Runway Visual Range

Problem presented by

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Problem statement

Runway Visual Range (RVR) is the horizontal distance a pilot can see on the runway. It is affected by the atmospheric conditions, by the background illumination, and by the quality of the runway lighting. An airport control tower reports the RVR to incoming flights. If the reported RVR is large enough, and if the pilot can see the runway lights at his minimum decision height at the start of the final approach then he proceeds with the landing, but if not then he will divert elsewhere. Many airports have systems for estimating the RVR, based on standardised values. More advanced methods involve measuring light transmission on the runway and the ambient light level.

If RVR is underestimated, a pilot may be ordered land elsewhere even though landing would in fact have been safe.

By analysing data from Birmingham Airport, the Study Group was able to quantify, in terms of airport throughput, the benefit of using measured light intensities compared to the standardised values.

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1 Introduction

Runway Visual Range (RVR) is defined to be the horizontal distance a pilot can see on the runway[1].

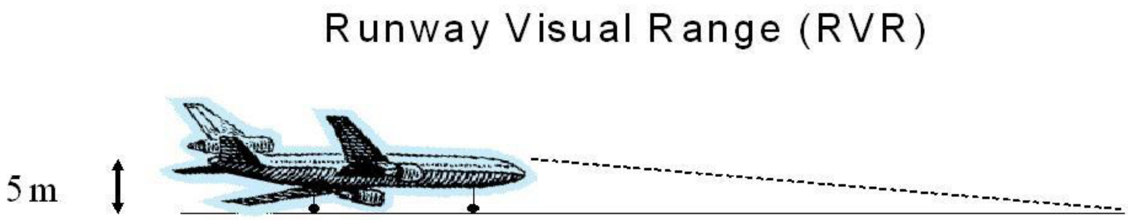


Figure 1: Runway Visual Range

International Regulations require that an airport should calculate the local RVR in order to determine whether it is safe to land and how many aircraft can be landed safely per hour. These regulations are authorised by the International Civil Aviation Organization (ICAO). There are two ways that RVR can be calculated:

- Either a human observer on the runway makes a judgement by counting the number of lights visible down the runway from a fixed observation point; or
- one uses Allard's Law[2] together with measurements of absorption and background illumination and values for the intensity of the lamps on the runway.

At Birmingham International Airport (BHX) the second method is used. Absorption and background illumination are both easily measured, but the intensity of lamps can vary considerably along the runway. The intensity of individual lights can be measured, but Birmingham (along with most other airports) chooses to use standardised values conservatively estimated. Conservative estimates of light intensity lead to lower than necessary estimates of RVR. BHX uses RVR to determine four operational states; these states dictate how many aircraft are permitted to land per hour.

State 1:	$\text{RVR} > 1000\,\text{m}$	22 planes/h
State 2:	$1000\,\text{m} > \text{RVR} > 550\,\text{m}$	18 planes/h
State 3:	$550\,\text{m} > \text{RVR} > 300\,\text{m}$	13 planes/h
State 4:	$300\,\text{m} > \text{RVR}$	10 planes/h

In this way, the RVR estimate determines the maximum permitted number of landings per hour.

[1] www.allweatherinc.com/reference/definitions.html
[2] www.allweatherinc.com/reference/definitions.html

The principal question amounts to this: **What is the gain in terms of airport throughput of using measured light intensities as an input to Allard's law compared to the conservative estimated values?**

To answer this, the Study Group first investigated the effect of using more less conservative light intensity values in Allard's Law on RVR. If less conservative values could be seen to give a significant benefit in terms of airport throughput then it would be economically sensible for the airport to invest in an accurate measurement system for light intensity values.

Then the Study Group analysed the data provided for BHX to determine how a revised value for RVR may be significant in the scheduling of aircraft landings. Data on the minute by minute variation of background illumination and absorption over the course of an entire year was available for analysis. The Study team developed an efficient algorithm to determine the state of the airport in hypothetical light intensity conditions.

2 Calculating RVR

2.1 Allard's Law

Allard's Law is an equation used in predicting the visual range of self-luminous targets.[3] The illumination from a single lamp is

$$E = \frac{Ie^{-\sigma R}}{R^2}, \tag{1}$$

where I is the intensity of the lamp, σ the extinction coefficient, and R the distance from the lamp. Larger σ indicates poorer visibility conditions.

The *Visual Range* for a single lamp is the R that solves the equation

$$E_T = E \tag{2}$$

where E_T is the *Illumination Threshold*, i.e., the minimal value of the illumination E which can be distinguished from the background illumination.
Note that E_T and σ are both easily measured (current means of estimating σ is by transmissometers and this is thought to be quite accurate). We are looking to solve for R. What is less well understood is the correct value for I. TMS Photometrics offers an accurate assessment of what I is for each lamp.

We can solve for σ and obtain

$$\sigma = \frac{\log(I/E_T) - 2\log \mathrm{RVR}}{\mathrm{RVR}} \tag{3}$$

The graphs below indicate that largest sensitivity to the intensity I is when σ is small, i.e., in reasonable weather conditions.

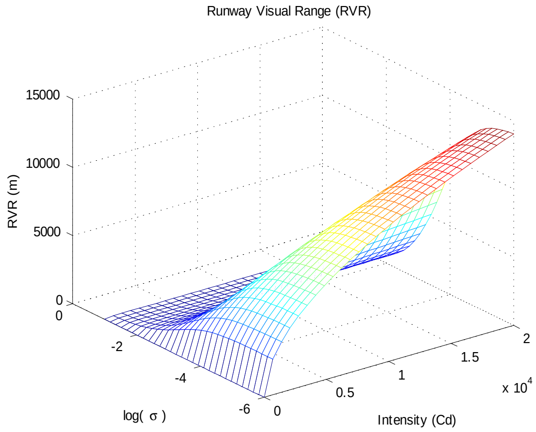
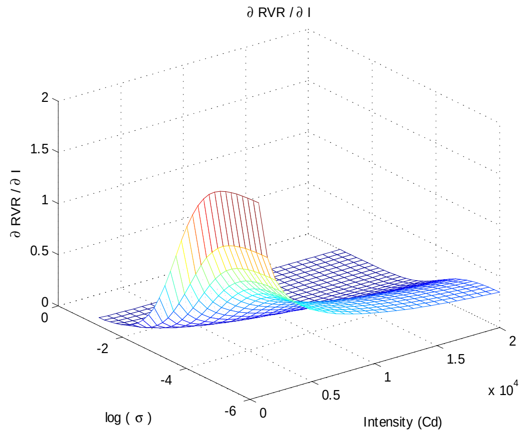


Figure 2: Sensitivity, RVR



Sensitivity, $\partial RVR/\partial I$

This means that, in good weather conditions, a less conservative (that is, higher) estimate for I is likely to have quite a big impact on RVR. What is required is to understand the impact when the weather conditions are bad! The general case requires a more careful analysis.

2.2 Koschmeider's Law

The ICAO *Manual of Runway Visual Range Observing and Reporting Practices*[4] describes the internationally approved standard algorithm to calculate RVR. In addition to Allard's Law, it also employs Meteorological Optical Range and Koschmeiders's Law. In order to explain the algorithm, we first need to describe these ideas.

The **Meteorological Optical Range** (MOR)[5] is the length of the path in the atmosphere required to reduce the luminous flux in a collimated beam from an

[3] See the *Glossary of Meteorology* http://amsglossary.allenpress.com/glossary/search?id=allard-s-law1

[4] Available at `http://www.icao.int/`

[5] `www.allweatherinc.com/reference/definitions.html`

incandescent lamp at a colour temperature of 2,700 K to 0.05 of its original value, the luminous flux being evaluated by means of the photometric luminosity function of the International Commission on Illumination

Koschmieder's Law[6] describes a relationship between the apparent luminance contrast of an object, seen against the horizon sky by a distant observer, and its inherent luminance contrast, i.e. the luminance contrast that the object would have against the horizon when seen from very short range.

According to Koschmieder's Law, the Meteorological Optical Range is given by

$$\mathrm{MOR} = -\frac{\log(0.05)}{\sigma} \approx \frac{3}{\sigma}. \tag{4}$$

Substituting for σ we have that

$$\mathrm{MOR} = \frac{\log(0.05)\mathrm{RVR}}{\log(I/E_T) - 2\log\mathrm{RVR}} \approx \frac{3\mathrm{RVR}}{\log(I/E_T) - 2\log\mathrm{RVR}}. \tag{5}$$

The general relationship for MOR against RVR for a typical value of the ratio I/E_T is shown in the graph below (Figure 3)

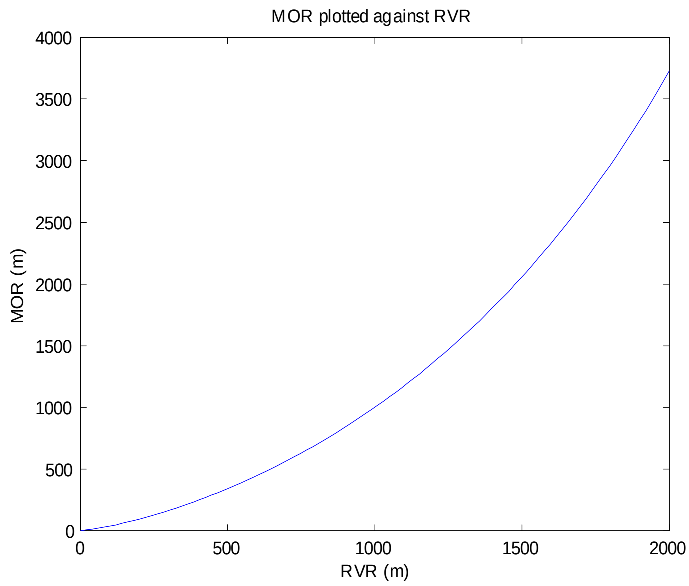


Figure 3: MOR against RVR

Now we can turn to the ICAO Algorithm for calculating RVR.

2.3 Algorithm for Calculating RVR

The ICAO mandates the following simple algorithm for calculating Runway Visual Range using standardised values for runway light intensities:

[6] `www.allweatherinc.com/reference/definitions.html`

(1) Calculate RVR using Allard's Law with I set to the intensity of runway edge lights. If RVR $> 550\,\text{m}$ then that is the final RVR value. Otherwise proceed to step 2.

(2) Calculate RVR using Allard's Law with I set to intensity of runway centre line lights. If RVR $\leq 200\,\text{m}$ then that is the final RVR value.

(3) Otherwise

- Calculate MOR_{550} corresponding to RVR $= 550\,\text{m}$ using the intensity of the edge lights.
- Calculate MOR_{200} corresponding to RVR $= 200\,\text{m}$ using the intensity of the centre line lights.
- Using Koschmeider's Law, calculate the actual MOR.
- Compute α such that $\text{MOR} = \alpha\text{MOR}_{550} + (1-\alpha)\text{MOR}_{200}$. Then the final value of RVR $= 200 + 350\alpha$.

Throughout the values for E_T and σ are the measured values. The crucial point to note here is that in good visibility, the edge lights are deemed sufficient. In poorer visibility centre lights are given greater priority.

Calculating RVR requires a numerical solution to Allard's law, a transcendental equation in RVR. With 500,000 data points the study group looked for a more efficient algorithm for determining the state of the airport, without having to calculate RVR.

2.4 σ-algorithm to avoid calculating RVR

The state of Birmingham Airport is based on three critical values of RVR, viz 1000m, 550m and 300m. By manipulating Allard's law, this can be turned into three critical values for σ given intensity I and illumination threshold E_T. (Allard's Law is a decreasing bijection between $\sigma \in [0,\infty)$ and RVR $\in (0, (I/E_T)^{\frac{1}{2}}]$. The significance of this critical pair of values $\sigma = 0$ if and only if RVR $= (I/E_T)^{\frac{1}{2}}$ is clear - even in perfect visibility ($\sigma = 0$), there is still a finite range of visibility of the light because if you go too far away the light becomes indistinguishable from the background illuminance.

$$\sigma_{RVR} = \frac{\log(I/E_T) - 2\log \text{RVR}}{\text{RVR}} \qquad (6)$$

(1) Calculate σ_{1000} using intensity of the edge lights. If $\sigma < \sigma_{1000}$ then the airport is in state 1.

(2) Calculate σ_{550} using intensity of the edge lights. If $\sigma < \sigma_{550}$ then the airport is in state 2.

(3) Otherwise.

- Calculate σ_{200} using intensity of the centre line lights.

- Calculate σ_{300} from σ_{200} and σ_{550} using the formula. (This comes from the earlier linear interpolation of MOR.)

$$\sigma_{300} = \frac{1}{\frac{5}{7}\frac{1}{\sigma_{200}} + \frac{2}{7}\frac{1}{\sigma_{550}}} \tag{7}$$

- If you obtain $\sigma < \sigma_{300}$ then the airport is in state 3.
- If you obtain $\sigma \geq \sigma_{300}$ then the airport is in state 4.

The Study Group used this algorithm to determine the status of Birmingham International Airport from the fog data given without having to calculate the RVR.

3 Data Analysed

At Birmingham International the specification of lights is $I = 10000$ for edge lights and $I = 5000$ for centre lights. However currently, BHX calculates RVR by using estimates of $I = 2000$ for edge lights, and $I = 1000$ for centre lights.

The minimum specification for lamps is $I = 5000$ for edge lights and $I = 2500$ for centre lights. But BHX does not use these figures at all.

The highest values permitted by the IACO in the RVR are $I = 8000$ for edge lights and $I = 2500$ for centre lights. At the time of drawing up regulations there was no reliable means to measure the intensity of lamps.

This information is summarised in the following table:

Intensities

	Edge lights	Centre lights
Actual standardised values used by BHX in their calculation of RVR	2000	1000
Legal minimum intensity of lights permitted by regulation	5000	2500
Maximum standardised values permitted to be used in the calculation of RVR	8000	2500
Specification of lights at BHX	10000	5000

3.1 Analysis Results

After analysing a year of weather data from Birmingham International Airport, the Study Group was able to distinguish the percentage of time that the airport was in each of states 1, 2, 3 and 4. This is given in the table below, along with the number of planes permitted to land per hour in each state.

This data analysis also indicated how these percentages would have differed had the calculation of RVR been based on other figures. For example, using minimum specification values would have allowed the airport to operate in state 1 for 65% of the time as opposed to merely 58% of the time in state 1 using current BHX conservative estimates.

Percentage of time that BHX operates in each state

Planes/h	BHX	Minimal	Regulations	Specs
22	58%	65%	69%	71%
18	29%	26%	23%	22%
13	9%	6%	5%	5%
10	4%	3%	3%	2%

The data can be further broken down to analyse the situation in peak periods, and this allows an interesting comparison of the number of extra planes permitted to land were there greater confidence in the accuracy of RVR calculations.

Morning peak hours (6:30–10:00)

Planes/h	BHX	Minimum	Regulations	Specs
22	31%	43%	50%	52%
18	45%	41%	37%	35%
13	15%	9%	7%	8%
10	9%	7%	6%	5%
Average	17.5	18.7	19.0	19.3

Evening peak hours (17:00–19:00)

Planes/h	BHX	Minimum	Regulations	Specs
22	70%	78%	82%	83%
18	25%	18%	15%	14%
13	4%	4%	3%	3%
10	1%	0%	0%	0%
Average	20.5	20.9	20.9	21.2

What is now clear is that in the morning, when fog is more likely, using conservative estimates of I results in the airport operating at a capacity significantly below that which is necessary. Merely by calculating with minimum values rather than conservative values, the airport would be able to allow on average over 1000 extra landings per year. (More than three extra landings per day on average.)

4 Other issues

The Study Group addressed a very particular practical problem relating to the intensities of runway lights on the ground. A number of points were not addressed, but would be of interest.

4.1 Slant Visual Range

The Study Group was not invited to consider issues of Slant Visual Range (SVR) or modelling of fog.

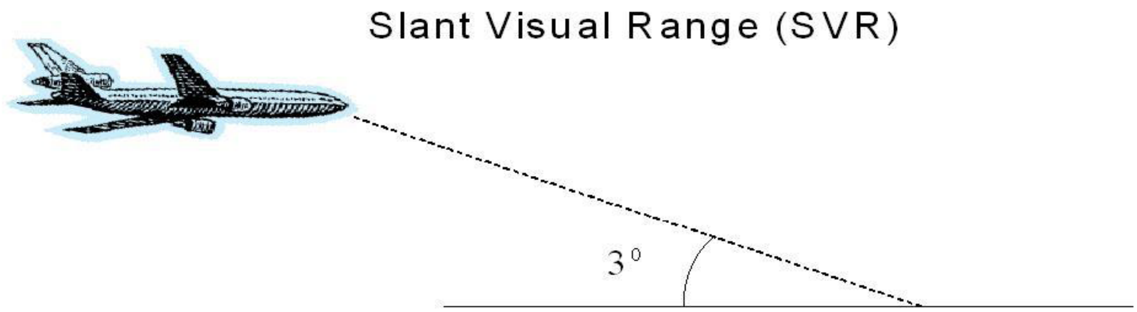


Figure 4: Slant Visual Range

Slant Visual Range may be a better gauge of safe landings than Runway Visual Range. When the regulations were drawn up, measuring SVR was considered too difficult. This may no longer be the case. Further investigation is required to determine whether this approach has utility.

4.2 Subtleties of measuring

The beams from runway lights are not uniform; the average intensity in the specified beam area may be 10000Cd, but the intensity received by the pilot may be more like 4000-6000Cd. It is important to measure the correct part of the beam.

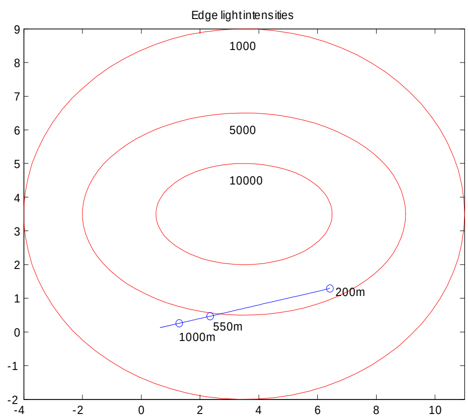


Figure 5: Edge Light Intensitities

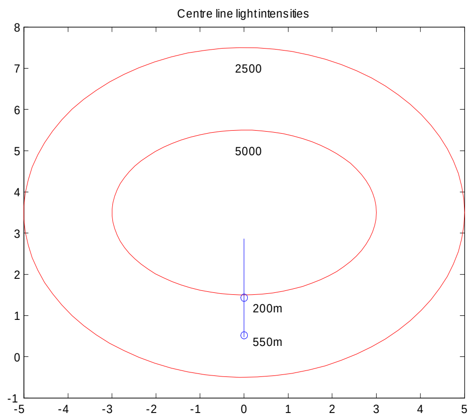


Figure 6: Centre Light Intenstities

Regulations suggest that this should be factored in to calculations. However the tools to measure the exact intensity with reasonable accuracy do not yet exist. Are there good reasons, safety reasons or commercial reasons, to model the benefit of developing such tools?

4.3 Anomalies in the Regulations

In principle, an airport could be operating with runway lights at the minimum specification (5,000 Cdls for edge lights and 2,500 Cdls for centre lights) having calculated its RVR using higher values permitter by the regulations (8,000 Cdls for edge lights and 2,500 Cdls for the centre lights.

Figures 2 and 2.1 indicate that this is an important distinction - working with the smaller figure has a significant impact on RVR. (That is, $\partial(RVR)/\partial(I)$ is sufficiently large to raise this as a concern.)

5 Conclusions and Possible Further Work

- From its data analysis, the Study Group demonstrated that substantial gain in airport throughput is possible by using actual light intensity rather than conservative estimates.
- A statistical model of the degradation of lamps between inspections is necessary to secure safety.
- A way to estimate SVR would enhance safety and is not impossible.