RADIANCE Visual Comfort Calculation

Gregory J. Ward
LESO-EPFL

1. Introduction

This document describes a visual comfort calculation developed by the LESO group at EPFL during Spring of 1991. The calculation uses the RADIANCE synthetic imaging system [Ward90] to compute luminance values from a computer model of an architectural space and the lighting and daylighting of that space. These luminance values are then applied to a selected glare calculation procedure to arrive at one or more discomfort glare indices.

Visual comfort calculations are inherently difficult to perform because they depend not only on the locations and brightnesses of light sources, but also on the apparent size (ie. solid angle) of the light sources as seen from a particular viewpoint. By automating the calculation procedure, we hope to improve reliability and ease of use of visual comfort metrics. Plus, since we are starting from a computer model of a space, it is possible to use visual comfort as a design criteria instead of measure of what's wrong after it's too late.

2. General Approach

2.1. Calculation Requirements

Although there are several different visual comfort metrics in current use around the world, there is general agreement on the factors which influence discomfort glare, and the various glare calculations in fact start from the same basic quantities. These quantities are the directions, solid angles and average luminances of the light sources, and the background luminance for a particular viewpoint [CIE83].

Ultimately, it is luminance in different directions from a particular point that must be known in order to calculate glare values. Since a RADIANCE picture is nothing more than a collection of radiance values from a particular point, this is a very convenient place to start. Unfortunately, using such an image in a glare calculation requires a very large field of view (180 degrees vertically and 180+ degrees horizontally). It is possible to generate such images using the fish eye view types provided by RADIANCE, but this is not usually done. We therefore need to augment most pictures with additional luminance values lying outside the image borders. To calculate individual luminance values, we use the program *rtrace,* designed for this purpose. It is even possible to do without a picture altogether, although this will take longer since all the luminances will have to be calculated from scratch.

As a footnote to the above, it may be possible to obtain a luminance image from somewhere besides RADIANCE and use it to compute glare using the methods and programs described in this paper. However, this would require a fish eye image with a very large dynamic range, and this is difficult to obtain in practice.

2.2. A Two Step Method

Since there are so many different glare indices in use, and since they all require more or less the same input, which is difficult to compute, it makes good sense to create a two stage glare calculation. The first stage computes the locations, sizes and brightnesses of the light sources and the background luminance level, and the second stage computes whatever glare index is desired. Multiple glare indices may be computed at virtually no cost, and new indices may be incorporated in the future with very little programming effort.

An example output file from the first stage program *findglare* is shown below. This file contains the command that made it and the viewpoint, followed by the locations, sizes and brightnesses of the light sources and the adaptation luminance in each of the requested directions.

```
findglare -ga 10-60:10 -v -vf vf/living2 -av .05 .05 .05 oct/nightcabin
VIEW= -vth -vp 26.8 16.8 5 -vd -0.667 -0.745 0 -vh 180 -vv 180

BEGIN glare source
   Direction (dx,dy,dz)                 Size (sr)   Bright (cd/m^2)
   -0.739601   -0.666543   0.093333    0.004289     37.523939
   -0.543836   -0.798999   0.256598    0.004605   1743.527453
    0.555815   -0.795908   0.240000    0.004253    219.619154
    0.794861   -0.498014   0.346667    0.008012    150.790377
   -0.767600   -0.520973   0.373333    0.009203   1790.000000
END glare source
BEGIN indirect illuminance
  Angle (deg)   Ind. Ill. (lux)
       60      9.131035
       50      9.810535
       40      10.533606
       30      11.260834
       20      11.963897
       10      12.521309
       0       12.875862
       -10     13.017022
       -20     12.946500
       -30     12.743195
       -40     12.472590
       -50     12.174556
       -60     11.806406
END indirect illuminance
```

Calculating the indirect illuminance in multiple directions is relatively inexpensive and it permits the calculation of glare values in these directions, thus indicating how visual comfort is affected by head orientation. Below is example output from the second stage Guth visual comfort probability (VCP) calculation [Guth63].

```
-60   85
-50   76
-40   66
-30   58
-20   53
-10   57
  0   55
 10   62
 20   65
 30   71
 40   78
 50   84
 60   90
```

This particular glare index is interpreted as the percentage of people who would say they were comfortable in a given situation. We see above that the center of view (0 degrees), 55% of the people would be comfortable, and at 60 degrees to the right, 90% would be comfortable. It is apparent in this example that visual comfort is strongly influenced by view direction.

2.3. Limitations

The two step approach as we have implemented it here does have some limitations.

First, we have limited ourselves to looking at glare changes only to the left and to the right, and not up and down. This is not a very serious limitation, because what is considered "horizontal" can be changed by changing the view up vector. Thus, left and right can be relative to any head/neck orientation, even changing its meaning to up/down.

Second, the adaptation level is computed using the indirect vertical illuminance as the background level. This value is the integral of luminance over the hemisphere weighted by the cosine about the central view direction, and excludes any direct contributions from the glare sources themselves. Although this is the value recommended by most glare calculations, some researchers claim that a different weighting of hemispherical luminance is desirable to obtain the most accurate adaptation level. It is possible to implement a different background luminance calculation in *findglare,* but it doesn't make much sense to use different adaptation levels for different glare indices since they all use it for the same purpose. We therefore chose to compute only vertical illuminance because it is better defined and more commonly used.

Finally, there is some difficulty in deciding what exactly is a glare source in a particular environment. All existing glare calculations were designed with electric lighting in mind, where the light sources are easily separated from the rest of the visual environment as well as from each other. In a daylight situation, the distinction between what is and what is not a light source is not so clear. Furthermore, it is difficult to decide where to divide daylight sources since windows are often placed quite close together. The algorithms and heuristics we have chosen for separating light sources from the background work well in most cases, but require conscientious control when large windows are present in an already bright environment [DiPasquale91].

3. Findglare Algorithm

Findglare is the program that takes a RADIANCE picture and/or octree, locates the glare sources and calculates the background levels (indirect vertical illuminances) for a specified view field. The basic technique it uses is to sample the visual field for bright areas, designate these as light sources, and use the rest of the samples to compute the indirect illuminance (ie. background level). This method, as we discovered, is much simpler in principle than it is in practice.

3.1. Sampling Strategy

Findglare uses a modified hemispherical sampling strategy. If a single view direction is selected, *findglare* samples uniformly on the projected hemisphere. This means that the actual directions sampled will be densest near the center of view, and sparser near the limits of view. For multiple view directions, a central view slice is opened up, leaving the ends as two half-hemispheres. The vertical sample density will still vary as the cosine of the angle within the central slice, but the horizontal sample density will be constant over the specified view field. (See Figure 1.)

A projected hemispherical sampling was chosen over a simpler uniform sampling (ie. equal solid angle for each sample) because it results in more accurate, faster glare calculations. Since the sources near the center have greater importance in all glare metrics, it is important to define these sources more accurately. Sampling the projected hemisphere puts more samples near the center, assuring that any sources found there will be sampled adequately. Furthermore, the indirect illuminance is simply the sum of samples not striking light sources on the hemispherical sample grid. This means that we are not wasting time sending too many rays to one part of the visual field at the expense of accuracy in another part. This is particularly important when the samples are coming from *rtrace* rather than a RADIANCE picture, since these samples involve new luminance calculations.

The maximum sample density is set with the *−r* (resolution) option, and is not adjusted adaptively by the program. Adaptive sampling might prove beneficial if very bright, small sources (such as the sun) are present in the visual field, but it is unnecessary for most environments. If all the samples needed are present in an input picture, it is relatively inexpensive to use a high sample density in the calculation, but it doesn't make sense to use a higher resolution than that of the input picture.

3.2. Identifying Sources

In manual glare calculations, light sources are usually delineated by the analyst's own notion of what is and is not a light source. In the case of direct electric lighting, this is an easy choice, but when the lighting is indirect or from one or more windows, the choice is less clear. The choice ought to be made based on viewer adaptation. If a particular direction is especially bright compared to the rest of the visual field, it should be considered as a glare source. This relative brightness criterion may or may not agree with one's intuitive notion of a light source. For windows in particular, there may be bright and dark areas of the view outside, and only part of the window may be bright enough to really act as a glare source. Likewise, parts of the window may be so bright that they completely drown out the electric lighting in a space, and the electric lights themselves may not be sources of glare in a daylighted environment.

The basic approach used by *findglare* to identify glare sources is called "thresholding". If a particular direction in the visual field is above a designated threshold value, then it must be part of a glare source. If the threshold value is not set by the user manually, it is obtained empirically by findglare by multiplying the average luminance of the visual field by 7. The number 7 was determined by some crude tests as producing a reasonable threshold for most scenes. Using an empirically derived threshold is not always the best approach, however, and that is why a manual threshold setting is provided. The user may use the program *ximage* or *rtrace* to obtain a threshold value that agrees with his or her notion of a glare source for that particular scene. Since there have been no studies, we do not know in general what value should serve as the threshold for a glare calculation. This is an important question, which certainly merits further investigation [DiPasquale91].

When a "glare sample" (ie. a sample above the threshold value) is found, it is merged with neighboring contiguous glare samples. Two glare samples are considered contiguous if they are separated by at most one non-glare sample. This allowed separation is to avoid the breakup of something like a window with venetian blinds into an unreasonable number of sources. Note that a glare source may have any number of holes in it and still be considered contiguous.

3.3. Splitting Sources

In order to avoid very long sources that might produce errors in the glare calculation due to their spread in the visual field, a heuristic test is applied to each glare source. If a source has a solid angle greater than 0.025 steradians and a linearity (linear regression correlation coefficient of its samples) of 0.8 or more, it is split into two smaller sources of roughly equal area. This continues recursively until the resulting pieces are compact by these criteria.

3.4. Merging Sources

If a source is very small and not very bright, it should not be treated as a glare source in most situations. Therefore, any source whose solid angle times its average luminance (ie. it's total emission) is less than 0.005 steradians times the threshold luminance is either merged with neighboring sources or "absorbed". A small source is merged with a neighboring source if that neighbor is closer than 4 times the radius of a 0.005 steradian disk. If no suitable neighbor exists, the source is absorbed by adding its contribution back into the background level and removing it from the list of glare sources.

Since it is not always desirable to remove small sources in this manner, a *−c* option is provided to tell *findglare* to use all sources it finds, no matter how small.

3.5. Indirect Illuminance

The indirect vertical illuminance values are computed for each selected view direction. If a single view direction is selected, the indirect illuminance will simply equal the sum of all non-glare samples. If multiple view directions are selected, *findglare* will weight each sample appropriately for each vertical direction. The total number of samples used is determined by the requested resolution and the width of the view field. It is not affected by the number of view angles within the view field, so increasing the number of view angles without increasing the width of the view field does not add much to the calculation time.

4. Glare Index Calculation

Thus far, we have implemented only two glare formula calculations, the Guth visual comfort probability and the CIE glare index due to Einhorn. Implementing other glare formulas is straightforward, but it was not clear to us which other formulas were useful. It seemed to us that providing a multitude of very similar formulas would not be very helpful to the designer.

The Guth visual comfort probability (VCP) is related to the more basic Guth discomfort glare ratio (DGR) by a simple formula. The DGR in turn is related to the background luminance, source locations and sizes, and source luminances. This information is given by *findglare* with the exception of background luminance. This term is somewhat poorly defined by Guth, so we take the indirect vertical illuminance and divide it by π to get the background luminance averaged over the projected hemisphere. The Guth calculation method is explained in detail in [IES84].

The CIE glare index (CGI) is the modified Einhorn equation given in [CIE83]. This formula is similar to the Guth DGR, but with a linear relationship to the source solid angle that results in better additivity (ie. breaking up light sources differently does not affect the results). The Guth position index is used by this formula as well, and its calculation is described in [Levin75]. Unfortunately, the CGI formula does not have a counterpart to the Guth visual comfort probability. Thus, the CGI value is a little harder for the designer to interpret than a simple percentage of satisfied customers. Nevertheless, this is the formula that is recommended by the CIE and therefore we take heed because it is a standard. Hopefully, the CIE will propose a correlation between their CGI value and VCP in the not too distant future.

5. Glare Script

To make *findglare* and the glare index calculation program *glarendx* easier to use, a script was written that asks the user simple questions before running these programs. This script also runs the program *xglaresrc* to identify sources in a displayed image that have been located by *findglare.* After finding the glare sources and displaying them in an image, the script *glare* allows the user to calculate the desired glare index. This index may be plotted as a function of view direction using the program *igraph,* and the plots may be sent to the printer. An example run of this script is shown with its output in the appendix.

6. Conclusions

The glare calculation presented here has undergone a partial validation and has been found to be reasonably accurate when compared to manual calculations of a daylighted office [DiPasquale91]. The calculation has also been compared with some simple test geometries to insure that it was performing as expected. Perhaps the most unreliable part of any glare calculation is the setting of the threshold which determines what is and is not considered as a glare source. Especially in daylight situations, this can have a large influence on the results of the calculation.

Further study is required into the nature of discomfort glare from daylight windows, since all of the existing glare formulations were developed and tested using electric light only. Although Guth claims that his formula is valid for large area sources and sources near the center of view, the sensitivity of the eye to light impinging from below the horizontal plane has not been studied adequately, and this is a frequent condition in daylighted spaces.

We believe that the institution of a general, automatic glare calculation is a very important step towards making visual comfort metrics practical for the designer. RADIANCE offers the advantage of considering all sources of glare in a simulated visual environment, not only from electric lights, but also from windows and reflections from specular surfaces.

7. References

[CIE83] Commission Internationale de l'Eclairage, ''Discomfort Glare in the Interior Working Environment,'' CIE Publication No. 55 (TC-3.4) 1983, pp. 15-18.

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[Levin75] Robert Levin, ''Position Index in VCP Calculations,'' *Journal of the Illuminating Engineering Society*, January 1975, pp. 99-105.

[IES84] John Kaufman, *IES Lighting Handbook*, Reference Volume, IESNA, New York, NY, 1984, pp. 9.46-9.49.

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