

Dual Oculometer System for Aviation Crew Assessment

Kara Latorella¹, Kyle K.E. Ellis², Bill Lynn³,

Dennis Frasca⁴, Dan Burdette⁵, Charles T. Feigh⁶, Alan Douglas⁴

1. Crew Systems & Aviation Operations, NASA Langley Research Center

2. The University of Iowa / NASA Graduate Student Researcher Program

3. Operations & Engineering Branch, NASA Langley Research Center

4. PSI International Incorporation

5. Lockheed Martin Corporation

6. Science and Technology Corporation

Oculometers are useful tools for ascertaining the manner in which pilots deploy visual attentional resources, and for assessing the degree to which stimuli capture attention exogenously. The aim of this effort was to obtain oculometer data comfortably, unobtrusively, reliably and with good spatial resolution over a standard commercial aircraft flight deck for both individuals in two-crew operations. We installed two remote, five-camera SmartEye systems in the Integration Flight Deck (IFD) simulation facility, replicating a modern commercial aircraft. We present here the results of validation exercises, lessons learned for improving data quality, and initial thoughts on the use of paired oculometer data to reflect crew workload, coordination, and situation awareness, in the aggregate. We conclude with a description of future work to improve this installation and extend oculometer capabilities to other simulation environments at NASA Langley.

Oculometers

Knowing where someone is looking is very useful in assessing their interaction with artifacts and their environment. As such, oculometers have been developed for eye tracking since the late 1800's/early 1900s (*e.g.*, Delabarre, 1898; Dodge & Cline, 1901; Judd *et al.*, 1905), and the history of their development is interesting (see Jacob & Karn, 2003). Early systems were impractical for naturalistic investigations; requiring participants' head to be motionless, or having elements of the apparatus on the participant's eye. Systems evolved towards this end, and became head-mounted, which made data collection more robust, but early implementations could be uncomfortable, and required special integration with other necessary equipment (headsets, helmets).

Image processing advances and digital technology provided the necessary technology to make significant advances in eye tracking capabilities and their use in less clinical settings. Head-borne systems became much more compact, robust, and comfortable; but they are still subject to artifacts associated with changes in registration once seated on the head. Further, most head-borne systems that are smaller and more comfortable do not provide head position data, and so are not able to provide true xyz coordinate data in the context of the operator's environment. Remote camera systems have the advantage of allowing participants to operate completely naturalistically, and free of encumbrances.

These systems illuminate the eye with infrared pulsed lights and strategically placed cameras obtain images of the head and eye. Images of the participant's face are taken from the perspectives of the different cameras. After the researcher identifies and marks features (for example, the inside corner of the eyes) on each image, the system creates a model of the head and eyes. Using assumptions of eye geometry and the environment's geometry, a calibration procedure in which the subject is asked to gaze at points in the environment allows the system to map identified eye positions to locations in the external space.

Oculometers designs include dark pupil, bright pupil, and recently those that can operate in both modes; typically bright pupil when able, but resorting to dark pupil when necessary. Bright pupils are obtained by having the illumination source coaxial to the optical path, which illuminates the retina and causes essentially "red eye." Bright pupil eye tracking is more robust in varying light levels, but is not appropriate for outdoors as the additional infrared from sunlight will interfere with system response. When the illumination source is not coaxial, the pupil is dark. Dark pupil systems rely on identifying the edge of the pupil from the start of the iris, and so can be difficult with light eyes (which appear dark when illuminated with infrared light). Both systems rely on the detection of pupil center with respect to a "corneal reflection", a spot of light that corresponds to the light source as reflected off the cornea.

Advances in the collection and interpretation of oculometer data are as important as the technology for obtaining gaze and head position data. Initially, and for some time, the data obtained by oculometers was simply the image of the eye moving. Advances in computational power allowed real-time analysis of oculometer data and the superimposition of point of gaze on the external scene available to subjects. More recently, oculometer data has been fused with other data streams to better characterize the interplay between a participant's attention deployment and environmental demands.

SmartEye Pro 5.5 Eye Tracking System

The SmartEye system has several setup parameters which must be met to yield robust eye tracking results. Each SmartEye system can utilize from two through six cameras to calculate both head position and eye gaze vectors.

The system calibrates itself with the real world using a checkerboard placed at a world model origin from which every user defined plane is specified. Each camera must be positioned so the checkerboard is clearly visible in each camera field of view, limiting the camera placement array to 180 degrees or less. The checkerboard origin is also the center of the subject head box, which is the intersection of all of the system cameras' field of view, within which the system can actively track a subjects head. To improve the accuracy of the gaze vectors, the system utilizes corneal reflection eye tracking, requiring the illuminators to shine on each of the subject's eyes producing a glint that can be detected and tracked by the system.

The NASA Integration Flight Deck Simulator

We installed the SmartEye oculometer in NASA Langley's Integration Flight Deck (IFD) simulation facility. The IFD generally simulates a modern commercial transport aircraft and provides researchers with a full-mission capability. The cab includes standard flight instrumentation and pilot controls, including the overhead subsystem panels. The collimated out-the-window (OTW) scene is produced by a Rockwell EP1000 graphics system, and provides approximately 200 degrees horizontal by 40 degrees vertical field-of-view at 26 pixels per degree. A FMS/CDU is located on the center console, and Electronic Flight Bags can be placed outboard of the instrument panels for each pilot.

Installation

The dual-operator, five-camera oculometer system installation was optimized to capture each pilot's eye gaze over a 90+ degree forward looking span region, 10

degrees above the horizon and 45 degrees below the horizon.

An eye-point was specified for this installation. Commercial aircraft are designed to have a pilot eye-point and pilots are taught to use sights and heuristics to achieve and maintain this eyepoint. An eye-point sighting device was mounted low on the glare shield such that each pilot could achieve the appropriate eye-point. This eyepoint location was the focal point for all installed cameras as well as the origin for the subject's head box and world coordinate model of the IFD.

Cameras were located such that at least two cameras could capture a crew member's eyes when they looked at the areas of interest. These areas of interest included: the instrument panel, the control display unit for the flight management (CDU/FMS) system, the mode control panel, and the forward view out the window. As a result, camera locations for each side of the flightdeck are: inboard of the CDU/FMS, inboard of primary flight displays on the mid-instrument panel, on the center post of the window, under the glareshield and above instrument panel, and on the outboard glareshield wing panel (Figure 1). The initial configuration used only 8mm lenses, but the final configuration used a combination of lens lengths (6, 8, and 12mm) to achieve best performance. Flash locations were constrained relative to the locations of cameras; they can be no closer than 10 cm from a lens, and must be placed such that as a set, they illuminate the face for all cameras (Figure 1). Cameras, except the two in the instrument panel, have a nearby flash.

There were several constraints and requirements that dictated the locations of cameras and flashes. While we aimed to achieve best oculometer performance for the viewing regions of interest, and to make the installation unobtrusive, we were constrained by a requirement that existing instrumentation and structures behind the panel not be compromised. In part due to these constraints, each camera could not have a paired, co-axial flash which means that the resulting implementation is a dark pupil system.

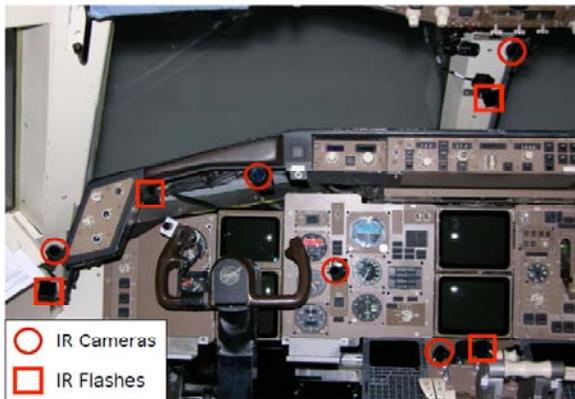


Figure 1. Camera & Flash Locations on the Pilot Side (which are mirrored on the left side of the flightdeck).

Validation Metrics

Head tracking quality (as calculated by the SmartEye system) for each of these points, is 100% for good quality tracking from at least two cameras, 50% for tracking with only one camera, and 0% for no tracking at all. Only a value of 100% is considered acceptable.

Eye tracking quality (ability of system to calculate a gaze vector, as recorded by the system) varied across the matrix of look points. Gaze quality values (as calculated by the SmartEye system) of 75% (normalized over time) were considered to be of good quality and 50% or less were considered of poor quality gaze vectors.

In addition to assessing head and eye tracking quality (which describes whether the system reported a good lock on features), we also assessed the spatial accuracy of the eye gaze vectors; that is, does the gaze vector accurately and precisely indicate the intended target of the participant's focus. Spatial accuracy was calculated by seeing if the gaze vector intersections were consistent with those points in the world coordinate model of the environment when participants were asked to look at certain calibration points.

Lab Validation Results

Initial testing was conducted on a scale replica of the IFD cockpit with three participants.

The initial IFD replica configuration was 100% capable of tracking two subjects' head positions over all specified regions of interest and included nearly 90% of the entire forward looking field of view. The subject with glasses was difficult to track in the inboard region of the out-the-window view because glasses' frames interfered with the camera's view.

Eye tracking quality in the IFD replica was better than 75% for most of the instrument panel, the forward out-the-window view, and the CDU region of the center console for initial participants without glasses. Eye tracking performance for the participant with glasses degraded in the regions just under the glareshield and the center instrument panel displays. In all subjects, the view OTW to the outboard side was not well tracked.

Spatial accuracies of less than 1° of visual angle were considered good, 1° through 2° acceptable, and greater than 2° considered poor (Figure 6).



Figure 2. Spatial accuracy of subject gaze across flight panel instruments (Green = $< 1^{\circ}$, Yellow = $< 2^{\circ}$)

For reference, if a pilot is sitting at a normal distance of 33" from the primary flight display, Figure 7 shows the size of the gaze vector spatial distribution error that 1° and 2° of visual angle represents.



Figure 3. Visual angle depiction.

Experiment Validation Results

The lab validation was used to test locations of cameras and flashes. This process resulted in design requirements for the actual IFD installation (Figure 1). The first experiment conducted with this installation

provided an opportunity to obtain validation data in the context of actual use during flight operations and procedure use, and with a wider variety of individuals.

For this study, 22 commercial airline pilots flew the IFD simulator in two-crew operations in the busy, terminal area surrounding Boston Logan airport. Crews were exposed to four experimental conditions (voice communication only, Data Comm only, Data Comm with Moving Map Display, Data Comm with Moving Map displaying taxi route), and each condition was used to during both an arrival and a departure scenario. Data Comm conditions required the crew to respond to an uplinked message via the CDU located on the center console. Data from all experimental conditions were used for validation of oculometer performance.

In summary, the results we obtained during the study were acceptable for the purpose of supporting the experiment, but were not as good as obtained in our initial lab configuration. Figure 4 shows the mean and standard deviations for head and eye tracking quality, averaged over session duration, for both Pilots Flying (PF) and Pilots Monitoring (PM).

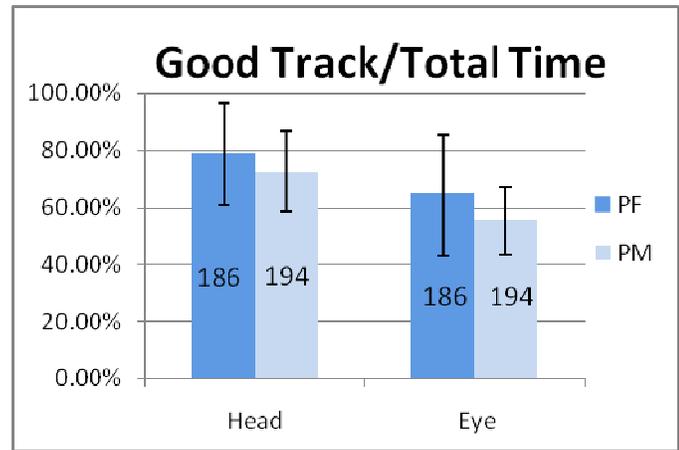


Figure 4. Bar charts for head & eye quality, PF & PM

Because we encountered significant differences between the results of participants with and without glasses in the lab validation, we wanted to see how experimental subjects with and without glasses fared in the experimental validation. Figure 5 indicates that pilots without glasses yielded higher average gaze quality than pilots with glasses; however, differences were minimal with less than 10% difference between the two groups.

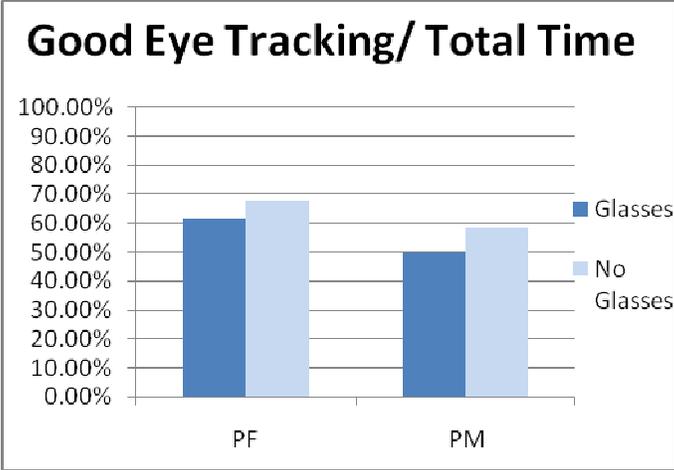


Figure 5. Bar chart for eye quality glasses/no glasses.

To evaluate the accuracy of data while looking in the areas of interest for this study, we assessed the average eye tracking quality when the system reported hits in these AOIs. Figures 5 and 6 show the averaged eye gaze quality for PF and PM, respectively, for each AOI.

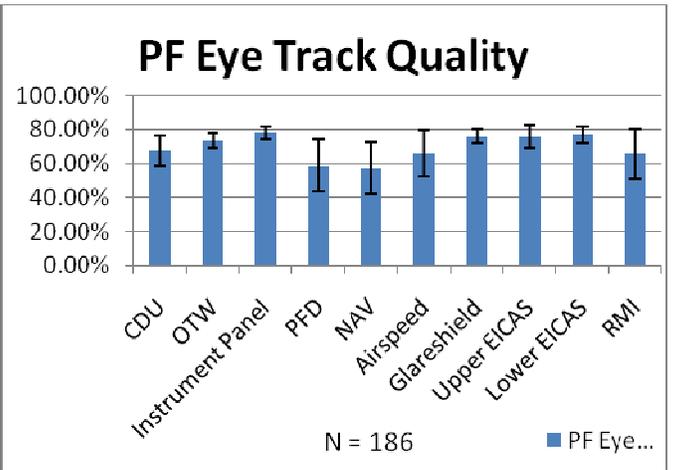


Figure 6. PF Eye Quality for AOIs

Data required to assess spatial accuracy for the experimental sessions was not available for analysis

Lessons Learned

Variance in performance can be attributed to several factors, including camera coverage variation across the flight deck, individual differences in facial features, camera calibration error, and profile generation errors. All of these factors can be calculated and mitigated except for camera coverage which is corrected by the installation.

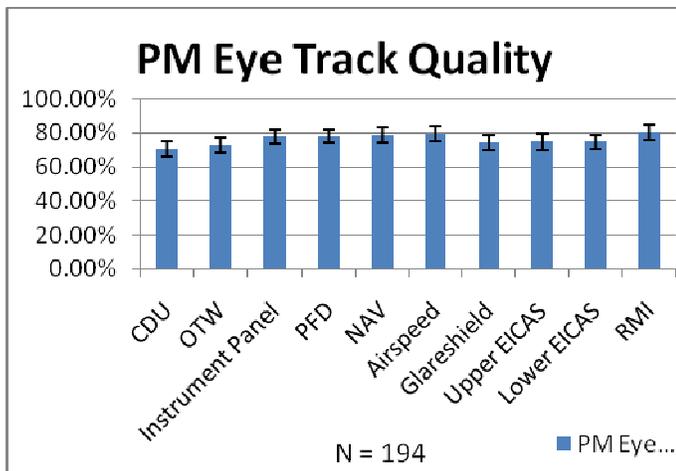


Figure 7. PM Eye Quality for AOIs

Cameras and flashes were placed according to the requirement that at least two cameras have a good image of the eyes for all points of interest. While the lab assessment provided a good estimate for placement, we realized later that the participants were being more restrictive in their head movements than subjects were in the experiment. This was particularly true for the PMs; who interacted more with the CDU and would sometimes lean down when interacting with this device. While the lab participants attempted to replicate these actions, it was clear to us that the actual participants' movements were, in contrast, not constrained by thoughts of system performance, and more naturally varying.

For the SmartEye system, eye tracking quality is dependent on the subject remaining in the defined head box (the intersection of the cameras' fields of view). For typical PF tasks (left seat), the initially designed head box was sufficient. However PMs, in the right seat, moved much more to accomplish their tasks, and so tended to exceed the boundaries of the defined head box region. One solution would be to increase the head box region, but this effectively reduces the resolution of the images and therefore negatively affects eye tracking. To at least assure accurate head tracking of the PM, and at the sacrifice of some eye tracking quality, smaller focal length lenses were used on some right side cameras. This effectively increased the size of the head box for the PM. This allows researchers to track at least head movements of the PM consistently, while still maintaining an acceptable level of eye tracking quality when s/he was in the head box.

In the experimental validation, we encountered a broader set of facial characteristics. Certain facial characteristics are difficult (e.g. droopy eyelids, squinty eyes) but by

far, glasses presented the most difficulty. SmartEye flashes created reflections on some glasses which could interfere with feature detection for eye corners. We have since learned that computer glare coatings tend to cause problems. In addition, glasses could occlude some of the facial features differently for different camera views.

One method for alleviating this problem is to mark visually distinct features of the glasses as an "other" feature in the facial profile. This method improved the success of tracking subjects with glasses, and highlights the fact that selecting the right features for the SmartEye to discern eye and head position is a large part of obtaining good eye and head tracking. Good features are those with high contrast; those that are clearly visible in at least 3 of the camera views; and which, as a set, span the operator's face. One feature commonly used is the earlobe. In the aviation context, pilots often wear headsets, which cover this feature. We affixed a label to the headset center and used this as an "other" feature. While this is not a perfect solution, since the label can move relative to the head, pilots typically find a comfortable position for a headset and this position appeared to be relatively stable over the 12-17 minute runs we observed in the experimental validation.

Future Work

The goal of this installation is to provide NASA Langley researchers with a built-in capability to sensitively and unobtrusively assess attention allocation in novel avionics and procedure designs, and to be able to assess the impact of these not only on single pilot performance and workload, but also on the crew as a unit. We aim to develop oculometric measures of individual workload, and measures that characterize crew situation awareness and workload. This is the subject of ongoing dissertation research following in the vein of earlier work on individual workload modeling (Ellis & Schnell, 2009). We are also investigating methods by which to improve the rapid characterization of oculometer data quality.

Currently, the data resulting from this initial installation resides in two separate SmartEye systems, and is collected with a common GPS timestamp that is also provided on simulation aircraft parameter datafiles and event files. Future work will include the coordination of these data. One approach we are investigating is the University of Iowa's Cognitive Aviation Toolkit (Schnell, Keller & Macuda, 2007) which will allow the integration of simulation state data, images from the simulation displays, point of gaze data, and physiological data. This system would need to be extended to accommodate a second stream of gaze data.

Work is also underway to not only improve the IFD installation, but to extend oculometer capabilities to two other simulation cabs at NASA Langley; the Research Flight Deck (RFD) and the Generic Flight Deck (GFD). The RFD Simulator is an advanced all-glass jet transport simulator. The GFD is an advanced all-glass generic simulator, which can be used to represent a wide range of vehicle types including advanced transports and spacecraft. In addition, we aim to ruggedize these installations such that they can be used in these simulation cabs while they are on a motion-base platform.

References

Ellis, K.K.E, & Schnell, T. (2009) Eye Tracking Metrics for Workload Estimation in Flight Deck Operations. *MODSIM World Conference and Expo 2009*, Virginia Beach, VA.

Delabarre, E.B. (1898) A method of recording eye-movements, *Psychological Review* 8, 572-74.

Dodge and Cline (1901). The angle velocity of eye movements. *Psychological Review*, 8, 145-157.

Jacob, R.J.K. & Karn, K.S. (2003) Eye Tracking in Human-Computer Interaction and Usability Research: Ready to Deliver the Promises (Section Commentary), in *The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research*, ed. by J. Hyona, R. Radach, and H. Deubel, pp. 573-605, Amsterdam, Elsevier Science.

Judd, C.H., McAllister, C.N. & Steel, W.M. (1905). General introduction to a series of studies of eye movements by means of kinetoscopic photographs. In J.M. Baldwin, H. C. Warren & C.H. Judd (Eds.) *Psychological Review, Monograph Supplements*. 7:1-16. The Review Publishing Company, Baltimore.

Schnell, T., Keller, M., & Macuda, T. (2007) Application of the Cognitive Avionics Tool Set (CATS) in Airborne Operator State Classification. *Augmented Cognition International*, Baltimore, MD.