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THE SOUND CHANNEL OF THE BALTIC SEA

by

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Abstract

The annual march of the vertical distribution of the speed of sound in the Baltic Sea is analysed. It is stated that between April and October all the sounds in the Baltic Sea are refracted away from the surface layer, while in December until February the sounds can be heard also at the surface. The sound channel of the Baltic is found to appear very close to the surface in March, it sinks slowly during the summer months, and disappears in November at a depth of some 100 metres.

The speed of sound in sea water (or in any liquid) may be computed using the equation of LAPLACE

$$v = \sqrt{\frac{\gamma \alpha}{K}}, \qquad (1)$$

where $\gamma = \frac{c_p}{c_v}$ is the ratio of the specific heats,

α is the specific volume, and

K is the true compressibility.

Further the specific heat at constant volume, c_v, may be computed from the following equation:

$$c_v = c_p - \frac{\alpha T e^2}{KJ}$$

where T is the absolute temperature,

$e = \frac{1}{\alpha}\frac{\partial \alpha}{\partial T}$ is the coefficient of thermal expansion, and

J is the mechanical equivalent of heat.

Furthermore

$$K = \frac{k + p\frac{dk}{dp}}{1 - kp},$$

where k is the mean compressibility between the pressures O and p as defined by

$$\alpha_p = \alpha_0(1 - kp).$$

The reliability of the equation of LAPLACE (1) has been verified through numerous measurements also in sea water. However, its pratical value for numerical computations is rather limited, since γ, α and K are functions of temperature, salinity and pressure in a manner indicated above. The empirical formulas, originally based upon the measurements of WOOD and BROWNE, have proved more practical. The speed of sound in sea water at the surface is commonly given as MAURER's [7] formula, however, at present in the following form [cf. KOCZY, 4]:

$$v = 1445.5 + 4.62t - 0.0452t^2 + (1.32 - 0.007t)(S - 35). \qquad (2)$$

This numerical formula gives the speed of sound in m s^{-1}, if the temperature t is given in centigrades and the salinity S in parts per thousand. Furthermore also MAURER [8] has given, principally on the basis of the studies of EKMAN [1] on the compressibility of sea water, methods how to take into account also the effect of pressure (depth). The tables of speed of sound published for instance by KUWAHARA [5] and MATTHEWS [6] are based in principle upon the above results.

The formula (2) gives directly

$$\left\{\begin{aligned} \frac{\partial v}{\partial t} &= 4.62 - 0.0904t - 0.07(S - 35), \\ \frac{\partial v}{\partial S} &= 1.32 - 0.007t. \end{aligned}\right. \qquad (3)$$

Therefore it can be concluded that

(1) if the temperature of sea water is increased by one degree centigrade, the speed of sound increases 4.6 m s^{-1}, and

(2) if the salinity of sea water is increased by one part per thousand, the speed of sound increases 1.3 m s^{-1}.
(3) Furthermore the tables of KUWAHARA show that a step of 100 m vertically downward in the sea increases the speed of sound 1.8 m s^{-1}.

When we know in which limits the temperature and salinity vary in the Baltic Sea (in this case mainly in the northern part of the Baltic proper), the corresponding effects upon the speed of sound can be given as follows:
(a) The changes in temperature between 0—20°C cause a change of 92 m s^{-1} in the speed of sound.
(b) The changes in salinity, say, between 2 and 10 parts per thousand bring about a change of 10.4 m s^{-1} in the speed of sound.
(c) The speed of sound at a depth of 300 meters is approximately 5.4 m s^{-1} higher than at the surface. This effect would cause in the echo sounding of a depth of 300 metres an error of slightly more than half a metre only. A typical vertical summer distribution of the different factors involved is shown in Fig. 1.

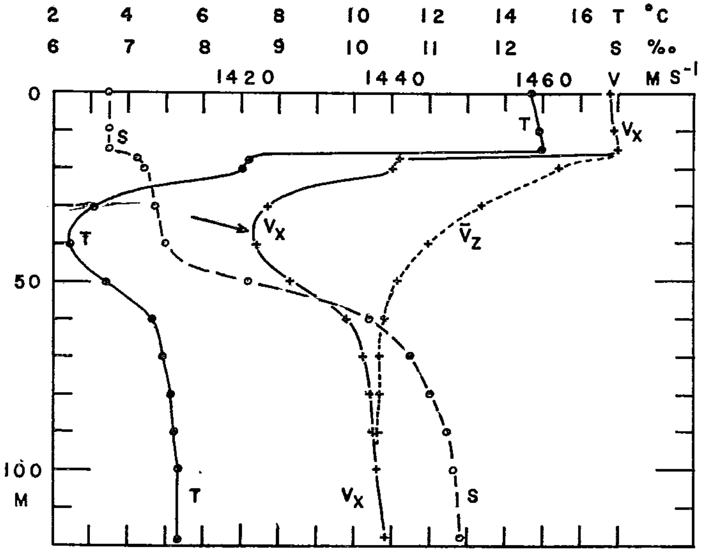

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Fig. 1. Typical hydrographic conditions in the Northern Baltic in July; t stands for temperature, S for salinity in parts per thousand, v_x is the (horizontal) speed of sound, and $\bar{v}_z$ is the mean vertical speed of sound between surface and the depth z at which the speed is marked.

It is evident that in the Baltic Sea especially the temperature and also the salinity affect the speed of sound in a significant manner. Fortunately for many practical purposes the accuracy obtained through the temperature alone is quite sufficient which makes the sampling by means of modern apparatus simple.

The purpose of this paper is to analyse the annual march of the vertical distribution of the speed of sound. To start with, the temperature and salinity data were used from the Bogskär lighthouse ($\varphi = 59^0 31'$; $\lambda = 20^0 31'$), based upon observations and sampling carried out three times a month during the years 1899—1914 at depth intervals of 10 metres [SIMOJOKI, 9]. The annual changes in the vertical distribution of the speed of sound are shown in Fig. 2. In the layer of 0—10 metres the speed of sound varies between 1411 m s^{-1} in March and 1472 m s^{-1} in August. In the layer of 140—150 metres the corresponding interval is 1425—1429.5 m s^{-1}.

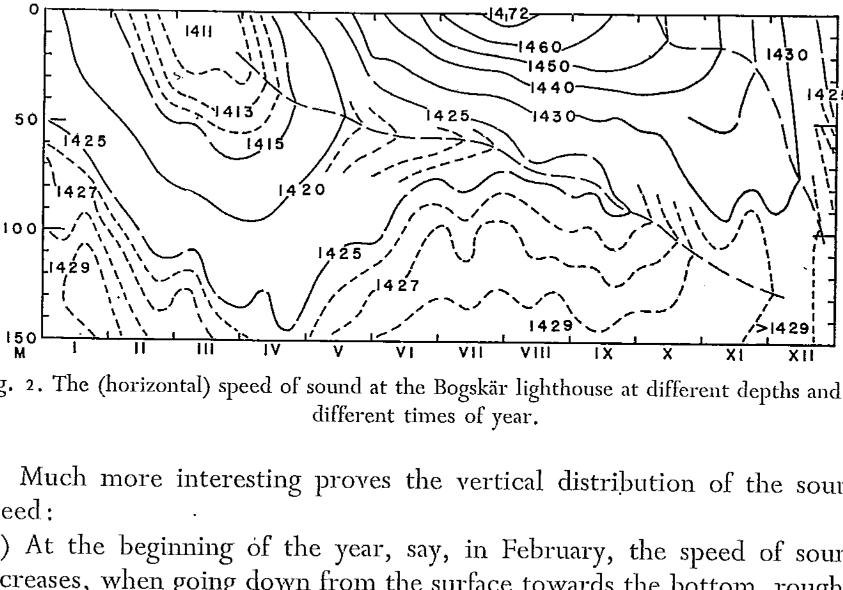

Fig. 2. The (horizontal) speed of sound at the Bogskär lighthouse at different depths and at different times of year.

Much more interesting proves the vertical distribution of the sound speed:

(1) At the beginning of the year, say, in February, the speed of sound increases, when going down from the surface towards the bottom, roughly in the limits 1413—1428 m s^{-1}.

(2) Developing late in March there exists until early November a layer of minimum speed of sound which slowly sinks down. For instance in April this layer is observed at a depth of 35, in July of 60 and in October at a depth of 100 metres. From the minimum layer the speed of sound

increases both downwards and especially upwards. For instance in July the speed of sound is in the layer of 0—10 metres 1468, at the minimum speed 1423, and at 140—150 metres 1429 m s^{-1}.
(3) In October a weak maximum of sound speed appears in the surface layer. This maximum sinks down very rapidly appearing already in December at the depth of 140—150 metres. Towards the end of November the speed of sound is at 0—10 metres 1435.5, at the depth of maximum speed 1436 and at 140—150 metres 1429 m s^{-1}.

According to the normal practice in the Baltic Sea, the pressure corrections have not been applied in the former results. Nevertheless it is necessary to mention that due to this procedure the above values for the speed of sound are at the 140—150 metres 2.6 m s^{-1} too small. Correspondingly all the other values of sound speed are too small, the errors being relative to the depth. If the pressure effect is taken care of, the following changes are brought about in the above list.
(1) Due to the pressure effect the speed of sound increases, at the beginning of the year, still more rapidly than shown in Fig. 2.
(2) Due to the pressure effect the minimum of sound speed is more pronounced also downwards than in Fig. 2.
(3) Due to the pressure effect the weak maximum of sound speed still loses some of its identity.

In connection with the echo sounding it is necessary to know the mean speed of sound in a total vertical water column from surface to bottom, that is,

$$\bar{v}_z = \frac{1}{z} \int_z^0 v_x \, dz \,, \tag{4}$$

where v_x is the horizontal speed of the sound. The results of this computation are shown as Fig. 3.

Going back to Fig. 2, it may be stated, that a sound leaving a liquid acoustically denser for a liquid acoustically less dense, is refracted, according to the following law of SNELLIUS, away from the normal of the surface between the liquids.

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{v_1}{v_2} = n \,. \tag{5}$$

The same law can be applied (Fig. 4) for the sea with different layers. In Fig. 5 is given the annual march of the vertical distribution of the

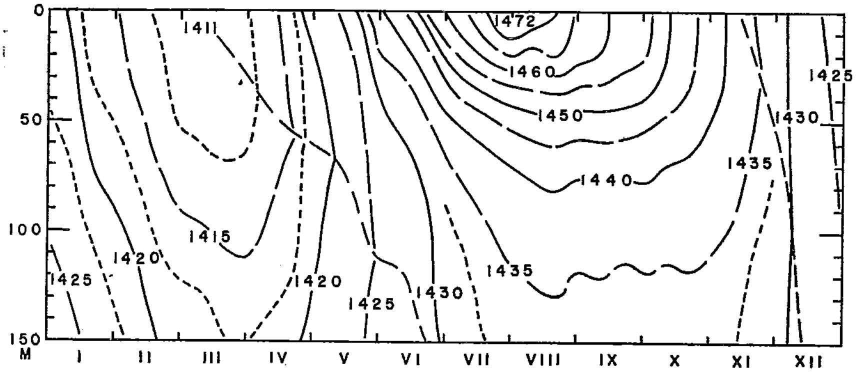

Fig. 3. The mean vertical speed of sound, at the Bogskär lighthouse, between the surface and the depth z at which the speed is marked.

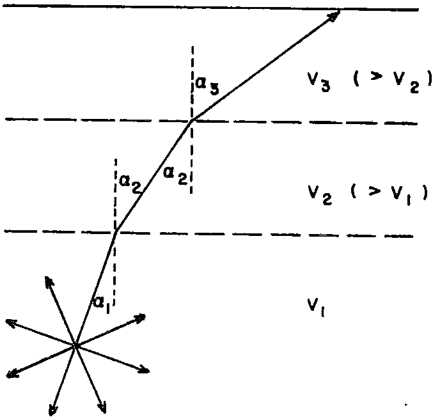

Fig. 4. A schematic representation of the refraction of the sound in the sea.

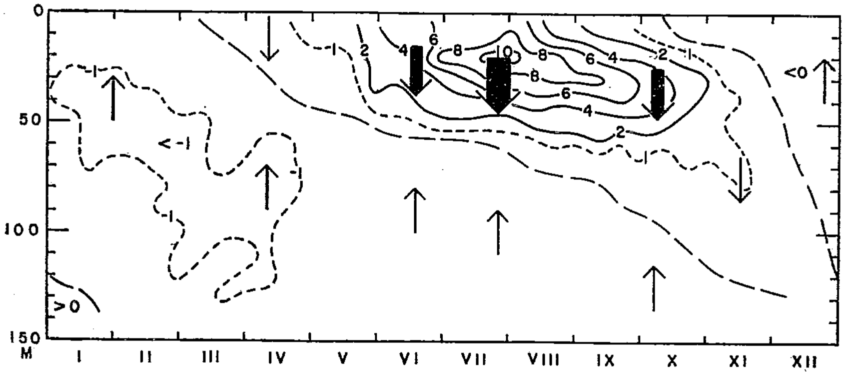

Fig. 5. The annual march of the vertical distribution of the refraction coefficient n of the sound (actually: $1000(n-1)$).

refraction coefficient, n, (actually in the form of $1000\,(n-1)$), computed from the surface downwards in steps of 10 metres. By means of arrows the direction of the vertical component of the refraction is indicated, the thickness of the arrows being relative to the magnitude of $1000(n-1)$. There are two especially interesting features in the above vertical distribution.

First of all, between April and October all the sounds in the sea are refracted away from the surface layer, while in December until February the sounds in the sea can be heard also at the surface.

Secondly the layer of minimum speed of sound becomes significant as a typical »sound channel». In the sound channel of the oceans the upper limitation is brought about by the decreasing temperature while the lower limitation is due to the increasing pressure. Our Fig. 5 shows that also the Baltic Sea has its sound channel, although with the following basic differerences.

The sound channel of the Baltic Sea is not a permanent feature: it appears every year close to the sea surface in March, sinks slowly during the summer months, and disappears in November in this case at a depth of 100 metres. The lower limitation of the Baltic sound channel is mainly due to the increasing salinity. Furthermore, since the depth of the Baltic

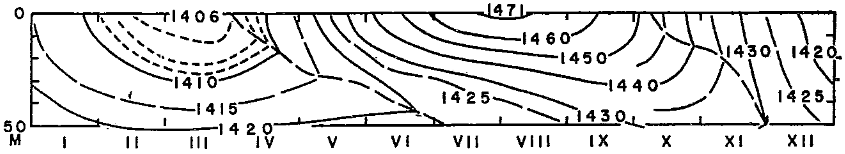

Fig. 6. The (horizontal) speed of sound at the Söderskär lighthouse at different depths and at different times of year.

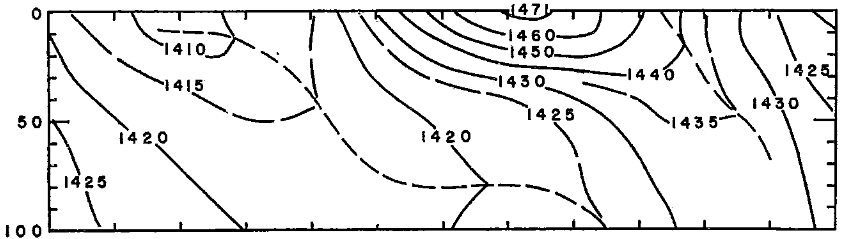

Fig. 7. The (horizontal) speed of sound at the Märket lighthouse at different depths and at different times of year.

sound channel is only 0—100 metres, while the sound channel of the oceans appears at a depth of 1000—1500 metres, it is most probable that the absorption of the sound energy is much faster due to plankton, organic detritus etc.

The Figures 6 and 7 correspond to Fig. 2 and show the annual march of vertical distribution of the sound speed at Söderskär ($\varphi = 60^0 06'$; $\lambda = 25^0 26'$) and Märket ($\varphi = 60^0 18'$; $\lambda = 19^0 08'$), based upon observations and sampling carried out three times a month during the years 1921—30 at depth intervals of 10 metres [GRANQVIST, 3]. In spite of the minor differences in the speed values and in the depths of the sound channel, these representations show the general validity of the above conclusions.

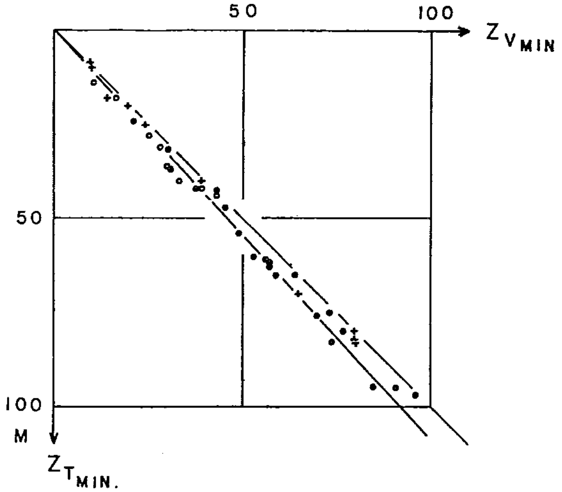

Fig. 8. The relationship between the depths of the sound channel, v_{min}, and of the temperature minimum, t_{min}. The points refer to Bogskär, the rings to Söderskär and the crosses to Märket.

Finally, the depth of the sound channel is compared with the depth of minimum temperature (Fig. 8). It is seen relatively clearly that the depth of the former one is some 8 per cent less than the depth of minimum temperature. This minor difference can be referred to the effect of salinity gradient, while the existence of the Baltic sound channel is connected with the layer of minimum temperature. The unity of the layer of minimum temperature — and thus indirectly of the Baltic sound channel — can be seen [Wüst, 10] in the longitudinal »Südfall» section of thermal microstructure between Kiel and Helsinki in August 1956. This section shows a continuous and well defined layer of temperature minimum which appears in the Bornholm basin at a depth of 60 metres and at the mouth of the Gulf of Finland at 50 metres.

The layer of minimum temperature for its part can be connected genetically with the cold water mass which is brought into existence at the surface in the winter time. Due to the warming up, starting from the surface, and due to other processes of mixing and conduction the coldest water appears deeper and deeper in the water column and finally disappears after October.

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