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# IMPROVED RVR SIMULATION VIA HIGH-DYNAMIC RANGE RENDERING

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## ABSTRACT

*Transition to landing training under Instrument Meteorological Conditions (IMC) is of primary importance in any Instrument Flight Rules (IFR) pilot training program. The visual system presentation of precision IFR runway approaches in simulator-based training must closely match the real world under given pilot briefings of Runway Visual Range (RVR). Clearly, a negative transfer-of-training to the real aircraft of critical pilot decision-height responses could be very dangerous.*

*This paper presents a comprehensive approach to RVR simulation based on GPU high-dynamic range and physics-based rendering techniques derived from the EO/IR sensor simulation and photo-realistic rendering communities. Previous full-flight simulators used calligraphic displays with inherent capabilities to draw very bright light-points with high-dynamic range. Such displays were used to advantage in providing very realistic low visibility scenes even in challenging daylight Category III IMC conditions. Today's systems have moved to lower-cost fixed matrix displays, which inherently have limited dynamic ranges. Our challenge is to optimize the RVR simulation given limited display capabilities.*

## INTRODUCTION

**Runway Visual Range** (RVR) is a key parameter in determining whether it is prudent or legal for a pilot to attempt a landing under limited visibility conditions. Instrument approaches to an airport employ navigational aids to 1) find an airport, 2) hold in airport vicinity if required, 3) execute a runway approach, 4) perform a landing if an adequate visual reference for a safe landing is obtained, or 5) execute a missed approach if the visibility is below the minimums required for a safe landing. ICAO categorizes instrument approach minimums as shown in Table 1, which shows landing Decision Height and the associated minimum RVR for each category. Figure 1 shows a typical runway view at Decision Height. Clearly, a high-fidelity, repeatable RVR simulation is critical to effective flight simulator-based IMC pilot training.

**Table 1 Approach Categories**

| Category | Decision Height (ft) | Min RVR (ft) |
|---|---|---|
| Nonprecision | MDA | 2400 |
| Category I | > 200 | 1800 |
| Category II | < 200 | 1200 |
| Category IIIa | < 100 | 700 |
| Category IIIb | < 50 | 150 |
| Category IIIc | none | 0 |

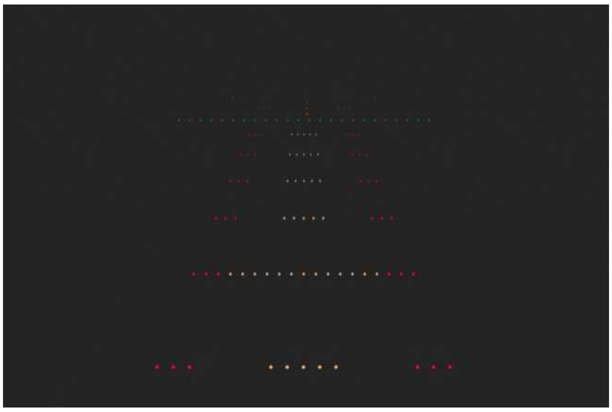

**Figure 1 Decision Height**

Runway Visual Range is defined *as the range over which the pilot of an aircraft on the center line of a runway can see the runway surface markings or the lights delineating the runway or identifying its center line.* [ICAO, 2001]. RVR is a horizontal visual range, not slant range. RVRs are communicated to pilots via automated reports (METARs) or via air traffic controllers. The maximum RVR reading is 6,500 feet, above which RVR is not significant and thus does not need to be reported.

Originally RVR was measured by a person, either by viewing the runway lights from the top of a vehicle parked on the runway threshold, or by viewing special angled runway lights from a tower at one side of the runway. Today most airports use automated instrumentation to compute and report RVR. Older installations use *transmissometers* (see Figure 2) mounted on 14-ft towers spaced at 250 ft intervals to directly measure the attenuation of light

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(a) (b)

**Figure 2 Typical Older Transmissometer (a) and Newer Forward Scatter Meter (b)**

due to rain, snow, dust, fog, haze, or smoke. Newer installations use a *forward scatter visibility meter* (also shown in Figure 2) to measure the scattering of light from a light transmitter to a light receiver mounted at a offset. Both the scatter meter transmitter and receiver mount together on a single 14-foot tower. Other inputs to the RVR computation include the current ambient light measurement and the current runway light intensity settings. [FAA, 2003] Normally, airports provide three instruments for each runway covering aircraft touchdown, mid-point, and roll-out ranges.

In general, RVR is distinct from visibility. Various definitions of visibility are of interest:

**Meteorological Optical Range (MOR)** is the distance that light from a 2700° K light source travels before it is reduced 0.05 times its original value. As such, MOR characterizes only the state of the atmosphere.

**Aeronautical Visibility** is the greater of the visibility by contrast (MOR) and perception of 1000 candela light sources. [ICAO, 2001] Aeronautical visibility thus accounts for the increased perception of light sources at night. RVR is a special case of Aeronautical Visibility accounting for intense lighting along the axis of the runway, the background luminance, and the intensity of the runway lighting.

**Flight Visibility** is average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent unlighted objects may be seen and identified by day and prominent lighted objects may be seen and identified by night. Note that Flight Visibility is referenced from the aircraft cockpit.

## RVR SIMULATION OBJECTIVES

The motivation for our RVR Simulation improvement effort included:

1. **Transition from calligraphic to raster lights** – Our legacy systems used calligraphic lightpoints, which inherently have a high-dynamic brightness range. The transition to raster-only systems means that we must perform critical transition-to-landing training with low-dynamic range raster lightpoints. We must optimize the use of the dynamic range that is available. We will support calligraphic lights going forward. The new design must seamlessly accommodate both raster and calligraphic lights and must automatically take advantage of the higher dynamic range available with calligraphics.

2. **Transition to physics-based models –** Our legacy systems accommodated the varying characteristics of the end display system using a combination of comprehensive but subjective scene modeling processes and ad hoc image generator functions. Clearly, driving the whole process with physics-based models leads to robust system operation and improved system configuration management.

3. **Ease of calibration –** Ideally, no interactive calibration of RVR would be required given a properly calibrated display system. However, the subjective nature of RVR calibration, the variability of cockpit lighting levels, and the variability of airport lighting systems inevitably result in a need for such interactivity. The associated interactive controls must be intuitive.

4. **Portable calibration values –** A specific RVR calibration setup should be portable from one system to another. Two identical simulators side-by-side should not require different calibrations.

## RVR SIMULATION OVERVIEW

Figure 3 shows the organization of our improved RVR simulation. The paragraphs below provide overviews of the constituent functions.

The Instrument Simulation function accurately models the characteristics of the airport instrumentation used to derive RVR briefings for approaching aircraft. Such instrumentation considers current atmospheric transmittance, atmospheric illumination, and runway light levels to compute the current reported RVR. Instrument Simulation executes this model in reverse in order to determine the atmospheric transmittance associated with the instructor's current RVR, illumination, and runway light level selections. We use a Real-World Illumination model [Lloyd, 2008] that is traceable to real-world data for lunar illumination condi-

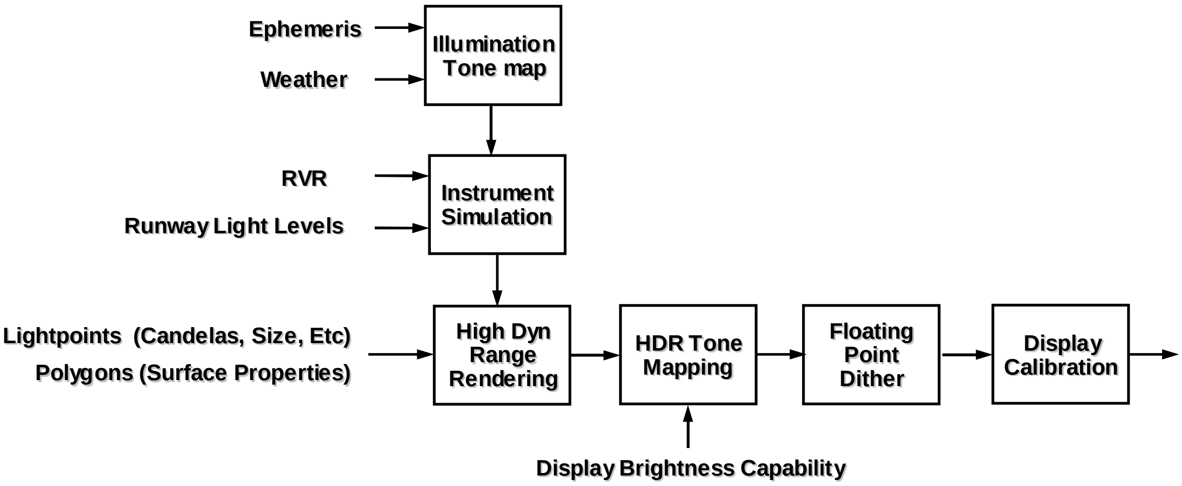


**Figure 3 RVR Simulation Organization**

tions. The current illumination is a function of the current ephemeris and weather. The illumination is used both in simulating the RVR instrumentation and to illuminate the scene during rendering.

High Dynamic Range Rendering operations use the atmospheric densities provided by Instrument Simulation to render scene lightpoints and surfaces. The rendering is a combination of CPU and GPU floating point operations that apply the underlying physics model. The physics model uses a combination of Koschmieder's Law and Allard's Law (discussed further below) to determine the required brightness and contrast of scene surfaces and lightpoints. The CPU/GPU rendering pipeline uses a full floating point dynamic range when computing lightpoint and luminous surface illumination quantities derived from physics-based visual database attribution.

Tone Mapping functions are integrated with high-dynamic range rendering. Tone Mapping [Reinhard, 2006] is defined as the optimal conversion of physics-model high-dynamic range floating point quantities to display levels that are within the capabilities of a low-dynamic range display. Under tone mapping, a lightpoint physical brightness on the display matches that in the real-world if that brightness is achievable. Alternatively, if the real-world brightness is not achievable, the tone mapping process produces a display value that maintains the pilot's subjective or relative sense of brightness. The brightness capability of the display at hand is a fundamental input to the tone mapping process. Obviously, brighter displays can reproduce brighter objects before having to compress the higher brightness values.

We use 8-bit video to drive our displays. A GPU Floating Point Dither operation is used to convert high-dynamic range floating point values to dithered 8-bit video in a power law perceptual video space with gamma typically set to 2.2. Interestingly, a high-dynamic range dither on 8-bit perceptual video is virtually artifact free even down to dark night and NVG stimulation levels. See companion paper [Lloyd, 2009] for support for this assertion.

RVR simulation must be repeatable. For given RVR conditions, the pilot must be presented with the same view of the environment. Accordingly, the simulation must be invariant under differing display setups and alignments. A Display Calibration function compensates for variances due to photometric and colorimetric characteristics of the given display.

## Atmospheric Models

RVR instrumentation [FAA, 2003] uses three basic internal sensors:

1. visibility sensor
2. ambient light sensor
3. runway light intensity sensor

The instrumentation computes two RVR values from the above sensor inputs:

1. RVR for surfaces/objects
2. RVR for lights

The reported RVR is taken as the larger of the two values. The instrumentation derives current surface/object RVR only from the atmospheric density using Koschmieder's Law [Koschmieder, 1924]:

$$C_t = e^{-\sigma R}$$

where: $C_t$: contrast threshold, taken as 0.05

σ: atmospheric extinction coefficient
R: RVR

In our RVR simulation, we reverse this to determine an atmospheric extinction given an instructor RVR setting, or:

$$\sigma = -\frac{\ln(.05)}{R}$$

Koschmieder's Law is not used at night. The basic FAA instrumentation specification [FAA, 2003] dictates that the Koschmieder RVR value be zeroed when the background luminance falls below 2 ft L (6.85 cd/m$^2$). However, we did not implement this threshold clamp since it would lead to RVR discontinuities at dawn and dusk as documented in [Seliga, 2008] and would result in abrupt changes in atmospheric extinction **(MOR)** during continuous time-of-day operations.

RVR instrumentation uses Allard's Law [Allard, 1876] to model the atmospheric effects on lightpoints in low ambient light and low visibility conditions. Allard's Law is stated as:

$$E_t = \frac{I}{R^2} e^{-\sigma R}$$

Where: $E_t$ = visual threshold in lux
σ = atmospheric extinction coeff in m$^{-1}$
R = RVR in meters
I = runway light intensity in candelas

Again, we reverse this process within RVR simulation to compute atmospheric extinction for current RVR, runway light intensities, and background illumination, or:

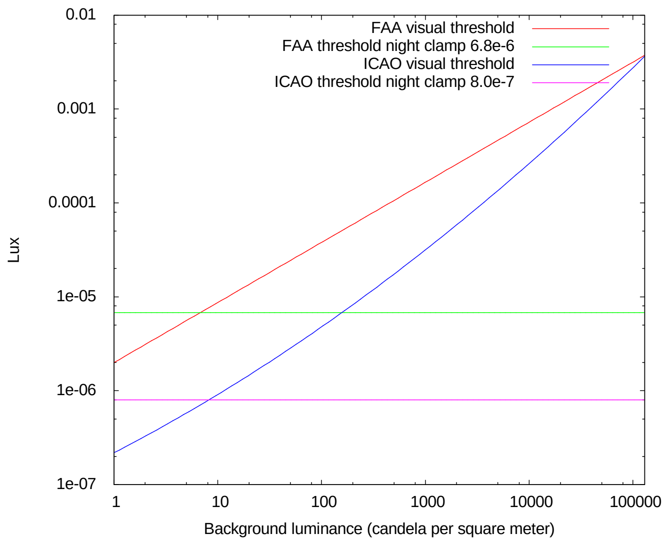


**Figure 4 FAA and ICAO Visual Threshold Functions**

$$\sigma = -\frac{1}{R} \ln \frac{R^2 E_t}{I}$$

$E_t$ is a function of background luminance. The FAA and ICAO define this function for instrumented RVR reporting systems as:

FAA $\log_{10} E_t = .64 \log_{10} B - 5.7$

Night threshold limit 6.8x10$^{-6}$

ICAO $\log_{10} E_t = .57 \log_{10} B + .05 (\log_{10} B)^2 - 6.66$

Night threshold limit 8.0x10$^{-7}$

See Figure 4.

To get an intuitive sense of these values, note that only the brightest star in the sky, Sirius at about 1e-5 lux, is brighter than FAA night limit while a total of twenty stars are brighter than the ICAO limit. Accordingly, using either of these functions proved to be problematic. The subjective approach to establishing RVR calibration in the simulator required the implementation of a custom visual threshold function.

## Tone Mapping

The underlying physics models of our RVR simulation assures that RVR presentations naturally and properly track over the full range of atmospheric densities and day/night/twilight illumination conditions. However, maximum real world luminance can easily exceed the maximum simulated luminance by factors of a thousand for white paint on a clear day, by tens of thousands for airport lighting, and by millions for the solar disk. We use the illumination tone mapping compression function

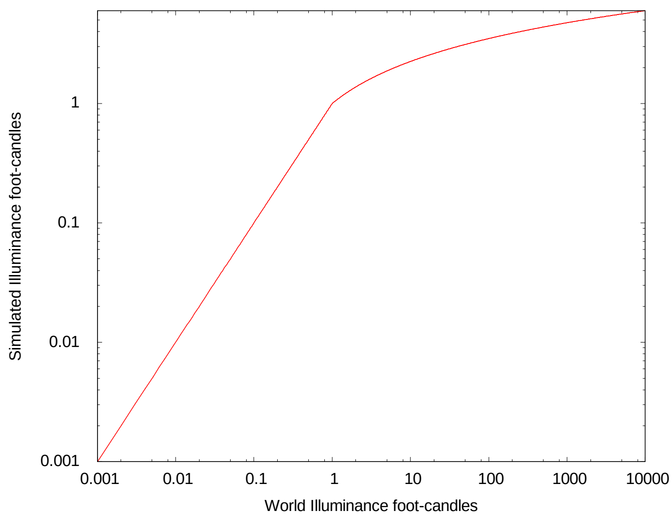


**Figure 5 Tone Map Compresses Photopic Range**

shown in Figure 5 to compress the photopic range of human vision in the final display. This tone mapping has the benefit of preserving physically accurate luminances for night vision goggle stimulation as well as avoiding the more difficult aspects of tone mapping operations for mesopic and scotopic vision. The values range from darkest moonless night to bright day. Displays with limited contrast ratio, i.e., high black levels also require compression at low levels to fully optimize display dynamic range usage. The function operates on both raster and calligraphic lights.

## Contrast Threshold Retention

The final tone map following high dynamic range rendering transforms the luminous object intensities into a displayable range. Retention of the original intensity at the visual contrast threshold is essential. Otherwise, RVR calibration would be adversely impacted. The worst case range of display luminance available for this tone map is computed in the following paragraphs.

Our maximum fog luminance level is forty percent of peak display luminance. Applying this background luminance to the FAA visual threshold function and solving for the visual threshold with FAA part 60 minimal requirement of a 5 arc-minute lightpoints with 20 cd/m$^2$ peak display brightness:

$$B = 20 * .4 \text{ background luminance cd/m}^2$$

$$A = \frac{\pi}{4}\left(\frac{5}{60}\frac{\pi}{180}\right)^2 \text{ lightpoint steradians}$$

$$\log_{10} E_t = .64 \log_{10} B - 5.7$$

The resulting FAA brightness at the visual threshold is:

$$\frac{E_t}{A} + B = 12.54 \text{ cd/m}^2$$

Similarly using the ICAO visual threshold function:

$$\log_{10} E_t = .57 \log_{10} B + .05(\log_{10} B)^2 - 6.66$$

And the ICAO brightness at visual threshold is:

$$\frac{E_t}{A} + B = 8.47 \text{ cd/m}^2$$

This leaves the luminance range from either 12.54 or 8.47 cd/m$^2$ through 20 cd/m$^2$ for the tone map. Our manually calibrated visual threshold curves are closer to the ICAO function rather than the FAA function.

## Validation

Blackwell's 1946 research "Contrast Thresholds of the Human Eye" provided invaluable data towards validating our tone mapping operations. Figure 6 plots Blackwell's Table VIII data along with the "critical visual angle" from Blackwell.

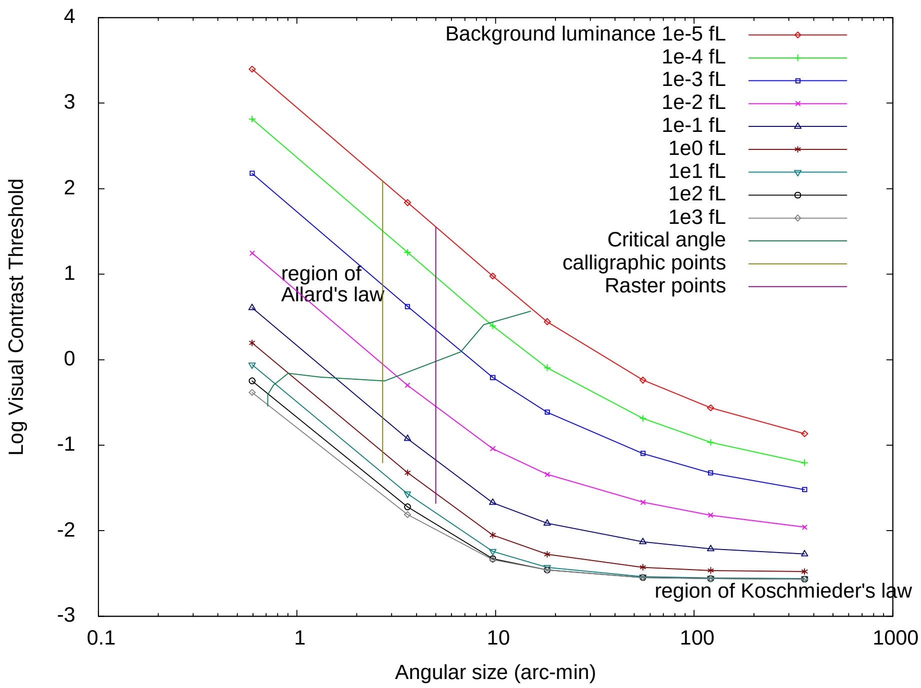


**Figure 6 Blackwell Data with Allard's and Koschmeider's Law Regions**

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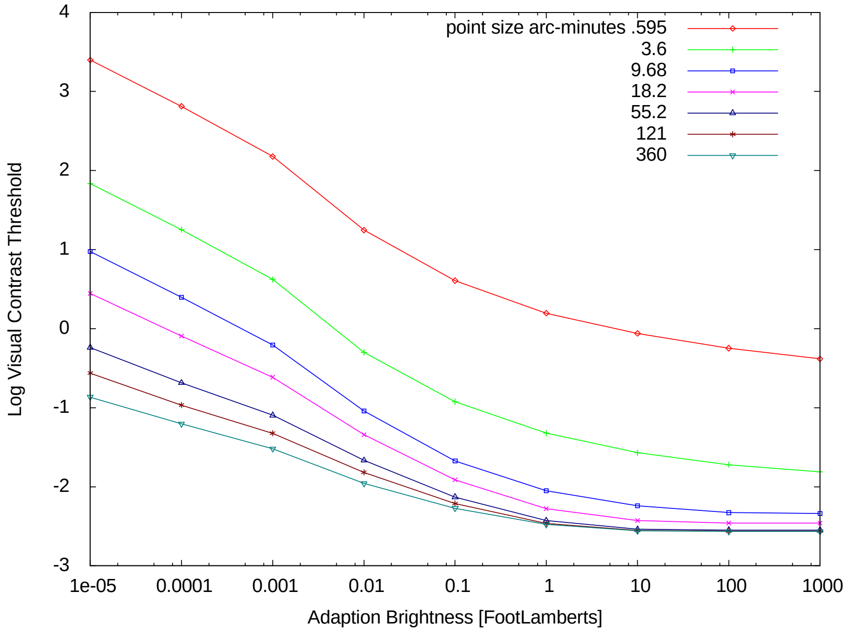


**Figure 7 Blackwell Visual Contrast Threshold By Adaptation Brightness**

Allard's law requires a "point source". Blackwell defines a "point source" with respect to the visual contrast threshold as one where the product of area and brightness is a constant. In other words only the energy of the light is important, not the angular extent over which it is spread. The "critical angle" line marks the transition where constant energy no longer holds. Our raster lightpoint size by regulation must be 5 arc-minutes or less. Dim calligraphic lightpoints have been measured at 2.7 arc-minutes. Our maximum background luminance is about 2.4 foot-lamberts or forty percent of peak display brightness. The vertical lines mark the range of raster and calligraphic lightpoints. At higher background luminance levels these points fall outside the "point source" region required for Allard's law. This error is minor with a worst case energy deviation from an ideal point source of about 10% and 20% for calligraphic lights and raster lights respectively. Since this error is a function of background luminance, it is compensated with our custom visual threshold calibration curve. Brighter displays require a decreasing lightpoint size to keep this error small.

Koschmieder's law contains a constant contrast threshold that only applies to black surfaces above a given background luminance. Blackwell states, "For a 121(arc)-minute stimulus, for example, there is no appreciable change in threshold contrast as adaption brightness is reduced from 100 to 1 foot-lambert". Illuminance tone mapping compresses real world illuminance values between one and ten thousand foot candles into a typical display range of one to six foot candles. As seen in the Blackwell data, this makes no significant change in the contrast threshold of large objects. So Koschmieder's law is unaffected by the illuminance tone map. As can be seen in Figure 7, small points of .595 and 3.6 arc-minutes do not have constant contrast thresholds over this range. Their contrast changes by about a factor of three. This is a function of background luminance and is compensated when the illuminance tone map is applied to lightpoints.

Relative intensity falloff of $1/R^2$ must be faithfully modeled at any given background luminance level to maintain RVR calibration accuracy. Accurate intensity across background luminance level changes is desirable for unlimited visibilities but minor deviations will be corrected by the custom visual threshold calibration curve.

## Physical Models

Without physical attributes for airport lighting and runway signage producing simultaneously consistent visibility of all airport elements is hardly possible. We attached new lightpoint attributes carrying candela brightness and physical light lens size to our existing airport models. Similar attributes are used to attribute internally illuminated airport signage with its surface luminosity.

Lightpoint angular size and surface brightness of are mapped to an appropriate rendered point spread function to represent a given light at a given distance. An initialization function computes the size and brightness of each available lightpoint profile. A selection function then chooses from among these profiles for the most appropriate representation for the light given its physical size and its raster/calligraphic attribute. Its intensity is determined strictly by the physical $1/R^2$ function.

We are continuing the refinement of the high-dynamic range tone mapping function as well as the set of available lightpoint profiles.

## Runtime Refinement

Our improved RVR simulation seeks fully deterministic operation. Ideally, a system with a properly calibrated display and properly assigned physical models will not require any interactive tweaking. However, the exigencies of the system certification and acceptance process require that we have an interactive facility to make refinements at runtime. Two such tools are shown in Figure 8 and Figure 9. The Figure 8 tool adjusts lightpoint sizes and candela ratings, and the Figure 9 tool adjusts lightpoint thresholds.

## ISSUES AND LESSONS LEARNED

Issues and lessons learned from this project are summarized below.

**User acceptance of scatter meter simulation –** As described above, airport scatter meters compute RVR values as a function of atmospheric density, currently runway light setting, and current ambient illumination. As a result, when Allard's Law is in effect and the user increases the runway light intensity setting, the RVR simulation adjusts the atmospheric extinction to retain the RVR setting, i.e., the lights get brighter but they are not visible any further downrange. This is a direct consequence of how scatter meters work and is counter-intuitive to many users. User education is often required

**Visibility acceptance –** Applying the principles of RVR simulation to the calibration of visibility (as distinct from RVR) as an aeronautical visibility was not well received. On approach, bright runway lights were visible too far past the specified visibility. Rather, treating visibility as cockpit-centric *flight visibility* is more acceptable, although this is not explicitly stated in the regulations. As the aircraft is positioned at increasing distance from the runway, a greater number of lightpoints visually coalesce into an area of increasing brightness. This requires a corresponding increase of the candela brightness of the "point source" input to Allard's law. This correction is applied for visibilities beyond the range valid for RVR.

**FAA and ICAO visibility limit acceptance** – Pilot evaluators did not accept standard FAA and ICAO visibility limits. The limits are far too conservative, although the ICAO values were closer to being acceptable. Our standard configuration uses thresholds derived from interactive tuning with pilot reviewers.

**Two ft-Lambert discontinuity –** As can be seen in figure 7 the contrast threshold of large objects is not constant at low light levels. Limiting the application of Koschmieder's law to luminance levels above two foot-lamberts prevents overestimation of RVR at the cost of gross underestimation and large discontinuities in reported RVR values just below the two foot-lambert threshold. Using the custom visual threshold curve along with a somewhat less conservative background luminance limit for Koschmieder's law alleviates this issue. Use of a variable contrast threshold at low light levels is being considered.

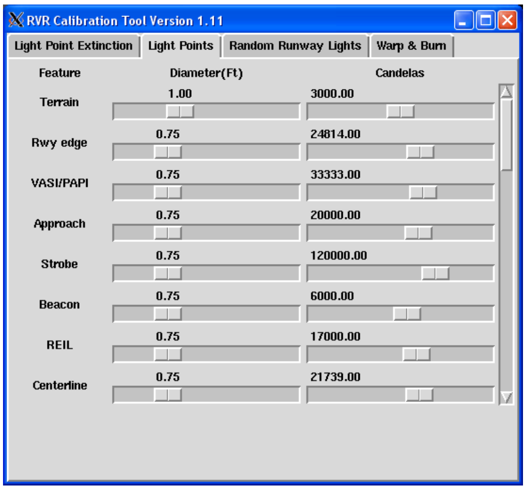


**Figure 8 Light Property Adjustment**

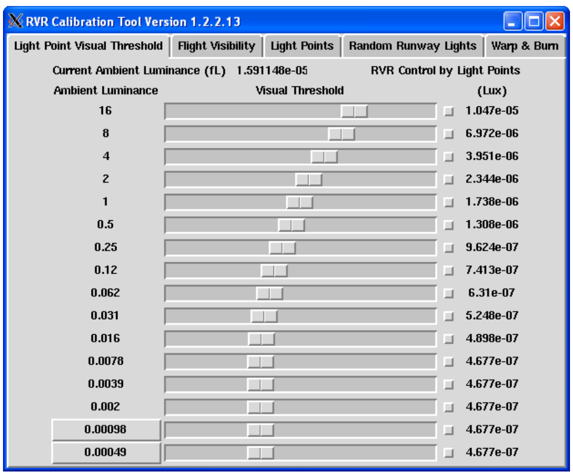


**Figure 9 Lightpoint Visual Threshold Adjustment**

## CONCLUSION

All simulator visual systems require tone mapping even if it is not acknowledged in their design. Our prior tone mapping functions involved a subjective artistic scene modeling approach as well as a number of ad-hoc functions in our image generating software. We achieved our goal of moving modeling from the subjective artistic realm to an objective reproducible physical realm without extensive airport database rework. This was essential for quickly achieving physically based RVR. We also achieved our secondary goals of easy calibrations, interchangeability of raster versus calligraphic lightpoints, and the portability of calibration values from system to system.

## ABOUT THE AUTHORS

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