Hydraulics Research
Wallingford

SHIP MOVEMENT RECORDER

I E Shepherd C.Eng., M.I.E.R.E., M.Inst.M.C.

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Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

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ABSTRACT

A system has been developed by Hydraulics Research of interest to port and harbour engineers concerned with measuring wave-induced movements experienced by ships moored alongside quays. It is intended for use in harbours where long waves penetrate and cause excessive ranging of ships. Simultaneous movements in three orthogonal axes of three points on the vessel are measured by means of taut wires running between the ship and three independent tensator mechanisms mounted on the quay. The angular and scope variations of the three wires in response to the movement of the ship are logged digitally to magnetic tape at a sampling rate of 2Hz. The resulting nine channels of raw data are subsequently processed at Wallingford to give heave, roll, pitch, surge, sway and yaw of the vessel. Although the complete system is bulky the individual components are suitable for reasonably rapid and short-term installation at typical berths. A laboratory simulation and a subsequent short field trial indicate that relative movements of the attachment points on the ship can be determined with the necessary precision. Recorded resolutions on position measurements at points as far as 30m from their respective quayside machines approximate to ±1 cm, ±1 cm and ±10 cm which correspond to the resolving power for wire length, inclination and azimuth, respectively.

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1. INTRODUCTION

The movements of moored ships are obviously critical to the design of good harbours and jetties. In order to further refine the measurements on models and improve the theoretical analyses of harbour and moored ship performance, it is necessary to implement the measurement of real ship movements and to establish the effects of scaling.

Many methods for measurements on models have been developed at Hydraulics Research Ltd (HR) over the years (Refs.1 and 2). On model applications, it is imperative that the technique used for measuring does not influence the actual movement. On real ships on the other hand, the magnitude of the forces are such that there is little risk of interfering with the ships freedom of movement but the logistic and physical problems of establishing a measuring system become the overriding considerations.

A system which could be simply deployed has previously been developed for application to container ships in a new harbour in El Salvador where excessive ship movements were causing some difficulty (Ref.3). The method consisted of using a taut wire attached to the ship and referenced to a fixed point on the shore. The three orthogonal components of movement were measured at three different points of attachment along the length of the ship. From these nine measurements, all six degrees of ship motion could be computed.

The results of this investigation suggested that improved accuracy was desirable, and so HR set out to develop a system which could meet this requirement.

2. PRINCIPLE OF OPERATION

There are many possible techniques. An important requirement was that the method should not require significant ship-board installation and that the entire system could be moved either from one ship to another in one location, or from one harbour to another, without undue difficulty. The use of optical, radar, accelerometer and gyro techniques were all considered but rejected on grounds of cost, inconvenience of installation, potential accuracy or some other reason. Eventually it was decided that a taut wire attachment method would be most practicable again, but adopting a completely different and much more accurate sensing system than that used in the previous application in El Salvador. There, it was thought that one of the major sources of error was possibly due to lack of precise orthogonality between the three measurement axes. When a large movement occurs in, say, the lateral axis, a very small angular error can produce a spurious vertical deflection. Another error source was the catenary effect in the wire.

The present design incorporates a frame which maintains the orthogonality irrespective of position. Initial testing in the laboratory suggests that the cross-talk errors are within the system resolution. The measurement definitions are shown in figure 1. The objective was to permit the identification of position of a point in space (the point of attachment of the wire to the ship) within a 10m cube at distances up to 30m from the measuring point.

In use, the active range of the wire extension is 10m, but the absolute operating distance can be increased by using an extra length of wire to the attachment point. This permits measurements on ships which rise and fall with the tide and to allow for possible movements away from the edge of the jetty.

Apart from the sensitivity of the measuring instrument itself, there are several sources of potential error.

(i) The wire will hang in a catenary, the precise shape of which depends on:

- (a) relative displacements of each end;
- (b) wire tension;
- (c) wind drag;
- (d) temperature coefficients of expansion etc.

(ii) Wire stretching.

iii) Bearing friction.

(iv) Arc effects from the wire guide at the machine.

Calculation and estimation showed that the major source of error was likely to be (i) above. Consequently considerable effort was expended in selection of the best wire to use and in calculating the necessary tension to render the errors insignificant. A wire of 1.2mm diameter was chosen. A tension of 220 N was sufficient to keep the wire straight and properly aligned.

The desired measurement resolution and the cost/complexity determined the selection of the transducers. Those considered included:

(i) Multi-turn pots

(ii) Synchro-resolvers and linvar

(iii) Digital contact

(iv) Optical encoders.

Absolute optical shaft encoders were selected for the lateral (11 bit) and vertical (13 bit) measurements, and a 16 turn 11 bit digital brush contact sensor for measuring the wire extension.

2.1 System arrangements

A block diagram of the system is shown in figure 2. Each measurement station incorporates the three transducers for the three axes of measurement. The transducer power supplies are derived from the central data logging unit and transmitted up the multicore cables to the instruments. The signals from the transducers are transmitted in parallel back to the interface unit for processing. There are no additional electronic circuits at the instruments other than the internal parts of the transducers.

This arrangement was considered to offer the simplest, most reliable configuration. Other options considered were:

(i) Individual power supplies at the instrument;

(ii) Individual data logging;

(iii) Multiplexed serial data transmission.

The extra cost of the cabling incurred by the parallel data transmission is offset by the extra complexity (and hence probably reduced reliability) of the alternatives. Central logging also permits easy data synchronisation.

3. MECHANICAL DESIGN

A sketch of the operating principle is shown in figure 3. The wire which attaches to the ship is shown at (1). It passes through a guide (2) which is carried on a light weight frame (3). The frame is pivoted on shafts at (4) retained by ball bearings. The guide frame is carried on a rigid rectangular frame (5) and the whole assembly is pivoted in the vertical axis on bearings (6). The wire passes over a pulley (7), down through the frame and over a tension detecting pneumatic valve (8). A drum (9) takes up the wire, which is held under constant tension by the "tensator" (rotating leaf-spring motor) (10). Brake shoes (11) operate on a drum and are held open by a spring return pneumatic piston (12). The piston is controlled from the valve (8) which is supplied with compressed air from a cylinder (13).

As the ship moves, the wire is taken up or paid out from the drum (9). If there is a loss of tension (due to breakage or loss of attachment at the ship) the valve (8), rapidly operates the brake to prevent any uncontrolled rewind of the wire. The frame (3) is moved up and down by a vertical ship movement, and frame (5) is moved from side to side by a lateral movement. Transducers attached to the relevant shafts measure these movements. The horizontal displacement of the wire is measured by a multi-turn shaft encoder driven by the shaft of the take-up drum. The whole machine has been designed and constructed to a high accuracy, so that when levelled on site the cross-talk effects between the three axes are minimised.

The construction is shown in plate 1. The vertical beam sections at the front support the column from which the pivoted frame structure is suspended. The rear beam, together with the front, is used to support the protective cover (not shown). The vertical and lateral shaft encoders can be seen at the front.

Plate 2 shows a rear view. The single central drum is the wire take-up, and the two outer drums on the central shaft collect the "tensator" motor springs as they unwind from the four corner positions. As the wire is pulled out, the drum rotates and takes up the spring motors, thus producing the continuous tension by applying a restoring torque to the drum shaft. The horizontal displacement transducer is on the left side of the drum shaft, and the brake on the right side. The cable connecters are at the left bottom and the air cylinder with its regulator on the right of the picture.

A plate on the top of the machine has been designed to take a two axis spirit level for initial levelling by the three point base screws, or marker indicators for installation alignment of the three machines using a line or a telescope.

The small air cylinders can be easily removed for recharge from a master cylinder. A frame has been constructed for attachment of the wire free end to the ship. It is clamped to a suitable place on the superstructure and a small hand winch is used to take up the unused extension wire.

4. CIRCUIT DESIGN AND DATA LOGGING

A block diagram of the electronic arrangement is shown in figure 4. The signals from the transducers are in Gray code and are transmitted in parallel down the field cables to the interface and logger cabinet. Plate 3 shows the cabinet with the lid open, and Plate 4 the electronics of the interface chassis. The three transducers from each station require a total of 35 signal lines (13 bit + 11 bit + 11 bit), so there are 105 channels of line receiving buffers. The Gray code is then converted into binary for convenience in the data logging using a conventional gate interconnection. Output latches which are strobed on command from the logger hold the data stable during the logging process. A reel to reel logger was chosen because of its high storage capacity, which makes possible the sampling of all channels at 1 per second for up to 8 hours. The data logger also has a facility for analogue inputs since it is ultimately intended to include the capability of storing mooring line tension values simultaneously.

A switching system selects the most significant 8 bits of one of the three transducers from each station. These signals are then applied to a digital to analogue converter, and, via a zero and span setting analogue interface, are displayed on an analogue panel meter. The meters are not graduated, since they are used solely as an operater convenience to confirm functionality and indicate trends. Hence the meter showing the bow signal for example, can be switched to show the movements of the vertical, lateral or horizontal components. Monitor points for checking the power supplies and analogue outputs are provided on the front panel.

The data tapes are returned to the laboratory for translation and analysis.

The development proved to be difficult and time consuming due to the large number of data lines to process. An unforeseen complication was that the input buffers on the data logger were only powered up during the data sampling periods, so if the electronics was tested when the logger was not running, the outputs of the latches were driving into unpowered CMOS gates - an unacceptable situation. Suitable switching had to be incorporated to overcome this. During the logging operation, the +5V line to the decoding boards is supplied from the data logger so that now power-up is applied simultaneously.

5. CALIBRATION

In order to establish the accuracy and resolution of the system, it was necessary to provide a controlled and known movement of the free end of the wire. The most critical lateral and vertical movements occur when the horizontal extension is longest, resulting in the smallest angular deflections at the machine.

The angular resolution at the machine produced by linear movements determines the linear resolution at the ship. Hence the linear resolution varies, depending on the position of the attachment to the ship relative to the horizontal axis at the machine normal to the jetty. The purpose of the calibration experiment was to show that the angular resolution at the machine was what could be predicted from a knowledge of the transducer resolution. For convenience, the measurements were done near to the horizontal normal axis.

A rectangular frame was constructed carrying two scales at right angles, and a moveable slider to which the wire could be attached. The frame could be clamped to the front of a Land Rover so that the wire could be extended in the horizontal axis by driving the vehicle in reverse. The scales were used to measure the vertical and lateral displacements of the wire at a known distance from the machine. The geometry is shown in Figure 5. If d is very small relatively to x, then x changes are insignificant as d changes, and ϕ is easily determined. The same arrangement was used in the horizontal plane. The machine is held firm on the ground by applying concrete weights to the lid.

The point d was incremented in 2cm steps with x at approximately 20m, and the point at which the logged data digits changed was recorded. The results of the vertical calibration for each of the three machines is shown in Figure 6. As would be expected there are a few places where d changes by 2cm and the output changes by two digits. Also plotted is the result of an output digit changing at precisely 2 cm intervals for comparison.

The average slope of the calibration was measured (the three machines are virtually identical), and the calculated resolution compared with the theoretically predicted resolution. Agreement was very close, confirming the 2.63 minutes of arc expected.

A similar procedure was carried out on the lateral transducer, producing Figure 7. The figures for the stern machine gave the measured resolution to be 10.15 minutes of arc, and the calculated resolution to be 10.55 minutes of arc.

The horizontal axis was calibrated by moving the vehicle backwards in steps and measuring the wire length for each recorded digital output (figure 8). The results show a slope calibration of about 0.5 cm/digit. The theoretical resolution is for the 11 bit transducer is 0.49 cm.

6. FIELD TEST

During June 1984 arrangements were made with the Port Authorities at Dover to install the equipment on a moored cargo vessel. The ship selected was the "Vendee" a container ship of overall length 142m, and estimated displacement of 14,936 tonne. The distances of the bow and beam to the centre of gravity were obtained from field measurements and data from the instruments, and used in the computation of movements from the measured readings. Plates 5 and 6 show a general view of the installation site.

The taut wires were clamped to convenient positions on the superstructure, as shown in plates 7 and 8. Considerable practical difficulty was experienced during the installation procedure since the "time window" available for the work was very small. The ship docked at about 1700 hrs on 25 June and unloading began almost immediately, involving the movement of heavy trucks up and down the quayside. The equipment was installed by about 1700 hrs on 27 June and had to be removed again by about 1930 hrs on the same day so that loading could be started again.

During the deployment the sea state was calm, so the movements to be measured were quite small. This was, however, quite useful since it permitted confirmation of the expected system resolution.

The three machines were lined up by measurement from the edge of the quay, and levelled in with a spirit level. The initial length of wire between the clamping point and the instrument pivot reference was measured.

The data was logged for a period of about 40 minutes using a sampling rate of 2 data values per sensor per second. The data tape was subsequently returned to HR for analysis. Plates 9 and 10 show the bow and midships machines, and plate 11 is the data logger.

7. RESULTS

Figure 9 shows a sample plot of the computed components derived from the nine sets of data values (one linear, two angular movements from each of three machines). The movements are on relative scales.

The differing frequency components are immediately obvious. For example, the pitch records show distinctly higher frequency components than the yaw. Note, however, that the scales are different, so that a visual comparison does not give a true impression of the relationship between the two components. The heave records show very small vertical movements (in the order of 10mm) and help to confirm the predicted resolution of the system (although in this case the movements measured were less than 10m from the machines). The heave also shows the steady increase in level produced by the rising tidal level. It is difficult to detect any correlation between the records by superficial observation.

Figure 10 is another section of the record. (Note that the scales are now much more coarse). During the experiment the ship gave a sudden lurch, possibly the result of friction against the quayside as the tide was rising, although this was considered unlikely due to the fendering used. It shows that the ship moved suddenly in surge and heave; the apparently very large deviation was caused by the measurement wire on the bow recorder going slack for a short time. It was a useful indication of the system's ability to respond to large, rapid changes.

Table 1 is a sample print of the spectral analysis of each component. This is the energy density spectrum, not simply the frequency spectrum. It suggests that the narrow band energy was highest for surge, but that the spectrum of heave was much broader when comparing the linear movements. This supports the perceived impression from Figure 9.

The roll is clearly the most significant part of the angular components, again confirmed by inspection of Figure 9.

8. CONCLUSIONS

A system has been designed and constructed for measuring the six degrees of motion of a ship moored alongside a quay. The performance of each of the three machines which together make up the complete taut-wire measuring system has been evaluated in a laboratory simulation of ship movement. This has demonstrated that relative movements of the wire at its attachment to the ship some 30m from the quayside machine can be resolved to approximately ±1 cm, ±1 cm, and ±10 cm in terms of wire length, inclination and azimuth respectively. A field trial at a working port, albeit under conditions of meagre ship movement, has been carried out and suggests that the resolutions obtained by the laboratory simulation should be achievable in practice.

Software developed under a separate research contract for extracting the degrees of motion from the recorded angular and scope variations at the three machines has been fully tested with the data from the short field trial.

The equipment is of necessity heavy and the laying of cable along a busy quayside clearly present some difficulties on installation. Nevertheless it is considered that a three-man team can typically install the land-based items and their interconnecting cables in three to four hours. The fixing of the three wires to the ship under study can occupy a further two hours. Thereafter recording can be initiated as required with one man remaining in attendance for the duration of the measurements.

It is intended to undertake a second field trial within the scope of another research contract funded by the Department of the Environment. The future trial will hopefully sample greater ship movements than encounterd previously as well as providing an opportunity to test a number of minor modifications to facilitate the handling of the equipment. The system together with its operating staff and the backing computation service will be available on lease to interested port authorities for short-term deployments.

9. ACKNOWLEDGEMENTS

The development has been continuing over a long period, but the substantial part has been supervised by Mr M J Crickmore in the Services Department at Hydraulics Research Ltd. Initial specifications and proposals were by Mr D K Fryer and the basic mechanical design concept was by Mr J Molyneux, with manufacturing design by Mr R Aked. The field deployment was carried out by Mr R Aked, Mr I Knight and Mr J Spencer. The software for computing the ship movements from the three sets of orthogonal transducer data, the graphical movement plots, and the spectral analysis was designed by Mr J Spencer. I am grateful to these and other colleagues who have contributed to the development.

10. REFERENCES

1. "Measurement of movement of ships and structures in models". Equipment Note No.3. H.R. Ltd.

2. E C BOWERS. Model simulation of ship movements. Dock and Harbour Authority, 58, 681, 1977

3. A J STAMMERS and C J WENNICK. Investigation of vessel mooring subject to wave action. Dock and Harbour Authority, 57, 677, 1977.

Figures

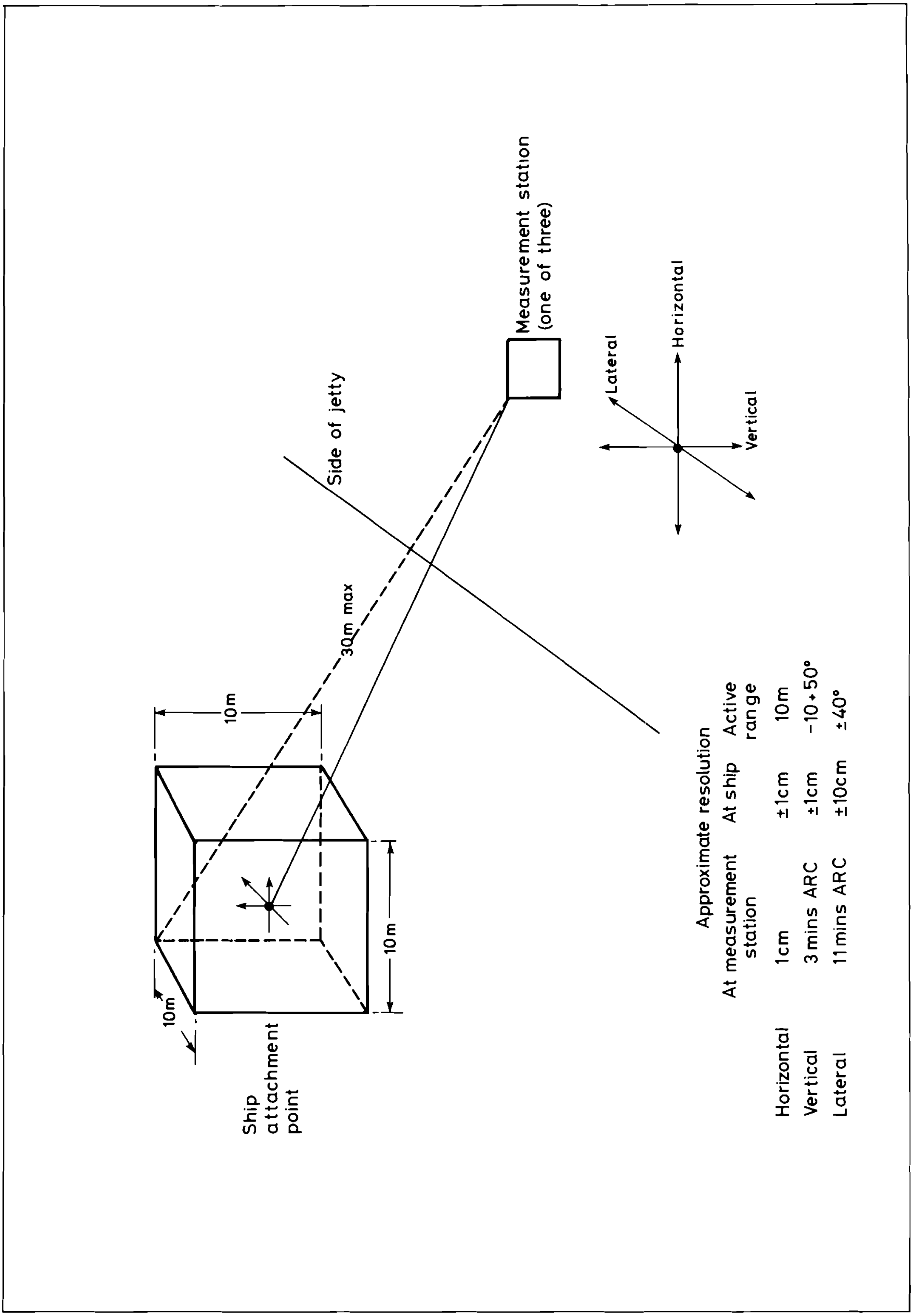

Fig 1 Measurement definitions

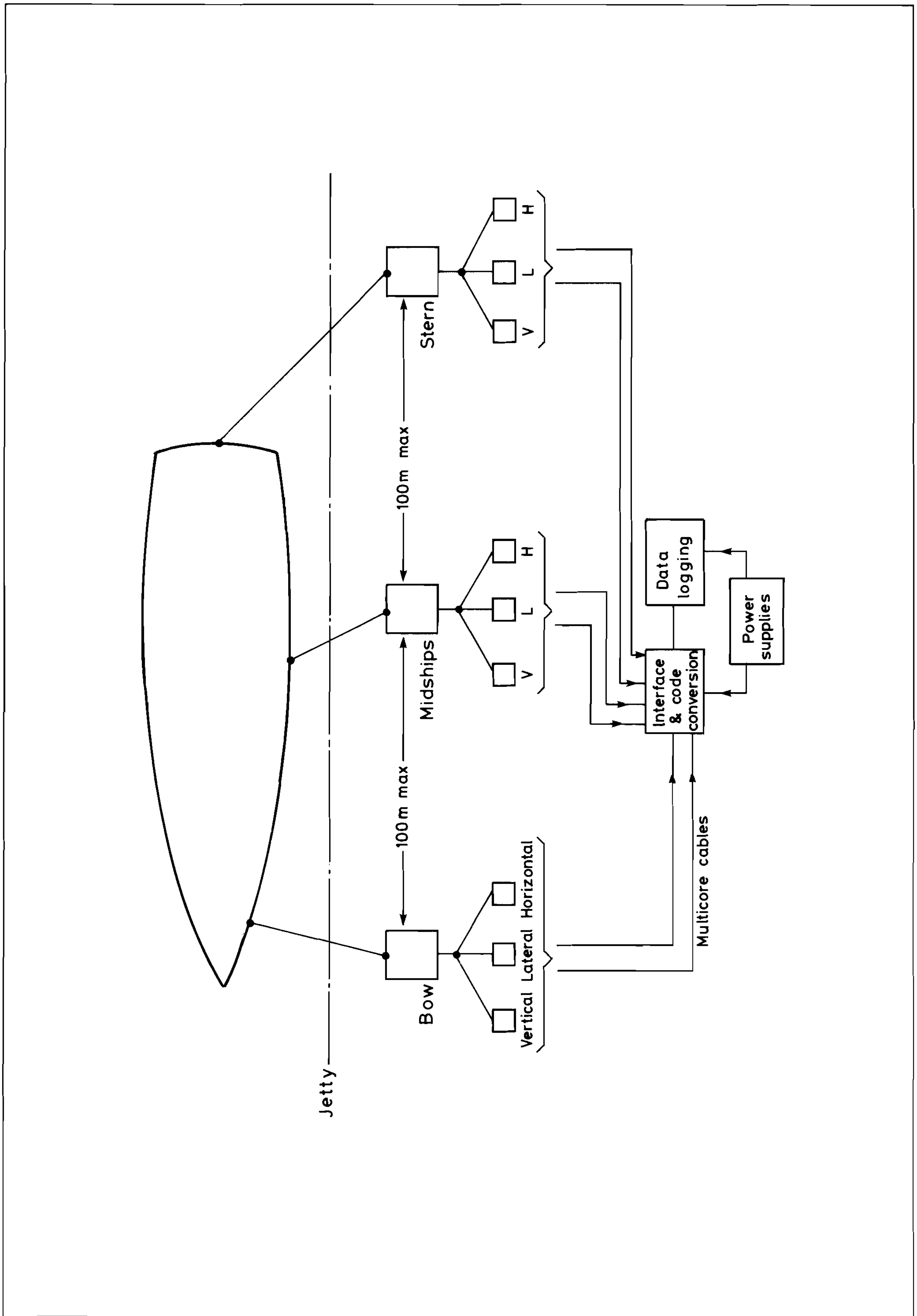

Fig 2 System arrangement

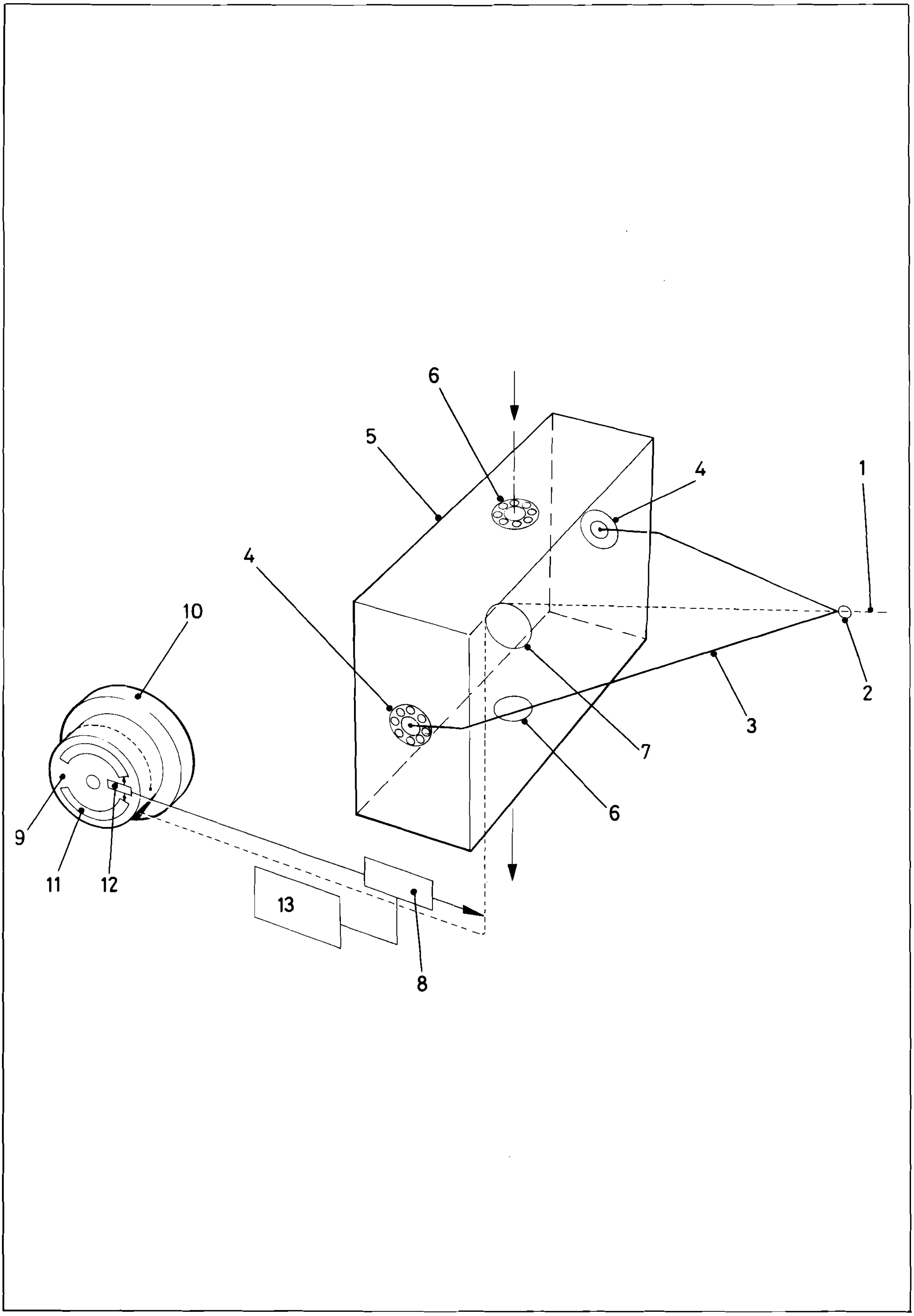

Fig 3   Operating principle

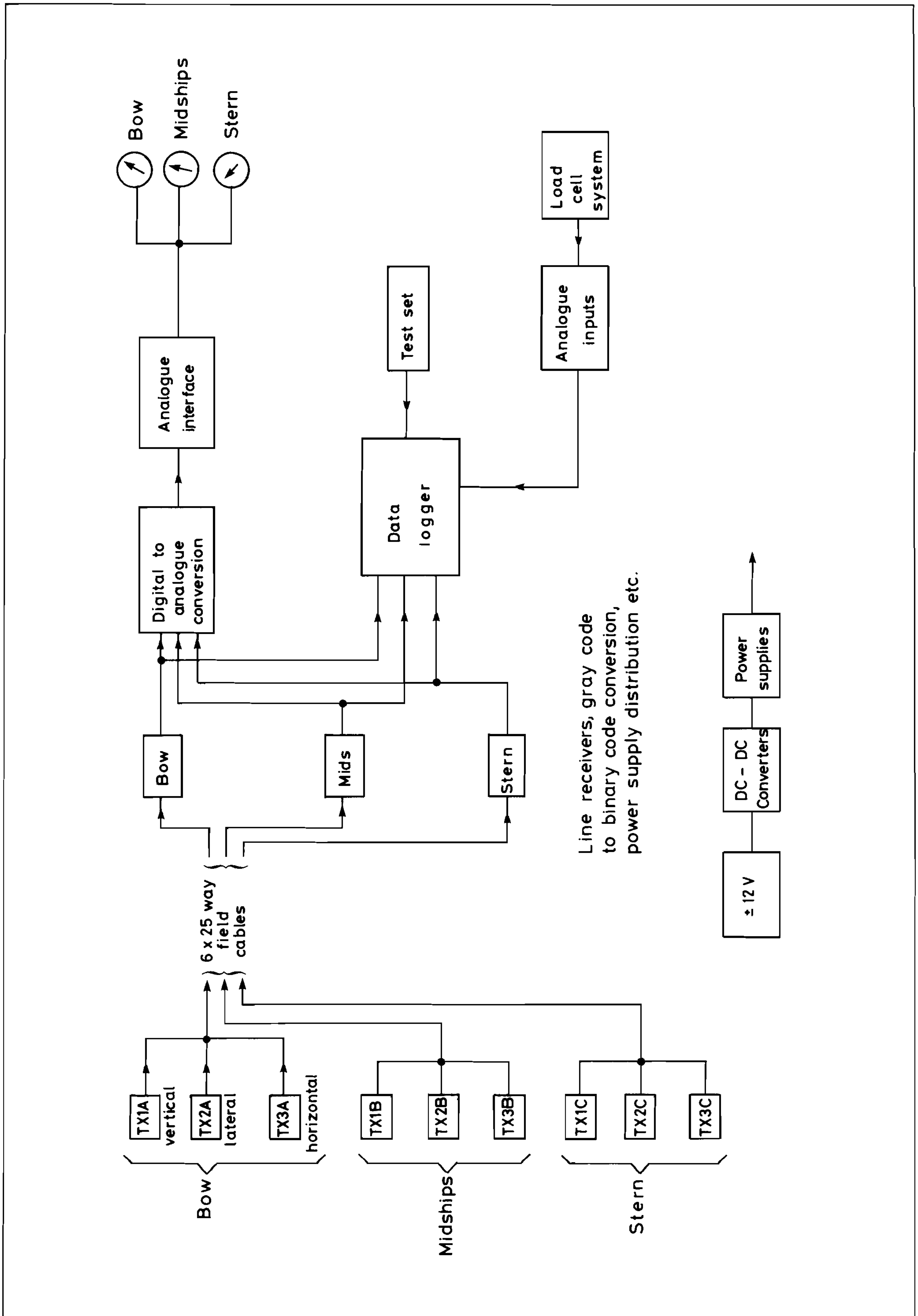

Fig 4 Electronic block diagram

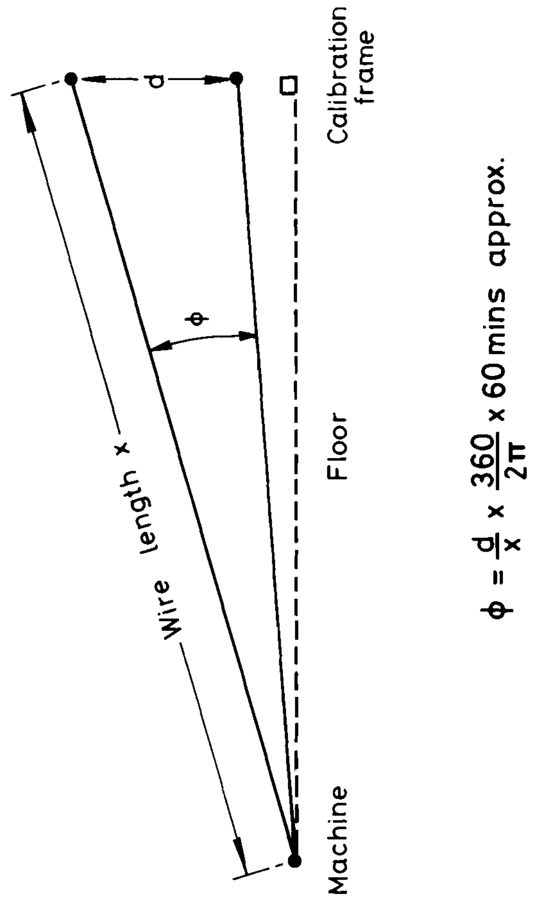

Fig 5 Calibration geometry

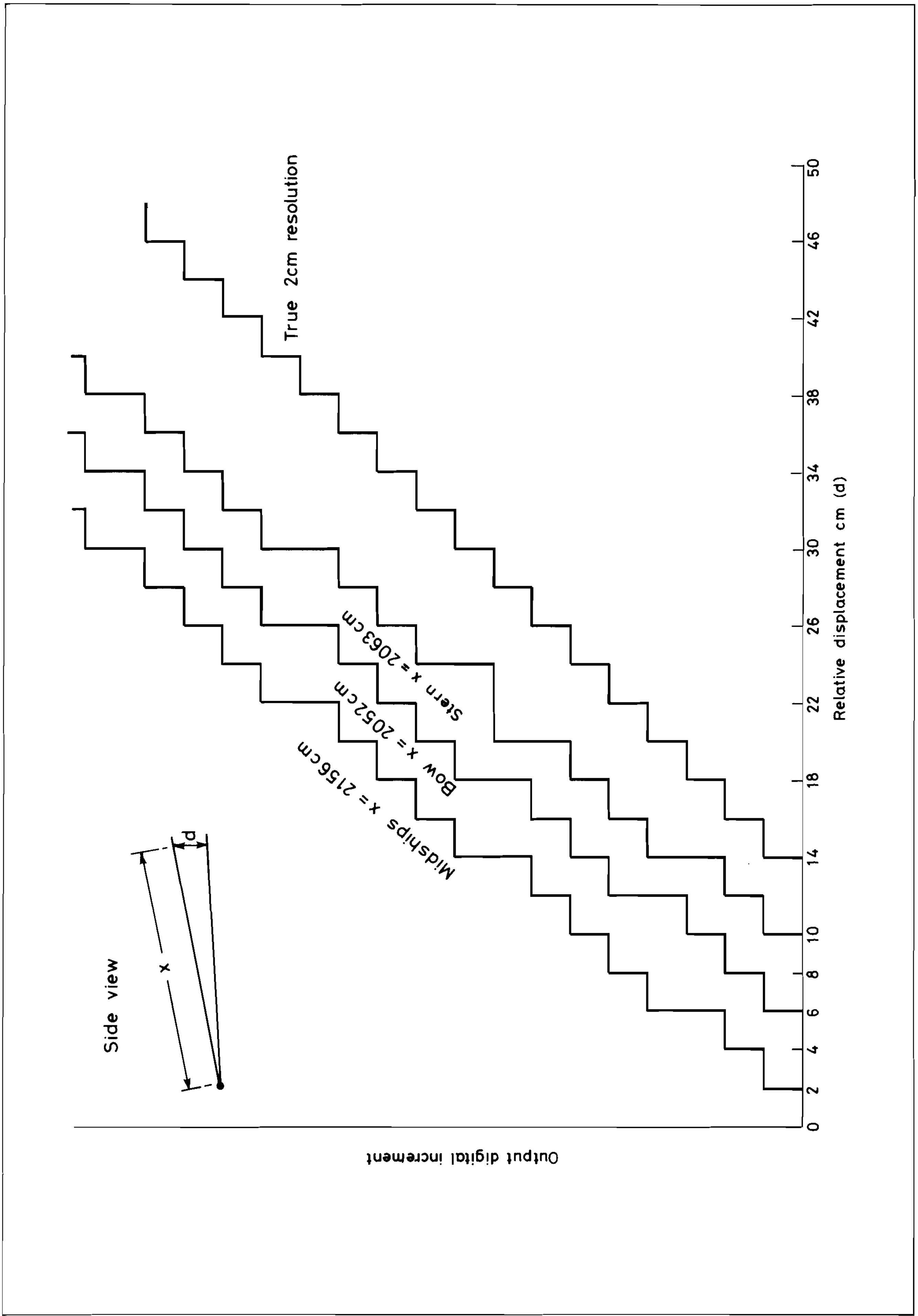

Fig 6 Vertical calibration

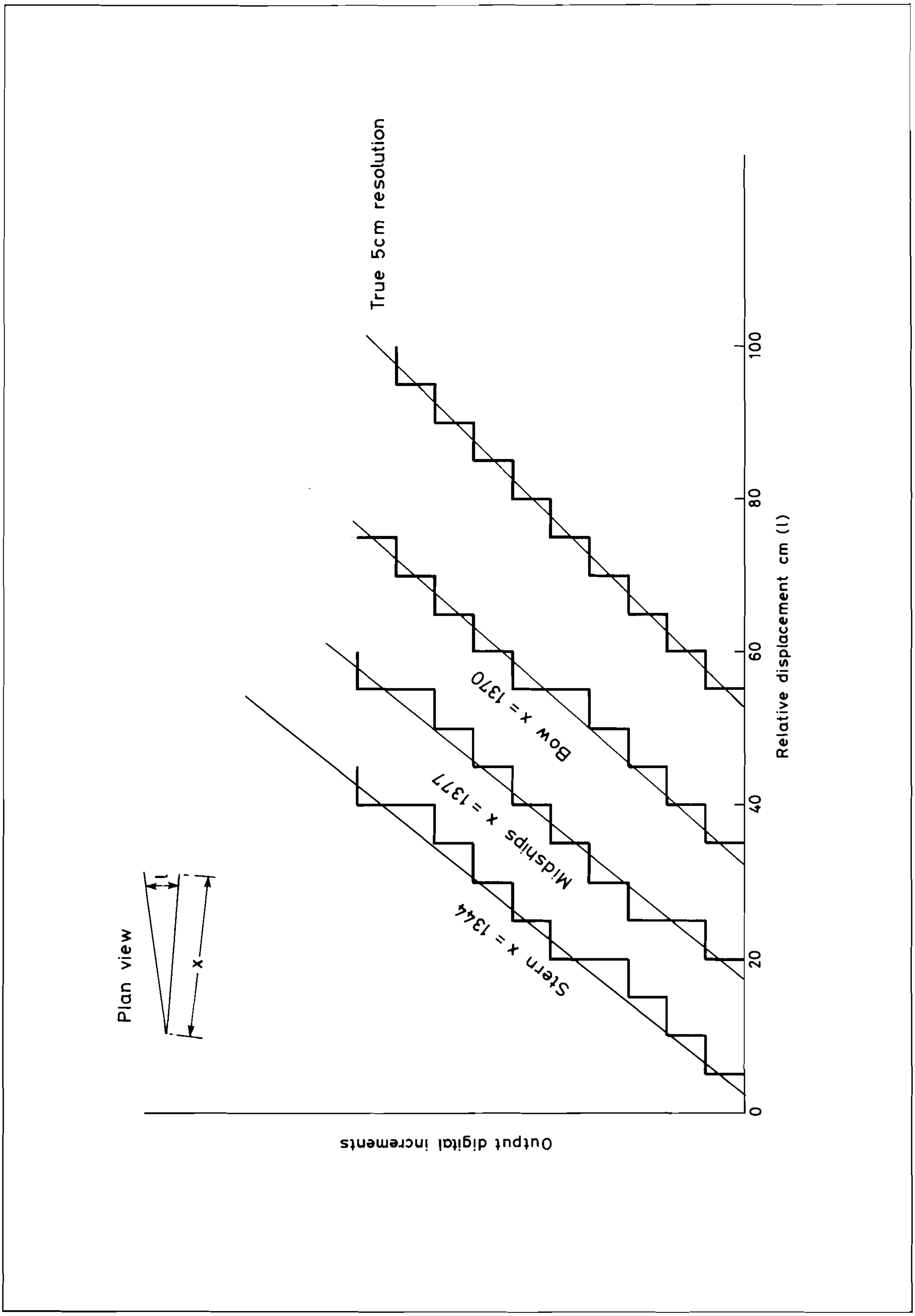

Fig 7 Lateral calibration

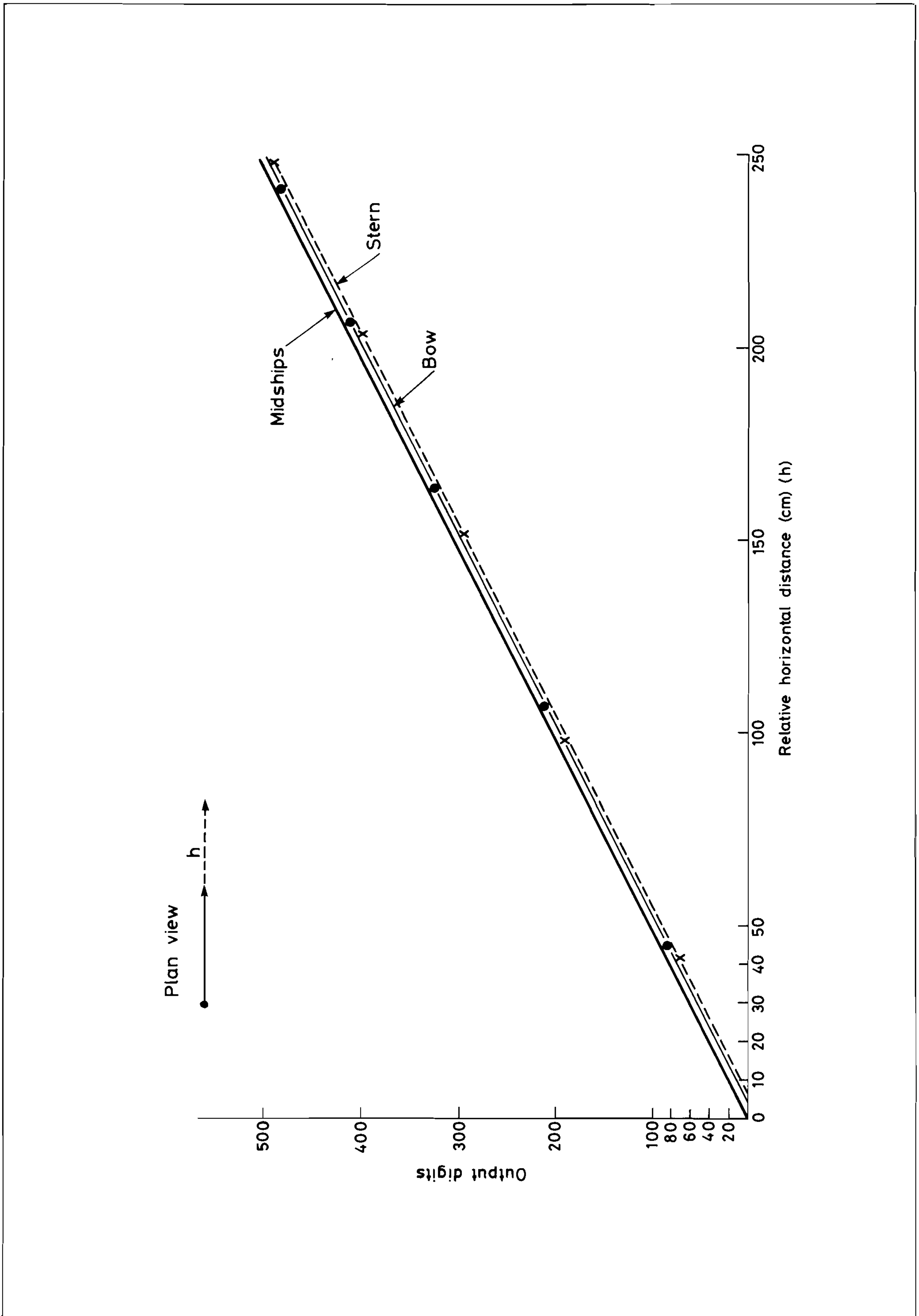

Fig 8 Horizontal calibration

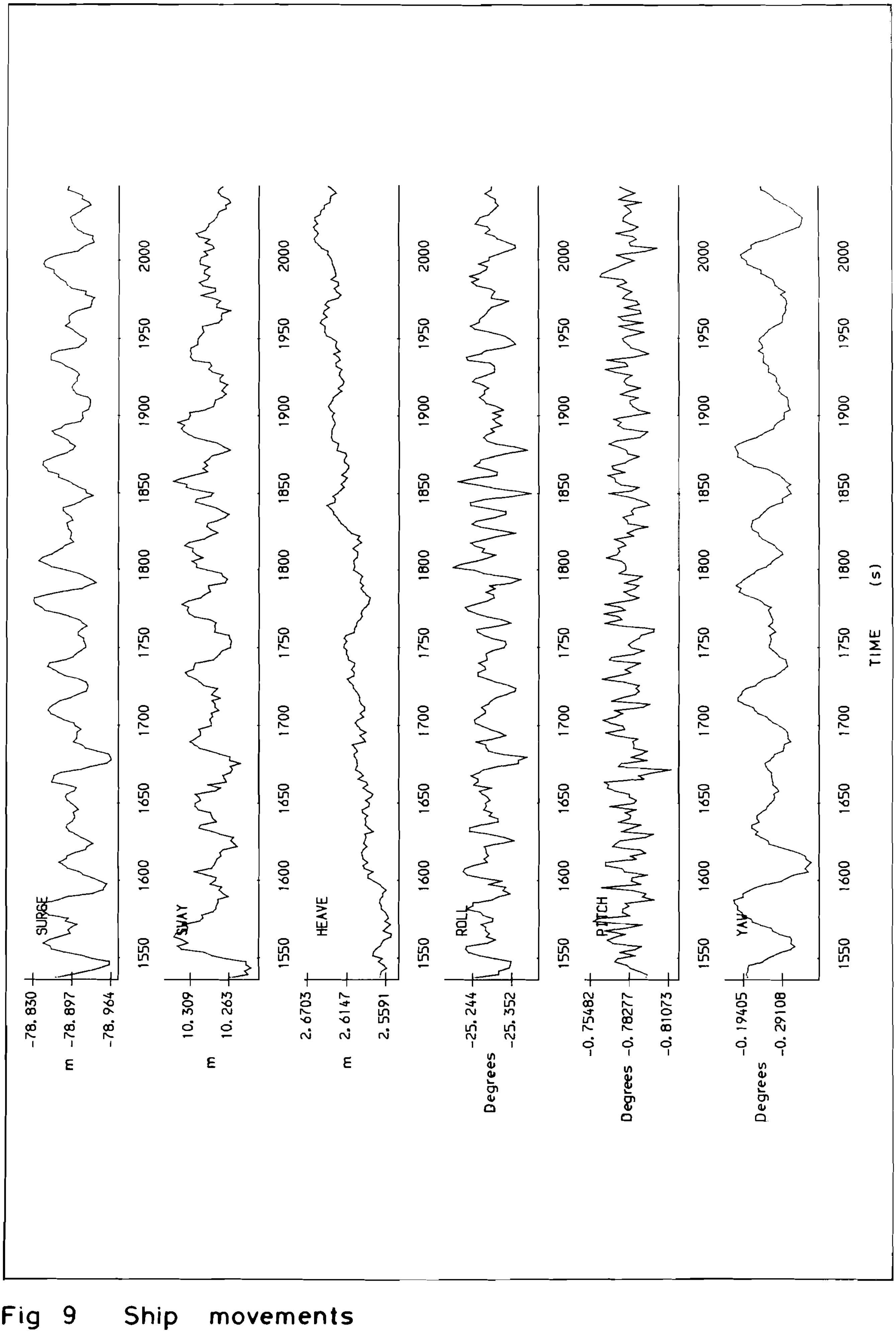

Fig 9 Ship movements

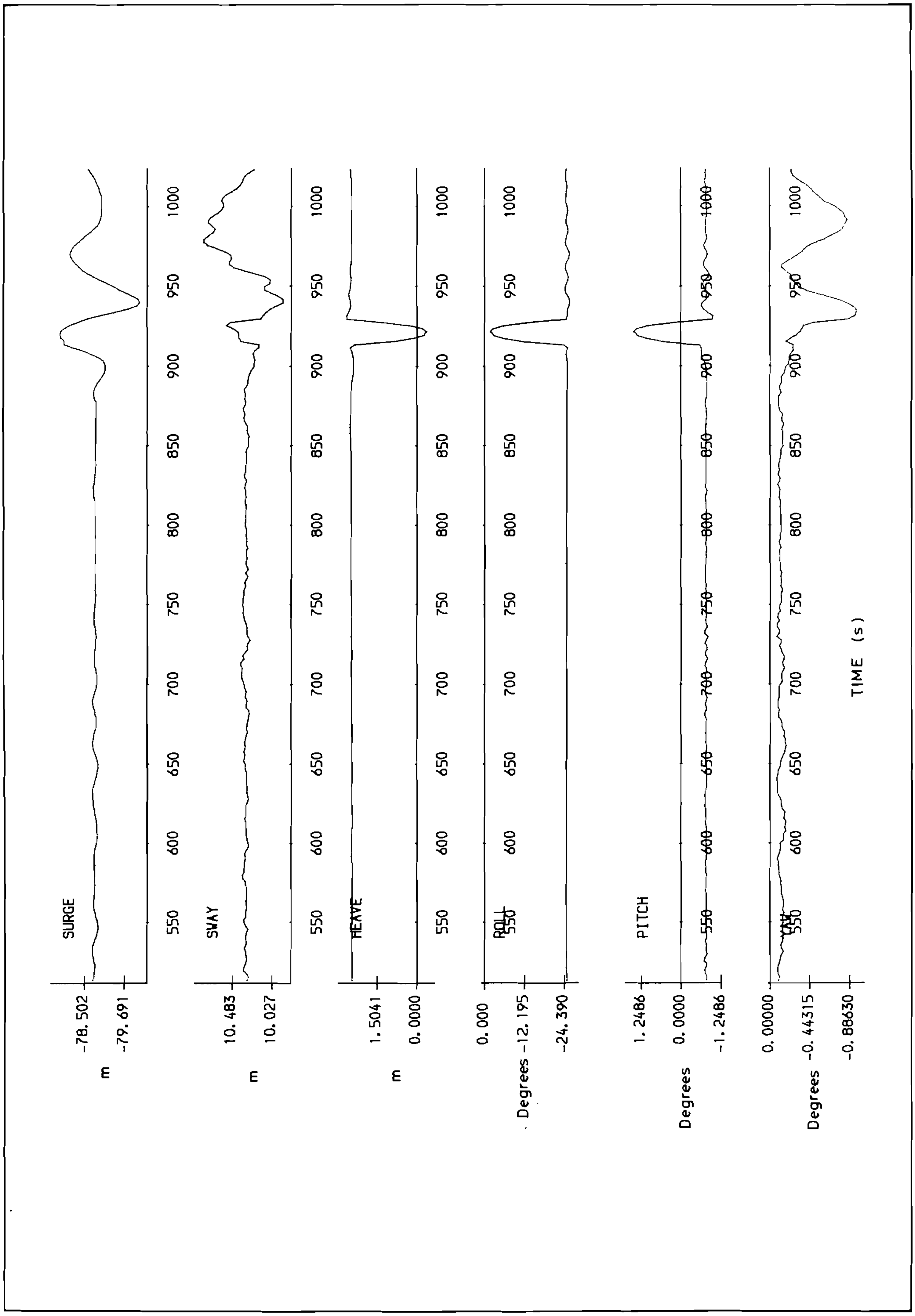

Fig 10 Ship movements

Table

TABLE 1 Printer listing of ship movement

SPECTRA

	FREQ HZ	SURGE MSQ/HZ	SWAY MSQ/HZ	HEAVE MSQ/HZ	ROLL DEGSQ/HZ	PITCH DEGSQ/HZ	YAW DEGSQ/HZ
1	0.00293	0.13729E+00	0.12463E+00	0.63033E+00	0.39526E+02	0.41185E+00	0.17159E+01
2	0.00684	0.50483E-01	0.26003E+00	0.96804E+00	0.67306E+02	0.67600E+00	0.61876E+00
3	0.01074	0.37058E+00	0.29623E+00	0.94003E+00	0.64087E+02	0.60929E+00	0.25594E+00
4	0.01465	0.14533E+01	0.22940E+00	0.84156E+00	0.60820E+02	0.56298E+00	0.59752E+00
5	0.01855	0.22162E+01	0.11201E+00	0.82601E+00	0.59662E+02	0.58077E+00	0.33648E+00
6	0.02246	0.13266E+01	0.94500E-01	0.72850E+00	0.52868E+02	0.45706E+00	0.22416E+00
7	0.02637	0.61198E+00	0.25373E-01	0.63059E+00	0.50906E+02	0.40365E+00	0.54660E-01
8	0.03027	0.32724E+00	0.90819E-02	0.57123E+00	0.44722E+02	0.33163E+00	0.23909E-01
9	0.03418	0.15341E+00	0.17366E-01	0.57675E+00	0.39114E+02	0.29312E+00	0.19999E-01
10	0.03809	0.57892E-01	0.10254E-01	0.48169E+00	0.32147E+02	0.25622E+00	0.17308E-01
11	0.04199	0.25753E-01	0.32273E-02	0.40781E+00	0.24341E+02	0.22552E+00	0.76231E-02
12	0.04590	0.29086E-01	0.45022E-02	0.34057E+00	0.20310E+02	0.20534E+00	0.42100E-02
13	0.04980	0.90621E-02	0.56962E-02	0.25356E+00	0.16656E+02	0.15720E+00	0.34552E-02
14	0.05371	0.10453E-01	0.52178E-02	0.20999E+00	0.12198E+02	0.12120E+00	0.22546E-02
15	0.05762	0.73747E-02	0.53286E-02	0.16252E+00	0.80370E+01	0.10361E+00	0.11480E-02
16	0.06152	0.65742E-02	0.41615E-02	0.11026E+00	0.46282E+01	0.90816E-01	0.91666E-03
17	0.06543	0.55163E-02	0.54458E-02	0.79750E-01	0.32947E+01	0.66715E-01	0.47547E-03
18	0.06934	0.27242E-02	0.13751E-01	0.44783E-01	0.36322E+01	0.54089E-01	0.10599E-02
19	0.07324	0.18437E-02	0.81900E-02	0.17090E-01	0.25784E+01	0.34877E-01	0.17839E-02
20	0.07715	0.13119E-02	0.36597E-02	0.85985E-02	0.74933E+00	0.15268E-01	0.13908E-02
21	0.08105	0.10194E-02	0.73298E-03	0.11704E-02	0.10707E+00	0.81342E-02	0.16795E-02
22	0.08496	0.48478E-03	0.79752E-03	0.23491E-03	0.25343E-01	0.39298E-02	0.15178E-02
23	0.08887	0.83050E-03	0.16899E-02	0.17360E-02	0.15228E+00	0.37970E-02	0.11270E-02
24	0.09277	0.69481E-03	0.17413E-02	0.46708E-02	0.35973E+00	0.48719E-02	0.11210E-02
25	0.09668	0.35593E-03	0.24913E-02	0.92250E-02	0.63693E+00	0.79615E-02	0.12957E-02
26	0.10059	0.95376E-03	0.23217E-02	0.13381E-01	0.90330E+00	0.12475E-01	0.15690E-02
27	0.10449	0.31353E-03	0.11836E-02	0.13625E-01	0.10300E+01	0.12634E-01	0.13159E-02
28	0.10840	0.42787E-03	0.16227E-02	0.16194E-01	0.11892E+01	0.11957E-01	0.91790E-03
29	0.11230	0.38646E-03	0.14898E-02	0.15647E-01	0.11900E+01	0.10917E-01	0.92733E-03
30	0.11621	0.29828E-03	0.10293E-02	0.14973E-01	0.11110E+01	0.85324E-02	0.59222E-03
31	0.12012	0.30022E-03	0.11337E-02	0.16606E-01	0.11187E+01	0.12383E-01	0.39571E-03
32	0.12402	0.27451E-03	0.61665E-03	0.12693E-01	0.88259E+00	0.11400E-01	0.75767E-03
33	0.12793	0.29558E-03	0.66522E-03	0.10202E-01	0.72410E+00	0.49656E-02	0.42804E-03
34	0.13184	0.23866E-03	0.38795E-03	0.74263E-02	0.53416E+00	0.76477E-02	0.43448E-03
35	0.13574	0.39133E-03	0.58098E-03	0.57566E-02	0.37973E+00	0.58405E-02	0.16756E-03
36	0.13965	0.17376E-03	0.36895E-03	0.34329E-02	0.22701E+00	0.49738E-02	0.41206E-03
37	0.14355	0.35270E-03	0.80045E-03	0.10863E-02	0.84808E-01	0.23977E-02	0.11929E-02
38	0.14746	0.25997E-03	0.18340E-03	0.38110E-03	0.35564E-01	0.80807E-03	0.11027E-02
39	0.15137	0.16421E-03	0.50857E-03	0.21896E-03	0.92358E-02	0.72826E-03	0.35543E-03
40	0.15527	0.20341E-03	0.31662E-03	0.25315E-03	0.92810E-02	0.97900E-03	0.10288E-03
41	0.15918	0.29540E-03	0.24256E-03	0.41265E-03	0.33579E-01	0.23629E-02	0.53826E-03
42	0.16309	0.23582E-03	0.52713E-03	0.17337E-02	0.95428E-01	0.19554E-02	0.17613E-03
43	0.16699	0.18767E-03	0.46514E-03	0.17846E-02	0.12944E+00	0.19111E-02	0.87508E-03
44	0.17090	0.20606E-03	0.32995E-03	0.24835E-02	0.19674E+00	0.16900E-02	0.17112E-03
45	0.17480	0.27782E-03	0.46572E-03	0.31347E-02	0.23039E+00	0.25895E-02	0.55730E-03
46	0.17871	0.95983E-04	0.46359E-03	0.35308E-02	0.24006E+00	0.40566E-02	0.46952E-03
47	0.18262	0.15785E-03	0.36752E-03	0.33634E-02	0.27901E+00	0.20537E-02	0.55673E-03

Plates

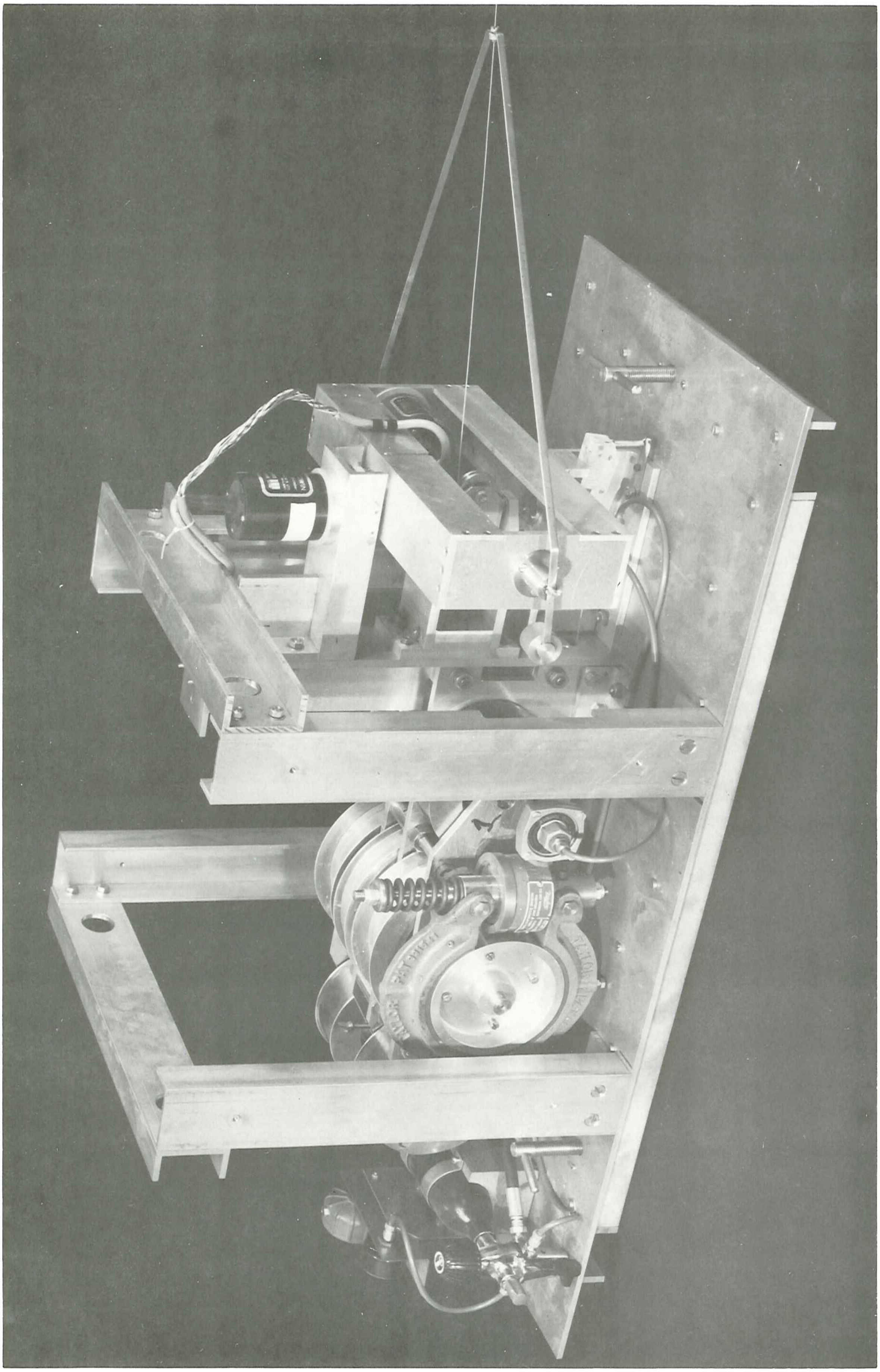

PLATE 1 Construction of measuring system

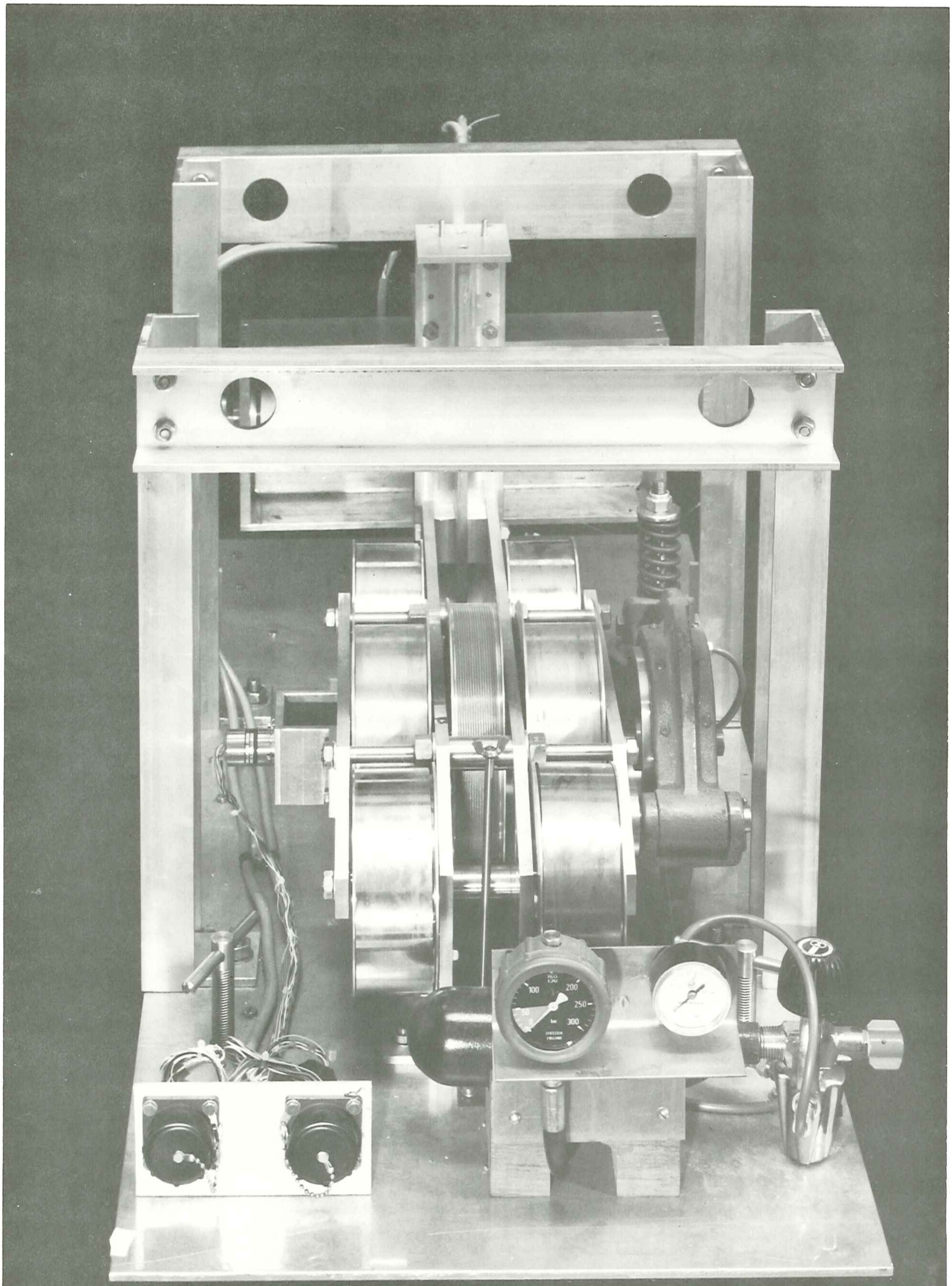

PLATE 2 **Rear view of tensator mechanism**

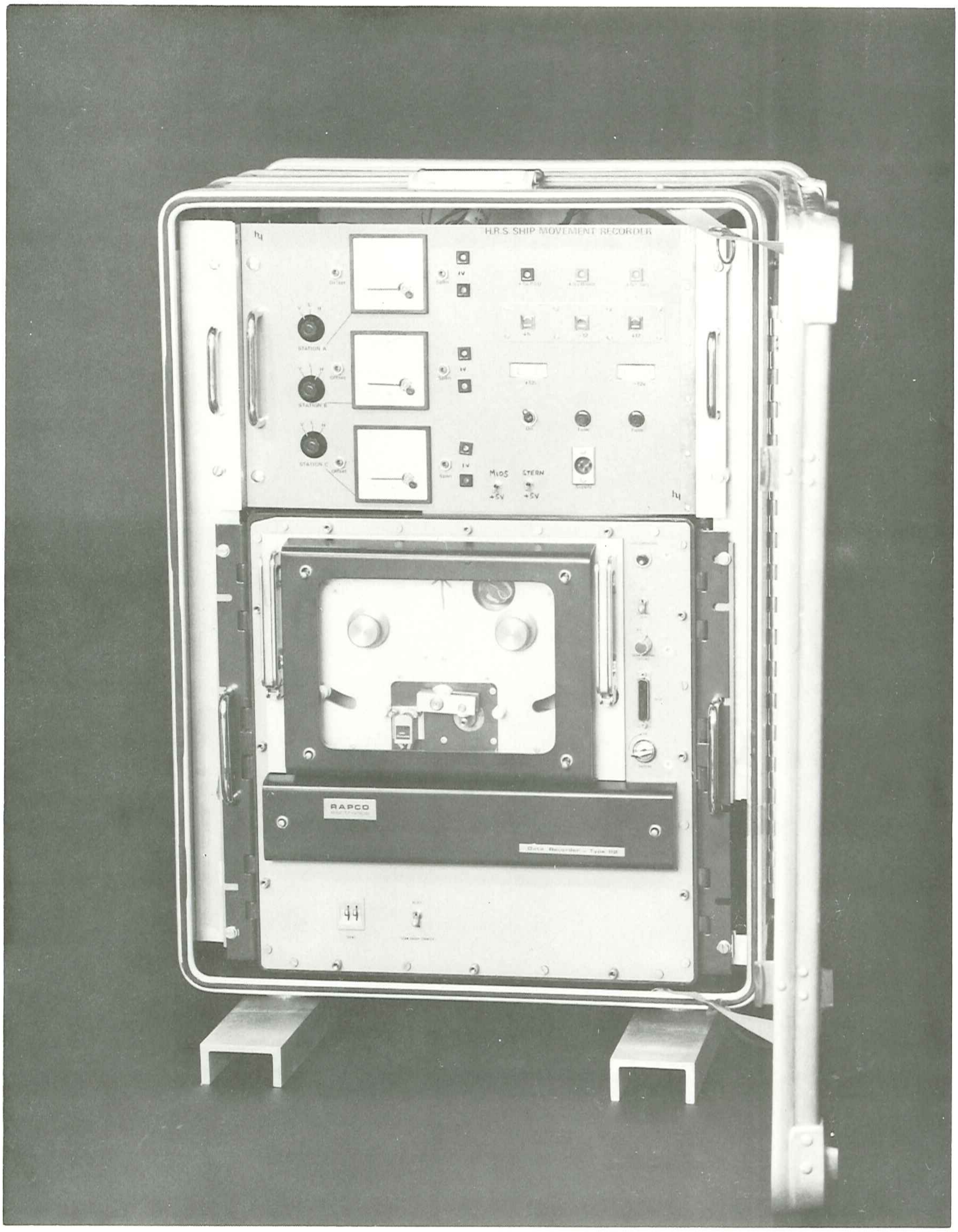

PLATE 3 **Logging cabinet**

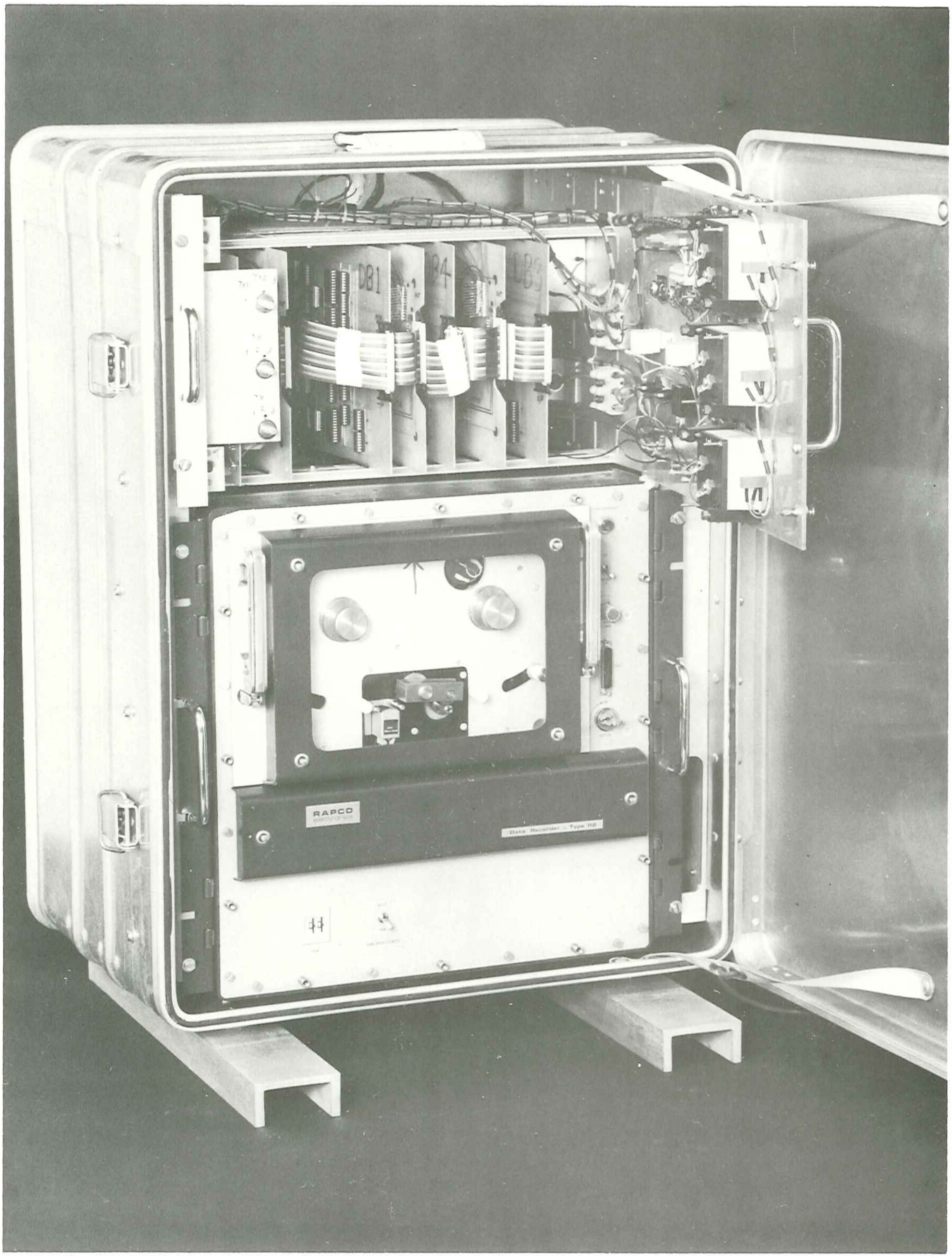

PLATE 4 Logging cabinet showing electronics of the interface chassis

PLATE 5 **Vessel used in trial**

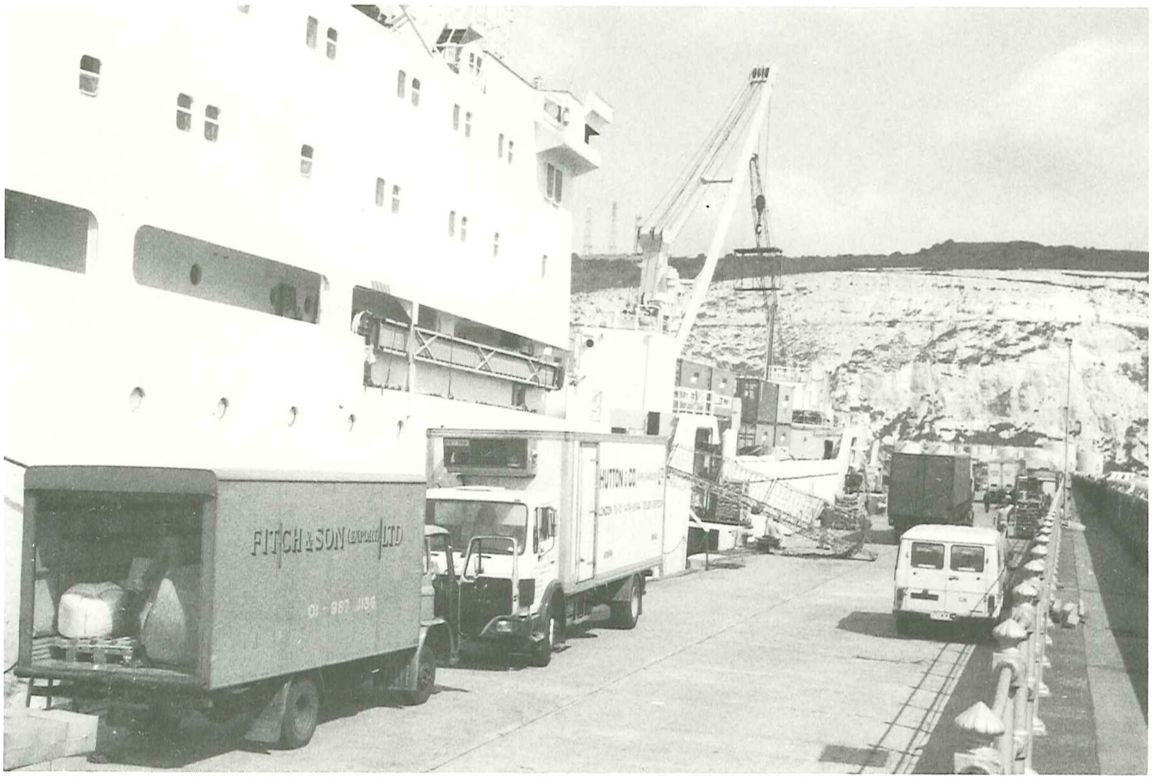

PLATE 6 Field trial site

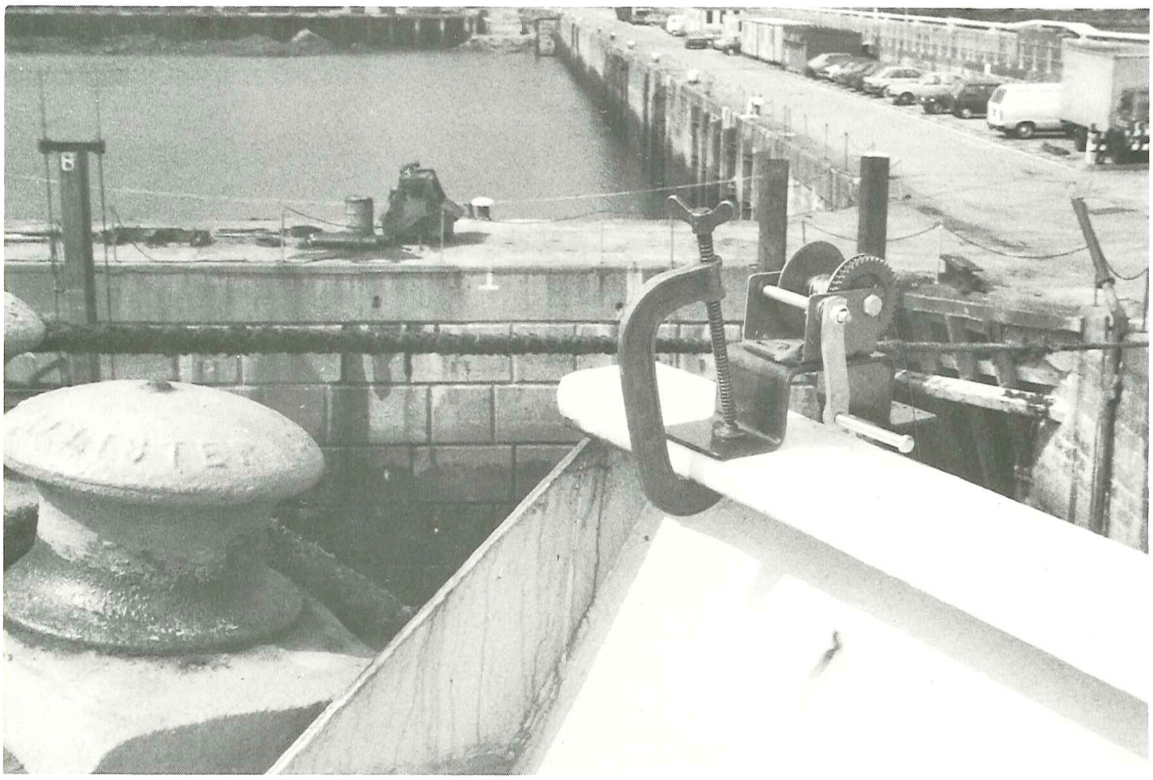

PLATE 7 Taut-wire attached to vessel

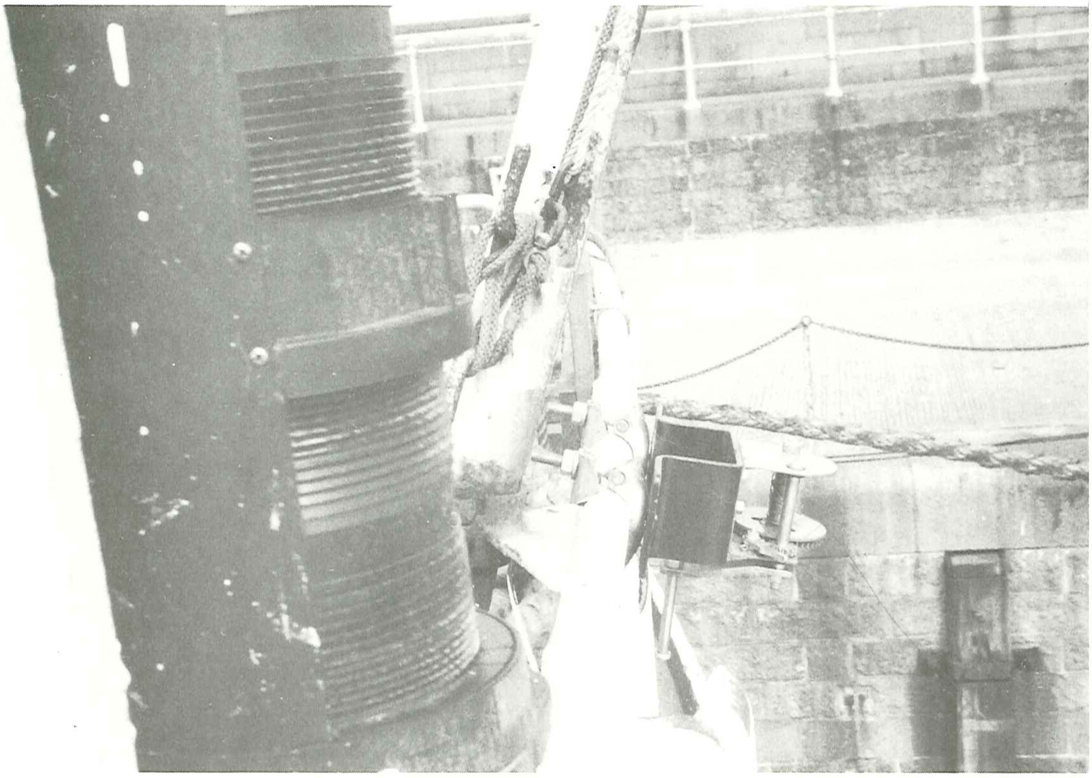

PLATE 8 Taut-wire attached to vessel

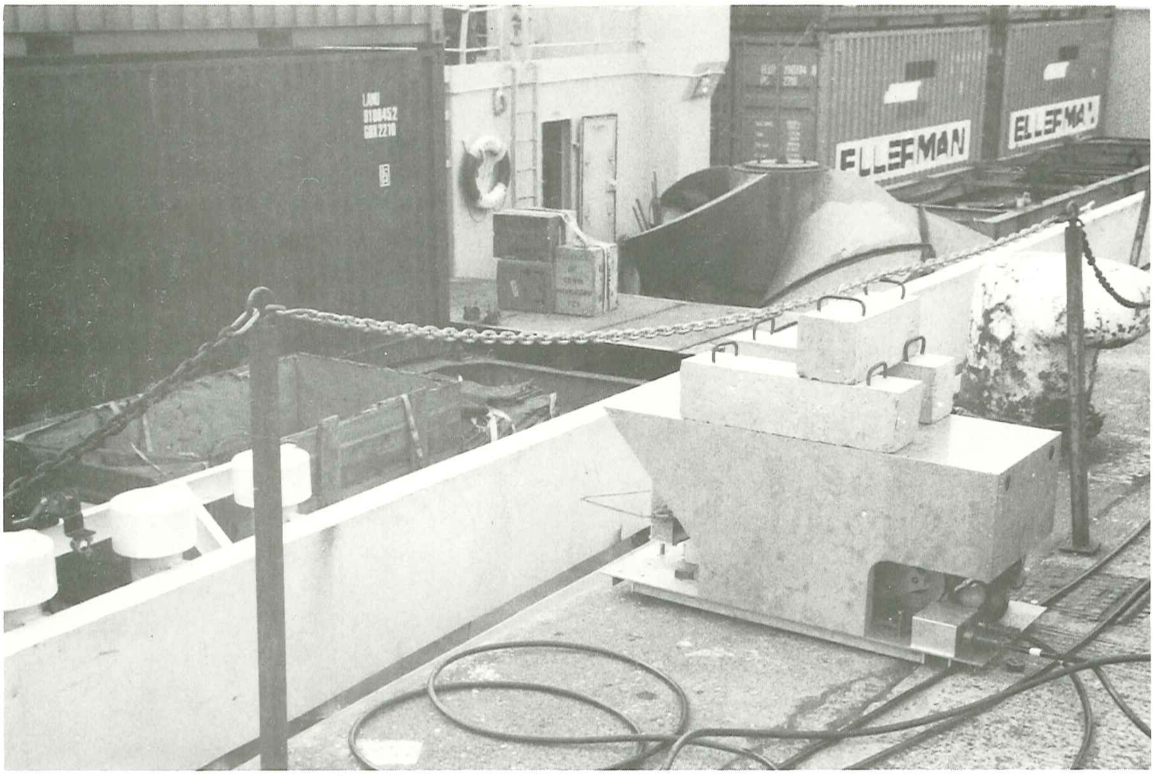

PLATE 9 Machine connected amidships

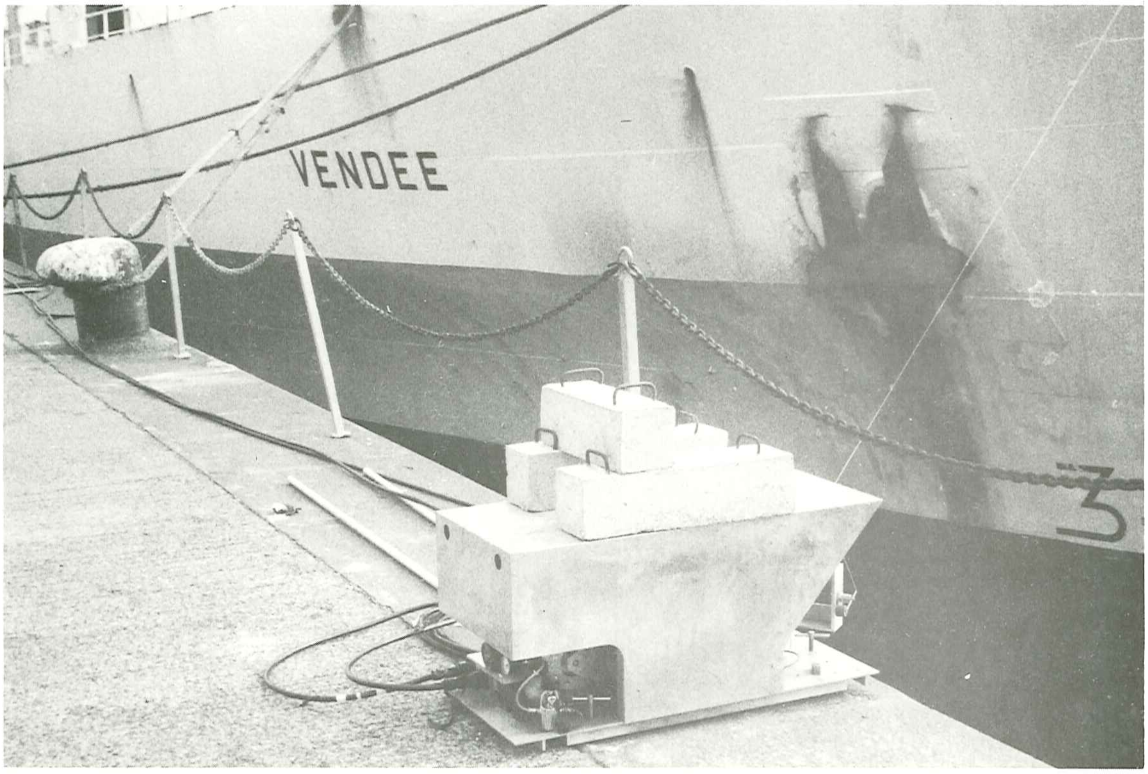

PLATE 10 Machine connected to bow

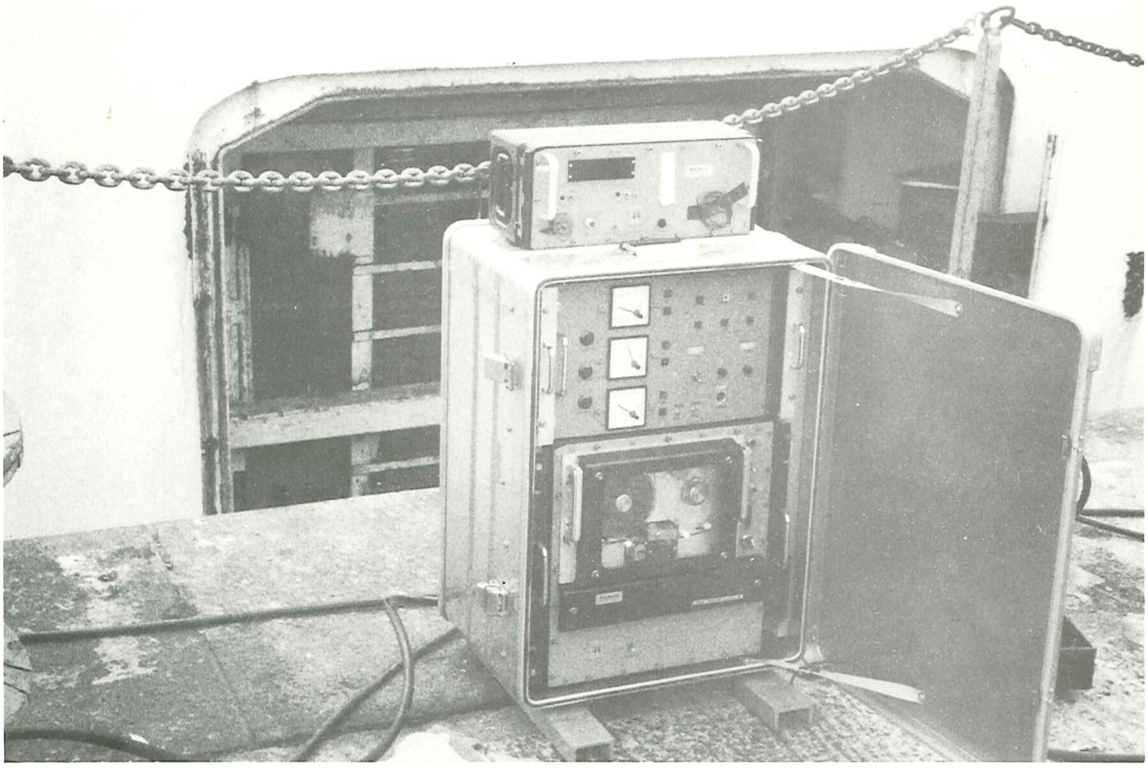

PLATE 11 Logging cabinet on site