A NEW SOUND VELOCITY METER

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SUMMARY

The design of a new instrument for measuring the velocity of sound in sea water with improved accuracy is described. A particular feature of the instrument is that it may be towed through the water without causing appreciable errors.

1. — INTRODUCTION

The standard technique for measuring the velocity of sound in a liquid is to make use of the " sing-around " principle (see figure 1) in which a short pulse of sound is transmitted over a precisely known path. When the pulse is received it immediately retriggers the transmitter so that the p.r.f. of the system is given by :

$$f = \frac{1}{T} = \frac{C}{L} \qquad (1)$$

where T is the travel time of the pulse, L is the path length and C is the velocity of sound.

If the liquid is moving past the instrument with a component of velocity v parallel with the instrument as shown in figure 1 (a) there is of course an error in the measurement since equation (1) is modified to :

$$f = \frac{1}{T} = \frac{C + V}{L} = \frac{C}{L}\left(1 + \frac{V}{C}\right) \qquad (2)$$

In several instruments which are commercially available this error is reduced by folding the path as shown in figure 1 (b) so that, if the flow is smooth, and if the angle φ is small, equation (2) becomes :

$$f = \frac{1}{T} = \frac{1}{\dfrac{L}{2(C + V)} + \dfrac{L}{2(C - V)}} \doteqdot \frac{C}{L}\left(1 - \frac{V^2}{C^2}\right) \qquad (3)$$

However, in practical cases the flow is turbulent, v varies along the track of the pulse and errors can be considerably higher than equation (3) indicates.

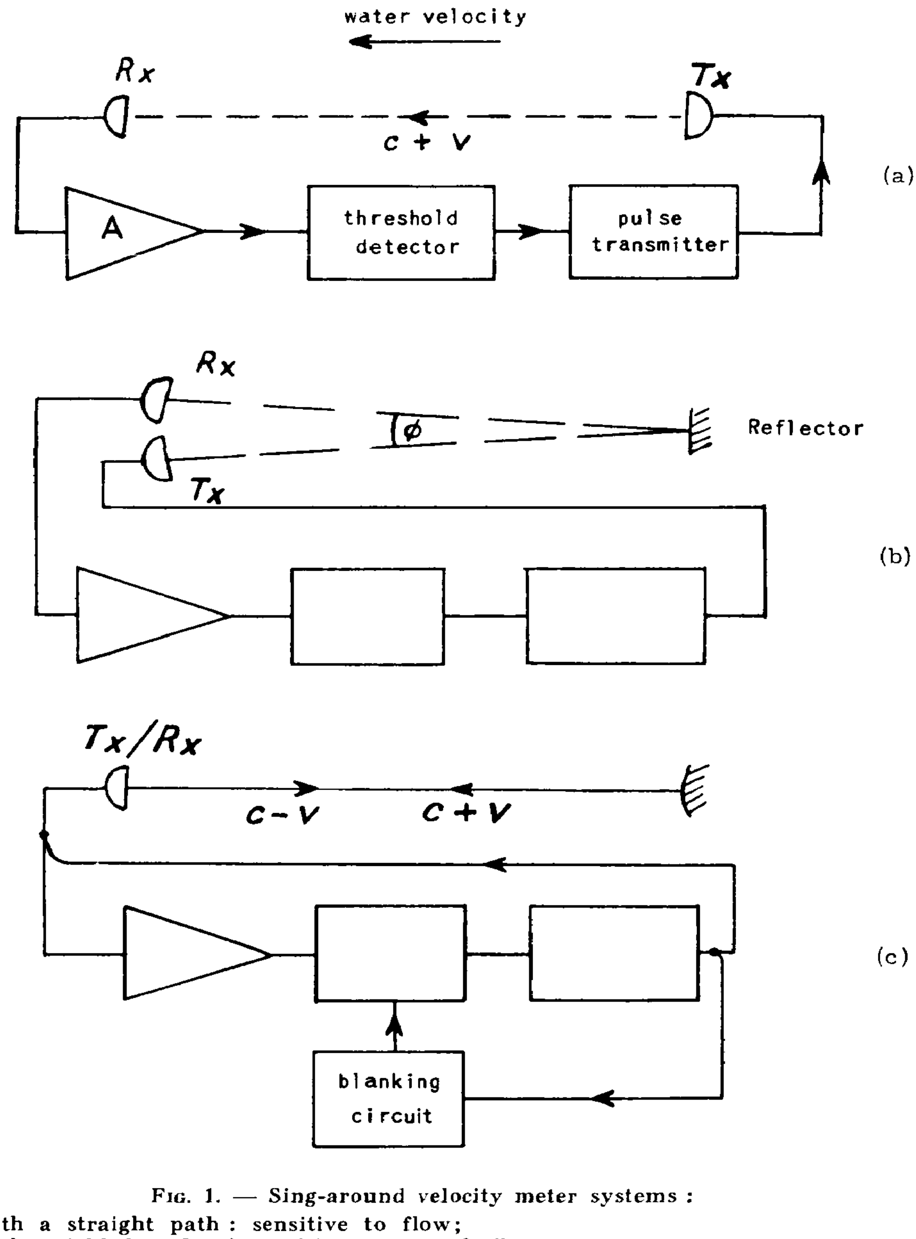


FIG. 1. — Sing-around velocity meter systems :
(a) With a straight path : sensitive to flow;
(b) With a folded path : insensitive to smooth flow;
(c) With a single transmit-receive transducer : insensitive to turbulent flow.

This new instrument uses the arrangement shown in figure 1 (c), where the go and return paths are coincident so that first order errors are cancelled, whether the flow is turbulent or not, and the maximum error which can occur is indicated by equation (3) with v now representing the average velocity along the path.

For $v = 25$ ft/sec (15 knots) and $C = 5\,000$ ft/sec this maximum error is about 1 in 40 000 so the design aim has been to limit all other sources of error to comparable values.

2. — MECHANICAL DESIGN

The instrument head consists of a housing for the transmit/receive transducer, a reflector, and three spacing bars to define their separation. The electronics are housed in a stainless steel tube coaxial with the instrument head so that the whole instrument is 61 cm long and 5 cm in diameter.

The operating temperature range is — 4 °C to + 20 °C and the pressure range 0 to 8 800 p.s.i. (although the head itself has been tested to 10 000 p.s.i.) so that the problems of mechanical design are threefold :

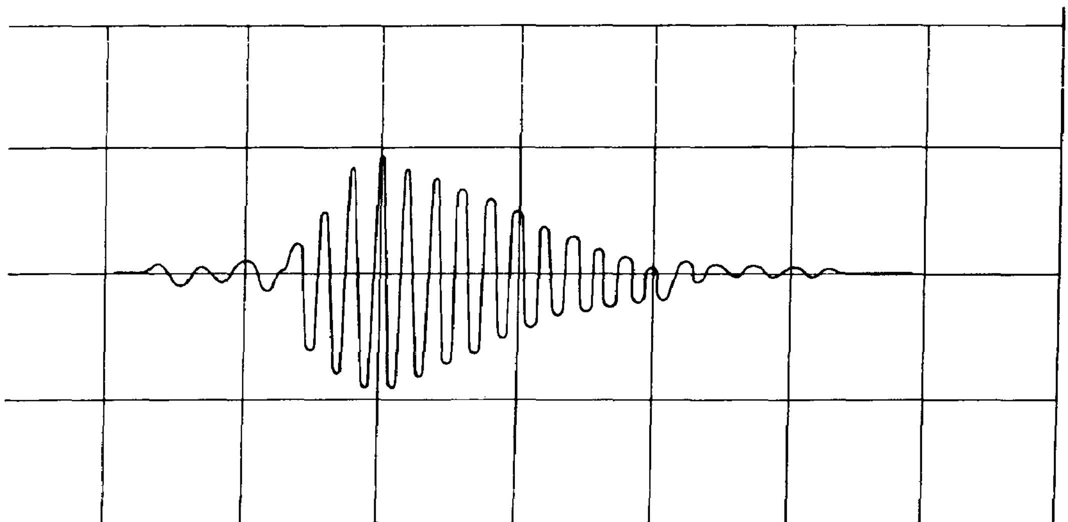
(*a*) To ensure that the path length is independent of temperature;

(*b*) To ensure that it is independent of pressure;

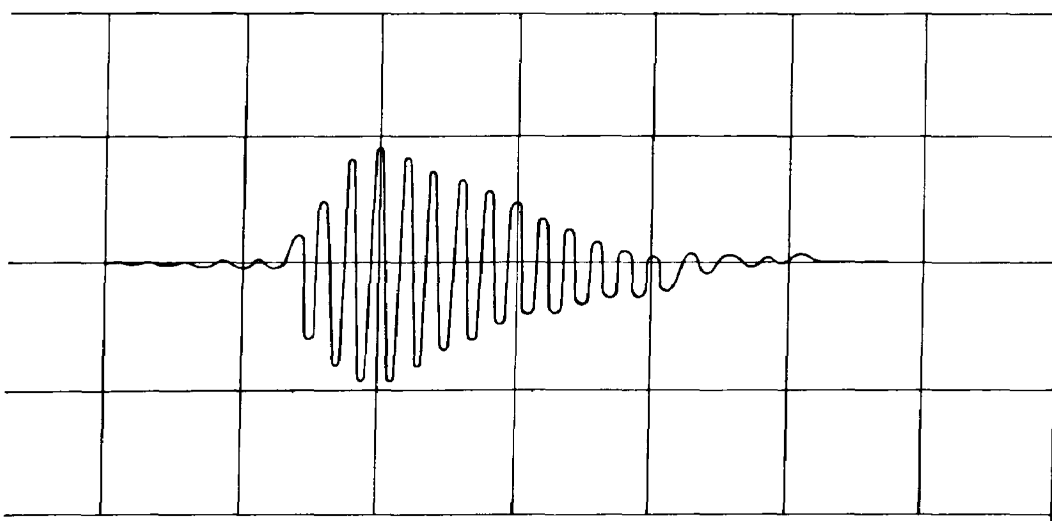
(*c*) To arrange that the only significant acoustic path is the direct one of the transducer - reflector - transducer, and that interfering secondary signals are kept to a minimum. (Since the secondary signals combine with the wanted signal in a very uncertain phase relationship their effect is to make the system hypersensitive to small changes in signal amplitude or in sound velocity).

The spacers are constructed from invar which has a temperature coefficient of expansion of only 4 p.p.m./°C and both the reflector and the transmit receive transducer are mounted on stainless steel stalks whose coefficient is 20 p.p.m./°C. Since, as in a " grid-iron " pendulum, the expansion is in opposite directions and since the lengths of the spacers and the stalks are arranged to be in a 5/1 ratio the overall temperature coefficient of the path length is nominally zero and, in practice, can be relied on to be less than 1 p.p.m./°C which is not significant. The invar spacers are fitted inside oil filled stainless steel tubes with O-ring seals in order to minimise corrosion.

Changes of static pressure will distort the position of the transducer relative to the reflector unless a pressure balancing mounting technique is used, and in this instrument this has been done by filling the rear of the transducer assembly with oil which is at ambient pressure. The transducer itself is a PZT ceramic disc, 10 mm in diameter and 0.4 mm thick, which is platinum plated on the surface exposed to the seawater and silver plated on the other, electrical connections being made via the carefully machined support rim (which is part of the main body of the instrument and is at ground potential) and via a coil spring which makes a pressure contact on the silver plated surface. The disc is kept in position against its support rim by compressing an O-ring whose mean diameter is the same as the diameter of the disc, and the O-ring (which acts both as a seal and as a locating mechanism) is compressed by a screwed tube which is fitted with an inner insulating sleeve. The pressure balance oil reservoir consists of a flanged neoprene rubber tube which has seawater at ambient pressure on its outer surface. The seawater has access via holes drilled in the front face of the transducer assembly so that both static pressures at depth and dynamic pressures which could arise when the instrument is towed through the water are balanced. The effect of the whole arrangement is that changes in neither pressure nor temperature can exert any force tending to distort the transducer.



(a)



(b)

FIG. 2. — *Acoustic baffle effect :*
(a) Without baffle;
(b) With baffle.

The reflector is mounted on an adjusting screw so that fine adjustments to the path length can be made, and it has an accurately ground spherical surface with a radius of 2 inches so that difficulties of alignment are minimised. The curvature also helps to reduce the amplitude of the secondary signal which has been reflected twice from the reflector and once from the crystal. A further source of unwanted signal is from the front face of the support rim which emits energy slightly in advance of the main beam because the velocity of sound in the stainless steel of the support rim is higher than it is in seawater. The amplitude of this interfering signal is reduced by the acoustic baffle which has an aperture smaller than the effective diameter of the disc. The baffle is so constructed that it has no surface parallel to the plane of the disc so that the unwanted part of the signal is reflected out of the system. The effect which the baffle has is illustrated in figure 2. (This picture is, of course, that obtained under open loop conditions. Under normal conditions with the loop closed all but the first fraction of the received signal is smothered by the next transmitter pulse).

3. — ELECTRONIC DESIGN

Equations (1) to (3) are not exact, since there is a delay t between the receipt of a signal and the next transmission. The more exact equation for still water is therefore :

$$f = \frac{1}{T + t} \doteqdot \frac{C}{L}\left(1 - \frac{Ct}{L}\right)$$

The practical implications of this are twofold. Firstly the output frequency is not exactly proportional to sound velocity, so that if no correction for this is made a systematic error will result. It is consequently important to make t as small as possible. Secondly, variations in t, due for instance to changes in temperature or in signal amplitude, will give rise to errors so it is also important to make t as constant as possible.

In this instrument T is about 100 microsec and t is of the order of 100 nanosec so the systematic error is about ± 1 in 16 000 over the velocity range 4 700 ft/sec to 5 000 ft/sec. (The instrument is initially set up near the middle of this range). The error can be reduced by a factor of ten or more if a nominal correction is made and, of course, can be eliminated almost entirely by carrying out two calibrations at widely differing velocities and constructing a calibration curve.

The total delay of about 100 nanosec is made up of several components which with only slight oversimplification may be listed as follows :

(*a*) A delay of about 10 nanoseconds occurs from the time at which the received signal exceeds the trigger level to the instant where the maximum transmitting voltage is applied to the transducer. The delay depends on the switching times of the semiconductors used and is consequently temperature dependent by about ± 10 % over the working range, so the resulting error in measured sound velocity is only ± 1 in 10^5.

(*b*) A delay of about 50 nanoseconds occurs between the maximum voltage being applied to the transducer and the maximum strain appearing at its surface. The delay is relatively constant in value since it depends only on the thickness of the transducer disc and the velocity of sound in it. A similar delay occurs on reception.

(*c*) There is a delay of about twenty-three nanoseconds in the receiver.

(*d*) The above delays are reduced by about 33 nanoseconds, since the threshold of the triggering circuit is set at about half the peak of the first cycle of the received signal.

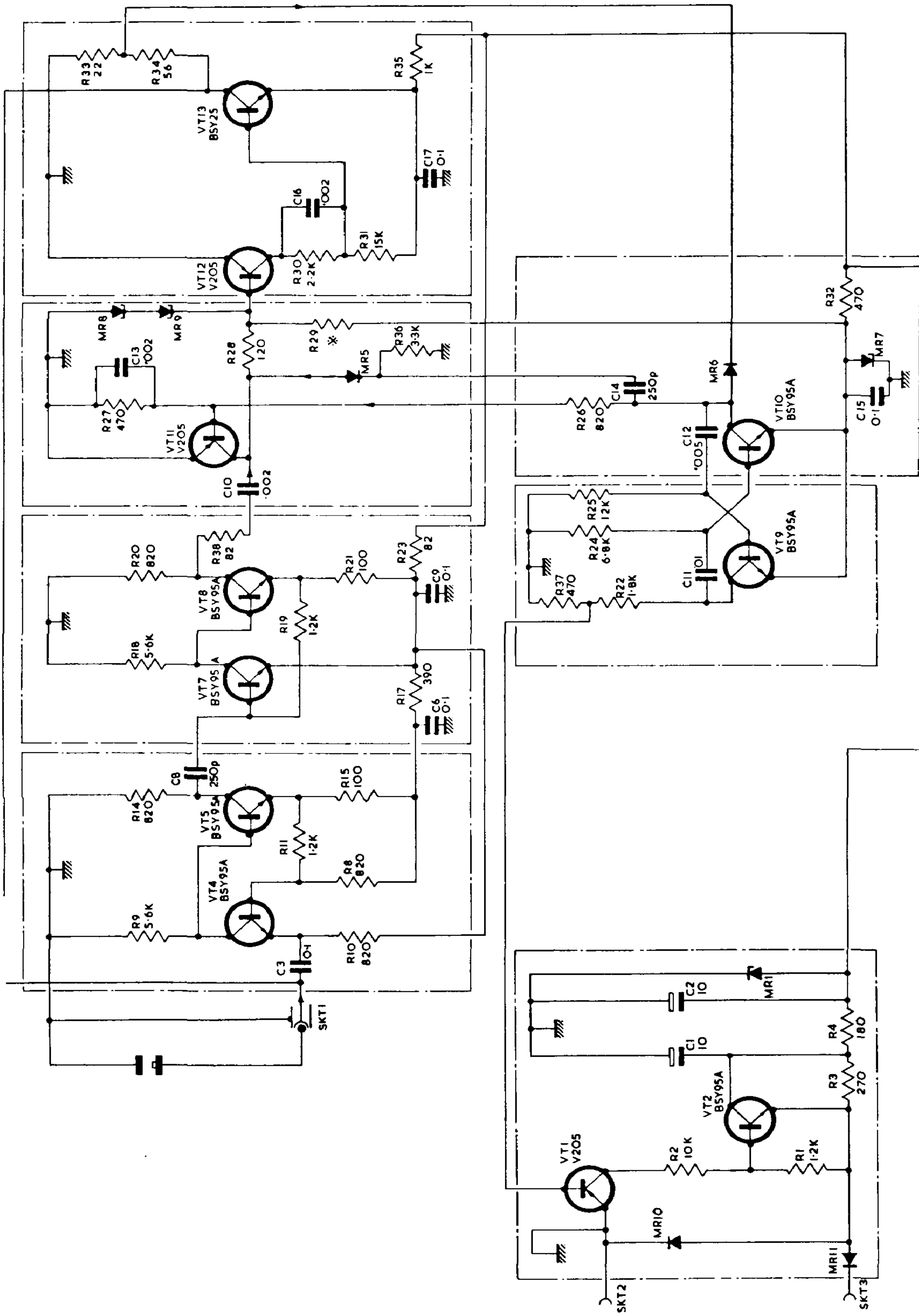
The last delay can obviously be altered by a change in the triggering level, in the transmitter power, or in receiver gain, the effect being small if the carrier frequency of the pulse is high. At the chosen carrier frequency of about five Mc/s (which is about as high as can conveniently be obtained with a robust electrostrictive crystal) a change in triggering level of 3 % is equivalent to a change in circuit delay of approximately 1 nanosecond. To achieve this order of stability the receiver amplifiers have heavy negative feedback, metal oxide resistors are used to define circuit gain, supply rails are stabilised with zener diodes, and the triggering threshold itself is set by the peak current of the tunnel diodes which varies by less than 1 % over the operating temperature range.

The delay can, of course, also be altered by changes in the amplitude of the received signal which could arise from a dependence on pressure or temperature of transducer sensitivity, reflector alignment, or attenuation in the water path. The stress free method of mounting the transducer and the use of a spherical reflector have, in this instrument, eliminated the first two effects and any variations in attenuation due to pressure changes are too small to be measurable. However, changes of attenuation with temperature are probably just significant, since at a frequency of 5 Mc/s the attenuation at 20 °C is about 5 dB's per yard which implies a loss over the path length of the instrument of less than 1 dB. Little information on the temperature dependence of this loss is available but if, as seems reasonable, it can vary by no more than ± 1/2 dB over the temperature range then the maximum error introduced by this mechanism is less than ± 1 in 50 000.

4. — CIRCUIT DETAILS

The circuit diagram of the instrument is shown in figure 3.

The receiver amplifier consists of two feedback pair amplifiers (VT4 and 5 and VT7 and 8) which are identical except for the fact that in the first pair the signal is injected on the emitter of VT4 instead of the base in order to obtain a polarity inversion. Each pair has an open loop current gain of about 60 dB and a closed loop gain of 26 dB.



THIS RESISTANCE ※ TO BE SELECTED ON TEST

FIG. 3. — Circuit diagram of Sound Velocity Meter, type MO31.

The transmitter which consists of VT13 driven by VT12 is capable of delivering a peak current of about 1 amp. A very rapid rise time is achieved by supplying a large excess base drive of almost 5 mA to VT12. This drive is switched on when the combined signal current (via C10 and R28) and preset bias current (via R29) exceeds the triggering current of the tunnel diodes MR8 and MR9. This current is nominally 5 mA and their switching time is about 2 nanosec. R29, which is the only adjustable component in the circuit, is selected on test so that the triggering point is about half the peak signal amplitude. Components R30, R31 and C16 are introduced to ensure that the mean current under non-typical conditions (when, for example, R29 is being adjusted) cannot rise to destructive levels.

The astable multivibrator (VT9 and 10) which is designed to free-run at a little less than the lowest possible sing-around frequency has three functions :

(*a*) To trigger the system into operation when first switched on. This it does by routing a negative going spike to the tunnel diodes via the differentiating circuit C14, R36 and MR5.

(*b*) To prevent the reverberations which occur immediately after the transmitter pulse from falsely retriggering the transmitter. This it does by clamping the signal line to earth for about the first two thirds of the reception period via R26 and VT11.

(*c*) To provide an output signal via C7 to the divide by 2 bistable (VT3 and VT6).

The multivibrator is synchronised to the sing-around frequency by a fraction of the transmitter pulse which is injected via MR6, so that function (*a*) occurs only when no sing-around signal is present.

The instrument is designed to operate with any length of single core cable between 0 and 6 000 metres. The surface unit (which uses no novel techniques and is therefore not described in detail in this article) operates from either 90 to 250 V AC, 40 to 600 c.p.s. or from 10 to 30 V DC and delivers a constant current supply stabilised at 45 mA. Within the instrument, the supply is smoothed by C1, C2 and R4, and is stabilised to 15 V (positive earth) with the zener diode MR1. The artifice of using a constant current supply enables MR1 to work at a constant power level which does not depend on the length or resistance of the cable. Diodes MR10 and MR11 prevent damage which might otherwise be caused by attempting to use incorrect power supplies.

The output signal is, because of the division by 2 action of the bistable consisting of VT3 and VT6, an exactly symmetrical square wave whose frequency is one half the sing-around frequency. This system has the merits that the output signal can be made exactly equal to the speed of sound in feet per second with a convenient crystal-reflector separation of 3″ and that, being symmetrical, the output signal has no even harmonic content and a maximum fundamental component. This output signal is used to square wave modulate the terminal voltage of the supply cable by intermittently shorting out R3 with VT2. The resulting signal is extracted at the surface unit by means of a current transformer, amplified, and fed to any general purpose frequency counter.

5. — CALIBRATION AND TESTING

It would ideally be useful to carry out calibrations to an accuracy of 1 in 100 000 which implies that the water temperature must be held steady to .004 °C. Attempts to obtain stability of this order from a thermostatic control were not successful, and the method finally adopted was to use a large 2 000-gallon tank situated in a temperature-controlled room. A small five-gallon tank containing triple distilled water in which the instrument was immersed was placed within the larger tank and the whole assembly allowed to stabilise at room temperature. This arrangement gave sets of readings which were stable over a period of hours to better than 1 in 100 000, and allowed checks to be made that variations in power supplies had no significant effect.

The calibration technique now adopted with production instruments uses the same tank. The temperature is read to an accuracy of ± .02 °C, and the reflector is adjusted with its micrometer screw until the reading obtained agrees with that indicated by Wilson's tables for the measured temperature. The reflector is then locked into position with its special tapered lock nut and the instrument rechecked. It is considered that this provides an initial setting repeatability of 1 in 20 000 although the overall stability of the instrument may well be better than this.

In May 1965 a prototype instrument was taken aboard R.S. *Discovery* and, with the help of the National Institute of Oceanography, simultaneous readings were made of salinity (by a Nansen bottle and subsequent laboratory measurement), depth and temperature (with reversing thermometers) and sound velocity (with the prototype instrument). The measured values of sound velocity were then compared with ones obtained by calculation from Wilson's tables. The results obtained are shown in table 1. The average difference is about 1 in 10 000, which is considered to be within the experimental error, since the measurement accuracies of temperature, depth and salinity were estimated at ± .02 °C, ± 1 %, and ± .03 $^0/_{00}$ respectively, and these lead to uncertainties in the calculated velocity of about ± 0.2 ft/sec, ± 0.6 ft/sec and ± 0.1 ft/sec.

TABLE 1

Sea Trials in R.S. Discovery

Depth metres	Velocity Meter feet/sec	Calculated Velocity feet/sec	Discrepancy feet/sec
50	4 910.6	4 910.7	— 0.1
200	4 912.9	4 913.7	— 0.8
500	4 926.7	4 928.1	— 1.4
1 000	4 936.4	4 936.0	+ 0.1
1 500	4 916.4	4 916.3	+ 1.0

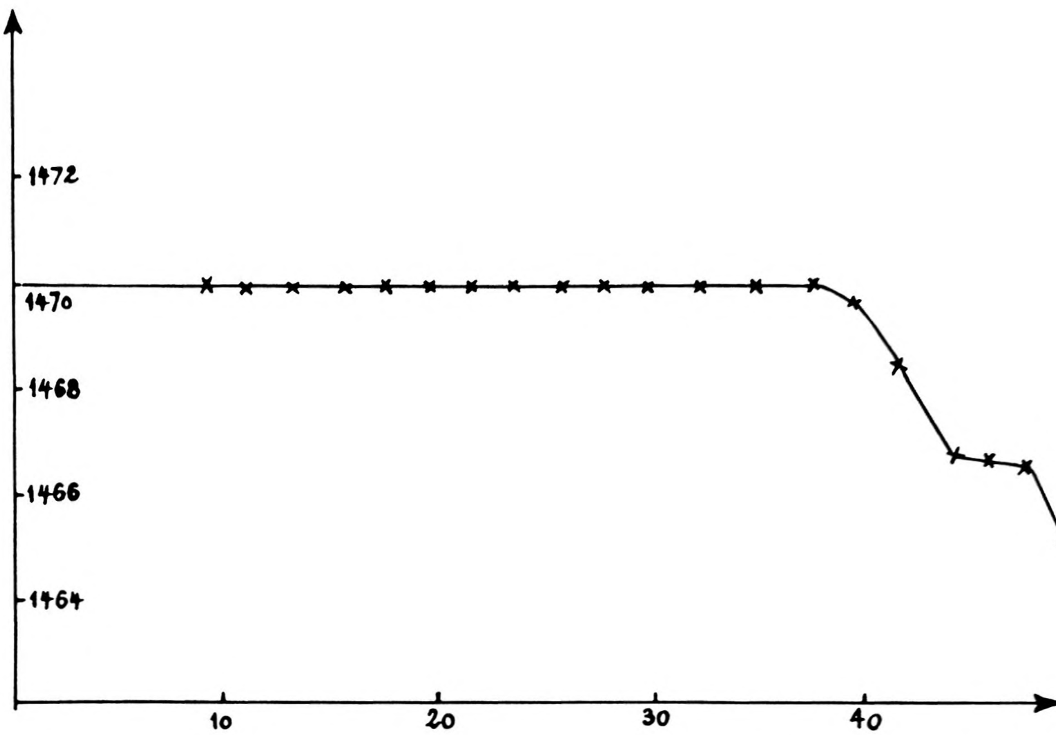


FIG. 4. — Towing tank trials. Sound velocity versus towing speed.

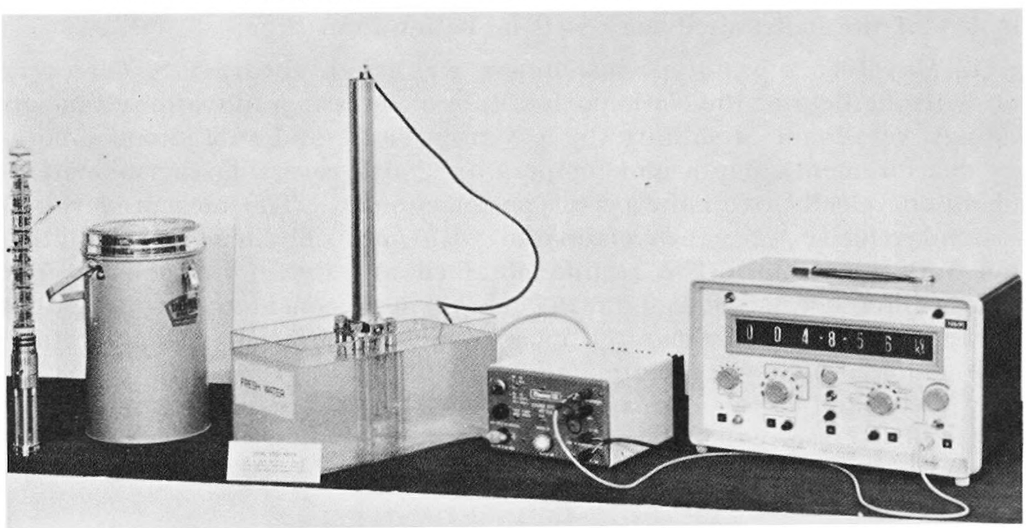


FIG. 5. — Display of equipment.

An instrument has also been mounted on the rotating arm of the circular tank of the Admiralty Research Laboratories, Teddington. The results obtained are shown in figure 4. (The version of the instrument used was one which indicates directly in metres/sec, the separation of crystal and reflector being 5 cm and the division by 2 bistable omitted). Reliable readings with a scatter of less than 0.1 metre per sec were obtained at towing speeds of up to 36 ft/sec (22 knots), but above this speed the readings begin to fall suddenly. What causes this is as yet problematical, but it is considered likely that it is due to the presence of small air bubbles induced by cavitation. If this is so, higher towing speeds will probably be satisfactory at greater depths.

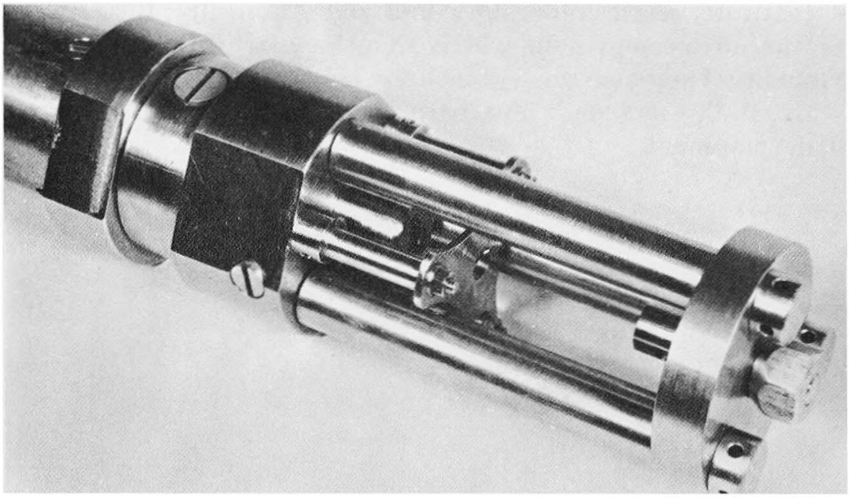


FIG. 6. — Instrument head.

From the overall results of the test programme it has been concluded that the instruments have a long-term overall accuracy of better than 1 in 10 000 within the temperature range of — 4 °C to + 20 °C, and for depths of up to 2 000 metres with towing speeds of up to 22 knots. Attempts to devise a testing technique which is capable of unambiguously indicating any spurious short-term fluctuations have, so far, proved to be unsuccessful. In still water at room temperature any such fluctuations are less than 1 in 100 000.

6. — DERIVATIVES

Two versions of the instrument have been developed : the one described here which indicates velocity in feet per second, and another which indicates metres per second. A third version which incorporates a pressure transducer and a fourth which will have full ocean depth capability are under development.

A subsidiary application of the instrument has been discovered to be the detection of the presence of very small air bubbles which have a marked effect on sound velocity.

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