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ROTATING MIRROR CAMERA DESIGN

Written by:

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Albert J. Lipinski

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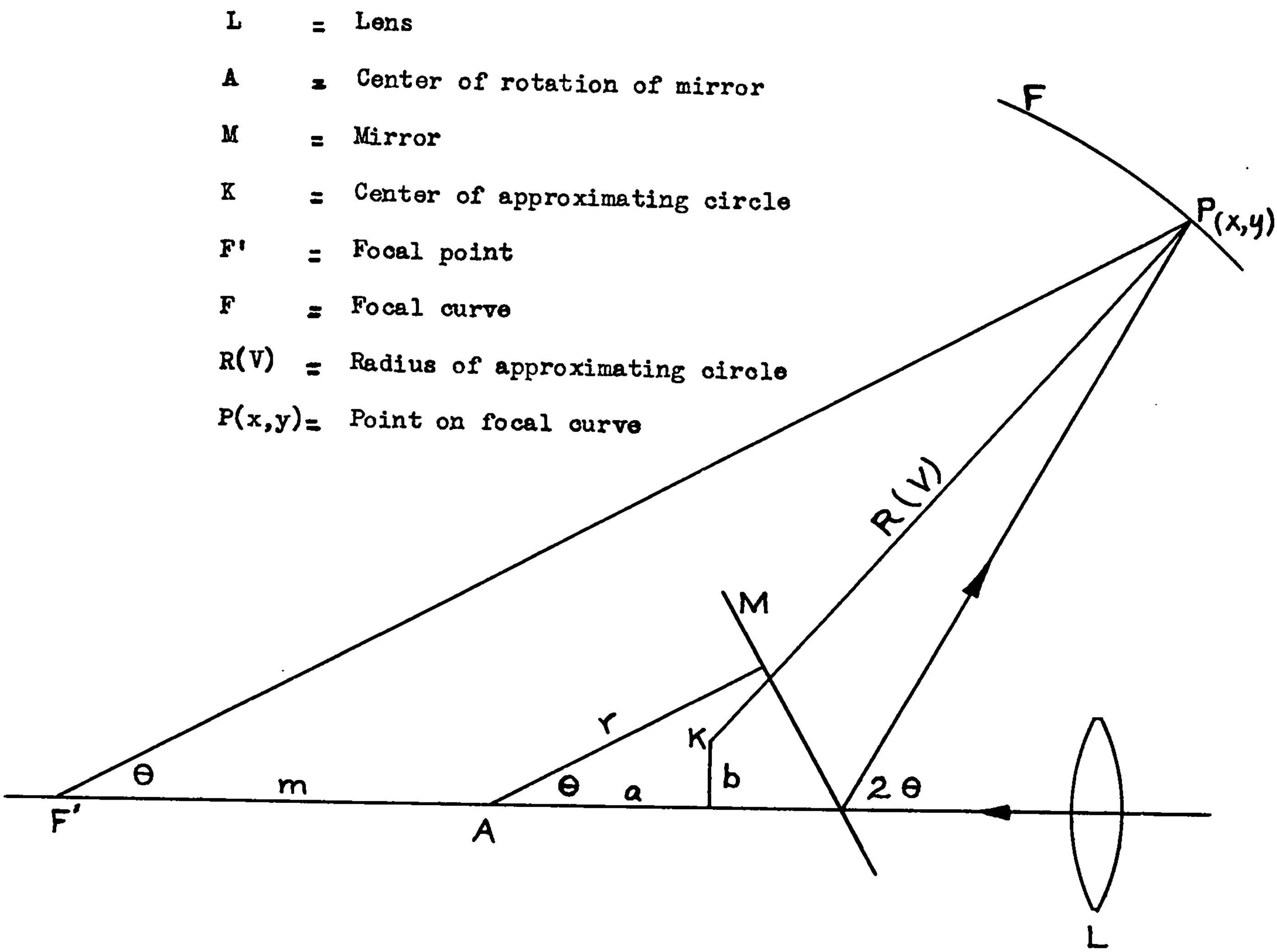


Fig. I Schematic sketch of rotating mirror camera illustrating the terms used in the various writing speed equations.

ROTATING MIRROR CAMERA DESIGN

Many cylindrical film-plane rotating mirror cameras have been designed and built[1,2,3,4], but little of the detail has been given. It is the purpose of this paper to detail the principles used and clarify points only implied in previous papers. The solution of a sample problem is also carried out in detail.

A cross section of the general arrangement of such a camera is shown in Figure I. The lens L images an object on the film F, after reflection by the rotating mirror M. The locus of the points of sharpest focus is a circle when the mirror plane passes through the axis of rotation and the image writing speed is constant. It is impractical to apply this condition to mirrors used at high rotational speeds because of balancing requirements. A thick symmetrical mirror construction is usually used and this separates the mirror plane from the axis of rotation. The locus of sharp focus is then a limaçon[2], and the image writing speed is variable.

The Bowen Camera[1] body was of wood construction, and a circular film surface was used to approximate the limaçon of sharp focus over a range of 100°. The wood construction dimension tolerance is greater than the error in the circle approximation to the limaçon. The depth of focus of the f/20 optical system is slightly greater than this dimensional tolerance. The various defects of this camera are thus seen to be of about the same order of magnitude.

The total resolution of a complex photographic recording system has been shown to be approximately equal to the sum of the various resolutions contributing to the formation of the film image.[5]

To obtain the highest resolution it is necessary to go to metal construction so that the dimensional tolerance can be made small. All-metal models[3] have been designed, using a circular film frame over an angular focal range of 50 to 60 degrees or less. For this range the approximating focus can be held to ±.001 inch. When the specifications called for a camera with the same angular range as the wooden Bowen it was found that the best approximating circle (determined by a least square solution) would vary by ±.018 inch from the limaçon. This large deviation hence becomes the limiting factor in an all-metal construction where the over-all construction can be kept to ±.005 inch. Since the lens on the camera would be working at a low aperture (f/20), the depth of field of ±.020 inch would cover the approximation variance, but this is pushing the optics to the very limit and is not desirable.

Although it is not necessary to have a constant writing speed, it is important that we know what that speed is for any angular position (2θ) on the film. In the available literature there are several equations which may be used to compute the desired values if the constants of the camera are known. In the following section these are listed chronologically and their terms compared in Table 1. Equations (1), (2), and (4) are identical in that they contain identical terms and give the writing speed along the limaçon. Equation (4) differs from the other two by being expressed in rectangular coordinates. Equation (3) gives the writing speed along a circle (film plane) approximation to the limaçon and will give, over the 100 degree range, writing speed agreement within 0.1 per cent of the limaçon, see Figure II. The writing speed agreement depends on how closely the circle approximates the limaçon. For angular focal ranges of 40 degrees or less,[4] the agreement will be within 0.02 per cent. Equation (3) has the advantage of using all the parameters in the camera design and hence an error in any one of them may be used to calculate the corresponding writing speed error produced. It has the disadvantage of being more difficult to compute than (1) and (2). Equation (4) was originally used as a check for Equation (3). The parametric form of the equations for x and y are very useful in determining points along the transcendental curve. These points are used to determine the best approximating circle to the transcendental curve by a least square solution. If the transcendental curve is to be constructed, the use of rectangular coordinates is more advantageous in machine shop layout.

Writing Speed Equations and Comparison of Terms

I. S. Bowen (April 27, 1945)

$$S = 2\,(r^2 + m^2 + 2rm\cos\theta)^{\frac{1}{2}}\ \frac{d\theta}{dt} \qquad (1)$$

S = writing speed

r = radius of mirror

m = $\sim$ lever arm

θ = angle of incidence on mirror

$\frac{d\theta}{dt}$ = mirror velocity

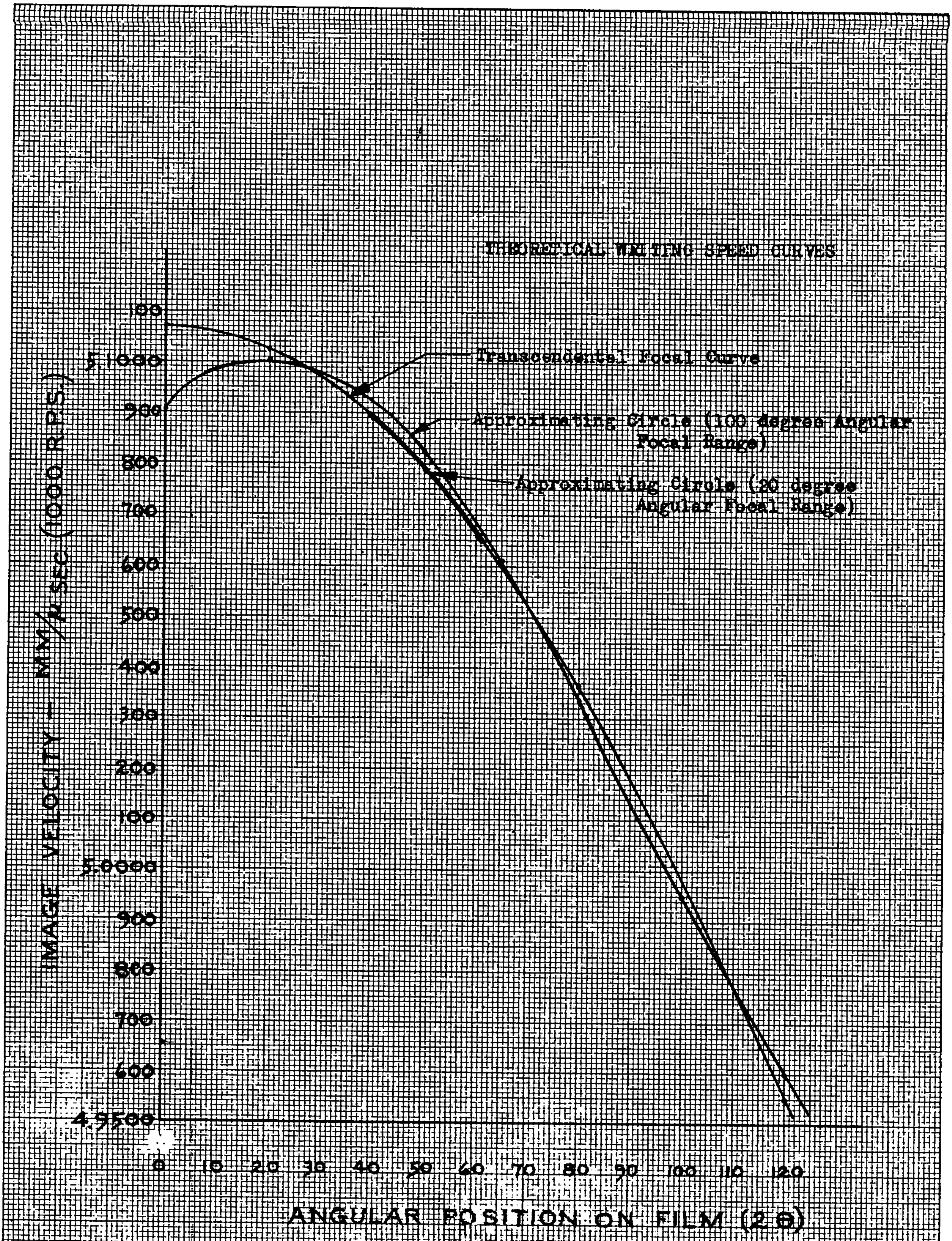

THEORETICAL WRITING SPEED CURVES
Transcendental Focal Curve
Approximating Circle (100 degree Angular Focal Range)
Approximating Circle (20 degree Angular Focal Range)
IMAGE VELOCITY — MM/μ SEC (1000 R.P.S.)
100
5.1000
900
800
700
600
500
400
300
200
100
5.0000
900
800
700
600
4.9500
0
10
20
30
40
50
60
70
80
90
100
110
120
ANGULAR POSITION ON FILM (2θ)

Fig. II

Julian E. Mack (December 15, 1947)

$$v = 2\omega(a^2 + 2a^2\beta\cos\Theta + a^2\beta^2)^{\frac{1}{2}}$$

but, $\beta = \frac{b}{a}$ and $\omega = \frac{\Theta}{t}$

$$v = 2(a^2 + b^2 + 2ab\cos\Theta)^{\frac{1}{2}}\ \frac{\Theta}{t} \qquad (2)$$

v = writing speed

b = radius of mirror

a = ~lever arm

Θ = angle of incidence on mirror

$\frac{\Theta}{t}$ = mirror velocity

(Note similarity of Equations (1) and (2))

Perry, Igel and Hamann (February 9, 1950)

$$\frac{ds}{dt} = 2V\left[1 - \frac{r\cos\Theta - a\cos 2\Theta - b\sin 2\Theta}{\left[V^2 - (2r\sin\Theta - a\sin 2\Theta + b\cos 2\Theta)^2\right]^{\frac{1}{2}}}\right]\frac{d\theta}{dt} \qquad (3)$$

$\frac{ds}{dt}$ = writing speed

V = radius of circular film frame

r = radius of mirror

Θ = angle of incidence on mirror

a, b = coordinates of center of circular film frame with center of rotation of mirror as origin of coordinate system

$\frac{d\theta}{dt}$ = mirror velocity

B. Brixner (February 19, 1950)

$$x = \frac{r}{\cos\theta} + \left[\frac{r}{\cos\theta} + m\right] \cos 2\theta$$

$$y = \left[\frac{r}{\cos\theta} + m\right] \sin 2\theta$$

$$\frac{dx}{dt} = \left[r \tan\theta\sec\theta - 2r \sec\theta \sin 2\theta + r \cos 2\theta \tan\theta \sec\theta - 2m \sin 2\theta\right]\frac{d\theta}{dt}$$

$$\frac{dy}{dt} = \left[2r \sec\theta \sin 2\theta + r \sin 2\theta \tan\theta \sec\theta + 2m \cos 2\theta\right]\frac{d\theta}{dt}$$

$$\frac{ds}{dt} = \left\{\left[\frac{dx}{dt}\right]^2 + \left[\frac{dy}{dt}\right]^2\right\}^{\frac{1}{2}}$$

$\frac{ds}{dt}$ = writing speed

r = radius of mirror

m = ~lever arm

θ = angle of incidence on mirror

$\frac{d\theta}{dt}$ = mirror velocity

Relation of Corresponding Terms in the Four Equations

Equation 1		Equation 2		Equation 3		Equation 4
s	=	v	≠	$\frac{ds}{dt}$	≠	$\frac{ds}{dt} = 1,2$
m	=	a	=		=	m
r	=	b	=	r	=	r
				V		
				a		
				b		
θ	=	θ	=	θ	=	θ
$\frac{d\theta}{dt}$	=	$\frac{\theta}{t}$	=	$\frac{d\theta}{dt}$	=	$\frac{d\theta}{dt}$

Table 1

As a result of the limitation imposed by the 100 degree focal range of the approximating circle for a good focus, it was decided to attempt a construction of the exact transcendental film curve to obtain the best focus throughout the length of the film. Rectangular coordinates were determined for the construction of the camera sides by the use of Brixner's parametric equations. Rectangular coordinates were used to facilitate machine shop work. Polar coordinates were also computed by Bowen's equation to serve as a check on the completed camera side plates. The construction checked to ±.003 inch. To insure that the central ray intersects the center of the rotating mirror, the lens can be rotated about its axial focal point as shown in Figure III, without changing the constants in any of the equations. Although this is hinted in Figure 2 of the original Bowen Report[1], the principle is not clearly stated.

The previously constructed cameras have had adjustable mounts for the mirror axis of rotation and the lens system. This practice is not desirable because precise adjustment is difficult and the precision of adjustment cannot be checked very easily. It is recommended that there be no allowance for adjustment of the mounts for these components and that sufficiently close machining tolerances be specified so that none is necessary.

Design of an All-Metal Bowen Camera

An outline of steps used in making calculations follows:

(1) Using Brixner's parametric equations, a number of points on the focal curve were determined from our starting constants r, m, and

A = Axis of rotation of mirror

M = Mirror

F' = Focal point of lens

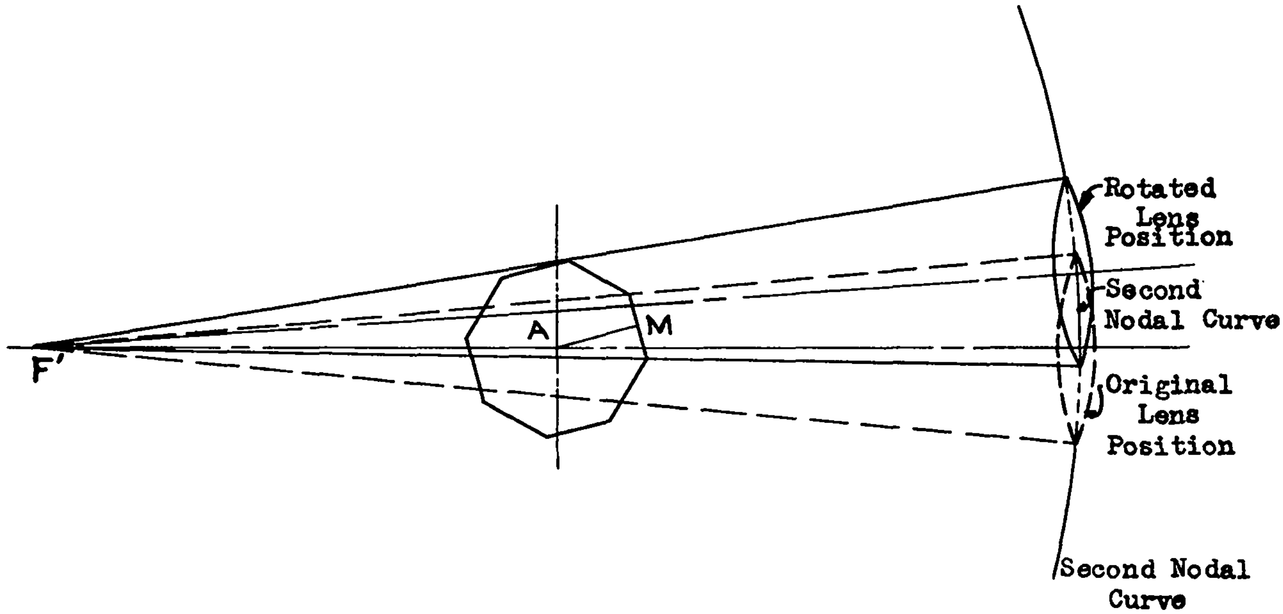


Fig. III Rotation Principle

For a perfect lens, the nodal curve is a sphere or in the x, y plane, a circle about F'. Hence we can consider a ray originating from a point on the nodal curve within the lens or on the extended section which will pass through A and F'. This condition then satisfies Bowen's equations.

Θ over required angular range.

(2) The extreme and center points were chosen, and the center of the approximating circle and radius were determined by the perpendicular bisector method.[3] This gives the starting point for subsequent least square solutions.

(3) A more accurate center of the approximating circle was then found using a least square solution of seven points from the focal curve and the approximate solution values from step (2).

(4) The allowable displacement was found to be too large over our selected angular range, so the range was decreased and the above procedure in step (3) was again followed. The displacement from the focal curve was reduced, but was still large.

(5) More points were calculated over the angular range to make our displacement curve (ΔR vs. 2Θ) more accurate.

(6) It was decided that the limaçon focal curve would be used rather than a compromise of the focal curve with an approximating circle. Rectangular coordinates were determined for layout of the camera body.

(7) Polar coordinates were calculated for ease in checking construction, and a writing speed curve was calculated and plotted for the selected angular range.

(8) A lens combination consisting of a 24 inch and a 34 inch achromat with a 1/2 inch spacing was found to be satisfactory for use as a relay lens in the camera.

The All-Metal Bowen Camera is very similar to the previous wooden model. The optical writing arm is about 20 inches, an octagonal mirror with faces 1.250 inches from the axis is used, and an angular focal range of 100 degrees or more is required. A schematic view is shown in Figure IV. The design steps outlined above follow:

(1) The coordinates of points on the limaçon were calculated by use of the following equations:

$$x = \frac{r}{\cos\theta} + \left[\frac{r}{\cos\theta} + m\right] \cos 2\theta$$

$$y = \left[\frac{r}{\cos\theta} + m\right] \sin 2\theta$$

CALCULATED VALUES WITH STARTING CONSTANTS

r	m	θ	2θ	x	y
1.250	18.58	10	20	19.9215	6.78886
↓	↓	$12\frac{1}{2}$	25	19.2800	8.39336
		15	30	18.5056	9.93705
		20	40	16.5823	12.7980
		24	48	14.7163	14.8245
		$27\frac{1}{2}$	55	12.8745	16.3742
		30	60	11.4551	17.3408
		36	72	7.76408	19.1401
		40	80	5.14150	19.9047
		45	90	1.76776	20.3478
		50	100	-1.61942	20.2129
		54	108	-4.27206	19.6932
		60	120	-8.04000	18.2558
		$62\frac{1}{2}$	125	-9.50270	17.4374
		65	130	-10.8865	16.4989
		$67\frac{1}{2}$	135	-12.1813	15.4477
		70	140	-13.3780	14.2923

$$x = L + (L + m)\cos 2\theta$$

$$y = (L + m)\sin 2\theta$$

or

$$x = \frac{r}{\cos\theta} + \left[\frac{r}{\cos\theta} + m\right]\cos 2\theta$$

$$y = \left[\frac{r}{\cos\theta} + m\right]\sin 2\theta$$

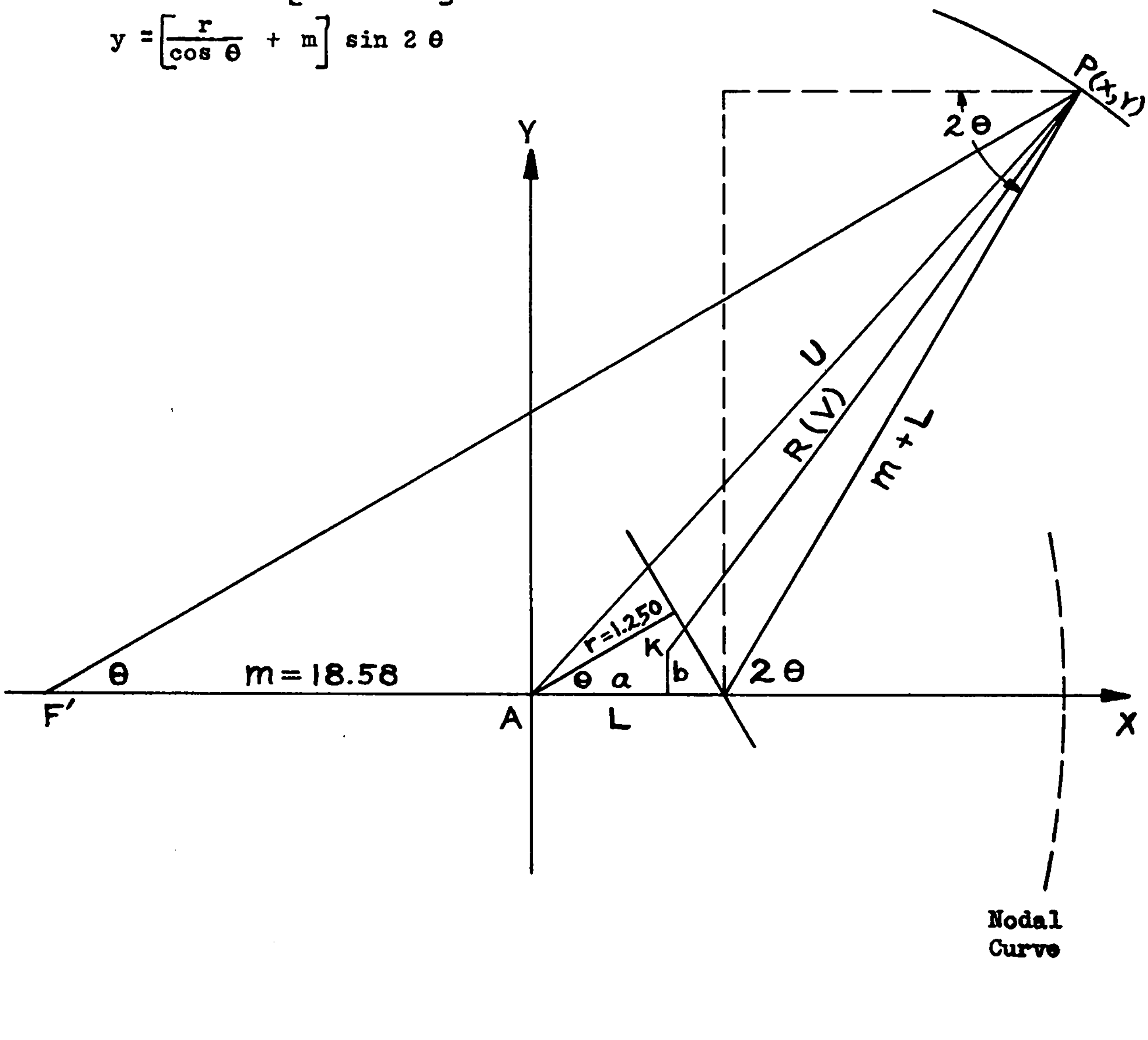


Fig. IV Schematic View of All-Metal Bowen Rotating Mirror Camera

(2) The coordinates of K (a,b) and radius of approximating circle over a 120 degrees focal range was calculated by passing a circle through the three points at $\theta =$ 10 degrees, 40 degrees, and 70 degrees. The values obtained were:

$$a = .967799$$

$$b = .315800$$

$$R = 20.0286$$

(3) With the above values as an approximate solution, a least square solution was obtained using seven points determined by the parametric equation, as follows:

Least Square Equations for the Fitting of a Circle to a Transcendental Curve

$$(1)\ \Sigma y - yg\Sigma n - \Sigma\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}} = \Delta y\Sigma n + \Delta r\Sigma\frac{rg}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}} + \Delta x\Sigma\frac{(x-xg)}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}}$$

$$(2)\ \Sigma xy - yg\Sigma x - \Sigma x\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}} = \Delta y\Sigma x + \Delta r\Sigma\frac{xrg}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}} + \Delta x\Sigma\frac{x\ (x-xg)}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}}$$

$$(3)\ \Sigma x^2y - yg\Sigma x^2 - \Sigma x^2\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}} = \Delta y\Sigma x^2 + \Delta r\Sigma\frac{x^2rg}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}} + \Delta x\Sigma\frac{x^2\ (x-xg)}{\left[rg^2-(x-xg)^2\right]^{\frac{1}{2}}}$$

where,

$y =$ Coordinate of point on transcendental curve

$x =$ Coordinate of point on transcendental curve

$xg =$ Trial coordinate of center of approximating circle

$yg =$ Trial coordinate of center of approximating circle

$rg =$ Trial radius of circle

$\Sigma n =$ Number of points used in calculation

Compute Δr, Δx and Δy and final values of x_0, y_0, r_0 where,

$$x_0 = xg + \Delta x$$

$$y_0 = yg + \Delta y$$

$$r_0 = rg + \Delta r$$

The following points were used in least square equations:

θ	x	y
10°	19.9215	6.78886
20°	16.5056	12.7980
30°	11.4551	17.3407
40°	5.14150	19.9047
50°	-1.61942	20.2129
60°	-8.04000	18.2558
70°	-13.3780	14.2923

The coordinates of the center and radius of the trial approximating circle are, from step (2) above:

xg (a) =	.967799	Equations	x_0 (a) =	.945602
yg (b) =	.315800	Solution	y_0 (b) =	.318209
rg (R) =	20.0286	Yields	r_0 (R) =	20.0329

(4) The distance from k (a,b) to points on the transcendental curve was calculated by the normal analytic geometry equation of the distance between two points. The difference between this value and the approximating radius R was used to plot a curve of ΔR vs. angular range

(2Θ). See Figure V. Since the displacement curve showed a $\pm .030$ inch focal error over the 120 degree range, it was lowered to 100 degrees and the above procedure repeated with seven points over the range $\Theta = 15$ degrees to 65 degrees. The trial values of a, b, and R were the same as used in (3). The values obtained were:

$$a = .913853$$

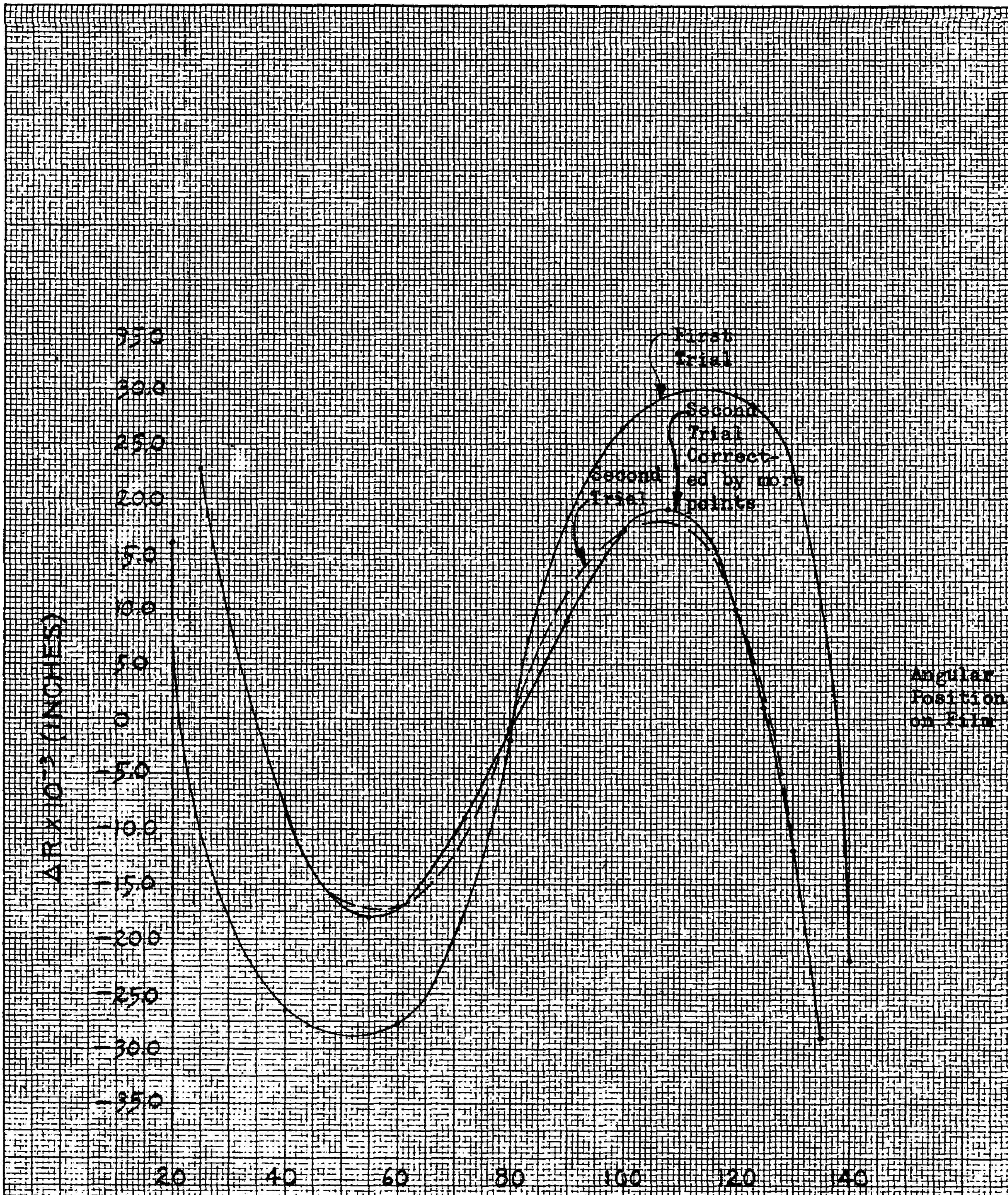
$$b = .316263$$

$$R = 20.0403$$

Displacement values were again calculated and another ΔR vs. angular range plotted. The displacement was $\pm .018$ inch for the minimum useful range, see dashed curve of Figure V.

(5) More points were used to determine the displacement curve with greater accuracy as shown in the solid curve of Figure V. Incidentally, the seven points used in the least square solutions avoided the cumbersome calculation involved in a greater number of points, while still maintaining a high degree of accuracy.

(6) Since the approximating circle taxed the full depth of field that was available, it was decided that a transcendental film curve would be constructed. The rectangular coordinates calculated in (1) are used for the construction of the camera side plates. The Rotation Principle, Figure III, is now employed to make the central ray of the lens pass through the center of the mirror system. Since the optic axis of the lens system is most easily used in a horizontal position, the



FOCUS VARIATION OF APPROXIMATING CIRCLE FROM FOCAL CURVE OVER ANGULAR RANGE 2 Θ

Fig. V

mirror axis and limaçon are rotated through an appropriate angle about the focal point F', see Figure VI. The origin is first translated from A to F' by adding m = 18.58 to the x coordinates, as shown in the following table.

θ	X	x'	y (y')
10	19.9215	38.5015	6.78886
$12\frac{1}{2}$	19.2800	37.8600	8.39336
15	18.5056	37.0856	9.93705
20	16.5823	35.1623	12.7980
24	14.7163	33.2963	14.8245
$27\frac{1}{2}$	12.8745	31.4545	16.3742
30	11.4551	30.0351	17.3408
36	7.76408	26.3441	19.1401
40	5.14150	23.7215	19.9047
45	1.76776	20.3478	20.3478
50	-1.61942	16.9606	20.2129
54	-4.27206	14.3079	19.6932
60	-8.04000	10.5400	18.2558
$62\frac{1}{2}$	-9.50270	9.07730	17.4374
65	-10.8865	7.69350	16.4989
$67\frac{1}{2}$	-12.1813	6.39870	15.4477
70	-13.3780	5.20200	14.2923
K $(\frac{x}{a},\frac{y}{b})$	.913853	19.4939	.316263
A	0	18.5800	0
F'	-18.58	0	0

The mirror axis A and limaçon points P--- are rotated about F' by an angle $\Delta\theta$, using the equations below.

$$x = x' \cos\Delta\theta - y' \sin\Delta\theta$$

$$y = x' \sin\Delta\theta + y' \cos\Delta\theta$$

An arbitrary value of $\Delta\theta$ = 1 degree 55 minutes was obtained from a graphic layout of the camera's geometry. The new values are shown in the following table.

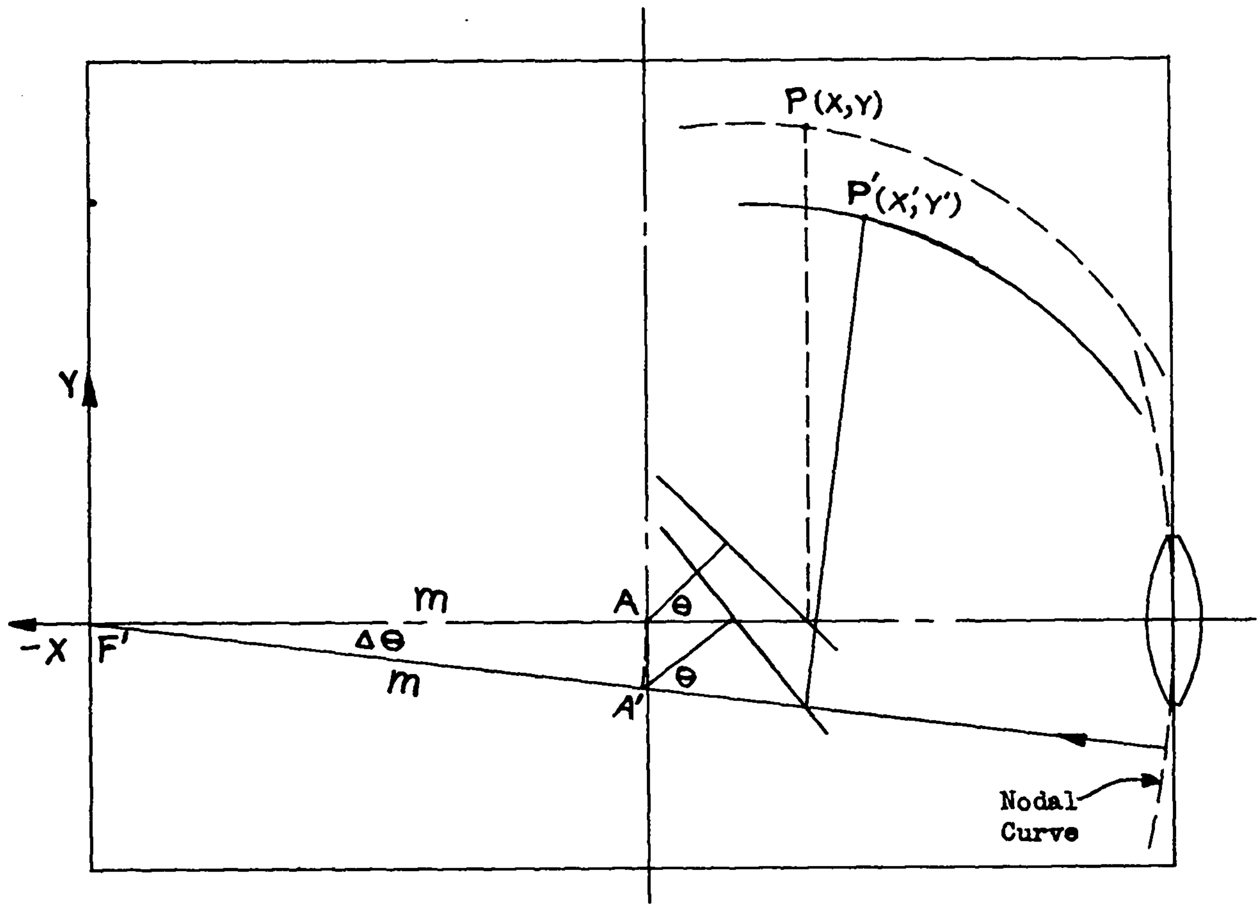


Fig. VI Rotation of Mirror About Focal Point to Fully Illuminate Mirror

θ	x	y
10	38.7071	5.49735
$12\frac{1}{2}$	38.1195	7.12240
15	37.3973	8.69114
20	35.5706	11.6148
24	33.7735	13.7026
$27\frac{1}{2}$	31.9846	15.3130
30	30.5983	16.3265
36	26.9696	18.2483
40	24.3739	19.1002
45	21.0170	19.6558
50	17.6271	19.6343
54	14.9586	19.2037
60	11.1447	17.8931
$62\frac{1}{2}$	9.65544	17.1241
65	8.24102	16.2324
$67\frac{1}{2}$	6.91178	15.2251
70	5.67711	14.1103
$K\binom{x,y}{a,b}$	19.4936	-.335907
A	18.5696	-.621427
F'	0	0

(7) Bowen's equations[1] were used to calculate U and the writing speed S, as tabulated below and plotted in Figure VII.

$$U = (4r^2 + m^2 + 4r\,m\cos\theta)^{\frac{1}{2}}$$

$$S = 2\,(r^2 + m^2 + 2\,r\,m\cos\theta)^{\frac{1}{2}}\ \frac{d\theta}{dt}$$

$\frac{d\theta}{dt}$ = 1000 rps

r = 1.250

m = 18.58

θ = 10 to 65 degrees

θ	U (inches)	S $\frac{mm}{\mu sec}$	θ	U (inches	S $\frac{mm}{\mu sec}$
10	21.0465	6.3238	38	20.6076	
12	21.0318	6.3213	40	20.5580	6.2414
14	21.0144	6.3184	42	20.5062	
16	20.9945	6.3150	44	20.4522	
18	20.9719	6.3112	46	20.3961	6.2143
20	20.9467	6.3069	48	20.3379	
22	20.9189		50	20.2776	
24	20.8886	6.2971	52	20.2154	6.1841
26	20.8558		54	20.1512	
28	20.8205		56	20.0852	6.1625
30	20.7827	6.2792	58	20.0174	
32	20.7425		60	19.9478	
34	20.6999	6.2653	62	19.8766	6.1280
36	20.6549		64	19.8038	
			65	19.7668	

(8) Optical System of the Camera.

Figure VIII shows a schematic view of the optical system. The objective A forms an image of an object on a slit S. This image is relayed to the film by the lens B operating at 1:1 magnification. A mirror, not shown, is used to reflect the image to the film plane. The field lens C forms an image of lens A at lens B and the full cone of light from all points along the slit is then admitted through lens B. This field lens avoids vignetting of the off-axis parts of the image without resorting to a large aperture first objective.

The rotating octagonal mirror is placed about 20 inches from the film plane and has faces 1 x 1 inch. Two adjacent mirror faces must be illuminated simultaneously by lens B. The effective area of the two

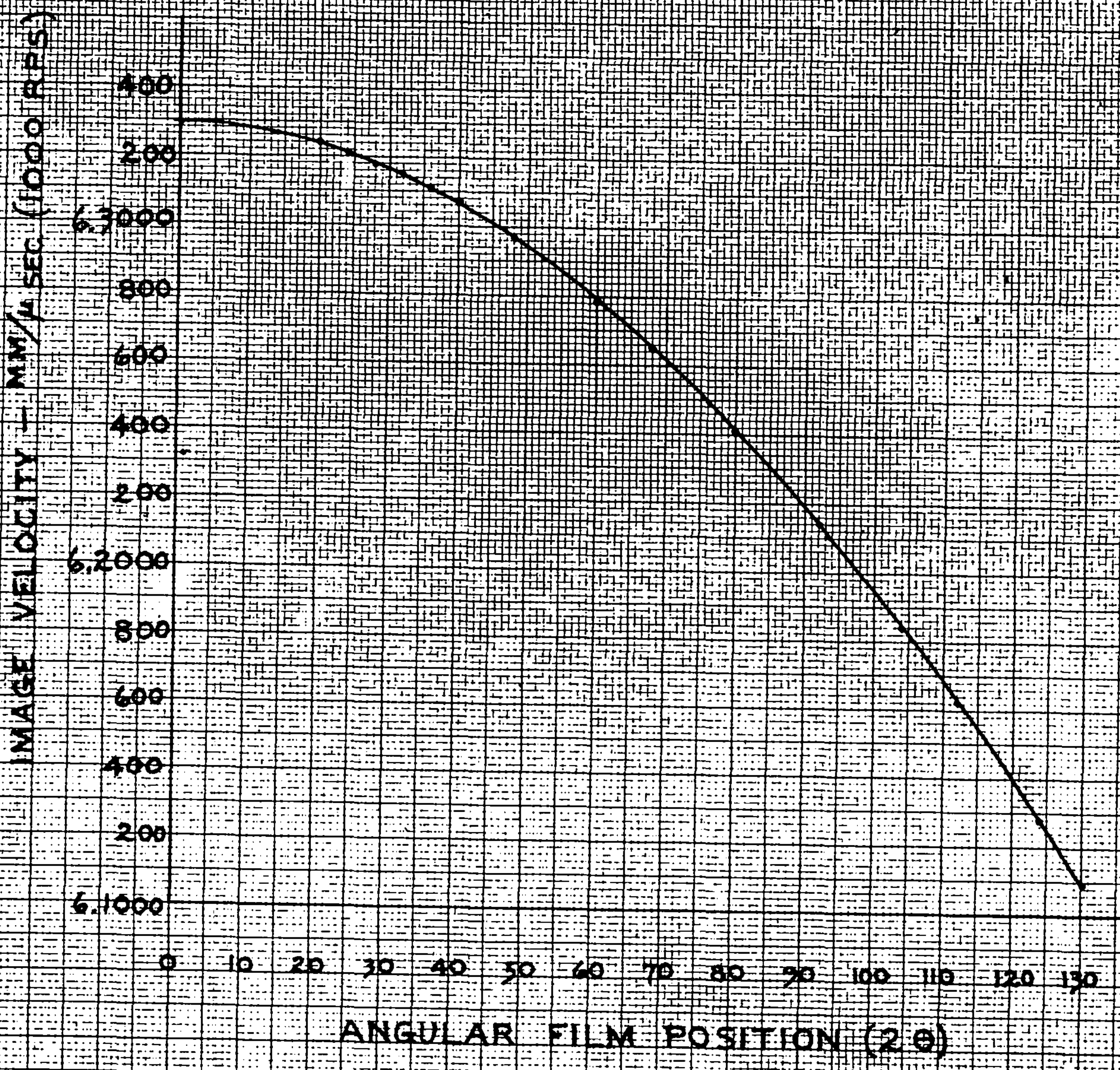


Fig. VII Theoretical Writing Speed

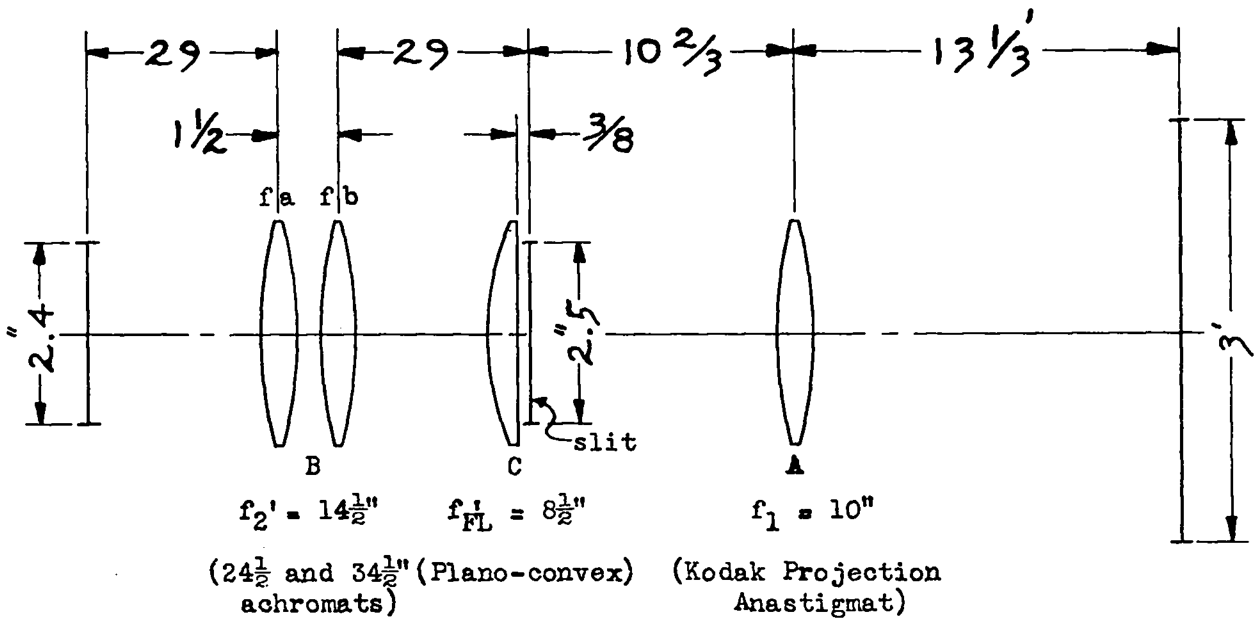

29
29
10 2/3
13 1/3'
1 1/2
3/8
f a
f b
2.4"
2.5"
3'
slit
B
C
A
$f_2' = 14\frac{1}{2}''$
$f'_{FL} = 8\frac{1}{2}''$
$f_1 = 10''$
(24½ and 34½" (Plano-convex)
achromats)
(Kodak Projection
Anastigmat)

Fig. VIII

faces is 1 x 1.5 inches, the diagonal is therefore 1.8 inch. The f number of the system is therefore 20 inches per 1.8 inches or f/11. To avoid masking part of the light reflected by the mirror, the lens should clear the mirror by at least 6 inches. The effective focal length must therefore be 26 inches or greater. A suitable relay lens was made by mounting two telescope objectives of 24.5 inches and 34.5 inches focus with 1/2 inch spacing between them. This gave an effective focal length of 29 inches at 1:1 magnification. The lenses were 3 inches in diameter and hence operated at about f/10.

A 10 inch f/4.5 Kodak Projection Anastigmat was selected, because of its flat field and good definition, for use as the first objective A. It operates at a magnification of 1:15 and hence its back focus is 10.7 inches. It is used at f/8.

The field lens C was placed 3/8 inch behind the slit, to allow for construction of a shutter near the slit plane. With focal distances of 29 5/8 inches and 11 inches, the field lens should be 8 inches focal length. A lens of 8 1/2 inches focal length was used as it was available and was a satisfactory approximation.

Conclusion

The imagery of the above camera is very good and is found to be about the same at all points on the film. The effective resolution of the film image may be computed by the method of Katz[5], as follows:

(1)	Film Resolution	0.011mm (EK Super XX Panchromatic)
(2)	Optical Resolution	0.040mm (25 lines per mm.)
(3)	Image Movement on Film	0.150mm (0.075mm slit moving 0.075mm)
	Total	0.201mm or 5 lines per mm.

This resolution was confirmed by a dynamic test. With an image velocity of 4.5mm per microsecond it is seen that the resolution is 0.05 microsecond. It appears that redesign of the camera could improve this resolution to a practical limit as follows:

(1)	Film Resolution	0.009mm (E. K. S.B. Panchromatic)
(2)	Optical Resolution	0.010mm (f/10 operation, 100 lines/mm)
(3)	Image Movement	0.025mm (0.012mm slit
	Total	0.044mm or 23 lines/mm

The image velocity can be raised to 14mm per microsecond to give a resolution of 0.003 microsecond. If events with a rise time of 10^{-9} second are to be studied, the image movement is reduced to 0.014mm, to give a resolution of 0.002 microsecond.

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1) I. S. Bowen: "The CIT Rotating Mirror Camera (Mod 2)", CIT K 3.1, 27 April 1945

2) J. E. Mack: "Optical Methods and Instruments", LA 1032 "General Equipment and Techniques", Vol. I, Part III, Section C, Chapter 22, pp. 11-21, 15 December 1947

3) E. A. Igel: "Progress Report on Focus and Writing Speed Problems of Rotating Mirror Cameras", Group GMX-7, Los Alamos Scientific Laboratory, September 1947

4) H. F. Hamann: "Theoretical Considerations and Experimental Measurements of Writing Speed of a Rotating Mirror Camera", Group GMX-7, Los Alamos Scientific Laboratory, February 1950

5) A. H. Katz: "Aerial Photography Equipment and Application to Reconnaissance", JOSA, pp. 604-610, July 1948