IMAGE 2010 Conference

PRACTICAL GEOMETRY ALIGNMENT CHALLENGES IN FLIGHT SIMULATION DISPLAY SYSTEMS

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ABSTRACT

Flight simulator training systems require accurate display system geometric alignments to minimize distortion of the pilot's view of the simulated world. Since their introduction in the early 1980s, Cross-Cockpit Collimated Displays have been the system of choice for a wide range of flight training applications. This class of display system presents special geometric alignment challenges.

Today's alignment system instrumentation can routinely fully characterize the distortion over the full field of view from the pilot, copilot, and design eye positions. Unfortunately, it is not possible to simultaneously remove all distortions from all eye positions.

This paper analyzes and categorizes the types of distortions that arise in visual display systems. It describes, illustrates, and discusses four distinct types of distortions that fall into basic correctable and uncorrectable categories.

It also describes a practical method for performing a rapid comprehensive distortion characterization from the cockpit. That characterization includes a comprehensive analysis function that quantifies non-stationary distortion errors for specific display systems.

INTRODUCTION

Flight simulator training systems require accurate display system geometric alignments to minimize distortion of the pilot's view of the simulated world. Such distortions could critically affect pilot judgments of direction, attitude, altitude, and rate of closure. As a result, such distortions could impart negative training.

Fortunately, automated alignment systems have become common-place in visual flight simulation applications. Automated alignment systems provide rapid, accurate, unassisted geometric alignments that assure consistent pilot usability, enhanced system maintainability, and minimal system life-cycle costs.

Cross Cockpit Collimated Displays (CCCDs) are pervasive in full-flight simulators. This class of display system presents special geometric alignment challenges due to the design challenges associated with collimating large fields of view. Automated alignment systems are evolving from a strategy of providing a "nominal" image on the Back-Projection (BP) screen to one of using an image sensor in the cockpit to combat the geometric distortion caused by mirror imperfections.

Training system users commonly expect that the display should be distortion free after geometric alignment. That expectation can be shown to be unachievable when accommodating multiple eye points. A more critical issue is caused by head dependent geometric distortion. The purpose of this paper is to identify, to characterize, to explain the physics of such systems, and to describe an efficient way to measure these displays. It is now possible to rapidly and easily take measurements that fully characterize display system distortion from the pilot's and copilot's eye points. The challenge now is how to optimally apply corrections based on that wealth of measurement data.

Figure 1 Typical cross cockpit collimated visual system

Presented at the **IMAGE 2010** Conference
Scottsdale, Arizona – July 2010

BACKGROUND

Since their introduction in the early 1980s, Cross-Cockpit Collimated Displays (CCCDs) have been the system of choice for a wide range of flight training applications. These systems support side-by-side pilot/copilot cockpit configurations with a collimated display that 1) simultaneously minimizes distortion of the pilot and copilot's sense of direction, 2) provides a cross-cockpit view that is crucial to the pilot's situational awareness, and 3) is compatible with full-motion simulator platforms.

Figure 1 shows a typical system. Figure 2 illustrates typical cross cockpit system construction. Projectors mounted on top of the simulator project onto a translucent Back-Projection (BP) screen. The back side of the screen reflects off a spherical mirror into the cockpit. The optical configuration collimates the image, thereby moving it towards infinity thus minimizing distortion of the pilot and copilot's sense of direction. Other implementations use front projection screens rather than a translucent back projection screen. Cross cockpit display system mirrors are typically constructed either from glass mirror segments or from metalized polyester film draped over a vacuum plenum, which deforms it into an approximate spherical shape.

The display system must be "geometrically aligned" to compensate for distortions that arise from the inherent optical system design, optical system component variances, or visual system installation. In particular, the plasticity of polyester film can be troublesome, particularly with larger vertical fields of view. Display systems can be manually aligned using a pre-computed projected overlay to establish geometric truth. Manual geometry alignments have been largely replaced by automated systems for improved quality and reduced labor costs.

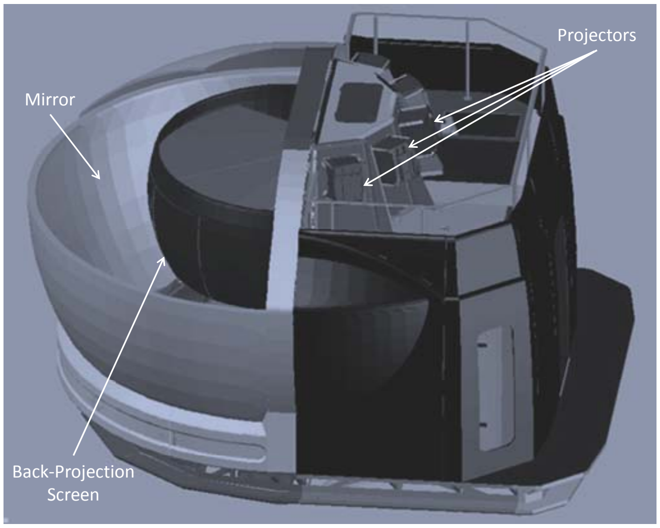

Figure 2 Typical cross cockpit display construction

AUTOMATED SPATIAL DISPLAY ALIGNMENT METHODS

Most automated spatial display alignment systems in use today align the image to an "ideal" position and shape on the back projection screen irrespective of mirror distortion. Obviously, using measurement data taken in the cockpit through the mirror would improve alignment accuracy. Some systems have the capability of accepting a "vertical profile" distortion function that characterizes the mirror distortion at zero azimuth over the full extent of elevation. The alignment system corrects for one component of mirror distortion in this way, thus simplifying Head Up Display (HUD) alignment and improving fixed wing pilot's height perception.

We are currently fielding a more general method of rapidly measuring the image distortion over the entire field-of-view from within the cockpit. Figure 3 shows the fixture and devices that capture the out-the-window images needed for compensating inherent and mirror distortions.

By measuring a test pattern from multiple eye points and also from the alignment system camera, it is possible to detect distortion in the optical system and remove it, if possible. Initially, the alignment system measures as much of the total field-of-view as possible from the design eye point. The system makes additional measurements from the pilot and copilot's eye points to increase the coverage. By knowing where the dots are measured from within the cockpit and where they are measured from the alignment camera, the system computes a transform that tells the alignment system where the dots must be positioned to minimize distortion.

This type of system greatly reduces the amount of

Figure 3 Image capture apparatus

geometric distortion as seen by the pilots. However, such a system must be capable of processing different types of distortions for CCCD systems. The following describes some of the aspects of characterizing and processing image distortions.

CAUSES OF GEOMETRY ERRORS

Geometric errors are caused by the following:

- misalignment of the image on the front or back projection screen,
- inherent errors in CCCD systems due to ubiquitous off-axis tilted mirror optical systems,
- shape variations in optical elements or inaccurate placement of optical elements,
- movement of observer's eye location relative to the design eye-point.

SPECIFYING GEOMETRIC DISTORTION

Typically, present-day specifications have two parts:

1. absolute error in azimuth and elevation for specific FOV zones and at the design eye point and the pilot/copilot eye point (In addition, a viewing volume is often specified that encompasses the normal range of pilot head movement. A less stringent absolute error specification is often used for all possible eye locations in the viewing volume),
2. rate-of-change error for adjacent areas.

System compliance to specification is commonly validated by point-by-point measurement of the errors occurring at a representative set of azimuth and elevation pointing angles using a theodolite. This is in generally a laborious and time-consuming process.

The process of correcting a non-compliant system may not be straight-forward – i.e. "what's at fault". A faster method of analyzing many alignment points from different viewing locations is highly desirable. Such a methodology is described later in the paper.

CLASSIFYING GEOMETRIC DISTORTION

The classification of geometric distortion errors is important from a specification point-of-view. A common language and a framework for establishing feasible customer expectations are important. The classification methodology can center on the following aspects of visual system distortion:

- cause,
- cure,
- portion of the field-of-view with distortion,
- head motion dependency,
- impact on training,
- pilot acceptability.

The categorization considered here centers on whether aligning the image on the screen is sufficient to remove the geometric distortion as seen by an off-axis observer in the cockpit. Thus, the two categories of interest are as follows:

1. those that can be corrected by aligning, i.e. warping, the image on the screen, and
2. those that cannot be corrected by warping the image.

Two types of display systems dominate the installed visual system base at present – direct view and collimated using a tilt-mirror and screen. (Refractive systems using large lenses or Fresnel lenses or holographic components are presently not widely used.)

Direct View Systems: Direct view systems are those that have no reflective or refractive elements between the viewer's eye and image source. **These systems can always be aligned by image warping**, assuming adequate adjustment range and spatial frequency response of the image warper.

However, errors in azimuth and elevation are a function of viewer location. The radius of the dome or cylinder or the distance from eye to the flat screen, governs the magnitude of the geometric distortion. The distortion as a function of viewer location can be computed by simple trigonometry. Image collimators are used to minimize the image distortion due observers that are positioned away from the design center of the display.

Cross-Cockpit Collimated Displays (CCCD's): This class of visual system displays is more problematic. The geometric errors can be of either type. The second class i.e. those that cannot be corrected by manipulating the image, fall in to two subclasses:

a. those that present with opposite signs from pilot and copilot eye point locations, defined as odd-functions, as opposed to even-functions which can be corrected, and
b. those that are sensitive to viewer's location, defined as non-stationary here.

Odd-function: These errors cannot be "aligned" out of the system except for a single point. The pilot and copilot have a similarly distorted view of the displayed image, but see it with errors that are in opposite directions. These errors are caused by one or both of the following:

1. inherent errors in CCCD systems due to ubiquitous off-axis tilted mirror optical systems,
2. shape variations in optical elements or inaccurate

placement of optical elements.

Non-Stationary (NS): These errors cannot be "aligned" out of the system except for a single point. Once the observer moves his head, the image again appears to be distorted. These errors are caused by one or both of the following:

1. inherent errors in CCCD systems due to off-axis tilted mirror optical systems,
2. shape variations in optical elements or inaccurate placement of optical elements

The geometric distortions of interest in this paper are the ones shown in the gray boxes in Figure 4. The challenges associated with direct view systems are not of the same magnitude or type as the ones associated with CCCD's. Our attention now turns to only those systems types.

ODD FUNCTION DISTORTION GENESIS

Odd function distortion can result from two sources:

1. The physics of off-axis viewing of a CCCD system. (Ray tracing the optical elements of the system demonstrates this effect.),
2. Deviation of the mirror shape from spherical or misplacement of mirror or screen

Inherent distortion: The optical system design of a CCCD is one of trade-offs. The designer has constraints on the shape and maximum size of the optical elements, i.e., mirror and screen, used in the design. He has to consider the size of the cockpit to be accommodated, as well as, the total field-of-view requirements. In general, customer specifications control the range on collimation, dipvergence, horizontal distortion and vertical distortion. (Discussion of collimation and dipvergence are beyond the scope of this paper.) The system parameters are optimized to provide the best optical performance possible. The completed design can never provide perfect performance, but embodies a set of trade-offs. The designer has to find a design that meets the specification tolerances in all areas, knowing that a perfect system is impossible.

Figure 5 shows the theoretical distortion predicted by ray tracing the optical elements of the system for an observer located 21 inches left of the center line of the optical system. An 11 ft system, i.e., a system with an 11 ft radius mirror, is used here for the example. The distortion plot shows that the pilot does not get a distortion free view of the outside simulated world. Figure 6 shows the distortion from the right seat. One can see that the errors in horizontal distortion and horizon tilt are in opposite directions for the two pilot viewing locations which does not allow for eliminating the error by aligning the image on the back projection screen. The alignment can make the image seen by either observer be essentially distortion free at the expense of the other observer who will suffer with twice the theoretical distortion. Such a trade-off is not usually chosen, but has been used in a limited number of applications.

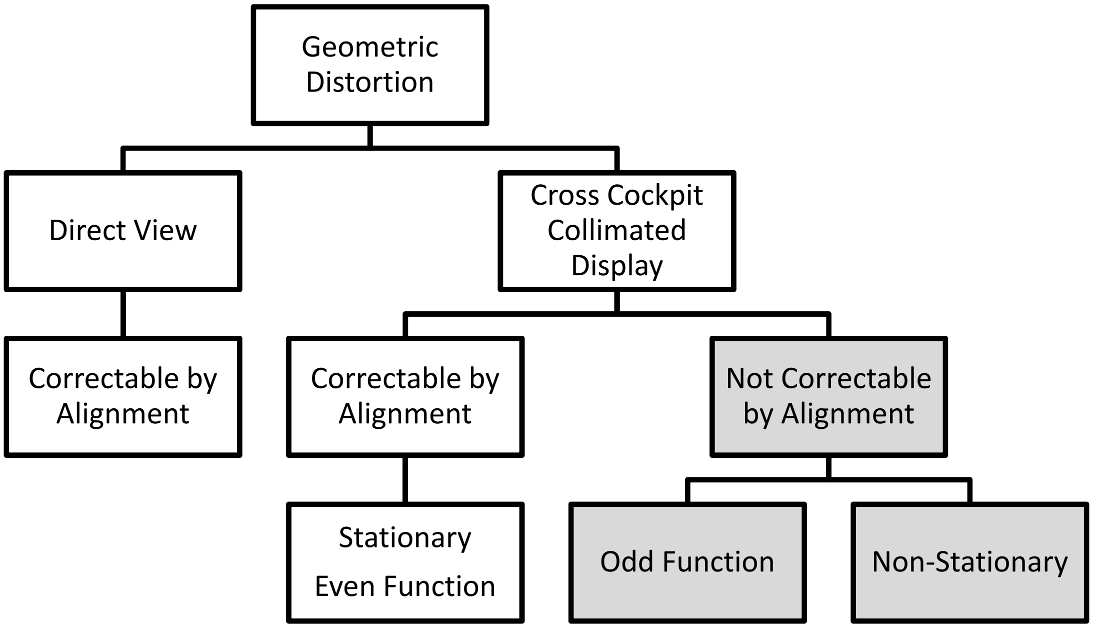

Figure 4 Breakdown of geometric distortion types

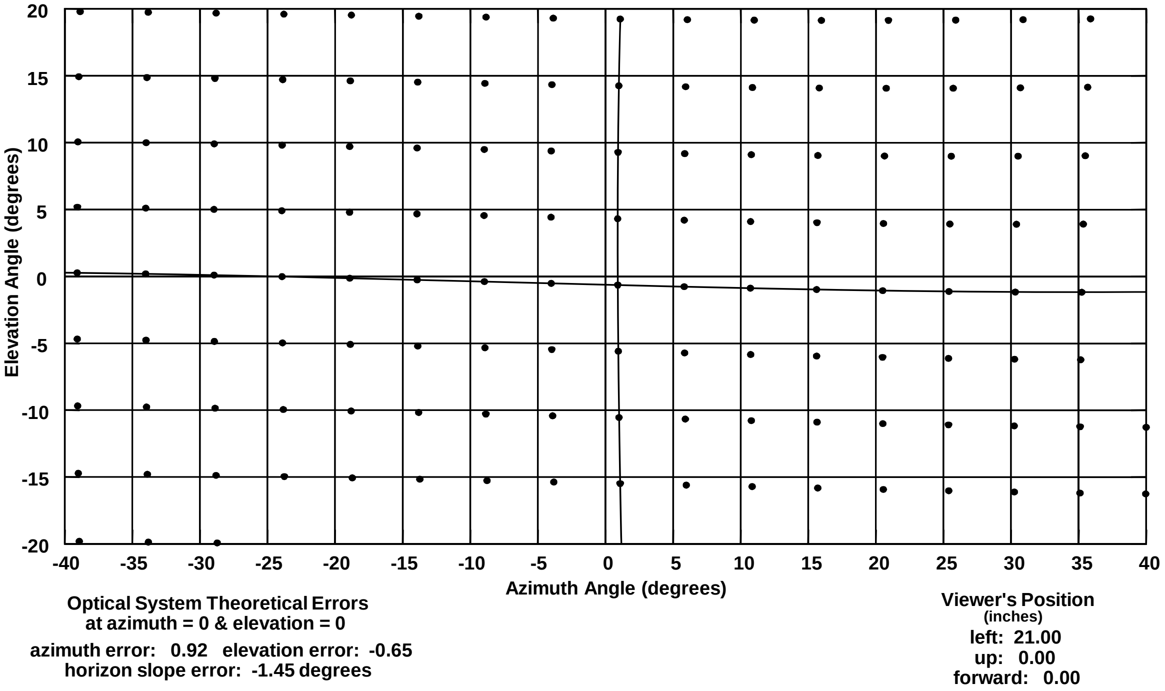

Figure 5 Theoretical optical distortion - 11 ft mirror radius - left seat

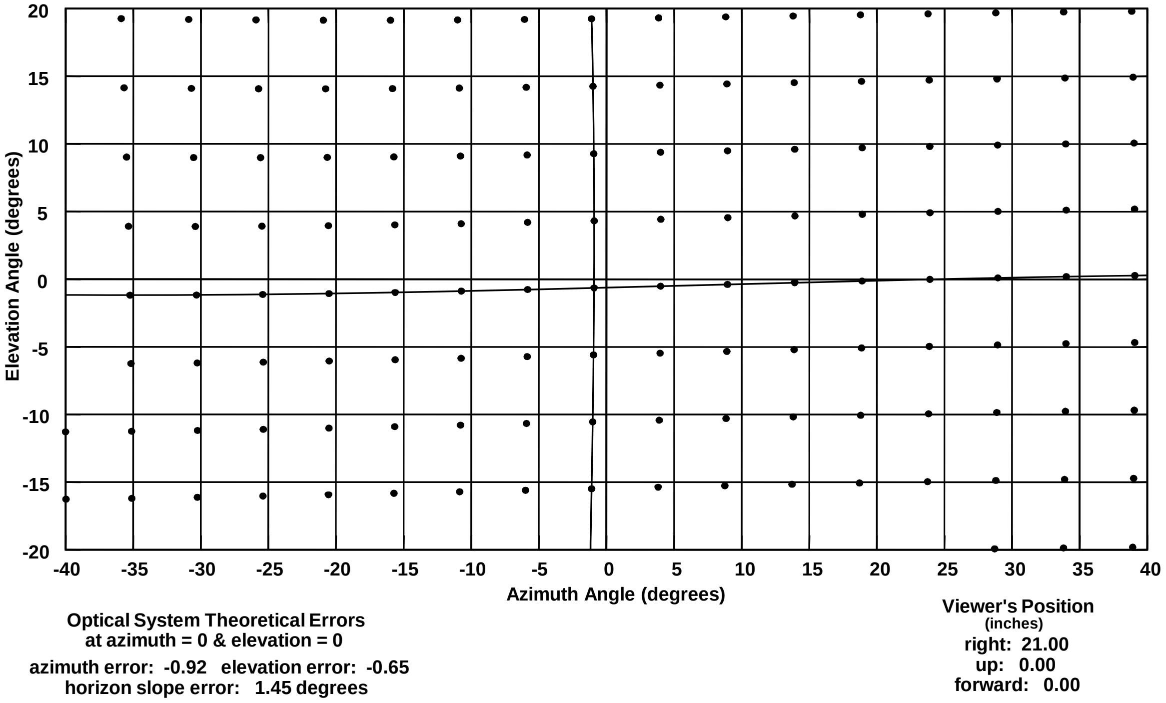

Figure 6 Theoretical optical distortion - 11 ft radius - right seat

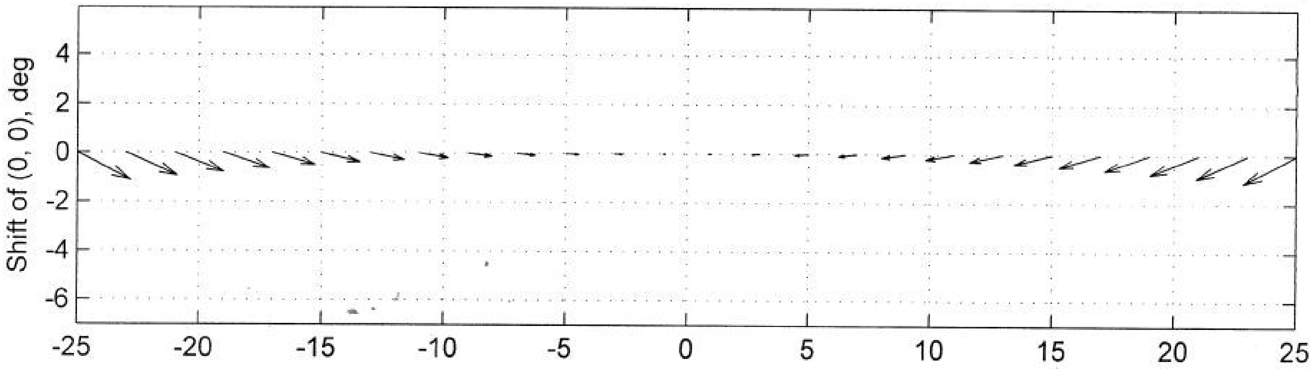

Figure 7 Toe in and declination of the (0, 0) point as a function of eye position.

From each pilot's viewing location, the inherent distortion due to the optical system is an example of stationary global distortion. In a well designed optical system, the amount of distortion changes for "small" head movements is in general not noticeable to the pilots; thus, the inherent characteristics of the optical system does not introduce significant global non-stationary distortion. Non-stationary distortion, i.e. head motion dependent, is in general caused by the mirror deviating from a perfect spherical shape.

The farther away from the center line of the optical system, the greater is the odd function error that we know of no way to align out for two eye points. Figure 7 is a quiver plot showing how the error varies as a function of eye position relative to the center line.

Mirror shape and placement: The mirror shape is dependent upon the technology used to implement the mirror, as well as, the mirror installation outcome for stretched film type mirrors or fabrication/installation factors for hard mirrors. Mirror placement issues can be detected by mechanical measurements and resolved in a straightforward manner. This error type is not a major factor during the alignment phase. Polyester mirrors do not generally have strong bias relative to the centerline; thus, do not contribute significantly to odd-function distortion relative to theoretical.

NON-STATIONARY DISTORTION GENESIS

Non-stationary distortion can result from two sources:

1. Poor optical design
2. Mirror deviation from spherical

Poor optical design: Optical designs are normally done in such a way as to minimize the effect of image "swimming" as a function of head position. Specialized optical design programs are often used to determine the amount of swimming by analysis. The designer tries to minimize the amount of swimming while maintaining all other important performance parameters.

Mirror deviation from spherical: The mirrors used for modern visual flight simulation are typically in the range of 8 to 11 foot radius. Fabricating these large mirrors is a challenge. Deviations of the mirror from a perfect spherical mirror can cause OTW image swimming with changes in head position. The larger the slope of the deviation relative to a perfect spherical shape, the greater is the non-stationary distortion produced by the mirror. From an alignment point-of-view it is important to measure these errors quickly to determine the suitability of the mirror.

Figure 8 Example of non-stationary geometric errors

EXAMPLE

Non-stationary Geometric Errors

An example of non-stationary geometric error is shown in Figure 8 for the left seat side window. The squares are 5 degrees on a side. The system has a vertical field-of-view of ±20°; thus, the top and bottom rows are 2.5 degrees high.

An observer looking at the checkerboard image in Figure 8 while maintaining a fixed head position would not be able to determine whether the distortion (i.e. non-uniformity of the square sizes) is due to poor alignment of the image on the BP, mirror distortion or the theoretical optical distortion described in the section on "Odd Function Distortion Genesis".

Figure 9 and Figure 10 show two photos that have been cropped to show approximately the upper 15° of the image for two head positions. The following computations show that the image changes with head position. The vertical dimension of the top checkerboard "square" as indicated by UEP_1 is 19.5% larger that the same checkerboard "square" as seen from the lower eye point location. The third checkerboard squares are shown by calculation to be the same height for both eye point positions. This type of simple measurement and analysis shows that the NS type geometric distortion can be identified by taking photos from two different eye points. A limited amount of information can be extracted from this type of measurement and analysis. A better way is use a calibrated camera in conjunction with powerful analysis software that can do hundreds of points and provide a probability distribution function of the size of the geometric distortion. This approach is outlined in the following section on "Measuring Non-Stationary Errors". The simple example with a checkerboard was used because is it the type of test pattern along with a sphere pattern that users are most familiar with. The approach of the next section uses a less familiar test pattern which can provide far more information in a timely manner.

$$100 \times (UEP_1 - LEP_1)/ LEP_1 = 19.5\%$$

$$100 \times (UEP_2 - LEP_2)/ LEP_2 = 4.5\%$$

$$100 \times (UEP_3 - LEP_3)/ LEP_3 = 0.0\%$$

When viewing static images in a collimated display system employing stretched film mirrors, one can readily observe unnatural movement of portions of the image that result from moving the head. For example, an observer rocking a few inches towards and away from the cockpit window while observing the top of the FOV will see an unnatural vertical "acceleration" of objects near the top of the FOV that are related to the speed of the head movement. Similarly, an observer who rocks a few inches from side to side while viewing objects near the end of the mirror will see an unnatural horizontal acceleration of these objects.

Measuring Non-Stationary Errors

The most complex and significant errors in display system geometry occur in systems using stretched film collimators. It was argued above that the presence of strong localized non-stationary errors is disruptive to training in its own right. In this section, it is pointed out that these distortions affect the quality of the display system in a second important way. The presence of *non-stationary* localized distortions makes it impossible to eliminate the *stationary* errors because the image measurement apparatus inside the cockpit must be positioned at several locations to get the necessary FOV coverage in most all trainers because of cockpit structure obscuration. For this typical scenario, the *non-stationary* component of the measurements changes from position-to-position causing the *stationary* errors to be measured incorrectly. The exception is the rare case when the cockpit can be removed, allowing a single measurement position i.e. design eye point to cover the total FOV.

An engineer from the FAA summarized this dilemma well when he lamented:

> *"You can't accurately measure geometry in a collimated system because the results depend on where you sit."*

There is great truth in this statement, however, the assertion sounds too much like an admission of defeat. Thus, the statement can be reinterpreted as a challenge by turning it around to read:

> *"The change in geometry as a function of head movement is an essential attribute of the quality of a training display system."*

It would be no surprise to hear groans from anyone who has been forced to make measurements of large numbers of alignment points using the traditional theodolite. The assertion implies that one would have to at least triple the number of measurements required to characterize a collimated display system as each alignment mark would have to be measured from at least three head positions.

Not to worry, however, because the next section describes the use of a more modern method of measuring alignment marks that increases the rate of data collection by a factor of 1000.

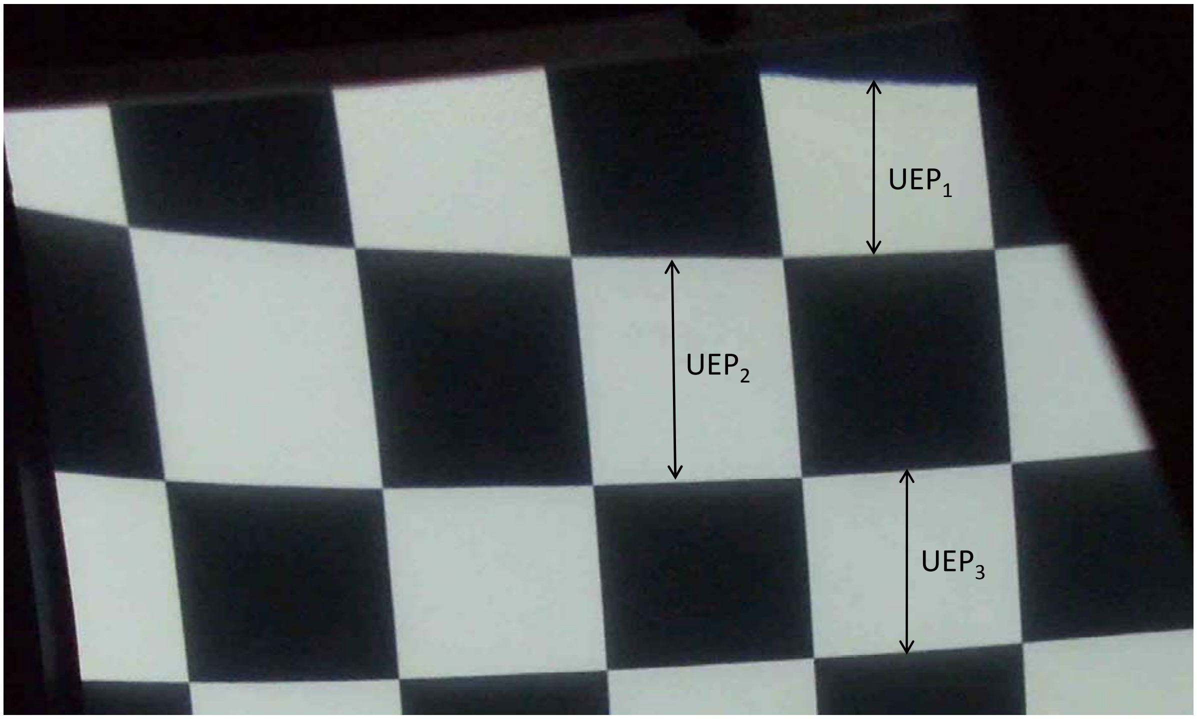

Figure 9 View from upper eye point position

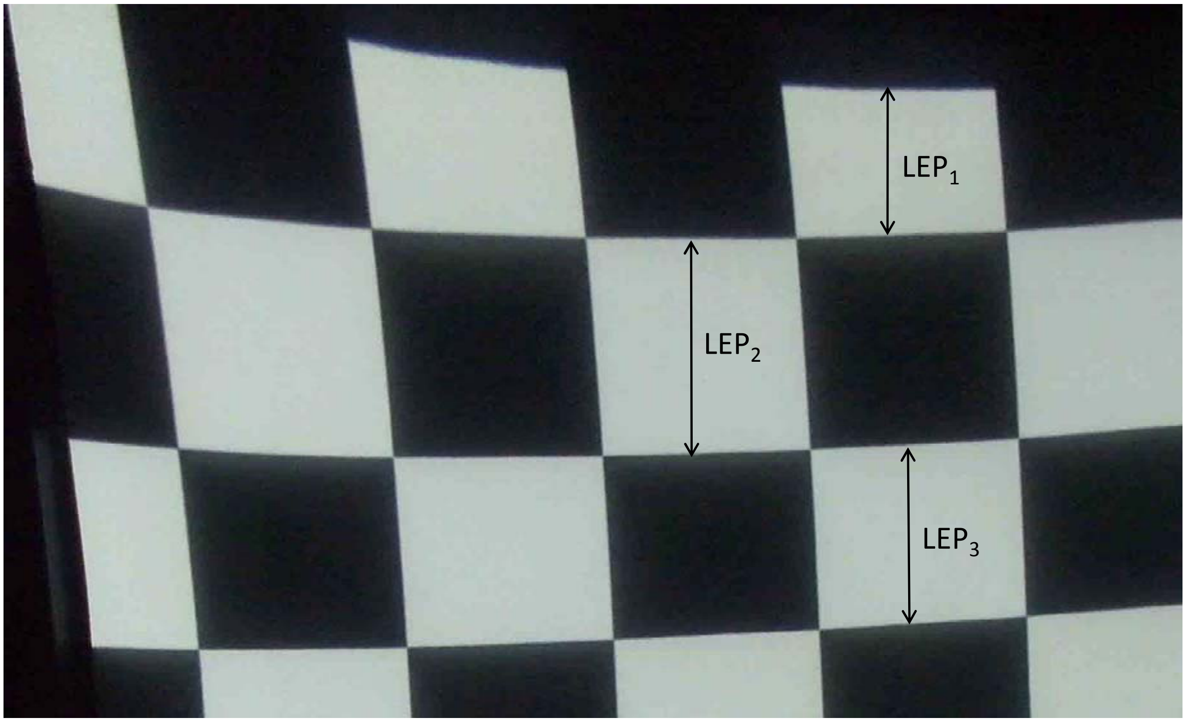

Figure 10 View from lower eye point position

A Camera based Method for Measuring NS Geometry Errors

One can evaluate head position dependency by taking a picture of dots in a special purpose test pattern from one eye point and then taking a second picture from 2 inches away from the first. Statistical plots are then created using image processing software. By taking four shots, two up and down and two more 2 inches to the side, one can quantify the errors in both vertical and horizontal axes. All of this can be used to help quantify the amount of NS geometric error.

To calculate the error, a software process detects the dots in the camera images, correlates the dots in the two images, and then creates a plot that shows the distance between dots from both images. The error distribution provides the bulk of the information as to the acceptability of the mirror and the usability of image as viewed by the pilots.

With the use of modern and affordable cameras and image processing techniques, the amount of localized head position dependent distortion can be quickly and accurately measured.

The data shown in Figure 11 below are from a stretched film collimating mirror and were measured using a camera that was calibrated such that the relative positions of each point in the image can be measured to within a fraction of an arc-minute. Two camera images were captured with the camera being translated vertically 2 inches for the second image relative to the first. The dots in Figure 11 show the geometric measurements from one of these positions while the circles show the measurements of the same pattern from the other camera position. Examination of the figures shows that most of the dots line up quite well with the circles, indicating head position has little effect on geometry for these regions of the FOV. However, the dots at the top of the image show a noticeable vertical displacement relative to the circles indicating the geometry in this portion of the FOV is affected by small changes in head position.

The summary statistics at the bottom of Figure 11 show that the 99th percentile change in geometry due to a 2 inch change in vertical head position was 19.7 arc-min.

For comparison, the data shown in Figure 12 below were measured in the same way, but for a different mirror which exhibits significantly less head position dependent distortion at the top of the FOV. The 99th percentile change in geometry at the top of the field is 3.46 arc-min.

Figure 13 shows a magnified view of the top regions of Figure 11 and Figure 12.

CONCLUSIONS

Some errors can be corrected and some errors cannot. This paper segregates geometric distortions into categories of odd-function distortions, even-function distortions, stationary distortions, and non-stationary distortions. The categories determine whether a particular distortion is correctable or not.

The odd-function distortions described in this paper are not correctable. Given a particular optical design, the user must live with the errors. Odd-function errors do complicate the alignment process. Even though not correctable, they have to be accounted for by taking measurements from multiple locations so they can be distinguished from the distortions that can be corrected.

A method has been developed to rapidly measuring *non-stationary* distortion in Cross-Cockpit Collimated Displays. With this method, stationary errors are subtracted out. The measurement is based upon taking photos from two locations using a calibrated camera. Based on the differences between these two images, statistics are generated for approximately 1,500 dots in a special purpose test pattern. Off-line analysis tools rapidly evaluate the errors and provide statistics. The statistics give a quantitative measure of the “quality” of the mirror. In practice, one would take measurements at the tops and bottoms of each field-of-view along with the outer edges of the most out-board FOVs for images at the extremes of the viewing volume. Non-stationary distortions have a major impact on pilot acceptability and our ability to achieve an acceptable spatial alignment using warping. As an industry, we must start quantifying the mirror and come to a consensus on where the limits exist on acceptable distortion.

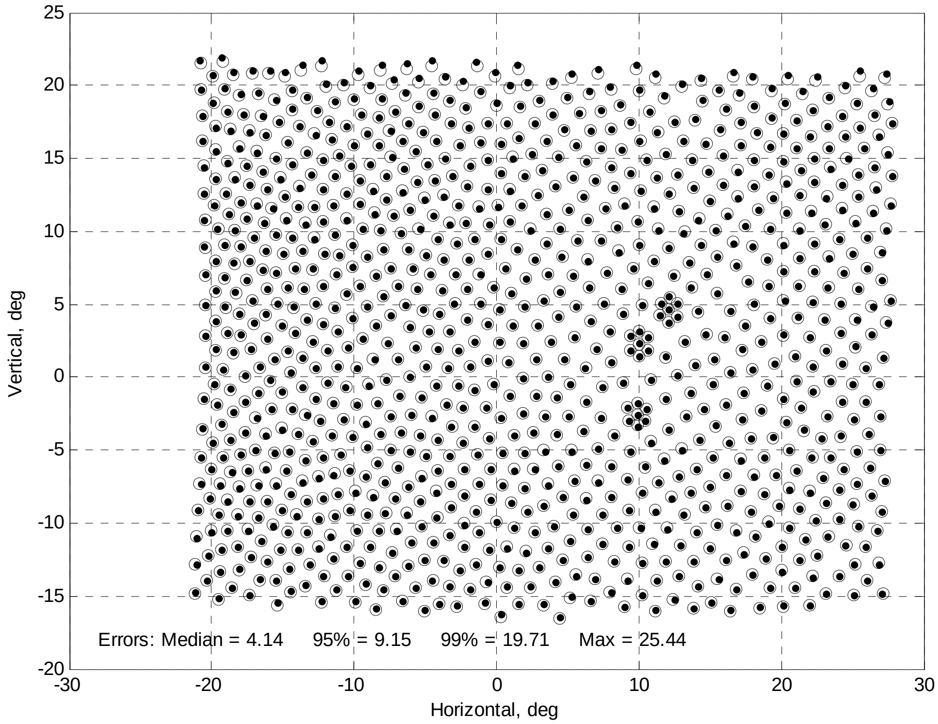

Figure 11 Comparison of geometry measurements made with a 2 inch vertical displacement of the camera for a low quality mirror

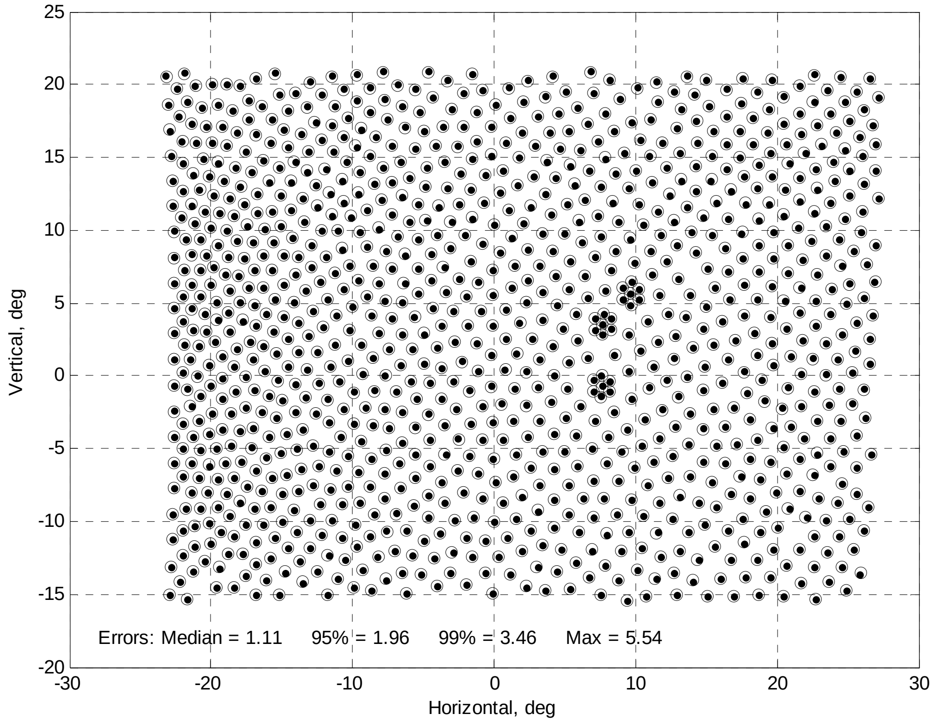

Figure 12 Comparison of geometry measurements made with a 2 inch vertical displacement of the camera for a high quality mirror

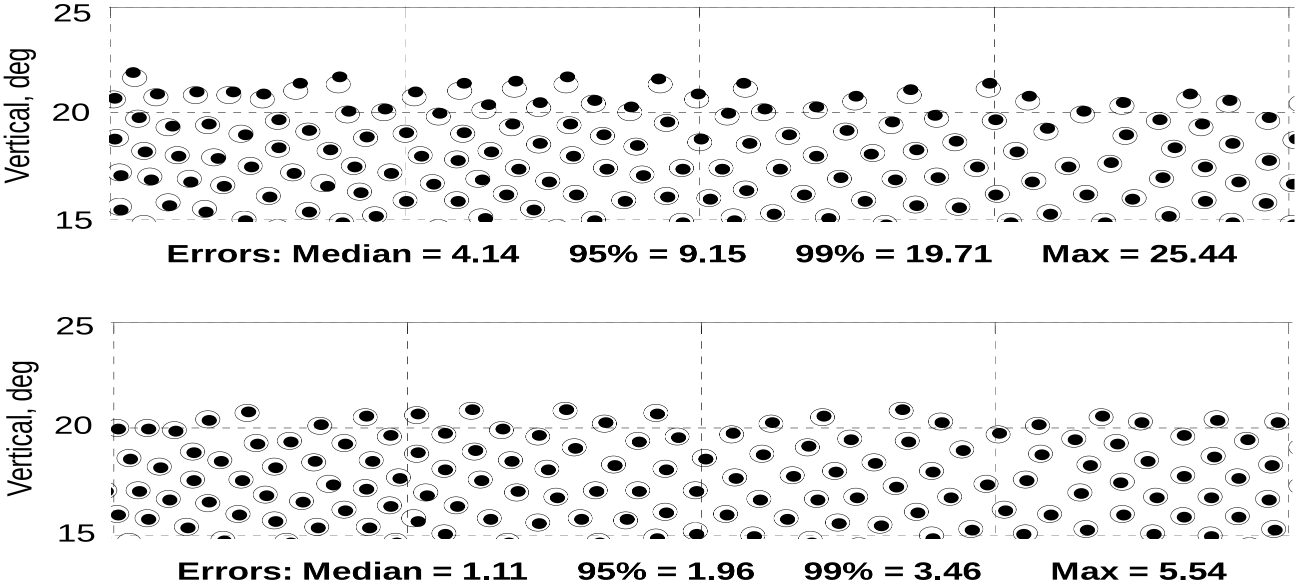

Figure 13 Comparison of geometry measurements made with a 2 inch vertical displacement of the camera for low and high quality mirrors

AUTHOR BIOGRAPHIES

Dr. James L. Long has worked on the Vital product line for the past 32 years. During that period he has worked on texture development, weather simulation, realtime database management, projector/display development, anti-aliasing techniques, special effects, automated alignment, display color/luminance calibration and membrane mirror methodologies. Jim is presently working on display analysis tools for domes, collimated systems and flat screen rear projection systems. He retired from FlightSafety International in 2008 and is presently a contractor there. Jim received his B.S. degree from Kansas State University. He received his M.S. and Ph.D. from University of Illinois, Urbana.

Dr. Charles J. Lloyd has 24 years of experience in the area of display systems and applied vision research at such organizations as the Displays and Controls Lab at Virginia Tech, the Advanced Displays Group at Honeywell, Lighting Research Center at Rensselaer Polytech, Visual Performance Inc., and BARCO Projection Systems. Charles joined FlightSafety International where he managed the development of next-generation display and alignment systems. Charles is currently working at L-3 Communications in Mesa, AZ. Charles has published/presented more than 50 papers in the field.

David A. Beane is a Lead Software Engineer at FlightSafety International Visual Simulation Systems. For the past 4 years, he has been designing systems architectures for new products such as the Display Management System. Previously, he spent five years at BARCO Projection Systems creating their automated alignment system for raster calligraphic CRT-based display systems. Dave received a B.S degree in Electrical Engineering from Wright State University in 1990 and has 20 years of software development experience.

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