ON THE RELIABILITY OF AERIAL FOG SIGNALS

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INTRODUCTION.

In 1925 my interest was aroused by an article on Navigation in Foggy Weather by Dr. O. KROGNESS, Director of the Geophysical Observatory at Tromsö in Norway. This article was based primarily on researches by the eminent Norwegian meteorologist, the late Dr. MOHN, sometime scientific adviser to the Norwegian Lighthouse Board. The article below was prepared subsequently at the Kungliga Sjökarteverket, Stockholm ; it was based mainly on Dr. MOHN's book (*See* Bibliography below), but includes also results from some later investigations, as well as an attempt to formulate some practical rules for navigation in fog ; it is printed as an appendix to the new editions of the Swedish Sailing Directions "Svensk Lots". At the invitation of the Directing Committee of the International Hydrographic Bureau the article has been translated for reproduction in the *Hydrographic Review*. The article was elaborated by Mr. P. COLLINDER, M. A., of this Hydrographic Service.

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ON THE RELIABILITY OF AERIAL FOG SIGNALS

Ever since sound-signals in fog were first used, it became more and more evident, as time went on, that the audibility of fog-signals through the air varies very much, and that these signals can only be used with great caution for guidance in navigation. The following will give some information on this matter, based chiefly upon the researches of the late Dr. MOHN, the well-known meteorologist, who was, in his day, the scientific adviser of the Norwegian Lighthouse Service.

In June 1924 two Norwegian passenger steamers belonging to what is called "hurtigruten" (express steamers) collided in foggy weather in the Norwegian Vestfjord. One, the *"Haakon Jarl"* went down 5 minutes after the collision and 17 people lost their lives. It appeared that the signals of the *"Haakon Jarl"* had been heard for the last quarter of an hour, on board the other ship, the *"Kong Harald"*, while it was only three minutes before the collision that the signal of the latter ship had been feebly caught on board the *"Haakon Jarl"*.

The Vestfjord disaster is by no means the first case to show the unreliability of the usual fog-signals and the untenability of the view generally held at the time when stationary fog-signals were first introduced, *viz.* that the sound of a bell, a siren, or a gun spreads uniformly in all directions.

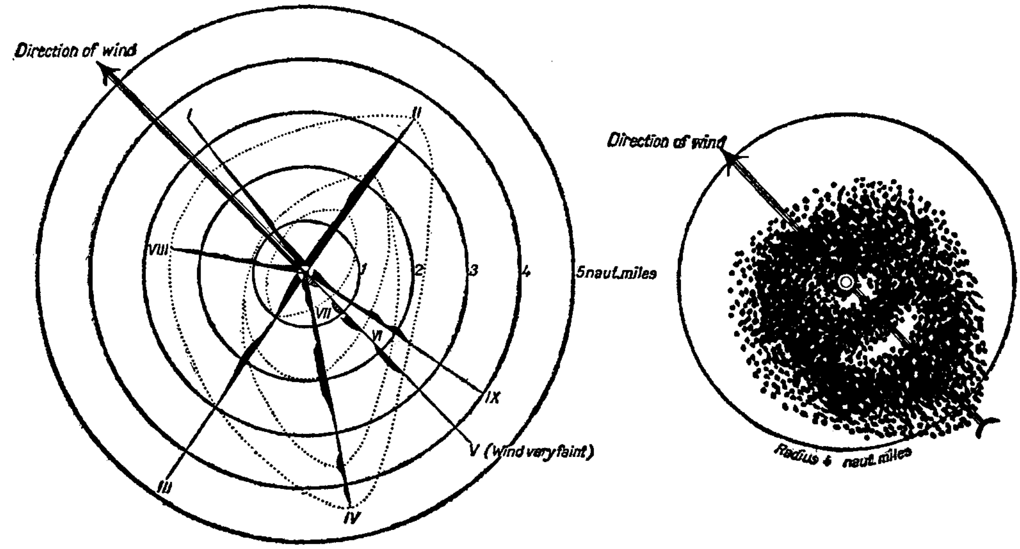
In Long Island Sound, off New-York, there is a little islet, Gull Island, provided with a powerful steam siren which, under favourable circumstances, is usually audible within 25 nautical miles. In May 1881, in a thick fog and calm weather, the steamship *"Galatea"* of 1500 tons grounded here at a distance of about 200 metres from the fog-signal station. There was evidence to prove that the siren had been in full play at the time of the accident; other ships near by had heard the fog-signal at the same time, and people on shore had heard the siren in a direction opposite to that from the siren to the *"Galatea"* and at a distance of 6 to 8 nautical miles.

In July 1895 the British steamship *"Catalonia"* passed in hazy weather at a distance of 500 metres from the lightship off Daunt Rock on the south coast of Ireland. The officers of the *"Catalonia"* observed the smoke of the signal gun that was fired several times while the lightship was in sight, but could not hear the report of the gun until the steamer had moved to a little more than 1.5 nautical miles *away* from the lightship, when the gun was heard quite distinctly.

Before entering upon the physical explanations of these many peculiarities of sound, we cannot pass by a very interesting set of observations made from the lightship *"Eider"* off the mouth of the Eider river in January 1895 and published in the review *"Hansa"* of 20th July 1895. The wind was S.E. to S., then S.E., its force was 3 Beaufort, at times 3 to 4, but not quite 4 (a fresh breeze). There was a thick haze, but no fog to speak of; the temperature 7° C. (+ ?) (44.5° F.). The lightship was provided with a siren.

The vessel used for the experiments now started from, and turned towards the lightship in no less than seven different directions, all the while observing the intensity of the sound heard till it vanished completely. Fig 1 represents an attempt briefly to show the results graphically. The wind is here supposed to have been constant from S.E., although as above stated, it varied a little. Anyhow, the courses have been indicated so as to be in a true relation to the actual direction of the wind. (The arrow flies with the wind).

Fig. 1.



Fog-signal observations at Elder light-vessel 16 January 1895. Fog-siren. Wind SE; 3—4 Beaufort. Temperature 7° C (+?).

Probable distribution of sound-intensity. Area of audibility shown by dark dots.

In the left-hand figure the narrow radii drawn from the centre (the lightship) show the courses shaped, the concentric circles show the distances from the siren in nautical miles. The black "hills and dales" along these radii represent attempts at showing approximately the intensity of the sound of the fog-signals as heard on board the ship at different points of the courses indicated. No great accuracy should be expected in this connection, nor should we compare the intensity of sound on different courses. A "hill" shows the sound was strong, a "dale", on the contrary, shows that it was weaker or had vanished entirely.

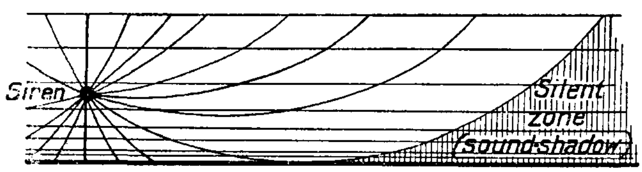
To leeward conditions were found to be fairly regular; but to windward zones of strong sound alternated with silent areas, and straight to windward of the siren short belts of strong sound alternated with areas of complete silence, although the sound had only to go against a wind that was very weak on this occasion, at any rate at sea level. Observations VI and VII were made immediately after each other with the ship going in opposite directions.

The right-hand figure shows an attempt to delineate the whole area of audibility round the siren on these occasions. Its dark parts indicate more or less clear signals, whereas the white belts are areas where a more or less complete silence prevailed. Here, on going straight from windward towards the siren, the sound was very feebly audible at a distance of 3 to 4 nautical miles; it increased in strength at first, but then quickly decreased, and ceased completely at a distance of about 1 3/4 miles. At 1 1/2 miles the sound suddenly became very strongly audible, but then again at a distance of 3/4 of a mile, it suddenly vanished. After that the siren was not heard until the observer was within 400 metres only of the lightship, when all at once the sound became very strong.

The clearing up of the causes of these phenomena has required many observations and laborious calculations, which were made by Dr. MOHN, who published the results in the *Annalen der Hydrographie* of 1892, 1893, 1895 and in his book *Om Taagesignaler* (On fog-signals) mentioned above.

The causes of practically all the irregularities mentioned are to be found in the fact that the sound from a fog-signal apparatus is propagated in a straight line only when the air is quite even and homogeneous as regards temperature, humidity and wind.

Every seaman knows that light does not always travel in a straight line, but deviates from it, *e.g.* in the case of mirages, which arise when the temperature of the air is unevenly distributed. Refraction, too, is due to the light being bent in a curve towards the earth, the air being denser there than higher up.



Sea level

Temperature decreases normally upwards.

Fig. 2a.

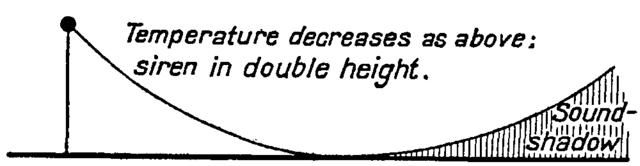


Fig. 2b.

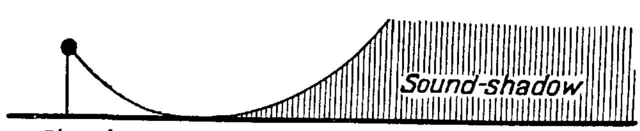


Fig. 2c.

Siren in same height as in 2:a; temperature decreasing upwards in double rate

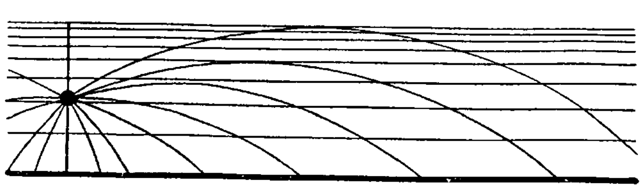


Fig. 3.

Temp. increasing upwards: No silent zone

The difference between sound and light in this connection is chiefly this, that sound travels nearly a million times less fast than light, and also the sonorous ray is much more liable to fall a victim to the irregularities of the air than is the ray of light. The simplest and most frequent case is that shown in fig. *2a*. where the temperature is assumed to be decreasing as the altitude increases,

Here the sonorous rays will bend in the direction of the cooler air, in other words, they will bend upwards along arcs instead of going straight from the fog-signal to the ear. A ray of sound starting horizontally from the source of sound, after covering a certain distance, takes a slanting upward direction, and a ray starting in a certain slanting downward direction may bend so as to meet the surface of the sea, run horizontally touching it, and then rise again with a constant bend. In the area beyond this limiting ray the fog-signal becomes practically inaudible For the rays rising higher can never enter this silent area, as they, too, must bend upwards, and the rays sinking lower down meet the surface of water at acute angles and are reflected by it in a slanting upward direction. The silent zone will not be completely silent, it is true, but the sound is so considerably weakened that this vague "air echo" need not be taken into account.

In this silent zone, then, it makes no difference even if the source of sound is made twice as powerful. The sonorous rays none the less must follow the same lines as before. which depend solely upon the condition of the atmosphere, and they are still unable to penetrate into the silent zone. It will be seen also from the figure that, at sea-level, the range of audibility is less than higher up: consequently a look-out in the top will catch the fog-signal of a siren very much earlier than the navigator on the bridge. Fig. *2b* shows the effect of placing the source (of sound) higher up; this increases the range of audibility ; doubling the height does not, however, mean doubling the range of audibility. Lastly, fig. *2c* shows the influence of greater variation of temperature; if as altitude increases the temperature falls more rapidly, this diminishes the range of audibility.

The table below shows how strongly ranges of audibility may be limited by this normal decrease of temperature as the altitude increases. This table indicates the audibility of a source (of sound) at a height of 15.6 metres (51.2 ft) for different heights of the observer on board a ship. The variations of temperature at different heights which are given here are met with fairly frequently.

RANGES OF AUDIBILITY IN NAUTICAL MILES.

Height of ear above sea-level	*Temperature lower* 1/2° *per* 100 *metres height*	*Temperature lower* 1° *per* 100 *metres height*
0 metre	1.0 n. m.	0.7 n. m.
2 »	1.4 n. m.	0.9 n. m.
5 »	1.6 n. m.	1.1 n. m.
10 »	1.8 n. m.	1.3 n. m.
20 »	2.1 n. m.	1.5 n. m.
30 »	2.4 n. m.	1.7 n. m.

But what if the reverse should happen, *viz.* that the air temperature round the signal-station increases with the altitude, in other words, that there is a warmer layer of air on top of a colder one ?

This occurs fairly frequently during fog—indeed, it is one of the chief causes of fogs. Then fortunately it happens that the sound-rays bend downward towards the surface of the sea, and, as shown in fig. 3, no sound-shade is brought about. No doubt it is due mainly to this circumstance that fog-signalling through the air is not even more inefficient than is actually the case.

But it is vain to seek, in the explanations given above, for a clue to the strange phenomena met with in the instances adduced, *viz*, the silent zone or zones within the limit of audibility, and quite close to the source of sound, which is called by English navigators "*the Ghost*". This phenomenon is to be accounted for by wind conditions.

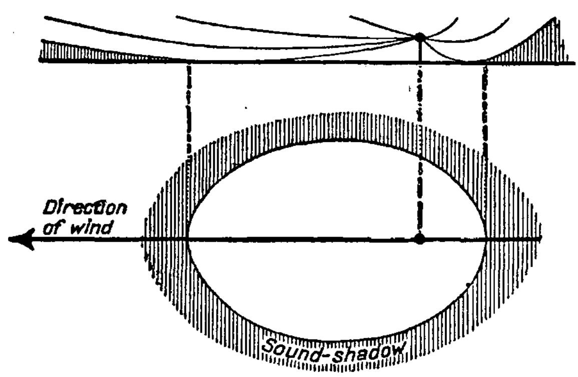


Fig. 4a.

First, let the normal case be taken, *i.e.* that the temperature falls from sea-level upwards, and besides, that there is not too strong a wind. Then the sound-rays will take up some such form as that shown on top of fig. 4*a*. The wind increases in strength as the altitude increases, which has the effect of bending the sonorous rays to windward of the source, and this is the reason why the rays are more strongly bent to windward of the source, as there they travel against the wind. To leeward of the source the bending of the rays becomes less than usual, as the reduced velocity of sound in higher and cooler layers of air is partly counterbalanced by the greater velocity of wind in these higher layers. The range of audibility here diminishes to windward of the siren and increases to leeward, the whole area of audibility forming an oval (the white inner area of the lower part of the figure).

Still assuming that temperature decreases with altitude but that there is a stronger wind, conditions may be as shown in fig. 4*b*. Here the range of audibility to windward diminishes still more in the case in question down to 4/5 of a nautical mile. To leeward the sonorous rays would still be expected to bend upwards owing to falling temperature, but the diminished velocity of sound is outbalanced by the much increased velocity of wind in the higher layers, and the rays of sound finally bend towards the earth. There will be no silent zone to leeward, but the range of audibility here will depend on the power of the source of sound only. The form of the area of audibility at

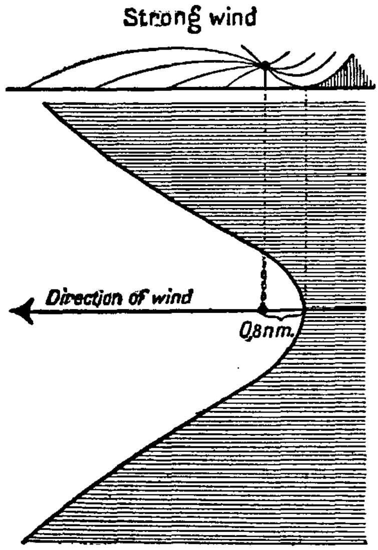


Fig. 4b.

sea-level is shown in the lower part of fig. 4*b*. An increase in the power of the source cannot increase the range of audibility to windward or athwart the wind, but within a certain angle to leeward of the source an increased intensity of sound may increase the range of audibility to an unlimited degree.

It should perhaps be pointed out that in these figures the bending of the rays is considerably exaggerated with reference to reality.

The last example given may well conform with conditions at the time of the accident off Long Island mentioned above when the *S.S.* "*Galatea*" ran aground close to the siren, the sound of which had been heard by other ships in the vicinity as well as by people on shore to leeward of the signal-station.

But the "*Ghost*" still remains to be explained.— To obtain a silent zone within the extreme limit of audibility a case must be assumed which may seem farfetched but still is not very rare, *viz.* that the wind blows in one direction at sea-level and in another direction or else in the same direction but with less velocity higher up. This, as was pointed out above, is not infrequently to be ascertained by comparing the direction of the wind at sea-level with the direction of the movement of the lower clouds. It is known, for instance, that a common night breeze (land-breeze) is brought about by the warmer air over the sea rising and being replaced by less warm air rushing out from the cooled land. Higher up in the air, conditions are just the opposite, the wind there blowing landward. The off-shore night-breeze, consequently, may be limited above at a fairly low level by a wind in an opposite direction. Here then conditions favourable to the "*Ghost*" are found; *see* fig. 5*a*.

In this figure, *S* is the source of sound, *HH'* is the sea-level. The arrows indicate directions of winds and fly with them, and GG' is the boundary between the directions. The temperature is assumed to fall with altitude. Now let a sonorous ray be considered which goes from the siren towards the

Fig. 5a.

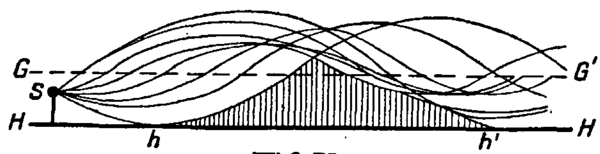


Fig. 5b.

lower wind, or, from the point of view of an observer near the sea-level, to windward. In accordance with the conclusions mentioned above, this ray will first bend upwards (*cf.* fig. 4*a*, on the right). When it has got above the boundary layer, it begins to bend downwards, for here the wind blows in the direction of the sound and increases in force with altitude, (*cf.* fig. 4*b*, on the left). Every sound-ray under these circumstances takes the form of a wave-line, and all together they form a "sound-sheaf" as shown in fig. 5*b*. Here, it will be seen that a silent zone is formed, which stretches from *h* to *h'* at sea-level but narrows the higher the observer stands, finally disappearing entirely. Inside as well as outside this silent zone the fog-signal is audible.

This phenomenon of the "*Ghost*" is always most prominent to windward of the source and grows less distinct on both sides ; it may be observed even athwart the wind as appears in the instance of the "Eider" lightship. The fact that here the "*Ghost*" was so strongly pronounced directly to windward of the lightship in a very light wind was probably due to the upper wind being particularly strong just then and the wind boundary being low.

It may be worth pointing out that the results given above of calculations as to the ranges of audibility under different circumstances are by no means "vagues theories" unconnected with reality, but agree well with facts observed at sea. The observations near the "Eider" lightship (fig. 1) and other instances adduced in the beginning of this paper are referred to.

Furthermore it should perhaps be pointed out once more that the limits of audibility given above in various cases are practically independent of the energy of the source; even if the power of a siren or diaphone is doubled, this has practically no effect on a ship in a silent zone.

On the other hand, it is expedient to place the source high up, the silent zones being then, as a rule, smaller.

The audibility of one and the same signal may vary exceedingly in a period of two or three hours. Thus at Faerder light in Norway on 31st January, 1893, the siren at that station could be heard up to a distance of

1 nautical mile at 11 a.m., but at 2. p.m. up to a distance of 8 nautical miles. The range of audibility had altered by no less than 7 miles in 3 hours, probably owing to a shift of wind and a change of temperature.

Similar and considerably more rapid alterations are proved by the diagram below which shows the varying intensities of sound from the English lightship *"Tongue"*, as registered automatically for 45 minutes at a distance of some nautical miles from the lightship.

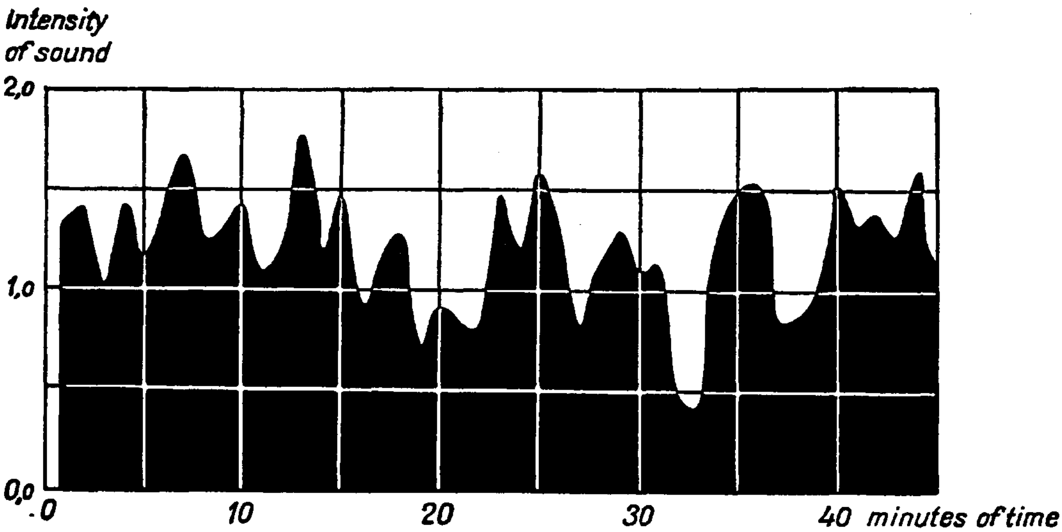


Fig. 6.

From this, as well as from all that has been said above, it follows that the distinctness with which the signal is heard does not afford the least certainty in estimating the distance to the signal. Sometimes one and the same signal can be heard strongly at great distances; sometimes it is heard feebly or not at all, although the listener is close to the station. The same thing, of course, holds good for signals from ships.

Nor can the direction to a source of sound be estimated with any high degree of certainty. MOHN states that the direction in which the sound seems to be heard may sometimes be erroneous up to more than 50°.

What, then, is the distance at which it is possible to count with certainty on being warned by a fog-signal? Theory as well as long and fatal experience proves that this distance is not more than 1/4 of a nautical mile for the most powerful as well as for weaker sirens.

And it is, as a matter of fact, impossible for a navigator to foresee when these dangerously short ranges of audibility may be expected as, for that purpose, he would have to know the direction and force of the wind, and the temperature and humidity of the air not only at sea-level but also at different altitudes above the sea.

With a range of audibility of from 400 to 500 metres, a navigator will not have much time to avoid an accident. With an assumed range of 1/4 of a nautical mile it is easy to calculate the time that will elapse from the moment when two ships which are meeting are within this range to that when they will pass each other.

Speed of each ship	*Length of time*
6 knots	1 min. 15 sec.
8 »	0 » 56 »
10 »	0 » 45 »
12 »	0 » 38 »
20 »	0 » 22 »

This table shows to the full the importance of the regulations as to low speed in foggy weather.

It has proved to be impossible to lay down definite rules for navigaton by ordinary fog-signals. The only thing certain is that, as a rule, the range of audibility is considerably shortened to windward of a source. A ship that supposes herself to be to windward of a fog-signal station and wants to make it by the sound, should navigate with the greatest caution. The same holds good of a ship running with the wind, for on board of her the risk may be run of not hearing the signal of a meeting ship at more than 400 to 500 metres distance.

This does not preclude the fact that in many cases fog-signals may be, and often are, a valuable help in navigation. But they cannot give *reliable* information: if the signal is but feebly audible it is not certain that it is far away; if it is strong its nearness cannot be relied upon; if it be heard decidedly coming from a certain direction, it may be in another direction differing from the apparent one by as much as 50°.

It will be found, then, that there are good reasons for the gradual transition from sound-signals through the air to submarine signals, the propagation of which latter can be regarded in most cases as very nearly rectilinear, and which are audible at far greater distances. In a few years there will probably be on the market submarine receivers so simple and cheap as to be within the reach of most ships. The same, no doubt, holds good of wireless direction-finding too.

The following precautions for avoiding collisions between ships meeting in fog might be recommended.

1. *A ship running with the wind* (easily audible, but hearing badly) need not signal more often than usual, but should go at low speed, with a look-out *aloft*, and listen very attentively; ready to stop and *back* as soon as

a signal is heard from to leeward (in, or a little to either side of, the direction of the course).

2. *A vessel running against the wind* (not easily audible, but hearing well) may go at a higher speed. As soon as a signal is heard from to windward, the vessel should slow down or, if the intensity of the sound increase rapidly, stop and work the *steam-whistle* with only very *short interruptions* (but not quite continuously) in order that the signal be heard by the meeting ship as soon as she has arrived within the zone of audibility.

3. *In a calm* both ships must proceed with the greatest caution. It is only with a contrary wind that a vessel will be fairly sure to hear meeting ships at least 1 to 2 nautical miles.

In navigation by fog-signals situated on shore the following facts should be kept in mind :

1. *The intensity of a sound* can give no definite information as to the distance from its source. The sound may be feeble although the source be not far away; it may be strong though the source be not near..

2. When the *signal is not audible* it may still be within 1/4 of a nautical mile, or if it be known with certainty that the source is to windward, within 1 to 2 nautical miles.

3. *The apparent direction of sound* may be misleading, deviations up to 50^{0} being possible.