NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-384

Solar Simulator Optimization Through Defocusing: A Result of Computerized Optical System Ray-Tracing Study

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PASADENA, CALIFORNIA

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Abstract

Collimation and uniformity in the simulated solar beam are the main objects of interest in this analysis. With the simple computer program used, the effect of varying certain parameters – the height of the mixer, the radius of the mixer, and the height of the test plane – could be determined easily. It was found that a theoretical uniformity could be improved from 5.28 to 5.01%, and collimation could be improved from 1.6 to 1.078 deg by defocusing the optical system. The findings were used to locate the mixer most advantageously during its installation in the JPL 25-ft space simulator solar system.

Solar Simulator Optimization Through Defocusing: A Result of Computerized Optical System Ray-Tracing Study

I. Introduction

Computer programs were developed to determine the mixing lens location in the JPL 25-ft space simulator that would produce the best simulated solar light beam characteristics for spacecraft testing. Optical system ray-tracing analyses were made to show the effects of different lens positions on the beam's collimation (see Section II) and its uniformity of intensity (see Section III) in the test volume of this facility. The programs were written for the generalized case and, therefore, are applicable to any similar system. The analyses that were undertaken refined, within the adjustment range, the actual installation measurements for the multiple-lens mixer.

A. Configuration of JPL 25-ft Space Simulator

The basic configuration and some of the principal dimensions of the 25-ft space simulator, including the installation of the solar simulator system used in this investigation, are illustrated in Fig. 1. The structure was designed for environmental testing of unmanned spacecraft under simulated interplanetary conditions of extreme cold, high vacuum, and intense solar radiation. To provide the simulated solar energy, light created by thirty-seven 20-kW xenon arc lamps travels through a double array of nested lenses that consists of entrance (condensing) lenses and exit (transfer) lenses; each 19-lens mixing unit (Fig. 2) is approximately 20 in. in diameter. From the mixer, the light travels to strike a 23-ft collimating mirror, from which it is reflected downward in a 15-ft cylindrical shaft to the spacecraft testing area. The center of the reflecting mirror is positioned to be concentric with the chamber centerline. The angular position of the spherical mirror directs the beam to the testing area so as to minimize the collimation angle of the light.

B. Basic Reference Points Used in Analysis

The *radius of curvature* R of the spherical collimating mirror is 1200 in. The center of this radius is used as the origin of the coordinate system for this study. The basic horizontal x ordinate passes through the point of origin in a north–south direction. The y ordinate, the principal axis, is a line through the origin of the coordinate system, parallel to the chamber centerline.

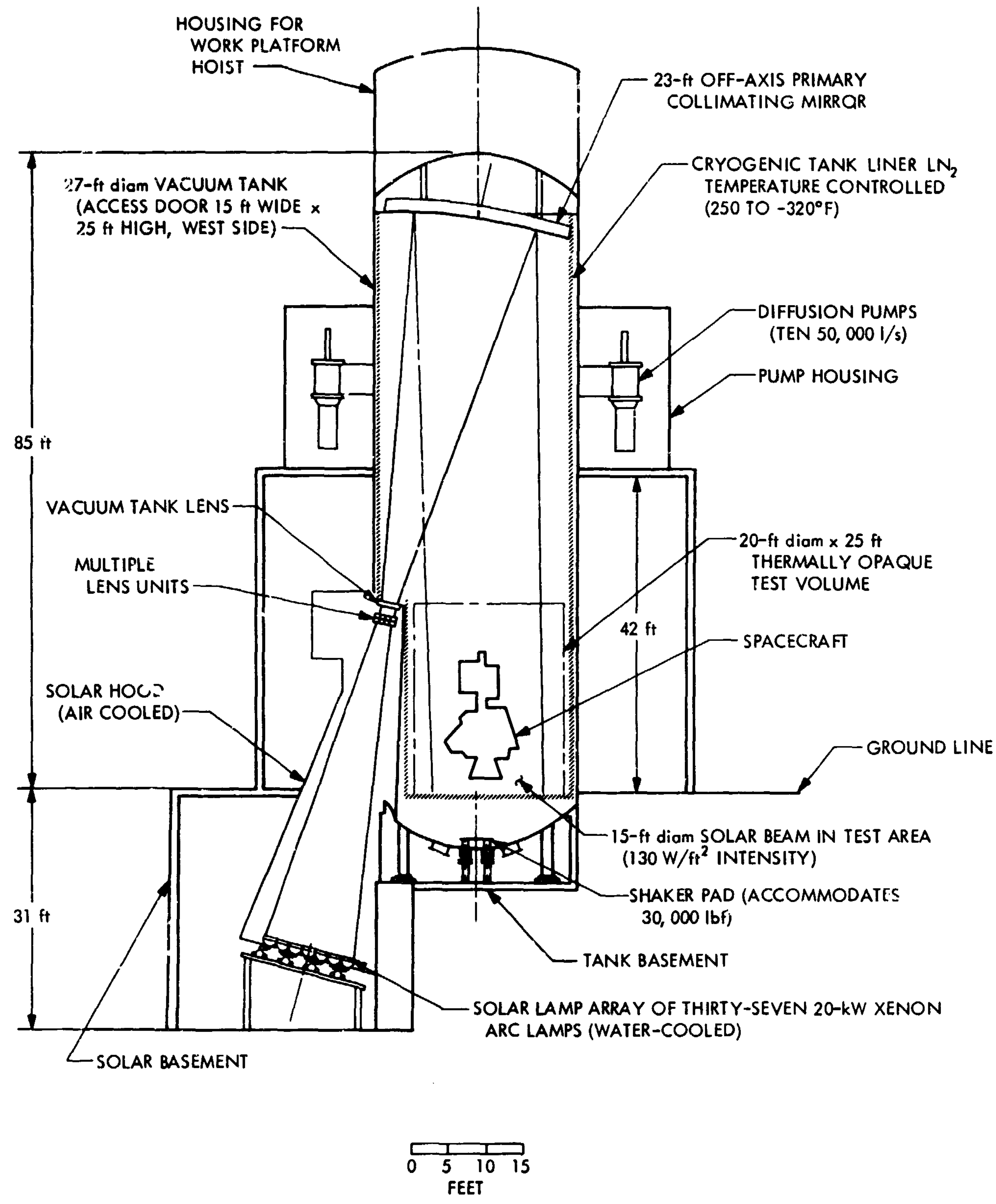


Fig. 1. Configuration of JPL 25-ft space simulator

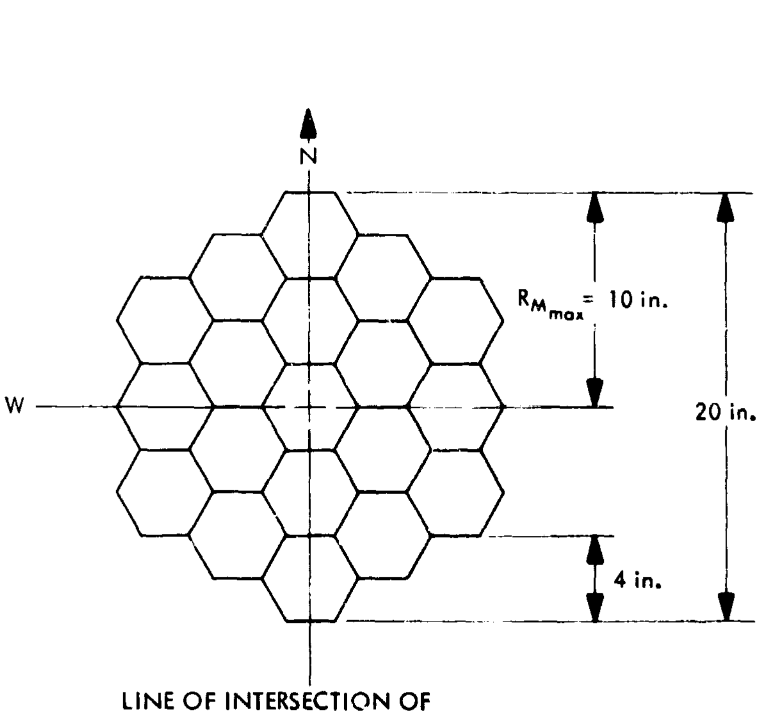


Fig. 2. Outlet array of 19-lens mixer

Horizontal planes of reference are normal to the centerline of the chamber and are measured in height H from the x axis. The horizontal test plane (TP) in the test volume of the chamber (shown in Fig. 1) is at $H = 360$ in. Distances measured in the direction of the x axis from the principal axis to a vertical test plane are cited as XTP.

The part of the space simulator chamber that is used in testing the spacecraft is referred to as the test volume. The test volume in the JPL 25-ft space simulator extends from the chamber floor to a plane 25 ft above the floor and is symmetrical about the centerline. To use the solar system economically, the beam size can be changed by changing mixers so that the diameter of the test volume can be a function of spacecraft requirements.

II. Mixer Position vs Collimation

To determine the effect of the mixing lens position on the collimation of the simulated solar beam, a program was written for the IBM 1620 to trace any ray in the vertical plane of reference by the geometry of Fig. 3. In this report, collimation angle is defined as the slope of any simulated solar light ray in the test volume with respect to the centerline of the test chamber. When used in reference to a system quality, collimation angle is the angle of the ray with maximum absolute slope in the test volume.

A. Focusing Position

The focus of a spherical mirror – such as the collimating mirror at the top of the chamber – is on the principal axis at a distance of half the radius of the curvature from the mirror. With the mixer in any other position, the system is considered to be defocused. Collimation measurements were made in these analyses with the mixer in two positions: (1) focused, with constant $\mathcal{A} = 0.500$, and (2) defocused, with $\mathcal{A} = 0.515$. In Figs. 3 and 4, the mixer is shown in the focused position.

B. Calculations

Figure 5 is a printout of the computer program for calculating collimation; Fig. 6 duplicates typical data cards for the input.

Calculations were performed for three variations of mixer radius for each mixer location – $\mathcal{A} = 0.500$ and $\mathcal{A} = 0.515$. The three dimensions used for the radius on the mixer (R_M) in the calculations of the collimation angle were $R_M = 0$ and the maximum limits: $R_{M_{max}} = 10$ and $R_{M_{max}} = -10$.

C. Results

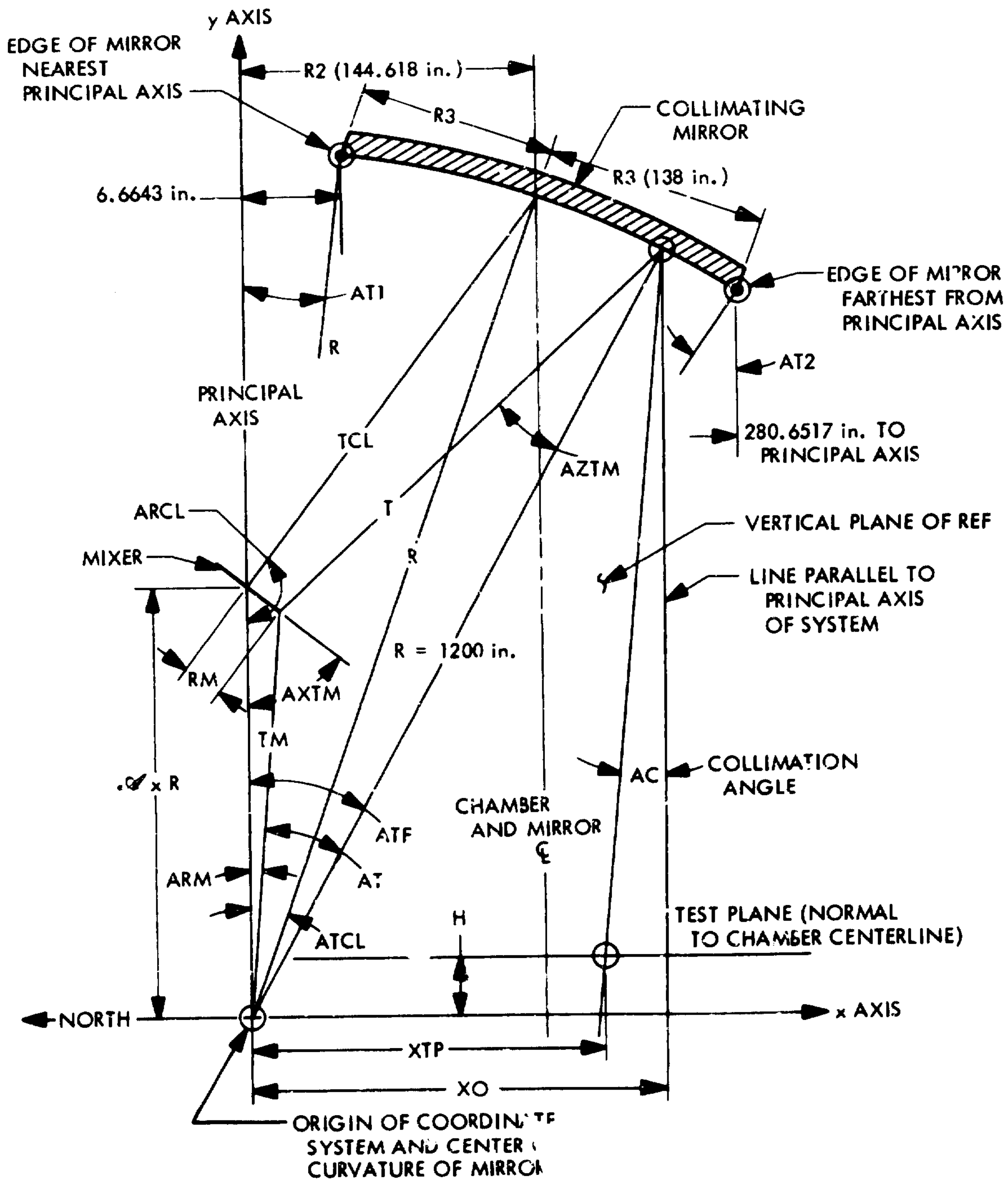
1. For mixer at $\mathcal{A} = 0.500$. Solutions for collimation with the above-mentioned variables are printed out in Fig. 7. The collimation angle vs location in the test plane (XTP) is plotted in Fig. 8. The collimation of the system would be 0.7 deg if all the necessary energy could be radiated from the point at the focus of the mirror.

Collimation on the test plane of rays originating at the extremes of the mixer ($R_M = \pm 10$ in.) are calculated in Figs. 7b and 7c, and collimation vs location is plotted in Fig. 8.

This system has a collimation of 1.6 deg because this is the maximum angle of any light ray that leaves the collimator and penetrates the test volume.

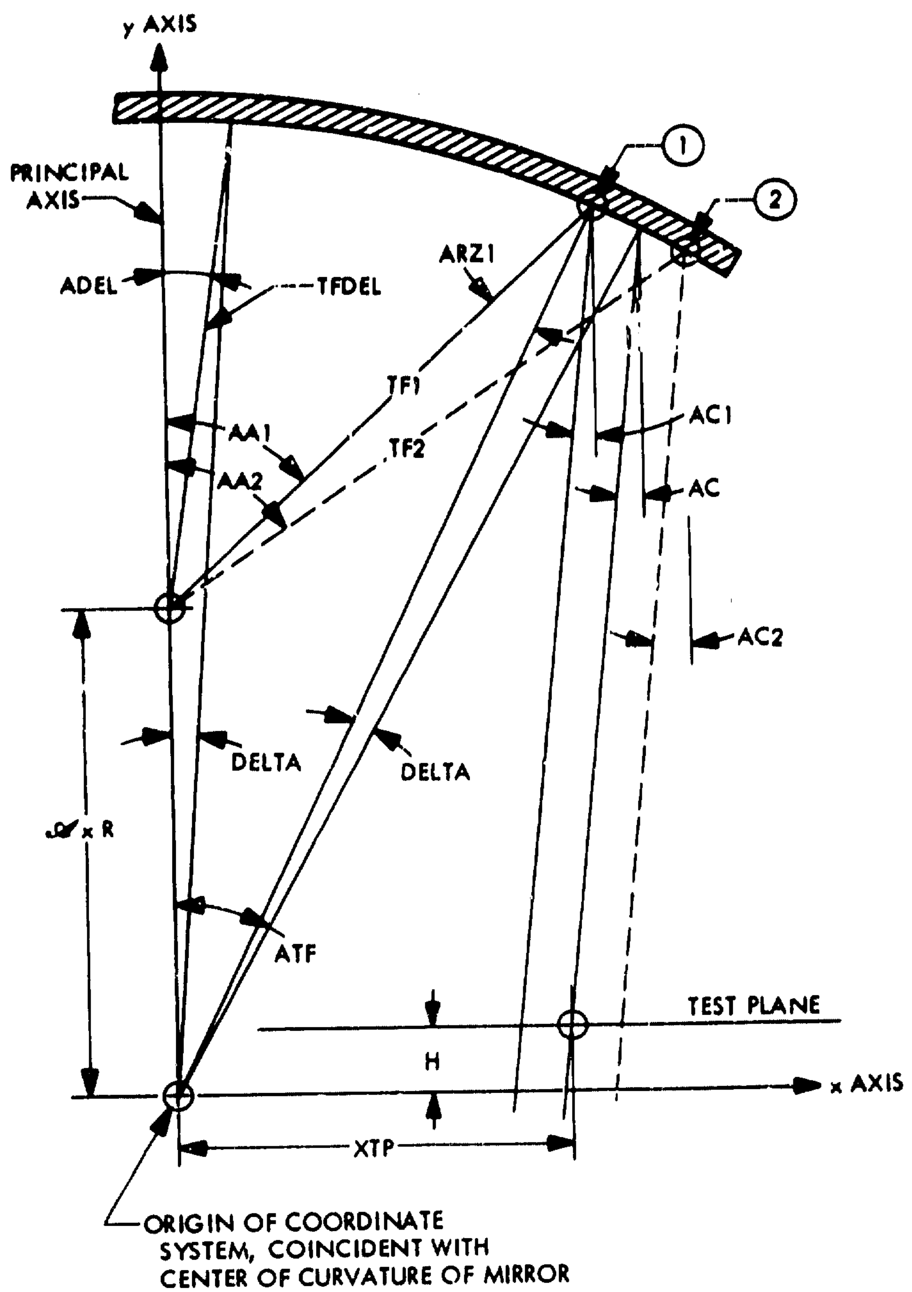
2. For mixer at $\mathcal{A} = 0.515$. If the mixer is moved vertically 18 in. ($\mathcal{A} = 0.515$) and the collimation angle recalculated, the results at $R_{M_{max}} = 0, \pm 10$ in. are as tabulated in Fig. 9 and as plotted in Fig. 8. The maximum positive angle receiving light from the entire mirror at this time is 0.872 deg. The maximum negative angle is -1.284 deg. If the system is rotated clockwise 0.206 deg, the collimation angle is ± 1.078 deg.

This mixer height and the optical system rotation (around center of collimating mirror) were incorporated



$\mathscr{A}$	RATIO OF THE DISTANCE ON THE PRINCIPAL AXIS, FROM THE ORIGIN OF COORDINATES, TO R
AC	COLLIMATION ANGLE OF RAY FROM SOURCE REFLECTED FROM MIRROR AT ATF INDICATED
ARCL	THE OBTUSE ANGLE BETWEEN THE PRINCIPAL AXIS AND TCL
ARM	ANGLE BETWEEN PRINCIPAL AXIS AND A LINE FROM THE ORIGIN OF THE COORDINATE SYSTEM TO ANY POINT ON THE MIXER IN THE PLANE OF REFERENCE
AT	AT = ATF - ARM; AN ANGLE USED IN TRIANGULATING TOWARD THE DETERMINATION OF COLLIMATION ANGLE AC
AT1	ANGLE BETWEEN PRINCIPAL AXIS AND NEAREST EDGE OF COLLIMATING MIRROR
AT2	ANGLE BETWEEN PRINCIPAL AXIS AND FARTHEST EDGE OF COLLIMATING MIRROR
ATCL	ANGLE BETWEEN PRINCIPAL AXIS AND RADIUS TO CENTER OF COLLIMATING MIRROR
ATF	ANGLE BETWEEN PRINCIPAL AXIS AND R IN VERTICAL REFERENCE PLANE
AXTM	ANGLE OF PRINCIPAL AXIS WITH FACE OF MIXER
AZTM	ANGLE BETWEEN R AND ANY RAY LEAVING THE MIXER
H	HEIGHT ABOVE x AXIS
R	RADIUS OF SPHERICAL COLLIMATING MIRROR
RM	RADIUS FROM THE CENTER OF THE MIXER
T	A LINE, IN THE PLANE OF REFERENCE, FROM ANY POINT ON THE MIXER TO ANY POINT ON THE COLLIMATING MIRROR
TCL	LENGTH OF RAY FROM CENTERLINE OF MIXER TO MIRROR
TM	A LINE, IN THE PLANE OF REFERENCE, THAT JOINS THE CENTER OF CURVATURE OF THE COLLIMATING MIRROR TO THE POINT IN THE MIXER FROM WHICH THE RAY BEING ANALYZED IS LEAVING
XTP	DISTANCE FROM PRINCIPAL AXIS TO POINT IN TEST PLANE
XO	DISTANCE FROM PRINCIPAL AXIS TO POINT OF IMPINGEMENT ON MIRROR SURFACE OF RAY BEING ANALYZED

Fig. 2. Ray-tracing schematic for collimation measurements



α	RATIO OF THE DISTANCE ON THE PRINCIPAL AXIS, FROM THE ORIGIN OF COORDINATES, TO R
AA1	INNER CONIC ANGLE OF LIGHT FLUX AREA BEING CALCULATED
AA2	OUTER CONIC ANGLE OF LIGHT FLUX AREA BEING CALCULATED
AC	COLLIMATION ANGLE OF RAY FROM SOURCE REFLECTED FROM MIRROR AT ATF INDICATED
AC1	COLLIMATION ANGLE OF RAY FROM SOURCE REFLECTED FROM MIRROR AT ATF − DELTA
AC2	COLLIMATION ANGLE OF RAY FROM SOURCE REFLECTED FROM MIRROR AT ATF + DELTA
ADEL	INCREMENTAL CONIC ANGLE FROM SOURCE TO MIRROR (WITH α = 0.500) USED TO DETERMINE NORMALIZING INTENSITY
ARZ1	ANGLE BETWEEN MIRROR RADIUS AND CONE DEFINED BY CONIC ANGLE AA1
ATF	ANGLE BETWEEN PRINCIPAL AXIS AND SPHERICAL MIRROR RADIUS
DELTA	INCREMENTAL ANGLE OF ATF THAT DETERMINES MAGNITUDE OF AREA OVER WHICH FLUX IS BEING AVERAGED
H	HEIGHT ABOVE x AXIS
R	RADIUS OF SPHERICAL COLLIMATING MIRROR
T	A LINE, IN THE PLANE OF REFERENCE, FROM ANY POINT ON THE MIXER TO ANY POINT ON THE COLLIMATING MIRROR
TF1	A LINE, IN THE PLANE OF REFERENCE, DEFINED BY CONIC ANGLE AA1
TF2	A LINE, IN THE PLANE OF REFERENCE, DEFINED BY CONIC ANGLE AA2
TFDEL	A LINE, IN THE PLANE OF REFERENCE, DEFINED BY CONIC ANGLE ADEL
XTP	DISTANCE ALONG x AXIS FROM ORIGIN OF COORDINATES

Fig. 4. Ray-tracing schematic for uniformity measurements

```
                                                                      PAGE   1
      PRINT 100
  100 FORMAT(50H              OPTICAL SYSTEM RAY TRACE-COLLIMATION   //)
      READ 1000,A,R,RM,R2,R3,H
 1000 FORMAT(9X2H   F8.6,2X2H  F6.0,2X3H   F6.2,2X3H   F8.3,2X3H   F5.0,
     C2X2H  F5.0)
      PRINT1001,A,R,RM,R2,R3,H
 1001 FORMAT(9X2HA= F8.6,2X2HR=F6.0,2X3HRM=F6.2,2X3HR2=F8.3,2X3HR3=F5.0,
     C2X2HH=F5.0   //)
      PRINT 200
  200 FORMAT(50H      ATF        ATCL       TCL       ARCL       AXTM
     C 60H       ARM          T         AZTM       AC          XO        XTP /)
      ATCL=57.29578*ATANF((R2/R)/SORTF(1.-(R2/R)**2))
      AT1=ATCL-57.29578*ATANF((R3/R)/SORTF(1.-(R3/R)**2))
      AT2=ATCL+57.29578*ATANF((R3/R)/SORTF(1.-(R3/R)**2))
      TCL=SORTF(R**2+(A*R)**2-2.*A*(R**2)*COSF(ATCL/57.29578))
      X=R*SINF(ATCL/57.29578)/TCL
      ARCL=180.-ATANF(X/SORTF(1.-X**2))*57.29578
      AXTM=ARCL-90.
      TM=SQRT(RM**2+(A*R)**2-2.*RM*A*R*COSF(AXTM/57.29578) )
      Y=RM*SINF(AXTM/57.29578)/TM
      ARM=ATANF(Y/SORTF(1.-Y**2))*57.29578
   10 READ 300,ATF
  300 FORMAT(5H ATF=F6.2)
      IF (ATF-AT1)20,20,30
   20 ATF=AT1
   30 IF(AT2-ATF)40,40,50
   40 ATF=AT2
   50 AT=ATF-ARM
      T=SORTF(R**2+TM**2-2.*R*TM*COSF(AT/57.29578))
      Z=TM*SINF(AT/57.29578)/T
      AZTM=57.29578*ATANF(Z/SQRT(1.-Z**2))
      AC=ATF-AZTM
      XO=R*SINF(ATF/57.29578)
      YO=R*COSF(ATF/57.29578)
      YD=YO-H
      XTP=XO-YD*SINF(AC/57.29578)/COSF(AC/57.29578)
      PRINT 2000,ATF,ATCL,TCL,  ARCL,AXTM,ARM,T,AZTM,AC,XO,XTP
 2000 FORMAT(11F10.4)
      GO TO 10
      END
```

Fig. 5. Program for IBM 1620 for tracing any ray in vertical plane of reference for collimation

in the 25-ft chamber during installation to minimize collimation angle.

Collimation of rays originating on the mixer outside the vertical plane of reference (distance D from it) will be the square root of the sum of the squares of the following defined angles:

(1) The collimation angle of the ray originating at R_M of normal from the point of origin of the ray to the vertical plane of reference (see Fig. 8).

(2) The angle described by arctan D/T (see T in Fig. 3 and in the printouts in Figs. 7 and 9).

In the 25-ft simulator system, the maximum collimation angle will be in the vertical reference plane.

If a collimation survey is made in a plane that includes the principal axis but not the chamber centerline, the results will be identical with Fig. 8, except that the cutoff at 21.04 in. (see Fig. 9c) and at 268.37 in. (see Fig. 9b) for the edges of the mirror will be in a different location. As the plane is rotated around the principal axis away from the vertical plane of reference, these cutoff points will draw closer together.

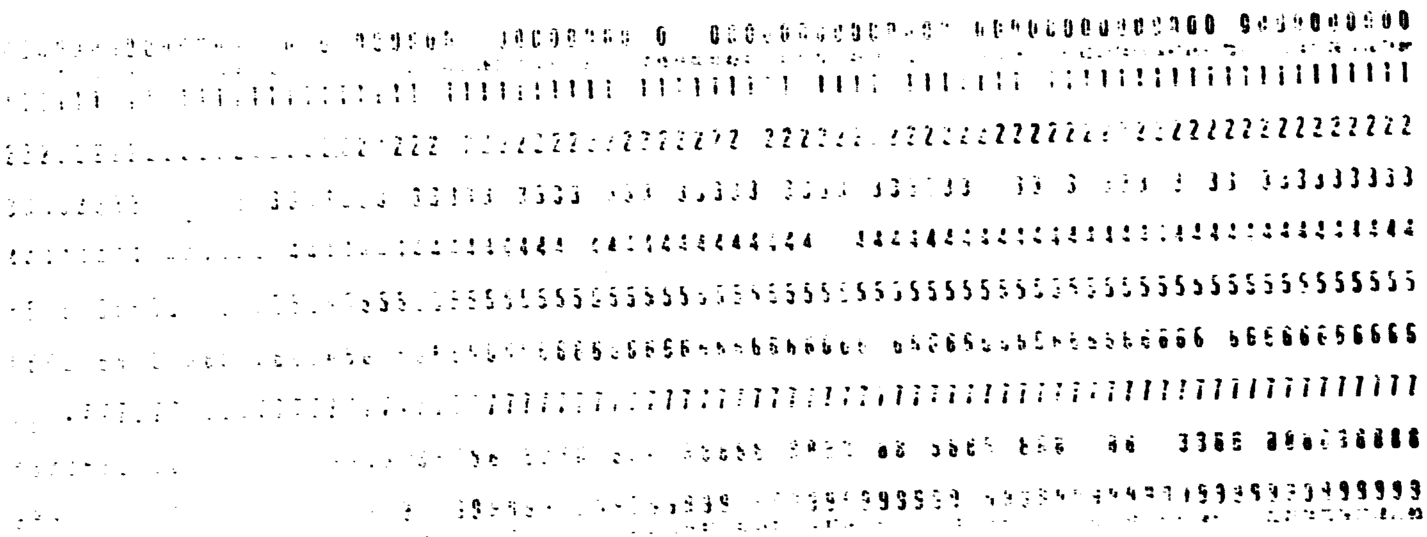
III. Mixer Position vs Uniformity

Uniformity is defined as the variation of simulated solar intensity within the test volume, which is expressed as I/I_N where I is the local intensity and I_N is the intensity on the principal axis when the mixer is located at the focal point of the collimating mirror.

If the light intensity I (energy flux per unit area) into the mixer is symmetrical, and if the mixer elements are small enough, the mixer becomes an infinite number of light sources. Under these conditions, the theoretical uniformity can be approximated by considering the light energy to be furnished by a single source at the center of the mixer.

(a) INPUT CARD NO. 1

[illegible]



(b) TYPICAL INPUT CARD FOR ALL FOLLOWING NO. 1 CARD

ATF= 4.00

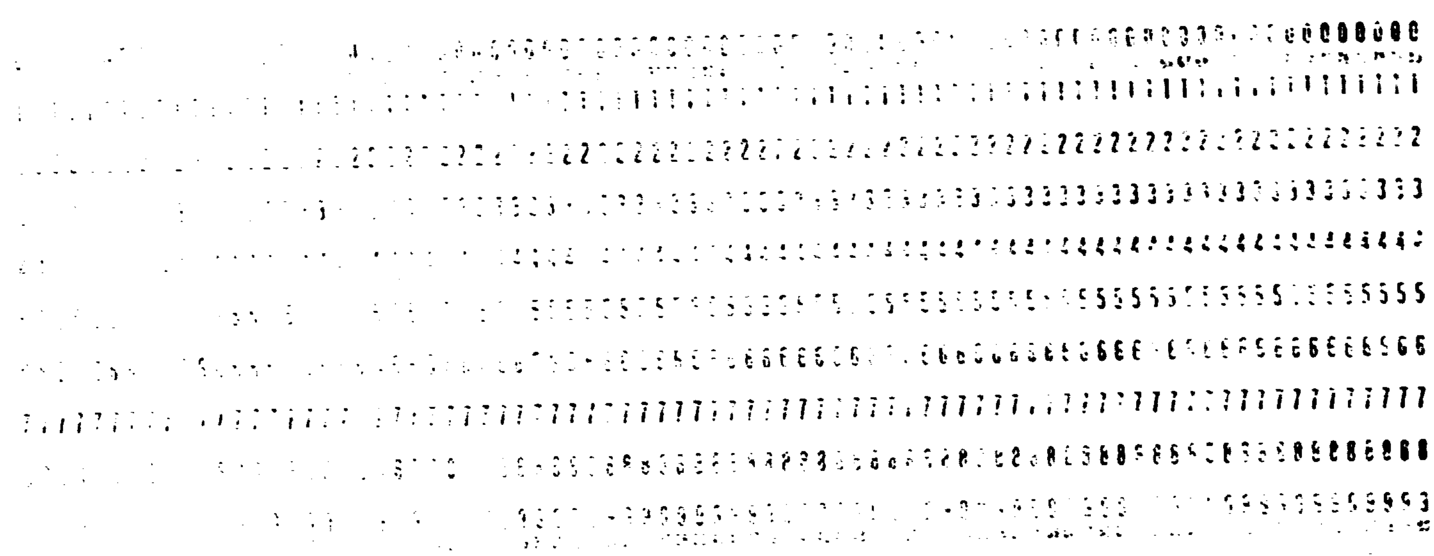


Fig. 6. Data cards for ray-tracing analysis of solar beam collimation

(a) FOR $R_M = 0$

A= .500000 R= 1200. RM= 0.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	608.6834	166.2555	76.2555	0.0000	600.0185	.3181	0.0000	6.6643	6.6641
1.0000	6.9218	608.6834	166.2555	76.2555	0.0000	600.1828	.9996	.0003	20.9428	20.9384
2.0000	6.9218	608.6834	166.2555	76.2555	0.0000	600.7306	1.9975	.0024	41.8793	41.8437
3.0000	6.9218	608.6834	166.2555	76.2555	0.0000	601.6473	2.9918	.0081	62.8031	62.6832
4.0000	6.9218	608.6834	166.2555	76.2555	0.0000	602.9160	3.9806	.0193	83.7077	83.4246
5.0000	6.9218	608.6834	166.2555	76.2555	0.0000	604.5491	4.9622	.0377	104.5868	104.0348
6.0000	6.9218	608.6834	166.2555	76.2555	0.0000	606.5381	5.9350	.0649	125.4341	124.4899
7.0000	6.9218	608.6834	166.2555	76.2555	0.0000	608.8789	6.8974	.1025	146.2431	144.7553
8.0000	6.9218	608.6834	166.2555	76.2555	0.0000	611.5668	7.8477	.1522	167.0076	164.8062
9.0000	6.9218	608.6834	166.2555	76.2555	0.0000	614.5964	8.7845	.2154	187.7213	184.6180
10.0000	6.9218	608.6834	166.2555	76.2555	0.0000	617.9618	9.7064	.2935	208.3778	204.1679
11.0000	6.9218	608.6834	166.2555	76.2555	0.0000	621.6565	10.6122	.3877	228.9707	223.4354
12.0000	6.9218	608.6834	166.2555	76.2555	0.0000	625.6736	11.5007	.4992	249.4940	242.4025
13.0000	6.9218	608.6834	166.2555	76.2555	0.0000	630.0057	12.3707	.6292	269.9412	261.0537
13.5254	6.9218	608.6834	166.2555	76.2555	0.0000	632.4055	12.8202	.7052	280.6526	270.7228

(b) FOR R_M = +10 in.

A= .500000 R= 1200. RM= 10.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	608.6834	166.2555	76.2555	.9311	602.3651	-.6082	.9264	6.6643	-6.9189
1.0000	6.9218	608.6834	166.2555	76.2555	.9311	602.2979	.0682	.9317	20.9428	7.2849
2.0000	6.9218	608.6834	166.2555	76.2555	.9311	602.5941	1.0602	.9347	41.8793	28.1132
3.0000	6.9218	608.6834	166.2555	76.2555	.9311	603.0727	2.0503	.9496	62.8031	[illegible]
4.0000	6.9218	608.6834	166.2555	76.2555	.9311	604.0024	3.0367	.9632	83.7077	69.6339
5.0000	6.9218	608.6834	166.2555	76.2555	.9311	605.2910	4.0177	.9822	104.5868	90.2427
6.0000	6.9218	608.6834	166.2555	76.2555	.9311	606.9362	4.9915	1.0084	125.4341	110.7629
7.0000	6.9218	608.6834	166.2555	76.2555	.9311	608.9343	5.9564	1.0435	146.2431	131.1053
8.0000	6.9218	608.6834	166.2555	76.2555	.9311	611.2816	6.9110	1.0889	167.0076	151.2623
9.0000	6.9218	608.6834	166.2555	76.2555	.9311	613.9730	7.8536	1.1463	187.7213	171.2079
10.0000	6.9218	608.6834	166.2555	76.2555	.9311	617.0034	8.7828	1.2171	208.3778	190.9180
11.0000	6.9218	608.6834	166.2555	76.2555	.9311	620.3668	9.6973	1.3026	228.9707	210.3708
12.0000	6.9218	608.6834	166.2555	76.2555	.9311	624.0569	10.5958	1.4041	249.4940	229.5466
13.0000	6.9218	608.6834	166.2555	76.2555	.9311	628.0667	11.4772	1.5228	269.9412	248.4282
13.5254	6.9218	608.6834	166.2555	76.2555	.9311	630.2995	11.9330	1.5923	280.6526	258.2263

(c) FOR R_M = −10 in.

A= .500000 R= 1200. RM=-10.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	608.6834	166.2555	76.2555	-.9238	597.8299	1.2516	-.9334	6.6643	20.3504
1.0000	6.9218	608.6834	166.2555	76.2555	-.9238	598.2273	1.9374	-.9374	20.9428	34.6847
2.0000	6.9218	608.6834	166.2555	76.2555	-.9238	599.1186	2.9401	-.9401	41.8793	55.6517
3.0000	6.9218	608.6834	166.2555	76.2555	-.9238	600.3751	3.9374	-.9374	62.8031	76.5212
4.0000	6.9218	608.6834	166.2555	76.2555	-.9238	601.9940	4.9276	-.9276	83.7077	97.2612
5.0000	6.9218	608.6834	166.2555	76.2555	-.9238	603.9719	5.9089	-.9089	104.5868	117.8408
6.0000	6.9218	608.6834	166.2555	76.2555	-.9238	606.3047	6.8796	-.8796	125.4341	138.2306
7.0000	6.9218	608.6834	166.2555	76.2555	-.9238	608.9877	7.8382	-.8382	146.2431	159.4032
8.0000	6.9218	608.6834	166.2555	76.2555	-.9238	612.0154	8.7833	-.7833	167.0076	178.3328
9.0000	6.9218	608.6834	166.2555	76.2555	-.9238	615.3818	9.7133	-.7133	187.7213	197.9958
10.0000	6.9218	608.6834	166.2555	76.2555	-.9238	619.0804	10.6270	-.6270	208.3778	217.3710
11.0000	6.9218	608.6834	166.2555	76.2555	-.9238	623.1041	11.5231	-.5231	228.9707	236.4397
12.0000	6.9218	608.6834	166.2555	76.2555	-.9238	627.4455	12.4007	-.4007	249.4940	255.1854
13.0000	6.9218	608.6834	166.2555	76.2555	-.9238	632.0968	13.2586	-.2586	269.9412	273.5944
13.5254	6.9218	608.6834	166.2555	76.2555	-.9238	634.6621	13.7013	-.1756	280.6526	283.1286

Fig. 7. Computer tabulations for optical system ray-trace analysis of solar beam rays with mixer at $\mathcal{J}$ = 0.500 (see Fig. 3 for definitions of column headings)

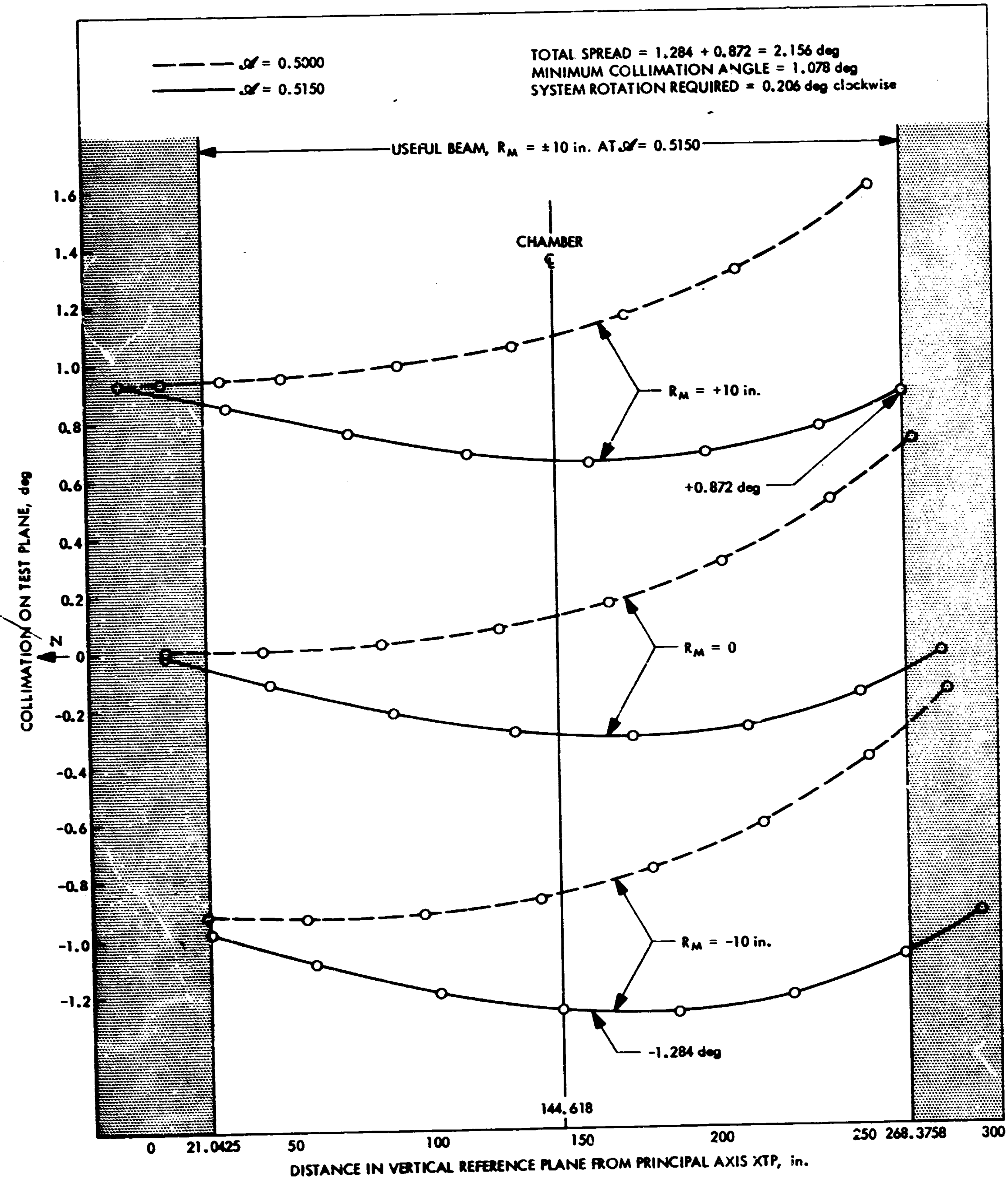


Fig. 3. Mixer location vs collimation

(a) FOR $R_M = 0$

A= .515000 R= 1200. RM= 0.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	591.2143	165.8411	75.8411	0.0000	582.0196	.3378	-.0196	6.6643	6.9527
1.0000	6.9218	591.2143	165.8411	75.8411	0.0000	582.1941	1.0615	-.0615	20.9428	21.8444
2.0000	6.9218	591.2143	165.8411	75.8411	0.0000	582.7757	2.1209	-.1209	41.8793	43.6508
3.0000	6.9218	591.2143	165.8411	75.8411	0.0000	583.7436	3.1762	-.1762	62.8031	65.3817
4.0000	6.9218	591.2143	165.8411	75.8411	0.0000	585.0958	4.2253	-.2253	83.707[illegible]	87.0000
5.0000	6.9218	591.2143	165.8411	75.8411	0.0000	586.8288	5.2663	-.2663	104.5868	108.4701
6.0000	6.9218	591.2143	165.8411	75.8411	0.0000	588.9390	6.2972	-.2972	125.4341	129.7577
7.0000	6.9218	591.2143	165.8411	75.8411	0.0000	591.4216	7.3162	-.3162	146.2431	150.8304
8.0000	6.9218	591.2143	165.8411	75.8411	0.0000	594.2714	8.3216	-.3216	167.0076	171.6578
9.0000	6.9218	591.2143	165.8411	75.8411	0.0000	597.4819	9.3117	-.3117	187.7213	192.2117
10.0000	6.9218	591.2143	165.8411	75.8411	0.0000	601.0467	10.2850	-.2850	208.3778	212.4666
11.0000	6.9218	591.2143	165.8411	75.8411	0.0000	604.9583	11.2401	-.2401	228.9707	232.3997
12.0000	6.9218	591.2143	165.8411	75.8411	0.0000	609.2089	12.1757	-.1757	249.4940	251.9908
13.0000	6.9218	591.2143	165.8411	75.8411	0.0000	613.7901	13.0907	-.0907	269.9412	271.2228
13.5254	6.9218	591.2143	165.8411	75.8411	0.0000	616.3269	13.5628	-.0374	280.6526	281.1794

(b) FOR R_M = +10 in.

A= .515000 R= 1200. RM= 10.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	591.2143	165.8411	75.8411	.9024	584.4355	-.6154	.9336	6.6643	-7.0243
1.0000	6.9218	591.2143	165.8411	75.8411	.9024	584.3716	.1027	.8972	20.9428	7.7905
2.0000	6.9218	591.2143	165.8411	75.8411	.9024	584.6016	1.1558	.8441	41.8793	29.5128
3.0000	6.9218	591.2143	165.8411	75.8411	.9024	585.2162	2.2066	.7933	62.8031	51.1935
4.0000	6.9218	591.2143	165.8411	75.8411	.9024	586.2138	3.2531	.7468	83.7077	72.7958
5.0000	6.9218	591.2143	165.8411	75.8411	.9024	587.5923	4.2934	.7065	104.5868	94.2838
6.0000	6.9218	591.2143	165.8411	75.8411	.9024	589.3486	5.3255	.6744	125.4341	115.6226
7.0000	6.9218	591.2143	165.8411	75.8411	.9024	591.4787	6.3475	.6524	146.2431	136.7789
8.0000	6.9218	591.2143	165.8411	75.8411	.9024	593.9780	7.3576	.6423	167.0076	157.7213
9.0000	6.9218	591.2143	165.8411	75.8411	.9024	596.8411	8.3542	.6457	187.7213	178.4204
10.0000	6.9218	591.2143	165.8411	75.8411	.9024	600.0619	9.3356	.6643	208.3778	198.8491
11.0000	6.9218	591.2143	165.8411	75.8411	.9024	603.6337	10.3003	.6996	228.9707	218.9827
12.0000	6.9218	591.2143	165.8411	75.8411	.9024	607.5493	11.2470	.7529	249.4940	238.799[illegible]
13.0000	6.9218	591.2143	165.8411	75.8411	.9024	611.8009	12.1744	.8255	269.9412	258.2800
13.5254	6.9218	591.2143	165.8411	75.8411	.9024	614.1667	12.6535	.8718	280.6526	268.3759

(c) FOR R_M = −10 in.

A= .515000 R= 1200. RM=-10.00 R2= 144.618 R3= 138. H= 360.

ATF	ATCL	TCL	ARCL	AXTM	ARM	T	AZTM	AC	XO	XTP
.3182	6.9218	591.2143	165.8411	75.8411	-.8953	579.7663	1.2988	-.9806	6.6643	21.0425
1.0000	6.9218	591.2143	165.8411	75.8411	-.8953	580.1807	2.0271	-1.0271	20.9428	36.0003
2.0000	6.9218	591.2143	165.8411	75.8411	-.8953	581.1161	3.0918	-1.0918	41.8793	57.8747
3.0000	6.9218	591.2143	165.8411	75.8411	-.8953	582.4391	4.1504	-1.1504	62.8031	79.6390
4.0000	6.9218	591.2143	165.8411	75.8411	-.8953	584.1467	5.2009	-1.2009	83.7077	101.2564
5.0000	6.9218	591.2143	165.8411	75.8411	-.8953	586.2348	6.2414	-1.2414	104.5868	122.6915
6.0000	6.9218	591.2143	165.8411	75.8411	-.8953	588.6989	7.2700	-1.2700	125.4341	143.9110
7.0000	6.9218	591.2143	165.8411	75.8411	-.8953	591.5336	8.2848	-1.2848	146.2431	164.8833
8.0000	6.9218	591.2143	165.8411	75.8411	-.8953	594.7327	9.2843	-1.2843	167.0076	185.5792
9.0000	6.9218	591.2143	165.8411	75.8411	-.8953	598.2893	10.2669	-1.2669	187.7213	205.972[illegible]
10.0000	6.9218	591.2143	165.8411	75.8411	-.8953	602.1959	11.2311	-1.2311	208.3778	226.0382
11.0000	6.9218	591.2143	165.8411	75.8411	-.8953	606.4449	12.1756	-1.1756	228.9707	245.7563
12.0000	6.9218	591.2143	165.8411	75.8411	-.8953	611.0276	13.0992	-1.0992	249.4940	265.1084
13.0000	6.9218	591.2143	165.8411	75.8411	-.8953	615.9353	14.0009	-1.0009	269.9412	284.0793
13.5254	6.9218	591.2143	165.8411	75.8411	-.8953	618.6412	14.4655	-.9401	280.6526	293.8906

Fig. 9. Computer tabulations for optical system ray-trace analysis of solar beam rays with mixer at $\mathcal{A} = 0.515$ (see Fig. 3 for definitions of column headings)

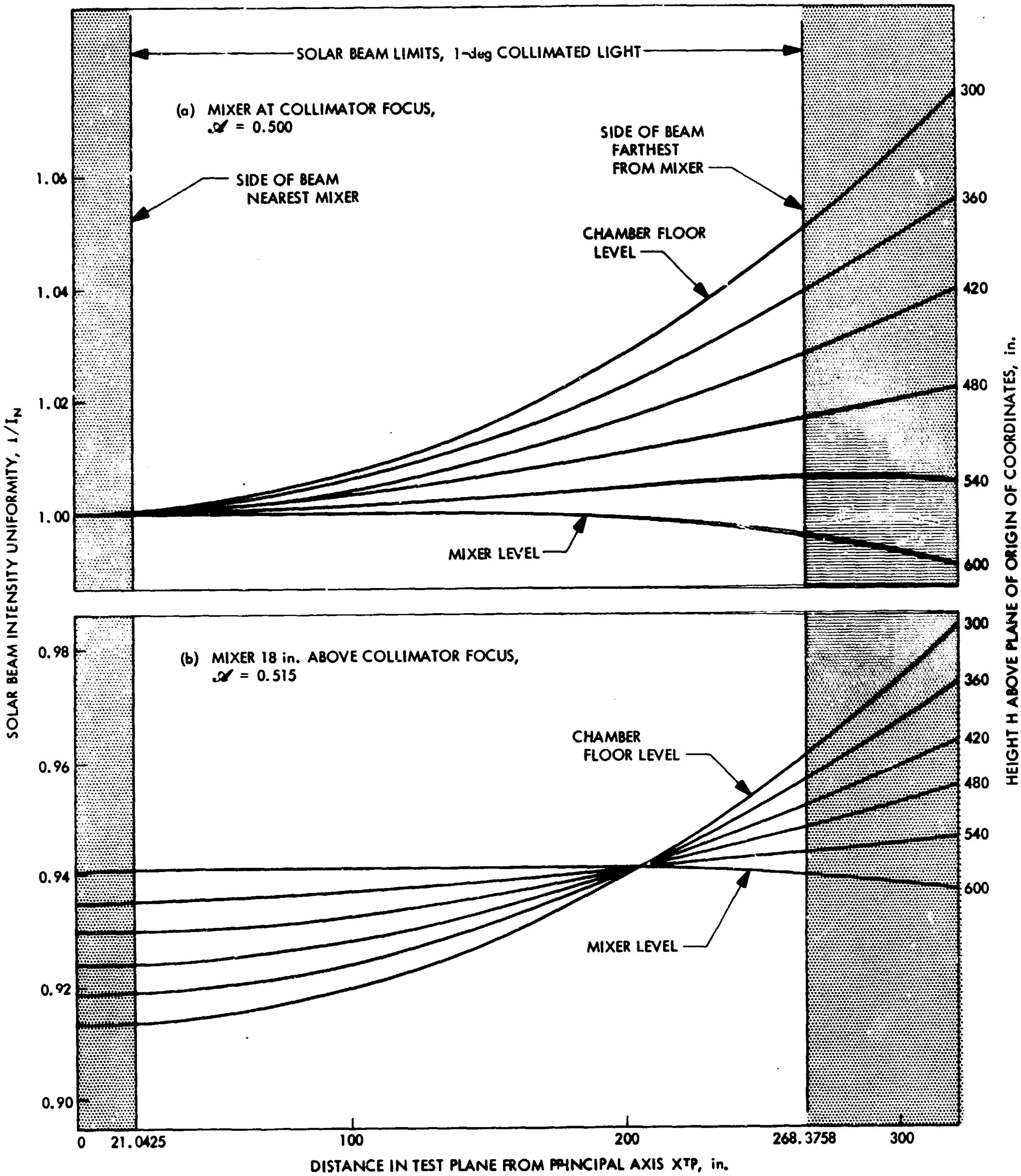


Fig. 10. Theoretical uniformity of solar beam

A. Ray-Tracing Intensity

A ray traced from the center of the mixer to the collimating mirror will develop a cone if the mixer is rotated about the principal axis. This cone will intersect a finite area on a unit sphere whose center is coincident with the energy source.

If the rays that make up the conic surface are reflected from an enlarged collimating mirror and continued through the test volume, they will enclose a finite area on a plane that includes the test plane.

The intensity on an incremental area in the test plane is, therefore, proportional to the ratio of the incremental area subtended on the unit sphere [between conic angles AA1 and AA2 (Fig. 4)] to the area subtended on the test plane. These ratios are normalized to the same ratio on the principal axis with $\mathcal{A} = 0.500$ for presentation on the intensity curves of Fig. 10.

B. Calculations

The same trigonometric procedure was used to ray-trace the uniformity as was used in the collimation calculations. The geometry of Fig. 4 represents the test setup for the calculation sequence. Figure 11 shows the computer format used; and Fig. 12 shows the data location on the input cards.

```
                                                                    PAGE   1
      PRINT 100
  100 FORMAT(52H            OPTICAL SYSTEM RAY TRACE - UNIFORMITY //)
      READ 1000,A,R,H,DELTA
 1000 FORMAT(9X2H  F8.6,2X2H  F6.0,2X2H  F5.0,2X6H      F4.2 )
      PRINT 1001,A,R,H,DELTA
 1001 FORMAT(9X2HA=F6.4,2X2HR=F6.0,2X2HH=F5.0,2X6HDELTA=F4.2  //)
      PRINT 200
  200 FORMAT(55H      ATF        XTP         XTP1     XTP2     XTP/R     ITP)
      TFDEL=SQRTF(R**2+(A*R)**2-2.*R*A*R*COSF(.5    /57.29578))
      Z3=R*SINF(.5    /57.29578)/TFDEL
       ADEL=ATANF(Z3/SQRT(1.-Z3**2))*57.29578
      USFA=2.*3.1416*(1.-COSF(ADEL/57.29578))
      XDEL=R*SINF(.5    /57.295'8)
      XDELA=3.1416*XDEL**2
      UNITY=XDELA/USFA
    5 READ 10,ATF
   10 FORMAT(5H ATF=F6.2)
      TF=SQRTF(R**2+(A*R)**2-2.*(A*R)*R*COSF(ATF/57.29578))
      Z1=R*SINF(ATF/57.29578)/TF
       AA=ATANF(Z1/SQRTF(1.-Z1**2))*57.29578
      Z2=A*SINF(AA/57.29578)
      RZ=ATANF(Z2/SQRTF(1.-Z2**2))*57.29578
      X=R*SINF(ATF/57.29578)
      Y=R*COSF(ATF/57.29578)
      AC=ATF-RZ
      XTP=X-(Y-H)*SINF(AC/57.29578)
      TF1=SQRTF(R**2+(A*R)**2-2.*R*A*R*COSF((ATF-DELTA)/57.29578))
      Z4=R*SINF((ATF-DELTA)/57.29578)/TF1
      AA1=ATANF(Z4/SQRTF(1.-Z4**2))*57.29578
      USFA1=2.*3.1416*(1.-COSF(AA1/57.29578))
      Z5=A*SINF(AA1/57.29578)
      ARZ1=ATANF(Z5/SQRTF(1.-Z5**2))*57.29578
      X1=R*SINF((ATF-DELTA)/57.29578)
      Y1=R*COSF((ATF-DELTA)/57.29578)
      AC1=ATF-DELTA-ARZ1
      XTP1=X1-(Y1-H)*SINF(AC1/57.29578)
      ATP1=3.1416*XTP1**2
      TF2=SQRTF(R**2+(A*R)**2-2.*R*A*R*COSF((ATF+DELTA)/57.29578))
      Z6=R*SINF((ATF+DELTA)/57.29578)/TF2
      AA2=ATANF(Z6/SQRTF(1.-Z6**2))*57.29578
      USFA2=2.*3.1416*(1.-COSF(AA2/57.29578))
      Z7=A*SINF(AA2/57.29578)
      RZ2=ATANF(Z7/SQRTF(1.-Z7**2))*57.29578
      X2=R*SINF((ATF+DELTA)/57.29578)
      Y2=R*COSF((ATF+DELTA)/57.29578)
      AC2=ATF+DELTA-RZ2
      XTP2=X2-(Y2-H)*SINF(AC2/57.29578)
      ATP2=3.1416*XTP2**2
      UNITI=(ATP2-ATP1)/(USFA2-USFA1)
      RITP=UNITY/UNITI
      DIML=XTP/R
      PRINT 300,ATF,XTP,XTP1,XTP2,DIML,RITP
  300 FORMAT(4F10.4,2F8.4)
      GO TO 5
      END
```

Fig. 11. Format for IBM 1620 program used for solar beam uniformity measurements

Fig. 12. Data cards for ray-tracing analysis of solar beam uniformity

Tabulations of computer output for data with the mixer located at the focus of the collimating mirror are recorded in Fig. 13. Figure 14 presents tabulations of data with the mixer in the defocused position. The height of the test plane for tests at each mixer position was varied in 60-in. increments from 300 to 600 in.

C. Results

1. For mixer at $\mathcal{A}$ = 0.500. With the mixer located at the collimator focus ($\mathcal{A}$ = 0.500), the highest and lowest intensity in the test volume takes place at the edge of the beam farthest from the mixer (see Fig. 10a). Highest

(a) FOR *H* = 600 in.

A= .5000 R= 1200. H= 600. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8539	39.7643	43.9429	.0348	1.0000
4.0000	83.5058	81.4310	85.5795	.0695	1.0000
6.0000	124.7618	122.7112	126.8109	.1039	.9998
8.0000	165.4441	163.4261	167.4603	.1378	.9994
10.0000	205.3974	203.4191	207.3735	.1711	.9986
12.0000	244.4941	242.5612	246.4246	.2037	.9970
14.0000	282.6379	280.7545	284.5188	.2355	.9945
16.0000	319.7657	317.9340	321.5947	.2664	.9905
18.0000	355.8478	354.[illegible]86	357.6244	.2965	.9847
20.0000	390.8871	389.1595	392.6122	.3257	.9767
22.0000	424.9172	423.2389	426.5933	.3540	.9659
24.0000	457.9994	456.3666	459.6301	.3816	.9518
26.0000	490.2194	488.6273	491.8096	.4085	.9341

(b) FOR *H* = 540 in.

A= .5000 R= 1200. H= 540. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8513	39.7621	43.9400	.0348	1.0002
4.0000	83.4855	81.4122	85.5577	.0695	1.0010
6.0000	124.6938	122.6465	126.7395	.1039	1.0020
8.0000	165.2846	163.2725	167.2948	.1377	1.0032
10.0000	205.0900	203.1207	207.0570	.1709	1.0047
12.0000	243.9713	242.0509	245.8890	.2033	1.0057
14.0000	281.8226	279.9558	283.6868	.2348	1.0063
16.0000	318.5734	316.7627	320.3813	.2654	1.0058
18.0000	354.1280	352.4345	355.9388	.2951	1.0039
20.0000	388.6655	386.9682	390.3599	.3238	.9999
22.0000	422.0367	420.3936	423.6772	.3516	.9934
24.0000	454.3620	452.7694	455.9523	.3786	.9837
26.0000	485.7276	484.1805	487.2726	.4047	.9703

(c) FOR *H* = 480 in.

A= .5000 R= 1200. H= 480. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8488	39.7600	43.9370	.0348	1.0005
4.0000	83.4652	81.3934	85.5358	.0695	1.0019
6.0000	124.6258	122.5819	126.6681	.1038	1.0042
8.0000	165.1252	163.1108	167.1294	.1376	1.0072
10.0000	204.7627	202.8222	206.7406	.1706	1.0108
12.0000	243.4484	241.5406	245.3535	.2028	1.0146
14.0000	281.0074	279.1571	282.8547	.2341	1.0183
16.0000	317.3011	315.5914	319.1670	.2644	1.0215
18.0000	352.5203	350.8003	354.2933	.2937	1.0236
20.0000	386.4430	384.7770	388.1076	.3220	1.0241
22.0000	419.1561	417.5403	420.7611	.3492	1.0223
24.0000	450.7246	449.1721	452.2745	.3756	1.0174
26.0000	481.2358	479.7330	482.7359	.4010	1.0088

(d) FOR *H* = 420 in.

A= .5000 R= 1200. H= 420. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8462	39.7578	43.9341	.0348	1.0007
4.0000	83.4449	81.3746	85.5140	.0695	1.0029
6.0000	124.5579	122.5172	126.5967	.1037	1.0064
8.0000	164.9657	162.9652	166.9640	.1374	1.0111
10.0000	204.4753	202.5238	206.4241	.1703	1.0170
12.0000	242.9256	241.0303	244.8179	.2024	1.0235
14.0000	280.1921	278.3584	282.0227	.2334	1.0305
16.0000	316.1888	314.4200	317.9543	.2634	1.0376
18.0000	350.8686	349.1662	352.5677	.2923	1.0440
20.0000	384.2221	382.5857	385.8553	.3201	1.0493
22.0000	416.2755	414.7030	417.8450	.3468	1.0526
24.0000	447.0872	445.5749	448.5967	.3725	1.0531
26.0000	476.7440	475.2870	478.1985	.3972	1.0499

(e) FOR *H* = 360 in.

A= .5000 R= 1200. H= 360. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8437	39.7556	43.9311	.0348	1.0009
4.0000	83.4246	81.3558	85.4921	.0695	1.0039
6.0000	124.4899	122.4525	126.5253	.1037	1.0087
8.0000	164.8062	162.8115	166.7986	.1373	1.0151
10.0000	204.1679	202.2253	206.1077	.1701	1.0232
12.0000	242.4028	240.5200	244.2824	.2020	1.0326
14.0000	279.3768	277.5597	281.1906	.2328	1.0430
16.0000	314.9965	313.2487	316.7409	.2624	1.0541
18.0000	349.2089	347.5321	350.8822	.2910	1.0651
20.0000	382.0005	380.3944	383.6030	.3183	1.0754
22.0000	413.3950	411.8577	414.9290	.3444	1.0843
24.0000	443.4498	441.9777	444.9189	.3695	1.0908
26.0000	472.2523	470.8403	473.6615	.3935	1.0938

(f) FOR *H* = 300 in.

A= .5000 R= 1200. H= 300. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	41.8411	39.7534	43.9282	.0348	1.0012
4.0000	83.4043	81.3369	85.4703	.0695	1.0049
6.0000	124.4219	122.3879	126.4539	.1036	1.0109
8.0000	164.6468	162.6579	166.6332	.1372	1.0191
10.0000	203.8605	201.9268	205.7912	.1698	1.0296
12.0000	241.8799	240.0097	243.7468	.2015	1.0418
14.0000	278.5616	276.7610	280.3586	.2321	1.0558
16.0000	313.8042	312.0774	315.5274	.2615	1.0710
18.0000	347.5492	345.8979	349.1966	.2896	1.0868
20.0000	379.7788	378.2031	381.3508	.3164	1.1027
22.0000	410.5144	409.0124	412.0129	.3420	1.1177
24.0000	439.8125	438.3805	441.2411	.3665	1.1308
26.0000	467.7605	466.3935	469.1244	.3898	1.1408

Fig. 13. Computer tabulations for optical ray-tracing analysis of solar beam intensity uniformity with $\mathcal{A} = 0.500$

(a) FOR H = 600 in.

A= .5150 R= 1200. H= 600. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.1443	40.9907	45.2973	.0359	.9408
4.0000	86.0560	83.9195	88.1914	.0717	.9409
6.0000	128.5126	126.4038	130.6197	.1070	.9411
8.0000	170.3103	168.2390	172.3797	.1419	.9412
10.0000	211.2724	209.2465	213.2958	.1760	.9410
12.0000	251.2544	249.2804	253.2257	.2093	.9403
14.0000	290.1485	288.2309	292.0632	.2417	.9388
16.0000	327.8850	326.0263	329.7407	.2732	.9361
18.0000	364.4322	362.6332	366.2283	.3036	.9318
20.0000	399.7953	398.0548	401.5329	.3331	.9254
22.0000	434.0128	432.3282	435.6948	.3616	.9164
24.0000	467.1539	465.5210	468.7843	.3892	.9044
26.0000	499.3138	497.7273	500.8980	.4160	.8889

(b) FOR H = 540 in.

A= .5150 R= 1200. H= 540. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.2709	41.1112	45.4299	.0360	.9354
4.0000	86.2920	84.1507	88.4321	.0719	.9362
6.0000	128.8239	126.7124	130.9336	.1073	.9377
8.0000	170.6472	168.5759	172.7162	.1422	.9395
10.0000	211.5710	209.5487	213.5906	.1763	.9414
12.0000	251.4385	249.4722	253.4019	.2095	.9434
14.0000	290.1317	288.2263	292.0340	.2417	.9450
16.0000	327.5728	325.7312	329.4111	.2729	.9458
18.0000	363.7241	361.9473	365.4977	.3031	.9454
20.0000	398.5866	396.8736	400.2964	.3321	.9433
22.0000	432.1969	430.5452	433.8456	.3601	.9387
24.0000	464.6233	463.0287	466.2152	.3871	.9313
26.0000	495.9622	494.4193	497.5027	.4133	.9203

(c) FOR H = 480 in.

A= .5150 R= 1200. H= 480. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.3975	41.2318	45.5626	.0361	.9301
4.0000	86.5280	84.3818	88.6728	.0721	.9316
6.0000	129.1351	127.0209	131.2474	.1076	.9343
8.0000	170.9840	168.9179	173.0527	.1424	.9377
10.0000	211.8695	209.8509	213.8853	.1765	.9419
12.0000	251.6226	249.6640	253.5781	.2096	.9465
14.0000	290.1150	288.2218	292.0048	.2417	.9512
16.0000	327.2606	325.4364	329.0816	.2727	.9557
18.0000	363.0160	361.2615	364.7671	.3025	.9593
20.0000	397.3780	395.6925	399.0599	.3311	.9617
22.0000	430.3809	428.7621	431.9965	.3586	.9620
24.0000	462.0926	460.5364	463.6461	.3850	.9595
26.0000	492.6107	491.1113	494.1073	.4105	.9535

(d) FOR H = 420 in.

A= .5150 R= 1200. H= 420. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.5242	41.3524	45.6953	.0362	.9248
4.0000	86.7640	84.6130	88.9135	.0723	.9270
6.0000	129.4464	127.3295	131.5613	.1078	.9308
8.0000	171.3208	169.2499	173.3893	.1427	.9360
10.0000	212.1680	210.1530	214.1800	.1768	.9423
12.0000	251.8067	249.8558	253.7542	.2098	.9495
14.0000	290.0982	288.2172	291.9755	.2417	.9575
16.0000	326.9485	325.1411	328.7521	.2724	.9657
18.0000	362.3079	360.5756	364.0364	.3019	.9736
20.0000	396.1693	394.5114	397.8235	.3301	.9807
22.0000	428.5649	426.9791	430.1473	.3571	.9862
24.0000	459.5622	458.0442	461.0770	.3829	.9892
26.0000	489.2591	487.8033	490.7120	.4077	.9889

(e) FOR H = 360 in.

A= .5150 R= 1200. H= 360. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.6508	41.4730	45.8279	.0363	.9196
4.0000	86.9999	84.8442	89.1542	.0724	.9225
6.0000	129.7576	127.6380	131.8751	.1081	.9274
8.0000	171.6577	169.5868	173.7258	.1430	.9342
10.0000	212.4666	210.4552	214.4747	.1770	.9427
12.0000	251.9908	250.0476	253.9304	.2099	.9527
14.0000	290.0814	288.2127	291.9463	.2417	.9639
16.0000	326.6363	324.8461	328.4225	.2721	.9759
18.0000	361.5997	359.8897	363.3058	.3013	.9883
20.0000	394.9606	393.3303	396.5870	.3291	1.0005
22.0000	426.7490	425.1960	428.2982	.3556	1.0115
24.0000	457.0317	455.5519	458.5079	.3808	1.0205
26.0000	485.9076	484.4953	487.3166	.4049	1.0266

(f) FOR H = 300 in.

A= .5150 R= 1200. H= 300. DELTA= .10

ATF	XTP	XTP1	XTP2	XTP/R	ITP
2.0000	43.7775	41.5936	45.9606	.0364	.9144
4.0000	87.2359	85.0754	89.3949	.0726	.9179
6.0000	130.0689	127.9466	132.1890	.1083	.9241
8.0000	171.9945	169.9238	174.0624	.1433	.9325
10.0000	212.7651	210.7574	214.7694	.1773	.9431
12.0000	252.1749	250.2394	254.1066	.2101	.9558
14.0000	290.0647	288.2082	291.9171	.2417	.9704
16.0000	326.3241	324.5510	328.0930	.2719	.9864
18.0000	360.8916	359.2038	362.5751	.3007	1.0034
20.0000	393.7520	392.1492	395.3505	.3281	1.0209
22.0000	424.9330	423.4130	426.4490	.3541	1.0379
24.0000	454.5011	453.0596	455.9388	.3787	1.0536
26.0000	482.5560	481.1873	483.9213	.4021	1.0667

Fig. 14. Computer tabulations for optical ray-tracing analysis of solar beam intensity uniformity with $\mathcal{A}$ = 0.515

intensity is at the bottom ($I/I_N = 1.050$ when $H = 300$), and the lowest intensity is at the top ($I/I_N = 0.996$ when $H = 600$). Intensity variation is:

$$\frac{(I_{max} - I_{min})/(I_{max} + I_{min})}{2}\,100 = 5.28\%$$

2. For mixer at $\mathcal{A}$ *= 0.515.* With the system defocused (the mixer raised 18 in., $\mathcal{A} = 0.515$) the highest and lowest intensity is at the bottom of the test volume. The highest intensity (Fig. 10b) is on the far side of the beam from the mixer ($I/I_N = 0.961$ when $H = 300$), and the lowest intensity is on the near side ($I/I_N = 0.914$). Intensity variation is:

$$\frac{(0.961 - 0.914)/(0.961 + 0.914)}{2}\,100 = 5.01\%$$

Uniformity is slightly better in the defocused case. Figure 15 shows the calculated beam uniformity of the solar simulation system for the general case. Note the large decrease in uniformity as the speed of the system (XTP/R) increases.

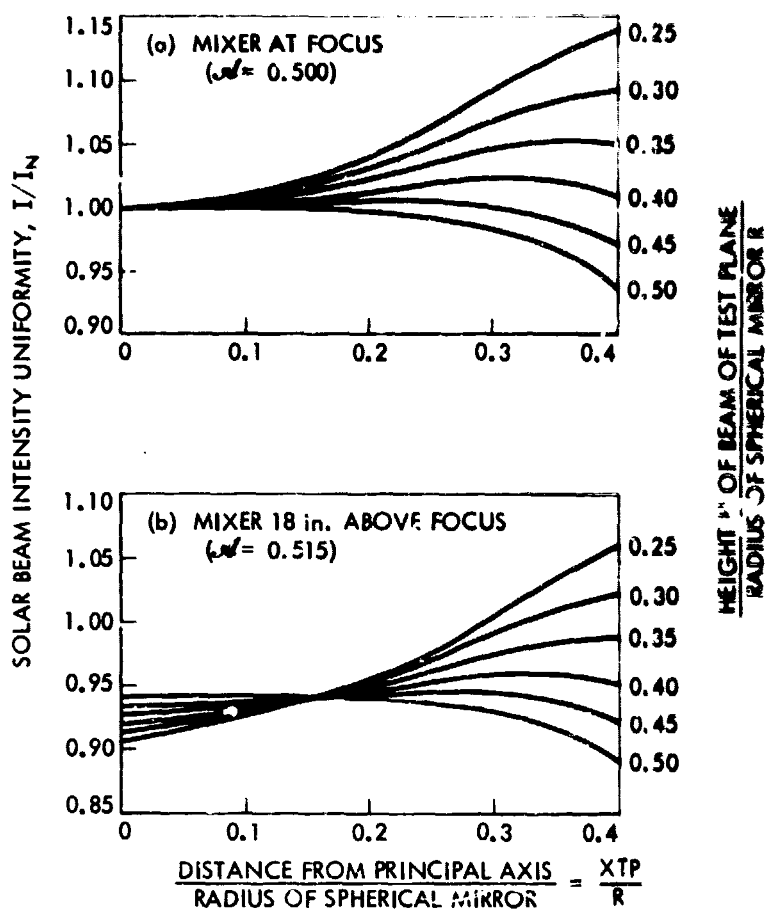


Fig. 15. Theoretical uniformity of solar beam, general case

IV. Conclusion

Both collimation and uniformity of the light beam were demonstrated to be improved by defocusing the optical system in the JPL 25-ft space simulator. Defocusing was accomplished by moving the mixer 18 in. vertically and changing the ratio of $\mathcal{A}$ from 0.500 to 0.515. Improvement in collimation was from 1.6 to 1.078 deg. Uniformity improvement that resulted from the defocused position was from 5.28 to 5.01%.