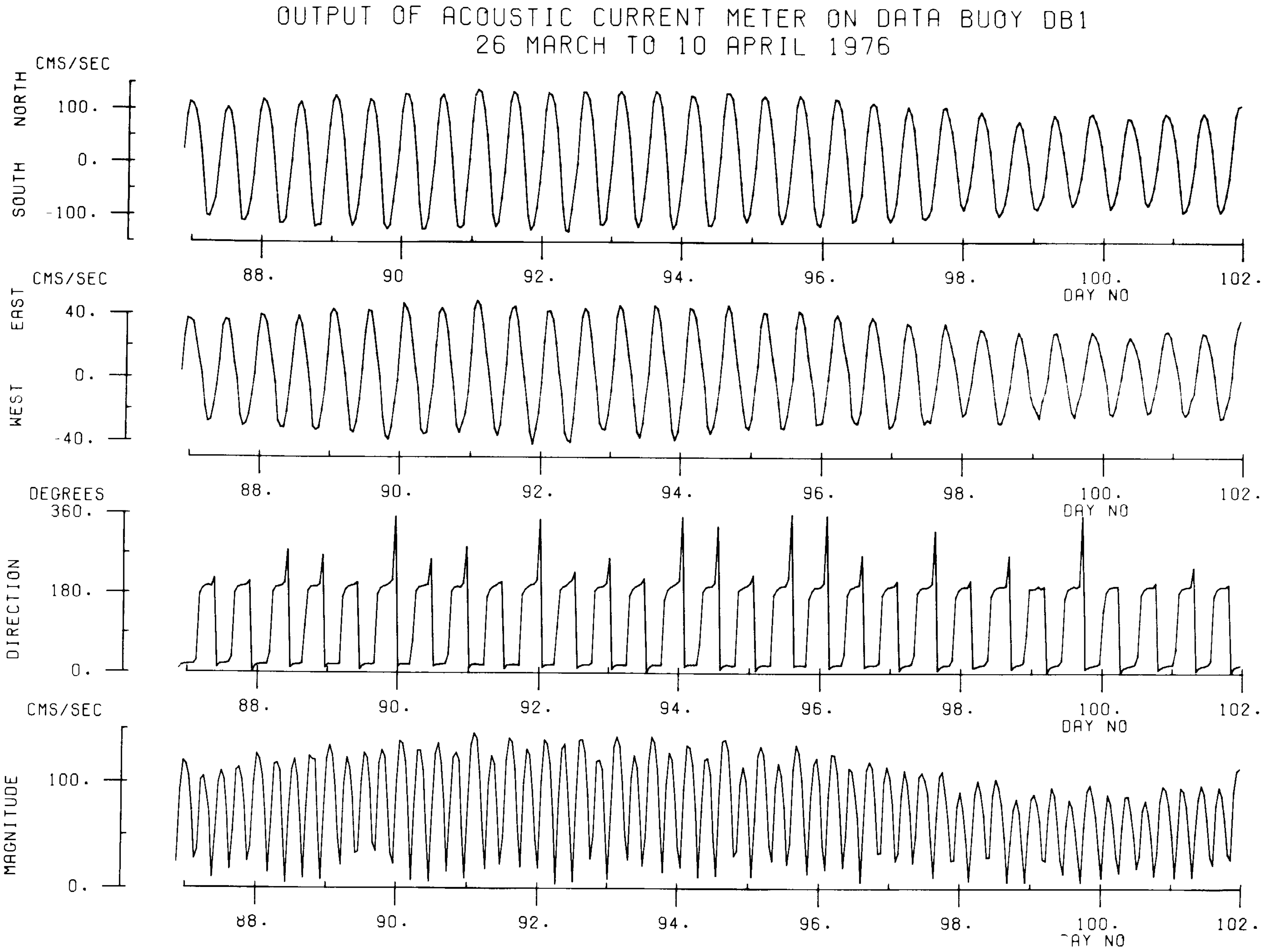

Fig. 3 Output of acoustic current meter on data buoy, 26th March-10th April 1976
(Note that the sample points have been joined by straight lines during plotting)

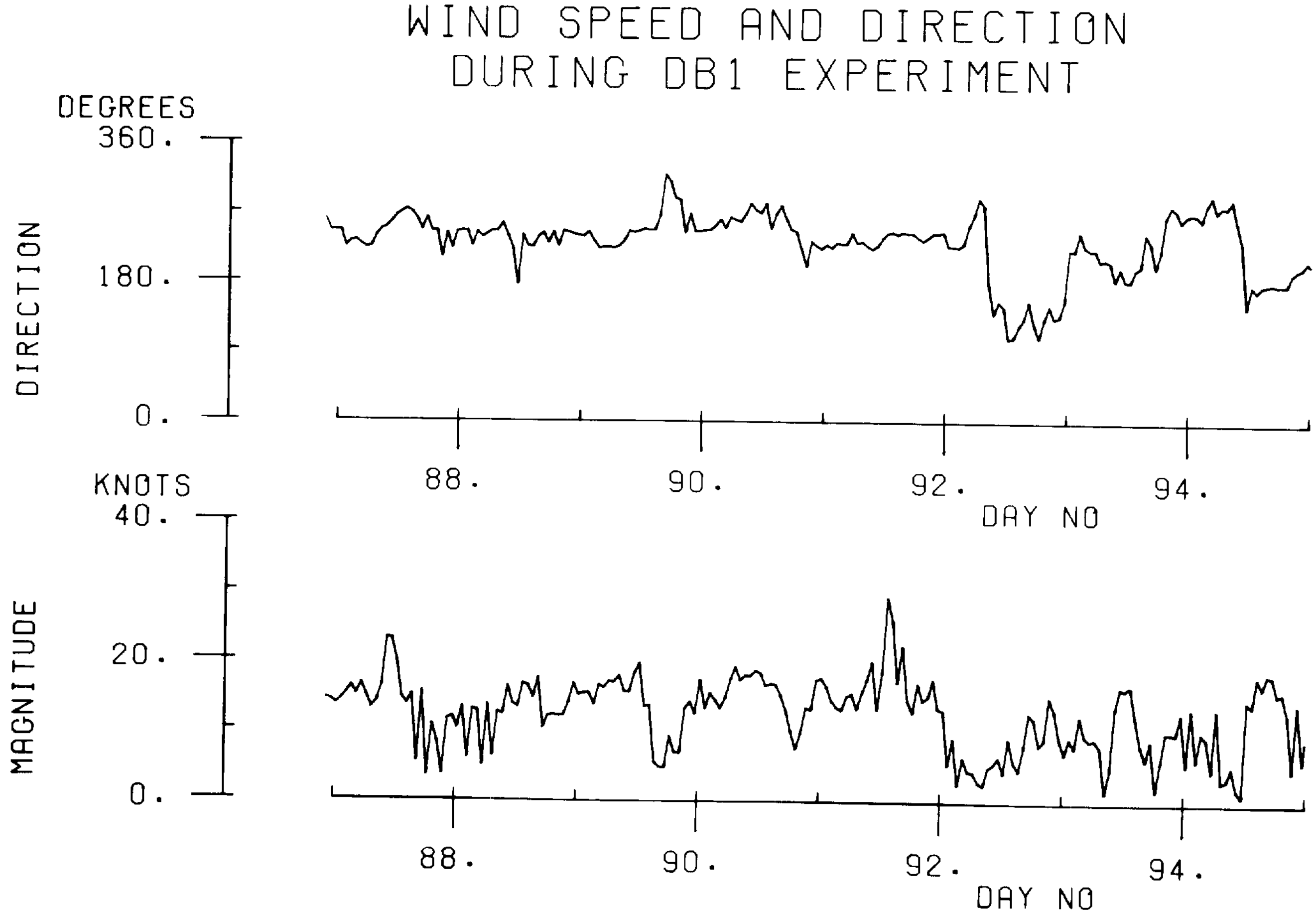

Fig. 4 <u>Wind speed and direction during DB1 experimen</u>

(Sample points joined by straight lines durin
plotting).

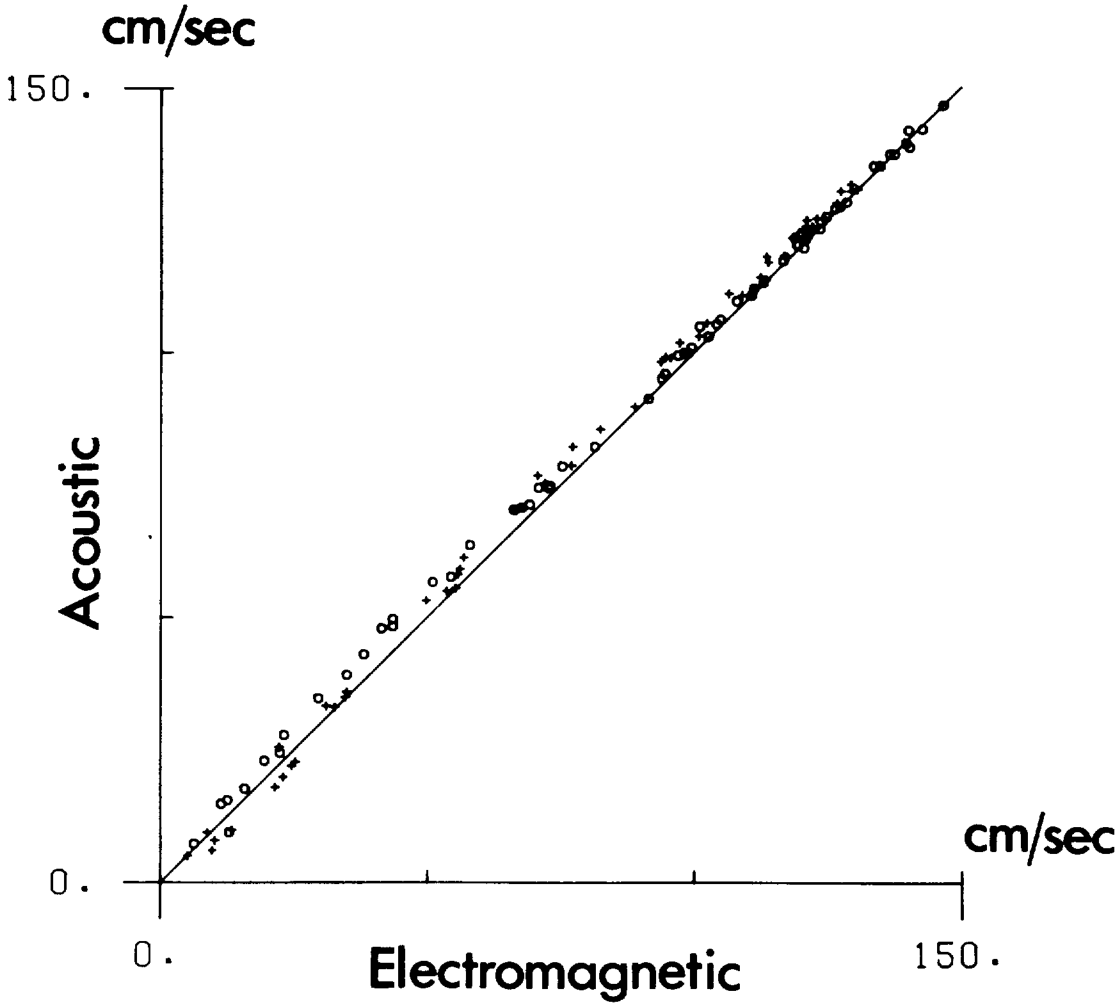

Fig. 5 Comparison of magnitudes of current vectors for electromagnetic and acoustic current meters

(O Northward flow
+ Southward flow)

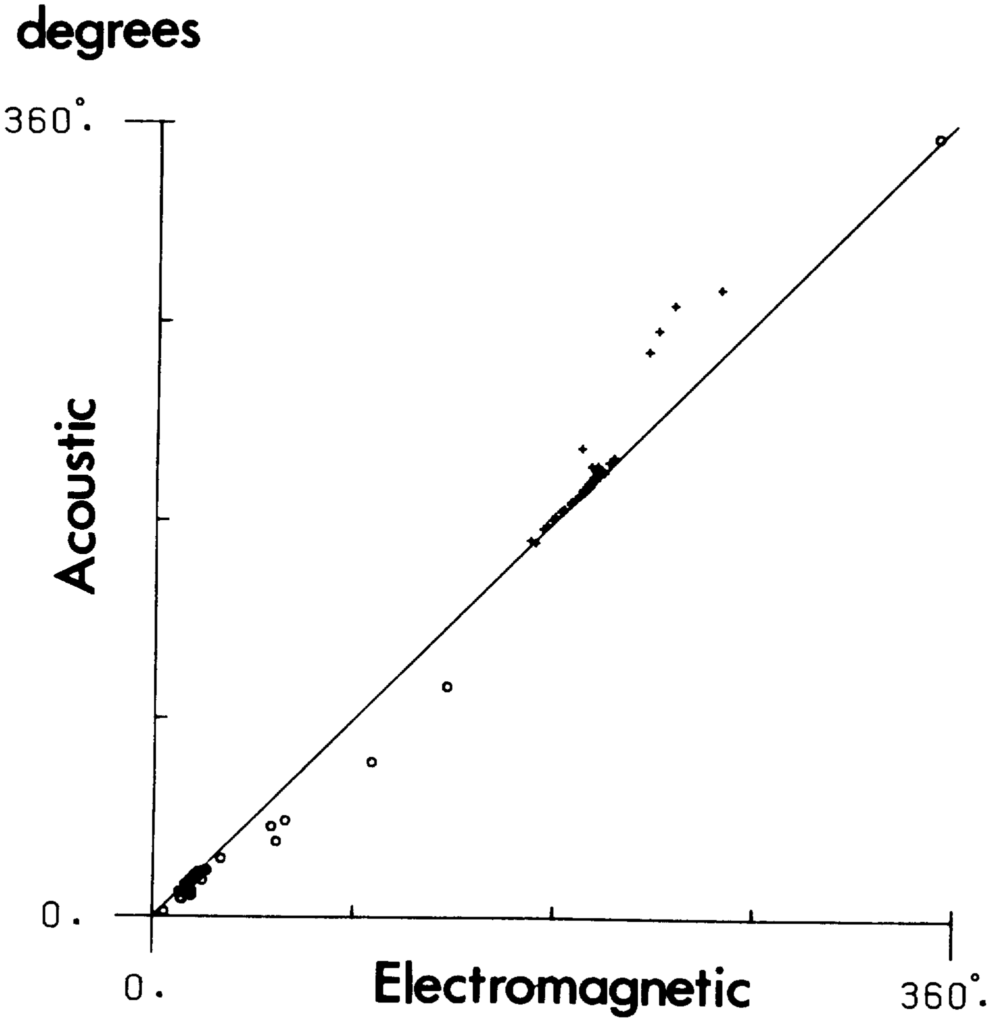

Fig. 6 Comparison of directions of current vectors obtained from electromagnetic and acoustic current meters

(O Northward flow
\+ Southward flow)

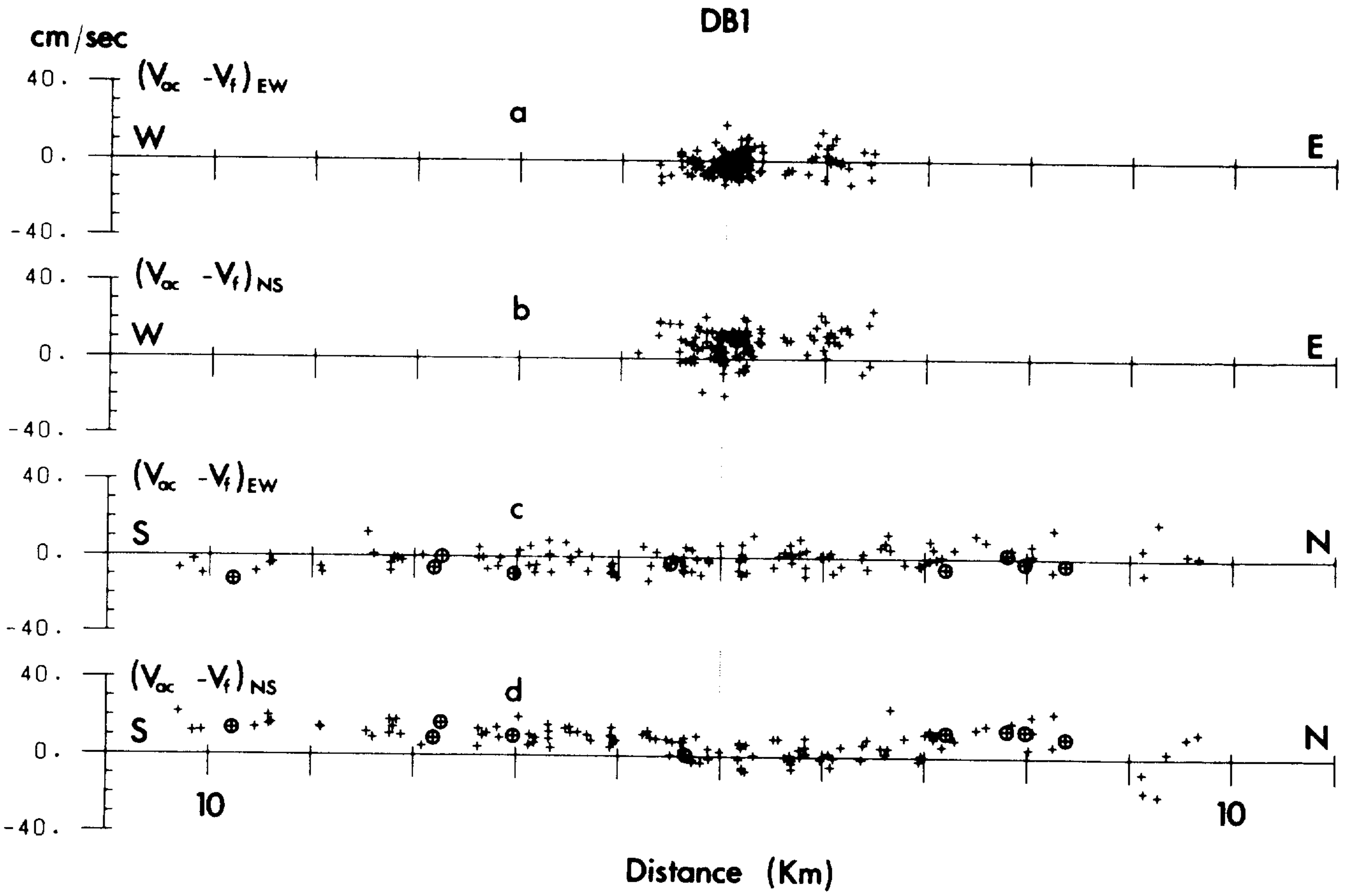

Fig. 7 (Northward flow)

Differences between currents measured by drifting floats (V_f) and DB1 (V_{ac}) current meter, plotted against distance from data buoy DB1

Note: Currents and distances are resolved into components along (N-S) and orthogonally to (E-W) principal flow directions, which are at 018°, 198° relative to true North.

Encircled points are those comparisons made in relatively weak flow conditions. (< 70cm/sec). The great majority of float positions were determined in flow > 110cm/sec N-S.

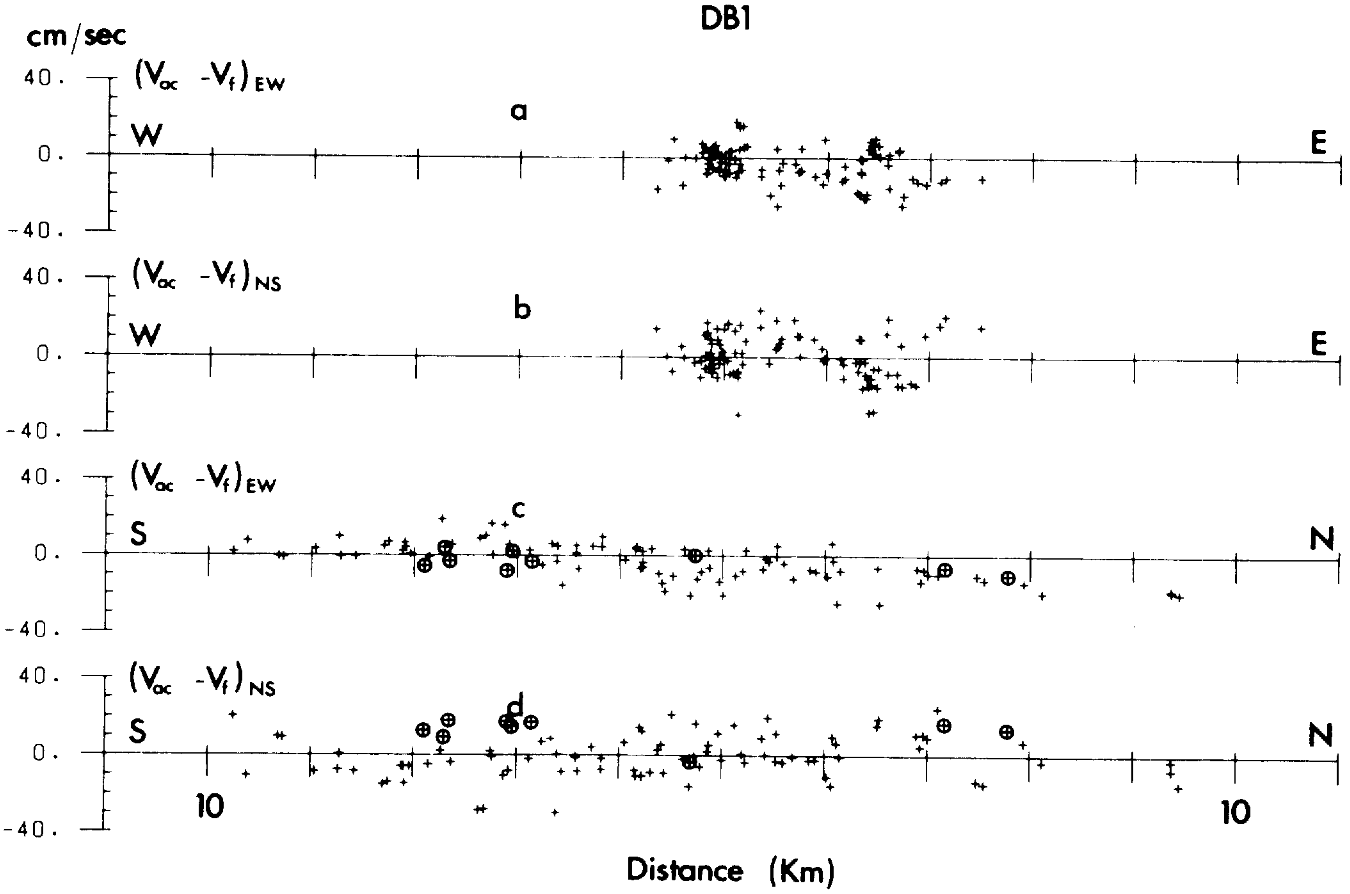

Fig. 8 <u>(Southward flow)</u>

<u>Differences between currents measured by drifting floats (V_f) and DB1 (V_{ac}) current meter, plotted against distance from data buoy DB1</u>

Note: Currents and distances are resolved into components along (N-S) and orthogonally to (E-W) principal flow directions, which are at 018°, 198° relative to true North.

Encircled points are those comparisons made in relatively weak flow conditions. (< 70cm/sec). The great majority of float positions were determined in flow >110cm/sec N-S.

DATA BUOY DBI

Harwell Acoustic Current Meter type 3244

by: W.R. Loosemore and F.H. Wells

1. Introduction

The problem of measuring the current flow of seawater with reference to the nominally fixed location of an anchored data-buoy may be solved in a variety of ways of which the following three techniques are especially appropriate to modern electronic methods of averaging and data collection. These are:

(a) Electromagnetic: a magnetic field must be generated and the method is susceptible to distortion of magnetic field by the data-buoy structures whilst the induced voltages picked up on the measurement probes are so small that electrical interference must be kept very low. In addition, the electromagnetic probe structure must be immersed in the water giving localised disturbance of the flow patterns.

(b) Ultrasonic Doppler frequency shift: this method depends on scattered ultrasonic energy from a small volume of the water, this volume being the intersection of the beams from the separate transmitting and receiving ultrasonic transducers. Thus this technique has the major advantage of measuring at a distance from the ultrasonic probe structure so that the water movement is not significantly affected by the technique. However, the received signals are very small since the ultrasound is scattered by small bubbles or solids contained in the seawater.

(c) Ultrasonic velocity measurement: this method is a direct signal transmission from transmitter probe to receiver probe so that received signals are relatively high but the probes must be immersed in the water. Thus the seawater movement being measured must be moderately close to the data-buoy and the transmitter and receiving transducers must be widely separated so that water disturbance in the vicinity of each probe does not cause serious error.

Of these three techniques Harwell had had much past experience with the application of the ultrasonic velocity technique to the one-dimensional case of river-flow and pipe-flow water velocity measurement. Thus it was a natural extension of the technique to the two-dimensional case of the data-buoy where sea velocity and direction measurements in the horizontal plane were needed. In addition consideration of the relative advantages and disadvantages of the three techniques suggested that the ultrasonic velocity method could produce a rugged design with a mean electrical power consumption of less than 500mW.

2. Acoustic Current Meter Principles

2.1 General Principles

These principles are now well-known, the operation being based on a precise measurement of the time taken for an ultrasonic pulse to travel through the seawater from a transmitter ultrasonic transducer to a similar receiving ultrasonic transducer. This time of travel is primarily dependant on the velocity of sound in seawater and the distance travelled but is also slightly increased or decreased by the movement of water. For example, in the data buoy configuration the time of travel in still water is about 2000µS which increases to 2000.7µS if the water starts to flow at 50cm/s (about 1 knot) against the direction of the ultrasonic path and decreases to 1999.3µS if the water flow is reversed. Thus a time measurement resolution and stability of about 0.01µS in a period of 2000µS is needed.

The velocity of sound varies considerably with temperature, salinity, etc, (e.g. 1% for 4°C) so that one time measurement as above is impractical and instead a time measurement in each direction along the identical path is made; the difference between these two measurements almost removes the effects of changes in the velocity of sound. However, by taking the difference of the reciprocal of these two timing measurements, the effects of changes in the velocity of sound are virtually removed to give finally an accurate measurement of the average velocity of the seawater. Two such measurements may then be made on two independent ultrasonic paths at right angles to give information on direction of flow. This direction is then compared with a reference magnetic compass to finally give components of current flow along NS and EW directions.

2.2 Theoretical Basis

Fig. 1 shows the block schematic diagram of the electronics associated with one ultrasonic path whilst Fig. 2 shows the angles associated with the two paths and magnetic compass. An analysis of the system gives the following results.

$$v_x = \frac{L_x}{2M_x}\left[(f_1 - f_2)\left(1 + \frac{2ac}{L_x}\right)\right] - \frac{dL_x}{2t_1^2} \qquad \ldots\ldots\ldots\ 1$$

$$v_y = \frac{L_y}{2M_y}\left[(f_1' - f_2')\left(1 + \frac{2a'c}{L_y}\right.\right] - \frac{d'L_y}{2t_1^2} \qquad \ldots\ldots\ldots\ 2$$

$$v_{NS} = v_x \sin A + v_y \cos A \qquad \ldots\ldots\ldots\ 3$$

$$v_{EW} = v_x \cos A + v_y \sin A \qquad \ldots\ldots\ldots\ 4$$

where: v_x, v_y : the water velocities in the directions of the two ultrasonic paths

L_x, L_y : the path lengths

c : the velocity of sound in water

a : various electronic delays associated with the measurement, in addition to the water delay

$f_1 = M/(t_1 + a)$: automatically controlled by electronics

$f_2 = M/(t_2 + a)$: " " " "

M is an electronic constant.

$2ac/L \ll 1$: established by keeping "a" small in the electronic design.

d, d^1: small differences in electronic delay "a" between forward and reverse transmission.

It will be seen from equations 1, 2 that a difference frequency measurement is needed giving both amplitude and sign followed by the complex trigonometrical computation in equations 3, 4. In all equations the signs are important to give the final correct directions of flow.

3. Electronic Design Principles

It would be inappropriate in this brief summary to discuss the detailed design of the complex electronics but the following highlights the more important features.

3.1 Transmission/Receiving Ultrasonic Timing: the transmitted waveform is initiated by a step voltage waveform whilst the ultrasonic transducer crystals have a longitudinal mode resonance at 1.25MHz so that the final receiver output is a short train of 1.25MHz waveform. The transducers are heavily damped so that only a few cycles are obtained and the time of arrival is determined by a zero crossover circuit operating on the second major crossing of the base line. The result is an accurate timing circuit reasonably independant of amplitude variations of the signal.

3.2 Signal Amplitude and Marine Growth: the amplifier gain is many times (about 30) greater than necessary so that some marine growths over the transducer surface can occur, (causing signal attenuation), before the signal is reduced below the minimum acceptable signal level.

3.3 Analogue memory and interruption of ultrasonic path: it is of the utmost importance that the ultrasonic path can be briefly interrupted without causing complete failure of measurement. Interruption by fish, debris, etc cause failure of signal but in this event the two oscillators f_1, f_2 in the circuit continue at the last reading and form a short-term memory. This is very effective and up to 90% of transmissions can fail in 10 secs before a fault indication is registered; e.g out of 800 transmissions in 10 secs the electronics require of the order of 80 successful ultrasonic pulses.

3.4 Time delay matching in electronics: reference to equation 1 will show that the term involving d represents a zero error when the water is stationary. Thus time delays in electronics and cables ("a") must be well matched to reduce the value of d: for the data-buoy a matching accuracy of about 3nS is probably good enough but this must include variations of electronic delay with temperature.

3.5 Multiplex operation: to avoid ultrasonic interactions between the various transmissions the operation of the four transmitters is in a regular time sequence taking about 12ms for the four transmissions. Since such transmissions are time sequenced it is possible to switch some of the circuits so that the same circuit is used on each transmission. This feature is very important to reduce the value of "d" in para. 3.4 although it adds complexity to the overall circuit conception.

3.6 Trigonometrical Computation: this is a fully digital circuit with a table of sines of angles from 0° to 90° (resolution ± 0.7 degree) stored on a Read only memory integrated circuit. All digital circuits use CMOS technology except for the sine table ROM which was not available in CMOS.

3.7 Measurement Averaging: the design averages the results from the successful transmissions, see para 3.3, this averaging being on the NS, EW components of velocity. The latter is necessary because the data-buoy is swinging at anchor so that the angle with respect to magnetic north is continually changing by small amounts.

3.8 Fault recording: a fault signal is produced if less than 10% of the received signals on any ultrasonic path are above a preset amplitude.

3.9 Power Consumption: as the Data buoy power availability to be severely restricted the flow measurement is restricted to 5 mins. in each hour and during this 5 mins the circuits are only energised when needed. By such care in design the average power consumption has been kept to 200mW total; an exceedingly low figure for this electronic performance.

4. Mechanical and Ultrasonic Design

The major uncertainty in this project was the question of Marine growth destroying the efficiency of the ultrasonic transducers. There was no quantitative information on this aspect during the design phase and we are pleased to report that operation has been successful over at least a year's trials. Thus this Marine growth has been much less than "feared" and it will be interesting to examine the transducers during the next period in Dock.

Fig. 3 shows an impression of the mechanical design. The spars carrying the ultrasonic transducers must be retractable during towing operations so that these main movable spars are inside fixed tube walls of 1ft diameter in the Data-Buoy hull. The actual small transducers can be withdrawn through the movable spars to permit changing from the buoy deck but this has not been necessary.

4.1 Angular precision: the axis of the beams must be precisely aligned since the ultrasonic angular beam width is only a few degrees. This necessity for angular alignment proved to be a serious constructional difficulty.

4.2 Electronic Construction: all electronics are in a sealed environmental case and use a modular construction for ease of maintenance.

5. Future system: the "way ahead" would be to reduce the ultrasonic path length so that all four transducers could be mounted on one spar with perhaps a 30cm path length instead of the present 300cms. This would give problems in preserving sufficient accuracy of measurement but it would give good mechanical alignment and reduce the data-buoy constructional difficulties to only one fixed large diameter tube through the data-buoy hull. Harwell considers such an extension of the present design to be feasible and very desirable for any future data-buoy developments.

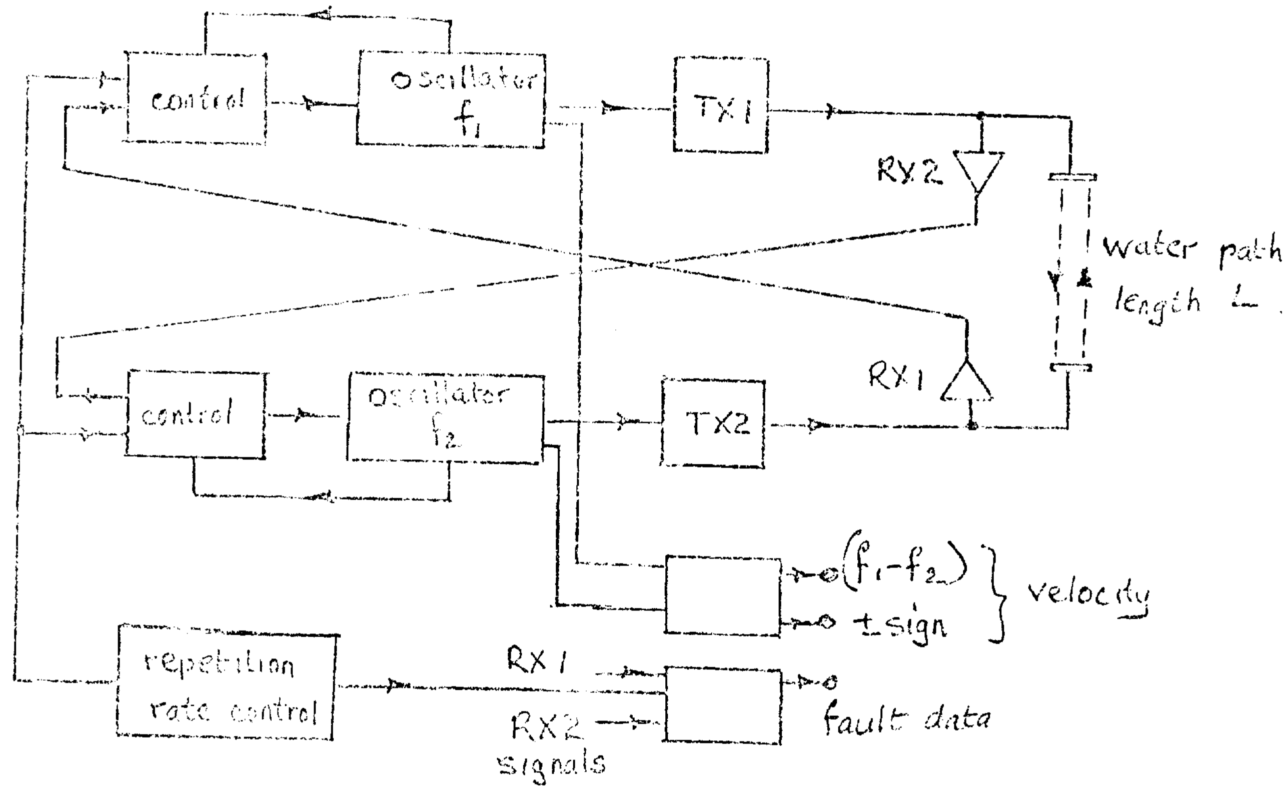

fig. 1 Electronics block schematic

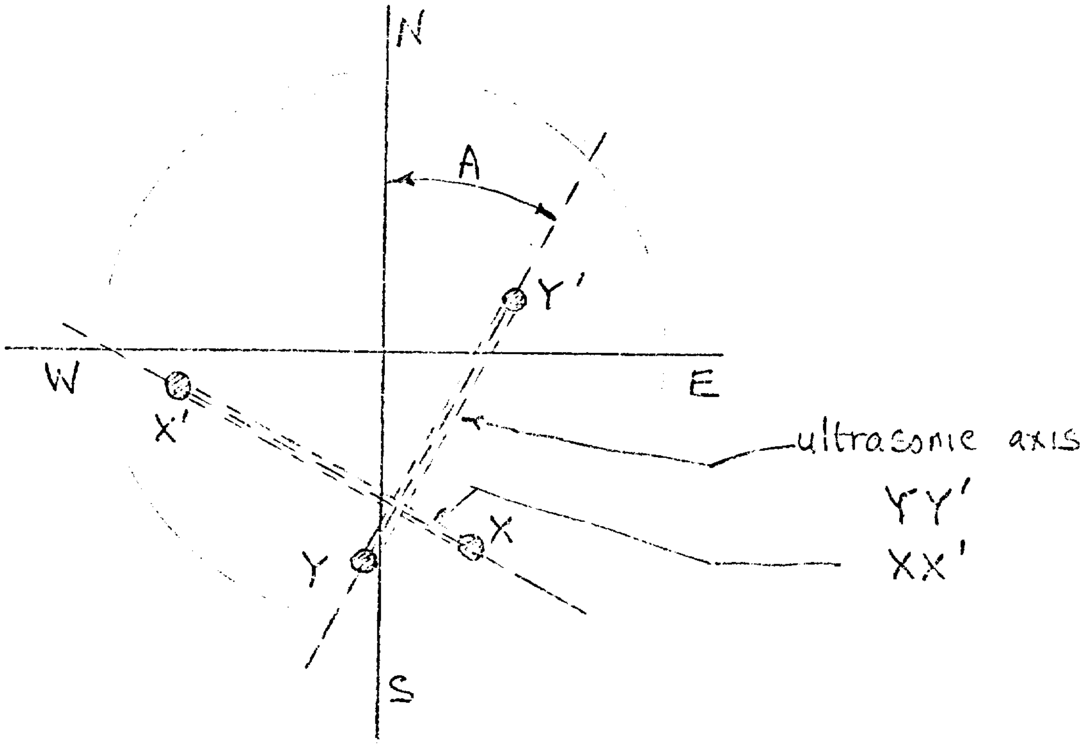

fig 2 Angles relative to magnetic north

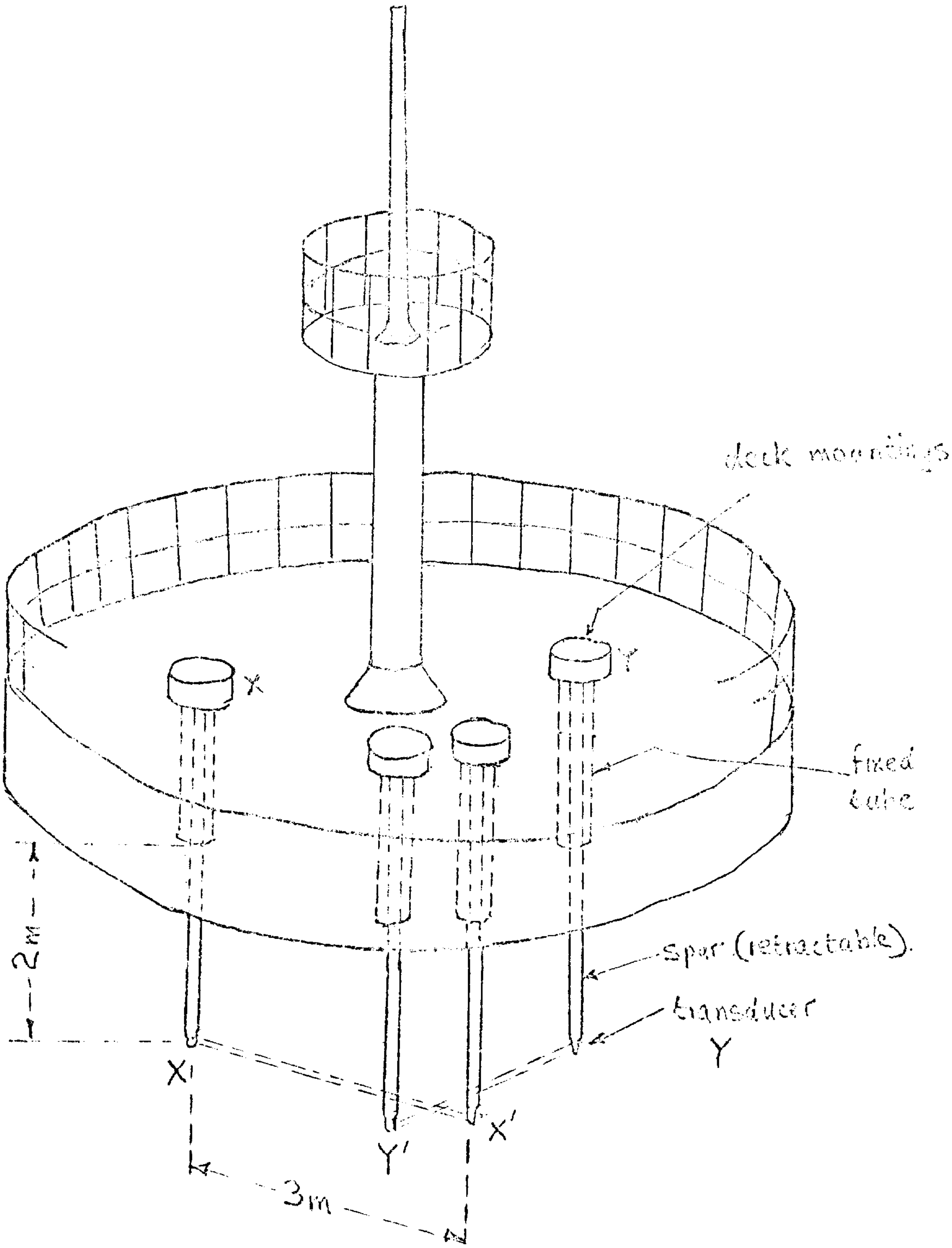

fig 3. Acoustic current meter arrangement