# 3D Eyebox in Augmented and Virtual Reality Optics

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## Abstract
***The eyebox volume is a key design parameter in the optical design of augmented and virtual reality optics. The extent of the eyebox volume determines the experience of a user in seeing the entire virtual magnified image. Furthermore, a 3D description of eyebox facilitates the design of augmented and virtual reality products for a population of users. We define 3D eyebox and discuss visualization approaches to communicate it within interdisciplinary product design groups focused on research and development of augmented and virtual reality optics.***

## Author Keywords
Eyebox; augmented reality; virtual reality; eyewear displays; near-eye displays; head-worn displays; AR; VR

## 1. Introduction:

In all head-worn augmented or virtual reality displays, the eyebox volume plays a central role in user experience. The eyebox volume is critical in determining fit requirements (e.g., coverage for a population of users) for head-worn devices. The "eyebox" volume is loosely defined in the literature as a 3D volume in space within which the pupil of an eye must be positioned in order to satisfy a series of viewing experience criteria. One such criteria is that the user can see the four edges of the magnified virtual image. Multiple criteria can be included in the definition but we emphasize the importance on nonuniformity with resolution as a secondary criterion. This results in an eyebox that is not box-shaped at all, but encloses an anisotropic volume.

At the time of this writing, we are unable to cite a comprehensive definition for eyebox that can be applied in optics simulations or used in lab measurements. For example, some optical designers refer to unvignetted pupil dimensions at the nominal eyerelief plane; some refer to the amount of motion a pupil of a particular diameter can have; others include some illumination falloff criterion in their definitions [2, 3]. None of the commercially available head-worn display products explicitly specify their eyebox definition. In summary, there is no consistent usage and definition of eyebox that can be applied to near-eye optical system design at the time of this writing.

There are various ways of classifying augmented and virtual reality optics. It is possible to organize the optical architectures for augmented and virtual reality optics by field of view, form factor, and mode of operation (optical see-through, video see-through, or occluding (virtual reality)). Another classification with respect to optics is whether the optical design is pupil forming or not. Pupil-forming and non-pupil-forming systems can have very different eyebox characteristics.

In this context, pupils are images of the aperture stop. In a pupil-forming system, we are mostly concerned with the exit pupil (the location at which chief rays cross the optical axis). An example of pupil-forming optical system is a telescope composed of an objective lens and an eyepiece. The pupil-forming system will form an exit pupil at the nominal eyerelief. The exit pupil can be imaged on a screen such as a piece of paper. That is, there will be a real image of the pupil, for example, a disc shaped image (assuming circular aperture within the optical system), on the piece of paper when the paper is held at the exit pupil location. In a pupil-forming system, the exit pupil of the optics is matched in location with the entrance pupil of a human eye. Typically pupil-forming systems are more sensitive to optic exit pupil and eye entrance pupil location matching.

An example non-pupil-forming system is a magnifier. If you hold a piece of paper at the nominal design position of a user's pupil, in a magnifier system you will not see a disc of light. For near-eye display applications, magnifiers (non-pupil forming) are generally preferred due to their compactness and weight.

## 2. Definition of 3D Eyebox

To define the 3D eyebox, where the definition has a practical application in simulation and lab measurements, we conceptualize a 3-dimensional evaluation volume V in space (units mm^3) as illustrated in Fig. 1. The volume V is evaluated given a pupil diameter D, emission cone extents in angle, source configuration (e.g., cross pattern), a set of criteria C, and thresholds T for the criteria. The result of the evaluation is the eyebox volume E. A summary of quantities involved in the definition of 3D eyebox is provided in Table 1. Note that the pupil plane is about 3.5 mm inside the cornea. Eyerelief is typically defined from the instrument to the cornea, however, for eyebox analysis we are primarily concerned with the pupil plane. For each criterion in C, a threshold must be specified. As these thresholds vary by application, we cannot expect a universal agreement on how these thresholds should be set. This poses a problem in comparing the eyebox specifications across systems. Therefore, the thresholds must be reported along with the other parameters discussed above to obtain a clear understanding of a simulated or measured 3D eyebox volume.

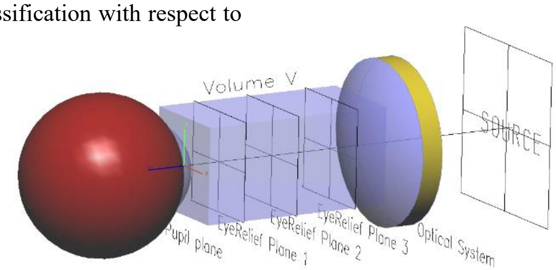


Figure 1 The eyebox is a volume E that is the result of evaluating a given volume, V, pupil diameter D, set of criteria C and corresponding thresholds T, an optical system, and emission cones (often asymmetric) from a lightsource. In this figure, the blue box represents the evaluation volume, V. As a user looks at portions of the field of view, their pupil will rotate about the center of rotation of the eye. Three eyerelief planes are illustrated within volume V as an example sampling plan (lateral sampling not shown).

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| Quantity | (units) Notes |
|---|---|
| Evaluation volume (V) | ($mm^3$) |
| Nominal eyerelief (ER) | (mm) Defined from closest eyefacing point on optic to cornea |
| Sampling plan | - Number of eyerelief planes<br>- Number of lateral samples at a particular eyerelief |
| Pupil diameter (D) | (mm) |
| Field of view along two dimensions | (degrees) Horizontal and vertical, full extent |
| Emission cone along two dimensions | (FWHM, degrees) LCOS and LCD microdisplays have asymmetric emission cones. |
| Source configuration | - Number of field points<br>- Location of field points (e.g., in a cross pattern, includes corners or not). Location of the field points may consider a "safe zone", for example, 90% of the field of view. In addition, distortion of the optics may be considered in placement of sources.<br>- Size of field points |
| Set of Criteria (C) | Example criteria, not exhaustive:<br>- (Michelson %) Global Nonuniformity<br>- (Michelson %) Local Nonuniformity<br>- (% lum/deg) Gradient of uniformity across the field<br>- (arcminutes) Resolution<br>- (diopters) Field curvature<br>- (% distortion) Distortion<br>- Lateral color<br>- (Δ% distortion/ pupil shift) Pupil swim [4]<br>- (ΔE2000) Color uniformity<br>- Artifacts |
| Thresholds for C (T) | Each criterion has a corresponding threshold. Thresholds determine the isocontours for each eyerelief slice. |
| Eyebox volume (E) | ($mm^3$) Subset of V satisfying all criteria C and thresholds T for the given pupil diamater and safe zone requirements. |

Table 1 Summary of quantities involved in definition of 3D eyebox.

### *Eyebox geometry*

The first order unvignetted eyebox (UE) diameter for a pinhole pupil at the eyerelief plane, depends on the diameter of the collimator optic (DO), eyerelief from the cornea to the optic (ER), focal length of the optic (f), as well as the half-diagonal length dimension of the microdisplay (M).

$$UE = DO - \frac{2 \cdot M \cdot ER}{f} = DO - 2 \cdot tan(\theta) \cdot ER$$

θ is the half-diagonal field of view. Note that our discussion is for the case where the microdisplay is placed at the back focal length of the magnifier and the image is at infinity. The discussion will have to be extended for multifocal or variable focus systems, which we do not cover here. We can see that the 2D eyebox reduces linearly to first order with increased field of view and eyerelief. Lagrange invariant is an alternative approach for seeing this relationship. Assuming circular apertures and no vignetting, the eyebox volume in 3D can be approximated as a cone and the eyebox volume will decrease proportional with the square of the field of view for fixed focal length. The first order eyebox geometry, along with the impact of emission cone, and eye rotation and decentration is illustrated in Fig. 2.

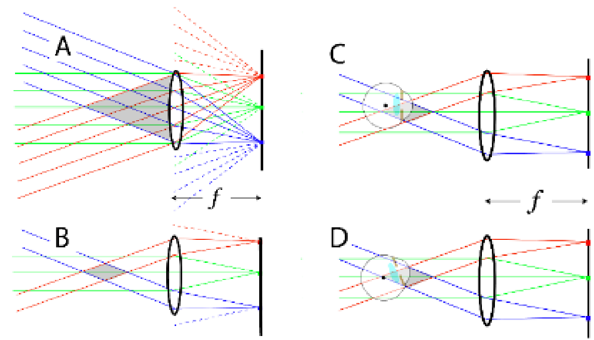


Figure 2. A) In case of a broad emission cone (e.g., an OLED emitter), there is a triangular shape area behind lens within which entire virtual image is visible. B) With narrow display emission, there is a diamond-shaped region at a particular relief distance in which the full image is visible (assume pinhole pupil). In order to see a complete image, a pupil of the eye must receive rays from all parts of the field. If the pupil is not filled, there is vignetting, that is, dimming of corresponding portion of virtual image. C) User looking at center pixel. Representative of an as-worn state where there is a mismatch between nominal design pupil and actual use, for example IPD mismatch between design and as-worn state. The user perceives the top portion of the image dimmer D) The eye is rolled upwards to look at the top edge of the virtual image.

## 3. Case study: An eyepiece

In this section, we use an off-the-shelf eyepiece from Edmund Optics (part #30-941) and simulate the 3D eyebox of this eyepiece. This eyepiece is designed by Edmund Optics to have a full field of view of 45 degrees, an 18.8 mm eyerelief, and an effective focal length of 21.5 mm. The eyepiece consists of 3 all-refractive elements. The optical layout of the eyepiece along with optical performance in visual space is shown in Fig. 3. The optical prescription of the eyepiece can be downloaded from the Edmund Optics website. When the eyepiece is used with a 10 mm diameter object, the full field of view is about 27 degrees, and the eyepiece is limited by astigmatism and lateral color, however, still performs at <3 arcminute RMS spot diameter resolution given +0.7 diopter of refocusing of a user's eye. For this case study, we use illuminance nonuniformity at the retina as the criterion. We define nonuniformity using Michelson contrast: (max−min)/(max+min) consistent with the standard specs for heads-up displays, typically used in automotive industry [1]. A nonuniformity value of 1

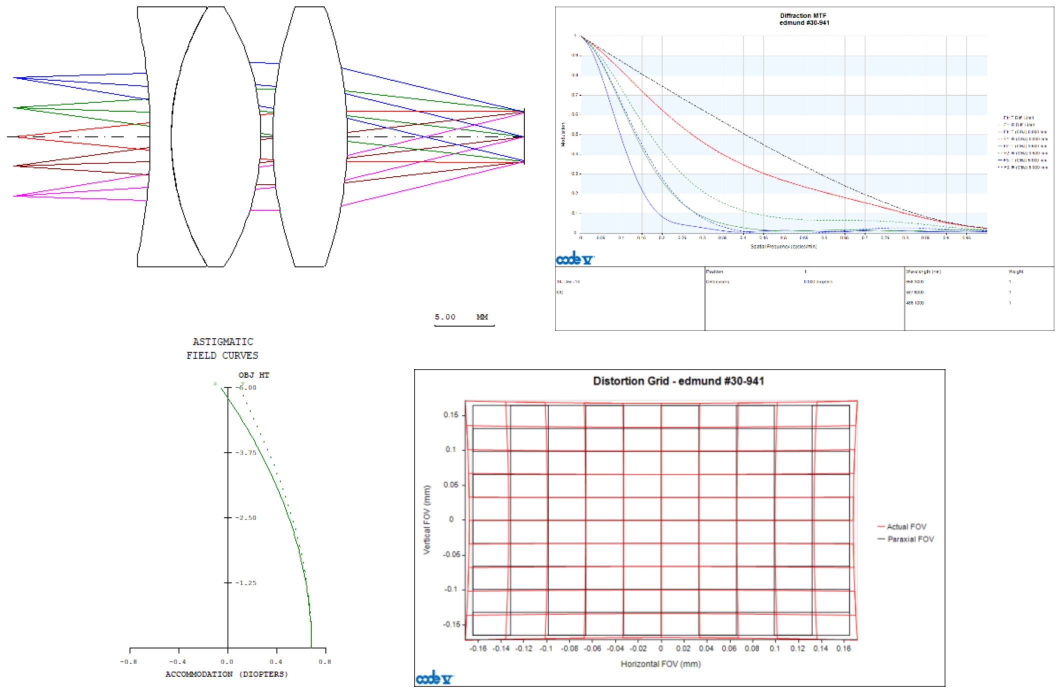


Figure 3 (top left) Optical layout for off-the-shelf Edmund Optics part #30-941 eyepiece. (top center) Optical performance (MTF in visual space with units cycles/arcminute) of the eyepiece with accommodation allowed (bottom left) Maximum field curvature is +0.7 diopters (bottom right) distortion grid.

indicates that at least one of the source points cannot be seen for a particular eye position. A nonuniformity value of 0 indicates that all points taken in the nonuniformity calculation have the same retinal illuminance value. Lower nonuniformity values are desirable. An example illuminance simulation is shown in Fig. 4 for 5 sources in a cross pattern.

## 4. 3D Eyebox Modeling and Visualization

We used LightTools to model the light collected by the viewer's pupil. The method described here can be applied in other raytrace codes as well. We construct an optical model of an off-the-shelf eyepiece, emission cones, and a 17 mm focal length perfect lens representing a human eye. The volume V in this case is 24x24x26 mm^3 (24 mm^2 laterally, 26 mm along eyerelief).

The volume V for this testcase is evaluated with 5 sources arranged in a cross pattern. The lateral dimension of the sources are 100 microns square. The emission cone is symmetric in this case and has a FHWM of 47 degrees symmetric along both dimensions. The human eye is modeled as a perfect paraxial lens with a 17 mm focal length. The pupil diameter (D) of the paraxial lens is set to 4 mm. We sampled the eyerelief within volume V at 6 planes. For each eyerelief plane, we sampled volume V at 11 x 11 locations laterally. The criterion (C) is nonuniformity. The threshold (T) on C is set to 50%. A safe zone is not used. A total of 726 simulations are performed that generate the slices for the 3D eyebox surface. Eyeroll is not taken into account in this early work.

One 11x11 nonunifomity slice from this run at the nominal eyerelief plane is shown in Fig. 5 as a heatmap. The x and y axis of the heatmap correspond to the (x,y) location of the pupil at nominal eyerelief plane (z=0), and the value in the heatmap is the nonuniformity of the 5 sources as viewed through the optics. Each discrete slice from each eyerelief location can be stitched together to plot the 3D eyebox surface. In Fig. 6 (top), we show the output from a MATLAB function `isosurface` that is used to plot the nonuniformity isocontours for a 50% threshold value. The resulting red surface is the eyebox surface E. As long as the center of the pupil is within this red eyebox surface E, a user can view the virtual image that meets criteria C for threshold T. As a convenience, we note that the `isosurface` function outputs faces and vertices, which facilitates converting eyebox surface E to an STL file format, suitable for use in commercial CAD software and 3D printers.

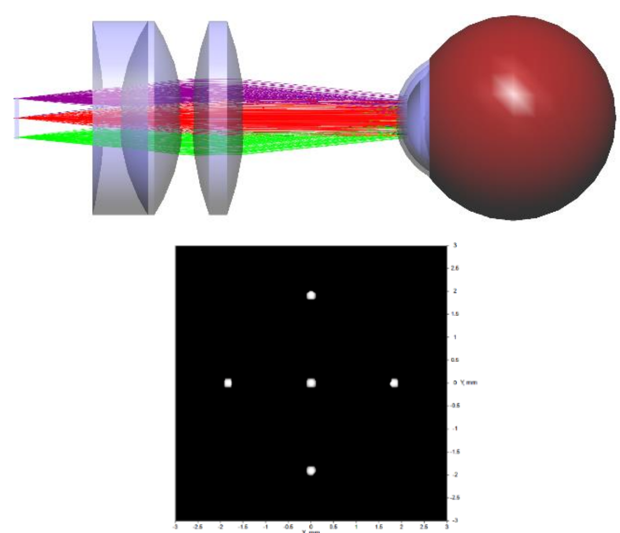

Figure 4 (top) Nonuniformity simulation model of source, eyepiece, and eye model (bottom) Illuminance of 5 sources at the retina.

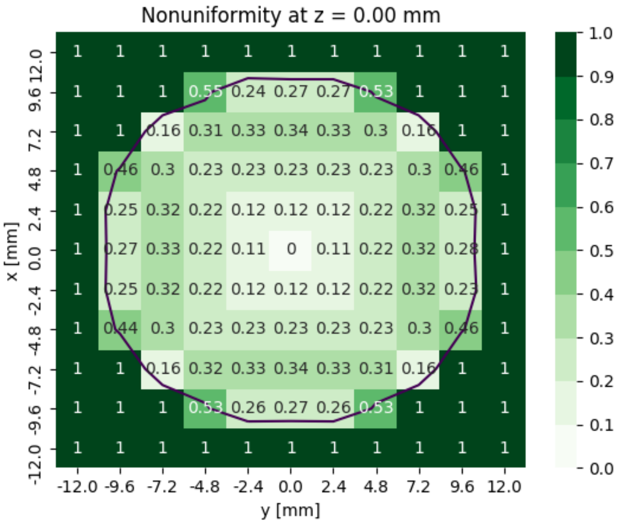


Figure 5 11x11 Nonuniformity slice at the nominal eyerelief plane. The center of the pupil is moved +/- 12 mm laterally along x and y. The threshold for nonuniformity isocontour is set to 0.5.

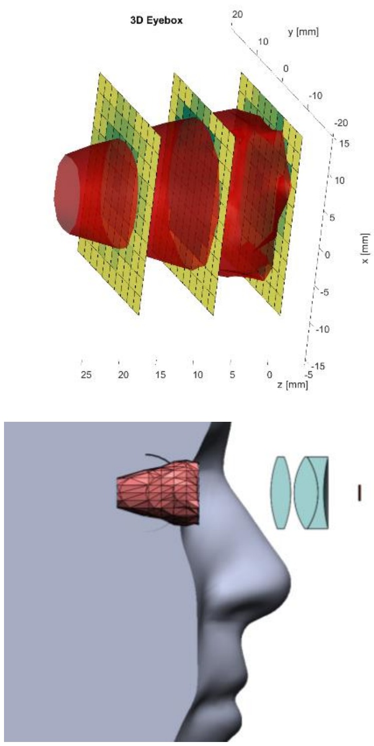


Figure 6 (top) 3D eyebox surface generated from the 24x24x26 mm^3 evaluation of the volume with the 50% nonuniformity criterion. The volume V was sampled at 6 eyerelief distances and 121 (11 by 11) pupil locations laterally at each eyerelief. 100k number of rays were traced per source. Total runtime was 10 hours (bottom) 3D eyebox STL shown at nominal eyerelief plane, the eyepiece optics, and the source.

## 5. Handling more than one eyebox criterion

For each pupil location in the sampling plan, all of the criteria are calculated. Each criterion becomes a 2D array of values at a particular eyerelief plane. It is possible to handle multiple criteria by simply treating each criterion slice as a binary mask. For each criterion that is calculated, its corresponding threshold is applied. If the criterion at a particular pupil location is above its corresponding threholds, it is marked with 1, otherwise marked with a 0. Multiple criteria can be combined using a logical AND across the slices. This is illustrated in Fig. 7. The 3D eyebox isosurface would now be generated from the resulting slice that incorporates multiple criteria (in this example nonuniformity and resolution).

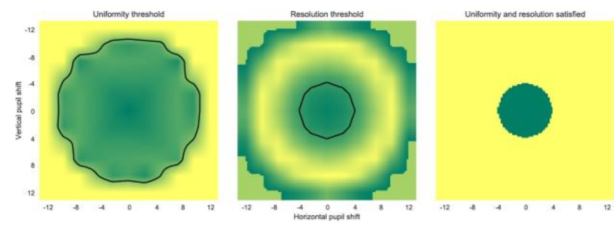


Figure 7 (left) Nonuniformity as a function of pupil location with threshold isocontour (center) Average RMS spot diameter in arminutes as a function of pupil location with threshold isocontour (right) combined region that meets both criteria.

## 6. Conclusion

We provided a definition for 3D eyebox and illustrated the definition with an off-the-shelf eyepiece. Nonuniformity has been used as the primary criterion. It is possible to handle multiple criteria with this approach. In our experience, a 3D visualization of the eyebox facilitates communication across interdisciplinary groups involving designers with various backgrounds (optical design, mechanical engineering, product design, user experience, human factors, and so on) typically involved in design and development of augmented and virtual reality optics.

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