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White Paper

Introduction to atmospheric visibility estimation

Dr AlecBennett PhD MInstP FRMetS CMet

Visibility is usually referred to as the maximum horizontal distance through the atmosphere that objects can be seen by the unaided eye. Visibility will depend upon several factors, for example:

- ***The size and colour of the object to be observed against the sky in the horizon***
- ***The brightness of the sky itself (background luminance)***
- ***Whether the object is emitting light (particularly important at night!)***
- ***The skill of the observer at resolving the object against its background. This is referred to as the minimum contrast between the object and sky. During the night, the illumination of the object relative to the background light levels is most appropriate.***
- ***The amount of particles in the atmosphere between the observer and the object and how effectively they can absorb and scatter light. This factor is defined by a term called the atmospheric "extinction coefficient".***
- ***For observations in clear air, there will be a natural limit of ability to observe a distant object near the horizon due to the curvature of the Earth. In the case of an illuminated object, the reduction of light intensity due to any spreading of the beam will also be important.***

Visibility can be estimated by an observer during the day simply by recording the maximum distance that a suitably large, dark coloured object can be seen on the horizon against the sky. This estimation can however be difficult to provide accurately when there are not many objects at a known distance from the observer for comparison. The manual estimation will have additional sources of uncertainty such as variation in the skill and eyesight of the observer. Visibility estimates can also be made during the night by observing the maximum distance that a light of known intensity can be identified, although this has the same sources of ambiguity as daytime estimates, with the additional effect of light intensity loss by spreading that produces a natural limit to the distance it can be seen by an observer, even under perfectly clear conditions.

An alternative to manual observation of visibility is to use an instrument called a visiometer. A visiometer measures the amount of scattering (and sometimes absorption) of visible light by the atmosphere and uses this to estimate the extinction coefficient, which is needed to estimate visibility. Since modern electronics can be used to detect very small changes in light intensity (more so than the human eye), the amount of atmosphere required to be sampled does not need to be large, even for clean air.

Visiometers usually operate using one of two basic principles:

- Measurement of transmittance, where a beam of light is emitted horizontally to a sensitive receiver several metres away and the reduction in intensity is used to estimate the visibility.
- Measurement of scattering by particles suspended in the air, which is normally the dominant factor in determining visibility. A beam of light is emitted at an angle from a sensitive receiver and the amount of light scattered into the receiver is measured. By

choosing the correct angle between the transmitter and receiver the extinction coefficient is estimated. An advantage of such instruments is that they do not require careful alignment of transmitter and receiver like for a transmittance measurement. Visiometers based upon scattering do not need to sample a large portion of the atmosphere (sample volume), so the separation between transmitter and receiver can be less than 1 metre. It should be considered however that such a small sample volume will require appropriate positioning to ensure the sample volume is representative of the wider atmospheric conditions.

Both types of visiometers are used at airports, where estimation of visibility is particularly important since it will determine the distance at which the runway (or its lights) is visible to the pilot on approach. As such, visibility is normally referred to as Runway Visual Range (RVR) by the aviation community. Another term used for visibility is the Meteorological Optical Range (MOR), defined by the World Meteorological Organisation (WMO) as:

"the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a colour temperature of 2700 K, to 5 per cent of its original value, the luminous flux being evaluated by means of the photometric luminosity function of the International Commission on Illumination. For aeronautical purposes, the surface MOR is measured at a height of 2.5 m above the surface."

This definition has the advantage of being unrelated to the illuminance contrast-resolving or night-vision ability of a human observer. Given the practicalities of making such an observation using the WMO definition, the MOR is often approximated by other visibility estimation methods.

Once the extinction coefficient is known from visiometer measurements, it can be used to estimate visibility using one of two formulae (or "Laws"). During the daytime, it is the contrast between a dark object set amongst the background of the horizon sky that is considered for the calculation of visibility. The appropriate formula relating the extinction coefficient to maximum visibility of such an object is defined by "Koschmieder's Law". During the night, the definition used for Koschmieder's Law is not really appropriate given that it ultimately involves sunlight being used to identify distant objects. In practise however it still offers a suitable conversion between extinction coefficient and visibility so is often used all the time. For the purpose of estimating Runway Visual Range at night, the ability of a pilot to see the runway lights is of practical significance. The formula used to convert values of extinction coefficient and runway light intensity to an estimate of visibility is defined by "Allard's Law".

The Runway Visual Range (RVR) has been calculated for different extinction coefficients using both the "day" (Koschmieder's Law) and "night" (Allard's Law) visibility algorithms and plotted as Figure 1. Since Allard's Law involves light intensity it has been plotted for three different source intensities. The curves representing Allard's Law are clearly different between day and night and for different light source intensities. The difference between the two Laws at night shows the under-estimation of RVR using a light source compared to using the extinction coefficient alone when the visibility is moderate to good.

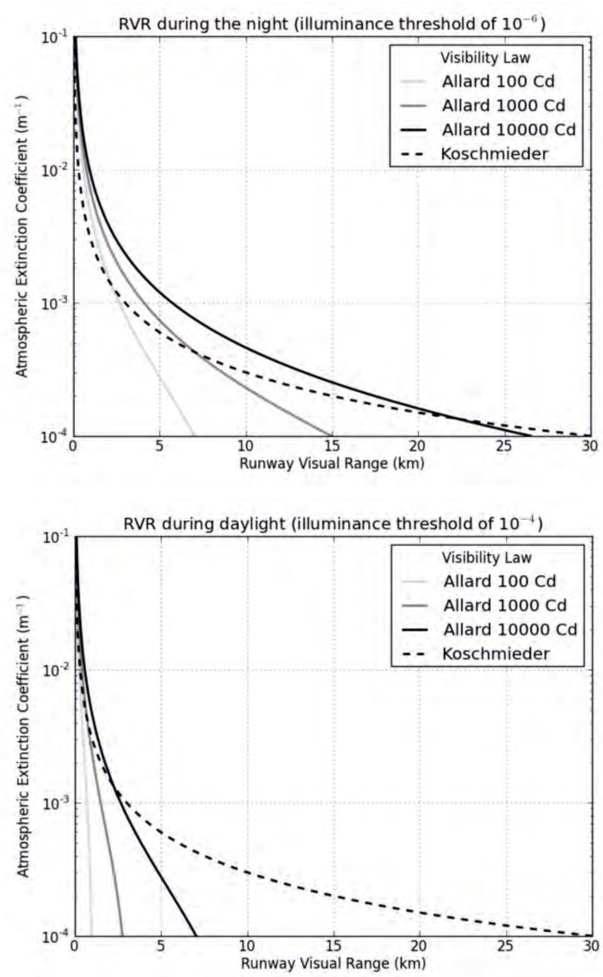

Figure 1: Comparison of Runway Visual Range (RVR) using Koschmieder's and Allard's Law for typical (a) night and (b) day visual thresholds of illuminance and runway light intensities.

It is therefore unsurprising that the estimation of RVR made automatically by a visiometer can differ greatly from that estimated manually by a human observer during the night, even though both are correct for their chosen methods. At night there will be a tendency for the visiometer (which uses Koschmieder's Law) to report significantly lower visibilities during fog and mist compared to estimations made manually from runway lights using Allard's Law. For example, an extinction coefficient of 0.0046m^{-1} will produce a visibility estimate of 650m if estimated using Koschmieder's Law indicating fog will be reported at the aerodrome. However, if Allard's Law is used the visibility will be greater than 1km for light source intensities exceeding 100 Cd and therefore imply only mist. The opposite will be true during good visibility, with the visiometer using Koschmieder's Law reporting larger RVR than an observer using Allard's Law. The ratio of Allard's and Koschmieder's Laws with different extinction coefficients and source light intensities during the night is shown in Figure 2 for ease of comparison.

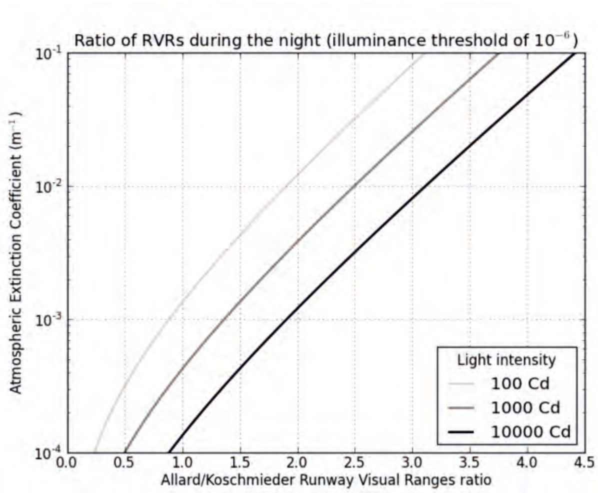

Figure 2: Ratio of Runway Visual Range (RVR) calculated during the night using Allard's and Koschmieder's Laws as a function of extinction coefficient and light source intensity (for use in computation of Allard's Law).

With the difference between the two Laws in mind, most visiometers include a value of extinction coefficient in their report (or a related value, called transmissivity) which can therefore be used in combination with source light intensity, background luminance and an appropriate lookup table to convert into RVR based upon Allard's Law, if desired.

Ultimately whether to use Koschmieder's or Allard's Law in determination of visibility will depend upon the specific situation, customer needs and official regulation. If the observation is for a pilot approaching a well-lit runway at night then Allard's Law would seem most appropriate, but if the pilot is approaching during the day or twilight when visibility is generally good then Koschmieder's Law would likely be used as the contrast of the dark airport structures against the daytime or twilight horizon will better define the location than the runway lights (if on), especially if their intensity is less than 10,000 Cd.

Mathematical definition and interpretation of the two visibility laws

During the day, visibility is measured using Koschmieder's Law, which relates the minimum observable contrast between an appropriately large, black object against the horizon sky (called the contrast threshold) as a function of the atmospheric extinction coefficient and the distance to the target (e.g. the visibility) as described by equation (1):

$$C_T = e^{-\beta V} \qquad (1).$$

where C_T is the observer's contrast threshold, V denotes visibility in metres (or more specifically Runway Visual Range for aviation purposes) and β is the atmospheric extinction coefficient, in m^{-1}. Equation (1) can be rearranged to make visibility the subject of the equation after taking natural logarithms of both sides to produce:

$$V = \frac{-\ln(C_T)}{\beta} \qquad (2).$$

The original formula used by Koschmieder assumed a minimum contrast identifiable by an observer as 0.02, whereas subsequent investigations concluded that a value of 0.05 was more realistic. The modern interpretation of Koschmieder's Law for daytime visibility estimation therefore uses C_T=0.05, making the numerator of equation (2) equal to 3.00 if rounded to two decimal places as described by equation (3), which is also used in practise for the calculation of Meteorological Optical Range (MOR) despite MOR being technically defined by light source transmittance where as Koschmieder's Law relates to visibility of dark targets against bright sky:

$$V = \frac{3.00}{\beta} \qquad (3).$$

For visibility estimation in low light levels (e.g. during the night), the use of a point source of light of known intensity is clearly more appropriate than visibility of dark targets against the horizon sky, given the lack of sufficient ambient illumination for unaided visibility. For aviation purposes, night conditions are defined by the US Federal Aviation Authority as having background luminance of 6.85 Cdm^{-2}, a value which determines whether the use of Koschmieder's Law for Runway Visual Range is appropriate. The relationship between the observable distance of a light source depends on the atmospheric extinction coefficient, the light source intensity (I) and the visual threshold of illumination (E_T), the latter of which describes the lowest light level detectable by the human eye above the ambient light and therefore provides a similar function to the contrast threshold C_T of Koschmieder's Law. These factors are related by Allard's Law, which was originally devised in the nineteenth century for estimating the night time range of lighthouses:

$$E_T = \frac{Ie^{-\beta V}}{V^2} \quad (4).$$

Unfortunately, the relationship between the atmospheric extinction coefficient and visibility is not as straightforward as Koschmieder's Law of equation (3) due to the necessity to account for transmittance of a point source of light through the atmosphere (which gives equation (4) the exponential form of the numerator) and that the light source radiates in all directions (introducing the square term in the denominator). It can be seen that determination of the visibility (V) using Allard's Law is nontrivial and requires an iterative procedure to solve, or a prepared look-up table of values.

To solve equation (4) iteratively in order to determine visibility for a given set of values for β, E_T and I, the equation can be rearranged to place V on both sides of the equation:

$$e^{-\beta V} = \frac{V^2 E_T}{I} \quad (5).$$

then take natural logarithms of both sizes and rearrange to make the equation equal to zero:

$$V + \frac{1}{\beta}\ln\left(\frac{V^2 E_T}{I}\right) = 0 \quad (6).$$

Using a suitable iterative method such as that described by Brent (1973)[1] for scalar function root finding it is possible to determine V to satisfy equation (6) and hence the visibility for known values of light source intensity, backscatter coefficient and threshold illumination.

[1] *Brent, R. P., (1973). Algorithms for Minimization Without Derivatives. Englewood Cliffs, NJ: Prentice-Hall, Ch. 3-4.*

About the Author
Dr Bennett is the Meteorological Products Manager for Biral, UK. He has a PhD in Atmospheric Electricity and 10 years' experience in research and development of lightning detection systems, including working at the UK Met Office and is a visiting Research Fellow at the University of Bath. He has written over 20 papers on atmospheric electricity, which have been published in peer-reviewed international journals.