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MULTIPLE IMAGES IN THE F/FB-111 AIRCRAFT WINDSHIELD: THEIR GENERATION, SPATIAL LOCALIZATION, AND RECORDING

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By reviewing basic laws of geometrical optics and applying some fundamentals of physiological optics, ~~we~~ one can explain the generation and behavior of multiple images in the F/FB-111 windshield. The refinement of windshield optical laboratory technics yields information for predicting and recording individual-windshield multiple-image patterns.

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INTRODUCTION

Visual problems associated with high-performance aircraft often are unforeseen. One such example is the windshield-generated multiple (ghost, secondary, internally reflected) images experienced by aircrews during night flight in the F/FB-111 aircraft.

Multiple images can cause annoying and sometimes confusing visual effects in ophthalmic lenses and compound optical systems. In most cases, the lens design and antireflective coatings minimize multiple-image intensities to a level where visual adaptation is sufficient to render the system acceptable. Multiple-image complaints associated with automobile and aircraft windshields have occurred sporadically. Recently, however, this problem has become a serious concern to the U.S. Air Force. Certain aircraft transparencies, because of their highly sloped installation angle and complex geometric design, generate multiple-image patterns that are disturbing to aircrews particularly during night flight. Crew-station design engineers have given greater priority to structural and performance factors than to visual requirements (see Military Standard 850B). Antireflective coatings for windshields are difficult to design and effect for the high angles of incidence, and even if successfully applied, would suffer from severe environmental exposure.

At this point, a review of the genesis of the USAF School of Aerospace Medicine (USAFSAM) windshield effort may be helpful. The F/FB-111 aircraft, because of its capability to operate at very high speed while at very low altitude, is apt to encounter birdstrikes of enormous force. Numerous strikes have occurred in which birds penetrated 0.33-in-thick (0.85-cm), three-ply, chemically tempered glass windshields, resulting in aircraft loss. The U.S. Air Force, concerned about future loss potential, requested the development of a windshield that would withstand birdstrikes at mission-profile velocity and altitude. PPG Industries, under contract, developed a ten-ply, approximately 1-in-thick (2.54-cm) windshield composed of acrylic and polycarbonate plastic, with interlayers of proprietary material sufficiently strong to survive such an impact. The Air Force Flight Dynamics Laboratory (AFFDL), charged with the development program management, chose to field-test ten shipsets of the PPG windshields and to monitor aircrew acceptance of the optical properties imparted in the manufacture of these sets. The USAFSAM participation in this program involved, in part, the optical evaluation of all the test windshields before aircraft installation. This report provides a portion of the data generated by this effort.

PROBLEM AND PURPOSE

Although previous studies had addressed multiple-image problems in aircraft windshields, numerous questions remained unanswered. In response to aircrew complaints of disturbing multiple images in the early-production glass windshields and now evident in the test windshields, an effort was initiated at USAFSAM to provide answers to manufacturers and flyers in explaining and resolving ghost-image difficulties. This paper reports three investigations undertaken: (1) to review the basis of the geometrical/physiological optics that would explain the generation of multiple images; (2) to determine if some correlation existed between multiple-image patterning and other windshield optical properties; and (3) to develop a method to elicit and record multiple-image patterns in aircraft windshields generally.

Geometrical/Physiological Optics Considerations

The human eye can be considered an instrument consisting of a compound optical system and an active image plane, the retina. In association with the visual system, the retina performs many complex tasks; one is the spatial localization of objects in the visual field of view. Light rays emanating from an object are refracted and focused upon the retina of the eye, forming an image of this object. The spatial localization of this object is determined by a "mental," or visual, projection of this retinal image out from the eye into space, usually in the direction from which the light originated.[1] As an example, light rays emanating from optical-infinity-point source object arrive at the eye parallel to one another (Fig. 1). The rays that enter the pupil are focused and imaged on the seeing center of the retina, the fovea. This image will be visually projected from the fovea through the nodal point, localizing the object in space directly ahead. The higher the object from which light rays emanate, the lower the point below the fovea at which they are imaged on the retina. The visual projection of the image in Figure 2 will be from the point below the fovea, through the nodal point, and will localize this object at a relatively higher point in space than the object visioned in Figure 1. In like manner, light rays emanating at the same time from two objects (one above the other) will enter the eye from two directions, resulting in two retinal images--the first being projected directly ahead, the second projected above the first (Fig. 3).

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[1] For simplicity, no eye movements are considered; and only monocular visual projection in two-dimensional space (X and Y coordinates) is addressed. The optics of the eye are overly simplified. For more detail, texts of physiological optics are suggested in the bibliography.

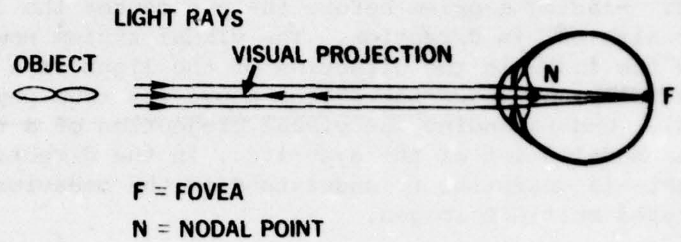

Figure 1. Visual projection of single image striking fovea (F = fovea; N = nodal point).

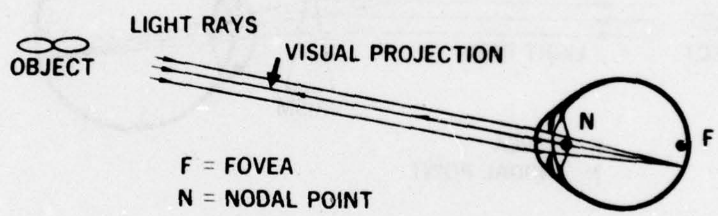

Figure 2. Visual projection of single image striking below fovea.

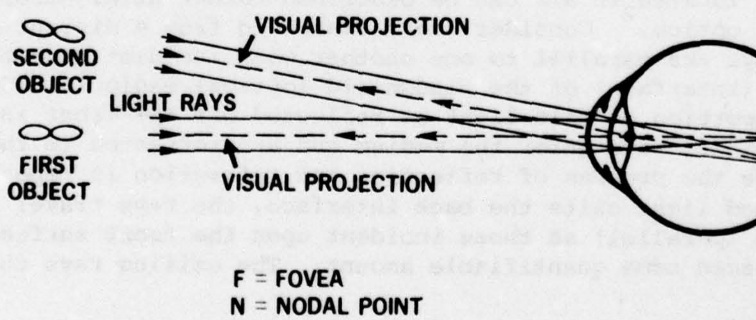

Figure 3. Visual projection of two images striking retina.

The visual system can be "fooled" into visually projecting the image of an object into space in a direction other than from where the light originated. Placing a prism before the eye causes the light to be refracted, or altered, in direction. The visual system now, as before, projects the image in the direction of the light rays entering the eye, but spatially localizes the object above its true physical position (Fig. 4). Understanding the visual projection of a retinal image through the nodal point of the eye--i.e., in the direction of the entering light--is essential to understanding the behavior of windshield-generated multiple images.

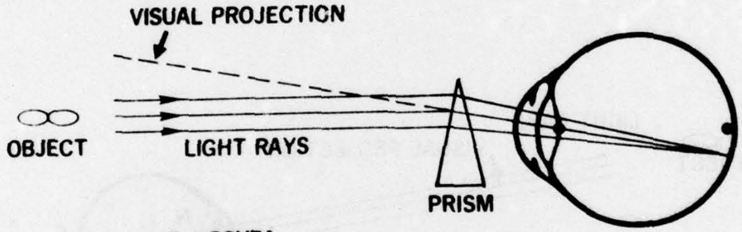

Figure 4. Visual projection of image when light rays have been deviated by prism.

The origin of multiple images within a flat, parallel-surfaced optical medium located in air can be described rather straightforwardly by geometrical optics.[2] Consider light emanating from a distant object so that the rays are parallel to one another when incident upon the front surface (interface) of the windshield (optical medium). (See Figure 5.) A portion of this light is reflected off the front interface; the remaining rays enter the medium and are refracted to the back interface where the process of reflection and refraction is repeated.[3] As the refracted light exits the back interface, the rays travel in the same direction (parallel) as those incident upon the front surface, although displaced some quantifiable amount. The exiting rays that

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[2] The purpose of this paper is strictly conceptual; therefore, all ray trace formulations are purposefully omitted. See optics texts for formulations.

[3] The percentage of reflected to refracted light depends on the angle of incidence and the media index differences. Light loss will occur within the media, dependent upon scatter and absorption properties.

have not been reflected (only refracted) are termed the primary rays and constitute what will be visually projected as the primary light source. The rays internally reflected from the back interface strike the front interface; a portion of this light is refracted and exits the front of the transparency, and the other portion is again reflected upon the back interface. (This process continues within the medium until the edge is reached.) The light rays that have been internally reflected before being refracted and exiting the back surface are termed the secondary rays. These are of special concern because they constitute what may be projected as the secondary, or multiple-image, light source. Whether a multiple image will be discerned (by the visual system), as well as the spatial location it will assume, depends upon the direction of the secondary (internally reflected) rays relative to the direction of the primary rays.

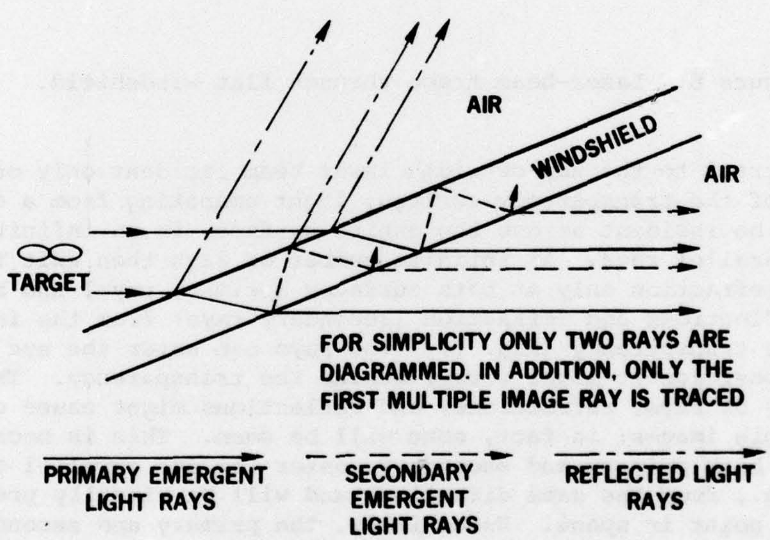

Figure 5. Light ray behavior within a plane parallel-surfaced transparency; object (target) at optical infinity.

This optics process can be easily demonstrated by projecting a narrow collimated light beam (such as a small HeNe laser might produce) through an inclined thick, flat transparency (windshield). The light will be divided into a number of beams exiting the back of the transparency. Light beams reflected off the front surface can also be demonstrated above the transparency (Fig. 6).

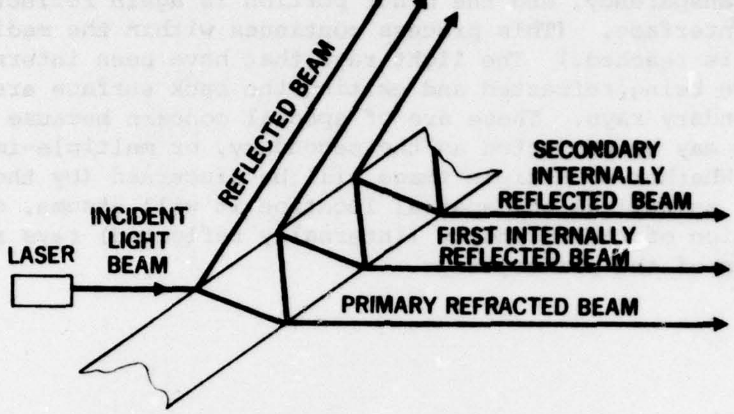

Figure 6. Laser-beam trace through flat windshield.

In contrast to the narrow-width laser beam incident only on a small area of the transparency surface, light emanating from a distant source will be incident across the entire surface, in an infinite number of parallel rays. An infinite number of rays then exit the rear surface by refraction only at both surfaces (primary rays) and by internal reflections and refraction (secondary rays) from the interfaces of the transparency (Fig. 7). The rays can enter the eye at almost any position it might occupy behind the transparency. This multiplicity of rays, refractions, and reflections might cause concern about multiple images; in fact, none will be seen. This is because the light rays, both primary and secondary, enter the eye parallel to one another--i.e., from the same direction--and will be visually projected to the same point in space. Essentially, the primary and secondary (multiple) sources will be superimposed.

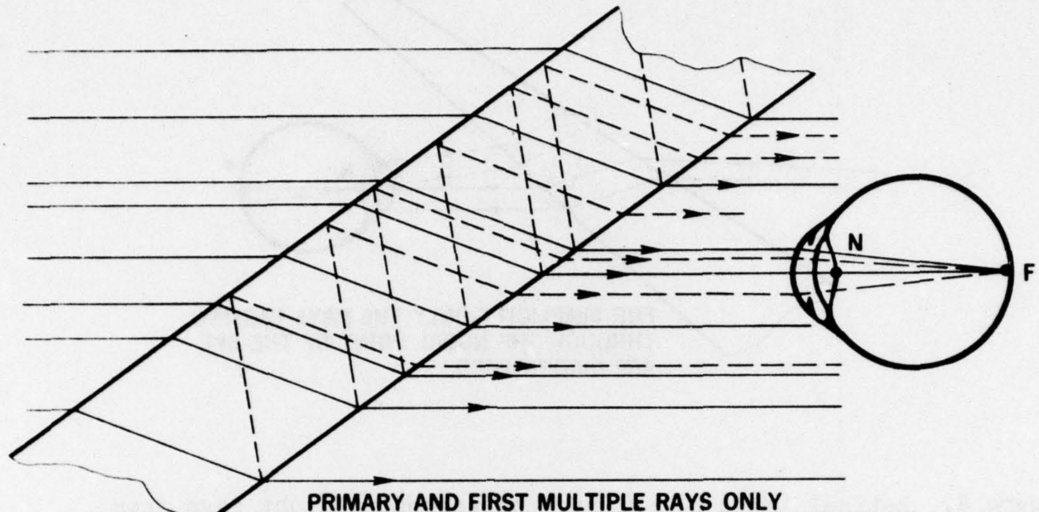

Figure 7. Retinal image formation of primary and secondary rays from infinity light source through parallel-surfaced transparency.

Light passing through a transparency of plane, nonparallel surfaces that form a wedge or prism (Fig. 8) will act differently than light passing through parallel surfaces. With nonparallel surfaces, light rays refracted directly through the rear surface (primary rays) will exit nonparallel to the incident rays. As a result, the primary image will be visually projected in a direction opposite to the base of the prism. The internally reflected light (secondary rays) will exit nonparallel to both the incident rays and the primary (exiting) rays. (This situation is similar to Figure 3 in that rays enter the eye from two different directions.) A secondary image will now be discerned and will be visually projected above the primary image.[4] Conversely, if a prism had its wedge base-up, the secondary image would project below the primary. The separation of the primary and secondary depends upon factors such as the amount of prism, slope of the transparency to the incident light, and projection distance into space.

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[4]For multiple images to be seen, existing conditions must include relatively small targets and high target-background contrast.

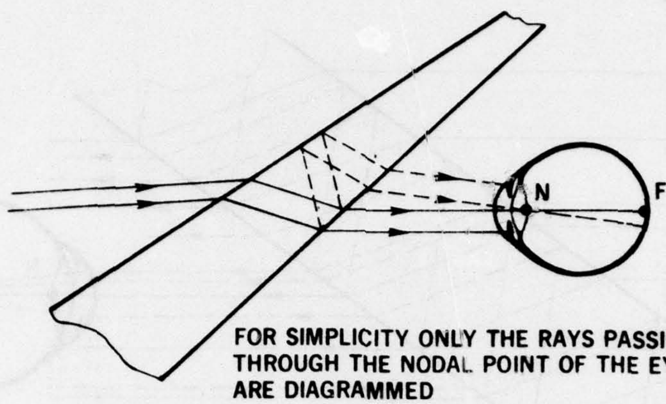

Figure 8. Retinal image of primary and secondary light rays from infinity light source through wedge or prism transparency. (For simplicity, only the rays passing through the nodal point of the eye are diagrammed.)

Correlation in Image Patterning and Windshield Optics

Aircrew interviews reveal that the frequency and severity of complaints are related to multiple-image patterning--more specifically, the relative multiple-image locations and changes in location with respect to the primary image as objects are viewed throughout the extent of the windshield. Multiple images that change vector (swirl) about the primary image as it is viewed through various areas of the windshield are reported to be most disturbing. Images widely separated from and vectored above the primary are also reported as particularly annoying. This type pattern was assumed to be one of the factors which contributed to the aircrew rejection of a test windshield. In an attempt to determine if these patterns could be predetermined from existing windshield optical information, all data were reviewed.

The F/FB-111 windshield optical evaluation included determining the prismatic characteristics throughout the transparency to relate to boresight specifications.[5] In production windshields, this procedure is performed by viewing a spot of light, at a normal angle through the windshield and visually projecting the secondary image on a calibrated ring. This provides deviation and direction (vector) information. By

[5]See General Dynamics Report FZM-12-10952A, 20 May 1970.

this method, 3 minutes of arc minimum can be obtained, which is adequate for the boresight information. To determine prism values to a tolerance of 1 minute of arc, a laser-beam-projection method, developed at USAFSAM, was used on all plastic field-test windshields. To perform deviation mapping, the windshield was divided by a template overlay into approximately 5-in (12.5-cm) squares; then the windshield was suspended normally to the incident HeNe laser beam (Fig. 9).

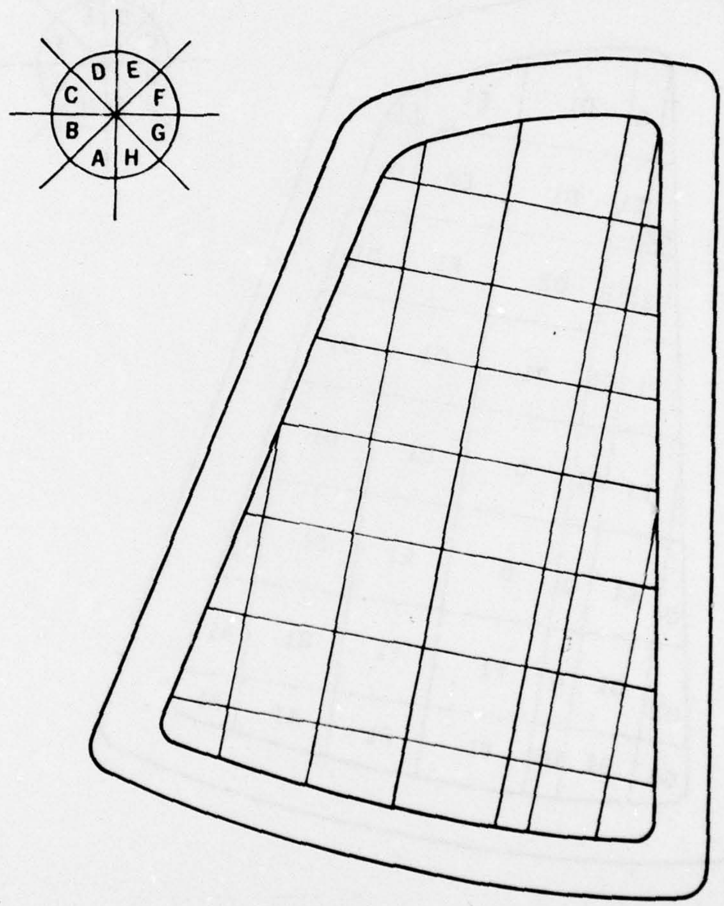

Figure 9. Windshield deviation-pattern template.

The laser was projected through the center of each square, and the deviation of the beam was read directly off a calibrated target for extent and direction. Two sample prism deviation records are shown in Figures 10 and 11. In each section, the number indicates the prismatic effect in minutes of arc, and the letter, the direction of the effective prism base. A and H vectoring indicate the base direction up, or toward the aft arch of the windshield; D and E vectoring, toward the fore arch. On-site evaluations of aircraft in the field revealed that those with prism-base vectoring in sectors D and/or E were likely to elicit negative comments from aircrew, even when the recorded values were as low as 1 minute of arc (Fig. 10).

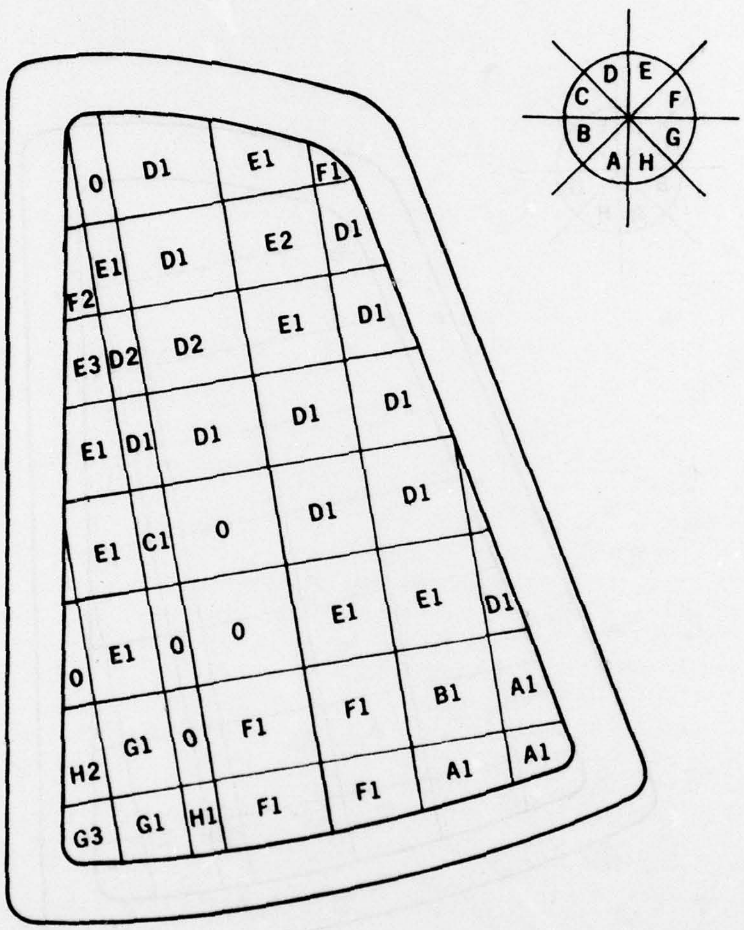

Figure 10. Windshield sample deviation record (D and E vectoring).

Conversely, windshields with little or no D or E vectoring (Fig. 11) either showed little image separation or showed image vectored below or to the side of the primary image. By and large, aircrews favor windshields with little D or E vectoring. Geometrical and physiological optics laws of visual projection agree with the empirical findings and aircrew complaints of multiple-image patterns.

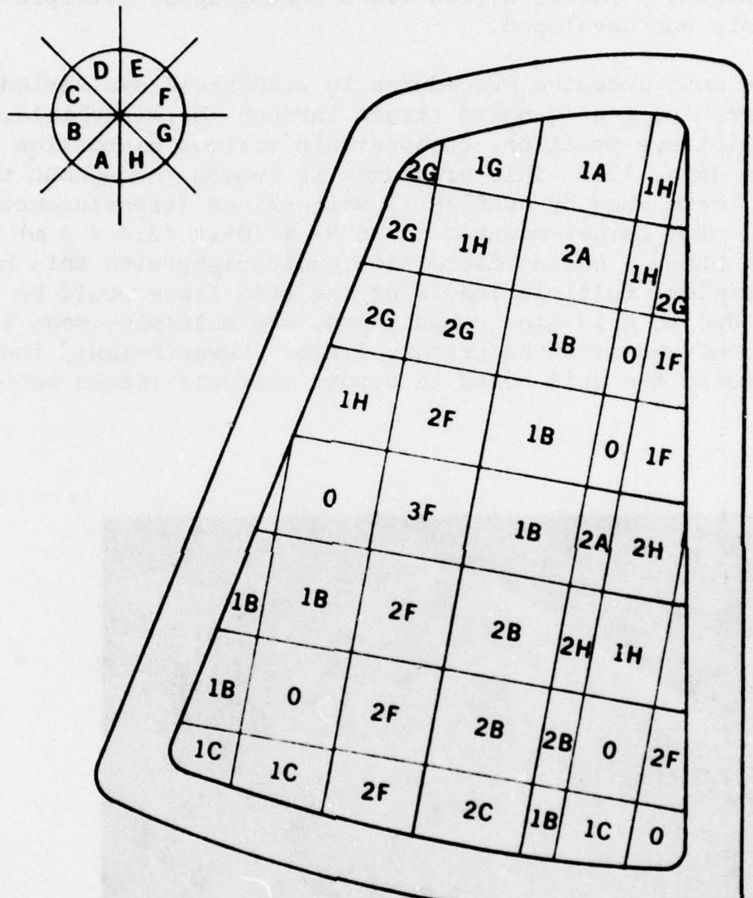

Figure 11. **Windshield sample deviation record (A and H vectoring).**

Demonstration and Recording of Multiple-Image Patterns

Because aircrews had so many negative comments pertaining to windshield-generated multiple images, it was deemed important to develop a method to display and permanently record the multiple-image pattern of each test windshield. A literature review revealed that multiple-image specifications had only been established for the A3J aircraft windshield.[6] These specifications called for observing 625 lights aligned in vertical rows, viewed through the windshield from the designed pilot-eye position. Windshields were rejected when specified numbers and patterns of lights were observed to double. Although this procedure evidently proved adequate, no permanent record was made for each windshield. So that permanent records could be made for each F/FB-111 windshield, a modified grid-board photographic multiple-image recording technic was developed.

One of the most accepted procedures in windshield evaluation is that of photographing a grid-board target through the windshield, from the designed pilot-eye position, to ascertain various distortion characteristics (Fig. 12). This procedure is common throughout the industry. The board used by USAFSAM is white-lined (transluscent) 0.5-in (1.3-cm) grid target mounted in an 8- X 10-ft (2.4 X 3 m) frame which is backlighted.[7] During distortion photography with this board and test windshields, multiple images of the grid lines could be discerned; but due to grid-line compactness, the multiple-image lines became easily confused with the primary lines. Nevertheless, the potential for using the grid board to record multiple images seemed evident.

Figure 12. Windshield grid-board photograph for distortion evaluation.

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[6] North American Aviation, Inc., Report ST0115HA008, 17 Feb 1967.
[7] Mylar grid target obtained from Lockheed Corporation.

To more easily distinguish the secondary-line images from the primary lines, a procedure was attempted to increase their separation by diminishing background line clutter. Black cardboard overlays, 8 in (20.3 cm) square, were chosen and then taped to the grid board, yielding line separations of 9 in (22.9 cm). This modified grid board was photographed, through windshields, using a range of f-numbers and exposure times. The results were encouraging: the multiple images showed good contrast against the black background. In the interest of cost and space, rather than build another complete grid-board system in designing a permanent target, an overlay was constructed that occluded all but the grid lines on the basic USAFSAM board at 9-in intervals. The 0.5-in (1.3-cm) separation between the opaque blocks allows the reference crossing lines to be visible, giving a crosstie effect. This enhances the line visibility and allows rapid measurement of multiple-image separation. In applying this technic to grid boards of differing dimensions, grid-line spacing and overall target size can be altered to fit the needs of the user. Camera settings will necessarily vary with lighting conditions and transmissivity. Our present exposure with a grid-board luminance of 40 ft-L (137 cd/m^2) is 15 seconds with an f-32 setting, using TRI X film, ASA 320.

DISCUSSION

The visual projection associated with multiple images described above is valid only for plane-surfaced transparencies of a homogeneous medium. Curved and complex geometries will influence the visual projection and, therefore, the multiple-image pattern.. These effects have been investigated and will be presented in a mathematical format in a follow-on report.

Several test windshields exhibiting a D and/or E vectoring pattern (displaying multiple images above the primary) were tolerated by using aircrews. For this reason, a suggestion that all windshields displaying D and/or E vectoring be rejected was not acceptable on a cost-effective basis. The differences in aircrew responses to these windshields are not fully understood; however, such factors as aircrew attitude and aircraft mission profile can be theorized as contributing factors. Unfortunately, the prism pattern is not fixed in a windshield until near completion, when the manufacturing cost is already quite high. Most windshields exhibit an overall vectoring pattern in one dominant direction or another--e.g., fore arch (D and E) or aft arch (A and H). If windshields exhibiting vectoring toward the fore arch could be reversed fore to aft before the cutting and edge attachments were completed, fewer multiple images would occur above the primary images. Because the geometry of the F/FB-111 windshield is conic, fore-to-aft reversal cannot be made before final fabrication. However, a cylindrical geometry, as used in other aircraft (e.g., the B-1), could potentially be reversed to avoid fore-arch prism vectoring. This potential should be considered by aircraft manufacturers involved with cylindrical aircraft-transparency fabrication.

Using the backlighted grid board to photograph multiple-image patterning contains one extraneous factor that must be taken into account. In laboratory photography the windshield center is placed 10 ft 9 in (3.3 m) from the grid board. Because this distance is within optical infinity, the secondary images will be produced slightly above the primary images, near the beam area, and vectored off toward the sill side conforming with the geometry of the windshield. This will occur even in a perfectly parallel-surfaced transparency and is caused by the fact that light rays emanating from a source within optical infinity will not be parallel to one another when incident upon the transparency. The internally reflected rays will therefore exit the back interface nonparallel to one another, at an apparently different direction from the primary rays (Fig. 13). This effect must be taken into account when evaluating a photograph of the target board. A grid line viewed through an F/FB-111 windshield at the 10-ft 9-in (3.3 m) distance, from directly ahead of the pilot-eye position, will elicit a multiple line approximately 0.25 in (0.64 cm) above the primary (one-half hash mark), provided the windshield front and back surfaces are parallel to that point.[8] Even without taking this factor into account, the multiple-image pattern seen by an F/FB-111 aircrewmember in night flight will correspond closely with that recorded by the grid-line photograph. In addition, the pattern compares well with the deviation mapping. The deviation map and the multiple-image photograph shown in Figures 10 and 14, respectively, are of the same windshield; and in Figures 11 and 15, of another windshield.

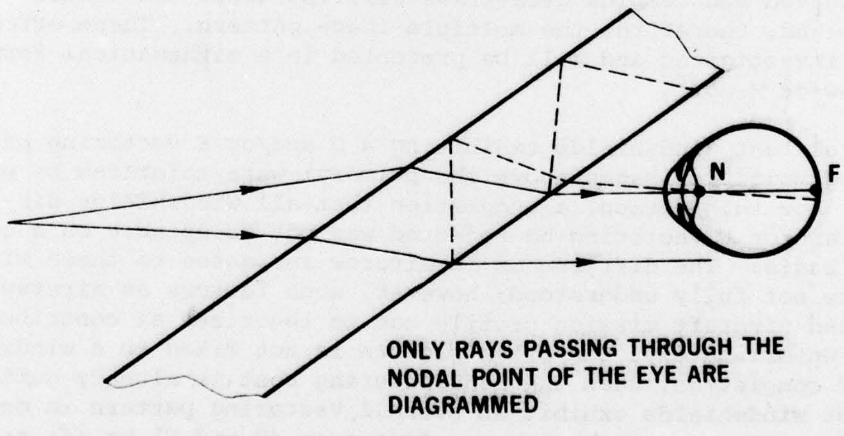

Figure 13. Retinal-image formation of primary and secondary light rays from light source within optical infinity. (Only rays passing through the nodal point of the eye are examined.)

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[8] Calculation for this factor will be included in a forthcoming report.

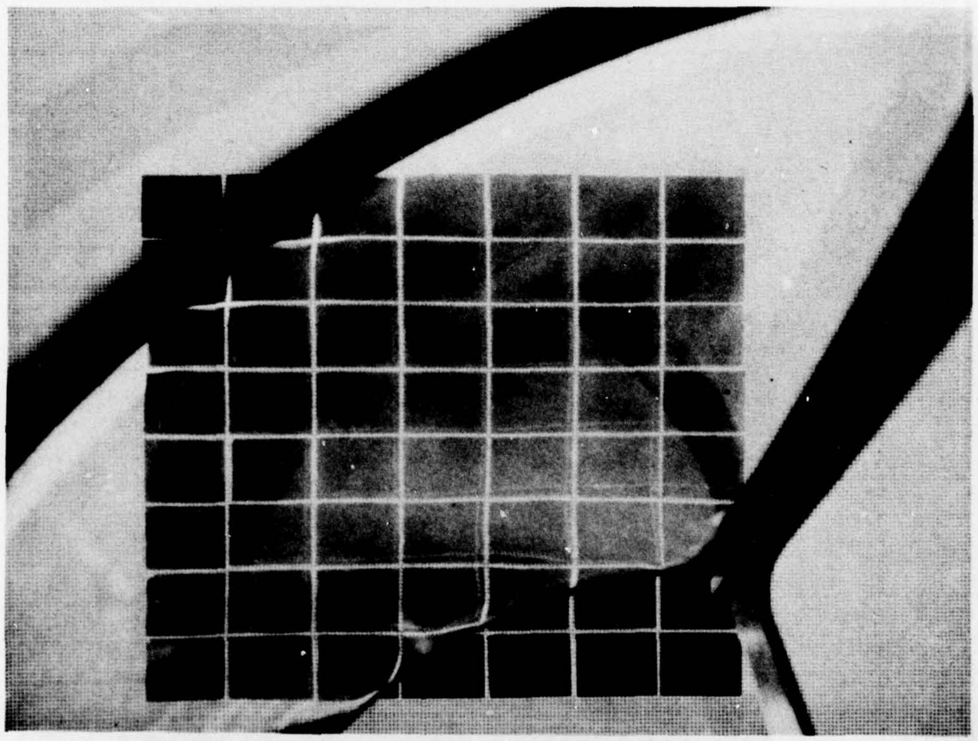

Figure 14. Windshield multiple-image photograph (D and E vectoring).

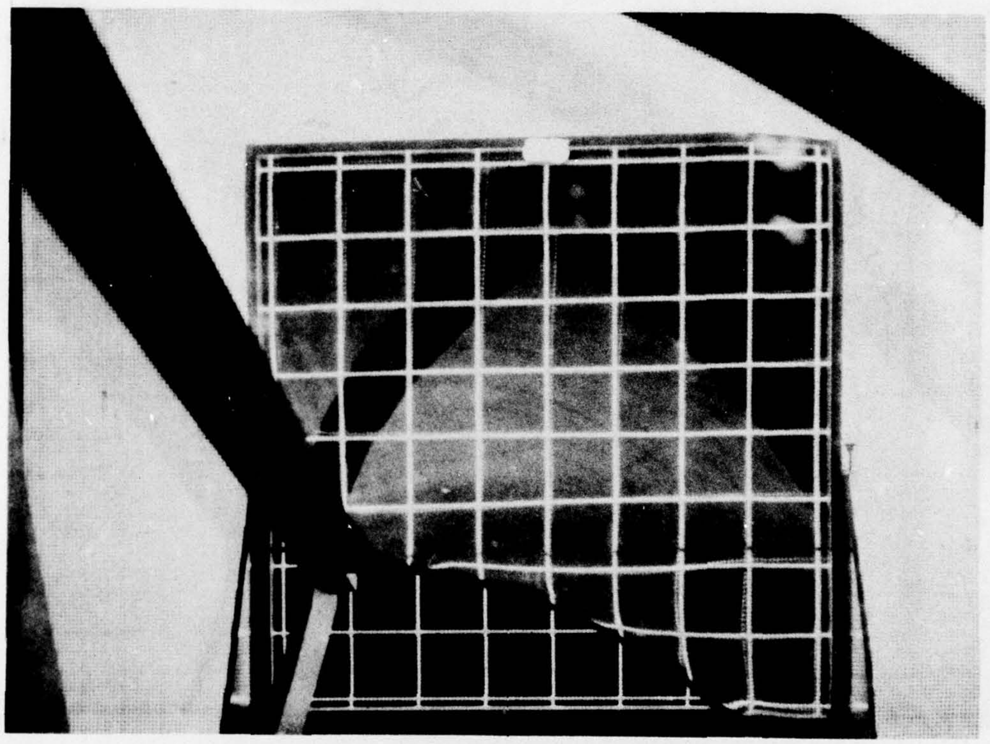

Figure 15. Windshield multiple-image photograph (A and H vectoring).

The photograph information illustrating the above technic is a monocular effect only. Two distinct sets of multiple images can frequently be seen with each eye; nevertheless, this grid-board method is a convenient way to generate and record multiple-image patterns.

In summary, this USAFSAM effort yielded three products: (1) Application of fundamental geometrical and physiological optics can explain much about the cause and movement of multiple images in the F/FB-111 windshield; (2) refinement of the standard deviation-mapping technic makes it possible to predict the multiple-image pattern of any F/FB-111 windshield; and (3) a standardized method has been developed for recording the multiple-image patterns of any given transparency.

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