HOWALDT BATHYSONDE :

USES, OPERATION, AND CALIBRATION PROCEDURES

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PRESENTATION AND DISCUSSION OF THE RESULTS OF A FIELD CALIBRATION DURING THE MEDOC 69 PROJECT

(15 January - 11 March 1969)

Foreword

The appearance on the market of the electronic *sonde* — or to give a fuller description, of chains of automatic measurements that make it possible to take continuous measurements of the principal physical parameters of sea water (pressure, temperature, conductivity, velocity of sound) and which can be adapted to automatic processing — has marked an important stage in the evolution of oceanographic measurement equipment and methods, one that in classical hydrography is comparable to the superseding of the leadline by an ultrasonic sounder.

These sondes are easier to use at sea than the traditional hydrological techniques, and they make it possible to reach the fine structure of the marine environment at all levels. They are therefore destined to become the principal tool for hydrologic investigations.

In December 1966 the Bureau d'Etudes Océanographiques (B.E.O.) (*) acquired a three-sensor Howaldt chain (pressure, temperature and conductivity) and at the present time possesses four such bathysondes and two onboard units.

The current use of this new equipment, together with the continued use of traditional instruments, has in fact posed many problems which for over two years we have been endeavouring to solve.

(*) The Bureau d'Etudes Océanographiques is based at Toulon, and forms part of the central Hydrographic Office. The *Origny*, a converted sea-going minesweeper, is its principal support at sea.

Some of the factors that have retarded the achievement of exploitable data are the immense volume of information supplied by the sonde — which had first of all to be adapted for use in conjunction with a computer — and its technical shortcomings and malfunctionings as well as the complexity and inadaptation of modes of recording. As a consequence the Howaldt bathysonde has been viewed with some reservations in various quarters.

The MEDOC 69 project was centred on research and on a study of the evolution of certain characteristic profiles of sinking surface water, and only later did it come within the more specialized field of the uses of the bathysonde. *With the help of correct* in situ *calibrations this programme has made it possible to attain for the first time accuracies equivalent to those of the classical procedures over the 83 stations observed, albeit in the very special hydrologic conditions of a Mediterranean winter, conditions that restrict bathysonde work to a very narrow range of temperatures.*

This first definite step towards mastering the instrument — the result of two years of effort, adjustments and technical improvements — justifies a description of the present situation. It justifies, especially, drawing conclusions from the present analysis and discussion that will allow us to make further progress, and thus we shall be able to define possible research openings that should be explored in the near future.

In the present paper I therefore propose to throw some light on the Howaldt bathysonde (*) so that the complexity of the problems encountered may be better understood, as well as to make a re-evaluation of the *notion of calibration*, a notion too often either abandoned or poorly understood, Calibration is, however, absolutely essential when measuring with any electronic circuit.

I. 1. - *THE HOWALDT CHAIN AND ITS PRINCIPLES OF OPERATION*

The Howaldt chain permits the plotting of continuous profiles of temperature and conductivity versus pressure in depths of from 0-2 000 m (2 500 m for certain soundings).

Salinity is determined from pressure, temperature and conductivity, and we shall be considering it as a function of these three parameters.

The chain is composed of :

— a submersible probe;

— an onboard unit of measurement circuits and various recording instruments.

A winch drum of 5.7 mm single core suspension and current cable and a revolving mercury contactor serve to join the two parts of the chain.

(*) Manufactured by Kieler Howaldtswerke, Kiel, Federal Republic of Germany.

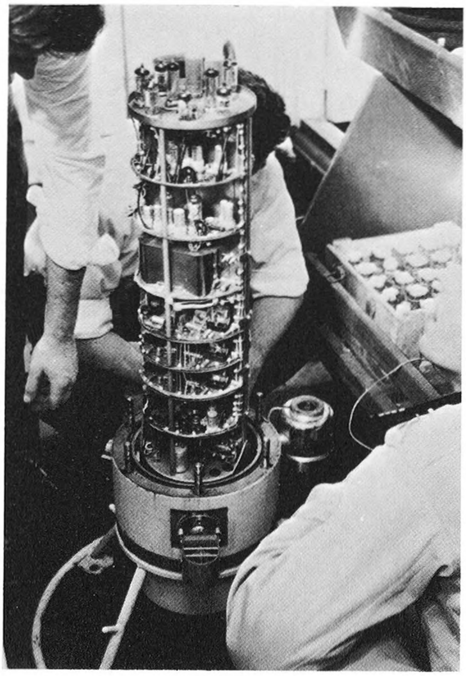


FIG. 1. — The probe's electronic unit.

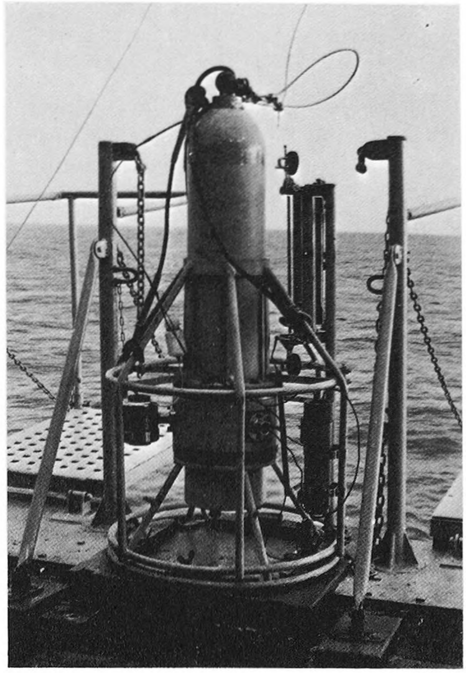


FIG. 2. — The Howaldt Bathysonde mounted on its cradle ready for use.

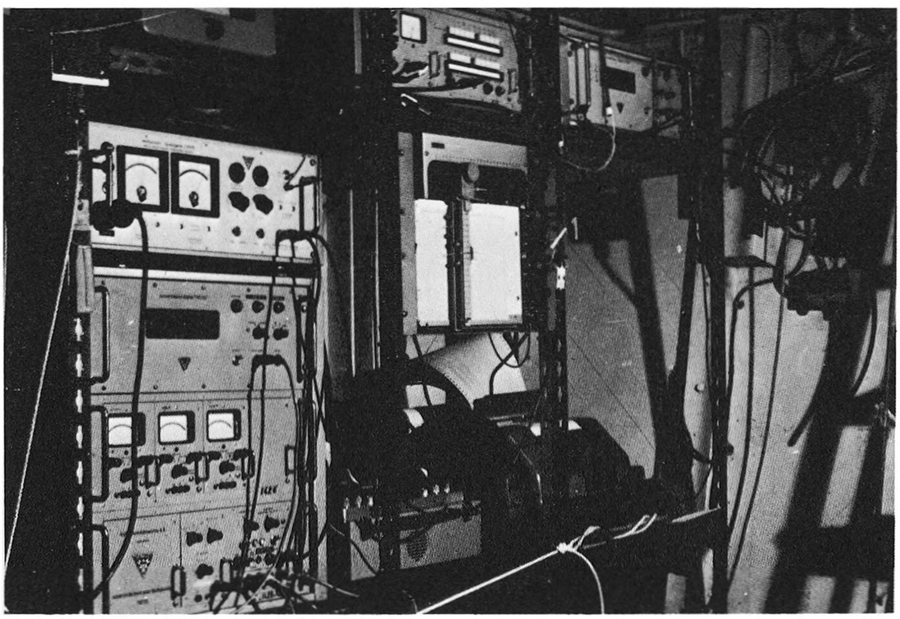


FIG. 3. — General view of the onboard unit.

I.1.1. - The bathysonde instrument

The probe which weighs about 100 kg is packaged in a compressed gas bottle around which is a casing to protect the three sensors :

— a temperature sensor which is a cotton-insulated platinum resistor enclosed in a pressure proof gold metal tube;

— a conductivity sensor consisting of two coils coupled by means of a column of sea water enclosed in a crystal tube (at present a pyrex tube);

— a plunger-fitted Bourdon tube serves as pressure sensor.

Each of these three sensors acts on the frequency of the oscillating circuits. A remote command for changing the ranges switches over to the various units of the circuit, so that each measuring frequency can be maintained in a well defined channel.

The ranges are as follows :

— a single pressure range of from 0 to 2 000 decibars;

— a single temperature range (range 1) of from − 3° C to + 34° C, backed up by 9 sub-ranges each corresponding to a temperature variation of about 4° C.

— a single conductivity range (range 1) of from 20 to 70 mS/cm backed up by 9 sub-ranges each corresponding to about 5 mS/cm.

The width of the sub-range bands, and consequently the resolution of the temperature and conductivity measurements, is thus sufficient without the channel width (about 1 500 Hz) being too large.

The three sinusoidal signals are mixed in the "fish" and pass through the single core cable to the revolving contactor and then to the onboard instrument where they arrive superposed on the D.C. supply (250 volts) of the fish.

Accessories : The probe has two additional principal accessories :

— a bottom detector (controlled by guide rope) that releases a bell and lights a pilot light when the probe reaches a certain adjustable position from the bottom.

— a trigger switch for the test bottle mounted on the probe. This switch is remote controlled from on board and releases a messenger which closes the reversing bottle.

I.1.2. - The onboard unit

The signals from the probe arriving at the surface are recorded on one of the tracks of a tape recorder at the same time as a pilot frequency. The other track is available for recording the reference pips or any spoken observations.

This memorized multiplexed signal theoretically allows an exact restitution of the raw signal received on board at the time of measurement.

At the same time the multiplexed signal is fed through a group of filters set on the three measurement channels. The pure frequencies are then put into form and are switched onto :

— either an analogue measurement chain that includes a Moseley graphic recorder, with the possibility of amplification by means of a magnifying glass;

— or else a digital counter which samples the frequencies at a rate selected among several types of sequence and then converts them to punched tape and lists them on a Siemens teleprinter.

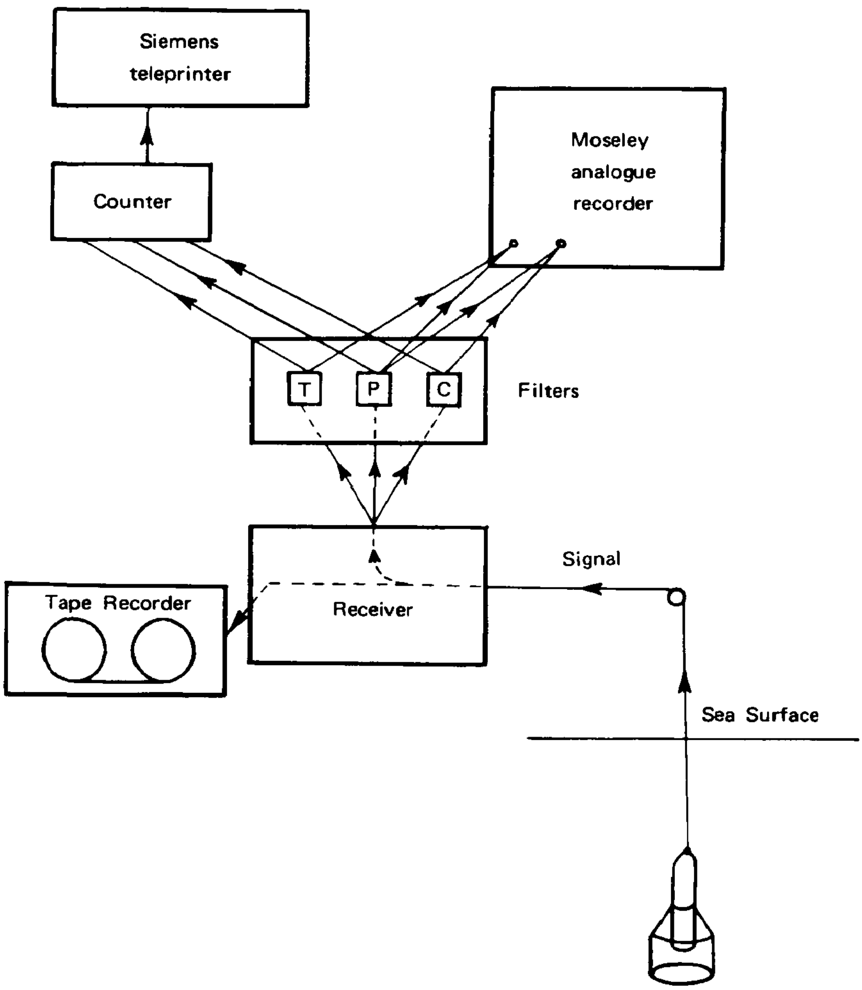


FIG. 4. — Flow diagram of the measurement processes.

Although the analogue recorder provides valuable information on the functioning of the instrument as it is lowered, and on the areas of particular interest that would justify a slowing down of the probe, it cannot be thought of as a mode of quantitative exploitation and final storage as the parameters are not expressed linearly in terms of the frequencies.

I.1.3. - Modes of recording and first processing

The makers propose two methods of digital processing :

a) During the measurement the multiplexed signal is merely recorded on the tape concurrently with the time pips which are registered, either automatically or else manually on examination of the graphic record, on the second track. The magnetic tape is then reread three times to examine each time one of the three parameters recorded. Each recorded pip on the track releases a reading. The value of the three parameters at one and the same instant is thus theoretically obtained by re-assembling the readings obtained at each passage three by three.

b) During the measurement the selector successively scans the three tracks according to the following 8-second cycle :

0 - 1	sec	:	pressure count	
1 - 1.75	,,	:	,,	transcription
1.75 - 2.75	,,	:	temperature count	
2.75 - 3.50	,,	:	,,	transcription
3.50 - 4.50	,,	:	conductivity count	
4.50 - 5.25	,,	:	,,	transcription
5.25 - 8	,,	:	Idle period	

The frequency values for the three parameters are punched and consecutively typed on a single line of the teleprinter at the rate of a complete measurement every 8 seconds, with a time shift of 1.75 seconds, and this represents about 2 metres during the bathysonde lowering.

This method simplifies the processing. It has, however, the disadvantage of serious shortcomings which will be discussed in I.2.

Whatever the mode of recording selected, the Howaldt bathysonde thus supplies measurements of the parameters P, T and C in the form of frequencies, and these frequencies have to be converted into true values by a first processing.

The true values can be fairly well represented by polynomials of the third degree in frequency. The coefficients for the polynomials are computed from the values obtained during the laboratory calibration.

I.1.4. - The particular case of conductivity. Definition of the form factor

We have seen that conductivity is measured by coupling two coils through a calibrated tube of sea water.

It is obvious that it is not possible to carry out exact measurements in the laboratory for finding the formula for converting frequency into conductivity, since this would necessitate far too large a volume of water of known conductivity.

Therefore in order to establish the correlation, in the laboratory we simulate the coil coupling by a circuit of known and variable conductances.

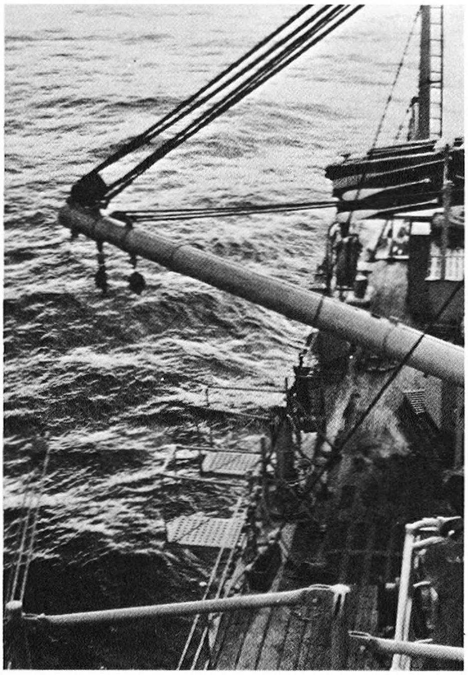


FIG. 5. — The *Origny*'s starboard deck, with derrick in working position.

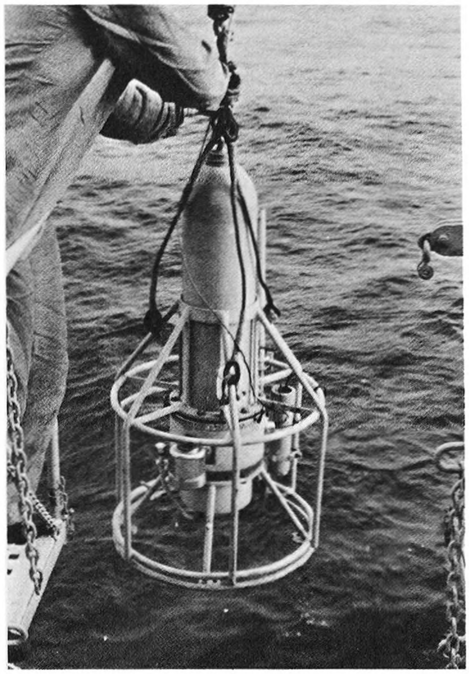


FIG. 6. — The Howaldt Bathysonde being lowered into the water.

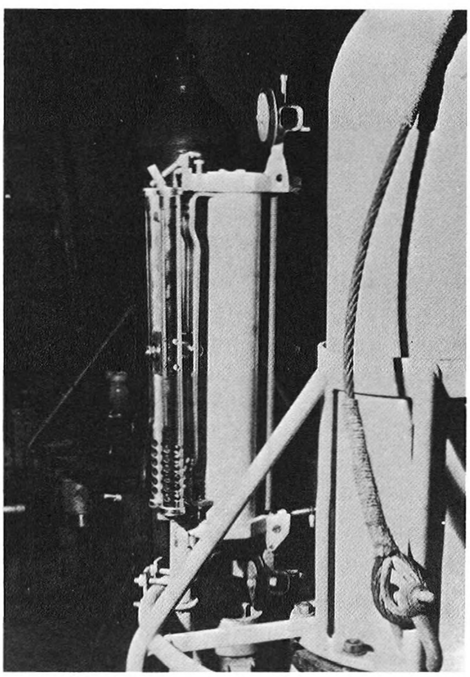


FIG. 7. — A view of the test bottle.

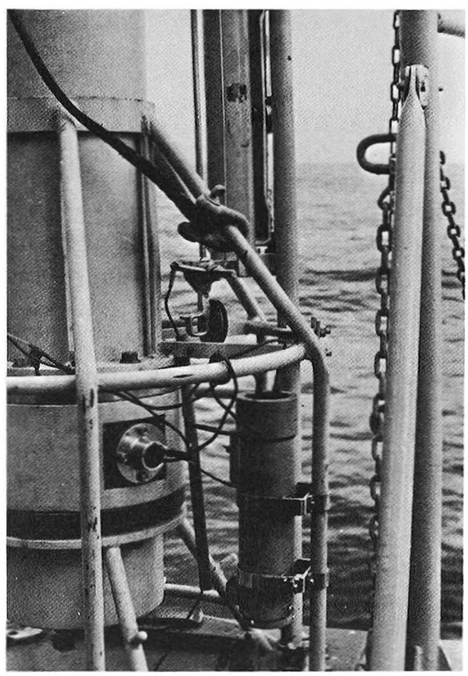


FIG. 8. — A view of the test bottle's remote controlled trigger switch.

Definition

The factor by which the conductivity value deduced from laboratory-established calibration tables must be multiplied to obtain the true *in situ* conductivity is called the form factor φ of the sensor.

This form factor is obtained by comparing the conductivity for the bathysonde to a sample taken at sensor level in a bottle fixed to the probe.

The form factor depends on the geometry of the probe, and in particular that of the crystal tube.

I.1.5. - **Operation aboard the *Origny***

The method employed aboard the *Origny* for lowering and retrieving the probe is both simple and rapid, and it can be carried out by members of one watch (1 winchman and three men).

The suspension cable is shortened until the probe is between the two oceanographic work bridges and about 1.50 metres below the counting pulley, when it is grabbed by two men stationed on these bridges.

The upper eye of the probe is then lashed to the hook of tackle at whose other end is a pulley block fixed to the upper corner of the laboratory. The probe is then returned to its rests by slowly paying out the pulley cable.

This exercise can be performed satisfactorily without special equipment.

I.2. - *BACKGROUND TO THE PROBLEMS RAISED AND THE DIFFICULTIES OF OPERATION, AND A DISCUSSION OF THE SOLUTIONS FURNISHED BY THE B.E.O.*

Rather than give a detailed historical background of the many and continual difficulties which impede the progress of the development of the Howaldt chain, we shall attempt here to give a general picture, pointing out the remedies we have discovered and the problems remaining to be solved.

I.2.1. - **Problems of a purely technical order**

The technical imperfections, the operational shortcomings, and the frequent breakdowns of this new equipment — which seems to have been put on the market a little prematurely — have been discussed in detail in various different technical reports as well as in the reports on work carried out by the B.E.O. since December 1966.

It will be worthwhile recalling the principal troubles for which a remedy had to be found.

I.2.1.1. - *The sensors*

— The temperature sensor. Initially the temperature sensor was a fine platinum wire in a pressure proof gold tube. As it was impossible to solder the gold tube the connections were insulated with araldite.

After noting important pressure effects when measuring temperature it was observed that this type of sealing was not watertight under pressure; water was infiltrating into the gold tube and this resulted in unwanted resistances, giving rise to errors of as much as several tenths of a degree Celsius.

The firm of Howaldt remedied this defect in the summer of 1968 by replacing the araldite insulation with elastomer silicon, the whole being embedded in a block of araldite.

As gold was not absolutely essential, it was replaced by nickel without any notable effect on the sensor's time constant which remained around 0.25 second.

The B.E.O.'s four probes are now fitted with these new sensors, and the *in situ* calibration made during the MEDOC 1969 project shows that there is every reason to be satisfied with the result.

— The pressure sensor. It is not at present possible to improve the performance of the Bourdon tube which, particularly when being lifted, has a pronounced magnetic lag. This problem is at present being studied by the manufacturers.

— The conductivity sensor. This will be discussed later on for its study has only just been started.

In reality, since the temperature and pressure errors have an important bearing on the calculation of salinity from *in situ* conductivity, and because the measureents can only be checked by comparison with salinities obtained from the classical analytical procedures, *it is unrealistic* either to hope to obtain accurate estimates of salinity or to be able to analyse the source of sensor errors so long as there is no means of making an accurate temperature measurement simultaneously with the conductivity measurement.

1.2.1.2. - *Operations of the probe and the onboard equipment*

Besides the sensors' shortcomings — which had the effect of falsifying the measurements — the internal electronic circuits of both the fish and the onboard chain often became faulty and gave rise to frequent breakdowns which were often difficult to detect.

Probe N° 731, which was delivered in July 1968, has benefited from the experience acquired, and is actually much more reliable in operation.

On the older probes :

— It was necessary to remedy a certain number of workmanship faults and mistakes in the circuit cabling.

— The ageing of the oscillating circuits led to an important drift in measurement. The resistors in these circuits were replaced by components of better quality. It should be noted that this ageing obliged us to follow the behaviour of the probes very closely, and later led us *to establish a calibration station at the B.E.O.*

— Switching to the sub-ranges by remote control remains uncertain, and often even quite impossible. It necessitates, in particular, both the bathysonde and the recordings being stopped in order to avoid encumbering the record with erroneous values. This switch often releases the closing mechanism of the test bottle or the bottom detector bell. Conversely, the manual release of the bottle sometimes disconnects the sub-range.

All this is due to the fact that during these operations we are transmitting into the probe powerful frequencies whose harmonics can excite certain oscillating circuits.

This problem has not yet been resolved, and it *renders the use of the bathysonde difficult in the Atlantic.*

— The recording of raw data on the tape recorder with practically no possibility of a check during measurement is a far from reliable method, and the play back of the tapes is often aleatory. In fact, both the quality and the performance of the Uher tape recorder appear to be inadequate, and it is extremely sensitive to interference which superposes itself on the pips, releasing a number of unwanted readings at the time of the play-back.

— Finally, it sometimes happens that the thread of the flange closing the conductivity sensor takes on play because of poor machine tooling and this means that water infiltrates, and thus all measuring becomes impossible.

I.2.2. - **Problems arising from the basic principle of recording modes and calibration procedures**

I.2.2.1. - *Modes of recording*

Since the beginning of 1967 — that is after the bathysonde had been used for the first time — it has become apparent to those using the Howaldt chain that the modes of recording are ill-adapted to the information supplied by the "fish" : that is to say :

— The graphic recording will only be qualitative, on account of the non-linearity of the frequency-parameter correlation;

— The recording of the multiplexed signal on magnetic tape, in addition to the troubles due to the quality of the recording which we have already mentioned, has the drawback of requiring a playback time of at least three times as long as the original station, i.e. about 4 hours.

The processing and the transcription onto special cards for further automatic data processing have both to be done entirely by hand. This entails many delays, and leads to an accumulation of magnetic tapes.

Manual registration of pips for angle points during the lowering would certainly decrease the number of points to be retained as compared with automatic registration, but the operator already fully occupied in supervising the equipment would need to be an acrobat.

— Sequential recording on punched or printed tape, although it makes for easier automatic processing, nevertheless has the following defect :

— the sampling rate is too low to follow certain abrupt changes in the environment;

— there are large errors in salinity caused by lags in the measurement of T and C when linear interpolation is no longer valid.

The method adopted at the B.E.O. — after comparing the two methods in practice — is in fact a mixture of the three procedures outlined above. That is to say that both during the lowering and the retrieval all three modes of recording were in action.

The recurrence rate for the reference pips corresponding to the reading sequence was eight seconds. Perturbed areas were marked on the tape during this operation.

The processing method then consisted of extracting the angle points from the magnetic tape simply for the perturbed areas (for this the band must be run through five times). These angle points, which correspond to the simultaneous measurements of the three parameters, then replaced the values obtained automatically every 8 seconds.

In actual fact it did not prove possible to combine these two modes of treatment on the computer, and the work had therefore to be done manually.

A glance at this hybrid method shows how unwieldy it proved, and how difficult in application.

It was for this reason, that as early as 1967 the first specifications were sketched out for developing an improved bathysonde — the SCAMO — in which the sub-ranges are omitted, and which incorporates simultaneous and rapid counting of the parameters.

I.2.2.2. — *Laboratory calibration*

The bathysondes are delivered complete with a frequency-parameter conversion table, as well as the polynomials employed to obtain this table from the calibrations carried out by the manufacturers.

In practice the continuous change in the electronic circuits due to the lapse of time necessitated frequent verifications and obliged us to set up a calibration station at Toulon, and this enabled us to control the probes both before and after the work campaigns.

The instrumentation set up in this way is described in detail in the manuscript report "Instrumentation 1969" dated 2 May 1969.

Each sensor is separately calibrated, and thus three curves are obtained:

$$P = f(F_1)$$
$$T = g(F_2)$$
$$C = h(F_3)$$

The problem then consists of determining the coefficients for the third degree polynomial most closely approaching the curves established during the calibration. This is done using the least squares method.

We shall see later that this computation introduces some distortion into the frequency-parameter conversion, in the form of systematic errors which have to be eliminated.

I.2.2.3. — *The* in situ *calibration*

On account of the form factor mentioned above a systematic *in situ* calibration is necessary.

The test bottle — a bottle for taking a sample at sensor level at the time of a conductivity measurement — had been fixed to the probe, but was very soon lost. At this point, therefore, it was assumed that the probes could be calibrated by comparison with classical hydrological measurements that would be carried out either immediately before or after the bathysonde was lowered. It was assumed then that the exact Howaldt profile could be obtained by submitting the measured profile to a translation and a rotation so as to make it fit the profile resulting from the classical methods.

Although this procedure appeared satisfactory it turned out to be the wrong one. In practice the extended use of the bathysonde revealed the existence of significant and very rapid fluctuations in time and space, and this precluded the possibility of comparing the two profiles taken an hour apart.

It was only the values for the more stable bottom water that could be validly compared. But as the dependence of sensors on pressure was, however, unknown, this made the plotting of the exact profile impossible.

I.2.3. - **Problems of processing and exploiting bathysonde information**

It was impossible to consider manual treatment on account of the volume of information obtained with the probe and the complexity of the computations required. This obliged the B.E.O. to work out the necessary computer programmes for exploiting the data without delay.

However, this proved a relatively lengthy matter in view of the absence of specialist personnel, and thus the perfectioning of the Howaldt probe, which was already proving difficult, was further retarded.

It should be noted that these programmes were recast and adapted several times on account both of the development of computers and amendments to computing algorithms.

The programmes developed since 1967 and currently being used are the following :

— Working out the laboratory calibration, and the computation of third degree polynomials and frequency-parameter conversion tables;

— Conversion of frequencies into true values, and the computation of salinity from the Bradshaw and Sleicher laws as well as those of Ribe and Howe for the simultaneous measurement points.

— Adaptation of the TRADOC programme (computation of σ_t and the dynamic anomaly) to bathysonde data;

— Plotting of curves T (P), S (P) and T (S) with an automatic plotter.

The processing of the punched tape is the only remaining difficulty.

THE PARTICULAR CASE OF THE MEDOC 69 PROJECT
(15 January - 11 March)

II. 1. - *GENERALITIES : RESTRICTIONS*

In view of the progress made by the B.E.O. (described in Part I) and of technical improvements to the probe, it was decided to profit by the MEDOC project to carry out an elaborate sea test with the Howaldt chain aboard the *Origny*.

The object was to achieve by means of a close *in situ* calibration a determination of the raw corrections to be made the bathysonde data to enable them to be plotted with an accuracy equivalent to classical hydrology, and this without the need to enter into the technology of the probe, but simply taking the reliability of the electronic circuits into account.

To do this was essential :

1. To have available a sufficiently reliable system for *in situ* calibrations;
2. To obtain simultaneous data for at least temperature and salinity, in a manner that is both certain and simple.

We had for this one extremely important asset. This was that *in winter the waters of the Western Mediterranean are practically isothermal and isohaline from the surface right down to the bottom.*

This means that we avoided the difficulties — at present the most important — of switching sub-ranges, and could thus carry out a single *in situ* calibration that was valid for 0 to 2 000 metres in the temperature range 5 and conductivity range 6.

II. 2. - *TECHNICAL MODIFICATIONS TO THE CHAIN*

II.2.1. - Description of the *in situ* calibration system employed

As we have seen, this *in situ* calibration consists in comparing the bathysonde measurements of P, T and S obtained through C with the values determined by classical methods of a sample taken simultaneously at sensor level.

For want of a multisampling instrument that would provide several basic check points during a lowering we were obliged to make do with a single sampling bottle supplying only one point per station.

The reversing bottle we used is a converted plastic bottle of Mecabolier make :

— It is rigidly fixed onto the protective casing of the probe and therefore no longer reverses itself. The closing of the valves is controlled by a lever fixed underneath the bottle;

— The closing of the valves frees the thermometer holder which is pivoted by a spiral spring around a fixed horizontal axis half way up the bottle.

This system resembles the one used by the British National Institute of Oceanography.

The bottle is closed by the free fall of a messenger released by remote control from on board.

This system which had been set up in a rough and ready way at the very last minute was to prove excellent, and it functioned well. Over the 83 stations it functioned 69 times, and this to my way of thinking is an excellent performance.

II.2.2. - **Modification of the recording system**

The second necessity was to obtain simultaneous measurements of temperature and conductivity in a way that was both simple and reliable.

On account of the equipment already existing at the B.E.O., and because of the inconveniences of recording on magnetic tape, the measurement chain was modified as follows.

Two counters were used at the filter output and linked to two Siemens teleprinters.

The counting and printing sequences remained eight seconds, but the order on each counter was changed. The following is the revised scheme.

		1st Teleprinter	2nd Teleprinter
0 - 1	sec :	Temperature count	Conductivity count
1 - 1.75	,, :	,, transcription	,, transcription
1.75 - 2.75	,, :	Pressure count	Pressure count
2.75 - 3.50	,, :	,, transcription	,, transcription
3.50 - 4.50	,, :	Conductivity count	Temperature count
4.50 - 5.25	,, :	,, transcription	,, transcription
5.25 - 8	,, :	Idle period	

It is then clear that the bringing together of the two printed or punched tapes supplies simultaneous measurements of temperature and conductivity at the rate of approximately 4 seconds.

This allows us to obtain pressure values by interpolation. These pressure values are furthermore used as references on the listings for determining the simultaneous measurements of T and C.

The tape recorder, at the ready, is turned on if one of the teleprinters or counters breaks down during the operation.

This was a very easy system to set up with existing equipment, and it proved perfectly reliable, owing partly to the robustness of the Siemens teleprinters and partly to the constant check supplied by the record during the operation.

For the MEDOC 69 project both the regrouping of the simultaneous measurements and the interpolations between pressure data were done by hand, as were also the transcriptions onto the programme input forms.

Automatic mixing for punched tape is being studied for use in future projects.

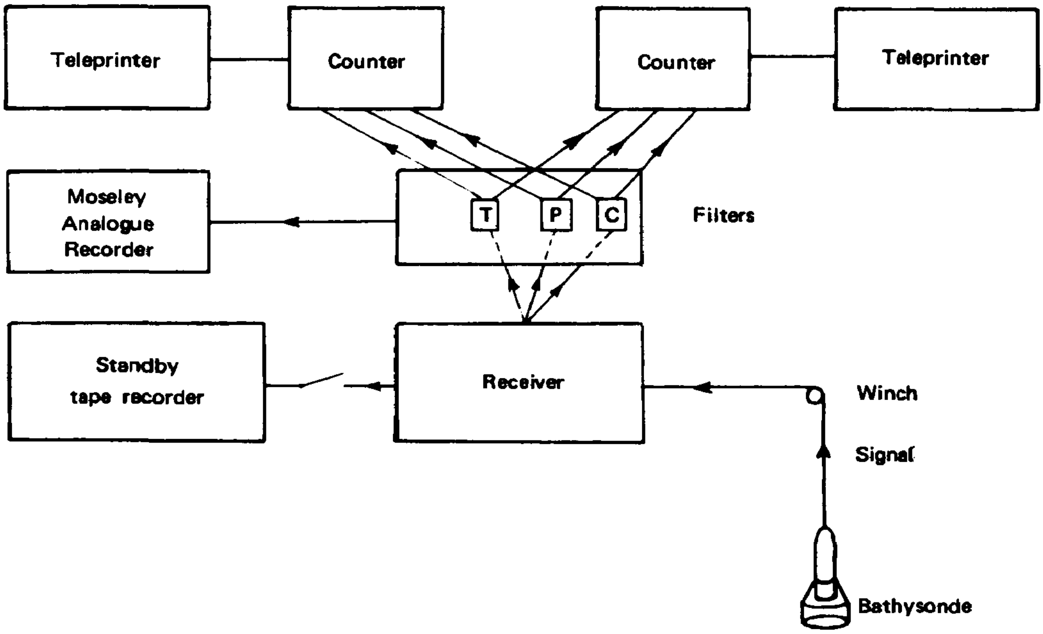


FIG. 9. — Flow diagram of the recording system used during the Medoc 69 Project.

II. 3. - *DISCUSSION OF THE MEDOC 69* IN SITU *CALIBRATION*

The values for P_W, T_w and S_W (S_W is obtained from C_W, P_W and T_W through computation) can now be compared with the test bottle P_H, T_H and S_H values at about 69 points.

The data were obtained simultaneously, and as far as possible were distributed in depths of between 0 and 2 000 metres.

The relative values, as well as the raw deviations, are recapitulated in the two tables forming Plates I and II.

It should be noted that :

1. There are two distinct tables. The reason for this was that the conductivity sensor broke between stations 51 and 52. This meant that we had to alter the form factor for the computation of salinity.

There was therefore :

A single pressure calibration for about 69 points;
A single temperature calibration also for about 69 points;
Two distinct calibrations for salinity, the first ($\varphi = 0.9834$) for 44 points, and the second ($\varphi = 0.99847$) for 24 points.

2. A rapid survey of the temperature calibration showed that T_W had to be corrected by -0.04 °C, and this was taken into account when working out the tables, in order that the S_W salinities should be as correct as possible.

Before analysing and discussing this calibration sensor by sensor it will be useful to recall some figures and orders of magnitude that will be of help in elucidating the text which follows.

1. With this probe the resolution for a frequency measurement is ± 1 Hertz :

— In pressure measurements : 1 Hertz represents a depth difference of 0.4 decibar at the surface, 1 decibar at 1 500 metres and 1.2 decibars at 2 000 metres;
— In conductivity measurements : 1 Hertz represents a difference of between 0.006 and 0.002 mS/cm for range 6;
— In temperature measurements : 1 Hertz represents a difference of between 0.004 °C and 0.003 °C for range 5.

2. The P_H, T_H and S_H values obtained by classical procedures include an error which in view of the sensitivity of the Howaldt sensors is quite sizeable:

— pressure inaccuracies are of the order of about 10 decibars;
— temperatures T_H are read on the thermometers to within the hundredth of a degree;
— salinities S_H are obtained to within ± 0.005 g/kg.

There can be no figure for human error, so that reading errors will entail certain abnormal points.

The Howaldt measurements are relatively more accurate and homogeneous than those of the classical procedures, and as a result the corrections must take account of the reference values, and if we are to make the best use of the accuracy this probe provides this would necessitate *a large number of observations* in order to be able to draw up actual statistics.

3. Salinity S_W is a complicated function of conductivity C_W, temperature T_w and pressure P_W.

— An error of 0.01 °C on T_W leads to an error of 0.01 ‰ approx. on S_w.
— An error of 0.01 mS/cm on C_w leads to an error of 0.01 ‰ on S_W.
— 5 decibars on P_w leads to an error of 0.003 ‰ on S_W at 2 000 m.

Planche n° I

PRESENTATION DES RESULTATS BRUTS DE L'ETALONNAGE IN SITU REALISE AU COURS DE MEDOC 69.

(1° Partie : station 1 à 51 φ.09834)

Nota : PH, TH, SH proviennent de la bouteille test.
Pw, Tw, Sw proviennent de la bathysonde.

N° Station	PH	Pw	ΔP = PH - Pw	TH	Tw - 0,04	ΔT = TH - Tw - 0,04	SH	Sw	ΔS = SH - Sw	Observations
3	1994	1977	+ 17	13°,02	13,008	+ 0,012	38,404	38,428	- 0,024	H 3
4	2015	1977	+ 38	13,03	13,008	+ 0,022	38,409	38,443	- 0,034	4
5	840	828	+ 11	13,18	13,177	+ 0,003		38,453		5
6	607	600	+ 07	13,38	13,339	+ 0,041	38,495	38,476	+ 0,019	6
7	341	335	+ 06	13,28	12,285	- 0,005	38,371	38,306	+ 0,065	7
8	1514	1501	+ 13	12,97	12,963	+ 0,007	38,410	38,399	+ 0,011	8
9	1010	997	+ 13	12,94	12,952	- 0,012	38,422	38,395	+ 0,027	9
10	1210	1200	+ 10	12,98	12,987	- 0,007	38,433	38,411	+ 0,022	10
11	1400	1398	+ 02	12,95	12,942	+ 0,008	38,414	38,401	+ 0,013	11
12	2002	1978	+ 24	13,02	13,008	+ 0,012	38,412	38,437	- 0,025	
13	186	191	+ 05	12,92	12,938	- 0,018	38,421	38,334	+ 0,087	12
14	2006	1978	+ 28	13,02	13,005	+ 0,015	38,413	38,447	- 0,034	
15	93	88	- 05	12,73	12,744	- 0,014	38,273	38,165	+ 0,108	13
16	2004	1978	+ 26	13,01	13,008	+ 0,002	38,411	38,440	- 0,029	
17	506	502	+ 04	13,14	13,139	+ 0,001	38,476	38,435	+ 0,041	
18	1980	1955	+ 25	13,00	13,005	- 0,005	38,404	38,424	- 0,020	14
19	241	241	+ 00	13,57	13,567	+ 0,003	38,530	38,516	+ 0,014	
20	795	796	- 01	13,03	13,032	- 0,002	38,405	38,412	- 0,007	15
21	1112	1098	+ 06	12,99	12,994	- 0,004	38,422	38,418	+ 0,004	
24	1884	1870	+ 14	13,00	13,005	- 0,005	38,404	38,459	- 0,055	
25	142	137	+ 05	12,99	13,005	- 0,015	38,240	38,184	+ 0,056	17
26	1500	1500	+ 00	12,95	12,966	- 0,016	38,404	38,427	- 0,023	
27	1295	1295	+ 00	12,99	12,980	+ 0,010	38,413	38,424	- 0,011	
28	1848			13,00	13,032	- 0,032	38,403	38,444	+ 0,041	18
29	512	511	+ 01	13,26	13,265	- 0,005	38,494	38,487	+ 0,007	
30	1698	1693	+ 05	12,98	12,987	- 0,007	38,402	38,440	- 0,038	
31	879	995	- 116	13,02	13,012	+ 0,008	38,431	38,441	- 0,010	
32	387	387	+ 00	13,25	13,258	- 0,008	38,493	38,485	+ 0,008	19
33		695			13,084		38,453	38,460	- 0,007	
34	1401	1405	- 04	12,98	12,970	+ 0,010	38,406	38,431	- 0,025	
35	1610	1588	+ 22	12,97	12,970	+ 0,000	38,404	38,433	- 0,029	
36	698	697	+ 01	13,06	13,074	- 0,014	38,453	38,457	- 0,004	
37	2024	1992	+ 32	13,02	13,008	+ 0,012	38,399	38,495	- 0,096	
38	1695	1694	+ 01	12,99	12,980	+ 0,010	38,400	38,455	- 0,055	
39	1206	1205	+ 01	12,98	12,984	- 0,004	38,420	38,450	- 0,030	
40	1808	1798	+ 10	12,99	12,984	+ 0,006	38,400	38,466	- 0,066	
42	294	294	+ 00	13,32	13,336	- 0,016	38,500	38,513	- 0,013	
45	835	943		12,99	12,991	- 0,001	38,434	38,462	- 0,028	23
46	413	406	+ 07	13,38	13,389	- 0,009	38,469	38,507	- 0,038	
47	2006	1980	+ 26	13,02	13,005	+ 0,015	38,403	38,477	- 0,075	
48	1025	992	+ 33	13,04	12,991	+ 0,049	38,430	38,452	- 0,022	
49	1702	1698	+ 04	12,99	12,977	+ 0,013	38,404	38,462	+ 0,058	
50	213	201	+ 12	13,12	13,101	+ 0,019	38,442	38,433	- 0,009	
51	1598	1600	- 02	12,98	12,966	+ 0,014	38,410	38,497	- 0,087	

Planche n° II

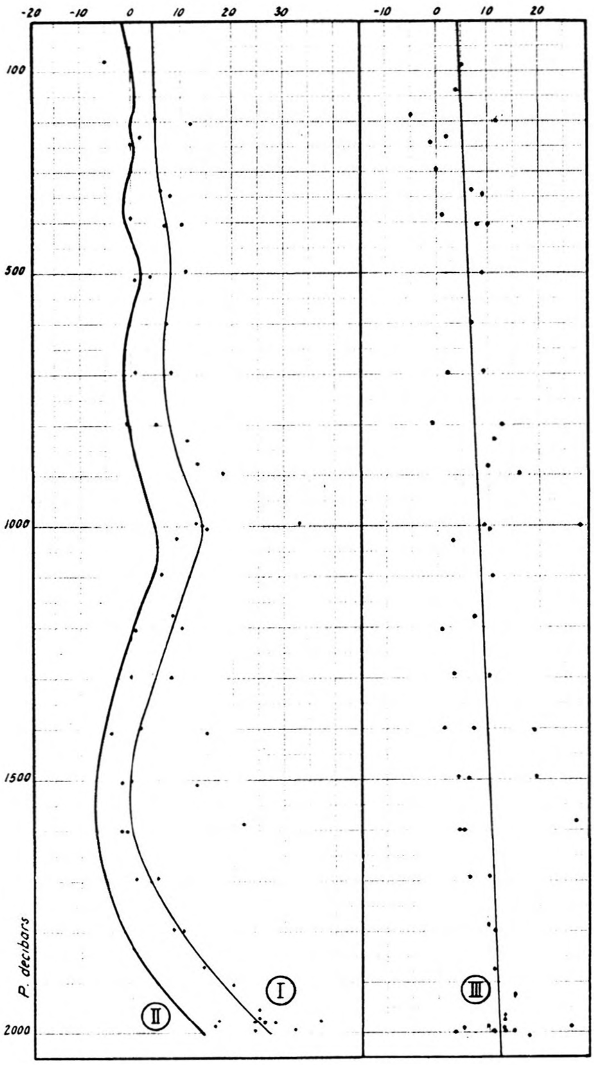
PRESENTATION DES RESULTATS BRUTS DE L'ETALONNAGE IN SITU REALISE AU COURS DE MEDOC 69

(II° Partie : station 52 à 83 φ = 0 99847)

Nota : P_H, T_H, S_H proviennent de la bouteille test.
P_W, T_W, S_W proviennent de la bathysonde.

N° Station	P_H	P_W	$\Delta P = P_H - P_W$	T_H	$T_W - 0{,}04$	$\Delta T = T_H - T_W + 0{,}04$	S_H	S_W	$\Delta S = S_H - S_W$	Observations
52	1032	1023	+ 9	13,00	13,008	- 0,008	38437	38,324	+ 0,113	
53	1995	1970	+ 25	13,00	13,005	- 0,005	38413	38,374	+ 0,039	
54	233	231	+ 2	13,29	13,295	- 0,005	38483	38,380	+ 0,103	
55	1599	1600	- 1	12,94	12,963	- 0,023	38425	38,374	+ 0,051	
56	488	604		13,09	13,081	+ 0,009	38475	38,416	+ 0,059	
57	1185	1177	+ 8	12,96	12,963	- 0,003	38426	38,394	+ 0,032	
58	1010	996	+ 14	12,97	12,973	- 0,003	38416	38,415	+ 0,001	
60	1998	1976	+ 24	13,01	13,005	+ 0,005	38392	38,435	- 0,043	
61	1016	1001	+ 15	12,96	12,970	- 0,010	38410	38,419	- 0,009	
62	1800	1792	+ 8	13,00	12,980	+ 0,020	38395	38,440	- 0,045	
63	812	797	+ 5	13,04	13,039	+ 0,001	38436	38,451	- 0,015	
64	1423	1408	+ 15	12,96	12,956	+ 0,004	38392	38,434	- 0,042	
66	1499	1501	- 2	12,99	12,980	+ 0,010	38385	38,440	- 0,055	
67	1307	1299	+ 8	12,98	12,959	+ 0,021	38398	38,430	- 0,034	
68	507	496	+ 11	13,02	13,036	- 0,016	38416	38,433	- 0,017	
69	357	349	+ 8	13,16	13,163	- 0,003	38455	38,469	- 0,014	
70	701	693	+ 8	13,07	13,070	- 0,000	38435	38,469	- 0,034	
71	200		+		13,396		38485	38,515	- 0,030	
76	892	879	+ 13	13,02	12,987	+ 0,033	38393	38,451	- 0,058	
78	2000	1984	+ 16	13,10	13,012	+ 0,088	38388	38,478	- 0,110	
79		877	+		13,084		38384	38,354	+ 0,030	
80	1924	1904	+ 20	13,00	12,994	+ 0,006	38350	38,478	- 0,128	
81	913	895	+ 18	13,03	13,012	+ 0,018	38389	38,461	- 0,072	
83	412	402	+ 10	13,42	13.412	+ 0,008	38444	38,561	- 0,117	

Planche n° III



Etalonnage en pression de la sonde n° 731

Courbe (I) $\Delta P(P) = P_H - P_W$ *Courbe d'étalonnage in situ*
(Corrections fonction de P à apporter aux pressions Howaldt)

Courbe (II) $\Delta' P(P)$ *Courbe traduisant les erreurs introduites par le calcul de traduction fréquence-paramètre*

Courbe (III) $\Delta'' P(P) = \Delta P - \Delta' P$ *Caractéristique du capteur pression.*

Etalonnage en laboratoire du capteur pression

Pression calculée	Pression mesurée en labo	Fréquence	Différence
2	0	6018	-206
50	50	6150	+007
100	100	6280	+002
148	150	6399	+165
200	200	6519	+034
249	250	6630	+058
300	300	6738	000
351	350	6843	-123
401	400	6942	-144
449	450	7032	+130
498	500	7123	+193
549	550	7214	+094
600	600	7302	+008
651	650	7387	-051
701	700	7469	-071
751	750	7549	-100
751	750	7549	-092
800	800	7629	-026
849	850	7705	+101
898	900	7779	+182
948	950	7851	+228
995	1000	7918	+468
1044	1050	7985	+562
1096	1100	8053	+431
1148	1150	8120	+226
1199	1200	8184	+114
1251	1250	8248	-137
1303	1300	8309	-273
1353	1350	8367	-274
1404	1400	8425	-392
1456	1450	8483	-628
1507	1500	8538	-703
1556	1550	8590	-600
1606	1600	8642	-593
1656	1650	8693	-586
1705	1700	8742	-471
1753	1750	8790	-342
1802	1800	8837	-193
1848	1850	8881	+191
1895	1900	8925	+503
1940	1950	8967	+961
1986	2000	9009	+1352

ANALYSIS AND DISCUSSION OF THE *IN SITU* CALIBRATION

III. 1. - ***PRESSURE CALIBRATION*** (See plate III)

Out of the 69 successful test bottle samplings only 61 pressure measurements resulting from the comparison between the two reversing thermometers were exploitable. Those wasted were the result of a malfunctioning of the thermometers.

If we plot the raw deviations $\Delta P(P) = P_H - P_W$ we obtain a whole crowd of points which tend to fall into a damped sine curve which is hardly to be accounted for by the dynamics of the sensor.

Thus, we have to refer back to the laboratory calibration and especially to the computation of the third degree polynomial :

$$P = f(F_p)$$

This is the polynomial best representing the laboratory calibration.

For P, the variation interval (0.2000) is too large for the deviations between function and calibration values to be small. A single polynomial no longer suffices, and we are obliged to split the variation interval into two parts.

In spite of this the computation for converting frequency into parameter still introduces a distortion, i.e. a systematic error, that has to be evaluated.

The table supplying the errors $\Delta P'(P)$ as functions of frequency and artificially introduced by the computation is given as part of Plate III, and the corresponding curve (curve II) has been drawn up at the same scale as curve I. We then see that curves I and II are roughly parallel.

If we now plot the values $\Delta P'' = \Delta P - \Delta P'$ (curve III) the corresponding collection of points will be distributed about a mean straight line which is characteristic of the *in situ* calibration of the pressure sensor.

The mean of the residual deviations from this straight line is practically nil, and the standard deviation is :

$$\sigma_P = 6 \text{ decibars}$$

45 out of 61 points are within the ± 6-decibar bracket.

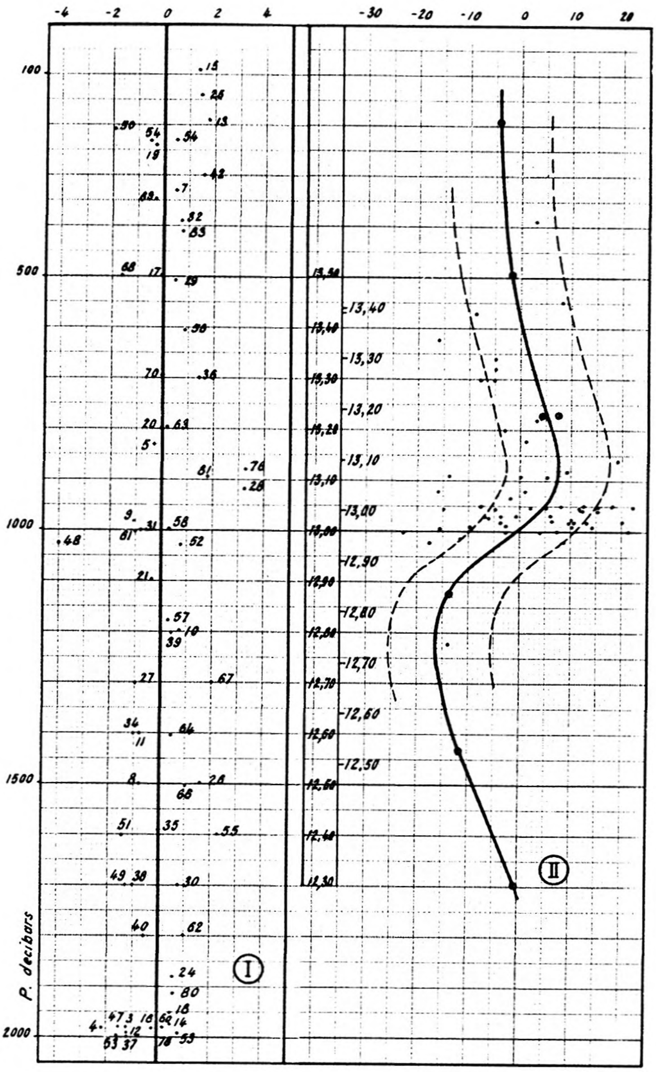
This means that these deviations are entirely aleatory and principally due to the lag of the sensor on the one hand and to the inaccuracy of the reference pressure on the other.

To sum up :

Curve $\Delta P(P) = P_H - P_W$ (Curve I) enables us to correct to within ± 6 decibars the pressures obtained from the frequencies using an inaccurate polynomial.

The straight line III is characteristic of the sensor. It is slightly influenced by pressure and of relatively good repeatability.

Planche n° IV



Etalonnage en laboratoire
de la gamme de température n°5

Tw calculée	Tw mesurée	Fréquence	Différence
10,025	10,009	1769	- 0.016
10,350	10,345	1844	- 0005
10,719	10,727	1931	+ 0008
10,990	11,009	1996	+ 0019
11,284	11,285	2068	+ 0001
11,616	11,629	2151	- 0013
11,932	11,931	2232	- 0001
12,312	12,311	2332	- 0001
12,589	12,576	2407	- 0013
12,894	12,879	2492	- 0015
13,227	13,231	2588	+ 0004
13,223	13,231	2587	+ 0008
13,515	13,513	2674	- 0002
13,806	13,801	2764	- 0005
14,149	14,149	2875	0000
14,523	14.528	3003	+ 0005

Etalonnage en température de la sonde n° 731

Graphique (I) $\Delta T(P) = T_H - (T_W - 0.04)$ en degrés Celsius. Courbe d'étalonnage in situ.

Graphique (II) $\Delta' T(T)$ Courbe traduisant les erreurs introduites par le calcul de traduction fréquence paramètre

- ● Points issus du tableau ci contre exprimant l'étalonnage en laboratoire
- . Points d'abscisse $\Delta T = T_H - T_W$

Nota : Les indices des points correspondent aux numéros de station

III. 2. - ***TEMPERATURE CALIBRATION (range 5)*** (See Plate IV)

This calibration was limited to range 5 and was for the 65 exploitable points. Five abnormal points can be noted. Following the same procedure as in the foregoing section, plate IV is made up of :

— a graph of the raw deviations

$$\Delta T(P) = T_H - (T_W - 0.04) \text{ in degrees Celsius;}$$

— a table showing the errors $\Delta T'(T)$ artificially introduced as a result of the frequency/parameter conversion;

— a graph expressing the raw ΔT's superposed on the $\Delta T'(T)$ curve.

This plate, when read in connection with the tables in plates I and II shows that :

1. To within the measurement accuracy there is no longer a pressure effect.

2. In view of the uncertainty regarding the reference measurements, the −0.04 °C correction adopted as a result of a rapid rough survey remains valid.

The mean of the raw deviations, after a −0.04 °C correction, is nil and the standard deviation is :

$$\sigma_T = 0.014 \text{ °C}$$

3. In view of the fact that the temperatures measured remained around 13.05 °C it was not possible to determine the temperature effect on the sensor.

The only detectable temperature effect arises from the systematic errors introduced during the frequency-temperature conversion.

If these errors are corrected, it is seen that the standard deviation decreases and becomes :

$$\sigma_T = 0.0105 \text{ °C}.$$

The scatter of the measurements in my opinion arises from inaccuracies in thermometer readings and not from the probe itself. If reference values read to the thousandth of a degree had been available it is very likely that it would have been possible to refine the correction to be made to the T_W measurements.

To sum up :

By means of the constant correction selected this particular study of temperature enables us to attain the accuracy of classical hydrology for temperature measurements with the probe, that is to within 1/100th of a degree Celsius.

The improvements to the sensor have therefore proved entirely satisfactory, and by doing away with the pressure effect they greatly simplify the exploitation of the measurements, in particular the deduction of salinity corrections.

III. 3. - ***SALINITY CALIBRATION*** (see plates V and VI)

Since December 1966, and thanks to the modifications adopted, for the first time correct measurements of temperature and pressure are available. We can therefore tackle the problem of salinity calculated from the Howaldt measurements.

In view of the close dependence of salinity on pressure, temperature and conductivity, the *in situ* calibration of salinity can in fact be considered as a test of the bathysonde as a whole.

For the user, it is firstly a question of making a simple comparison of S_W — a function of P_W, T_W and C_W — with the salinity of the test bottle sample, in the same way as has already been done for the other parameters.

These first comparisons, moreover, permit the determination of a mean form factor, and thus a new calculation of the exact S_W values to be used in the comparison is possible.

III.3.1. - **General aspect of this calibration**

a) As we have seen, it was necessary to adopt two different form factors, and thus to split the calibration into two parts.

— The first part concerns the comparison of 43 salinity values ($\varphi = 0.9834$) where we were able to compare our theories with the results from 23 classical stations carried out immediately after certain of the bathysonde stations.

— The second part concerns the comparison of 24 salinity values measured after the crystal tube had been changed ($\varphi = 0.99847$).

Obviously our analysis and discussion will principally concern the first, in view of the large amount of analagous information gathered from the environment.

b) The tables in plates I and II list the raw Δ S's obtained :

$$\Delta S = S_H - S_W$$

At a first glance they vary to a considerable degree, i.e.

from $+ 0.108\ ^0/_{00}$ to $-0.075\ ^0/_{00}$ for the first part of the calibration, and

from $+ 0.113\ ^0/_{00}$ to $-0.117\ ^0/_{00}$ for the second part.

c) When the 43 values of the first part of the calibration are plotted on a single graph versus pressure, each accompanied by their station number, it is seen that in spite of the apparent irregularity (see plate V) there do in fact exist certain rhythms which can be explained by :

— a discontinuous ageing of the sensor;

— a considerable and non-linear pressure effect.

Planche n° V

1^ere^ PARTIE DE L'ETALONNAGE EN SALINITE

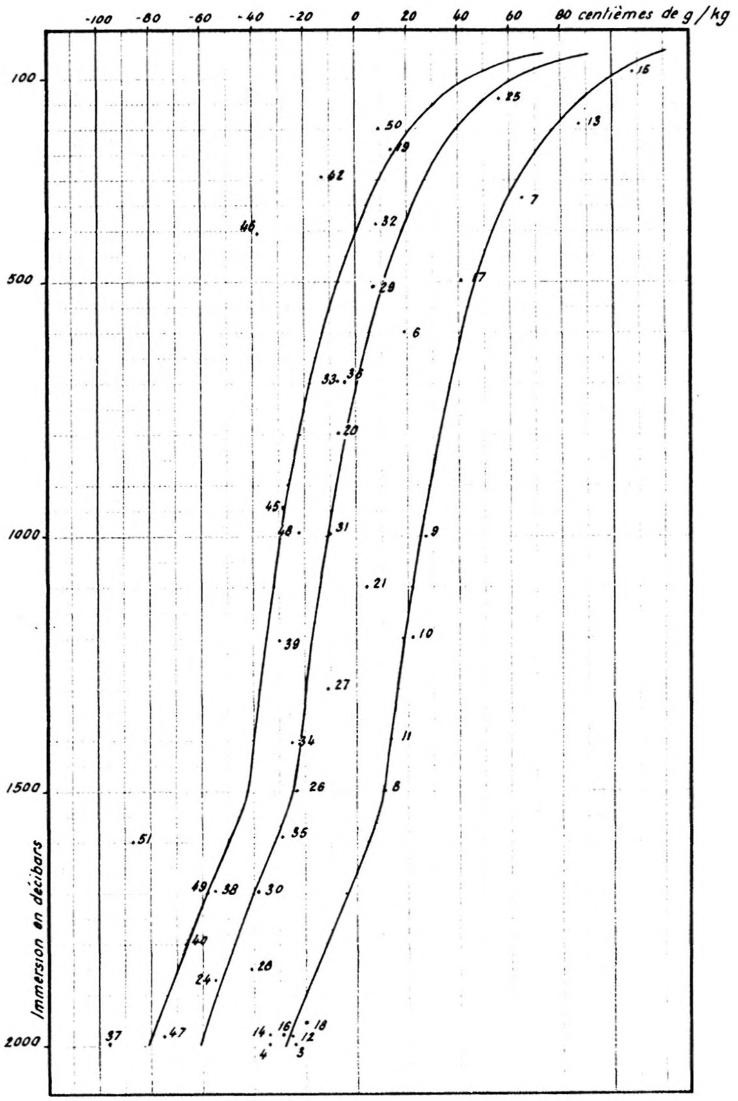


Planche n° VI

I^ère PARTIE DE L'ETALONNAGE EN SALINITÉ

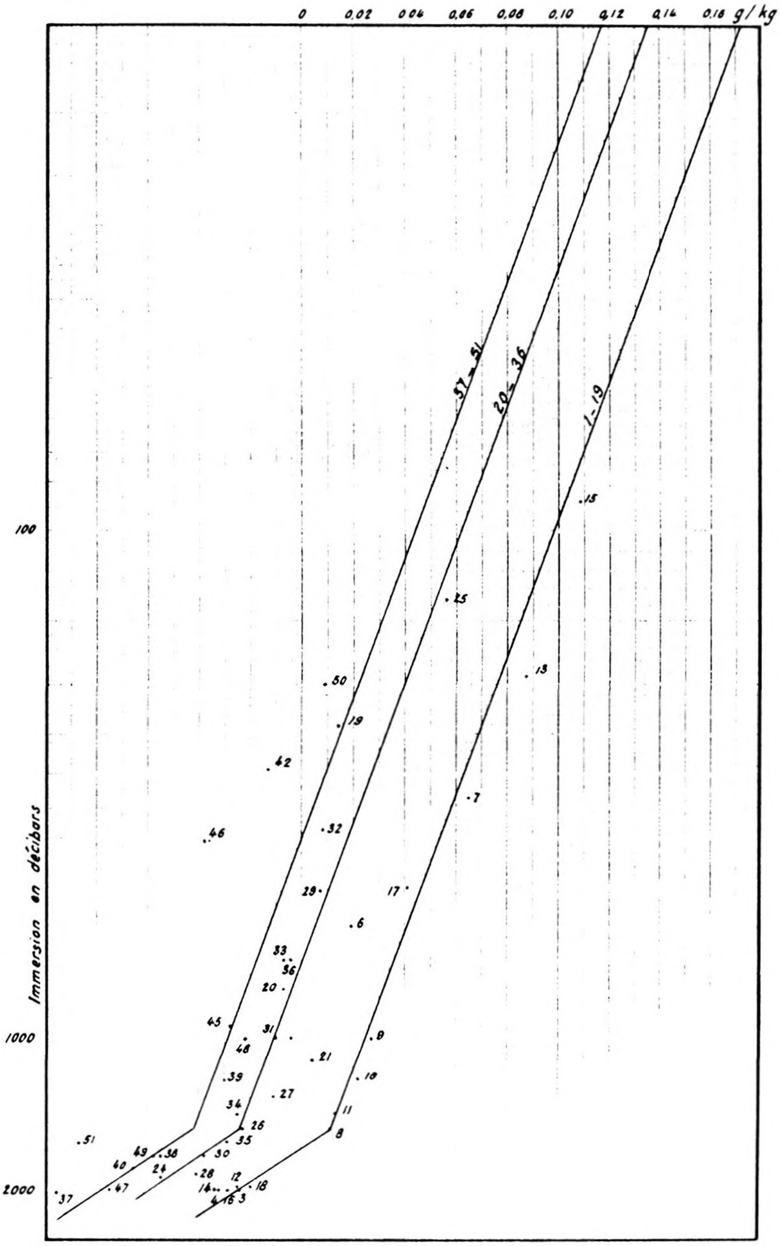
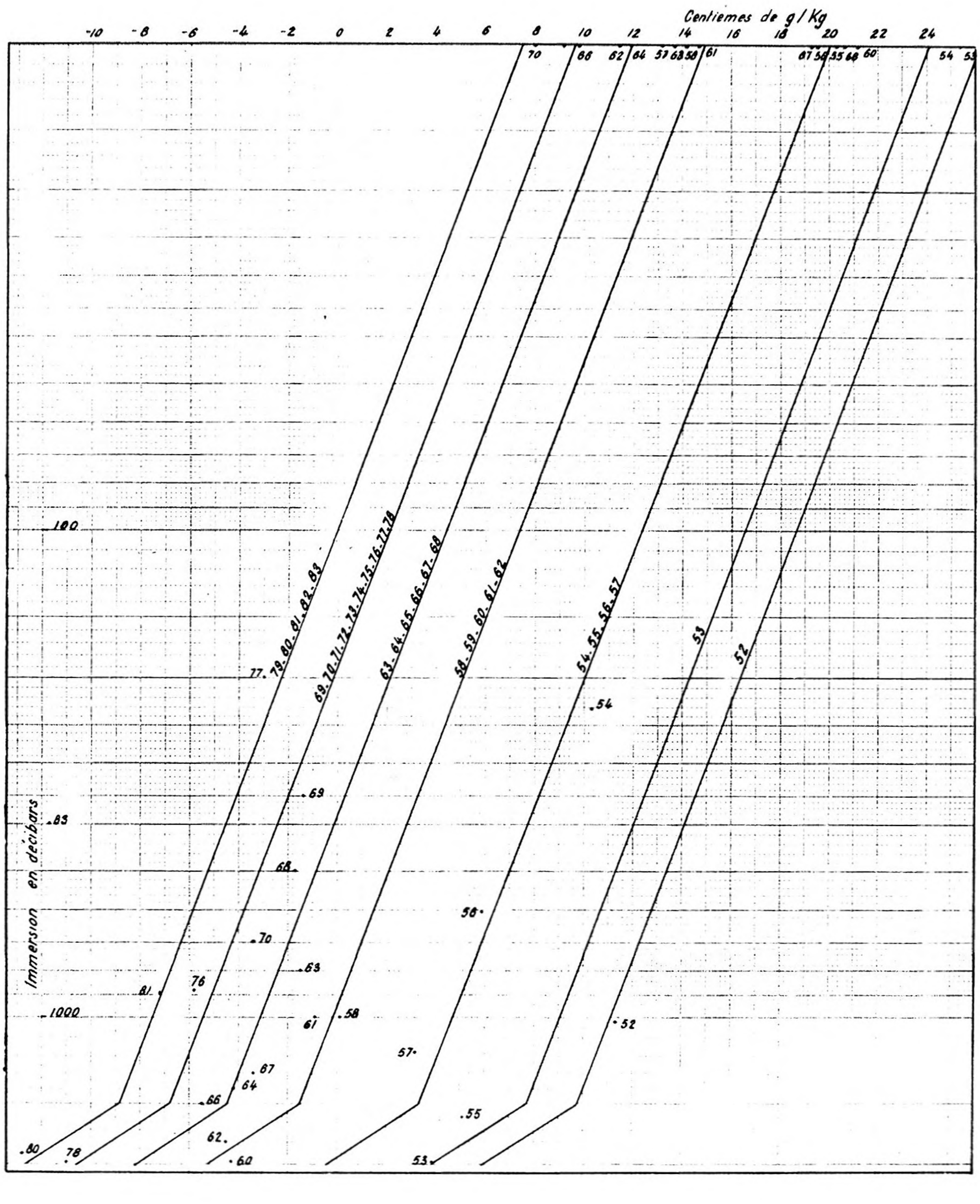


Planche n° VI   I^e PARTIE DE L'ETALONNAGE EN SALINITE



This leads us to classify the first 43 comparisons into three different groups and we find that the raw Δ S correction can be lined up on three exactly parallel curves with deviations of the order of 0.01 ‰.

The pressure effect is determined by the shape of these curves, and their progressive shifting from right to left enables the ageing of the sensor to be reckoned.

Curve I in plate V is for the first 19 stations; curve II is for stations 20 - 36 inclusive, and curve III for stations 37 - 51 inclusive.

Apart from certain abnormal points (19, 42, 46 and 51), the standard deviation for these raw points is :

$$\sigma_{1S} = 0.0084\ ‰ \text{ for } 40 \text{ values.}$$

d) The non-linearity of the pressure effect curve and the shape of the curve itself lead us quite naturally to plot the same graph against pressure in *logarithmic scale.*

The curve then shows up rather strangely as two straight lines of different slope joining at 1 500 metres (see plate VI).

e) If the 24 Δ S's of the second part of the calibration are plotted against a logarithmic scale it is seen that the resulting straight lines for this calibration are similar to those on plate II. They have the same slopes, but the ageing appears more rapid.

The standard deviation of the Δ S's from these curves is $\sigma_{2S} = 0.010$ ‰ for 22 points. It should be pointed out that to use the term standard deviation for such a small number of comparisons is a little irregular. Nevertheless it is fairly representative of the degree of accuracy attained.

III.3.2. - **Proof of the shape of the curves**

It is obvious that our reasoning about the shape of these curves is at this juncture entirely subjective and intuitive since *a priori* there is no more reason for dividing the Δ S's into groups belonging to a single correction curve than there would be to consider that they are due to other causes, as for instance the scatter of sensor data.

In order to remove this ambiguity with certainty we can call on a considerable amount of information on the classical hydrological data which will I hope convince the reader.

To simplify matters tables have been established for comparing the bathysonde salinity values at different depths to those of the classical procedures of sample analysis. The series of plates given below have been drawn up in illustration, and they merit close inspection.

a) Plates VIII and IX compare the Howaldt data, corrected according to the curves determined in III.3.1., with salinity values for surface samples :

— either taken with a bucket thermometer at the time the probe is lowered;

— or else taken during the classical hydrological station carried out immediately afterwards.

Planche n° VIII

COMPARAISON ENTRE LES SALINITES DE SURFACE PROVENANT DE LA BATHYSONDE ET DE L'HYDROLOGIE CLASSIQUE

(I° Partie : φ 0,9834)

Données bathysonde			Echantillon prélevé au cours de la descente		Echantillon de surface provenant de l'hydro-classique	
N° Station Haswell	Salinité brute de surface	Salinité Corrigée SW	Salinité échantillon de surface S_{H_1}	$\Delta_1 = S_{H_1} - S_W$	Salinité de surface S_{H_2}	$\Delta_2 = S_{H_2} - S_W$
1	37,861	38,033	38,031	− 0,002	38,004	− 0,029
2	37,984	38,156	38,156	0,000		
3	37,926	38,098	38,134	+ 0,036	38,041	− 0,057
4	38,006	38,178	38,206	+ 0,028	38,195	+ 0,017
5	37,783	37,955	37,960	+ 0,005	37,982	+ 0,027
6	37,904	38,076	38,062	− 0,014	38,021	− 0,055
7	37,892	38,064	38,371	+ 0,307	38,014	− 0,050
8	37,821	37,993			37,994	+ 0,001
9	38,076	38,248			38,187	− 0,061
10	38,115	38,287			38,252	− 0,035
11	38,152	38,324	38,461	+ 0,137	38,353	+ 0,029
13	38,146	38,318			38,311	− 0,007
15	37,988	38,160			38,126	− 0,034
17	37,982	38,154	38,215	+ 0,061		
18	37,908	38,080			38,033	− 0,047
19	37,908	38,080	38,036	− 0,044		
20	37,865	38,005			38,059	+ 0,054
21	37,898	38,038	38,050	+ 0,012		
22	37,922	38,062	38,060	− 0,002	38,054	− 0,008
25	37,874	38,014			37,983	− 0,031
26	38,037	38,177	38,190	+ 0,013		
27	37,846	37,986	38,114	+ 0,128		
28	37,946	38,086	38,074	− 0,012	38,060	− 0,026
29	37,886	38,026	38,066	+ 0,040		
30	37,870	38,010	37,981	− 0,028		
32	37,965	38,105			38,128	+ 0,013
33	37,854	37,994	38,000	+ 0,006		
34	37,912	38,052	38,014	− 0,038		
35	38,022	38,162	38,192	+ 0,030		
36	37,862	38,002	38,087	+ 0,085		
38	37,829	37,951	38,139	+ 0,188		
39	37,906	38,028	38,024	− 0,004		
40	37,931	38,053	38,031	− 0,022		
41	37,937	38,059			38,065	+ 0,006
43	38,099	38,221			38,121	− 0,100
45	37,811	37,933			38,110	+ 0,177
47	37,947	38,069	38,269	+ 0,200		
48	37,912	38,034	38,254	+ 0,220		

Planche n° IX

COMPARAISON ENTRE LES SALINITES DE SURFACE PROVENANT DE LA BATHYSONDE ET CELLES PROVENANT D'ECHANTILLONS PRELEVES AU COURS DE LA DESCENTE

(II° Parhe = φ 099847.)

	Echantillon de surface	Données bathysonde		
N° Station	Salinité de Surface SH	Salinité brute	Salinité corrigée SW	SH - SW
52	38.267	37,867	38,129	+ 0,138
53	38.215	37,956	38,200	+ 0,015
54	38,300	38,046	38,256	+ 0,044
55	38,291	38,088	38,298	- 0,007
56	38,278	38,083	38,271	+ 0,007
57	38,273	38,141	38,329	- 0,056
58	38,251	38,089	38,243	- 0,012
60	38,280	38.069	38,223	+ 0,057
61	38.298	38,151	38,291	+ 0,007
62	38.263	38,149	38,277	- 0,014
63	38,288	38,151	38,279	+ 0,009
64	38,311	38,193	38,301	0,000
65	38,246	38,097	38,215	+ 0,031
66	38,198	38,100	38,206	- 0,008
67	38.190	37,996	38,102	+ 0,088
68	38,166	37,960	38,066	+ 0,100
69	38,350	38,122	38,228	+ 0,122
70	38,261	38,181	38,287	- 0,026
71	38,243	38,199	38,297	- 0,054
72	38,166	38,065	38,167	- 0,001
73	38,333	38,181	38,279	+ 0,054
74	38,190	38,117	38,205	- 0,015
75	38,255	38,112	38,210	+ 0,045
76	38,215	38,035	38,119	+ 0,096
77	38,092	37,941	38,025	+ 0,067
78	38,214	38,066	38,150	+ 0,064
79	38,153	38,107	38,179	- 0,026
80	38.226	38,234	38.306	- 0,080
81	38,303	38,273	38,345	- 0,042
82	38,274	38.250	38,322	- 0,042
83	88,325	38,232		

The plates each concern one part of the calibration, and furthermore they enable us to define the ends of the curves in small depths.

Unfortunately they show a fairly large scatter, the deviations being due, it would seem, to the rapid fluctuations of surface water, since this scatter is of the same order as that between the deviations in two samples taken at about an hour's interval.

We should however note that not only do the deviations Δ_1 and Δ_2 remain distinctly smaller than the corrections made but also since the correction curves tend asymptotically to infinity when the instrument is at the surface, it is not surprising to find such variation between one point and another.

b) This comparison with classical hydrology is now applied to other levels that are less favourable than the surface. We shall see — and this is logical — that the deviation bracket decreases with depth, that is to say progressively as the water becomes more stable, and as a result gives rise to increasingly justifiable comparisons at intervals of both time and place. Thus :

— plate X gives a table of comparisons around the 15-decibar level.

The deviations range between $-0.057\,^0/_{00}$ and $+0.024\,^0/_{00}$ over 22 points, whereas the corrections made are of the order of $0.15\,^0/_{00}$.

— plate XI sets out the same comparison at approximately the 800-decibar level.

Here the scatter of the deviations, varying between $+\,0.042\,^0/_{00}$ and $-0.014\,^0/_{00}$, is distinctly less, and there is a good fit with the correction curves :

— at the 1 500-decibar level (see plate XII) the deviation bracket is even better. The mean of the deviations is nearly zero, and over 34 comparisons the standard deviation is $0.014\,^0/_{00}$. (For this comparison the values obtained both when lowering and raising the bathysonde have been used);

— plate XIII is a little different, containing besides the foregoing comparisons the salinity values observed at 2 000 decibars over 49 stations. It is a known fact that at this time of year and at this depth these waters are particularly stable and that their salinity is close to $38.407\,^0/_{00}$, and this in fact is what is obtained with a standard deviation of $0.008\,^0/_{00}$ and confirmed by classical hydrological measurements.

Note :

Plate XIII also provides an additional piece of information which is that, contrary to what might have been thought at the beginning, the ageing is continuous, not discontinuous. It is only perceptible when it is sufficiently significant, i.e. about $0.02\,^0/_{00}$.

This is very easy to see where the salinity values vary at 2 000 db, for so long as only a single correction curve is concerned, these values increase slowly and progressively from station to station until they regain their normal value at the point where the curves change.

Planche n° X

COMPARAISON ENTRE LES DONNEES BATHYSONDE ET L'HYDROLOGIE CLASSIQUE AUX ALENTOURS DE 15 DECIBARS

(I° Partie)

Résultats hydrologie classique			Données bathysonde			
N° Station	Salinité Hydro à 10 mètres	Salinité Hydro à 13 mètres	N° Station	Salinité brute à 15 mètres	Salinité corrigée	Ecarts $S_H - S_W$
1	38,006	38,012	1	37,884	38,042	- 0,030
2	38,186	38,191	2	38,018	38,176	+ 0,015
3	38,043	38,044	3	37,920	38,078	- 0,034
4	38,161	38,173	4	38,022	38,180	- 0,007
5	37,984	37,380	5	37,879	38,037	- 0,057
6	38,023	38,023	6	37,913	38,071	- 0,048
7	38,011	38,012	7	37,897	38,055	- 0,043
8	38,002	38,004	8	37,888	38,046	- 0,042
9	38,200	38,208	9	38,075	38,233	- 0,025
10	38,252	38,253	10	38,112	38,270	- 0,017
11	38,352	38,348	11	38,219	38,377	- 0,029
12	38,321	38,327	13	38,185	38,343	- 0,016
13	38,128	38,127	15	37,995	38,153	- 0,026
14	38,033	38,030	18	37,913	38,066	- 0,036
15	38,060	38,060	20	37,910	38,036	+ 0,024
16	38,053	38,054	22	37,938	38,064	- 0,010
17	37,982	37,985	25	37,884	38,024	- 0,039
18	38,062	38,063	28	37,934	38,060	+ 0,003
19	38,117	38,126	32	38,010	38,136	- 0,010
20	38,040	38,041	41	37,940	38,048	- 0,007
21	38,118	38,179	43	38,059	38,167	+ 0,012
23	38,113	38,114	45	38,017	38,125	- 0,011
24	37,993	38,003				
25	38,240	38,261				

Planche n° XI

COMPARAISON ENTRE LES DONNEES BATHYSONDE ET LES RESULTATS DE L'HYDROLOGIE CLASSIQUE AUX ALENTOURS DE 800 DECIBARS

1° Partie de l'étalonnage en salinité

Résultats hydrologie classique			Données bathysonde					
N° Station	Immersion bouteille	Salinité S_H	N° Station	Correction immersion	Immersion corrigée	Salinité brute	Salinité corrigée	Ecarts $S_H - S_W$
1	783	38,465	1	-5	778	38,410	38,440	+ 0,025
						38,425	38,456	+ 0,009
3	772	38,453	3	-5	767			
4	711	38,459	4	-5	706	38,422	38,456	+ 0,003
5	760	38,475	5	-5	755	38,443	38,473	+ 0,002
						38,450	38,480	- 0,005
6	873	38,467	6	-5	868	38,430	38,460	+ 0,007
						38,450	38,480	- 0,013
8	757	38,475	8	-5	752	38,406	38,438	+ 0,037
						38,412	38,444	+ 0,031
9	804	38,452	9	-5	779	38,394	38,424	+ 0,028
						38,406	38,434	+ 0,018
10	836	38,461	10	-5	831	38,418	38,448	+ 0,013
						38,426	38,456	+ 0,005
11	792	38,448	11	-5	787	38,392	38,422	+ 0,026
						38,409	38,439	+ 0,009
12	773	38,442	13	-5	768	38,403	38,433	+ 0,009
						38,406	38,436	+ 0,006
13	816	38,444	15	-5	811	38,428	38,458	- 0,014
						38,423	38,453	- 0,009
14	808	38,456	18	-5	803	38,414	38,444	+ 0,012
						38,434	38,464	- 0,008
15	820	38,457	20	-5	815	38,418	38,418	+ 0,039
						38,415	38,415	+ 0,042
16	800	38,466	22	-5	795	38,460	38,460	+ 0,006
						38,460	38,460	+ 0,006
17	819	38,481	25	-5	814	38,443	38,443	+ 0,038
						38,452	38,452	+ 0,029
18	813	38,454	28	-5	808	38,459	38,459	- 0,005
						38,444	38,444	+ 0,010
19	816	38,453	32	-5	811	38,441	38,441	+ 0,012
						38,458	38,458	- 0,005
20	810	38,454	41	-5	805	38,447	38,430	+ 0,020
						38,472	38,454	0,000
21	814	38,447	43	-5	809	38,463	38,445	+ 0,002
						38,479	38,461	- 0,014
22	802	38,475	44	-5	797			
23	780	38,454	45	-5	775	38,382	38,364	
						38,475	38,457	- 0,003

Planche n° XII

COMPARAISON ENTRE LES DONNEES DE LA BATHYSONDE ET LES RESULTATS DE L'HYDROLOGIE CLASSIQUE AUX ALENTOURS DE 1500 DECIBARS

(1° Partie de l'étalonnage en salinité)

Résultats hydrologie classique			Données bathysonde					
N° Station	Immersion de la bouteille	Salinité S_H	N° Station	Correction immersion	Immersion corrigée	Salinité brute	Salinité corrigée S_W	Ecarts $S_H - S_W$
1	1465	38,440	1	8	1457	38,386	38,396	+ 0,044
						38,400	38,410	+ 0,030
4	1452	38,411	4	8	1448	38,412	38,422	- 0,011
						38,411	38,421	- 0,010
8	1490	38,421	8	8	1482	38,398	38,408	+ 0,013
						38,403	38,413	+ 0,008
9	1511	38,435	9	8	1503	38,407	38,417	+ 0,018
						38,411	38,421	+ 0,014
10	1560	38,422	10	8	1552	38,415	38,425	- 0,003
						38,419	38,429	- 0,007
11	1518	38,412	11	8	1510	38,402	38,412	0,000
						38,406	38,416	- 0,004
12	1563	38,408	13	8	1555	38,405	38,415	- 0,007
						38,413	38,423	- 0,015
13	1537	38,411	15	8	1529	38,419	38,429	- 0,018
						38,428	38,438	- 0,027
14	1519	38,423	18	8	1511	38,398	38,408	+ 0,015
						38,400	38,410	+ 0,013
15	1544	38,419	20	8	1536	38,426	38,406	+ 0,013
						38,423	38,403	+ 0,016
16	1500	38,431	22	8	1492	38,447	38,427	+ 0,004
						38,444	38,424	+ 0,007
17	1545	38,416	25	8	1537	38,430	38,410	+ 0,006
						38,434	38,414	+ 0,002
18	1531	38,414	28	8	1523	38,438	38,418	- 0,004
						38,432	38,412	- 0,002
19	1532	38,420	32	8	1524	38,447	38,427	- 0,007
						38,451	38,431	- 0,011
20	1500	38,415	41	8	1492	38,457	38,417	- 0,002
						38,457	38,417	- 0,002
21	1498	38,411	43	8	1490	38,459	38,419	- 0,008
						38,466	38,426	- 0,015
23	1462	38,431	45	8	1454	38,458	38,418	+ 0,013
						38,464	38,424	+ 0,007

Planche n° XIII

RELEVEE DES SALINITES BATHYSONDE A 2000 DECIBARS ET COMPARAISON AVEC L'HYDROLOGIE CLASSIQUE

(1° Partie de l'étalonnage en salinité)

Données bathysonde					Résultats hydrologie classique			
N° Station	Immersion	Salinité brute	Salinité corrigée S_w	Moyenne Montée - descente	N° Station	Immersion	Salinité S_H	Observations
1	1973	38,424	38,396	38,396				
2	1966	38,432	38,404	38,404				
	1978	38,431	38,403					
3	1978	38,431	38,403	38,404	3	1965	38,444	SH douteux
	1958	38,434	38,406					
4	1977	38,444	38,416	38,415	4	1970	38,400	
	1978	38,442	38,414					
9	1895	38,438	38,410	38,406				
	1881	38,431	38,403					
11	1979	38,442	38,414	38,416	11	2046	38,410	
		38,446	38,418					
12	1979	38,434	38,406	38,408				
		38,438	38,410					
13	1978	38,442	38,414	38,414				
		38,442	38,414					
14	1974	38,448	38,420	38,420				
	1978	38,449	38,421					
15	1981	38,446	38,418	38,421	13	2052	38,396	
	1967	38,432	38,424					
16	1978	38,443	38,415	38,419				
	1981	38,451	38,423					
17	1981	38,453	38,425	38,422				
	1985	38,448	38,420					
18	1970	38,429	38,401	38,397	14	2030	38,447	SH douteux
	1948	38,421	38,393					
19	1976	38,444	38,416	38,413				
	1946	38,438	38,410					
20	1978	38,463	38,403	38,400	15	2064	38,416	
	1973	38,458	38,398					
21	1968	38,465	38,405	38,403				
	1960	38,461	38,401					
22	1969	38,467	38,407	38,402	16	2000	38,418	
	1955	38,458	38,398					
23	1978	38,453	38,393	38,393				
	1962	38,454	38,394					
24	1978	38,462	38,402	38,402				
25	1972	38,462	38,402	38,404	17	2061	38,409	
	1983	38,467	38,407					
26	1988	38,452	38,392	38,391				
	1988	38,451	38,391					
27	1975	38,468	38,408	38,406				
	1982	38,465	38,405					

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N° Station	Immersion	Salinité brute	Salinité corrigée Sw	Moyenne Montée-descente	N° Station	Immersion	Salinité S_H	Observations
28	1982	38,462	38,402	38,402	18	2046	38,406	
		38,463	38,403					
29	1975	38,470	38,410	38,408				
	1976	38,466	38,406					
30	1983	38,472	38,412	38,408				
	1985	38,464	38,404					
31	1980	38,466	38,406	38,408				
	1980	38,471	38,411					
32	1968	38,478	38,418	38,419	19	2043	38,407	
		38,480	38,420					
33	1981	38,474	38,414	38,411				
	1971	38,469	38,409					
34	1972	38,481	38,421	38,417				
	1970	38,473	38,413					
35	1979	38,472	38,412	38,412				
	1984	38,473	38,413					
36	1980	38,475	38,415	38,411				
	1980	38,468	38,408					
37	1989	38,483	38,403	38,402				
	1992	38,481	38,401					
38	1978	38,486	38,406	38,408				
	1978	38,480	38,400					
39	1973	38,479	38,399	38,398				
	1962	38,478	38,398					
40	1986	38,486	38,406	38,406				
41	1984	38,482	38,402	38,403	20	2038	38,407	
	1948	38,484	38,404					
42	1979	38,489	38,409	38,409				
43	1978	38,495	38,415	38,413	21	1992	38,407	
	1979	38,491	38,411					
45	1971	38,496	38,416	38,417				
	1967	38,499	38,419					
47	1980	38,470	38,390	38,388				
	1977	38,467	38,387					
49	1974	38,493	38,413	38,413				
	1974	38,494	38,414					

To sum up :

This has been a somewhat lengthy and irksome examination of the question, but in my belief wholly necessary, for it fully corroborates the curves which had initially been chosen rather by intuition.

The final adoption of these curves leads to the adoption of an overall precision of ± 0.009 g/kg for the 81 stations, the exception being perhaps the first ten metres.

III.3.3. - **Refining the precision**

The above investigation, or rather the establishment of the curves of plates VI and VII from tables I and II, does not in fact take into account the errors artificially introduced when converting frequencies into the parameters for P_W, T_W and C_W.

And this is for the essential reason that such errors are introduced by the computer and their correction is not a simple matter, and will demand yet further time-consuming adjustments in computer programming.

Nevertheless we have seen that if we confine ourselves to the established calibration formulae the accuracy of the Howaldt data when processed and calculated is :

± 0.014 °C for temperature
± 0.009 $^0/_{00}$ for salinity

The pressure accuracies vary between 8 and 30 decibars, according to depth.

We have also seen that if computation errors are taken into account we are able to reduce the accuracies to :

± 6 decibars for pressure

and

± 0.010 °C for temperature

Let us now see what exactly will be the accuracy we may hope to obtain for salinity.

In order to do this I have had the salinity values of the first part of the calibration computed from the bathysonde P, T and C values and then corrected manually for all errors introduced by the frequency-parameter conversion algorithms.

This computation led to the table shown as plate XIV which is derived from plate VI.

If the points for Δ S (P) are marked on a graph (see plate XIV) opposite points of the same definition from plate I we shall see that the curves do not differ from those of plate VI, the only exception being depths of over 1 500 metres where the error is dominant. The standard deviation alone decreases, becoming

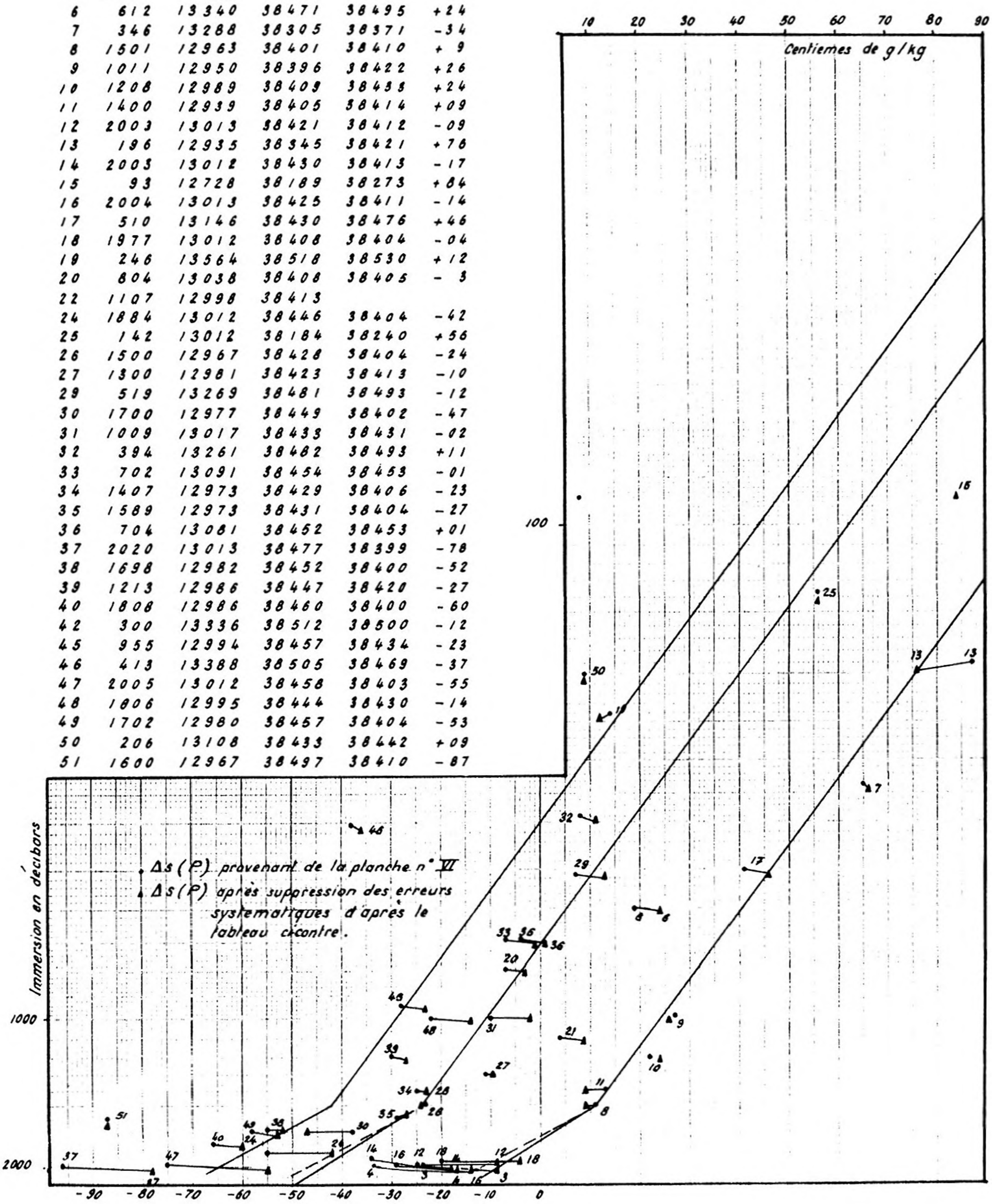
$$\sigma_S = 0.0081 \ \%.$$

And this is thus the accuracy which may be obtained for salinity using the Howaldt bathysonde.

N° Station	Pw corrigée	Tw corrigée	Sw corrigée	S_H	Δs
3	2002	13013	38413	38404	-09
4	2002	13013	38428	38409	-09
6	612	13340	38471	38495	+24
7	346	13288	38305	38371	-34
8	1501	12963	38401	38410	+ 9
9	1011	12950	38396	38422	+26
10	1208	12989	38409	38433	+24
11	1400	12939	38405	38414	+09
12	2003	13013	38421	38412	-09
13	196	12935	38345	38421	+76
14	2003	13012	38430	38413	-17
15	93	12728	38189	38273	+84
16	2004	13013	38425	38411	-14
17	510	13146	38430	38476	+46
18	1977	13012	38408	38404	-04
19	246	13564	38518	38530	+12
20	804	13038	38408	38405	- 3
22	1107	12998	38413		
24	1884	13012	38446	38404	-42
25	142	13012	38184	38240	+56
26	1500	12967	38428	38404	-24
27	1300	12981	38423	38413	-10
29	519	13269	38481	38493	-12
30	1700	12977	38449	38402	-47
31	1009	13017	38433	38431	-02
32	394	13261	38482	38493	+11
33	702	13091	38454	38453	-01
34	1407	12973	38429	38406	-23
35	1589	12973	38431	38404	-27
36	704	13081	38452	38453	+01
37	2020	13013	38477	38399	-78
38	1698	12982	38452	38400	-52
39	1213	12986	38447	38420	-27
40	1808	12986	38460	38400	-60
42	300	13336	38512	38500	-12
45	955	12994	38457	38434	-23
46	413	13388	38505	38469	-37
47	2005	13012	38458	38403	-55
48	1806	12995	38444	38430	-14
49	1702	12980	38457	38404	-53
50	206	13108	38433	38442	+09
51	1600	12967	38497	38410	-87

Planche n° XIV

Etalonnage en salinité après suppression des erreurs introduites par la transformation fréquence-paramètre



III.3.4. - **Remarks on the present investigation**

The aims I set myself at the beginning of the MEDOC 69 project have, I think, been largely attained, and the present study shows both sufficiently and clearly that measurements with the Howaldt bathysonde are *in certain cases* able to broadly rival the classical measurements.

But to my mind there is still a necessity to go further into the matter, and to seek some theoretical justification for the shape of the curves and their evolution in time. For this we need to return to the conductivity sensor.

1. The conductivity sensor is made up of two μ-metal insulated coils coupled through a crystal or pyrex tube filled with sea water.

The two coils which are connected to the outer cover of the bathysonde are naturally placed in a container that is pressure proof. This container is ring-shaped and can be in the form of a thick-walled hollow cylinder open at both ends in which the crystal tube can be inserted.

As it will never be possible to make the cavity between container and tube a perfect fit it is filled with insulating oil (denser than water) and is pressure-balanced by means of an oil-filled vial placed on top of the sensor and linked to the cavity by a tiny tube.

It is obvious that this equipressure is essential, in order to avoid the tube breaking or buckling.

Two things should be noted :

— the oil in the vial comes into direct contact with the less dense sea water through a hole at the top of the vial;

— in view of the difficulties of inserting the crystal tube between the cylinder joints and on account of the system for filling the cavity from the vial it will be impossible to eliminate air bubbles in the pressure balanced cavity.

2. Relating these two facts to the curves obtained it is thought that the following checks should be made as soon as possible :

— that the pressure effect, plotted as a straight line as a function of log (P), is due to the variation of the volume of the air bubbles, leading to a variation in the coil coupling. (This phenomenon is strangely similar to the one encountered in laboratory conductimeters.)

It should be noted that :

— the compression of the tube, itself leading to a variation of the form factor, can also introduce the pressure effect;

— in addition to the ageing of the circuits, the rapid and considerable changes in the sensor can be due to the fact that the sea water mixes partially and progressively with the oil, or else even simply that certain ions are miscible.

This happens as a result of the pressure effect, thus giving rise to a decrease in the oil's resistivity and consequently a variation in the sensor.

In this connection it is important to note the flattening of the curves at the left hand side, as if there were a tendency towards saturation. This phenomenon is particularly clear on plate VI for the case of the first stations after the tube (and consequently the oil) had been changed.

These entirely intuitive conjectures will be well worth following up, and this is shortly to be undertaken at the B.E.O.

To do away with the bubble effect it will in fact be necessary to use an oil bath in which the processes of filling the cavity and inserting the tube are carried out, thus eliminating the bubbles.

As to the ageing of the oil itself, it will suffice to carry out the pressure balancing in a watertight pressure-sensitive vial of sea water.

A series of sea trials incorporating these small modifications will probably confirm these theories.

We may note that the above procedure is the one used by HYTECH.

3. Finally, to explain the variation in slope of the calibration beyond 1 500 metres — which can no longer be logically explained by the bubble effect — it is permissible to consider, all else equal, that the abrupt decrease in the salinity correction — and consequently the equivalent increase in conductivity — may be due to an *ionic dissociation under the pressure effect* of certain weak molecules such as carbonic acid CO_3H_2 (see RILEY) or sulphate of magnesium SO_4Mg.

This third hypothesis will be much more difficult to verify, and also more troublesome, since it demands a more precise definition of salinity from conductivity, but it would be possible if the four-sensor SCAMO bathysonde of the future becomes available as this would enable speed of sound in addition to pressure, temperature and conductivity to be measured, thus allowing verification of this speed computed from other three parameters by a comparison with the actual measured speed of sound.

However, basing ourselves on the stability of near bottom waters, preliminary tests can be carried out in the near future making separate use of a velocimeter and the Howaldt bathysonde. It is not certain, however, that this experiment will be very convincing in view of environmental variations and of certain approximations in the formulae for computing the velocity of sound.

A GENERAL CONCLUSION, AND PROSPECTS FOR THE FUTURE

In spite of the very restrictive conditions of the MEDOC 69 project a first step has undeniably been made.

It is important that we now draw some conclusions for the future.

We are still in fact far from being at the end of our difficulties for :

— the conductivity sensor must be improved so as to reduce the excessively large amount of corrections to the salinity values;

— the sub-range switch must be made to function reliably, or alternatively the system must be completely modified;

— the programmes for computing and processing the data must be improved (as well as their storage processes), and an entirely automatic processing must be achieved;

— the calibration procedures at sea will have to be precisely defined, and they will have to be adapted to allow for changes in range;

— from these first prototypes definite conclusions on both use and operation remain to be drawn in order to be able to make practical improvements to future probes.

I hope that this paper will have allowed me to reveal — in simple language for the non-expert — some of the secrets of the mysterious and puzzling devices that bathysondes nevertheless still remain. I hope too that I shall have contributed to the increased use of electronic probes, to their improvement and to their unrestricted use. I should also like to recall the main principles of use for these probes for it is these alone that have made such accurate results possible. It is an absolute necessity that :

— all measurements entering into the computation of parameters whose laws of variation we are seeking be simultaneous (probably to within the sensors' time constant);

— additional laboratory and *in situ* measurements be evolved and then carried out with great rigour. In particular the reference measurements and the probe measurements must be simultaneous both in time and space. Moreover, a *time loss* has now to be accepted so that the probe can be calibrated from time to time during the campaign, as well as after any damage to the sensor as a result of a station of extended duration for obtaining about 20 check points between 0 and 2 000 metres.

This operation will doubtless be greatly facilitated by the use of the remote-controlled multi-samplers supplying 6 check points per lowering that are now being designed at the B.E.O.

It will then perhaps be possible to do away entirely with the traditional techniques based on the reversing bottle, which are long and tedious and necessitate manual handling, by providing the means of carrying out rapid automatic stations combining the use of a probe for measuring physical parameters and a remote controlled multi-sampler. We should thus be able to control the probe as well as to obtain measurements of the chemical parameters.

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Editor's note : In addition to the appendix published here, the author included one showing the computation of salinity from *in situ* measurements of electric conductivity at temperature T and pressure P.

This appendix has been omitted as it was not considered indispensable to the understanding of the present article. The reader may refer to the article "Redefinition of salinity" published in the July 1970 issue of the *International Hydrographic Review*.

Appendix

COMPARAISON DE DIAGRAMMES T. S OBTENUS
A L'AIDE DE LA BATHYSONDE ET DE L'HYDROLOGIE CLASSIQUE