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PERI-APOLLAR 360 DEGREE LENS DISTORTION FREE LINEAR MAPPING.(U)
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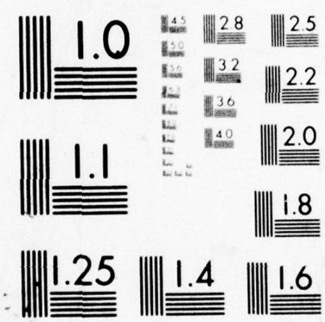

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TECHNICAL NOTE: NAVTRAEQUIPCEN TN-55

PERI-APOLLAR 360 DEGREE LENS DISTORTION FREE LINEAR MAPPING

Electronics and Acoustics Laboratory
Naval Training Equipment Center
Orlando, Florida 32813

February 1977

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Peri-Apollar 360 Degree Lens Distortion Free Linear Mapping

JOHN C. MC KECHNIE
Electronics and Acoustics Laboratory

February 1977

Approved:

H. [illegible]
Head, Electronics and Acoustics Laboratory

J. F. [illegible]
[illegible]
[illegible]

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Several methods, including fiber-optics are considered for producing a distortion free linear image transfer at both the optical probe and projection lens image planes of a 360 degree nonprogramed visual display. A description of five methods is given and each alternative examined analytically.

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SECTION I

INTRODUCTION

The 360° nonprogrammed visual display requires a near-perfect linear mapping between the probe lens and the display lens. Inherent in the design is a photo charge coupled device to convert the image produced by the optical probe lens into an electrical video signal to produce an image by means of lasers, electro-optical modulators and a projection lens. Earlier work had measured the characteristics of the existing Peri-Apollar probe lens image plane and the analytically determined Design A projection lens.

It remains to select a suitable method of compensating for the determined nonlinearities within the image planes of both lenses.

The Peri-Appolar 360° lens produces a flat circular image with varying radial resolution and distortion. The proposed image projection lens for the combined closed circuit visual simulation system is similar but has different inherent distortion, with a similar but inverted (inner to outer radius) image plane. It is necessary to match the two image planes, possibly by using optical fibers to result in a uniform mapping of the model scene onto the projection screen.

SECTION II

STATEMENT OF THE PROBLEM

The problem is to transfer a panoramic image from the circular image plane of the Peri-Apollar lens onto an optical CCD sensor within given linearity format constraints.

The purpose is to first; locate the optical CCD in a removed area and second; arrange the optical fiber light guide array to produce uniform resolution at the final projected image on the projection screen.

SECTION III

PROCEDURE

First a close examination was made of the overall 360 degree video system with particular attention to the probe lens image plane and the projection lens image plane. Measured data was available from the probe lens and calculated data was available for the projection lens proposed.

Five schemes were conceived to make the object space map more accurately into the projected image space. The first two used optical fibers, two used shifting of the probe image or projection screen image planes and one used electronic means.

The five methods were then evaluated based upon known data, from earlier reports and measurements, either graphically or by mathematics. Since several different schemes were evaluated, the order of final recommendations were made based upon: convenience, probable cost, and probability of success.

SECTION IV

RESULTS

An evaluation of the fiber-optic approach shows the image plane light level would be reduced to approximately 50% by the optical fiber image transfer. A method of compensating for radial image distortion by varying the CCD scanning rate within one CCD sweep cycle period can compensate for up to a $\pm$20% variation in image distortion.

Modification of the projection screen to produce a linear image seems to require a range and size of configuration almost too great to be useful. A change in the image plane radius of either or both probe and display lenses can reduce distortion to about 5%. To maintain equal resolution with no distortion, however, a complex variable fiber diameter, coherent fiber-optic bundle would probably be necessary.

SECTION V

DISCUSSION

1. Five possibilities are examined here for achieving that goal:

    a. Non-linear distribution of individual optical fibers.

    b. Best resolution of optical fibers.

    c. Change in radius of image plane.

    d. Variable clock rate CCD Scan.

    e. Distortion compensating display screen.

2. These five approaches are briefly examined below.

    a. FIBER OPTIC NONLINEARLY DISTRIBUTED INDIVIDUAL OPTICAL FIBERS.

By scanning the Peri-Apollar lens image plane with optical fibers the minimum resolution can be improved. The optical fibers can be arranged radially at the Peri-Apollar revolving image plane in equal resolution increments but nonequal radial distances. The fibers would be matched to corresponding sequential CCD sensor elements as shown in figure 1.

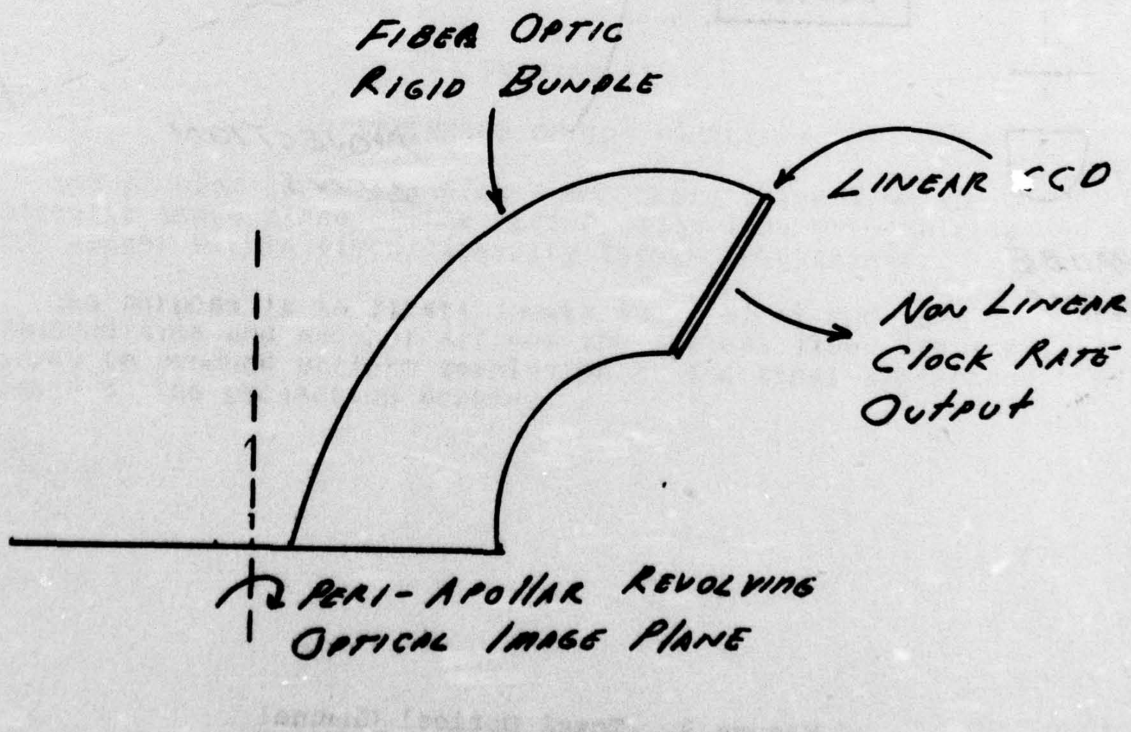

Figure 1. Image to CCD Fiber Optics

It would be necessary to "read out" the CCD sensors at an uneven clock rate; faster at the high resolution radii and slower at the low resolution radii. This would allow compensation at the Peri-Apollar lens revolving image plane to produce a final projected screen image, at the projector with an even resolution distribution. The variable clock rate is described in greater detail in this report under Solution D, Variable Clock Rate CCD Scan. The required system block diagram is shown in figure 2.

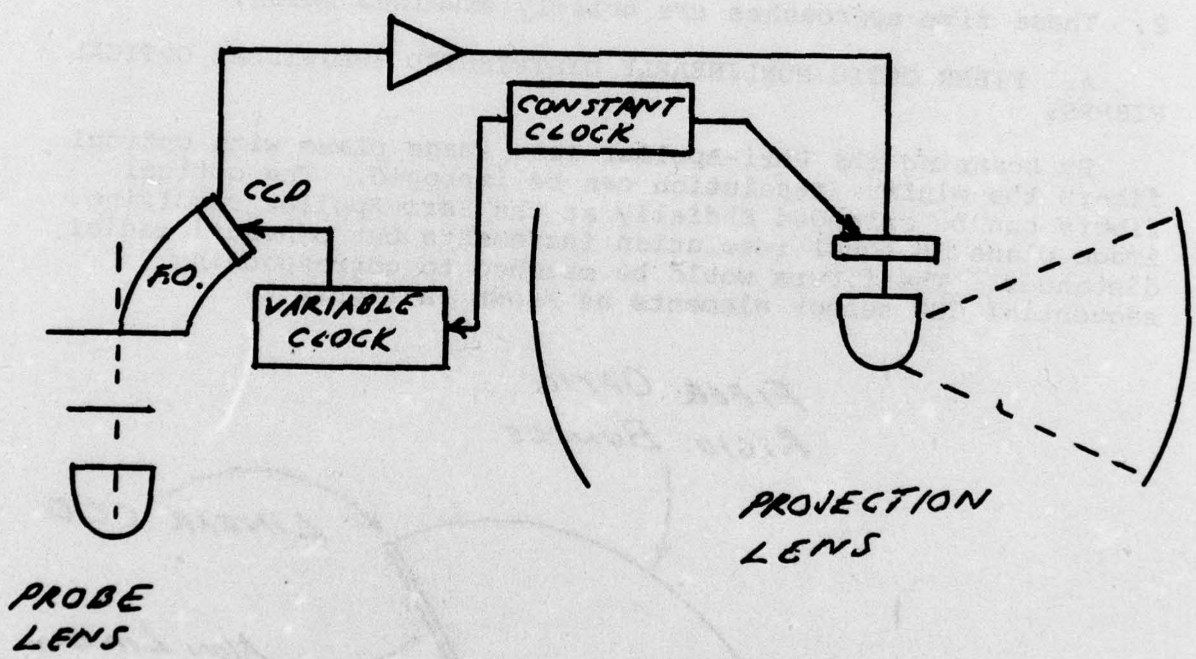

Figure 2. Total Optical Channel

A detailed look at a single light fiber shows the arrangement.

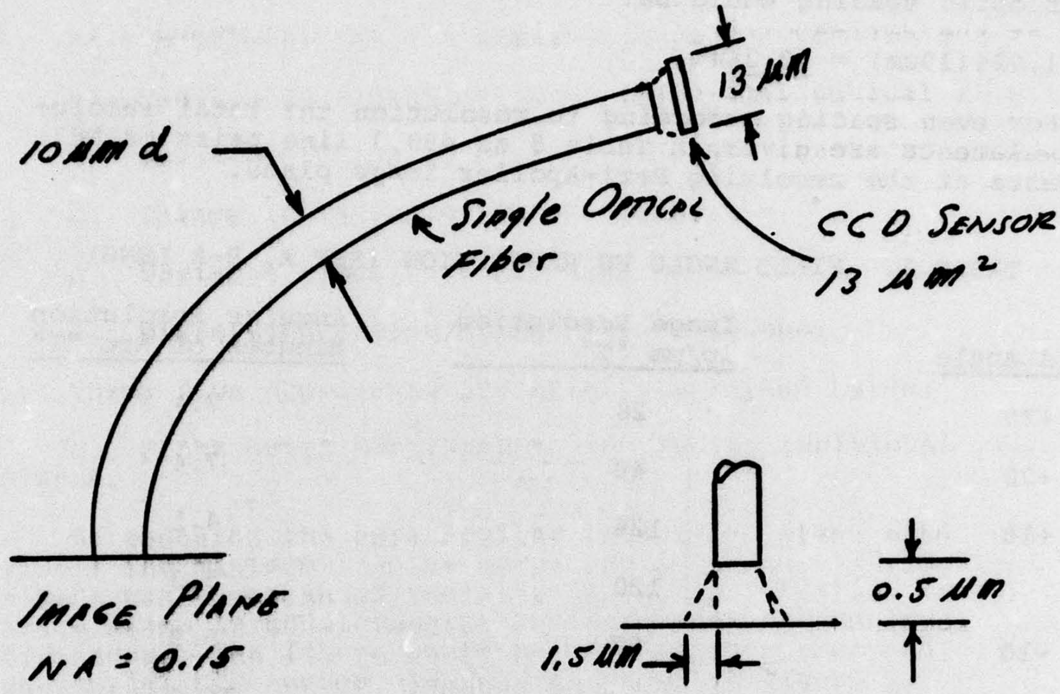

Figure 3. Single Fiber Interface

A 10 um fiber would match into each CCD sensor chip. Since spacing of the fiber end to the chip surface would cause spilling over of the light output, actual fiber optics (FO) to chip bonding would be most suitable.

13um sensor - 10 um fiber OD = 3 um

3 um/2 = 1.5 um fiber light output spreading each side

for a FO with NA = 0.35

(0.35)(1.5um) = 0.5um sensor to fiber end gap allowable

A means of controlling uniform resolution may be to adjust the image plane to optical fiber distance at the Peri-Apollar lens. The differences of numerical aperture between the image plane NA = 0.15 and the fiber optics NA = 0.35 would cause some additional light intensity losses. To adjust resolution by this means the fiber optics to image plane distance would need to vary by (126-28)(0.5/3) = 16 um, Table 1.

For distribution of the total 1024 optical fibers 10um in diameter radially along the image plane, the minimum overall fiber optic spacing would be:

1.024(10um) = 10.24mm

For even spacing according to resolution the total resolution elements are given in Table 5 as 493.3 line pairs or 987 elements at the revolving Peri-Apollar image plane.

TABLE 1. FIELD ANGLE VS RESOLUTION (REF A, P-A LENS)

Field Angle	Image Resolution lp/mm "T"	Angular Resolution Minutes of Arc "T"
+30	28	7.4
+20	40	7.4
+10	126	4.1
0	120	5.3
-10	87	9.3
-20	59	16.5
-30	48	26.6

An average angular distribution would be:

$$\frac{(60 \text{ degrees})(60 \text{ minutes})}{1024 \text{ elements}} = 3.52 \frac{\text{minutes}}{\text{element}}$$

The range in T (tangential) lp/mm resolution is:

$$\frac{126}{28} = 4.5{:}1$$

While the range in "T" angular "minutes of arc" resolution is:

$$\frac{26.6}{7.4} = 3.6{:}1$$

This means that while the F.O. spacing should allow an average of 3.5 minutes of image arc per fiber, the fiber spacing and the CCD chip clock speed would have to vary by either 3 1/2 or 4 1/2 to 1. When the spacing between individual fibers is increased from the minimum 10um up to 45 um, considerable image plane light would be lost.

An alternate approach would be to make the mapping function of the Peri-Apollar lens revolving image match the Design A projection lens (Reference B).

The mapping function relationships between the Peri-Apollar lens and the "design A" projection lens is illustrated in figure 4. If the Peri-Apollar image is to be mapped linearly into the Design A projection lens, the inner and outer image diameter of the P-A lens can be modified by fiber optics to fit the CCD.

Under these conditions:

$$t: R_{-}^{+}\ \theta = t: r_{+}^{-}, \theta$$

Referring to Figure 4 the Peri-Apollar lens image plane can be mapped into the photo sensitive elements of the CCD.

TABLE 2. FIELD ANGLE VS OPTICAL FIBER PLACEMENT

Field Angle in Degrees	Image Radius in mm	Length Along CCD in mm	Sequential CCD Sensor Number
-30	4.75	0	1
-24	5.25	1.33	102
-18	5.50	2.66	205
-12	5.75	3.99	307
-6	6.00	5.32	410
0	6.50	6.66	512
+6	7.25	7.99	614
+12	7.75	9.32	717
+18	8.50	10.65	619
+24	10.0	11.98	922
+30	11.8	13.3	1024

The projection lens in Design A is very nearly equal to the fiber optic modified sweep of the CCD output as shown in figure 4 by the dashed lines. It might be used directly without further adjustments.

B. Dr. Gottfried Rosendahl et al, Design Study of an Optical Systems for Panoramic Imagery, NAVTRAEQUIPCEN IH-254, June 1976.

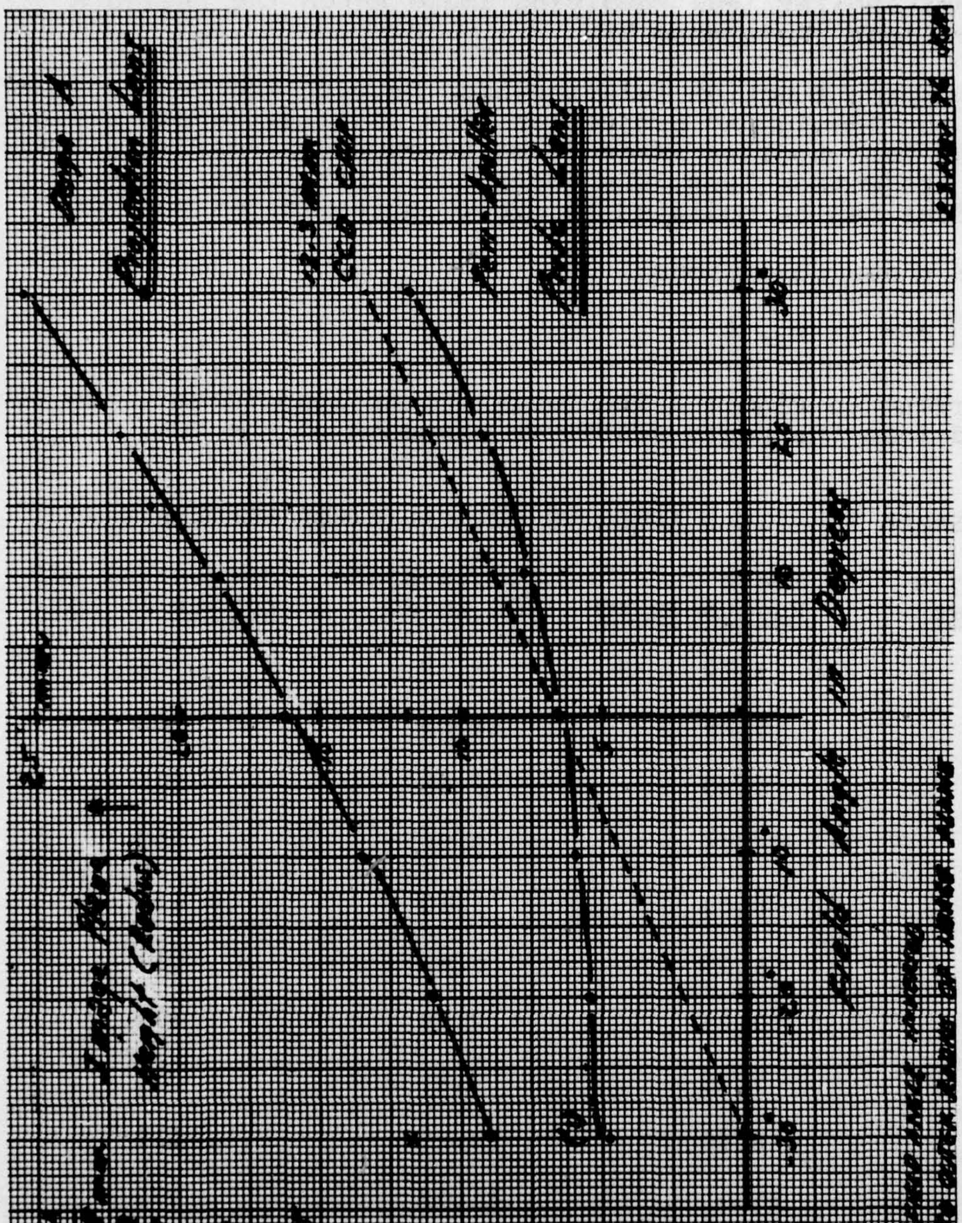

Figure 4. Mapping Function of Peri-Apollar Probe Lens and "Design A" Projection Lens

This approach would be difficult using fiber optics but would remove distortion in the system.

b. FIBER OPTIC COHERENT BUNDLE

Some related characteristics of optical fibers available are:

a. individual fibers

b. 2um minimum fiber diameters

c. 10um standard sub pack fiber

d. 25um standard fiber

e. tapered bundles available

f. formable (bendable)

g. magnifying bundle 1:1 to 5:1

TABLE 3. SOME OPTIC FIBER NUMERICAL APERTURES AVAILABLE (REF. BENDIX)

NA	Included Angle
.35	20.5°
.55	33.4°
.66	41.3°
.88	61.6°

Two alternate linear image sensors have been considered, the Fairchild CCD121 and the CCD131. The physical characteristics of both are listed in Table 4.

TABLE 4. CCD PHYSICAL COMPARISON

	Cell Size	Number of Elements	Total Active Length	Resolution
CCD 121	13um by 17um	1728	2.25cm	76.8 lins/mm
CCD 131	13um	1024	1.33cm	76.9 lins/mm

Because of the capability of appearing to move at higher shift speeds, it is understood that the CCD 131 image sensor will be used. Note: CCD 121, Ref. C; CCD 131, Ref. D.

Using the resolution data in Reference A, for the Peri-Apollar lens the total number of angular vertical resolution elements can be determined: as $\frac{\theta_2 - \theta_1}{\theta}$:

TABLE 5. TOTAL PROJECTED RESOLUTION ELEMENTS

Angle (Degrees)	Minutes of Arc	Number of Line Pairs
+30 to +25	7.4	40.5
+25 to +15	7.4	81.1
+15 to +5	4.1	146.3
+5 to -5	5.3	113.2
-5 to -15	9.3	64.5
-15 to -25	16.5	36.4
-25 to -30	26.6	11.3
	TOTAL	493.3 line pairs equals 986.6 elements or lines

While the required overall resolution of 987 lines is exceeded by either CCD, it would be very difficult to match the variation of the displayed screen image resolution at the probe circular image plane using a fiber optics bundle. This variation is illustrated in figure 5.

As one approach, a uniformly coherent fiber optics 1:1 bundle with 3 um fibers will be considered for coupling the probe revolving image into a stationary CCD 131 image sensor; figure 6.

A. Memorandum, F. J. Oharek, Peri-Apollar 360° Lens; performance evaluation of, 11 November 1971.
C. CCD121, 1728 - Element Linear Image Sensor, Fairchild Preliminary Data Sheet, August 1975.
D. CCD131, 1024 - Element Linear Image Sensor, Fairchild Preliminary Data Sheet.

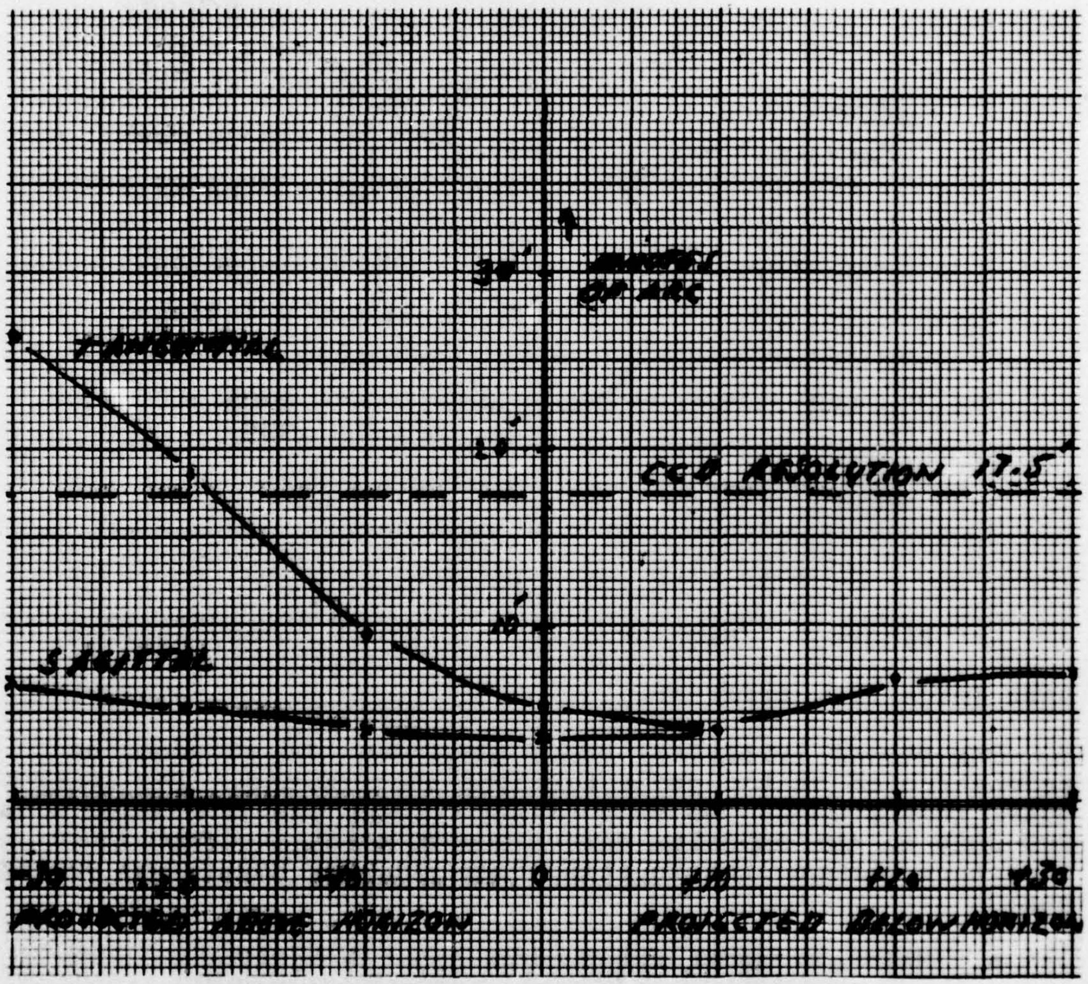

Figure 5. Resolution in Minutes VS Field Angle of Peri-Apollar Lens

Compensation within the fibers for the nonuniform characteristics of the image may be overly difficult. Therefore, the approach of coupling the image by means of uniform optical fibers having much greater resolution than the CCD image sensor will be used:

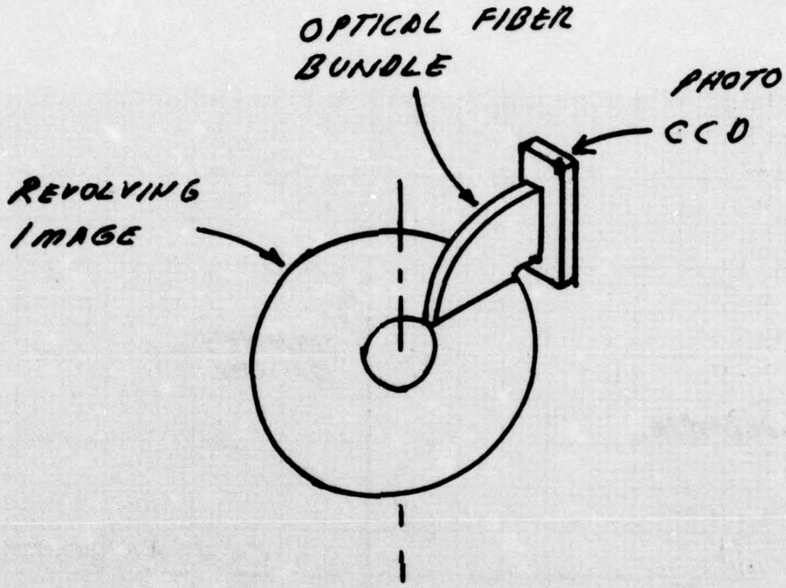

Figure 6. High Resolution Optical Fiber Coupling

Best image F.O. transfer.

The second (rotating) probe image must be inverted and reconstructed at the projector lens image plane. The inner to outer inversion can be done easily by scanning the image sensor CCD chip in the opposite direction; however, a fiber optic interface between the rotating image and the CCD image sensor can:

a. Maintain equal resolution

b. Flatten the image plane.

Looking at the image to be transferred:

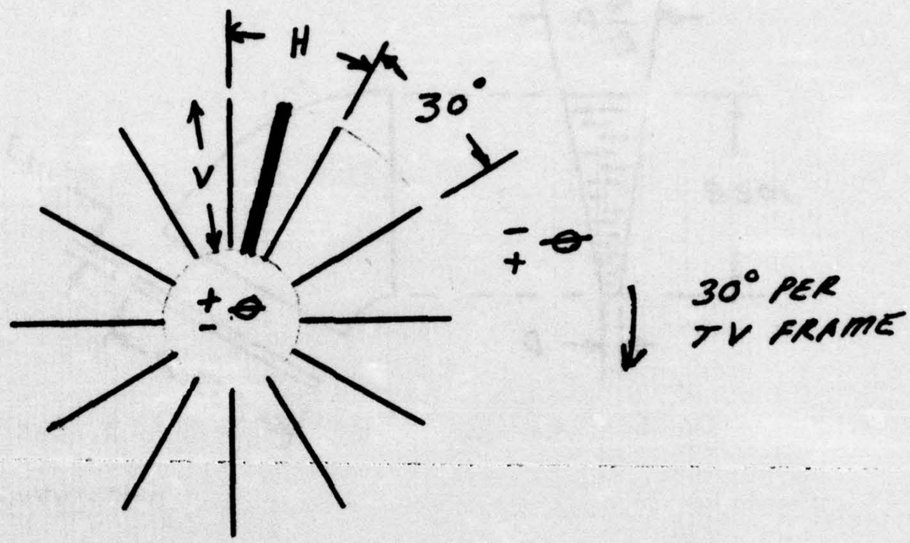

Figure 7. Peri-Apollar Revolving Image

All of the resolution data used here has been for a flat Peri-Apollar image plane. An image plane curvature might improve the image, as is the case for the projection lens, Reference B, page 29. The Fiber Optic bundle necessary to transfer the image from a curved image plane to the flat CCD sensor can be specified.

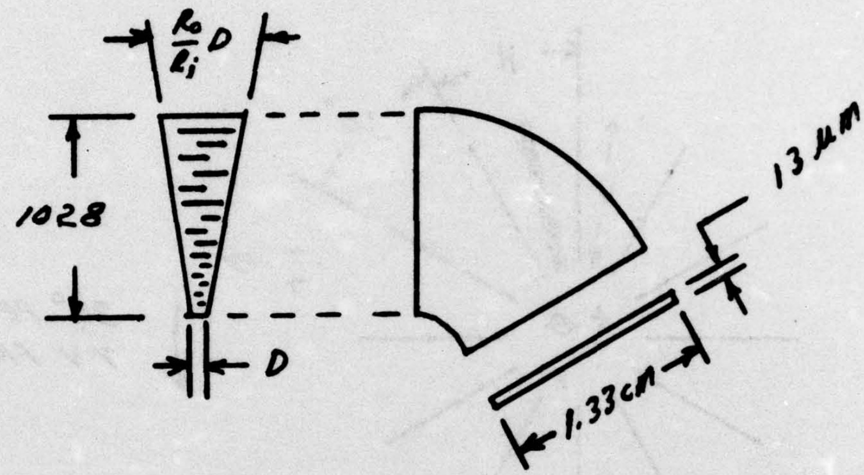

Figure 8. Fiber Optic Segment

fiber size	3um
fiber losses	10%/foot length
	6%/interface loss
	20%/coupling loss
fiber numerical aperature	0.35

Resolution - Since the 3um fused fiber bundle will resolve 167 lp/mm while the CCD image sensor resolves 76.9 lines/mm there will be little degradation by the fiber optics.

$$R_T = \frac{(R_o^2\ R_s^2)\ 1/2}{(R_o^2+R_s^2)}$$

$$R_o = NR_s$$

$$N = 167/38.45$$

$$= 4.34$$

$$R_T = R_s \frac{N^2}{N^2+1}$$

$$R_T = (38.45)(0.949)$$

= 37.47 lp/mm resultant output

The light loss will be:

l_1: $\frac{10\%}{12}$ per foot X 3 inches = 2.5%

l_2: two ends at 6% each end, entrance and exit losses

l_3: assume a film to fiber and a fiber to detector loss of 20% each

$$T = (1-l_1)(1-2xl_2)(1-2xl_3)$$

$$= (1 - 0.025)[1 - 2(0.06)][1 - 2(0.20)]$$
$$(0.975)(0.88)(0.60)$$
$$= \underline{0.5148}$$

or 52% light transfer

The mapping function from Reference A of the Peri-Apollar lens image plane can be compared to the effective resolution of the CCD - fiber optic combinations.

The original mapping function from Reference A, and the "multiplier modified" mapping function for the Peri-Apollar image plane are shown in figure 9.

The resulting angular resolution is listed in Table 6.

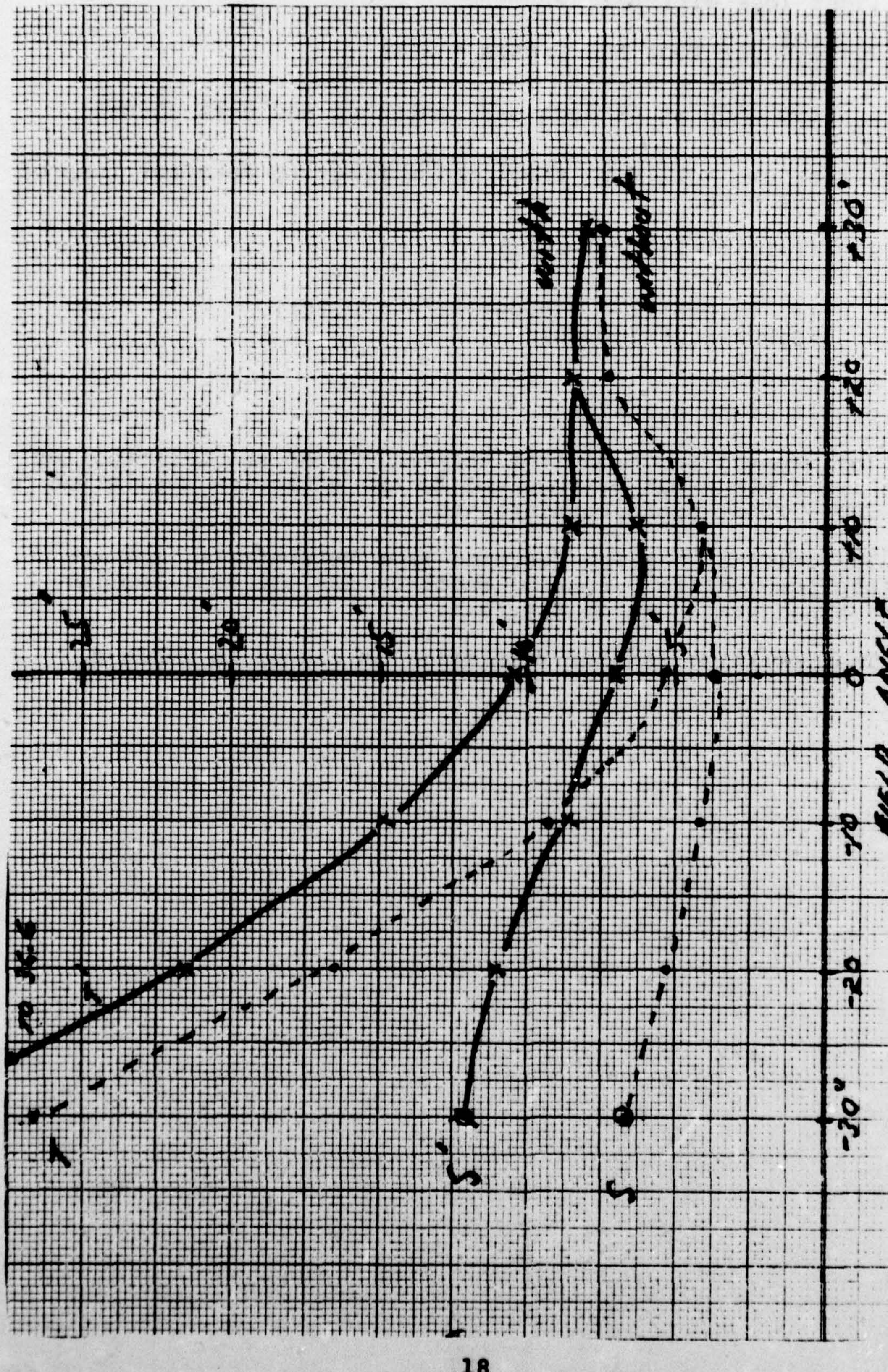

Figure 9. Angular Resolution of Peri-Apollar Lens With and Without Fiber Optics

TABLE 6. RESOLUTION CAUSED BY PERI-APOLLAR IMAGE PLANE AND FIBER-OPTIC - CCD READOUT

Field Angle	Image Point Radius	Modified l.P. Radius (1)	Resolution l/mm T/S	Adjusted Resolution Caused by Field Expansion (2)	Modified Subtended Arc Caused by CCD 38.45 lp/mm (3)	Modified by FO and CCD N=37.47 (3)	WAS T'/S'	T'/S' CCD (4)	T'/S' CCD+FO (4)
+30	11.8mm	22.26	28/27	14.8/14.8	13.8/13.8	13.77/ 13.77	7.4/ 7.4	7.9/ 7.9	7.9/7.9
+20	9.3	17.54	40/40	21.2/21.2	18.56/ 18.56	18.45/ 18.45	7.4/ 7.4	8.5/ 8.5	8.5/8.5
+10	7.7	14.53	126/84	66.8/44.5	33.3/29.1	32.7/ 28.7	4.1/ 4.1	8.2/ 6.4	8.4/6.4
0	6.6	12.45	120/114	63.6/60.4	32.9/32.4	32.3/ 31.8	5.3/ 3.7	10.2/ 6.9	10.5/7.02
-10	5.8	10.94	87/129	46.1/68.4	29.5/33.5	29.0/ 32.9	9.3/ 4.1	14.5/ 8.4	14.8/8.5
-20	5.2	9.81	59/94	31.3/49.8	24.2/30.4	24.0/ 23.6	16.5/ 5.2	21.3/ 8.5	21.5/11.0
-30	4.75	8.96	48/77	25.4/40.8	21.2/ 27.98	18.45/ 22.4	26.6/ 6.6	31.9/ 9.6	36.6/12.0

Note: $m = \frac{13.3}{11.8 - 4.75}$

$= 1.8765$

(1) Modified 1P radius - (1P radius) X (m)

(2) Adjusted resolution = (resolution ÷ (m)

(3) Let $N = R_2/R_1$

Then R = (N /N+1) 1/2

(4) AR^1 = (original angular resolution) X (modified lp/m/field expanded resolution)

Two companies making optical fibers and fused coherent bundles applicable to these requirements are the American Optical Company of Southbridge, Massachusetts and the Bendix Electro Optics Division of Sturbridge, Massachusetts.

c. IMAGE PLANE CHANGE

The image plane at the Peri-Apollar lens is the area within two concentric circles. Reference A shows that the projected representative field elevation angle is not uniformly related to the image plane radius. This nonlinearity and difference in resolution between the inner and outer circle can be minimized by minimizing the inner and outer circle difference.

While a firm value for the probe and projector lenses image diameters has not yet been established, References A and B list the following:

TABLE 7. IMAGE PLANE ASPECT/RATIO

Reference	Location	Type	Outer Image Diameter	Inner Image Diameter	Image Thickness	r_o/r_i
a	probe	Peri-Apollar	23.6mm	9.5mm	7.0mm	2.5
b	projector	Design A	49.5	8.6	20.5	5.8
c	projector	Design B	95	42	26	2.3

Using a CCD 131 image sensor with 1024 of 13um sensing elements, the total effective radial length would be 13.3mm without a fiber optic or glass lens scale change.

The difference in effective circumference on the rotating Peri-Apollar image plane would be:

$d_o = 2t_s + d_i$ — d_o = outside diameter

$C_i = d_i$ — d_i = inside diameter

$C_o = (d_i + 2t_s)$ — t_s = sensor thickness

$$\frac{C_o}{C_i} = \frac{2t_s}{d_i} + 1$$

C_o = outside circumference

C_i = inside circumference

By forming the Peri-Apollar image within a radius of the image plane corresponding to the equivalent uniform slope, (elevation angle VS image plane radius) of the projection lens system, this distortion could be minimized. See figure 4. Uniformity of resolution could be compensated for by fiber optics or other means.

If an outer image plane diameter at the Peri-Apollar probe of 50mm is possible, then with a sensor radius of 13.3 mm (CCD 131), the Cs/Ci ratio needed would be:

$$Co/Ci = \frac{2(13.3)}{23.4} + 1$$

$$= 2.14$$

The image plane dimensions would be:

OD = 50mm
1D = 23.4mm
ring thickness = 13.3mm

By shifting the image plane radius of the probe lens and projection lens, as they are shown in figure 4, it would be possible to improve their linear relationship. They need not have the same radial slopes, only uniform slopes.

d. VARIABLE CLOCK RATE CCD SCAN

The mapping function between the Peri-Apollar probe lens and the Design A projection lens are not uniform. By varying the clock rate of the CCD, and operating the projection scan with a uniform sweep, the projection display can be made uniform. For example:

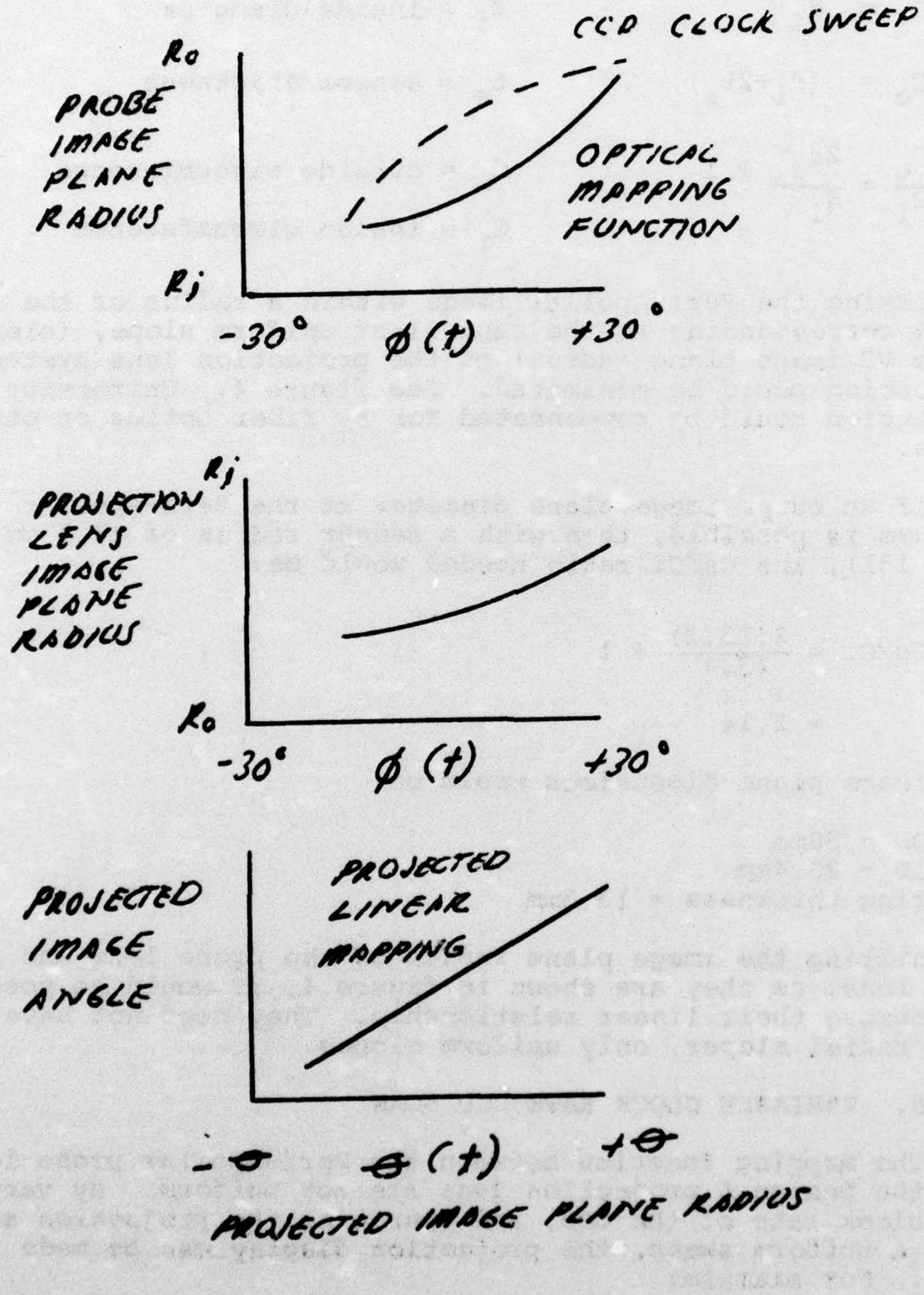

Figure 10. Clock Compensating Optical Distortion

Expressing this mathematically in terms of time compensated spatial distortion:

Distortion in the Peri-Apollar probe combined

$$\theta(t)_{P-A} - \theta(t)_{DesA} = \text{(time distortion)}$$

Optically

$$\theta_{P-A} - \theta_{Des-A} = \text{Spatial projection distortion}$$

Electronically

$$\theta(t')_{P-A} - \theta(t')_{DES-A} = \text{Compensation (electrical)}$$

Results

$$\theta(t-t')\,\theta_{(t)\,P-A}\ \text{(Compensation)}_{f(t)} = \theta(t)_{DES-A}\ \text{(compensated)}$$

So that: $\theta(t)$ probe space = $\theta(t)$ projected image space.

The clock rate of a Fairchild 131CCD normally runs at 20MHz = 2X(10MHz). The maximum effective clock rate is 24MHz = 2X(12MHz). This "over capacity" in scanning velocity will allow the CCD to operate above the nominal 20MHz to compensate for the sweep time that it must operate below MHz.

The variable CCD clock approach used earlier in the report for fiber optics nonlinear compensation is illustrated in figure 2.

The required clock rate variation to accommodate the probe and projector image planes can be determined from figure 11.

Slope variation for the projector lens is:

$$m = \frac{(10/13) - 10/23)}{10/13}(100)$$

$$= \frac{(1 - 13/23)}{1}(100)$$

$$= 43.4\%$$

by choosing a midrange value:

$$\frac{43.4\%}{2} = \pm 21.7\%, \text{ within the capabilities of the CCD}$$

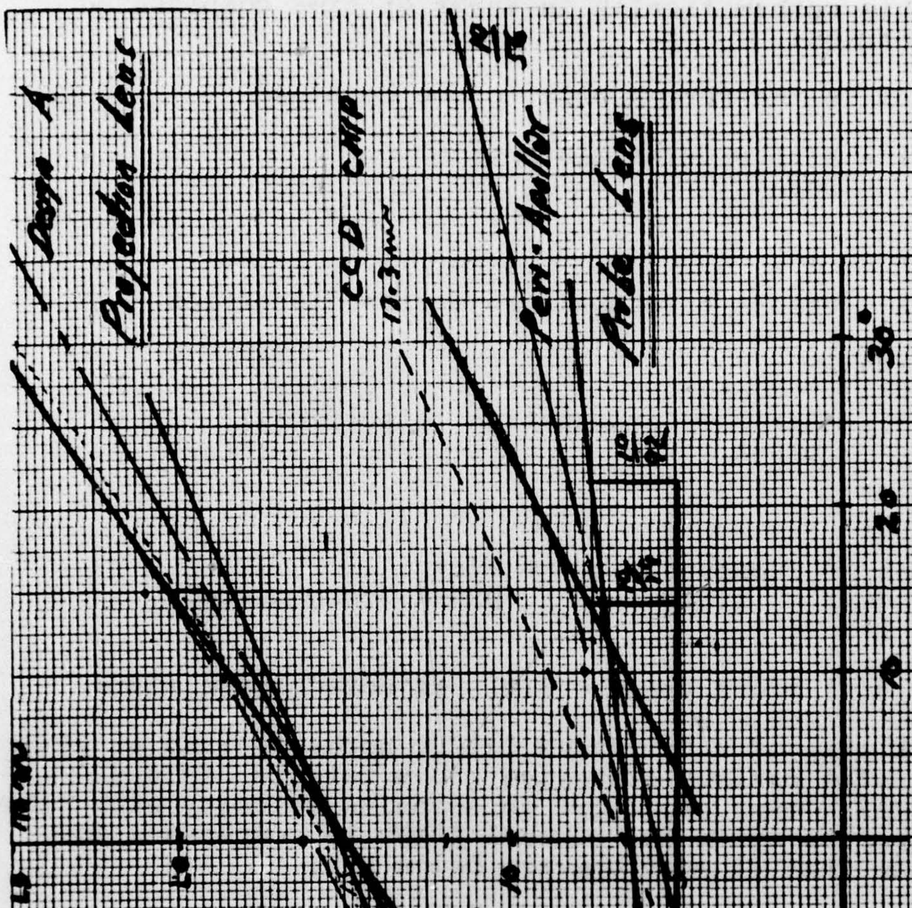

Figure 11. Probe and Projection Lens Image Plane Slope Variation

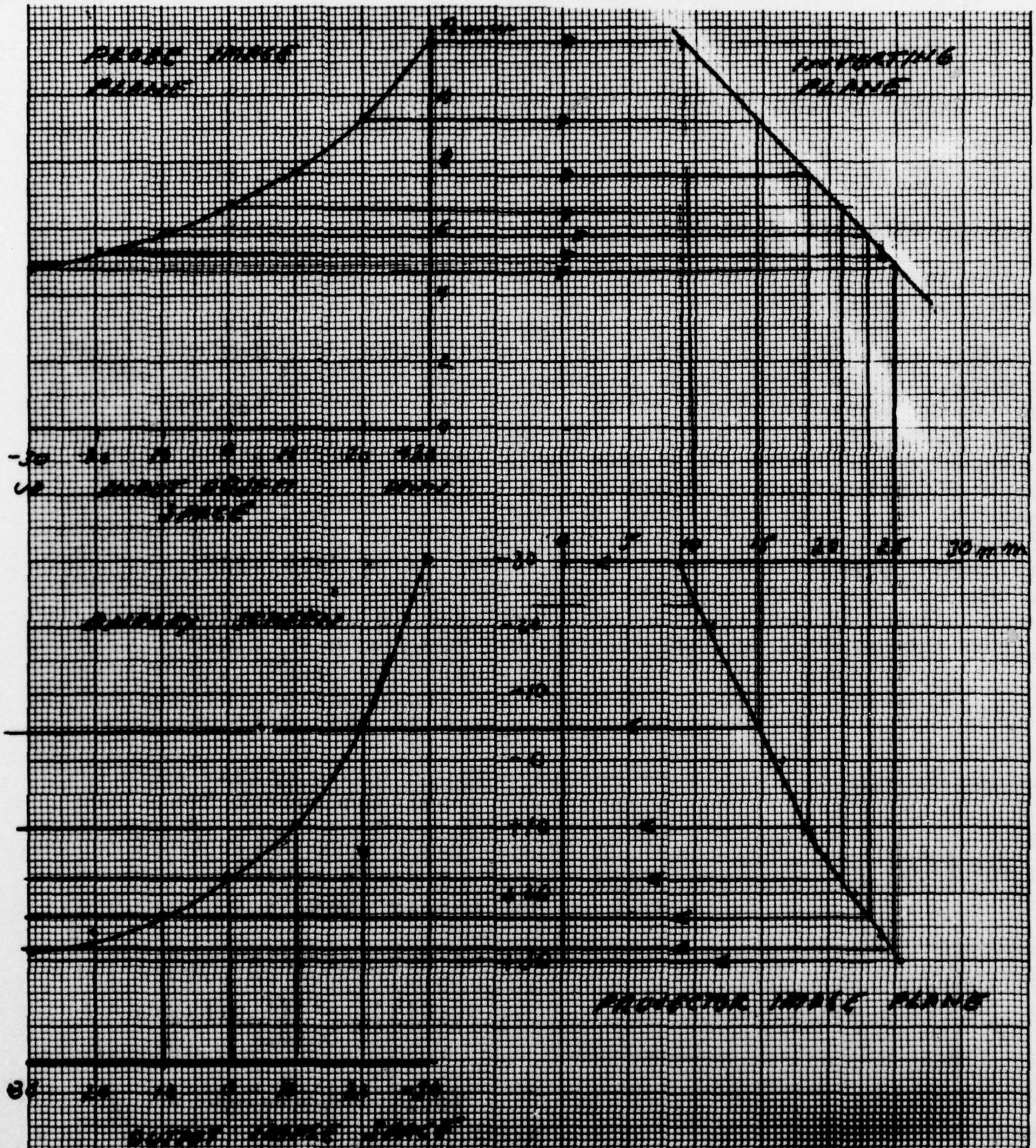

Figure 12. Distortion Compensating Display Screen

The slope variation for the probe lens is:

$$m = \frac{(10/19 - 10/92)}{10/19} (100)$$

$$= \frac{(1 - 19/92)}{1} (100)$$

$$= 79.3\%$$

again by choosing a midrange value

79.3%/2 - ± 40%, possibly within the CCD capabilities with modification to the image plane.

Note that the projection lens image plane is inverted, inner to outer, since each image plane is being compared to its average value "uniform slope"; the variation in slope for each image plane holds true. The variable CCD clock rate may be implemented as shown in figure 13. There are several alternate means of generating a variable clock sweep rate. Figure 13 is meant to be a representative example. The analog shift register transport clocks vary through the CCD sweep cycle to accommodate nonlinearities in the lens image plane. Both the transfer gate clocks and the reset clocks remain constant to retain a constant periodicity for each photo sensor and to retain synchronism within the optical system effective 20MHz.

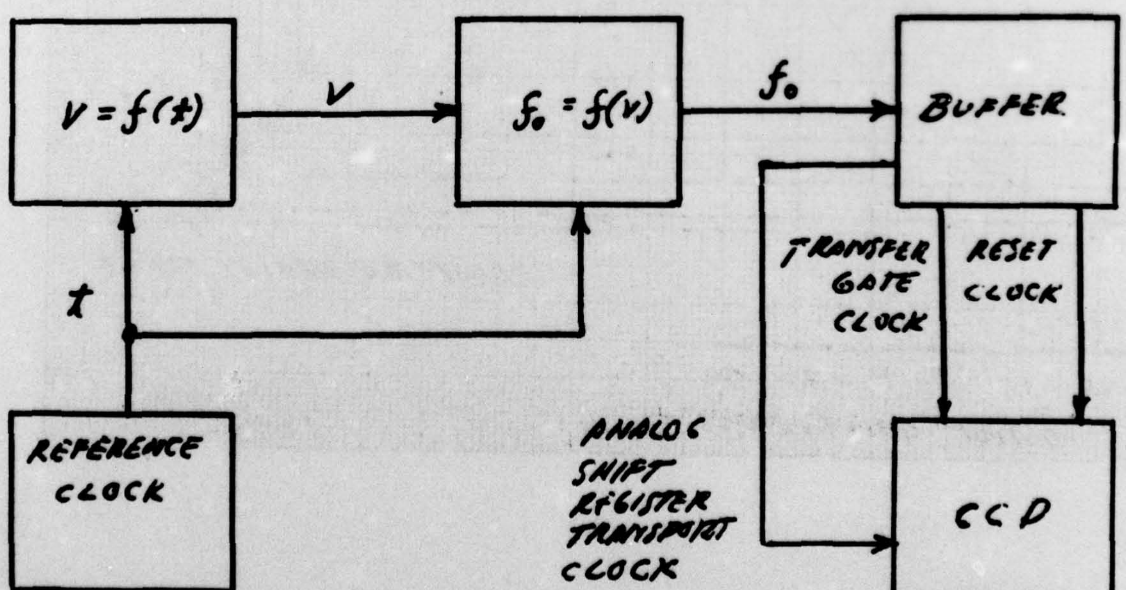

Figure 13. CCD Linear Image Sensor Variable Clock Rate

e. PROJECTION SCREEN MODIFICATION

As a final possibility for producing a linear projection screen image, the projection screen itself may be distorted to produce a linear image. By mapping the nonlinear radius distortion of the pickup lens image; through the nonlinear radius distortion of the projection lens, onto a compensating form projection screen, the viewed image can be made linear. This is shown in figure 12. The difference in resolution will need to be compensated for by other means such as described earlier in this report.

SECTION VI

CONCLUSIONS

This report shows that the problem of transferring the panoramic image from the circular image plane of the Peri-Apollar lens onto an optical CCD sensor with restored spatial linearity can be accomplished by means of fiber optics. A light loss of approximately 50% would result with little degradation of resolution. Several supplementary and alternative schemes include varying the CCD scan rate to restore spatial linearity, shifting the image plane radius, and modifying the projection screen.

SECTION VII

RECOMMENDATIONS

Since the 360° Optical System has not yet been finalized in design, a "best alternative" cannot yet be chosen. Fiber optics can be expensive, particularly when using nonlinear compensating optical fibers. As a cost effective approach the order of recommended solution would be:

a. Change the annular radius of the Peri-Apollar lens circular image plane.

b. Vary the charge coupled device clock scan rate.

c. Utilize a rigid high resolution uniform optical fiber bundle.

d. Construct a nonlinear distribution of individual optical fibers.

e. Construct an image compensating projection screen.

Optical fibers may be used to unify the projected image resolution and make the overall image linear. However, the fiber optics would be complex. A combination of uniform rigid high resolution fiber optics and a variable CCD scanning rate should be considered. This would be a less costly and simpler approach than the accurate nonlinear placement of individual compensating optical fibers with a linearity distortion of more than 4:1.

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