LUMINOUS INTENSITY AND RANGE OF LIGHTS : GEOGRAPHICAL RANGE

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Note on the authors

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INTRODUCTION

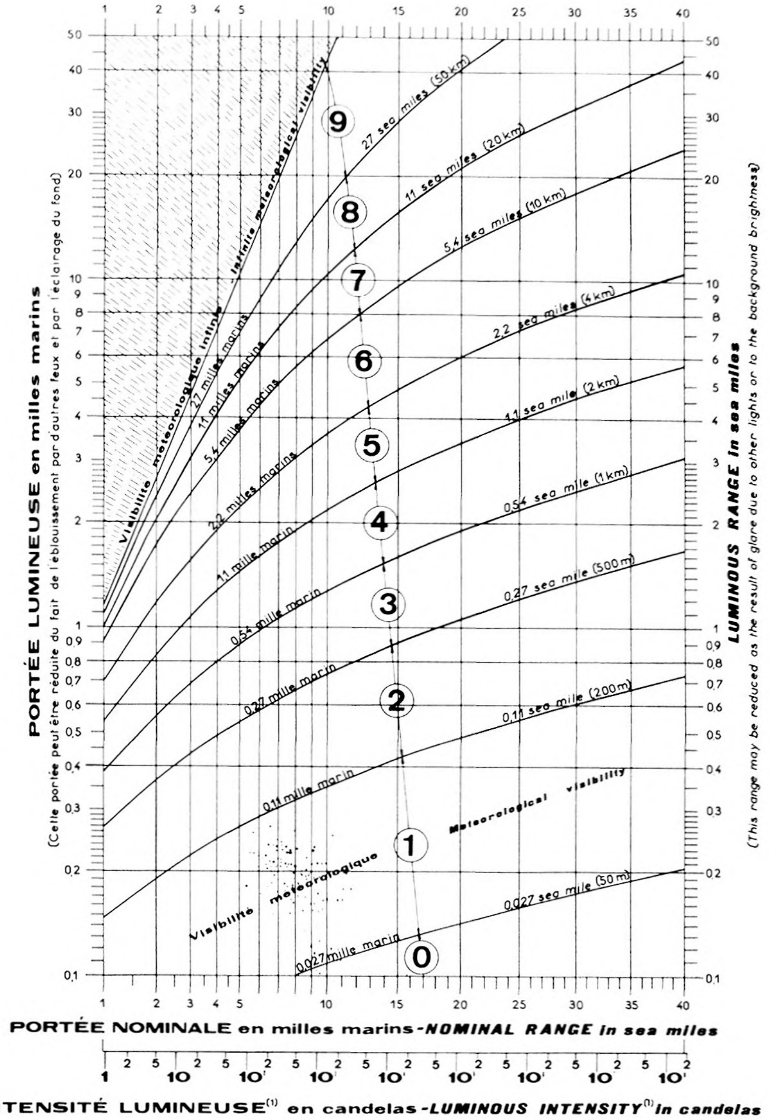
In the *Hydrographic Review* of November 1925 there was published a report on "Observations of the visibility of lights". Since that time remarkable progress has been made towards a standardization of methods. The International Association of Lighthouse Authorities (IALA) has lastly (1966) adopted a Recommendation for the Notation of Luminous Intensity and Range of Lights. In consequence, the Hydrographic Offices of several countries decided to amend as follows their Light Lists and charts when reprinting their publications.

A. — (1) Light Lists will carry the IALA - recommended luminous range graph (Appendix I) which shows :
As abscissae — a double scale giving both luminous intensity I, in candelas, and nominal range P_N, in sea miles;
As ordinates — luminous range P, in sea miles;
As parameter — the meteorological visibility V, in sea miles.
(2) Light Lists will carry both the intensities of lights, in candelas, and their nominal ranges, in sea miles.
(3) Light Lists will no longer include either the ranges of lights in "fair weather" or their ranges in "average weather".
(4) For certain cases only, the Light Lists will also include geographical ranges, in sea miles.

B. — Charts will show the nominal ranges of lights, in sea miles, and the geographical ranges merely if need be.

These changes call for some explanations.

GRAPHIQUE DE PORTÉE LUMINEUSE
GRAPH OF LUMINOUS RANGE



(1) Pour les feux à éclats brefs, l'intensité lumineuse à prendre en compte est celle qui résulte de la formule de BLONDEL-REY.

(1) *For short flashing lights the luminous intensity to be considered is that derived from the BLONDEL-REY formula.*

LUMINOUS INTENSITY AND LUMINOUS RANGE

(1) The intensity of a light

(*a*) Sometimes the luminous intensity of a light is reckoned from the characteristic features of the installation (source of light, optics, glass panes of the lantern, etc.) by either the manufacturer or the service in charge (*).

(*) In the case of a short-flashing light, the duration of the flash must be taken into account and the Blondel-Rey formula applied.

Sometimes the luminous intensity for the projector as a whole (source of light and optics) is measured in a photometric laboratory.

At other times the luminous intensity for the lighthouse itself is measured on site by comparison with a calibrated projector set up close to the lighthouse projector.

This least method is certainly the best, but in any case the scattering in measurements may be significant; in many instances the approximation may amount to over 50 %.

It can be asserted that it would be advisable not only to improve accuracy but first of all to standardize methods.

These tasks have recently been entrusted to an IALA Sub-Committee.

Until this work is concluded the luminous intensities of lights published in the various light lists cannot be considered suitable for comparison with each other.

(*b*) The notation of intensities entails the use of a physical unit — the candela — the definition of which is complex, and which with a scale extending from 1 to 100 000 000 implies an illusory accuracy that is very exaggerated in relation to the possible accuracy of measurements.

It would therefore seem preferable to replace the idea of luminous intensity and its notation in candelas by some other concept, or at least to set down both side by side.

(2) Luminous range of a light

(*a*) The luminous range of a light P — that is the maximum distance at which the eye of the navigator can perceive the light through the atmosphere — depends on three factors :

(1) The intensity of the emitting light;

(2) The imperfect transparency of the atmosphere; (*) which is an aleatory variable evaluated by means of :

— a coefficient T (originally called the coefficient of transparency for unit of distance, but later called the coefficient of atmospheric transmission for unit of distance);

or else :

— a coefficient σ (called the coefficient of optical density for unit of distance) which is related to coefficient T by

$$\sigma = -\operatorname{Log} T^{(**)} \qquad (1)$$

(*) As a light beam penetrates the atmosphere its intensity is reduced through scattering owing to the presence of transparent particles in suspension, such as water droplets, and through absorption owing to the presence of opaque particles, such as soot and dust.

(**) The symbol Log designates the Napierian logarithm; σ is sometimes called the Napierian optical density per unit of distance.

(3) The threshold of perception E_s of the eye of the navigator, i.e. the minimum illuminance on the eyeball necessary to produce a sensation.

The universally accepted Allard formula :

$$E_s = I \frac{T^P}{P^2} \qquad (2)$$

permits P to be calculated, provided that I, E_s and T are known. This formula can likewise be written

$$E_s = I \frac{e^{-\sigma P}}{P^2} \qquad (3)$$

e being the base for Napierian logarithms. Thus P may be computed, provide I, E_s and σ are known.

The first of these factors, intensity I, can be measured approximately, as was shown above.

The second factor, the threshold of perception E_s (*) is the subject of an agreement between the experts of the various nations fixing the value as 0.2 microlux (**).

As regards the third factor, neither coefficient T nor coefficient σ has as yet been adequately measured. The observers have generally been lighthouse keepers who are far from being specialists in measuring. Values measured at only a few sites have been improperly applied to a whole area. The measurements, moreover, have been spread over one or two years, and this is too short an interval of time.

(*b*) The luminous ranges included in Light Lists are either

— "fair weather" ranges P_C, computed for a particular atmospheric state by means of an arbitrarily chosen coefficient T (or a coefficient σ), for instance T = 0.8;

or

— " average weather " ranges, $P_{0.5}$, established statistically from observations and having a 50 % probability of being exceeded.

From these various procedures there results a certain amount of confusion which needs to be remedied.

(3) Meteorological visibility

Great strides have been made in meteorological observations during the course of the last few decades, chiefly for the benefit of air navigation. Such observations have led to a world standardization of a distance V, the "meteorological visibility", defined as "the greatest distance at which a black object of suitable size can be seen and recognized against the horizon

(*) With respect to seeing the lights, it is here a question of photopic vision, i.e. perception by the central part of the retina (called the fovea) that is normally used by day for seeing the details of an object.

(**) Conference of Heads of Lighthouse Authorities, Paris 1933. The threshold of perception $E_s = 2 \times 10^{-7}$ lux is approximately four times higher than a threshold of perception to which a probability of 50 % is attached.

sky (the threshold of contrast C (*) being fixed by agreement at 0.05) ", reckoned in km, and distributed for the purpose of telegraph coding into ten groups numbered from ⓪ to ⑨ according to Code 4300 of the World Meteorological Organization (WMO),

⓪ signifying visibility almost nil (V < 50 m)

① signifying thick fog (50 m < V < 200 m)

and up to

⑨ signifying visibility excellent (50 km < V).

The Koschmieder relation

$$T^V = C \tag{4}$$

which can also be written

$$e^{-\sigma V} = C \tag{5}$$

relates, using the agreed value C = 0.05, the coefficient of atmospheric transmission T (or the optical density per unit of distance σ) to the meteorological visibility V.

By definition meteorological visibility is a notion tied to daytime light. However it has been extended to night conditions of observation — i.e. those of lighthouses — by using the following convention. Night visibility would be the visibility obtained by assuming that the general illumination were increased to the point where it attains the normal intensity of daylight. In this way night visibility is tied to the same atmospheric transparency as daytime visibility.

The Allard formula can then be written in the form

$$E_s = I \frac{C^{\frac{P}{V}}}{P^2} \tag{6}$$

or, for computing

$$0{,}2 \times 10^{-7} = I \frac{0{,}05^{\frac{P}{V}}}{P^2} \tag{6a}$$

I being reckoned in candelas, P and V in metres.

Appendix 1 shows in graphic form the solution of this equation for P (in sea miles), provided I (in candelas) and V (in sea miles or km) are known.

In their shipping forecasts radio stations broadcast values of V for the various maritime areas several times a day and even at night (**).

(*) In the case of a small object of uniform colour seen against a much larger background that is also of uniform colour, the "contrast" is characterized by the ratio of the difference (in absolute value) between the luminances of the background and of the object to the luminance of the background. In meteorology it is assumed that, with a black object chosen as a reference, visibility exists if the contrast with the background is higher than a certain value C, named the threshold of contrast.

(**) In cable messages visibility is expressed by the number of the WMO code. In certain forecast bulletins in plain language (as distinct from encyphered) for navigators, the visibility is expressed in sea miles, contrary to the general rule of expressing visibility in km.

Little by little navigators have become familiar with the meteorological visibility broadcast by radio. This has led the IALA to take into account this parameter V rather than the coefficient of atmospheric transmission T or the optical density per unit of distance σ, neither of which has in fact ever been in practical use.

The introduction of the parameter V in the graphical representation of luminous ranges (Appendix 1) constitutes an undeniable step forward.

(4) Nominal range

The "nominal range" adopted by the IALA does not differ very much from the fair weather range P_C computed for a particular value of T.

However the arbitrary value 0.8 initially chosen for the coefficient T has a corresponding value for meteorological visibility V of 13.4 sea miles. The IALA has preferred to use the value of 10 sea miles (characteristic of the decimal system) as a reference value of V. Therefore the value chosen for the coefficient T has been altered from 0.8 to 0.74 so as to change from 13.4 to 10 the number of sea miles selected for the meteorological visibility V. The IALA has adopted the corresponding range as the reference range, and has called it "nominal range", defining it as follows : "luminous range in a homogeneous atmosphere in which the meteorological visibility is 10 sea miles (or 18.52 km) ". This is written as P_N.

Expressed in sea miles — one of the units most frequently used by navigators — on a scale graduated from 1 to 40 miles (this scale range appearing reasonable), this nominal range is more easily understood and easier to use than the intensity I.

However it must be clearly understood that these two conceptions basically cover one and the same thing — commonly, although incorrectly, called the "power of the light".

Indeed, for the nominal range (reckoned in sea miles) the Allard formula gives :

$$0.686 = I \frac{0.05^{\frac{P_N}{10}}}{P_N^2} \qquad (7)$$

whence for each value of P_N we obtain one, and only one, value for I. P_N and I are therefore linked as soon as P_N becomes the particular value of P that corresponds to $V = 10$ miles.

The nominal range values will be given in Light Lists and on charts as and when these are reprinted.

In Light Lists the intensity I (expressed in candelas) will continue to figure alongside the nominal range P_N (expressed in sea miles) for a certain number of years in order to accustom users to dropping the term intensity and replacing it with nominal range, the notation of which is simpler.

(5) Use of these data

The navigator who is looking for a light during the night will find the value of its intensity I and its nominal range P_N in the List of Lights. Thus he will know the abscissa value to be entered on the IALA graph (Appendix 1).

He takes note of the meteorological visibilities V broadcast in the weather forecast bulletins for the area where he happens to be. He then takes into account the way the visibility in the vicinity is developing (fog getting thicker, or clearing up) and thus he estimates the actual V for his precise time and place. It is this value of the parameter V which he enters on the graph. He then reads from the ordinate scale the *actual luminous range* P of the light he is looking for.

The IALA graph (Appendix 1) shows up the fact that in thick fog (V less than 200 m) the most powerful light in the world (I = 100 000 000 candelas) does not even attain a range of 1 mile. Visible light does not pass through fog. (*)

INVESTIGATION OF LUMINOUS RANGE IN EITHER AVERAGE OR RELATIVELY DULL WEATHER

The Heads of two Lighthouse Authorities have observed that the "nominal range" P_N, as defined by IALA, deviates notably from the luminous range in average weather $P_{0.5}$(**) which on the coasts of their own country has a 50 % probability of being exceeded.

From another aspect : the luminous range P for the time and place may be not adequate for those who have to design new lights and to give their specifications, and who must justify expenses.

In order to answer both problems statistics and probabilities must be called in.

Let us first consider the particular atmospheric state where the meteorological visibility has a 50 % probability of being exceeded. We shall denote this visibility as $V_{0.5}$. Let us assume that in a first coastal area the visibility in average weather, $V_{0.5}$, is 5 miles all around, that in a second coastal area it is 10 miles and in a third 15 miles. On the basis of the IALA graph (Appendix 1) the following table, reckoned in sea miles, can be drawn up.

(*) Experiments made with infra-red rays show that these rays do not have a better penetration.

(**) In statistical language this range is called "median range".

	Average weather	Range of a light I = 10000 candelas (P_N = 15)
Area 1	$V_{0.5}$ = 5	$P_{0.5}$ = 9
Area 2	$V_{0.5}$ = 10	$P_{0.5}$ = 15 = P_N
Area 3	$V_{0.5}$ = 15	$P_{0.5}$ = 24

In area 1 the range in average weather, $P_{0.5}$, is 9 miles and thus clearly less than the nominal range, P_N, which is 15 miles.

In area 3 the opposite is the case : $P_{0.5} = 24$ miles, whilst $P_N = 15$ miles.

Only in area 2 does the average weather range equal the nominal range.

The observation of the Heads of Lighthouse Authorities is therefore well-grounded if a single area is under consideration. However the nominal range P_N retains all its advantages with respect to achieving standardization of notation if the three areas are being considered as a whole.

Let us now consider another probability, for instance 0.95, i.e. the state of the atmosphere is such that the visibility has a 95 % probability of being exceeded. We shall denote this visibility as $V_{0.95}$ and shall call this weather "relatively dull weather".

V	0.11	0.27	0.54	1.1	2.2	5.4
Dunkerque	0.986	0.980	0.970	0.923	0.827	0.498
Boulogne	0.9919	0.9860	0.9790	0.9530	0.7719	0.4117
Dieppe	0.9904	0.9783	0.9667	0.9514	0.8941	0.5976
La Hève	0.9807	0.9708	0.9631	0.9489	0.8873	0.6182
La Hague	0.9934	0.9866	0.9812	0.9570	0.9048	0.7271
Pte du Roc	0.9912	0.9868	0.9817	0.9690	0.9155	0.7285
Bréhat	0.9932	0.9898	0.9852	0.9776	0.9392	0.7284
Ouessant	0.9856	0.9755	0.9648	0.9564	0.9115	0.7038
Penmarch	0.9955	0.9889	0.9830	0.9768	0.9445	0.7886
Belle-Ile	0.9960	0.9875	0.9828	0.9805	0.9618	0.8293
St-Sauveur	0.9973	0.9890	0.9848	0.9824	0.9655	0.7301
Chassiron	0.9916	0.9868	0.9834	0.9796	0.9466	0.6898
Cap-Ferret	0.9955	0.9918	0.9863	0.9744	0.9127	0.4177
Cap Bear	0.9952	0.9930	0.9913	0.9899	0.9814	0.8125
Sète	0.9957	0.9929	0.9912	0.9890	0.9826	0.8604
Cap Pomègue	0.9983	0.9971	0.9964	0.9950	0.9856	0.7921
Porquerolles	0.9975	0.9948	0.9910	0.9891	0.9822	0.8338
Cap Camarat	0.9994	0.9977	0.9951	0.9933	0.9785	0.7515
Cap Ferrat	1.0000	0.9998	0.9996	0.9992	0.9973	0.9120
Cap Corse	0.9998	0.9993	0.9988	0.9988	0.9986	0.9621
Cap Cavallo	0.9962	0.9938	0.9904	0.9898	0.9855	0.9178
Pertusato	0.9987	0.9983	0.9974	0.9964	0.9942	0.8956

As weather forecasters have made systematic observations of visibility at 22 points along the coasts of France from 1951 to 1960 inclusive it has been possible to tabulate the results (Appendix 2).

This Appendix 2 allows us to draw up the second column of the table given below which shows in sea miles the ranges for a given light (one with intensity of 10 000 candelas) for the 0.95 probability. Then Appendix 1 allows us to draw up the third column of the table.

	Relatively dull weather	Range of a light $I = 10000$ candelas ($P_N = 15$)
DUNKIRK North Sea	$V_{0.95} = 0{,}8$	$P_{0.95} = 2{,}3$
USHANT Atlantic	$V_{0.95} = 1{,}2$	$P_{0.95} = 3$
PORQUEROLLES Mediterranean	$V_{0.95} = 3$	$P_{0.95} = 6$

We note that the 0.95 probability at Dunkirk corresponds to a WMO Index of ④ (1 km $< V <$ 2 km); at Ushant it corresponds to ⑤ (2 km $< V <$ 4 km), and at Porquerolles to ⑥ (4 km $< V <$ 10 km).

If engineers wish to have a complete picture of the luminous ranges of lights of various intensities at a particular place, Dunkirk for example, they can draw a graph similar to the one in Appendix 3 that shows as abscissae the luminous range P in sea miles, as ordinates the chances t of perceiving the light (reckoned in probability), and as parameter the intensity I in candelas.

If these engineers have to work to the particular probability 0.5 or even to smaller probabilities, they must ask their Meteorological Service to makes observations at greater distances, of the order of 20 to 40 miles. These observations could concern not only the meteorological visibility V but also the visibility of the large lighthouses. A curve of the percentage of visibility as a function of distance could be drawn up for each of these lighthouses. Reciprocally, this same curve will provide, for a given percentage of time t, the distance at which the light can be perceived, i.e. its range P_t.

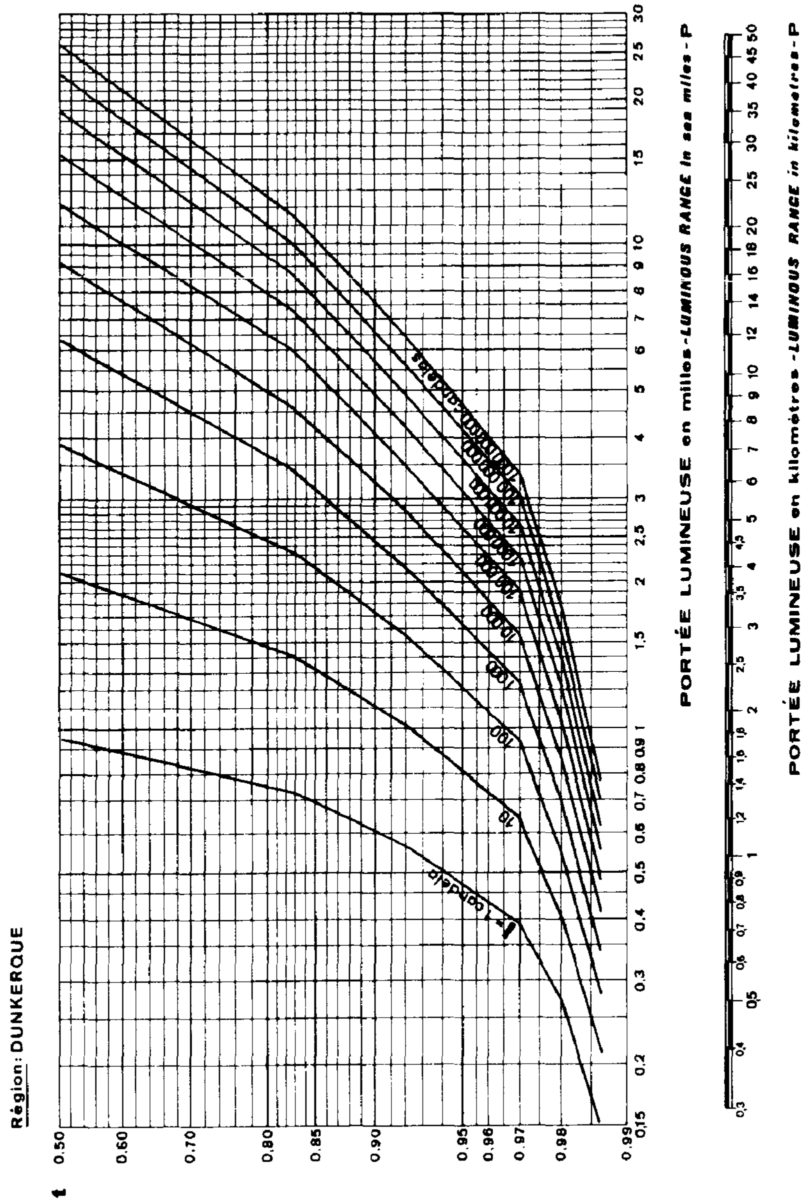
By this means engineers will be able to compare not only the ranges resulting from direct observations of lights but also the ranges computed with the Allard formula (6), reckoned from the visibility values V supplied by meteorologists, and they will thus be able to prove the validity of the Allard formula.

Finally, there are two points to be made in reply to the observations of these Heads of Lighthouse Authorities, and to the preoccupations of the engineers.

(1) The nominal range P_N for any light in any area whatever is a conventional reference value, and is valid for all coasts the world over.

Proportion du temps t pendant laquelle un feu d'intensité I a une portée lumineuse supérieure ou égale à P

The time proportion t during which a light of intensity I has a luminous range greater or equal to P



The fact that the IALA graph has an abscissae scale applicable to every lighthouse in the world gives it an universal value.

(2) Lighthouse Authorities in all countries could make new data available to their staff if they were to carry out methodical observations of visibility at a large number of points along the coast, and if the resulting statistics are worked out over long periods, for say 10 years.

This would permit the ranges of lights to be known for various values of probability. Engineers would use these results for their new light projects and for the economic appraisal of their usefulness.

GEOGRAPHICAL RANGE

When the atmosphere is very clear a light of high intensity can be seen from a long way off. It is then the curvature of the earth that prevents the navigator from seeing the light, even although the projector has been installed on a elevation, and even if the bridge of the ship is high above the water line. The water mass at the horizon forms a screen. The resulting limit of visibility is called the *geographical range*. As a first approximation this range is given by the formula :

$$P_g = \sqrt{2rH} + \sqrt{2rh}$$

where r is the radius of the terrestrial sphere, H the height of the light above sea, and h the height of the navigator's eye at sea level. (*)

The geographical range P_g would thus be a fixed value for a given light and a given ship.

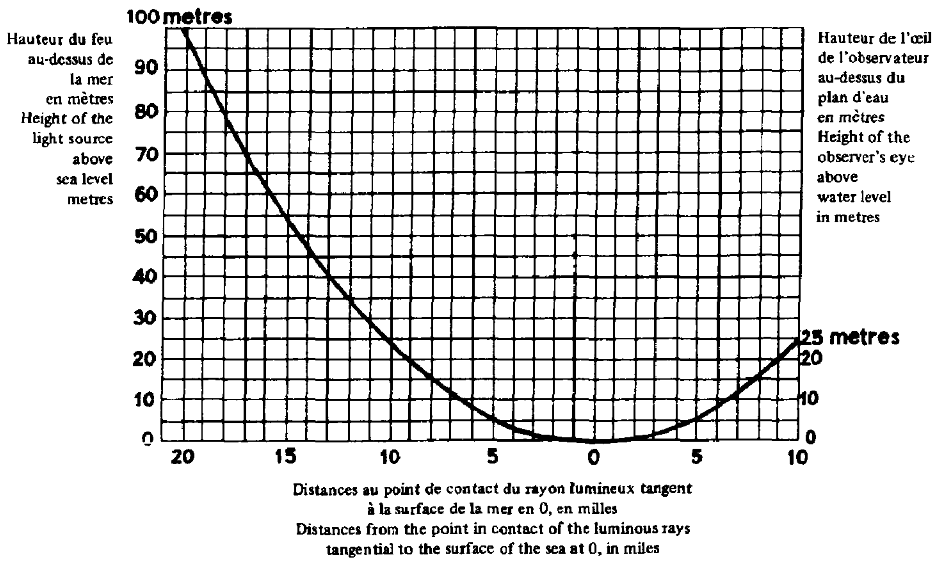
In reality, however, P_g depends a little on atmospheric conditions. The various air strata are often of unequal temperature, pressure and humidity and consequently of a different refractive index, so that the luminous rays are not rectilinear but concave, the concavity being generally downwards. In these circumstances the light can be seen beyond its geographical range; frequently up to 40 % farther, and occasionally even farther, and this phenomenon is difficult to predict.

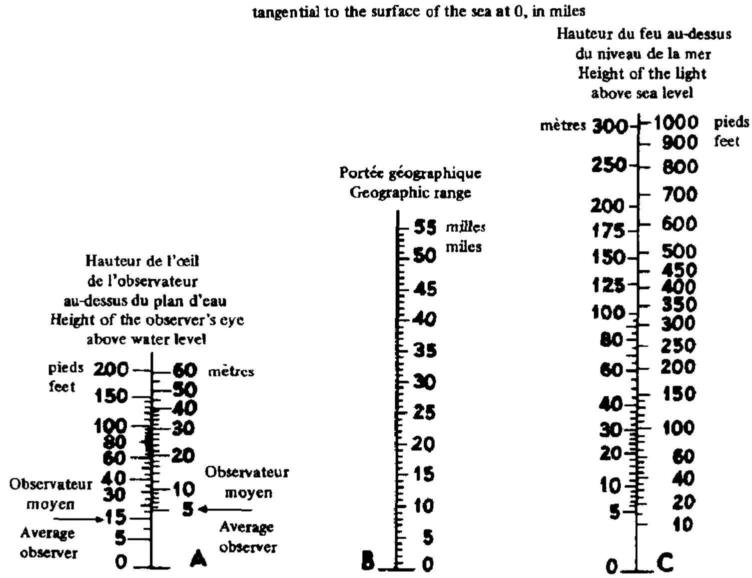
While the geographical range constitutes a maximum for the actual luminous range this maximum is not entirely a fixed number.

Nevertheless the geographical range can be read from the graph (or the nomogram) given in Appendix 4. These have been drawn up for an average value of the refractive index in the atmosphere.

Finally there are quite a few instances where this maximum does not operate. The projection apparatus of the large lighthouses, made up of revolving panels, emits powerful beams of light that sweep the sky and are visible even when their source of light is no longer in direct view. By their "loom" in very clear weather the navigator can locate the light

(*) It is assumed that the average height of the navigator's eye is 15 feet (5 metres).





at greater distances than the geographical range, sometimes to the extent of 50 % further.

Buoy lights are difficult to see, due more often to local sea conditions than to being below the horizon.

A good many lights inside ports are only used for short distances, so that the question of their geographical range does not arise.

CONCLUSION

The nominal range P_N, as well as the luminous intensity I, is a characteristic of the projector.

The geographical range P_g is a characteristic of the location and of the height of the light, just as the dark sectors and the coloured sectors are characteristics of the lantern.

The nominal range P_N, and also intensity I, make it possible in every case to compute the local and instant luminous range P, and this is what is of interest to every navigator, provided he knows the meteorological visibility V.

In certain instances the geographical range P_g sets a maximum for the luminous range P.

Methodical observations followed up by statistics will make it possible to determine for any particular percentage of time t the luminous range P_t of any light in any locality. This will be of great value to all engineers responsible for lights.