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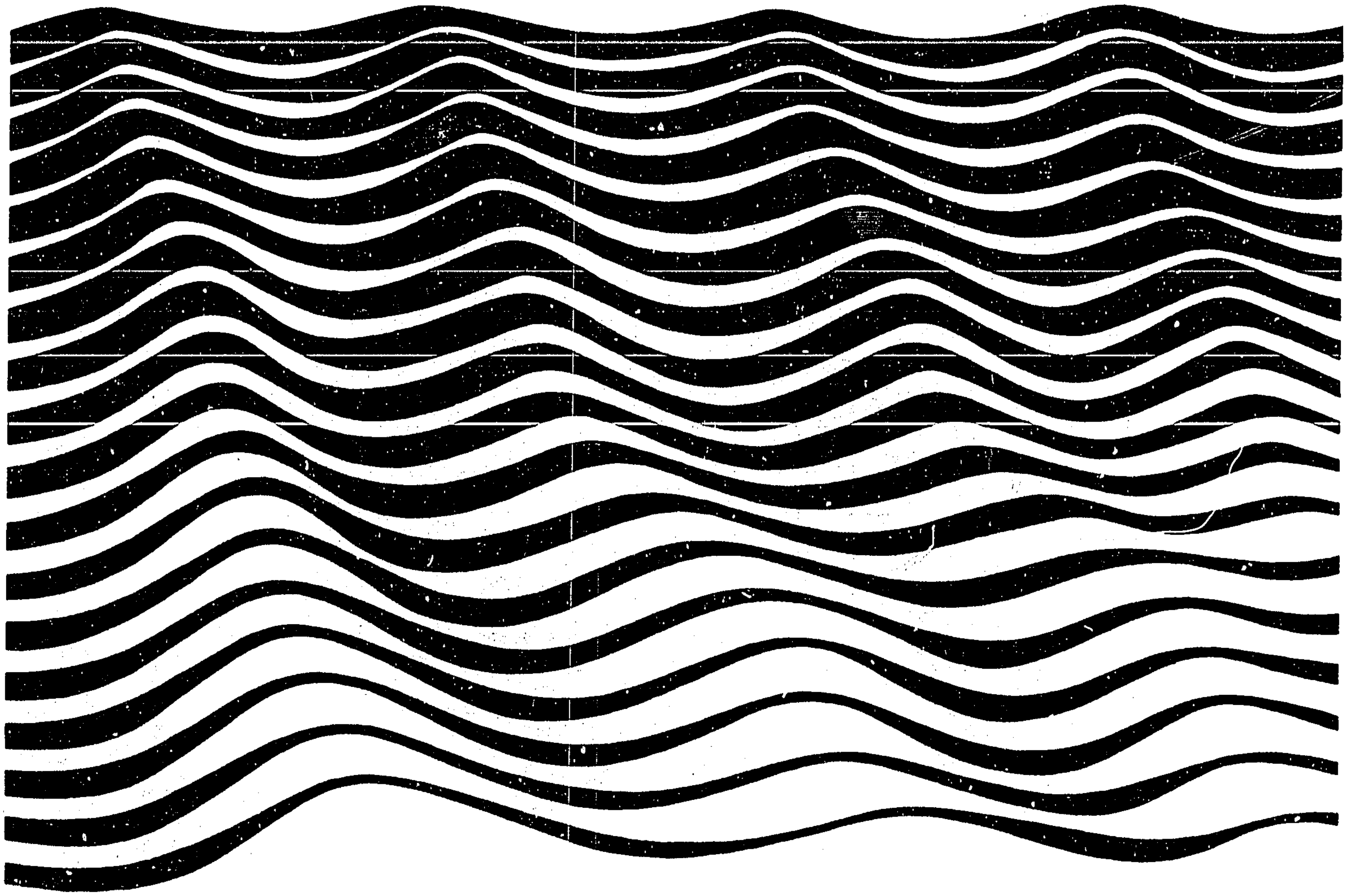
# An intercomparison of open sea tidal pressure sensors

Report of SCOR working group 27:
"Tides of the open sea"



Unesco 1975

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| No. | | Year | SCOR WG |
|---|---|---|---|
| 9 | Report on intercalibration measurements, Leningrad, 24-28 May 1966 and Copenhagen, September 1966; organized by ICES | 1969 | – |
| 13 | Technical report of sea trials conducted by the working group on photosynthetic radiant energy, Gulf of California, May 1968; sponsored by SCOR, IAPSO, Unesco | 1969 | WG 29 |
| 15 | Monitoring life in the ocean; sponsored by SCOR, ACMRR, Unesco, IBP/PM | 1973 | WG 29 |
| 16 | Sixth report of the joint panel on oceanographic tables and standards, Kiel, 24-26 January 1973; sponsored by Unesco, ICES, SCOR, IAPSO | 1974 | WG 10 |
| 17 | An intercomparison of some current meters,report on an experiment of Research Vessel Akademic Kurchatov, March-April 1970, by the working group on Current Velocity Measurements; sponsored by SCOR, IAPSO, Unesco | 1974 | WG 21 |
| 18 | A review of methods used for quantitative phytoplankton studies; sponsored by SCOR, Unesco | 1974 | WG 33 |
| 19 | Marine Science Teaching at the University Level. Report of the Unesco Workshop on University Curricula – *Also published in French and Spanish* | 1974 | — |
| 20 | Ichthyoplankton. Report of the CICAR Ichthyoplankton Workshop | 1975 | — |
| 21 | An intercomparison of open sea tidal pressure sensors. Report of SCOR working group 27: "Tides of the opean sea" | 1975 | WG 27 |

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# An intercomparison of open sea tidal pressure sensors

Report of SCOR working group 27:
"Tides of the open sea"

Unesco 1975

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Scientific and Cultural Organization

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# PREFACE

This series, the Unesco Technical Papers in Marine Science, is produced by the Unesco Division of Marine Sciences as a means of informing the scientific community of recent developments in oceanographic research and marine science affairs.

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# I INTRODUCTION

SCOR working group 27 was set up in 1965, under the chairmanship of Professor Walter H. Munk, with the remit :

"To encourage and assist with the design of instruments for measuring tides on the continental shelf and in the deep sea; to establish criteria concerning precision, sampling times and related considerations; to co-ordinate the observational programmes and ultimately to bring about some uniform analyses of the deep sea data".

At that time, the pioneering deep sea capsules of Eyries and of Snodgrass had only just been brought into operation, and there was little other activity in the field. By 1971, at least nine different types of instruments were being used in various parts of the world, some in deep water, others limited to continental shelf depths. At its meeting in Venice, October 1971, the working group decided that the time was ripe for an intercomparison exercise with the objectives :

1. to compare the performance of various tidal pressure sensors in close proximity at sea;
2. to enable users to compare techniques of mooring and recovery in marine conditions;
3. to encourage the international collaboration necessary for a substantial attack on the problems of oceanic tides.

In order to handle both deep and shallow capsules in one operation, and achieve some measure of comparison between them, it was agreed that the test area should be in the vicinity of a steep continental shelf edge. It was at first planned that a French research ship would be used, with a British ship as 'support', but it later transpired that no French ship was free at convenient times, and the whole operation was finally based on two 15-day cruises of the British R.R.S. 'Discovery' in November and December 1973, respectively. These cruises were entirely devoted to the objectives of this experiment. The French naval hydrographic service (SHOM) offered to supply a ship from Brest in case of emergency, but this was never required. The deployment area, chosen by the British and French representatives, was the shelf edge near 'Banc de la Chapelle', (47°45'N, 7°10'W) about 120 n. miles southwest of Brest. 'Shallow' capsules were to be laid on that sandbank, about 180 m deep, and 'deep' capsules on another gently sloping plateau, the "Meriadzec Terrace' (47°30'N, 8°30'W), about 2200 m deep. (Later, when a capsule limited to 150m appeared in the programme, a third test site was identified, about half way between Banc de la Chapelle and Brest, about 140 m deep). The main plan was to lay the capsules in the appropriate sites during the first cruise, and recover them on the second cruise just over a month later, a month being a good period for tidal analysis of the records.

Notices, inviting all possessors of suitable equipment to join the exercise, were circulated in late 1972 by members of the working group, and advertised in SCOR *Proceedings* vol. 8 no. 2. Within a fairly short time, we had made arrangements for seven organizations to join the exercise, some of whom wished to test two capsules. This filled the available laboratory space and time for deployment. We regret that we were unable to include the Victoria, B.C. branch of Environment Canada , whose application arrived too late. Dr. J.B. Matthews of the University of Alaska was eventually unable to find a sponsor for the large freightage costs necessary to bring his tidal capsule to England, and his place was taken at short notice by SHOM at Brest. The few other existing tidal pressure recorders whose owners did not join the experiment, for various reasons, are described in papers presented at the IEEE Conference at Halifax in August 1974. The participating equipment is described fully in Section 2 of the present report. A short account of the cruise proceedings themselves is given in Section IV.

Tidal pressure recorders described in the report are, for the most part, prototypes which are not available commercially. Indications of approximate construction cost, including reference to commercially available components, are given to assist scientists in the development of similar equipment. Any comments on the use of these, or other, tidal sensors would be welcomed by the sponsors.

Using a tidal pressure recorder does not end with the operations at sea, testing and hazardous as they are. Special techniques are required for laboratory calibration of the sensors; these are discussed in Section III. Another important branch of expertise is then required to analyse the recorded data in order to extract an optimum set of tidal 'constants' and measures of the 'noise' content of each record. There are many individual approaches to the tidal analysis of one month's data, evolved over the last few decades, some of which give results obviously different from others. A comparison of such methods is therefore a natural counterpart to the main exercise. Accordingly, we staged an 'Analysis workshop', in which participants in the exercise and others were invited to analyse a given one-month pressure series by their preferred methods, and to compare the results. There were ten contributors to the 'Analysis workshop', each presenting a different method and set of results. A general discussion on this work was held at the Institute of Oceanographic Sciences, Wormley, on 9 November 1973, immediately after the first cruise. An account is given in Section V of this report.

One predictable result of the 'Analysis workshop' was that the records from different instruments in the main exercise should all be analyzed by the digital technique, for proper comparison. In fact, two different techniques were chosen as being representative of two fundamentally different approaches, and all records were analyzed by both methods for the purpose of this report. The results are presented and discussed in Section VI.

Finally, in Section VII we offer some general conclusions on the work as a whole, with some recommendations.

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This report was prepared by the following members of SCOR working group 27 :

D.E. Cartwright (Chairman); G.C. Dohler, J.-L. Hyacinthe, W.H. Munk, R. Radok, B.D. Zetler, with the assistance of A. Demerliac, D.I. Gaunt, and F.E. Snodgrass.

Participants in the sea exercise were :

G. Auffret, M. Baron, D.E. Cartwright, P.G. Collar, G.C. Dohler, D.I. Gaunt, M. Gournay, T.J.P. Gwilliam, J.-L. Hyacinthe, W. Iseley, L.F. Ku, A. Madgwick, C.A. Pearson, R. Perchoc, A. Quelen, J.B. Rae, L.M. Skinner, J. Smallbone, F.E. Snodgrass, R. Spencer, W. Strudwick, M. Wimbush and Officers and Crew of R.R.S. 'Discovery'.

Contributors to the 'Analysis workshop' were :

D.E. Cartwright, J.-L. Hyacinthe, L.F. Ku, C.A. Pearson, R. Radok, F. Schott, J.M. Vassie, D.J. Webb, M. Wimbush, and B.D. Zetler.

The working group is indebted to all the above individuals; and to the sponsoring international organizations, SCOR, IAPSO, and Unesco, for providing travel funds,

to the British Institute of Oceanographic Sciences (IOS) for putting the Royal Research Ship 'Discovery' with associated facilities at the disposal of the organizers of this experiment,

and finally, to the following organizations :

Canadian Marine Sciences Directorate (Ottawa),
Centre océanologique de Bretagne (Brest) - 'COB',
Service hydrographique et océanographique de la Marine (Brest) - 'SHOM',
United States National Oceanographic and Atmospheric Administration (Rockville), - 'NOAA',
Institute of Geophysics and Planetary Physics (La Jolla), 'IGPP',

who, together with IOS supplied the very expensive instrumentation and freightage costs necessary for carrying out the experiment.

# II INSTRUMENT TECHNICAL INFORMATION

Devices used in the tide gauge intercalibration experiments (November-December 1973) will be described under the following headings :

1. Mechanical components and accessories
2. Electronic recording components
3. Sensors
4. Operation at sea
5. Financial elements
6. Reports describing equipment
7. Responsible persons and their addresses.

These technical details permit an exhaustive comparison of the apparatus and of the methods of measurement.

The following general remarks may be made :

- Some of the apparatus aim to obtain optimum performance irrespective of price and their construction in large numbers was not envisaged : IGPP with seven sensors, IOS Bidston with five sensors. Other instrumentation aims at possible serial production : NOAA, COB, Canada, SHOM, IOS Wormley.

- Instruments used to depths in excess of 5,000 m are those of IGPP, NOAA, COB (and IOS Wormley deployed one limited to 4,000 m some time later at the same site). Others have been designed for the continental shelf.

- The sensors employ Bourdon tube, Hewlett Packard quartz crystal, strain gauge and are characterized by varying drifts. Comments on drift are made in Section VI.2.

- Deployment by an autonomous system (pop-up with acoustic release) proved to be most reliable in the deep ocean as well as on the continental shelf.

Other equipment, not employed in this experiment, has been described in the proceedings of the IEEE 'Ocean 74' conference (Halifax, August 20-23, 1974).

## II.1 IGPP deep sea instrument capsule

### II.1.1 Mechanical components and accessories (Fig. II.1.1.)

- Vertical 'Figure eight' shaped centreplate with an attached aluminium instrument frame and four Alcoa Corp. hard-anodized aluminium hemispheres 2.54 cm thick, 56 cm internal diameter.

- Iron anchor frame attached at the centre point by two coupled releases through a. T-link.

- Releases : a solenoid-operated hook and a Bermite Corp exploding bolt.

- International Transducer Corp. Hydrophone.

- International Transducer Corp. Pinger.

- Ocean Applied Research radio beacons 27 MHz (2)

- Ocean Applied Research flashing light.

- Electrical connexions to external components : Electro-oceanic bulkhead penetrators in the centreplate.

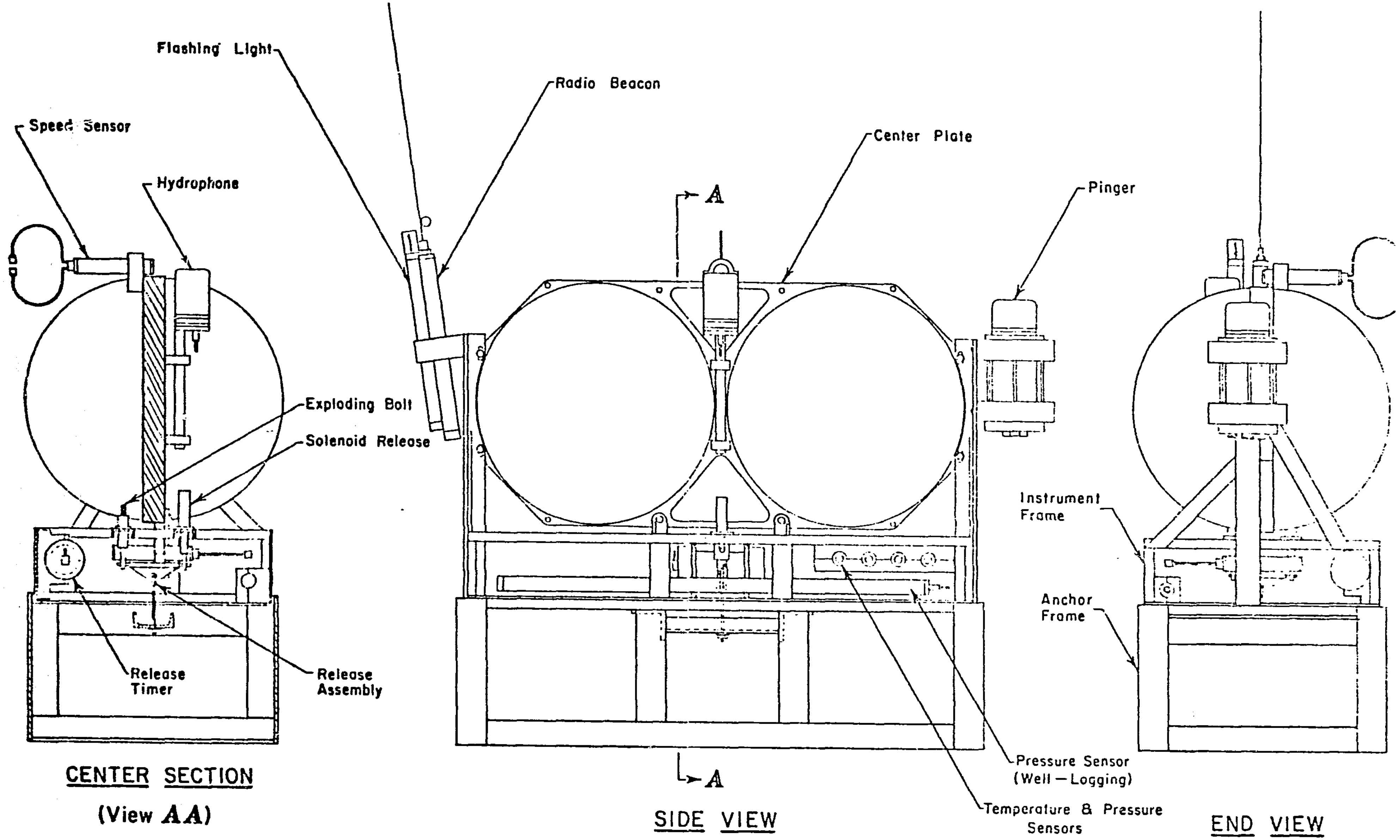


Figure II.1.1 IGPP deep sea instrument capsule - *mechanical components and accessories.*

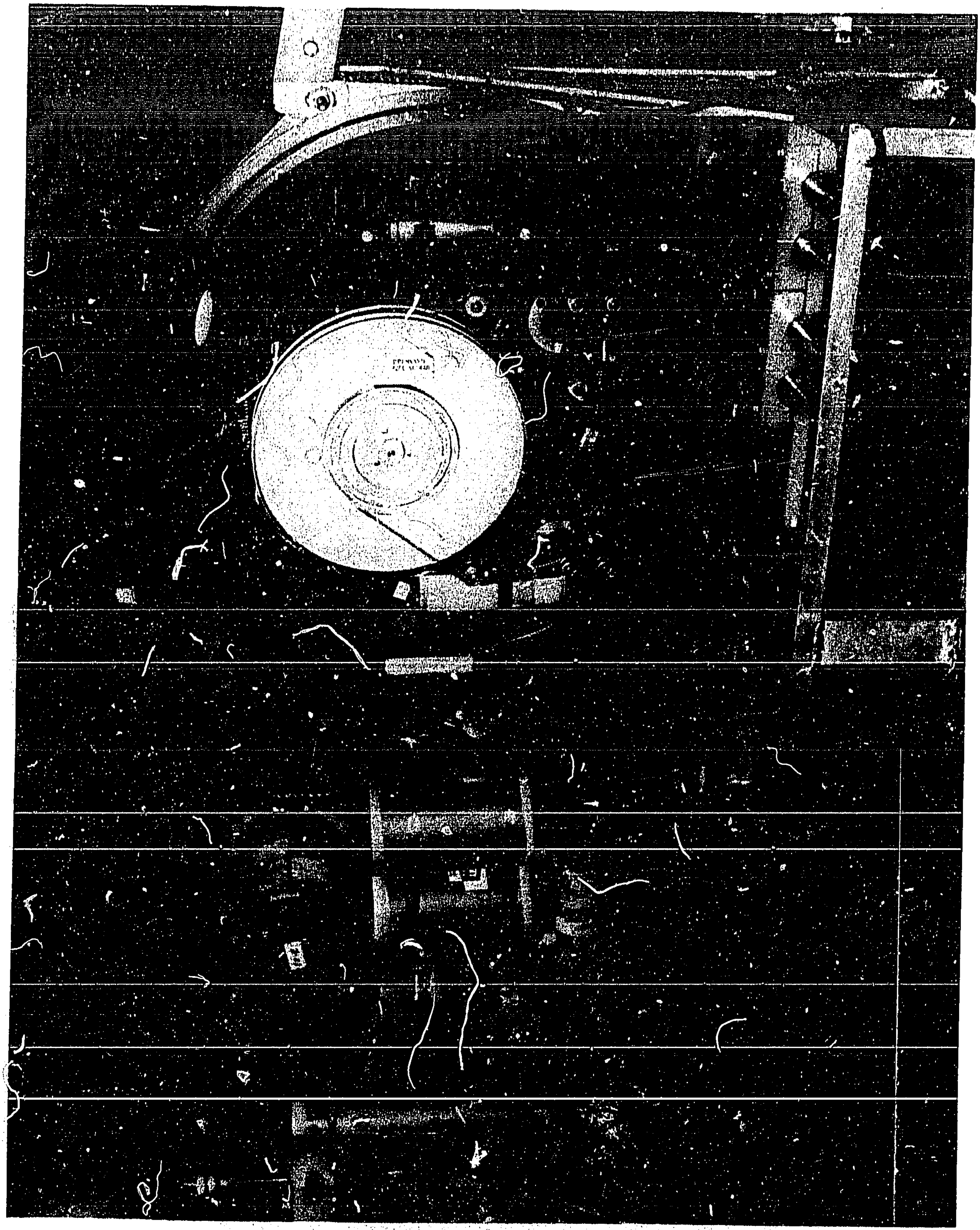


Figure II.1.2 IGPP deep sea instrument capsule - *electronic recording components (view one).*

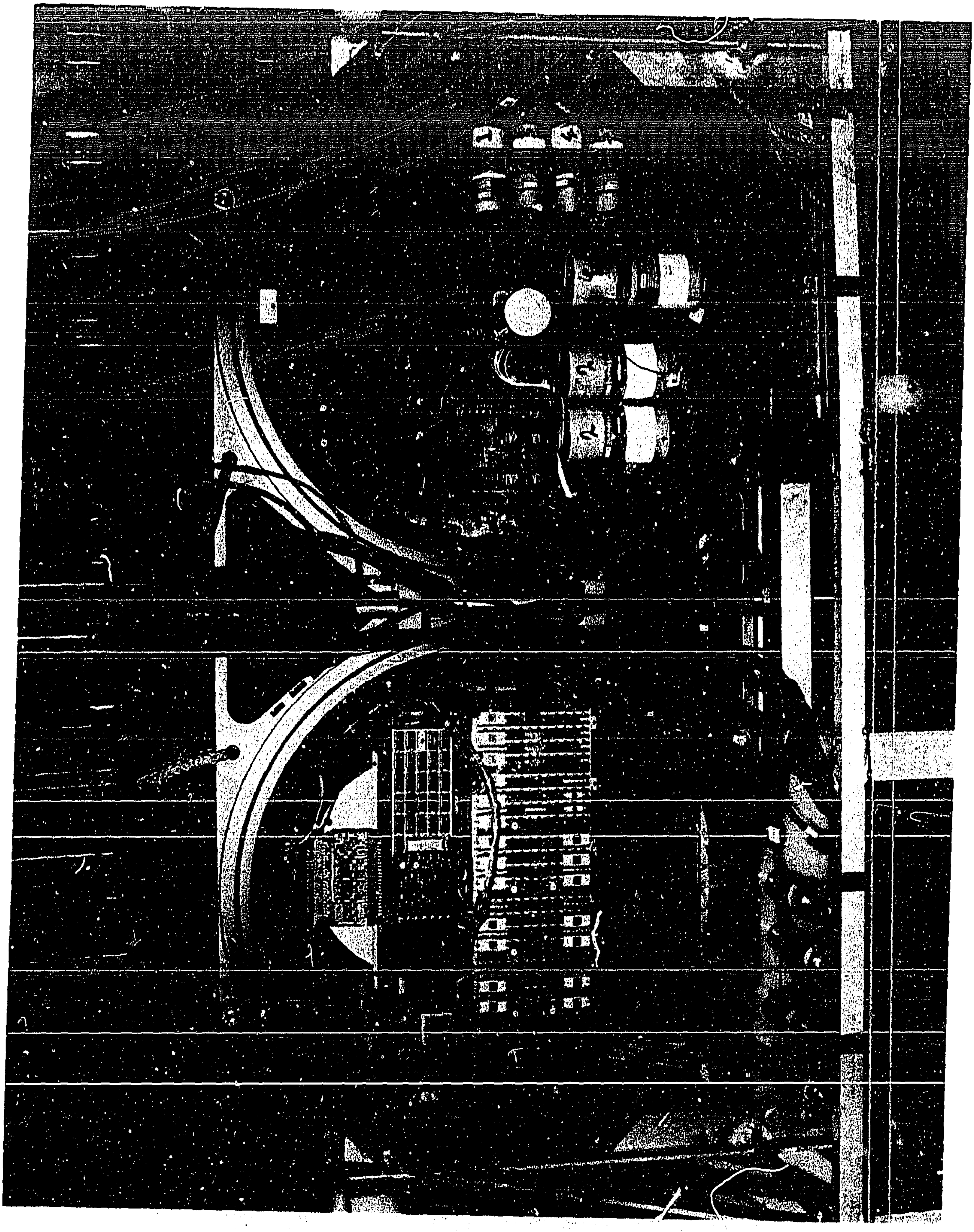


Figure II.1.3 IGPP deep sea instrument capsule - *electronic recording components (view two).*

- Electrical isolation of dissimilar metals : PVC separators, polypropylene mounts and brackets; Teflon washers and sleeves for stainless steel mounting bolts.

- Purge-plug on the centreplate for refilling with dry nitrogen and evacuation to about 25 cm Hg internal pressure; test for leaks by monitoring the pressure.

- Entire apparatus :

  . dimensions : 1.15 m x 1.30 m x 0.65 m
  weight (with anchor) : 325 kg in air, 80 kg in water (fall speed : about 1 m/s).

- The capsule system has been used at depths to 550 m (working pressure of the sphere : 530 atmospheres).

### II.1.2. Electronic recording components (Fig.II.1.2 and II.1.3)

- Maximum number of sensor inputs : seven.

- F.M. signals simultaneously counted during an adjustable sampling interval in excess of five seconds (e.g. 10 minutes used during the SCOR experiment).

- Digi-Data Model 1401 LP magnetic tape recorder with motor powered separately : a full 2,400 foot reel of tape ($2.6.10^5$ samples) required 10 A hours at 12 V.

- Standard computer 200 bpi seven track format.

- Low power C-MOS logic : power consumption 3 mA at 6.75 V.

- Acoustical communication between the ship and the instrument capsule : 9 frequency-coded commands (with combination of four frequencies between 15 and 15 kHz) for operations from the ship; time-coded 8 kHz pinger pulses giving 10 diagnostic signals from the capsule.

### II.1.3. Sensors (Fig. II.1.4.)

- All sensors employ resonating quartz-crystals as sensing elements giving, by heterodyning the signal with a reference crystal oscillator, a F.M. signal of near audiofrequency.

- Pressure sensors : all Hewlett Packard sensing element. Pressure sensitivity is about 12.3 Hz/m of sea water. Drifts are about 1 cm of sea water pressure per month. The sensing element is used with :

  a) Hewlett Packard electronics (type oceanic) : power requirement 30 mA at 9.5 V; least count of recording 0.15 mm.

  b) Hewlett Packard electronics (type well-logging) : power requirement 14 mA at 12 V; least count of recording 0.7 mm.

  c) Integrated Circuit Instruments Corp. electronics (type oceanic): power requirement 2 mA at 8V; least count of recording 0.8 mm.

- Temperature sensors :

  a) Two with Hewlett Packard sensing elements and Integrated Circuit Instruments Corp. electronics : power requirement 2 mA at 8V; least count of recording 2 $\mu$ °C.

  b) Sea Data Corp. sensing element and electronics : power requirement 6 mA at 12 V; least count of recording 4 $\mu$ °C.

- Current Speed Sensor :

Hewlett Packard sensing element and electronics : power requirement 2 mA at 8V; least count of recording $10^{-4}$cm/s at 2 cm/s.

- All sensors are powered by Mallory Corp. low-temperature mercury batteries.

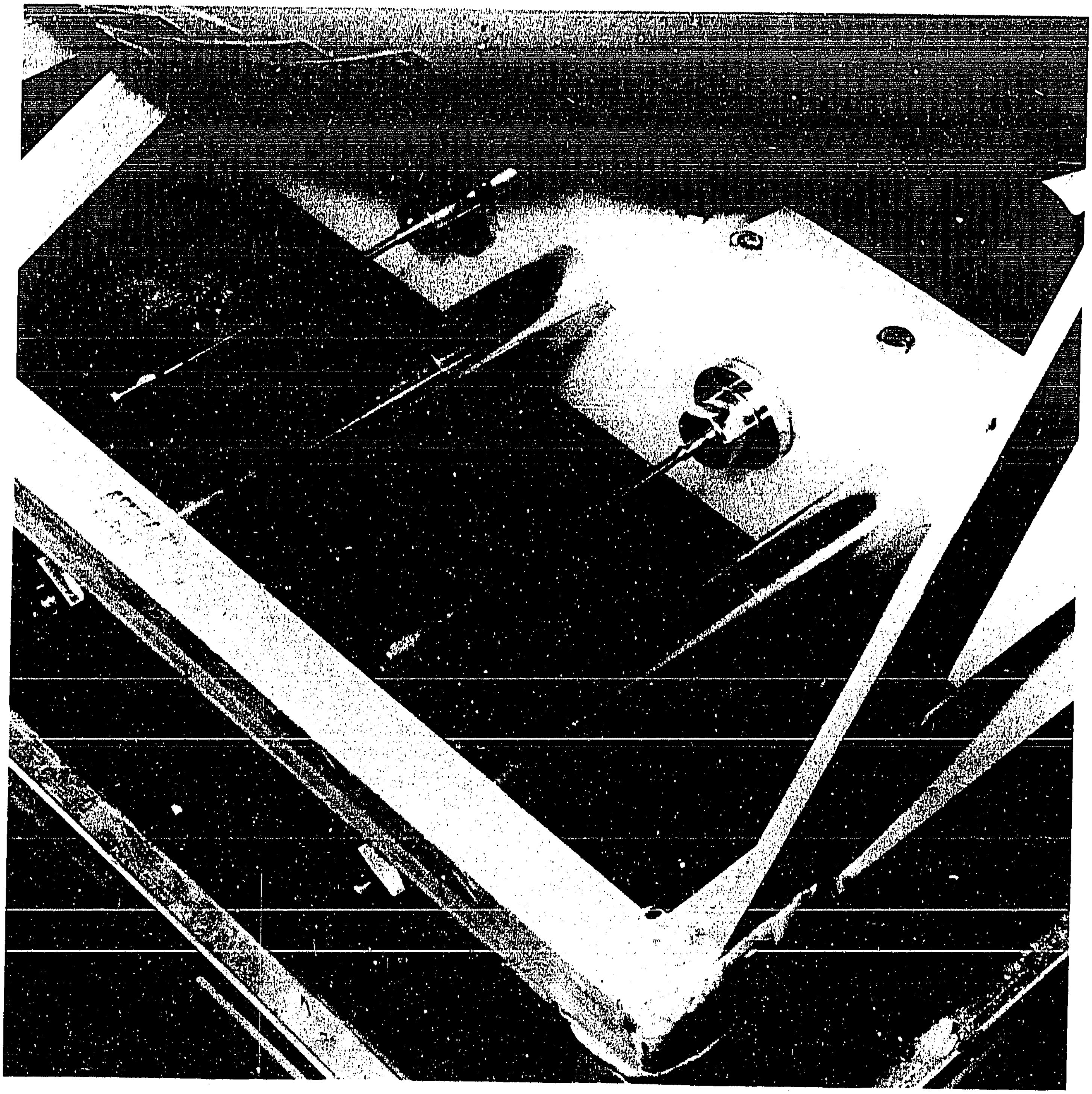


Figure II.1.4 IGPP deep sea instrument capsule - *sensors.*

### II.1.4. Operation at sea

- Capsule released by means of a drop hook.
- Acoustical checks.

### II.1.5. Financial elements

| | |
|---|---|
| - Shipboard items : | $ 13,654 |
| - Capsule items : | |
| . tape recorder | $ 3,000 |
| . pressure probe (well-logging) Hewlett Packard | $ 8,125 |
| . " " (oceanogr.) Hewlett Packard | $ 5,000 |
| . temperature sensor Hewlett Packard | $ 2,250 |
| . " " Sea Data Corp. | $ 1,400 |
| . velocity sensor | $ 2,250 |
| . pinger | $ 1,170 |

### II.1.6. Reports describing equipment

- Snodgrass F.E. (1968) Deep sea instrument capsule. Science 162, 78-87.
- Irish J.D. and Snodgrass F.E. (1972) Quartz crystals as multi-purpose oceanographic sensors - I Pressure. Deep Sea Research, 19, 165-169.
- Caldwell D.R., Snodgrass F.E. and Wimbush M.H. (1969) Sensors in the deep sea. Physics Today, 22 No. 7, 34-42.
- Snodgrass F.E. and Wimbush M.H. (1974) Evaluation of deep sea tide gauge sensors. IEEE International Conference on Engineering in the Ocean Environment, Inst. Electrical and Electronic Engineers, New York (2 vols.).

### II.1.7. Responsible addresses

F.E. Snodgrass : Institute of Geophysics and Planetary Physics,
University of California,
Post Office Box 1529
La Jolla, California 92037 (USA)

M.H. Wimbush : NOVA University
Physical Oceanographic Laboratory,
8000 North Ocean Drive
Dania, Florida 33044 (USA)

## II.2 NOAA deep sea tide gauge

### II.2.1 Mechanical components and accessories (Fig. II.2.1)

- One 56 cm internal diameter aluminium sphere housing the tide gauge, mounted on an aluminium base placed atop the steel tripod (1,350 pounds; 618 kg) serving as the anchor.

- Two AMF acoustic release-transponders Model 322, also mounted on the aluminium base and flanking the sphere, bridged by a steel bar which is held by a chain to the tripod.

- Evacuation of the sphere to about 500 microns prior to launching; internal pressure is monitored by a strain gauge transducer, providing a check for leaks.

- Floatation provided by a 3M syntactic foam buoy with a density of 42 $lb/ft^3$ (673 $kg/m^3$) giving a net buoyance of 390 pounds (177 kg).

- Beacon light and beacon transmitter on the syntactic foam buoy.

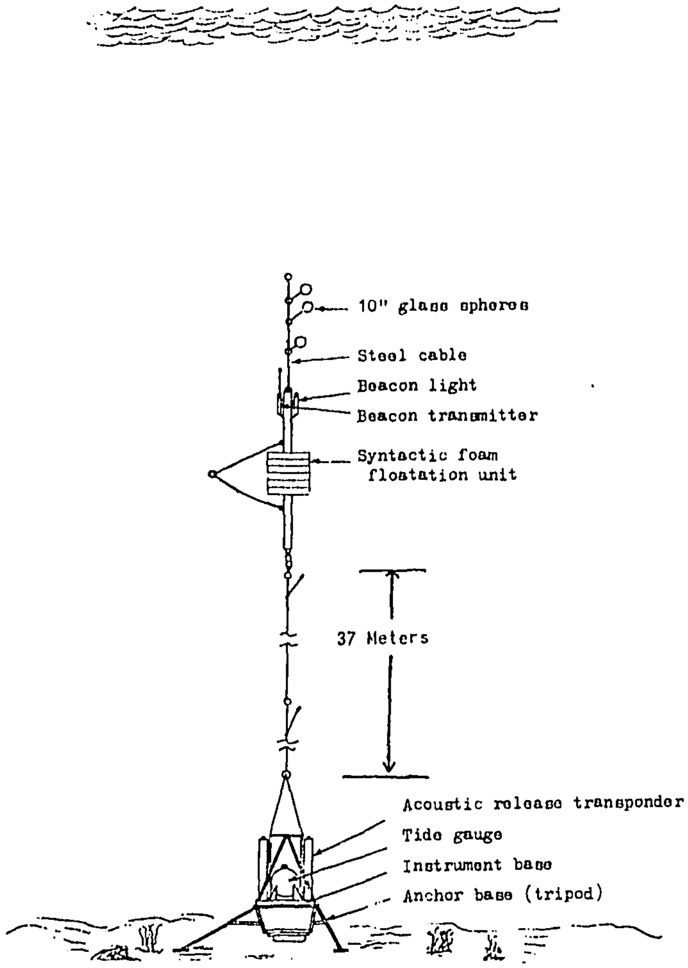


Figure II.2.1 NOAA deep sea tide gauge - *principle of mooring.*

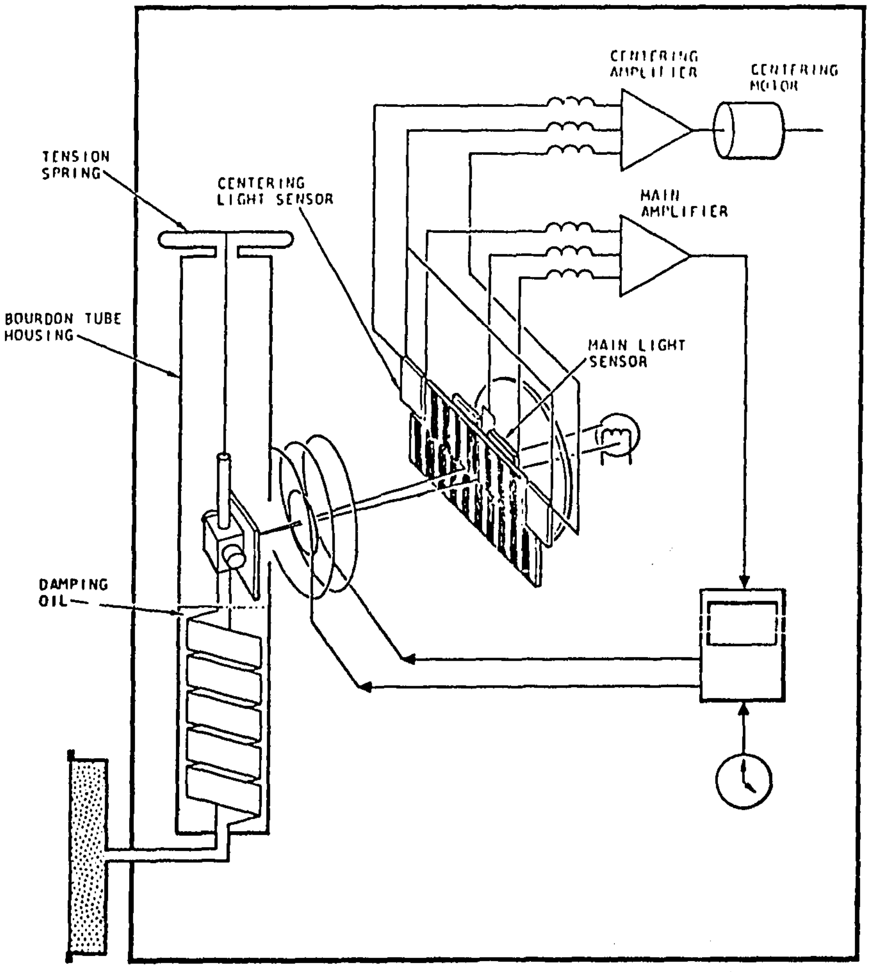


Figure II.2.2 NOAA deep sea tide gauge - *principle of instrument.*

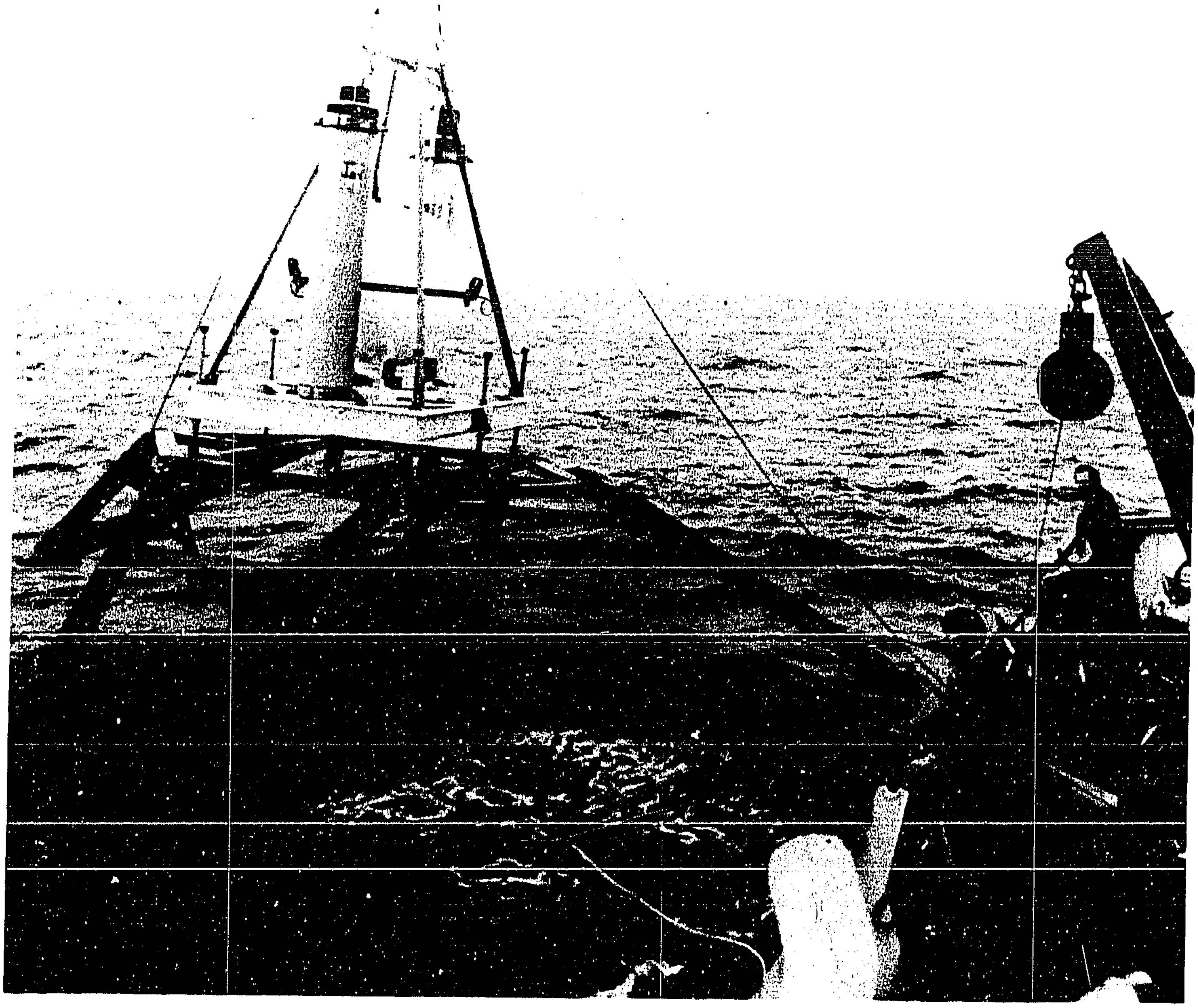


Figure II.2.3 NOAA deep sea tide gauge - *operation at sea.*

### II.2.2 Electronic recording components

- Frictionless optical readout; the minute rotations of the sensor caused by the initial fluctuations are detected by means of an optical lever, with a mirror on the sensor (Fig. II.2.2.).

- Reading every six or thirty minutes controlled by an Accutron timer. Possible record of about 45 days at a rate of 10 points per hour.

- Resolution of better than 1 cm.

- Time mark every three hours.

- Precise centering of the optical lever on the bottom.

- Tilt switch in one of the releases, and a leak-detecting circuit connected to the sphere in the other, doubling the reply ping rate of the releases if the tide gauge is tilted more than 30° or if the sphere floods.

- Rustrak strip chart recorder started by the Accutron contact.

- Shipboard equipment: AMF Model 301 acoustic range and bearing relocation system. Radio direction finder receiver.

### II.2.3 Sensor

- Oil filled Bourdon tube constructed of Ni Span C alloy and immersed in an oil bath to prevent vibration; it rotates about 60° over the full range of depths from 0 to 5 km.

- Logarithmic creep, generally less than 1 m for the period of a month.

### II.2.4 Operation at sea (Fig. II.2.3)

- Presetting of the optical lever to within 500 metres of the depth.

- Interrogation of releases with system suspended 200 metres below the surface for tilt and leak.

- Falling rate to the bottom : about 1.4 m/s.

### II.2.5 Financial elements

| | |
|---|---|
| - Sensor not available commercially | |
| - Shipboard equipment : AMF Model 301 | $ 13,375 |
| - AMF Model 322 release | $ 6,190 |
| - Syntactic foam from Minnesota Mining and Manufacturing :<br>one cubic foot block of 36 lb/ft$^3$ (577 kg/m$^3$). | $ 360 |

### II.2.6 Reports describing equipment

- Filloux, J.H.:Bourdon tube deep sea tide gauges. *Tsunamis in the Pacific Ocean*, W.M. Adams, ed., University of Hawaii, 1970, p. 223-238.

- Filloux, J.H. Deep Sea Tide Observations from the Northeastern Pacific. *Deep Sea Res.*, v.18, 1971, 275-284.

- Pearson, C.A. Report on the National Oceanic and Atmospheric Administration's deep sea tide gauge instrumentation and mooring techniques as used in the SCOR intercalibration experiment.

### II.2.7 Responsible addresses

- Design : J.H. Filloux : Scripps Institute of Oceanography
P.O. Box 109
La Jolla, California 92037, USA.

- Operation : C.A. Pearson : NOAA National Ocean Survey
6001 Executive Boulevard
Oceanographic Division, C33
Rockville, Maryland 20852, USA.

## II.3 COB deep sea tide gauge

### II.3.1 Mechanical components and accessories

- Depths up to 6,000 m.

- Stainless steel electronics container 48 x 20 cm internal diameter (2.4 cm thick).

- Reference pressure system with a transfer type hydropneumatic accumulator (nitrogen at an initial 200 bars pressure for a 6,000 m working depth), a diver's regulator and a suppression valve ( for returning at the surface).

- Possibility to incorporate a modified Aanderaa current meter.

- Two configurations :

  . In-shore configuration (Fig. II.3.1) with a mooring line termination by a separate ballast release system. Instrument capsule dimensions : 110 cm x 55 cm x 55 cm; weight : 160 kg in air, 110 kg in water.

  . Deep sea tide configuration (Fig. II.3.2) : instrumental frame includes an AMF release retaining an anchor disk; dimensions about 170 cm high, 70 cm diameter, weight : 350 kg in air, 230 kg in water.

- Surface signalling beacons activated by pressure switches.

### II.3.2 Electronic recording components

- MOS digital circuits electronics

- Low power incremental recorder. Memodyne 200 series ($2.10^6$ bits at 615 bpi).

- More than six months recording time with a five-minute sampling time.

- Frequency averaged on 100 s and measured to an accuracy of $10^{-2}$ Hertz on each five minutes.

- A 24 bits sequence is recorded at each writing time.

- Possibility of an accelerated test on given frequencies simulating the sensor.

- Quartz crystal oscillator for timing functions (precision $7.10^{-6}$).

- Battery pack : 6V 12 Ah mercury battery for the electronics;
  3 x 4V 2Ah mercury batteries for the recorder motor.

- Electrical connexions through Marsh Marine connectors and bulkhead connectors.

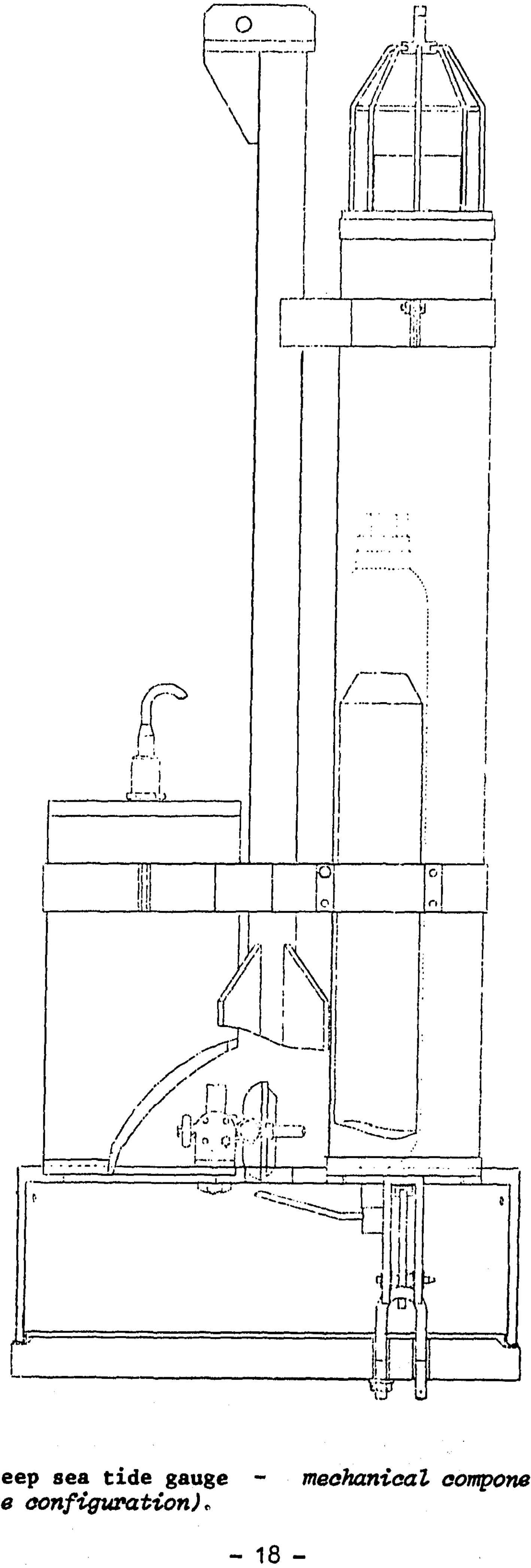


**Figure II.3.1** COB deep sea tide gauge - *mechanical components and accessories (shore configuration)*.

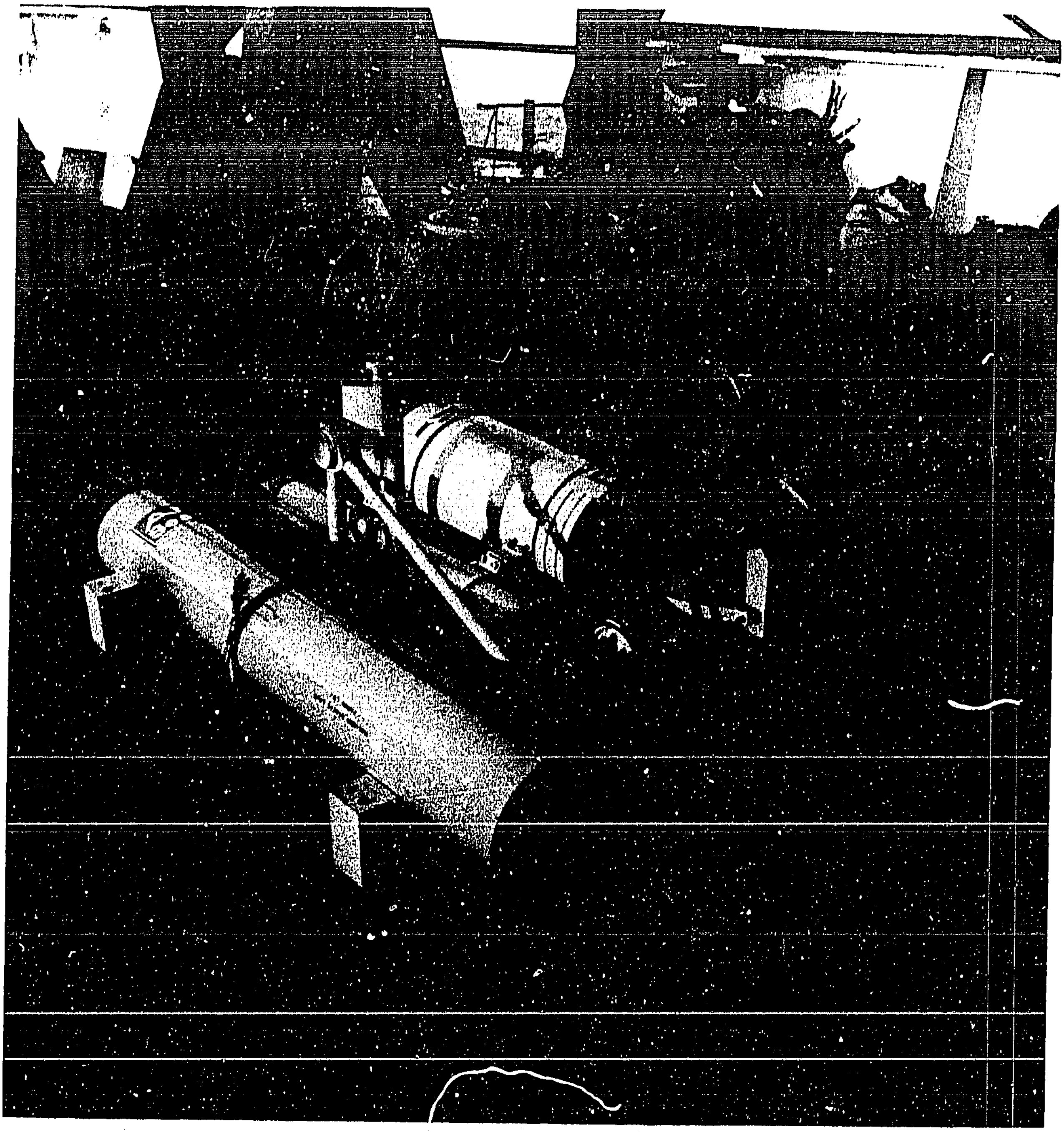


Figure II.3.2 COB deep sea tide gauge - *mechanical components and accessories (deep sea tide configuration).*

### II.3.3 Sensor

- Telemac differential pressure and temperature sensor with two stainless steel vibrating wires 10 cm long.

- The differential pressure, acting on a stainless steel diaphragm, gives to it an inflection always far from the elastic limit, causing variation in the natural frequency of the manometric wire.

- The thermometric wire is attached to an invar frame : variations of temperature are used for correction of the reference pressure variations.

- Precision : 0.5 cm and 5 m°C.

- In the sensor, a valve, electrically operated when the capsule is on the sea bed, gives an interior reference pressure close to the mean ambiant surface pressure.

### II.3.4 Operation at sea

- Electronic container is washed and filled with freon.

- Buoyancy provided by Corning Glass spheres 16" (41 cm) diameter.

- Nylon mooring line for the in-shore configuration 1 cm diameter; the line is under the surface but lifted up from the bottom by means of 8" (20 cm) diameter Corning Glass spheres.

- Normal retrieval by means of acoustical or timed release; dragging retrieval is also possible in the in-shore configuration.

- For reading tapes, adaption of the Memodyne model 122 read only system with output on computer compatible punched tape.

### II.3.5 Financial elements

| | |
|---|---|
| - Telemac sensor | 25,000 F |
| - Reference pressure system, electronics and connectors, containers and mechanical parts | 35,000 F |
| - Aanderaa modified current meter (optional) | 25,000 F |
| - AMF acoustic releases | 42,000 F |
| - Surface signalling beacons | 2,500 F |
| - Corning Glass spheres | 7,000 F |
| - Shipboard equipment | 60,000 F |

### II.3.6 Reports describing equipment

- Eyries M., Dars M., Erdely L. - Marégraphie par grand fond. Cahiers océanographiques, XVIè année, No. 9, Nov. 1964.
- Eyries M. - Marégraphes de grandes profondeurs. Symposium 'Marées en Mers Profondes', Berne, Sept. 1967.
- COB - Marégraphe grande profondeur : Etude de l'électronique, 1973.
- Hyacinthe J.-L. - COB Deep Sea Tide Recorder, 1974.

### II.3.7 Responsible address

J.-L. Hyacinthe : Centre océanologique de Bretagne
B.P. 337
29273 Brest Cédex (France).

## II.4 IOS Wormley continental shelf tide gauge

### II.4.1 Mechanical components and accessories (Fig. II.4.1)

- Depths of up to 300 m.

- 56 cm diameter aluminium sphere of 1.27 cm wall thickness mounted in a tubular aluminium frame attached to a disposable steel ballast weight by a pyrotechnic release unit and corrodible magnesium alloy links.

- Acoustic command system developed at IOS to switch on or off a pinger beacon or fire the release.

- An external acoustic command pinger beacon (10 kHz pulse with 1 second repetition rate).

- Pressure operated pinger of a different repetition rate that operates near the surface.

- Pressure operated flashing lamp to aid location.

- All metal parts of aluminium or insulated by nylon or polypropylene.

### II.4.2 Electronic recording components

- Continuous sampling recording the data every 15 minutes on magnetic tape for 40 days.

- Normalair-Garrett type 10/20 data logger with four digital and eight analogue input channels.

- Input frequency is reduced to 100 Hz before application to the logger.

- Electronic crystal clock with stability of 1 in $10^5$.

### II.4.3 Sensors

- Two pressure transducers developed at IOS.

- Capacitance plate pressure transducer (cf. Harris and Tucker paper). Pressure coefficient at 100 m depth : 1.9 cm/hz. Temperature coefficient between 25 and 40 cm/°C. Drift rate in the order of 10 cm per month.

- Strain gauge pressure sensor. Pressure coefficient can be between 20 and 40 cm/Hz. Temperature coefficient not more than 10 cm/°C. Drift rate is less than 10 cm/month.

- Two temperature sensors, the first providing a spot value of temperature at the recording period each 15 minutes, having a resolution of 0.05 °C. The second is a platinum resistance thermometer incorporated in an oscillator circuit and providing a resolution of 0.8 milli °C over the 15 minute sampling period and a stability better than 10 milli °C/month.

### II.4.4 Operation at sea (Fig. II.4.2)

- Laying by free fall from the surface of by lowering the gauge to within ten metres of the seabed (judged by comparing direct and bottom echoes of the command pinger signal). A mechanical release, tripped by the arrival of a messenger weight, allows the gauge to fall the remaining distance.

- At the end of the recording period, the instrument is located by the acoustic command beacon.

- The pyrotechnic unit is fired on command from the surface ship.

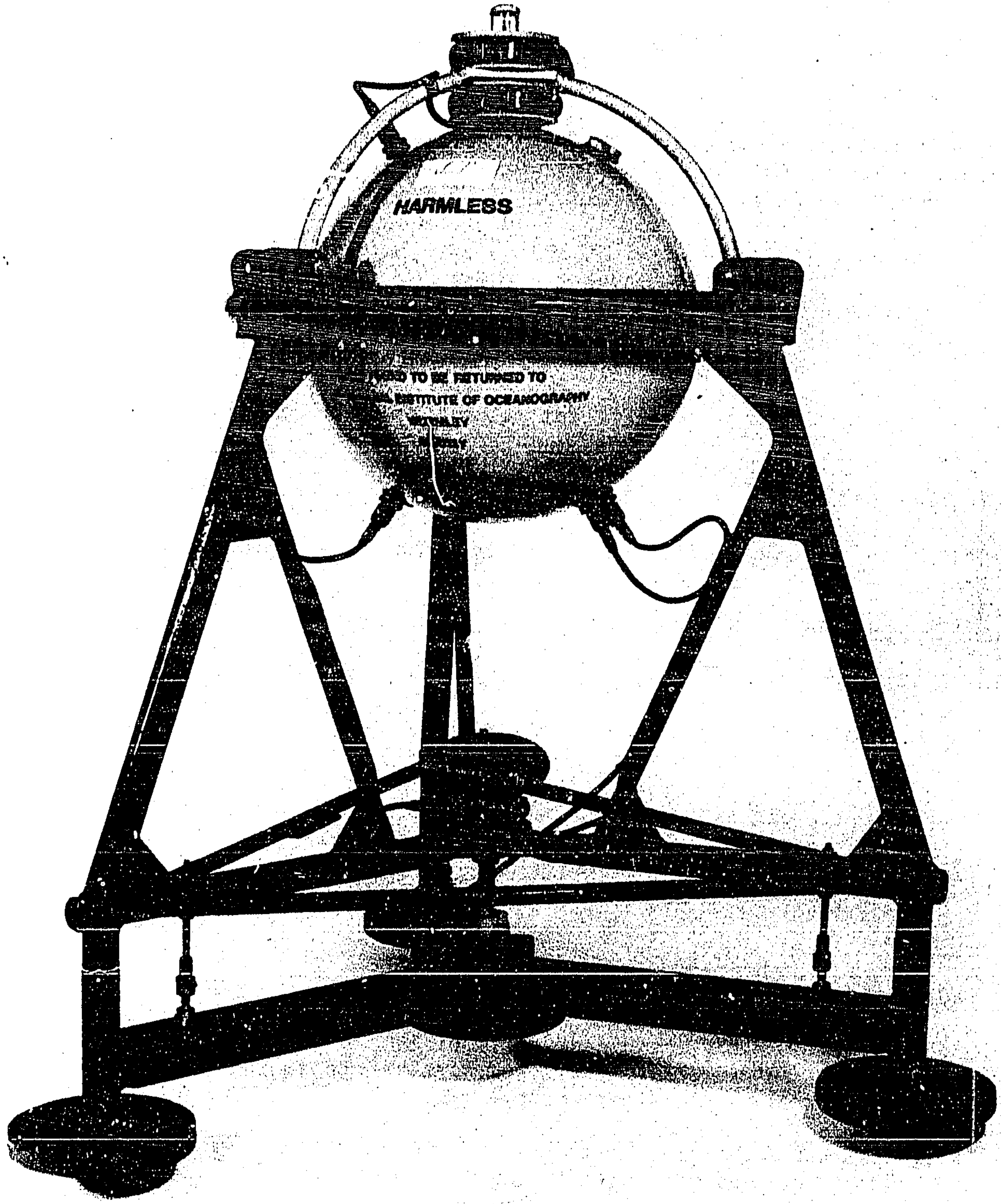


Figure II.4.1 IOS Wormley continental shelf tide gauge - *mechanical components and accessories.*

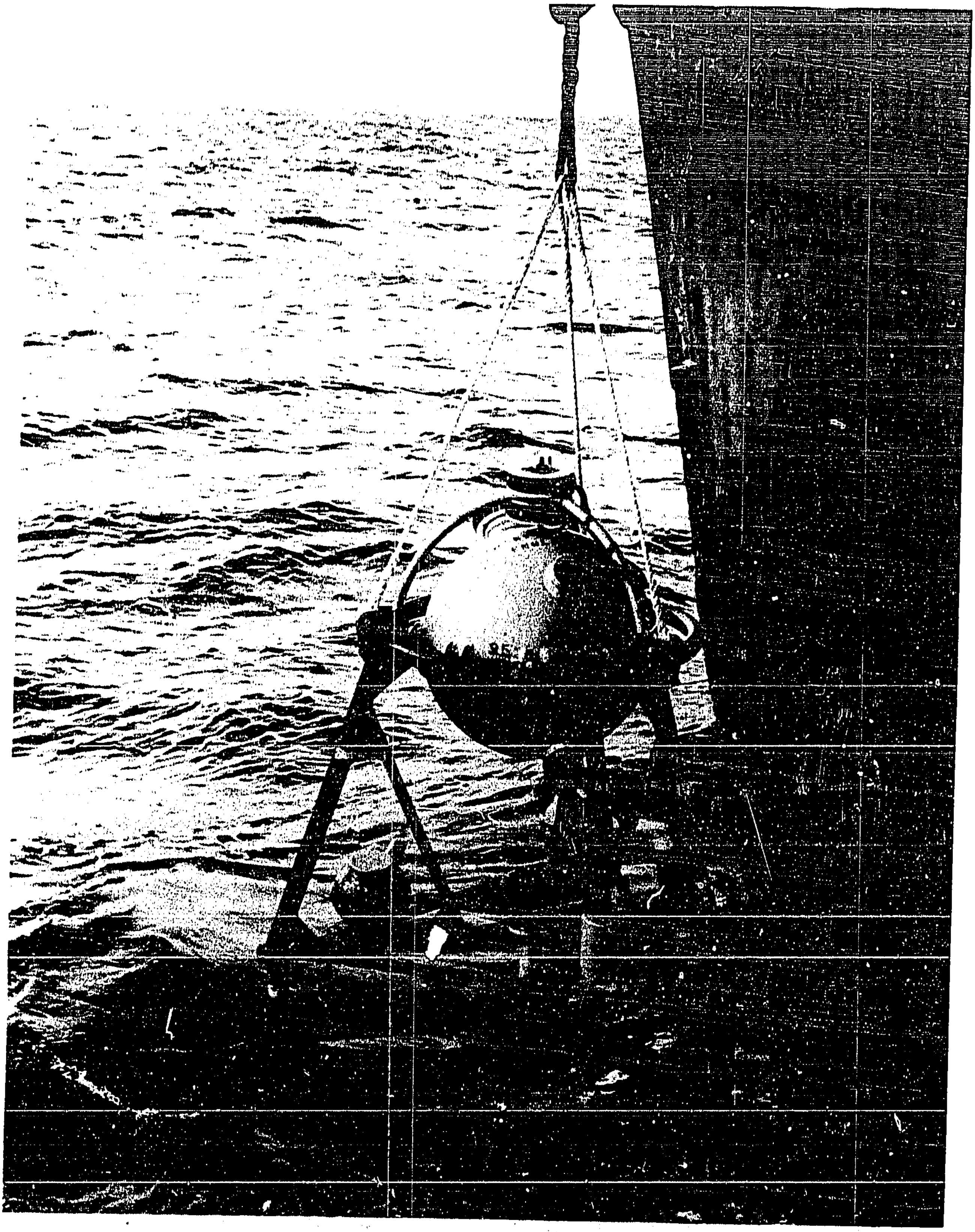


Figure II.4.2  IOS Wormley continental shelf tide gauge - *operation at sea.*

### II.4.5 Financial elements

| | |
|---|---|
| - Complete tide gauge with one pressure sensor, calibrated and tested | £ 6,600 |
| - Normalair Garrett data logger | £ 1,900 |
| - Pressure and temperature sensors | £ 280 each |
| - External acoustic command pinger | £ 760 |
| - Surface spherical pinger | £ 230 |
| - Ballast frame, corrodible links and pyro-release | £ 280 |

### II.4.6 Reports describing equipment

- Collar P.G. and Spencer R. : A digitally recording offshore tide gauge. Proceedings of the IERE conference on 'Electronic Engineering in Ocean Technology', London, 1970, 341-352.
- Collar P.G. and Cartwright D.E. : Open sea tidal measurements near the edge of the northwest European continental shelf. Deep Sea Research 1972, vol. 19, p. 673-684.
- Collar P.G. and Gwilliam T.J.P. : On the use of a frequency modulating strain gauge transducer for measuring continental shelf tides. IOS internal report (in preparation, 1974).
- Harris M.J. : Acoustic command system, Oceanology International, 1969.
- Harris M.J. and Tucker M.J. : A pressure recorder for measuring sea waves. Instruments Practice, October 1963, p.1055-1059.

### II.4.7 Responsible addresses

D.E. Cartwright
R. Spencer : Institute of Oceanographic Sciences
Bidston Observatory,
Birkenhead
Cheshire L43 7RA (UK)

T.J.P. Gwilliam : Institute of Oceanographic Sciences
Brook Road,
Wormley
Godalming
Surrey GU8 5UB (UK)

## II.5 IOS Wormley deep sea tide gauge

### II.5.1 Mechanical components and accessories (Fig. II.5.1)

- Depths up to 4,000 m.

- Forged aluminium alloy sphere 66 cm diameter consisting of two halves bolted to a central equatorial ring. Sphere mounted in a tubular aluminium frame mounted on a steel ballast weight.

- System contains two acoustic systems developed at IOS either one of which will switch on or off a pinger beacon or fire a T type release.

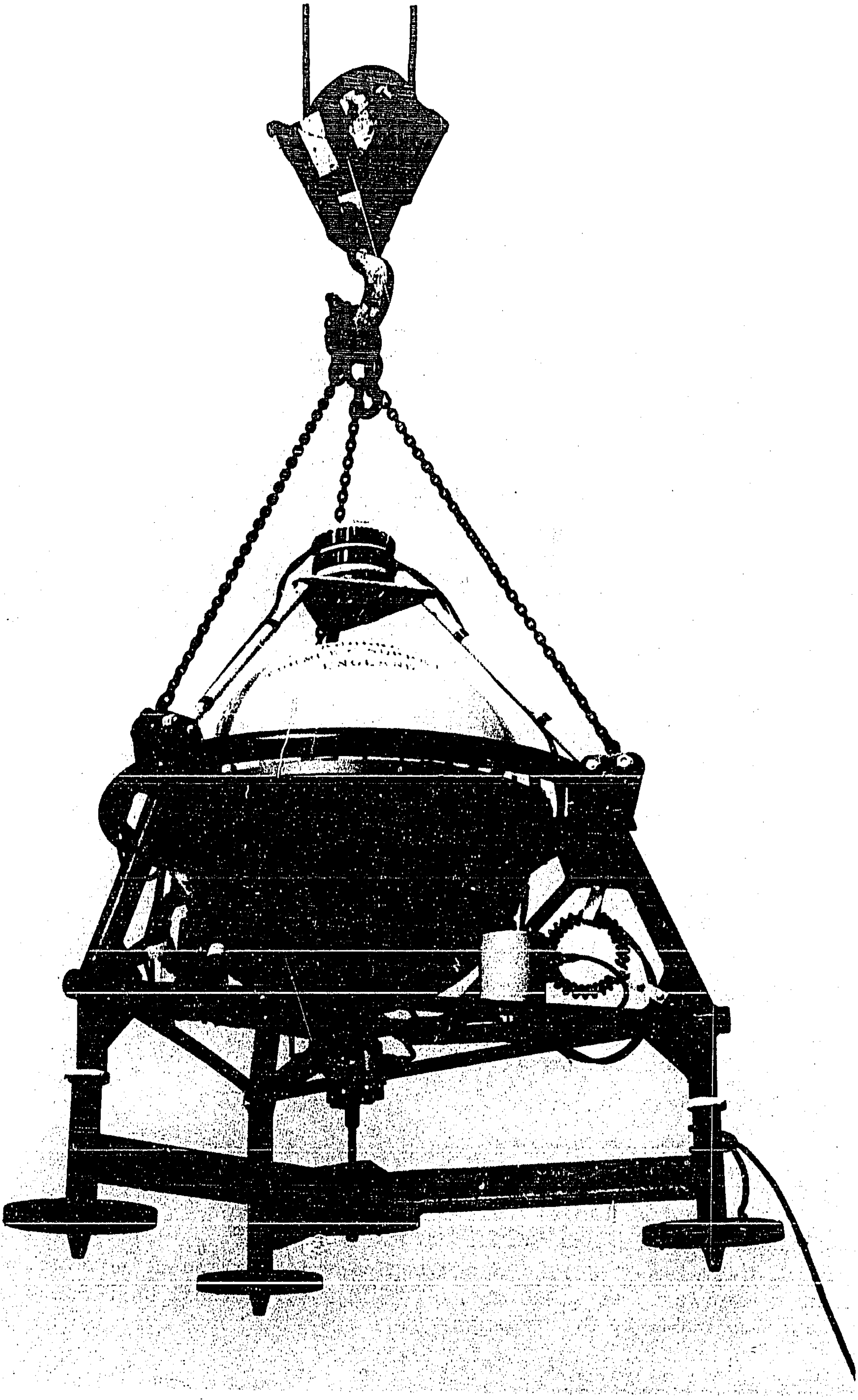


Figure II.5.1 IOS Wormley deep sea tide gauge - *general view.*

### II.5.2 Electronic recording components

- Continuous sampling, recording the data every 15 minutes on magnetic tape for 40 days.

- Normalair-Garrett type 10/20 data logger with four digital and eight analogue input channels.

- All systems powered by Mallory mercury batteries housed in sphere.

- Timing functions controlled by electronic crystal clock with stability of 1 in $10^5$.

### II.5.3 Sensors

- Sensors have been developed by IOS. Mounted external to sphere in pressure housings complete with electronics, giving a frequency output.

- Pressure sensor incorporates a Bell and Howell strain gauge. Pressure sensitivity is 30 mb/Hz and overall drift has not been more than 30 mb in a 40 day record. Temperature coefficient of sensor between 0 and 100 mb/°C depending on unit and working depth.

- Temperature sensor mounted in self-contained housing similar to pressure transducer. Uses a platinum resistance thermometer incorporated in an oscillator circuit and providing a resolution of 0.8 milli °C of the 15 minutes sampling period and a stability better than 10 milli °C/month.

### II.5.4 Operation at sea

- Laying by free fall from the surface - descent about 1 m per sec.

- At the end of the recording period, instrument located by the acoustic command beacon.

- The release mechanism is fired on command from the surface ship, and self buoyancy brings unit to surface.

### II.5.5 Financial elements

| | |
|---|---|
| - Complete tide gauge with 2 pressure and 1 temperature sensor, calibrated and tested | £ 10,000 |
| - Normalair Garett data logger | £ 1,900 |
| - Pressure and temperature sensors | £ 280 each |
| - Ballast frame and release unit | £ 400 |

### II.5.6 Reports describing equipment

- Spencer, R. Gwilliam, T.J.P. : A sea bed capsule for measuring tidal pressure variations at depths up to 4,000 metres, IEEE International Conference on Engineering in the Ocean Environment, Proceedings.

### II.5.7 Responsible addresses

R. Spencer : Institute of Oceanographic Sciences
Bidston Observatory
Birkenhead
Cheshire L43 7RA (UK)

T.J.P. Gwilliam : Institute of Oceanographic Sciences
Brook Road
Wormley,
Godalming, Surrey GU8 5UB (UK)

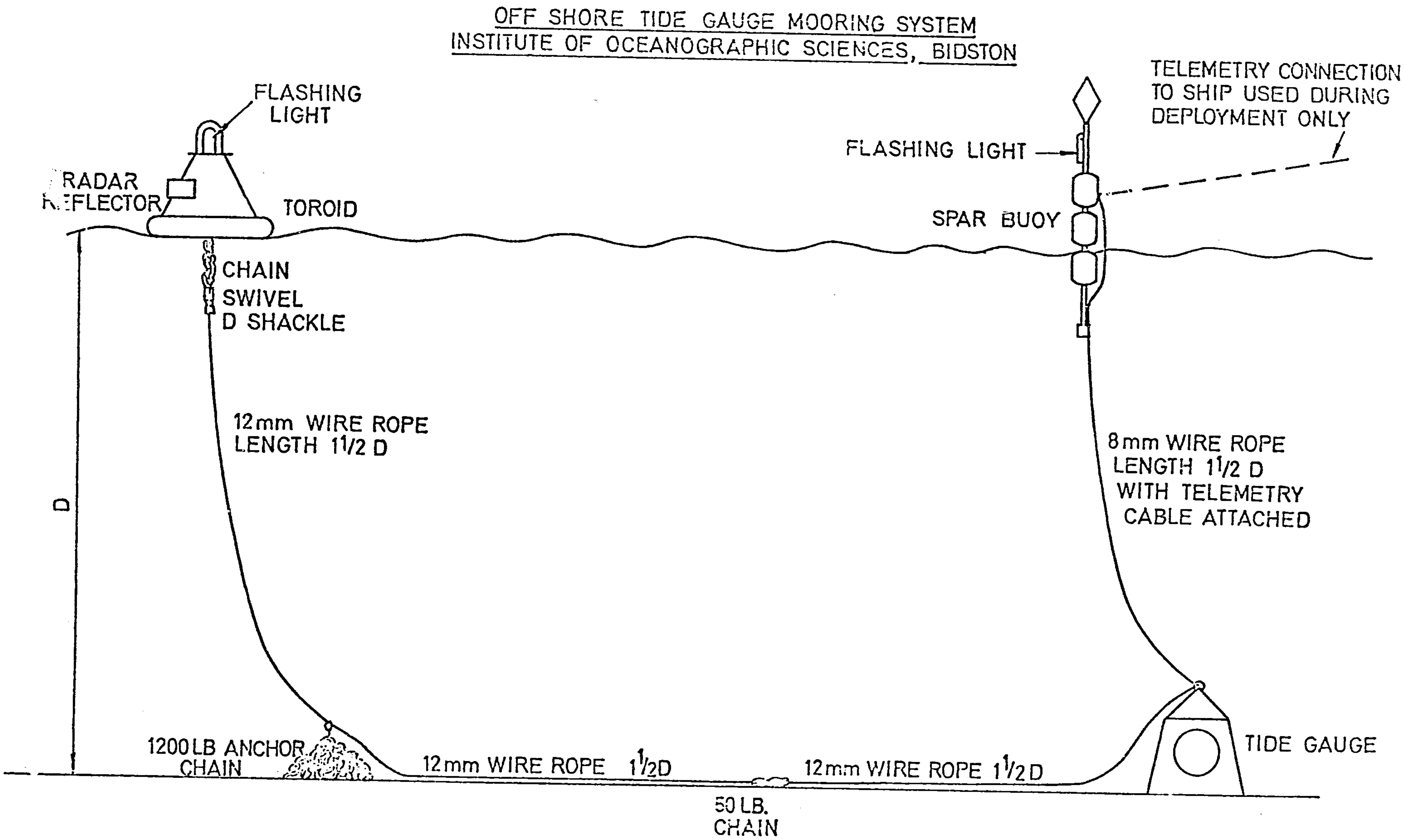


**Figure II.6.1** IOS Bidston offshore tide gauge - *mooring principle.*

## II.6 IOS Bidston offshore tide gauge

### II.6.1 Mechanical components and accessories (Fig. II.6.1)

- Depths of up to 200 m.

- Data logger and acoustic command system in a 0.56 m diameter aluminium sphere.

- Sensors in completely self-contained units with their own sensor electronics and power supplies.

- Acoustic command system for location purposes and switching on or off transmission.

- The sphere and the sensor packs are mounted in an aluminium subframe which is protected during deployment and recovery by a heavy steel outer frame.

### II.6.2 Electronic recording components

- Twenty channels (analogue or frequency modulated data) for recording.

- Redundancy introduced by the use of a parallel information flow.

- CMOS circuit elements for low power consumption and good reliability.

- Recording in an IBM computer compatible format (7 tracks, 200 bit/inch NRZI) on a Precision Instruments P.I. 1387 Incremental Digital Recorder.

- System timing giving variable integration times for each individual channel unit and variable sampling times from 1 7/8 to 60 minutes.

- Direct wire telemetry link provided as an output from the logger and giving possibility of acquiring tidal data in real time.

- Power supplies : mercury cells.

- Unattended operation for at least 40 days.

- Shipborne equipment : telemetry and acoustic system.

### II.6.3 Sensors (Fig. II.6.2)

- Five pressure sensor packs :
    - 1 Hewlett Packard Quartz Crystal
    - 1 Vibrotron
    - 1 OAR vibrating wire sensor
    - 2 Bell and Howell strain gauge sensors.
- Five platinum resistance thermometers (resolution 10 m°C).

### II.6.4 Operation at sea (Fig. II.6.3)

- Use of a buoyed system.
- The tide gauge is recovered by lifting either buoy (or by dragging for the 12 mm wire rope ground line).

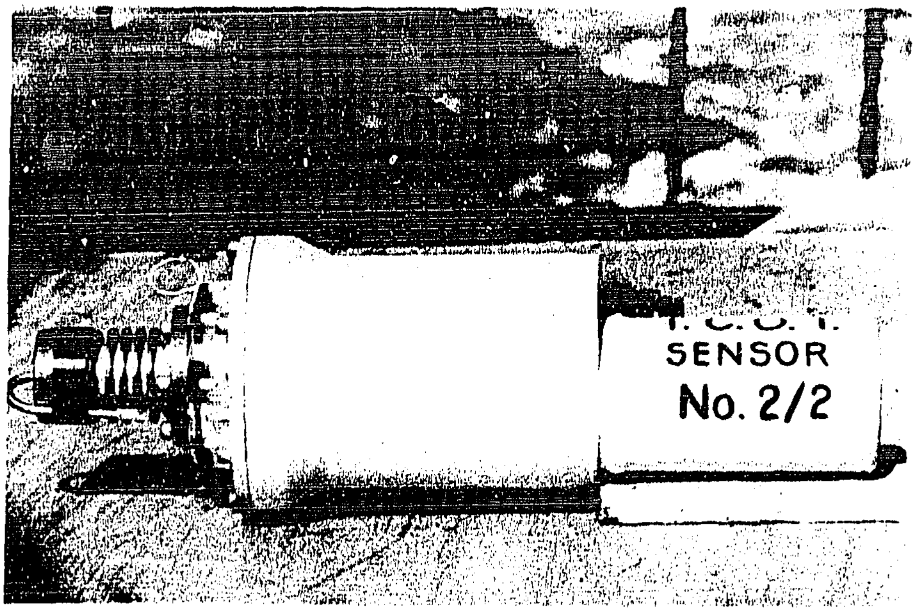


Figure II.6.2 IOS Bidston offshore tide gauge - *strain gauge sensors.*

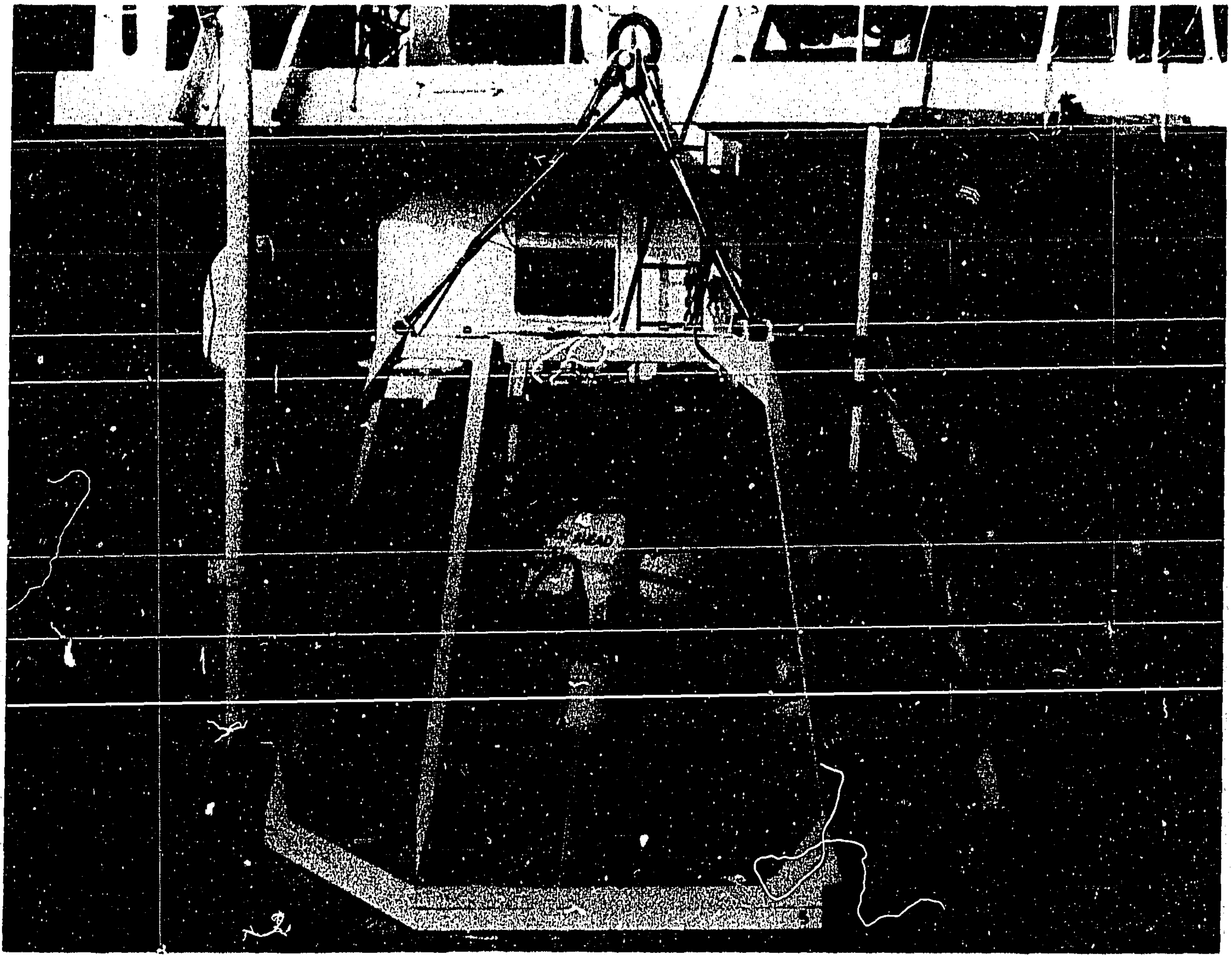


Figure II.6.3 IOS Bidston offshore tide gauge - *general view.*

### II.6.5 Financial elements

| | | |
|---|---|---|
| - United Control Vibrotron (not available commercially) | £ 750 | (1971) |
| - Hewlett Packard Quartz Crystal | £ 2,300 | (1971) |
| - Ocean Applied Research Corp. wire sensor | £ 780 | |
| - Strain Gauge | £ 97 | |
| - Acoustic command system (Underwater and Marine Equipment Ltd. England) | £ 800 | |
| - Logger | £ 6,200 | |
| - Sphere | £ 340 | |
| - Frameworks | £ 600 | |
| - Ancillary equipment (buoy) | £ 1,450 | |

### II.6.6 Reports describing equipment

- Skinner L.M. and Rae J.B. : Problems associated with the design of an offshore tide gauge for continental shelf use. Proceedings Interocean Conference Dusseldorf, 1973, 2, 895-906.

- Skinner L.M. : IOS Bidston offshore tide gauge.

### II.6.7 Responsible address

J.B. Rae : Institute of Oceanographic Sciences
Bidston Observatory
Birkenhead
Cheshire L43 7RA (UK)

## II.7 Canadian offshore tide gauge

### II.7.1 Mechanical components and accessories (Fig. II.7.1)

- Depths up to 600 ft (183 m).

- 316 stainless steel capsule : 48" (122 cm) long x 14" (36 cm) diameter, weight 200 lb (91 kg) in air.

- Reference pressure system with a rubber diaphragm, a piping system and an electrically-operated valve : a low-water pressure is taken as reference.

### II.7.2 Electronic recording elements

- Servo-operated OTT punch tape recorder, recording data in CCITT code.

- Tape capacity : approximately one year of data sampled at hourly intervals.

- A balanced bridge technique is used to sense and encode the parameter to be recorded.

- 24 h electronic clock with BCD output used to control the various timing functions and to provide hourly and daily signals.

- Dry cell pack : 6.75 V Mallory Duracell Mercury battery, type TR-235 R.

- Duration : three months.

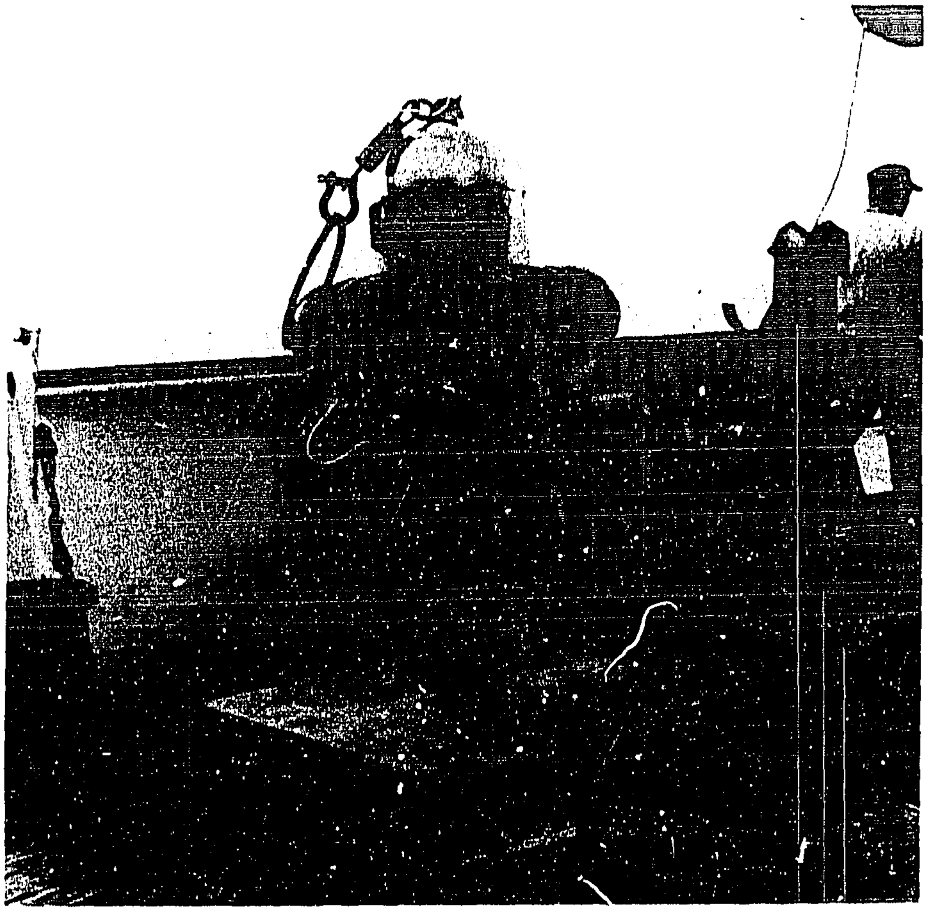
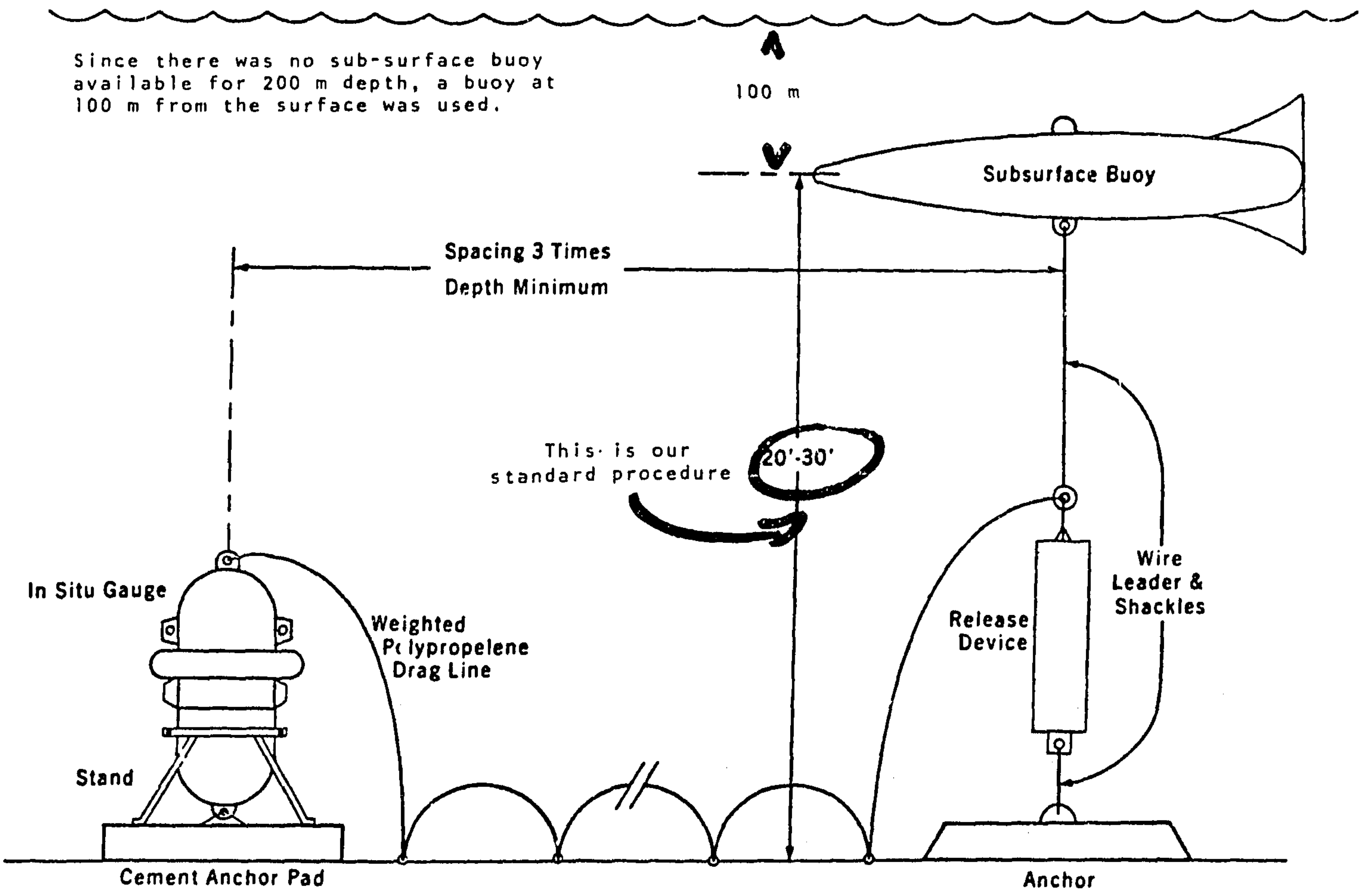


Figure II.7.1 Canadian offshore tide gauge - *general view.*



Since there was no sub-surface buoy available for 200 m depth, a buoy at 100 m from the surface was used.

This is our standard procedure

Figure II.7.2 Canadian offshore tide gauge - *mooring principle.*

### II.7.3 Sensor

- Low range differential pressure transducer Conrac Model 451212 with a 10,000 ohm potentrometric output and a -5 + 15 PSID range : this range is equivalent to -11.5 to + 34.5 feet head water pressure with reference to the lower port.

- YSI # 44033 precision 0.10 °C thermistor calibrated to give true readings for a 5 °C span between 3 °C and 8 °C.

### II.7.4 Operations at sea (Fig. II.7.2)

- A mooring line is used with a subsurface float, an anchor and an AMF release device, model 242, with back up timer and tilt switch.

- Retrieval by means of acoustic or timed released device.

### II.7.5 Financial elements

| | |
|---|---|
| - Housing | $ 1,870 |
| - OTT punch mechanism | $ 1,291 |
| - Sensor panel | $ 1,239 |
| - Electronic control section | $ 434 |
| - AMF release device, model 242 | $ 4,540 |

### II.7.6 Reports describing equipment

- Submersible tide gauge, by W. Zubrycky, H. Thurm, Marine Sciences Directorate, Ottawa, October 1973.

### II.7.7 Responsible address

G.C. Dohler : Chief, Tides and Water Levels
Marine Sciences Directorate
615 Booth Street
Ottawa, Ontario, KIA 6E6, Canada.

## II.8 SHOM offshore tide gauge

### II.8.1 Mechanical components and accessories (Fig. II.8.1)

- Housing in painted steel cylinder 1 m long and 0.5 m diameter.

- Weight : 250 kg in air.

### II.8.2 Electronic recording components

- Averaged measure on 12 minutes.

- 16 mm photographic recording

- CMOS circuitry; Hewlett Packard displays; Golay quartz clock with $10^{-6}$ stability.

- Mean power consumption : 30 mA; batteries : 7 x 1.5 V.

- Autonomy : 40 days.

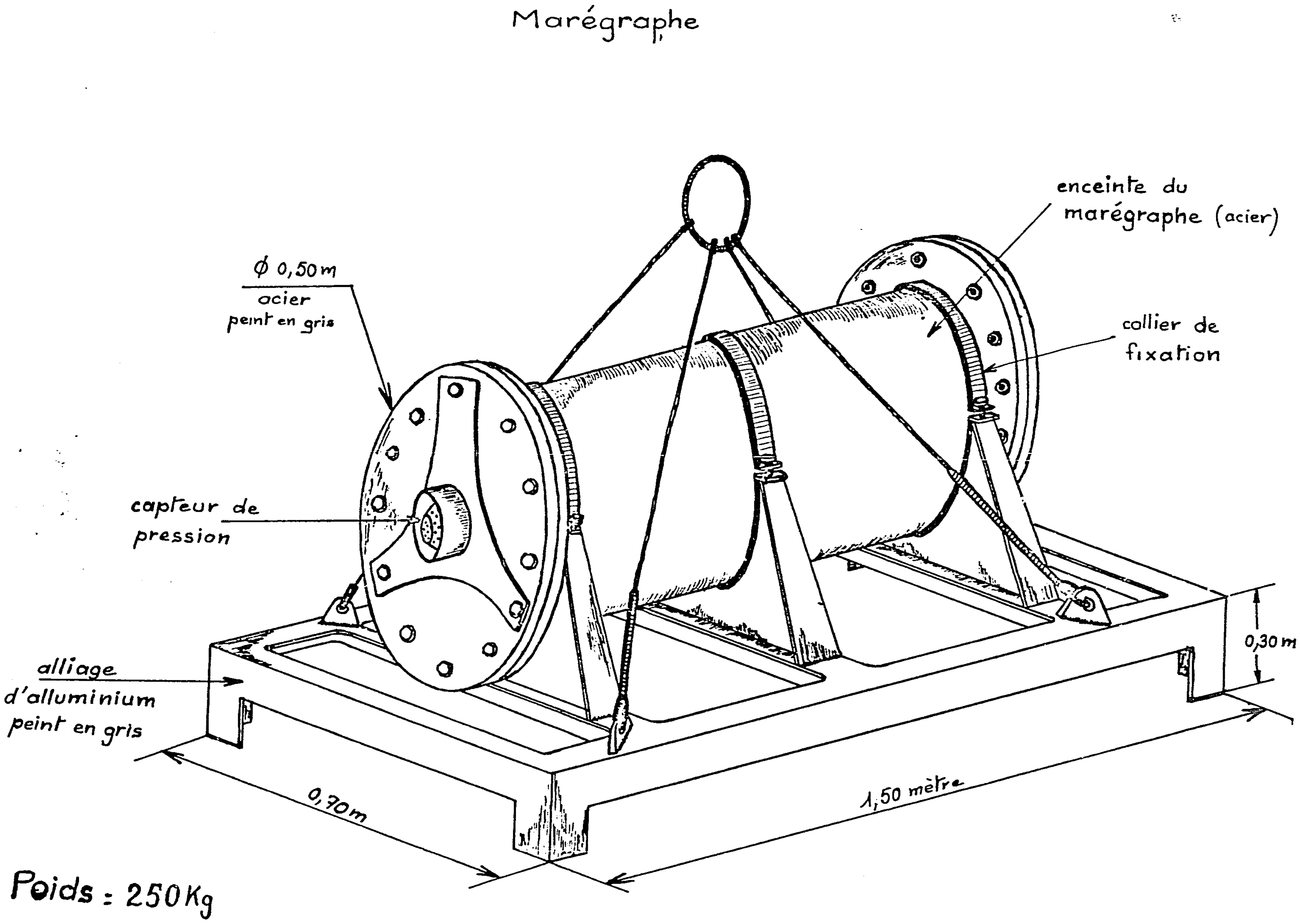


Figure II.8.1 SHOM offshore tide gauge - *mechanical components and accessories.*

### II.8.3 Sensor

- Telemac absolute pressure vibrating wire sensor.

- Depth capability 200 m.

- Sensitivity : 1 cm of water corresponds to $1.5.10^{-2}$ Hz variation of frequency.

- No thermal correction.

### II.8.4 Operation at sea

- Description of the mooring line (Fig. II.8.2) with steel rope, buoys and :

  a Suber pyrotechnic acoustic release

  a Thomson - CFS pinger 36 kHz.

### II.8.5 Financial elements

| | |
|---|---|
| - Tide gauge | 30,000 F |
| - Acoustic release | 12,000 F |
| - Pinger | 1,600 F |

### II.8.6 Reports describing equipment

- SHOM : Marégraphe de plateau continental, note du 13 mai 1974.

### II.8.7 Responsible address

L. Pieretti : Service hydrographique et océanographique de la Marine
Etablissement principal
29283 Brest Cédex (France).

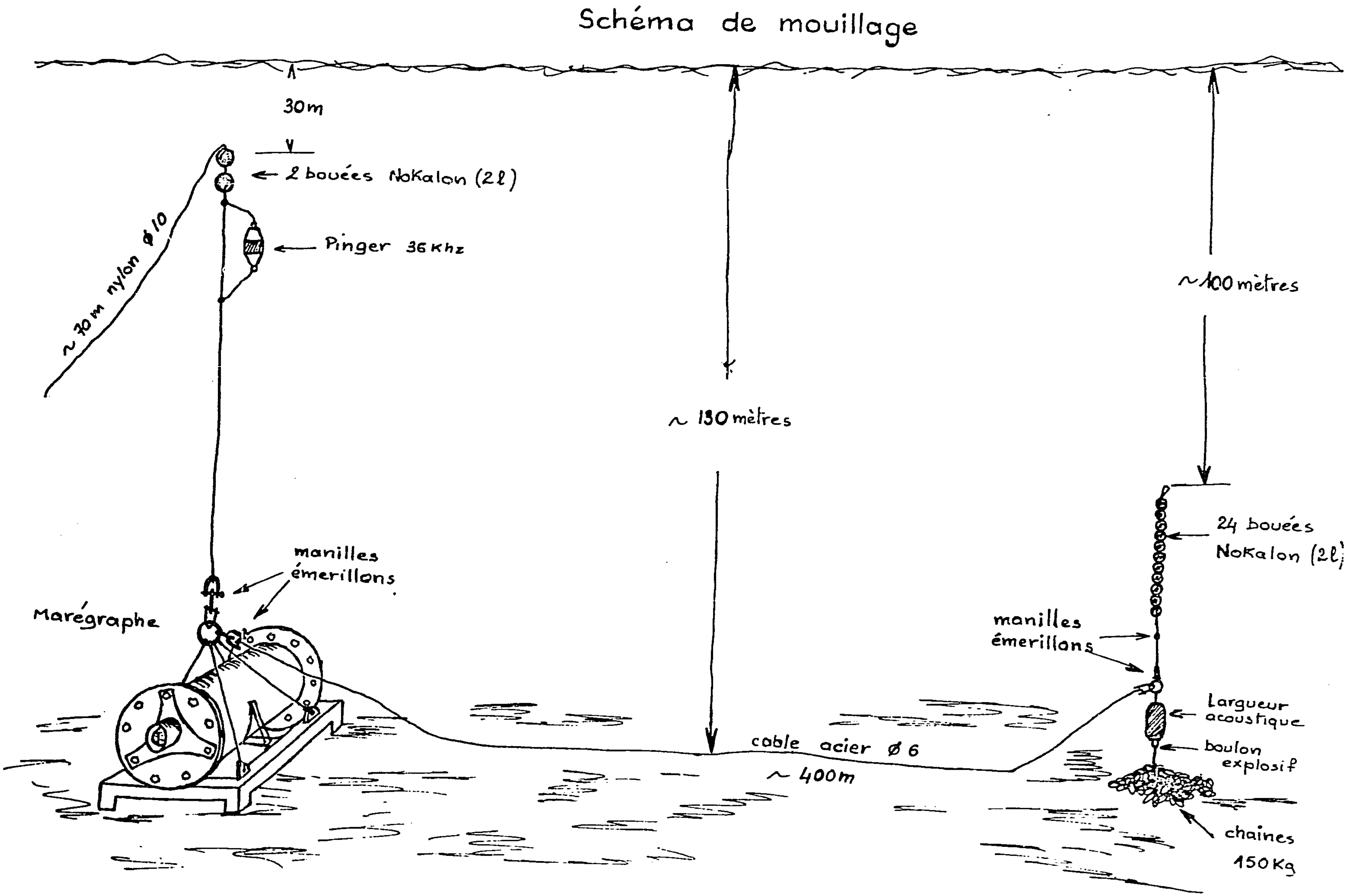


Figure II.8.2 SHOM offshore tide gauge - *mooring principle.*

# III CALIBRATION TECHNIQUES

## III.1 General discussion

Intercomparison of the measured amplitude of the strong tidal lines can serve to evaluate instrument calibrations by virtue of their large amplitudes compared to the instrumental and environmental noise amplitude. The intercomparison becomes erratic and unreliable for the weak tide lines as the signal-to-noise ratio becomes small.

In Table III.1.1 a percentage amplitude difference, $\Delta H_n = 100\ (H_n - \overline{H})/\overline{H}$, is calculated where $H_n$ is a tidal constituent amplitude determined by instrument n and $\overline{H}$ is the average amplitude determined by all sensors at the site. Differences calculated for the $S_2$ constituents at the deep site are not consistent with values for $M_2$ and $N_2$ due to radiational effects. Not only are the amplitudes affected by the methods of analyses, which involves fundamental definitions of the techniques, but also all sensors were not operated simultaneously and radiational effects were undoubtedly different during the two test periods. Amplitude differences for $M_2$ and $N_2$ are reasonably consistent. These imply that the relative calibration of the FSMW quartz-crystal sensors were low by about 0.5%, the NOAA Bourdon tube sensors are about average, and the two IOSW sensors 0.25% to 0.5% high.

Sensors at the shallow site are compared as above in Table III.1.2; relative amplitudes vary about $\pm$ 0.75%. Sensor IOSB/SG was not functioning properly, as evidenced by the larger residuals in the detided record (see Section VI.2). The amplitudes measured by sensor IOSB/SG therefore were not used in determining $\overline{H}$ at the shallow site.

A detailed study of calibration techniques can provide an assessment of absolute errors but the procedure is very laborious. The FSMW sensors were calibrated by a commercial company (devoted solely to calibration of oceanographic sensors) that convincingly claim an accuracy of 0.1%. Other investigators (personal communication) are equally certain about calibration accuracies, yet there are 1%-1.5% differences. If these discrepancies are important to the studies of deep-sea tides, perhaps an exchange of sensors for calibration by various investigators, followed by a critical examination of results, may reveal sources of error.

Accounts of calibration procedures provided by the participating groups were basically descriptive, with little assessment of the calibration accuracy. Some discussion of the precision of pressure reference standards was included; in some cases the effects of temperature, battery voltage and water velocity were discussed. These descriptions are summarized briefly in Section III.2 to indicate the wide range of sensors and calibration procedures.

If we wish to measure weak tidal constituents, the instrumental problem is not that of calibration accuracy, but rather that of instrumental noise. Ideally the instrumental noise is sufficiently low so that the measurement of the tidal line spectrum is limited primarily by the continuum spectrum of the pressure signal. The spectrum of the detided pressure record provides a good estimate of the continuum pressure spectrum. The instrumental noise spectrum (often not negligible compared to the continuum spectrum) can be estimated from the difference in readings of duplicate sensors.

Two Hewlett-Packard quartz-crystal sensors were installed on the FSMW capsule for this purpose (Snodgrass, F.E. and M. Wimbush, "Evaluation of deep sea tide gauge sensors", Proc. IEEE Conf. Ocean 74, Vol. 1, p 350-358). The instrumental noise was found to be about 20 db below the continuum spectrum at near-tidal frequencies. Consequently, measured weak constituents compare well between the two sensors even though the accuracy of the measurement may not be good; the measurement would be contaminated by the continuum energy identically at the two sensors. Measurements of weak constituents by sensors separated by a few miles would compare less favourably, even though all sensors have low instrumental noise, by the extent to which the continuum energy is incoherent. All installations, other than the NOAA gauge, carried at least two sensors. Instrumental noise spectra therefore can be obtained for comparison to the recorded spectra and the continuum spectra. These analyses should be useful in understanding the accuracy of these measurements and thus the differences in weak constituent measured amplitudes.

In general, some standardization of calibration technique and accuracy appears desirable. Furthermore, future large-scale experiments should include a site for direct comparison of different types of recorders in close proximity. Evidently, the pelagic tide recorder has not reached the status of confidence of, say, the oceanographic thermometer.

| Constituent /Analysis | | Average Value (mb) | Nov - Dec 1973 | | | Feb - Mar 1974 | |
|---|---|---|---|---|---|---|---|
| | | | FSMW/HP1 | FSMW/HP2 | NOAA/BT | IOSW/SG9 | IOSW/SG10 |
| $M_2$ | RES | 122.48 | -0.39 | -0.47 | +0.09 | +0.26 | +0.51 |
| $M_2$ | HAR | 122.66 | -0.53 | -0.53 | +0.03 | +0.44 | +0.60 |
| $S_2$ | RES | 42.12 | +0.19 | +0.43 | +0.19 | -0.76 | -0.05 |
| $S_2$ | HAR | 41.22 | -2.23 | -1.75 | -1.02 | +2.37 | +2.62 |
| $N_2$ | RES | 26.66 | -0.60 | -0.60 | +0.15 | +0.53 | +0.53 |
| $N_2$ | HAR | 25.72 | -0.47 | -0.47 | -0.08 | -0.08 | +1.09 |
| Average of $M_2$ and $N_2$ | | | -0.50 | -0.52 | +0.05 | +0.29 | +0.68 |

Table III.1.1 Measured amplitude differences (percent) for five sensors at the deep position relative to the average measured constituent amplitude of all sensors. Constituent amplitudes (for the three strongest lines) determined by both the response (RES) and harmonic (HAR) methods of analyses were obtained from tables in Section VI.3. Values for $S_2$ at the deep position, contaminated by radiation effects, are not included in the average for each instrument.

| Constituent /Analysis | | Average Amplitude (mb) | Nov - Dec 1973 | | | | |
|---|---|---|---|---|---|---|---|
| | | | IOSB/HP | IOSB/SG | IOSB/VIB | IOSW/SG9 | IOSW/SG10 |
| $M_2$ | RES | 130.55 | +0.57 | -1.95 | +0.19 | -0.04 | -0.73 |
| $M_2$ | HAR | 130.33 | +0.44 | -2.40 | +0.44 | -0.10 | -0.79 |
| $S_2$ | RES | 45.25 | +0.77 | -1.66 | +0.33 | -0.11 | -0.99 |
| $S_2$ | HAR | 43.53 | +1.07 | +0.16 | -0.53 | +0.16 | -0.76 |
| $N_2$ | RES | 28.13 | +0.25 | -2.60 | -0.11 | +0.25 | -0.46 |
| $N_2$ | HAR | 27.05 | +1.29 | +3.51 | -0.93 | +0.18 | -0.55 |
| Average of $M_2$, $S_2$ and $N_2$ | | | +0.73 | - | -0.10 | +0.06 | -0.71 |

Table III.1.2 Measured amplitude differences (percent) for sensors at the shallow position relative to the average measured constituent amplitude. Values obtained from sensor IOS/SG were not used to determine the average amplitude since the gauge did not appear to be functioning properly.

## III.2 Calibration procedures

### IGPP deep sea instrument capsule

Sensors

- 2 each Hewlett Packard quartz crystal pressure sensor.
- 2 each Hewlett Packard quartz crystal temperature sensor.

Calibration technique

- Absolute pressure calibration using dead weight tester at several temperatures in a temperature controlled bath.
- Temperature calibration reference: platinum wire standard.
- Calibration data fitted to third degree polynomial.
- Calibration performed by Ramsey Engineering Co., specialists in oceanographic instrument calibration.
- Calibration accuracy assumed to be ± 0.1%.

## NOAA deep sea tide gauge

Sensor

- 1 each oil filled Bourdon tube of Ni SPAN C alloy.

Calibration technique

- Mechanical zero of Rustrac recorder and electrical zero of electronics adjusted to zero - no input signal.
- Calibration reference 200 cm water column.
- Rustrac readings at 1 cm water level intervals noted and cross-over points determined - scale width represents about 0.8 metres of water.

## IOS Wormley deep sea pressure sensor

Sensors

- 2 each Bell and Howell strain gauge sensors of IOS design.
- 2 each temperature sensors(platinum resistance).

Calibration technique

- Absolute calibration prior to cruise over 0 - 220 bars range using a Budenberg dead weight tester with sensor in temperature controlled water bath.
- Post-cruise calibration of pressure calibration slope by calibrating over 1 bar range about mean operating pressure of tests.
- Post-cruise calibration at six temperatures near test temperature.
- Calibration data fitted to polynomial maximum errors did not exceed 1.5 mbars.
- Temperature coefficients of pressure sensors also determined by applying mean pressure and varying temperature over 9 °C range.
- Temperature calibration reference : Hewlett Packerd quartz crystal probe, with triple point cell + 10 m°C check prior to use.
- 15 temperature calibration points fitted to polynomial; maximum point error less than 8 m°C.

## IOS Wormley continental shelf tide gauge

Sensors

- 1 each IOS capacitance plate pressure sensor.
- 1 each IOS strain gauge pressure sensor.
- 2 each temperature sensors (of platinum wire).

Calibration technique

- Absolute calibration 0 - 30 bars at several temperatures between 2°C and 20°C in temperature controlled bath.
- Pressure reference : servo-controlled pressure using Texas Instruments precision pressure gauge (quartz Bourdon tube).
- Accuracy better than 2 mbars. Short term stability ± 0.15 mbars.
- Temperature measured by platinum resistance thermometer.
- Two pre-cruise and one post-cruise calibration.
- Calibration over entire sensor range and more detailed over 5 bar range at operating depth.

## IOS Bidston offshore tide gauge

Sensors

- 5 pressure sensors each accompanied by a platinum wire temperature sensor.
- Hewlett Packard quartz crystal vibrotron.
- OAR vibrating wire sensor.
- Bell and Howell strain gauge.

Calibration technique

- Calibration equipment and procedure basically the same as IOS Wormley.
- Calibration data fitted to low-order polynomial using a least squares method.
- Hysteresis determined from increasing and decreasing pressure data.
- Effect of changes in water velocity up to 1.5 m/s was studied.
- Variation of sensor output with supply voltage was measured at various temperatures.

## Canadian offshore tide gauge

Sensors

- Conrad Model 451212 low range differential pressure transducer (-5 to 15 PSID).
- YSI 44033 precision 0.10°C thermistor to give true readings between 3°C and 8°C.

Calibration technique

- Pressure calibration reference : mercury column indicator of compressed air applied to sensor.
- Zero pressure applied and encoder adjusted to read 10.00; equivalent to 30 feet (9 m) of water pressure applied and encoder adjusted to read 40.00.
- Check reading for both increasing and decreasing pressure in steps of 6 feet (1.8 m).
- System accepted if linearity and hysteresis are less than .03 feet (≃ .9 cm).
- Factory calibration of thermistor used for temperature calibration. System calibration uses precision resistor box in place of thermistor sensor. Temperature encoder adjusted at minimum and maximum temperature.

## COB deep sea tide gauge

### Sensors

- Telemac differential pressure and temperature sensor with two stainless steel vibrating wires.

### Calibration technique

- The sensor can be described by $\Delta P = K_p (N^2 - N_o^2)$ where N is the frequency of vibration of the wire, $N_o$ the frequency at zero pressure for a difference pressure $\Delta P$. A similar coefficient $K_t$ is defined for temperature.
- The constant $K_p$ depends upon geometry of the sensor.
- Theoretical value of $K_p = 1.96.10^{-4}$ m/Hz$^2$, and $K_t = 1.25.10^{-4}$ °C/Hz$^2$.
- $K_p$ found to vary about 15% as depth increases from 0 - 5000 psi.
- $K_p$ and $K_t$ must be determined by laboratory calibration and, if possible, 'in situ'.

# IV RRS DISCOVERY CRUISES 56 AND 58

'Discovery' left Southampton for the 'laying' cruise (No. 56) on 30 October 1973 with the technical teams from Canada, UK and USA, and their six capsules and associated gear. The two French teams with two capsules and gear boarded the following day at Brest. In both cruises, the Principal Scientist was David Cartwright, while Dennis Gaunt organized engineering and electrical requirements and general liaison between scientists and crew. Arnold Madgwick made photographic records of most operations performed in daylight, and later compiled a cine film based on the exercise, all of which material is available, from A. Madgwick at IOS, Wormley.

As mentioned in the Introduction, three laying sites were decided upon to suit different instrumental depth requirements. These are denoted by the letters A1 (130 m), A2 (170 m) and B (2100 m) in the accompanying track chart, Figure IV.1. The distances A1A2 and BA2 are each 60 n miles, and the line A1A2B makes a bearing 254°.4. At each site, a dan buoy with radar transponder was laid for navigation purposes, and the capsules were laid at 120° spacing round a 3-mile radius circle centred on the buoy, according to the geometry sketched below the track chart. (This was about the closest one could safely place the capsules without danger of entanglement between their rope anchoring systems). The best estimates of the laying positions and times are summarized in Table IV.1.

The duplicate Canadian capsule, labelled 'Canada-2' was laid in the shallowest position A1 in order to provide a direct comparison with the SHOM capsule, not because of any instrumental depth restriction. (Unfortunately, neither of these two capsules was recovered - see later). A shallow version of the COB capsule was originally to be included in the programme, but was withdrawn for other tests. The deep capsule recently developed by IOS (Wormley) would have been included at position B, but had not been recovered from a mooring in the ICES Overflow 73 exercise in time for this cruise. It was recovered in November, placed at position B in a later cruise of 'Discovery' in February 1974. and recovered in March. Its tidal records are compared with the others in Section VI.

There is no need here for detailed accounts of the laying operations. Each mooring presented its own problems which had to be solved in the usually unfamiliar setting of the ship's deck gear, without previous trial. Most of these problems were overcome satisfactorily by collaboration between the technicians and the ship's staff, but there were occasional cases of minor damage to equipment. The rather bulky tripod supporting the NOAA capsule proved difficult to handle in a 3-metre swell, and had to be launched three times, on one of which occasions the auxiliary release gear was damaged. Frank Snodgrass's capsule was apparently laid successfully on 2 November, but was found 15 hours later by its radio transmitter, floating on the surface, having released itself from the bottom on leaking a small quantity of water. The leak was caused by a fragment of hair adhering to one of the O-ring seals. Two current sensing crystals were damaged on recovering this capsule in darkness, but the assembly was reinstated with a new ballast frame by 4 November, and a successful launch achieved.

The five moorings which employed long ground lines and separate anchors required the most elaborate deck work and ship manoeuvring, which might have been difficult in bad weather. Thanks to moderate weather throughout the cruise, all these operations were accomplished without apparent mishap. By far the least time-consuming operation of all was the launching of the IOS (Wormley) capsule, completed within 20 minutes.

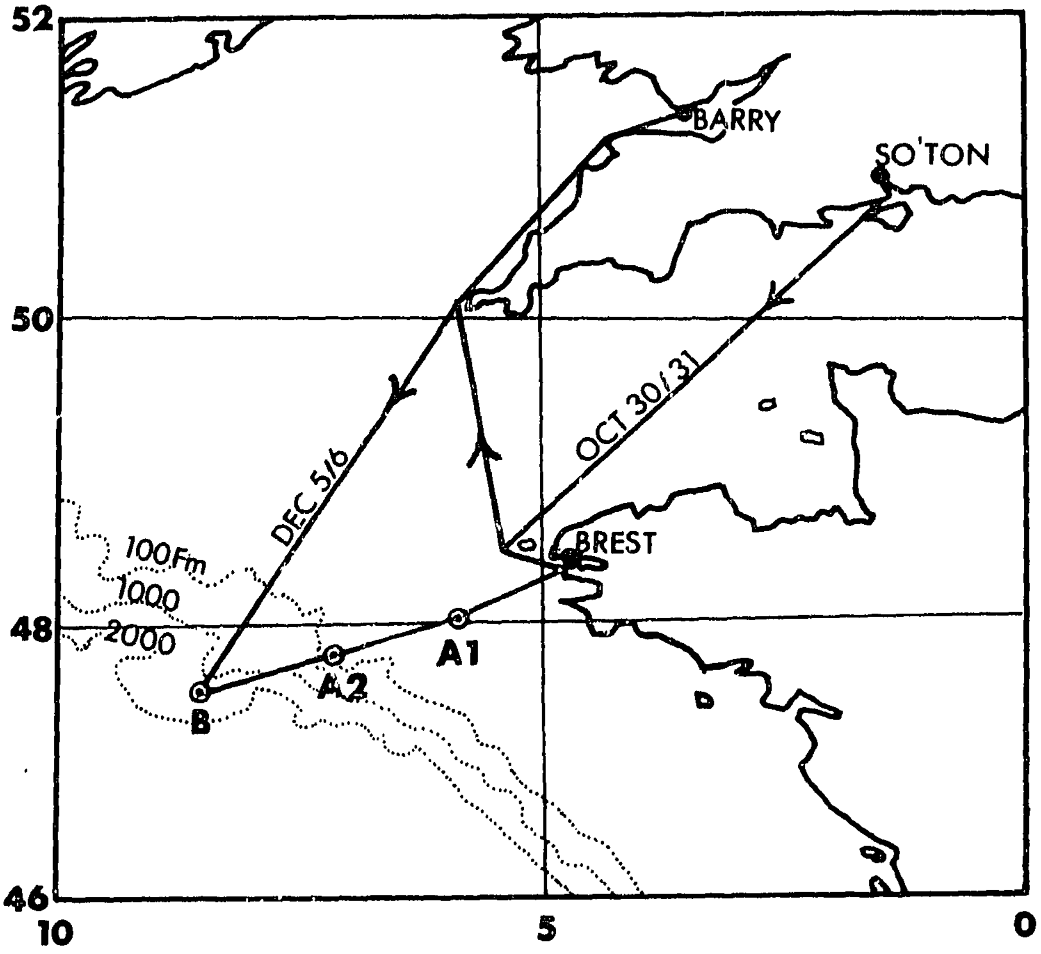
The wide variety of techniques of mooring and instrumentation compared on this cruise provided valuable experience to all participants.

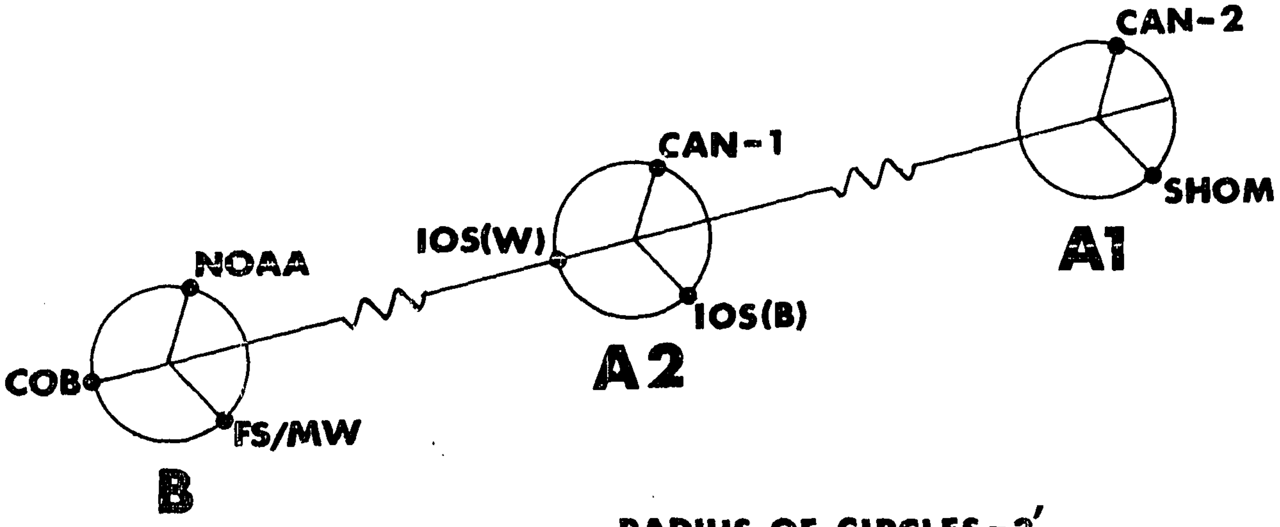
On the 'recovery' cruise (No. 58), 'Discovery' left Barry early on 5 December and proceeded directly to the deep position B. The NOAA capsule and the Snodgrass/Wimbush capsule were successfully recovered in quick succession, the following day. The AMF release gear, attached to the COB capsule by a kilometre length of buoyed rope, was soon activated acoustically, but failed to rise to the surface, for reasons unknown. Some 16 hours were spent manoeuvring with a drag line on 6-7 December,

Table IV.1 Station numbers and mooring positions

| 'DISCOVERY' STATION NUMBER | OWNER OF MOORING | TIME OF LAUNCH | DEPTH (M) | CAPSULE POSITION R - DECCA - G | ANCHOR POSITION DECCA | BEARING OF ANCHOR RE CAPSULE |
|---|---|---|---|---|---|---|
| 8462 | SNODGRASS/WIMBUSH | NOV 4<br>0927 Z | 2160 | 47°26.8' 8°26.5'<br>F8.16 F30.15 | - | - |
| 8463 | C.O.B. | NOV 2<br>1931 Z | 2175 | 47°28.6' 8°34.7'<br>F5.46 F32.41 | 47°28.1' 8°33.3'<br>F6.19 F31.94 | 0.8' 120° |
| 8464 | N.O.A.A. | NOV 2<br>2259 Z | 2010 | 47°32.2' 8°29.0'<br>F4.35 F32.04 | - | - |
| 8465 | I.O.S.(B) | NOV 3<br>1300 Z | 165 | 47°43.7' 7°05.0'<br>F23.4 D44.4 | 47°44.0' 7°05.2'<br>F23.1 D44.5 | 0.3' 324° |
| 8466 | I.O.S.(W) | NOV 3<br>1605 Z | 171 | 47°45.0' 7°14.0'<br>F19.28 E30.51 | - | - |
| 8467 | CANADA-1 | NOV 3<br>2005 Z | 164 | 47°49.9' 7°8.0'<br>F18.0 D47.6 | 47°49.5' 7°7.8'<br>F18.42 D47.36 | 0.5' 170° |
| 8468 | S.H.O.M. | NOV 5<br>1344 Z | 129 | 47°57.6' 5°46.8'<br>H00.30 B40.55 | 47°57.6' 5°47.1'<br>H00.17 B40.75 | 0.2' 270° |
| 8469 | CANADA-2 | NOV 5<br>1648 Z | 126 | 48°02.1' 5°50.3'<br>G18.70 B43.70 | 48°02.5' 5°49.9'<br>G18.35 B43.47 | 0.4' 040° |

Fig. IV.1





RADIUS OF CIRCLES-3′
DISTANCE BETWEEN CENTRES-60′

using the pinger as homing signal, and another 16 hours on the 12th, without success. Some of this time was wasted by errors in navigation greater than 0.5 n mile, but there were at least two occasions when the dynamometer registered a 'catch' by the dragline which later 'escaped', either by slipping off the hook or by parting of the rope. Further attempts at recovery were to be made later by COB.

Both shallow sites A1 and A2 proved to be heavily infested by fishing trawlers, which were probably responsible for the further losses experienced. The only successful recoveries were of the two IOS capsules. The IOS (Wormley) capsule, having no draglines or floats, escaped all damage and was recovered normally on 9 December. The IOS Bidston capsule however had had both its surface recovery buoys cut from their moorings (one was later reported at Concarneau), and had to be recovered by dragging.

It was most regrettable that neither of the two Canadian capsules was found. A pinger, which may have been an AMF release, was heard for a few hours on the 9th, located at a position about 4 miles from the Canada lay position at A2, but dragging here and elsewhere for many hours produced no result. No contact of any sort was made at position A1. The A1 sub-surface float and release gear were recovered some months later by a trawler. The moorings were evidently wrecked by some external agent, but it should be observed that both sub-surface floats were set considerably higher in the water than in normal Canadian practice, owing to an apparently minor misunderstanding between technicians at Ottawa and Wormley. One release gear was recovered by a fishing boat in January, some miles from its lay position.

The Canadian release gears had both been preset to fire automatically on 13 December. As a last resort, lookout teams were posted to search for the surface floats in the mooring areas for a few hours on that day, without result. On expiry of her allotted cruise period, 'Discovery' then returned to Barry, via Brest.

Recovery of the SHOM capsule from position A1 had been left to a French naval ship by prior arrangement. It was later heard that only the release gear had been found, some miles from the lay position, with the steel wire groundline severed.

However, despite the most unfortunate losses of all French and Canadian capsules, those instruments recovered bore a total of ten independent tidal pressure sensors, of which eight functioned very well indeed, as evidenced by section VI of this report. A further two deep sensors were later added by the February-March deployment of the IOS capsule in position B.

# V ANALYSIS WORKSHOP AND RELATED MATTERS

Tidal analysis has been blessed by a high signal-to-noise ratio. But there is some danger in this; it has fostered a lack of urgency in developing optimal methods, and a failure to appreciate the underlying noise considerations which impose the ultimate limit to tidal analysis. The deep-sea measurements, by virtue of their high cost in effort and in money, have given a much needed incentive.

A workshop on tidal analysis was organized because of concern that discrepancies in the intercomparison exercise may be due not so much to the various measurements than to differences in the analysis (this is apt to be the case). Accordingly, two months of bottom pressure observations in Baltasound off Unst, Shetland Islands, were distributed for intercomparison analysis. Table V.1 is a summary of the results by eleven contributors*. The data were divided into two 29-day sections X and Y, and two 15-day sections X' and Y'. The variances of the X and Y records are 2796 and 3000 cm$^2$, respectively. The autovariance refers to the residual variance, after substraction of the predicted tide, using the X-record for X-prediction and the Y-record for Y-prediction. The X-crossvariance refers to the residual variance of X after substraction of the X-prediction based on the Y-record; similarly, the Y-crossvariance refers to the Y-record minus the predicted tide for Y based on an analysis of the X-record. Residual variances are of the order of 1% of the total variance. Crossvariances are larger than autovariances, as expected. Breaking the records into two parts was introduced to keep the exercise honest (so to say); it should not be necessary if objective statistical tests are used[1], [2].

In Table V.2, the best samples[3] of the exercise have been chosen to illustrate the two principal methods of analyses, the harmonic and response method. In each case one can do better by using a nearby reference station (Lerwick), and six years of Lerwick is better than one year. Other things remaining equal, the response method does somewhat better than the harmonic method, and so the best overall result is achieved by the response method referring to a six-year Lerwick reference, with essentially identical results for Cartwright and Zetler (lines 5 and 6).

Residuals are principally the contributions at the tidal frequencies by the geophysical continuum, and not of instrumental noise. Thus, a tidal analysis of record length T inevitably contains a noise contribution from a bandwidth $T^{-1}$ centered at the tidal frequencies. This contribution is enhanced by the cusping of the continuum at the tidal frequencies, probably the effect of baroclinic tides that have become phase-incoherent with the tide-producing forces in their propagation through a variable ocean. Another manifestation of the underlying continuum can be found in the year-to-year variation of the harmonic constants[4].

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*Full accounts of all methods of analysis are held by the Chairman of working group 27.

[1] A. Lambert : Earth tide analysis and prediction by the response method. Dept. of Energy, Mines and Resources, Ottawa, Canada, Earth Physics Branch Contr. No. 506, 1974.

[2] R. McMurtree and D.J. Webb : Tidal response functions around Australia from harmonic constants. In preparation, 1974.

[3] Lines 4 and 5 refer to Zetler analysis subsequent to, and not included in Table V.2.

[4] J.M. Vassie : Report on analysis of test pressure series (Unpublished manuscript).

# TABLE 5.1

| | ZETLER | | | | TERAMOTO | | | | PEARSON | | | | VASSIE | | | | SCHOTT | | | | HYACINTHE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X | | Y | | X | | Y | | X | | Y | | X | | Y | | X | | Y | | $X^{28}$ | | $Y^{28}$ | |
| | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE |
| $Q_1$ | 2.3 | 331.8 | 2.0 | 325.0 | 2.9 | 335.6 | 2.2 | 332.7 | 1.5 | 319.3 | 1.5 | 314.0 | 2.4 | 340.5 | 2.4 | 328.5 | 3.0 | 331.3 | 2.2 | 333.3 | 2.5 | 333.9 | 1.9 | 335.1 |
| $O_1$ | 7.6 | 20.1 | 7.4 | 20.3 | 8.6 | 20.9 | 8.0 | 19.8 | 7.5 | 23.7 | 7.6 | 22.4 | 7.6 | 19.8 | 7.3 | 19.5 | 9.4 | 20.8 | 8.8 | 20.1 | 7.6 | 21.1 | 7.2 | 19.8 |
| $P_1$ | 2.2 | 139.9 | 2.6 | 141.7 | 2.3 | 152.5 | 3.1 | 153.4 | 2.3 | 152.5 | 3.1 | 159.2 | 2.1 | 142.4 | 2.4 | 139.5 | 1.7 | 98.4 | 1.3 | 209.1 | 2.0 | 137.6 | 2.3 | 141.1 |
| $K_1$ | 6.8 | 154.1 | 8.0 | 153.5 | 6.8 | 152.5 | 9.3 | 153.4 | 6.9 | 152.5 | 9.2 | 159.2 | 6.7 | 158.5 | 7.7 | 155.6 | 9.0 | 152.1 | 9.9 | 167.9 | 6.9 | 153.1 | 7.9 | 156.6 |
| $N_2$ | 14.7 | 268.1 | 13.8 | 270.0 | 16.6 | 264.4 | 11.8 | 269.5 | 13.7 | 270.9 | 14.4 | 271.0 | 14.6 | 269.0 | 14.1 | 269.9 | 14.2 | 268.4 | 14.0 | 270.8 | 13.5 | 271.9 | 13.6 | 271.3 |
| $M_2$ | 69.2 | 290.3 | 69.0 | 289.8 | 68.2 | 290.3 | 68.7 | 289.3 | 68.7 | 290.0 | 69.2 | 290.0 | 68.9 | 290.0 | 69.4 | 290.1 | 67.9 | 289.5 | 67.1 | 289.1 | 68.7 | 290.5 | 69.1 | 289.6 |
| $S_2$ | 24.4 | 325.0 | 25.6 | 324.4 | 23.0 | 324.2 | 24.8 | 324.7 | 25.0 | 325.7 | 25.1 | 324.7 | 25.1 | 325.0 | 24.9 | 324.1 | 24.2 | 302.7 | 26.3 | 332.8 | 25.3 | 326.7 | 24.5 | 323.8 |
| $K_2$ | 6.5 | 327.2 | 6.8 | 327.0 | 6.2 | 324.2 | 6.7 | 324.7 | 6.8 | 325.7 | 6.8 | 324.7 | 7.0 | 321.5 | 6.9 | 320.6 | 12.6 | 217.0 | 3.6 | 300.6 | 7.4 | 325.2 | 7.1 | 322.3 |
| Group Variance | 2796.27 | | 2999.65 | | | | | | 2796.27 | | 2999.65 | | 2796.12 | | 2999.50 | | | | | | 2796.27 | | 2999.65 | |
| Auto Variance | 17.50 | | 24.26 | | 30.4 | | 26.59 | | | | | | | | | | 44.86 | | 30.64 | | | | | |
| Cross Variance | 20.33 | | 26.55 | | 49.45 | | 45.08 | | 31.96 | | 29.47 | | 21.45 | | 25.91 | | 292.96 | | 82.21 | | 31.83 | | 27.28 | |
| Standard Deviation | 4.51 | | 5.15 | | 7.03 | | 6.71 | | 5.65 | | 5.43 | | 4.63 | | 5.09 | | 17.12 | | 9.07 | | 5.64 | | 5.22 | |

| | X' | | Y' | | X' | | Y' | | X' | | Y' | | X' | | Y' | | X' | | Y' | | $X'^{17}$ | | $Y'^{28}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE |
| $Q_1$ | 2.4 | 335.3 | 2.2 | 325.5 | 4.4 | 334.7 | 3.2 | 318.0 | 1.7 | 308.3 | 1.4 | 305.0 | 2.6 | 324.8 | 2.4 | 323.3 | 2.9 | 335.8 | 2.0 | 328.6 | 2.1 | 319.3 | 1.7 | 317.8 |
| $O_1$ | 7.4 | 15.4 | 6.8 | 17.9 | 7.5 | 15.5 | 6.6 | 17.2 | 8.5 | 16.8 | 7.3 | 14.5 | 7.2 | 19.6 | 6.6 | 18.1 | 9.9 | 15.3 | 8.2 | 16.7 | 6.8 | 15.0 | 5.5 | 13.5 |
| $P_1$ | 2.1 | 133.5 | 2.3 | 138.2 | 2.3 | 149.8 | 3.0 | 147.5 | 1.9 | 153.9 | 2.7 | 153.6 | 2.1 | 139.0 | 2.3 | 135.7 | 2.3 | 103.8 | 1.1 | 215.0 | 1.5 | 139.6 | 1.7 | 153.6 |
| $K_1$ | 6.6 | 150.2 | 7.4 | 151.1 | 6.9 | 149.8 | 9.1 | 147.5 | 5.5 | 153.9 | 8.2 | 153.6 | 6.6 | 155.1 | 7.5 | 151.8 | 9.6 | 158.0 | 9.9 | 164.9 | 5.4 | 155.1 | 6.1 | 169.1 |
| $N_2$ | 14.8 | 267.4 | 13.4 | 269.1 | 20.6 | 266.8 | 11.7 | 266.2 | 13.7 | 269.5 | 13.6 | 270.8 | 14.4 | 268.3 | 14.4 | 267.8 | 14.7 | 266.6 | 8.7 | 267.4 | 13.1 | 267.1 | 13.7 | 266.3 |
| $M_2$ | 68.9 | 290.7 | 68.8 | 290.1 | 65.3 | 289.1 | 67.1 | 289.9 | 70.8 | 287.7 | 70.7 | 290.0 | 68.7 | 290.4 | 69.0 | 289.9 | 66.4 | 290.7 | 66.5 | 290.5 | 62.1 | 286.4 | 64.8 | 285.6 |
| $S_2$ | 24.1 | 324.9 | 25.9 | 324.5 | 21.0 | 324.1 | 25.5 | 326.5 | 24.5 | 321.5 | 26.3 | 325.8 | 24.1 | 324.0 | 25.3 | 323.4 | 25.8 | 16.0 | 25.2 | 334.5 | 23.5 | 313.6 | 23.4 | 324.7 |
| $K_2$ | 6.4 | 326.9 | 6.9 | 326.9 | 5.7 | 324.1 | 6.9 | 326.5 | 6.7 | 321.5 | 7.2 | 325.8 | 6.7 | 320.5 | 7.0 | 319.9 | 22.5 | 358.2 | 2.8 | 327.2 | 6.8 | 312.1 | 6.8 | 323.2 |
| Group Variance | 3267.32 | | 2961.37 | | | | | | | | | | | | | | | | | | | | | |
| Auto Variance | 10.84 | | 23.42 | | | | | | | | | | | | | | 67.63* | | 28.69* | | | | | |
| Cross Variance | 20.77 | | 28.14 | | 51.88 | | 86.10 | | 29.41 | | 38.37 | | 29.21 | | 25.76 | | 737.25* | | 150.75* | | 71.60 | | 85.38 | |
| Standard Deviation | 4.56 | | 5.31 | | 7.20 | | 9.25 | | 5.42 | | 6.19 | | 5.41 | | 5.08 | | 27.15* | | 12.28* | | 8.46 | | 9.24 | |

| | CARTWRIGHT | | | | DOHLER-KU | | | | RADOK | | | | WIMBUSH | | | | HYACINTHE | | | | DEMERLIAC | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X | | Y | | $X^{11}$ | | $Y^{11}$ | | $X^{16}$ | | $Y^{16}$ | | X | | Y | | $X^{8}$ | | $Y^{8}$ | | X | | Y | |
| | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE |
| $Q_1$ | 2.6 | 329.9 | 2.4 | 329.5 | 2.5 | 334.1 | 1.9 | 336.5 | 2.6 | 332.2 | 2.0 | 330.0 | | | | | | | | | 2.4 | 339.1 | 2.5 | 333.5 |
| $O_1$ | 7.4 | 20.4 | 7.3 | 20.3 | 7.8 | 20.6 | 7.4 | 20.0 | 7.6 | 20.4 | 7.2 | 18.2 | | | | | | | | | 7.7 | 19.2 | 7.3 | 19.5 |
| $P_1$ | 2.2 | 139.7 | 2.3 | 143.0 | 2.1 | 139.1 | 2.4 | 141.5 | 1.9 | 152.8 | 3.0 | 90.2 | | | | | | | | | 2.2 | 144.0 | 2.7 | 144.6 |
| $K_1$ | 7.2 | 155.1 | 7.7 | 158.8 | 7.0 | 154.4 | 7.9 | 156.8 | 6.6 | 150.6 | 5.8 | 155.9 | | | | | | | | | 6.7 | 154.1 | 8.1 | 154.7 |
| $N_2$ | 14.3 | 269.8 | 14.3 | 268.6 | 15.1 | 272.6 | 15.6 | 272.7 | 16.8 | 262.4 | 11.9 | 271.4 | | | | | | | | | 14.4 | 269.4 | 14.3 | 270.8 |
| $M_2$ | 69.2 | 290.3 | 69.1 | 289.9 | 69.3 | 290.3 | 69.8 | 289.5 | 69.0 | 290.3 | 69.8 | 289.7 | | | | | | | | | 68.9 | 290.3 | 69.3 | 290.6 |
| $S_2$ | 25.2 | 324.2 | 24.9 | 325.2 | 22.7 | 328.6 | 24.6 | 322.5 | 23.5 | 324.0 | 24.4 | 330.0 | | | | | | | | | 24.4 | 325.6 | 25.5 | 324.3 |
| $K_2$ | 7.1 | 319.5 | 6.9 | 320.6 | 6.4 | 333.3 | 6.9 | 327.2 | 5.6 | 317.4 | 4.8 | 305.3 | | | | | | | | | 6.6 | 328.4 | 6.9 | 327.0 |
| Group Variance | 2796.27 | | 2999.65 | | | | | | 2796.27 | | 2999.65 | | | | | | | | | | | | | |
| Auto Variance | | | | | 19.93 | | 27.97 | | 12.27 | | 12.00 | | | | | | | | | | | | | |
| Cross Variance | 17.85 | | 23.98 | | 36.25 | | 44.93 | | 59.91 | | 53.94 | | 22.0 | | 27.1 | | 36.48 | | 35.06 | | 22.6 | | 26.6 | |
| Standard Deviation | 4.22 | | 4.90 | | 6.02 | | 6.70 | | 7.74 | | 7.34 | | 4.71 | | 5.21 | | 6.04 | | 5.92 | | | | | |

| | X' | | Y' | | $X'^{8}$ | | $Y'^{8}$ | | $X'^{8}$ | | $Y'^{8}$ | | X' | | Y' | | $X'^{8}$ | | $Y'^{8}$ | | X' | | Y' | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE | AMP. | PHASE |
| $Q_1$ | 2.6 | 329.3 | 2.3 | 328.8 | 2.7 | 329.4 | 2.4 | 329.7 | 4.3 | 344.8 | 3.5 | 328.5 | | | | | | | | | 1.7 | 315.5 | 1.4 | 313.1 |
| $O_1$ | 7.3 | 19.4 | 7.1 | 18.9 | 7.6 | 19.1 | 6.7 | 19.4 | 6.9 | 7.5 | 6.0 | 7.1 | | | | | | | | | 8.8 | 20.6 | 7.3 | 19.0 |
| $P_1$ | 2.1 | 137.5 | 2.3 | 141.1 | 2.1 | 141.5 | 2.1 | 136.0 | 8.2 | 198.4 | 8.8 | 103.7 | | | | | | | | | 2.0 | 142.1 | 2.3 | 141.8 |
| $K_1$ | 7.1 | 152.9 | 7.6 | 157.0 | 6.9 | 156.8 | 7.0 | 151.3 | | | 5.8 | 99.9 | | | | | | | | | 6.0 | 151.9 | 6.9 | 151.8 |
| $N_2$ | 14.3 | 269.7 | 14.2 | 268.5 | 14.6 | 270.5 | 14.0 | 268.6 | 20.0 | 267.0 | 11.5 | 263.6 | | | | | | | | | 13.6 | 271.7 | 13.5 | 273.0 |
| $M_2$ | 69.4 | 290.3 | 68.7 | 289.8 | 70.4 | 291.3 | 67.5 | 289.4 | 66.6 | 289.0 | 67.8 | 290.6 | | | | | | | | | 70.0 | 290.3 | 69.5 | 290.8 |
| $S_2$ | 25.3 | 324.5 | 24.8 | 325.3 | 21.8 | 312.1 | 22.9 | 323.4 | 18.4 | 309.3 | 26.9 | 327.8 | | | | | | | | | 23.6 | 325.0 | 25.9 | 323.9 |
| $K_2$ | 7.1 | 319.8 | 6.9 | 320.6 | 6.1 | 316.8 | 6.4 | 328.1 | | | 5.1 | 338.1 | | | | | | | | | 6.4 | 327.9 | 7.0 | 326.6 |
| Group Variance | | | | | | | | | | | | | | | | | | | | | | | | |
| Auto Variance | | | | | 55.70 | | 35.99 | | 48.20 | | 34.78 | | | | | | | | | | | | | |
| Cross Variance | 17.95 | | 24.37 | | 40.31 | | 48.64 | | 149.85 | | 306.79 | | 24.2 | | 29.4 | | 62.84 | | 80.46 | | 24.9 | | 33.1 | |
| Standard Deviation | 4.24 | | 4.94 | | 6.35 | | 6.97 | | 12.24 | | 17.52 | | 4.92 | | 5.42 | | 7.92 | | 8.97 | | | | | |

Superscripts refer to number of harmonic constants employed

Table V.2 Selected residual variances (cm$^2$), 29-day series

| | | X from Y | Y from X |
|---|---|---|---|
| 1. | Hyacinthe harmonic | 31.83 | 27.28 |
| 2. | Vassie harmonic, ref. Lerwick (5 yrs) | 21.45 | 25.91 |
| 3. | Zetler response*, ref. grav. potential | 20.33(2,3) | 26.55(2,3) |
| 4. | " , ref. Lerwick (1 yr) | 22.10(3,3) | 28.21(4,4) |
| 5. | " " (6 yrs**) | 17.60(1,1) | 23.96(2,2) |
| 6. | Cartwright response, ref. Lerwick (6 yrs**) | 17.85 | 23.98 |

* Numbers in () refer to optimum numbers of weights (complex) for diurnals and semidiurnals, respectively.

** Using Cartwright response weights.

The consistency of the results of the harmonic and response methods have been discussed in a compilation[5] of differences in amplitude and phase as computed by the investigators (tables V.3, V.4). Some of the more fundamental issues have been discussed elsewhere[6]. The response method has the advantage of separating explicitly the astronomic forcing from the ocean response. Further, a station seems to be more simply described (less station constants) in admittance space, and this tells one that the ocean is not characterized by a dense distribution of high Q resonances. On the other hand, the response method carries with it the obligation of a complete set of realistic input functions. It is like the difference between a Kodak and a Hasselblad : with little input the former gives the better pictures, but when properly used, the Hasselblad can improve the result.

Some of the criteria (ii to v) for a proper use of the response method have developed only as a result of the Analysis Workshop and the recent deep-sea experiments off Brest and Bermuda[7]. The results will be summarized here :

(i) Nonlinearity. Shallow water stations require the squares and cubes of forcing functions as additional inputs, leading to bi- and tri-linear analysis, respectively. Cartwright[8] has demonstrated the important role of quadratic friction in producing tri-linear interactions. Analyses limited to bilinear terms showed a 2 cycle-per-year jitter in the admittances, which was removed upon further expansion.

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[5] L.F. Ku : Evaluating the stability of tidal constituents computed by different methods.(Unpublished manuscript).

[6] W.H. Munk and D.E. Cartwright : Tidal spectroscopy and prediction. Phil. Trans. Roy. Soc. London, A, 259, p 533-581, 1966.

[7] B.D. Zetler and W.H. Munk : The optimum wiggliness of tidal admittances. To be submitted to J. Mar. Res., 1974.

[8] D.E. Cartwright : A unified analysis of tides and surges round North and East Britain. Phil. Trans. Roy. Soc. London, A, 263, p. 1-55, 1968.

(ii) Reference stations. In its original development the response method used the gravitational potential as a reference (input) series, but it soon became evident, particularly for relatively short offshore records, that one can do better by referring to a nearby tide station[9]. The underlying principle is that the input and output series be as similar as possible, thus leading to very simple transfer functions. The method consists of two steps : (a) an analysis of the reference station, possibly by the response method and referring to the tidal potential as reference, and (b) the analysis of the offshore station relative to the reference station. Implicit in this procedure is that the reference station should have at least one year and preferably nine years of record. The principle of similarity excludes stations on wide continental shelves as reference for offshore measurements.

(iii) Number of weights. The response prediction consists of the sum of lagged, weighted values of the input function. Munk and Cartwright have argued for lags of 0, ±2 days, ±4 days, .. Once the lags are chosen the appropriate weights are computed in a straightforward fashion. In an effort to produce good results there has been a tendency to employ too many weights, with the result that the computed admittance was unrealistically wiggly, and that the prediction actually suffered. We now find that 2 or 3 (complex) weights are often optimum, but the precise choice depends on signal/noise considerations and record length[10].

(iv) Retarded potential. There has been a tendency to use lags that were symmetrical relative to the prediction time. But for Baltasound it was learned that better results were obtained by centering the lags to a potential retarded by the age of the tide. This is not surprising, and follows from the principle that input and output series should resemble one another as closely as possible.

(v) Radiational tides. The most sensitive issue in a response prediction concerns the nongravitational forcing of tides, such as the diurnal land and sea breeze regime, thermal response to seasonal variations, etc. The effects are too large to be ignored. The radiational frequencies necessarily coincide with the solar gravitational frequencies; but a separation can nonetheless be achieved by the difference in line-splitting resulting essentially from the circumstance that the Earth is opaque to radiation and transparent to gravitation. Typically, this calls for nine years of record. The traditional harmonic method lumps gravitational and radiational effects, and this is unsatisfactory. The exact way radiational tides are to be handled depends on circumstances. For the MODE* data (reference Bermuda) best results were obtained from a transfer function to a combined gravitational plus radiational input series, but for Baltasound there was some advantage to a separate gravitational input.

One unsatisfactory situation has to do with the instability of the prediction weights to slight changes in the choice of parameters. This arises from the lack of orthogonality in the prediction formalism, so that with each additional weight all previous weights are revised. Groves and Reynolds[11] have remedied this situation by the introduction of orthonormal tides (orthotides). As we understand it, the procedure will lead to virtually identical prediction with the response method, but with a marked advantage in characterizing the admittance at any given port with a stable set of constants. The innovation is of importance, and we here sketch the principal considerations.

* Mid-Ocean Dynamics Experiment.

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[9] D.E. Cartwright, W.H. Munk and B.D. Zetler : Pelagic tidal measurements - A suggested procedure for analysis. EOS, 50, 1969, p. 472-477.

[10] B.D. Zetler and W.H. Munk, op. cit.

[11] G.W. Groves and R.W. Reynolds : An orthogonalized convolution method of tide prediction. In preparation, 1974.

|  |  | RESPONSE METHOD |  |  | HARMONIC METHOD |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Constituent | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 29 days | Q1 | .02 | .05 | .00 | .03 | .18 | .18 | .25 | .18 | .33 |
|  | O1 | .01 | .02 | .01 | .05 | .08 | .08 | .18 | .09 | .18 |
|  | P1 | .01 | .08 | .33 | .05 | .05 | .05 | .32 | .92 | .83 |
|  | K1 | .15 | .72 | 2.75 | .52 | .53 | .42 | 3.13 | .36 | 1.25 |
|  | Diurnal | .19 | .87 | 3.09 | .65 | .84 | .73 | 3.88 | 1.55 | 2.59 |
|  | N2 | .01 | .43 | .25 | .13 | .01 | .13 | 11.71 | 12.62 | .06 |
|  | M2 | .03 | .07 | .13 | .13 | .23 | .24 | .30 | .39 | .35 |
|  | S2 | .07 | .74 | .03 | .04 | .44 | 2.60 | 1.63 | 1.19 | 23.66 |
|  | K2 | .02 | .05 | .00 | .01 | .06 | .19 | .13 | .47 | 50.58 |
|  | Semi-diurnal | .12 | 1.29 | .41 | .31 | .74 | 3.16 | 13.77 | 14.67 | 64.65 |
|  | Total | .31 | 2.16 | 3.50 | .96 | 1.58 | 3.89 | 17.65 | 18.63 | 67.24 |

Table V.3. A measure of squared vector differences in $cm^2$ between harmonic constants for two 29-day series of tide observations at Unst analyzed by various analysis procedures 1 – 9, corresponding to values furnished by Cartwright, Zetler, Pearson, Vassie, Hyacinthe, Ku, Teramoto, Radok and Schott, in that order.

|  |  | RESPONSE METHOD |  |  | HARMONIC METHOD |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Constituent | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 15 days | Q1 | .05 | .04 | .05 | .02 | .08 | .05 | .87 | .47 | .42 |
|  | O1 | .02 | .19 | .73 | .18 | .85 | .41 | .41 | .41 | 1.45 |
|  | P1 | .02 | .02 | .32 | .02 | .04 | .01 | .25 | 19.70 | 1.58 |
|  | K1 | .16 | .32 | 3.65 | .43 | .49 | .06 | 2.43 | – | .22 |
|  | Diurnal | .25 | .57 | 4.75 | .65 | 1.46 | .53 | 3.96 | 20.58 | 3.67 |
|  | N2 | .02 | 1.00 | .02 | .00 | .18 | .21 | 39.6 | 44.29 | 18.00 |
|  | M2 | .29 | .07 | 1.01 | .09 | 3.74 | 4.86 | 1.73 | 1.16 | .01 |
|  | S2 | .14 | 1.62 | 2.07 | .73 | 2.58 | 3.02 | 10.24 | 42.52 | 40.99 |
|  | K2 | .02 | .13 | .16 | .05 | .22 | .23 | .73 | – | 196.29 |
|  | Semi-diurnal | .47 | 2.82 | 3.26 | .87 | 6.72 | 8.32 | 52.31 | 87.99 | 255.28 |
|  | Total | .72 | 3.39 | 8.01 | 1.52 | 8.18 | 8.85 | 56.27 | 108.55 | 258.96 |

Table V.4. Same as in Table V.3 for two 15-day series.

The response method leads to the prediction

$$\tilde{\zeta}(t) = \sum_s w_s^* \, c(t-s\Delta t), \qquad c(t) = a(t) + ib(t),$$

where a(t) is the tide-producing potential and b(t) its Hilbert transform (a and b are in quadrature at all frequencies). The complex weights $w_s$ (for each station) for each lag $\tau = s\Delta t$ are determined by least-square fit to the measured tide $\zeta(t)$ :

$$\langle [\zeta(t) - \tilde{\zeta}(t)]^2 \rangle = \text{minimum.}$$

The complex admittances are the Fourier transforms

$$Z(\omega) = \int_{-\infty}^{\infty} w(\tau)\, e^{-i\omega\tau}\, d\tau\,, \qquad \tau = s\Delta t.$$

Groves and Reynolds write the prediction as a converging sum of orthotides $\tilde{\zeta}_n(t)$ :

$$\tilde{\zeta}(t) = \sum_n \; a \, \tilde{\zeta}_n(t), \qquad \tilde{\zeta}_n(t) = \sum_s \; w_{ns} \, c(t-s\Delta t)$$

with the orthogonality conditions

$$\langle \tilde{\zeta}_n \tilde{\zeta}_m \rangle = \delta_{nm}, \qquad \langle \tilde{\zeta}_n \zeta \rangle = a_n \quad .$$

With the tide potential c(t) given, Groves and Teynolds have tabulated $w_{ns}$ and the associated orthoadmittances

$$Z_n(\omega) = \int_{-\infty}^{\infty} w_n(\tau)\, e^{-i\omega\tau}\, d\tau\,, \qquad = s\Delta t$$

consistent with the required conditions of orthogonality. $Z_n$ shows increased wiggliness with increasing n (as with higher Fourier components). The values of $w_{ns}$ and functions $Z_n(\omega)$ are determined once and for all; station admittances are characterized by a table of coefficients $a_n$.

These remarks apply to a tide potential as reference. For any other reference, a set of orthogonal weights $w_{ns}$ can be similarly constructed.

Finally, some comments on tidal currents. There is every reason why the horizontal components of tidal motion should be treated jointly with the vertical component. This working group has held this view. The first five years of tidal measurements with the seafloor Snodgrass capsule involved current meters as well as pressure devices. The pressure measurements turned out to be of better quality. This is surprising if one considers that they represent fluctuations by 1 part in $10^4$, whereas tidal currents constitute something like 80% of the total bottom motion. There is just no satisfactory way of measuring low velocities (~ 1 cm/s) at this time, even from a fixed instrument frame, and the difficulties multiply as one gets off the bottom.

But there are more fundamental issues. First, we note for comparison the following typical values for the ratio residual/recorded tidal variance offshore California[12]:

| | Pressure | Offshore Current | Longshore Current |
|---|---|---|---|
| Diurnals | $10^{-3}$ | 0.5 | 0.4 |
| Semidiurnals | $10^{-4}$ | 0.8 | 0.15 |

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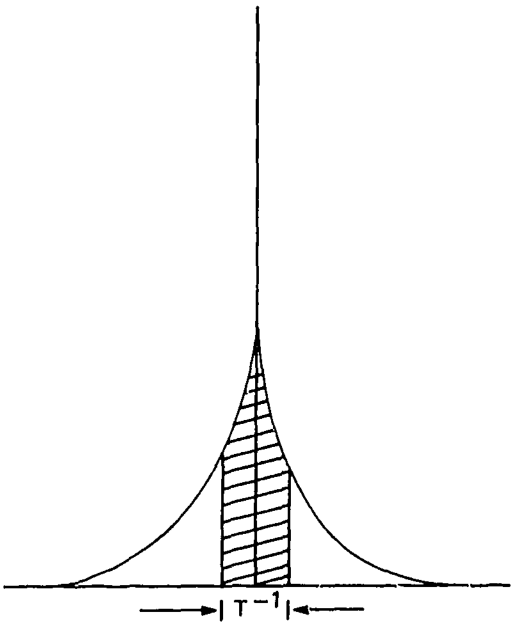
[12] Munk W.H., F.E. Snodgrass and M. Wimbush,: Tides offshore - transition from California coastal to deep sea waters. Geophys. Fl. Dynam., 1970, 1, p. 161-235.

Most of the tidal energy was found in the longshore semidiurnals, and here the ratio is 10 db for the current compared to 40 db for the pressures.

Secondly, most of the pressure tides are associated with the barotropic wave mode, whereas for the currents the energy appears to be about equally divided between barotropic and baroclinic components. Perhaps this is saying the same thing as above in different words, inasmuch as much of the residual variance may in fact be in the baroclinic modes. The problem is not well-posed, and depends on the record length and associated frequency resolution. Consider a spectrum consisting of a cusp and a line (if there is such a thing; the line may just be the central cusp). Then for a record of length T the spectral energy of the line inevitably includes the cusp energy within a bandwidth $T^{-1}$. The operational question is : from a vertical string of current meters, determine the distribution of energy among the various modes as a function of frequency, with emphasis to near-tidal frequencies within the resolution limits available.



Of particular interest is the role of the barotropic mode, and here the pressure records are of particular interest. The MODE expedition gave the opportunity for such a comparison in the deep sea[13]. Four pressure stations, two oriented roughly east-west, two north-south, and separated by about 200 km, permitted the calculation of the $M_2$ tidal current, which could be compared to the direct analysis of current records by Ross Hendry, MIT :

| | Eastward | | Northward | |
|---|---|---|---|---|
| | cm/s | °G | cm/s | °G |
| Pressure gradients | 0.49 | 110 | 0.80 | 258 |
| Measured barotropic | 0.60 | 110 | 0.55 | 328 |

There are many difficulties. The calculation based on the measured pressure gradients must allow for the direct gravitational attraction, and for the tidal displacement of the seabed. The mode separation is not straightforward. The baroclinic components may have a significant contribution to bottom currents even when averaged horizontally over 200 km ( $\lambda$ = 160 km for the lowest baroclinic mode).

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[13] B. Zetler, W. Munk, H. Mofjeld, W. Brown and F. Dormer : MODE Tides. To be submitted to *J. Phys. Oceanogr.*, 1974.

# VI ANALYSIS OF INTERCALIBRATION RECORDS

## VI.1 General

All records retrieved from the exercise were calibrated by their owners in terms of sensitivities to variation in pressure and temperature. (See Section III). The resulting records of pressure in millibars were then corrected for drift, if necessary, and reduced to hourly (GMT) series on punched cards. Copies of all card decks were sent to Zetler (California) for uniform graphical presentation and comparison of low frequency variations, to Demerliac (France) for uniform tidal analysis by a good 'Harmonic' method, and to Cartwright (UK) for uniform tidal analysis by a good 'Response' method, as discussed in Section V.

Records from three independent sensors were obtained from the deep position 'B' (47°30'N 8°30'W) during the principal cruises, to which, for tidal analysis, we may add the records from the two strain gauge sensors used on the IOS deep recorder deployed in February /March 1974 at the same site. Records from five different sensors were obtained from the shallow position 'A2' (47°45'N 7°10'W) during the principal cruises. It was convenient to deal with integral numbers of complete days, starting 0h GMT. Numbers of days varied from 29 to 36, according to the laying and recovering dates and the operations of drift removal, but all durations were entirely adequate for tidal analyses of one-month type. The sensors concerned and their time spans are specified in Table VI.1.

Table VI.1 - Analyzed records

| Owner | Sensor | First day | Last day | No. of days |
|---|---|---|---|---|
| | | DEEP POSITION | | |
| FSMW | Hewlett-Packard 1 | 6 Nov | 5 Dec | 30 |
| FSMW | Hewlett-Packard 2 | 6 Nov | 6 Dec | 30 |
| NOAA | Filloux-Bourdon Tube | 4 Nov | 4 Dec | 31 |
| IOSW | Deep strain gauge 9 | 18 Feb | 25 Mar | 36 |
| IOSW | Deep strain gauge 10 | 18 Feb | 25 Mar | 36 |
| | | SHALLOW POSITION | | |
| IOSB | Hewlett-Packard | 5 Nov | 9 Dec | 35 |
| IOSB | Strain gauge | 5 Nov | 9 Dec | 35 |
| IOSB | Vibrotron | 8 Nov | 6 Dec | 29 |
| IOSW | Shallow strain gauge | 5 Nov | 8 Dec | 34 |
| IOSW | Capacitance plate | 5 Nov | 8 Dec | 34 |

## VI.2 Graphical and low frequency comparisons

Computer plots of the pressure records for eight sensors and the temperature records for four sensors are presented in Fig. VI.2.1 and VI.2.2.

In the plot of bottom pressures, the top three records were obtained in deep water, the remaining five in shallow depths. Perhaps the most exciting aspect of these plots is that they are so dull and unexciting in that they essentially look identical. This is a fine tribute to the state-of-the-art, since many gauges, with significantly different characteristics, produce records that look so completely alike. Thus, there is no reason to suspect any serious calibration problem; more precise comparisons can be made using the harmonic constants. Furthermore, since the times of high and low waters appear to the eye to be essentially the same at all stations, one must turn again to the harmonic constants for precise time comparisons.

Pressure residuals have been computed by substracting a harmonic prediction obtained using the constants from the response analysis for each set of data (eight constituents listed plus additional inferred constants at 1 and 2 cpd). These are plotted on a greatly enlarged scale in Fig. VI.2.3. As noted elsewhere in this report, the IOS Bidston strain gauge has significantly greater residuals than any of the others. The IOS Wormley strain gauge shows some drift. The residuals for the three deep-water gauges are very similar but the FSMW No.2 has a more detectable drift than FSMW No.1; a logarithmic creep has been removed from the NOAA record but the FSMW records have not been high passed in any way.

There are small low to medium frequency variations during the test period that are consistant among most of the station residuals; they are exaggerated in the IOSB strain gauge record (presumably instrumental noise) and apparently they were removed by a severe high pass filter that was applied to the IOSB vibrotron record in order to correct for an unusual transient drift in mid-record. However, since very low frequencies have been removed from some records as 'drift' whereas others, at least the FSMW records, have not been high passed in any sense, a comparison of residuals for low and medium frequencies ($<1$ cpd) without accompanying information on the drift-removing filters is unsatisfactory.

In the plots of residual spectra, $\Delta f \simeq 0.1$ cpd. The low frequency peaks fall at the first point (near 0.1 cpd) and therefore are a measure of the drift in the residuals that has not been removed by filtering. The greater drift for FSMW No.2 than No.1 is more readily apparent in the spectra. The flat plot at low frequencies in the IOSB vibrotron record is due to the severe high pass filter.

Inasmuch as the detiding was limited to 1 and 2 cpd, the peaks at 3 and 4 cpd are total energy at these frequencies whereas the residual peaks at 1 and 2 cpd are tidal cusps. Other than the peaks at very low frequencies attributed to drift in the residuals, there do not appear to be any statistically significant peaks below 1 cpd although several plots suggest a very slight rise in energy at about 0.5 cpd.

The two top temperature plots were obtained in the same instrument package, deployed in deep water. The bottom two plots were obtained from two instruments in shallow water. All four are plotted to the same scale. One finds, as anticipated, a much greater range of temperature in shallow water and a very much greater high-frequency (tidal period) variation in shallow water. The two shallow temperature records have somewhat similar long period fluctuations. However, their high frequency modulations are not well correlated in that there are large differences between the semi-daily ranges of the two records from day to day but the ratio of the ranges is very variable. Had these ratios been reasonably uniform, one might suspect calibration or response-time problems. Since they are not, the variability is presumed to be the result of intermittant intrusions of strong local vertical temperature gradients.

The range of temperatures at a depth of 2.2 km during the month is roughly five times as great as that observed at 5 km in the MODE experiment. This degree of variation appears reasonable in view of the large difference in depth and the exercise location on the continental slope off Brest. The MODE ranges of temperatures were noteworthy in that they were larger by a factor of 10 than those measured in a comparable experiment in the Pacific.

A detailed discussion of the paired pressure and temperature sensors on the FSMW capsule has been published as 'Evaluation of Deep Sea Tide Gauge Sensors' by Snodgrass and Wimbush, Ocean.74, 1974 IEEE International Conference on Engineering in the Ocean Environment.

In the study of subtidal frequencies, problems of instrumental drift are paramount. Demands for long-range stability present a fundamental experimental challenge, far more difficult than attaining precision at tidal frequencies. The plot of pressure residuals is not easily interpreted for the drifts. In the case of NOAA and the

IOSB and IOSW instruments there has been some drift removal by various schemes, whereas for the FSMW Hewlett Packards (and probably for the IOSB Hewlett Packard) there was no such drift removal. Prior to any drift removal, the rough orders of drift are estimated as follows :

| | | | |
|---|---|---|---|
| FSMW 1 | 1 mb/month | | |
| FSMW 2 | 10 | " | |
| NOAA | 100 | " | |
| IOSB HP | ? | | |
| IOSB strain | 20 | " | |
| IOSB vibr. | 100 | " | (probably not typical) |
| IOSW cap. | 20 | " | |
| IOSW strain | 10 | " | |

None of these is satisfactory for direct monitoring of 'climatic' variations in sea level. However, we repeat that all the above instruments gave quite good results on tidal analysis, despite their relatively large drift.

## VI.3 Comparison of tidal analyses

'Harmonic' and 'Response' analyses were carried out by the methods used in the Analysis Workshop (Section V), as described by Demerliac (SHOM) and Cartwright (IOS) respectively. The methods give fairly similar results for the larger tidal constituents, as seen in Section V, and they complement each other in supplying different information. The 'Harmonic' results, summarized in Tables VI.3.1., VI.3.2 and VI.3.3, cover a larger range of constituents than considered in the Workshop, including the linear ter-diurnal $M_3$ and the leading nonlinear terms in species 4 and 6. We restricted the 'response' results to the eight major constituents, but included information on species-band noise levels. These are summarized in Tables VI.3.4, VI.3.5, VI.3.6. Amplitudes H in these tables are expressed in millibars for all pressure records and in centimetres for Brest sea level records. The conversion factor for pressures at 2,000 m depth is 1 cm = 1.0125 mb.

Table VI.3.3 shows the results of 'harmonic' analyses of records from the tide gauge at the mouth of the River Penfeld in the centre of Brest harbour, for a 29-day period roughly simultaneous with the pelagic records, for the whole year of 1973, and for an 3-year period, 1953-70. The three sets of results give direct measures of the variability one can expect from such different time spans, and of the enhanced nonlinear terms on shore as compared with the open shelf-edge.

Brest was also an obvious choice as 'reference tide' for the 'response' method, but an important feature should be noted, which was not well brought out in the 'Workshop'. The tide at Brest contains considerable nonlinear terms in species 1 and 2 as well as in 4 and 6, due largely to tidal friction. In analyzing the tide at Brest, these terms have to be included, but in forming a reference tide for the linear pelagic stations they were omitted. The harmonic constituents for the 'reference tide', detailed in Table VI.3.6, therefore differ from the full constituents for Brest in Table VI.3.3, being mostly larger in amplitude and earlier in phase. The 'response' analysis of Brest (Penfeld) covered six years at three-year intervals in the period 1921-1936, as discussed in Cartwright (1972)*. The associated admittances can be seen from the lower part of Table VI.3.6 to be smooth functions of frequency. Small secular changes in the tides between 1921-36 and 1973 are absorbed in the response admittances, and are therefore irrelevant in the present context.

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* Cartwright D.E. : Secular changes in the oceanic tides at Brest, 1711-1936. Geophys. J. R. Astr. Soc. (1972), 30, 433-449.

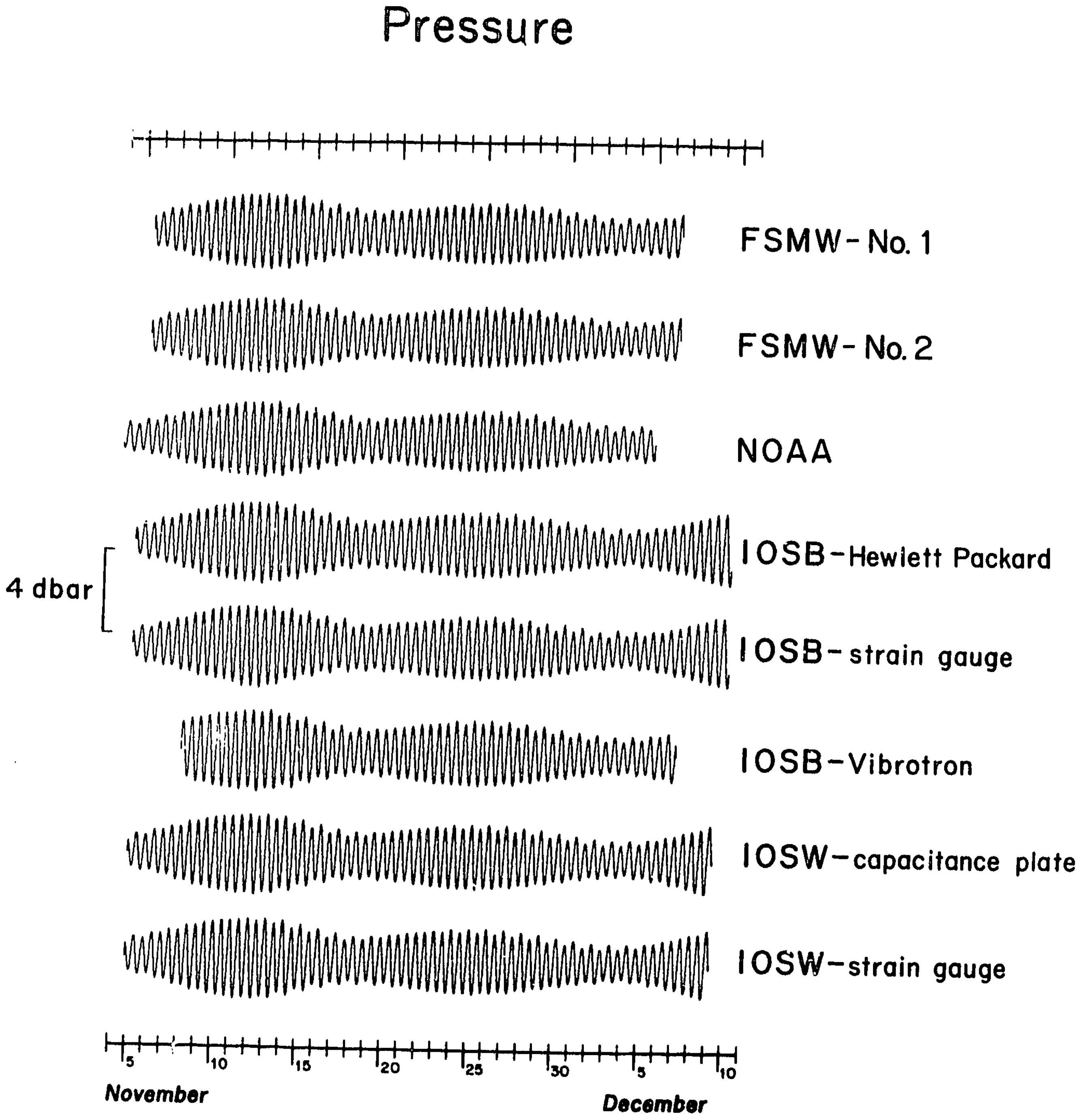

Figure VI.2.1 Pressure records for 8 sensors.

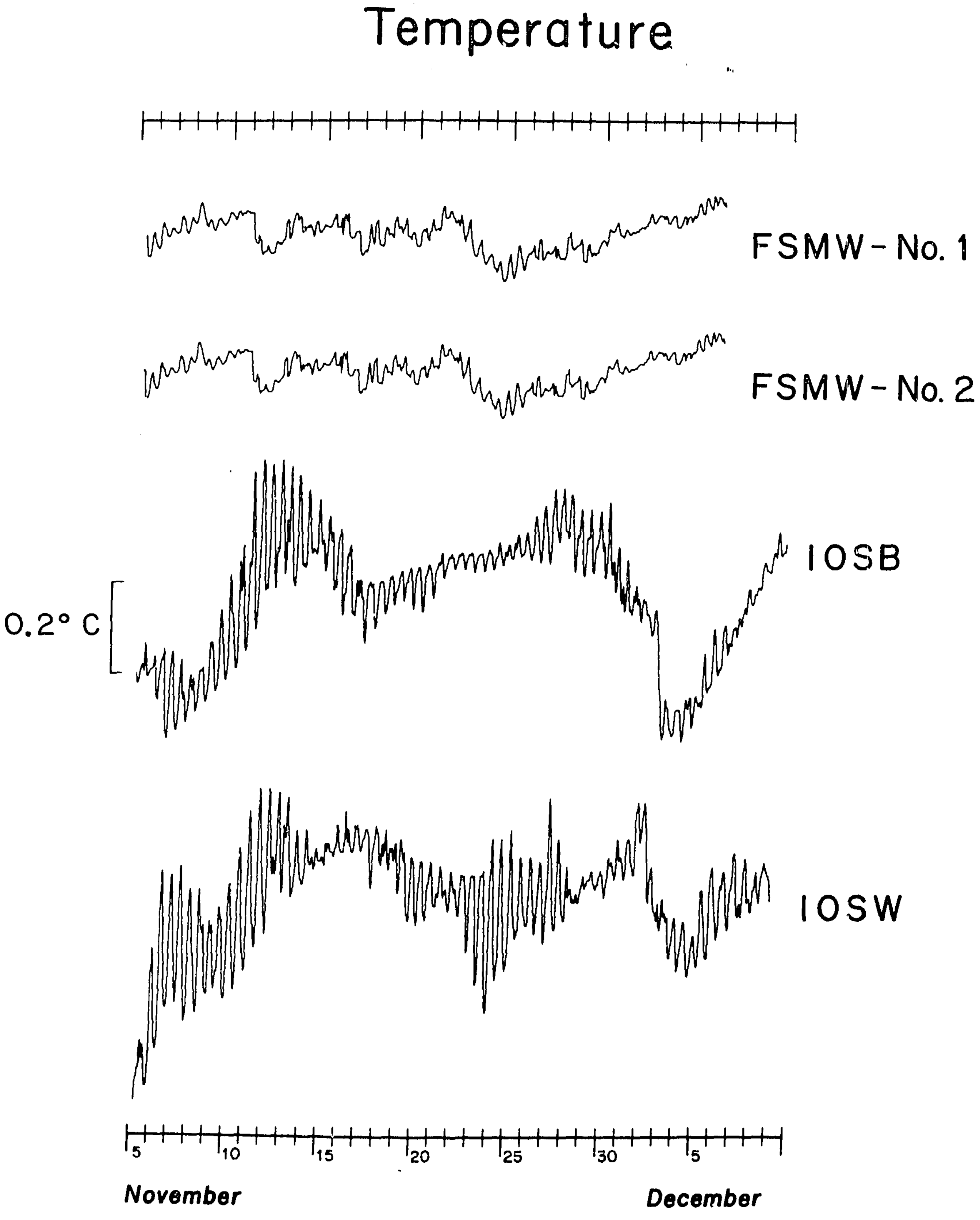

Figure VI.2.2 Temperature records for 4 sensors.

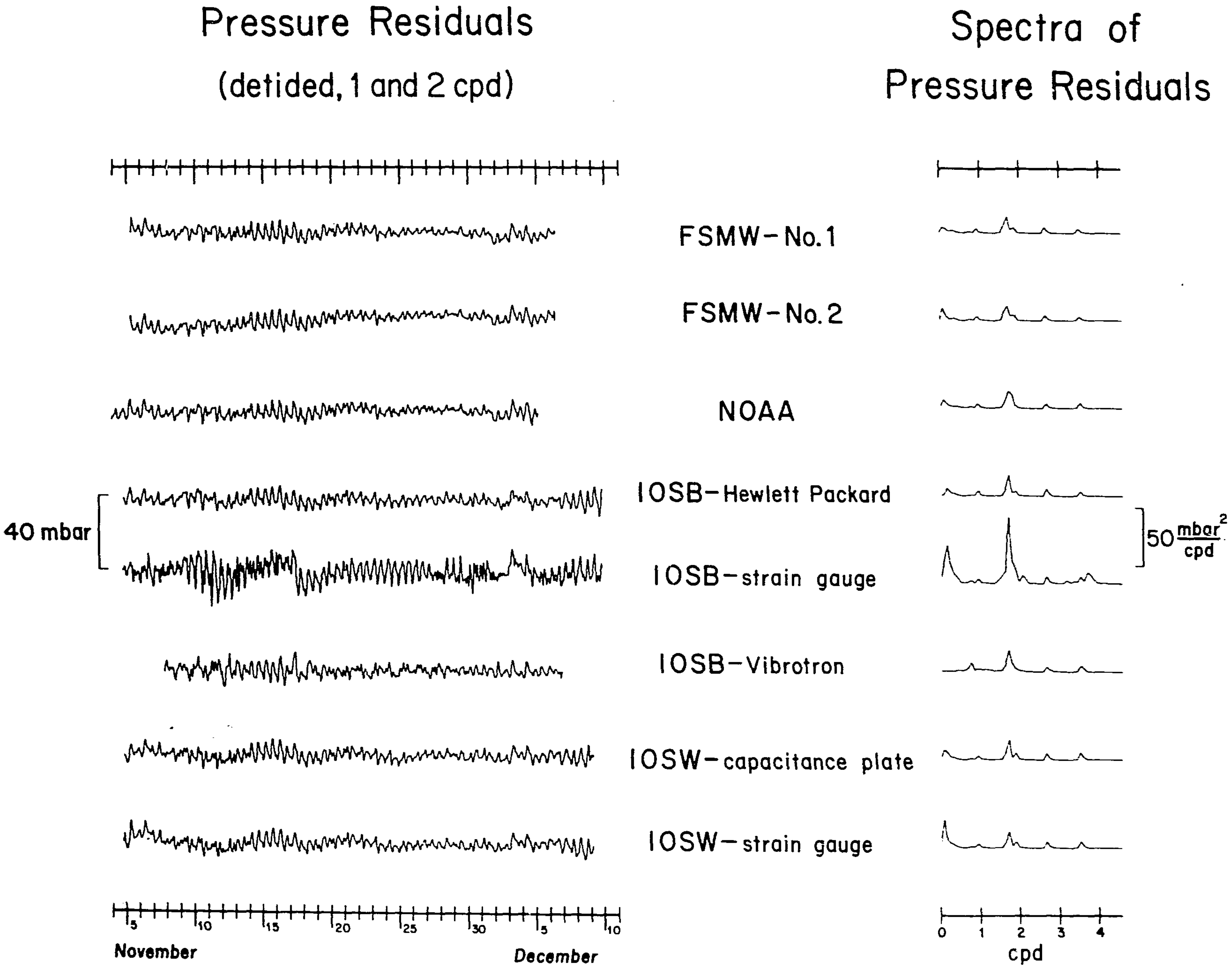

Figure VI.2.3 Tidal residuals from 8 pressure records, and their spectra.

The results from the open sea must be compared separately in two groups, deep and shallow, because of obvious differences in the tides at the two locations. Semi-diurnal amplitudes and phases increase towards Brest, diurnal amplitudes and phases slightly decrease. Averages of the major constituents from the two groups of five sensors from both methods are tabulated below.

| | 'Harmonic' method | | | | 'Response' method | | | |
|---|---|---|---|---|---|---|---|---|
| | Deep | | Shallow | | Deep | | Shallow | |
| | mb. | deg. | mb. | deg. | mb. | deg. | mb. | deg. |
| $O_1$ | 7.1 | 326.3 | 7.1 | 326.5 | 7.2 | 328.2 | 6.8 | 327.2 |
| $K_1$ | 7.2 | 77.0 | 6.7 | 76.5 | 7.6 | 75.2 | 6.9 | 74.0 |
| $M_2$ | 122.6 | 102.1 | 129.7 | 103.2 | 122.5 | 101.7 | 130.0 | 102.7 |
| $S_2$ | 41.2 | 132.8 | 43.5 | 136.2 | 42.1 | 133.6 | 45.1 | 136.1 |

These are not necessarily the 'correct' station values of course, but they show the trends along the 60 nautical miles across the shelf edge, compared with which the true tidal differences round the 3-mile circles of the mooring positions, (as distinct from differences in calibration), may be considered negligible. The table also shows certain differences due to the analytical methods, which will not be discussed further here.

Recorded and residual noise variances in tidal species 1 and 2, and their corresponding Standard Deviations are listed for each record in Tables VI.3.4 and VI.3.5. The S.D's partly account for sampling errors due to finite record lengths in independent samples, (as between the IOSW deep records from Feb/March 1974 and the rest), and partly for individual instrumental noise. Among the deep records, the IOSW strain gauges show the highest noise levels, while the NOAA Bourdon tube shows the lowest. All standard deviations are of order 5% in species 1, 1% in species 2, and may be considered satisfactory.

The shallow records show higher noise levels than the deep records in species 2, probably because of the much larger temperature variations at the shallow station. The IOSB strain gauge shows the highest noise level, also found in smoothness tests of the data series. The IOSW capacitance plate sensor shows the lowest noise level; a surprising result, since earlier comparisons between the two types of Wormley shallow sensor consistently showed capacitance plates to be noisier than strain gauges. The IOSW strain gauge is however a good 'second best' in the present comparison of noise levels. The Hewlett-Packard crystals gave good results in both deep and shallow locations.

Other possible indicators of noise are the amplitudes and phases of the nonlinear terms such as $2SM_2$ and in species 4 and 6. Except for a slight suspicion of irregularity in IOSW strain gauge No. 10, all the deep sensors (Table VI.3.1) give results at the very low level of nonlinear noise evidently present in the tide itself. Among the shallow sensors (Table VI.3.2) only the IOSB strain gauge shows a slightly anomalous noise level in the third-order interactions $2SM_2$ and $M_6$.

Most of the irregularities in the principal harmonic constants, of similar magnitude in both 'harmonic' and 'response' results, must be due to small errors in laboratory calibration, which we have shown (Section III) to be a difficult and sensitive procedure. The most common symptom is a greater or smaller amplitude than average in all the major constituents. The species 2 amplitudes from the IOSW deep strain gauges (Tables VI.3.1, VI.3.4) agree in being roughly 1% higher than the NOAA amplitudes, which are close to the average, while the FSMW H-P crystals agree in being about 0.5% lower. (Discrepancies at $S_2$ and $K_2$, apparent in the 'harmonic' results, do not appear in the corresponding 'response' results). The species 1 amplitudes from the same records suggest a similar pattern, but the variability due to greater noise/signal ratios and to the later epoch of the IOSW strain gauge records make these results a little inconsistent. On the whole, the agreement between the analyses of the deep records is remarkably good, considering the difficulties in the three independent calibration procedures.

The shallow records show somewhat greater variability, probably because of the greater temperature variations. Species 2 amplitudes vary within a range of about 3%, but here there is no real consistency from one species 2 constituent to another, so it is not possible to identify one sensor as being consistently high or low in calibration. It is probable that the basic calibrations are again consistent within 2%, but that a random error of order 2% is introduced by the more turbulent sea conditions on the shelf. This again may be considered a fairly satisfactory comparison.

Table VI.3.1 Analysis by "Harmonic" method - Deep position

| | FSMW/HP1 | | FSMW/HP2 | | NOAA/BT | | IOSW/SG9 | | IOSW/SG10 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G | H | G | H | G |
| $Q_1$ | 2.1 | 286.0 | 2.1 | 285.7 | 2.0 | 284.8 | 1.9 | 262.7 | 2.0 | 268.6 |
| $O_1$ | 7.1 | 327.5 | 7.1 | 327.8 | 7.2 | 328.5 | 7.1 | 322.9 | 7.2 | 324.7 |
| $M_1$ | 0.4 | 311.7 | 0.4 | 312.2 | 0.5 | 316.5 | 0.8 | 331.2 | 0.8 | 330.2 |
| $P_1$ | 2.3 | 69.2 | 2.4 | 69.2 | 2.4 | 69.5 | 2.2 | 66.8 | 2.4 | 68.4 |
| $K_1$ | 7.2 | 77.5 | 7.2 | 77.4 | 7.2 | 77.7 | 6.8 | 75.2 | 7.3 | 76.8 |
| $J_1$ | 0.7 | 71.8 | 0.7 | 69.7 | 0.7 | 75.3 | 0.6 | 104.8 | 0.9 | 97.8 |
| $2N_2$ | 3.4 | 65.1 | 3.4 | 64.9 | 3.4 | 64.4 | 3.4 | 57.1 | 3.5 | 60.0 |
| $\mu_2$ | 4.3 | 64.8 | 4.2 | 65.5 | 4.1 | 65.2 | 3.4 | 54.5 | 3.4 | 60.3 |
| $N_2$ | 25.6 | 83.6 | 25.6 | 83.5 | 25.7 | 83.8 | 25.7 | 79.3 | 26.0 | 80.9 |
| $\nu_2$ | 4.9 | 86.0 | 4.9 | 86.0 | 5.0 | 86.4 | 5.0 | 82.2 | 5.0 | 83.7 |
| $M_2$ | 122.0 | 102.1 | 122.0 | 102.1 | 122.7 | 103.1 | 123.2 | 101.5 | 123.4 | 101.9 |
| $L_2$ | 3.3 | 120.2 | 3.2 | 120.0 | 3.4 | 126.6 | 3.3 | 114.4 | 3.8 | 116.7 |
| $T_2$ | 2.3 | 131.6 | 2.4 | 131.5 | 2.4 | 132.2 | 2.5 | 131.1 | 2.5 | 131.6 |
| $S_2$ | 40.3 | 132.9 | 40.5 | 132.7 | 40.8 | 133.4 | 42.2 | 132.3 | 42.3 | 132.8 |
| $K_2$ | 10.9 | 135.4 | 11.0 | 135.2 | 11.1 | 135.9 | 11.5 | 134.8 | 11.5 | 135.3 |
| $2SM_2$ | 0.2 | 49.0 | 0.2 | 22.5 | 0.2 | 25.2 | 0.4 | 103.1 | 0.9 | 114.2 |
| $M_3$ | 1.0 | 343.1 | 1.0 | 342.9 | 1.0 | 346.6 | 0.8 | 342.5 | 1.0 | 8.8 |
| $MN_4$ | 0.5 | 298.5 | 0.5 | 296.6 | 0.5 | 290.8 | 0.4 | 266.8 | 0.4 | 250.7 |
| $M_4$ | 0.8 | 315.2 | 0.9 | 316.1 | 1.0 | 316.4 | 0.8 | 320.9 | 0.9 | 335.0 |
| $MS_4$ | 0.5 | 30.2 | 0.4 | 24.9 | 0.3 | 22.3 | 0.4 | 11.5 | 0.3 | 33.3 |
| $2MN_6$ | 0.1 | 132.2 | 0.1 | 104.2 | 0.1 | 88.0 | 0.1 | 116.8 | 0.3 | 70.2 |
| $M_6$ | 0.1 | 112.3 | 0.1 | 110.5 | 0.1 | 125.6 | 0.1 | 129.5 | 0.1 | 255.2 |
| $2MS_6$ | 0.1 | 195.8 | 0.1 | 184.4 | 0.1 | 174.7 | 0.1 | 167.7 | 0.1 | 134.3 |

Table VI.3.1 Analysis by "Harmonic" method - Deep position

| | FSMW/HP1 | | FSMW/HP2 | | NOAA/BT | | IOSW/SG9 | | IOSW/SG10 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Symbol | H | G º | H | G | H | G | H | G | H | G |
| $Q_1$ | 2.1 | 286.0 | 2.1 | 285.7 | 2.0 | 284.8 | 1.9 | 262.7 | 2.0 | 268.6 |
| $O_1$ | 7.1 | 327.5 | 7.1 | 327.8 | 7.2 | 328.5 | 7.1 | 322.9 | 7.2 | 324.7 |
| $M_1$ | 0.4 | 311.7 | 0.4 | 312.2 | 0.5 | 316.5 | 0.8 | 331.2 | 0.8 | 330.2 |
| $P_1$ | 2.3 | 69.2 | 2.4 | 69.2 | 2.4 | 69.5 | 2.2 | 66.8 | 2.4 | 68.4 |
| $K_1$ | 7.2 | 77.5 | 7.2 | 77.4 | 7.2 | 77.7 | 6.8 | 75.2 | 7.3 | 76.8 |
| $J_1$ | 0.7 | 71.8 | 0.7 | 69.7 | 0.7 | 75.3 | 0.6 | 104.8 | 0.9 | 97.8 |
| $2N_2$ | 3.4 | 65.1 | 3.4 | 64.9 | 3.4 | 64.4 | 3.4 | 57.1 | 3.5 | 60.0 |
| $\mu_2$ | 4.3 | 64.8 | 4.2 | 65.5 | 4.1 | 65.2 | 3.4 | 54.5 | 3.4 | 60.3 |
| $N_2$ | 25.6 | 83.6 | 25.6 | 83.5 | 25.7 | 83.8 | 25.7 | 79.3 | 26.0 | 80.9 |
| $\nu_2$ | 4.9 | 86.0 | 4.9 | 86.0 | 5.0 | 86.4 | 5.0 | 82.2 | 5.0 | 83.7 |
| $M_2$ | 122.0 | 102.1 | 122.0 | 102.1 | 122.7 | 103.1 | 123.2 | 101.5 | 123.4 | 101.9 |
| $L_2$ | 3.3 | 120.2 | 3.2 | 120.0 | 3.4 | 120.6 | 3.3 | 114.4 | 3.8 | 116.7 |
| $T_2$ | 2.3 | 131.6 | 2.4 | 131.5 | 2.4 | 132.2 | 2.5 | 131.1 | 2.5 | 131.6 |
| $S_2$ | 40.3 | 132.9 | 40.5 | 132.7 | 40.8 | 133.4 | 42.2 | 132.3 | 42.3 | 132.8 |
| $K_2$ | 10.9 | 135.4 | 11.0 | 135.2 | 11.1 | 135.9 | 11.5 | 134.8 | 11.5 | 135.3 |
| $2SM_2$ | 0.2 | 49.0 | 0.2 | 22.5 | 0.2 | 25.2 | 0.4 | 103.1 | 0.9 | 114.2 |
| $M_3$ | 1.0 | 343.1 | 1.0 | 342.9 | 1.0 | 346.6 | 0.8 | 342.5 | 1.0 | 8.8 |
| $MN_4$ | 0.5 | 298.5 | 0.5 | 296.6 | 0.5 | 290.8 | 0.4 | 266.8 | 0.4 | 250.7 |
| $M_4$ | 0.8 | 315.2 | 0.9 | 316.1 | 1.0 | 316.4 | 0.8 | 320.9 | 0.9 | 335.0 |
| $MS_4$ | 0.5 | 30.2 | 0.4 | 24.9 | 0.3 | 22.3 | 0.4 | 11.5 | 0.3 | 33.3 |
| $2MN_6$ | 0.1 | 132.2 | 0.1 | 104.2 | 0.1 | 88.0 | 0.1 | 116.8 | 0.3 | 70.2 |
| $M_6$ | 0.1 | 112.3 | 0.1 | 110.5 | 0.1 | 125.6 | 0.1 | 129.5 | 0.1 | 255.2 |
| $2MS_6$ | 0.1 | 195.8 | 0.1 | 184.4 | 0.1 | 174.7 | 0.1 | 167.7 | 0.1 | 134.3 |

Table VI.3.2 Analysis by "Harmonic" method - Shallow position

| | 1OSB/HP | | IOSB/SG | | IOSB/Vib | | IOSW/SG | | IOSW/Cap | |
|---|---|---|---|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G | H | G | H | G |
| $Q_1$ | 2.0 | 283.7 | 2.0 | 283.9 | 2.2 | 294.2 | 2.1 | 284.9 | 2.0 | 284.3 |
| $O_1$ | 7.1 | 326.8 | 6.9 | 327.1 | 7.3 | 324.9 | 7.1 | 327.0 | 7.1 | 327.0 |
| $M_1$ | 0.4 | 311.2 | 0.4 | 311.4 | 0.3 | 293.6 | 0.5 | 316.9 | 0.5 | 316.3 |
| $P_1$ | 2.2 | 67.9 | 2.2 | 68.7 | 2.2 | 68.6 | 2.3 | 68.0 | 2.3 | 68.0 |
| $K_1$ | 6.8 | 76.1 | 6.7 | 76.9 | 6.6 | 77.1 | 6.9 | 76.1 | 6.8 | 76.2 |
| $J_1$ | 0.7 | 69.2 | 0.1 | 80.0 | 0.4 | 82.3 | 0.6 | 72.1 | 0.6 | 75.8 |
| $2N_2$ | 3.6 | 65.2 | 3.7 | 63.9 | 3.6 | 66.1 | 3.6 | 65.2 | 3.6 | 65.1 |
| $\mu_2$ | 4.4 | 64.3 | 4.5 | 56.5 | 4.7 | 69.0 | 4.5 | 65.0 | 4.4 | 62.4 |
| $N_2$ | 27.4 | 84.3 | 28.0 | 83.3 | 26.8 | 84.8 | 27.1 | 84.3 | 26.9 | 84.3 |
| $\nu_2$ | 5.3 | 86.8 | 5.4 | 85.9 | 5.2 | 87.3 | 5.3 | 86.9 | 5.2 | 86.8 |
| $M_2$ | 130.9 | 103.3 | 127.2 | 102.8 | 130.9 | 103.4 | 130.2 | 103.5 | 129.3 | 103.4 |
| $L_2$ | 3.6 | 116.9 | 3.7 | 127.2 | 4.1 | 114.7 | 3.4 | 116.2 | 3.5 | 115.9 |
| $T_2$ | 2.6 | 135.2 | 2.6 | 134.9 | 2.6 | 135.0 | 2.6 | 134.6 | 2.5 | 134.5 |
| $S_2$ | 44.0 | 136.6 | 43.6 | 136.3 | 43.3 | 136.3 | 43.6 | 135.9 | 43.2 | 135.8 |
| $K_2$ | 12.0 | 139.3 | 11.9 | 139.0 | 11.8 | 139.0 | 11.9 | 138.5 | 11.7 | 138.4 |
| $2SM_2$ | 0.1 | 351.2 | 1.2 | 186.3 | 0.2 | 94.5 | 0.4 | 20.1 | 0.5 | 8.3 |
| $M_3$ | 1.2 | 343.8 | 1.2 | 343.0 | 1.0 | 350.0 | 1.1 | 345.1 | 1.1 | 345.8 |
| $MN_4$ | 0.5 | 276.5 | 0.3 | 267.4 | 0.6 | 281.6 | 0.6 | 285.7 | 0.6 | 288.8 |
| $M_4$ | 0.9 | 301.8 | 1.2 | 280.8 | 0.9 | 292.0 | 1.0 | 298.0 | 1.1 | 296.7 |
| $MS_4$ | 0.2 | 324.8 | 0.5 | 50.9 | 0.6 | 308.5 | 0.5 | 315.3 | 0.5 | 319.0 |
| $2MN_6$ | 0.2 | 17.1 | 0.4 | 31.6 | 0.2 | 325.6 | 0.1 | 339.1 | 0.0 | 336.4 |
| $M_6$ | 0.2 | 16.6 | 0.5 | 37.7 | 0.2 | 318.0 | 0.1 | 355.2 | 0.1 | 353.7 |
| $2MS_6$ | 0.2 | 62.6 | 0.2 | 130.7 | 0.2 | 35.1 | 0.2 | 32.7 | 0.2 | 26.2 |

Table VI.3.3

Analysis by "Harmonic" method - Brest (Penfeld) tide gauge

| | 29 days<br>Nov-Dec 1973 | | 365 days<br>Whole 1973 | | 18 years<br>1953-1970 | |
|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G |
| $Q_1$ | 2.0 | 292.4 | 1.7 | 289.1 | 2.0 | 282.5 |
| $O_1$ | 5.8 | 317.3 | 6.9 | 328.3 | 6.5 | 329.3 |
| $M_1$ | 0.3 | 294.0 | 0.6 | 291.6 | - | - |
| $P_1$ | 2.1 | 68.2 | 2.3 | 66.6 | 2.3 | 68.2 |
| $K_1$ | 6.3 | 77.2 | 6.1 | 73.4 | 6.3 | 75.8 |
| $J_1$ | 0.3 | 125.4 | 0.4 | 133.3 | 0.3 | 107.9 |
| $2N_2$ | 5.5 | 73.5 | 6.0 | 58.8 | 5.6 | 73.9 |
| $\mu_2$ | 7.5 | 121.5 | 8.7 | 106.0 | 8.7 | 102.4 |
| $N_2$ | 41.4 | 91.4 | 41.5 | 90.3 | 41.6 | 89.7 |
| $\nu_2$ | 8.0 | 93.8 | 7.4 | 90.5 | 7.5 | 85.5 |
| $M_2$ | 204.6 | 109.3 | 205.2 | 108.8 | 203.7 | 108.3 |
| $L_2$ | 4.6 | 106.0 | 6.9 | 108.1 | 6.7 | 103.8 |
| $T_2$ | 4.4 | 146.7 | 4.3 | 137.1 | 4.1 | 136.0 |
| $S_2$ | 74.7 | 148.2 | 75.8 | 148.3 | 74.9 | 147.5 |
| $K_2$ | 20.3 | 151.4 | 21.3 | 146.1 | 21.1 | 145.1 |
| $2SM_2$ | 1.7 | 259.0 | 1.5 | 307.1 | 1.9 | 304.0 |
| $M_3$ | 1.9 | 27.4 | 2.1 | 15.9 | 2.0 | 15.4 |
| $MN_4$ | 1.9 | 64.5 | 2.0 | 56.4 | 2.1 | 58.3 |
| $M_4$ | 5.0 | 95.1 | 5.4 | 103.0 | 5.8 | 103.0 |
| $MS_4$ | 3.1 | 187.3 | 3.4 | 184.0 | 3.3 | 187.8 |
| $2MN_6$ | 2.4 | 340.6 | 1.9 | 325.8 | 1.9 | 326.2 |
| $M_6$ | 3.5 | 347.9 | 2.8 | 353.3 | 2.9 | 354.3 |
| $2MS_6$ | 2.3 | 55.9 | 1.6 | 60.0 | 1.5 | 53.6 |

Table VI.3.5 Analysis by "Response" method - Shallow position

| | IOSB/HP | | IOSB/SG | | IOSB/vib | | IOSW/SG | | IOS/Cap | |
|---|---|---|---|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G | H | G | H | G |
| $Q_1$ | 2.0 | 282.4 | 2.0 | 282.5 | 2.0 | 280.3 | 2.0 | 282.8 | 2.0 | 282.7 |
| $O_1$ | 6.8 | 327.2 | 6.7 | 327.3 | 7.0 | 326.5 | 6.8 | 327.5 | 6.8 | 327.4 |
| $P_1$ | 2.4 | 61.3 | 2.4 | 61.7 | 2.4 | 61.0 | 2.4 | 61.4 | 2.4 | 61.3 |
| $K_1$ | 6.5 | 73.9 | 7.0 | 74.4 | 6.9 | 73.6 | 7.2 | 74.1 | 7.1 | 74.0 |
| Rec.Var. | 64.25 | | 61.67 | | 60.54 | | 68.86 | | 67.49 | |
| Res.Var. | 0.28 | | 0.39 | | 1.00 | | 0.24 | | 0.22 | |
| S.D. | 4.1% | $2^{\circ}.4$ | 5.0% | $2^{\circ}.8$ | 8.9% | $5^{\circ}.1$ | 3.8% | $2^{\circ}.2$ | 3.6% | $2^{\circ}.1$ |
| $N_2$ | 28.2 | 81.8 | 27.4 | 81.0 | 28.1 | 81.7 | 28.2 | 82.1 | 28.0 | 82.0 |
| $M_2$ | 131.3 | 102.8 | 128.0 | 102.2 | 130.8 | 102.8 | 130.5 | 102.9 | 129.6 | 102.8 |
| $S_2$ | 45.6 | 136.4 | 44.5 | 136.1 | 45.4 | 136.5 | 45.2 | 135.8 | 44.8 | 135.8 |
| $K_2$ | 13.1 | 133.9 | 12.7 | 133.7 | 13.0 | 134.0 | 13.0 | 133.3 | 12.8 | 133.2 |
| Rec.Var. | 9410.25 | | 8937.47 | | 9736.63 | | 9187.76 | | 9048.64 | |
| Res.Var. | 1.42 | | 4.13 | | 2.17 | | 1.37 | | 1.19 | |
| S.D. | 0.8% | $0^{\circ}.4$ | 1.3% | $0^{\circ}.8$ | 1.0% | $0^{\circ}.6$ | 0.8% | $0^{\circ}.4$ | 0.7% | $0^{\circ}.4$ |

Table VI.3.4 Analysis by "Response" method - Deep position

| | FSMW/HP1 | | FSMW/HP2 | | NOAA/BT | | IOSW/SG9 | | IOSW/SG10 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G | H | G | H | G |
| $Q_1$ | 2.0 | 284.0 | 2.0 | 284.8 | 2.0 | 284.7 | 2.2 | 280.5 | 2.1 | 284.5 |
| $O_1$ | 6.9 | 328.2 | 6.9 | 328.8 | 7.0 | 328.8 | 7.5 | 326.5 | 7.5 | 328.6 |
| $P_1$ | 2.5 | 62.0 | 2.5 | 62.3 | 2.5 | 62.7 | 2.6 | 62.5 | 2.8 | 63.1 |
| $K_1$ | 7.4 | 74.7 | 7.4 | 74.9 | 7.5 | 75.4 | 7.6 | 75.3 | 8.2 | 75.9 |
| Rec.Var. | 63.39 | | 63.21 | | 69.09 | | 44.75 | | 48.80 | |
| Res.Var. | 0.28 | | 0.29 | | 0.27 | | 0.26 | | 0.70 | |
| S.D. | 4.5% | $2^{\circ}.6$ | 4.6% | $2^{\circ}.6$ | 4.2% | $2^{\circ}.4$ | 4.7% | $2^{\circ}.7$ | 7.4% | $4^{\circ}.2$ |
| $N_2$ | 26.5 | 80.9 | 26.5 | 81.0 | 26.7 | 81.8 | 26.8 | 80.7 | 26.8 | 81.2 |
| $M_2$ | 122.0 | 101.5 | 121.9 | 101.4 | 122.6 | 102.4 | 122.8 | 101.5 | 123.1 | 102.0 |
| $S_2$ | 42.2 | 133.2 | 42.3 | 133.1 | 42.2 | 134.3 | 41.8 | 133.5 | 42.1 | 133.9 |
| $K_2$ | 12.0 | 130.6 | 12.0 | 130.5 | 12.1 | 131.6 | 12.0 | 130.8 | 12.1 | 131.3 |
| Rec.Var. | 8271.91 | | 8270.97 | | 8224.05 | | 9269.85 | | 9326.49 | |
| Res.Var. | 1.04 | | 0.98 | | 0.85 | | 2.26 | | 3.36 | |
| S.D. | 0.8% | $0^{\circ}.4$ | 0.7% | $0^{\circ}.4$ | 0.7% | $0^{\circ}.4$ | 1.0% | $0^{\circ}.6$ | 1.2% | $0^{\circ}.6$ |

Table VI.3.6 Reference tide for "Response" method;

linearised tide at Brest (Penfeld), based on analysis covering years 1921, 1924, 1927, 1930, 1933, and 1936.

| | Gravitational | | Radiational | | Total | |
|---|---|---|---|---|---|---|
| Symbol | H | G | H | G | H | G |
| $Q_1$ | 2.0 | 280.3 | - | - | 2.0 | 280.3 |
| $O_1$ | 6.7 | 327.5 | - | - | 6.7 | 327.5 |
| $P_1$ | 2.2 | 73.0 | 0.4 | 341.8 | 2.2 | 63.2 |
| $K_1$ | 6.5 | 79.0 | 0.4 | 341.8 | 6.4 | 75.8 |
| $N_2$ | 42.9 | 83.8 | - | - | 42.9 | 83.8 |
| $M_2$ | 207.0 | 104.6 | - | - | 207.0 | 104.6 |
| $S_2$ | 85.9 | 133.7 | 13.4 | 273.0 | 76.2 | 140.3 |
| $K_2$ | 22.8 | 136.0 | 1.2 | 273.0 | 21.9 | 138.1 |

Admittances at intervals of 1 cycle/month; reference tide to gravitational potential, and of sample deep and shallow records to reference tide

| Frequency c/day | | Ref/g.p. | | FSMW1/Ref | | IOSB1/Ref | |
|---|---|---|---|---|---|---|---|
| | | R | $\phi$ | R | $\phi$ | R | $\phi$ |
| 0.89293 | | 0.401 | 260.0 | 0.990 | -4.0 | 0.986 | -2.1 |
| 0.92954 | ($O_1$) | 0.254 | 212.5 | 1.027 | -0.7 | 1.013 | 0.3 |
| 0.96614 | | 0.192 | 149.0 | 1.087 | 1.1 | 1.056 | 1.7 |
| 1.00274 | ($K_1$) | 0.175 | 101.0 | 1.156 | 1.1 | 1.105 | 1.9 |
| 1.03934 | | 0.107 | 53.9 | 1.219 | -0.2 | 1.151 | 0.9 |
| 1.85907 | | 4.055 | 297.9 | 0.648 | 3.9 | 0.677 | 3.1 |
| 1.89567 | | 3.553 | 276.4 | 0.620 | 2.9 | 0.658 | 2.0 |
| 1.93227 | ($M_2$) | 3.275 | 255.4 | 0.589 | 3.1 | 0.634 | 1.8 |
| 1.96887 | | 3.158 | 238.4 | 0.563 | 4.8 | 0.613 | 2.6 |
| 2.00548 | ($K_2$) | 2.851 | 224.0 | 0.549 | 7.5 | 0.597 | 4.2 |

# VII CONCLUSIONS AND RECOMMENDATIONS

Our report has covered several rather different aspects of open sea tides, and this fact is symptomatic of the complexity of the subject. Open sea tide recording requires costly, high precision technology, and to extract the maximum information from the data demands complex computer analysis. The full range of activity, from preparing the instrument, through mooring and recovering it at sea, to processing the data, requires a variety of personal expertise. For the sake of clarity, our conclusions and recommendations are presented under the three headings : instrument technology, deployment of moorings, and tidal analysis. However, it must be appreciated that all these aspects are inter-related and are inseparable from the overall view of the subject.

## VII.1 Instrument technology

Results from different sensors were in relatively close agreement, and in this respect the exercise was a remarkable success. If one has to select one type of sensor for all-round performance in regard to drift, temperature coefficient and noise level, the choice falls on the quartz crystal, which gave excellent results in both deep and shallow situations. However, crystals with the required physical properties are expensive, and in some cases unobtainable commercially, whereas many much cheaper sensors were found adequate for most purposes.

In general, the technological solutions varied between the highest quality, elaborately controlled, but expensive device requiring expert supervision, as exemplified by Frank Snodgrass's capsule, and less-advanced designs, less expensive and easier to use, as in the Canadian and SHOM capsules. Choice between these extremes must depend on scientific purpose and required accuracy. Cost must be balanced against the risk of loss on one hand and the high cost of any ship operation on the other.

Loss of the French and Canadian capsules prevented us from making the rather important distinction between pressure recorders which back off the mean pressure against the strain of a solid or against a compressed gas. We recommend that the two types of recorders (e.g. the COB and the IOS deep capsules) be compared in a separate future experiment.

The technology is not advanced enough for us to investigate the feasibility of continuously 'on demand' acoustic links as distinct from 'in situ' recording. The former facility would be particularly useful in real-time bathymetric surveying. For purposes of tidal analysis, only occasional external monitoring, to check that the instrument is working, is sufficient. We do recommend, however, further research into long term (1 year) 'in situ' recorders, particularly for use under ice cover.

The great importance of calibrating all sensors in a realistic pressure and temperature ambiance is stressed. We recommend a move towards standardization of procedures of calibration. As a further step in this direction, future large scale field experiments should include when appropriate sample sensors at a common site.

## VII.2 Deployment of moorings

The mooring techniques used in the exercise were sharply divided between self-contained 'pop-up' units, and remote release systems involving ground-lines of various sorts. The fact that all capsules of the former type were either lost, or recovered only after lengthy dragging operations strongly suggests the superiority of pop-up units. They take much less time to handle on board ship, they are less likely to be fouled by fishing trawlers, and are less susceptible to problems of rope entanglement.

The unexpectedly serious losses of equipment do however teach us some lessons. International exercises of this nature in depths less than 200 metres should avoid all likely fishing grounds. The risk of loss of scientific equipment has significantly risen in recent years, owing to the intensification of trawling operations. Dragging operations again emphasized the need for the highest possible precision in positioning for this sort of work. An accuracy of 1/4 mile is essential, otherwise so much valuable time can be wasted.

## VII.3 Tidal analysis

The Analysis Workshop and the calibration exercise analyses have not only disclosed significant differences in results from various analytical procedures but also stimulated thought on how to optimize procedures. In comparing 'response' and 'harmonic' analyses, the results were significantly better for 'response' analyses. Inasmuch as open sea tide measurements will continue to be both rare and expensive, it is recommended that response analyses be used with such data.

In response analysis, the reference predicted series may be either a tidal synthesis for a nearby station or the gravitational potential. Predictions based on a long ($\geq 1$ year) series at an offshore island nearby to the open sea station are ideal. A coastal prediction may include different radiational inputs from those found in the open sea and therefore the gravitational potential may provide a better reference series. These and other criteria for response analysis procedures in Section V should be carefully considered.

Tidal current calculation in the 'MODE tides' study[*] indicated the need for a high order of accuracy in calculating slope gradients for input in the equations of motion. Future experiments of this kind should stress, in addition to careful analysis, uniformity in calibration and selection of array patterns conducive to orthogonal calculations.

Units of millibars and centimetres have been used for bottom pressure data; ordinarily these units can be converted by corrections of about 1%. Either is acceptable, millibars being more obvious as the parameter measured, but centimetres are desirable for comparison with co-range charts.

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[*] Section V, ref. 13.

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| 8 | Third report of the joint panel on oceanographic tables and standards, Berne, 4-5 October 1967. Sponsored by Unesco, ICES, SCOR, IAPO | 1968 | WG 10 |
| 10 | Guide to the Indian Ocean Biological Centre (IOBC), Cochin (India), by the Unesco Curator 1967-1969 (Dr. J. Tranter) | 1969 | – |
| 11 | An intercomparison of some current meters, report on an experiment at WHOI Mooring Site "D", 16-24 July 1967 by the working group on Continuous Current Velocity Measurements. Sponsored by SCOR, IAPSO and Unesco | 1969 | WG 21 |
| 12 | Check-List of the fishes of the North-Eastern Atlantic and of the Mediterranean (report of the third meeting of the Committee, Hamburg, 8-11 April 1969) | 1969 | – |
| 14 | Fifth report of the joint panel on oceanographic tables and standards, Kiel, 10-12 December 1969. Sponsored by Unesco, ICES, SCOR, IAPSO | 1970 | WG 10 |