International Association of Marine Aids to Navigation and Lighthouse Authorities

AISM Association of Internationale de Signalisation Maritime IALA

IALA Recommendation

E-200-2

On

Marine Signal Lights

Part 2 - Calculation, Definition and Notation of Luminous Range

Edition 1

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Document Revisions

Revisions to the IALA Document are to be noted in the table prior to the issue of a revised document.

Date	Page / Section Revised	Requirement for Revision

Recommendation on Marine Signal Lights Part 2 - Calculation, Definition and Notation of Luminous Range

(Recommendation E-200-2)

THE COUNCIL:

RECALLING the function of IALA with respect to Safety of Navigation, the efficiency of maritime transport and the protection of the environment;

RECOGNISING the need to publish the performance of marine signal lights;

RECOGNISING ALSO the need to specify, design and quantify the performance of marine signal lights worldwide;

NOTING this document only applies to marine Aid-to-Navigation lights installed after the date of this publication;

ADOPTS the tables and charts in the annex of this recommendation; and,

RECOMMENDS that National Members and other appropriate Authorities providing marine aids to navigation services design, specify and publish the performance of marine Aid-to-Navigation signal lights in accordance with the Annex to this recommendation.

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1 INTRODUCTION

1.1 Scope / Purpose

The scope of this recommendation is to permit providers and manufacturers of marine AtoN lights, as well as mariners, to determine the luminous range of lights as a function of their intensity and of the meteorological visibility. This recommendation provides a link between the physical and photometric features of marine AtoN lights and the luminous range information given to the mariner.

For providers of marine AtoN lights, this recommendation should be used to estimate the required luminous intensity when designing lights.Manufacturers of marine AtoN lights should quote the nominal luminous range (also known as the 'nominal range') of their lights in accordance with this recommendation.

1.2 Background / History

The IALA definition of the luminous range of lights was first introduced by a Recommendation in 1966 [1]. For many years this definition has been an important basis for the description of marine AtoN lights.

However, since 1966 several additions have been made to the definition of luminous range. These additions were spread over five IALA documents ([2], [3], [4], [5], [6]).

To avoid confusion the information from these six documents has been collated into a single document for the calculation, definition and notation of luminous range of lights, which helps to distinguish between the different required values of illuminance (required at the eye of the observer) and their application.

The two basic recommendations [1] and [3] included nomograms for luminous range estimation. These nomograms are still supported. However, the wide-spread use of computer modelling makes it feasible to base the estimation of luminous range on formulae. Therefore, these have been provided in this recommendation.

Previous IALA Recommendations and the IALA Dictionary use the "sea mile" as the unit of measure for luminous range, nominal range, and meteorological visibility. This document replaces the sea mile with the nautical mile as the preferred unit of measure and as the unit of measure used in definitions. The difference between a sea mile (about 1853.2 m) and a nautical mile (1852 m) is small, and of no practical consequence for these calculations. The nautical mile has been chosen as the unit of measure because it is used more widely than the sea mile.

For many countries the use of SI-units is obligatory. The 'nautical mile' and the units derived from it are outside this International System of Units. One aim of this recommendation is to give the reader the necessary formulae to convert between the SI-units and the units used in navigation.

2 PHYSICAL BASICS – ALLARD'S LAW

The illuminance of a signal light at the observer's eye can be calculated by a physical law called Allard's law.

2.1 Allard's law

Allard's law allows the calculation of the illuminance E as a function of distance d, luminous intensity I and an exponential factor z.

$$E(d) = I\,\frac{e^{-zd}}{d^2}$$

equation 1

The exponential factor z describes the atmospheric absorption and scattering (extinction). In practice, there are alternative ways of characterizing the prevailing atmosphere as follows.

2.2 Allard's law using the atmospheric transmissivity T

Atmospheric transmissivity (T) is defined as the ratio of the luminous flux transmitted by the atmosphere over a unit distance to the luminous flux which would be transmitted along the same path in a vacuum.

$$\mathrm{T} = \frac{\Phi(\mathrm{d}_\mathrm{U})}{\Phi_\mathrm{vacuum}(\mathrm{d}_\mathrm{U})}$$

equation 2

Where:

T is the atmospheric transmissivity (dimensionless)
$\Phi(d_U)$ is the luminous flux at the unit distance after passing through the atmosphere
$\Phi_{vacuum}(d_U)$ is the theoretical luminous flux at the unit distance after passing through a vacuum
d_U is the unit distance

Because the ratio of the luminous fluxes in equation 2 is the same as the ratio of the corresponding illuminance values, equation 2 can be rewritten as

$$\mathrm{T} = \frac{\mathrm{E}(\mathrm{d}_\mathrm{U})}{\mathrm{E}_\mathrm{vacuum}(\mathrm{d}_\mathrm{U})}$$

equation 3

Where:

$E(d_U)$ is the illuminance at the unit distance after passing through the atmosphere
$E_{vacuum}(d_U)$ is the theoretical illuminance at the unit distance after passing through a vacuum

Inserting expressions for $E(d_U)$ and $E_{vacuum}(d_U)$ from equation 1 into equation 3, and noting that for $E_{vacuum}(d_U)$ z = 0, equation 3 becomes

$$T = e^{-zd_U}$$

equation 4

Combining equations 1 and 4 yields

$$E(d) = I\,\frac{T^{d/d_U}}{d^2}$$

equation 5

2.3 Allard's law using the transmissivity T_M for 1 nautical mile

The unit distance for transmissitity is chosen to be one nautical mile. Expressed in all metric units equation 5 takes the form

$$E(d) = I\,\frac{T_M{}^{d/d_U}}{d^2}$$

equation 6

Where:

E(d) is the illuminance at distance d in metres
I is the luminous intensity in candela
T_M is the atmospheric transmissivity [dimensionless] for 1 nautical mile
d is the distance in metres
d_U is the unit distance that corresponds to the transmissivity [1852 m]

In practice the distance d is expressed in nautical miles. Using the fact that one nautical mile equals 1852 metres and suppressing the unit distance in the exponent equation 6 can be written as

$$E(d) = I\,\frac{T_M{}^{d}}{\left(1852\,\dfrac{metres}{nautical\ mile}\times d\right)^2}$$

equation 7

where d is the distance in nautical miles.

Simplifying and suppressing all units yields

$$E(d) = \frac{I}{(3.43\times 10^6)}\,\frac{T_M{}^{d}}{d^2}$$

equation 8

Where:

E(d) is the illuminance at the eye of the observer in lm/m^2 [lx]
I is the luminous intensity of the light [cd]
T_M is the transmissivity for one nautical mile of the atmosphere
d is the numerical value of the distance in nautical miles

2.4 Meteorological Visibility

The meteorological visibility is an alternative way to describe the extinction by the atmosphere of the object being viewed, which in the development above is quantitatively characterised by the atmospheric transmissivity.

Meteorological visibility is the greatest distance at which a black object of suitable dimensions can be seen and recognized by day against the horizon sky, or, in the case of night observations, could be seen and recognized if the general illumination were raised to daylight level [2].

By definition the relationship between the meteorological visibility (V) and the transmissivity is

$$V = \frac{\ln 0.05}{\ln T_M} \times d_U$$

equation 9

Where:

V is the meteorological visibility in nautical miles

T_M is the transmissivity [dimensionless] for one nautical mile

d_U is the unit distance of 1 nautical mile

Suppressing the units and suppressing the unit distance yields:

$$\mathrm{V} = \frac{\ln 0.05}{\ln \mathrm{T_M}}$$

equation 10

2.5 Allard’s Law based on Meteorological Visibility

It is recommended in the IALA dictionary that the atmospheric extinction be described by using meteorological visibility V rather than the transmissivity T_M.

Allard's law can be expressed using meteorological visibility V by combining equation 8 and equation 10.

$$E(d) = \frac{I}{(3.43 \times 10^6)} \frac{0.05^{\frac{d}{V}}}{d^2}$$

equation 11

Where:

E(d) is the illuminance at the eye of the observer [lx]
I is the luminous intensity of the light [cd]
d is the distance in nautical miles
V is the meteorological visibility in nautical miles

the units (not shown) associated with (3.43×10^6) are m^2/M^2

3 LUMINOUS RANGE

In the case of a light that appears as a point source, the **luminous range D** is defined as the maximum distance at which a light can be seen, as determined by the luminous intensity I of the light, the meteorological visibility V and the ‘required illuminance’ (formerly known as threshold) E_t at the eye of the observer. At this distance, the illuminance E at the observer’s eye is reduced to the value E_t.

Inserting these parameters into equation 11 and rearranging yields:

$$I = (3.43 \times 10^6) E_t D^2 (0.05)^{-\frac{D}{V}}$$

equation 12

Where:

I is the luminous intensity of the light [cd]
E_t is the required illuminance at the eye of the observer [lx] (see 4.1)
D is the luminous range in nautical miles
V is the meteorological visibility in nautical miles

Equation 12 is recommended for the calculation of the luminous range of signal lights. Due to the numerical character of equation 12, numerical iteration is necessary in order to calculate the luminous range D. A rough estimation of D can be derived from the nomograms provided in this recommendation.

4 NOMINAL RANGE

4.1 Definition of the nominal range of lights intended for the guidance of shipping

IALA recommends that the nominal range of maritime signal lights intended for the guidance of shipping should be defined as follows:

The nominal range of a maritime signal light is the distance in nautical miles at which this light produces an illuminance at the eye of the observer:

- *of* 2×10^{-7} *lx for night time range*
- *of* 1×10^{-3} *lx for day time range*

It should be assumed that meteorological visibility V equals 10 nautical miles (T_M *= 0.7411) and that the atmosphere is homogenous.*

Note: Please see A1.2.3 for further considerations of required illuminance values.

4.2 Notation of the nominal range of lights intended for the guidance of shipping

IALA recommends that the *following information on* nominal range of lights intended for the guidance of shipping should be published in the 'Lists of Lights':

- *The nominal range of lights intended for the guidance of shipping by night;*
- *Where applicable, the nominal range of lights intended for the guidance of shipping by day;*
- *Nomograms permitting mariners to estimate the luminous range of lights intended for the guidance of shipping by day or by night as a function of their nominal range, the prevailing meteorological visibility and, where applicable, the sky luminance in the direction of observation.*

5 IMPORTANT FACTORS IN THE DESIGN OF MARINE SIGNAL LIGHTS

The following important factors should be taken into account when selecting marine AtoN signal lights for installation. As a result, a different luminous intensity may be required to achieve the required range.

5.1 Service Condition Factor

In practical installations, the degradation of luminous intensity under service conditions, due to light source degradation, dirt and salting of lanterns etc., should be taken into consideration. It is recommended that the intensity used to calculate the nominal range for publication should include a service factor. It is recommended that this service factor be taken as 0.75 (corresponding to a reduction in intensity of 25%). Although this service conditions factor includes degradation of the light source output, it should be noted that some light sources, such as discharge lamps and LEDs, can degrade significantly more than 25% over their lifetime. When designing and installing AtoN signal lights, degradation over the service period as well as the lifetime of the equiment should be taken into consideration.

5.2 Local Conditions

The prevailing visibility conditions will vary over different geographical locations. Therefore, when selecting a light, this should be taken into account. Selection should be based on a practical luminous range value and not on nominal range.

5.3 Zone of Utilisation

The required range may vary over the zone of utilization of the light.

5.4 Background Luminance

Different levels of background luminance may require different values of required illuminance values (see Appendix 1).

5.5 Leading Lights

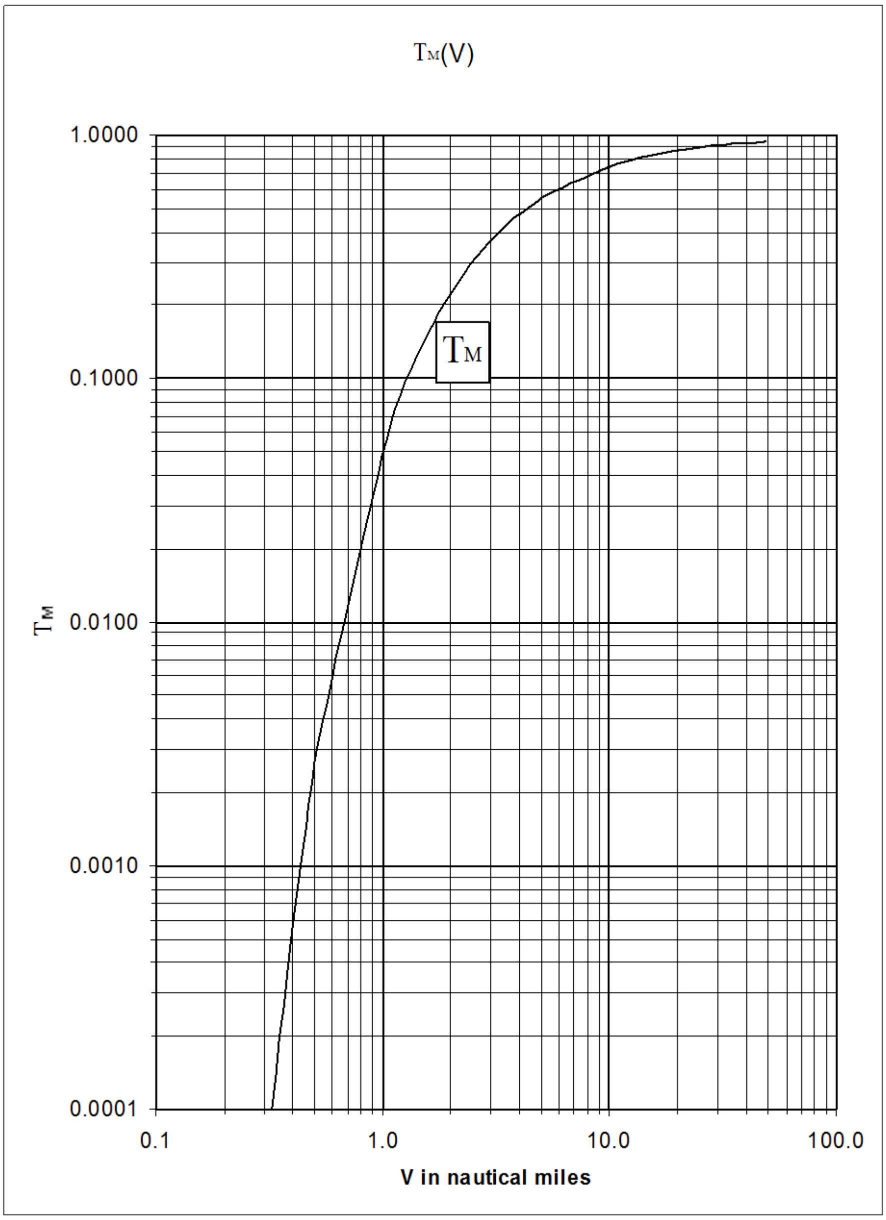
It is important to note that a leading light, like any other night-time light, will have a nominal range that corresponds to the distance at which the illuminance at the eye of the observer is 2×10^{-7} lx. However, IALA recommendation E-112 for leading lights [5] states that the illuminance required for an observer to use the leading lights for alignment at night must be at least 1×10^{-6} lx. Because the illuminance level that corresponds to nominal range is 5 times less than the level needed to align the lights in the useful segment, the concept of nominal range for a leading light is not typically used.

5.6 Assessment of Suitability

Where practicable, a subjective assessment of the signal light should be carried out to confirm the suitability of the signal light within its arc of utilisation.

APPENDIX 1 Diagrams and Tables

1 METEOROLOGICAL VISIBILITY AND TRANSMISSIVITY



$$V = \frac{\ln 0.05}{\ln T_M} * d_U = -\frac{3\ M}{\ln T_M} \qquad T_M = 0.05^{\frac{d_U}{V}} = 0.05^{\frac{1M}{V}}$$

Figure 1 A graph of meteorological visibility versus atmospheric transmissivity (T_m)

2 LUMINOUS RANGE FOR NIGHT TIME

The required value for illuminance is $\mathbf{E_t = 2 \times 10^{-7}}$ **lx**

$I = 0.686\ D^2\ (0.05)^{-D/V}$ where I is in candela, and D & V are numerical values in M

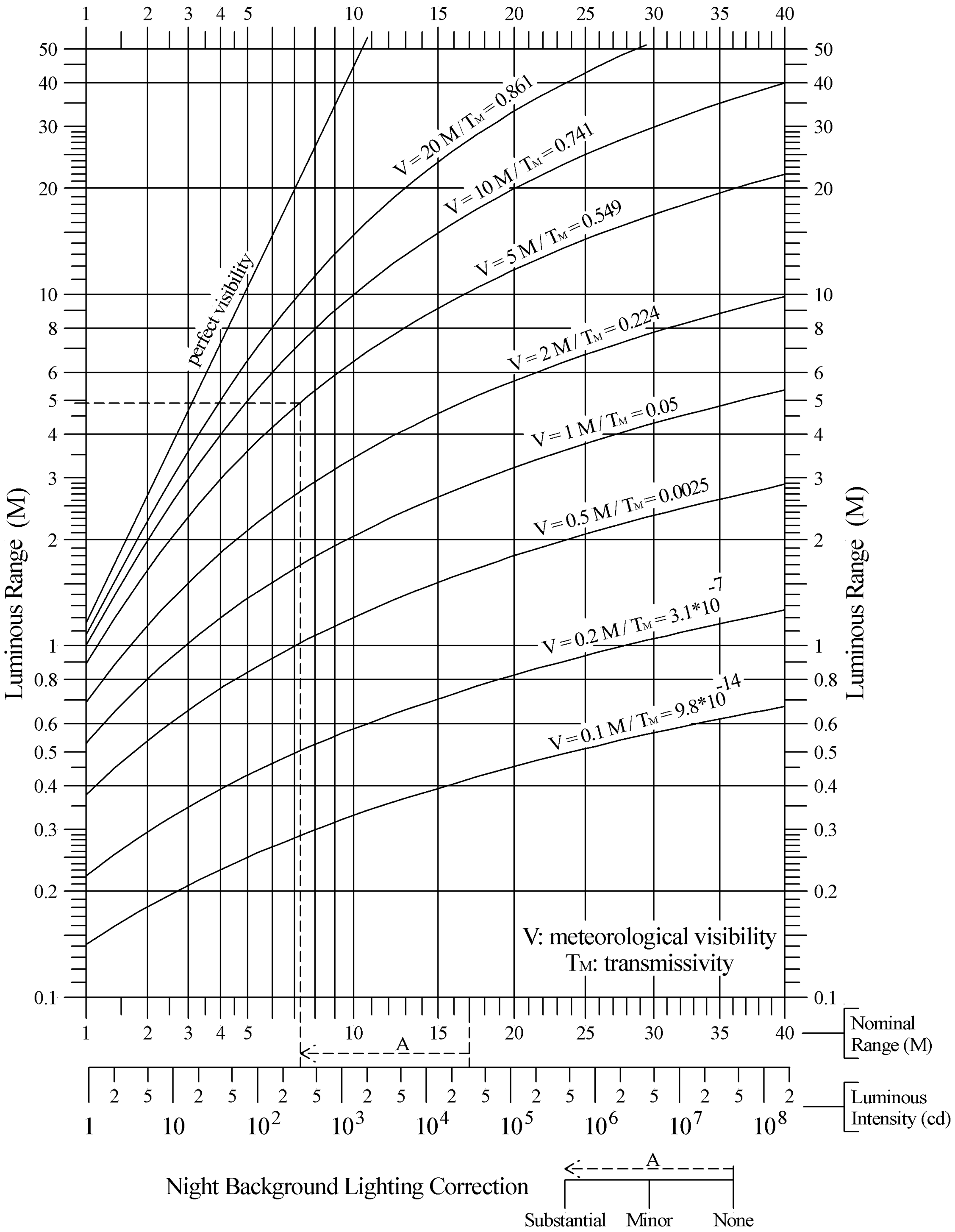


Figure 2 Luminous Range diagram – night time

3 NOMINAL RANGE FOR NIGHT TIME

Table 1 should be used to determine the night time nominal range rounded off to the nearest nautical mile

Table 1 Night time nominal range table (rounded off to the nearest nautical mile)

Luminous intensity	Nominal range (rounded)	Luminous intensity	Nominal range (rounded)	Luminous intensity	Nominal range (rounded)
candelas	nautical miles (M)	kilocandelas (10^3 cd)	nautical miles (M)	Megacandelas (10^6 cd)	nautical miles (M)
1 - 2	1	0.633 – 1.06	9	0.927 – 1.35	26
3 - 9	2	1.07 – 1.75	10	1.36 – 1.96	27
10 - 23	3	1.76 – 2.84	11	1.97 – 2.84	28
24 - 53	4	2.85 – 4.53	12	2.85 – 4.11	29
54 - 107	5	4.54 – 7.13	13	4.12 – 5.93	30
108 - 203	6	7.14 – 11.1	14	5.94 – 8.53	31
204 - 364	7	11.2 – 17.1	15	8.54 – 12.2	32
365 - 632	8	17.2 – 26.1	16	12.3 – 17.5	33
		26.2 - 39.7	17	17.6 – 25.1	34
		39.8 – 59.9	18	25.2 – 35.9	35
		60.0 – 89.8	19	36.0 – 51.2	36
		89.9 - 133	20	51.3 – 72.9	37
		134 -198	21	73.0 - 103	38
		199 - 293	22	104 -147	39
		294 - 432	23	148 - 209	40
		433 - 634	24		
		635 - 926	25		

Required value for illuminance $\mathbf{E_t = 2 \times 10^{-7}\ lx}$

3.1 Compensation for Background Lighting (nighttime)

The required illuminance of 2×10^{-7} lx at the eye of the observer corresponds to a situation with no background lighting. In most real situations the lights are viewed against a background that does have lights. This will reduce the luminous range.

The recommended method for compensating for background lighting is to use different values for the required illuminance.

Two different values should be used:

minor background lighting:	2×10^{-6} lx	factor 10 ×
substantial background lighting:	2×10^{-5} lx	factor 100 ×

For a light of given intensity the introduction of background lighting will reduce the luminous range.

According to equation 12 the required intensity should be increased by the factors above in order to compensate for background lighting and achieve the same luminous range.

The graph in A2.2.1 has been drawn for a required illuminance of 2×10^{-7} lx. For the other values of required illuminance (minor and substantial background lighting) mark off along the scale of abscissae the distance between 'No Background lighting (NONE)' and that under consideration as it appears on the auxiliary scale.

Example:

Suppose that it is required to find the luminous range of a light with a nominal range of 17 M and a luminous intensity of 32,300 cd for substantial background lighting and a visibility of 5 M.

Measure the distance A separating 'no background lighting (NONE)' and 'substantial background lighting (SUBSTANTIAL)'. Transfer this distance to the scale of the abscissae from graduation to 17 M (32,300 cd) in the same sense. A point slightly to the right of graduation corresponding to 7 nautical miles is obtained. Erect from this point a parallel to the axis of ordinates to meet the curve for 5 nautical miles visibilty. Read off the luminous range on the vertical scale against the point so obtained. We read approx. 5 nautical miles.

4 LUMINOUS RANGE FOR DAYTIME

4.1 Estimation of Required Illuminance for Daytime Range

The mariner should be able to estimate the luminous range of lights by day for different sky luminances. However, the required illuminance E_t in lx, produced by a light, depends on the luminance L of the sky in candelas per square metre, in the direction of observation according to the formula:

$$E_t = (0.242 \times 10^{-6)}) \times \left(1 + \sqrt{0.4L}\right)^2$$

equation 13

Where:

E_t is the required illuminance at the observer's eye in lm/m^2 [lx]
L is the sky (background) luminance in cd/m^2

The required illuminance **E_t** of **1×10^{-3} lx** thus corresponds to a sky luminance of 10,000 candelas per square metre. The calculated required illuminance E_t should be inserted in equation 12.

The required value for illuminance is $\mathbf{E_t = 1x10^{-3}\ lx}$

$I = 3430\ D^2\ (0.05)^{-D/V}$ where I is in candela, and D & V are numerical values in M

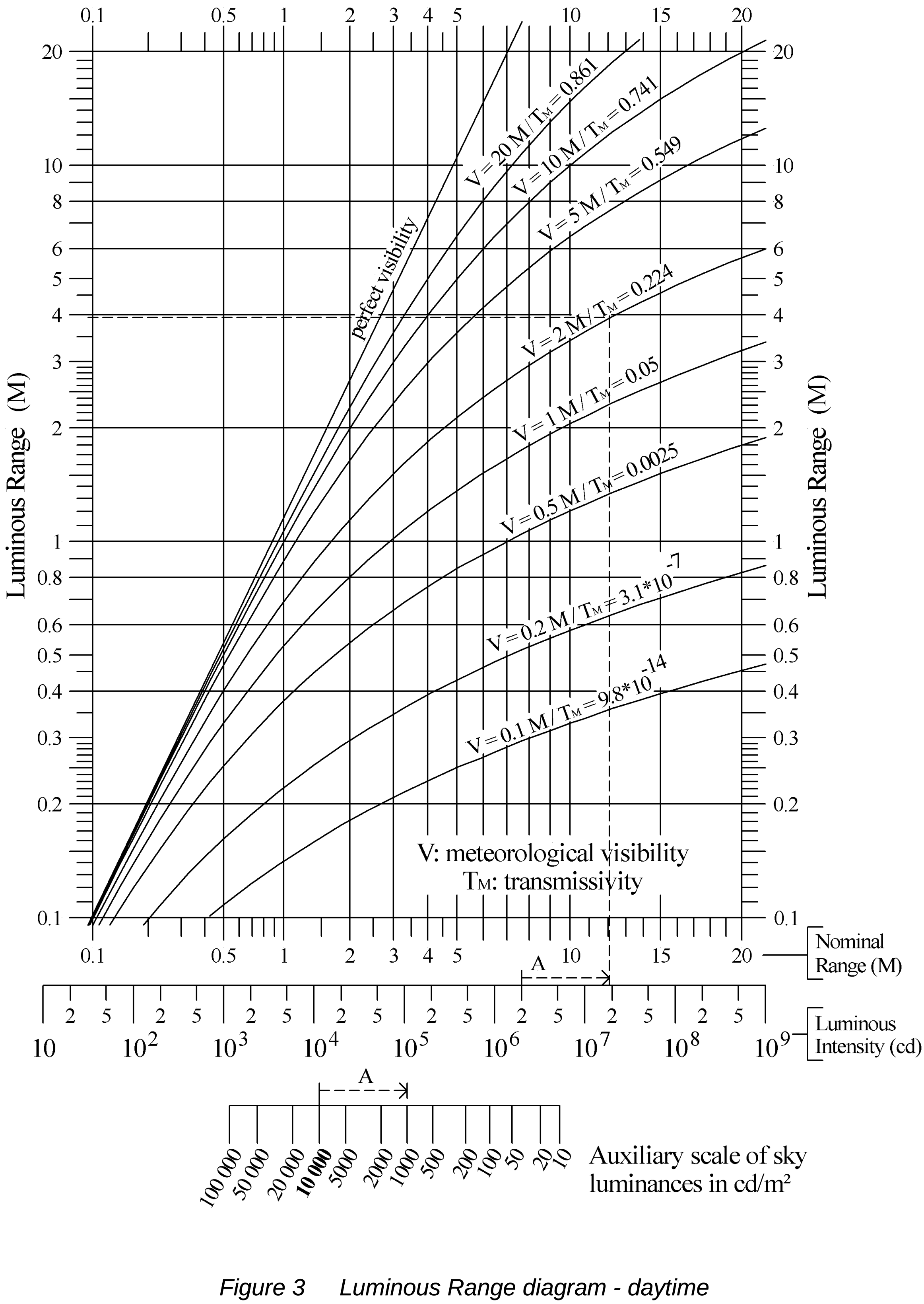


Figure 3 Luminous Range diagram - daytime

4.2 Explanation of daytime diagram

Calculation of required illuminance by day

$$E_t = (0.242 \times 10^{-6}\ lx) \times \left(1 + \sqrt{0.4 \times L/(cd/m^2)}\right)^2$$

E_t : required illuminance

L : luminance of sky in the direction of observation

Table 2 Background luminance in various meteorological conditions

Meteorological condition	Luminance in cd/m²	required illuminance E_t in 10^{-3} lx
Very dark overcast sky	100	0.013
Dark overcast sky	200	0.024
Ordinary overcast sky	1 000	0.107
Bright overcast sky or clear sky away from the direction of the sun	5 000	0.506
Bright cloud or clear sky close to the direction of the sun	10 000	1
Very bright cloud	20 000	1.98
Glaring cloud	50 000	4.91

4.2.1 Use of the graph (Figure 2):

The graph has been drawn for a sky luminance of 10 000 cd/m². For other values of sky luminance mark off along the scale of abscissae the distance between the luminance of 10 000 cd/m² and that under consideration as it appears on the auxilliary scale.

Example:

Suppose that it is required to calculate the luminous range of a light of 2 000 000 cd for a meteorological visibility of 2 nautical miles under an ordinary overcast sky (luminance 1 000 cd/m²).

Measure the distance A separating graduations 10 000 cd and 1 000 cd on the auxiliary scale. Transfer this distance to the scale of abscissae from graduation corresponding to 2 000 000 cd (2×106 cd) in the same sense. A point slightly to the right of graduation corresponding to 12 nautical miles is obtained. Erect from this point a parallel to the axis of ordinates to meet the curve for 2 nautical miles visibility. Read off the luminous range on the vertical scale against the point so obtained. We read approx. 4 nautical miles.

5 NOMINAL RANGE FOR DAYTIME

Table 2 should be used to determine the daytime nominal range rounded off to the nearest nautical mile

Table 3 Day time nominal range table (rounded off to the nearest nautical mile)

Luminous intensity	Nominal range (rounded)	Luminous intensity	Nominal range (rounded)
kilocandelas (10^3 cd)	nautical miles (M)	Megacandelas (10^6 cd)	nautical miles (M)
1 – 12.0	1	1.02 – 1.82	7
12.1 – 45.3	2	1.83 – 3.16	8
45.4 – 119	3	3.17 – 5.32	9
120 – 267	4	5.33 – 8.78	10
268 – 538	5	8.79 – 14.2	11
539 – 1010	6	14.3 – 22.6	12
		22.7 – 35.6	13
		35.7 – 55.5	14
		55.6 – 85.6	15
		85.7 – 130	16
		131 – 198	17
		199 – 299	18
		300 – 449	19
		450 – 669	20
		670 – 993	21
		994 – 1460	22

Required value for illuminance $\mathbf{E_t = 1x10^{-3}\ lx}$

Table 4 Nominal range table for various background luminance values (night and day)

For Guidance Only – not to be used for Nominal Range Publication

Nominal Range	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)	Intensity (cd)
Background Lighting or Metreological Condition (see 1.3.3)	**None**	**Minor**	**Substantial**	**Day VDO**	**Day DO**	**Day OO**	**Day BO**	**Day BC**	**Day VBC**
Luminance (cd/m^2)				100	200	1000	5000	10000	20000
Illuminance (lx)	2.00E-07	2.00E-06	2.00E-05	1.30E-05	2.39E-05	1.07E-04	5.06E-04	9.99E-04	1.98E-03
Transmissivity (per M)	0.74	0.74	0.74	0.74	0.74	0.74	0.78	0.79	0.81
Visibility (M)	10	10	10	10	10	10	12	13	14
Range (M)									
0.2	0.03	0.3	3	2	3	16	73	144	284
0.5	0.20	2	20	13	24	107	492	961	1,890
0.7	0.41	4	41	27	50	222	1,010	1,970	3,870
1	1	9	93	60	111	495	2,230	4,310	8,410
2	5	50	500	325	597	2,670	11,400	21,700	41,700
3	15	152	1,520	986	1,810	8,110	33,000	61,600	116,000
4	36	364	3,640	2,360	4,350	19,460	75,400	138,000	256,000
5	77	767	7,670	4,990	9,170	41,000	151,000	271,000	495,000
6	149	1,490	14,900	9,690	17,800	79,700	279,000	492,000	883,000
7	274	2,740	27,400	17,800	32,700	146,000	488,000	843,000	1,490,000
8	482	4,820	48,200	31,300	57,600	258,000	818,000	1,390,000	2,410,000
9	824	8,240	82,400	53,500	98,400	441,000	1,330,000	2,210,000	3,770,000
10	1,370	13,700	137,000	89,200	164,000	734,000	2,110,000	3,430,000	5,770,000
11	2,240	22,400	224,000	146,000	268,000	1,200,000	3,270,000	5,230,000	8,650,000
12	3,600	36,000	360,000	234,000	430,000	1,920,000	5,000,000	7,840,000	
13	5,700	57,000	570,000	370,000	681,000	3,050,000	7,530,000		
14	8,910	89,100	891,000	579,000	1,070,000	4,770,000			
15	13,800	138,000	1,380,000	897,000	1,650,000	7,390,000			
16	21,200	212,000	2,120,000	1,380,000	2,530,000				
17	32,300	323,000	3,230,000	2,100,000	3,860,000				
18	48,800	488,000	4,880,000	3,170,000	5,840,000				
19	73,400	734,000	7,340,000	4,770,000	8,770,000				
20	110,000	1,100,000		7,130,000					
21	163,000	1,630,000							
22	242,000	2,420,000							
23	357,000	3,570,000							
24	524,000	5,240,000							
25	767,000	7,670,000							
26	1,120,000								
27	1,630,000								
28	2,360,000								
29	3,420,000								
30	4,940,000								

Abbreviation	*Meteorological Condition*	*Luminance (cd/m²)*
Day VDO	*Very Dark Overcast Sky*	*100*
Day DO	*Dark Overcast Sky*	*200*
Day OO	*Ordinary Overcast Sky*	*1,000*
Day BO	*Bright Overcast Sky away from Sun*	*5,000*
Day BC	*Bright Sky or Cloud near Sun*	*10,000*
Day VBC	*Very Bright Cloud*	*20,000*
Day GC	*Glaring Cloud*	*50,000*

6 REFERENCES

[1] Recommendation for the notation of luminous intensity and range of lights. (IALA, November 1966)

[2] International Dictionary of Aids to Marine Navigation, Chapter 2, Visual Aids 2-1-265 to 2-1-285 (IALA 1970)

[3] Recommendation for a definition of the nominal daytime range of marine signal lights intended for the guidance of shipping by day (IALA 1974)

[4] Recommendations on the determination of the luminous intensity of a marine aid-to-navigation light (IALA 1977)

[5] Recommendation for leading lights (IALA, E-112, May 1998)

[6] Recommendation on the photometry of marine aids to navigation Signal lights (IALA, E-122, June 2001)