EEP18 Input paper Action Item 84 from EEP20

Agenda item 11.2

Task Number 3

Author(s) M. Nicholson

Vertical Divergence of Fixed Light Sources

# Introduction

One of the parameters measured when a lantern is tested is the intensity of light over a range of vertical angles. The beam divergence is then specified as the angle of the beam between points where the intensity has fallen to a fraction of the maximum intensity within the beam.

The vertical divergence is typically specified between the first points where the intensity falls to 50% of the maximum. See reference [1] for more detail. Figure 1 shows the plot from a measurement of intensity against vertical angle. The vertical divergence of this beam would be given as max +1.03°, min -1.35° and total 2.38°.

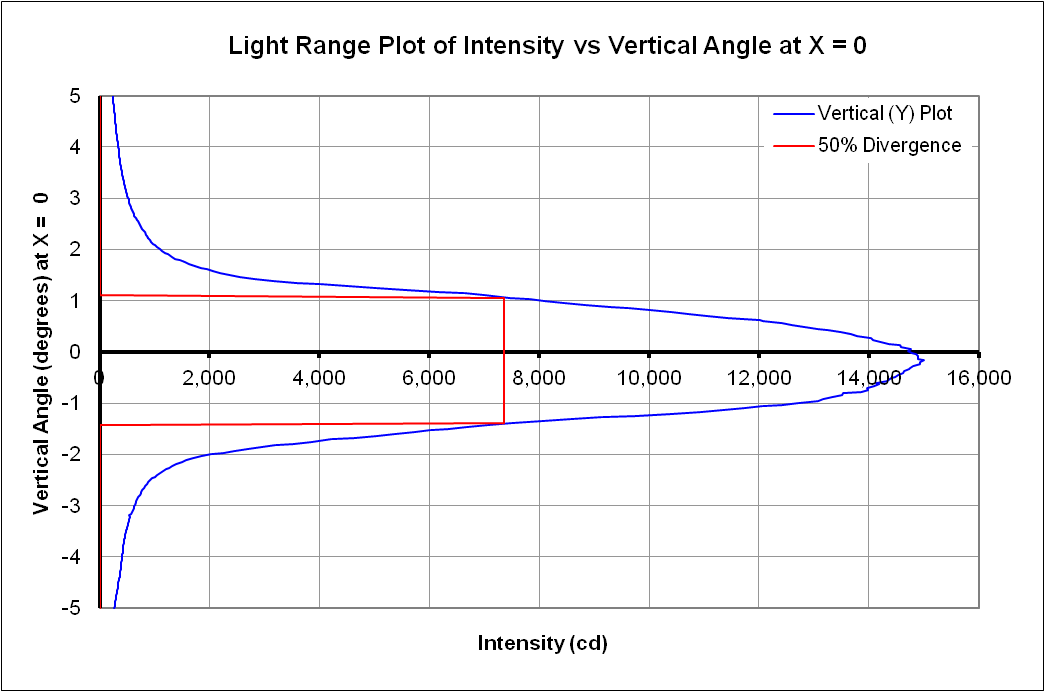


Figure – Plot of intensity against vertical angle with the 50% intensity points marked in red.

When the lantern is used on a buoy or lightvessel, where it’s angle is constantly changing due to the wave action and thus the beam is not always pointing towards the horizon, a wide vertical divergence is clearly an advantage.

If the lantern is used on a lighthouse where it’s position is fixed, the angle the observer views the light source is dependent upon the source height, the observer height and the distance between them. By selecting a source and observer height the viewing angle for given distances can be calculated and plotted.

Ref [2] Table 1 presents the minimum intensity required for given distances. The distances in the previously discussed plot can be replaced by the minimum intensity for each distance. The result of this new plot is the minimum intensity requirements for each viewing angle.

The plot can then be used as a tool to check a lantern has sufficient intensity at each viewing angle.

# Method

Due to refraction the light from a lantern will follow a slightly curved path. The curve will be assumed to have a fixed radius for the entirety of the path. The radius of the curved light path will be taken as 7 times the radius of the Earth. [3].

The radius of the Earth used will be 6371 km, the mean radius as taken from [4].

The validity of the above values is checked in Appendix A by using them to derive a formula presented in an IALA guideline (since the individual values are not presented).

The angle the observer views the lantern at will be calculated as: the angle of the line that is tangential to the curved path of light that intersects both the source and observer.

The angle to the observer will be calculated at various distances and plotted against the minimum intensity requirement for that distance. Appendix B and Appendix C contain the derivation of the formulas used for this.

It is noted that the wave action will affect the observer’s height but this will be negligible compared to the viewing distance for all but close range distances. By allowing a margin of safety in the intensity requirement this can be neglected.

Alternatively two plots could be produced for the maximum and minimum observer height to account for wave action. Furthermore, if already plotting two observer heights then the plots could be for the shortest observer height and the tallest observer height, thus for a given source height all observers are covered.

This concept can be extended further to produce a generalised plot covering a range of scenarios. The situations that will cause wide viewing angles are a short source height with tall observer and a tall source height with short observer. Both of these are somewhat limited by geographical range and as such only relevant for lower intensities. By using a tall source and tall observer a third series of points can be plotted giving relevant values out to larger ranges. The vertical beam plot of a measured lantern should enclose all plots to confirm suitability in all applications.

# Results

Figure 2 shows the minimum intensity requirements at viewing angles for a source height of 30 m and an observer height of 10 m. It is plotted for ranges between 1 M and 18 M.

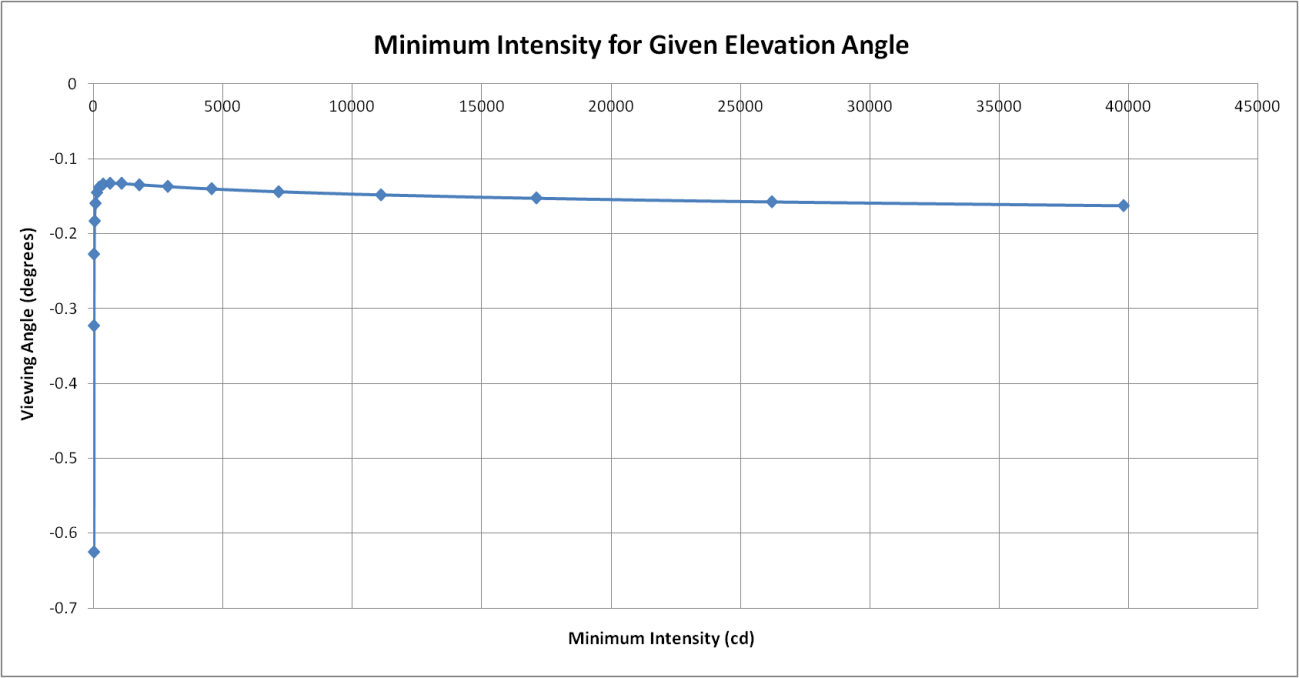


Figure – Minimum Intensities at Viewing Angles. Source height 30 m, observer height 10 m.

The plotted curve for a measured source must completely enclose (up to the required maximum intensity for the particular station) the minimum requirement shown in Figure 2.

For example, Figure 3 shows theoretical measurements of a light source that does not meet the intensity requirements. The measured beam is narrow and any failures will be by very small angles. Also the beam does not cross 0°. Clearly the beam is unusual compared to practical lanterns, but it is presented only as a means to demonstrate use of the graph.

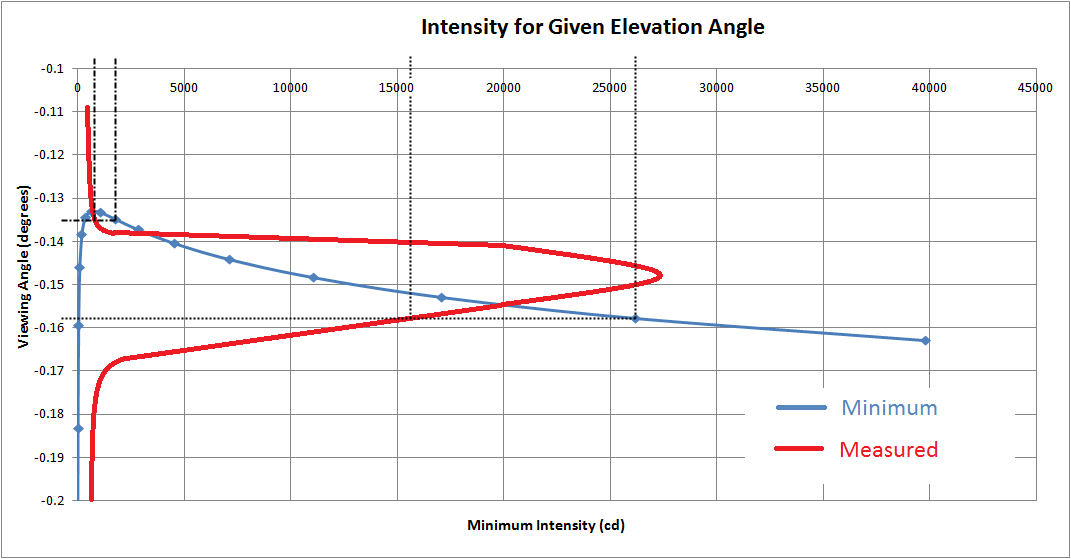


Figure – Example of Divergence Failure

There are 2 places the measured performance falls outside the minimum plotted line. These are both discussed below.

The peak of the beam is approximately 27,000 cd. This corresponds to a range of 17 M, but at this range the observer would be viewing the lantern at approximately -0.158° (as plotted by the minimum requirement). The 27,000 cd intensity occurs at -0.148° while this intensity is detectable at 17 M, in this case it is not in the direction of the observer and as such will not be viewed.

The maximum intensity that meets the minimum requirement is 20,000 cd, corresponding to a distance of 16 M. So while the lantern could potentially be detected at a distance of 17 M the observer will only be at appropriate angles to view the light out to 16 M.

The same scenario may be described another way: When viewing at -0.158° the observer would be at a distance such that the minimum intensity required is 26,200 cd. At -0.158° the lantern has an intensity of 16,000 cd, this is less than required. This concept is annotated by the dotted line.

It is important to note that the limitation of the lantern discussed above does not mean the lantern has failed, as any practical lantern will eventually cross the minimum requirement. Where it crosses determines the maximum useable intensity (any higher intensities measured are at unsuitable angles to be reach the observer at the corresponding distance). This is the maximum useable intensity considering only the viewing angle of the lantern, it does not account for geographical obstruction. Section 5 discusses the maximum geographical range.

As previously indicated the theoretical light source has a narrow beam compared to practical sources. As such the peak of the light source intensity (27,000 cd) is somewhat higher than the peak intensity that still encloses the requirement plot (20,000 cd). It is unlikely a practical lantern would exhibit such a large difference. The features discussed here have been exaggerated to enable them to be more clearly shown.

The second area where the lanterns measured performance falls outside the plotted requirement is between -0.133° and -0.138°. The measured intensities at these angles are lower than required for the observer to detect the light. For example, when viewing the lantern at -0.135° the observer will be at a distance requiring an intensity of 1,760 cd. The lanterns intensity at -0.135° is 1,000 cd. This concept is annotated by the dashed line.

The typical divergence specification given at intensities equal to 50% of the peak does not contain enough information to ensure the intensity at all relevant angles is sufficient. However, if the 50% divergence angle is larger than the plotted angles for all but the lowest intensities then it will likely meet requirements for practical viewing ranges. For example a lantern with a vertical divergence of ±0.25° at 50 % intensity would enclose the majority of the plotted line in Figure 2 (possibly by a large margin depending on what the 50% intensity actually is) and as the divergence at lower intensities typically increases it would likely meet requirements at all practical ranges.

Due to the non-linear relationship between range and intensity, moving closer greatly reduces the intensity required for the observer to reliably detect the light. Thus at close ranges where the magnitude of the viewing angles become larger, the intensity requirement is very low and changes little with angle. This is beneficial since at the larger angles, where lanterns typically emit less light, the intensity requirement is very low. Thus the shape of a lantern’s beam profile naturally suits the shape of the minimum requirement.

As discussed earlier, several scenarios could be plotted to cover the situations requiring wider divergence, and longer distances. One example of this is shown in Figure 4. Each series is plotted from 1 M up to the maximum geographical range for that scenario. To be suitable for all scenarios a lantern’s measured profile should enclose all of the plots.

# 

Figure – Intensity requirements for various height scenarios.

# Analysis of Divergence Profile

The shape of the plot will be analysed as a means of checking, to some degree, that the calculations correctly model the actual behaviour.

There are 2 distinct curves on the plot shown in Figure 2.

Upwards of minimum intensities of approximately 365 cd (7 M), as the observer moves further away from the source the magnitude of the angle between the light source and observer increases. The increasing angle with range is graphically shown in Figure 5. Clearly moving away from the light source requires greater intensity to meet the range so the curve has both increasing intensity and increasing angle.

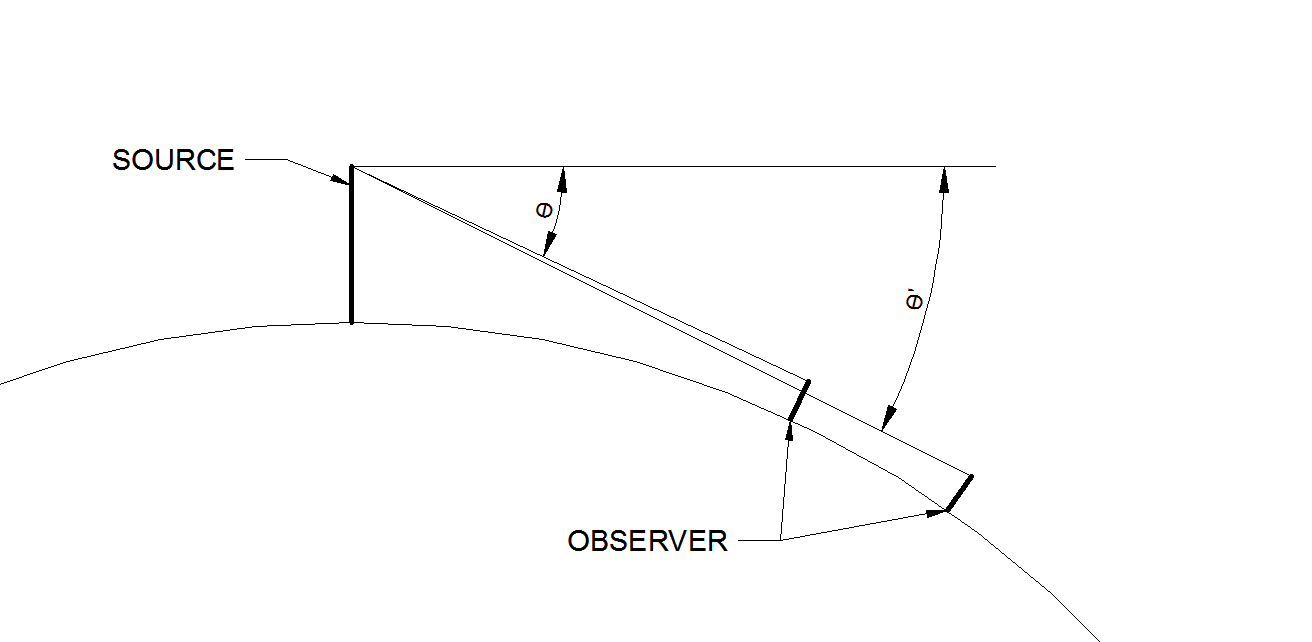


Figure - Increasing viewing angle with range

Below intensities of approximately 365 cd (7 M), as the observer moves away from the source the magnitude of the angle between the light source and observer decreases. The decreasing angle with increasing range is shown in Figure 6.

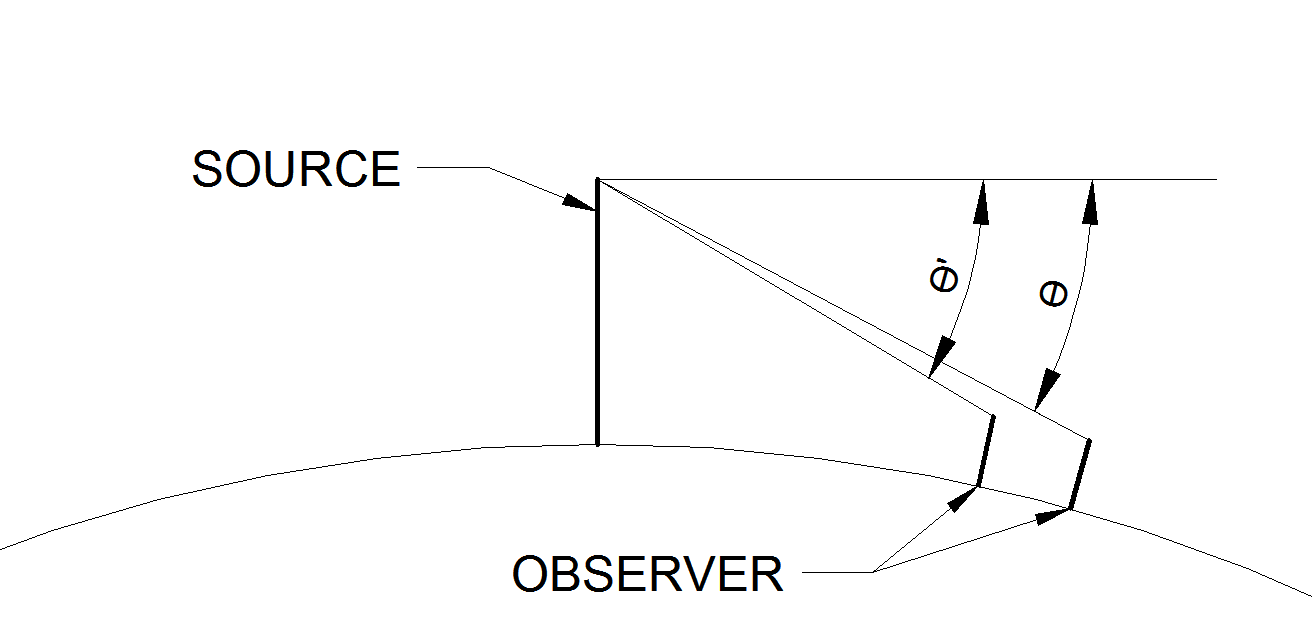


Figure - Decreasing viewing angle with range

The two regions of differing behaviour are caused by the curvature of the earth. When the observer is close to the light source, moving away has little effect on the vertical position of the observer and the angle is affected primarily by the horizontal change in distance and the angle reduces with increasing distance.

When the observer is further away from the light source moving away has a larger effect on the vertical position of the observer resulting in the angle increasing with distance. Figure 7 illustrates the gradient of tangents at varying distances. The tangents further from the source are much steeper and thus vertical position changes rapidly with distance.

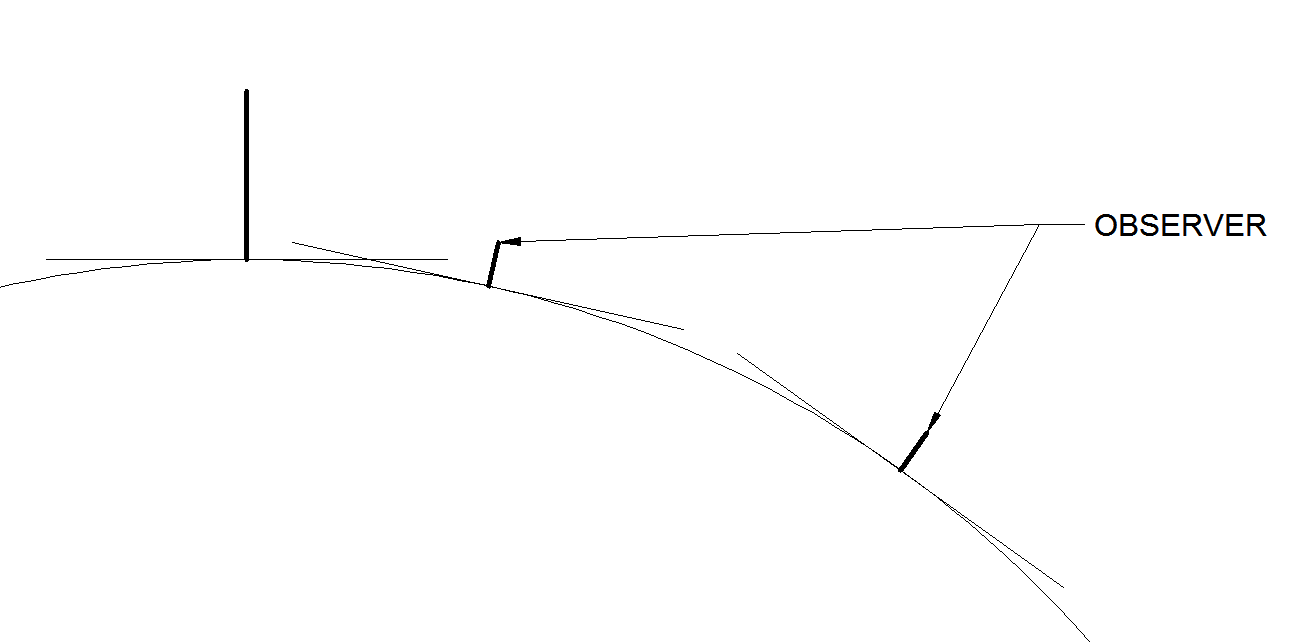


Figure - Tangent of earths curve at varying distance

If the source height as shown in Figure 5 is sufficiently increased the range at which the behaviour changes from one region to the next is increased. Figure 8 illustrates this.

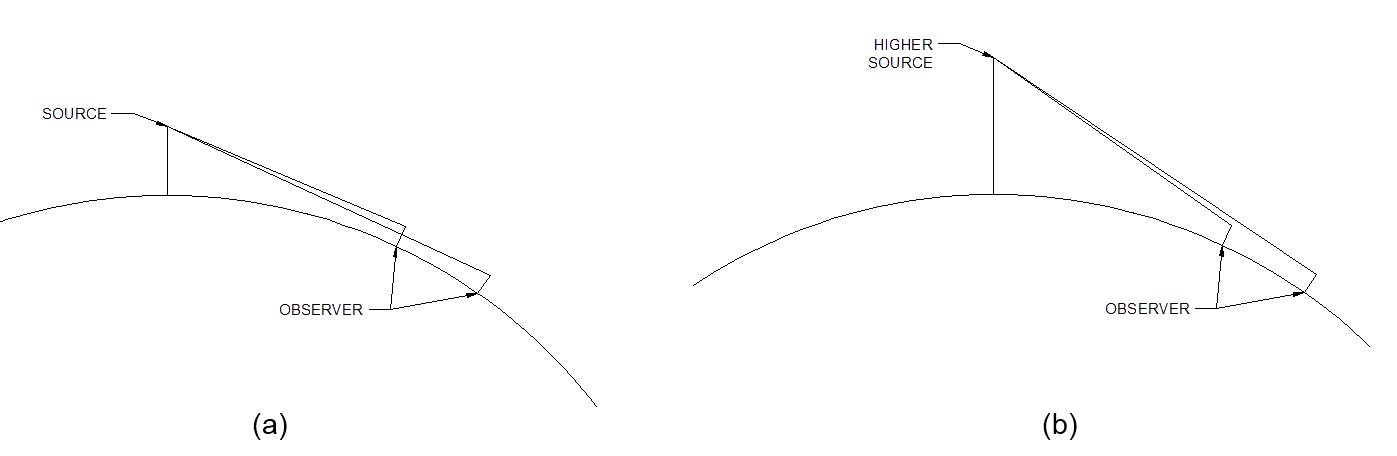


Figure - Effect of source height on how angle varies with range

Between Figure 8 (a) and (b) the distance between source and observers are the same. The only difference is the source height. In (a), the further observer views the source from a larger angle. In (b), the further observer views the source from a narrower angle. Clearly the heights of source and observer will affect the shape of the plot.

# Maximum Range

As the observer moves further away from the source, there will come a point where the lantern is obscured by the Earth. This is illustrated in Figure 9.

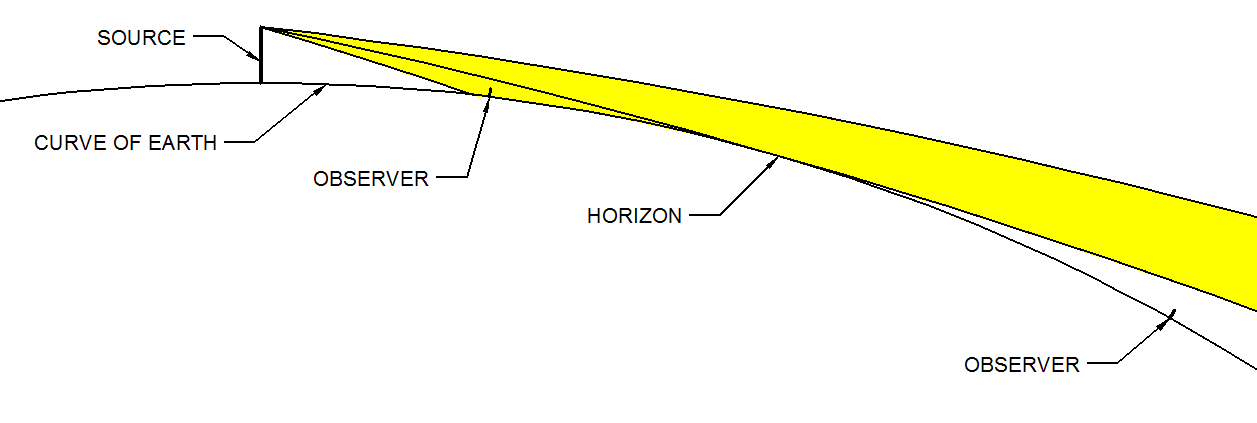


Figure – Effect of exceeding geographical range.

The formula to find the maximum geographic range is given in ref. [1] and is presented in Equation 1.

Equation

Where:

Rg = Geographical range (nautical miles)

Ho = Elevation of observer’s eye (metres)

Hm = Elevation of the mark (metres)

“The factor 2.03 accounts for refraction in the atmosphere, which causes the light path from the source to the observer to be slightly curved, and also for the conversion of units between the heights in meters and the range in nautical miles. Climatic variations around the world may lead to different factors being recommended. Typical range of factors is 2.03 to 2.12.” [1].

Section 3 discussed the concept of a maximum useable intensity of a lantern considering the angles it will be viewed from. Both the maximum useable intensity in section 3 and the maximum geographical range must be considered. The lesser of the two should be used as the maximum.

For example, for a given source and observer height:

If the maximum useable intensity from the methods presented in this document is 27,000 cd, then the maximum range is 17 M.

If the maximum geographical range is then calculated to be 15 M then, while the lantern has the appropriate intensity at appropriate angles up to a distance of 17 M, the Earth will obscure the light after 15 M.

Thus 15 M becomes the maximum range.

# Recommendations

The typical specification of a lantern’s vertical divergence does not necessarily contain enough information to confirm it is viewable at all intended distances.

However, a wide vertical divergence compared to the angles shown in the plots produced in this document will likely mean it meets the requirements.

It is recommended the measured and required plots be overlaid to confirm suitable performance, particularly where the measured divergence is narrow.

The minimum requirements presented in this document have had no margin applied. A margin should be applied to allow for errors due to assumptions and to allow a factor of safety.

# References

1. IALA Guideline No. 1065 on Aids to Navigation Signal Light Beam Vertical Divergence, International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Edition 1, May 2009.
2. IALA Recommendation E-200-2 on Marine Signal Lights. Part 2 – Calculation, Definition and Notation of Luminous Range, International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Edition 1, December 2008.
3. Distance to the Horizon, San Diego State University, Andrew T. Young, 2012. [online, accessed 18/10/12]

<http://mintaka.sdsu.edu/GF/explain/atmos_refr/horizon.html>

1. Physical properties of the Earth, NPL Kaye & Laby, Alan Cook. [online, accessed 18/10/12]

<http://www.kayelaby.npl.co.uk/general_physics/2_7/2_7_4.html>

1. Confirming values used with IALA Guideline

No curve radius for the refracted path of light is found in IALA guidelines. The values selected for use in the calculations will be used to derive a similar formula to that provided by IALA as a means of checking their validity.

The formula and explanation for geographical range is given Equation 1, see section 5.

The geographical distance will be calculated for a straight line and then factors for refraction and conversion of units will be added.

To simplify matters, the observer height will be considered to be 0 m. Thus .

Figure 10 shows Rg and some additional parameters required to calculate it.

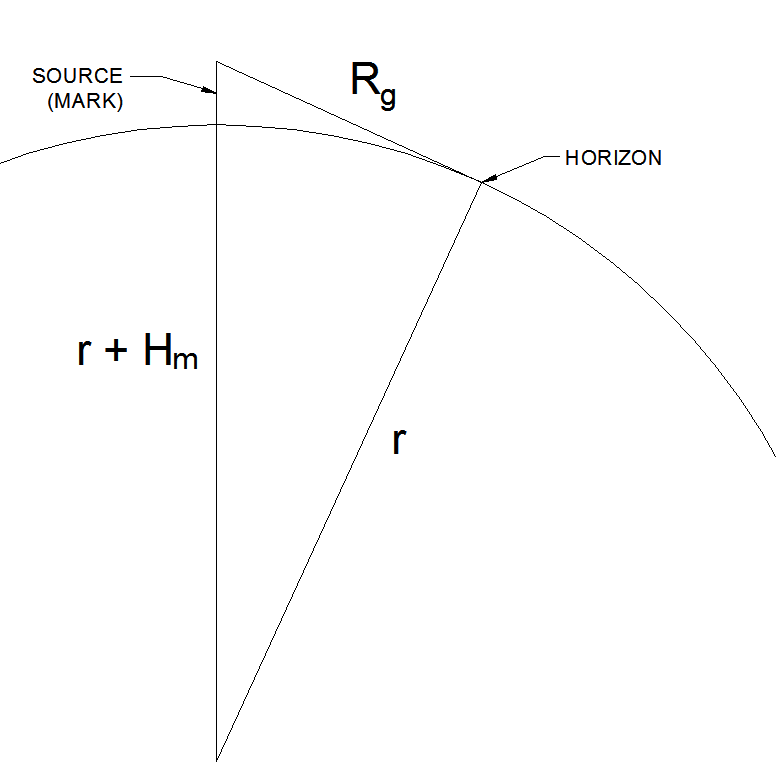


Figure – Distance to horizon.

Where r = radius of the Earth.

From Pythagoras’s theorem:

And since then:

The curved path of the light due to refraction, having a radius 7 times the radius of the Earth, may be accounted for by using an increased Earth radius, r’. Where . [3].

To convert from metres to nautical miles a factor of the value in meters is divided by 1852.

A value of 6371 km is used for the actual radius of the Earth.

This factor of 2.08 is in the centre of the range of IALA recommended factors and shows the values used are similar to the values used to form the IALA recommendations.

1. Finding Observer Coordinates

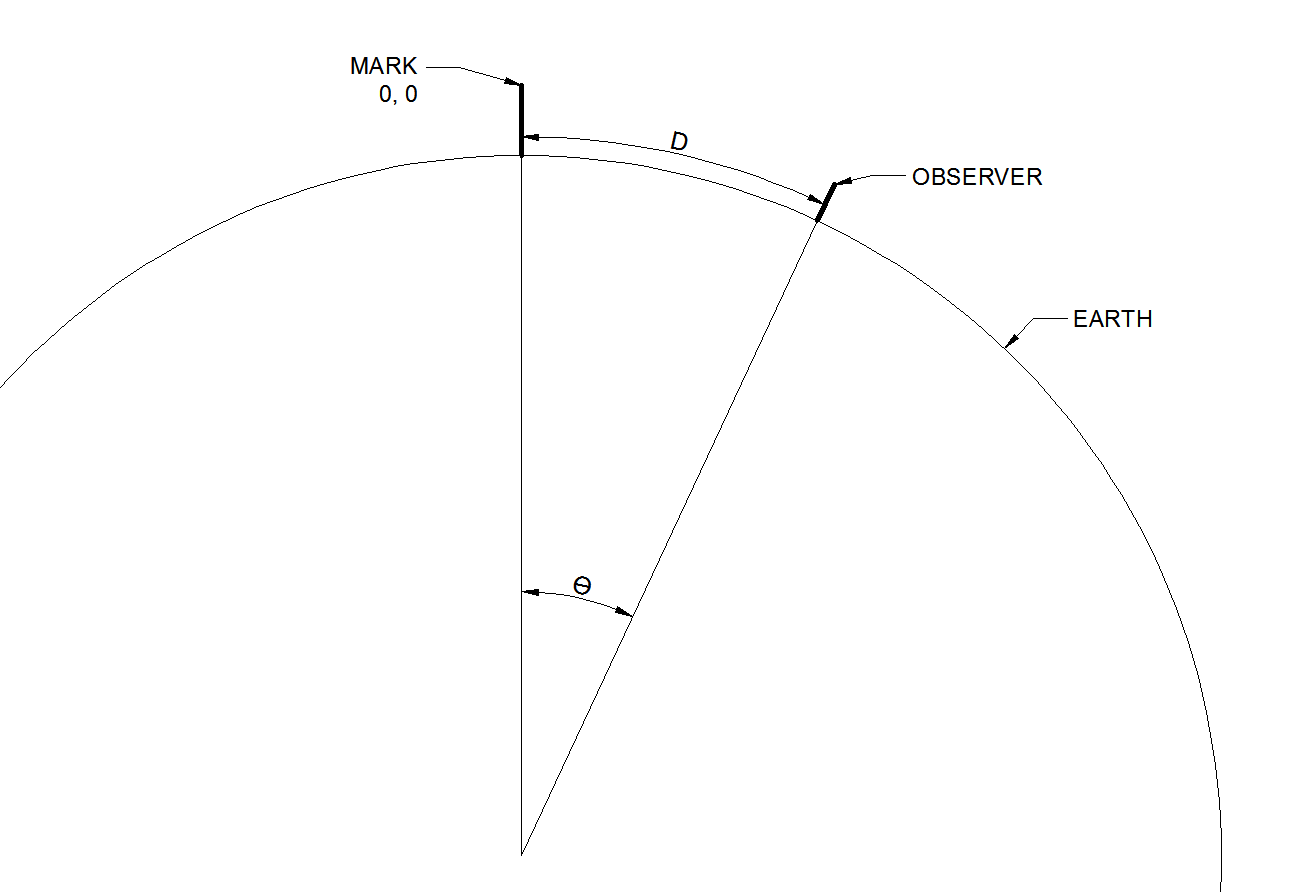


Figure - Finding Observer Coordinates

= Angle between source and observer orientation

D = Distance to observer along the Earth’s curved surface.

r = Radius of Earth.

Finding from the ratio of distance to circumference:

Or if using radians:

1. Finding Angle to Observer

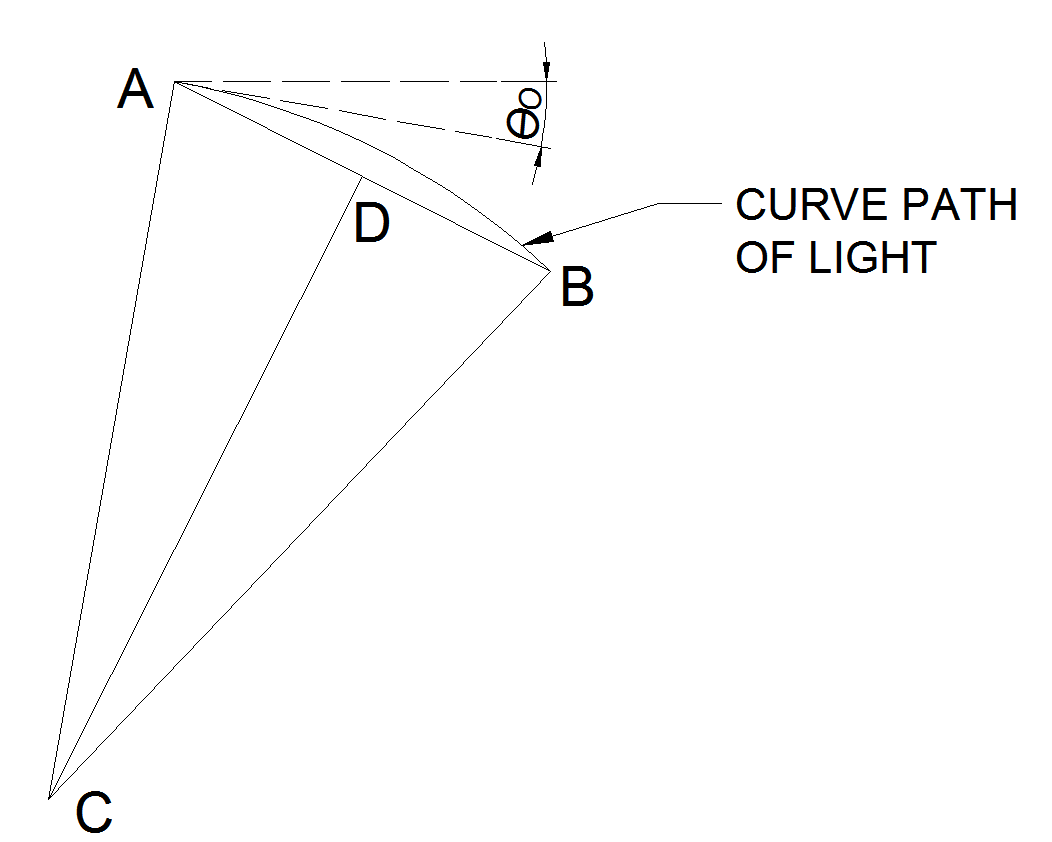


Figure – Angle to Observer

Where:

= Angle to Observer

A = Position of source: 0, 0.

B = Position of observer, this has previously been found.

C = Centre of path curve

D = Mid-point between AB

AC and BC both have a magnitude equal to the radius of the curve: r’.

The angle to the observer is: .

(-180° since the result will return first possible solution and the second is of interest. If the observer is higher than the source this is not required).

Since A is 0, 0 then

The coordinates of point C are now required:

AB is known as it is simply the position of the observer (since A is 0, 0).

The magnitude of DC can be found using Pythagoras’s theorem:

From these formulas all required information can be calculated. They can be combined into a single, unwieldy, equation but were used in their intermediate form in an excel spreadsheet for simplicity.

# Action requested of the Committee

The Committee is requested to:

1. Note the information above and consider how it can be incorporated into IALA Guideline 1065.