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WIDE ANGLE, INFINITE-DEPTH-OF-FIELD OPTICAL PICKUP FOR VISUAL SIMULATION

ALBERT H. NAGLER
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FARRAND OPTICAL CO., INC.

TECHNICAL REPORT AFHRL-TR-71-41

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FOREWORD

The program under which this Wide-Angle, Infinite-Depth-of-Field Optical Pickup for Visual Simulation was developed and evaluated was initiated by the Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, 45433.

The program was conducted by Farrand Optical Company, Inc., 4401 Bronx Boulevard, Bronx, New York 10470 under Contract F33615-68-C-1456. This report covers an inquiry into and development of a wide-angle, infinite-depth-of-field optical pickup for visual simulation, together with the construction and evaluation of an engineering feasibility model. The work herein reported was performed in support of Project Number 6114, "Simulation Techniques for Air Force Training," and Task Number 611405, "Visual Simulation for Aircrew Training." The research sponsored by this contract was initiated in April 1968 and completed in February 1971.

The principal authors of the study were Albert H. Nagler and Anthony R. Mazurkewitz. Technical Monitor for the U.S. Air Force was Mr. Arthur T. Gill of the Air Force Human Research Laboratories.

Two major items constituted the contractual objective of this program. They were:

1. Phase I Study and Development
2. Phase II Final Report, Design, Fabrication, Test and Evaluation of an engineering feasibility model.

This report constitutes both the Phase I study and final report. The engineering feasibility model was completed and demonstrated at WPAFB in October 1970. An experimental photographic and optical test program continued until Feb. 1971 when the feasibility model was formally delivered.

Item 1, Phase I Study and Development was completed and delivered in January 1969 as a preliminary draft.

This report was submitted by the authors November 1971

This technical report has been reviewed and is approved.

GORDON A. ECKSTRAND, PhD
Chief, Advanced Systems Division
Air Force Human Resources Laboratory

ABSTRACT

During Phase I of the program a study was undertaken to establish the most favorable approach toward producing a wide-angle, infinite depth-of-field, inclined-image plane viewing probe for purposes of simulation. The second phase involved fabrication, test and evaluation of an engineering feasibility model of such a device. This report describes both phases of the program.

Previous optical pickups for flight simulators were limited by slant range focus at close approaches to a model. Obtaining closer approaches has important size, cost and versatility advantages in making simulator terrain models and support equipment.

Phase I study results indicated the feasibility of producing a 140° circular field pickup with full pitch capability and a close approach of 4.1 mm. A preliminary but realistic design was developed and evaluated. The design approach was confirmed by photographing a runway model with a modified 110° probe.

Other concepts examined that had promise of improving resolution were dual sensor outputs and dual relays.

Component trade-offs, simplifications, and techniques were sufficiently developed for the design and fabrication phase of the program to proceed directly.

The Phase II design, fabrication and test program resulted in an engineering model that essentially met all of the design goals of the program. The probe system was evaluated numerically and photographically, working to an altitude of 0.2 inches. It has full functional operation in a static form and can readily be reworked to dynamic operation if desired.

SUMMARY AND CONCLUSIONS

PROBLEM

Historically, visual simulation image generation accomplished by means of optical probes has been limited to relatively narrow fields-of-view, and to medium quality resolution. In addition, picture quality further declined in low level flight situations such as approach, landing, and taxi, due to depth-of-field limitations in the optical probe. Future simulators will require wide field-of-view capabilities in conjunction with extended depth-of-field characteristics, and thus the state-of-the-art of optical probes must be advanced.

APPROACH

This program was comprised of two major objectives: (1) Phase I Study and Development, and (2) Phase II Design, Fabrication, and Test and Evaluation of an engineering feasibility model. During Phase I, a study was undertaken to establish the most favorable approach toward producing a wide-angle, infinite depth-of-field, inclined image plane viewing probe for purposes of simulation. A preliminary but realistic design was developed and evaluated, with the design approach being confirmed by photographing a runway model with a modified narrow field-of-view probe. Other concepts were examined that had promise of improving resolution, including dual sensor outputs and dual relays. Component trade-offs, simplifications, and techniques were sufficiently developed for the design and fabrication phase of the program to proceed directly. During Phase II, sophisticated computer optical design techniques were employed to optimize performance characteristics of the engineering feasibility model of the probe. The feasibility model probe was fabricated and evaluated both numerically and photographically.

RESULTS

A unique optical probe was developed which alleviates previous problems in field-of-view and depth-of-field in the simulation of low level flight, approach, landing, and taxi. The engineering feasibility model probe produced a 140 degree circular field-of-view capability while still retaining a "fast" optical speed. In addition, dynamic inclined-image-plane compensation was incorporated within the optical chain, thereby permitting an infinite depth-of-focus to be attained even at simulated aircraft touchdown. The optical pickup was fully articulated so that functions of roll, pitch, and yaw can be readily accomplished by virtue of pivot points, or joints, within the optical chain. Resolution capabilities of the probe on optical axis are essentially diffraction-limited, which identifies a new problem area for further research in that an extremely high-resolution TV camera will have to be developed and optically mated to the probe.

CONCLUSIONS

The engineering feasibility model probe developed as a result of this program essentially met all of the design goals of the program. It exhibits an extremely wide field-of-view capability and possesses essentially infinite depth-of-field characteristics. As such, this probe currently represents the state-of-the-art in optical probes for visual simulation applications. The success of this program warrants further research to develop a companion extremely high-resolution TV camera, and ultimately a complete prototype visual simulation system. Upon demonstration of the feasibility of the prototype visual simulation system, the technology should be incorporated in operational simulators.

ARTHUR T. GILL
Project Engineer
Air Force Human Resources Laboratory

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PHASE I

STUDY AND DEVELOPMENT

SECTION I

INTRODUCTION

1. GENERAL

The purpose of this program was to study, design, fabricate and evaluate an engineering feasibility model of a wide angle, infinite-depth-of-field optical pickup useful for visual simulation operations with the emphasis on aircraft landing simulation.

Since the Farrand Optical Co., Inc. had accomplished many of the basic aims of the study by developing automated optical pickups for the LEM program that have been operational for several years, much of the background and experience necessary to extend the state of the art to provide a 140^{o} field system was directly applicable.

While this program was limited to an engineering feasibility model, two important considerations not specifically requested in the study had important practical advantages:

1. Insofar as possible, all designs were geared toward future updating to automated operations as contained in present probes.

2. The optical output considerations such as field formats, image mapping functions, etc. were geared to mate well with current state-of-the-art visual display systems such as the Farrand infinity displays used in the Mercury, Gemini, Apollo and LEM simulators and the in-line, infinity display referred to as the "Pancake Window".

The study phase of the program also overlaps heavily into the design phase so that the results can be considered a preliminary design study and not limited to background theory.

The major positive results of the study phase are contained in Section III (Basic Probe Recommended Design Approach) while most of the relevant background material is covered in Section II (Concepts Studied) and the Appendix. Section III also details the comparison of design goals and expected results likely to be achieved in the hardware phase of the program.

This approach also stressed modularity in that relay lenses could be added later to achieve larger image formats, changes in image mapping functions, and multiple sensor outputs, features already incorporated into present designs.

The phase II design, fabrication, test and evaluation program generally followed the recommendations of the study phase. In addition, the dual relay concept was implemented, as explained in Section VI which discusses the optical design and layout. The engineering feasibility model construction is described in Section VII.

Actual performance of the probe is described in Section VIII which includes optical measurements and test photographs taken through the probe. A comparison of the design goals and measured performance is also included. The overall conclusions and recommendations are discussed in Sections IX and X.

SECTION II

CONCEPTS STUDIED

1. INTRODUCTION

The basic elements making up a "Scheimpflug" type of probe are:

1. Objective lens
2. Relay lens
3. Sensor

These can be considered in any multiple combination to increase the brightness and resolution capabilities of the display system chain.

Also basic to obtaining a minimum moving mass system is the inclusion of an elevation prism ahead of the objective rather than tilting the entire probe device. We can also assume that a simple optical derotator is desired instead of electronic derotation, especially where data would have to be transferred between independent electro-optical (multiple) chains.

a. SINGLE OPTICAL SYSTEM APPROACH

This was found to be clearly the simplest and most practical arrangement. It offers the most realistic approach to obtaining most of the design goals of the program by being based on extensions of operational hardware, as demonstrated at the start of this program. The design, manufacture, assembly and alignment is a time consuming, difficult task. It is felt that devices of this nature, that are even more complex, would be too expensive and too unserviceable (without highly trained personnel and extensive alignment tools) to render them more than laboratory curiosities. Indeed, the several simplifications to this approach found in the detail study make a single channel approach more desirable from a hardware standpoint. A full discussion of this recommended approach can be found in Section III.

The single optical system approach can also offer multiple sensor outputs to increase resolution, though at the expense of transmission loss.

b. MULTIPLE OPTICAL SYSTEM APPROACH

While multiple component chains offer theoretical advantages in light transmission and resolution, many disadvantages are apparent; one requirement seems to negate multiple chain approaches, even on a theoretical basis. This is the requirement for close approach combined with minimum moving mass.

Let us consider for simplicity the implementation of a dual optical system sensor chain as shown in Figure 1, with a common entrance pupil provided by the elevation prism system.

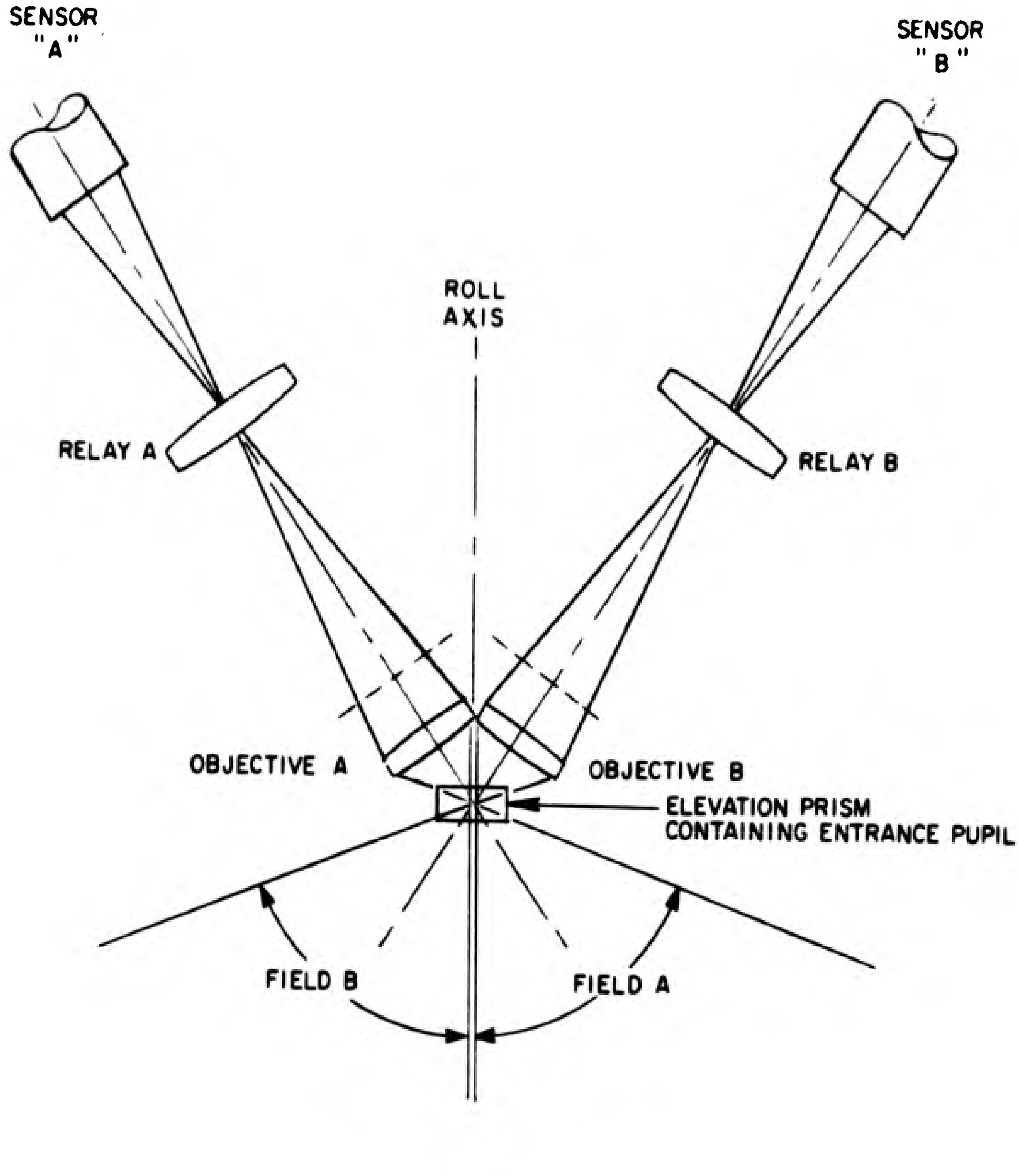


Figure 1. Multiple Optical System Approach

The roll axis is assumed to be in the center of the desired display field and clearly must roll the entire 140^{o} field about the single central axis. The roll prism cannot be placed behind the objective or relay because the necessary physical separation of the optical axis dictates an impractical prism path length even with the relay lenses side by side. Individual roll prisms cannot be used in these locations because object fields must be interchanged during a roll maneuver, that is, field A must be presented to sensor B and vice versa. Therefore, to implement this optically, requires the roll prism being placed ahead of the objective (in the common object space). A glance at Figures 5 and 6, front end layouts, shows that if we try to add a roll prism in front of the elevation prism, we would destroy the close approach attainment which is the very purpose of the program. If we eliminate the elevation prism and implement pitch maneuvers by rotating the entire probe device, we would greatly increase the dynamic mass, slowing pitch response and adding structural complexities.

It is clear then that multiple pickup approaches for this combination of wide field and close approach goals are impractical.

Other general problems related to multiple optical pickups with segmented corresponding display systems suggest avoiding any complex approaches. These are:

1. Problems of scene mismatch at display system interfaces due to the following system variations:

    a. Distortion and magnification

    b. Resolution

    c. Physical alignments

    d. Brightness changes across field

    e. Roll, Pitch and Yaw

    f. Sensor responses

    g. Display variations

2. Size, wieght, cost, complexity and maintenance factors.

c. FIELD FORMAT CONSIDERATIONS

The lack of symmetry in the field-of-view (FOV) requirements (70^{o}V x 140^{o}H) suggests an advantage to be exploited in closeness of approach of the probe to the model. This is not practical however when one considers the presentation to the final display. The field shape in the final display would be 70°V x 140°H. With a roll maneuver executed in the probe via the derotator, a truncated FOV is always presented to the sensor. The scene presented in the final display therefore will take a form, with roll, which does not fill the window configuration of the trainer, as illustrated in Figure 2.

To avoid this problem, then, the optical system must pass a complete 140° circular field of view. This argument however does not preclude the use of dual sensors as in Figure 15b because the sensor field shape is fixed to the window field shape and not to the real world field.

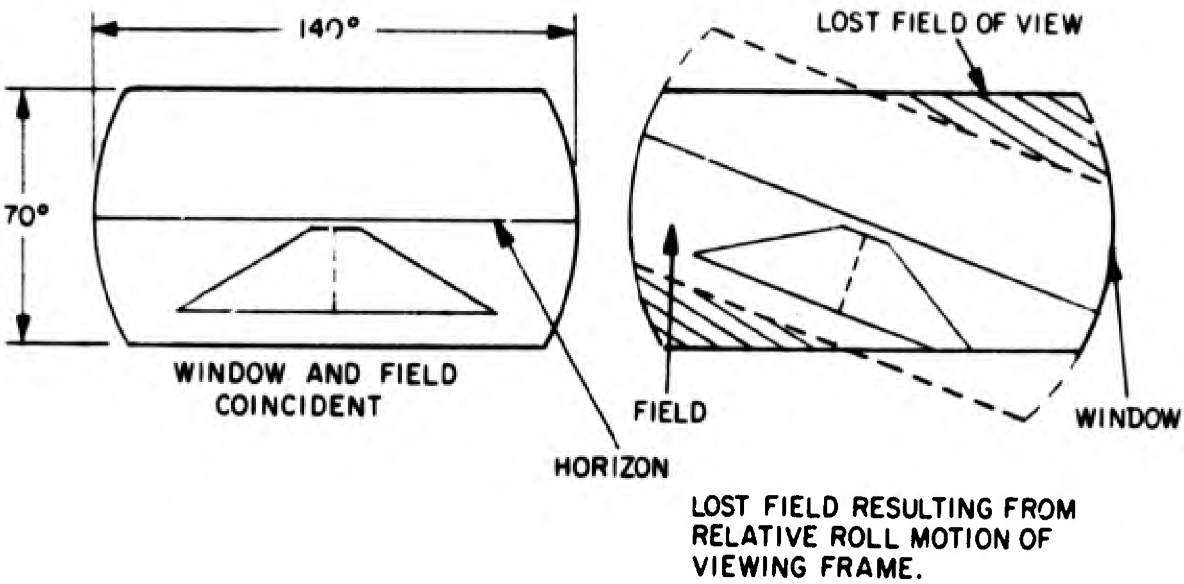


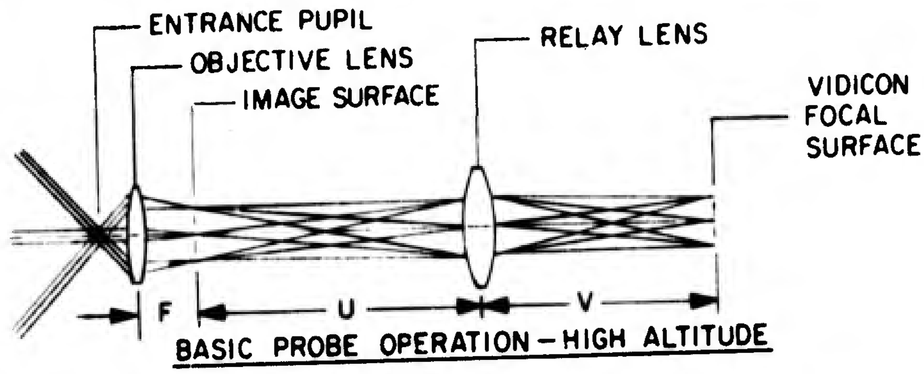
Figure 2. Field Limitations With Non-Circular Format

SECTION III

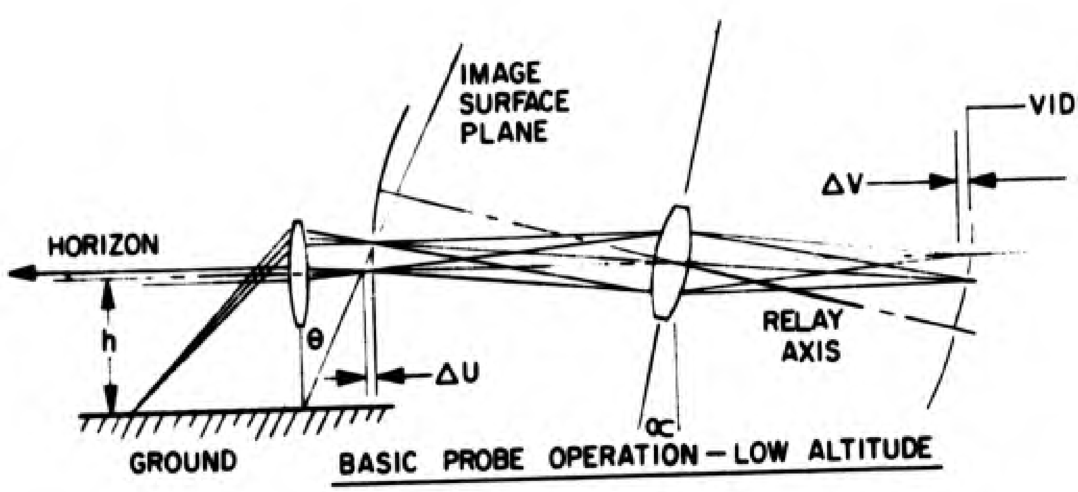
BASIC PROBE RECOMMENDED DESIGN APPROACH

1. SCHEIMPFLUG PROBE GEOMETRY

The derivation of the Scheimpflug probe geometry is given in Appendix B, Probe Theory. Figure 3 illustrates the resultant operation for level flight simulation.



$$\text{SYSTEM FOCAL LENGTH} = F \times \text{MAGNIFICATION} = F\frac{V}{U} \qquad m = \frac{V}{U}$$



$$\tan\theta = \frac{F}{h} \qquad \tan\alpha = \tan\theta\left(\frac{m}{m+1}\right) = \frac{F}{h}\,\frac{m}{(m+1)}$$

$$\Delta U = \frac{U}{\cos\alpha} - U$$

$$\Delta V = \frac{V}{\cos\alpha} - V$$

Figure 3. Scheimpflug Probe Geometry for Level Flight Simulation

At simulated high altitudes, the system can be considered as a normal in-line objective with a long focus relay lens of approximately 1 power magnification.

System focal length = F x m where F is the objective focal length and m is the relay magnification = $\frac{v}{u}$.

The relay in a fully functional probe requires long object and image distances to provice for focussing mirrors, prisms and a derotator. A long relay object distance "u" also permits the objective to function almost telecentrically, (i.e. chief rays are parallel in the image space) without the need of field lenses. The slight change in magnification of down-field objects as close approach is attained will not be visible in normal simulation activity because it is only 2.5% at closest approach and this effect is totally masked by the rapid angular increase in ground objects. Elimination of field lenses in selection of system elements reduces optical interface problems and consequently the complexity of an automated probe.

Considering the probe axis parallel to the ground as in Figure 3, Low Altitude, the image surface tilt is given by $\tan \theta = \frac{F}{h}$

where:

θ = objective image surface tilt angle

F = objective focal length

h = altitude

The relay lens tilt angle α necessary to restore the focal surface perpendicular to the system axis is given by:

$$\tan \alpha = \tan \theta \frac{(m)}{m+1}$$

where α is the relay tilt angle

θ as before is the objective image surface tilt angle

m is the relay magnification

Since $\tan \theta = \frac{F}{h}$ we can also say:

$$\tan \alpha = \frac{F}{h} \frac{(m)}{m+1}$$

This is the key relationship in optimizing the choice of F and m. It is desirable to reduce α to minimize the optical design problem of working with wide angle lenses. The relay lens must be a flat field design with a semi-field equal to the tilt angle α .

The obvious benefit of reducing the objective focal length F is restricted by the final image plane diameter at the vidicon sensor. For a single one inch sensor, a practical limitation is about 1/2 inch. Assuming Fθ mapping, (the linear relation between image size and object field angle that is normal for an external pupil objective),

$$F \text{ min.} = \frac{\text{image height}}{70^{\circ} \text{ object angle}} = \frac{6 \text{ MM}}{1.22 \text{ radians}} = \text{approximately 5 MM.}$$

Thus F x m = 5 is a restriction. The design goal however suggests a 1.0 mm diameter pupil minimum and an f/6.0 system relative aperture, making F = 6 the basic restriction. A plot of objective relative aperture vs relay tilt is shown in Figure 4. Quantity "h" is held constant at the 5 MM design goal minimum viewing altitude and the system focal length (F x m) = 6 MM.

This graph presents the designer with the task of attempting to moderately reduce relay tilt by accepting much faster relative apertures or increasing relay tilt and operating with slower relative apertures.

Design experience with previous Scheimpflug probes indicates that the region between f/6 and f/7 is a good compromise. The difficulty of the design task is typified by the case of f/6 where the relay is working at unity magnification with an effective aperture of f/3. This is exceedingly fast for a flat field design of over 60° total field.

The resultant Phase I preliminary design has the following characteristics:

1. Entrance pupil diameter = 1.0 MM
2. System focal length = 6.0 MM
3. Objective focal length = 6.3 MM
4. Relay magnification = .95
5. Final image plane diameter = 12.7 MM for 140°

Another basic probe operating function is illustrated in Figure 3, Low Altitude diagram; as the relay tilts, both U and V grow because the system axial image conjugates now represent field points in the normal relay focal planes. The increase in object and image distances due to relay tilt are given by:

$$\Delta U = \frac{U}{\cos \alpha} - U$$

$$\Delta V = \frac{V}{\cos \alpha} - V$$

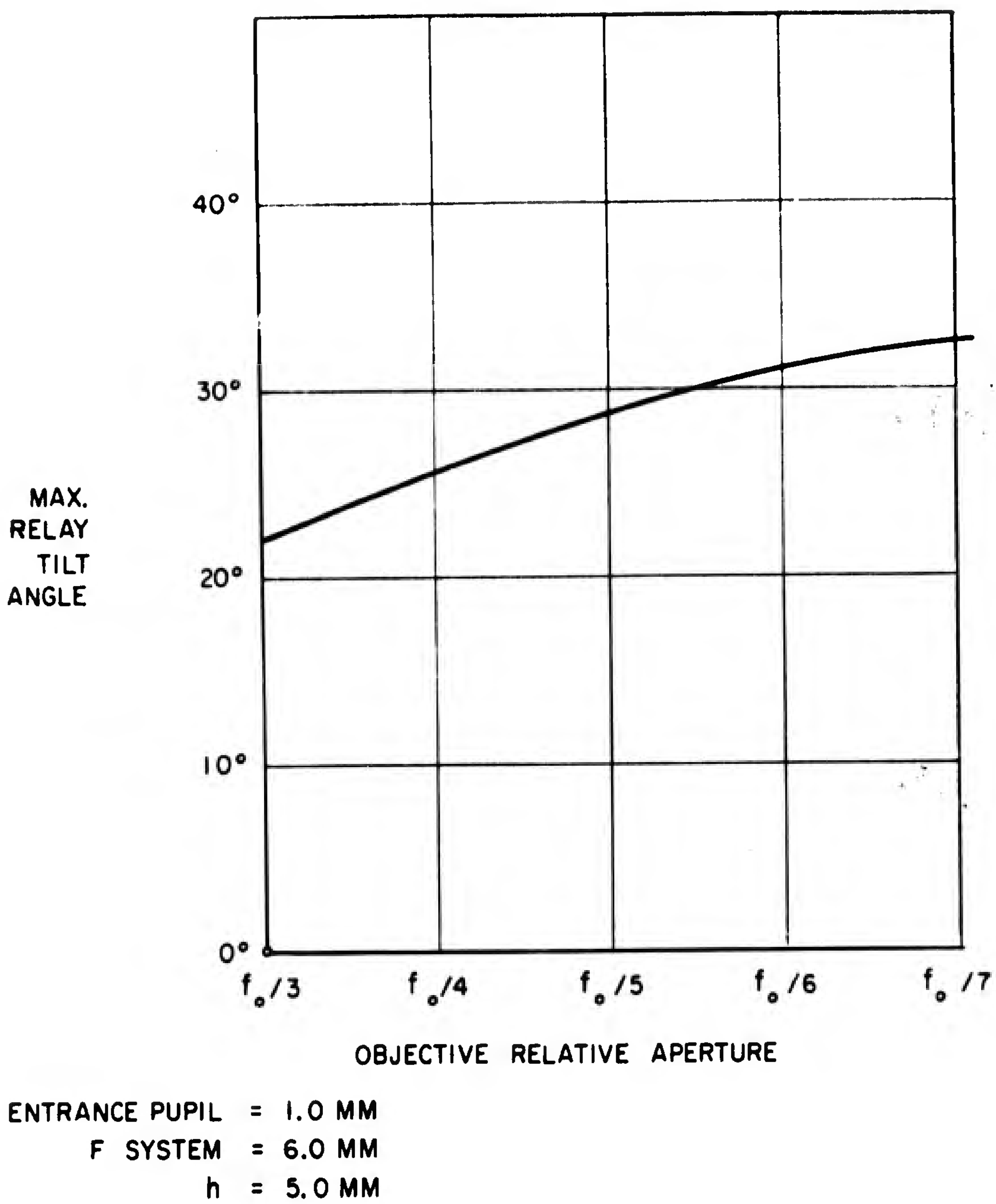


Figure 4. Objective Relative Aperture vs. Relay Tilt

These path length changes are taken up by mirror or prism motions so that the relay pivot, objective location and vidicon location are fixed for all operating modes.

Although not considered in the above analysis, pitch functions also affect θ, α, Δ U and Δ V. The governing condition is the relation:

$$\tan \theta = \frac{F}{h} \sin \gamma$$

Where γ is the viewing angle from nadir. Thus the above analysis considered only horizon viewing, where $\gamma = 90^{\circ}$ and $\sin \gamma = 1$.

The variables of pitch, altitude, yaw, and roll have been worked into the design of the mechanical computer used in previous automated 110° Scheimpflug probes built by this contractor.

2. OBJECTIVE LENS DEVELOPMENT

Two major approaches were investigated to obtain the 140° field with good optical correction and the ability to physically achieve a close approach.

a. DESIGN I, GALILEAN ARRANGEMENT. (See figure 5.)

This approach used a reverse Galilean telescope arrangement in front of a modified 110° probe objective. A front negative element compresses the incoming 140° conical field to allow passage through the elevation prism. A further compression is gained by the positive lens between the prisms because the effective pupil location is about 1 mm ahead of the positive lens. The elevation prism (between the lenses) could be made wide enough to cement the negative lens directly to the face.

Note that all components are just large enough to effect the appropriate optical folds while achieving a 2.7 mm minimum approach (with the elevation prism rotated 90° from the position shown, thus making the optical axis parallel to the model surface). If a full elevation maneuver is necessary at minimum approach, this 2.7 mm would increase to 3.5 mm to allow clearance for the lens edge during rotation.

Considerable design effort was expended in mating this approach to an objective lens but problems with undercorrect astigmatism and field curvature could not be controlled without sacrificing the close approach of the geometry or the wide field. The positive lens power between the prisms introduces excessive field curvature and it was felt that this lens should be eliminated if possible for mechanical reasons as well, i.e. small size (3 mm) and alignment sensitivity.

b. DESIGN II, NEGATIVE LENS IN FRONT OF PUPIL. (See figure 6.)

This approach, eliminating the positive element of Design I, evolved to a realistic compromise between many of the parameters desired in this study. The design was carried through to a point where both the physical and optical performance characteristics are representative of the final design.

For level flight, a close approach of 4.1 mm (0.161 inches) was attained. If a full elevation maneuver is necessary at minimum approach, 6.0 mm clearance would be required.

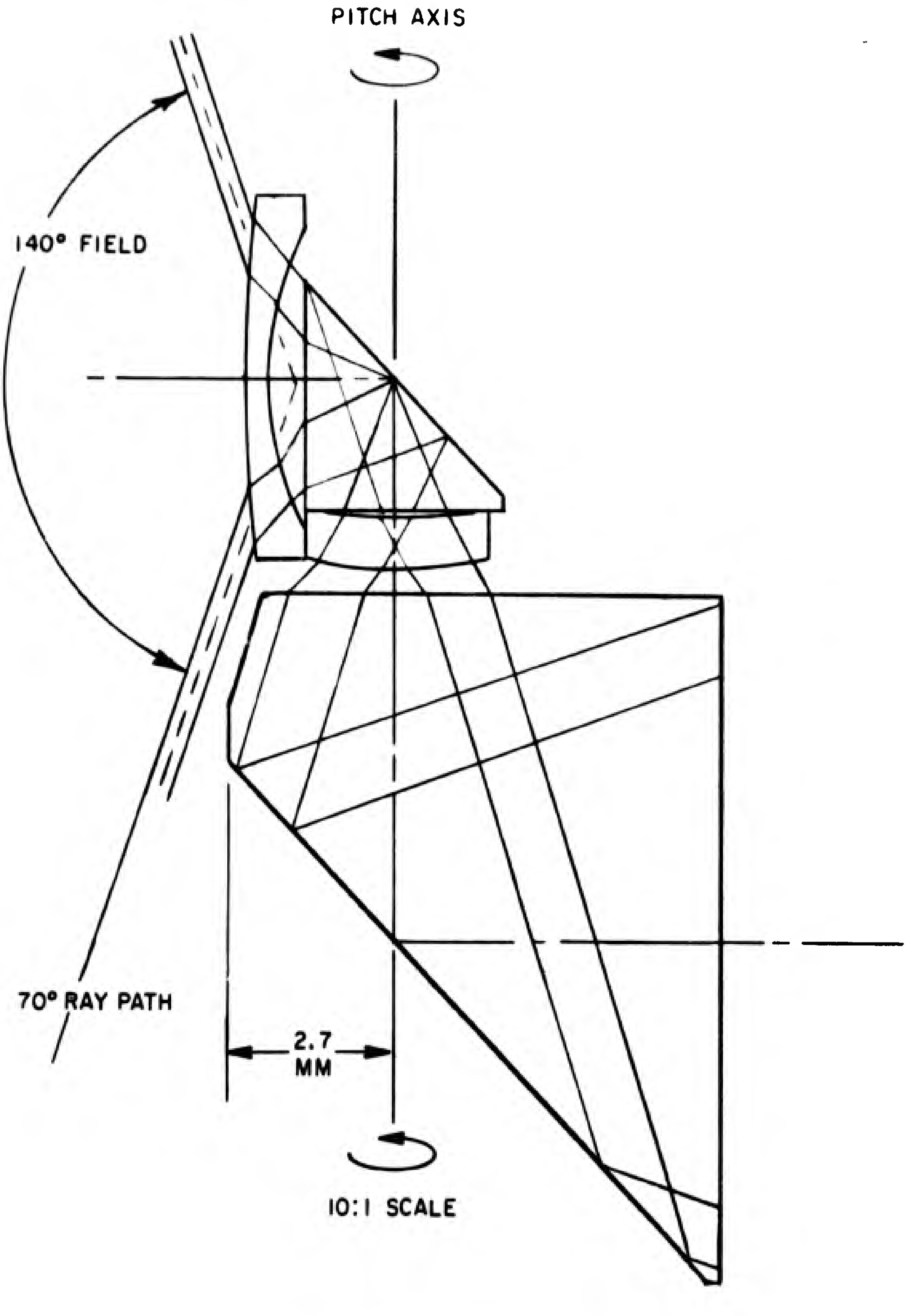


Figure 5. Galilean Arrangement

c. PERFORMANCE PARAMETERS

Because the objective is the major optical component and contains the entrance pupil or "look point" of the probe, the optimization and balancing of aberrations should be made with a firm view of the actual use of the device. For example, the following assumptions were made:

1. Full pitch and roll capability are only necessary to simulation of high altitude flying. A 35° downward field is normally available (70° total vertical field specification).

2. Pitch and roll capability will be severely restricted in simulation of very low altitude in approach and landing operations. Little if any downward pitch motion is expected in this case.

In completing the objective design during Phase II, it appeared judicious then to emphasize maximum correction at the higher altitudes since the severe imaging problems that occur at the lower field at low altitude-level flight situations will be ameliorated by the restricted 35° or less typical downward field available. Also while relay tilt compensation can be varied to optimize the match in fields between objective and relay under low altitude conditions, no such optimization is possible at high altitude because no relay tilt is used.

A realistic reference 140° design was developed using the in-house IBM 360 computer facility. Special optical programs are incorporated which were particularly helpful in the final design phase. Among these are evaluation through rotated optical components such as the relay lens. Also valuable would be the modulation transfer function (MTF) evaluations and semi-automatic design programs as used in the objective development.

The major design problem is how to maintain optical correction over a very large conjugate (object distance) range. High performance lenses are normally designed for very specific and limited conjugate ranges and are normally quite poor outside of their design range. Thus the designer must be keenly aware of the end use of the probe in making trade-offs in the detail design phase.

The working design evaluation tool has been the longitudinal aberration curves. Figure 7 illustrates these curves, presenting much useful information to the designer. Curves are drawn for the sagittal and tangential image planes for semi field angles of 0°, 15°, 30°, 45°, 55° and 70°. These are repeated for three object distances, infinity, 25.4 mm and 6.00 mm. Pupil diameters of 1.0 mm represent the vertical extent of each line. The sagittal direction is only recorded over .5 mm semi-diameter because of symmetry.

If the lens were perfect, all lines would be vertical and would have zero longitudinal error. A departure from zero for the 0° (axial) field angle would

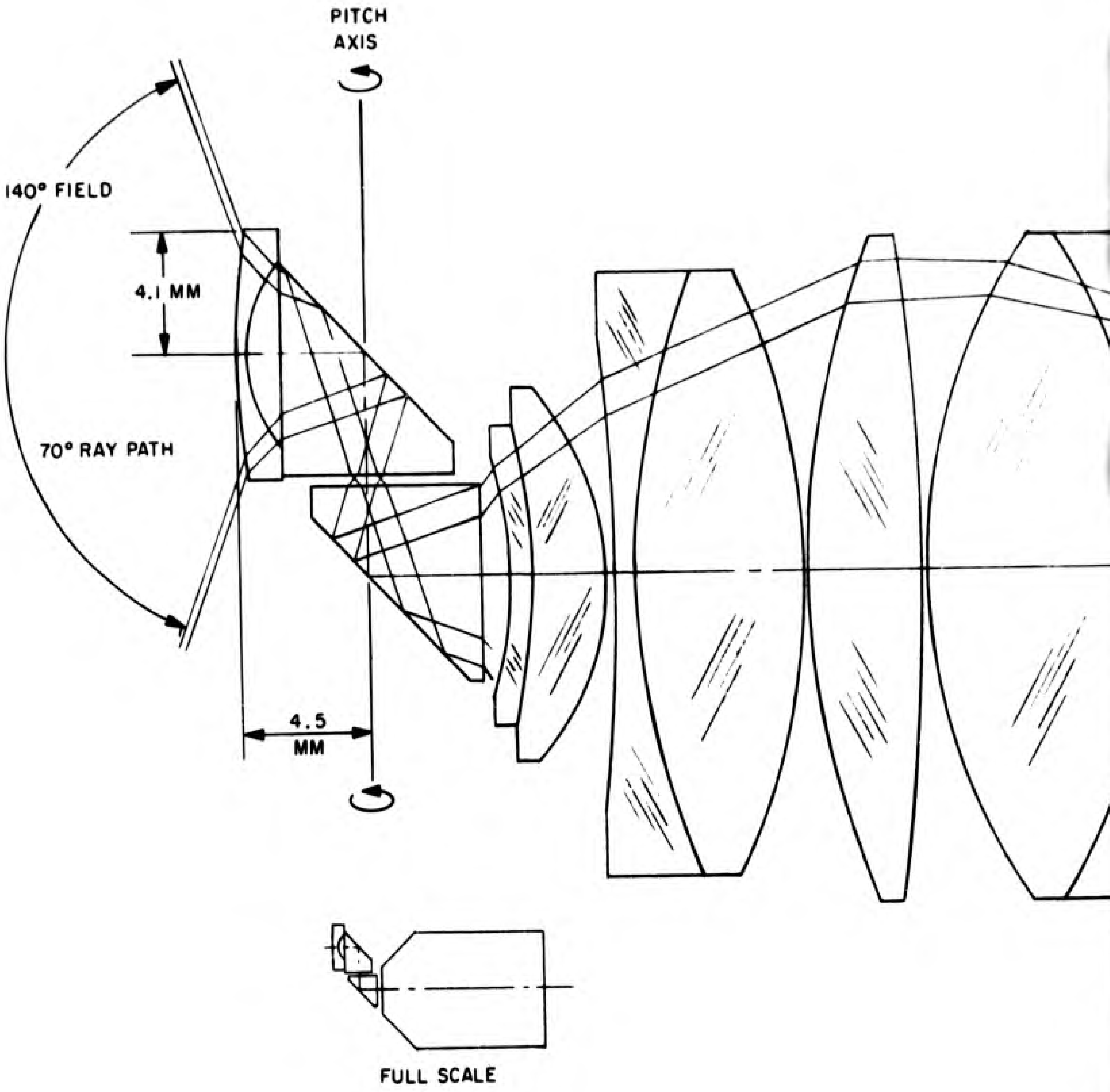
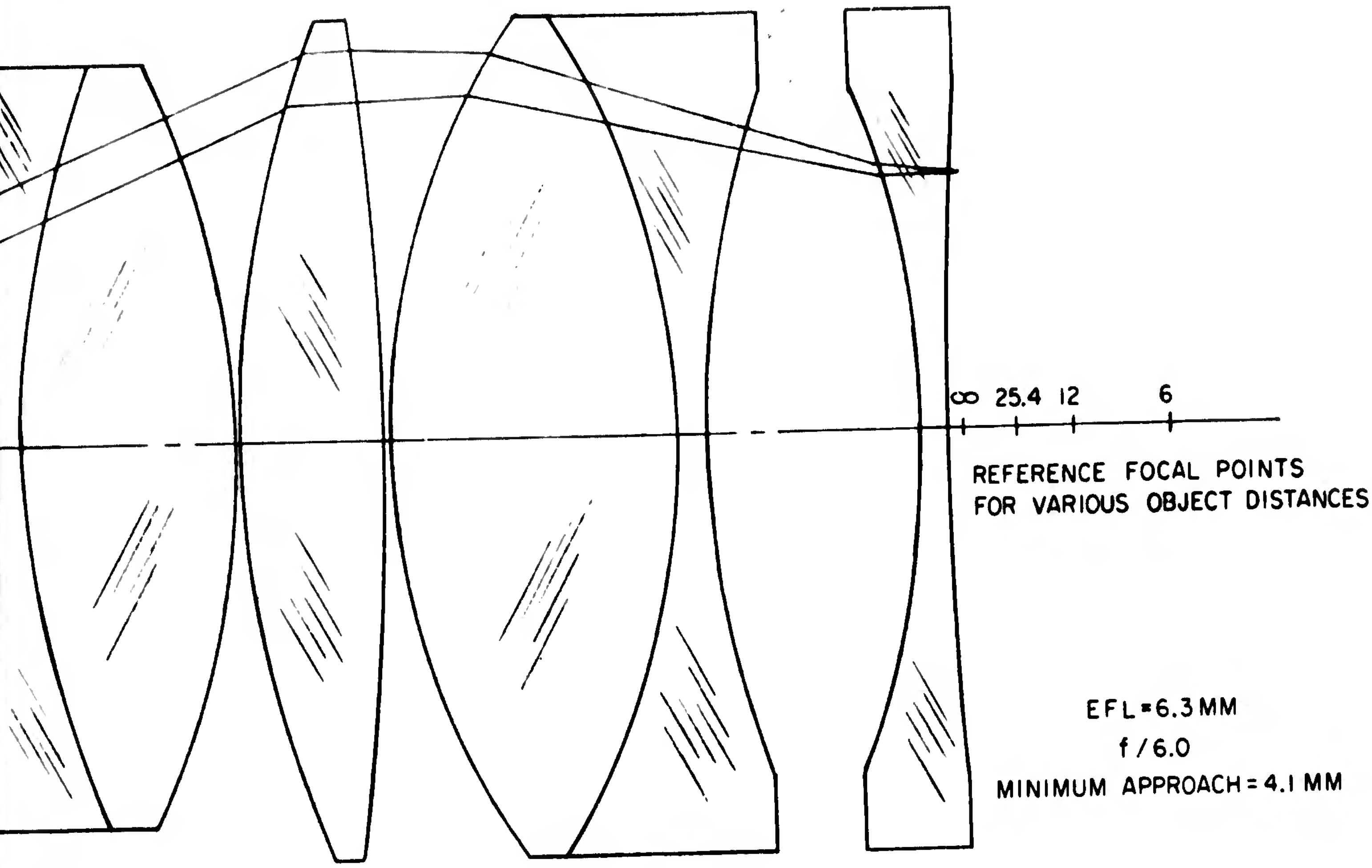


Figure 6. 140° Probe Objective Design II, Preliminary


∞ 25.4 12 6
REFERENCE FOCAL POINTS
FOR VARIOUS OBJECT DISTANCES
EFL=6.3 MM
f/6.0
MINIMUM APPROACH = 4.1 MM

eliminary

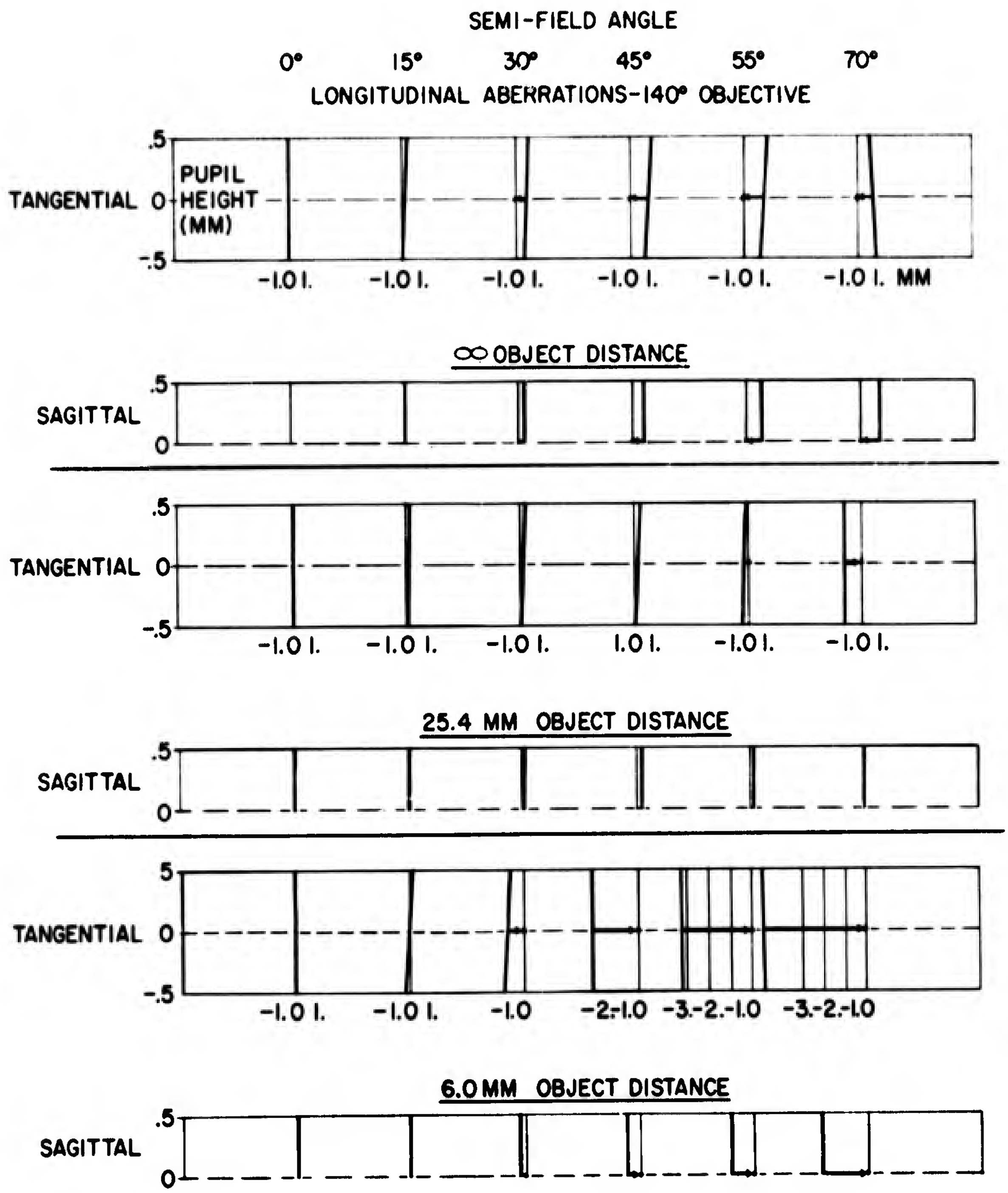


Figure 7. Longitudinal Aberrations - 140° Objective

represent spherical aberration. A tilt of any other line represents coma. Astigmatism is given by the horizontal difference between the sagittal and tangential lines where they cross the pupil center (at zero pupil height). Field curvature is obtained from the average departure from zero of the sagittal and tangential lines.

A cursory analysis of Figure 7 shows the following:

1. For infinity object distance, or approximately 5 inches or greater altitude, we have no significant spherical aberration, coma or astigmatism. Overcorrect (positive) field curvature is evident.

2. For a 25.4 mm (one inch) object distance, undercorrect (negative) astigmatism and field curvature appear for the larger field angles. Coma and spherical aberration are still under control.

3. At a 6 mm object distance, the astigmatism and field curvature grow quite severe.

The severe aberrations of the larger field angles will not be observed under actual use because under low altitude situations the down field will be limited to 35° or less, depending on aircraft pitch limitations. In addition, undercorrect field curvature is desirable at low altitudes to help compensate for lack of flatness of the objective's tilted focal surface under these conditions (lack of flatness at close approach is an inherent problem when $F \tan \theta$ mapping is not utilized).

It was planned during the final design stage to improve the field curvature (flatness) at high altitude and the astigmatism at the lowest altitudes. Lateral color and the mapping function were also to be investigated for further improvements as well as possible advantages by filtering.

Another very useful tool for evaluation is the modulation transfer function analysis shown in Figure 8. Frequency in line pairs per mm is plotted against modulation for various field angles, object distances and focus positions. A study of these curves together with the longitudinal aberrations helps greatly in optimizing the design and matching sensor characteristics.

For reference, a one inch vidicon used as a sensor will have a maximum resolution of about 420 optical line pairs, averaged over the field. Assuming $F\theta$ mapping and a 140° field, the resolution level is $\frac{140^{\circ}}{420}$ or 20 arc minutes. This corresponds to a cut-off frequency of 28.6 line pairs per mm for the optical system, as given by the following:

For F = 6 mm,

1 line pair for 20 arc minutes = 0.0058 x 6 mm = .035 mm

Reference resolution in line/pairs mm = $\frac{1}{.035}$ = 28.6 line pairs/mm.

d. OBJECTIVE MAPPING FUNCTIONS

Photographic lenses normally have a mapping function which is described by h = f tan θ where "h" is the height in the focal plane. The Probe objective has a mapping described by h = f θ, a linear function which is a result of the external entrance pupil being located at the front focal point of the objective lens. The large amount of natural barrel distortion introduced results in the f θ mapping. The pupil location is mandated because of the requirement for a telecentric objective, if the image of the scene is not to vary significantly in size with changes in object distances.

This f θ mapping has a beneficial effect because photographic lenses with their f tan θ mapping suffer from a reduction in illumination in the focal plane as a function of field angle. This is the familiar $\cos^4$ illumination drop-off. In f θ mapping, because of the heavy distortion, angular increments of scene in the object space are laterally compressed in the image plane. This has the effect of compensating for the $\cos^4$ effect, resulting in uniform illumination across the sensor (see Appendix C, Illumination and Mapping Functions).

Figure 9 shows the comparison of these two types of mapping functions and how the preliminary probe objective compares to f θ mapping.

One problem area stemming from lack of f tan θ mapping is that at close approach, the tilted objective focal surface becomes curved, rendering the near downward objects out of focus. (See discussion of Design II Performance Parameters.)

3. RELAY LENS DESIGN

a. RELAY DESIGN

The level of optical performance achieved in a complete probe depends primarily on the independent performance of the objective and relay lens. Only one major area of dependence exists, the match in shape of the common focal surface for any given altitude and pitch combination.

Since the Scheimpflug condition (see Appendix B) requires flat fields for both components, the relay must be designed as a well-corrected lens with a flat field object and flat field image. Very wide fleids and avoidance of significant image shifts due to nodal point separation was accomplished in the previous probe relay designs.

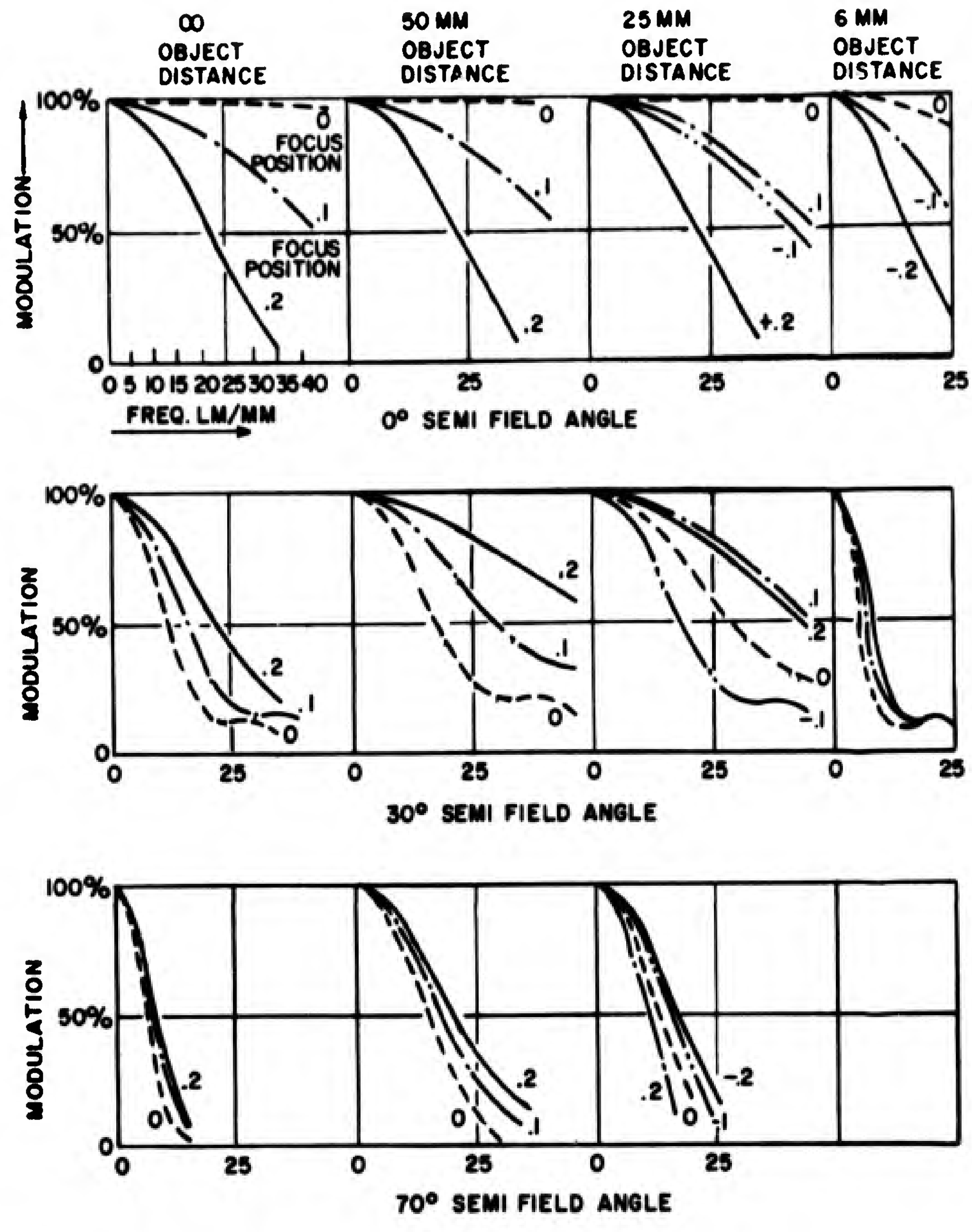


Figure 8. Modulation Transfer Function Analysis

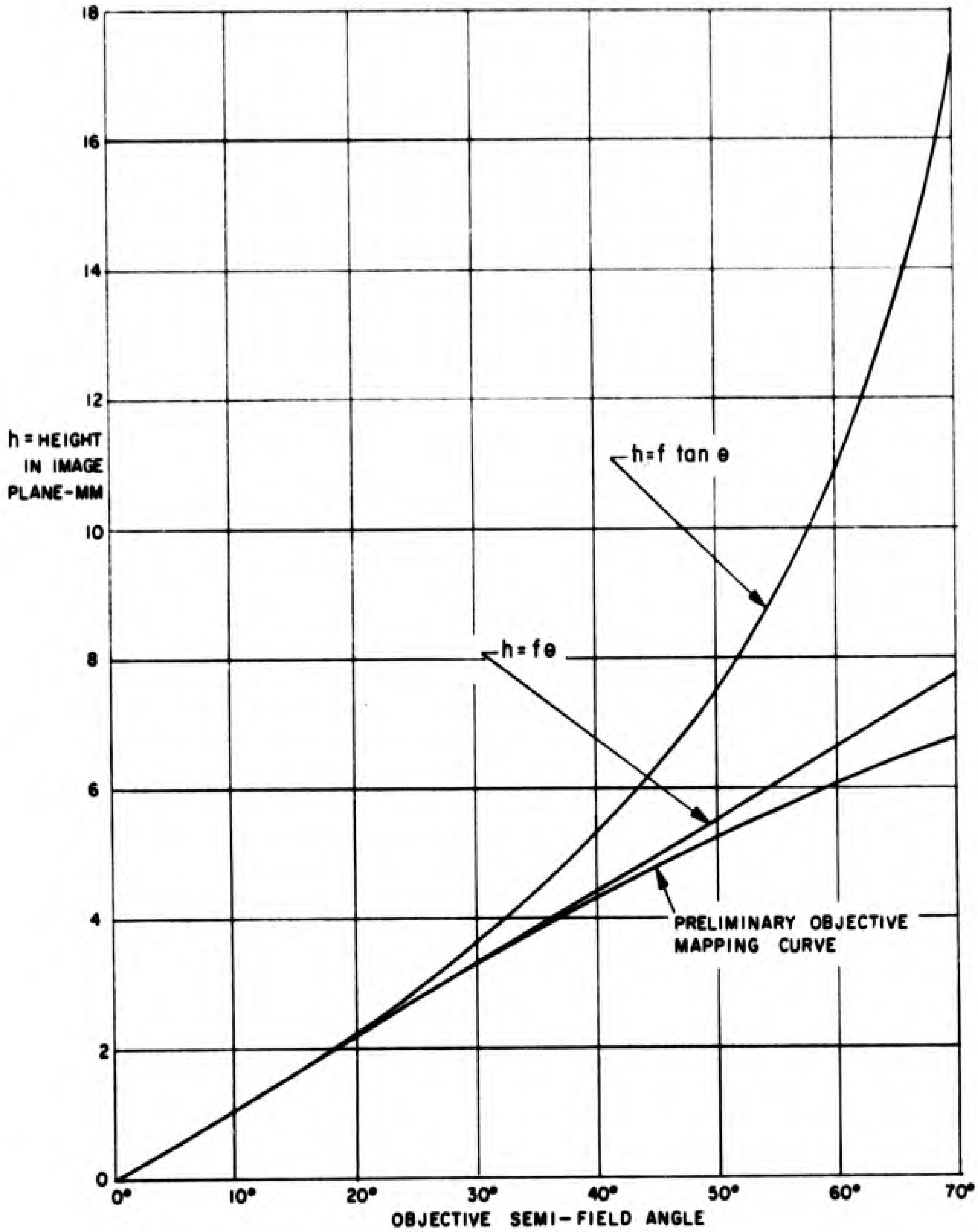


Figure 9. Probe Objective Mapping Functions

This basic design was used as a starting point in the Phase II final design stage, emphasizing improved aberrational correction at the expense of lateral image shift correction as discussed in the next section.

b. NODAL POINT SHIFT

One of the more serious conditions which manifests itself in the design of a Scheimpflug probe is the problem of a lateral image shift with relay lens tilt. This shift will result in a real world angular shift as viewed by a fictitious observer located at the "look point" of the probe.

The 110° FOV probe developed for the LEM program was so designed that the relay lens optically compensated for nodal point shift. For instance, at an altitude of 1/2" and a total relay lens tilt of 12°, the maximum angular nodal point shift was equivalent to only a 1/2° real world change. It was necessary however to compromise the optical correction of the relay lens to achieve this minimal nodal point shift. The complete elimination of nodal point shift becomes an overwhelming problem when one realizes that the probe is acting similar to a telescope, as shown in Figure 10. Nodal point shifts are magnified by the combination. The magnification typically would be

$$m = \frac{f_o}{f_e} = \frac{250 \text{ mm}}{7 \text{ m}} = 36 \text{ X}.$$

Rather than impose the most severe optical design weighting on nodal point correction, it appears advantageous to mechanically correct the residual errors and utilize the optical design freedom gained to improve the aberrational correction.

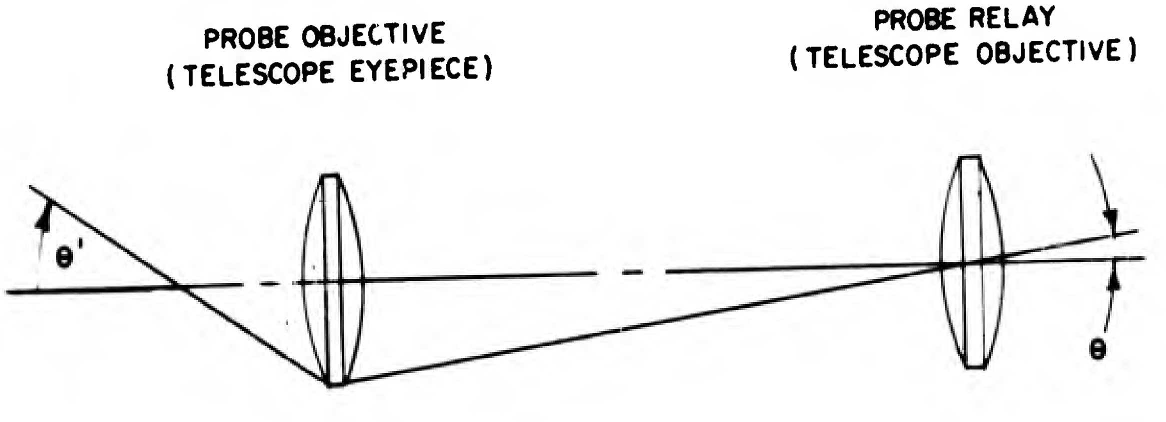


Figure 10. Probe-Telescope Analogy

Lateral image shifts can occur as a result of pitch and altitude, independent probe functions which tilt the relay lens.

(1) Pitch

The flight profile of normal aircraft requires that the optical axis of the probe be parallel or near parallel to the terrain model for landing purposes. With the probe in this orientation, pitch excursions produce small amounts of relay lens tilt resulting in negligible amounts of nodal point shift. The equation describing the relay tilt as a function of pitch angle γ is

$$\tan \alpha = \frac{Fo}{h} (\sin \gamma) \frac{m}{m+1}$$ as in Section III with the sin γ function also included

This equation is plotted in Figure 11 for various ratios of Fo/h. The small ratio of relay lens tilt to object plane tilt is due to operating around the peak of the sine curve. Note for example that at a 6 mm altitude $\left(\frac{Fo}{h} = 1\right)$, $\pm 5^{\circ}$ pitch motion changes the relay tilt by only 6 arc minutes and $\pm 10^{\circ}$ pitch motion results in only a 21 arc minute change. Changes in nodal point shift due to small changes in relay tilt are therefore second order effects and will be disregarded in this program.

(2) Altitude

The change in altitude as it affects relay lens tilt is plotted in Figure 12. The change in relay lens tilt is approximately 30° for an altitude change of 0.2 inches to ∞. This amount of tilt could produce a significant amount of angular error. This error may be easily compensated by a differential rotation of the pitch prism. No FOV loss will be seen at the sensor with this correction because a 140° vertical field is provided while only 70° is required by the design goal.

To recapitulate, nodal point shift due to pitch motions will be minimal in this application and may be disregarded while the larger nodal point shifts due to altitude change will be mechanically compensated in the probe. The savings in mechanical and electrical complexity and bulk in implementing only one of these corrections will be substantial. Of course, the relay pivot point will first be located to minimize the amount of residual errors to be mechanically compensated.

c. DUAL STAGE RELAY CONCEPT

The major problem in designing the relay is to obtain good correction over the very great tilt angles necessary at close approach. One method of easing the problem is using a dual stage relay as shown in Figure 13 where each relay tilts approximately half of the angle of the single relay equivalent.

This approach has several additional potential advantages but an extensive detail design program would be necessary to explore both the advantages and pitfalls of the approach.

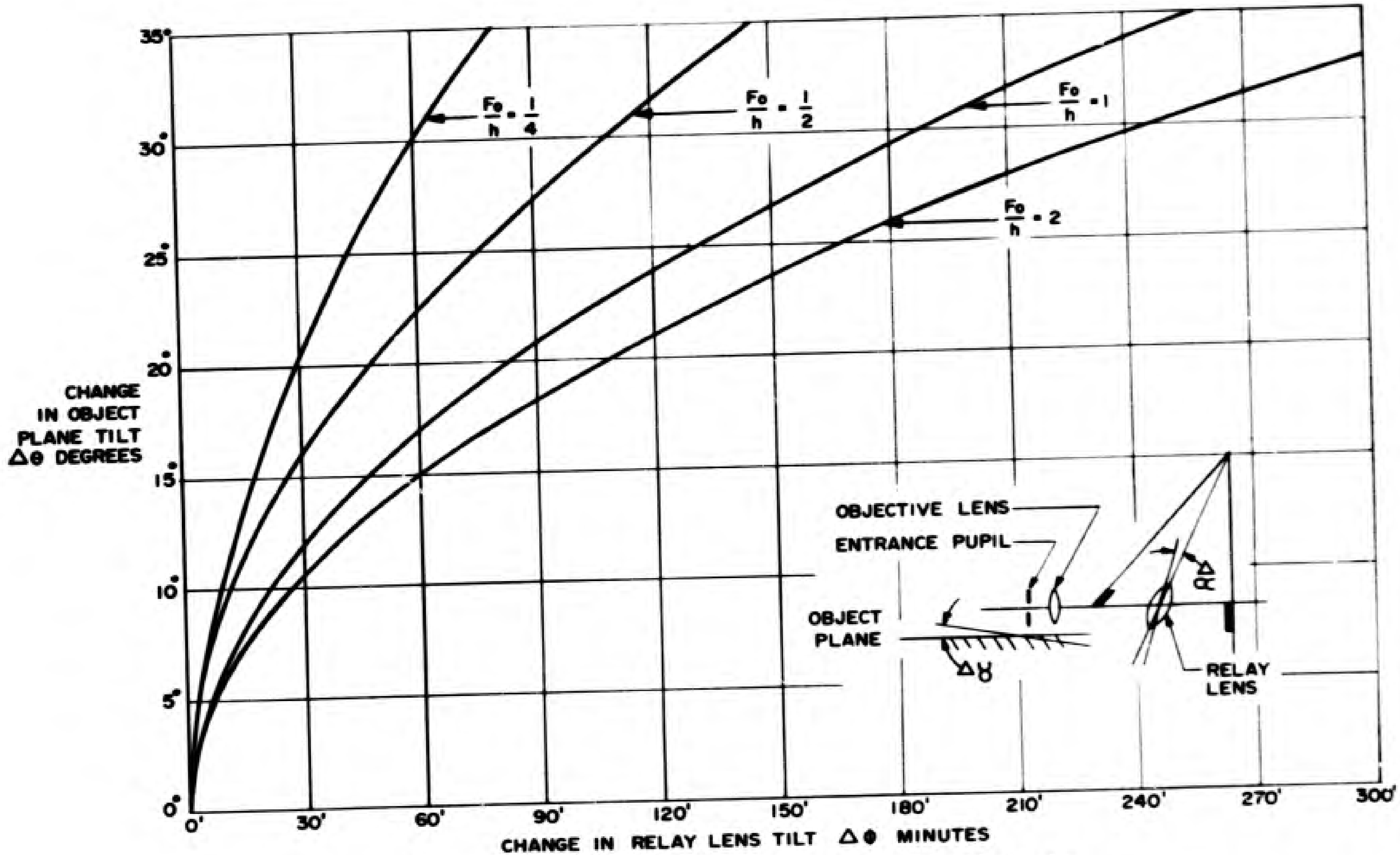


Figure 11. Change in Relay Tilt as a Function of Pitch Angle

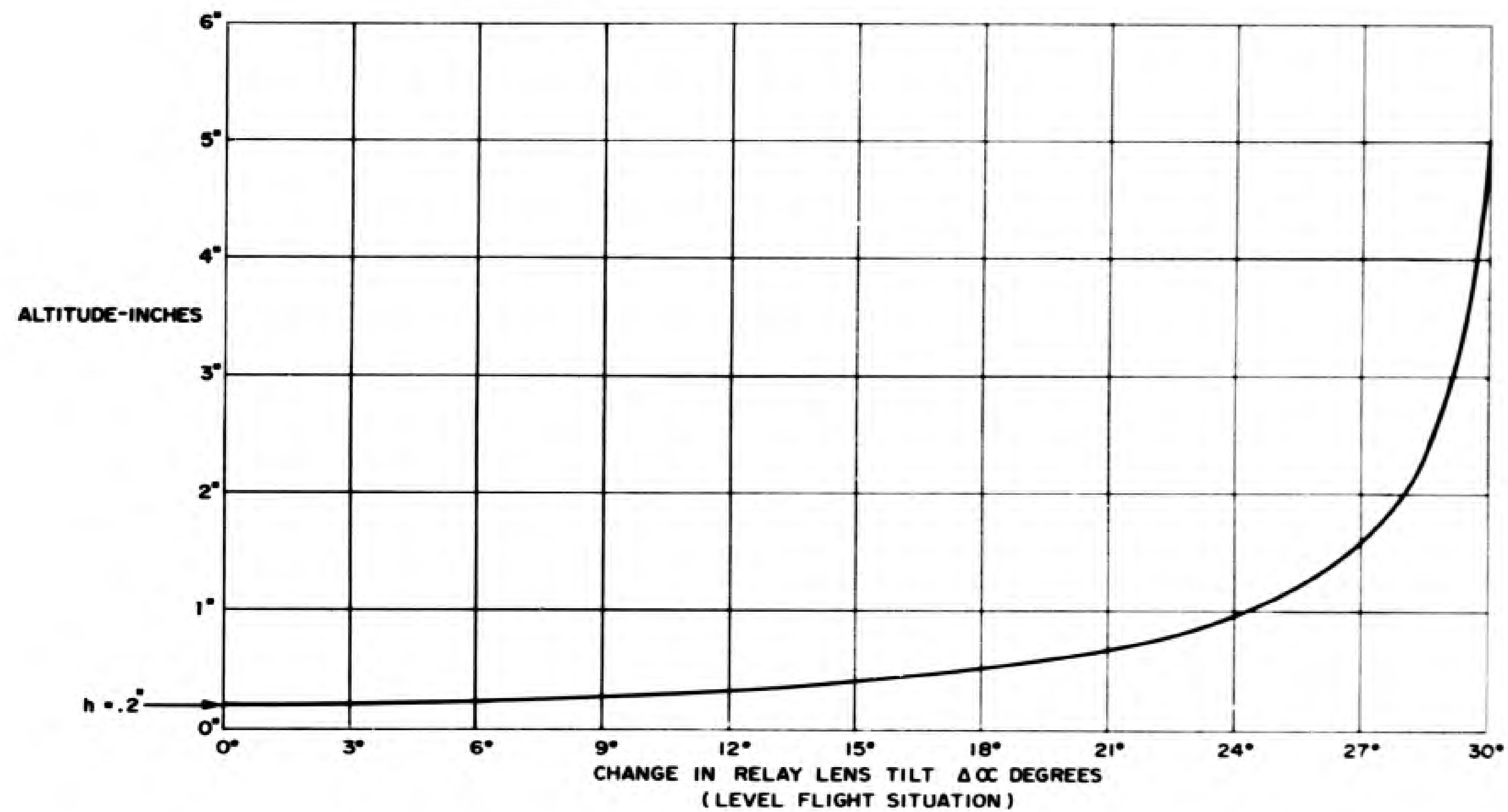


Figure 12. Altitude vs. Change in Relay Tilt

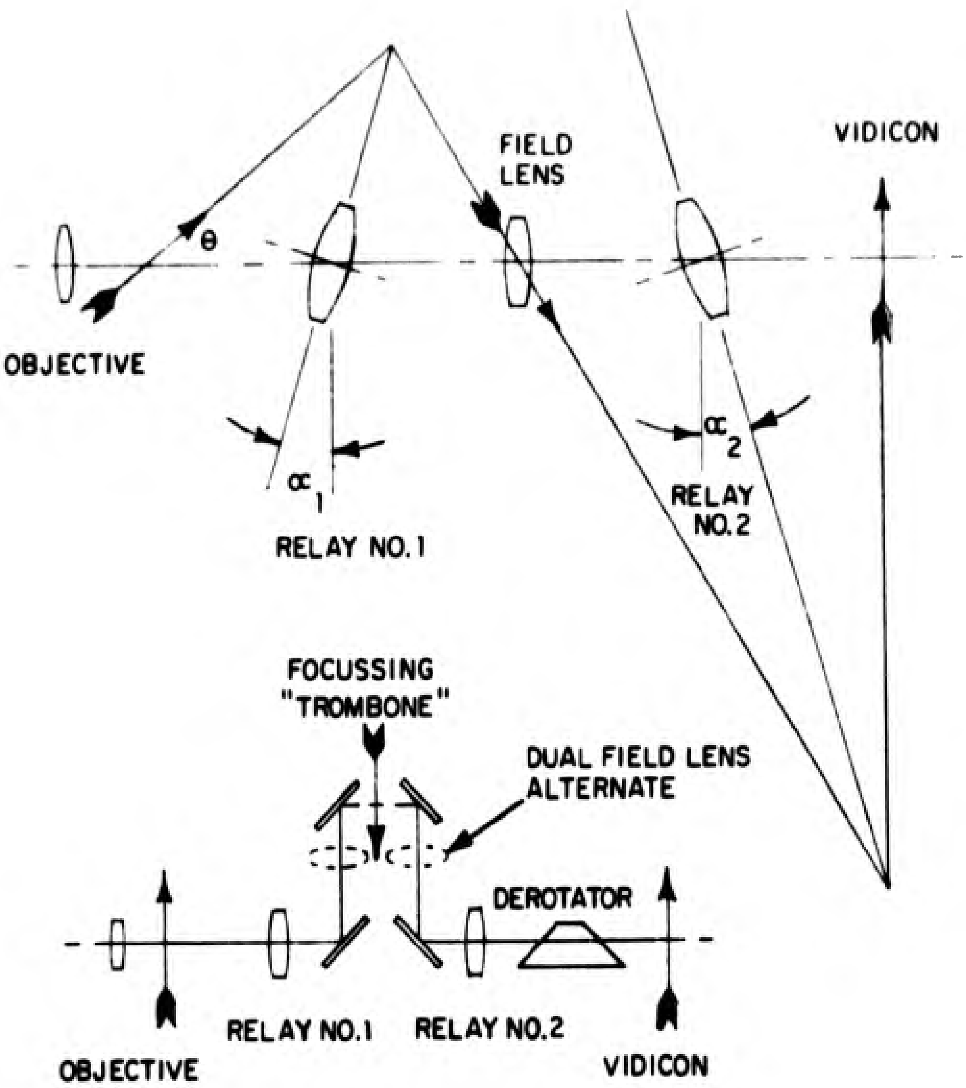


Figure 13. Dual Stage Relay

Potential advantages:

1. Superior aberration correction is available due to:

   a) reducing tilt angle

   b) offering lateral aberration corrections due to symmetrical design

2. One focussing "trombone" is eliminated

3. Nodal point shift may be partially compensated

Possible disadvantages:

1. Field lens may require lateral motion to compensate for nodal point shifts

2. Overall system length will be increased

In addition, considerable redesign of present probe mechanics will be necessary.

Other factors that are comparable are mass and light transmission. Each of the dual relays would be considerably smaller than a single relay so that the mass difference between approaches is not significant. The additional relay transmission loss is compensated by eliminating one focussing "trombone" although a rhomb prism will be necessary to account for the "dog leg" shift of the optical axis between the entrance pupil and objective axis.

Two "trombones" are necessary with a single relay to maintain the relay magnification with tilt $\frac{V + \Delta V}{U + \Delta U}$ = constant. In the dual relay case, however, U and V can be considered the two conjugates between the relays and are identical. Thus a single "trombone" between them takes up path differences while the outer conjugates remain constant.

4. PROBE SENSOR INTERFACE

Various configurations for implementing the multi-sensor approach are shown in Figure 14.

Figure 14 (A) shows a simple means for making possible the dual sensor approach.

Figure 14 (B) essentially utilizes the beamsplitter approach for a triple sensor, using prisms instead of mirrors - a more compact and stable arrangement. This could be used to present full field coverage for a color television camera setup, rather than improved resolution. The use of beamsplitters of course divides the signal amongst different sensors reducing the effective speed of the optical system.

Figure 14 (C) has a prism mirror located at the final focal plane where a relay lens transfers one-half of the field of view to each sensor. The relay lens may have other than unity magnification to adapt to different size sensors. This method of field splitting suffers from the problem of not providing any FOV for head motion to an observer in the final display. Field overlap is essential so that a pilot viewing a segmented infinity display may move left or right without field cutoffs.

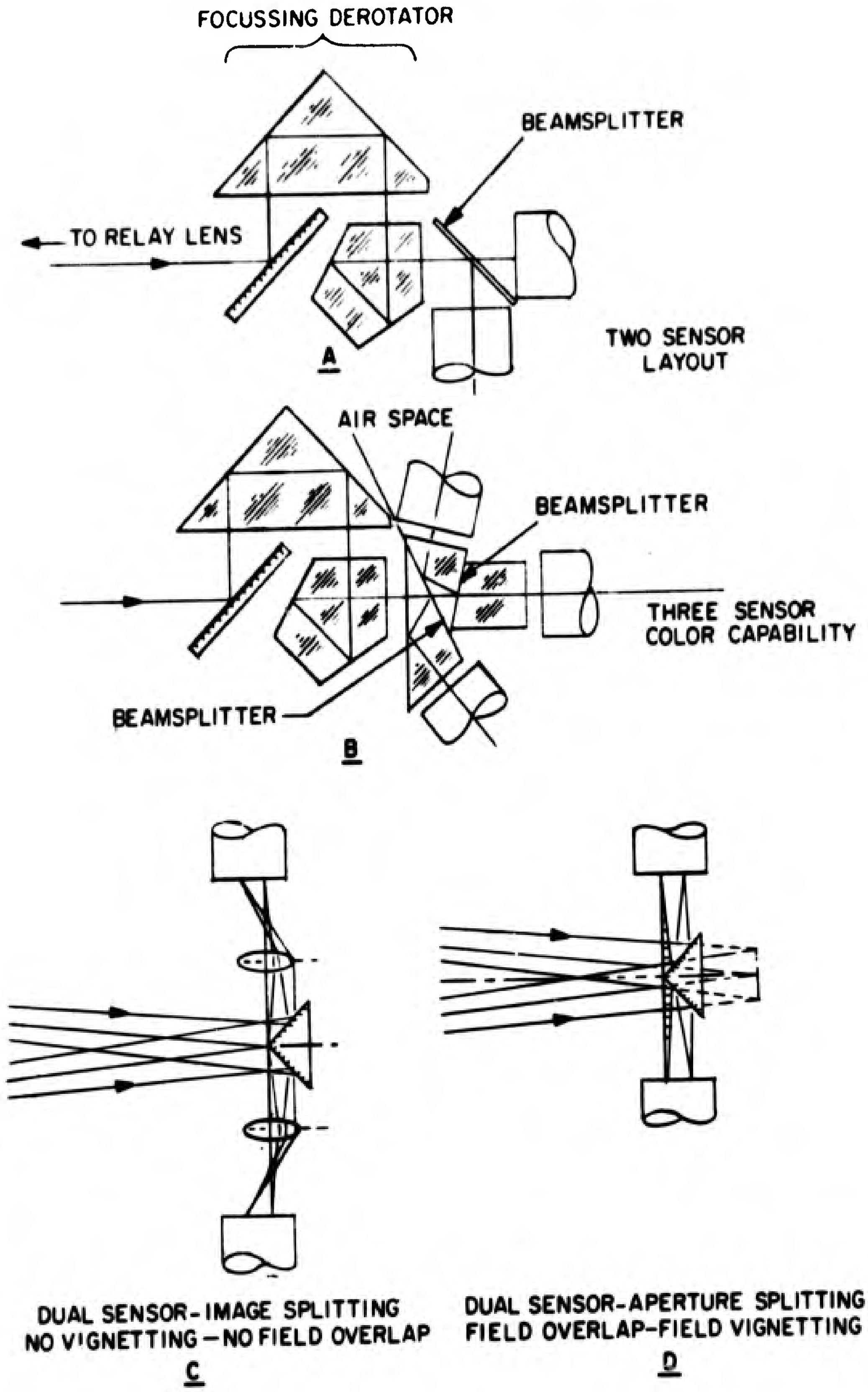


Figure 14. Sensor Interface Configuration

Figure 14 (D) uses a prism mirror located inside the focal plane. This alleviates the problem of FOV overlap but unfortunately zones in the area of the overlap suffer from vignetting in that this region does not receive full illumination bundles. Such an effect would be acutely noticeable in the final display.

As shown previously, present sensor technology limits the average resolution to about 20 arc minutes for a single vidicon covering a 140° field. A study of Figure 15 shows why it is impractical to divide the 70° by 140° field format into more than 2 parts to improve the resolution.

In each case, the system resolution is improved by the ratio:

$$\frac{\text{total field diameter}}{\text{sensor field diameter}}$$

The 140° by 70° field format mates well with a single or dual sensor with good field overlap in the second case. Attempting to fit 3 or 4 sensors to the format offers wasteful overlap regions and insignificant resolution improvements while reducing the illumination by further beamsplitting.

A dual arrangement as shown in Figure 14 (A) can allow an extension of resolution to approximately 13 arc minutes for dual sensors of 90° field each.

Of course, improvements in sensor technology would really be necessary to approach the design goal of 3 arc minutes resolution.

The final results of this program should go far in establishing whether the next big resolution gain will depend on optical or sensor performance improvements.

In general, the objective MTF evaluation indicates that the optical performance is far better than the sensor performance at the center of the field, parallels it at midpoints, and is less at the very edge.

An objective only slightly improved relative to the Phase I design mated to a well-corrected relay and a single or dual vidicon sensor should provide a very useful simulation chain.

This contractor's experience suggests that experimentation with the actual device will allow a trade-off between relative aperture and picture quality in the final display which will be satisfactory. Sometimes, a lower signal level (aperture) with greatly improved signal to noise (MTF) ratio, offers improved operating advantages.

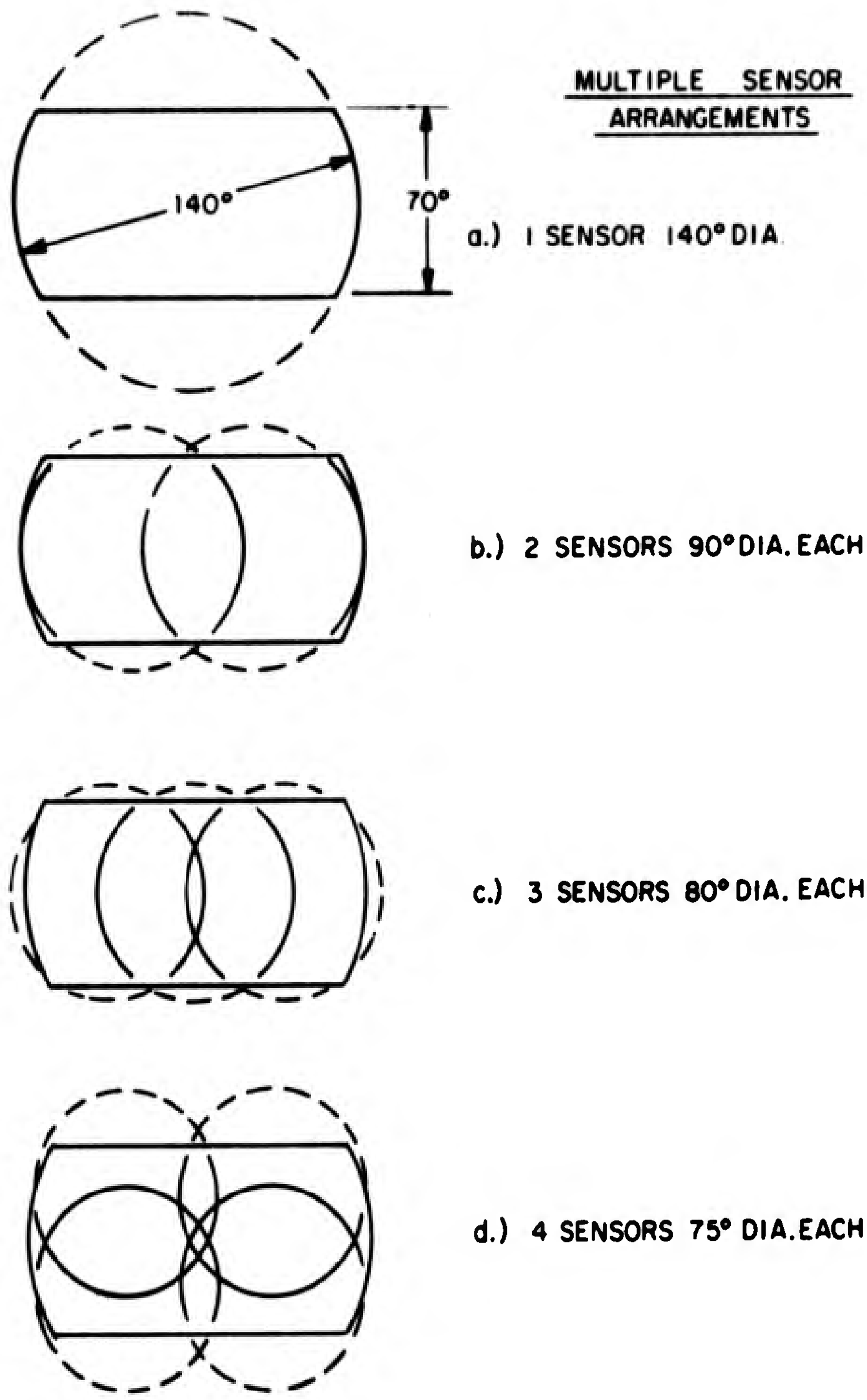


Figure 15. Multiple Sensor Arrangements, Showing Field Overlap

5. <u>EXPECTED PERFORMANCE VERSUS DESIGN GOALS</u>

a. FIELD OF VIEW - design goal 140°

A 140° circular field has been achieved in a single channel, unobstructed and unvignetted arrangement.

b. ENTRANCE PUPIL DIAMETER - design goal 1.5 ± .5 mm.

Objective dimensioned for a 1 mm diameter entrance pupil.

c. APERTURE - design goal f/6 to f/16 will be met.

d. SYSTEM FOCUS RANGE - design goal .2 inches to ∞

The system will focus from .2 inches to ∞

e. MINIMUM "LOOK-POINT" APPROACH - design goal 2.5 mm.

For level flight, the first optical element's diameter dictates the "look point" approach at 4.1 mm and increases to 6 mm if full pitch capability is desired at minimum approach. Close approach at nadir view equals the entrance pupil depth <u>inside</u> the lens, 2.4 mm. If it is felt important, the "look point" approach can be reduced during the final design if the pupil and field factors and optical performance can be used as trade-off parameters.

f. RESOLUTION - design goal 3 arc minutes over entire field.

Since the diffraction limit is 2.5 minutes for a 1 mm diameter pupil, this design goal is most difficult to meet. However, the central 30° diameter field will be essentially diffraction-limited over this range. For larger fields and closer approaches, resolution will be reduced in a gradual manner. See the detailed discussion in the section on objective lens development. The objective, for purpose of this study, is optimized for altitudes of 1 to 4 inches.

g. CONTRAST RATIO: 10:1 minimum design goal.

This design goal should be met.

h. SCAN SYSTEM: Roll-unlimited; Yaw-unlimited, Pitch ±55°.

These design goals will be met. Pitch can be made as great as $^{+55°}_{-90°}$.

i. TRANSMISSION – design goal, 40%.

Goal can be met by using multilayer coatings on all optical components.

SECTION IV

MAJOR RESULTS AND CONCLUSIONS OF THE STUDY PHASE

1. Feasibility of a single channel optical system presenting a high quality image of a 140° circular field was established. The overall performance should amount to a significant advance in the state-of-the-art of wide angle, close approach probe devices. Photographic confirmation of the validity of approach was also obtained. Most design goals were met except for obtaining diffraction-limited performance over the entire field and altitude ranges. Dual sensors for improved resolution or triple sensors for color TV presentation can be incorporated.

2. An optical design for the 140° objective with full pitch capability and close approach of 4.1 mm was developed and evaluated.

3. The important characteristics and trade-offs were delineated so that an engineering model of the Scheimpflug probe proposed to be built during Phase II could eventually be incorporated into an automated system, similar to the present 110° probes built by Farrand.

4. It was established that the objective and relay portions of the design could be treated independently once the basic optimum first order parameters such as focal length, field and magnification were developed. No field lenses or focussing lenses would be needed for interfacing the objective and relay.

5. Techniques were established to compensate for image shift due to relay tilt motions.

SECTION V

MAJOR RECOMMENDATIONS FOR PHASE II

1. Complete the final design of 140° objective.

2. Develop and finalize relay lens design based on present Farrand Scheimpflug relay lens.

3. Fabricate and test both components on an in-line optical bench type of mounting with no provisions for roll-, azimuth - or other optical components unnecessary for performance evaluation.

4. Incorporate elements in operating configuration with full additional complement of components to assure full functional use. This can be made a manually operated device or preferably, may be extended to a fully automated system. The design should be modular to allow for inclusion of dual sensors for improved resolution, or triple full field sensors for a color television system.

PHASE II

DESIGN, FABRICATION TEST AND EVALUATION

SECTION VI

OPTICAL DESIGN

1. OPTICAL DESIGN

The optical design of the feasibility model constructed under the Phase II program went considerably beyond the recommendations given at the completion of the study program. While the objective portion finalization proved difficult in terms of balancing aberrations over the range from close approach to infinity conjugates, it was completed in a straightforward manner. The meniscus lens approach allowed the achievement of the 140° total field with close approach capability.

It was further determined that the excellent performance of the objective would be severely compromised by attempting to design a single tilting relay that would properly image an object at 5 mm altitude. A renewed investigation of the dual relay concept was begun to explore its ramifications and resulted in a successful application of the concept.

Implementation of the new concept required abandoning the aim of being able to integrate the new optics into previous mechanical arrangements. However, several simplifications did ensue which resulted in simpler assemblies as well as greatly improved optical performance. The possible disadvantages of image shift mentioned in the study phase did not materialize, and the increased overall length was perhaps 8 inches.

2. OPTICAL LAYOUT

The final optical system layout is shown in Figure 16. Four major assemblies make up the complete probe. These are the objective, dual relays, focussing field lens assy, and derotator. A brief description of each follows:

a. OBJECTIVE ASSEMBLY

This unit consists of a 140° field, 6.5mm EFL objective having a 1 mm dia. entrance pupil and an attached elevation prism assembly. The elevation prism rotates as a function of the pitch required and secures the front negative meniscus lens which travels with it. A front aperture stop lies between the elevation and folding prisms. The entrance pupil lies 3 mm inside the first surface (or 2.7 mm ahead of the pivot point. A prism and mirror assembly behind the objective bring the optical axis back to coincidence with the bearing axis of the probe. This assembly is dimensioned as small as possible so as to provide the closest possible approach to the model with the slimmest physical profile. A 17MM field diameter at the objective focal plane corresponds to the 140° total field.

b. DUAL RELAY ASSEMBLY

The dual relays are tied mechanically to rotate together and tilt equally when tilt correction is applied. Each relay half is identical, thus simplifying the manufacture. Aperture stops are placed at the pivot points. The field lenses surrounding the common focal point between the relays serve to image one pivot to the other thus preventing vignetting. The dual relay concept as described previously provides image shift compensation because of its symmetry and allows a single focussing unit to control the total system focus. These relays cover a 28° flat field each and are as compact as the mounting of associated components such as the derotator permit. Each relay assembly (2 halves) weighs 2 lbs. 6 oz. Thus the total tilting assemblies weigh 4 lbs. 12 oz.

c. FOCUSSING UNIT

The focussing unit contains 2 fixed mirrors and a focussing assembly of 2 mirrors and 2 field lenses. As the relay lenses are tilted, the focussing assembly is moved out to compensate for the increased path length. The assembly does not rotate regardless of the azimuth head or tilting relay orientation, thus enhancing repeatability, alignment and maintenance.

d. DEROTATOR

The derotator assembly is self contained and provides a continuous roll function capability as well as roll compensation as a function of pitch.

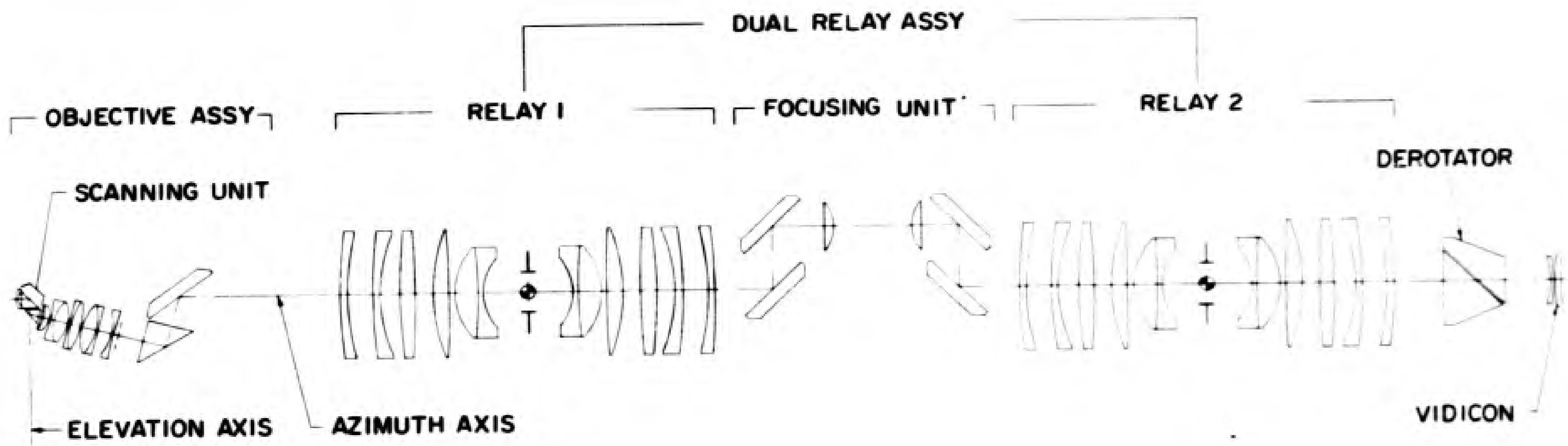


Figure 16. 140^{o} Probe Optical Layout

SECTION VII

ENGINEERING FEASIBILITY MODEL

1. GENERAL

The engineering feasibility model was constructed to allow laboratory evaluation of the performance potential of the design developed from the concepts of the Phase I study program. Recognizing the potential of the device, every step necessary to achieve optimum optical performance was taken. Tolerances on optical and mechanical parts associated with the functional operation of the device were held very tightly. The optical elements were measured for thickness individually and spacer adjustments were made according to a recomputed optimum optical design. Melt data (the slight residual differences from catalog values of the refraction indices for the actual individual glass elements) were also included in this tailoring process.

All adjustments necessary for precise optical component alignment were included in the model.

The result of these efforts assured that much more than feasibility would be proved; i.e. maximum performance would not be compromised by either the opto-mechanical design or opto-mechanical fabrication. An updated version for fully servo controlled operation would therefore not require rework of the optical assemblies.

2. MODEL COMPONENTS

a. The 140° Wide Angle probe is comprised of the following sub-assemblies:

Azimuth Head Assembly

Relay Drive Assembly, Left Hand

Relay Drive Assembly, Right Hand

Focus Drive Assembly

Derotator Assembly

Tilt Drive Assembly

Elevation Drive Assembly

Each of these assemblies is provided with a target and vernier readout to position the optical components in the correct attitude, with respect to changes in azimuth, roll, pitch and altitude.

3. FUNCTIONAL DESCRIPTION. (See Figures 17 and 18.)

a. ELEVATION INPUT. The elevation input elevates and depresses the LOS with respect to the horizon. Increasing dial readings will depress the LOS. Rotation of the elevation prism rotates the image about the optical axis and has to be erected by rotation of the relay lenses and dero assemblies. The control should be set to 0^o for horizon viewing, "+" readings are down (E.G. 90^o = Nadir).

b. AZIMUTH INPUT. The azimuth input rotates the head, carrying the elevation drive with it. Increasing azimuth readings require one to one decrease of relay azimuth and one to one increase of the derotator dial. Tilt and focus do not respond to azimuth motion.

c. ROLL INPUT. The roll input rotates the image about the optical axis.

d. ALTITUDE. Changes in altitude require change in Focus and Tilt. See Tables 1 and 2 and Figure 19.

4. SUGGESTED FUNCTIONAL OPERATION

a. A suggested sequence of functional operation is as follows:

1. Position probe over model to desired latitude, longitude and altitude, the altitude being measured from the average ground plane to the entrance pupil height.

2. With pitch set to zero (horizon viewing), orient azimuth control in desired direction.

A good reference starting point is:

Pitch	Azimuth	Relay Azimuth	Roll
0^o	90^o	90^o	0^o

The Relay Azimuth must be oriented with respect to both pitch and azimuth for correct operation. For a change in azimuth the Relay Azimuth dial reading must be changed the same amount in the opposite (sign) direction, while the Roll Control must be changed the same amount in the same direction to keep the image upright.

An example is:

Pitch	Azimuth	Relay Azimuth	Roll
0^o	45^o	135^o	315^o

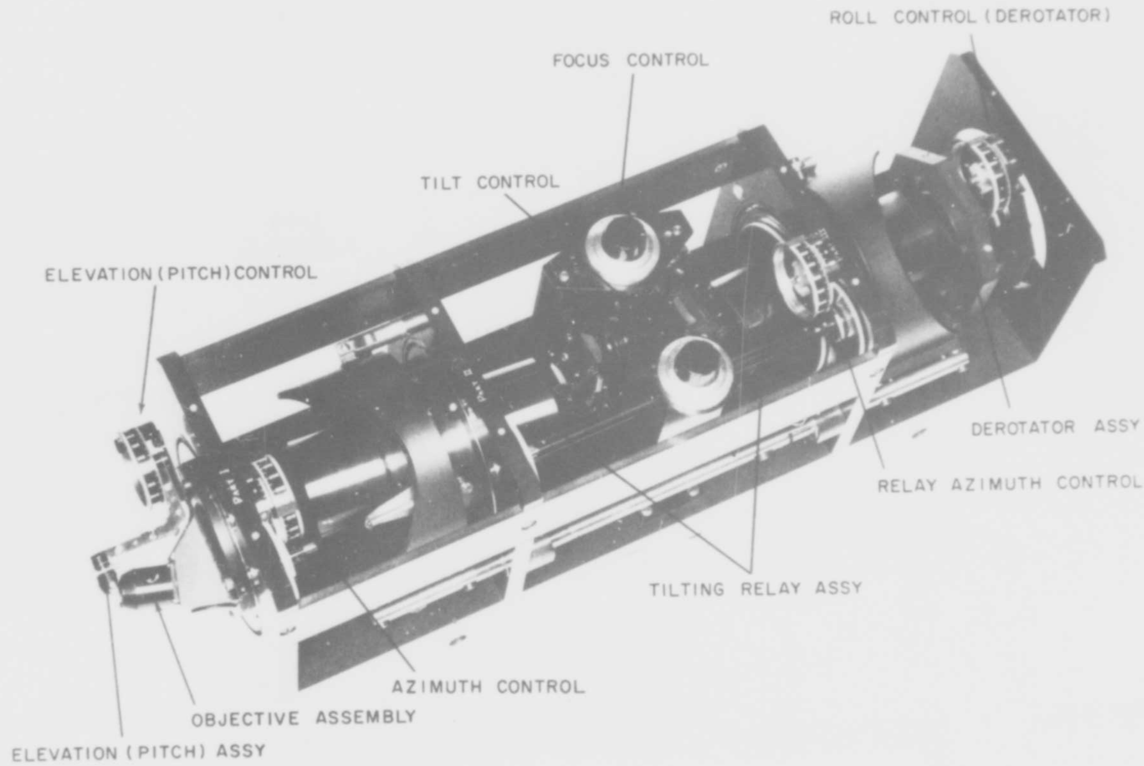


Figure 17. 140° Probe, Engineering Feasibility Model

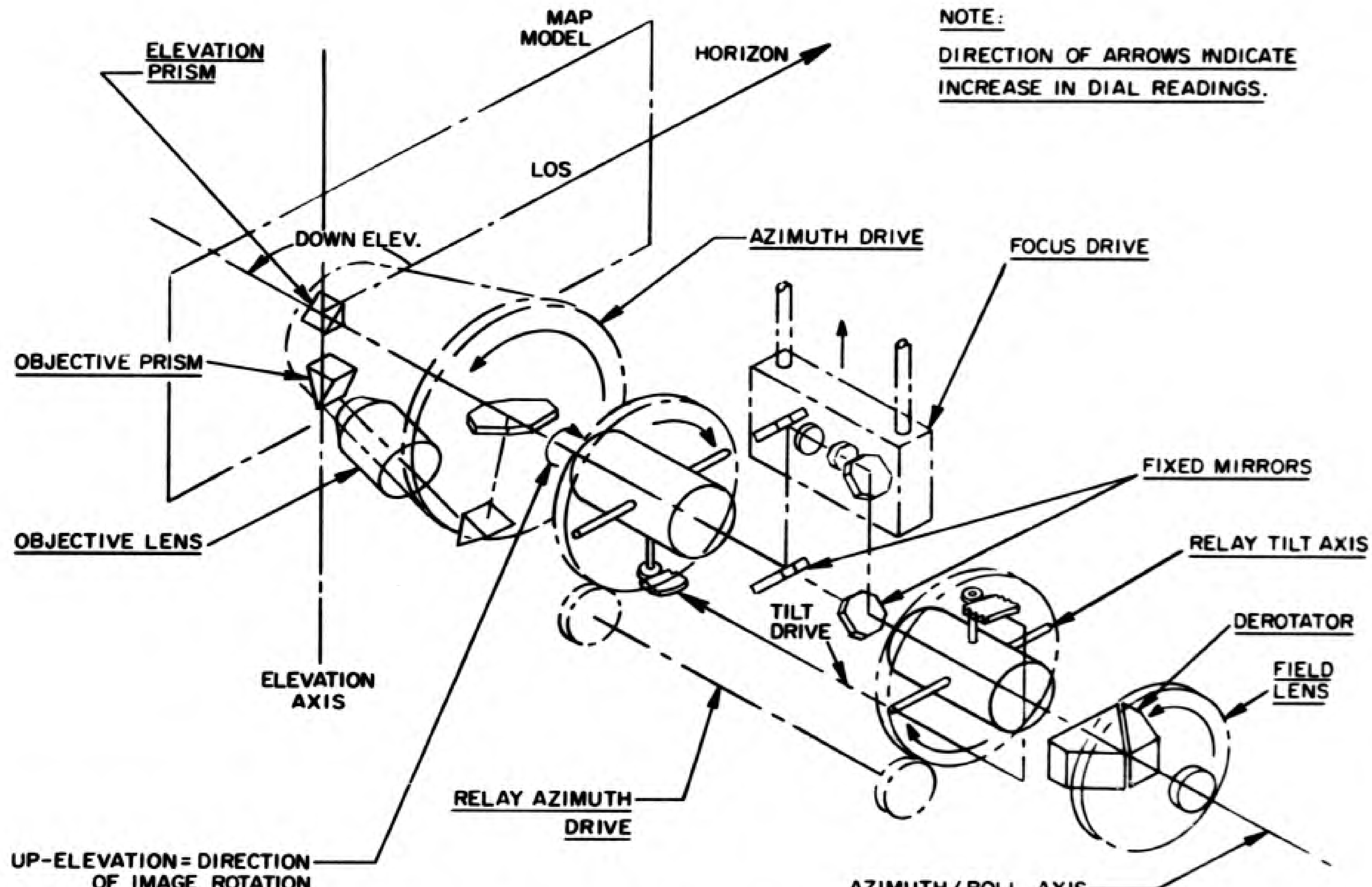


Figure 18. Probe Component Motions

3. At this point, the tilt focus operation should be exercised to optimize the focus over the entire field. The relay tilt dial should be set according to Table 1 and Figure 19, and the focus dial then set using Table 2. Slight trimming of the focus dial is desirable to optimize the focus since the actual altitude may not be known precisely. Moreover, the tilt control is not overly sensitive as noted by the suggested tolerance range of Table 1 and Figure 19, but the focus control must track the relay tilt control. This is because changing tilt alone also affects focus.

TABLE 1. 140° PROBE TILT CALIBRATION

ANGLE	INPUT	ANGLE	INPUT	ANGLE	INPUT
15'	0.21	6°	4.04	12°	7.50
30'	0.41	6°15'	4.19	12°15'	7.65
45'	0.60	6°30'	4.33	12°30'	7.80
		6°45'	4.49	12°45'	7.92
1°	0.79	7°	4.62	13°	8.04
1°15'	0.97	7°15'	4.79	13°15'	8.20
1°30'	1.12	7°30'	4.93	13°30'	8.32
1°45'	1.31	7°45'	5.10	13°45'	8.46
2°	1.42	8°	5.21	14°	8.60
2°15'	1.66	8°15'	5.35	14°15'	8.75
2°30'	1.80	8°30'	5.49	14°30'	8.89
2°45'	1.98	8°45'	5.63	14°45'	9.05
3°	2.15	9°	5.77	15°	9.21
3°15'	2.32	9°15'	5.92	15°15'	9.38
3°30'	2.48	9°30'	6.06	15°30'	9.51
3°45'	2.67	9°45'	6.20	15°45'	9.72
4°	2.81	10°	6.34	16°	9.86
4°15'	2.95	10°15'	6.50	16°15'	10.07
4°30'	3.10	10°30'	6.64	16°30'	10.22
4°45'	3.27	10°45'	6.80		
5°	3.42	11°	6.93		
5°15'	3.60	11°15'	7.10		
5°30'	3.74	11°30'	7.25		
5°45'	3.90	11°45'	7.37		

TABLE 2. PROBE FOCUS VS. TILT CALIBRATION FOR INFINITY OBJECT

Tilt Setting	Focus Setting
0	0
.5	.01
1.0	.08
1.5	.17
2.0	.30
2.5	.50
3.0	.77
3.5	1.09
4.0	1.48
4.5	1.93
5.0	2.49
5.5	3.16
6.0	3.87
6.5	4.66
7.0	5.60
7.5	6.63
7.75	7.15
8.0	7.76
8.25	8.47
8.5	9.00
8.75	9.70
9.0	10.45
9.25	11.05
9.50	11.78
9.75	12.40
10.0	13.10

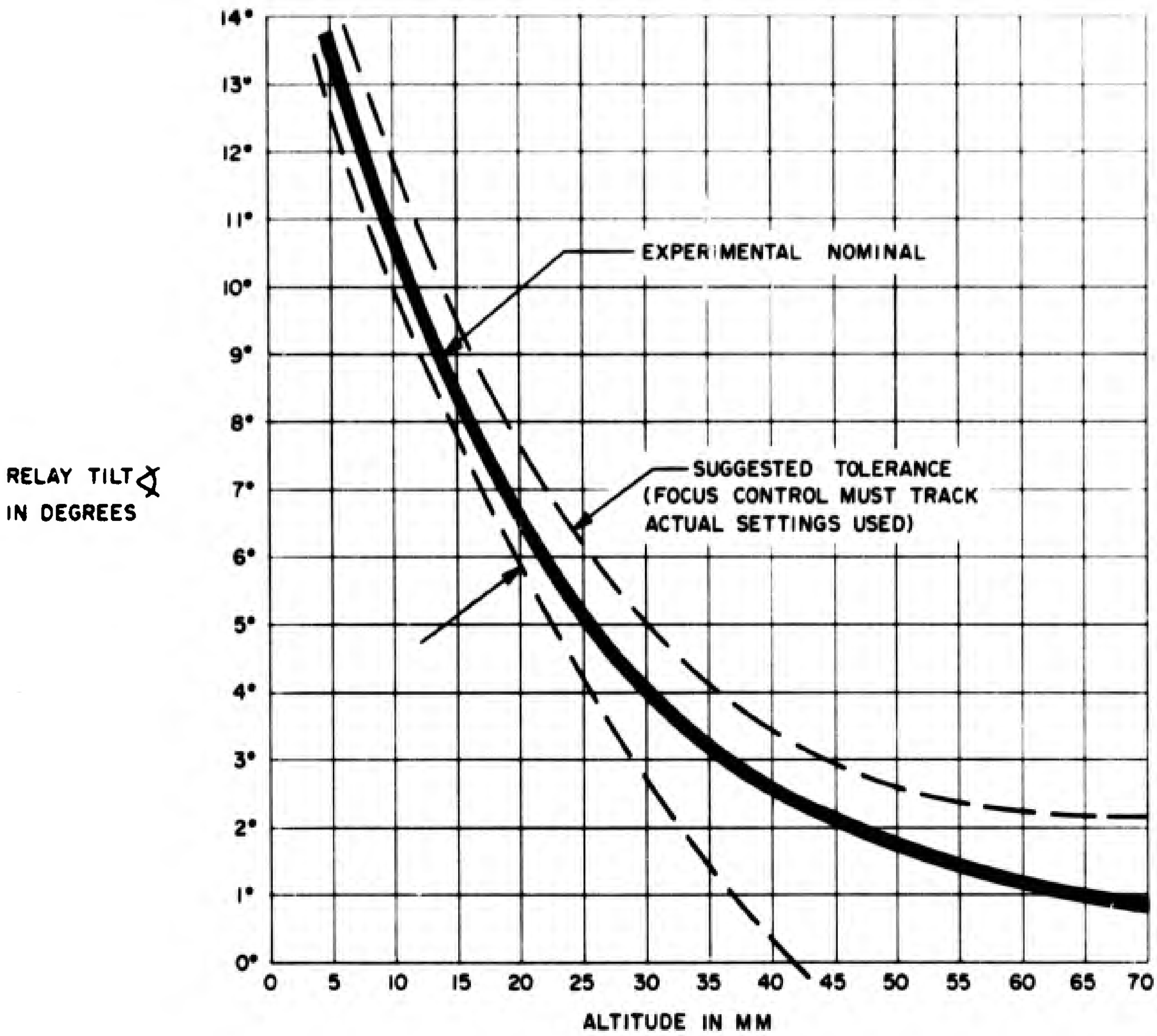


Figure 19. Relay Tilt vs Altitude

An example of settings for 10MM altitude would be:

Relay Tilt	Focus
10^{o} 45' = 6.8 Dial Reading	5.224 (interpolated)

NOTE

The orientation settings of azimuth, relay azimuth and roll can be operated to any azimuth or roll situation as described under step 2 without changing the Relay Tilt or Focus as long as the altitude is constant.

4. Roll can be exercised at any time without affecting the other functions. Roll is the only independent function.

5. Pitch variations can be introduced by rotation of the pitch dial with + (positive) readings meaning the line of sight is depressed. As pitching causes image rotation in the azimuth assembly, the relay azimuth must be reoriented to maintain the tilting action in the correct plane. The roll dial must also be used to maintain the upright image. Both motions are one to one with pitch motion. As an example, if we take our starting point:

Pitch	Azimuth	Relay Azimuth	Roll
0^{o}	90^{o}	90^{o}	0^{o}

and depress the line of sight 45^{o}, we should have;

Pitch	Azimuth	Relay Azimuth	Roll
45^{o}	90^{o}	45^{o}	45^{o}

6. Pitch motions reduce the required relay tilt by the cosine of the pitch angle, but this can usually be ignored in practical situations. At very low altitude, for example, large pitch angles would not be used. A 10^{o} pitch down setting at 10mm altitude would require the relay tilt to be .985 of the nominal 10.6^{o} relay tilt shown on Figure 19 or 10.44^{o} which is well within suggested tolerances.

At high altitude, where more pitch range is likely, the maximum tilt is small. As an example, at 65mm altitude only 1^{o} of tilt is required for nominal operation. A 45^{o} pitch change results in $.7^{o}$ of relay tilt. Note that Figure 19 suggests a range of 0^{o} to 2^{o} for this situation.

SECTION VIII

TEST AND EVALUATION

1. PERFORMANCE TESTS VS DESIGN GOALS

Tests were made to ascertain probe performance compared to the design goal specifications. Other tests were made, both photographic and optical, to illustrate performance under practical simulator conditions. A summary of actual performance vs. the design goals follows:

a. Field of view - design goal 140^{o} x 70^{o}
Measured value 135^{o} circular

b. Entrance pupil Dia. - design goal 1.5 ± .5 MM
Measured value 1.02 mm dia.

c. Aperture - design goal f/6 to f/16
Measured value f/6.2 to f/16

d. System Focus range - design goal .2 inches to infinity
Measured value .2 inches to infinity

e. Minimum "look-point" approach - design goal 2.5mm
Measured value 5mm (0.197")

f. Resolution - design goal 3 arc minutes over entire field
∞ Altitude measured values: 3 arc minutes over 60^{o} dia.
4 arc minutes from 60^{o} to 100^{o} dia
7 arc minutes max. at 135^{o} dia.

g. Contrast ratio 10:1 minimum design goal
Measured value: 15 steps in 20 step chart visible

h. Scan system Goals - Roll unlimited
Yaw unlimited
Pitch $\pm 55^{o}$
Measured values: Roll unlimited
Yaw unlimited
Pitch $+60^{o}$, -120^{o}

i. Transmission - design goal 40%

Measured value 35%. Goal can be met by using multilayer coatings on all optical components.

A short description of the optical test procedures and results follow:

2. PERFORMANCE TEST METHODS AND DATA

a. FIELD OF VIEW. The probe was fastened to a table with the prism head located above the center of a turntable. A collimator with a crossline target was fastened to the turntable so that known angular fields could be presented to the probe. A traveling microscope at the probe focal plane was then used to view and measure image location thus providing mapping data as well as field size. A calibrated focal length was also obtained from this data:

Field of View : 0.627 inches = 135° field dia.

Mapping data shown in Figure 20

Since basic mapping is $h = F\theta$, the focal length

$$F = \frac{\text{the linear height "h"}}{\text{the semi-field angle } \theta \text{ (radians)}} = 6.48\text{MM}$$

using a measured h of 3.39 mm for a 30° semi-field angle. It was determined that a slightly larger free aperture on the front meniscus lens would give the desired 140° field diameter.

b. ENTRANCE PUPIL DIAMETER. The entrance pupil was measured by placing a diffuse source at the probe focal plane and using a travelling microscope to measure the pupil diameter as seen through the elevation prism assembly. Since the pupil is an image of the aperture stop placed in either relay, its size and shape vary with that of the stop. A 3/4 inch diameter stop gave a measured pupil diameter of 1.02 mm.

c. APERTURE. A series of aperture stops were fabricated to provide an assortment of sizes and shapes for experimental purposes, the larger of which gives a system aperture of f/6.2. The aperture installs in a slide holder which can be placed in either relay member.

d. SYSTEM FOCUS RANGE. The system is capable of focussing for object planes at any obliquity to the optical axis and any altitude from infinity down to 0.2 inches from the look point. A series of resolution measurements for relay tilt angles covering the functional range illustrates this capability. (See discussion under paragraph f Resolution.)

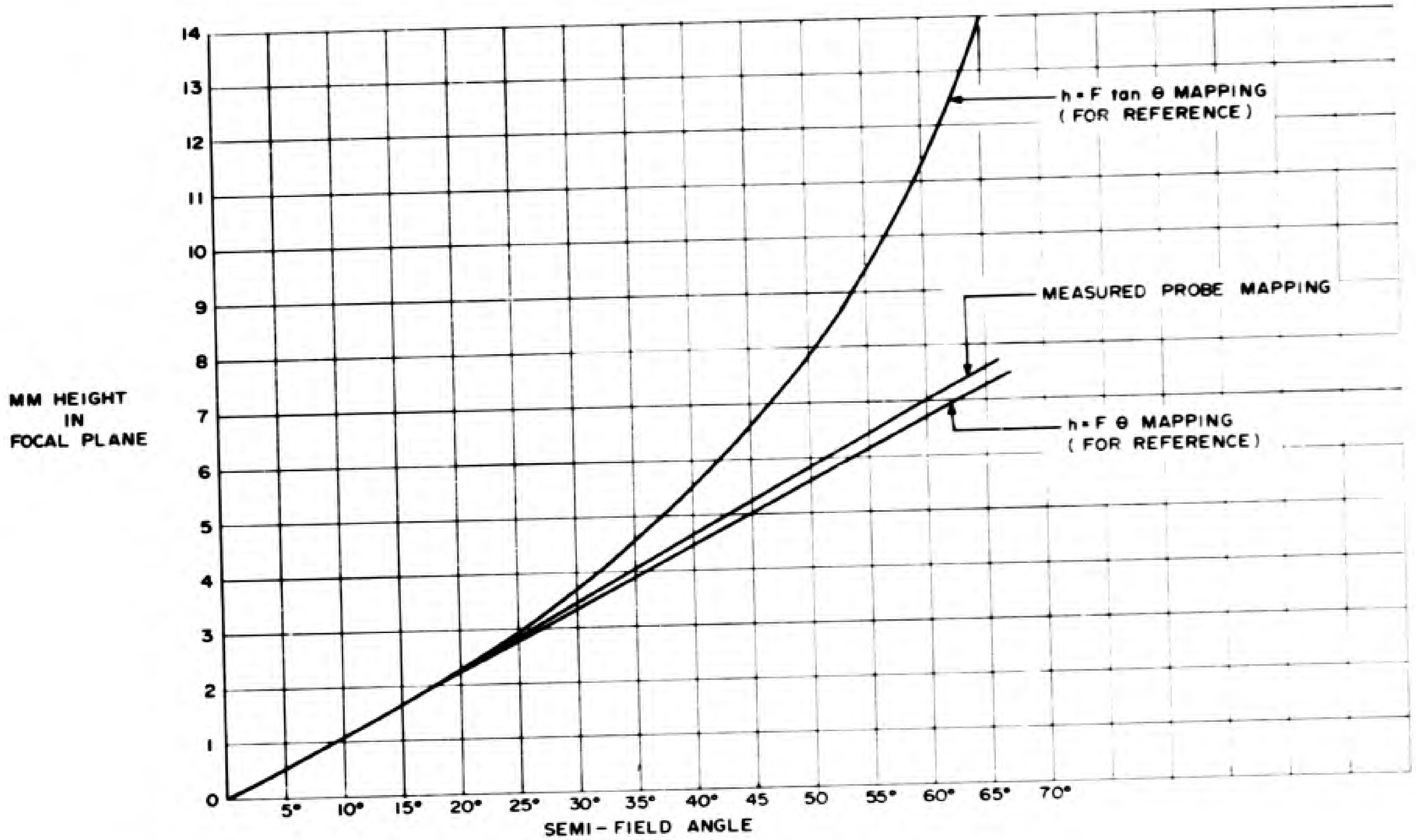


Figure 20. Mapping Data - 140° Probe

e. MINIMUM "LOOK POINT" APPROACH. This is determined by the physical diameter of the front meniscus element and elevation prism assembly, since optical performance does not otherwise limit the close approach. The look point can be placed 0.197 inches from the model at contact.

f. RESOLUTION. Probe resolution was measured visually and with MTF equipment. Visual tests were made over the entire field and over the entire altitude focus range. The visual tests used the criteria of simultaneous resolution in both the sagittal and tangential planes. Thus the numerical values represent resolution levels which may be exceeded under certain conditions. For reference, the theoretical resolution limit for a 1 mm aperture optical system is 2.5 arc minutes which corresponds to 214 line pairs per mm in the focal plane.

For the tests across the field, the set up was the same as that described for field of view tests with the exception of the use of a resolution chart, instead of a crossline reticle. For the tests covering the altitude range, the relay lenses were tilted to the appropriate angles while the collimator provided an infinity view at the center of the field (corresponding to the horizon). Because the full field represents only 15% of the focal plane the relays must effectively cover, it was deemed unnecessary to repeat the field readings for each altitude. We can simply subtract the resolution difference between the untilted and tilted readings and assume that this reduction in resolution applies uniformly over the field. As an example; the resolution at the center of the field is 3 arc minutes and at the edge is 7 arc minutes for the untilted (high altitude) case. The resolution at the edge of the field will become 9 arc minutes if the relays are tilted to where the central field is 5 arc minutes.

The resolution across the field is shown in Figure 21A and over the altitude range in Figure 21B.

An MTF test was also made to quantify the resolution performance. It was necessary to use a Super Farron relay lens at 3:1 magnification to provide enough back focal length for the MTF photomultiplier and slit analyzer head. A long focal length collimator with variable frequency square wave bars was used with tungsten illumination for this test. The photomultiplier utilized a 1P21 tube.

Tests were run for various frequencies on axis and for various relay tilt angles using a single frequency. Figure 22 illustrates the results.

g. CONTRAST RATIO. A 20:1 Foto video contrast strip was placed several inches in front of the probe. A low power microscope at the probe focal plane was used to count the steps visible. Fifteen steps were visible.

h. SCAN SYSTEM. Roll, and Yaw continuous rotation was observed. Pitch limits of $+60^{0}$ -120^{0} were observed using the pitch control dial.

i. TRANSMISSION. A standard diffused light source was calibrated to a 100% reading using a Pritchard photometer with a close up lens attachment. The photometer

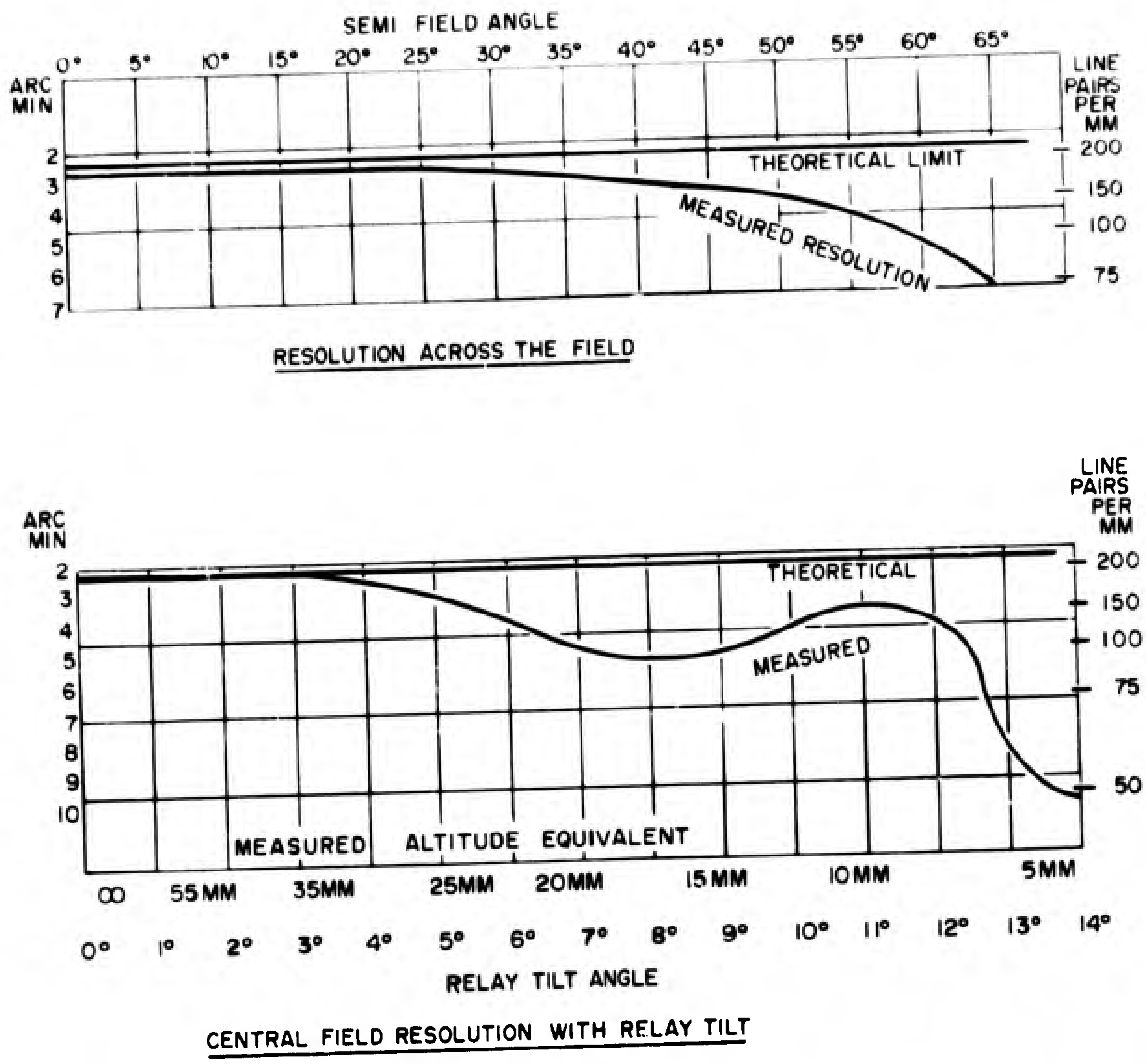
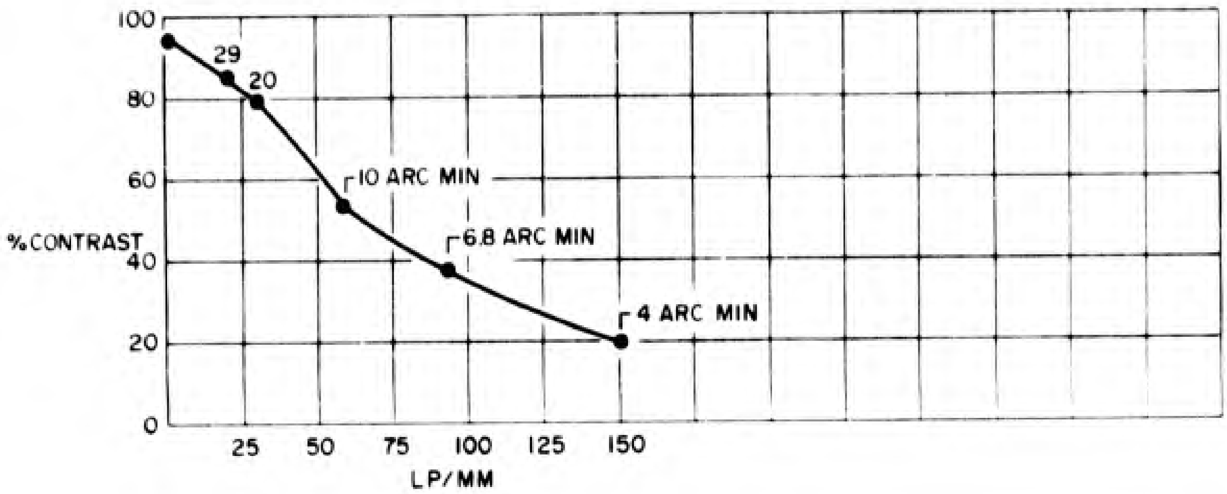
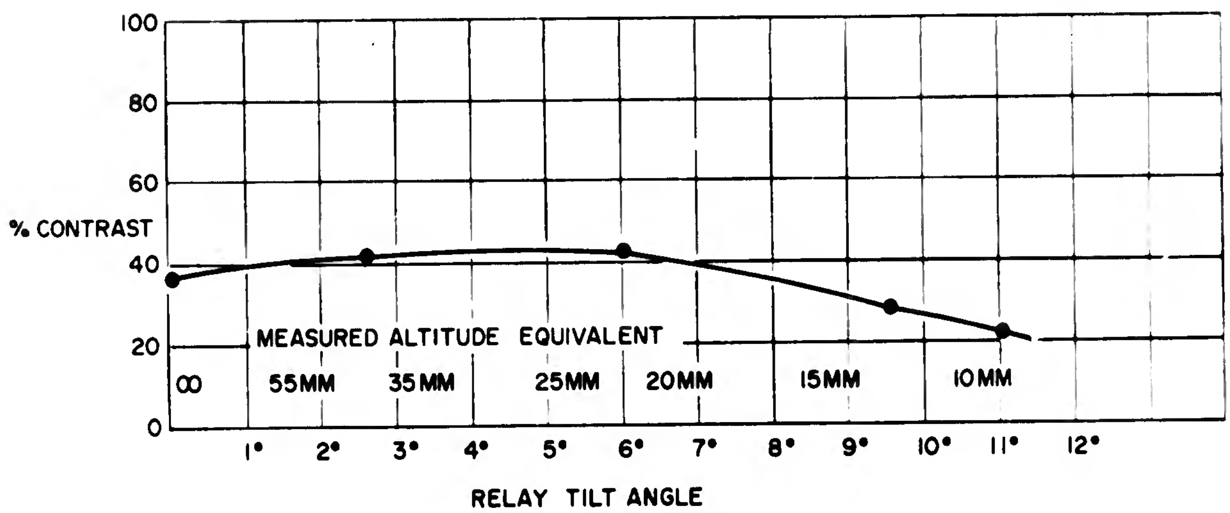


Figure 21. 140° Probe Resolution Measurements



AXIAL CONTRAST TRANSFER PERFORMANCE (MEASURED)
∞ TARGET



AXIAL CONTRAST TRANSFER VS. RELAY TILT (MEASURED)
∞ TARGET, FREQUENCY 92 LP/MM (6.5 ARC MIN. RESOLUTION)

Figure 22. 140° Probe Contrast Transfer Measurements

was then moved so as to view the entrance pupil of the probe without changing the photometer focus. The standard light source was then placed in the probe focal plane. A field stop in the photometer assured that only about 1/3 of the entrance pupil area was used for the test. A reading of 35% was obtained.

3. <u>OTHER OPTICAL TESTS</u>

a. Image wander as a function of relay tilt. The following measurements were made over the full relay tilt range; image shift in the tilt plane ±.0003 inches; and image shift perpendicular to the tilt plane ±.0015 inches.

b. Stray light was measured at approximately 6%.

c. The relay tilt angle was calibrated as a function of the dial input and is shown in Table 2.

d. A visual check of optimum relay tilt as a function of altitude is shown in Figure 19. This is not a sensitive setting in itself and the limits shown may be tolerable in an operational system. However, since the focus changes with relay tilt, the <u>focus</u> control must track the relay tilt control at all times. Table 2 shows the calibrated focus control as a function of the relay tilt control setting. Application of this assumes the line of sight is pointed toward the horizon, and will bring the probe to approximate focus. To achieve the critically sharp focus that the instrument is capable of, the focus calibration curve should be checked and adjusted if necessary under actual operational conditions.

4. <u>PHOTOGRAPHIC EVALUATION OF PROBE PERFORMANCE</u>

a. An extensive program of photographic documentation of the probe's performance was undertaken to provide a more meaningful evaluation under circumstances similar to use in an operating aircraft simulator. For convenience in taking black and white as well as Kodachrome slides, a Super-Farron finite conjugate relay lens was used at a 3:1 magnification. This permitted the use of a 35 mm reflex camera body although the full field was too large to be shown on this format. The fast f/no. of 0.87 was of course not fully used since the probe operates at f/6.2 but was nevertheless necessary since the edge-field principal rays leave the probe in an f/1.0 cone. Two 3-dimensional models were used in the photography. The first is shown with the probe in Figure 23 and reproduced at full scale in Figure 24.

b. Figure 25 was taken through the probe at the minimum approach altitude of .2 inches. A 4-40 machine screw was placed on the "grass" which was made from a green desk top blotter. Runway lights were simulated by 1/32 inch diameter steel balls. The model was fabricated on 3/8 inch plywood which when viewed at the .200 inch altitude shown some warpage near the horizon. (To avoid attributing this to an optical defect, a second model was fabricated and mounted on a steel "I" beam.) The horizontal field is approximately 96° and the vertical field from the horizon to the bottom edge is about 31°. A 2 second exposure on panatonic X film was used with the probe operating at approx. f/9.7 and appropriate relay tilt correction

Figure 23. 140° Probe Feasibility Model Shown at Minimum Altitude on Runway Model

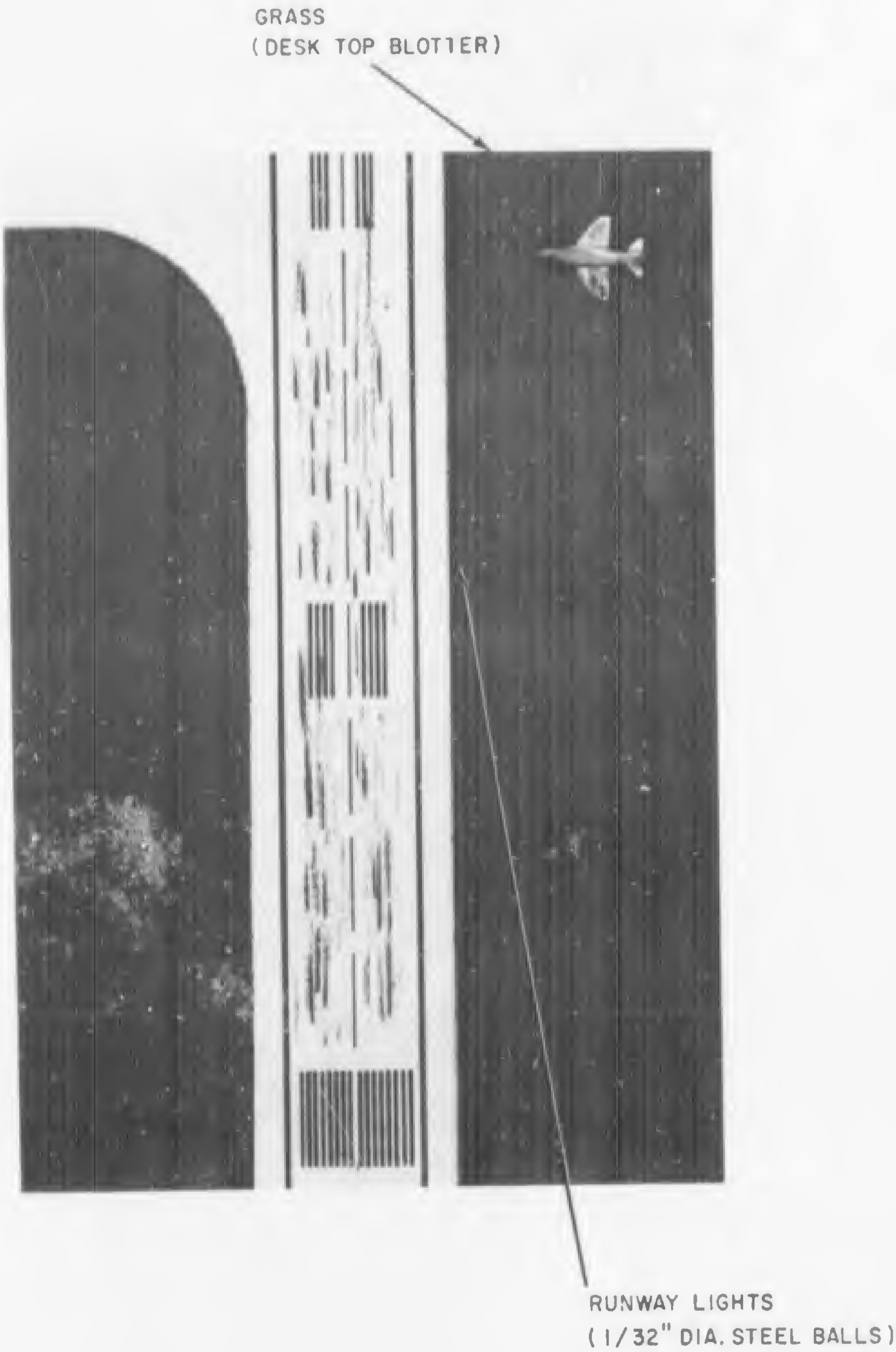


Figure 24. True Scale Photograph of Runway Model

PROBE OPERATED AT f/9.7 WITH 3:1 MAGNIFYING RELAY
HORIZONTAL FIELD = 96°
PANATOMIC X FILM
A 4-40 MACHINE SCREW ILLUSTRATES MODEL PROPORTIONS

Figure 25. Photograph Through 140° Probe at 0.200 " Altitude - Model I

applied. Figure 26 was taken under similar conditions but with the relay tilt correction deactivated. Note that aside from the dramatic resolution improvement when using tilt correction, no changes in perspective, magnification, distortion or vignetting are evident compared to the non-tilt corrected photograph.

c. The second model, shown with the probe, 3:1 relay and camera in Figure 27 was mounted on a 8 foot steel beam for flatness. Its 2 foot width was not sufficient to show a full horizon, causing horizon droop in the photographs. Runway lines were separated by 1.21 inches for the heavy inner lines, 1.73 inches for the thinner outer lines and 2.4 inches for the grass edges. A paper resolution chart was placed on the runway and is depicted at true scale above the photograph in Figure 28. Pattern 1-6 in the horizontal direction represents 11 arc minutes resolution for a line pair. A skyscraper (about 20 stories high) was placed near the runway to illustrate the depth of focus variation in the vertical direction.

d. The altitude was .200 inches and the probe was operated at f/7.0 for this photograph and for Figure 29 which is similar except for deactivation of the relay tilt correction. Note that in this case, the depth of focus lies along the runway and that the skyscraper is in the normal focal plane.

e. A one-cent piece was placed on the runway (Figure 30), but focus was held on the runway rather than the top of the coin which is slightly defocussed. The altitude is .250 inches.

f. Figure 31 is a black and white reproduction of a Kodachrome II original taken with the top of the coin placed in optimum focus rather than the runway surface. The coin upper surface was .140" altitude from the probe pupil, while the model surface was at the minimum physical approach altitude of .200". The picture indicates the close approach resolution, depth of focus and color correction achieved. (Significant color errors would cause image smearing).

g. An effort was also made to secure full field photographs at minimum altitude. Using special fixturing at the normal focal plane, high contrast copy glass plates provided the results shown in Figure 32. Difficulties in lighting and contrast are obvious but the picture does illustrate the relatively uniform illumination from center to edge predicted by the mapping function. (Refer to appendix C).

The limited focus of the near down field region is due to the sagittal oblique spherical aberration for the close finite conjugate and the extreme (65°) vertical down field shown. This is not a problem in actual use, since the vertical down fields would be limited to about 35°. Vertical down fields from 31° to 38° are shown in the photographs taken on 35 mm film.

PROBE OPERATED AT f/9.7 WITH 3:1 MAGNIFYING RELAY
HORIZONTAL FIELD = 96°
PANATOMIC X FILM

Figure 26. Photograph Through 140° Probe at 0.200" Altitude, No Tilt Correction Applied - Model 1

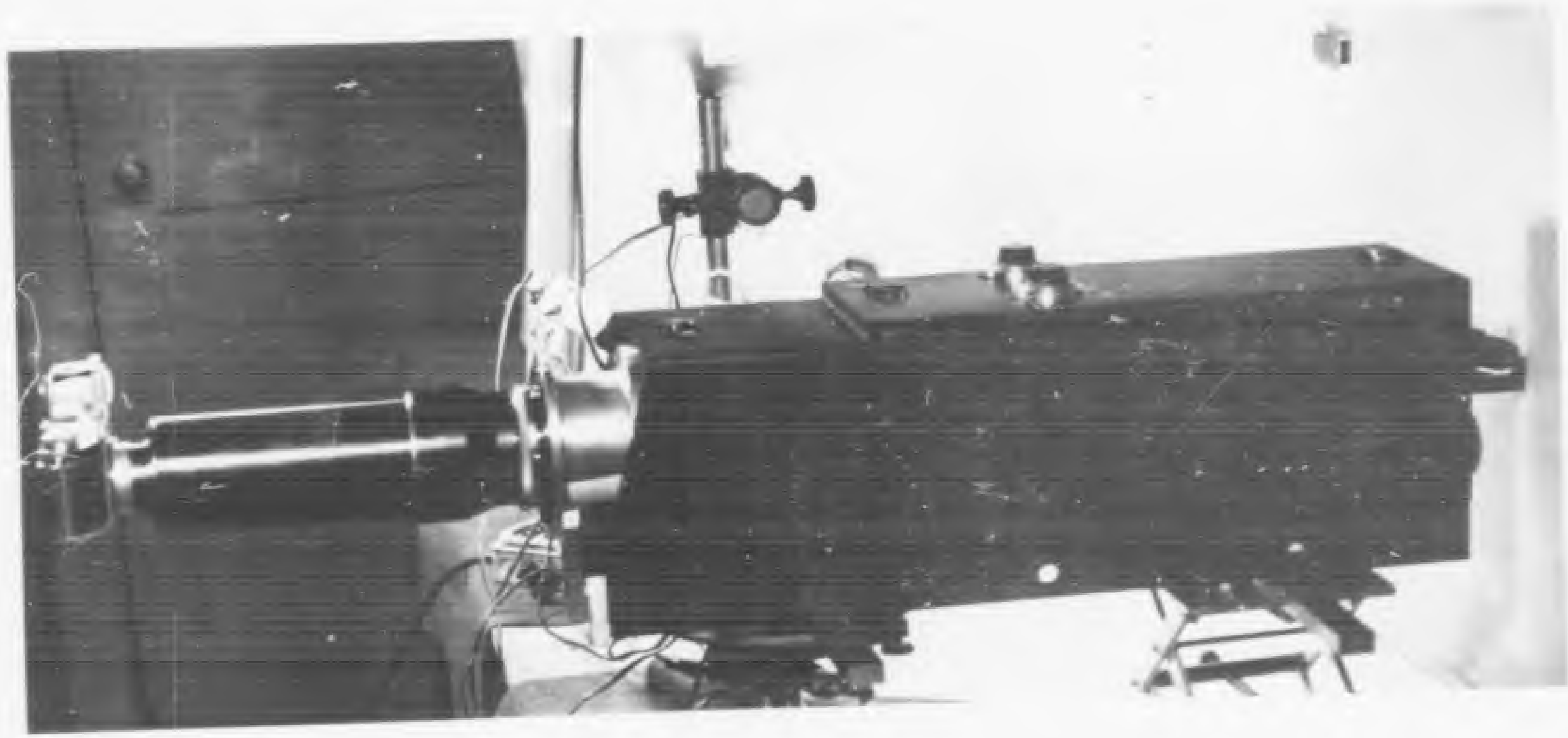
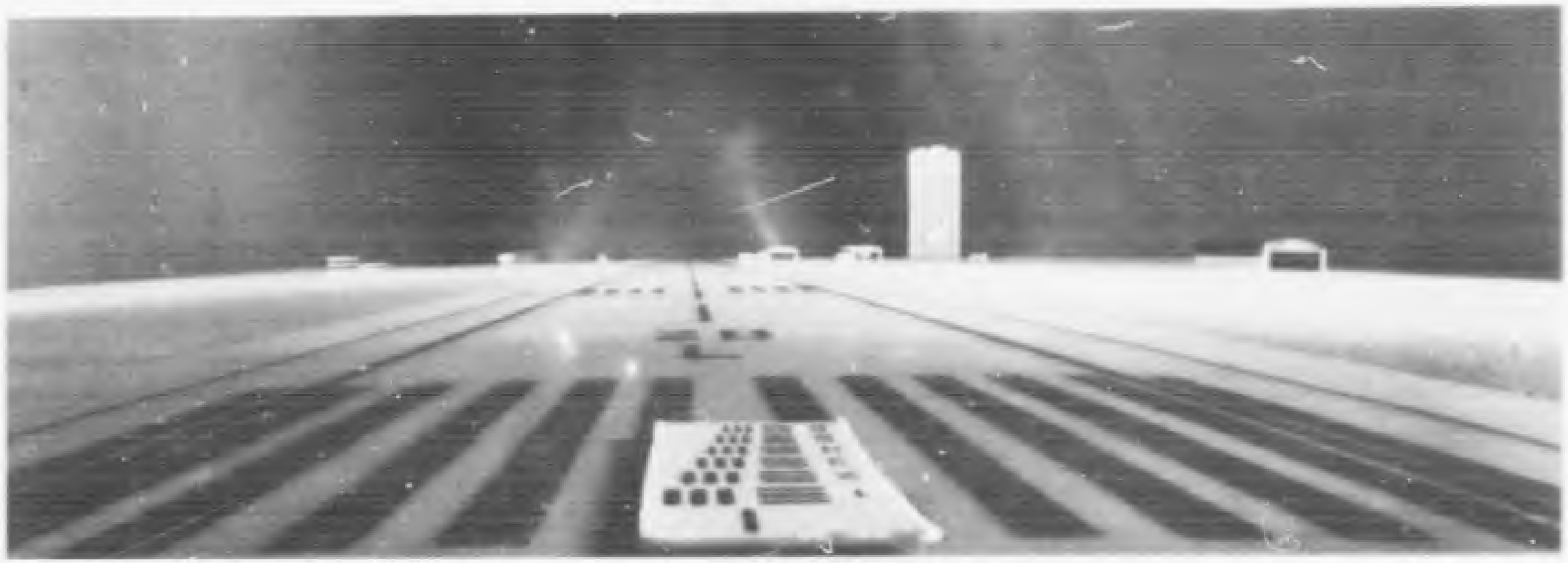


Figure 27. 140° Probe with Experimental 3:1 Relay Set-up - Model II Shown

ACTUAL SIZE OF RESOLUTION
CHART SEEN BY PROBE



PROBE OPERATED AT f7 WITH 3:1 MAGNIFYING RELAY
HORIZONTAL FIELD = 96°
PANATOMIC X FILM

Figure 28. 140° Probe at 0.200" Altitude - Model II

PROBE OPERATED AT f7 WITH 3:1 MAGNIFYING RELAY
HORIZONTAL FIELD = 96°
PANATOMIC X FILM

Figure 29. 140^{o} Probe at 0.200" Altitude, No Tilt Correction Applied - Model II

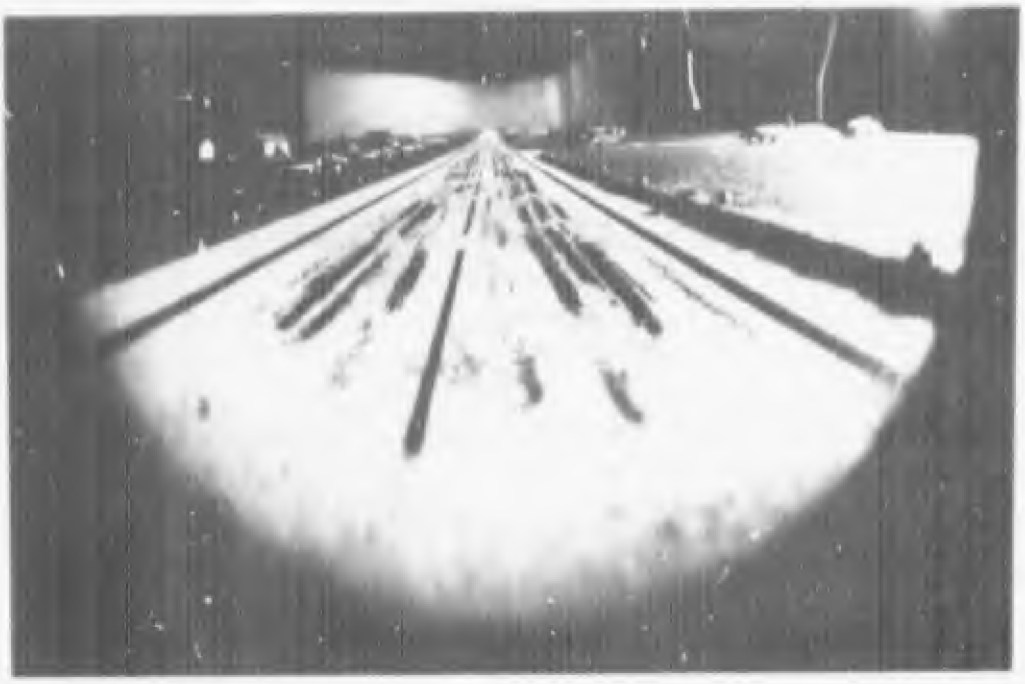
PROBE OPERATED AT f 7 WITH 3/1 MAGNFYING RELAY
HORIZONTAL FIELD=96°
PANATOMIC X FILM

Figure 30. Photograph Through 140° Probe 0.250" Altitude

PROBE OPERATED AT f7 WITH 3:1 MAGNIFYING RELAY
HORIZONTAL FIELD=96°
FROM KODACHROME II SLIDE ORIGINAL

Figure 31. Black and White Reproduction of Kodachrome II Original Taken Through 140° Probe

ACTUAL IMAGE SIZE
AT FOCAL PLANE



PHOTOGRAPH THROUGH PROBE AT .200 INCHES ALTITUDE
SHOWING 135° CIRCULAR FIELD OF VIEW

TAKEN WITH HIGH CONTRAST COPY FILM ON GLASS PLATE

Figure 32. Photograph Through Probe at Primary Focal Plane Showing Full Circular Field

SECTION IX

OVERALL CONCLUSIONS

1. OVERALL CONCLUSIONS.

a. The intent of this program was to develop and implement the techniques necessary to achieve an advance in the state-of-the-art of wide angle, close approach, optical pickups for visual simulation. Completion of these aims could result in more realistic, versatile, and cost-effective simulation systems in the future.

b. The study phase of the program resulted in the development of a number of concepts and design parameter relationships that were useful in establishing a basic design. Its flexibility could allow incorporation into various simulator system configurations e.g., color TV, multiple outputs, etc. Most of the material was studied with a view toward practical implementation of straight-forward principles so as to achieve a relatively simple yet effective optical pickup. Much of the study effort was also applied in the hardware phase, including implementation of the dual relay concept.

c. The engineering feasibility model appears to have established a new performance plateau for this type of device. Evaluations, both numerically and photographically show performance levels equalling or close to design goals in all respects. No significant or unusual problems were uncovered in the fabrication, assembly, test and operation of the feasibility model although a good deal of care and precision work was required. Many specialized assembly and test procedures were applied to assure that the actual device was limited more by its theoretical design constraints than by any shortcomings in fabrication and assembly. The near diffraction limited optical performance over much of the field and the minimum eccentricities or runouts of the moving components attest to the value of the techniques employed.

d. The hand operated engineering feasibility model has the following basic characteristics:

1. Field of view = 135°
2. Close approach = 5 mm
3. Entrance Pupil = 1 mm dia.
4. Relative Aperture = f/6.5, T/11
5. Maximum resolution = 3 arc minutes
6. Format = 17 mm

7. Scan System has unlimited roll and yaw functions, pitch = $+60^{o}$, -120^{o}

8. Approximate size = 7 x 8 1/2 x 27 inches

9. Approximate weight = 30 pounds

SECTION X

OVERALL RECOMMENDATIONS

1. It is recommended that the feasibility model be updated to a fully automatic servo controlled device for inclusion in a full simulator test program to explore its full potential to achieve a significant advance in aircraft simulation applications.

2. A relay lens could be designed to provide dual outputs for improving the resolution levels by using 2 sensors, each covering about 90^{o}. The format size could also be increased if desired using this relay.

SECTION XI

APPENDICES

1. APPENDIX A

a. PHOTOGRAPHIC CONFIRMATION OF CONCEPT

(1) A fully automated probe was made available in order to photograph a simulated runway to verify the 140° field of view design approach during the study phase of the program. Figure A-1 shows the normal 110° field view of a 2000:1 scale runway at 0.58 inches altitude from the probe pupil. Stand-up targets appear at 1000, 2000 and 4000 feet scale distances to illustrate the depth of focus effect. Figure A-1 is a 17 times enlargement of the full .44 inch image plane diameter. The horizon was positioned at the field center and a 1 mm probe pupil diameter was used.

(2) Figure A-2 was taken under the same conditions except that a negative meniscus lens was placed against the elevation prism face. Three-flats were ground on this lens to allow close positioning. These are seen as out-of-focus vignetted areas at the top and sides of the photograph. The lower portion however is not vignetted and illustrates the gain in field size. A field diameter of 122° is obtained from geometric measurements of the photograph and setup. Note that general picture quality is not significantly affected by the lens addition and that no unusual effects are created. This experiment confirms the general validity of the meniscus lens approach to obtain the 140° field.

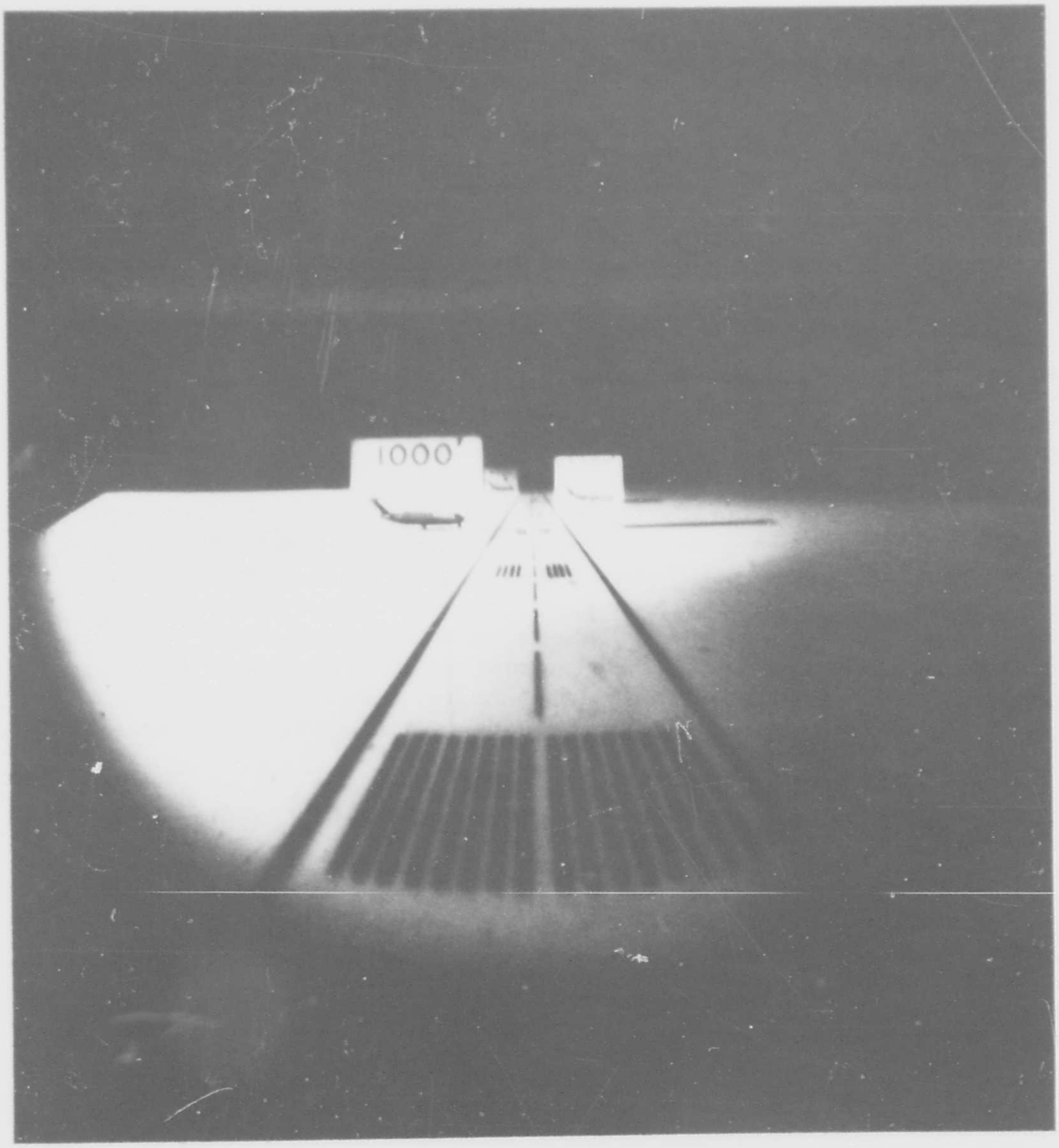


Figure A-1. 2000:1 Scale Runway, as Seen Through Probe Pupil, 0.58" Altitude, 110° Field of View

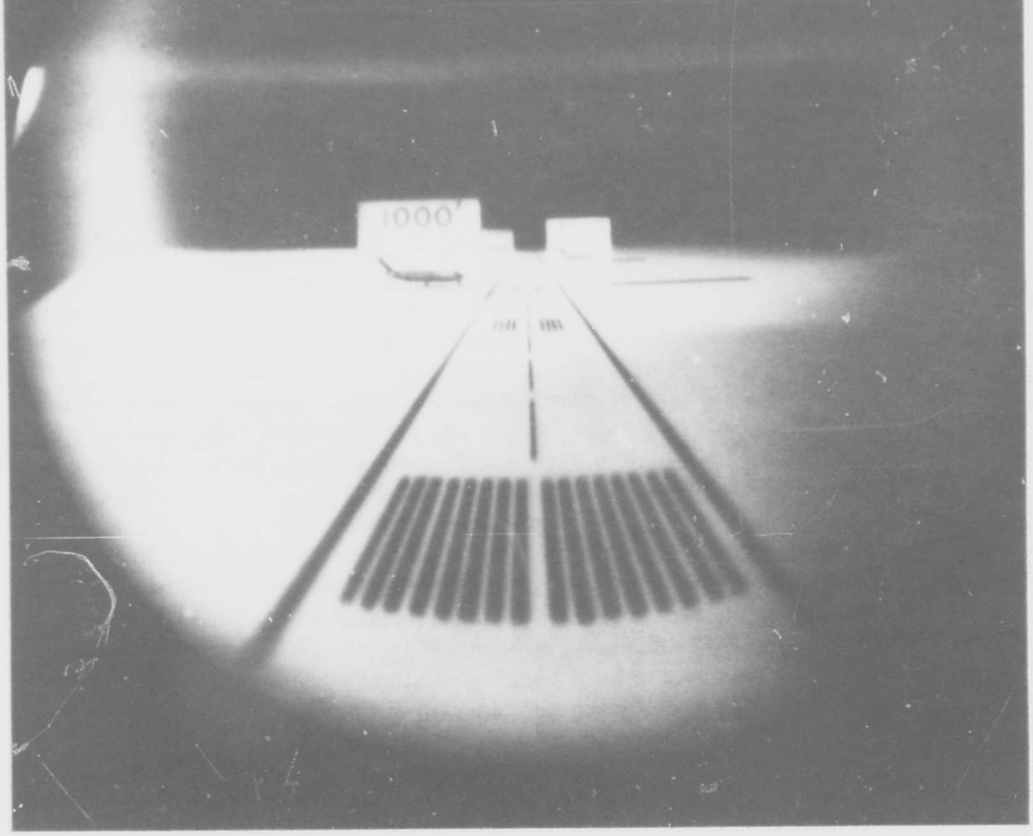


Figure A-2. 2000:1 Scale Runway, as Seen Through Probe Pupil (Meniscus lens placed against prism face). Field Diameter 122°.

2. APPENDIX B

a. PROBE DEVELOPMENT AS APPLIED IN LUNAR LANDING SIMULATION

(1) General

(a) The Farrand Probe is a wide angle probe designed and developed to satisfy the landing and ascent simulation requirements of the Lunar Excursion Module Trainer, the visual system which was recently delivered by this contractor. The main features of the probe are as follows:

Field of View: Full 110° Circular

Closest approach to model: 1/4 inch

F number f/5 (T/10)

Focus: Full field of view is maintained in exact focus regardless of slant range or angle of obliquity of the line of sight with the model plane.

(b) Current and past probe designs have been directed towards the problem of simulating flight with special attention paid to the landing phase. These probes are not usually required to cover exceptionally wide fields of view so that the real problems encountered are concerned with illumination, depth of field (or focus across the field) and closeness of approach to the model, since scale is an important parameter in maintaining a model of reasonable size. The Farrand Probe illustrated in Figures B-1 and B-2 covers a full 110° circular field of view, of which an 83° vertical by 110° horizontal portion is fed to the television camera.

(c) It should be noted that the Farrand Probe is capable of approaching the model to within 0.25 inch, measured from the center of the single entrance pupil. The entrance pupil is located within the elevation scanning prism. However, the apparent "look point" for purposes of simulating the observer's head position is slightly forward of the entrance pupil and is defined by the intersection of the undeviated edge rays of the field of view entering the scanning prism.

A true simulation of vehicle dynamics requires that the axis of rotation of the scanning prism be located, scalewise, a distance from this "look point" equal to the distance between the observer's head position and the center of rotation of the vehicle.

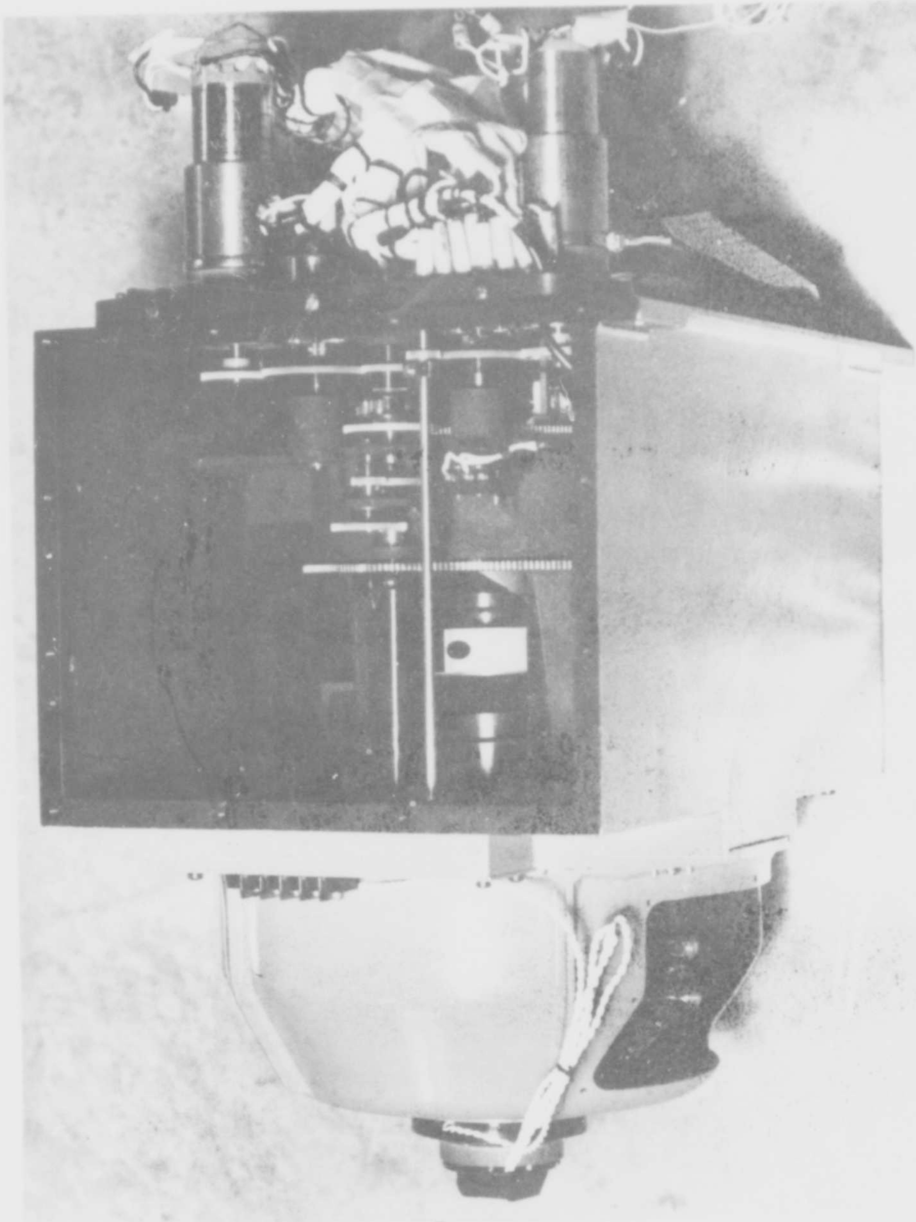


Figure B-1. Farrand Probe

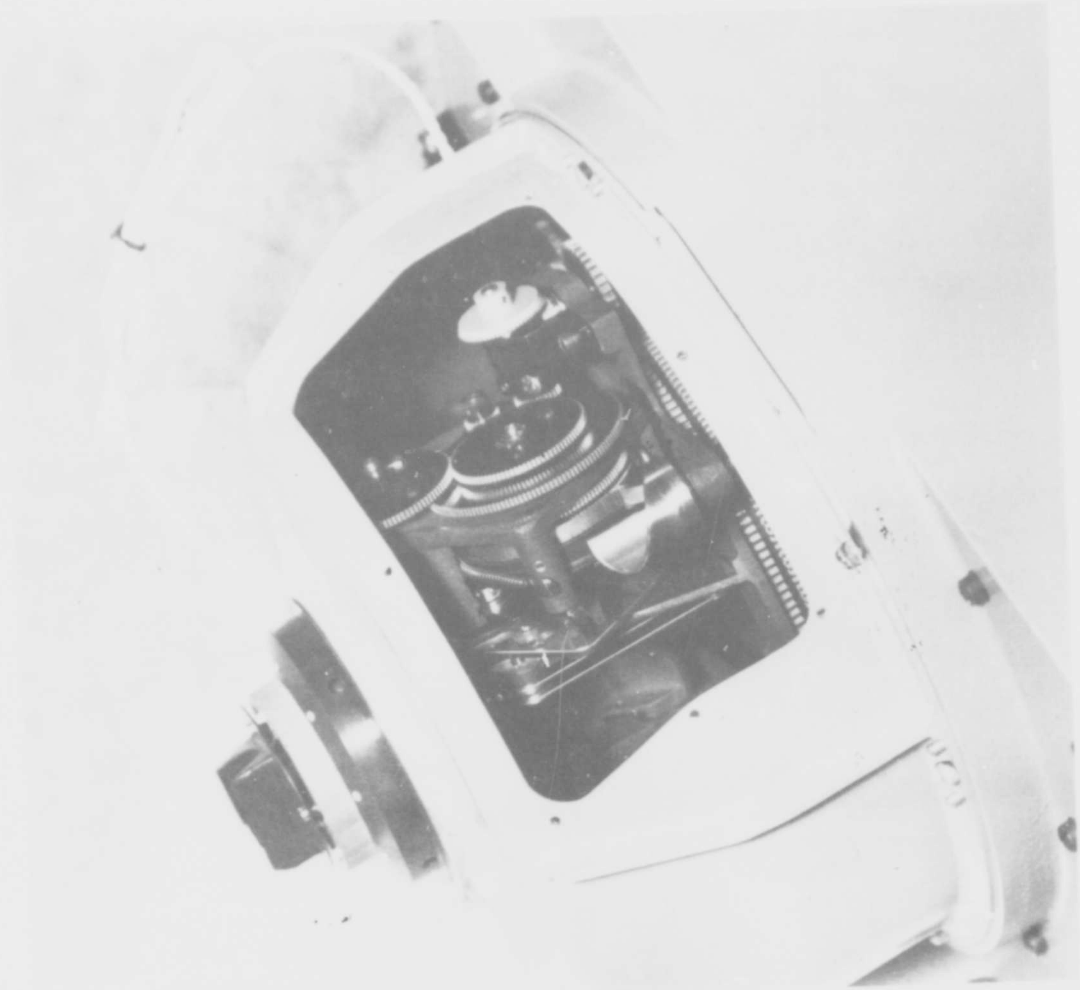


Figure B-2. Farrand Probe, Cover Removed, Showing Mechanical Analogue Mechanism for Focus, Tilt

(2) Probe Design Approach

(a) Current and past probe design approaches suffered some severe limitations concerning illumination, depth of field and resolution, in addition to the usual problems of effecting reasonable scan angles with wide instantaneous fields of view. The usual starting point in a probe design dictates a relatively small entrance pupil in order to achieve a large depth of field. This depth of field is required to maintain the field of view in a reasonably focussed condition when the center line of the line of sight is at some angle off nadir. (See Figure B-3.) However, even when resorting to a small entrance pupil, with wide fields and high angles of obliquity, such as horizon viewing, the focus across the field is notoriously poor because of the tremendous span of field depth compared to probe height above the model. The small entrance pupil approach also results in two very severe problems: (1) illumination and (2) resolution and contrast limitations.

(b) As mentioned previously, the pin-hole approach is merely a compromise as far as maintaining reasonable focus across the instantaneous field of view is concerned even though the probe is equipped with a focus control to accommodate for slant range. Using such a small aperture (F/50-F/60) the illumination conditions are so severe that an image orthicon camera must be used. In order to circumvent the technical problems associated with an orthicon, one tries to design for a vidicon camera. However, the vidicon must employ an F number somewhere between F/20-F/30 for satisfactory operation with a safe maximum illumination on the model.

(c) The small aperture for depth of field approach leads not only to the problem of insufficient illumination but also to the problem where the diffraction limitation influences the available resolution and the contrast rendition at the photocathode of the vidicon.

(3) The Farrand Approach to Probe Design

(a) The Farrand Optical Company conceived and designed an optical probe which largely circumvents all of the aforementioned problems. This design, known as the Farrand Probe, was manufactured for the LEM simulator which this contractor recently completed. The design features an F/5(T/10) optical system which permits a much lower level of illumination to be used on the model. By the same token the larger aperture assures not only a higher resolution on the photocathode of the vidicon but also eliminates any possible diffraction effects. This relatively "fast" design of the Farrand Probe is made possible by a proprietary feature in the optical system which permits the probe to

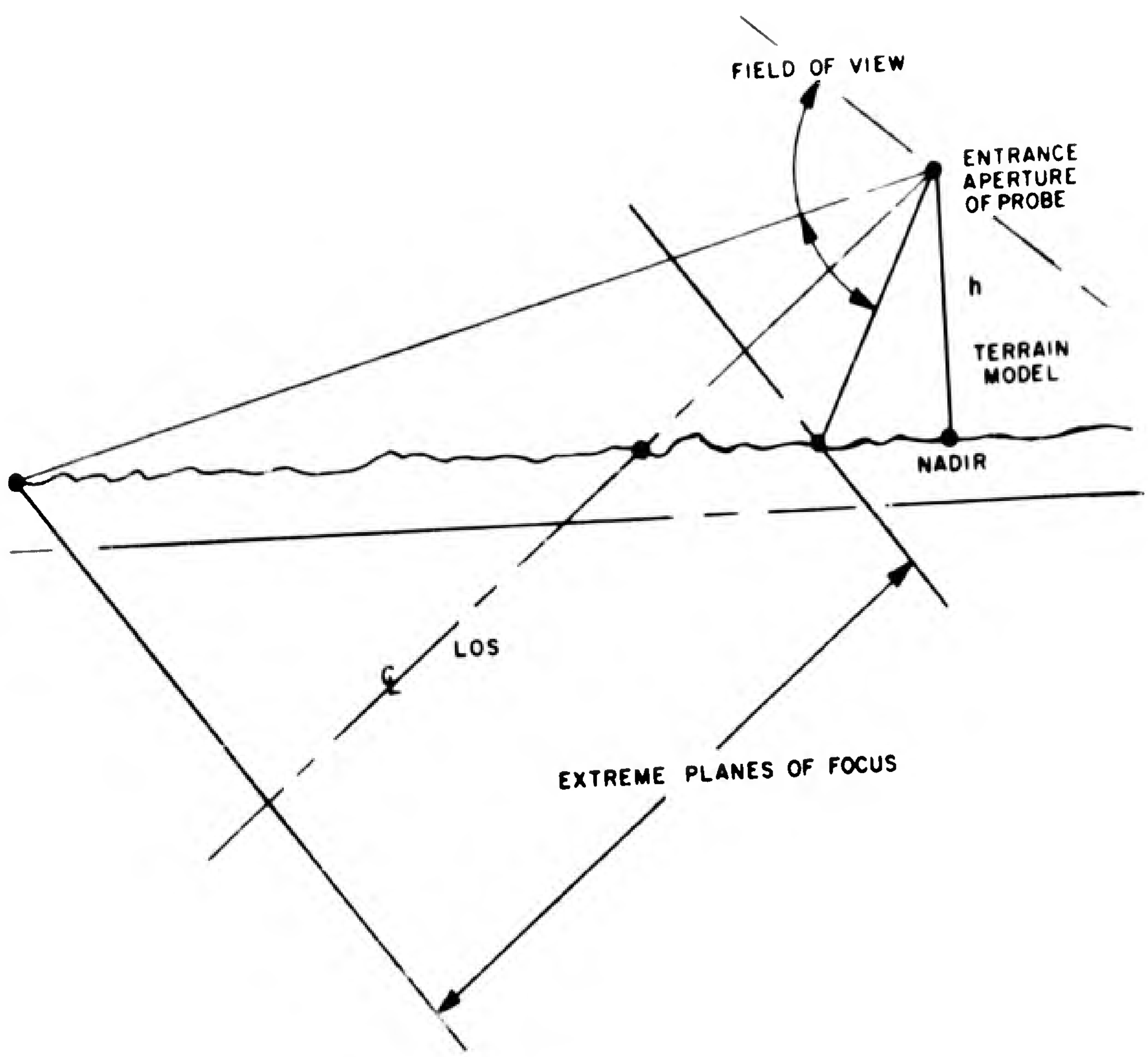


Figure B-3. Probe Geometry - Theory

be focussed not only for slant range but also across the full field for all obliquities of the optical line of sight with respect to the model's plane.

(b) The Farrand Probe is designed to accommodate vidicon cameras because of their reliability and quiet operation. It would be well to note that the illumination required on the photocathode of a vidicon for optimum performance is 1.5 ft candles. This value may be interpreted as illumination due to the model high-lights. For average scene brightness, the photocathode illumination should be between 0.75 and 1.0 foot candles. These values will permit the achievement of 1000 line resolution at a contrast ratio of 10:1. The illumination on the photocathode "I" may be found from the relation:

(1) $I = \frac{tB}{4N^2}$ for infinity focus, where

I = illumination on photocathode in foot candles

t = transmission of useful light by lens (ratio)

B = model highlight brightness in candles/ft^2

N = lens f number (ratio) = 5

For the case of closest approach a term describing the magnification must be considered. The relation is then modified to read:

(2) $I = \frac{B}{4N^2\left(1 + \frac{d}{D}\right)}$ where

d = image distance or focal length

D = object distance

the T number = $\frac{N}{t}$

$T^2 = \frac{N^2}{t}$ or $t = \frac{N^2}{T^2}$

The probe as illustrated in Figures B-1 and B-2 may be provided either with a collimating eyepiece to fill the entrance pupil of a camera lens or with a focal plane relay system. The relay system would permit feeding three separate vidicon tubes as required for a color presentation.

(4) Detail Design

(a) The probe as presently designed has unlimited freedom in azimuth and line of sight roll while providing a ±72° elevation scan. The probe itself is normally translated over the map model in accordance with X, Y, Z outputs of position from the computer. A second coordinate system (x, y, z) whose origin is located at the intersection of all probe axes is considered as the reference system for vehicle attitude. In other words, the "z" axis is co-linear with the probe azimuth axis while the "y" axis is co-linear with the vehicle pitch axis. The vehicle roll axis is then considered to be coincident with the line of sight axis of the probe optical system. If vehicle position in X, Y, Z is supplied to the system translating the probe, the probe will be servoed to the simulated vehicle position over the terrain model. Next, if vehicle headings, pitch and roll are supplied in that order to the probe, the proper vehicle attitude in terms of roll, pitch and yaw, with respect to inertial space will be exactly simulated through the coordinate system employed by the Farrand Probe. If the reference frame used to describe the attitude of the vehicle is different from the system just enumerated then a coordinate transformation will be necessary to properly orient the line of sight of the probe system to represent the vehicle reference frame.

(b) Figure B-1 illustrates the scanning prism whereby a $^{+55^o}_{-90^o}$ elevation scan is achieved. As mentioned in prior paragraphs, the intersection of the undeviated external field of view rays which define the "look point" is forward of the elevation axis since the pilot would normally be located forward of the center of rotation of the vehicle. This relationship can be varied to some extent and an attempt is usually made to suit the particular conditions of the vehicle being simulated. Roll can be simulated as roll about the line of sight for any number of complete rotations by merely driving a derotating prism. In other words there is an unlimited roll capacity in this probe.

(c) Azimuth rotation of the probe is unlimited since the optical components and their drives are being rotated without rotating the television camera assembly. This is accomplished by means of azimuth bearings and through the use of a derotator prism. This derotator serves not only to erect the line of sight on the photocathode of the vidicon when scanning in azimuth or yaw but it also serves to simulate roll of the aircraft which is normally taken about the line of sight which is in turn parallel to the aircraft roll axis.

(d) Dynamic characteristics of this contractor's latest probe design are as follows:

Maximum velocities:

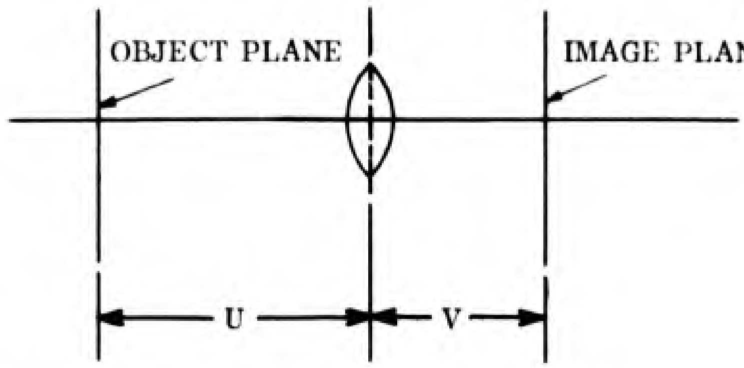
Azimuth	80^o/sec
Pitch	80^o/sec
Roll	150^o/sec

Maximum accelerations:

Azimuth	$80^{\circ}/sec^2$
Pitch	$80^{\circ}/sec^2$
Roll	$150^{\circ}/sec^2$

(5) Optical Design

(a) Optical systems used in probes work at finite conjugates. Such systems normally work with the optical axis perpendicular to an object and as a result the image formed is also perpendicular to the optical axis as shown below:

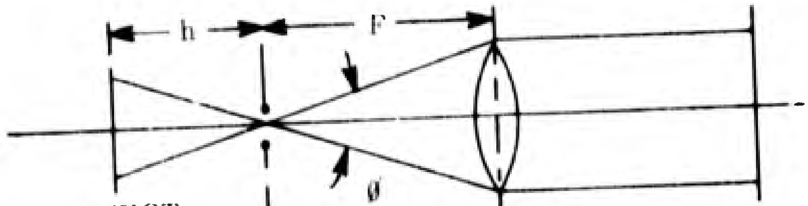


If the lens has a focal length F then the object distance and the image distance v (measured from the principal plane of the lens) are related as follows:

$\frac{1}{u} + \frac{1}{v} = \frac{1}{F}$ and the magnification is described as $M = \frac{v}{u}$

(b) The variation in magnification duplicates the conditions existing in the external world and as such it is desireable feature in a probe. However, the image plane moves longitudinally in focus and as a result the image formed by a given field angle Ø would also change in size on the image plane as the plane is moved into focus. This effect is undesireable.

(c) In order to overcome this effect the entrance pupil is located externally with respect to the objective. In actuality the entrance pupil is located in front of the first principal plane of the objective lens by a distance equal to the focal length F of the lens. The entrance pupil is then effectively at infinity and the system is said to be telecentric on the image side:



Motion of the image plane does not change the image size formed by the angle ø at the entrance pupil as the image plane is moved to maintain focus. Furthermore the magnification is still described by the function $M = \frac{v}{u}$. Therefore when a telecentric system is moved relative to the object at a scale "altitude" h (h measured from entrance pupil to object), the optical characteristics are:

$$u = h + F$$

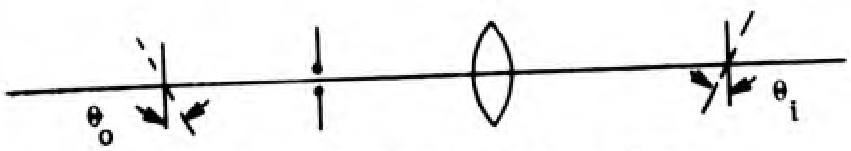
$$\frac{1}{V} = \frac{1}{F} - \frac{1}{h + F} = \frac{h}{F\,(h + F)}$$

$$v = \frac{F\,(h + F)}{h} \text{ and since } M = \frac{v}{u}$$

$$M = \frac{F}{h}$$

Now if the object is tilted through an angle $ø_o$ the image is tilted in the opposite sense through the angle $ø_i$:

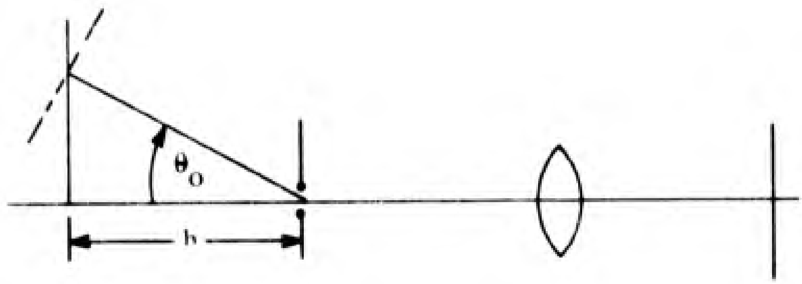
where:



(1) $\tan \theta_i = \tan \theta_o \times M$, and for a telecentric system

(2) $\tan \theta_i = \tan \theta_o \frac{F}{h}$

(d) If scanning is provided at the entrance pupil and the line-of-sight is turned through an angle θ_o:



(3) The object distance $u = F + \frac{h}{\cos \theta_o}$

(4) The image distance $\frac{1}{v} = \frac{1}{F} - \frac{1}{F + \frac{h}{\cos \theta_o}}$

(5) $$v = \frac{(F)\ (F)\ (F + \frac{h}{\cos \theta_o})\ \cos \theta_o}{h} = \frac{F}{h}\ (F \cos \theta_o + h)$$

(6) and $M = \frac{v}{u} = \frac{F}{h} \cos \theta_o$

substituting in (1):

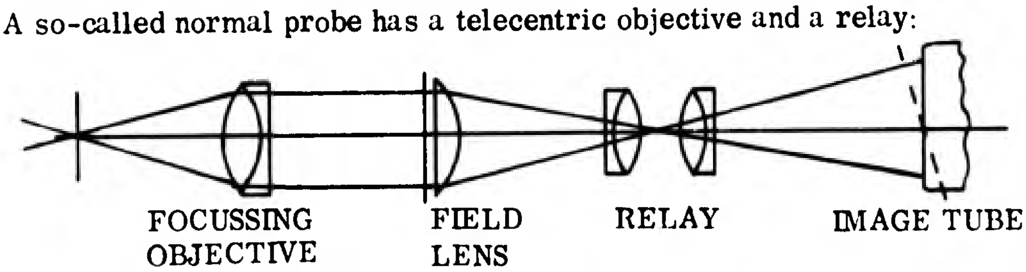
(7) $\tan \theta_i = \tan \theta_o \frac{F}{h} \cos \theta_o$

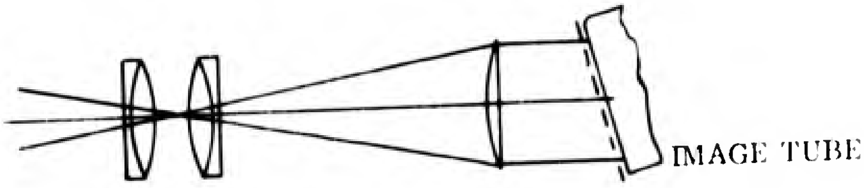
$\tan \theta_i = \frac{F}{h} \sin \theta_o$

The fact that the image tilt is limited and always considerably smaller than the object tilt even for $F/h = 1$, is an important consideration.

(6) The Farrand Probe

(a) A so-called normal probe has a telecentric objective and a relay:



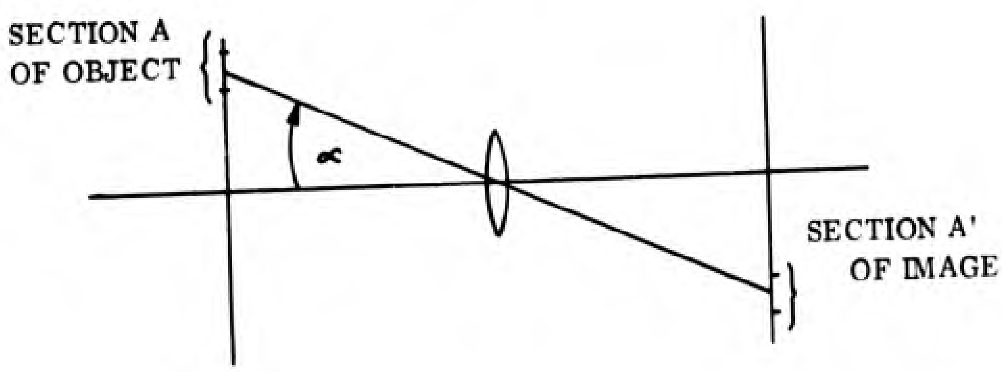


All results of tilt previously discussed for an objective with EFL = F apply to this system wherein F = EFL obj X Mag of relay.

(b) If we tilt the image tube to correspond to an image tilt then we put the system in focus and accept a variable magnification across the field of view in the plane of the tilt. However, from the prior discussion on telecentric systems we realize that if the image is made telecentric on the image side toward the tube and we tilt the tube we can put the system in focus while maintaining a constant magnification across the field of view in the direction of the tilt. This constant magnification in this tilt plane will differ from the magnification in the plane perpendicular to the tilt by a factor equal to the cosine of the tilt angle. This can be compensated for in one of several ways. For example, a cylindrical varifocal system may be inserted between the erectors and rotated to position its power in the tilt meridian. The magnification variation range is so limited that this varifocal system can be quite simple.

(c) However, the whole idea of mounting the tube in a gimbal for tilt is not desirable and a better solution has been achieved which permits the vidicon to remain stationary and aligned with the optical axis of the probe.

If we consider an optical relay as follows:



Section A of the object is imaged to section A' of the image. Both are at field angle α relative to the optical axis. Redrawing the above figure by tilting the relay lens, through an angle α, it is obvious that the image plane is tilted relative to the optical axis of the probe.

(d) In order to present the image plane perpendicular to the probe optical axis as required if the vidicon is to remain fixed, the tilt of the relay α_R relative to the tilt of the object plane α_o must satisfy the following relation:

$$\tan \alpha_R = \frac{\tan \alpha_o \, m_R}{m_R + 1}$$ where m_R is the relay

magnification from the objective focal plane to the vidicon focal plane.

(e) In effect this means that the optical design of the relay system is more difficult because the relay system must cover a field of view equal to its instantaneous field of view plus the tilt angle of the image. In addition the design of the relay must insure that the image does not wander on the face of the vidicon with changes in lens tilt. These difficult conditions were satisfied in the design of the relay and represent a major contribution to the success of the overall probe design.

3. APPENDIX C

a. ILLUMINATION AND MAPPING FUNCTIONS

An important consideration for the imaging of large FOV scenes onto any sensor is illumination fall-off with field angle. Considering a semi field angle of 70°, if the optics of the probe objective follow the $\cos^4\theta$ illumination law at 70° the illumination would only be 1.4% of that at the center of the field. This fall-off would manifest itself as a serious reduction in vidicon signal/noise at the edge of the field.

The $\cos^4\theta$ illumination law essentially requires a mapping function for the optics which follows the expression $h = f \tan\theta$. As mentioned previously, the probe object requires an image diameter which is constant for various object distances. This requirement dictates a telecentric design for the objective with the entrance pupil located at the front focal point of the lens. Such an arrangement contributes large natural amounts of negative or barrel distortion. This negative distortion alters the mapping of the objective to conform more closely to an $h = f\theta$ function. The effect of the various mapping functions to illumination across a field is illustrated in Figure C-1.

We see that curve "B" with an $h = f \sin\theta$ mapping function has illumination constant across the field. Of course this mapping function would not be suitable for our probe objective for reasons mentioned previously.

Following the procedures of Reiss, we will now determine the actual illumination at the 70° semi-field point of out objective.

E_θ = illumination at edge of field

E_o = illumination at center of field

$$\frac{E_\theta}{E_o} = \frac{f^2 \sin\theta \cos\theta}{h' (d h'/d\theta)}$$

where f = focal length of objective

θ = object semi-field

h' = image height

$\frac{d h'}{d\theta}$ = distortion expression

$$\frac{E_\theta}{E_0} = \frac{(6.296)^2 \sin 70^\circ \cos 70^\circ}{6.7408 (5.5176)} = 0.3425 \text{ or } \underline{34.3\%}$$

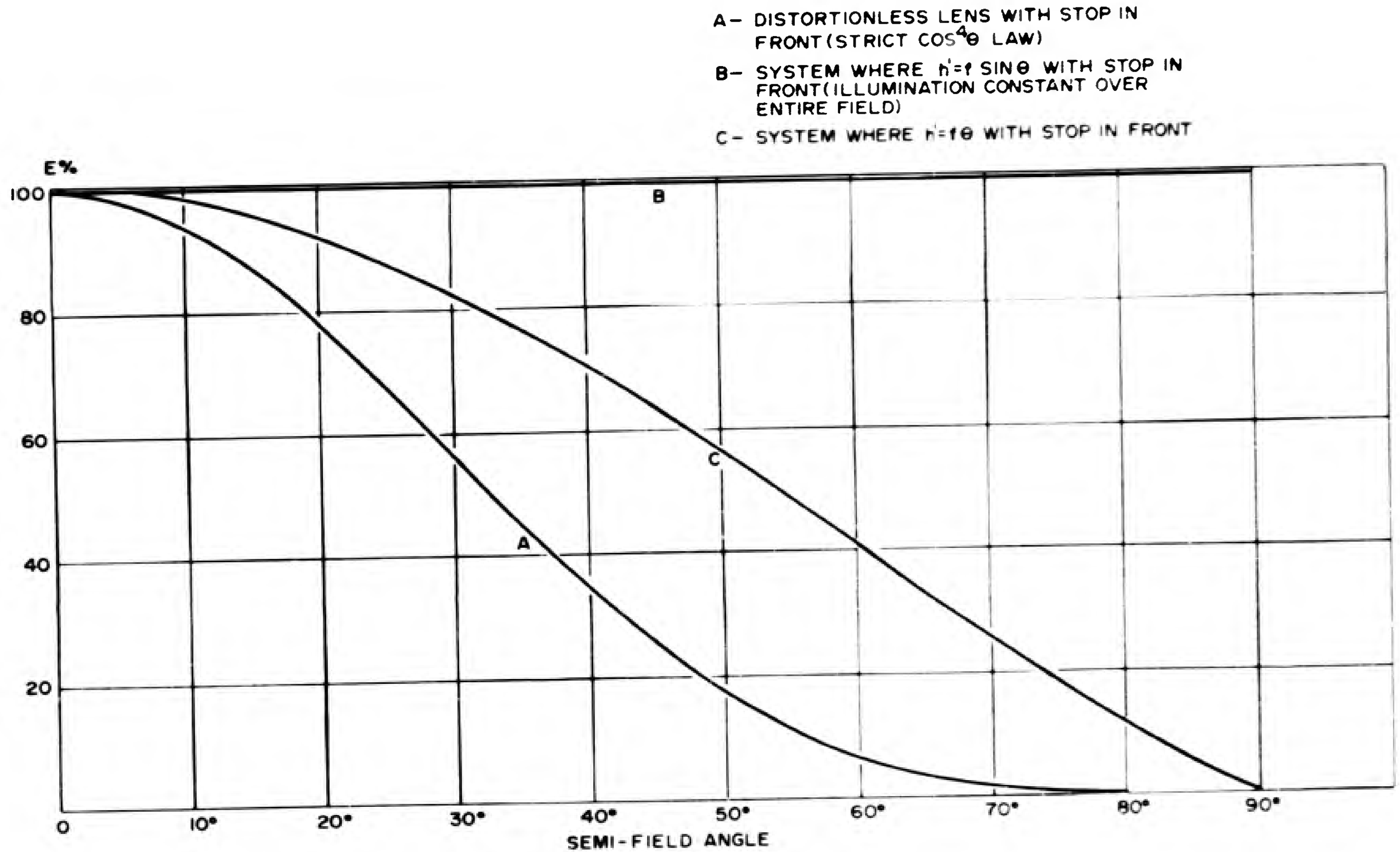


Figure C-1. f tan θ, f θ vs. f sin θ Mapping (Constant Illumination Across Field)

This compared to $\cos^4 \theta$ illumination is 1.4% vs 34.3%, a substantial increase.

It may be mentioned that the mapping function for our relay will not affect the mapping function for our objective because of the long conjugate at which the relay works. The image of the objective occupies only a small angular increment of the relay field at any one time, resulting in negligible dependence.

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13. ABSTRACT

During Phase I of the program, a study was undertaken to establish the most favorable approach toward producing a wide-angle, infinite depth-of-field, inclined-image plane viewing probe for purposes of simulation. The second phase involved fabrication, test and evaluation of an engineering feasibility model of such a device. This report describes both phases of the program.

Previous optical pickups for flight simulators were limited by slant range focus at close approaches to a model. Obtaining closer approaches has important size, cost and versatility advantages in making simulator terrain models and support equipment.

Phase I study results indicated the feasibility of producing a 140° circular field pickup with full pitch capability and a close approach of 4.1 mm. A preliminary but realistic design was developed and evaluated. The design approach was confirmed by photographing a runway model with a modified 110° probe.

Other concepts examined that had promise of improving resolution were dual sensor outputs and dual relays.

Component trade-offs, simplifications, and techniques were sufficiently developed for the design and fabrication phase of the program to proceed directly.

The Phase II design, fabrication and test program resulted in an engineering model that essentially met all of the design goals of the program. The probe system was evaluated numerically and photographically, working to an altitude of 0.2 inches. It has full functional operation in a static form and can readily be reworked to dynamic operation if desired.

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	ROLE	WT	ROLE	WT	ROLE	WT
Wide-Angle Field-of-View						
Infinite Depth-of-Field						
Inclined-Image Plane						
Optical Probe						
Visual Simulation						
Slant Range Focus						
Close Approach to Model						
Articulated Optical Path						
Scheimpflug Probe Geometry						

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