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R0109 (E-109) THE CALCULATION OF THE RANGE OF A SOUND SIGNAL

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THE COUNCIL

RECOGNIZING

- 1 The need to provide guidance on the calculation of the comparative ranges of sound signals in a consistent way.
- 2 That such guidance can be given by the provision of data to estimate the range of sound signals in certain defined conditions regarding meteorological state, noise on board and probability of signal perception.

CONSIDERING the proposals of the IALA Engineering Committee.

ADOPTS the method of calculation of the nominal range and the usual range of a sound signal, set out in the Annex to this Recommendation.

RECOMMENDS that IALA members and authorities Lighthouse Authorities use the method described in the Annex,

REVOKES IALA Recommendation for the calculation of the range of a sound signal, dated November 1968.



ANNEX A FOREWORD

The “Nominal range” and “Usual range” given in these Guidelines correspond to different conditions concerning noise on board and probability of signal perception. These conditions have been chosen in order to be as representative as possible of those encountered in practice. However, the attention of users is drawn to the fact that “actual range” may differ considerably from the “nominal range” or the “usual range” resulting from the use of the conventional calculation process.

Particularly:

The propagation of sound has been assumed to take place in rather calm weather as if there were no obstacles. In fact it is known that contrary winds are very unfavourable to the propagation of sound and also that turbulence produced by wind may prevent audition.

- 1 The calculation is based on the noise on board large vessels as found from inquiries and statistical data. However the amount of noise differs considerably from one vessel to another and also according to the position of the observer on board ship and to the ships’ manoeuvres. Small vessels are sometimes very noisy, especially if their speed is not reduced in fog. Technical developments may also eventually lead to an increase or decrease of noise levels on board.
- 2 The characteristics of the sound signal have been assumed to be determined in actual conditions and in a given direction. Therefore a “nominal range” or a “usual range” cannot be assigned to any specific type of sound signal unless the precautionary measures taken for the installation of the sound signal on shore and the direction taken into account from the sound signals to the ship are properly specified.



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1. INTRODUCTION

The fog signal emitters used by Lighthouse Services are of great variety.

It is therefore important to assess their respective performances, in order to decide on the apparatus which meets the operational requirements most effectively and to select the most economical types of equipment.

The essential performance of a fog signal emitter is its range, that is to say the maximum distance at which the sound signal it produces can be recognised.

The factors which govern range are numerous and complex and fluctuate in time and space.

Direct observation of the range leads to very scattered results because of the impossibility of reproducing accurately all the conditions which influence its value. Furthermore, its determination is often difficult and requires considerable resources.

In order to obtain a comparative estimate of the range of sound signals, one must :

- Analyse the different factors affecting the range.
- Select for these various factors conventional conditions or values which are as representative as possible of those which present themselves in actual maritime use but which are simple enough to permit easy determination of their influence on the range.
- Set up rules which will permit range calculation in the conditions specified.

For practical reasons it has been found useful to elaborate a double convention and to define on the one hand a “nominal range” and on the other hand a “usual range”.

2. FACTORS ON WHICH THE RANGE DEPENDS

These factors can be classified in three groups relating respectively to;

- the emission of the sound:
- the propagation of the sound: and
- the audibility on board ship.

The groups themselves are influenced by the position of the listener in relation to the fog signal emitter and especially by the bearing of the emitter from the ship.

The arrangement of the conditions of hearing and propagation must be such that the hearing does not enter into it. However, by reason of the pronounced directivity of certain fog signal emitters one cannot as a general rule make the same simplification where the emission is concerned; it will, therefore be necessary to specify in each case the bearing for which the range is indicated.

2.1. AUDIBILITY ON BOARD SHIP

The audibility on board ship will be investigated first, since it conditions to a large extent the manner in which the other two groups of factors must be taken into consideration.

Physiological acoustics tells us that the perception of a signal depends mainly on the noise prevailing at the listening point.

It is, therefore, important both to choose a noise of the kind usually prevailing on board ship and to be able to establish whether or not the signal will be heard in this noise.

2.1.1. THE CRITERION OF AUDIBILITY

To this latter problem physiological acoustics now provides a solution (x)¹ which appears quite adequate and makes it unnecessary to resort to direct and always long and costly audibility tests requiring the use of specialized laboratories, of which there are only a few available in the world.

The process is based on a special spectral analysis into “frequency groups”. These frequency groups represent special frequency bands, the limits of which are capable of varying in the spectrum continuously and the widths of which depend on the central frequency.

Figure 2 represents the law of variation of the band-width Δ of the frequency groups as a function of their central frequency, f . This band-width is practically constant and approximates to 100 Hz up to 500 Hz; beyond that it varies more or less proportionally to the frequency and is then near a third of an octave. Quantitative determinations of the formation of the audibility threshold have shown that, whatever the level, a sound of frequency f in excess of 2 kHz is at threshold when its sound pressure level is about 6 dB lower than that of the asking noise falling into the corresponding frequency group. Below 2 kHz the difference, S , of the levels becomes smaller, and in the case of very low frequencies it is reduced to approximately 3 dB; in figure 3 the variation, as a function of the frequency, of this difference in level can be seen.

When the sound is complex and of continuous spectrum, one observes a certain lowering of the threshold when the comparison of the sound pressure levels of the sound and the noise in several distinct frequency groups would lead to the same threshold. This lowering, M , depends on the number of liminal frequency groups concerned and its value is given in the curve of figure 3. (In practice, this reduction hardly ever exceeds 2 or 3 dB).

For short duration sounds the above rules apply as long as the duration of the sounds definitely exceeds 35 ms; for sounds of a duration approaching this value, or lower, it is found that hearing at the threshold has the property of integrating with a time constant of 35 ms.

The thresholds established as above correspond to a hearing probability of 50%; it is found that to obtain a hearing probability of 90%, sound pressure levels are required approximately 3 dB higher than the preceding levels.

The application of the above audibility criterion leads to the conventional masking noise being defined by its spectral level N_s . Because of their diversity, only general indications for the measurement of sounds can be formulated. If their spectral analysis leads to relatively spaced out discrete components, the acoustic pressure level of these components must be established. If their spectral analysis leads to continuous spectra or to discrete components which are too close, an analysis by thirds of an octave will be required. For fluctuating or very brief sounds, it will be advisable to ascertain the sound pressure levels, taking into account a temporal integration with 35 ms time constant.

2.1.2. NOISE ON BOARD SHIP

The noise on board depends on the ship concerned, on the position of the ship, on the operation of the various noise-producing machines and equipment on board, including the ship's engines, and also on the wind and the state of the sea.

1 (x) See, in particular, H. Scholl “über ein objectives Verfahren zur Ermittlung von Hörschwellen und Mithörschwellen”. Frequenz, vol.17, No.4, April 1963, pages 125 to 133

To choose a standard noise, measurements have been carried out in various countries. On large vessels the signal runs the risk of being heard in the wheel house in a very muffled and uncontrolled way since this part of the ship is fairly enclosed or sound proof. It has therefore been considered logical to take the bridge wing as the position of reference. In fact, a fog look-out is frequently posted outside to listen to the sound signal, and sometimes even in the bows. By choosing the bridge wing a realistic and not too favourable view is taken, since it has been found that, at least when the ship is under way, the noise here is greater than on the bow.

The noises measured on board the large merchant vessels in various countries are, on average, very much alike and little affected by the starting or stopping of the main engines. The effect of meteorological conditions on the noise has not been analysed specifically.

Small vessels are on the whole more noisy than large ones, but it has become evident that, where listening to a sound signal in fog is concerned, there is no hesitation to reduce speed and (for those charged specially with the listening) to proceed to a point of vantage; taking these precautions into account, the conditions of listening on small ships may, in general sense, be considered at least as favourable as those on larger vessels, for which reason it has been thought proper not to pay special attention to the small vessels in the determination of conventional noise.

Finally, it has been deemed advisable to take, as conventional noise, the noise prevailing on the wings of the bridge of large vessels travelling at slightly reduced speed as is usual in foggy weather. It has been decided to draw, as a result, the average curve of the spectral levels recorded under those conditions. In Figure 5 in which the logarithm of the frequency forms the abscissa and in which spectral level NB in decibels (ref. 20 μ Pa or 20 μ N/m² or 2.10⁻⁴ μ bars) per hertz, forms the ordinate, this curve is composed of a polygonal outline, the successive vertices of which are:

Table 1 Spectral noise as a function of frequency

25 hertz	80 decibels
100 hertz	56 decibels
2000 hertz	21 decibels
4000 hertz	10 decibels

Values for the standard deviation E of these spectral levels as measured on different ships have been taken as 8 dB up to 125 Hz, 7 dB at 250 Hz and 6 dB above 500 Hz.

2.2. PROPAGATION OF THE SOUND

Fog signals are intended to be heard at relatively large distances from the transmitter. The sound reaching the listener has characteristics which are affected by numerous parameters:

- the distance between emitter and listener;
- the bearings of the emitter;
- the variations of the propagation speed in the air, due to differences in temperature and humidity;
- the attenuation of the sound during propagation which itself is a function of the temperature, the humidity and the droplet content of the fog;

- the wind, the turbulence of the atmosphere and its lack of homogeneity which deflect and disperse the sound waves and progressively degrades the waveform (or spectrum) of the signal;
- obstacles, especially the surface of the sea and those placed in the vicinity of the emitter and the listener, obstacles which reflect or diffuse the sound energy, multiply the paths of propagation and cause interference.

One can imagine the great irregularity in time and space of the sound reaching the listener, an irregularity which increases greatly with distance.

In order to avoid prohibitive complexity in the range calculation one must radically simplify the actual conditions of propagation. It is assumed that sound propagates in a homogeneous atmosphere devoid of obstacles and perfectly still in the absence of the signal. As the sound source is always of very small dimensions in relation to the distance to the listener, the attenuation of the sound levels can therefore be calculated as resulting from a spherical divergence attenuation, O , and an excess attenuation, A , proportional to the distance, D , and related to various energy losses inherent in the sound phenomenon. One part of this attenuation proportional to the distance, which is of negligible importance except at very high frequencies, is due to the combined action of the viscosity and thermal conductivity of the air and the phenomenon of the relaxation of the rotational energy states of the air molecule the corresponding coefficient of attenuation can be taken as independent of the humidity of the air. The second part is due to the phenomenon of the relaxation of the vibrational states of the oxygen molecules in the air. This phenomenon depends very much on the presence of water molecules; the corresponding coefficient, therefore, varies with the humidity.

As sound signals are required at times of fog, it is naturally expedient to consider the matter of saturation humidity and not to ignore the attenuation effect due to the fog droplets suspended in the air – an effect, however, which is of secondary importance.

In the range of frequencies of interest to maritime signalling, the determination of the excess attenuation, A , encounters great experimental difficulties. In the open it is practically impossible to avoid disturbing effects of the same order of magnitude as the effect to be measured; in the laboratory the distances over which one can work do not permit the attainment of attenuations of sufficient magnitude to make an accurate measurement. One is confined to estimations by extrapolation of measurements taken at higher frequency, on the basis of theoretical considerations. The results taken into account for absorption are those of Cyril M. Harris, Department of Electrical Engineering, Columbia University, New York, "Absorption of sound in air versus humidity and temperature" (J.A.S.A., Vol. 40, No. 1, July 1966, pages 148 to 159). An air temperature has been assumed of 10°C and a relative humidity of 90%. This latter value has been chosen in the absence from Harris's results of curves for 100% relative humidity. The trend of Harris's curves shows that the absorption values for 100% relative humidity are very close (all other things being equal) to those for 90%, although slightly lower.

Here is the table of values of attenuation β in decibels per mile, due to absorption:

Table 2 Sound attenuation in decibels per mile due to absorption

Frequency f (in Hz)	Attenuation β (in dB/mile)
125	0.5
250	1.1
500	2.6
1000	6.5
2000	15.9
2500	22.4
3200	30.5
4000	42.5
5000	59.0

To the air absorption must be added the absorption due to fog. A standard fog has been taken into account, namely a homogeneous fog containing 0.1 g/cm³ of water condensed in uniform droplets of 25 micron diameter. As corresponding attenuation values we have adopted those given in the report on the U.S. Coast Guard Project CGTD J 15 – 1/5 Phase II Final Report “Investigation of the transmission of sound through fog over water” by Bolt, Beranek and Newman Inc., and which are shown in the following table:

Table 3 Sound absorption due to fog

Frequency f (in Hz)	Attenuation γ (in dB/mile)
100	0.97
400	1.38
640	1.46
1000	1.54
2000	1.64

No attenuation due to diffusion has been taken into account. The results of the interpolation calculations have been brought together in Table 3.

When the propagation occurs in windless conditions, or is at right angles to the wind, the sound pressure levels observed are, on average, in reasonable agreement with the values deduced from the preceding hypotheses. If the propagation occurs in a direction against the wind, the phenomenon of acoustic shadow comes into play and the sound pressure levels observed are, beyond a certain distance, much lower (at equal distance) than those observed when the wind is not opposing, and often vary greatly from one instant to another. Anyway, the excess attenuation in this case is definitely not proportional to the distance. The excess attenuation can, according to certain experiments, exceed by 30 decibels and more that which would result on the basis of the preceding simplifying hypotheses. On the other hand, in the direction of the wind, one finds a diminution of the excess attenuation which may reach several decibels.

Owing to the lack of accurate knowledge available in respect of propagation with the wind and against the wind, and also on account of their great irregularity, it has not been possible to take these types of propagation into consideration in determining the nominal range and the usual range.

2.3. EMISSION OF THE SOUND

- a) The dimensions of the sound sources are always very small in relation to the listening distance; they are generally still so in relation to the distances at which the excess attenuation proportional to the distance acquires a significant value.
- b) If we take into account the hypotheses made concerning propagation of sound for the determination of range, then, in an area around the source near enough for the excess attenuation to be negligible but far enough for the dimensions of the source to remain small in relation to the distance of the source, propagation of the sound occurs by purely spherical divergence and the sound pressure level N_D in decibels decreases in accordance with Equation 1 (Sound attenuation due to distance), i.e. 6 decibels each time the distance is doubled, or 20 decibels each time the distance is increased tenfold. In this case D is the distance to the sound source and D_0 a reference distance at which the sound pressure level is N_r .

$$N_D = N_r - 20 \log D/D_0 \quad (1)$$

Where:

N_D is the sound pressure level of a pure sound produced at 1 metre by a sound emitter (dB)

N_r is the sound pressure level of a pure sound emitted by the sound emitter at the reference distance 1 metre in the direction considered

D is the distance to the sound source

D_0 is a reference distance at which the sound pressure level is N_r

It will, therefore, suffice to know for each direction of emission of interest (i.e. for practically every emission direction in the horizontal plane) the sound spectrum of the signal at the reference distance for the properties of the sound source to be fully defined.

This reference distance has been chosen equal to 1 metre.

Appendix 1 gives details of the methods to be used to obtain the sound spectrum at the reference distance.

3. DEFINITION OF THE NOMINAL RANGE AND THE USUAL RANGE

The simplifying hypotheses and the data collected as set out above, permit the calculation of the range of a sound signal for various probabilities of hearing on ships, the noise on which corresponds to or exceeds that on a certain proportion of large merchant vessels.

3.1. NOMINAL RANGE

For the nominal range P_n , by agreement, a hearing probability has been chosen of 90% in a noise equal to or greater than that found on 84% of large merchant vessels. Therefore:

The nominal range is, by agreement, the distance at which, in foggy weather, a lookout positioned on the wing of the bridge has a probability of 90% of hearing the signal when subjected to a noise as defined by the IALA Sub-Committee on Sound Signals, which is equal to or in excess of that found on 84% of large merchant vessels, the propagation between the fog signal emitter and the listener occurring during relatively calm weather and with no intervening obstacles.

3.2. USUAL RANGE

For the usual range P_u , by agreement, a bearing probability has been chosen of 50% in a noise equal to or greater than that found on 50% of large merchant vessels. Therefore:

The usual range is, by agreement, the distance at which, in foggy weather, a lookout positioned on the wing of the bridge has a probability of 50% of hearing the signal when subjected to a noise as defined by the IALA Sub-Committee on Sound Signals, which is equal to or in excess of that found on 50% of large merchant vessels, the propagation between the fog signal emitter and the listener occurring during relatively calm weather and with no intervening obstacles.

3.3. FOG SIGNAL EMITTER

It is necessary to specify each time for what bearing from the fog signal emitter the nominal range or the usual range have been determined.

The usual range values, to which the above mentioned definition refers, are generally of the same order of magnitude as the ranges which earlier methods had attributed to the fog signal emitters. The nominal ranges are distinctly lower than the latter.

The classification of fog signal emitters according to usual range may not coincide with their classification according to nominal range.

3.4. NOMINAL AND USUAL RANGE CONCEPTS

The attention of users of the nominal range and usual range concepts is drawn specially to the fact that the actual range of a sound signal may have no relation whatever to the nominal or usual range and, in certain cases, may drop to very low values, particularly on account of strong wind or contrary wind, or when the listener is on a noisy ship.

4. CALCULATION OF THE NOMINAL RANGE AND THE USUAL RANGE

The simplifying hypotheses and the conventionally adopted data concerning the audibility and propagation of sound permit the calculation of sound pressure level N_r of a pure sound at the reference distance for a sound signal emitter, the nominal range or the usual range of which is given.

The results of these calculations permit the drawing of graphs of the nominal range P_n (Figure 7) or the usual range P_u (Figure 8) of a pure sound of frequency f , the sound pressure level N_r of which, at the reference distance is known. The relevant calculation tables are attached (Table 5 II and III).

The use of the graph of figures 7 and 8 permits in every instance calculation of the nominal range or the usual range.

4.1. PURE SOUND

In the case of a pure sound, the nominal and the usual ranges are read directly from the graphs.

4.2. COMPLEX SOUND

In the case of a complex sound, the use of the graph is similar, but the sound level in decibels to be taken into account is then that of the frequency group, the central frequency of which is taken as abscissa.

4.3. SOUND SPECTRUM

If the spectrum is continuous or contains numerous lines, the frequency may be selected at any frequency of the sound spectrum; in every case there will be a frequency group corresponding to it and a sound pressure level in the frequency group, and therefore a nominal or usual range, given for it by the appropriate graph. The nominal or usual range of the complex sound will be the maximum of the ranges for all possible frequency groups, subject to the correction given in figure 4. The frequency group (or groups) for which the maximum range is reached is (are) determined by trial and error.

If the sound has a spectrum of lines and if there is only one spectral line in the frequency group concerned, the sound pressure level in this frequency group is that of the line.

If there are several lines in the frequency group, the sound pressure level of the frequency group is obtained by combining the lines (or their resultants) two by two in accordance with the rule shown in the conversion scale of figure 1.

If the spectrum is continuous, the sound pressure level of the frequency group can be deduced from the spectrum level by adding: $10 \log \Delta$ (Δ = width of the frequency group), or from the third-octave level by adding: $10 \log \Delta - 10 \log T$ (T = width of the third-octave band); if the frequency group overlaps several third-octaves it must be divided into partial bands corresponding to these third-octaves, the sound pressure level in these partial bands will be calculated as above and the combination of these levels will be effected according to the procedure given in figure 1.

If there are, simultaneously, a continuous spectrum and a line spectrum and if the analysis has been made separately, one can also calculate the respective sound pressure levels and combine them by the method given in figure 1.

Naturally, and in the case of sound signals rich in harmonics this will frequently constitute the most convenient solution, the sound pressure levels of frequency groups can also be measured with the aid of band-pass filters, either normalized (for instance third-octave filters coinciding with the frequency groups above 500 Hz) or variable bandwidth filters.

If several frequency groups, in number v , non-overlapping, yield the same range, to within the measurement tolerance, it is necessary to make a correction given by the graph of figure 4. The corrected range will then be determined by increasing the sound pressure levels of the frequency groups, by the number M of decibels indicated by the graph.

4.4. SHORT OR FLUCTUATING AMPLITUDES

For short or fluctuating sounds one can look for the maximum amplitude on a measuring apparatus with a time constant equal to 35 ms, preceded by a band-pass filter corresponding to a frequency group. One thereafter proceeds as in the case of a complex sound, after having looked, by trial and error, for the frequency groups leading to maximum ranges.

One can also use a recording of the sound pressure curve as described in the aforementioned article (see note at the foot of page 8).

5. SYMBOLS

f	frequency, in hertz.
s	difference between the sound pressure level of a noise in a frequency group and the sound pressure level of a pure sound, audible in the noise with a probability of 50%, the frequency group concerned being centred on the frequency f of the pure sound.
M	lowering of the threshold of hearing, in decibels, when the threshold is reached simultaneously in several distinct frequency groups, of number ν .
N _s	spectral level, in decibels (ref. 20μ Pa or 20μ N/m ² or $2 \cdot 10^{-4} \mu$ bars) per hertz, of the masking noise.
N _B	spectral level, in decibels (ref. 20μ Pa or 20μ N/m ² or $2 \cdot 10^{-4} \mu$ bars) per hertz, of the noise reached or exceeded on 50% of large vessels.
E	standard deviation of the spectral level of the noise on large vessels.
Q	attenuation due to spherical divergence, between 1 metre and distance D, in decibels.
A	conventional excess attenuation between 1 metre and distance D for frequency f, in decibels.
D	distance from the fog signal emitter to the vessel.
β	excess attenuation due to absorption over a distance of 1 mile, in decibels.
γ	excess attenuation due to fog over a distance of 1 mile, in decibels.
N _D	sound pressure level, in decibels (ref. 20μ Pa or 20μ N/m ² or $2 \cdot 10^{-4} \mu$ bars), of a pure sound produced at 1 metre by a sound emitter which, by the effect of attenuation due only to spherical divergence, reaches a level N ₀ at distance D.
N _r	sound pressure level, in decibels (ref. 20μ Pa or 20μ N/m ² or $2 \cdot 10^{-4} \mu$ bars), of a pure sound of frequency f or of the frequency group of central frequency f, emitted by the sound emitter at the reference distance 1 metre in the direction considered.
P _n	nominal range of a sound emitter, in sea miles.
P _u	usual range of a sound emitter, in sea miles.
Δ	band-width, in hertz, of a frequency group, the central frequency of which is f.
T	band-width, in hertz, of a third-octave band, the central frequency of which is f.
ν	number of distinct frequency groups leading to the same threshold of hearings.
r	minimum measuring distance for a maximum margin of error of 0.5 decibel.
d	the largest dimension of the emitting part of the sound source or the group of the sound sources.
λ	wavelength corresponding to the highest frequency occurring in the measurement.
α	total excess attenuation over a distance of 1 mile, in decibels.



- N_G sound pressure level, in decibels (ref. $20 \mu \text{ Pa}$ or $20 \mu \text{ N/m}^2$ or $2 \cdot 10^{-4} \mu \text{ bars}$), of masking noise in a frequency group of central frequency f .
- N_o sound pressure level, in decibels (ref. $20 \mu \text{ Pa}$ or $20 \mu \text{ N/m}^2$ or $2 \cdot 10^{-4} \mu \text{ bars}$), of a pure sound, perceptible with the given probability in the masking noise.
- D_o reference distance (chosen equal to 1 metre) at which the sound pressure level is N_r .

APPENDIX 1 EXPERIMENTAL DETERMINATION OF THE CHARACTERISTICS OF A SOUND SOURCE

1. INTRODUCTION

In the first place it is necessary to set up the sound source in conditions which reproduce a “free field”, that is to say a homogeneous medium, free from obstacles and, in the absence of the signal, completely still.

Thereafter the distance limits must be found, within which the law of attenuation by spherical divergence comes into effect, and finally in this region the sound measurements must be taken in respect of all the directions in which one is interested. Application of the formula : $ND = Nr - 20 \log D/Do$ (see page 6) will permit ascertainment of the sound pressure level at the reference distance, which need not necessarily be in the region where the law of spherical divergence is effective.

2. EXPERIMENTAL ARRANGEMENT

In practice an excellent solution consists in operating in an anechoic chamber; such a chamber, lined on all walls with sound absorbing material, simulates an excellent approximation to a “free field”; it has the advantage of excluding all disturbances due to ambient noise from outside and above all it does not disturb the neighbourhood in the case of powerful signals.

However, at all times attention must be paid to the fact that the absorbent material is not fully effective at very low frequencies, and hence the conditions of the “free field” will only be satisfactorily realized above some frequency, which will be generally known by the habitual users of the room. Furthermore, the conditions of the “free field” do not prevail in the immediate vicinity of the walls. The usable space, therefore, of an anechoic chamber is only a fraction of the total volume of the chamber. Taking into account the always inevitably limited dimensions of such rooms, the use of anechoic chambers will be possible only if the sound emitting apparatus is not of too great a volume in relation to the size of the room.

If an anechoic chamber is not available or if the sound emitter is too large for any room that is available, it is necessary to work in the open. One is then exposed to the weather and it is quite difficult to find a location where the local population does not react strongly to the nuisance caused by repeated sound transmissions. One must also avoid disturbances caused by the presence of obstacles and especially the reflection from the ground. One is, therefore, obliged to place the apparatus on a light tower framework and to take measurements fairly close to the sound emitter, and at such a height that the effect of the earth reflection is negligible in relation to that of the direct path.

One may also make use of the flat roof of a high building; the sound transmitter must then be installed on the edge of the flat roof and the measuring microphone on an external support in a region which has been shown by experiment to be free from significant reflection.

The success of the experimental arrangements decided upon can be checked by verifying that in the direction chosen there is a region in which the spherical divergence conditions are met, i.e., where the sound pressure level varies in accordance with the law mentioned earlier.

By the way of indication, the minimum measuring distance, r , for a maximum margin of error of 0.5 dB is given by the formula in Equation 2:

$$R > \pi/4 \times d^2/\lambda \quad (2)$$

where

d is the largest dimension of the emitting part of the sound source or of the group of sound sources,

λ is the wavelength corresponding to the highest frequency occurring in the measurement.

(The distance r must never be taken below $2d$).

Naturally one must set a point of origin from which the directions and the distances relative to the source are evaluated. The positional accuracy of this point is, generally speaking, not very critical, owing to the fact that the measurements must be made in any case at a distance large compared with the dimensions of the emitting part of the apparatus. In practice it will be sufficient to select a point in the central zone of the emitting part. Where, for instance, a horn is concerned, the centre of the aperture is taken. Taking this choice into account, one finds that for an isolated horn the region in which the law of spherical divergence is verified can come very near to the apparatus, since on the axis it remains well verified up to a distance from the centre of the aperture of the horn equal to twice the diameter of this aperture.

If the apparatus is too cumbersome, or if it is difficult to separate the ground reflection from the direct ray, or, again, if one is concerned with an apparatus already set up, it may happen that experimentally one can find no region in which the law of spherical divergence can be satisfactorily verified. One will then be forced to an evaluation of the reflection effects which, if they are not too considerable, can be deduced from ground measurements, from the experimentally established law of attenuation or from measurements relating to the whole of a certain region of the sound field. One can then deduce from this the corrections to be effected in order to evaluate the part which relates to the direct path itself, and so determine the emission properties of the sound source in the absence of obstacles.

It may happen that the construction in which the sound apparatus is installed constitutes a sound baffle which greatly alters the directional properties of the emission. It may happen also that the sound apparatus has been provided with a sound baffle intended to concentrate the sound in certain directions or to substantially reduce the emission towards certain residential areas. In this case only those measurements taken under the exact conditions of the installation can give an objective evaluation of the nominal range and the usual range, but they may prove to be very difficult

3. SOUND MEASUREMENT AND ANALYSIS

As the criterion of audibility calls for a sound spectrum analysis, independent of the phases of the components, the classical methods of sound spectrum analysis may be applied.

The sound is always detected by means of a microphone which transforms the acoustic pressure into an electric voltage.

This microphone must have a constant sensitivity in the range of frequencies concerned and must function linearly without saturation up to the strongest sound levels to be measured. On the other hand one does not require a very high degree of sensitivity on account of the high intensity level of the sounds produced. One will normally be led to use microphones of small dimensions which have little effect on the sound field. In general, they will be omni-directional which will not permit, for example, isolation of the direct ray from the reflected ray. The microphones must be carefully calibrated but an additional precaution

would be to apply, prior to a series of measurements, a standard sound to the microphone, which would permit verification of the whole of the measuring system.

If we are concerned with a pure sound or a complex but periodic sound, or, more generally, a sound which only comprises discrete spectral components, modern wave analysers make it possible to separate the harmonics or partials to a high order by accurately measuring their frequency (to 1 Hz or 0.1 Hz approx.) and their sound pressure level (the accuracy may reach a decibel and even one-tenth of a decibel).

If the spectrum is continuous or composed of very close spectral lines, third-octave band-filters or variable bandwidth filters must be used.

Special precautions must be taken against saturation if the sound is composed of very pronounced impulsive sounds with a very high instantaneous pressure relative to average pressure. Such saturation is revealed by crosschecking measurements effected with different amplifications on the same sound.

If the sound fluctuates or is of short duration, it is obviously necessary to take the precaution of using with the band-pass filters (as there are in such cases no clearly discrete components in the spectral analysis) a measuring apparatus with a time constant of 35 ms.

If the source is to be measured in various directions, it must be in directions in the horizontal plane at the position of installation, which alone are of practical interest in application to marine service.

A horizontal emission pattern must therefore be plotted; the best method to use (if the apparatus is neither too heavy nor too cumbersome) consists of an automatic polar plotter with a revolving table, the microphone remaining stationary. Naturally, the recording may relate to any one element, the analysis of which is required, but it is clearly essential that the sound should be steady during the entire period of rotation.

If this condition is not realized, or if the apparatus is too heavy or too bulky to be fixed on the platform of the revolving table, one must if possible, proceed, point by point, with manual adjustment of rotation, the microphone remaining stationary.

If such a movement cannot be contemplated, for instance in the case of an apparatus already installed, the microphone must be moved relative to the sound emitter.

APPENDIX 2 THE DIFFERENT KINDS OF SOUND AND THEIR PROPERTIES

The sound emitters used by lighthouse services have been, and still are, of many different types. The sounds they produce have various waveforms, the respective properties of which must be appreciated according to their specific application.

1. PURE SOUNDS

They have a sinusoidal pressure wave which corresponds to a single line spectrum. The most widely used type of signal producing this sound is the electromagnetic oscillator. The sound can, of course, be obtained also by suitably driven loud-speakers and there are certain sirens which produce a sound very similar to a pure sound.

With pure sounds the energy of the signal is concentrated at a single frequency, and therefore in a single frequency group.

One may observe that with certain types of emitters, such as loud-speakers, a single pure sound permits the emission of greater power than any combination of sounds of different frequencies, provided that strict phase relationships are not maintained between the component frequencies in the latter case.

Owing to the existence of reflections from the surface of the sea and, possibly, from other obstacles (for instance the superstructure of vessels), an interference field is produced, in the case of a pure sound, between the direct sound and the reflected sound. As a result, the listener observes that the sound intensity appears to undergo strong fluctuations if he changes his position even slightly. If he remains in a fixed position, the listener observes sound intensity variations which are more or less rapid, depending on the atmospheric conditions. As in lighthouse service the elements of the character (“blasts”) are fairly short – generally of the order of 1 to 2 seconds – it appears as if from one blast to another the sound intensity varies considerably in a random manner. The order of magnitude of the standard deviation of the sound levels is commonly from 4 to 8 decibels at one kilo-metre. This variability makes it less easy to recognize the character of the signal.

A pure sound can prove difficult to detect if, by unfortunate coincidence, the masking noise has an especially high energy in the corresponding frequency group.

2. COMPLEX SOUNDS

In order, it would seem, to guard against this eventuality, as well as to smooth out the interference field and perhaps, above all, to provide easy identification for the listener, various types of sound warning system used for particular purposes make use of various devices such as rising frequency, a periodical varying frequency or two frequencies sounded together.

By deliberate design or owing to their construction many lighthouse sound emitters emit complex sound signals which to various degrees are capable of providing the above mentioned advantages.

Sirens and diaphones generally emit periodic sounds with one, two or three dominant harmonic components and some secondary harmonics.

Also, air diaphragm horns provide a periodic but quasi-impulsive sound; the corresponding very rich spectrum is composed of numerous harmonics, the sound pressure levels of which decrease only slowly with the frequency.

With such periodic sounds, overall coincidence between the spectral components of the signal and the dominant frequencies of the noise is of low or negligible probability and the variation of the intensity of the signal observed from one blast to another is reduced. The high frequency harmonics do not generally contribute to the limiting range but strengthen the subjective impression of intensity at short distances. A comparison at reduced distance will therefore be more favourable to those signals which are rich in high harmonics. By reason of the limited size of horns, the directivity of such sound apparatus increases with the order of the harmonic, so that it appears to be more directive if the listening is effected at a shorter distance.

On the other hand, it must be observed that, only a restricted number of the harmonics contributes to the range of the signal.

In a more systematic way, a number of pure sounds of fairly close frequencies (for instance three) could be combined in one signal. The energies of the elementary components can be added in one group of frequencies, while the interference field is more smoothed out. The coincidences with loud bands of masking noise are reduced and the signal takes on a characteristic tonality which helps towards easy recognition.

Furthermore, arrays of air diaphragm horns with different fundamental frequencies have been installed to the satisfaction of the users. They offer many of the advantages mentioned above.

It may be added finally that certain diaphones produce at the end of the blast a characteristic grunt clearly different in frequency and sound pressure level from the rest of the signal. This grunt may be the determining factor for the range and constitutes a characteristic element in the recognition of the type of signal.

APPENDIX 3 EXAMPLES OF CALCULATION OF THE NOMINAL RANGE AND THE USUAL RANGE

1. THE CASE OF A PURE SOUND

An electromagnetic oscillator emits a pure sound of frequency 300 Hz. The sound pressure level at a distance of 1 m, emitted on the axis of the horns, is $N_r = 140$ dB.

The nominal range and the usual range are read directly from the graphs in figure 7 and figure 8 respectively.

One obtains:

$$P_n = 1.3 \text{ sea miles}$$

$$P_u = 2.6 \text{ sea miles}$$

2. THE CASE OF A COMPLEX SOUND

2.1. SINGLE SPECTRAL COMPONENTS

A single spectral component is effective in the determination of P_n and P_u .

An air diaphragm horn emits a periodic complex sound the principal harmonics of which have values of frequency and of sound pressure level at 1 m as shown in the first two columns of the table below :

Table 4 *Principal harmonics of a periodic complex sound*

f	N_r	P_n	P_u
252	142.0	1.3	2.7
504	140.4	1.7	2.9
756	137.1	1.5	2.4
1008	133.0	1.2	1.9

These harmonics are so widely spaced that there is only one per frequency group. The nominal range and the usual range P_u , corresponding to the various harmonics, have been read from the graphs of figures 7 and 8 and appear in the third and fourth columns of Table 4.

The harmonic of frequency 504 Hz appears clearly most important in the determination of both the nominal and the usual ranges. One does not have to take into account the correction of figure 4.

One thus has for the complex sound :

$$P_n = 1.7 \text{ sea miles}$$

$$P_u = 2.9 \text{ sea miles}$$

2.2. SEVERAL SPECTRAL COMPONENTS

Several spectral components are effective in the determination of P_n and P_u

A sound emitter emits a complex sound of fundamental frequency 75 Hz, the harmonic analysis of which is given as far as the 21st harmonic in the first three columns of Table 5 at the end of this appendix.

One must first of all examine whether several harmonics fall into the same frequency group. One finds in accordance with figure 2 that the width of the frequency groups is approximately 90 Hz at low frequencies. As the spacing of the harmonics is by 75 Hz, there are always at least 2 harmonics per frequency group. At higher frequencies, the frequency groups widen and exceed a width of 150 Hz at approximately 900 Hz, according to figure 2. From 900 Hz upwards there are thus 3 harmonics per frequency group. The width of a frequency group reaches 225 Hz at approximately 1500 Hz, so that 4 harmonics must be combined. The harmonics above 1500 Hz do not affect the range calculation and they have not been taken into consideration.

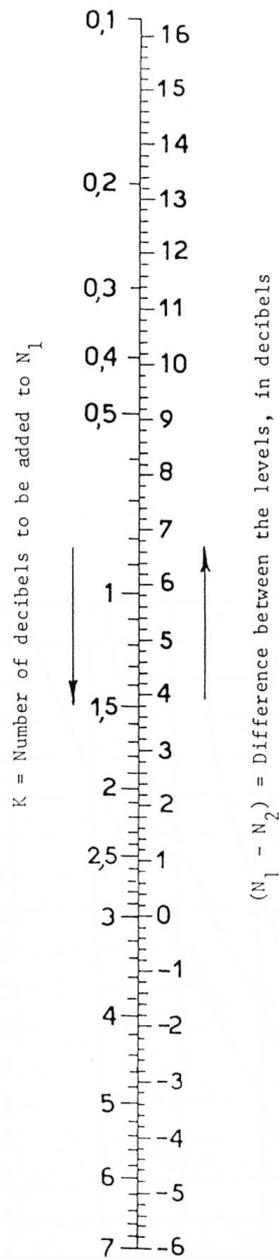
The combination in groups of 2 or 3 harmonics can be effected to two different ways, shown in columns 4 and 5 in one case and columns 6 and 7 in the other case in the Table 5, under the headings “first series” or “second series” respectively.

In columns 4 and 6 are entered the median frequencies of the frequency groups and in columns 5 and 7 the total sound pressure levels of the harmonics per frequency group. For the summation of the levels the conversion scale of figure 1 has been used.

The pairs of values so obtained (mean frequency and total level) are plotted on the graph at the end of this appendix (Extract from figure 7). The pairs of the first series are represented by dots, those of the second series by crosses. If the dots are considered first, one finds that the same nominal range of 1.6 sea miles corresponds to four frequencies: 413, 563, 713 and 863 Hz. The correction according to figure 4 must, therefore, be effected. On this figure one reads that for $\nu = 4$ frequency groups, the hearing threshold is lowered by $M = 2.8$ dB. One then adds this value to the level at the median frequency of the four frequency groups, which produces a nominal range of 1.85 sea miles (encircled dot).

If the same process is applied to the second series, one finds the same value of 1.6 sea miles for the five frequencies 338, 488, 638, 788 and 975 Hz. In this case one reads in figure 3, for $\nu = 5$, $M = 3.2$ dB. Adding this quantity to the level for 638 Hz one arrives at the same practical value of 1.85 sea miles for the nominal range.

This example shows that the method of grouping the harmonics in frequency groups has practically no influence on the value of the nominal range calculated.



The total sound pressure level N of two components having sound pressure levels N_1 and N_2 respectively is obtained by adding to the level N_1 of one of the components the value K given by the conversion scale shown.

Figure 1 Conversion scale for the determination of the total sound pressure level of two spectral components

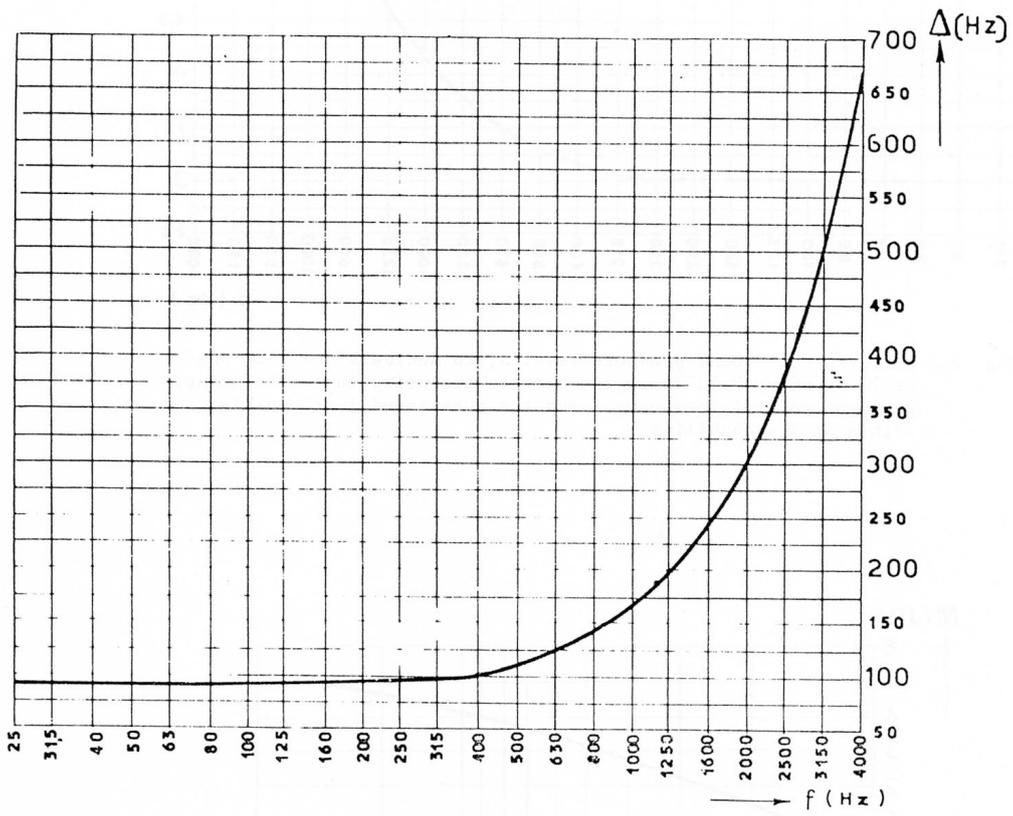


Figure 2 Band-width Δ of the frequency groups as a function of their central frequency f

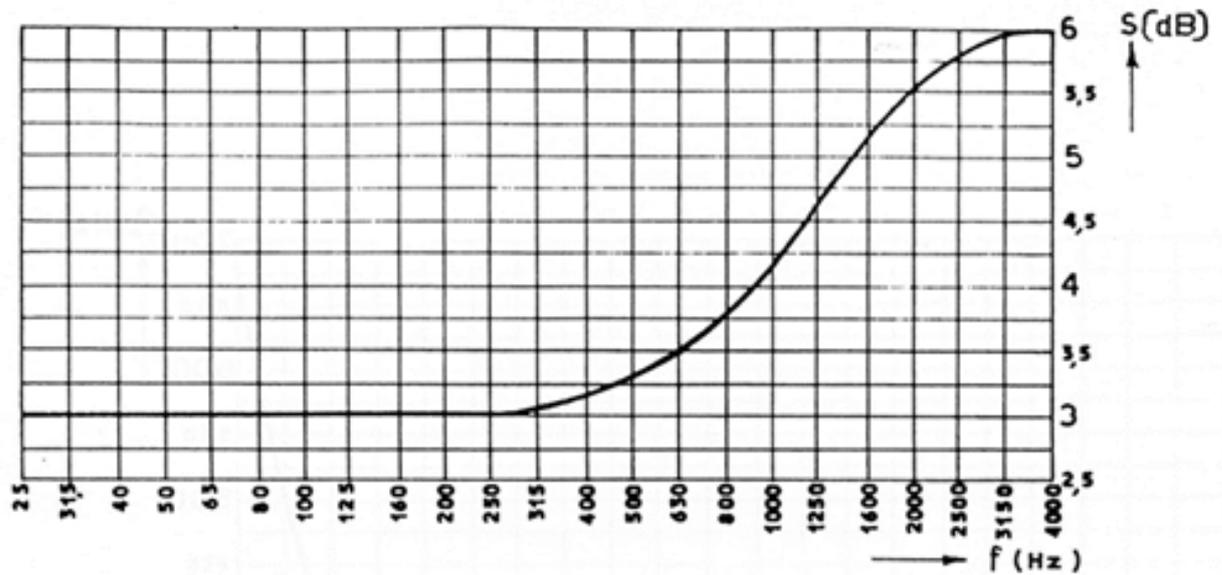


Figure 3 Difference of sound pressure level S , in decibels (ref. $20 \mu\text{Pa}$ or $20 \mu\text{N/m}^2$ or $2 \cdot 10^{-4} \mu\text{bars}$), between the noise in the frequency group of central frequency f and the pure sound just audible with a 50 % probability

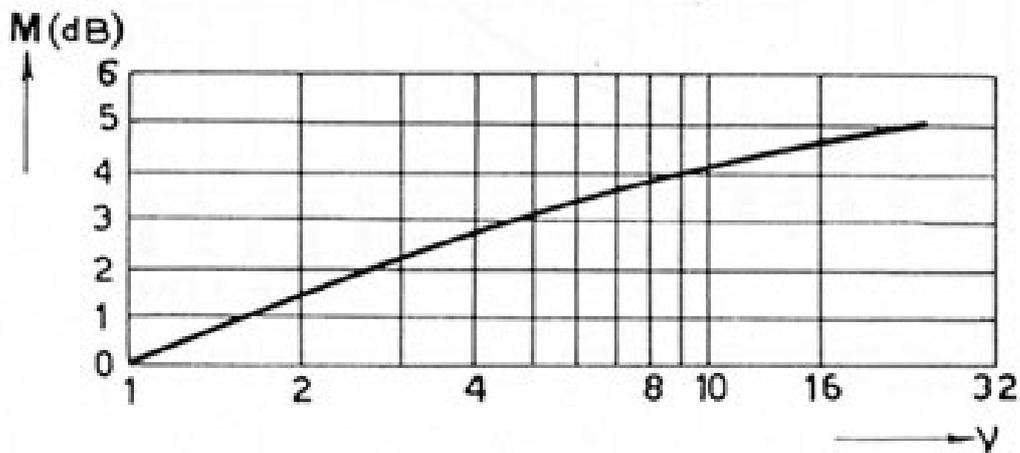


Figure 4 Reduction M of the threshold, in decibels, as a function of the number v of distinct frequency groups to the same threshold

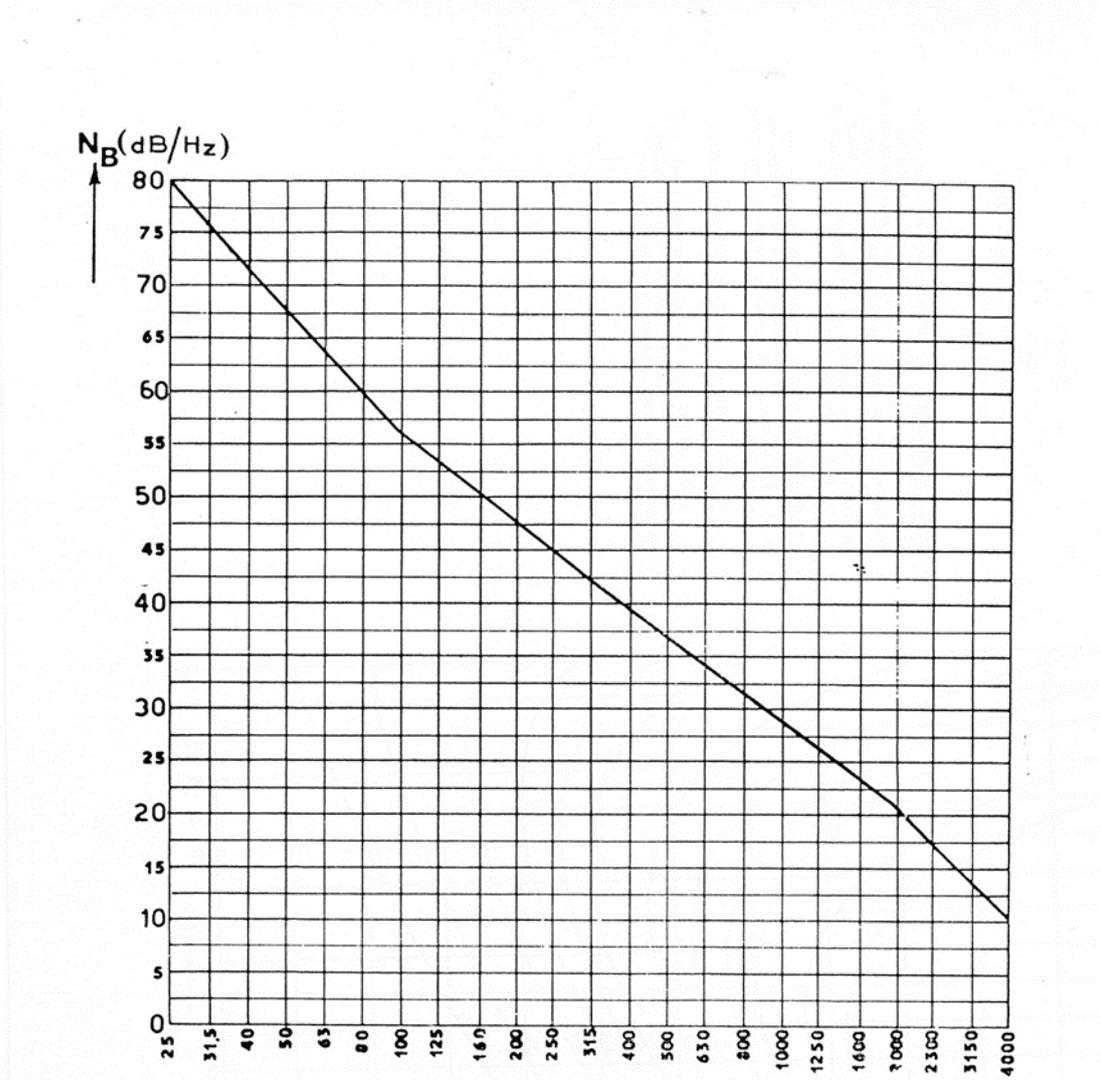


Figure 5 Conventional curve of average spectral level N_B , in decibels (ref $20 \mu\text{Pa}$ or $20 \mu\text{N/m}^2$ or $2 \cdot 10^{-4} \mu\text{bars}$) per hertz, recorded on large merchant vessels, as a function of frequency f

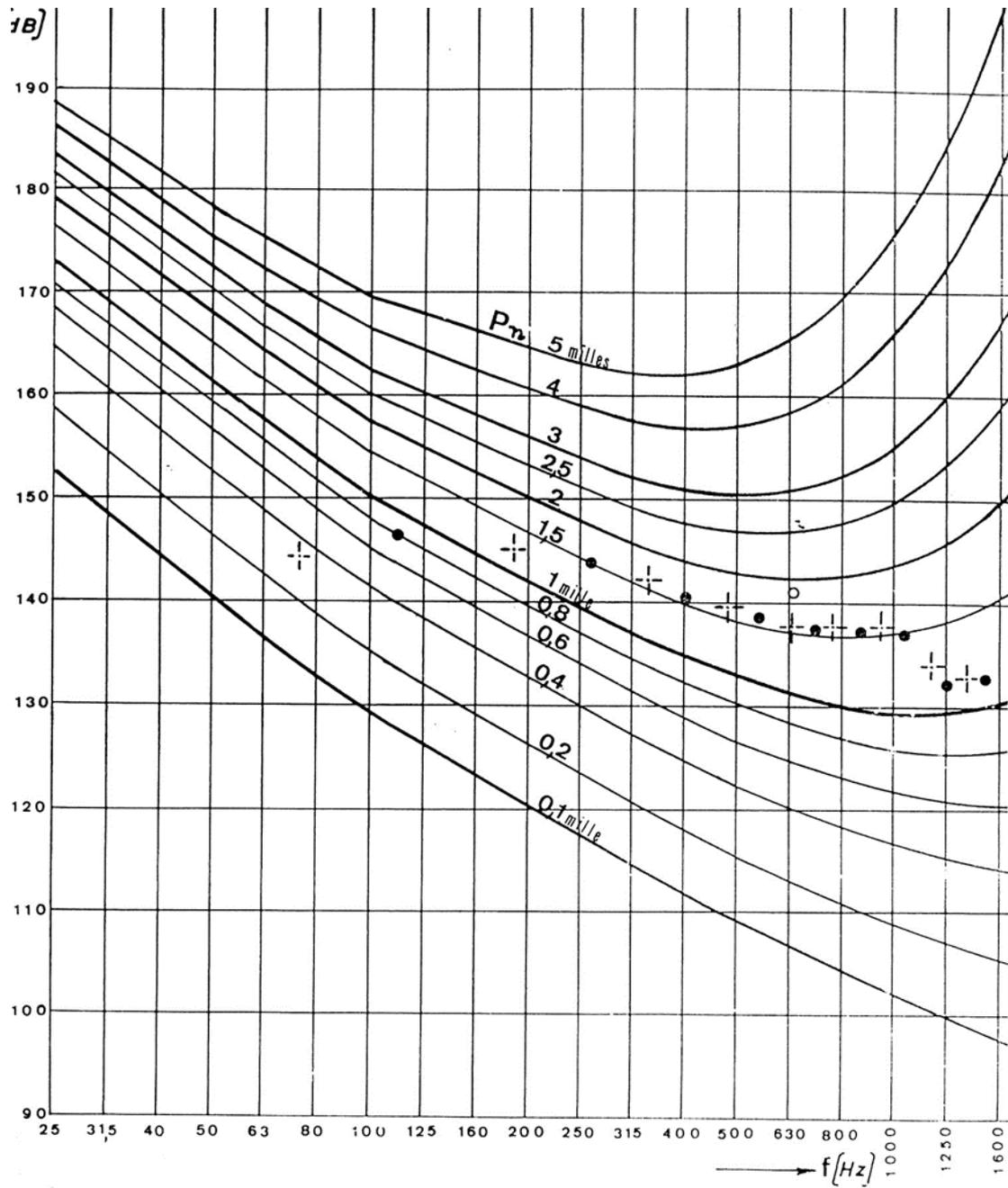


Figure 6 Extract from Fig. 7. Case of application in which several spectral components enter into the determination of the nominal range

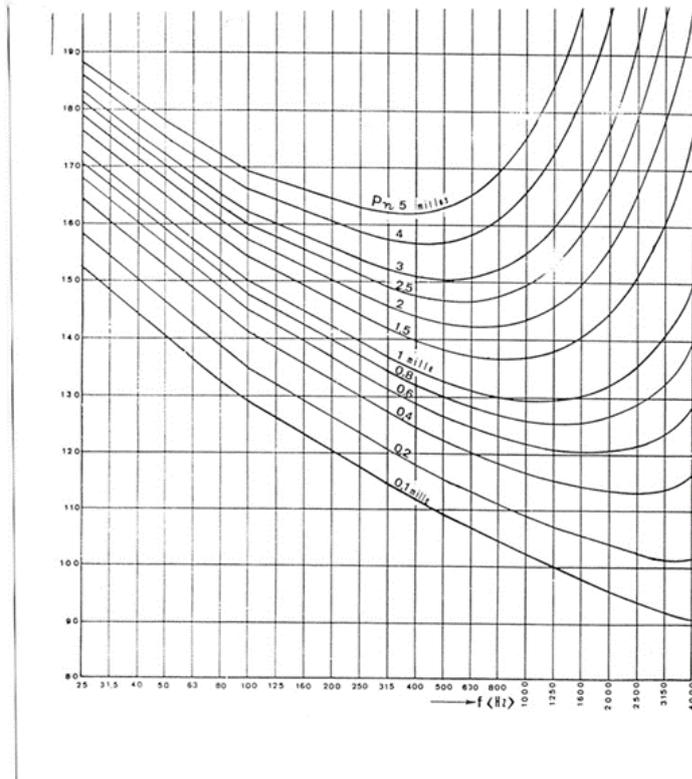


Figure 7 Graph for the determination of the nominal range of sound signals

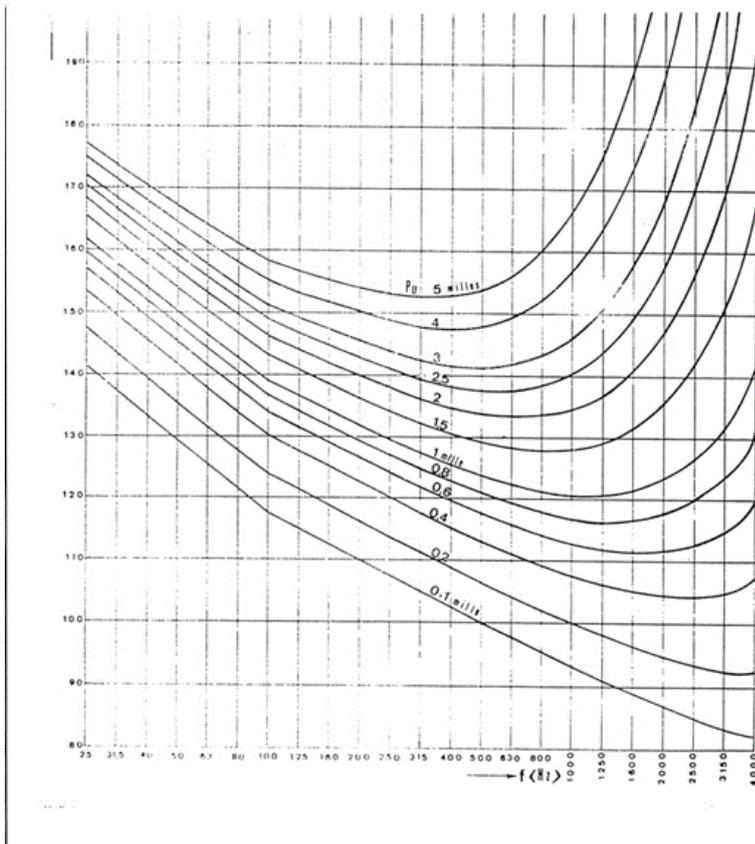


Figure 8 Graph for the determination of the usual range of sound signals

Figure 5

Case of a pure sound: The nominal range P_n in sea miles is read on the set of curves at the point at which the abscissa is the frequency f of the pure sound and at which the ordinate is the sound pressure level N_r , in decibels (ref $20 \mu\text{Pa}$ or $20 \mu\text{N/m}^2$ μbars) of the sound emitted by the sound emitter at the reference distance of 1 metre in the direction concerned.

Case of a complex sound: Find by trial and error the frequency group, of central frequency f and in which the sound pressure level is N_r , which gives the maximum value on the set of curves.

If there is only one such group, the maximum value so obtained is the nominal range.

If the maximum value is obtained simultaneously in v distinct frequency groups, apply the above procedure but increase the sound pressure level by the value M deduced from figure 4.

Figure 6
GRAPH

Case of a pure sound: The usual range P_u in sea miles is read on the set of curves at the point at which the abscissa is the frequency f of the pure sound and at which the ordinate is the sound pressure level N_r , in decibels (ref $20 \mu\text{Pa}$ or $20 \mu\text{N/m}^2$ μbars or $2.10^{-4} \mu\text{bars}$) of the sound emitted by the sound emitter at the reference distance of 1 metre in the direction concerned.

Case of a complex sound: Find by trial and error the frequency group, of central frequency f and in which the sound pressure level is N_r , which gives the maximum value on the set of curves.

If there is only one such group, the maximum value so obtained is the usual range.

If the maximum value is obtained simultaneously in v distinct frequency groups, apply the above procedure but increase the sound pressure level by the value M deduced from figure 4.

Table 5 Harmonics in a group of sounds

1	2	3	4	5	6	7
Order of the Harmonic	Frequency (In Hz)	Level at 1 m (in dB)	1st series		2nd series	
			Median frequency of the group (in Hz)	Total level in the group (in dB)	Median frequency of the group (in Hz)	Total level in the group (in dB)
1	75	144	113	146.1	75	144.0
2	150	142			188	145.0
3	225	142	263	143.8		
4	300	139			413	141.1
5	375	139	563	138.5		
6	450	137			713	138.0
7	525	136	863	137.5		
8	600	135			1050	137.3
9	675	135	1275	132.5		
10	750	135			1500	133.5
11	825	135	1575	128		
12	900	134				
13	975	134				
14	1050	132				
15	1125	131				
16	1200	129				
17	1275	127				
18	1350	127				
19	1425	127				
20	1500	130				
21	1575	128				