A NEW INFINITY IMAGE SYSTEM

MR. JOSEPH LaRUSSA
Manager, Advanced Engineering
Farrand Optical Company, Inc.

Although cockpit simulators have been developed to the point where aircraft dynamics and response to both external and pilot inputs are reproduced in a most realistic fashion, the same cannot be said of the corresponding visual displays currently available. Generally speaking, "aircraft visual flight simulators" of several years ago were used for pilot training in tasks of a particular nature. They were limited to particular or part tasks primarily because they were not capable of accurately reproducing all aircraft response to pilot initiated stimuli nor were they capable of introducing all the visual cues which a pilot requires to initiate the proper stimuli. It was recognized, therefore, that the "transfer" value from simulator to real flight was low. However, the value of such simulators was rationalized by terming these devices part task trainers. It is now felt that the lack of fidelity in both the display and image generation of these so-called part task trainers did not fulfill even the part task functions that they were rated capable of. In other words, we have come to the realization that the absence of visual cues for a complete simulator did not necessarily equip that simulator for a lesser task. This is true because many psychomotor responses are dependent, in an unknown manner, on human evaluation of many simultaneous cues, not all of which (nor the relative importance of which) are known. Therefore, instead of rationalizing a simulator to a lesser task, it appears that we should devote ourselves to the achievement of an external world display as realistic as it is possible to generate with current methods. Representative of these state-of-the-art techniques developed for visual spaceflight simulators are the following:

a. The use of colored film to provide full color and better resolution in unprogrammed flight than closed circuit TV systems are capable of. This development with an optical perspective generation system and six degrees of freedom known as a Mission Effects Projector or MEP provides both Earth and Lunar orbital views.

b. The design of a celestial sphere which projects over 1,000 stars that remain true point sources even under high magnification.

c. Development of 110° wide field infinity display systems,

d. multiple input infinity display systems which permit the generation of true parallactic angles between objects located at variable distances from the observer, and

e. new wide field camera probes of 110° field of view with tilt focus corrections to permit the use of apertures as fast as f/5.

As examples of simulators utilizing these Farrand developments we have the Mercury simulator in Figure 83, the Gemini simulators in Figure 84, the Apollo simulator in Figure 85, the LEM simulator in Figure 86, and the T-27 simulator in Figure 87. You will note, however, that because of the multiple and complex tasks required of the simulators, the image generation and visual display systems have been rather large and bulky. These systems, in fact, would not be compatible for use on aircraft motion base cockpits because of size, weight and the resultant degradation of the dynamic performance of the motion base.

Because of the high cost of in-flight training, the unavailability upon demand of varied weather conditions and the current congestion of airports, visual simulation for both military and commercial aircraft has assumed a new degree of urgency. In the commercial aircraft field, especially with the forthcoming introduction of super transports, all of the drawbacks of in-flight training are further accentuated. In light of this, the simulation of the external world with a high degree of fidelity becomes a necessity. This simulation should be capable of satisfying the following requirements:

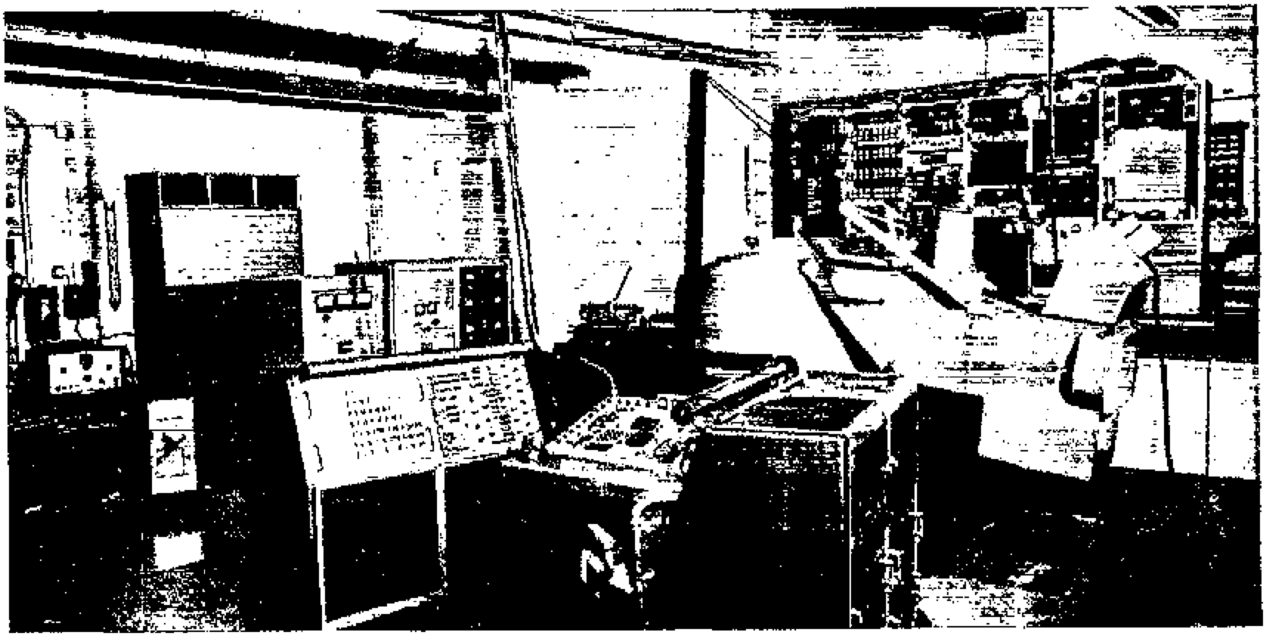

Figure 83. Mercury Visual Simulator

Figure 84. Gemini Visual Simulator

Figure 85. Apollo Visual Simulator

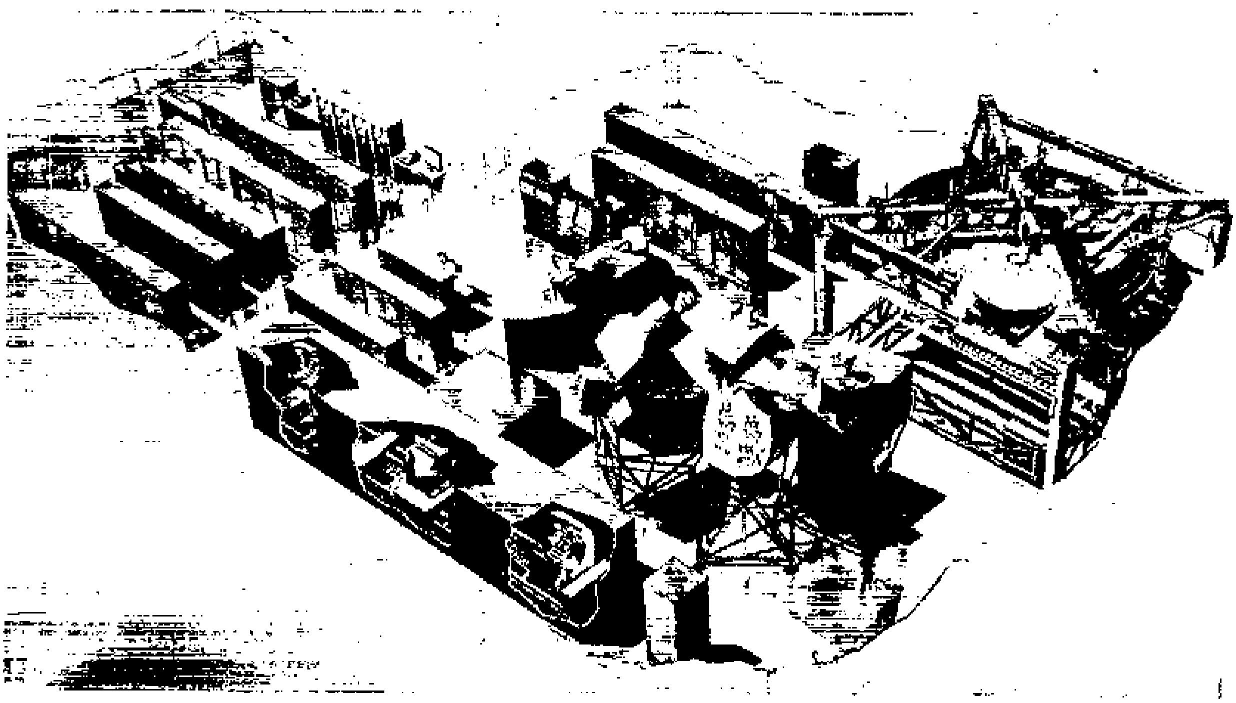

Figure 86. Lem Simulator (Visual and Image Generation by Farrand)

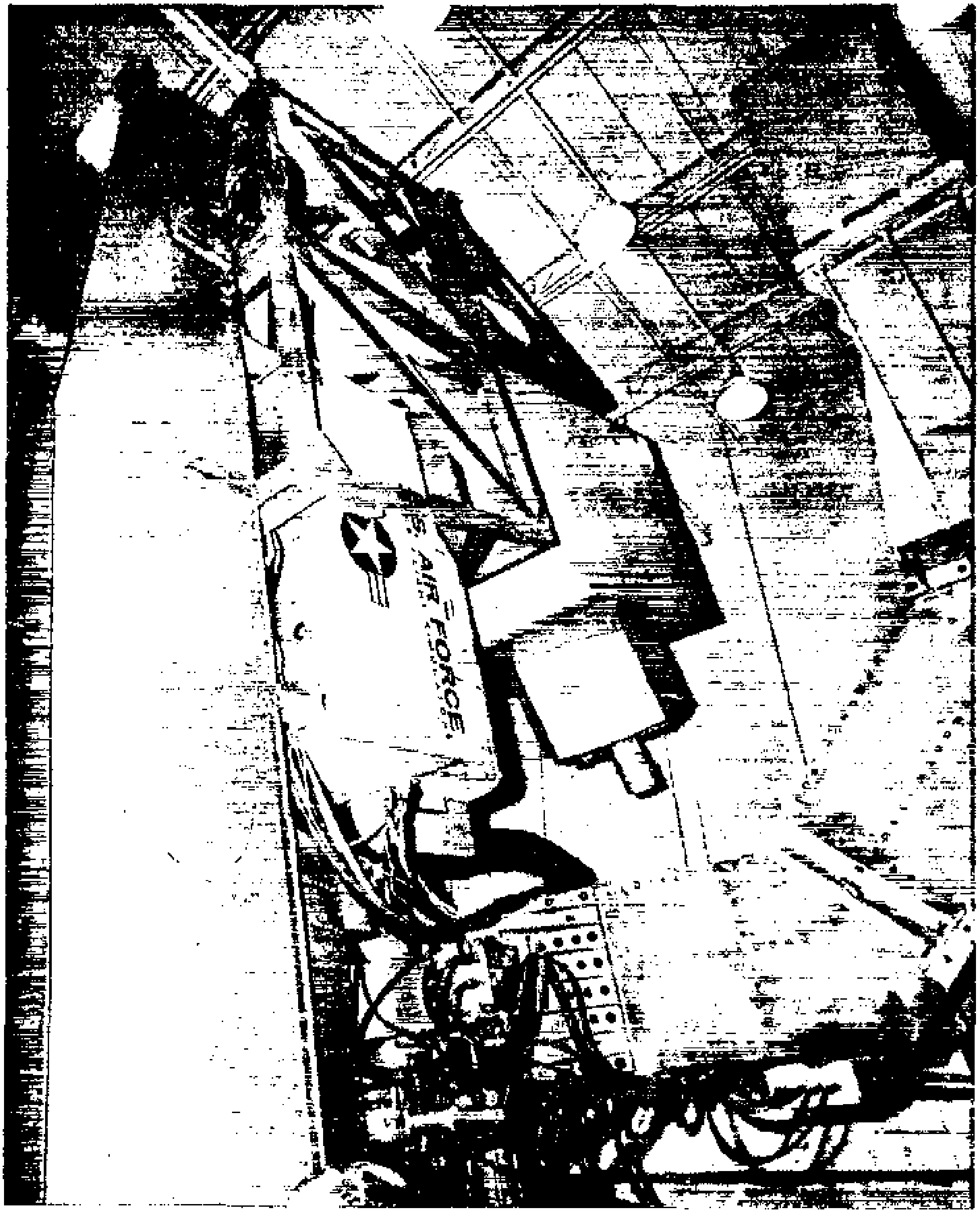

Figure 87. Edwards AFB, T-27 Simulator (Visual by Farrand)

1. Complete freedom over an approximate 10 mile radius from the runway in order that fly-around maneuvers may be executed at will.

2. A high resolution, high brightness, full color display of the external world.

3. The capability for a variety of weather conditions and illumination conditions extending from day into night and from clear visibility to category 3 landing conditions.

Although the requirements for an ideal commercial aircraft simulator are simply described, the fulfillment of these qualities is another proposition. It can be safely stated that all of the requirements can, at this time, be accomplished individually and several may be combined, but not all of the requirements can be achieved simultaneously at the present time. Trade-offs or compromises are, therefore, required.

When discussing a visual simulation system, it is best to make an arbitrary division of the overall system into two distinct categories to better focus on the shortcomings of each in order to effect the optimal compromises. The two categories referred to may be broadly defined as (a) the image generation system and (b) the display system. By the image generation system we mean the complement of equipment that is used to generate the external world scene in accordance with all of the aircraft motions and in accordance with illumination and weather conditions. This generated scene is not and should not be displayed directly to the pilot or co-pilot. Rather, it should be processed so as to render the appearance of the scene as realistic as possible and projected in a manner that will eliminate all parallactic errors due to pilot's head motion. This display of the generated scene must be accomplished with a minimal degradation of resolution, contrast and brightness. It is this portion of the system that we label the display end of the visual simulator and it is with this portion of the system that we shall be concerned today.

An infinity display system can provide an observer with a wide field of view and a controlled parallax from a number of various image generation devices. Most important, however, an infinity display system will become a necessity for future commercial aircraft simulators since head-up devices must be used in training for category 2 and 3 approaches and landings. Under these conditions, the head-up display projects symbols usually designating runway edges and touchdown point to infinity. That is to say, the symbology is actually projected against the ground so that pilot head motion does not result in relative motion between symbology and the real ground plane. The only type of simulator display system that can satisfy this requirement for the head-up display is, in fact, an infinity projection visual system. Equally important in a visual simulator is the generation of proper motion parallax between cockpit structure and the external scene. This is possible only with an infinity display system.

Briefly, there exist several different types of infinity display systems and these are depicted in the illustrations that follow. Before we examine the various systems, it is important to know that infinity display systems are themselves divided into two categories. Firstly, there exist the pupil forming types as shown in Figure 88 and secondly, there are the non-pupil forming types as shown in Figure 89. The pupil forming types are to be preferred where head motion is restricted or where small windows are involved since they are of the straight through optical variety where there are no intervening screens between the generated image and the exit pupil. As a consequence, their resolution and contrast rendition are excellent. In the aircraft simulator field, however, where the pilot's head motions may be large and where it may be desired to have both pilot and co-pilot view through each other's windows, it is more desirable to resort to the non-pupil forming infinity display system where the visual scene may be observed over large eye excursions without any cut-off. Figure 89 illustrates such a non-pupil forming infinity display. It will be noted that in the pupil forming display of Figure 88, pupil formation is caused by the F/number bundle associated with each point of the image formation. Hence, the complete field of view can be observed only when the observer's eyes are within the exit pupil volume. This becomes a definite restriction. In Figure 89, however, since the image is provided to the infinity display system by a diffusing screen, all of the aperture of the infinity optical system is illuminated by each image point and in reality the exit pupil of such a system is the aperture of the system. Due to their greater applicability to the aircraft simulator field we shall concern ourselves from this point on with non-pupil forming infinity image systems.

Figure 89B depicts a simplified mirror type of infinity display system with a large input screen which has several limitations as far as a commercial aircraft display system is concerned. First, the vertical field is severely limited to approximately 40°. Second, the screen input must be large for a wide field because the mirror focal length must be sufficiently long to permit the input to be located outside the observer's direct field of view. This requirement results in a bulky and heavy display. Finally, the system shown suffers from the drawback that the beam splitter significantly reduces the eye relief distance.

The purely refractive types of infinity display system previously illustrated in Figure 89A provides maximum eye relief but suffers from other disadvantages. For example, referring to Figure 90, it is seen that to attain a field of view θ with a given focal length f requires an image or screen size L_1. In refractive systems one strives to use as "weak" a lens as possible, meaning a longer focal length in order to use as simple a lens system as possible. A simple lens system may be defined as one comprising either one or two refractive elements. The long focal length associated with this requirement automatically dictates a large picture or screen size for a reasonable field of view. This means bulk and large swept volumes when such a display system is mounted on a moving base. It would be much more desirable to reduce the required screen size to a dimension such as L_2 wich can provide the same field of view as L_1 by shortening the focal length of the lens. This, in turn, however, requires a very fast f/# optical system which demands a high degree of correction involving multiple elements in the lens design. In other words, a compact refractive infinity system becomes very expensive and very heavy because of the multiple large diameter elements required. Even if one desired to produce such a system, the optical designers would be plagued by such problems as lateral color and sufficiently wide fields which might realistically approach 90°. Additionally, the design would be difficult since the human observer employs two eyes separated by approximately 2-1/2 inches. This really means that rays from a single point in the real field must emerge from the refractive system into the observer's eyes with a high degree of parallelism. If this is not the case and because the eyes are extremely sensitive to any convergent or divergent angles, "swimming" of the image and other distortions become readily apparent with head motion. One may conclude, therefore, that alonger focal length or weaker lens system is more desirable and one must accept the additional bulk and volume associated with such designs. This is not the end of the refractive lens problem. Referring to Figure 91A, it is seen that two side by side observers, looking at a single screen display, observe the same point in the visual scene as different spatial angles. The infinity display system properly designed

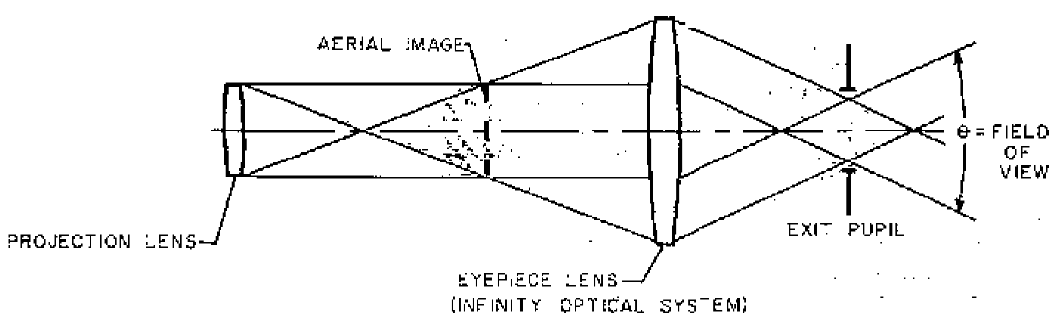

Figure 88a. Refractive Pupil Forming Infinity Display System

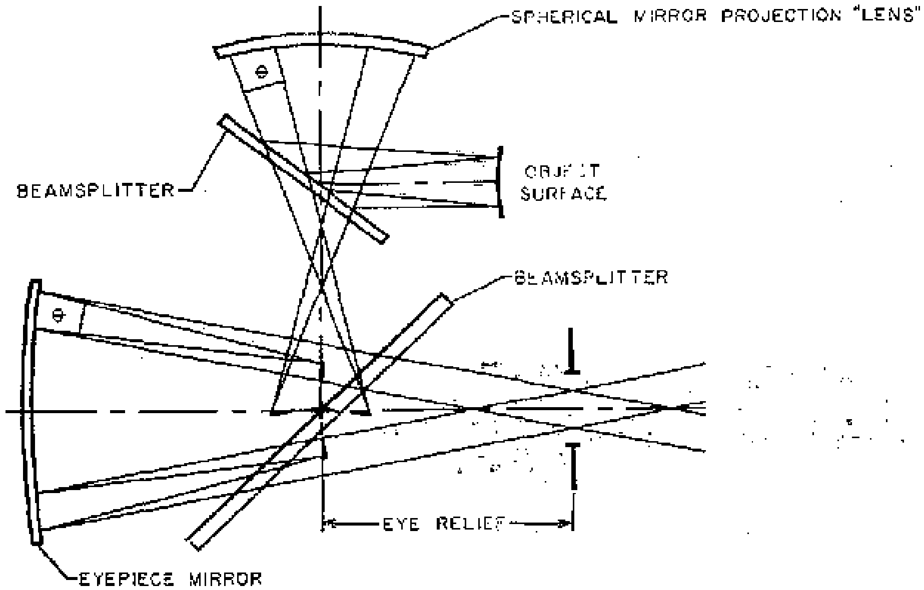

Figure 88b. Reflective Pupil Forming Infinity Display System

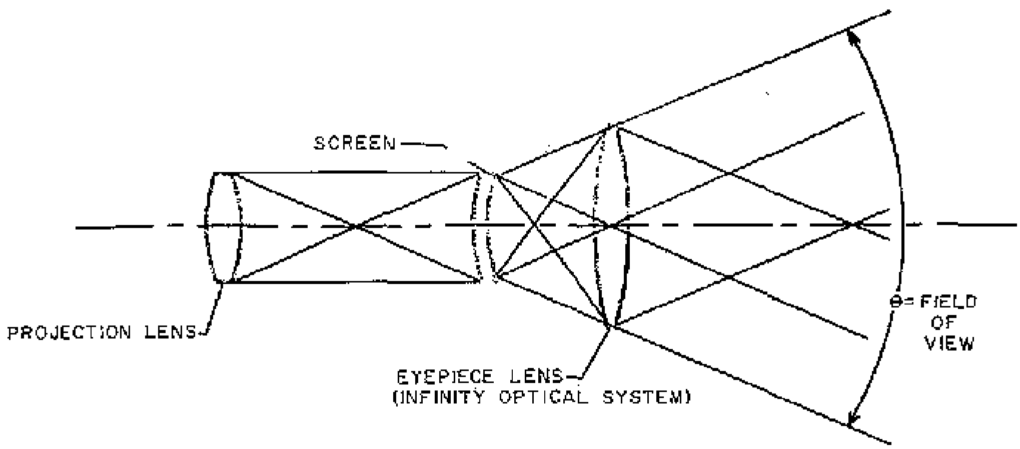

Figure 89a. Refractive Non-Pupil Forming Infinity Display System

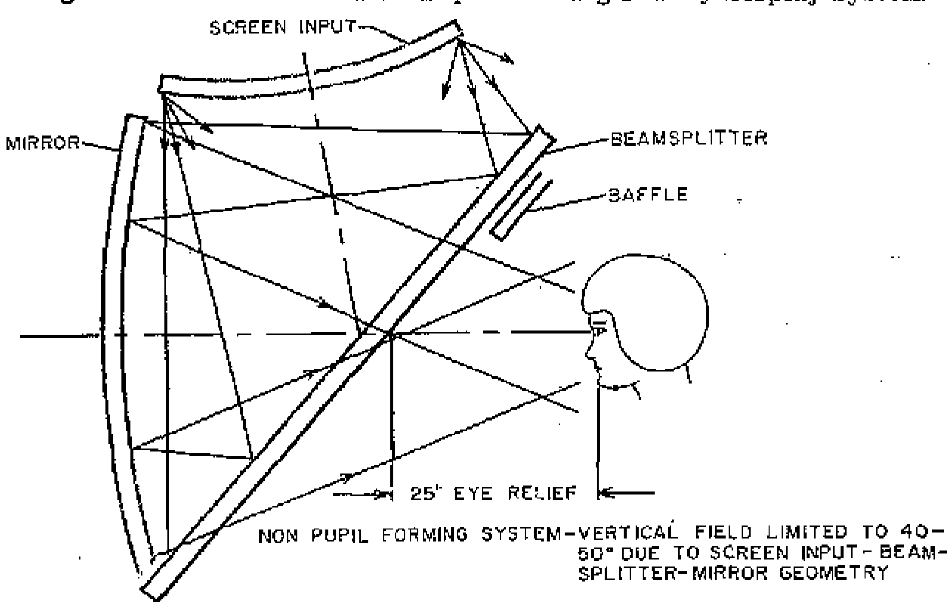

Figure 89b. Reflective Non-Pupil Forming Infinity Display System

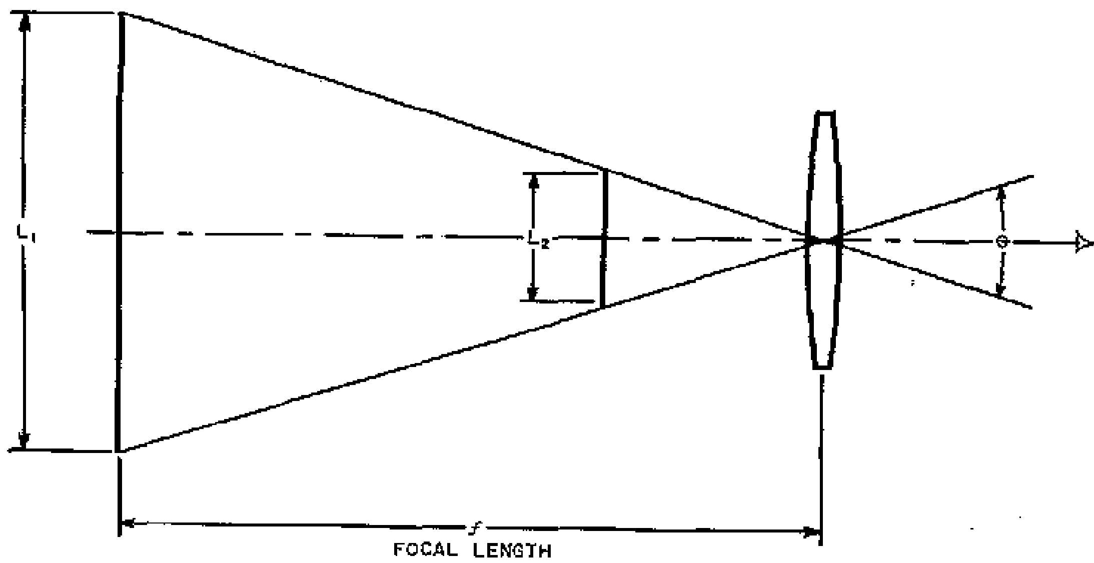

Figure 90. Refractive Infinity Display System

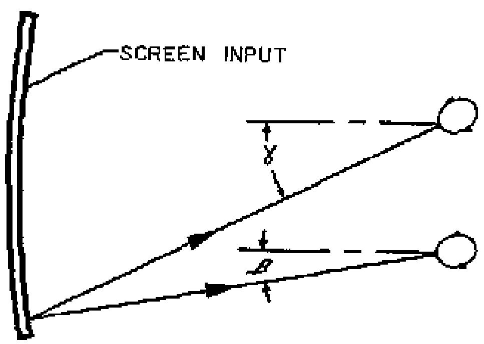

Figure 91a. Observers See Image at Different Spatial Angles

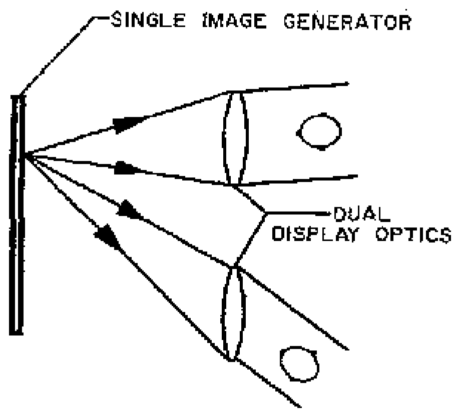

Figure 91b. Spatial Angles Not Correct

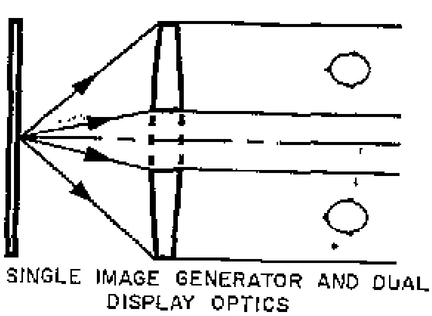

Figure 91c. Spatial Angle Correct

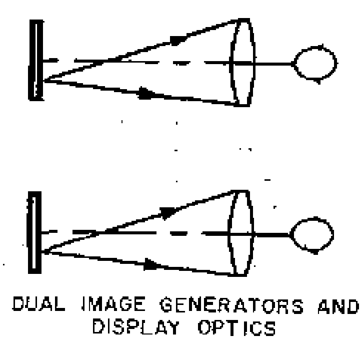

Figure 91d. Spatial Angle Correct

certainly corrects this obvious defect. However, one cannot employ the scheme of Figure 91B utilizing a single input since the spatial angle relationship is again incorrect. If a single generated image must be employed, then both observers must utilize the same lens system as shown in Figure 91C. In order to produce such large lenses economically, they must be cut as illustrated. A better solution is offered in Figure 91D where duplicate systems maintain the correct spatial relationship of equivalent points.

The use of multiple systems is not in itself an answer since the limited field of view of the refractive system does not assure the possibility of a design where both pilot and co-pilot can see out of each other's windows. In fact, even if one groups the refractive system in circular fashion about an observer's head as shown in Figure 92A, it will be seen that two different points in the field of view may have the same apparent direction which is, of course, totally wrong. Such a system may be corrected by employing the additional optical components illustrated in Figure 92b, but now the system gains an additional degree of complexity as well as an appreciable amount of weight.

An additional difficulty to which we have alluded previously emerges when considering infinity display systems. It is significant, however, that this added difficulty is more prev- a lent in the refractive type of system. In introducing this added consideration, it must be stated that in a well designed infinity display system, the required collimation of a displayed image is within 6 arc minutes on axis and within 40 arc minutes off axis. The specification does not indicate over what base length or pupil diameter this has to be achieved. We had mentioned previously that parallelism or collimation must be maintained over the interocular separation of approximately 2-1/2 inches. Hence, over this base length, the above decollimation corresponds to an object distance of 31 meters or a departure from infinity focus of 0.03 diopters. Experience with previous infinity image simulators has shown this to be a reasonable level. Systems with better performance than this can be achieved and systems with slightly worse performance than this may be utilized successfully, although somewhat uncomfortably over long periods of observation.

While decollimation is perhaps the most easily described defect in an infinity display system, the effects of decollimation are somewhat more subtle. The most important factor in decollimation is that the departure from infinity should be in the direction that makes the object appear to be closer than infinity as shown in Figure 93A. This corresponds to normal accommodation both in focus of the individual's eyes and in stereo accommodation. Appearance of the object apparently beyond infinity, corresponds to an unnatural effect landing to discomfort and possible nonfusion of the apparent imagery for the two eyes. This condition may be described by saying that the virtual image formed by the display system is convergent. It is of particular interest to note that a refractive type of infinity display system is more likely to have residual convergence across the field of view than a mirror system.

Generally speaking, therefore, it may be concluded that the mirror type of infinity display systems as pioneered and manufactured by the Farrand Optical Company are superior to refractive systems in terms of fields of view, optical correction (including especially the absence of lateral color over wide field), size and weight, and total field. The major drawback of mirror systems lies in the reduction of eye relief due to the inclined beamsplitter.

The Farrand Optical Company set out to eliminate this singular objection and has now arrived at a solution employing a spherical mirror alone without any refractive optics. This design is affectionately termed the Pancake Window* (Patent applied for) because of its minimal depth and, therefore, relatively flat appearance. The total depth of this new type of infinity display system is scarcely greater than the depth of the sagitta of the spherical mirror employed. Figure 94 illustrates the Pancake Window used as both a pupil forming display and a non-pupil forming display. It will be noticed from the illustration that the aerial image in Figure 94A or the screen image in Figure 94B appears to be on the concave side of the spherical mirror because of its reflection by the beamsplitter package. The spherical mirror, therefore, observes this aerial image and collimates rays emanating

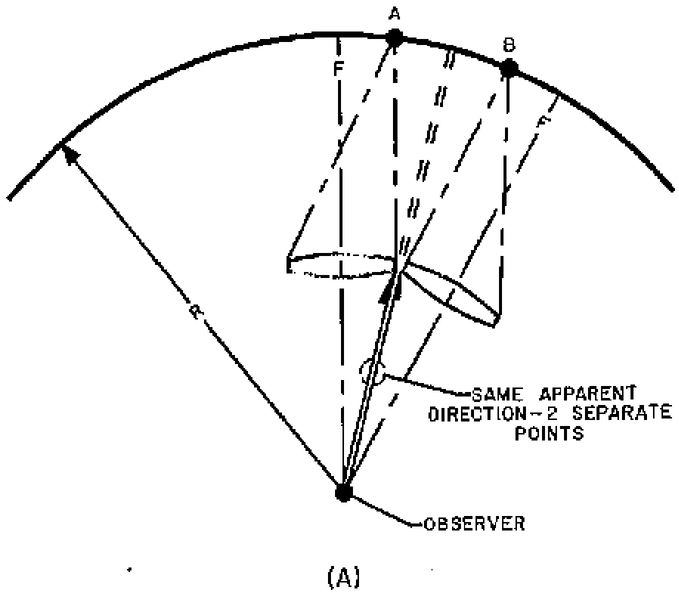

Figure 92a and b. Parallactic Error Correction for Refractive System

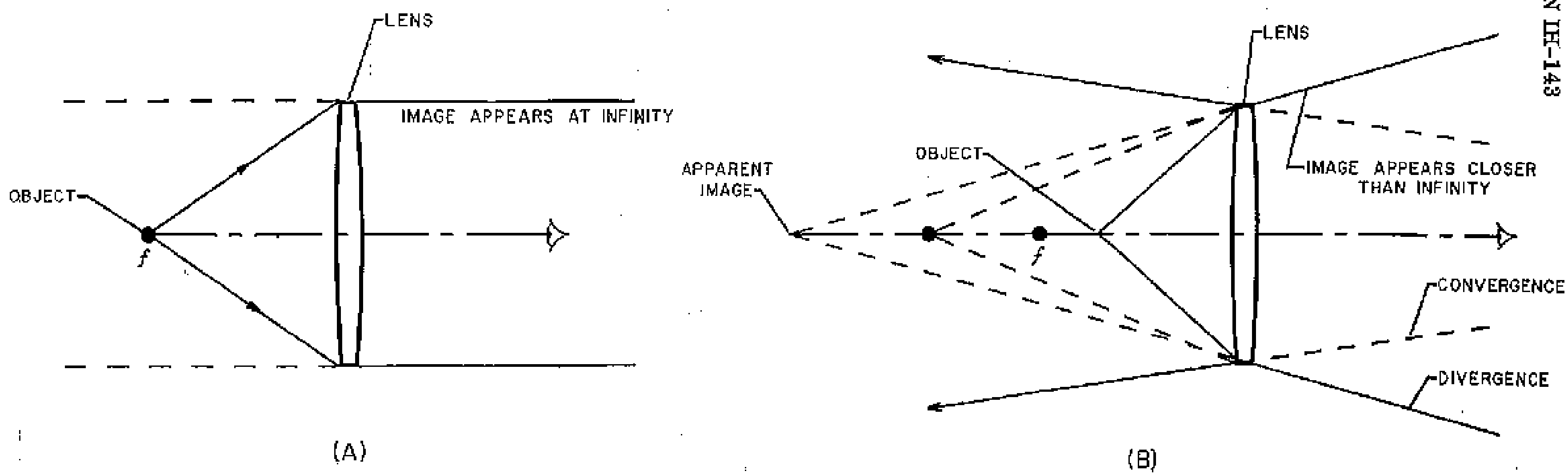

Figure 93a and b. Variation of Apparent Distances

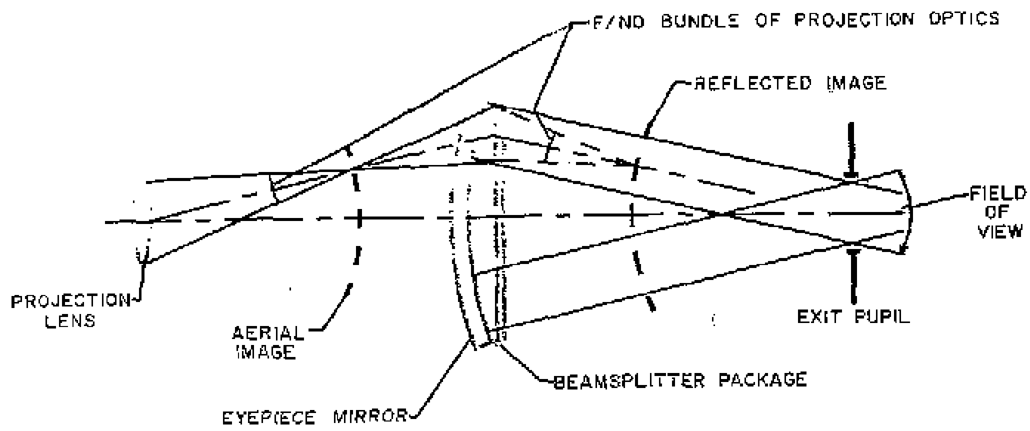

Figure 94a. Pupil Forming Pancake Window Assembly

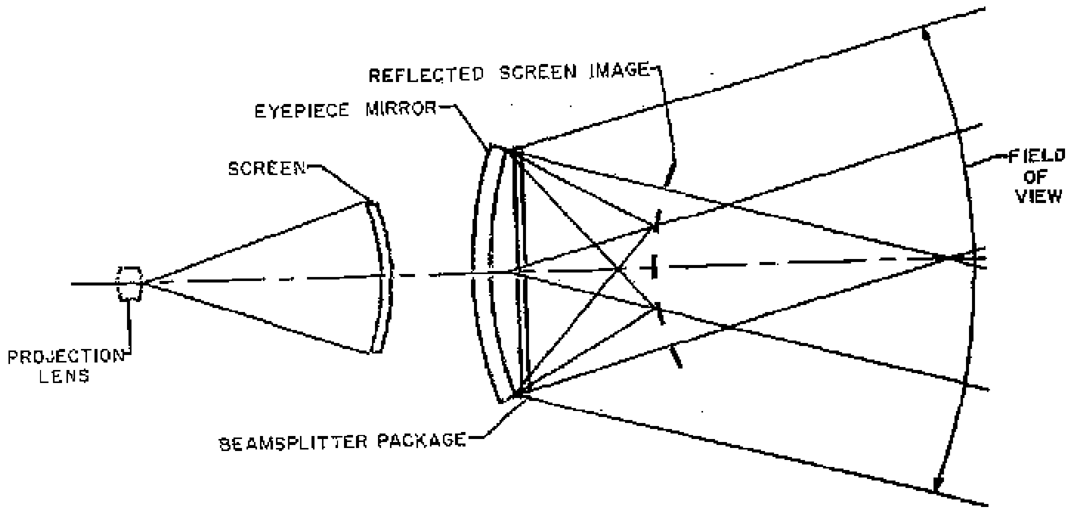

Figure 94b. Non-Pupil Forming Pancake Window Assembly (FARRAND PANCAKE WINDOW)

from each of the points in the aerial image to provide an image projected to infinity. Interestingly enough, the aerial image or the screen on the convex side of the spherical mirror cannot be seen by the observer because direct rays from these sources are stopped at the beamsplitter package. These rays are also redirected towards the spherical mirror as if they were emanating from the reflected image. Once the rays are in fact collimated by the spherical mirror, they are permitted to pass the beamsplitter package to reach the observers' eyes. In this manner, the observer sees only the image at infinity. It is significant that this mirror type of display system employs no inclined beamsplitter thereby eliminating the most serious encumbrance of mirror type infinity display systems while at the same time providing the equivalent of a very short focal length refractive system without the attendant disadvantages of the refractive type infinity optical system. Current designs of the Pancake Window may be equated to an F/0.5 refractive system! Most important, however, the complexity is infinitely less than would be required of an F/0.5 refractive system and, therefore, much more desirable economically. A typical system might have the following characteristics:

a. 29 inches eye relief for an 84° total field allowing 12 inches of head motion ("pupil" size) around the center of curvature of a 36" radius mirror.

b. The focal length would be 18 inches and the overall thickness only 9 inches.

c. Maximum decollimation would be 9 arc minutes over any head motion and any field angle.

d. No color, distortion, coma or astigmatism over an 84° total field.

Considering this typical system as a large eyepiece, we enjoy the remarkable combination of having an eye relief of 160% of the focal length and a physical thickness of only 50% of the focal length.

In conclusion, it may be said that the Pancake Window represents the latest state-of-the-art and a significant step forward in visual displays.