C04-10.4.3

GUIDELINE

G1023
DESIGN OF LEADING LINES

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DOCUMENT REVISION

Revisions to this document are to be noted in the table prior to the issue of a revised document. The latest edition of the Guideline is the only version in force unless the Guideline is explicitly revoked by the Council.

Date	Details	Approval
December 2001	Edition 1.0	
December 2005	Edition 1.1 Entire document reformatted to reflect IALA Documentation Hierarchy	
June 2026	Edition 2.0 More specific information on the design principle, the geometry, and the light calculations is included. The hidden equations and constants in the spreadsheet are extracted to be visible as mathematical equations, to preserve the knowledge and information of the leading line design	Council 04

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1. INTRODUCTION

Leading lines have been part of Marine Aids to Navigation (AtoN) for a long time. A leading line is a straight line produced by the alignment of two fixed AtoN used to mark straight sections of fairways or channels. It is common practice to guide ships along narrow fairways by means of leading lines or a series of leading lines in succession, the useful segments of which form a continuous series of straight lines.

Figure 1 shows the situation where the ship has deviated left from the leading line, indicated by the rear mark being seen left from the front one. The ship is on the leading line when the leading marks are vertically aligned, as seen on the Figure 2.

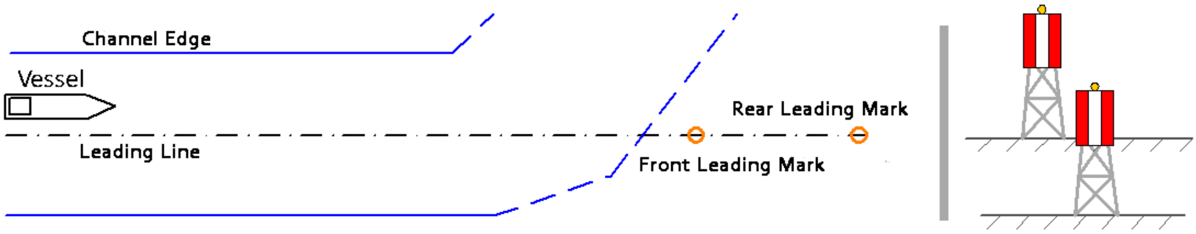

Figure 1 Geometry of a leading line and appearance of the leading marks for an observer left of leading line

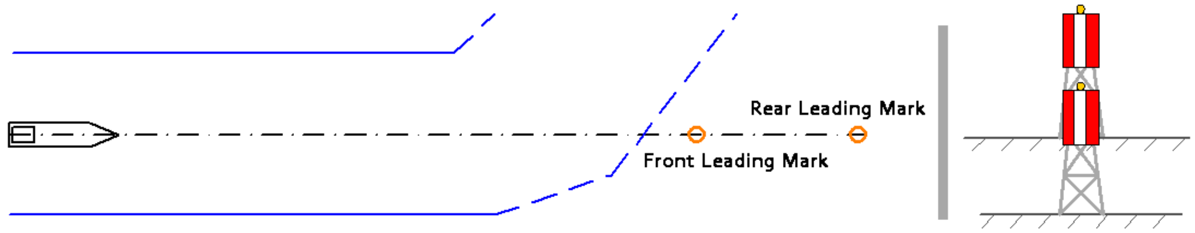

Figure 2 Geometry of a leading line and appearance of the leading marks for an observer on leading line

The AtoN producing a leading line can be daymarks or lights or consist of both and are called leading marks. The leading mark nearer to the mariner is called "front leading mark", and the one further and seen behind the front leading mark is called "rear leading mark".

Navigation along a leading line takes place within the area where the leading marks are perceived being vertically aligned. This area has a curvilinear, tapered form that widens towards the far end of the useful segment, see Figure 3. Its boundaries are defined by the positions at which a deviation y from the leading line results in the bearing difference θ at which the navigator detects misalignment. As the distance from the leading marks increases, a larger lateral deviation is required before the misalignment becomes detectable.

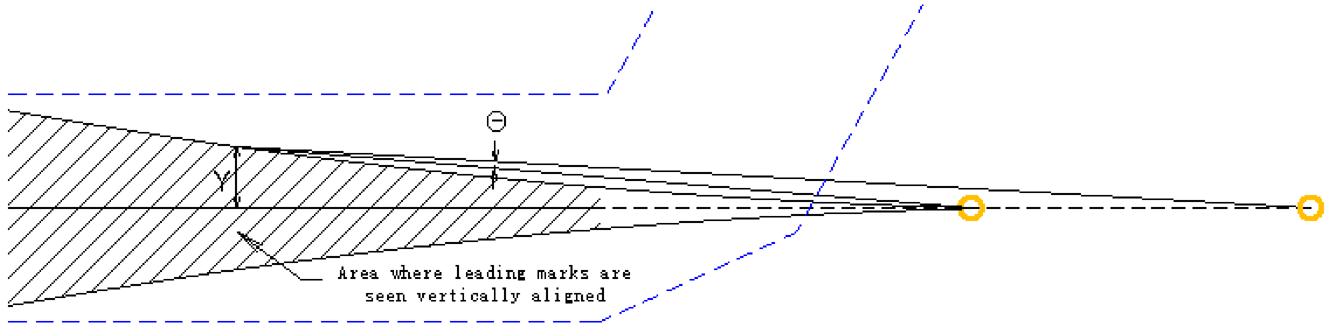

Figure 3 The area where leading marks are perceived being vertically aligned

The part of the leading line intended for navigating is called the "useful segment" of the leading line, see Figure 4. The end of a useful segment closer to the front leading mark is called the "near end", and the end further from the front leading mark is called the "far end" of the useful segment.

To safely reach a leading line, the mariner must be able to see the leading marks (or at least one of them) while approaching the useful segment of it from the seaward or from the previous leg of the fairway. This approaching area required for safely "acquiring" the leading line is referred to as the "acquisition region", see Figure 4. Considerations on determining the limits of the acquisition region are covered in the Section 5.1.

When using a leading line, the determination of the "usable width of a channel" or the position of the line to be marked in a natural channel for each particular case requires considering not only the accuracy (sensitivity) of the leading line, but also different 'nautical margins', such as those resulting from the breadth of ships, the space required for vessels to pass each other, the drift angle in case of transverse winds and currents, uncertainties resulting from inaccuracies in hydrographic surveys or possible changes in the sea bottom since the last survey, etc. From the designer's point of view, some of these are rather part of a fairway/channel design, but it may be possible to account for some of these margins also in the design of the leading line.

2. PURPOSE

The purpose of this document is to provide guidance on the principles of leading lines and the calculation used in their design.

Additional guidance on marking fairways with AtoNs, including leading lines, is provided in Guideline G1078 The Use of AtoN in the Design of Fairways [8].

3. DEFINITIONS AND PARAMETERS

The design of a leading line consists of determining:

- Geometric parameters and the layout of the leading line;
- Luminous intensity of the lights;
- Dimensions of the daymarks.

The performance of a leading line can only be guaranteed when all parameters work together. Therefore, extensive and iterative calculations are usually necessary.

Variables required for the design of a leading line are described in this section. The channel is idealized to a horizontal rectangle, which is symmetrical about the centreline, see Figure 4.

The front leading mark or light is abbreviated FL, and the rear leading mark is abbreviated RL.

SI Standard units are used:

- Lengths and heights in metres $[m]$

- Illuminance in lux $[lx]$
- Luminous intensity in candelas $[cd]$)
- Angles are in radians, unless otherwise stated. In many cases, the angles are small, and therefore some approximations are valid ($\alpha_{radians} \approx \sin\alpha \approx \tan\alpha$ and $\cos\alpha \approx 1$).

Other units used: Nautical mile (M) $[1\ M = 1852\ m]$

All dimensions are written with their units explicitly indicated. For example, instead of writing e^x, x is divided by one unit of distance e^{x/d_U}, so that the exponent becomes a plain number containing no units, since functions like eˣ work only with numbers, not with distances expressed in metres or nautical miles. This means the same equation works whether x is given in metres or in nautical miles: $e^{1000\ m/1\ M} = e^{1000\ m/1852\ m} = e^{0{,}54\ M/1\ M} = e^{0{,}54}$.

This is done for distance with a unit factor $d_U = 1\ M = 1852\ m$, height $h_U = 1\ m$ and illuminance $E_U = 1\ lx$.

For all equations, SI units are used unless stated otherwise.

3.1. GEOMETRY, PLAN VIEW

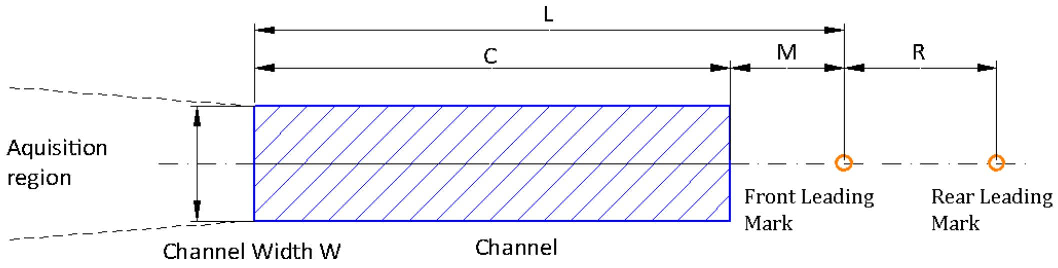

Figure 4 Parameters of leading line in plan view

- C Length of useful segment
- L Distance from front leading mark to far end of useful segment ($L = C + M$)
- M Distance from front leading mark to near end of useful segment
- R Distance between leading marks
- W Channel width

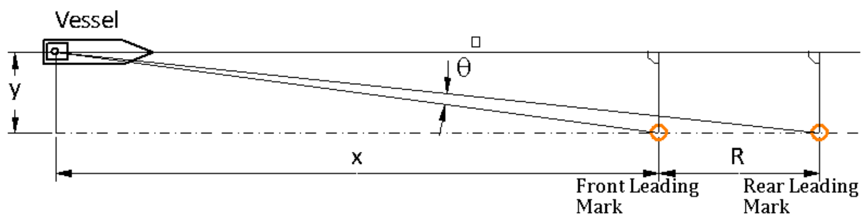

Figure 5 Parameters of observation in plan view

- x Distance of observer (vessel) from front tower (parallel to leading line)
- y Off-axis distance of observer (perpendicular to leading line)
- θ Bearing difference (horizontal angular difference between front and rear light)

3.2. GEOMETRY, SIDE VIEW

In this Guideline, the height of the observer on the vessel H_v is referenced to either mean high water (MHW) or mean low water (MLW) level at the vessel's locations along the useful segment, depending on the parameter calculated. All other heights are referenced to MHW. Mean sea level (MSL) can be used in place of MHW or MLW when the mean tidal range (MTR) is small or zero ($MTR < 0.3\ m$).

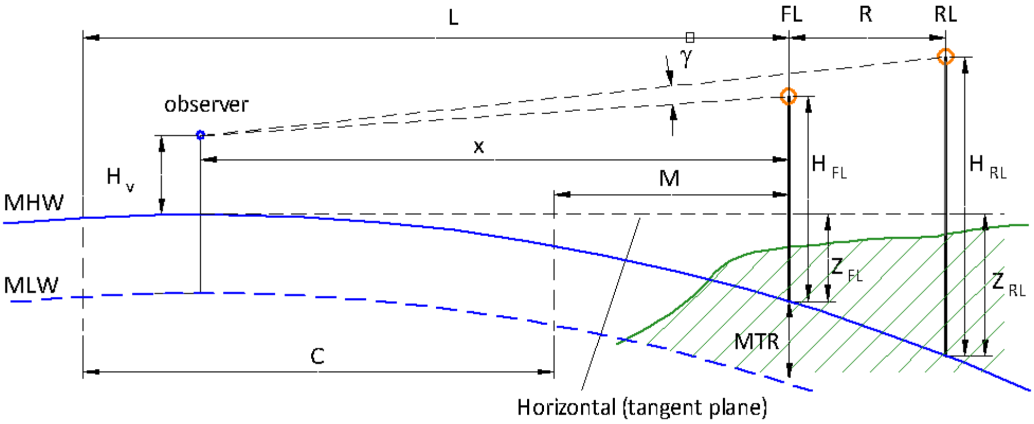

Figure 6 Parameters on leading line and observation in side view (vertical plane)

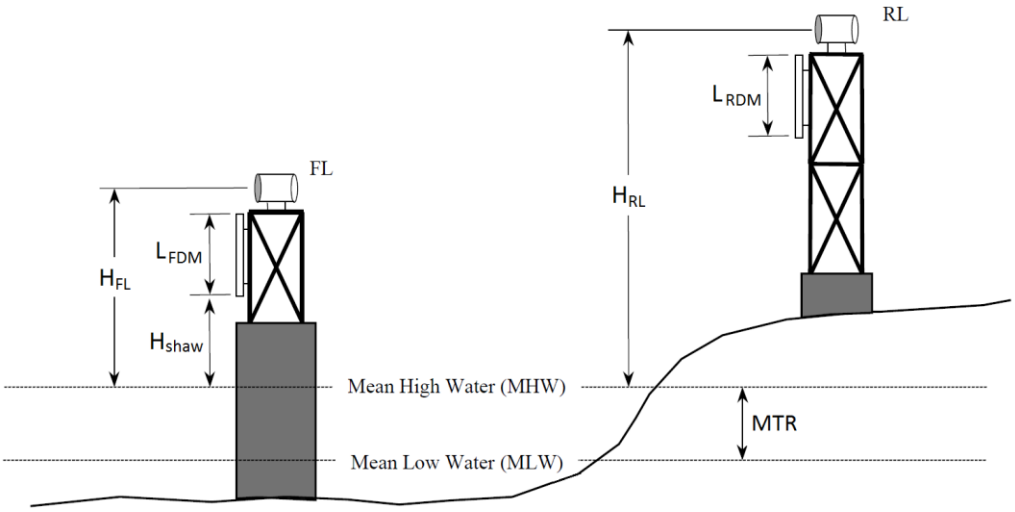

Figure 7 Heights of lights and daymarks

- H_v Height of observer (on vessel) above MHW or MLW, depending on the parameter calculated.
- H_{FL} Height of front light above MHW or MSL
- H_{RL} Height of rear light above MHW or MSL
- H_{shaw} Safe height above water
- L_{FDM} Vertical length of the front daymark
- L_{RDM} Vertical length of the rear daymark
- MHW Mean high water
- MLW Mean low water
- MSL Mean sea level
- MTR Mean tidal range

- Z_{FL} Height of the part of front leading mark obscured by the horizon
- Z_{RL} Height of the part of rear leading mark obscured by the horizon
- γ Vertical difference angle between front and rear light

3.3. GENERAL OVERVIEW OF DESIGN PROCESS

Throughout the leading line design process, the designer will calculate minimum and maximum values for parameters such as heights and luminous intensity, which set the range of viable solutions. These minimum and maximum calculations will then lead to recommended value calculations. Once a recommended value is obtained, then a design value is selected. The design or selected value may be the recommended value or another value between the minimum and maximum values. The calculations provide a specific recommended value that may not be practical, prudent, or cost effective in constructing the leading line. For example, the recommended height of the front leading mark may be 4.2 m. Instead of using the recommended value, the designer may select a front leading mark height of 5 m, which is a standard tower design in their country. As design value are chosen, the calculations are completed with the design values to check that the leading line works in the optimal way.

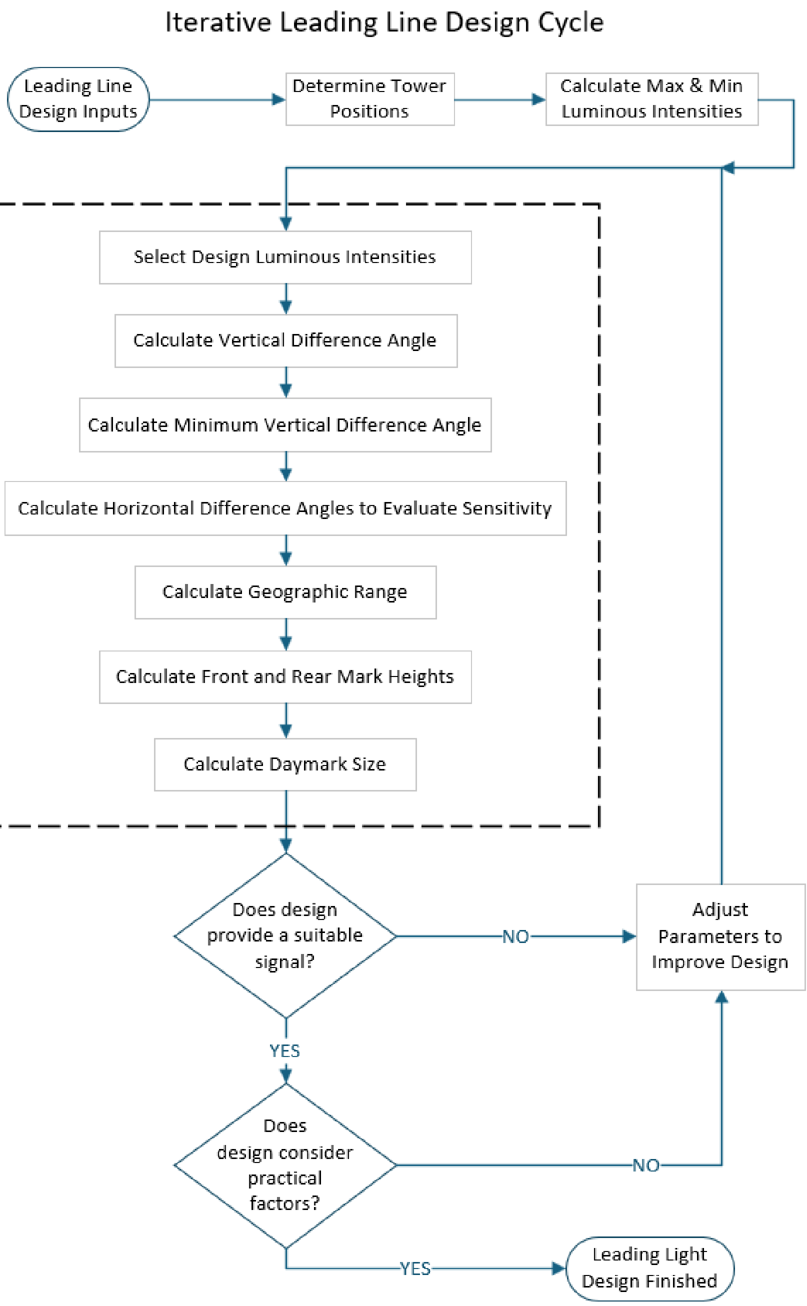

Figure 8 Iterative cycle of designing of leading line

3.4. PARAMETERS FOR LUMINOUS INTENSITY CALCULATIONS

Detailed information on calculations of luminous intensity needed for the design of leading lights can be found in Guideline G1148 Determination of Required Luminous Intensity for Marine Signal Lights [1]. Based on this guideline the parameters described below must be determined in the calculation of leading lights.

- E_{FL} Illuminance at the eye of the observer produced by the front light
- E_{RL} Illuminance at the eye of the observer produced by the rear light
- E_{min} Required minimum illuminance at the eye of the observer

The minimum illuminance at the observer's eye required for observing of the leading lights in the useful segment depends on the luminance of the background against which the lights are viewed. $E_{min} = 10^{-6}\ lx$ is used for situations without background lighting, $E_{min} = 2 \cdot 10^{-6}\ lx$ for minor and $E_{min} = 2 \cdot 10^{-5}\ lx$ for substantial background lighting. For a daytime light the required illuminance is $E_{min} = 10^{-3}\ lx$. In acquisition region $E_{min} = 2 \cdot 10^{-7}\ lx$ is sufficient for situations without background lighting.

- E_{max} Allowed maximum illuminance at the eye of the observer

Value of the allowed maximum illuminance at the eye of the observer is needed to avoid glare. $E_{max} = 0.01\ lx$ is used for situations without background lighting, $E_{max} = 0.1\ lx$ with background lighting. It is very unlikely to cause glare with daytime lights, so there is no need to check for this and no maximum value for the illuminance is defined for daytime lights.

- I_{FL} Luminous intensity of the front light
- I_{RL} Luminous intensity of the rear light
- V_{min} Minimum Meteorological Visibility

The minimum meteorological visibility should be selected by the designer based on the worst visibility conditions under which the leading lights must be usable, navigational requirements, practical limitations, etc. For guidance in selecting the optimal value for minimum meteorological visibility please refer to Guideline G1148.

V_{dsg} Design Meteorological Visibility

Design visibility is used to establish the recommended ratio of luminous intensities of the front and the rear light. As a practical consideration, use of a fixed value $V_{dsg} = 10\ M = 18\,520\ m$ is recommended.

V_{max} Maximum Meteorological Visibility

The potential for glare produced by the lights is calculated with the maximum meteorological visibility. Typically, $V_{max} = 20\ M = 37\,040\ m$ is chosen.

4. DESIGN EQUATIONS

4.1. POSITION OF LEADING MARKS

As a starting point, input values for the dimensions (C, W) of the rectangular useful segment must be defined.

When the locations of the leading marks are not prescribed by geographical or other restrictions the following formulas can be used for initial determination of their positions in relation to the channel to be marked.

Distance from the near end to the front leading marks:

$$M_{initial} = \frac{C}{5} = 0.2 \cdot C \qquad (1)$$

Distance between the leading marks:

$$R_{initial} = \frac{(M+C)}{\left[1000 * W / \left(3.4 \cdot (M+C)\right) - 1\right]} = \frac{L}{\left[\left(\frac{1000 \cdot W}{3.4 \cdot L}\right) - 1\right]} \qquad (2)$$

For the calculation of the initial value of $R_{initial}$ the formula assumes that the observer is able to detect deviation from leading line at the distance $y_d = 0.1 \cdot \mathrm{W}$ from leading line at the far end of the useful segment, which means the cross track factor (CTF) is 20%, inferring a ‘very good’ leading line, see **Erreur ! Source du renvoi introuvable.** in Section **Erreur ! Source du renvoi introuvable.Erreur ! Source du renvoi introuvable.**. Furthermore, it assumes that the elevation difference at this position is $\gamma = 1.5 \cdot 10^{-3}\ rad$ ($\approx 5'$) and the bearing difference is $\theta = 0.34 \cdot 10^{-3}$ rad ($\approx 1'$).

4.2. LUMINOUS INTENSITY

Calculation of intensity of lights needs the input of a distance x, a visibility V and an illuminance E at the eye of the observer and is calculated by the Allard’s Law as follows:

$$I = E \cdot x^2 \cdot 0.05^{-x/V} \tag{3}$$

When the intensity is known, the illuminance at the eye of the observer is:

$$E = I \cdot x^{-2} \cdot 0.05^{x/V} \tag{4}$$

4.2.1. MINIMUM LUMINOUS INTENSITY

The required minimum intensity of the front and rear lights is calculated for the selected minimum meteorological visibility (worst practicable atmospheric condition) and required minimum illuminance at the eye of the observer for both front and rear lights at the far end of the useful segment. The minimum luminous intensity should be calculated for night and for day, if the lights are also to be used during daylight. Principles of selection of V_{min} and E_{min} to equations 5 and 6 can be found in Section 3.4.

Minimum intensity of the front light:

$$I_{FL,min} = E_{min} \cdot (M + C)^2 * 0.05^{-(M+C)/V_{min}} \tag{5}$$

Minimum intensity of the rear light:

$$I_{RL,min} = E_{min} \cdot (R + M + C)^2 * 0.05^{-(R+M+C)/V_{min}} \tag{6}$$

Where：

E_{min}	required minimum illuminance at the eye of the observer;
V_{min}	minimum meteorological visibility;
$M + C$	distance from far end of the useful segment to the front leading mark;
$R + M + C$	distance from far end of the useful segment to the rear leading mark.

4.2.2. MAXIMUM LUMINOUS INTENSITY

To avoid glare, the luminous intensity should not exceed a certain maximum value. The maximum allowed intensity is calculated for both front and rear lights at the near end of the useful segment. Principles of selection of V_{max} and E_{max} to equations 7 and 8 can be found in Section 3.4.

Maximum intensity of the front light:

$$I_{FL,max} = E_{max} \cdot M^2 \cdot 0.05^{-M/V_{max}} \tag{7}$$

Maximum intensity of the rear light:

$$\mathrm{I_{RL,max} = E_{max} \cdot (R + M)^2 \cdot 0.05^{-(R+M)/V_{max}}} \tag{8}$$

Where：

E_{max}	allowed maximum illuminance at the eye of the observer;
V_{max}	maximum meteorological visibility;
M	distance from near end of the useful segment to front light;
$R + M$	distance from near end of the useful segment to rear light.

4.2.3. DESIGN LUMINOUS INTENSITY OF FRONT LIGHT

The designer of the leading line may choose any intensity for the front light ($I_{FL,dsg}$) between the minimum and the maximum value. Most commonly the minimum luminous intensity is selected.

4.2.4. DESIGN LUMINOUS INTENSITY OF REAR LIGHT

The illuminances at the eye of the observer provided by the two leading lights within the useful segment should be as equal as possible. Therefore, the ratio of the intensities is used to determine the design intensity of the rear light based on the design intensity of the front light. Allard's law and the ideal ratio are used to determine the design luminous intensity of the rear light.

The illuminance values for the lights at the design visibility V_{dsg}:

$$E_{FL} = I_{FL} \cdot x^{-2} \cdot 0.05^{x/V_{dsg}} \quad (9)$$

$$E_{RL} = I_{RL} \cdot (R + x)^{-2} * 0.05^{(R+x)/V_{dsg}} \quad (10)$$

The ratio of illuminances is:

$$\frac{E_{FL}}{E_{RL}} = \frac{I_{FL}}{I_{RL}} \cdot \frac{(R + x)^2}{x^2} \cdot \frac{0.05^{x/V_{dsg}}}{0.05^{(R+x)/V_{dsg}}} = \frac{I_{FL}}{I_{RL}} \cdot \frac{(R + x)^2}{x^2} \cdot 0.05^{-R/V_{dsg}}$$

The ideal ratio of the illuminances is equal to one, i.e., $\frac{E_{FL}}{E_{RL}} = 1$. Ratio of the intensities r giving this ratio of illuminances at the distance x:

$$r = \frac{I_{RL}}{I_{FL}} = \frac{(R + x)^2}{x^2} \cdot \frac{0.05^{x/V_{dsg}}}{0.05^{(R+x)/V_{dsg}}} = \frac{(R + x)^2}{x^2} \cdot 0.05^{-R/V_{dsg}}$$

However, the ratio depends on the observer's distance from the (front) light x. Since the ideal ratio can only be achieved at one location along the useful segment, it is recommended that the ratio $\frac{I_{RL}}{I_{FL}}$ be calculated at least twice, first for a position in the middle of the channel and secondly for a position at the far end.

These ratios are evaluated to determine the recommended ratio from which the rear light design luminous intensity is calculated. It is generally preferred to set the ratio to 1 at the far end to provide the best signal to the mariner in the acquisition region. The following factors should also be considered in setting the ratio of illuminances and the corresponding selection of the rear light design luminous intensity:

- For longer leading lines, it may be necessary to set the ratio of illuminances to 1 at, or closer to, the middle of the useful segment to avoid glare or blurring of the lights at the near end.
- As per Recommendation R0112 on Leading Lights, December 2005 [1], under favourable circumstances, the ratio of illuminances may be permitted to vary between 0.5 and 2.0. This ratio may sometimes deviate substantially from 1 ranging from 0.1 to 10 or even from 0.01 to 100 in special cases, for instance when an existing light is used as a part of new leading lights or when the distance between the lights is large compared to the maximum distance to the front light. This necessitates increasing the minimum values of the elevation difference to avoid blurring of lights and affects the sensitivity slightly, but the leading line remains usable.

In the IALA leading lines spreadsheet, the ratio of illuminances is calculated for every 10% increment of the useful segment length.

The distance from the middle of the useful segment to the front light (FL) is: $X_{FL,mid} = M + \frac{C}{2}$

The distance to the rear light (RL) is: $X_{RL,mid} = R + M + \frac{C}{2}$

With these equations the ratio r becomes:

$$r_{mid} = \frac{I_{RL}}{I_{FL}} = \frac{X_{RL,mid}{}^2}{X_{FL,mid}{}^2} \cdot \frac{0.05^{X_{FL,mid}/V_{dsg}}}{0.05^{X_{RL,mid}/V_{dsg}}} = \frac{\left(R+M+\frac{C}{2}\right)^2}{\left(M+\frac{C}{2}\right)^2} \cdot 0.05^{-R/V_{dsg}} \quad (11)$$

The distance from the far end of the useful segment to the front light (FL) is: $X_{FL,far} = M + C$

The distance to the rear light (RL) is: $X_{RL,far} = R + M + C$

With these the ratio of intensities becomes:

$$r_{far} = \frac{I_{FL}}{I_{RL}} = \frac{X_{FL,far}{}^2}{X_{RL,far}{}^2} \cdot \frac{0.05^{X_{RL,far}/V_{dsg}}}{0.05^{X_{FL,far}/V_{dsg}}} = \frac{(M+C)^2}{(R+M+C)^2} \cdot 0.05^{R/V_{dsg}} \quad (12)$$

To avoid excessively large brightness differences that would reduce the alignment performance of the leading lights and to maintain near-equal illuminances around the midpoint of the useful segment, the ratio between the luminous intensities of front and rear light is then selected as follows:

$$r = \frac{I_{RL}}{I_{FL}} = min^1 \left\{ r_{mid}, \frac{2}{r_{far}} \right\} \quad (13)$$

And the design luminous intensity of the rear light, $I_{RL,dsg}$:

$$I_{RL,dsg} = r \cdot I_{FL,dsg} \quad (14)$$

During daylight the luminous intensity of a light needs to be orders of magnitude higher than at nighttime. This may result in complex and expensive lighting systems with higher power consumption. Therefore, it is assumed that the design luminous intensity of daytime lights is the minimum luminous intensity.

4.3. VERTICAL DIFFERENCE ANGLE

It is essential that the navigator perceives a vertical separation between the front and rear leading lights at all points along the useful segment of a leading line. The vertical angle (γ_{FL}, γ_{RL}) refers to the angle between a light and the observer's horizontal plane. The vertical difference angle γ is the difference between the vertical angles of the front and rear lights as seen from the observer's position. This angle plays a critical role in the correct design of a leading line, as it affects the mariner's ability to distinguish the two lights. Vertical difference angle is calculated at Mean Low Water (MLW), since this condition typically results in the smallest vertical separation, which can challenge visibility and recognition of the leading line.

Equations 15 to 16 below are derived with reference to **Erreur ! Source du renvoi introuvable.**, which illustrates the geometric relationships involved.

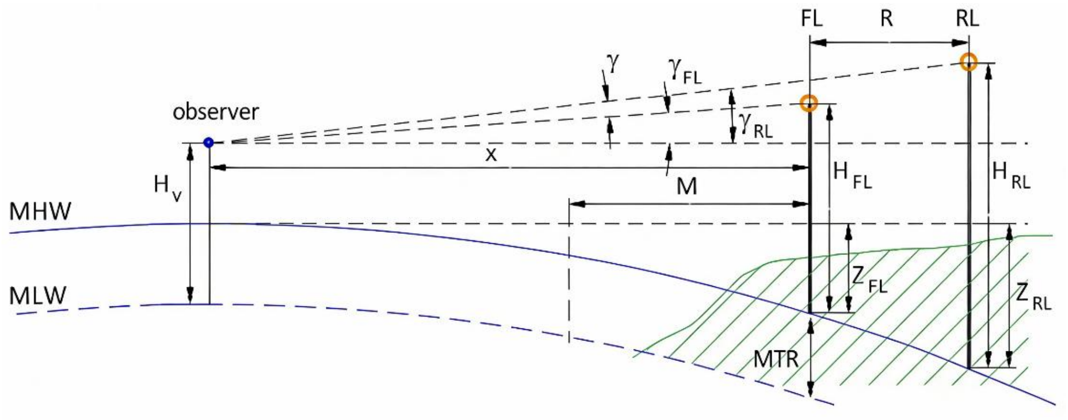

Figure 9 Vertical difference angle γ

1 "*min*" means the smaller of the two values.

The vertical angles are:

$$\gamma_{FL} \approx \tan\gamma_{FL} = \frac{H_{FL}-Z_{FL}+MTR-H_v}{x} \quad (15)$$

$$\gamma_{RL} \approx \tan\gamma_{RL} = \frac{H_{RL}-Z_{RL}+MTR-H_v}{x+R} \quad (16)$$

At longer distances, the apparent height of a light above the horizon is reduced by the part Z of the leading mark that is obscured by the horizon. The value of Z depends on the distance x between the observer and the light.

$$Z_{FL} \approx \alpha \cdot x^2 \quad (17)$$

$$Z_{RL} \approx \alpha \cdot (x+R)^2 \quad (18)$$

where $\alpha = 6.75 \cdot 10^{-8} m^{-1}$.

The vertical difference angle γ is then:

$$\gamma = \gamma_{RL} - \gamma_{FL} = \frac{H_{RL}-Z_{RL}-H_v+MTR}{x+R} - \frac{H_{FL}-Z_{FL}-H_v+MTR}{x} \rightarrow$$

$$\gamma = \frac{H_{RL}-\alpha\cdot(x+R)^2-H_v+MTR}{x+R} - \frac{H_{FL}-\alpha\cdot x^2-H_v+MTR}{x} \rightarrow$$

$$\gamma = \frac{H_{RL}-H_v+MTR}{x+R} - \frac{H_{FL}-H_v+MTR}{x} - \alpha \cdot R \quad (19)$$

where $\alpha = 6.75 \cdot 10^{-8} m^{-1}$.

The vertical difference angle will vary in practical use based on the current sea level, the observer's height and the distance.

4.4. MINIMUM VERTICAL DIFFERENCE ANGLE

For a leading line to be usable, the leading lights must appear vertically separated to the navigator, with the rear light clearly visible above the front light, allowing deviations from the line to be easily detected. There is a minimum value γ_{min} for the vertical difference angle, at which the lights are very close but can still be clearly seen as two separated lights.

The required minimum vertical difference angle $\gamma_{\min}$ between the lights depends on the illuminance at the eye of the observer generated by the lights. In general, all maritime signal lights are seen under angles smaller than the angular resolution of the human eye (approx. $1' = 0.291 \cdot 10^{-3} rad$). However, the lights appear larger or smaller for the observer's eye according to their brightness. This effect is known from astronomy as the 'apparent magnitude (of a star)'.

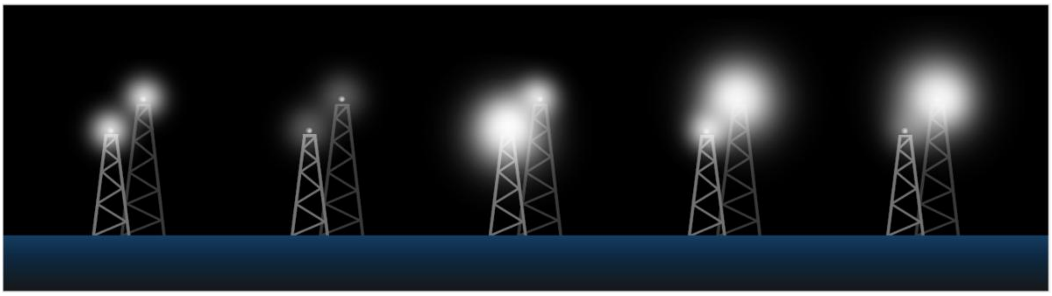

Figure 10 'Apparent magnitude of front and rear light'

To account for that effect and calculate the minimum required vertical difference angle for separation of lights γ_{min}, the luminous intensity of front and rear light must be selected.

- design luminous intensity of the front light (FL): $I_{FL,dsg}$
- design luminous intensity of the rear light (RL): $I_{RL,dsg}$

As the worst-case scenario giving the largest 'apparent magnitude', the illuminance at the eye of the observer is then calculated for very good viewing conditions ($V_{max} = 20\ M$). This is done for several equally spaced positions along the channel.

- illuminance from FL:

$$E_{FL} = I_{FL,dsg} \cdot x^{-2} \cdot 0.05^{x/V_{max}} \qquad (20)$$

- illuminance from RL:

$$E_{RL} = I_{RL,dsg} \cdot (x + R)^{-2} \cdot 0.05^{(x+R)/V_{max}} \qquad (21)$$

The minimum required difference angle is then:

$$\gamma_{min} = [2.4 - 0.06 \cdot |log(E_{RL}/E_{FL})| + 0.26 \cdot |log(E_{RL}/E_{FL})|^2 +$$

$$log\frac{E^+}{E_U} \cdot (0.2 - 0.02 \cdot |log(E_{RL}/E_{FL})| - 0.02 \cdot |log(E_{RL}/E_{FL})|^2)\Big] \cdot 10^{-3} rad \qquad (22)$$

Where：

$$E^+ = \begin{cases} max\text{[2]}\{E_{FL}, E_{RL}\} & for\ nighttime \\ max\{E_{FL}, E_{RL}\}/10000 & for\ daytime \end{cases};$$

$$E_U = 1\ lx.$$

Generally, a γ_{min} less than $1.5 \cdot 10^{-3}\ rad$ ($\approx 5'$) leads to blurring and should be avoided.

4.5. HORIZONTAL DIFFERENCE ANGLE AND OFF-AXIS DISTANCE

The horizontal angle describes the horizontal angle between the direction to a leading mark from the observer and a line parallel to the leading line. The horizontal difference angle θ is the horizontal angle between front and rear leading mark seen from the observer. The horizontal difference angle is calculated as the difference between the horizontal angles of the front and rear mark, and it depends on distance from the leading marks and the lateral distance of the vessel from the leading line.

The equations necessary for the calculations are derived from **Erreur ! Source du renvoi introuvable.**.

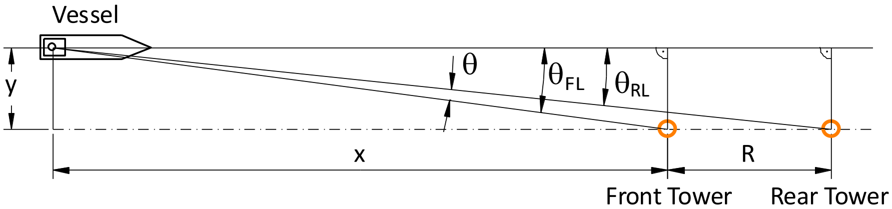

Figure 11 Horizontal angles and horizontal difference angle (θ)

The horizontal angles are:

$$\theta_{FL} \approx tan\,\theta_{FL} = \frac{y}{x}$$

2 *"max"* means the larger of the two values

$$\theta_{RL} \approx tan\,\theta_{RL} = \frac{y}{x + R}$$

The horizontal difference angle θ is then:

$$\theta = \theta_{FL} - \theta_{RL} = \frac{y}{x} - \frac{y}{x+R} = \frac{y \cdot R}{x \cdot (x+R)} \quad (23)$$

The distance from the leading line or off-axis distance y when the horizontal difference angle is θ is calculated as follows:

$$y \approx \theta \cdot \frac{x*(R+x)}{R} = \theta \cdot x \cdot \left(1 + \frac{x}{R}\right) \quad (24)$$

4.6. SENSITIVITY OF A LEADING LINE

Sensitivity of a leading line is described by the magnitude of deviation from the leading line needed for an observer to detect with certainty that the lights are not vertically aligned. Off-axis distance shows absolute sensitivity as a deviation in meters, while cross-track factor described in the next section shows relative sensitivity. Smaller deviation at the moment of detection means higher sensitivity and larger deviation means lower sensitivity.

Sensitivity of a leading line depends mostly on the distance between the leading marks – with greater distance between the marks, smaller deviations become detectable, meaning a higher sensitivity. To a smaller extent, sensitivity of a leading line is impacted by the elevation difference of the leading marks as well as illumination created by the leading lights at the observer's eye. To a certain limit, the closer the leading marks appear to each other vertically the higher the sensitivity, however, larger illuminance values need larger vertical separation between the lights, as explained in the Section 4.4.

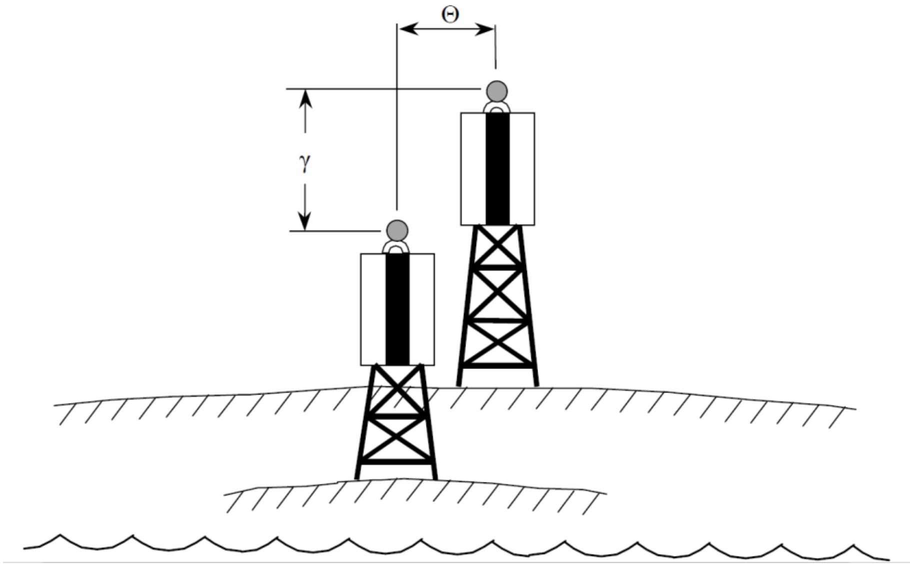

Figure 12 Bearing and elevation difference

Detection of deviation from the leading line occurs when the horizontal angular separation between the leading lights, expressed as the bearing difference θ, exceeds a certain value. This critical bearing difference θ_d at detection of being off the leading line, derived from the vertical difference angle γ between the lights, is calculated using the following formulae:

$$\theta_d = max\{\theta'_1, \theta'_2\} \quad (25)$$

Where:

$$\theta'_1 = \begin{cases} 0.16 \cdot 10^{-3} + 0.12 * \gamma & \text{for } \gamma \leq 5 \cdot 10^{-3} \text{ rad} \\ 0.31 \cdot 10^{-3} + 0.09 * \gamma & \text{for } 5 \cdot 10^{-3} < \gamma \leq 20 \cdot 10^{-3} \text{ rad} \end{cases};$$

$\theta'_2 = 0.224 \cdot \gamma_{min}$ (see Section 5.4).

Before calculating critical bearing difference θ_d, vertical difference angle γ must calculated at MHW using the equations below:

$$\gamma = \gamma_{RL} - \gamma_{FL} = \frac{H_{RL} - Z_{RL} - H_v}{x+R} - \frac{H_{FL} - Z_{FL} - H_v}{x} \rightarrow$$

$$\gamma = \frac{H_{RL} - \alpha \cdot (x+R)^2 - H_v}{x+R} - \frac{H_{FL} - \alpha \cdot x^2 - H_v}{x} \rightarrow$$

$$\gamma = \frac{H_{RL} - H_v}{x+R} - \frac{H_{FL} - H_v}{x} - \alpha \cdot R \qquad (26)$$

where $\alpha = 6.75 \cdot 10^{-8} m^{-1}$.

4.7. CROSS-TRACK FACTOR

Cross-track factor (CTF) is a measure of sensitivity of a leading line. The cross-track factor is calculated as the ratio of the off-axis distance at which the navigator can detect with certainty that the vessel is not on the leading line, y_d, divided by half the channel width, expressed as a percentage.

From equations (24) y_d is:

$$y_d \approx \theta_d \cdot x \cdot \left(1 + \frac{x}{R}\right) \qquad (27)$$

The CTF then becomes:

$$CTF = \frac{y_d}{0.5 * W} \cdot 100\% \qquad (28)$$

where CTF is the cross-track factor in percents of half of the channel width.

For a leading line design, the cross-track factor varies with the observer's position in the useful segment (x) and the observer's height H_v. Interpretation of acceptability of different cross-track factors is provided in Table 1.

Table 1 Cross Track Factor Acceptability Assessment

CTF	Suitability	Interpretation
over 75%	Not Acceptable	Leading line must be improved, or it may not be safe to use.
50% - 75%	Poor	Decrease the cross-track factor if possible.
30% - 50%	Fair	Decrease the cross-track factor only if moderate cost involved.
20% - 30%	Good	Decrease the cross-track factor only if little cost involved.
15% - 20%	Very Good	Do not expend more for decreasing the cross-track factor.
10% - 15%	Excellent	The cross-track factor should not be less than 10% at the far end of useful segment.

4.8. GEOGRAPHICAL RANGE

The geographical range R_g of a light or a daymark is calculated by the following equation.

$$R_g = 2.03\, d_U \cdot \left(\sqrt{\frac{H}{h_U}} + \sqrt{\frac{H_v}{h_U}}\right) \qquad (29)$$

Where：

H height of the light or lower end of the daymark;

H_v height of the observer on vessel;

$h_U = 1\,m$ unit for height;

$d_U = 1852\ m$ unit for distance, 1 M.

Remark: When heights are entered in metres and the result is expressed in nautical miles, the equation can be written in the following simplified form, widely used in navigation theory, because the conversion between metres and nautical miles (along with refraction in the atmosphere) is already included in the constant 2.03:

$$R_g = 2.03 \cdot \left(\sqrt{H} + \sqrt{H_v}\right)$$

When a required geographical range is given, then the minimum height of a light or a daymark for achieving that range can be derived from:

$$H = \left(\frac{R_g}{2.03 \cdot d_U} - \sqrt{\frac{H_v}{h_U}}\right)^2 \cdot h_U \qquad (30)$$

Remark: Written without unit factors, the equation is: $H = \left(R_g/2.03 - \sqrt{H_v}\right)^2$

4.9. HEIGHTS

The height of the front and rear light is governed by several visibility requirements. Each requirement results in a different minimum required height in the form of $H_{LIGHT} \geq H_{min}$ as shown below. Each minimum height resulting from individual requirements is given an index to identify them. The height of the lights is significantly controlled by the minimum observer height $H_v = H_{v,min}$ for which the leading line is designed. It is assumed that for observer heights lower than $H_{v,min}$ the leading line will not work in parts of or in the whole useful segment.

4.9.1. FRONT LEADING MARK

4.9.1.1. Safe Height above Water

To avoid damage from waves or vandals or obstruction by vegetation, the front light H_{FL} must be above a safe height above water (H_{shaw}):

$$H_{FL} \geq H_{FL,min1} = H_{shaw} \qquad (31)$$

When a daymark with length $L_{FDM,sel}$ is used, the lower end of the daymark shall be above H_{shaw}, $H_{FDM,lower\_end} \geq H_{shaw}$, and the light above the upper end of the daymark.

In this case the minimum front light height is:

$$H_{FL} \geq H_{FL,min2} = H_{shaw} + L_{FDM,sel} \qquad (32)$$

4.9.1.2. Geographical Range

The height of the front light above mean high water must be sufficient to be seen above the horizon i.e. its geographical range must exceed the distance from the front mark to the far end of the channel $R_g = M + C$.

$$H_{FL} \geq H_{FL,min3} = \left(\frac{R_g}{2.03\ d_U} - \sqrt{\frac{H_v}{h_U}}\right)^2 \cdot h_U \qquad (33)$$

When a daymark with length $L_{FDM,sel}$ is used, the lower end of the daymark must be high enough above mean high water so that its geographical range exceeds the distance to the far end of the channel.

$$\mathrm{H_{FDM,lower\_end}} = \left(\frac{\mathrm{R_g}}{2.03\ \mathrm{d_U}} - \sqrt{\frac{\mathrm{H_v}}{\mathrm{h_U}}}\right)^2 \cdot \mathrm{h_U}$$

When the light is positioned at the upper end of the daymark, the daymark length must be added to the minimum front light height.

$$H_{FL} \geq H_{FL,min4} = \left[\left(\frac{R_g}{2.03\ d_U} - \sqrt{\frac{H_v}{h_U}}\right)^2 + L_{FDM,sel}\right] \cdot h_U \qquad (34)$$

4.9.1.3. Avoiding Obscuring of Front Light and Daymark by Obstruction

When an obstruction is located between the front light and the observer and it seems to be relevant for the visibility of the front light, a calculation is necessary to determine whether the front light is obscured by it. The height of the obstruction H_{obs} and the distance S between the obstruction and the near end of the useful segment are needed for this calculation. $H_{FL,min}$ is only calculated for the observer at mean low water which is the worst-case situation for obstruction.

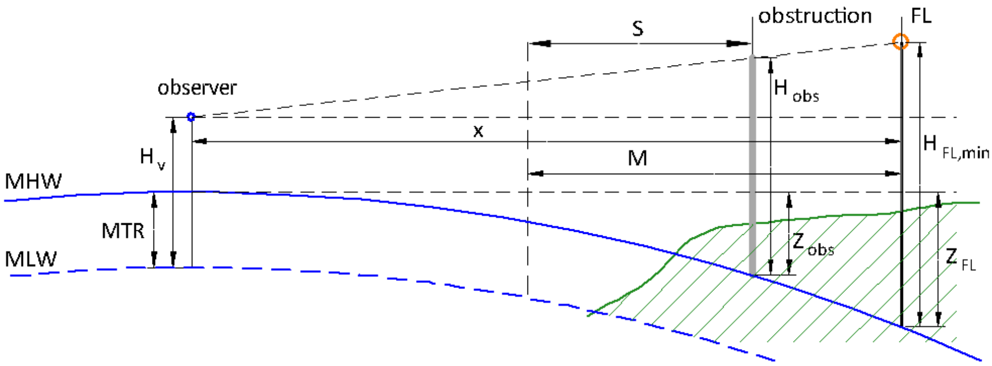

Figure 13 Minimum height of front light considering an obstruction

Considering presence of an obstruction as shown on Figure 13, the minimum height of the front light $H_{FL,min}$ can be derived.

$$\frac{H_{obs}-Z_{obs}-(H_v-MTR)}{x-M+S} = \frac{H_{FL,min}-Z_{FL}-(H_v-MTR)}{x} \rightarrow$$

$$H_{FL,min} = \frac{x}{x-M+S} \cdot (H_{obs} - Z_{obs} - H_v + MTR) + Z_{FL} + H_v - MTR$$

Height of the part of obstruction and front leading mark hidden below the horizon is:

$$Z_{obs} = \alpha \cdot (x - M + S)^2$$

$$Z_{FL} = \alpha \cdot x^2$$

where $\alpha = 6.75 \cdot 10^{-8} m^{-1}$.

The minimum height for the front light is then:

$$H_{FL,min} = \frac{x}{x-M+S} \cdot (H_{obs} - H_v + MTR) + H_v - MTR - \alpha \cdot x \cdot (x - M + S) + \alpha \cdot x^2 \rightarrow$$

$$H_{FL,min} = H_v - MTR + \frac{x}{x-M+S} \cdot (H_{obs} - H_v + MTR) + \alpha \cdot x \cdot (M - S)$$

The minimum height for the front light is calculated for $x = M + C$ (far end) and $x = M$ (near end) for the lowest height of eye $H_{v,min}$:

- Far end:

$$H_{FL,min5} = H_{v,min} - MTR + \frac{M+C}{C+S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (M + C) \cdot (M - S) \qquad (35)$$

- Near end:

$$H_{FL,min6} = H_{v,min} - MTR + \frac{M}{S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot M \cdot (M - S) \qquad (36)$$

When the front leading mark has a daymark with length $L_{FDM,sel}$, it is assumed that the lower end of the daymark must not be obscured and that the light will be at the upper end of the daymark. In this case, to obtain the minimum height of the front light, the selected length of the daymark $L_{FDM,sel}$ is added to the minimum front light height.

- Far end:

$$H_{FL,min7} = L_{FDM,sel} + H_{v,min} - MTR + \frac{M+C}{C+S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (M + C) \cdot (M - S) \quad (37)$$

- Near end:

$$H_{FL,min8} = L_{FDM,sel} + H_{v,min} - MTR + \frac{M}{S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot M \cdot (M - S) \quad (38)$$

4.9.1.4. Selected Front Light Height

The recommended minimum height $H_{FL,rec}$ is the maximum value of the minimum heights calculated above. With this value, all requirements stated before in this chapter are fulfilled.

$H_{FL,rec}$ may be the height selected for using in calculations ($H_{FL,sel}$), but there may be considerations that justify selecting a different value for $H_{FL,sel}$.

4.9.2. REAR LEADING MARK

The calculation of the height of the rear light requires that height of the front light ($H_{FL,sel}$) has already been selected.

4.9.2.1. Blur

The rear light must be sufficiently high to ensure that the vertical angular separation between the lights over the entire useful segment exceeds the minimum required angle γ_{min} (see Section 4.4), thereby avoiding blurring. This condition can be expressed as:

$$\gamma_{min} = \frac{H_{RL} - H_v + MTR}{x + R} - \frac{H_{FL,sel} - H_v + MTR}{x} - \alpha \cdot R \rightarrow$$

$$H_{RL,min} = (x + R) \cdot \left(\gamma_{min} + \frac{H_{FL,sel} - H_v + MTR}{x} + \alpha \cdot R\right) + H_v - MTR$$

The minimum height of the rear light for avoiding blur is calculated for $x = M + C$ (far end) and $x = M$ (near end) for the lowest height of eye $H_{v,min}$:

- Far end:

$$H_{RL,min1} = (C + M + R) \cdot \left(\gamma_{min} + \frac{H_{FL,sel} - H_{v,min} + MTR}{M + C} + \alpha \cdot R\right) + H_{v,min} - MTR \quad (39)$$

- Near end:

$$H_{RL,min2} = (M + R) \cdot \left(\gamma_{min} + \frac{H_{FL,sel} - H_{v,min} + MTR}{M} + \alpha \cdot R\right) + H_{v,min} - MTR \quad (40)$$

4.9.2.2. Geographical Range

From geographical range calculation of the front light (including the height of the part of the leading mark obscured by the horizon due to the curvature of the Earth) and the calculation for avoiding blur (ensuring the rear light is seen clearly above the front light), it is guaranteed that the rear light will always appear above the horizon as well. So, there is no need to check the rear light for geographical range. However, for List of Lights and charts the geographical range of the rear light may be calculated separately.

4.9.2.3. Avoiding Obscuring of Rear Daymark by Front Light

It is assumed that the lights are located at the upper edge of daymarks. Therefore, to ensure visibility of the rear daymark above the front one, the entire length of daymark of the rear leading mark must appear above the front light at the far end of the channel ($x = M + C$).

- Far end:

$$H_{RL,min3} = L_{RDM,sel} + H_v - MTR + (C + M + R) \cdot \frac{(H_{FL,sel} + MTR - H_v)}{M + C} + \alpha \cdot (C + M + R) \cdot R \quad (41)$$

At the near end of the channel ($x = M$) it is not necessary that the entire rear daymark is visible, because it appears much larger to the observer. An accepted compromise is that one half of the rear daymark is visible above the front light.

- Near end:

$$H_{RL,min4} = \frac{1}{2} \cdot L_{RDM,sel} + H_v - MTR + (M + R) \cdot \frac{(H_{FL,sel} + MTR - H_v)}{M} + \alpha \cdot (M + R) \cdot R \quad (42)$$

4.9.2.4. Avoiding Obscuring of Rear Light by Obstruction

The equations for the front light (Section 4.9.1.3) are valid for the rear light with the following transitions:

- $H_{FL,min} \rightarrow H_{RL,min}$
- $M \rightarrow M + R$

This leads to:

$$H_{RL,min} = H_v - MTR + \frac{x}{x - M - R + S} \cdot (H_{obs} - H_v + MTR) + \alpha \cdot x \cdot (M + R - S)$$

- Far end:

$$H_{RL,min5} = H_{v,min} - MTR + \frac{M+R+C}{C+S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (C + M + R) \cdot (M + R - S) \quad (43)$$

- Near end:

$$H_{RL,min6} = H_{v,min} - MTR + \frac{M+R}{S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (M + R) \cdot (M + R - S) \quad (44)$$

4.9.2.5. Avoiding Obscuring of Rear Daymark by Obstruction

At the far end of the channel ($x = M + C$) the entire length of daymark of the rear leading mark must appear above the obstruction. In this case the full length of the daymark is added to the minimum height of rear light.

- Far end:

$$H_{RL,min7} = L_{RDM,sel} + H_{v,min} - MTR + \frac{M+R+C}{C+S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (C + M + R) \cdot (M + R - S) \quad (45)$$

At the near end of the channel ($x = M$) it is not necessary that the entire daymark is visible, because it appears much larger to the observer. An accepted compromise is that one half of the rear light daymark is not occluded by the obstruction.

- Near end:

$$H_{RL,min8} = \frac{1}{2} \cdot L_{RDM,sel} + H_{v,min} - MTR + \frac{M+R}{S} \cdot \left(H_{obs} - H_{v,min} + MTR\right) + \alpha \cdot (M + R) \cdot (M + R - S) \quad (46)$$

4.9.2.6. Selected Rear Light Height

The recommended minimum height $H_{RL,rec}$ is the maximum value of the heights calculated before. With this value, all requirements stated before in this chapter are fulfilled.

$H_{RL,rec}$ may be selected for using in calculations ($H_{RL,sel}$), but there may be considerations that justify selecting a different value for $H_{RL,sel}$.

4.10. DAYMARKS

4.10.1. Shape of Daymarks

Shape of daymarks of leading marks is not restricted by MBS and there are different shapes used worldwide. However, rectangular is considered the optimal shape for daymarks as this remains recognizable at longest distance.

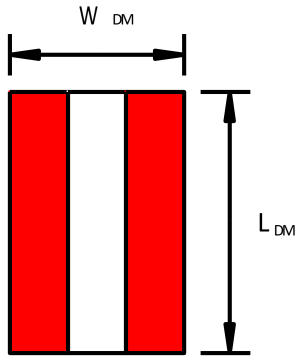

Figure 14 A typical rectangular daymark of leading line

Trapezoidal and triangular daymarks can be used for leading lines with shorter ranges. At longer ranges daymarks of these shapes are less recognizable than rectangular daymarks of the same size. However, at the background of e.g. city buildings, trapezoidal or triangular daymark may be more conspicuous than rectangular daymarks. Square daymarks are not recommended, as their shape becomes unrecognizable at the shortest distance.

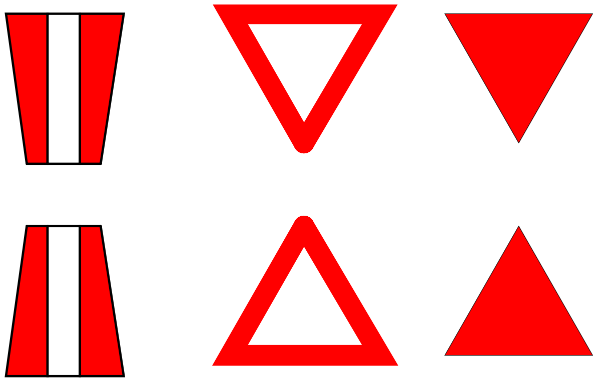

Figure 15 Examples of non-rectangular daymarks with the front and the rear daymark mirrored

As a rule, front and rear daymarks have the same shape. In exceptional cases daymarks with different shapes can be used.

4.10.2. Colour of Daymarks

Most typical colour scheme of daymarks of leading line is three vertical stripes, the middle one being in contrasting colour with the outer ones. Width of the central stripe is usually 1/4 to 1/3 of the width of the daymark.

Colour of daymarks is important to make them conspicuous against their background. As a rule, colour contrast plays a role at distances up to 2-4 km from the structure. At longer distances, due to haze in atmosphere, the colours of a structure are less discernible to the observer and luminous contrast becomes the main factor in conspicuity. So, for light background daymarks should be in a dark colour and for dark background the daymark should be in a light colour. Table 2 gives recommended colours for daymarks observed against some typical backgrounds. In case of three stripes, the colours recommended in the table should be the outer ones and the central one should be in a contrasting colour with them.

Table 2 Recommended colours for daymarks depending on colour of background

Background of a daymark	Recommended colour for the daymark
Green vegetation	White, yellow
Sky	Red, black
Sea	White, yellow
Yellow sand	Black, white
Dark rock	White, yellow
Snow	Red, black

4.10.3. DIMENSIONS OF DAYMARKS

According to G1094 Daymarks for AtoN, a daymark must form an angle of least 1’ for it to be visible. To distinguish more complicated shapes the daymarks must form an angle of at least 3’. For better conspicuity these values may be increased.

For rectangular daymarks shape recognition is not critical. At longer distance it is acceptable if the observer sees the daymark as a small single colour vertical bar, i.e. at a horizontal angle of 1’. The central stripe blends with the outer ones because the angular width of the stripes is already smaller than the eye resolution. When approaching along the leading line, the stripes become distinguishable and allow for more accurate aligning of the leading marks.

In some countries standardized ratios of width and length of rectangular daymarks, e.g. 1:1.5, 1:2 or even up to 1:5, are used. However, different ratios can be used. With width determined by the minimum subtense angle, at least 1’, the ratio determines the height of daymarks.

In case of triangular, trapezoidal or other shapes, all dimensions of the daymark must be at least 3’ for the shape to be recognizable. If better conspicuity is needed increasing this to e.g. 6’ may be considered.

The dimensions of a daymark depend on its required visual range – the longer the distance to far end, the bigger the daymark must be.

- Both length $L_{DM,rec}$ and width $W_{DM,rec}$ of the front daymark are calculated with the formula:

$$L_{DM,rec} \text{ or } W_{DM,rec} = 0.291 \cdot 10^{-3} \cdot a \cdot X_{FL,far} \quad (47)$$

- Both length $L_{DM,rec}$ and width $W_{DM,rec}$ of the rear daymark are calculated with the formula:

$$L_{DM,rec} \text{ or } W_{DM,rec} = 0.291 \cdot 10^{-3} \cdot a \cdot X_{RL,far} \quad (48)$$

Where：

$0.291 \cdot 10^{-3}$ value of 1’ in radians;

a required subtense angle of a dimension of the daymark in angular minutes (‘);

$X_{FL,far} = \mathrm{M} + \mathrm{C}$ distance from front light to far end of the useful segment;

$X_{RL,far} = \mathrm{M} + \mathrm{C} + \mathrm{R}$ distance from rear light to far end of the useful segment.

The graph on the **Erreur ! Source du renvoi introuvable.** shows dimensions of daymarks calculated for different ranges and different subtense angles.

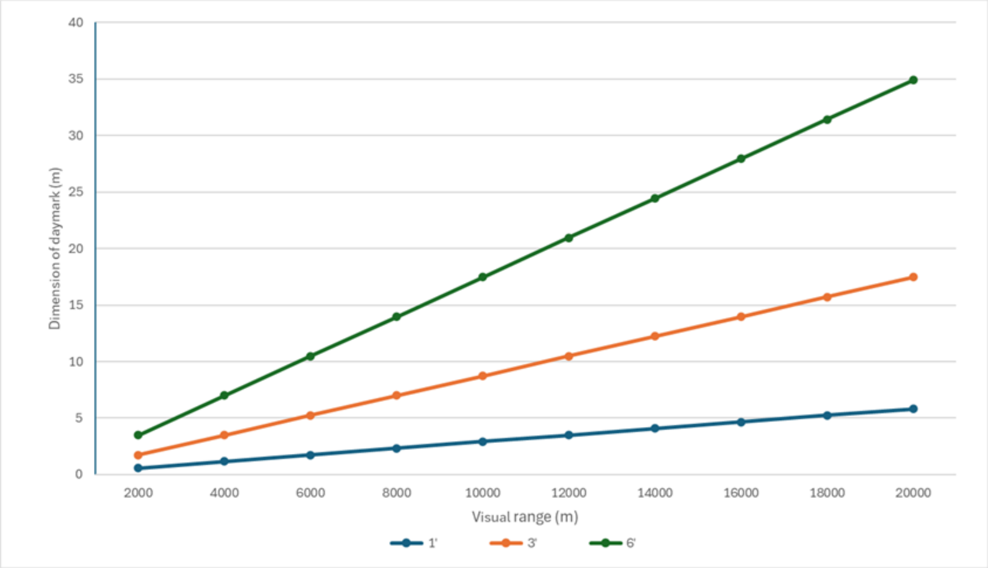

Figure 16 Dependence of dimensions of daymark on range and subtense angle

Some practical sizing considerations:

- 3’ is preferred length for rectangular or for any dimension for other shapes for most leading light designs.
- 6’ may be preferred length in certain conditions, like in areas of reduced visibility or at major fairways where increased conspicuity is needed.
- Other values can be used depending on required conspicuity or other considerations.
- 1’ is minimum width for rectangular daymarks. Less than this may not be usable without the use of binoculars.
- While providing a better signal to the mariner, larger daymarks require taller and stronger towers which will increase construction costs.

4.10.4. RETROREFLECTIVE MATERIAL ON DAYMARKS

Some Members use a sheet of retroreflective material as a substitute for light at night at leading marks on small craft routes and other less important fairways. They can also be useful as back up for damaged lights on other fairways. Such daymarks are intended to be illuminated with a vessel’s searchlight.

Intensity of retroreflected light of a searchlight is considerably lower than light of a leading light. Therefore, to obtain the best possible reflection, white retroreflective material should be used on leading marks. Calculation of the required area of retroreflective material should be done according to the Guideline G1145 Application of Retroreflecting Material on AtoN [9].

Retroreflective material is positioned on the daymarks so that they cover up to ¾ of the middle stripe that makes up to ¼ of the total area of the daymark. Due to the colour of white retroreflecting material not being perfectly white or being different from the rest of the middle stripe, too large reflectors can degrade the daytime conspicuity of daymark.

To provide maximum possible vertical angle between the reflectors for avoiding blurring, the reflector of the front mark is placed on the lower edge of the daymark and reflector of the rear mark on the upper edge of the daymark.

4.10.5. ENHANCING CONSPICUITY OF DAYMARKS

Mounting daymarks 10-20 degrees backwards from the direction of the leading line as seen on **Erreur ! Source du renvoi introuvable.** may create more favourable conditions of illumination for them.

Figure 17 A daymark tilt backwards for better illumination (Sviby rear leading mark by Tuderna, licence CC BY 2.5.)

Conspicuity of daymarks observed against the sun diminishes as the colours appear washed out. Conspicuity of such daymarks may be enhanced by using use semi-transparent material on daymarks that enables the sun to illuminate them from back, as seen on **Erreur ! Source du renvoi introuvable.**.

Figure 18 Daymarks made of semi-transparent material illuminated by the sun from the back

5. ADDITIONAL CONSIDERATIONS

5.1. ACQUISITION REGION

The size of the acquisition region and visibility of the leading marks in there must be considered when planning layout of a leading line. Required minimum width of the acquisition region depends on the speed of the vessels approaching the leading line, time for detecting the leading marks and making the decision and the turning radius of the vessels. In some countries it is approximated that the leading marks need to be visible at least 3 and better if 5 ship lengths along the approaching route before ships must start turning to the leading line.

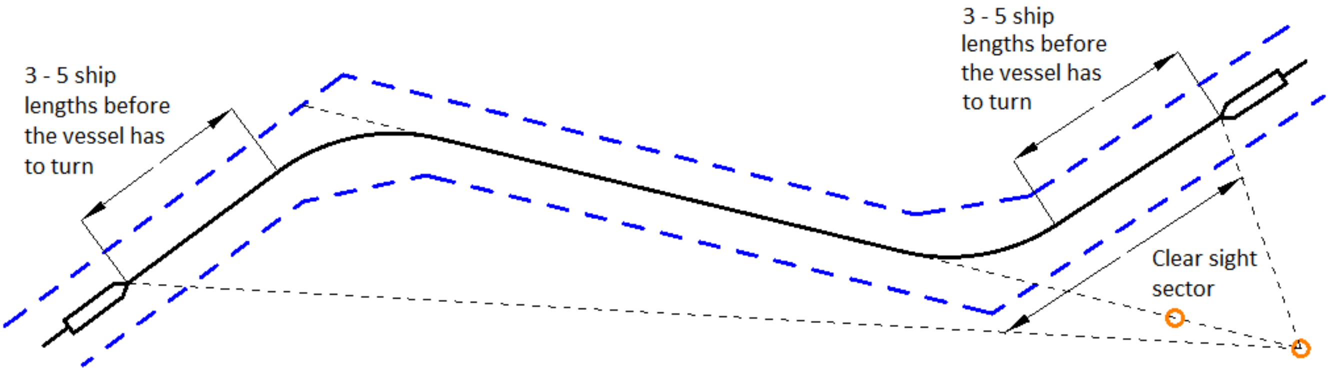

Figure 19 Minimum width of the acquisition region

5.2. LIGHTS

5.2.1. WIDE VERSUS NARROW BEAM LIGHTS

The lanterns of a leading line may have wide or narrow beam lights. Wide beam lights,large horizontal angular beam width, or omnidirectional lights are preferred when the required ranges are small and when the light should be visible far off the channel centreline. The use of omnidirectional lanterns also eliminates the need for passing lights,the lights showing the position of an AtoN for ships passing it, on towers located in navigable waters.

However, an omnidirectional light needs much more energy and may cause glare, when vessels are passing very close to it. In this case, it is better to choose narrow beam lights.

5.2.2. BEAM WIDTH

There may be confusion regarding the effect of a beam width of lanterns on the sensitivity of a leading line. The beam width of the optic has nothing to do with sensitivity of a leading line. The beam width is of some concern when a narrow beam lantern is used, as care must be taken to ensure that the minimum required illumination is provided over the full width of the far end of the channel as well as the acquisition region, see Section 3.4.

The required minimum angle of the beam width ϕ_{far}, equal to the angle subtended by the channel width at the far end of the useful segment (Figure 20), is given by:

$$\phi_{far} \approx \frac{W}{X_{far}} \qquad (48)$$

Where:

ϕ_{far}	in radians;
X_{far}	distance from the light to the far end of the channel in metres;
W	the width of the channel in metres.

This is the beam width in which illuminance at the eye of the observer of at least $E_{min} = 10^{-6}\ lx$ must be ensured.

<u>Remark:</u>

Written in degrees, the equation is: $\phi_{far}\ (°) \approx \left(\frac{57{,}3\,°}{1\ \mathrm{rad}}\right) \cdot \frac{\mathrm{W}}{X_{far}}$

The equation is used for front light (distance $X_{\mathrm{FL,far}} = \mathrm{M} + \mathrm{C}$) and rear light (distance $X_{\mathrm{RL,far}} = \mathrm{M} + \mathrm{C} + \mathrm{R}$), which result in two different values $\phi_{\mathrm{FL,far}}$ and $\phi_{\mathrm{RL,far}}$.

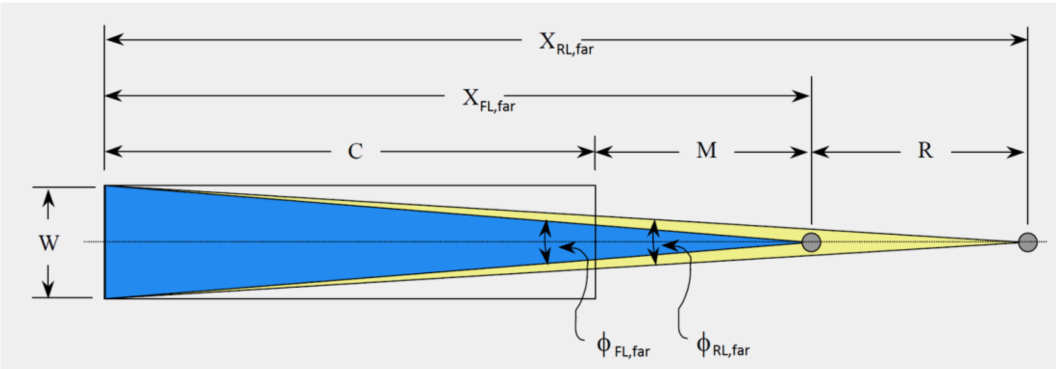

Figure 20 Beam Width of Leading Lights Required for the Channel

The required minimum angle of the beam width ϕ_A, equal to the angle subtended by the acquisition region width (Figure 21), is given by:

$$\phi_A \approx \frac{W_A}{X_A} \qquad (49)$$

Where:

ϕ_A	in radians;
X_A	distance from the light to the acquisition region in metres;
W_A	the width of the acquisition region in metres.

The equation is used for front light (distance $X_{\mathrm{FL,A}}$) and rear light (distance $X_{\mathrm{RL,A}}$), which result in two different values $\phi_{\mathrm{FL,A}}$ and $\phi_{\mathrm{RL,A}}$.

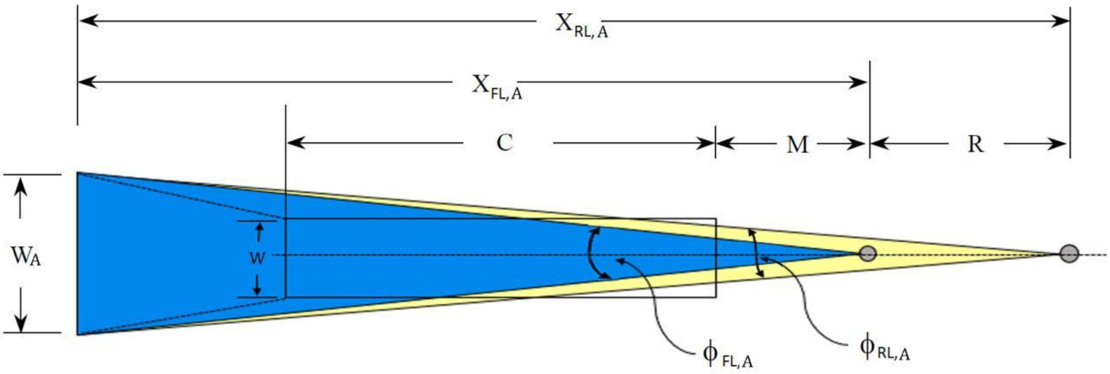

Figure 21 Beam Width of Leading Lights Required for the Acquisition Region

This is the beam width in which illuminance at the eye of the observer of at least $E_{min} = 2 \cdot 10^{-7}$ lx must be ensured.

However, for complex channel geometries such as shown in Figure 19, where on the right side of the leading line longer range and narrower beam width is needed than on the left side, a non-uniform horizontal intensity distribution, e.g., dividing the beam into multiple sectors) may be required to simultaneously satisfy the illuminance requirements for both regions.

5.2.3. PASSING LIGHTS

If the design does not use omnidirectional optics at night, and the structure is situated in middle of navigable waters, it may be necessary to add omnidirectional passing lights to the structure, showing its position to passing vessels. These additional lights should be mounted where they will not be blocked by the structure.

- Passing lights should be mounted at a low enough height to ensure that the lights will be visible to vessels with a low height of eye. As an example, if a leading line has a front tower height of 8 m and a rear tower height of 25 m, the additional light for the front tower can be mounted directly on top of the front leading light. The passing light should display the same characteristic as the leading light and should be synchronized with the leading light.
- On towers greater than about 12 m, the passing lights may be installed at a lower level than the leading light. In this case installation of passing light may require multiple lanterns to avoid obstruction of the light by the structure from some directions. In this case, due to potential to mislead a mariner, giving the passing lights a different colour and character than leading lights should be considered.

5.2.4. LANTERN PLACEMENT

Accurate positioning of the lanterns at the centre of leading marks is important for ensuring correct direction of the leading line. When using both day and night leading lights, the lower optic on the front tower and the upper optic on the rear tower should be the nighttime lights to keep them further apart as their possibility of blurring is higher. The only exception is when the front tower uses an omnidirectional nighttime light, which should be mounted on top of the leading mark above the daytime lights.

Multiple lanterns forming a daytime light should be installed as close to each other as possible to ensure the lights are viewed as a point source. All heights are measured to the centre of the (cluster of) lanterns.

5.2.5. COLOUR AND FLASHES

- It is advantageous to use the same colour and synchronized flashes for front and rear leading light of a leading line. In the presence of rival lights this will highlight that these two lights belong together.

- When a channel is marked by a series of leading lines in succession, each leading line should have a different flash character than the nearby ones.
- If the lights are not synchronized the length of flashes and periods of the front lights could be shorter than these of the rear light.
- Duration of the flashes should not be less than 0.5 s.
- Length of the flashes of the rear light should be selected based on maximum overlapping of the duration of the flashes of the leading lights. The narrower the channel the more the flashes must be seen simultaneously.
- Fixed (F) characteristics should be used sparingly, if at all. Lights displaying a fixed characteristic, especially white light signals, can be difficult to identify against even minimal background lighting. Furthermore, flashing lights displaying a character with a three second flash duration have an effective intensity equal to approximately 96% of the intensity of a fixed light while yielding longer lantern service intervals, having lower power consumption, and providing greater conspicuity than the fixed light signal.

5.3. DAYMARKS VERSUS DAYTIME LIGHTS

Traditionally leading lights, particularly those powered by batteries, were switched off during daytime, when the signal was provided by daymarks. Efficiency improvements in optics combined with solar power have allowed expanded use of daytime leading lights, even when mains power is not readily available. The following are some points to consider when deciding on using daytime lights:

- Daymarks are simple. Having no moving parts, they require little maintenance and so are more reliable than lights. Smaller daymarks are also easy to maintain, with no special training required for servicing personnel.
- Daytime leading lights provide a superior signal. In poor conditions they can be seen further than daymarks. Furthermore, using lights instead of large daymarks may result in less costly tower structures and foundations. Daytime lights, however, require more complex lighting and power systems, which will increase hardware costs and the technical demands on the servicing personnel. However, the higher initial equipment costs will likely be more than offset by reduced structural costs.

5.4. PLACEMENT OF LEADING MARKS

5.4.1. LOCATIONS FOR LEADING MARKS

The availability of suitable sites for leading marks may be an important factor in designing layout of sections of natural, narrow fairways or layout of artificial channels. Use of existing buildings or structures may be possible for installation leading marks.

5.4.2. ACCURACY OF POSITIONING OF LEADING MARKS

Locations of leading marks determine the position of the leading line. Positioning of leading marks along the leading line should be within ±3 meters of the determined position. Lateral error in placement of leading marks to either side of the leading line should not exceed approximately ±0.3 meters, to avoid significant misalignment of the leading line in relation to the channel to be marked. See **Erreur ! Source du renvoi introuvable.**.

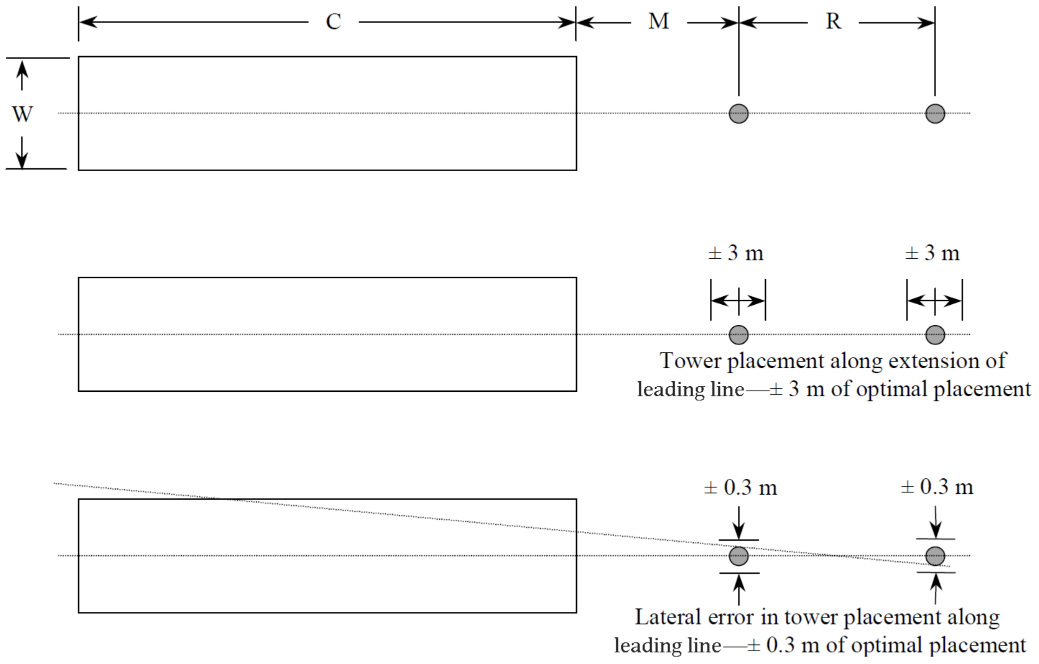

Figure 22 Placement of leading marks

6. ABBREVIATIONS AND TECHNICAL QUANTITIES

6.1. LATIN

Abbreviations in indices	Explanation
DM	daymark
d	detection
dsg	design
far	far, referencing the far end of the channel
FL	front light
FDM	front daymark
$initial$	initial iteration value
max	maximum
mid	middle, referencing the middle of the channel
min	minimum
$min1, min2 \ldots$	minimum according to the requirement referenced
$near$	near, referencing the near end of the channel
obs	obstruction
rec	recommended

RL	rear light
RDM	rear daymark
sel	selected
$shaw$	safe height above water
v	vessel, referencing the observer at the vessel
A	acquisition region

Abbreviation	Explanation	Chapter
a	required subtense angle of a dimension of the daymark in angular minutes (')	4.10.3
C	Length of useful segment	3.1
CTF	Cross-track factor	4.7
d_U	Unit distance ($d_U = 1852m = 1M$)	3
E	Illuminance at the eye of the observer	4.2
E_{FL}	Illuminance at the eye of the observer produced by the front light	3.4
E_{max}	Allowed maximum illuminance at the eye of the observer	3.4
E_{min}	Required minimum illuminance at the eye of the observer	3.4
E_{RL}	Illuminance at the eye of the observer produced by the rear light	3.4
E_U	Unit illuminance ($E_U = 1\ lx$)	3
E^+	Largest of the illuminance values from front light and rear light	4.4
I_{FL}	Luminous intensity of front light	3.4
I_{RL}	Luminous intensity of rear light	3.4
H_{FL}	Height of front light above MHW or MSL	3.2
$H_{FL,min1}$	Minimum height of front light (safe height above water)	4.9.1.1
$H_{FL,min2}$	Minimum height of front light with a daymark (safe height above water)	4.9.1.1
$H_{FL,min3}$	Minimum height of front light (geographical range)	4.9.1.2
$H_{FL,min4}$	Minimum height of front light with a daymark (geographical range)	4.9.1.2
$H_{FL,min5}$	Minimum height of front light (obstruction, far end)	4.9.1.3
$H_{FL,min6}$	Minimum height of front light (obstruction, near end)	4.9.1.3
$H_{FL,min7}$	Minimum height of front light with a daymark (obstruction, far end)	4.9.1.3
$H_{FL,min8}$	Minimum height of front light with a daymark (obstruction, near end)	4.9.1.3

Abbreviation	Explanation	Chapter
$H_{FL,rec}$	Recommended height of the front light	4.9.1.4
$H_{FL,sel}$	Selected height of the front light	4.9.1.4
$H_{FDM,lower\_end}$	Height of the lower end of the daymark	4.9.1.1
H_{obs}	Height of an obstruction above MHW or MSL	4.9.1.3
H_v	Height of observer (on vessel) above MHW or MLW, depending on the parameter calculated	3.2
$H_{v,min}$	Lowest height of observer (lowest height at MLW)	4.9.1.3
H_{RL}	Height of rear light above MHW or MSL	3.2
$H_{RL,min1}$	Minimum height of rear light (blur, far end)	4.9.2.1
$H_{RL,min2}$	Minimum height of rear light (blur, near end)	4.9.2.1
$H_{RL,min3}$	Minimum height of rear light with a daymark (front light not obscuring, far end)	4.9.2.3
$H_{RL,min4}$	Minimum height of rear light with a daymark (front light not obscuring, near end)	4.9.2.3
$H_{RL,min5}$	Minimum height of rear light (obstruction, far end)	4.9.2.4
$H_{RL,min6}$	Minimum height of rear light (obstruction, near end)	4.9.2.4
$H_{RL,min7}$	Minimum height of rear light with a daymark (obstruction, far end)	4.9.2.5
$H_{RL,min8}$	Minimum height of rear light with a daymark (obstruction, near end)	4.9.2.5
$H_{RL,rec}$	Recommended height of the rear light	4.9.2.6
$H_{RL,sel}$	Selected height of the rear light	4.9.2.6
H_{shaw}	Safe height above water	4.9.1.1
h_U	Unit height $h_U = 1\ m$	3
I	luminous intensity	4.2
$I_{FL,max}$	Maximum luminous intensity, front light	4.2.2
$I_{FL,min}$	Minimum luminous intensity, front light	4.2.1
$I_{FL,\mathrm{dsg}}$	Design luminous intensity, front light	4.2.3
$I_{RL,max}$	Maximum luminous intensity, rear light	4.2.2
$I_{RL,min}$	Minimum luminous intensity, rear light	4.2.1
$I_{RL,dsg}$	Design luminous intensity, rear light	4.2.4
L	Distance to front structure from far end of useful segment	3.1
L_{DM}	Vertical length of a daymark	**Erreur ! Source du renvoi introuvable.**

Abbreviation	Explanation	Chapter
$L_{DM,rec}$	Recommended vertical length of a daymark	4.10.3
L_{FDM}	Vertical length of the front daymark	3.2
$L_{FDM,sel}$	Selected vertical length of the front daymark	4.9.1.1
L_{RDM}	Vertical length of the rear light daymark	3.2
$L_{RDM,sel}$	Selected vertical length of the rear daymark	4.9.2.5
M	Distance to front structure from near end of useful segment	3.1
$M_{initial}$	Initial value of M for iteration process	4.1
MHW	Mean high water	3.2
MLW	Mean low water	3.2
MSL	Mean sea level	3.2
MTR	Mean tidal range	3.2
R	Distance between leading marks	3.1
$R_{initial}$	Initial value of R for iteration process	4.1
R_g	geographical range	4.8
r	ratio of intensities	4.2.4
r_{mid}	ratio of intensities, value in the middle of the useful segment	4.2.4
r_{far}	ratio of intensities, value in the far end of the useful segment	4.2.4
S	distance between an obstruction and the near end of the useful segment	4.9.1.3
V	visibility	4.2
V_{dsg}	Design Meteorological visibility	4.2.4
V_{max}	Maximum Meteorological visibility	4.2.2
V_{min}	Minimum Meteorological visibility	4.2.1
W	Channel width	3.1
W_{DM}	Width of a daymark	4.10.1
$W_{DM,rec}$	Recommend width of a daymark	4.10.3
W_A	Width of the acquisition region	**Erreur ! Source du renvoi introuvable.**
x	Distance of observer (vessel) from front leading mark	3.1
$X_{FL,mid}$	Distance from front light to middle of the useful segment	4.2.4
$X_{FL,far}$	Distance from front light to far end of the useful segment	4.2.4
$X_{RL,mid}$	Distance from rear light to middle of the useful segment	4.2.4
$X_{RL,far}$	Distance from rear light to far end of the useful segment	4.2.4

Abbreviation	Explanation	Chapter
$X_{FL,A}$	Distance from front light to the outer limit of acquisition region	4.2.4
$X_{RL,A}$	Distance from rear light to the outer limit of acquisition region	4.2.4
y	Observer's distance from leading line, off-axis distance	3.1
y_d	Off-axis distance at which the observer can detect with certainty that the vessel is not on the leading line	4.7
Z	Part of height of an object hidden below the horizon	4.3
Z_{FL}	Part of height of front leading mark hidden below the horizon	4.3
Z_{RL}	Part of height of rear leading mark hidden below the horizon	4.3

6.2. GREEK

Abbreviation	Explanation	Chapter
α	Factor for calculation of the part of height of an object hidden below the horizon ($\alpha = 6.75 * 10^{-8} m^{-1}$) that takes into account radius of the Earth and refraction in atmosphere	4.3
ϕ_{far}	Required beam width angle of a leading light, subtended by the channel width at the far end	**Erreur ! Source du renvoi introuvable.**
$\phi_{FL,far}$	Required beam width angle of the front leading light, subtended by the channel width at the far end	**Erreur ! Source du renvoi introuvable.**
$\phi_{RL,far}$	Required beam width angle of the rear leading light, subtended by the channel width at the far end	**Erreur ! Source du renvoi introuvable.**
ϕ_A	Required beam width angle of a leading light, subtended by width of acquisition region	**Erreur ! Source du renvoi introuvable.**
$\phi_{FL,A}$	Required beam width angle of the front leading light, subtended by width of acquisition region	**Erreur ! Source du renvoi introuvable.**
$\phi_{RL,A}$	Required beam width angle of the rear leading light, subtended by width of acquisition region	**Erreur ! Source du renvoi introuvable.**
θ	Horizontal difference angle (horizontal angle between front and rear light)	4.5
θ_d	Critical bearing difference i.e. the bearing difference at the moment of detection of not being on leading line	4.6
θ_{FL}	Horizontal angle, front light	4.5
θ_{RL}	Horizontal angle, rear light	4.5

Abbreviation	Explanation	Chapter
θ'_1	Alternative value 1 for critical horizontal angle	4.6
θ'_2	Alternative value 2 for critical horizontal angle	4.6
γ	Vertical difference angle	4.3
γ_{FL}	Vertical angle, front light	4.3
γ_{RL}	Vertical angle, rear light	4.3
γ_{min}	Minimum vertical difference angle	4.4

7. REFERENCES

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