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# Design of an eye limiting resolution visual system using commercial-off-the-shelf equipment

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**A feasibility study was conducted to determine if a flight simulator with an eye-limiting resolution out-the-window (OTW) visual system could be built using commercial off-the-shelf (COTS) technology and used to evaluate the visual performance of Air Force pilots in an operations context. Results of this study demonstrate that an eye limiting OTW visual system can be built using COTS technology. Further, a series of operationally-based tasks linked to clinical vision tests can be used within the synthetic environment to demonstrate a correlation and quantify the level of correlation between vision and operational aviation performance.**

## I. Introduction

THE United States Air Force tasked NASA's Ames Research Centers Simulation Laboratories and Human Factors organizations with conducting a feasibility study to determine if a flight simulator with an eye limiting resolution out-the-window (OTW) visual system could be built using commercial off-the-shelf (COTS) technology. This simulator would be used to evaluate the visual performance of Air Force pilots in an operations context. The project is known as the Operational Based Vision Assessment (OBVA) program. The objective of the OBVA program is to provide the Department of Defense with more accurate criteria and understanding of vision requirements that reflect actual operational tasks. This new understanding of visual criteria will be used to determine the validity of existing Air Force vision standards, as well as to assess proposed new standards. The OBVA program will enable the Air Force to conduct studies to investigate the correlation between operational task performance and vision in the controlled environment of a high-fidelity simulator. The Air Force currently maintains standards for visual acuity, color, depth perception, eye alignment and coordination, and peripheral vision. Many of the clinical criteria used today evolved from measuring "successful" and "superior" aviators' visual attributes during and after World Wars I and II, but there exists little scientific basis for determining how variance from these standards will affect operational performance. In addition to determining the validity of these standards, the Air Force is also interested in studying the effect of other visual characteristics (e.g. contrast sensitivity, attention, dynamic visual acuity, low-light performance) as well as medication on operational performance.

Most operational tasks are likely to be influenced by pilot vision. For example, fighter pilots are familiar with the operational tasks of "find, fix, target, track, and engage" or "$F^2T^2E$". Visual acuity is expected to be a major factor in this type of task; a pilot with 20/20 vision would need to be twice as close to an operational threat compared to a pilot with 20/10 vision. This might also be a factor affecting collision avoidance. Depth perception is believed to be important in formation flight, aerial refueling, and landing. A color vision defective pilot potentially needs to more closely approach such threats and terrain to "interpret" the scene, in addition to the difficulty of interpreting multi-color displays.

Two factors were identified as challenges in developing and using a flight simulator for evaluating visual performance. First, the majority of simulator visual systems in current operation and/or COTS technologies do not typically present visual information at a level of fidelity necessary for the repeatable systematic comparisons of pilots that are required to conduct this work. Second, vision is only one factor that contributes to the overall performance of a pilot; differences in attentional, motor, and cognitive skills can easily mask the effects of visual differences when measuring human performance.

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This paper discusses the feasibility study and resulting demonstration addressing the challenges associated with developing an out-the-window (OTW) visual system with sufficient fidelity for use in this research simulator, using COTS equipment. Several candidate COTS projectors are identified and visual system configurations are illustrated. It also describes several operationally based tasks linked to clinical vision tests. Scenarios developed from these tasks can be used within the synthetic environment to demonstrate the correlation and quantify the level of correlation between vision and operational aviation performance.

## II. Eye-Limiting Acuity in Terms of a Digital Image

The term or phrase "eye-limiting resolution visual system" can be very misleading unless it is put in proper context. The term "eye-limiting" implies that the resolution is being related to the characteristics of the human eye.

### A. Human Visual Acuity

To accurately describe eye-limiting, one must first understand how acuity is determined and the factors affecting acuity.

#### *1. Static Visual Acuity*

Nearly everyone is familiar with visual acuity examinations performed using an eye chart. Typically the examinee is asked to read the letters from a chart that is typically mounted on a wall at a distance of twenty feet from ones eye point. The Snellen chart (as seen in Figure 1), has eleven lines of block letters. The first line consists of one very large letter with subsequent rows that have an increasing number of letters that decrease in size. The symbols on the chart are referred to as "Optotypes." The smallest row that can be read accurately from a distance of 20 feet indicates the patient's visual acuity in the eye being tested. The numbers to the right of each row of letters indicate acuity of that line. If one could only read the top line then he or she would have 20/200 acuity, if he or she could read the bottom line then he/she would have 20/5 acuity. The first term in the acuity number is the distance from the eye point to the chart and the second number indicates how far a person with 20/20 acuity would have to be from the chart to clearly recognize the letter. Hence, a person with 20/5 acuity can see an object 20 feet away whereas a person with 20/20 acuity would only be able to clearly see the same object a distance of 5 feet. Conversely, a person with 20/20 acuity can clearly see on object at a distance of 70 feet that a person with 20/70 acuity could only clearly see at a distance no further than 20 feet. Optotypes have a geometry in which the thickness of the lines equals the thickness of the white spaces between the lines and the height and width of an optotype is five times the thickness of the line. Only nine letters are used in the Snellen chart, they are C, D, E, F, L, O, P, T, and Z.

The Air Force primarily uses a standard vision testing device, currently the OPTEC 2300 Vision Tester (Figure 2), to determine visual acuity and other visual measures[1] (such as color vision and depth perception).

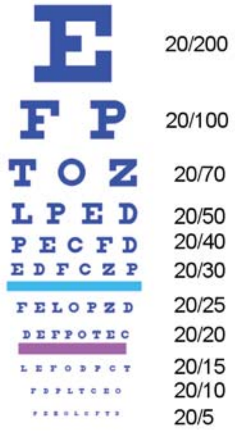

**Figure 1. Snellen Eye Chart**

**Figure 2. OPTEC Vision Tester**

#### *2. Dynamic Visual Acuity*

Humans typically have an instantaneous visual field (without eye or head movements) of approximately 200 degrees horizontal by 135 degrees vertical[2]. Highest visual acuity is achieved in the one-degree central portion, the foveal visual field. In order to retain good visibility of a feature that is moving, the eye must move to keep the feature in the foveal visual field.

Humans have two distinct types of voluntary eye movements: pursuit, which smoothly moves the eyes to track a moving target; and saccades, which ballistically and rapidly reorient the eye. It is pursuit eye movements that allow humans to retain good visual acuity even when the feature of interest is moving relative to the observer[‡]. Typically,

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[‡] Relative visual motion can be caused by observer motion (as in a moving vehicle or locomotion) and/or target motion.

humans can generate eye speeds that nearly match target speeds (i.e., gains in excess of 90%) with few catch-up saccades necessary for target speeds up to about 30 or 40 deg/s and can perform effectively up to about 60 deg/s where saccadic tracking then begins to dominate[3]. Pursuit eye movements will start for image motion of 0.5 to 1.0 deg/sec. Visual acuity does degrade with pursuit speed due to imperfect tracking; as described in ref. 4, visual acuity degrades by approximately .5 arc min per 10 degrees/sec of stimulus motion.

### 3. *Effect of Contrast Sensitivity*

Contrast in an image is created by a difference in light and dark areas of an image, or differences in luminance. When luminance difference drops below a certain threshold, image features cease to be visible. The measure of contrast typically used in clinical vision applications is the Michelson[5] formula:

$$C = \frac{L_{MAX} - L_{MIN}}{L_{MAX} + L_{MIN}} \tag{1}$$

where $C$ is contrast, $L_{MAX}$ is maximum luminance, and $L_{MIN}$ is minimum luminance. The highest achievable value for contrast is C = 1, corresponding to $L_{MIN} = 0$ (meaning the darkest darks are completely black). Human ability to discriminate luminance differences is a function of the spatial frequency of the feature, or the level of detail. This characteristic of human vision is called contrast sensitivity; the way in which contrast sensitivity varies with spatial detail is captured by the contrast sensitivity function. Typical human contrast sensitivity[6] is shown in Figure 3, and can be easily visualized with the Campbell-Robson Contrast Sensitivity Chart[7] in Figure 4. Contrast sensitivity is defined as the inverse of the contrast threshold (Contrast Sensitivity = $1/C_{\text{threshold}}$). The minimum contrast sensitivity is unity, corresponding to the point of maximum achievable contrast (as defined in Equation 1) of unity. Visual acuity measurement stimuli, typically black letters on a white background, have contrasts close to or equal to maximum achievable contrast of unity. As such, the typical visual acuity measurement represents only one point on the contrast sensitivity function: the spatial frequency at which the contrast sensitivity function intercepts the x-axis at a contrast sensitivity of unity.

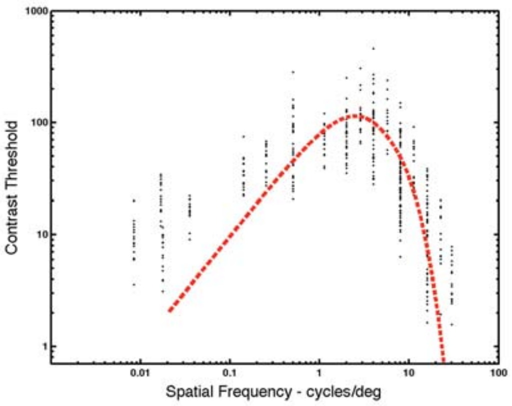


**Figure 3. Typical human contrast sensitivity function.** *The Modelfest visual dataset (vision.arc.nasa.gov/modelfest) is shown here with a contrast sensitivity function model (Ref. 6)*

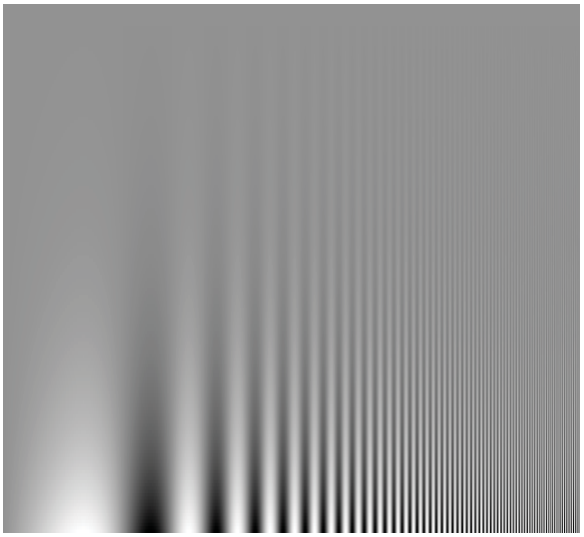


**Figure 4. Campbell-Robson Contrast Sensitivity Chart.** *The effect of contrast sensitivity is easily seen by noting the vertical location at which the frequency modulation is no longer visible.*

## B. Factors Affecting Resolution with Digital Projectors

A number of factors affect the true resolution that can be achieved with an out-the-window visual system.

### *1. Pixel Fill*

Digital projectors and/or monitors have become the primary technology for generating the Out-The-Window (OTW) image in high-fidelity simulators. They generate their image by producing a grid of colors that form an image when projected onto a screen or similar surface. The size of each square that forms the grid or image and the number of grid squares the projector is capable of generating determines its resolution. Given two projectors generating the same image, one generating the image with 5 million squares would have a higher resolution than the other generating the same image with only 1 million squares. Each individual square is commonly referred to as a pixel. A digital cameras resolution is classified by its ability to capture a digital image in megapixels. One megapixel equals one million pixels, 5 megapixel equals 5 million pixels, and so on. A higher the megapixel capability means a higher resolution camera. Digital projectors are similar to digital cameras. Digital projectors project digital images whereas digital cameras record images digitally.

### *2. Temporal Response*

The temporal characteristics of particular projection technologies can have a significant effect on their suitability for flight simulation applications.

<u>Motion-Induced Blur</u> Certain fixed-matrix display technologies such as liquid crystal displays (LCD) and liquid crystal on silicon (LCoS) exhibit blurring with moving visual images, including computer-generated imagery[8]. There are two factors that can produce this effect, 1) response time (i.e. rise/decay time of pixel luminance), and 2) 'hold-time' (amount of time that each pixel is illuminated per refresh). The first cause, response time, has been effectively addressed in the current technologies. The second cause, hold time, is due to an interaction between the display and pursuit eye movements. When the image is placed in motion, and the eye tracks the motion, the long illumination time of the pixel causes the light from a particular pixel to smear on the retina, causing blurring. The magnitude of the blur is proportional to the amount of image motion. Technologies with brief illumination times, such as cathode-ray tube (CRT) and laser[9] typically do not exhibit this artifact. Limiting illumination time through shuttering has been shown to reduce blur[10-11]; the amount of blur reduction is proportional to the duration of the shuttering. Unfortunately, blur reduction through this method also reduces the overall brightness of the display. It is expected that an increase in refresh rate (e.g., from 60 Hz to 90 Hz or 120 Hz) will reduce blur while retaining brightness.

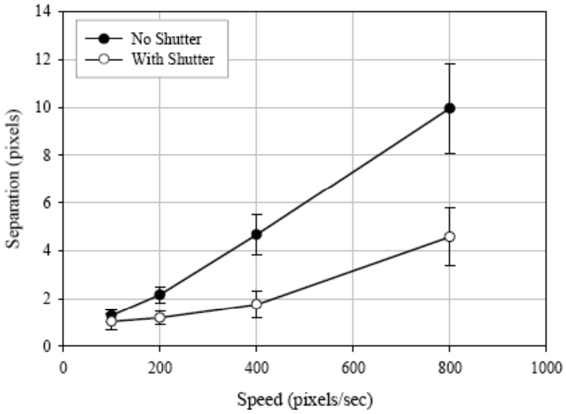


**Figure 5. Motion-induced blur with and without shuttering of an LCD display (from reference 10).** *Motion-induced blur is measured by determining the blur, in pixels, between two lines. Only 3ms reduction of illumination time (of a 16.7 ms frame) dramatically reduces blurring.*

Both sensor-based and perception-based methods exist to quantify motion-induced blur in displays. Ref. 12, the Video Electronics Standards Organization (VESA) display measurement standard for flat-panel displays, describes several types of sensor-based blur measurement techniques. Ref. 13 describes a simple perceptual-based measure which can be easily implemented and conducted without specialized sensors and apparatus.

<u>Spatio-Temporal Aliasing</u> The perception of motion created with a digital display is in fact an illusion created by a sequence of temporally sampled still images. The brain reconstructs this stimulus to create the perception of motion. This perception of smooth motion can be disrupted when the characteristics of the image sequence and presentation fall outside of certain bounds. Both temporal characteristics (such as update rate) and image content (such as spatial resolution and contrast) affect this artifact, called spatio-temporal aliasing. Whereas motion-induced blur, and its effect on perception and acuity, are easily quantified and demonstrated, the effect of spatio-temporal aliasing on motion perception and acuity are less understood and quantifiable[14]. It has been demonstrated that the

salience of this artifact is reduced by increasing update rate[9,15-16], and increased when spatial frequency content (i.e., image resolution) is increased[9, 15].

### *3. Contrast*

As was discussed earlier, contrast is created by the difference between the light and dark areas of an image. Common practice in the industry is to report contrast using a different measure than was defined previously for clinical work. Projector performance is frequently reported in terms of contrast ratio, or the ratio between the brightest bright (measured with a full white field) and the darkest dark (measured with a full black field). Unfortunately, this ratio does not accurately capture the type of contrast that the human visual system is sensitive to as defined in the Michelson contrast of Equation 1. Light scattering within the projector, losses in the lens, and light scattering and reflection at the projection screen surface can cause significant reductions in the achievable contrast, particularly at high spatial frequencies. The testing technique described in Ref. 13 incorporates measures of Michelson contrast at varying spatial frequencies. This technique has shown good correlation between measured contrasts and visibility of detail using perceptual measures.

## C. The Devil in the Details

The goal of the OBVA program to study the effect of vision on operational performance creates a set of requirements that are unprecedented in simulator visual system performance. Most simulator visual systems have perceptual artifacts, characteristics of the image that would not be present in a naturally occurring scene, but these artifacts are generally not considered to be problematic for the majority of training and research simulators. It will be of prime importance that the OBVA facility enable the study of human vision, not simulator visual system artifacts. Wherever possible, artifacts need to be eliminated, but when they cannot be eliminated at the very least they need to be understood in order to determine the range of operation within which vision study will be valid. Two particular areas of concern will be discussed; the consistency of visual system static and dynamic resolution, and the potential for image generator artifacts.

Static/Dynamic Resolution Consistency. There is a potential for mismatch between achievable static and dynamic resolutions in visual system design. As stated previously, motion blur is present with any display technology which exhibits long 'hold time', or period of time during which it is illuminated. This blur occurs any time the eyes are engaged in pursuit eye movements, and the magnitude of the blur is proportional to the speed of image motion.

Figure 6 illustrates this concept. If an observer has a static visual acuity of 20/10 this corresponds to the ability to discern a feature within 0.5 amin. Typical change in visual acuity with image speed (ref brown) is shown in blue. Hypothetical varying levels of motion-induced blur are shown, as linearly varying with image speed at different rates (the different levels of motion-induced blur can be achieved with shuttering).

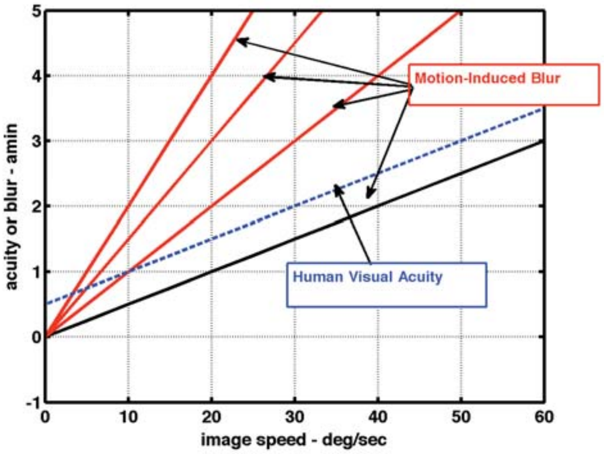


**Figure 6. Characteristics of human visual acuity and motion-induced blur as a function of image speed.**

For the motion-induced blur level shown in black, this artifact will remain below perceptible levels because the magnitude of motion-induced blur is always less than the visual acuity of the subject. If, however, motion-induced blur such as depicted with the three red lines occurs, the blur will become perceptible when the blur exceeds the human visual acuity for that speed, for these hypothetical conditions before 10 deg/sec image speed. The potential levels of motion-induced blur shown in this hypothetical situation are conservative. Consider the case of unshuttered motion depiction, a hold-time of 16 msec (corresponding to 60 Hz). The amount of blur potentially occurring at the modest image motion rat of 10 deg/sec would be 10 deg/sec * 60 amin/deg * .016 sec/refresh, or 9.6 amin/refresh. If the static resolution were 0.5 amin/pixel, the observer would see the visual system acuity jump from eye-limiting to 10 times worse than eye limiting with this modest level of image motion. Achieving levels of motion-induced blur below perceptual thresholds will be a considerable design challenge for the OBVA.

Image Generator Artifacts. Although IG technology already incorporates many capabilities to minimize artifacts, not everything rendered on an IG will be a faithful reproduction of the desired target or stimulus. In particular, effects of spatial sampling (i.e. projecting a model into a 2-D pixilated image) and anti-aliasing will produce a different image than would be obtained with a camera, or seen by the eye, with an actual out-the-window display. Simulated distances at which targets can be detected, even with eye-limiting resolution, tend to be different than operationally-typical detection distances[17]; detection ranges with IG imagery are less than with actual targets. IG-related sampling artifacts can also affect performance on tasks such as orientation discrimination[18] (such as determining which way a target aircraft is turning). Independently verification of the visual stimulus can be done with an imaging photometer to determine the presence and magnitude of IG related artifacts[17, 18].

## III. Requirements Definition

Requirements to meet the OBVA program requirements were determined with the following process (Fig. 7). NASA was provided with a set of clinical measures (Table 1) that were objectives to study within the OBVA program. This list included 1) measures for which Air Force standards exist, and 2) measures for which there are no current standards but were considered to be potential topics of investigation.

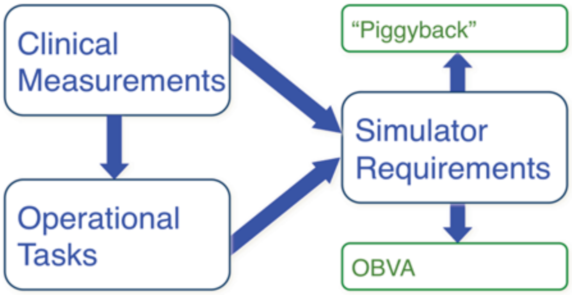


**Figure 7. OBVA Requirements Definition Process**

| Standard Measures | Non-Standard Measures |
|---|---|
| Visual Acuity | Contrast Sensitivity |
| Color | Low-Light Performance |
| Depth | Dynamic Aspects of Vision |
| Eye Alignment | Alignment and Targeting Ability |
| Eye Coordination | |
| Field-of-View | Visual Attention |

**Table 1. Standard and Non-Standard clinical measures of interest**

Given this set of clinical measures, a set of operational tasks was identified through interviews and meetings with pilots, pilot-physicians and flight surgeons. The majority of these tasks are shown in Figure 8, grouped with the aspect of vision for which the task is likely to be sensitive. In some cases, tasks are shown associated with only one aspect of vision; for example, taxi/wingtip clearance is associated with depth perception. Although in many or most operational settings, a pilot would have additional redundant cues on which to base this clearance judgment (such as shadows and perspective cues), it was also possible to construct a controlled scenario in which performance would likely be based primarily on that cue (i.e., for this task, taxiing on a dirt airfield at night). In some cases, tasks could not be isolated to a single cue; the 'detection, identification, localization and tracking' task performance will almost certainly be influenced by not only visual acuity, but also color vision and contrast sensitivity.

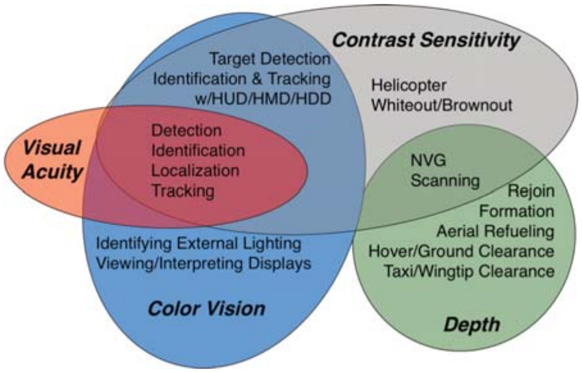


**Figure 8. Operational tasks identified likely to be affected by related visual component**

From this set of operational tasks, simulator requirements were determined which would enable the ability to conduct these tasks. Consideration was also given to the ability to correlate with clinical measures. Notional requirements for a dedicated OBVA simulator were determined, as well as considering the possibility of using existing simulation facilities to meet OBVA objectives.

## IV. Preliminary Visual System Design

It was determined early in the design process that the visual system would be the most challenging aspect of the simulator design. Preliminary designs to accomplish the OBVA objectives are described in terms of the three major visual system components: projectors, screen, and image generator.

### A. Projectors

When the term 'eye-limiting' is used, the question that must be answered, is: whose eyes? There are dramatic individual differences between observers. While 20/20 is generally thought to be average vision, the average pilot in the Air Force has 20/13 vision; a pilot with 20/20 vision is 2.5 standard deviations outside of the mean. Therefore, the goal of the OBVA program is to achieve resolutions on the order of 20/15 to 20/10 in order to study the effect of visual acuity on performance. However, this resolution, and the designs discussed here, remain preliminary and notional; many variables need to be examined and determined before deciding upon a desired resolution. Types of test scenarios, average visual acuity of the subjects that will be using the visual system, size of available buildings or facilities where the system would be located, common-off-the-shelf projectors, screens, and associated equipment, etc., are only a few of many factors considered when determining a required visual system acuity. A trade off analysis of variables for this project determined a 160-degree horizontal by 60-degree vertical field-of-view visual system with a minimum resolution of 20/15 was required but a visual system with a resolution of 20/10 was desired and the size of the screen could be no larger than 26 feet in diameter.

Initial designs demonstrated that building a 20/10 or 20/15 acuity resolution visual system was possible however the number of 1600 X 1200 pixel, high resolution, common off the shelf projectors typically used in high fidelity simulators would have been impossible to reasonably maintain. Analysis determined that sixty (1600 X 1200) pixel projectors are required to produce a 60-degree vertical by 180-degree horizontal field of view image on the interior of a 13-feet radius spherical screen. Producing a 20/10 resolution image on the same spherical screen requires 80 projectors. Maintenance of alignment, color balancing, edge blending, lumens "brightness" balancing, etc., on visual systems utilizing 3 or more projectors requires daily inspection and minor adjustment on a regular basis. On average, 30 minutes a day is spent on inspecting and adjusting three or four projector high fidelity simulator visual systems that typically have a 20/60 acuity resolution equivalent. Conducting daily inspection and maintenance on a system utilizing 80 or even 60 projectors would result in the system being maintained a greater percentage of time than it would be used to conduct visual research. Fortunately, during the design phase of this effort the Sony Corporation introduced its SXRS105 and SXRS110 projectors to the simulation market. These projectors are capable of producing images with 4098 x 2160 pixels. The S105 and S110 models produce 5000 and 10000 lumens of light, respectively. Using the Sony SXRS projector resulted in a significant decrease in the number of projectors required for a 20/15 or 20/10 acuity resolution visual system. If this projector were used, the 20/15 and 20/10 visual acuity resolution systems described above would require 15 and 20 projectors respectively. Figures 8 and nine depict renderings of each system. (Note: Shaded blue area represents path of image from projector to screen. Laser projectors were also investigated for use and showed great potential because of both the favorable temporal response (low motion-induced blur) and high pixel count. One projector produced 4 times the resolution of a Sony SXRS105. Unfortunately its reliability is currently very low and its cost is 4 times greater per pixel than the Sony SXRS105. In house-testing of both the SXRS105 and SXRS110 demonstrated that sufficient contrast can be obtained to achieve desired resolution.

When multiple projectors are used to generate a continuous and seamless image a blending process of overlapping pixels at the edge of each projector image is performed. This process is often referred to as "Tileing". Tileing is the process of overlapping approximately ten to fifteen percent of an image at its edges with ten to fifteen percent of the edges of the adjacent images. The pixels at the edge of each image projected with a given projector are overlapped with the pixels on the adjacent image. The pixels that overlap are dimmed such that when they are combined there overall brightness is equal to the brightness of the pixels comprising the part of the image(s) that are not overlapped. The process requires exacting individual pixel per pixel alignment, color and brightness balancing. If the blending is not correctly performed the image will appear to be dim, bright or blurred where the overlapping occurs. Edge blending will be a major hurtle to overcome for this effort however recent advancements in technology have led to the development of systems that perform alignment, brightness and color blending automatically. These systems perform alignment via an image distortion process that could degrade the acuity. Hence precise pixel alignment will be performed via optical alignment and color and brightness adjustment and blending will be automated.

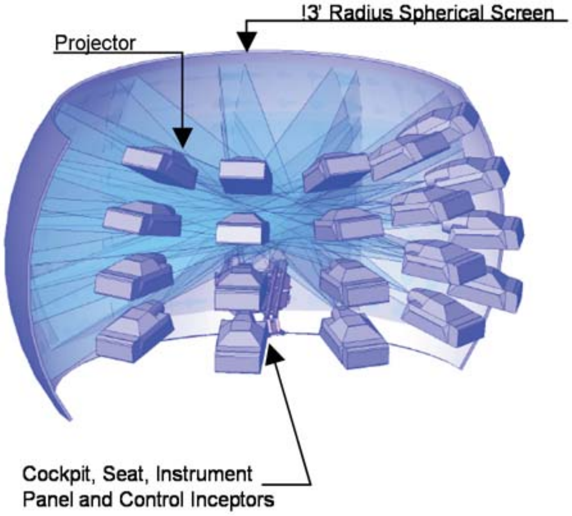


Figure 9. 20/15 Acuity Resolution System.

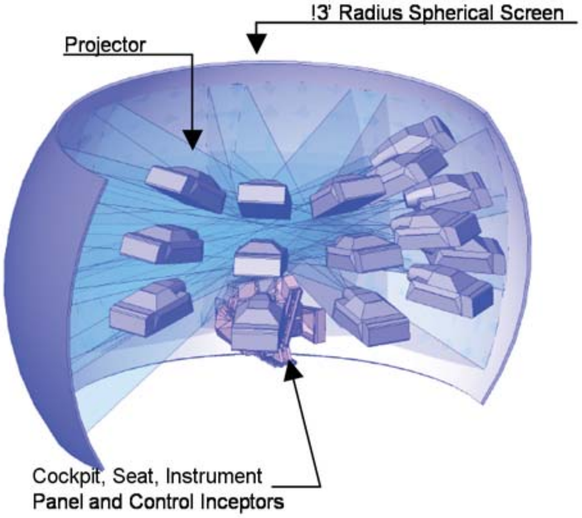
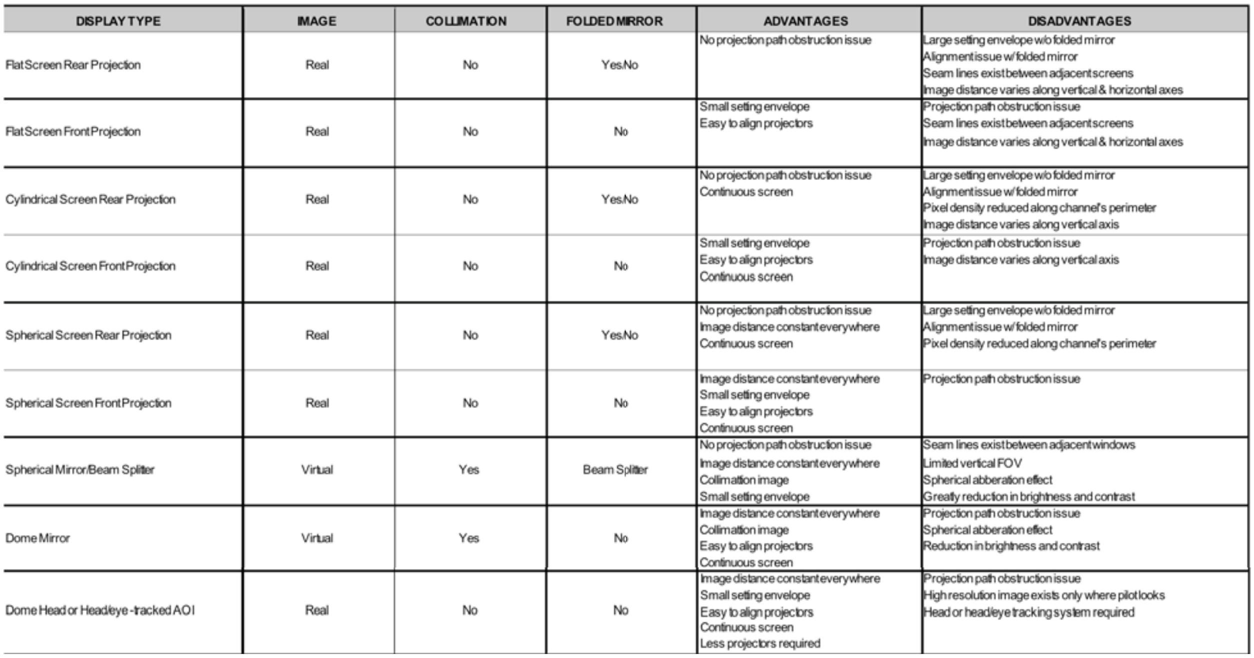


Figure 10. 20/10 Acuity Resolution System.

**B. Screens**

Figures 9 and 10 depict front projected, non-collimated, spherical screen visual systems. Rear projected, collimated, flat, and cylindrical systems, were investigated for this task but each system had characteristics that degraded image quality. Rear projected systems diffused the image causing minute image blurring, flat and/or cylindrical systems were considered inferior to spherical systems from a cockpit realism standpoint. Figure 5 identifies several additional approaches investigated along their advantages and disadvantages.



| DISPLAY TYPE | IMAGE | COLLIMATION | FOLDED MIRROR | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|---|---|
| Flat Screen Rear Projection | Real | No | Yes/No | No projection path obstruction issue | Large setting envelope w/o folded mirror<br>Alignment issue w/ folded mirror<br>Seam lines exist between adjacent screens<br>Image distance varies along vertical & horizontal axes |
| Flat Screen Front Projection | Real | No | No | Small setting envelope<br>Easy to align projectors | Projection path obstruction issue<br>Seam lines exist between adjacent screens<br>Image distance varies along vertical & horizontal axes |
| Cylindrical Screen Rear Projection | Real | No | Yes/No | No projection path obstruction issue<br>Continuous screen | Large setting envelope w/o folded mirror<br>Alignment issue w/ folded mirror<br>Pixel density reduced along channel's perimeter<br>Image distance varies along vertical axis |
| Cylindrical Screen Front Projection | Real | No | No | Small setting envelope<br>Easy to align projectors<br>Continuous screen | Projection path obstruction issue<br>Image distance varies along vertical axis |
| Spherical Screen Rear Projection | Real | No | Yes/No | No projection path obstruction issue<br>Image distance constant everywhere<br>Continuous screen | Large setting envelope w/o folded mirror<br>Alignment issue w/ folded mirror<br>Pixel density reduced along channel's perimeter |
| Spherical Screen Front Projection | Real | No | No | Image distance constant everywhere<br>Small setting envelope<br>Easy to align projectors<br>Continuous screen | Projection path obstruction issue |
| Spherical Mirror/Beam Splitter | Virtual | Yes | Beam Splitter | No projection path obstruction issue<br>Image distance constant everywhere<br>Collimation image<br>Small setting envelope | Seam lines exist between adjacent windows<br>Limited vertical FOV<br>Spherical abberation effect<br>Greatly reduction in brightness and contrast |
| Dome Mirror | Virtual | Yes | No | Image distance constant everywhere<br>Collimation image<br>Easy to align projectors<br>Continuous screen | Projection path obstruction issue<br>Spherical abberation effect<br>Reduction in brightness and contrast |
| Dome Head or Head/eye-tracked AOI | Real | No | No | Image distance constant everywhere<br>Small setting envelope<br>Easy to align projectors<br>Continuous screen<br>Less projectors required | Projection path obstruction issue<br>High resolution image exists only where pilot looks<br>Head or head/eye tracking system required |

Figure 5. Advantages and Disadvantages of Display Approaches Investigated

Ideal screen material and characteristics have not yet been determined. The parameter called screen 'gain' pertains to the way in which light reflects from a projection screen. Many dome systems utilize screen materials with a gain of one or unity. Unity gain screens scatter light equally in all directions; a wall painted with flat paint exhibits this characteristic. The benefit of unity gain is that the projected image appearance does not change with the location of the observer relative to the axis of projection. The disadvantage is that, particularly in a dome system, the scattered light then reflects off another portion of the screen, adding to the light that is directly projected at that point. This light scattering decreases the overall contrast and can reduce the effective resolution of the system; scene features look washed out, and fine scene detail can be lost.

Some of this effect can be mitigated by using a screen material with less than unity gain; this means that while the reflected light is scattered evenly in all directions, some is absorbed. With some light being absorbed with each reflection, screen gains lower than unity can help reduce the loss of contrast through light scattering. However, lower gain also results in some loss of brightness.

Screens can also have gains higher than one; instead of scattering the light everywhere equally, the light is scattered to a greater extent in one direction (a mirror is a special case in which the light is not scattered but totally reflected in one direction). Screen gains higher than unity can reduce light scattering, but the image quality and brightness is affected by the offset of the observer from the axis of light projection. This effect is lessened as the distance to the screen is increased.

A front projected spherical screen was selected over all of the alternatives; potential for a large, continuous field-of-view, low image distortion and large screen-to-eye distance were primary factors. A continues seamless sixty-degree-vertical and one hundred-eighty-horizontal visual field-of-view requirement eliminated flat and cylindrical screen options for this project due to their seams and/or varying eye-to-screen distance. The final configuration is expected to have a slightly less than one-hundred-eighty-degree field of view to eliminate secondary reflection. Optimal screen gain has not been determined, and will be the subject of further analysis and testing.

### C. Image Generators

An image generator computes the image the pilot would see in the out-the-window scene, based simulated position and orientation of the aircraft as computed in the host computer. A market survey was conducted of current image generator technology. The survey revealed that current IG technology is very advanced, and generally can create acceptable resolution levels with appropriate database design. Aspects of image generator performance that will be important for the OBVA program include the ability to sustain a constant, high (60 Hz or greater) update rate without missing refresh cycles or producing objectionable artifacts (such as level-of-detail pop-in artifacts). It is believed that many current-generation IG systems are capable of meeting the OBVA requirements, and that they will continue to evolve and become more powerful (or conversely, cost less for the same performance). Improved levels of IG performance will be necessary to achieve the higher update rates that are desirable for improved visual motion depiction.

## V. Conclusions

The term eye-limiting resolution can have many meanings regarding visual system requirements and specifications. Although this term is frequently used simply to express the pixel resolution, in pixels per degree, many other factors can affect the final system performance and suitability. These include:

1) Specific display technology (e.g. LCoS, LCD, laser)
2) Refresh Rate
3) Illumination hold-time
4) Illumination response time
5) Screen geometry
6) Screen material
7) Number of projectors
8) Field of View
9) Image Generator
10) Database Design

Until the ‘holodeck’ design concept popularized on Star Trek is realized, no simulator visual system will replace the experience of viewing an out-the-window scene from the actual cockpit. Any visual system design will involve trade-offs between design variables (e.g., refresh rate vs scene complexity, brightness vs visual motion depiction). Simulator visual system design requires careful specification of requirements, and in-depth knowledge of how design variables affect system performance and interact, in order to achieve desired performance.

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