

CSO Technical Memorandum M0900-001A

**Gaussian Beams And CSO Side Cab Optics: FORTRAN Tools  
For Aiding In The Optical System Analysis**

Richard A. Chamberlin  
Caltech Submillimeter Observatory  
Hilo, HI 96720

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version in ulu//home/cham/CSO-optics...

**Abstract**

To date, CSO optics have been designed with the assumption that simple geometrical optics provides a “close enough” approximation for predicting how the gaussian beams from the side cab receivers will propagate through the system. Experience and calculation show that the assumptions of geometrical optics are not adequate. For example, scans across planets show that only about 54% of the 230GHz power on the sky is coupling into the main beam, and that the primary is over illuminated. Direct measurements of the beam spot size at the secondary give an edge taper of about -5.2 dB, whereas about -10 to -14 dB was the design goal. In fact, as this memo shows, the observed behavior of the 230GHz beam is predictable using simple gaussian optics, and treating the optical elements as thin lenses. To aid in the analysis, some FORTRAN programs have been developed to model the CSO optical system. The programs are described in this memo.

# 1 Introduction

This memo assumes that the curved mirrors in the CSO optical system can be modelled by thin lenses and that the beams being propagated by the side cab receivers have a gaussian electric field profile. The theory of the propagation of gaussian beams through lens-like media is quite mature[1, 2] and will not be repeated here. The application of gaussian optics to quasi-optical millimeter wave systems is also quite well established and the papers of Goldsmith are often used as a standard reference[3]<sup>1</sup> for designers of quasi-optical systems.

Described here are two FORTRAN programs which model the CSO optical system. The first program, CSO\_OPTICS1.FOR takes as it inputs the desired edge taper on the secondary, and operating wavelength of the receiver. The output of the program is the resulting required F/ of the receiver and the required distance of the receiver focus from the fifth mirror. The program starts with the fundamental assumption that image of the receiver focus formed at the virtual focus behind the secondary mirror is constrained to form exactly at the place where the primary focus is supposed to form. As will be shown, this constraint has significant implications on the prediction as to where the image of the beam waist forms in the elevation torque tube. The question of where the torque tube beam waist forms is significant from the standpoint of determining how badly the beam will be truncated by optics in the torque tube such as the single side band filter which was recently installed.

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<sup>1</sup>Note that Eq. 13b in reference [3] is incorrect.

The second program takes as its input the operating wavelength of the receiver and the F/. It then propagates the beam through the entire optical system and then predicts what the beam full width at half maximum power (FWHM) will be on the sky. To model the beam size on the sky, the assumed gaussian beam was forced through the finite aperture of the primary and the resulting diffraction pattern in the far field was calculated using numerical integration. The integration was done successively and used with a root finding subroutine to find the FWHM beam power points.

## **2 Using CSO\_OPTICS1.FOR**

The CSO optical system was modelled as series of thin lenses, see Figure 1. Appendix A is a source code listing of CSO\_OPTICS1.FOR and its associated subroutines. As configured in this memo, CSO\_OPTICS1.FOR is setup to predict the required receiver F/ for a range of possible secondary edge tapers, ET, and a range of possible fifth mirror focal lengths:  $ET_{min} \leq ET \leq ET_{max}$ , with the ET's in dB's. The range of modelled fifth mirror focal lengths, Ffifth, is from 13 inches to 20 inches. ALAMBDA, is the operating wavelength of receiver in millimeters. All of the program calculations are done in millimeters. Fsec is the effective focal length of the secondary mirror and, Fcass is the effective focal length of the third mirror. The values of the focal lengths for these two mirrors, and other CSO optical parameters, were derived from a CSO optics diagram produced by W. Schall, dated 10-18-1996, and repeated in Figure 2.

The output of the program is written as a table of data to the file

CSO\_OPTICS1.OUT, see Table I. The left data column of CSO\_OPTICS1.OUT shows the input value of the secondary edge taper, ET. The rightmost output column, Fno, shows the resulting receiver F/ at the  $1/e^{*2}$  power points.

The other data columns show the results of the some of the intermediate calculations and they can be interpreted with the aid of Figure 1. For example, the second column, Wo1sec, is the size of the gaussian beam waist formed behind the secondary mirror. ( Wo1sec is a virtual waist, of course. See Fig1.) The units of Wo1sec, etc, are in millimeters.

Significant in CSO\_OPTICS1.OUT is the column Z2cas which is the distance of the beam waist in the elevation torque tube from the third mirror. If this quantity is negative, then we can expect that there is no beam waist formed in the torque tube. Rather, the beam waist in the torque tube is virtual and it forms to the right of the third mirror (from the perspective someone standing in the control room). In case we are concerned about beam truncation in the single side band filter, or edge taper on the forth and fifth mirrors, the actual position of where the torque beam waist forms is relevant. For example, in the case of a 13" fifth mirror and a 14 dB edge taper, Z2cas is predicted to be -740.25 mm (F/ receiver = 2.67). Thus the distance from this virtual waist to the exit aperture of the single side band filter is about 1900 mm. Wo2cass is the virtual beam waist radius, 27.93 mm. Using gaussian optics, the size of the beam waist radius at the exit aperture of the single side band filter is predicted to be about 40mm. The clear aperture radius of the single side band filter is only about 41 mm (diameter = 3.2"). Thus, we can predict beam truncation occurring at about the -9.1 db level. Beam truncation of this magnitude, and at this position in optical train is quite

undesirable and it will no doubt contribute to spectrum baseline problems and generally degrade the performance of the telescope optics and coupling.

### **3 Using CSO\_OPTICS2.FOR**

The program CSO\_OPTICS2.FOR (see Appendix B) takes as inputs the receiver F/ and the wavelength. It then computes the resulting secondary edge taper and the resulting FWHM of the beam on the sky. The program displays some other interesting intermediate results such as the predicted secondary focus error, “foc err”, see Table II for a list of the output file CSO\_OPTIC2.OUT. “foc err” is in units of millimeters and a negative value implies that the image of the receiver focus is forming closer to the secondary than the nominal position of the primary focus. (The nominal position of the primary focus 9.2 inches behind the secondary.)

Jacob Kooi reported from direct measurements on the 230 GHz rx beam that the F/ of the receiver is 4.1. Thus, CSO\_OPTICS2.FOR was run for that F/. The output is in CSO\_OPTICS2.OUT, Table II. Column 1 of the output, “Dis”, is the distance of the receiver focus from the third mirror: units are inches. Column 9, “FWHM” is the predicted size of the beam on the sky. According to Jacob Kooi’s direct measurements, “Dis”, actually 13.4” which corresponds to row 3 of the program data output. Thus according to this program, the resulting predicted edge taper on the secondary is -5.12 dB, the focus error is -.11mm, and main beam FWHM is predicted to be 28.84 arc seconds. The values are in reasonable agreement with the observed secondary edge taper of -5.2 dB (Kooi, 11Jan97), and main beam FWHM of 26.8 arc

seconds (Chamberlin, 11Jan97).

A second tabulation in Table 2 shows the result of CSO\_OPTICS2.FOR with the condition that the fifth mirror focal length is changed to 18 inches. In this case we can see the present receiver,  $F/ = 4.1$ , could get quite a good match to the sky if the focus of it was placed 19.6 inches from the fifth mirror: from Table II, given "Dis" = 19.6 inches; secondary edge taper (ET) = -11 db, secondary focus error offset (foc err) = 0.00; and the beam FWHM = 30.09.

Various possible primary illumination patterns are tabulated in Table 3. In the case of uniform illumination of the primary aperature[4], we would expect the FWHM of the beam to be 26.1". The observed beam FWHM was 26.8" CSO\_OPTICS2.FOR, which assumed a gaussian beam profile incident on the primary, predicted 28.8". The design goal of a 14 dB edge taper would have given a 31.0" FWHM. The 31.0" FWHM has been assumed by most CSO observers to be accurate. This incorrect assumption leads to about a 30% overestimate of the telescope coupling efficiency. Therefore, the source brightness temperatures of extended objects would have been underestimated by the same amount.

According to the results presented in Table 3, the primary illumination pattern is probably near to uniform. CSO\_OPTICS2.FOR, which predicted a slightly greater value for the FWHM than observed, assumed a gaussian illumination pattern on the primary. This assumption neglects the substantial beam truncation occurring at the secondary: -5.2 dB edge taper. This beam truncation must be causing excessive diffraction and thus spreading out the illumination pattern on the primary.

## 4 Discussion

Jacob Kooi's March 1997 memo, "CSO Sidecab Optics, Problems and Solutions", presents his detailed measurements of the beam from all of the side cab receivers. Jacob discussed two of the particular problems associated with correcting the 230GHz receiver optics: a  $F/ 2.7$  beam would provide a good match with the existing 13 inch mirror, but it would be truncated by the LO beam splitter; and although a longer focal fifth mirror ( $F_{fifth} = 16$  inches, with receiver  $F/ = 3.3$  in Kooi's memo) could give quite a good match to the receiver, there is no room to conveniently accommodate it.

However, the calculations in Kooi's March 1997 which are used to predict the correct receiver  $F/$  start with the assumption that the image of the receiver focus should be constrained to coincide with the casegrain focus. This constraint is not quite the correct one for achieving the best telescope focus. If the telescope is actually brought into its best focus, then this assumption leads to an erroneous prediction of where the beam waist would form in the elevation torque tube. The more realistic constraint, used in CSO\_OPTICS1.FOR, which is that image of the receiver focus coincides with the telescope primary focus, leads the conclusion that a  $F/ 2.7$  230GHz beam will be truncated by the single sideband filter at about the -9.1 dB level.

## 5 Conclusion

CSO\_OPTICS1.FOR starts with the constraint that image of the receiver focus forms at the primary focus. Given a desired secondary edge taper, ET, the program predicts the corresponding receiver  $F/$ . The intermediate results

of the program can be used for predicting the size of the beam anywhere in the optics train. In the case of a  $F/\lambda = 2.7$  230 GHz receiver used with a 13 inch fifth mirror, significant beam truncation at the position of the single side band filter in the torque tube is predicted when the telescope is brought into its best focus.

CSO\_OPTICS2.FOR starts with assumption the receiver  $F/\lambda$  is given and propagates through beam all way through the CSO optical system and onto the sky. Useful predictions from the program include the edge taper on the secondary, ET, the secondary mirror z-focus offset, "foc err", and the actual telescope beam FWHM on the sky. With a little more effort, CSO\_OPTICS2.FOR could be adapted to predict the main beam efficiency and the cold spill over efficiency.

Table 1: CSO\_OPTICS1.OUT

```

LAMBDA = 1.300000
ET  W01sec  Z2sec  W01cas  Z2cas  W02cas  Z2fif  W02fif  Fno
**fifth mirror focal len = 13 in
4.0  0.23  7074.84  6.83  -498.76  52.20  336.98  2.32  2.78
6.0  0.28  7072.66  8.37  -644.78  42.64  342.34  2.49  2.98
8.0  0.32  7069.61  9.66  -695.96  36.93  346.66  2.49  2.98
10.0 0.36  7065.71  10.80 -719.61  33.04  349.82  2.42  2.90
12.0 0.39  7060.93  11.83 -732.50  30.16  352.09  2.33  2.79
14.0 0.42  7055.31  12.77 -740.25  27.93  353.72  2.24  2.67
16.0 0.45  7048.80  13.64 -745.30  26.12  354.91  2.14  2.56
**fifth mirror focal len = 15 in
4.0  0.23  7074.84  6.83  -498.76  52.20  389.94  2.69  3.22
6.0  0.28  7072.66  8.37  -644.78  42.64  397.12  2.88  3.46
8.0  0.32  7069.61  9.66  -695.96  36.93  402.95  2.89  3.47
10.0 0.36  7065.71  10.80 -719.61  33.04  407.24  2.82  3.39
12.0 0.39  7060.93  11.83 -732.50  30.16  410.34  2.72  3.26
14.0 0.42  7055.31  12.77 -740.25  27.93  412.56  2.61  3.13
16.0 0.45  7048.80  13.64 -745.30  26.12  414.20  2.50  2.99
**fifth mirror focal len = 17 in
4.0  0.23  7074.84  6.83  -498.76  52.20  443.19  3.06  3.67
6.0  0.28  7072.66  8.37  -644.78  42.64  452.43  3.29  3.95
8.0  0.32  7069.61  9.66  -695.96  36.93  460.02  3.31  3.97
10.0 0.36  7065.71  10.80 -719.61  33.04  465.64  3.23  3.88
12.0 0.39  7060.93  11.83 -732.50  30.16  469.72  3.11  3.74
14.0 0.42  7055.31  12.77 -740.25  27.93  472.67  2.99  3.59
16.0 0.45  7048.80  13.64 -745.30  26.12  474.84  2.87  3.44
**fifth mirror focal len = 19 in
4.0  0.23  7074.84  6.83  -498.76  52.20  496.69  3.43  4.12
6.0  0.28  7072.66  8.37  -644.78  42.64  508.28  3.70  4.45
8.0  0.32  7069.61  9.66  -695.96  36.93  517.88  3.72  4.48
10.0 0.36  7065.71  10.80 -719.61  33.04  525.05  3.64  4.38
12.0 0.39  7060.93  11.83 -732.50  30.16  530.27  3.52  4.23
14.0 0.42  7055.31  12.77 -740.25  27.93  534.06  3.38  4.06
16.0 0.45  7048.80  13.64 -745.30  26.12  536.86  3.24  3.90

```

**Table 2: CSO\_OPTICS2.OUT**

RX F/ = 4.100000  
 LAMBDA = 1.300000  
 F FIFTH = 13.00000

Dis	Z1fif	wo2cass	z2cas	Z1cas	Wo1cas	ET	foc err	FWHM
13.0	330.20	40.27	2927.35	-768.50	6.38	3.57	-0.10	28.51
13.2	1022.74	39.61	2234.81	-767.25	6.99	4.29	-0.10	28.60
13.4	1593.03	37.82	1664.52	-760.84	7.63	5.12	-0.11	28.84
13.6	1981.55	35.32	1276.00	-746.83	8.25	6.01	-0.12	29.25
13.8	2196.88	32.52	1060.67	-723.37	8.78	6.85	-0.15	29.83
14.0	2281.67	29.74	975.88	-691.09	9.11	7.44	-0.18	30.63
14.2	2281.63	27.15	975.92	-654.35	9.16	7.61	-0.22	31.69
14.4	2232.18	24.81	1025.37	-619.96	8.91	7.28	-0.26	33.01
14.6	2157.00	22.75	1100.55	-593.42	8.44	6.57	-0.30	34.57
14.8	2070.57	20.93	1186.98	-576.48	7.83	5.70	-0.32	36.34
15.0	1981.30	19.34	1276.25	-567.87	7.19	4.81	-0.33	38.33

RX F/ = 4.100000  
 LAMBDA = 1.300000  
 F FIFTH = 18.00000

Dis	Z1fif	wo2cass	z2cas	Z1cas	Wo1cas	ET	foc err	FWHM
18.0	457.20	55.76	2800.35	-824.50	5.76	2.87	-0.04	27.50
18.2	1784.91	54.85	1472.64	-833.73	6.20	3.32	-0.03	27.57
18.4	2878.25	52.37	379.30	-843.22	6.71	3.87	-0.02	27.68
18.6	3623.10	48.90	-365.55	-852.56	7.28	4.54	0.00	27.88
18.8	4035.92	45.02	-778.37	-860.95	7.93	5.39	0.01	28.16
19.0	4198.49	41.18	-940.94	-867.03	8.68	6.43	0.01	28.50
19.2	4198.39	37.59	-940.84	-868.54	9.50	7.71	0.02	28.94
19.4	4103.61	34.36	-846.06	-861.99	10.40	9.24	0.01	29.46
19.6	3959.46	31.50	-701.91	-842.72	11.32	11.00	0.00	30.09
19.8	3793.77	28.98	-536.22	-805.87	12.17	12.84	-0.04	30.83
20.0	3622.63	26.78	-365.08	-749.33	12.82	14.48	-0.10	31.72

**Table 3: Primary illumination patterns versus FWHM**

CONDITION	FWHM	SOURCE
Uniform Primary Illumination	26.1"	Krauss, p. 856 [4]
Observed, 11Jan97	26.8"	Deconvolved scan on Saturn
Predicted for current optics ( -5.1 dB edge )	28.8"	CSO_OPTICS2.FOR, Rx F/=4.1
Gaussian illumination, 10dB ET	29.3"	CSO_OPTICS2.FOR, Rx F/=2.90
Parabolic Illumination Pattern (10 dB edge taper on primary)	29.7"	Kraus, P. 856 [4]
Gaussian illumination, 14dB ET	31.0"	CSO_OPTICS2.FOR, Rx F/=2.67

## References

- [1] H. Kogelnik. On the propagation of gaussian beams of light through lenslike media including those with a loss and gain variation. *Appl. Opt.*, 4:1562, 1965.
- [2] A. Yariv. *Optical Electronics*. Holt, Rinehart and Winston, New York, 1985.
- [3] P. F. Goldsmith. *Quasi-Optical Techniques at Millimeter and Submillimeter Wavelengths*, page 278. Academic Press, 1982.
- [4] J. D. Kraus. *Antennas*. McGraw-Hill, New York, NY, 1988.

## A CSO\_OPTICS1.FOR

```
program CSO\_optics1
c
c Language: PCL (punched card language (VAX Fortran))
c Programmer: RACHamberlin, 20-Mar-97
c Location: CSO, Hilo, HI
c
c purpose: Given desired edge taper on secondary, ET,
c program starts at prime focus of CSO telescope and
```

```

c  uses gaussian optics to propagate the beam back to the
c  rx. The program predicts the F/ of the rx (to the 1/e**2 pwr
c  points) which will give the desired match.
c
REAL NA

C  ...EDGE TAPER ON SECONDARY...
ETmin = 4
ETmax = 16

C  ...FIFTH MIRROR RANGES...
FfifthMIN = 13
FfifthMAX = 20

ALAMBDA = 1.3
Fsec = -241.66 !mm
Fcass = -34.0 * 25.4
Ffifth = 13.0 * 25.4

OPEN(10, FILE='CSO\_OPTICS1.OUT', STATUS='NEW')
WRITE(6,*) 'LAMBDA = ', ALAMBDA
WRITE(6, 1010)
WRITE(10,*) 'LAMBDA = ', ALAMBDA
WRITE(10, 1010)

C  ...DO A LOOP OF FIFTH MIRROR FOCAL LENGTHS...
DO IFfifth = FfifthMIN, FfifthMAX, 2

TYPE*, '**fifth mirror focal len = ', IFfifth, ' in'
WRITE(10,*) '**fifth mirror focal len = ', IFfifth, ' in'
Ffifth = float(IFfifth)*25.4

C  ...NEST A LOOP ON ET's...

DO ET = ETmin, ETmax, 2
C
C  ...SPOT SIZE ON SECONDARY...
Wsec = 290.7 * sqrt( 2/((ET/10.0) * LOG ( 10.0 )) )
c      ^radius of secondary

C  ...WAIST AT PRIME FOCUS POSITION...
Z1sec = 233.68 ! 9.200"
Wolsec = W0(Wsec, Z1sec, ALAMBDA)
R1sec = R(Wolsec, Z1sec, ALAMBDA)

```

```

c
c ...find distance to cass focus waist...
c (...Z1 .LT. zero since it's a virtual focus...)
Z2sec = C7(Fsec, Wo1sec, -Z1sec, ALAMBDA)
c
c ...find cass focus waist size...
Wo1cass = C8(Fsec, Wo1sec, -Z1sec, ALAMBDA)
c
c ...find distance from cass focus to third mirror...
Z1cass = 244.783*25.4 - Z2sec
c      ^distance from secondary to third mirror
c
c ...find distance from 3rd mirror to real focus in torque tube...
c (may be virtual focus in the case 230 rx)
Z2cass = C7(Fcass, Wo1cass, Z1cass, ALAMBDA)
c
c ...find waist size...
Wo2cass = C8(Fcass, Wo1cass, Z1cass, ALAMBDA)
c
c ...find distance to fifth mirror...
Z1fifth = (94.25+34.0)*25.4 - Z2cass
c
c ...find distance to rx...
Z2fifth = C7(Ffifth, Wo2cass, Z1fifth, ALAMBDA)
c
c ...find rx waist size...
Wo2fifth = C8(Ffifth, Wo2cass, Z1fifth, ALAMBDA)
c
c ...calculate numerical aperature & F/ of rx...
NA = ALAMBDA/(3.142*Wo2fifth)
Fno = 1.0 / (2 * TAN( NA ) )

write(6,1000) ET, Wo1sec, z2sec, Wo1cass, Z2cass,
$      Wo2cass, Z2fifth, wo2fifth, Fno
write(10,1000) ET, Wo1sec, z2sec, Wo1cass, Z2cass,
$      Wo2cass, Z2fifth, wo2fifth, Fno

ENDDO
ENDDO

1000  FORMAT( ' ', F4.1, ' ', 9(F8.2, ' ' ) )
1010  FORMAT( ' ', T3,'ET',T8,'Wo1sec',T17,'Z2sec', T26, 'Wo1cas',
$      T35, 'Z2cas', T44, 'Wo2cas', T53, 'Z2fif', T62,
$      'W02fif', T71, ' Fno')
END

```

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION C8(F, Wo1, Z1, ALAMBDA)

z0 = 3.142 * Wo1**2/ ALAMBDA

C8 = Wo1 * sqrt( 1.0/( ((Z1/F)-1 )**2 + (z0/F)**2 ) )

RETURN
END
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION C7(F, Wo1, Z1, ALAMBDA)

z0 = 3.142 * Wo1**2/ ALAMBDA

C7 = F + (Z1 - F)/( ((Z1/F)-1 )**2 + (z0/F)**2 )

RETURN
END

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION R(W0, Z, ALAMBDA)
C Computes radius of constant phase surface distance Z from
c waist radius W0.
c
z0 = 3.142 * W0**2/ ALAMBDA

R = Z * ( 1 + (z0/Z)**2)
RETURN
END

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION w0(W,Z,lambda)
C
C Given spot size, W, and distance to waist, Z, finds beam
c waist radius, w0.
c
IMPLICIT NONE
C
C ...OPTICS STUFF...
REAL W, Z, LAMBDA
REAL CW, CZ, CLAMBDA
COMMON/OPTICS/ CW, CZ, CLAMBDA

```

```

C
C ...ROOT FINDER STUFF...
  INTEGER DIV, NROOTS
  REAL ROOTS(10), A, B, EPSLN
  A=.001
  B=10.0
  DIV = 1
  EPSLN=.0001
C
  CW = W
  CZ = Z
  CLAMBDA = LAMBDA
C
  CALL ROOT(A,B,DIV,EPSLN,NROOTS,ROOTS)
  WO = ROOTS(1)
  RETURN
  END
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  REAL*16 FUNCTION FUNC(WO)
  IMPLICIT NONE
  REAL WO, W, Z, LAMBDA, ZO
  COMMON/OPTICS/ W, Z, LAMBDA
  ZO = 3.142 * WO**2/LAMBDA
  FUNC = W - WO * SQRT( 1 + (Z/ZO)**2 )
  RETURN
  END
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C
  SUBROUTINE ROOT(AO, BO, DIV, EPSLN, NROOTS, ROOTS)
C
C LANGUAGE:   VAX-11 FORTRAN
C PROGRAMMER: RACHamberlin
C DATE:      3 JULY 87
C
C This subroutine tests for roots on the interval and sub-intervals
C specified by the user.  If it finds a root it uses the bisection
C method to locate it with the specified precision EPSLN.
C
C INPUT VARIABLES:
C
C   AO = lower bound of interval
C   BO = upper bound of interval
C   DIV = number of sub-intervals to test
C   EPSLN = mesh of interval in which to find root

```

```

C
C OUTPUT VARIABLES:
C
C     NROOTS = number of roots found on interval
C     ROOTS  = array containing roots found
C
C FUNCTION SUBROUTINES REFERENCED:
C
C     FUNC(x) = user supplied function for which to find roots
C
C SUBROUTINES REFERENCED: NONE
C
C     IMPLICIT NONE
C     EXTERNAL FUNC
C     REAL ROOTS(10), A0, B0, A, B, C, EPSLN, INT, X(200)
C     INTEGER I, DIV, NROOTS
C     REAL*16 FUNC
C
C     INT  = (B0 - A0)/DIV
C     NROOTS = 0
C
C     DO I=0, DIV
C     X(I+1) = A0 + INT*I
C     ENDDO
C
C     I = 1
C
C 110 CONTINUE
C     A = X(I)
C     C = X(I + 1)
C     IF ( FUNC(A)*FUNC(C) .GT. 0.0) GOTO 120
C
C 150 IF( (C-A) .LT. EPSLN) GOTO 130
C     B = A + (C - A)/2
C
C     IF ( FUNC(A)*FUNC(B) .GT. 0.0) GOTO 140
C     C = B
C     GOTO 150
C
C 140 CONTINUE
C     A = B
C     GOTO 150
C
C 130 CONTINUE
C     NROOTS = NROOTS + 1

```

```
        ROOTS(NROOTS) = A + (C-A)/2
C
120 CONTINUE
    I = I + 1
C
    IF ( I .LT. DIV) GOTO 110
    RETURN
    END
```

## B CSO\_OPTICS2.FOR

```
program cso_optics2
c
c Language: PCL (punched card language (VAX Fortran))
c Programmer: RAChamberlin, 20-Mar-97
c Location: CSO, Hilo, HI
C
C PURPOSE: Given operating wavelength, ALAMBDA, and receiver
c F/, FNO, program propagates CSO receiver beam from side cab
c to the sky. The output file shows the predicted secondary
c edge taper and the predicted FWHM of the beam on the sky.
c FNO is defined the beam 1/e**2 power points (-8.7dB). The results of a
C range of possible receiver to fifth mirror distances are calculated.
c
REAL NA

c ...Range of possible distances of the rx focus from the fifth mirror...
c                                     (inches)
Z2FIFMIN = 13.0
Z2FIFMAX = 15.0

c
c ...rx specifics...
ALAMBDA = 1.3
FNO = 4.1

c ...mirror specifics...
Fsec = -241.66 !mm
Fcass = -34.0 * 25.4
Ffifth = 13.0 * 25.4
Fprime = 162.333*25.4

WRITE(6,*) ' RX F/ = ', FNO
WRITE(6,*) ' LAMBDA = ', ALAMBDA
WRITE(6,*) ' F FIFTH =', FFIFTH/25.4
WRITE(6, 1010)

OPEN(10,FILE='CSO_OPTICS2.OUT',STATUS='NEW')
WRITE(10,*) ' RX F/ = ', FNO
WRITE(10,*) ' LAMBDA = ', ALAMBDA
WRITE(10,*) ' F FIFTH =', FFIFTH/25.4
WRITE(10, 1010)
```

```

C ...COMPUTE NUMERICAL APERATURE OF RX...
NA = 1/(2*FNO)
C
C ...COMPUTE WAIST IN RX...
WoRx = alambda/(3.142*NA)
C
C ...COMPUTE FOR DIFFERENT DISTANCES TO FIFTH MIRROR...

DO IZ2= Z2FIFMIN*10, Z2FIFMAX*10, 2

Z2FIFTH = FLOAT(IZ2)/10.0*25.4

Z1fifth = C7(Ffifth, WoRX, Z2fifth, ALAMBDA)
C
c ...find torque tube waist size...
Wo2cass = C8(Ffifth, WoRX, Z2fifth, ALAMBDA)
c
c ...find distance to third mirror...
Z2cass = (94.25+34.0)*25.4 - Z1fifth
c
c ...find position of cass virtual focus...
c ...find distance to fifth mirror...
Z1cass = C7(Fcass, Wo2cass, Z2cass, ALAMBDA)
c
Wo1cass = C8(Fcass, Wo2cass, Z2cass, ALAMBDA)
c
c ...distance to secondary...
Z2sec = 244.783*25.4 - Z1cass
c
c ...spot size on secondary...
ZoCass = 3.142*Wo1Cass**2/alambda
Wsec = Wo1cass*sqrt(1 + (Z2sec/ZoCass)**2 )
c
c ...edge taper..
pr = exp( -2* (290.7/Wsec)**2 )
ET = -10*log10( pr)
c
c ...secondary virtual focus...
Z1sec = C7(Fsec, Wo1cass, Z2sec, ALAMBDA)
c
c ...diff between correct sec focus & this one...
err = -9.200*25.4 - Z1sec
c
c ...waist at prime focus...

```

```

wo1sec = C8(Fsec, Wo1cass, Z2sec, ALAMBDA)
C
C ...prime focus distance...
Zprime = err + (253.983 - 91.650)*25.4
C
C ...effective primary waist...
wo1prime = C8(Fprime, Wo1sec, Zprime, ALAMBDA)
C
C ...distance of effective primary waist from primary center...
Z2prime = C7(Fprime, Wo1sec, Zprime, ALAMBDA)
C
C ...numerical aperature of primary...
primeNA = alambda/(3.142*wo1prime)
C
C ...(for untruncated beam) FWHM (arc seconds)...
UNTRUNFWHM = primeNA*1.177 * (180.0/3.142)*3600
C

C ...CALCULATE truncated beam FWHM (arcseconds)...
TRUNFWHM = FWHM(WO1PRIME,Z2prime,alambda)

write(6,1000), Z2FIFTH/25.4, Z1fifth, wo2cass, z2cass,
$      z1cass, wo1cass, ET, err, trunFWHM
write(10,1000), Z2FIFTH/25.4, Z1fifth, wo2cass, z2cass,
$      z1cass, wo1cass, ET, err, trunFWHM
ENDDO

1000  FORMAT( ' ', F4.1, ' ', 9(F8.2, ' ' ) )
1010  FORMAT( ' ', T3,'Dis',T8,'Z1fif',T17,'wo2cass', T26, 'z2cas',
$      T35, 'Z1cas', T44, 'Wo1cas', T53, 'ET', T62,
$      'foc err', T71, ' FWHM ')
END
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION C8(F, Wo1, Z1, ALAMBDA)

z0 = 3.142 * Wo1**2/ ALAMBDA

C8 = Wo1 * sqrt( 1.0/( ((Z1/F)-1 )**2 + (z0/F)**2 ) )

RETURN
END
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
REAL FUNCTION C7(F, Wo1, Z1, ALAMBDA)

```

```
z0 = 3.142 * Wo1**2/ ALAMBDA
```

```
C7 = F + (Z1 - F)/((Z1/F)-1)**2 + (z0/F)**2 )
```

```
RETURN  
END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC  
C  
C FUNCTION FWHM(SPOTSIZE,Z, ALAMBDA)  
C  
C Calculates FWHM of CSO beam for a given waist (SPOTSIZE).  
C Z is the distance of the waist from the primary.  
C  
C SPOTSIZE, and Z are used to propagate the beam back to the  
C plane of the primary aperature. The electric field pattern  
C for each position in the plane of the primary aperature is computed.  
C Huygens principle (each location at each point the aperture is  
C considered a separate radiator and the electric fields from all  
C the separate radiators are summed) is used to compute (by  
C numerical integration over the aperature) the electric field  
C (and power) of the beam for a given angle away  
C from the z axis of the primary (computed in the far field).  
C  
C The results of the computation are used with a root finding  
C routine to locate the FWHM power angle of the beam. The  
C final FWHM is expressed in seconds of arc.  
C  
C INTEGER DIV  
C REAL ROOTS(10)  
C COMMON/ROOTFUNC/ WAIST, WAVELENGTH,Z2  
C  
C ...ARC SECOND RANGE FOR ROOTFINDER...  
C A = 5  
C B = 30  
C  
C DIV = 6  
C EPSLN = .0125  
C  
C WAIST = SPOTSIZE  
C WAVELENGTH = ALAMBDA  
C Z2 = Z
```

```

C
C
  CALL FWHMROOT(A, B, DIV,EPSLN,NROOTS,ROOTS)
  FWHM = 2*ROOTS(1)
  RETURN
  END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
  FUNCTION ROOTFUNC(X)
  COMMON/ROOTFUNC/ WAIST, WAVELENGTH
  WO =WAIST
  ALAMBDA = WAVELENGTH

  ROOTFUNC = .5 - BEAMPWR(X,ALAMBDA,WO)
  RETURN
  END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
  SUBROUTINE FWHMROOT(AO, BO, DIV, EPSLN, NROOTS, ROOTS)
C
C   LANGUAGE:   VAX-11 FORTRAN
C   PROGRAMMER: RAChamberlin
C   DATE:      3 JULY 87
C
C   This subroutine tests for roots on the interval and sub-intervals
C   specified by the user.  If it finds a root it uses the bisection
C   method to locate it with the specified precision EPSLN.
C
C   INPUT VARIABLES:
C
C     AO = lower bound of interval
C     BO = upper bound of interval
C     DIV = number of sub-intervals to test
C     EPSLN = mesh of interval in which to find root
C
C   OUTPUT VARIABLES:
C
C     NROOTS = number of roots found on interval
C     ROOTS = array containing roots found
C
C   FUNCTION SUBROUTINES REFERENCED:
C
C     ROOTFUNC(x) = user supplied function for which to find roots
C
C   SUBROUTINES REFERENCED: NONE

```

```

C
  IMPLICIT NONE
  EXTERNAL ROOTFUNC
  REAL ROOTS(10), A0, B0, A, B, C, EPSLN, INT, X(200)
  INTEGER I, DIV, NROOTS
  REAL ROOTFUNC
C
  INT   = (B0 - A0)/DIV
  NROOTS = 0
C
  DO I=0, DIV
  X(I+1) = A0 + INT*I
  ENDDO
C
  I = 1
C
  110 CONTINUE
  A = X(I)
  C = X(I + 1)
  IF ( ROOTFUNC(A)*ROOTFUNC(C) .GT. 0.0) GOTO 120
C
  150 IF( (C-A) .LT. EPSLN) GOTO 130
  B = A + (C - A)/2
C
  IF ( ROOTFUNC(A)*ROOTFUNC(B) .GT. 0.0) GOTO 140
  C = B
  GOTO 150
C
  140 CONTINUE
  A = B
  GOTO 150
C
  130 CONTINUE
  NROOTS = NROOTS + 1
  ROOTS(NROOTS) = A + (C-A)/2
C
  120 CONTINUE
  I = I + 1
C
  IF ( I .LT. DIV) GOTO 110
  RETURN
  END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C

```

```

FUNCTION BEAMPWR(ANGLE,ALAMBDA,Wo)

C  DOUBLE INTEGRAL TO SOLVE FOR BEAM PWR AT GIVEN ANGULAR
C  DIRECTION, ANGLE (arc sec), GIVEN SPOT SIZE ON PRIMARY, WO, ETC.
C  SEE NUMERICAL RECIPIES P129 FOR METHOD OF DOUBLE INTEGRATION

COMMON/INTEGRAND/ ITYPE, AK, ANG,Woo

C
C  COMPLEX H, SB, ST
C  EXTERNAL H

C  ...CSO Primary RADIUS (MM)..
C  R = 10400.0/2.0

C  PI=3.14159

C
C  ...WAVENUMBER..
C  AK = 2*PI/ALAMBDA
C  Woo = Wo

C
C  ...ANGLE IN RADIANS..
C  ANG = ANGLE/3600.0 * (PI/180.0)

C
C  ...CALCULATE TOP INTEGRAL
C  ITYPE = 1

C  CALL QSIMP_PHI(H,0,2*PI,ST)

C  ...CALCULATE BOTTOM INTEGRAL

C  ITYPE = 2

C  CALL QSIMP_PHI(H,0,2*PI,SB)

C
C  BEAMPWR = REAL( ST* CONJG (ST) / ( SB * CONJG (SB) ) )

C
C  RETURN
C  END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C  COMPLEX FUNCTION H(PHIPHI)

```

```

COMPLEX G, SS
EXTERNAL G
COMMON/XYZ/PHI, R
PHI = PHIPHI
C ...CSO Primary RADIUS (MM)..
RADIUS = 10400.0/2.0
CALL QSIMP_R(G,1,RADIUS,SS)
H = SS
RETURN
END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
COMPLEX FUNCTION G(RR)
COMPLEX FWHMFUNC
EXTERNAL FWHMFUNC
COMMON/XYZ/ PHI, R
R = RR
G = fwhmFUNC(PHI, R)
RETURN
END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
COMPLEX FUNCTION fwhmFUNC(PHI,R)

COMPLEX EQ4, ARG1, ARG2, ARG3

COMMON/INTEGRAND/ ITYPE, AK, ANG, Wo
COMMON/ROOTFUNC/ WAIST, WAVELENGTH,Z2

Z0 = 3.142*WAIST**2/WAVELENGTH
W = WAIST*SQRT(1 + (Z2/Z0)**2 )
RCURVE = Z2*( 1 + (Z0/Z2)**2 )
C
ARG0 = -AK*Z2
ARG1 = CMPLX(0.0,ARG0)
C
ARG0 = -3.142*R**2/(WAVELENGTH*RCURVE)
ARG2 = CMPLX(0.0,ARG0)
C
ARG0 = ATAN(Z2/Z0)
ARG3 = CMPLX(0.0,ARG0)

C ...PHASE AND AMPLITUDE W.R.T. PLANE APERTURE...
C ...SEE EQ4, GOLDSMITH...
EQ4 = WAIST/W * EXP(-R**2/WAIST**2) * CEXP( ARG1 ) *

```



```

    if (n.eq.1) then
        s=0.5*(b-a)*(func(a)+func(b))
    else
        it=2**(n-2)
        tnm=it
        del=(b-a)/tnm
        x=a+0.5*del
        sum=0.
        do 11 j=1,it
            sum=sum+func(x)
            x=x+del
11      continue
        s=0.5*(s+(b-a)*sum/tnm)
    endif
    return
END
C (C) Copr. 1986-92 Numerical Recipes Software i#.

```

```

    SUBROUTINE qsimp_R(func,a,b,s)
    INTEGER JMAX
    COMPLEX FUNC,ST,S,OST, OS
    REAL a,b,EPS
    EXTERNAL func
    PARAMETER (EPS=1.e-4, JMAX=40)
CU   USES trapzd
    INTEGER j
C
    ost=CMPLX(-1000000000, 0)
    os= CMPLX(-1000000000, 0)
    do 11 j=1,JMAX
        call trapzd_R(func,a,b,st,j)
        s=(4.*st-ost)/3.
        if (Cabs(s-os).lt.EPS*Cabs(os)) return
        os=s
        ost=s
11   continue
    pause 'too many steps in qsimp'
    END
C (C) Copr. 1986-92 Numerical Recipes Software i#.

```

```

    SUBROUTINE trapzd_R(func,a,b,s,n)
    COMPLEX FUNC
    COMPLEX S, SUM
    INTEGER n
    REAL a,b

```

```

EXTERNAL func
INTEGER it,j
REAL del,tnm,x
if (n.eq.1) then
  s=0.5*(b-a)*(func(a)+func(b))
else
  it=2**(n-2)
  tnm=it
  del=(b-a)/tnm
  x=a+0.5*del
  sum=CMPLX( 0, 0 )
  do 11 j=1,it
    sum=sum+func(x)
    x=x+del
11  continue
  s=0.5*(s+(b-a)*sum/tnm)
endif
return
END
C (C) Copr. 1986-92 Numerical Recipes Software i#.

```

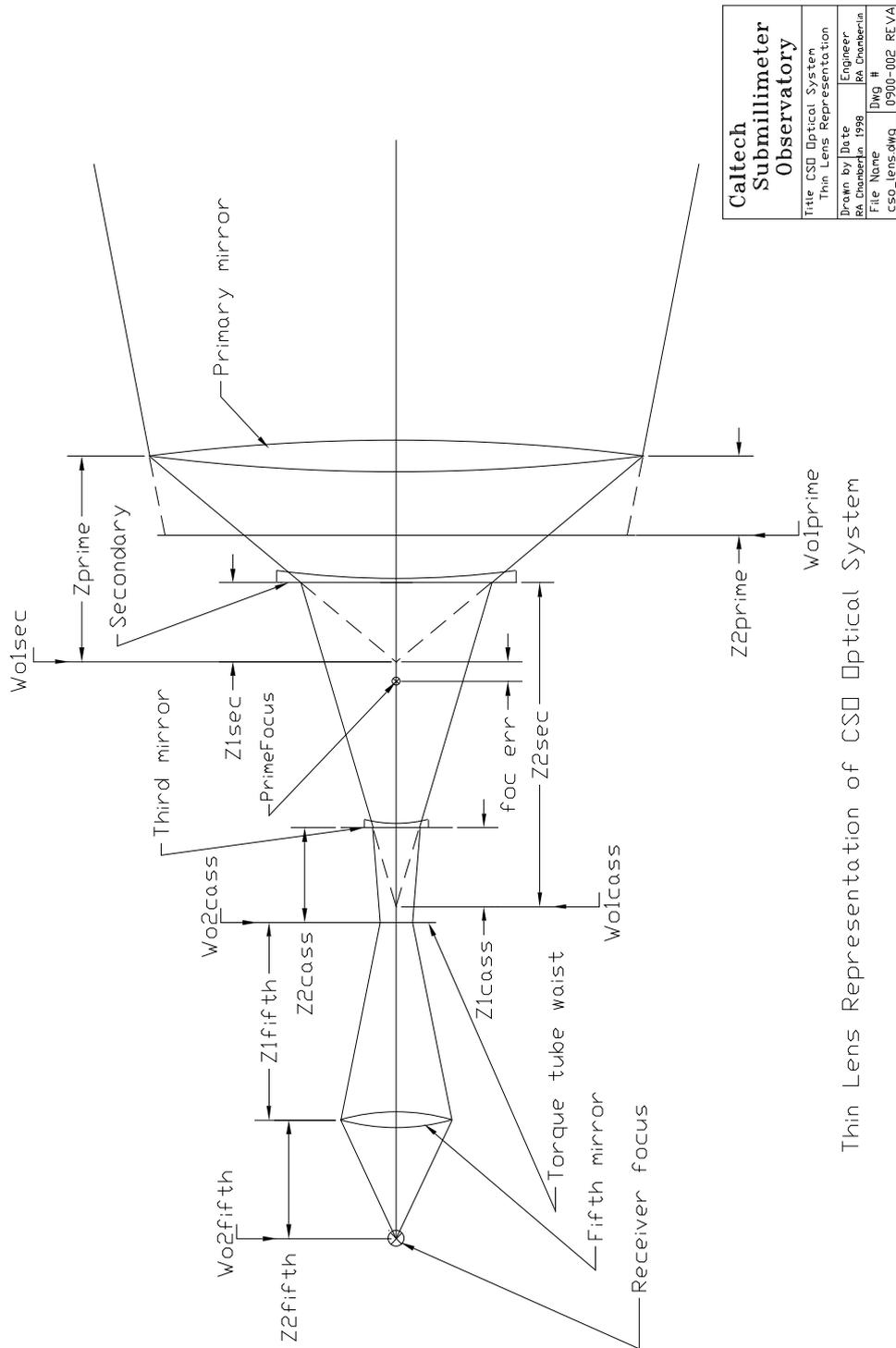


Figure 1: Thin lens representation of the CSO-sidecab optical system.

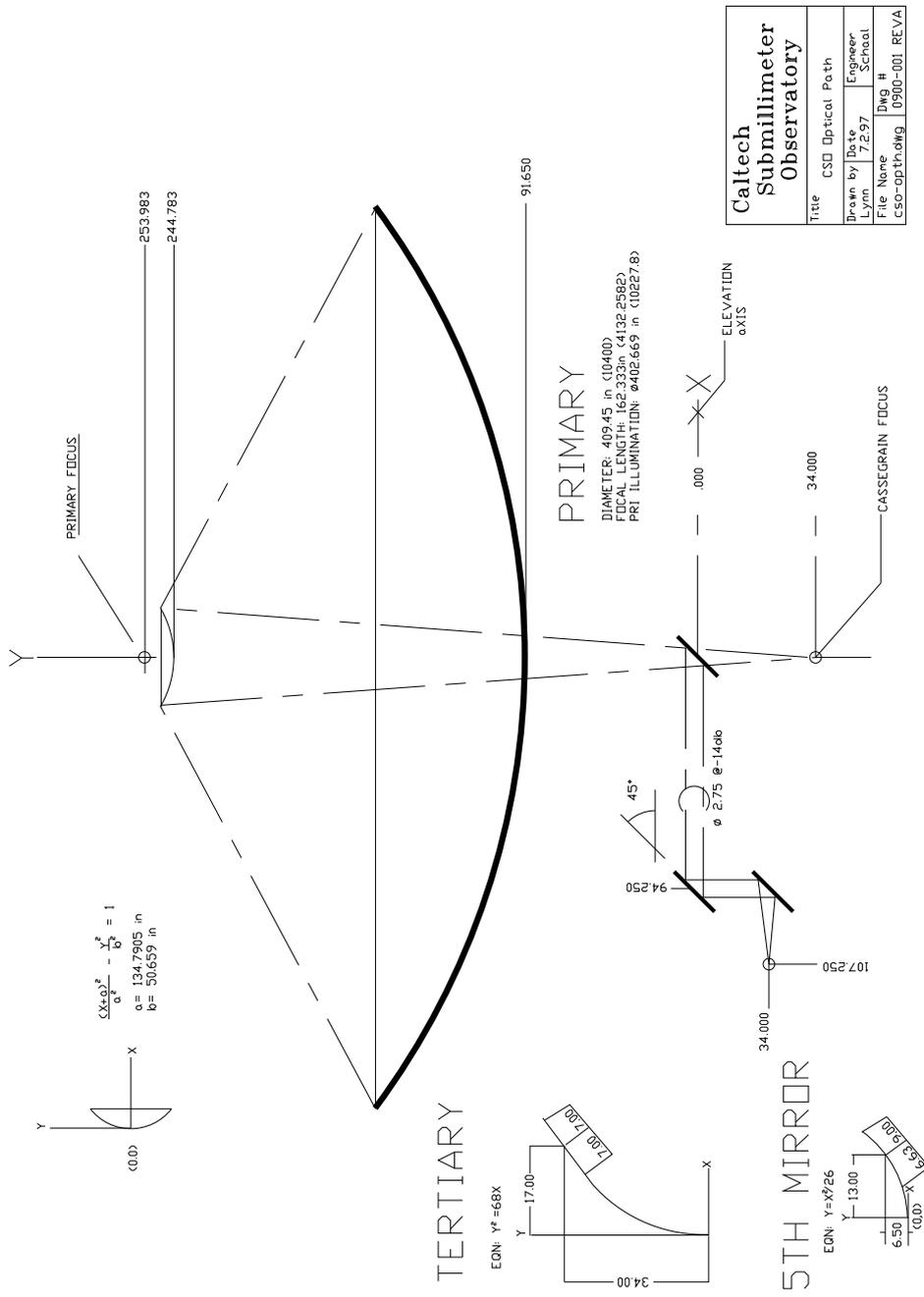


Figure 2: Literal representation of the CSO-sidecab optical system.