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Head Worn Display System for Equivalent Visual Operations

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Honeywell International, Phoenix, Arizona

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1.1 Introduction & Background Material

1.1.1 Introduction

Providing a display that affords the user a head-up condition (as opposed to head-down) can result in several advantages, including a reduction in cognitive demand, increased visual awareness (e.g., for the detection and identification of objects), and increased operational safety. Such advantages in the military domain, for example, can lead to increased operator responsiveness, survivability, and lethality (Cornelius, 1991). Conversely, if not designed and implemented appropriately, such displays can result in visual clutter—and may even obscure the outside environment, possibly reducing operational safety.

Head-worn displays (HWD) present symbolic or pictorial data to the user through one or two miniature visual displays that are attached to the head through the use of a helmet, headband, or visor. The use of HWDs can provide advantage for users over traditional displays (e.g., cathode-ray tube, CRT) in the form of increased situation awareness and mobility. HWDs typically are one of three types with respect to the optics that are used: 1) *monocular,* wherein images are presented to one eye, while the other eye sees the 'outside world' (although some designs do not preclude the HWD-presented eye from also seeing the outside world, such as for open or semi-transparent designs), 2) *biocular,* wherein the same images are presented to both eyes, and 3) *binocular,* wherein different images (i.e., those associated with humans' natural binocular disparity) are presented to both eyes.

There are relative advantages and disadvantages to each HWD optics type, depending upon operation and context of use. Generally, monocular systems are (comparatively) lightweight, and some designs allow the user to see the outside world while they are in use, as mentioned. However, also by their design, monocular systems preclude natural attention to stereoscopic cues (Rash, McLean, Mora, Ledford, & Mozo, 1998; Hart & Brickner, 1989). Biocular systems may be more natural for the user, but they can limit peripheral cues and obstruct the view of other instruments, and they typically have more mass (which can impact the user's center-of-gravity) than do monocular designs. With regard to binocular systems, while they too may seem more natural for users but, along with their increased mass, the "technical problems associated with fusing imagery from two sensors to provide a natural binocular image have not been solved adequately for operational use" (Hart & Brickner, 1989, p. 13-8). Further, Lippert (1990) reported problems with the "two-eyed HWD approach" in image alignment and in the overall design, manufacturing, procurement, and maintenance of such systems (p. 190). Additional considerations in the design and implementation of HWD systems are discussed below.

1.1.2 HWD Design Issues

Naturally, humans are used to their visual system 'automatically' providing the appropriately-focused depth of field—the range of distances in object space within which all objects appears in sharp focus—which is typically optical infinity. When users don an

HWD system, this automatic function can be disrupted as the human vision system tries to adjust and refine the depth of field. Users of HWDs have experienced a variety of perceptual issues when systems are not implemented properly, including headache, eye strain, dizziness, nausea, and a general disorientation, called 'cybersickness' (similar to simulator sickness) (Patterson, Winterbottom, & Pierce, 2006). The cause of these issues can be traced to a condition wherein users are presented with visual situations that are unnatural; that is, the image that stimulates the optic nerve results in a perception that does not gel with that generally experienced by users through their natural sight. The use of HWDs in simulated aviation operations, for example, has resulted in user cybersickness due to a lack of correlation between visual and vestibular sensory inputs (Patterson et al., 2006). Typically, when HWD systems present images to a user that results in an inappropriate depth of focus (the range of distances in image space within which an image appears in sharp focus), perceptual issues of the sort mentioned above can result.

With a monocular HWD, one eye is viewing the outside world, and the other is viewing HWD images, or may even be viewing both the HWD images *and* the outside world simultaneously. Thus, the visual input to the two eyes differs greatly; this is termed *dichoptic viewing*. The condition of *binocular rivalry,* wherein each eye 'competes' with the other for visual dominance, results from viewing conflicts between what the aided eye is seeing from the HWD's images and what the unaided eye is seeing from the outside world (Patterson et al., 2006). With dichoptic viewing, binocular rivalry typically occurs, which often results in visual processing that lacks stability. When rivalry presents, studies have indicated that target recognition and visual performance generally decreases (Hershberger & Geurin, 1975). While research suggests that monocular HWDs of the occluded variety (i.e., those that are not transparent, thereby disallowing a view of the outside world) should not be worn for more than 5 minutes (Hakkinen, 2003), whether binocular competition would present similar issues for open or semi-transparent designs is not yet fully understood (Patterson et al., 2006). Patterson et al. (2006) suggest a possible remedy for this competition: HWD systems should incorporate a design that promotes *binocular fusion,* which requires that both eyes view the same or very similar images. Open or semi-transparent designs may promote such fusion.

Perceptual and discomfort issues can also arise due to inappropriate HWD image brightness and contrast. *Dark focus* or *dark vergence*, which is the state of accommodation to which the eyes naturally tend to move and rest (about 1m in front of the observer), are important considerations for HWD designers. Both of these terms relate to the accommodative activity of the eye in low brightness levels (or levels of luminance when considering an HWD image), suggesting that HWD designers must consider displays that provide appropriate image brightness and contrast in order to avoid users' misperception of distance, size, depth, and/or velocity (Patterson et al., 2006). The accommodative response of the eye appears to be valid to a luminance level between 6.9 – 342.6 cd/m^2 (Johnson, 1976; Liebowitz & Owens, 1975). Contrast has been recommended for HWD imagery at a minimum Michelson level of 0.10 (Velger, 1998). Designers must consider the other side of the coin as well: they must ensure that HWD systems are capable of producing the appropriate levels of brightness and contrast when their images are presented to a user operating in the light of day, or in bright ambient lighting conditions. In such conditions, the luminance of the HWD image should be in the neighborhood of 27,400 cd/m^2, which results in a contrast (defined as the ratio of the luminance of the HWD image to that of measured daylight) of about 1.2 (Velger, 1998). If the HWD image is not bright enough, its elements cannot be readily distinguished and/or resolved against a daylight background.

An HWD's field of view represents another important design consideration, the impact of which is dependent upon several factors, including the design of the HWD and its physical placement. Woods, Fetchenheuer, Vargas-Martin, & Peli, in a comparison of binocular and monocular HWD designs, showed that vision may be reduced or even obstructed (i.e., scotoma) by both the veiling luminance of the display itself, and also the HWD's supporting structure (2003). Typically, the larger the field of view, the better the simulation of 'natural' viewing, in that the human visual system maintains a field of view that is 200° horizontal by 130° vertical, with the central 120° as the region of binocular overlap (Velger, 1998). Simply increasing the field of view—while creating a greater sense of user immersion—does not by itself result in a superior HWD design. This is because an increased field of view is achieved through the costs of HWD size and associated mass and through a concomitant decrease in display resolution. Either issue may result in problems: for the former, the increased size and weight of a system that is capable of reproducing the human field of view may preclude useful mobility, or it may produce an intolerable head and neck moment for the user; for the latter, a decrease in resolution achieved through increased field of view may result in a decreased sense of immersion for the user. Researchers have suggested that, for the tasks of targeting and recognition of objects, a field of view as small as 40° may suffice (Patterson et al., 2006). For tasks that involve control of a moving vehicle (relative to other vehicles around the user, such as formation flying), a field of view up to 127° is required (Kruk & Runnings, 1989). These concerns were evidenced in experiments conducted by Brickner and Foyle (1990). In their research involving a simulated helicopter flight task, pilots performed worst in a slalom completion task when their field of view was more restricted (25°) as compared to the least restricted condition (55°). Although the experimental conditions compared a head-down display with a head-up display (with field of view manipulated via a black background beyond the evaluated degree regions), the results may well transfer to HWD design. The researchers concluded that the results were an indication that the pilots' perception of the display was that of the *entire world* as opposed to a *window* of it.

1.1.3 HWD Application Research

For military aviation applications, such as for rotorcraft and/or tactical fighters, HWDs perform one or more of the following functions (Buchroeder, 1987):

1. Display pilot or gunnery imagery from image intensification or forward-looking infrared (FLIR) sensors.
2. Serve as an information management system by presenting tactical, strategic, and/or operational data on demand.
3. Sense head/eye position and motion toward target designation, sensor and weapons direction, and/or activating switches.

Tracking systems are required to accomplish the third function described above. Systems may detect only changes in head position (head trackers), only changes in eye position (eye trackers), or a combination (both head and eye position tracking). In some current military rotorcraft, trackers are used to direct pilotage, targeting sensors and weaponry through a visually-coupled system (e.g., U.S. Army's Apache IHADSS, discussed below). Examples of commercially-available head tracking systems include those from InterSense, Ascension Technologies, Polhemus, and Origin Instruments. Such systems continually monitor the line-of-sight direction of the aviator's head (Rash, 1998). Numerous technological options exist for head tracking, including magnetic, electro-optical, acoustical, and mechanical, but most include magnetic technology due to its high accuracy and low impact on HWD mass. Head position needs to be determined for two reasons: 1) to mimic natural viewing as users make *voluntary* head movements, and 2) to maintain clear vision while working in the flight environment (which involves acceleration and/or vibration) which results in *involuntary* head movements (Patterson et al., 2006). As the HWD moves with the pilot's head, so does the camera platform from which its images emanate. Eye trackers must have sufficient spatial and temporal resolution to accommodate the high speed and accelerations endemic to saccadic eye movements, and must operate over a wide range of illumination levels, pupil sizes, and other physical ocular variations (Rash, 1998). Examples of commercially-available eye tracking systems include the VISION2000 (El-Mar, Inc.) and the X- and T-Series models (Tobii Technology, Inc.). These systems ascertain where in position space the head (and thus the eyes) is facing at any given time. Considering the guidelines to which head-up display (HUD) technologies are designed and implemented in aircraft—specifically in the process of 'boresighting' (i.e., ensuring that the HUD line-of-sight is precisely aligned with the aircraft body axes)—it appears quite a difficult task indeed to try and apply them to HWD systems integration. Boresighting guidelines stipulate variation of no more than 1 mrad for conformal symbols, and a maximum of 3 mrad for symbols that are non-conformal. When one considers the fact that the use of an HWD introduces many more degrees of freedom when compared to a HUD, such specifications seem quite challenging. Head tracking accuracies are typically 2 mrad from the boresight but can increase to 10 to 15 mrad off-boresight (Velger, 1998).

Nevertheless, the advantages of an appropriately integrated HWD in the cockpit are difficult to ignore. When open or semi-transparent HWD designs are used in conjunction with helmet-mounted sights married to high off-boresight weapon systems, pilots are provided with the valuable tactical advantage of being able to designate targets that are up to 90° off the aircraft's nose (Nelson, Bolin, & Russell, 2000). To realize such benefits, however, the pilot must have near-instantaneous system response, which can be negatively affected with temporal delays that may exist between the tracking technology (eye- and/or head-tracking) and the HWD's image presentation—especially when the pilot is looking off-boresight (Martinsen, Havig, Post, Reis, & Simpson, 2003). Such delays can give rise to spatial mismatches between the real world position of an object and its display via HWD to the pilot. Excessive lags in the visual feedback loop can lead to degraded tracking performance, increased pilot workload, and disorientation/physical discomfort on the part of the pilot (Jennings, Craig, & Link, 2002). In addition to target acquisition, other situations in which very fast and highly accurate presentation of tracked HWD images would be required include during takeoff/landing, nap-of-the-earth flying, unusual attitude recovery, and navigation. If an HWD's symbology and imagery does not respond in coordination with head or aircraft movements, then the ability to lock onto potential targets and to fly to specific waypoints may be reduced (Martinsen et al., 2003).

Nelson, Hettinger, Haas, Warm, Dember, & Stoffregen (1998) showed that the addition of a 67 ms time delay negatively impacted performance efficiency in a head-slaved tracking task for users wearing an occluding HWD. In a series of rotorcraft simulation experiments, Wildzunas, Barron, and Wiley found decrements in pilot performance at 400 ms and 533 ms, but not at 267 ms delays and below; also, a significant reduction in accidents was revealed in the last of three trials, suggesting that pilots were able to adapt to system delays (1996). Given the possible utility of an open or see-through HWD in affording the ability for multi-tasking (e.g., tracking and designating targets while monitoring critical control displays), Nelson et al. (2000) investigated the effects of both time delay and a secondary, visual monitoring task on performance efficiency and operator workload for a head-slaved tracking task. Interestingly, the researchers discovered that the addition of the secondary monitoring task—during which system lag was as high as 146 ms—did *not* negatively affect the HWD tracking task, nor did it affect subjective operator workload, suggesting that time delay in HWD systems may not be as much of a limiting factor in a multi-task operational environment as was anticipated, although the limited sample size, laboratory environment, and modest tracking task complexity in the experiment may limit their finding's generalizability. Laramee & Ware (2002) reported that users took longer to obtain certain data from an HWD when viewing its image in front of a dynamic background image when compared to a non-dynamic one, suggesting that the HWD improves performance only when the background image/conditions are very stable. It appears that additional research efforts investigating HWD use in dynamic operating conditions—such as flight—are warranted.

A series of studies investigated aviators' experiences using the integrated helmet and display sight system (IHADSS, a monocular, semi-transparent helmet mounted display) that is integral to the U.S. Army's AH-64 Apache attack helicopter (Behar, Wiley, Levine, Rash, Walsh, & Cornum, 1990; Hale & Piccione, 1990; Crowley, 1991; Crowley, Rash, & Stephens, 1992). The IHADSS receives its visual input from FLIR sensors, and presents the resulting imagery to the right eye of the Apache aviator. The studies represent an invaluable, comprehensive investigation into the efficacy of a monocular, semi-transparent HWD in the operational aviation environment, providing insight into how well the system operates, what that characteristics of the users are (e.g., ocular health, experience levels), as well as their impressions of the system. The researchers identified evidence of increased workload, stress, visual fatigue (both *during* and *after* flight), and mental fatigue on the part of aviators who used the device. Among other findings, aviators reported having to close one eye to either suppress or produce attention-switching. Also, the user-adjusted dioptric (focus) settings of the helmet display unit (HDU; the HWD optics and flight helmet system), measured prior to flight, indicated that those settings (i.e., negative diopters, requiring positive accommodation by the eye to offset them) were a likely source of the subsequent headaches and discomfort that were reported. Also, aviators indicated that they experienced faulty slope and height judgments, undetected aircraft drift, and visual discomfort while flying with the system. The results led to a concern about possible degradations in mission performance.

About a decade after the initial studies discussed above, Rash, Suggs, Mora, van de Pol, Reynolds, & Crowley conducted an internet-based survey of over 200 Apache pilots who had used IHADSS to collect additional data on Apache aviator issues with respect to visual complaints, helmet fit, and acoustics (2000). The researchers found that, in addition to an increase in the frequency of visual complaints from the previous research efforts, 92% of respondents reported at least one visual complaint either during or after IHADSS flight, and that there was no association between complaint frequency and eye preference, age or experience (2000). While many of the issues noted were related to the inappropriate fitting of gear (e.g., poor helmet fit leads to poor FOV via the IHADSS and resulting visual issues), others suggested that monocular, semi-transparent HWDs had not yet reached a level of appropriate design and/or integration such that issues of user discomfort and binocular rivalry were rare. However, many respondents indicated that they thought their difficulties in (for example) recognizing and distinguishing HWD imagery were not due to the IHADSS, but were instead a result of the first-generation FLIR system from which the HWDs imagery was produced (Rash et al., 2000). Whether the aviators' issues with IHADSS would be mitigated through the use of a more advanced FLIR system remains an open question.

Questions with respect to appropriate HWD display design and formatting abound. Of course, appropriate display technology, formatting, and the symbology used will be dependent upon context and application. In military applications, several research and development issues in performance optimization throughout all mission areas must be solved, including answering the questions: 1) what is the *appropriate amount and type* of information to be displayed, 2) what is the *most effective presentation* of that information, and 3) what is the *most effective method(s) for optimizing the integration of information presented via the HWD with other visual and non-visual displays* (Shaw, 2002)? In tactical aircraft, the primary function of the HWD is to provide target acquisition information to the pilot. In this vein, and as Geiselman reported (1999), the HWD's first design requirement with respect to symbology should be that the system "get(s) the pilot's eyes on a target and lead(s) a sensor to a point of interest" (p. 1). However, there is perhaps a competing interest—that specific formats of symbology intended for use in air-to-air operations should be designed to minimize the visual area that they occupy (Fechtig, Boucek, & Geiselman, 1998). Based on this consideration and on issues of ensuring that appropriate own-ship information is presented to the pilot, Geiselman (1999) created a list of symbology design principles for tactical fighter aircraft, which included two broad classes of visual information that can be displayed in a HWD: targeting and flying. In stratifying the needed user visual information in a similar manner based on context, such a listing may aid HWD developers when making design decisions with respect to how and when to appropriately display symbology.

In other domains, performance advantages have been identified with HWD use, particularly in anesthesia. HWDs have resulted in increased time spent looking at the patient, a decreased number of times physicians switched their attention to a standard visual monitor, decreased the amount of time spent handling critical patient events (Ormerod, Ross, & Naluai-Cecchini, 2002), and decreased the time anesthesiologists took to detect certain critical events when compared to the standard visual monitor (Via, Kyle, Kaye, Shields, Dymond, Damiano, & Mongan, 2003). However, while similar results have been obtained in the aviation domain, critical event detection has been mixed.

Lorenz, Tobben, & Schmerwitz (2005) evaluated a retinal scanning, monocular semi-transparent HWD in aviation operations and noted that pilots had difficulty detecting the critical event of an incursion on a runway upon which they were cleared to land. The problem appears to be that of *attention capture.* Krupenia & Sanderson (2006) reported that, while the use of an HWD affects users' ability to detect unexpected events when compared to a standard visual display, its effects on visual attention were even stronger. The phenomenon of attention capture has been found in other head-up systems as well, including HUDs (Hofer, Braune, Boucek, & Pfaff, 2001; Wickens & Long, 1995), with a head-down pathway flight aid (Flemisch & Onken, 2000), and with a combination HUD/pathway (Fadden, Ververs, & Wickens, 2001). Thus, in the introduction of HWDs to naturalistic, safety-critical environments and knowledge-rich work domains, care must be taken—especially in ensuring that operators do not assume that the use of HWDs can preserve their ability to detect unexpected events (Krupenia & Sanderson, 2006).

A possible means of mitigating or removing the detrimental effect of attention capture with HWD use in an aviation application was utilized by Tobben, Lorenz, & Schmerwitz (2005), wherein HWD flight path and associated symbology was successively reduced or removed—through a process called *phase-adaptive decluttering*—when a conformal outside (i.e., real-world) element (e.g., a runway) became visible. The researchers suggest that the phase-adaptive technique effectively reduces clutter and emphasizes important information by reducing or removing the amount of overall information presented in the center of the display. Examples of visual information that is reduced or removed as the aircraft approaches the runway include a reduction in the shape of the flight pathway and removal of the terrain model (Tobben et al., 2005). Pilots flying with the system detected a simulated runway incursion 2 sec slower with the phase-adaptive decluttering HWD when compared to a head-down display, suggesting that attention capture remains a considerable concern for HWD integration in aviation applications.

1.1.4 Monocular Versus Biocular Study References

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1.2 Monocular Versus Biocular Experiment

1.2.1 Introduction

The use of collimated virtual displays (e.g. HUDs) by pilots has become more commonplace in aircraft. After decades of development and deployment by all branches of the military, FAA certified HUDs are standard equipment on many airliners. The success of HUDs is leading researchers to apply other forms of collimated virtual displays; one form that shows promise is the near to eye display (NTE). An NTE is simply a virtual display with the projection lenses placed at close distance directly in front of one or both of the pilot's eyes. This type of display is generally mounted on some type of helmet. With the development of such a display come several research questions.

Most obvious is the question of whether to use one display or two displays (monocular versus biocular), and are there any associated pilot performance effects? Binocular rivalry is one concern during the use of a monocular display. Binocular rivalry is a phenomenon that occurs when dissimilar stimuli are presented to the eyes, such as a virtual display presented to one eye, while the other eye has a clear view of the instrument panel or environment outside the aircraft. The brain reacts to these stimuli by going into an unstable state characterized by monocular dominance. Monocular dominance is the alternation of dominance and suppression phases between the two eyes. The duration with which each eye dominates visual perception or is suppressed is presently unpredictable and also unrelated to the duration of any previous dominance/suppression phases. However, it is known that the introduction of a transient image or animation to the suppressed eye will return that eye to dominance. Individuals have no conscious control over the dominance/suppression phases (Lamaree & Ware, 2002).

The dominance/suppression phasing of binocular rivalry can be induced by a monocular head mounted display (HMD) and is certainly a consideration when answering the monocular versus biocular questions for NTE displays. In fact, a number of authors have already identified binocular rivalry as a potentially serious perceptual problem related to HMDs (Blackwood et al., 1997; Peli, 1990). There also seems to be anecdotal evidence that pilots have perceptual problems related to binocular rivalry while utilizing a monocular display. Rush et al. (1990) reported that some pilots stated having resorted to closing one eye because of the difficulty switching attention between eyes while using a monocular display during flight operations. The last question related to binocular rivalry and monocular displays would be over which eye should the NTE be situated? Previous research has shown that dominant eye imagery is generally seen more frequently and for longer duration during periods of binocular rivalry. Therefore, there may be performance advantages to locating the monocular NTE display over the dominant eye (longer dominant phase with the virtual symbology visible). Conversely, there may be performance advantages to locating the monocular NTE display over the non-dominant eye (longer dominant phase with the outside world visible). These monocular versus biocular questions will be addressed in this study.

In addition to the issue of binocular rivalry, general criticisms of collimated virtual displays which arose during HUD development must also be addressed to ensure that NTE displays are safe and effective for pilot use. One of the most noted criticisms is that pilots have a tendency to focus on the HUD combining glass instead of the outside world. The cause was theorized that our eyes do not focus well at optical infinity when viewing collimated virtual images, but have a tendency to focus inward to resting accommodation at a distance of approximately arm's length (Hull, Gill, & Roscoe, 1982; Roscoe, 1985; Roscoe, 1987). The conclusion that the misaccommodation of the eyes at optical infinity and the associated loss of visual acuity would portend performance degradation the detection and identification of potential targets in the outside world. This study intends to directly measure a pilot's ability to accommodate optical infinity while detecting and identifying an unobtrusive measure of visual acuity.

While this physiologically-based explanation was partially refuted by later research (e.g. Wise & Sherwin, 1989), an alternative cognitively-based explanation is put forth by other researchers. Their research observations state that a display may be so compelling that a pilot's ability to divide attention is degraded, leading to difficulty identifying potential targets in the outside world (McCann et al., 1993; Crawford & Neal, 2006). This performance effect may be caused by the phenomenon known as inattentional blindness. Inattentional blindness occurs when observers fail to perceive an unexpected object or event, even if it appears in the central field of view, due to the observer's attention being diverted to another object or task, (Simons & Chabris, 1999). This possibly degrades a pilot's ability to detect unexpected objects and events and will also be included as a factor in the present study.

1.2.2 Experimental Design

The design of the NTE investigation was a completely within-subjects (3 x 4 x 4 x 10) experiment. The study consisted of three independent variables and five categories of dependent variables, with some categories consisting of multiple dependent measures. The fully within-subjects design means that all participants received all levels of the three independent variables, one level at a time, in a varying completely counterbalanced order, over multiple runs. This design was chosen to make use of the participants as their own control. This methodology generally increases the sensitivity of the experiment due to relief from the high levels of between-subject variability likely to occur in a between-subjects or a mixed-measures design. Furthermore, a within-subject design is especially important to a study involving pilots in moderate workload scenarios. Pilots are generally encouraged in training to develop strategies and procedures to cope with the rigors of flight. These individualized, idiosyncratic strategies can differ widely from pilot to pilot increasing the inter-subject variability.

1.2.3 Independent Variables

As previously mentioned, there were three independent variables manipulated in this study. The first variable includes three levels of different NTE display configurations, biocular, monocular over dominant eye, and monocular over non-dominant eye. Each NTE display configuration was worn by every pilot through all types of meteorological conditions, and runway incursion variable levels. The next independent variable included in the study is the meteorological condition within which the approaches were flown. Four meteorological conditions were chosen to test the NTE displays, day and night visual meteorological conditions (VMC), and day and night instrument meteorological conditions (IMC). The last independent variable was a runway incursion trial. This variable consisted of two levels. The first level was a clear active runway on which the pilots were able to land. The second level of the variable was the appearance of ground traffic on the approach end of the runway on which the pilot was cleared to land. Misses, correct identifications, and misidentifications of the runway incursion event were recorded for each approach the ground traffic appears.

1.2.4 Dependent Measures

Primary Task (Flight) Performance. There were six dependent measures which were collected as primary task metrics to measure the effects of the independent variables on flight performance during the approaches. These six metrics directly measured the pilot's flight performance and included magnetic heading, barometric altitude, latitude, longitude, localizer track deviation, and glideslope deviation.

Visual Acuity. Throughout each approach the pilot flew, Landolt rings were displayed at random time intervals. The Landolt rings, classic measures of visual acuity, were used to measure the pilot's physical ability to accurately see and identify outside targets. Landolt rings consist of a shape that resembles the letter O except that a notch is cut out of the circle (see Figure 1-1), where the stroke width is one-fifth the diameter and the gap width is the same. The visual acuity test is a measure of whether the participant can identify the location of the notch according to a standard clock face (e.g. the notch is at 3 o'clock). The Landolt rings were projected onto the simulation screen which displayed the outside world flight simulation. All Landolt rings were scaled for 20/20 visual acuity. Misses and correct identifications were recorded for every approach.

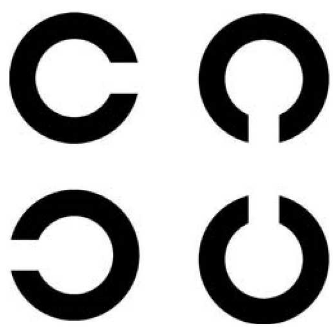

Figure 1-1. Examples of Landolt C Acuity Test

Comfort Ratings. At the end of each approach flown by the pilot (12 approaches in total), pilots were given a comfort rating scale requiring them to rate aspects regarding comfort according to respective bipolar descriptors. This scale was developed by Casali and Grenell (1990), and has already been validated for aviation headset comfort studies. The scales were modified to include dimensions important to pilot comfort while wearing NTE displays.

Runway Incursion Event. In one of the four approaches the pilot flies for each display configuration, a runway incursion event was triggered. If the pilot correctly identified the runway incursion event, a correct identification was recorded. If the pilot failed to perceive the event, a miss was recorded. Lastly, if the pilot perceived the event, but failed to correctly identify the situation, a misidentification was recorded. Misidentifications, misses and correct identifications were recorded for every approach that includes a situation awareness event.

1.2.5 Methods

1.2.5.1 Participants

Twelve certificated pilots participated in this investigation. Eleven of the 12 were Airline Transport Pilot (ATP) rated. The mean flight experience in terms of total flight time was 12017.0 hours and the mean flight experience with heads-up displays (HUDs) was 2275.0 hours. Six of the 12 pilots wore corrective lenses.

1.2.5.2 Apparatus

The testing apparatus consisted of the head mounted NTE display which was constructed by integrating two Microvision Nomad displays and a custom-built head mount which had an adjustment to accommodate differences in head size. The Nomad displays were mounted in such a way that an adjustment could be made to the displays to accommodate differences in inter-pupil distance. The displays had a hardwired control pad and internal menu structure which allowed the experimenter to make adjustment to the position of the symbology on the display to account for individual differences in dipvergence (see Figure 1-2).

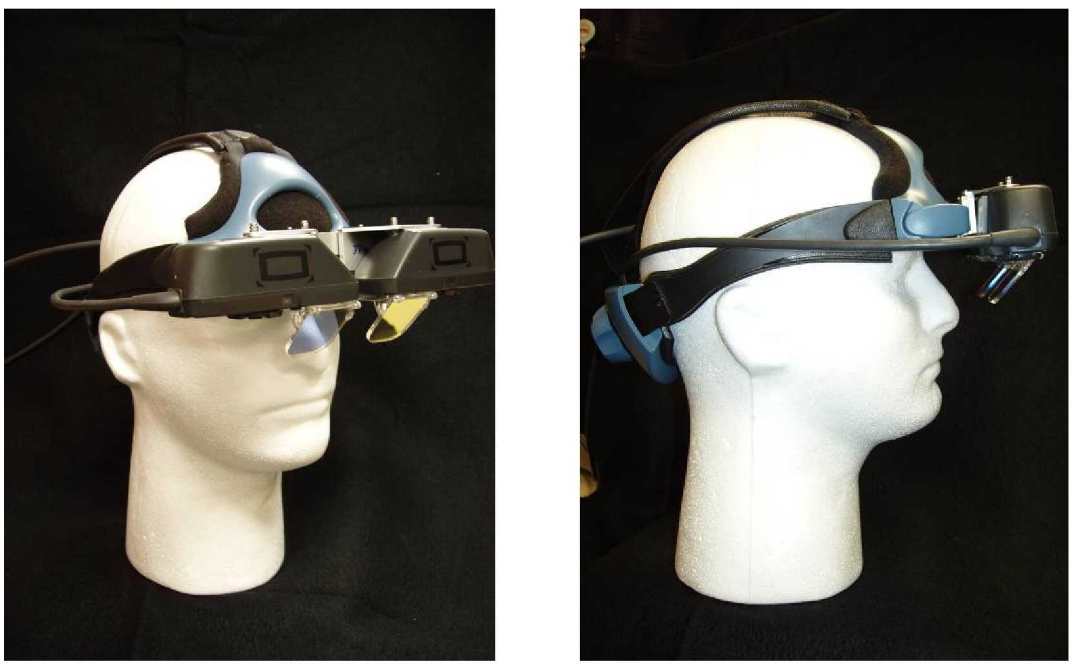

Figure 1-2. Photos of the experimental near to eye display worn by the participants.

Additional equipment used in the experiment included the Ascension Phasor Bird, which provided head tracking data to ensure the display imagery was stable as the pilot moved his head during the simulated approaches (see Figure 1-3). The simulated ILS approach into Chicago-Midway runway 4R was driven by Microsoft Flight Simulator X and aircraft control was provided by an off-the-shelf control yoke. The heads down primary flight display (PFD) was displayed on a Honeywell 1310 LCD display. The screen onto which the flight simulation was projected was located at a distance from the pilot effectively equal to optical infinity (approximately 26 feet).

Figure 1-3. Photo of the head tracker and cockpit set-up.

1.2.5.3 Procedure

Before the calibration of the NTE display was begun, pilots reviewed the informed consent form, asked any questions, and if they agreed to participate, signed the form. They were given a copy of the signed form. Then a short instruction period was given where the basic purpose of the experiment and the flight performance which was expected from them was explained. They were also assigned their participant number, and told what responses are appropriate for the appearance of the Landolt rings. The last part of this initial element of the experiment was a test to determine the pilot's dominant eye. The eye dominant was tested through the classic "hole in the card test." Participants were given and index card will a hole cut out in the center. They were told to focus on an object in the room through the hole in the card, while the card was held by the participant at arm's length. Then while keeping the object in the center of the hole, they were instructed to bring the card back to their face. They then were told to close one eye at a time and asked with which eye they could see the object through the hole in the card. The participant's dominant eye was recorded on a data collection sheet. The beginning portion of the experiment lasted approximately 30 minutes.

NTE Display Calibration. Pilots fitted themselves with the head mounted display and made adjustments until the HMD felt snug but comfortable. The experimenter then adjusted the NTE displays to match the participant's inter-pupil distance. Lastly, a calibration screen was presented on the NTE display and a calibration target was displayed on the simulator screen so that the experimenter and participant could make adjustments to the head tracker and accommodate differences in dipvergence, bringing the symbology shown on the NTE display into a converged focused picture. When pilots stated the symbology was properly focused and they no longer saw double imaging or ghosting, then calibration was complete. This portion of the experiment typically lasted between 20 – 30 minutes.

Experimental Session. Each pilot flew four approaches (one approach contained one level of meteorological condition and one level of runway incursion event) through the use of a fixed-base flight simulator with each of the three display configurations for a total of 12 approaches in an experimental session. The order of the display configurations, different meteorological conditions, and the runway incursion variable was counterbalanced using a full Latin Square design. The Latin Square design counterbalanced the order in which the participants experienced each one of the different levels of the independent variables and insured that ordering effects did not confound the data and experimental results.

The following scenario is an example of a pilot's experience during one of the 12 simulated approaches. The pilot was placed in the flight simulator and, following calibration of the NTE display, the experimental session began with the five mile straight-in instrument landing system (ILS) approach to runway 4R at Chicago Midway airport. This example illustrates a straight-in approach in IMC conditions. The flight began with the aircraft centered on the localizer for an ILS approach. Throughout the approach, Landolt rings were displayed at random time intervals at a fixed location in the outside field of view. Pilots were required to identify the appearance of the Landolt ring and the location of the Landolt ring notch (e.g. 4 o' clock). As the pilot captured the glideslope, he or she continued to identify the appearance of Landolt rings until breaking out of the cloud layer. At this point, the flight simulation showed ground traffic taxiing onto the runway for the pilot to identify the hazardous situation and react appropriately.

1.2.5.4 Data Analysis Overview

The following analyses were conducted with the data collected during the experimental trials.

Primary Task (Flight) Performance. The data were grouped and analyzed using a (3 x 4 x 4 x 10) multivariate analysis of variance (MANOVA). If the Wilk's Lambda MANOVA resulted in main effects and/or interaction effect significance, the individual flight measures were separated and analyzed using a (3 x 4 x 4 x 10) univariate analysis of variance (ANOVA). Post-hoc comparisons were conducted on significant ANOVA results using a Tukey HSD test.

Visual Acuity. The nominal data of the Landolt ring correct identifications and misses were analyzed using a Fisher's Exact Test. Since some data cells of the experimental design contained values of less than five, it was determined that the Chi-Squared test was not the appropriate tool, rather a Fisher's Exact Test was the correct analysis in this case (Ott & Longnecker, 2001). Where significant differences were found, further pairwise contrasts were performed using additional Fisher's Exact Test procedures.

Comfort. Each bipolar scale rating was converted into numerical scores ranging from 1 (on the far left) to 7 (on the far right) and analyzed separately using the ANOVA procedure as carried out by Park & Casali (1991). Further post-hoc analysis was carried out using the Tukey HSD procedure.

Runway Incursion. The nominal data of the runway incursion event correct identifications, misidentification, and misses were analyzed using a Fisher's Exact Test. Since some data cells of the experimental design contained values of less than five, it was determined that the Chi-Squared test was not the appropriate tool, rather a Fisher's Exact Test was the correct analysis in this case (Ott & Longnecker, 2001). Where significant differences were found, further pairwise contrasts were performed using additional Fisher's Exact Test procedures.

1.2.6 Results

Runway Incursion Event. A Fisher's Exact Test was used to compare the pilots' ability to correctly identify a runway incursion event while wearing the three different display configurations. Results of the statistical analysis have shown no differences between the biocular configuration or either of the dominant eye and non-dominant eye monocular configurations ($p = 0.40$).

Table 1-1. Mean Runway Incursion Identification Accuracy Scores

Display Configuration	Mean Identification Accuracy	Standard Deviation
Biocular	72.73%	0.467
Dominant Eye Monocular	91.67%	0.289
Non-Dominant Eye Monocular	91.67%	0.289

Visual Acuity. A Fisher's Exact Test was used to compare the visual acuity of pilots. Results have shown a significant difference between the three display configurations ($p < 0.001$). Further pairwise comparisons using Fisher's Exact Test showed pilots correctly identified more Landolt Rings while wearing the monocular display over the dominant eye than while wearing the biocular display ($p < 0.001$). Pairwise comparisons also showed that pilots correctly identified more Landolt Rings while wearing the monocular display over the non-dominant eye than while wearing the biocular display ($p < 0.001$). No differences were found between the dominant eye and non-dominant eye monocular displays ($p = 0.15$; see Figure 1-4).

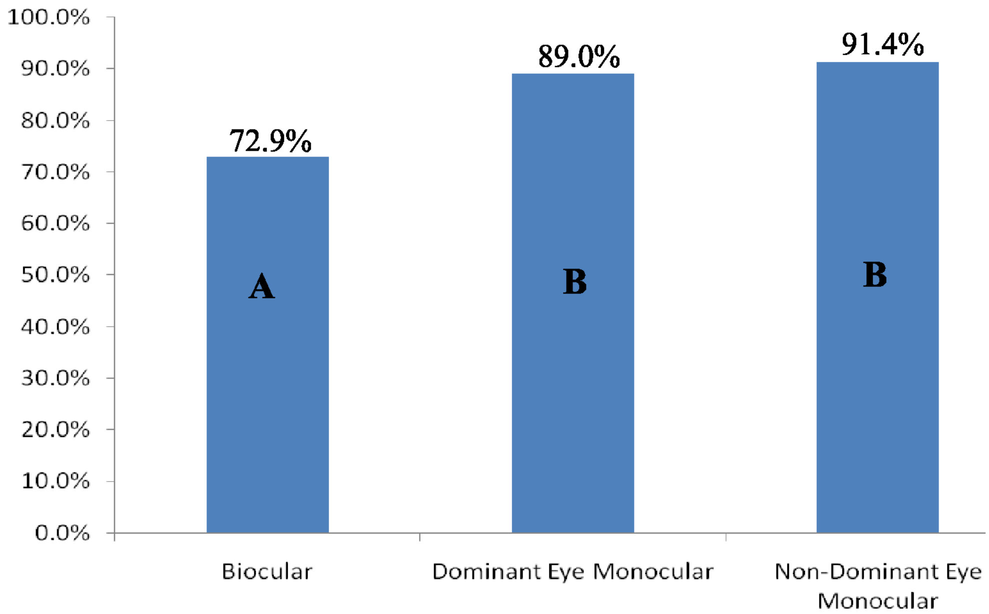

Figure 1-4. Mean identification accuracy of Landolt ring visual acuity test by display configuration. Different letters represent significant differences at the $p < 0.05$ level.

Comfort Ratings. The ratings given by pilots for each scale were analyzed by a repeated measures ANOVA. Except for the rating scale for the blurred display and the scale for blurred outside visuals, all comfort ratings showed non-significant results between the three display configurations.

Painless/Painful:	$F = 1.15, p = 0.34$
Uncomfortable/Comfortable:	$F = 1.10, p = 0.35$
No Uncomfortable Pressure/Uncomfortable Pressure:	$F = 0.18, p = 0.84$
Intolerable/Tolerable:	$F = 1.54, p = 0.24$
Not Bothersome/Bothersome:	$F = 0.57, p = 0.57$
Heavy/Light:	$F = 0.28, p = 0.76$
Cumbersome/Not Cumbersome:	$F = 0.27, p = 0.77$
Eyes Strained/Eyes Not Strained:	$F = 1.49, p = 0.20$
Feel Pain in Neck/No Pain Felt:	$F = 0.37, p = 0.69$
Feel Pain in Shoulders/No Pain Felt:	$F = 0.49, p = 0.62$
Eyes Dry/Eyes Tearing:	$F = 0.11, p = 0.90$

Table 1-2. Mean Painless/Painful Rating (0 = Painless, 7 = Painful) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	2.761	0.278
Dominant Eye Monocular	2.333	0.2
Non-Dominant Eye Monocular	2.438	0.186

Table 1-3. Mean Uncomfortable/Comfortable Rating (0 = Uncomfortable, 7 = Comfortable) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	4.891	0.266
Dominant Eye Monocular	5.104	0.2
Non-Dominant Eye Monocular	5.375	0.178

Table 1-4. Mean Not Uncomfortable Pressure/Uncomfortable Pressure Rating (0 = No Uncomfortable Pressure, 7 = Uncomfortable Pressure) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	2.587	0.223
Dominant Eye Monocular	2.729	0.222
Non-Dominant Eye Monocular	2.937	0.226

Table 1-5. Mean Intolerable/Tolerable Pressure Rating (0 = Intolerable, 7 = Tolerable) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	5.326	0.229
Dominant Eye Monocular	5.688	0.191
Non-Dominant Eye Monocular	5.563	0.160

Table 1-6. Mean Not Bothersome/Bothersome Rating (0 = Not Bothersome, 7 = Bothersome) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	3.522	0.31
Dominant Eye Monocular	3.292	0.263
Non-Dominant Eye Monocular	3.104	0.246

Table 1-7. Mean Heavy/Light Rating (0 = Heavy, 7 = Light) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	4.87	0.208
Dominant Eye Monocular	4.979	0.172
Non-Dominant Eye Monocular	4.813	0.17

Table 1-8. Mean Cumbersome/Not Cumbersome Rating (0 = Cumbersome, 7 = Not Cumbersome) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	4.478	0.248
Dominant Eye Monocular	4.646	0.235
Non-Dominant Eye Monocular	4.729	0.245

Table 1-9. Mean Eyes Strained/Eyes Not Strained Rating (0 = Eyes Strained, 7 = Eyes Not Strained) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	3.804	0.279
Dominant Eye Monocular	5.021	0.232
Non-Dominant Eye Monocular	4.938	0.189

Table 1-10. Mean Neck Pain Felt/No Neck Pain Felt Rating (0 = Neck Pain Felt, 7 = No Neck Pain Felt) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	5.522	0.224
Dominant Eye Monocular	5.729	0.22
Non-Dominant Eye Monocular	5.542	0.219

Table 1-11. Mean Shoulder Pain Felt/No Shoulder Pain Felt Rating (0 = Shoulder Pain Felt, 7 = No Shoulder Pain Felt) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	5.957	0.155
Dominant Eye Monocular	6.063	0.167
Non-Dominant Eye Monocular	6.063	0.164

Table 1-12. Mean Eyes Dry/Eyes Tearing Rating (0 = Eyes Dry, 7 = Eyes Tearing) by Display Configuration.

Display Configuration	Mean Rating	Standard Deviation
Biocular	3.587	0.163
Dominant Eye Monocular	3.646	0.17
Non-Dominant Eye Monocular	3.625	0.151

Display blurred showed significant differences between the three display configurations ($F = 4.24$, $p = 0.03$). The Tukey comparison showed pilots rated both monocular configurations as significantly less blurred than the biocular configuration. No significant differences were found between the two monocular conditions (see Figure 1-5). Outside visuals blurred also showed significant differences between the three display configurations ($F = 4.49$, $p = 0.02$). The Tukey comparison showed pilots rated both monocular configurations as significantly less blurred than the biocular configuration. No significant differences were found between the two monocular conditions (see Figure 1-6).

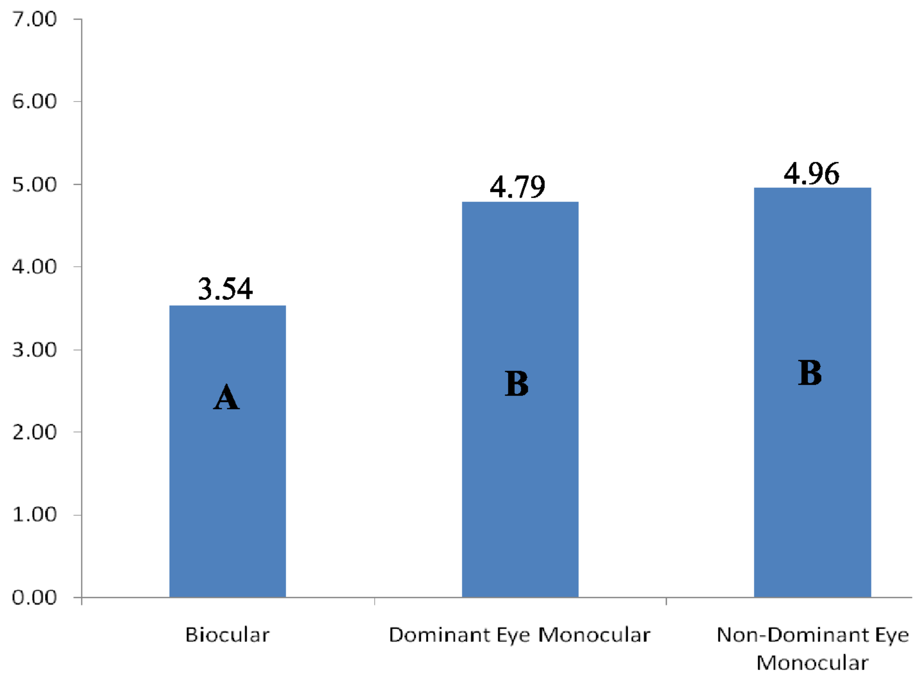

Figure 1-5. Mean pilot ratings of the display image blurring levels for each display configuration (0 = Display Image Blurred, 7 = Display Image Clear). Different letters signify significant differences at the $p < 0.05$ level.

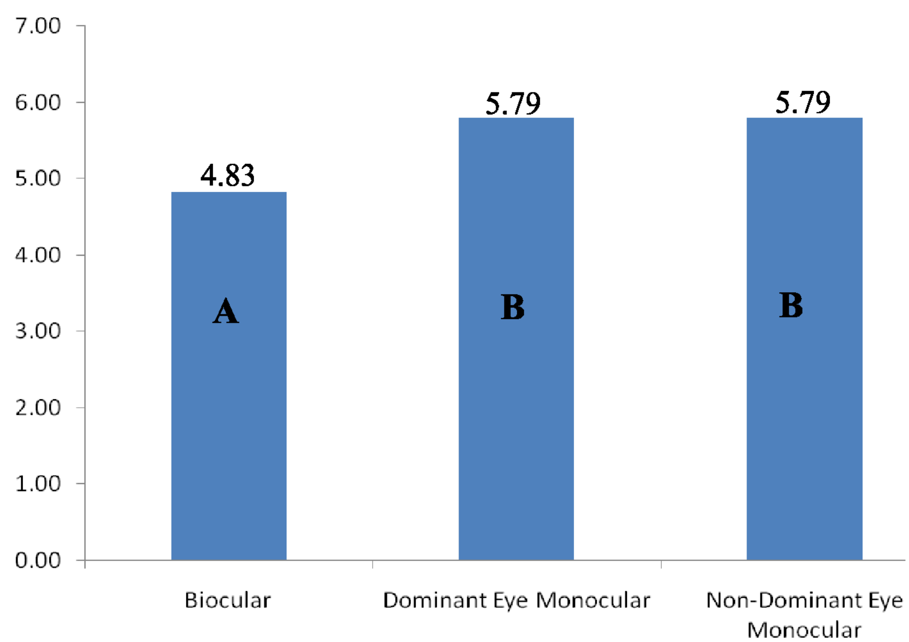

Figure 1-6. Mean pilot ratings of the outside image blurring levels for each display configuration (0 = Outside Image Blurred, 7 = Outside Image Clear). Different letters signify significant differences at the $p < 0.05$ level.

Primary Task (Flight) Performance. Six measures of flight performance (latitude, longitude, magnetic heading, barometric altitude, localizer deviation, glideslope deviation) were collected at a sampling rate of 10 seconds during each simulated approach. The flight performance was then compared with the ideal flight performance of the simulated approach and flight performance deviations from the ideal were analyzed by a repeated measures MANOVA. Results of the MANOVA revealed that the main effect for display configuration showed no significant differences between the three display configurations (Wilk's Lambda = 0.31, $p = 0.93$). The main effect for meteorological condition also revealed no significant differences in flight performance across the four different conditions (Wilk's Lambda = 1.88, $p = 0.06$). Lastly, the interaction effect between display configuration and meteorological condition revealed no significant interaction (Wilk's Lambda = 0.78, $p = 0.73$). Due to the non-significance of the MANOVA results, no further analysis of the individual performance measures would be appropriate.

Table 1-13. Mean Glideslope Deviation by Display Configuration.

Display Configuration	Mean Glideslope Deviation (dots)	Standard Deviation
Biocular	0.834	0.391
Dominant Eye Monocular	0.835	0.453
Non-Dominant Eye Monocular	0.83	0.392

Table 1-14. Mean Glideslope Deviation by Meteorological Condition.

Meteorological Condition	Mean Glideslope Deviation (dots)	Standard Deviation
Day VMC	0.797	0.203
Day IMC	0.931	0.246
Night VMC	0.741	0.209
Night IMC	0.874	0.286

Table 1-15. Mean Localizer Deviation by Display Configuration.

Display Configuration	Mean Localizer Deviation (dots)	Standard Deviation
Biocular	0.197	0.148
Dominant Eye Monocular	0.168	0.104
Non-Dominant Eye Monocular	0.183	0.128

Table 1-16. Mean Localizer Deviation by Meteorological Condition.

Meteorological Condition	Mean Localizer Deviation (dots)	Standard Deviation
Day VMC	0.16	0.082
Day IMC	0.223	0.148
Night VMC	0.141	0.099
Night IMC	0.209	0.154

Table 1-17. Mean Magnetic Heading Deviation by Display Configuration.

Display Configuration	Mean Magnetic Heading Deviation (degrees)	Standard Deviation
Biocular	3.345	0.269
Dominant Eye Monocular	3.334	0.166
Non-Dominant Eye Monocular	3.329	0.180

Table 1-18. Mean Magnetic Heading by Meteorological Condition.

Meteorological Condition	Mean Magnetic Heading Deviation (degrees)	Standard Deviation
Day VMC	3.28	0.08
Day IMC	3.377	0.292
Night VMC	3.316	0.124
Night IMC	3.373	0.262

Table 1-19. Mean Barometric Altitude Deviation by Display Configuration.

Display Configuration	Mean Barometric Altitude Deviation (feet)	Standard Deviation
Biocular	92.769	37.63
Dominant Eye Monocular	97.445	38.36
Non-Dominant Eye Monocular	96.369	35.414

Table 1-20. Mean Barometric Altitude by Meteorological Condition.

Meteorological Condition	Mean Barometric Altitude Deviation (feet)	Standard Deviation
Day VMC	94.568	41.573
Day IMC	95.428	37.211
Night VMC	91.842	37.351
Night IMC	100.241	32.49

Table 1-21. Mean Flight Path Deviation (Latitude) by Display Configuration.

Display Configuration	Mean Latitude Deviation (degrees)	Standard Deviation
Biocular	0.005	0.004
Dominant Eye Monocular	0.006	0.005
Non-Dominant Eye Monocular	0.005	0.004

Table 1-22. Mean Flight Path Deviation (Latitude) by Meteorological Condition.

Meteorological Condition	Mean Latitude Deviation (degrees)	Standard Deviation
Day VMC	0.006	0.004
Day IMC	0.005	0.004
Night VMC	0.006	0.004
Night IMC	0.004	0.003

Table 1-23. Mean Flight Path Deviation (Longitude) by Display Configuration.

Display Configuration	Mean Longitude Deviation (degrees)	Standard Deviation
Biocular	0.006	0.005
Dominant Eye Monocular	0.007	0.005
Non-Dominant Eye Monocular	0.006	0.004

Table 1-24. Mean Flight Path Deviation (Longitude) by Meteorological Condition.

Meteorological Condition	Mean Longitude Deviation (degrees)	Standard Deviation
Day VMC	0.007	0.005
Day IMC	0.006	0.004
Night VMC	0.007	0.005
Night IMC	0.005	0.004

1.2.7 Conclusions

This study sought to investigate potential differences between monocular and biocular NTE displays. Binocular rivalry was a potential problem reported previously in the literature but did not seem to affect pilot performance along any data collected during this experiment. Furthermore, no subjective statements in the post-experiment interviews revealed either awareness of dominance/suppression phases of the eyes, trouble focusing on the flight symbology or the outside world visuals while wearing either of the monocular display configurations. This is not to say binocular rivalry was not present. It may not have reached a level that made pilots consciously aware of it or affected their performance on any of the dependent measures.

The visual acuity data directly measured the pilot's ability to accurately detect, focus on, and identify a target at optical infinity. The results of this study directly contradict those of previous studies (Hull, Gill, & Roscoe, 1982; Roscoe, 1985; Roscoe, 1987). With accuracy scores of 72.9%, 89.0%, and 91.4% for the biocular, dominant eye monocular, and non-dominant eye monocular displays, respectively, the results of this study clearly indicate that not only do pilots have the physiological capability to accommodate between the near field and optical infinity, but they are able to utilize this capability very effectively when identifying potential targets at optical infinity. The visual acuity analysis of this study also revealed significant differences between the display configurations. Pilots had significantly greater visual acuity while wearing either of the monocular display configurations than wearing the biocular display, with no differences found between the two monocular displays. This may be due to the unobstructed view of the outside world afforded to one eye by the monocular display, which may enable the pilot to more easily perceive and focus on the outside visual targets.

The significant results found on the display image blurred and outside world image blurred subjective comfort rating scales showed the same relationship between monocular and biocular displays as the visual acuity test. Pilots rated image blurring (both display images and outside world simulated images) as significantly more blurred when wearing the biocular display. A clear visual pathway to the outside world may also explain the differences reported by pilots on the subjective comfort ratings. Again, binocular rivalry seemed not to be a factor as both monocular displays were preferred over the biocular display. In general, pilots also stated they felt no differences between locating the monocular display over their dominant or non-dominant eyes.

Results of the flight performance measures showed no significant differences between any of the three display configurations. This is not unexpected and can be easily explained by the level of training and experience in the participants used in this study. By design, pilots are trained to cope with highly dynamic, high-workload flight conditions. Therefore, the absence of significant differences could be the result of the pilots' ability to cope with the three displays and maintain the flight performance standards given to them at the beginning of the experiment. In all likelihood, even if there are differences between the three display configurations, they will not show up in the flight performance measures for a routine simulated ILS approach.

Looking at the results and their possible interpretations as a whole, it seems that the pilot's ability to adapt to different displays hides potential advantages and shortcomings when attempting to compare those displays. However, this study has revealed one very important piece of evidence for the developing NTE display. Pilot's visual acuity at optical infinity was significantly more accurate with a monocular display than a biocular display. The ability to accurately perceive and identify a potential target or conflict has not only a major safety advantage but also an advantage in terms of solving the conflict in a way that is most advantageous to the pilot's mission. Therefore, the evidence of this study supports an advantage of NTE monocular displays over their biocular counterpart.

1.2.8 Monocular Versus Biocular Experiment References

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2 Latency Study

2.1 Tracker Latency Measurement Method

This report describes the test setup (Figure 2-1) and data collection method for the measurement of latency for a tracker system.

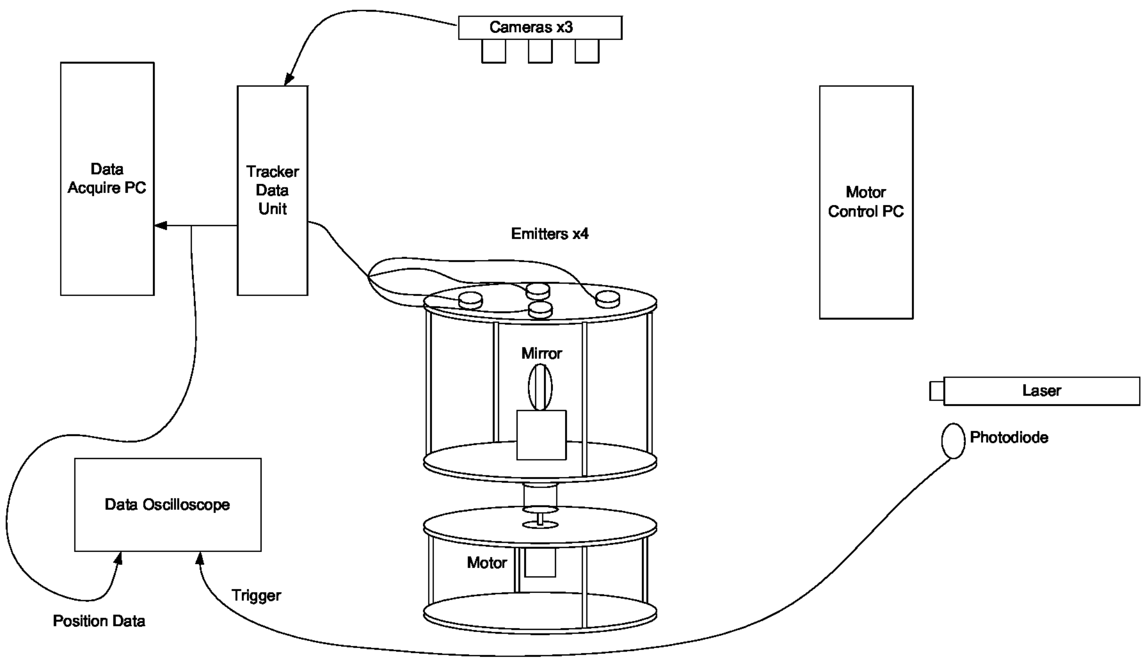

Figure 2-1. Test Setup

The latency is measured by moving the tracker fixture through the same circle twice. The first movement is a static run which is done to gather three angles of reference associated with reflections of a laser beam off a mirror assembly. Each reflection is detected by a photodiode which has its output monitored by an oscilloscope. The second reflection is used as a trigger for the oscilloscope and the other two angles are used as additional reference points. Each laser beam reflection is associated with a fixed angle position. The three angles of reference are collected from the output of the tracker data unit during the static run. During the dynamic run the tracker fixture moves through the circle and position data is collected from the tracker data unit's output and into the data oscilloscope.

The latency between the reported tracker position and the three reference angles will have a slight shift between the reference angles and the dynamic run. This slight shift will be comprised of a phase difference measured in milliseconds and a position difference measured in degrees; see Figure 2-2.

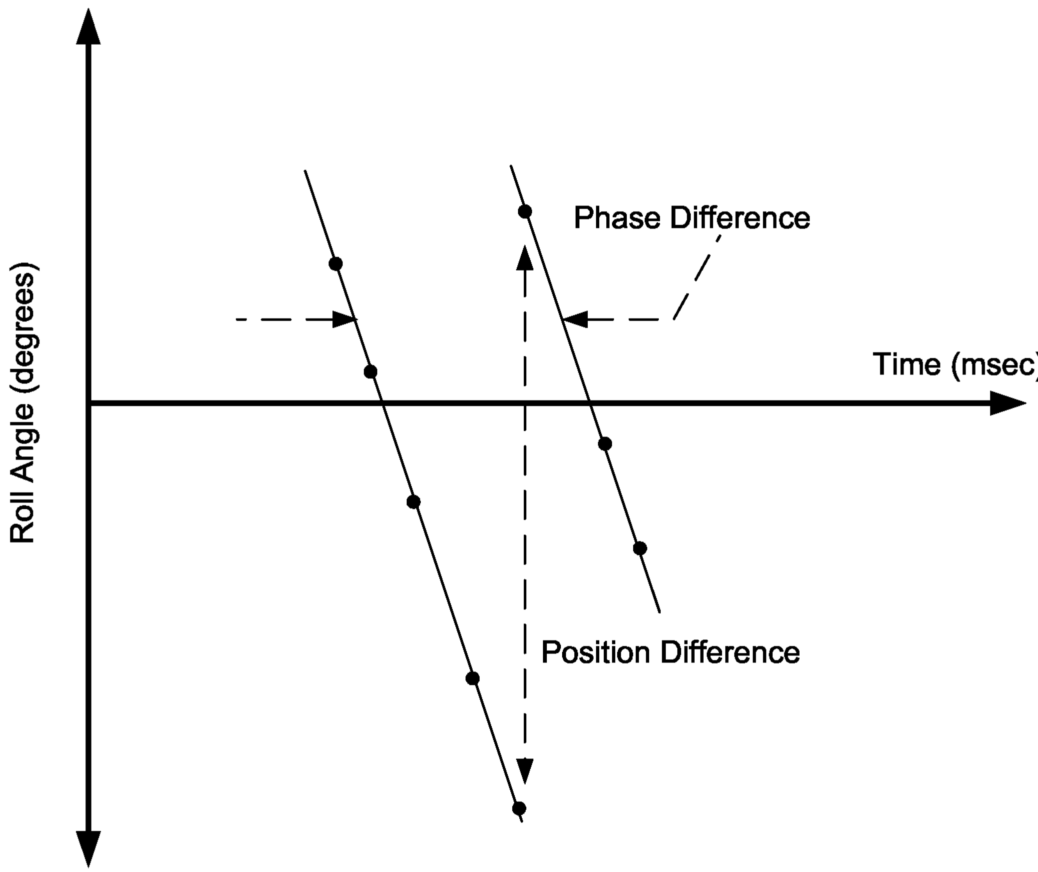

Figure 2-2. Phase and Position Difference

The trackers used were a phasorBIRD and laserBIRD from Ascension Technologies. The output position data from the tracker data unit is an RS-232 serial line operated at 115200 baud. When the tracker fixture moves through the three reference angle positions the oscilloscope starts to record the RS-232 data when the trigger angle is reached. Fifty percent of the data is saved before the trigger and fifty percent of the data is saved after the trigger. This ensures that the first and third reference angles are recorded. The data is decoded to both binary and HEX values and saved as an Excel spreadsheet. The decoded RS-232 data is related to the trigger angle as time elapsed since the trigger occurred. The three reference angles are shown as independent events on channel 2 (green trace) of the oscilloscope. The RS-232 data format contains 6 HEX words ordered as 0 to 5 with the roll angle being contained in words 4 and 5. The binary RS-232 data is then converted into degrees of roll and plotted against the three reference angles with respect to time.

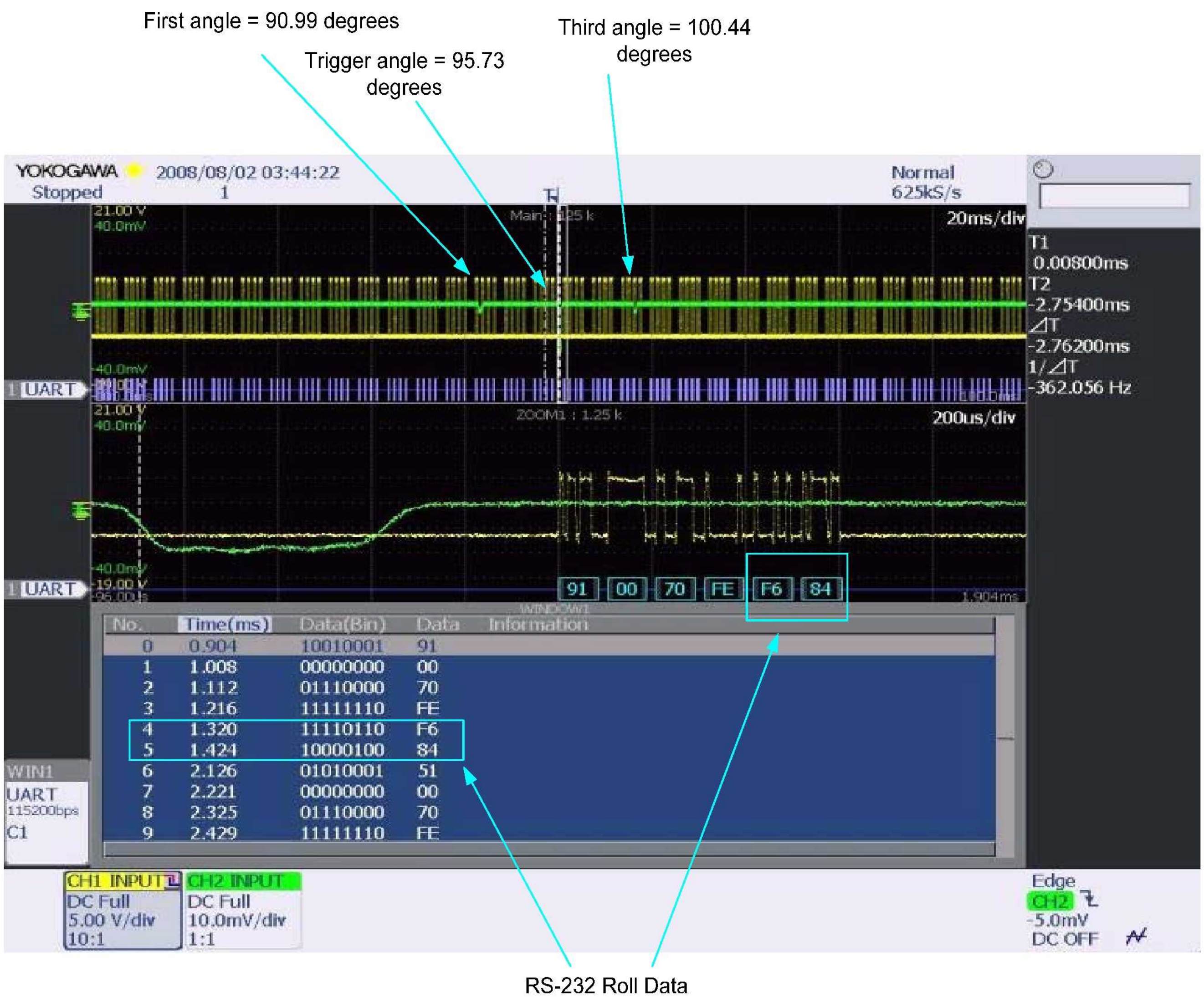

Figure 2-3. Oscilloscope data

The first reference angle is 90.99 degrees, trigger angle is 95.73 degrees, and the third angle is 100.44 degrees. Each angle position is noted and the RS-232 Roll Data is highlighted in Figure 2-3. When the data that was recorded over the dynamic range was plotted it was noticed that the tracker fixture did not have a constant velocity. It was ensured that reference angles were beyond the acceleration and deceleration of the tracker fixture's motion by adjusting the motor control parameters for constant velocity during the recorded dynamic run. The changing velocity was verified by the optical encoder mounted to the motor shaft.

With 3 DOF (pitch, yaw and roll) the tracker data output has a 500 us reporting time as shown in Figure 2-3. The measurement rate is 820 Hz maximum during four reporting cycles and then there is delay of 2 ms for internal tracker system maintenance before the next 4 reporting cycles. For the data collection shown in Figure 2-3 the prediction interval is turned off and the stream mode for data collection is used. With 6 DOF the RS-232 reporting time is 1.0 ms and has a measurement rate of 667 Hz maximum with 0.25 ms for internal tracker system maintenance before the next reporting cycle.

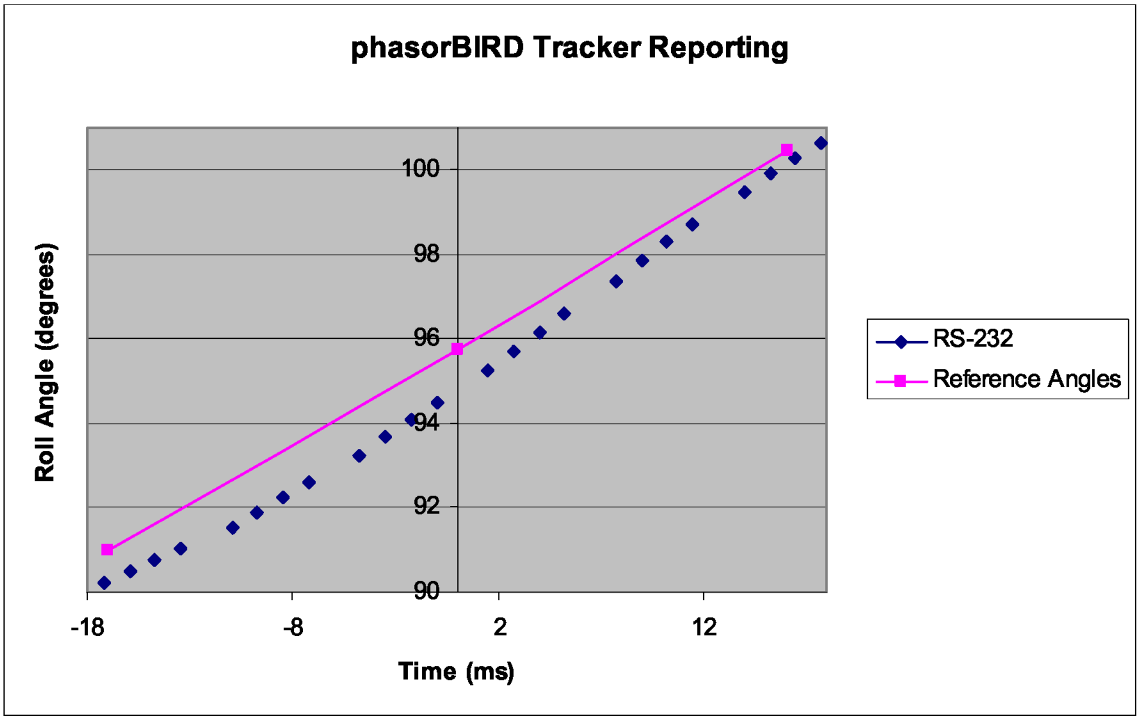

Figure 2-4. phasorbird Tracker Reporting from 90 degrees to 110 degrees of roll

As clearly seen in Figure 2-4, the reported tracker position has a changing velocity which is from the tracker fixture motion. The three reference angles are 90.99 degrees, 95.73 degrees and 100.44 degrees. The first reference angle is in an area of changing velocity and hence has the largest difference between phase and position. The second angle is in an area where velocity has become consistent for four reporting cycles and hence has a tighter phase and position value. The third reference angle is in an area where the velocity has been constant for 14 reporting cycles and has the tightest phase and position difference. Results are summarized in **Error! Reference source not found.**.

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	Reference Angle (deg)	Time (ms)	Phase Difference (ms)	Position Difference (deg)
1	90.99	-17.03	3.6	0.78
2	95.73	0	2.7	0.48
3	100.44	16.08	1.1	0.3
		Averages	2.5 ms	0.52 deg

The test setup was modified for the Ascension's laserBIRD tracker system. Only one reference angle was used and the tracker test fixture was adjusted to an area where the velocity was nearly constant for the trigger angle. The table position is plotted as an equation of motion using the stepper motor parameters. Figure 2-5 laserBIRD tracker reporting, shows the phase and position difference and is summarized in **Error! Reference source not found.**. The laserBIRD had all filters turned on and the prediction interval was set to 0 ms. When data was collected with all filters turned off the output reporting of the laserBIRD tracker was a pronounced SAW wave. Which was very difficult to relate to position hence data was collected with filters turned on.

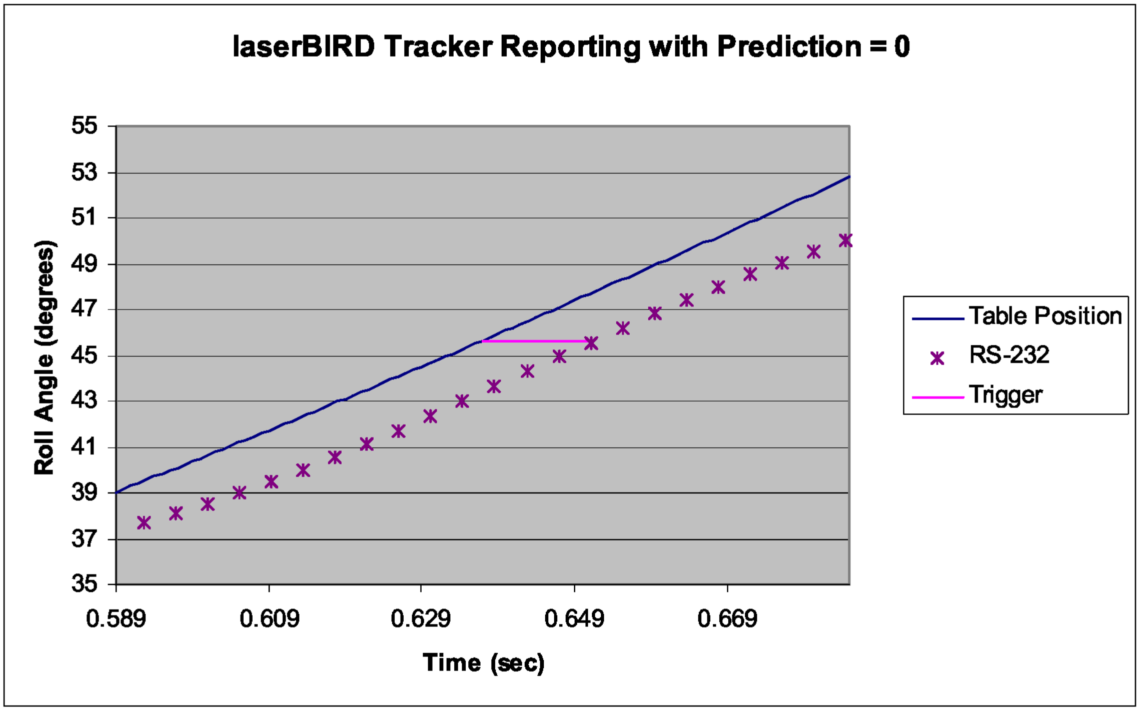

Figure 2-5. laserBIRD Tracker Reporting

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	Reference Angle (degrees)	Time (ms)	Phase Difference (ms)	Position Difference (degrees)
1	45.64	0.637	14 (ms)	2.26 (degrees)

2.2 Latency Summary

The phasorBIRD provides improvement in accuracy over the laserBIRD in both position and phase. The update rate of 667 Hz for a 6 DOF phasorBIRD tracker is a significant improvement over the laserBIRD design. A test fixture design problem occurred with using the stepper motor to drive the rotation of the platform. The proposed method to measure the rotational spin of the motor shaft was to detect and record an optical encoder on the spinning motor shaft. Using an oscilloscope, it was observed that the optical encoder pulses were varying in time and number when the stepper motor was commanded to be in a constant velocity. With this issue it was impossible to get an accurate position by triggering on the optical encoder output. The effort to record the position of the platform was then switched to use a laser light reflection to a photodiode which in turned triggered the recording of the tracker output. The laserBIRD position measuring was done with one reflection of the laser and shown as a single measurement in Figure 2-5. The laserBIRD had a phase difference of 14 ms and position difference of 2.26 degrees. When the prediction interval was set to 10 ms the position difference was reduced to 1 degree and phase difference was reduced to 4 ms; any further increase in the prediction interval lead to an oscillation around the reference position of the spinning platform. With the addition of two more lenses on the mirror mounted on the test platform it was possible to record two more positions for reference of the platform. This was done for the phasorBIRD only, as the laserBIRD was unavailable for this test setup. Each laser beam reflection is associated with a fixed-angle position. The three angles of reference are collected from the output of the tracker data unit during the static run. For the phasorBIRD the results are an average phase difference of 2.5 ms and position difference of 0.52 degrees. During one test run of the phasorBIRD it was noticed that the reporting data stopped updating for three reporting cycles, then jumped to the current position. This observation leads to a suggested design requirement that all critical systems have a data integrity check before the image is displayed for use.

A proposed near-to-eye system is shown in Figure 2-6. The data from the emitter and camera array to the tracker processor is 667 Hz by design. That data is then an input to the processor and graphics generator where the near to eye symbology is generated and textured video is overlaid on the symbology. By design requirement, the processing and graphics generation is a system maximum of 80 Hz. The image to be rendered is then buffered, warped and CRC checked for 20 lines of LCD data. The LCD's display bus operates at 60 Hz to create the image for the pilot's eye. This proposed architecture gives 31 ms of latency for the end to end system. Improvements in the system bus design are on going to give a bus rate of 120 Hz and improvements in the display bus for the LCD image to 75 Hz. This would provide a maximum latency of 23 ms which is the desired goal of a near-to-eye system.

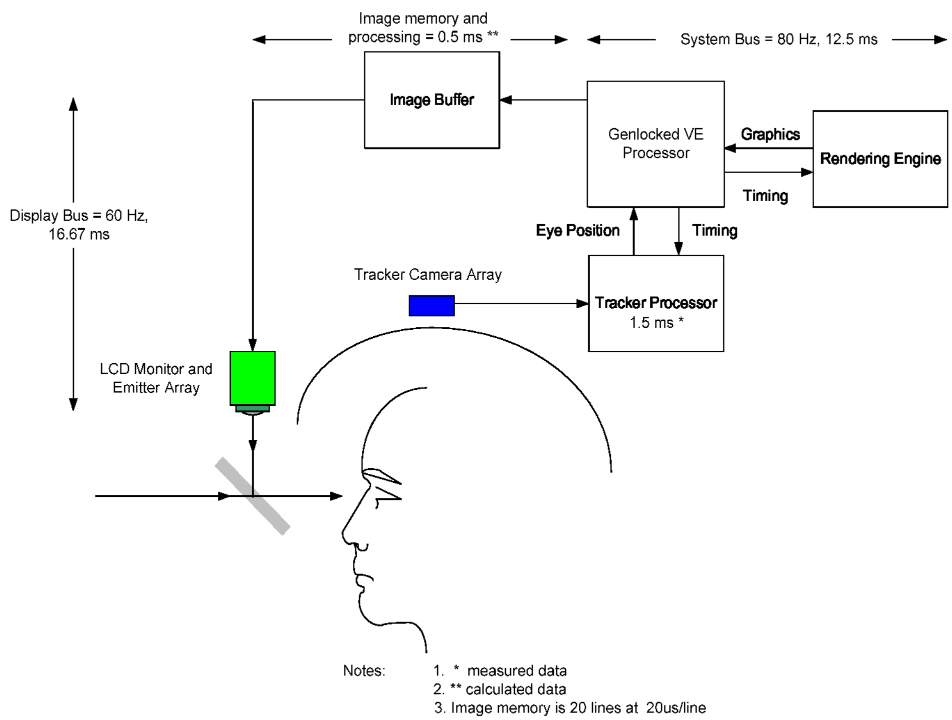

Figure 2-6. Proposed Near-to-eye System with 31 ms latency

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Item	Manufacture	Description or Part Number	QTY
1	Metrologic	Neon Laser	1
2	UDT	Photodiode	1
3	Belden Cable	RG-59 coax cable	1
4	Newport	VPH-2 Stand	1
5	Newport	Convex Lenses	2
6	Newport	VPH-3 Stand	1
7	Newport	Scissor Jack	1
8	Yokogawa	DL9710L Digital Oscilloscope	1
9	Yokogawa	Scope Probe 701943	1
10	Newport	Reflective Mirror	1
11	Newport	Mirror Position Stand	1
12	Honeywell	Phoenix Tracker Fixture	1
13	Belden Cable	RS-232 Cable	2
14	Belden Cable	RS-232 Splitter Cable	2
15	B & B Electronics	Model 485SD9TB, RS-232 to RS-485 Converter	1
16	Anaheim Automation	Power Supply 12V & 5V	1
17	Ascension Technology	phasorBIRD or laserBIRD system	1

2.3 Latency References

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14. ABSTRACT
Head-Worn Displays or so-called, near-to-eye displays have potentially significant advantages in terms of cost, overcoming cockpit space constraints, and for the display of spatially-integrated information. However, many technical issues need to be overcome before these technologies can be successfully introduced into commercial aircraft cockpits. The results of three activities are reported. First, the near-to-eye display design, technological, and human factors issues are described and a literature review is presented. Second, the results of a fixed-base piloted simulation, investigating the impact of near to eye displays on both operational and visual performance is reported. Straight-in approaches were flown in simulated visual and instrument conditions while using either a biocular or a monocular display placed on either the dominant or non-dominant eye. The pilot's flight performance, visual acuity, and ability to detect unsafe conditions on the runway were tested. The data generally supports a monocular design with minimal impact due to eye dominance. Finally, a method for head tracker system latency measurement is developed and used to compare two different devices.

15. SUBJECT TERMS
Augmented Reality; Biocular; Equivalent Visual Operation; Head-Worn Display; Latency; Monocular; Vision System

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