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Measurement of salinity with a new  
ultrasonic salinity sensor.

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Summary

The paper describes a way of measuring salinity by direct measurements of the fraction of total sound velocity that is dependent of salinity only. Preliminary experiments indicate an obtainable precision of appr.  $1/100$  ‰. The design seeks to obtain a high degree of long term stability at the cost of reduced bandwidth.

## Introduction

Measurements of salinity are essential for the determination of density structures and for the identification of water masses in the ocean. Before the era of electronics the salinity was computed from chlorinity measured by filtration of a water sample taken as a result of a hydrographic cast. The development of various electronic sensors has now made it convenient to perform in situ measurements of salinity as a function of conductivity. Several empirical equations are at present available and used to compute salinity from measurements of conductivity, pressure and temperature. Empirical equations that relate salinity to sound velocity, temperature and pressure are also available. These equations have a typical appearance like,

$$C = C_0 + A_1 \Delta T + A_2 \Delta P + A_3 \Delta S + A_4 \Delta P \cdot \Delta T \cdot \Delta S \quad (1)$$

where  $C_0$  represents the sound velocity at a reference condition (e.g.  $0^\circ\text{C}$ , 1atm,  $35,000^\circ/\text{oo}$ ).

$A_1$ ,  $A_2$ ,  $A_3$  and  $A_4$  are fourth orders polominals, and  $\Delta T$ ,  $\Delta P$  and  $\Delta S$  represent the difference between the actual physical conditions and the reference condition.

The best known equations that express the sound velocity as a function of pressure, temperature and salinity are made by Vilson (ref.1), Del Grosso (ref.2) and Lovett (ref.3).

Although they have been often referred to , they have til now been of little practical use for the determination of salinity.

This is both due to the low precision obtained when trying to use them and the increasing sophistication in the development of salinity sensors based on the measurement of conductivity.

However from an instrumentation point of view, the measurement of sound velocity can now be done with a much better confidence than a measurement of conductivity.

A conductivity measurement normally involves an electrode to water interface. This interface is always dependent of a number of unknown electro-

chemical processes that take part at the surface. Fouling of the conductivity cell - which will always happen in the long run - tend to both disturb the electrochemical stability and to change the conductivity cell constant due to changes in the cell geometry.

In comparison ultrasonic waves from a sound velocity sensor may emerge from electrically completely insulated piezoelectric elements. Thus no electrochemical activity will take place. Fouling of the sound velocity sensor surfaces have normally a neglectable effect on the sound velocity measurement, as the ultrasonic signals involved penetrate biological fouling materials with no measurable extra damping.

When using the referred equations to determine salinity, one normally experiences an error in the determination ranging from about  $0,2^{\circ}/\text{oo}$  to  $0,05^{\circ}/\text{oo}$ . According to a recent analysis by Emery (ref.4) the errors are both due to errors in the determination of sound velocity, temperature and pressure and to errors in the equations. Fig.1 shows a comparison of salinities computed from equations made by Lovett, del Grosso and Wilson. Obviously not all of them can be right.

A way to measure the salinity by acoustic methods and simultaneously overcome the imperfections of the equations has now been developed by a group from The Institute of Marine Research, the Geophysical Institute and Chr. Michelsen's Institute in Bergen. Their contribution is the acoustical salinity cell as shown on Fig.2.

The new cell has predominantly been developed to make possible long term stable monitorings of the salinity in regions where frequent access to the instrument is impractical. This applies in particular to polar regions where access to the instrument often is limited to once per year. The main goal with the design has thus been to obtain stability. Response time which is very important in f. ex. profiling CTD's is of minor importance in this application.

The sensor consists of two piezoelectric crystals mounted side by side. At a fixed distance from the crystals - kept in position by a three bars made from invar steel - is a common reflector. When excited by electrical impulses both crystals emit a damped train of acoustical oscillations that penetrate the encapsulation and propagate to the reflector and back to the crystals.

One of the acoustical signal paths is completely encapsulated by a glass tube. This tube is filled with seawater of precisely known salinity, and sealed with a membrane that allows pressure equilibration.

The other acoustical signal path is in open water.

The operation of this sensor is based on perfect thermic and pressure equilibrium between the water inside and outside the cell.

Provided this is so, the difference in sound velocity between the two paths will become a simple function of the salinity only. Thus the sensor simply measures the difference in travel time  $t_w - t_R$  when  $\Delta P$  and  $\Delta S$  are zero. The travel time difference  $\Delta t$  is expressed as a salinity difference  $\Delta S$  between the unknown seawater salinity  $S_w$  and the internal reference salinity  $S_R$ .

Thus the knowledge of the equations referred to is not necessary. The penalty to be paid for this simple approach is a reduced bandwidth. With the present design the thermal time constant for the reference cell is in excess of 30 seconds. In order to improve the bandwidth and to make sure that temperature equilibrium exists, a platinum thermometer is mounted parallel to each of the two acoustic paths, making possible a measurement of both differential and absolute temperatures. By measuring both the travel time differences and the temperature differences use can be made of f.ex. Lowetts equation when the temperature difference is not zero.

#### Electronic design

To give an idea of the temporal resolution needed, a calculation of some typical time differences is useful.

In the new salinity cell the total acoustic pathlength is 19 cm.

In seawater at 35<sup>o</sup>/oo, 0<sup>o</sup>C the sound velocity is 1449,15 m/sec. In seawater at 30<sup>o</sup>/oo, 0<sup>o</sup>C the sound velocity is 1442,28 m/sec.

Referred to travel time across a 19 cm pathlength

$$\begin{array}{rcl} t_{35} & = & 131,1113 \text{ } \mu \text{ sec.} \\ t_{30} & = & 131,7358 \text{ " } \\ \Delta t = t_{35} - t_{30} & = & \underline{0,6245 \text{ } \mu \text{ sec.}} \end{array}$$

The mean travel time difference per ‰ salinity from 30 - 35‰

$$\frac{\Delta t}{\Delta S} \approx 125 \text{ ns/} \text{ } \text{‰}$$

If the goal is to measure salinity with a resolution of 1/1000 ‰,  $\Delta t$  must be determined with a resolution of appr. 0,12 ns.

The need for temperature information.

Difference in sound velocity may also be caused by a temperature difference along the paths.

$$\text{at } 30 \text{ } \text{‰}, 0 \text{ } ^\circ \text{C} \quad c = 1442,48 \text{ m/sec.}$$

$$\text{at } 30 \text{ } \text{‰}, 5 \text{ } ^\circ \text{C} \quad c = 1464,31 \text{ m/sec.}$$

In our cell the corresponding travel times  $t_0$  and  $t_5$  becomes 131,717 and 129,754  $\mu$  sec. giving a mean temperature coefficient  $\frac{\Delta t}{\Delta T}$

$$\approx 392,6 \text{ ns/} \text{ } ^\circ \text{C}$$

$$\frac{\frac{\Delta t}{\Delta S}}{\frac{\Delta t}{\Delta T}} = \frac{\Delta T}{\Delta S} \approx \underline{3,14}$$

If salinity is measured in ‰ units and the temperature in  $^\circ \text{C}$  - units this implies that the temperature must be determined with a precision of about 3 times better than the wanted salinity resolution. With a practical resolution in differential temperature of 1 milli-degree, the practical limit in precision with an acoustical salinity sensor seems to be around 3/1000 ‰.

### Electronic design.

For the practical designer acoustic measurements of salinity means a transfer of problems from that of measuring low voltage potentials burried in noise to that of detecting extremely short time intervals.

Fig. 3 shows the situation at the piezoelectric crystals when the returned echoes from the reflector arrive. The detection work consists in measuring the elapsed time from the moment when the signal from crystal 1 crosses the reference potential  $V_1$  until the signal from crystal 2 crosses it. The moment of crossing is detected by two voltage comparators which in effect start and stop a timing circuit.

### Sources of error.

Being of a magnitude of maybe less than one nanosecond a range of other parameters than the salinity difference may contribute to the measured value of  $\Delta t$ .

The main sources of errors are,

1. Variations in internal delays in the electronic detection circuits.
2. Variations in receiving and transmission sensitivity of the piezoelectric crystals causing internal variations between  $U_{REF1}$  and  $U_{REF2}$

(This will make the timing start at different phase angles of the incoming signal).

3. Non damped "ringing" from the excitation as the received signals are detected.
4. Uneven changes in the distance between crystals and reflector.
5. Changes in the reference water salinity.

To take care of the first problem the electronic circuits measure  $\Delta t$  by first sending the received signal from one of the crystals to both comparators. The timing circuits will consider this as a signal with  $\Delta t = 0$  and present an output signal  $S_1$ . At the next impulsation the received signals will come from both crystals and the timer presents an output signal  $S_2$ .  $S_1$  is caused by false  $\Delta t$  contributions while  $S_2$  is caused by false contributions + contributions from the sound velocity

differences. The timer therefore finally performs the subtraction  $S = S_2 - S_1$  giving a signal  $S$  which is proportional to the salinity differences only.

Variations in the received signal amplitude will cause the two voltage comparators to trigger on different phase angles.

Fig. 4 shows an extreme example on what may happen. If the signal from crystal 2 has a much lower amplitude than the signal from crystal 1,  $\Delta t$  will get a false contribution which will not be compensated for.

This kind of error is reduced by keeping the reference level as close to zero as possible. If it - due to the signal shape - is not possible to operate near the zero crossing level, a two reference circuit is used.

$\Delta t$  is first measured at a reference level Ref. 2 - then at a reference level Ref. 1. If the received amplitudes  $U_{A1}$  and  $U_{A2}$  are equal,  $\Delta t_1$  is equal to  $\Delta t_2$ . If during operation the amplitudes change unevenly,  $\Delta t_1 - \Delta t_2$  will show variations.

According to Fig. 4 - the correct  $\Delta t$  may be calculated by means of  $\Delta t_1$ ,  $\Delta t_2$ , Ref. 1 and Ref. 2.

Ringling in the transducers is caused by imperfect acoustical matching between the piezoelectric crystals and the surroundings. Parts of the acoustical energy that is transmitted are reflected from the protective encapsulations several times during the time following excitation. Such reflections may cause an uneven signal baseline which will add to the received signal and cause unpredictable changes in the  $U_{A1}$  and  $U_{A2}$  level as sound velocity changes.

The remedy against ringling is improved transducer design. By appropriate combination of operating frequency and choice of encapsulation material, the ringling can be completely damped out when the received signal arrive.

Changes in the acoustic path length can be avoided by using materials with an extremely small temperature coefficient. In the present design the distance between crystal and reflector is kept constant by bars of steel. If that is unpractical, the actual metal temperature must be

monitored and the corresponding elongation must be computed. The demands for high mechanical stability is significant. During  $10^{-10}$  sec - which correspond to the highest resolution obtainable - the acoustical wavefront only moves appr.  $1,5 \cdot 10^3 \cdot 10^{-10} = 1,5 \cdot 10^{-7}$  meter.

Changes in the reference water may take place if the water can evaporate or if the water can receive or release ions. It is therefore important to have the reference water surrounded by nonporous, nonmetallic surfaces. Unfortunately such materials have a low heat conduction ability thus increasing the time constant.

#### Electronic solution.

Fig.5 shows a simple block diagram of the acoustic sensor electronics.

At a fixed repetition rate - determined by a main oscillator - the piezo-electric transducers are impulsed. First transducer A is connected to both voltage comparators  $K_A$  and  $K_B$ . After the elapsed travel time the received signal cross the reference level REF1 and  $K_A$  and  $K_B$  are triggered simultanuesly. The travel time difference as seen from the time interval to voltage converter is computed and the result is stored in an analogue memory.

At the next crystal impulsation the crystals are connected to one comparator each, and the new time interval between the arrival of the two signals is computed. The difference between this time interval and the previously stored time interval is computed, and the result is fed to an output sample and hold memory. Next the comparator level is increased to REF2 and the described cycle repeated. The measuring process described is performed at a repetition rate of about 20Hz..

#### Results.

Fig.6 shows a calibration diagram. The calibration was made by gradually, diluting 38<sup>o</sup>/oo sea water with distilled water.

For each dilution the salinity was measured with a table salinometer to a precision of about 1/1000 <sup>o</sup>/oo. The output of the acoustic instrument was read when the accosiated temperature bridge showed temperature equilibrium within appr. 2/1000<sup>o</sup>C.



Planned use of the sensor.

Presently the sensor described is being tested for long term stability, temperature and pressure coefficient. The Institute of Marine Research will use the sensor for monitoring of the salinity at King's Bay in the Svalbard Islands. The Geophysical Institute will try it for long term monitoring of the salinity at the Jan Mayen Islands. The sensor will also be used to automatically monitor and record surface salinity and temperature along the Norwegian Coast by installing it in the cooling water system on ships that routinely travel up and down the Norwegian coast.

Presently it seems that the sensor can measure salinity with a reliable precision of appr.  $1/100$  ‰. The greatest drawback with it is the long time it takes to find thermic equilibrium.

To increase response time the travel time  $t_{REF}$  in the reference cell may be exchanged by a precisely known time interval that corresponds to f.ex. the travel time if the cell had been filled with distilled water at  $0^{\circ}\text{C}$ , 1 atm. pressure. As the sound velocity in fresh water-as a function of temperature and pressure-is very well described, the measured travel time in the described instrument subtracted by the calculated travel time for fresh water at the simultaneously measured temperature and pressure condition should give results with similar resolution as obtained with the reference cell configuration.

Conclusion.

A new salinity cell based on measuring the difference in acoustic travel time over the same pathlength between seawater with unknown salinity and seawater with known salinity has been made.

Tests being presently done with it indicate an obtainable resolution in the field of appr.  $1/100$  ‰. The greatest drawback is a time constant of appr. 40 seconds. The time constant can be reduced to less than  $1/10$  second if an exact formula relating sound velocity to temperature, salinity and pressure can be found.

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Fig. 1. Comparison of salinities computed from equations by Levett, Del Grosso and Wilson (according to Emery, ref. 1).

Fig. 2. Mechanical design of acoustical salinity cell.

1. Cover
2. Glass-encapsulation for reference water
3. Internal thermometer
4. O-ring seal
5. Reflector
6. Distance bar of invar steel
7. Piezoelectric crystals
8. Outlet to pressure membrane.

Fig. 3. The situation as the acoustical signals enter the detection circuits.

Fig. 4 The effect of uneven received signal amplitudes.

Fig. 5. Block diagram of the electronic circuit.

Fig. 6. Calibration diagram for the acoustical salinity sensor.

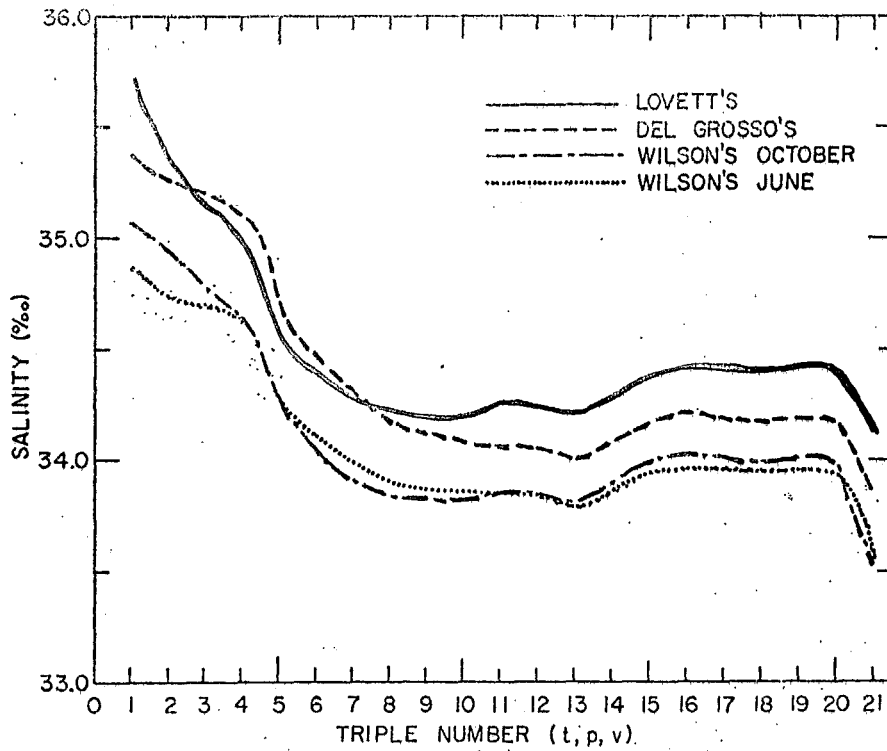


Fig. 1.

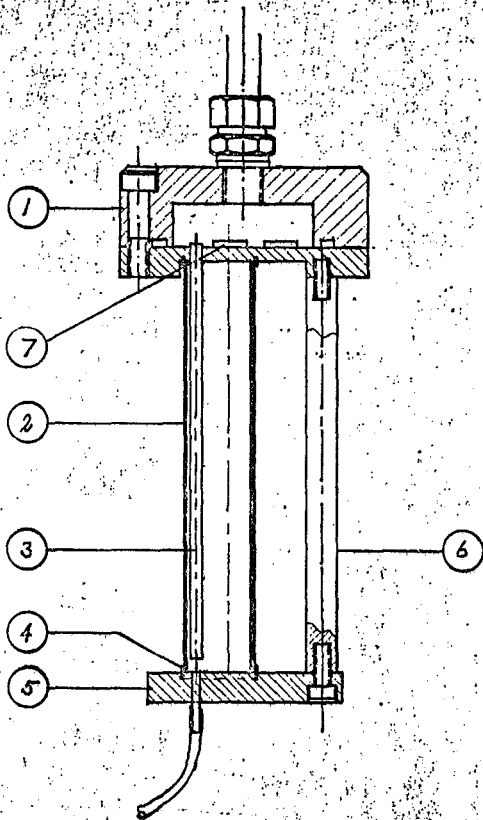


Fig. 2.

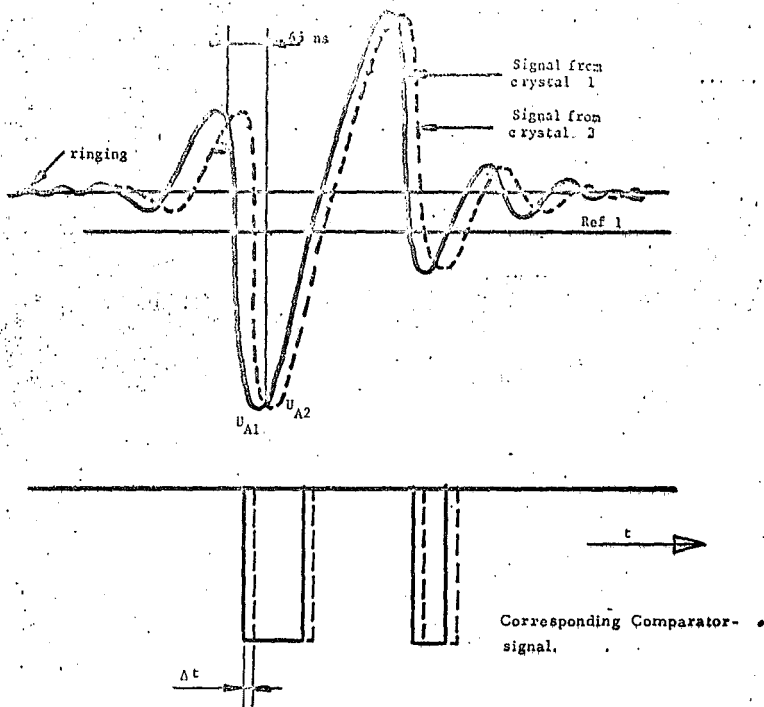


Fig. 3.

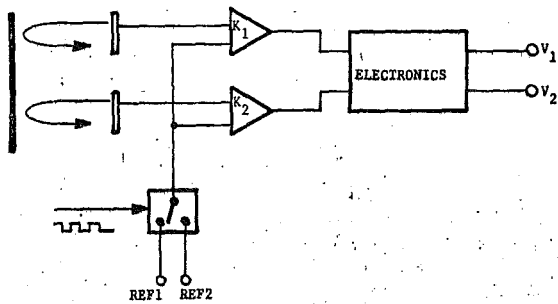
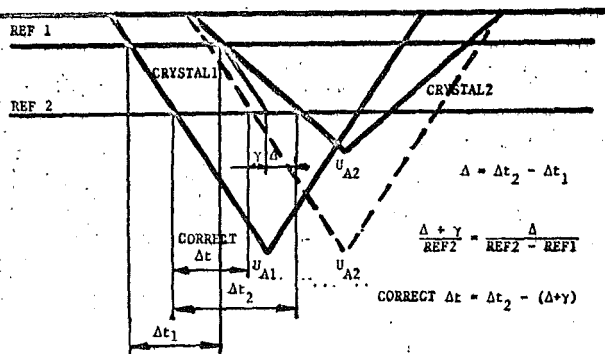
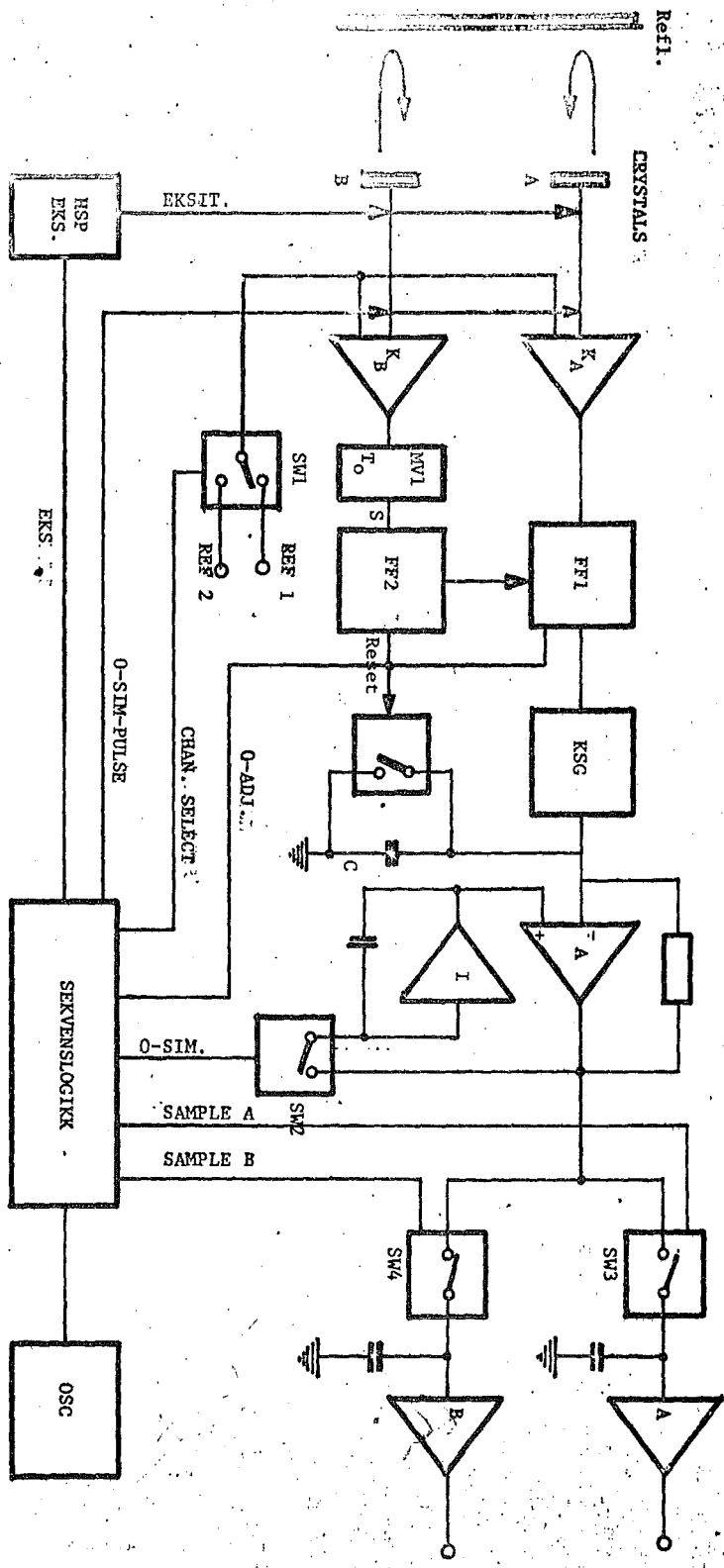


Fig. 4.

Fig. 5.



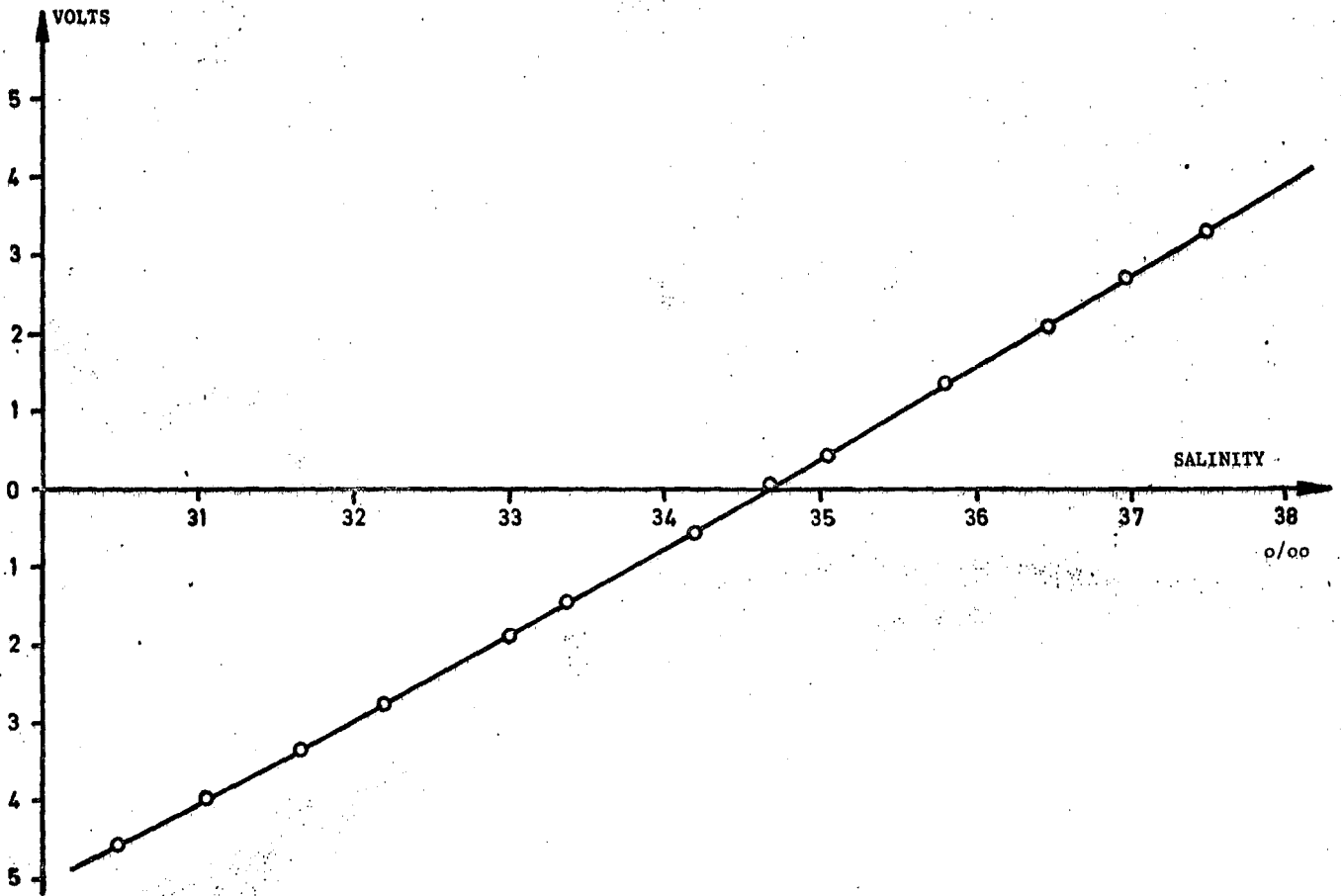


Fig. 6.