

INTERACTIVE PROGRAM FOR  
SETTING UP TWO-MIRROR SYSTEMS

by

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## ABSTRACT

Much of the time in lens design is spent on finding a starting design satisfying the design requirements closely enough to be input into a computer minimization program. In this thesis an interactive program to shorten this amount of time in the design of two mirror telescope objectives is described.

## CHAPTER 1

### INTRODUCTION

The purpose of the interactive program described in this paper is to aid in the design of two-mirror systems by quickly finding a useful set of starting parameters to be used in a more sophisticated design program.

Since the program is to aid in finding a suitable set of starting parameters, a maximum amount of communication between the user and the computer is desired. This amount of communication or interaction requires the use of a conversational programming language that is readily available to the largest number of users, simple to use, and easy to learn. For these reasons the BASIC conversational language was used in the program. BASIC is one of the most universal languages and its small number of clear commands can be quickly learned.

With an initial set of starting parameters [aperture height, image height, effective focal length, magnification of secondary (M), and the ratio of the mirror separation to the back focal distance (L)] the program calculates all the first-order properties in addition to the Petzval radius. If the Petzval radius is too small, the program indicates which starting parameters must be changed to increase it. When the desired Petzval radius is obtained, the program gives a paraxial ray trace and lists the five Seidel aberration values for two

spherical mirrors. Then a series of questions are asked to determine the Seidel aberrations that are to be minimized and what if any conditions are set on the values for the aspheric constants. With this information the appropriate aspheric constants and new Seidel aberrations are calculated. If a different combination of aberrations is now desired to be minimized, the program repeats the questions and calculations until it has the combination the designer wants. With this combination, the aspheric depths of the mirrors, the total surface depths of the mirrors, the vertex thickness of each mirror, the inside radius of the primary, the center of mass of the system, the total weight of the system, and the moment of inertia of the system are calculated. Then if the designer wants, the system is input to the ACCOS 5 program.

This program is limited to a design having the stop at the primary mirror and an object with infinite conjugates. Only third-order Seidel aberrations are calculated and once the Petzval radius is chosen, only the aspheric constants of the mirrors are allowed to vary. With these two variables the program will find exact solutions for  $S_1$  and  $S_2$ ,  $S_1$  and  $S_3$ , or  $S_1$  and  $S_5$  each equal to zero. If three or more aberrations are desired to be exactly zero, a change in the starting parameters may be required. To find this right combination of starting parameters (specifically  $M$  and  $L$ ) the most inclusive reference is the two-page survey by Shack (1969). Note that the  $L$  parameter used in this program is the inverse of the one used in the survey ( $L = 1/L'$ ).

When listing the first-order properties of the system, the program lists the radius of the secondary. This radius is important and must be closely observed by the designer because the program does not give any indication when the obstruction is too large. To calculate the radius of the obstruction the following equation was used:

$R = |y| + |\bar{y}|$ , where  $y$  is the marginal ray height at the secondary mirror, and  $\bar{y}$  is the chief ray height at the secondary mirror. When the radius of the secondary becomes larger than the radius of the primary, the system may still be usable as will be noted in the following chapter. An informative plot of the obstruction ratio ( $R/H$ ) where  $H$  is the radius of the entrance aperture is contained in Chapter 5.

## CHAPTER 2

### FIRST-ORDER PROPERTIES OF TWO-MIRROR SYSTEMS

#### Design Parameters

To define the optical configuration completely five design parameters are needed. The choice of the five parameters depends on the user's interests, or which parameters the user is most familiar with, or which ones the user is most concerned about observing. The choice of parameters (M and L) in this program are very similar to those chosen by Shack (1969). Another possible choice could have been those used by Wetherell and Rimmer (1972, p. 2818). Their choice also includes M (magnification of secondary) but then uses a normalized vertex back focus ( $\beta$ ), which is the distance from the vertex of the primary mirror to the principle focal point divided by the focal length of the primary mirror. Their parameter  $\beta$  and the parameter L used by this program are related by the following equation:  $\beta = M(1-L)/(1+ML)$ .

The design parameters used in the program are the basic three: aperture height (H), image height (D), and effective focal length (F); in addition to the two, the magnification of the secondary mirror ( $M = F/F_1$ , where  $F_1$  is the focal length of the primary), and the ratio of the mirror separation to the image distance from the secondary (L).

The aperture stop is located at the primary mirror for all the cases considered. An image height (D) is used instead of the half

field angle but is equal to  $-F\theta$  where  $\theta$  is the half field angle. Note that if  $M$  is greater than zero, the system is of the Cassegrain type in Fig. 1; if  $M$  is less than zero and  $F$  is greater than zero, the system is of the inverse Cassegrain type in Fig. 2; and, if  $M$  is less than zero and  $F$  is less than zero, then the system is of the Gregorian type in Fig. 3. Also if  $L$  is less than zero then the image is virtual, and if  $L$  is greater than zero then the image is real.

The sign convention is standard: a distance to the right of a reference point is positive, and a distance to the left is negative.

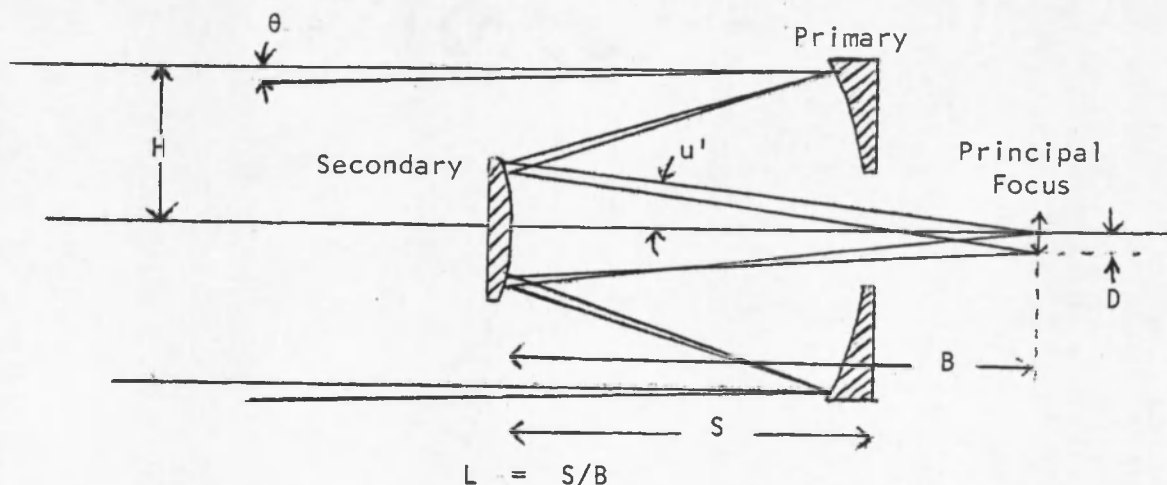


Fig. 1. Cassegrain.

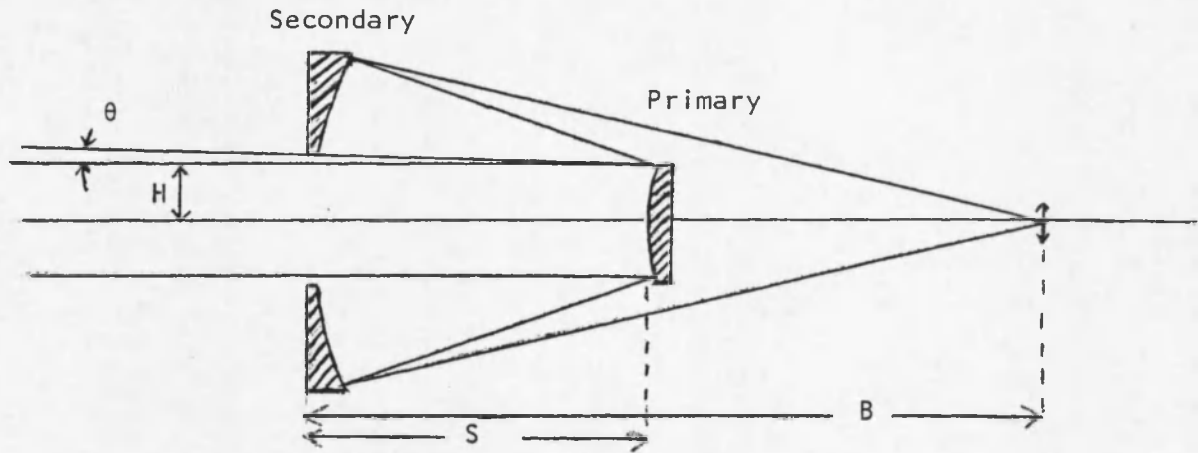


Fig. 2. Inverse Cassegrain.

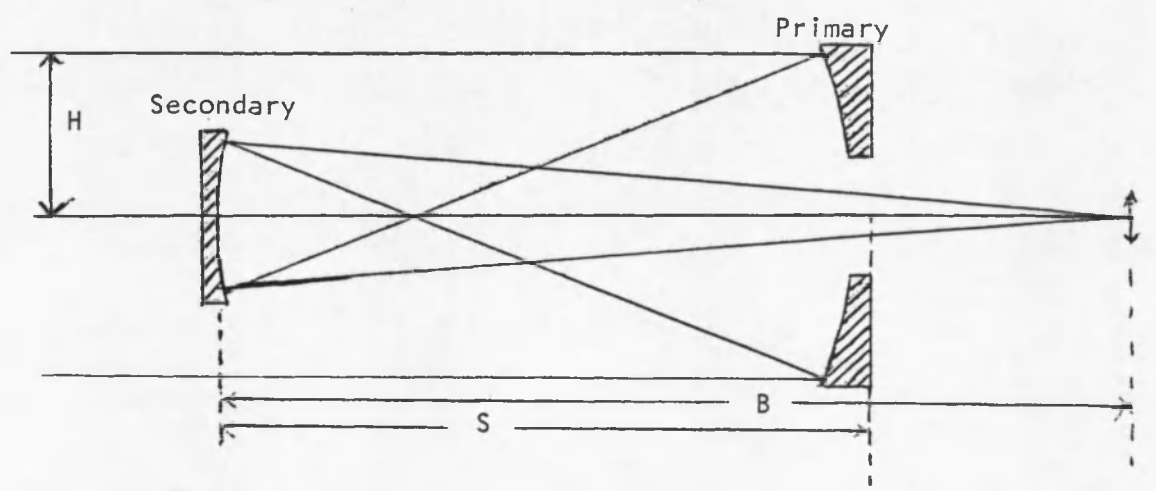


Fig. 3. Gregorian.

y -  $\bar{y}$  Diagram

In Fig. 4 the equation for the line from point 1 to point 2 is

$$Dy + HM\bar{y} = HD, \quad (1)$$

and the equation for the line from point 0 to point 2 is

$$DLy - H\bar{y} = 0. \quad (2)$$

Solving Eqs. (1) and (2) for the  $(y, \bar{y})$  values for point 2 we get

$$y = H/(1 + ML), \quad \bar{y} = LD/(1 + ML). \quad (3)$$

Note that the entrance pupil is at surface (1) and the exit pupil is at  $E'$ .

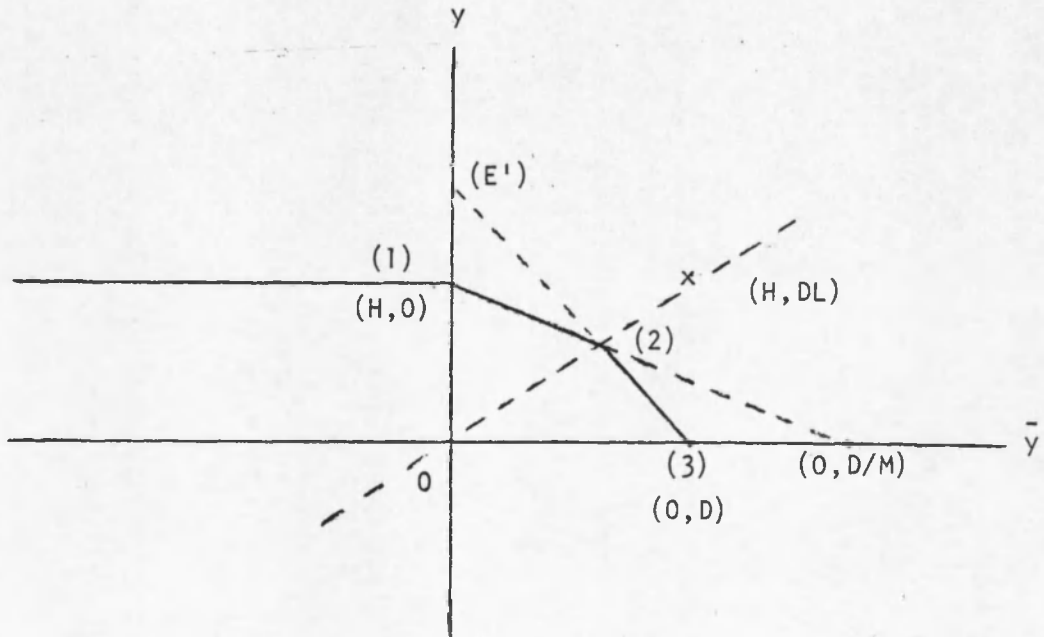


Fig. 4.  $y - \bar{y}$  Diagram.

Using these values for  $(y, \bar{y})$  at point 2, and the values  $(H, 0)$  for point 1, and  $(0, D)$  for point 3, and the following equations from Shack (1973, pp. 127, 136):

$$T = \frac{1}{W} \begin{vmatrix} y & \bar{y} \\ y' & \bar{y}' \end{vmatrix}, \quad \phi = \frac{1}{W} \begin{vmatrix} w & \bar{w} \\ w' & \bar{w}' \end{vmatrix}, \quad T = t/n$$

$$w = y/T, \quad \bar{w} = \bar{y}/T, \quad w = nu, \quad \bar{w} = n\bar{u}$$

$$c = -\phi/2n, \quad \phi = n/F, \quad (4)$$

where  $W = \text{Lagrange invariant} = HD/F$  and the following table is filled in as follows.

Table 1. First-order Properties.

Surface	0	1	2	3	E'
Index (n)	1	1	-1	1	1
y	0	H	$\frac{H}{1+ML}$	0	$\frac{H}{1-(1-M)L}$
$\bar{y}$	$\frac{-D(10^{10})}{F}$	0	$\frac{LD}{1+ML}$	D	0
T	$10^{10}$		$\frac{LF}{1+ML}$	$\frac{F}{1+ML}$	
w	0		$\frac{-HM}{F}$	$\frac{-H}{F}$	
$\bar{w}$		$\frac{D}{F}$	$\frac{D}{F}$	$\frac{D(1+ML-L)}{F}$	
$\phi$		$\frac{M}{F}$	$\frac{(1-M)(1+ML)}{F}$		
t	$10^{10}$		$\frac{-LF}{1+ML}$	$\frac{F}{1+ML}$	
c		$\frac{-M}{2F}$	$\frac{(1-M)(1+ML)}{2F}$		

## CHAPTER 3

### SEIDEL ABERRATIONS OF TWO-MIRROR SYSTEMS

#### General Conics

The sagitta of an aspheric surface from a plane tangent to its vertex as a function of the radial distance  $r$  from the optical axis is given by:

$$z(r) = cr^2 / \left( 1 + \left( 1 - (K+1)c^2r^2 \right)^{\frac{1}{2}} \right), \quad (5)$$

where  $K$  is the conic constant of the surface, and  $c$  is the vertex curvature of the surface. A list of conic surfaces for various values of  $K$  is:

$K < -1$	Hyperboloid
$K = -1$	Parabola
$0 > K > -1$	Prolate ellipsoid
$K = 0$	Sphere
$K > 0$	Oblate ellipsoid.

If  $c = 0$ , the surface can still be aspheric and the sag is then given by  $z(r) = dr^2$ , where  $d$  is the aspheric constant.

Aberrations as Functions of Conic Constants

Using the equations given by Welford (1974, p. 196) for the Seidel aberrations of a thin lens with a remote stop, with the following substitutions:  $n = -1$ ,  $\phi = K$  (the power of the surface),  $B = 1$  (the shape factor of the lens),  $Q = HE = \bar{y}/y$  (the stop position factor),  $W = H$  (the Lagrange invariant),  $y = h$  (marginal ray height at the surface), and  $\bar{y} = \bar{h}$  (chief ray height at the surface), we obtain the equations for the Seidel aberrations of a mirror with a remote stop:

$$\begin{aligned}
 S1 &= \frac{y^4 \phi \cdot C^2}{4n_o^2} \\
 S2 &= \frac{y^2 \phi^2 W C}{2n_o^2} + Q S1 \\
 S3 &= \frac{W^2 \phi}{n_o^2} + \frac{Q y^2 \phi^2 W C}{n_o^2} + Q^2 S1 \\
 S4 &= \frac{-W^2 \phi}{n_o^2} \\
 S5 &= \frac{2 Q W^2 \phi}{n_o^2} + \frac{3 Q^2 y^2 \phi^2 W C}{2n_o} + Q^3 S1,
 \end{aligned} \tag{6}$$

where:  $C = \frac{u + u'}{u - u'}$  (the conjugate factor).

The effect of aspheric surfaces on the Seidel aberrations can be calculated by:

$$\begin{aligned}
 \Delta S1 &= a \\
 \Delta S2 &= a Q \\
 \Delta S3 &= a Q^2 \\
 \Delta S4 &= 0 \\
 \Delta S5 &= a Q^3,
 \end{aligned} \tag{7}$$

where:  $a = K c^3 y^4 \Delta(n)$  for a conic with the conic constant  $K$ , or  
 $a = 8 d y^4 \Delta(n)$  for a plane with the aspheric constant  $d$ ,  
 $\Delta(n) = n' - n$ , or  $-2$  for the primary mirror, and  $2$  for  
secondary mirror.

From Table 1 we can obtain the following values for the  
primary mirror:  $Q = 0$ ,  $\phi = M/F$ ,  $C = -1$ ,  $n_o = 1$ , and  $a = H^4 M^3 A4/(4F^3)$   
where:  $A4 = K$  [the conic constant in Eq. (5)]. Substituting these  
values into Eqs. (6) and Eqs. (7) and then combining the two sets we  
obtain the Seidel aberrations for the primary:

$$\begin{aligned}
 S1 &= \frac{H^4 \cdot M^3 (1 + A4)}{4F^3} \\
 S2 &= \frac{-H^2 W M^2}{2F^2} \\
 S3 &= \frac{W^2 M}{F} \\
 S4 &= \frac{-W^2 M}{F} \\
 S5 &= 0.
 \end{aligned} \tag{8}$$

From Table 1 we can also obtain the following values for the  
secondary mirror:  $Q = W L F/H^2$ ,  $\phi = \frac{(1-M)(1+ML)}{F}$ ,  $n_o = -1$ ,

$C = \frac{M+1}{M-1}$ , and  $a = \frac{H^4(1-M)^3 A_3}{4F^3(1+ML)}$ , where:  $A_3 = K$  (the conic constant in Eq. (5) for the secondary conic). Substituting these values into Eqs. (6) and (7) and combining the two sets we obtain the Seidel aberrations for the secondary:

$$\begin{aligned}
 S1 &= \frac{H^4(1-M)^3}{4F^3(1+ML)} \left( \frac{(M+1)^2}{(M-1)^2} + A_3 \right) \\
 S2 &= \frac{H^2 W}{2F^2} \left( M^2 - 1 + \left(\frac{L}{2}\right) \left( \frac{(1-M)^3}{1+ML} \right) \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right) \\
 S3 &= \frac{W^2}{F} \left( (1-M)(1+ML) + L(M^2-1) + \left(\frac{L}{2}\right)^2 \left( \frac{(1-M)^3}{1+ML} \right) \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right) \\
 S4 &= \frac{-W^2(1-M)(1+ML)}{F} \\
 S5 &= \frac{2W^3}{H^2} \left( L(1-M) - \left(\frac{L}{2}\right)^2 (1-M)(3-M) + \left(\frac{L}{2}\right)^3 \right. \\
 &\quad \left. \left( \frac{(1+M)^3}{1+ML} \right) \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right). \tag{9}
 \end{aligned}$$

To get the Seidel aberrations for the two mirror system we then can add Eqs. (8) and (9):

$$\begin{aligned}
 S1 &= \frac{H^4}{4F^3} \left( M^3(1+A_4) + \frac{(1-M)^3}{1+ML} \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right) \\
 S2 &= \frac{H^2 W}{2F^2} \left( -1 + \frac{L}{2} \left( \frac{(1-M)^3}{1+ML} \right) \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right) \\
 S3 &= \frac{W^2}{F} \left( 1 - (1-M)L + \left(\frac{L}{2}\right)^2 \left( \frac{(1-M)^3}{1+ML} \right) \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right) \\
 S4 &= \frac{W^2}{F} - 1 - ML(1-M) \\
 S5 &= \frac{2W^3}{H^2} \left( L(1-M) - \left(\frac{L}{2}\right)^2 (1-M)(3-M) + \left(\frac{L}{2}\right)^3 \left( \frac{(1-M)^3}{1+ML} \right) \right. \\
 &\quad \left. \left( \frac{(1+M)^2}{(M-1)^2} + A_3 \right) \right). \tag{10}
 \end{aligned}$$

If the curvature of the secondary is zero then the new  $A_3 = 0$ , and we have a new set of Seidel aberrations using Eq. (7) given by:

$$\begin{aligned}
 S1^* &= S1 + \frac{16 H^4 A_9}{(1+ML)^4} \\
 S2^* &= S2 + \frac{D L 16 H^4 A_9}{H (1+ML)^4} \\
 S3^* &= S3 + \left(\frac{D L}{H}\right)^2 \frac{16 H^4 A_9}{(1+ML)^4} \\
 S4^* &= S4 \\
 S5^* &= S5 + \left(\frac{D L}{H}\right)^3 \frac{16 H^4 A_9}{(1+ML)^4} ,
 \end{aligned} \tag{11}$$

where  $A_9 = d$  (the aspheric constant of the secondary), and  $S1$ ,  $S2$ ,  $S3$ ,  $S4$ , and  $S5$  are given in Eq. (1) with  $A_3 = 0$ .

## CHAPTER 4

### INTERACTIVE PROGRAM

#### Minimization Method

In choosing a minimization method for a computer optimization program in lens design an excellent reference is Jamieson (1971) who presents a number of techniques. But this program's aim is that of obtaining a useable set of starting parameters for input into a more detailed optimization program, so one of the simplest methods was chosen. Another reason for choosing the following method is that once the Petzval radius is chosen by the user, the only variables allowed to vary are the aspheric constants of the two mirrors. In other words, we only have two variables which behave in a linear fashion.

Looking at Eqs. (10) and (11) we see that there are only two variables in  $S_1$  and only one variable for  $S_2$ ,  $S_3$ ,  $S_5$ . These variables are the  $A_3$  and  $A_4$  (conic constants), or  $A_9$  and  $A_4$  when  $A_3 = 0$ . Thus for any given set of parameters:  $S_2$ ,  $S_3$ , and  $S_5$  are linear functions of  $A_3$  (or  $A_9$ ), and  $S_1$  is a linear function of  $A_4$  and  $A_3$ . Therefore we can find values for  $A_3$  and  $A_4$  such that  $S_1$  and any other Seidel aberration (except  $S_4$ ) will be exactly zero for a given set of parameters.

The method used is that of finding the slope of the aberration that is a function of  $A_3$  alone, calculating its intersection

with  $S(A_3) = 0$ ; using this value of  $A_3$  as a constant in the equation for  $S_1$ , and repeating the procedure for the value of  $A_4$  where  $S_1 = 0$ .

To calculate the intersection of the linear function of  $A$  with the  $S(A) = 0$ , the following is done (refer to Fig. 5): For arbitrary values of  $A$  (say  $A_1, A_2$ ) we calculate  $S(A_1)$  and  $S(A_2)$ . We then equate the slopes of the line through  $A_1, A_2, A_3$ : where  $S(A_3) = 0$ :

$$\frac{-S(A_1)}{A_3 - A_1} = \frac{S(A_1) - S(A_2)}{A_1 - A_2} \quad \text{and solving for } A_3:$$

$$A_3 = A_1 - \frac{S(A_1)(A_1 - A_2)}{S(A_1) - S(A_2)}$$

In the program  $A_1$  is arbitrarily set at 0.5 and  $A_2$  at 1.0.

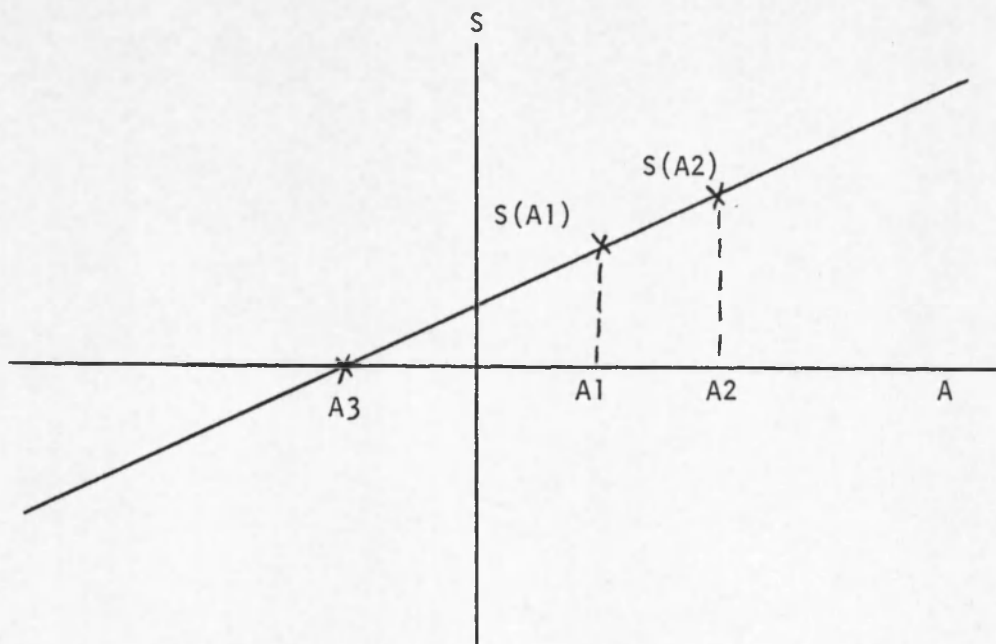


Fig. 5. Minimization Method.

If more than one of the aberrations which are a function of  $A_3$  alone are to be minimized, the aberrations are added together and their sum (which is also linear with  $A_3$ ) is minimized by the same slope method. As a demonstration of this, a plot of the aberrations (S2, S3, and S5) for the sample run with  $M = 3$ ,  $L = 0.8$  is given in Fig. 6.

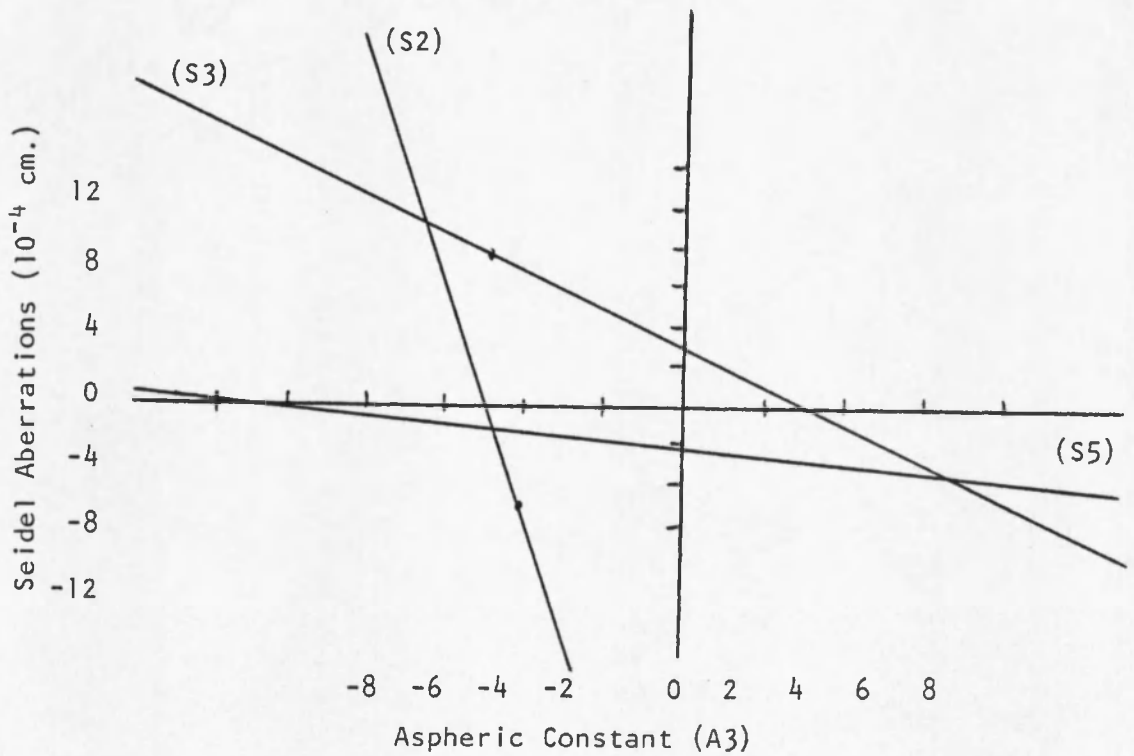


Fig. 6. Behavior of Aberrations for Sample Design Run.

From the plot we see that the slope of S2 is the steepest, and thus when we want it minimized along with S3 or S5, the minimum value of their sum will be given by an A3 very close to the value of A3 for minimum S2 alone. We can also see that for the combination of S3 and S5 minimized, the value for S2 will be large.

#### Possible Combinations Minimized

The possible combinations of Seidel aberrations minimized with a list of possible conics is shown in Table 2.

Table 2. Possible Combinations Minimized.

<u>Aberrations</u>	<u>Parabolic Primary</u>	<u>Spherical Primary</u>	<u>Aspheric Primary and Secondary</u>
S1*	X	X	
S2	X	X	
S3	X	X	
S5	X	X	
S1, S2	X	X	X
S1, S3	X	X	X
S1, S5	X	X	X
S2+S3	X	X	
S2+S5	X	X	
S3+S5	X	X	
S1, S2+S3	X	X	X
S1, S2+S5	X	X	X
S1, S3+S5	X	X	X
S2+S3+S5	X	X	
S1, S2+S3+S5	X	X	X

\*For S1 another possible combination is a spherical secondary.

### Sample Design Run

Randomly picking an example which may be useful, the following parameters were chosen. To design a one meter aperture,  $F/10$ , 10 cm radius field, with secondary mirror magnification between 3 and 5, and a ratio  $L$  from 0.8 to 1.0 the following run was used (Fig. 7):

1. One at a time the program asks for the aperture height, image height, focal length, magnification of secondary, and  $L$ . The units used on this run are centimeters.

2. The program lists the starting parameters, the first order properties, the radius of the secondary, and the Petzval radius.

3. We decide the Petzval radius is too small, the program states which parameters to change, and asks their new values. We change  $L$  from 1.0 to 0.8.

4. The program repeats part 2 for the new  $L$ .

5. We again decide the Petzval radius is too small, and this time change  $M$  from 5 to 3, and  $L$  back to 1.0.

6. This Petzval radius is more reasonable so the program lists the paraxial ray trace, and the Seidel aberrations for spherical surfaces.

7. We want two aspheric surfaces and  $S1$ ,  $S2$ , and  $S3$  minimized, so the program lists the aspheric constants and the new set of aberrations.

8. We try different combinations and observe that the combination \*\* (two aspherics and minimum  $S1$  and  $S2$ ) looks best.

RUN

CASEGR. 40

10:37

29-JUL-76

THE UNITS ON THE FOLLOWING CALCULATED VALUES WILL BE THE SAME AS THE UNITS ON YOUR INPUT VALUES

WHAT IS THE APERTURE HEIGHT?  
?50

WHAT IS THE IMAGE HEIGHT?  
?10

(1) WHAT IS THE FOCAL LENGTH?  
?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?  
?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY  
?1

H	F	M	L	D
50	1000	5	1	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.024	166.667	166.667	
(2) CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.012	2	2.4995	
RADIUS OF SECONDARY				
8.335				
S4	PETZVAL RADIUS			
0.00475	-52.6316			

IS THE PETZVAL RADIUS TOO SMALL ?  
?YES

TO INCREASE PETZVAL RADIUS: INCREASE FOCAL LENGTH, DECREASE THE MAGNIFICATION OF THE SECONDARY, OR DECREASE L

(3) WHAT IS THE FOCAL LENGTH?  
?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?  
?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY  
?.8

H	F	M	L	D
50	1000	5	0.8	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.02	160	200	
(4) CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.01	2	2.49968	
RADIUS OF SECONDARY				
10.0013				
S4	PETZVAL RADIUS			
0.00375	-66.6667			

IS THE PETZVAL RADIUS TOO SMALL ?  
?YES

TO INCREASE PETZVAL RADIUS: INCREASE FOCAL LENGTH, DECREASE THE MAGNIFICATION OF THE SECONDARY, OR DECREASE L

(5) WHAT IS THE FOCAL LENGTH?  
?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?  
?3

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY  
?1

Fig. 7. Sample Design Run

```

H      F      M      L      D
50     1000     3     1     10
1ST POWER 2ND POWER SEPARATION B FOCAL DIST
0.003    -0.008    250    250
CURVATURE 1 CURVATURE 2 PRIMARY F# SECONDARY F#
-0.0015  -0.004    3.33333  4.999
RADIUS OF SECONDARY
12.5025
S4     PETZVAL RADIUS
0.00125  -200
IS THE PETZVAL RADIUS TOO SMALL ?
?NO
SURF      CURVATURE      INDEX      THICKNESS
0         0             1         1.00000E+10
1         0             1         0
(6) 2     -0.0015        -1        -250
3         -0.004         1         250
4         0             1         0
SURF      AXIAL Y      AXIAL U      CHIEF Y      CHIEF U
0         0             5.00000E-9  -100000000   0.01
1         50.          5.00000E-9  0            0.01
2         50.          0.15        0            -0.01
3         12.5        -5.00000E-2  2.5          0.03
4         7.03335E-6  -5.00000E-2  10           0.03
5         7.03335E-6  -5.00000E-2  10           0.03
THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE
S1      S2      S3      S4      S5
2.96875E-2 -0.003125  0.00025  0.00125  -0.0003
HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5
?3
WHICH THREE ABERRATIONS MINIMIZED ? DENOTE S1+S2+S3 BY 1,
S1+S2+S5 BY 2, S2+S3+S5 BY 3, S1+S3+S5 BY 4
?1
DO YOU WANT THE PRIMARY PARABOLIC ?
?NO
(7) CAN BOTH SURFACES BE ASPHERIC ?
?YES
SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2+S3 ARE
CONIC CON.1 CONIC CON.2 ASPHERIC CON.2
-0.987654   -3.83333    0
S1          S2          S3          S4          S5
1.86265E-9  -7.29167E-4  7.29167E-4  0.00125    -2.04167E-4
DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?
?YES
HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5
?2
WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6
?1
DO YOU WANT THE PRIMARY PARABOLIC ?
?YES
SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2 ARE
CONIC CON.1 CONIC CON.2 ASPHERIC CON.2
-1          -4.16667    0
S1          S2          S3          S4          S5
5.20835E-4  -5.20833E-4  7.70833E-4  0.00125    -1.95833E-4
(8) DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?
?YES
HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5
?2
WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6
?1

```

Fig. 7. Sample Design Run, Continued.

\*\*

DO YOU WANT THE PRIMARY PARABOLIC ?  
 ?NO  
 CAN BOTH SURFACES BE ASPHERIC ?  
 ?YES  
 SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE  
 CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2  
 -1.07407        -5.                    0  
 S1            S2                    S3                    S4                    S5  
 -1.86265E-9    -2.32831E-10    8.75000E-4    0.00125        -1.75000E-4  
 DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
 ?YES  
 HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5  
 ?2  
 WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
 S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6  
 ?1  
 DO YOU WANT THE PRIMARY PARABOLIC ?  
 ?NO  
 CAN BOTH SURFACES BE ASPHERIC ?  
 ?NO  
 SEIDEL ABERRATIONS FOR SPHERICAL PRIMARY AND MIN S1+S2 ARE  
 CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2  
 0                7.08333            0  
 S1            S2                    S3                    S4                    S5  
 7.55208E-3    -7.55208E-3    -6.35417E-4    0.00125        -4.77083E-4  
 DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
 ?YES  
 HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5  
 1  
 ?WHICH ONE MINIMIZED ? DENOTE S1 BY 1, S2 BY 2, S3 BY 3, S5 BY 5  
 ?1  
 DO YOU WANT THE PRIMARY PARABOLIC ?  
 ?YES  
 SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1 ARE  
 CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2  
 -1                -4                    0  
 S1            S2                    S3                    S4                    S5  
 6.98492E-10    -6.25000E-4    7.50000E-4    0.00125        -2.00000E-4  
 DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
 ?YES  
 HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5  
 ?1  
 WHICH ONE MINIMIZED ? DENOTE S1 BY 1, S2 BY 2, S3 BY 3, S5 BY 5  
 ?1  
 DO YOU WANT THE PRIMARY PARABOLIC ?  
 ?NO  
 DENOTE WHICH SURFACE ASPHERIC: PRIMARY BY 1, SECONDARY BY 2  
 ?2  
 SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1 ARE  
 CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2  
 0                9.5                    0  
 S1            S2                    S3                    S4                    S5  
 2.56114E-9    -9.06250E-3    -9.37500E-4    0.00125        -5.37500E-4  
 DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
 ?YES  
 HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5  
 ?1  
 WHICH ONE MINIMIZED ? DENOTE S1 BY 1, S2 BY 2, S3 BY 3, S5 BY 5  
 ?2  
 DO YOU WANT THE PRIMARY PARABOLIC ?  
 ?YES  
 SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S2 ARE  
 CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2  
 -1                -5                    0  
 S1            S2                    S3                    S4                    S5  
 3.12500E-3    -2.32831E-10    8.75000E-4    0.00125        -1.75000E-4

(8)

Fig. 7. Sample Design Run, Continued.

```

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?
?NO
DO YOU WANT ANY OF THE STARTING VALUES (H,F,M,L,D) CHANGED ?
?YES
WHAT IS THE APERTURE HEIGHT?
?50
WHAT IS THE IMAGE HEIGHT?
?10
WHAT IS THE FOCAL LENGTH?
?1000
WHAT IS THE MAGNIFICATION OF THE SECONDARY ?
?3
WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE
FROM THE SECONDARY
?.8
H          F          M          L          D
50         1000         3          0.8         10
1ST POWER  2ND POWER  SEPARATION  B FOCAL DIST
0.003      -0.0068      235.294    294.118
CURVATURE 1  CURVATURE 2  PRIMARY F#  SECONDARY F#
-0.0015    -0.0034      3.33333    4.99936
RADIUS OF SECONDARY
14.7078
S4          PETZVAL RADIUS
9.50000E-4  -263.158
IS THE PETZVAL RADIUS TOO SMALL ?
?NO
SURF        CURVATURE    INDEX      THICKNESS
0           0             1          1.00000E+10
1           0             1          0
2           -0.0015       -1         -235.294
3           -0.0034       1          294.118
4           0             1          0
SURF        AXIAL Y      AXIAL U     CHIEF Y     CHIEF U
0           0             5.00000E-9 -100000000  0.01
1           50.         5.00000E-9  0           0.01
2           50.         0.15        0           -0.01
3           14.7059     -5.00000E-2 2.35294     0.026
4           6.67572E-6  -5.00000E-2 10          0.026
5           6.67572E-6  -5.00000E-2 10          0.026
THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE
S1          S2          S3          S4          S5
2.74816E-2  -2.97794E-3  2.73529E-4  9.50000E-4  -2.20235E-4
HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5
?3
WHICH THREE ABERRATIONS MINIMIZED ? DENOTE S1+S2+S3 BY 1,
S1+S2+S5 BY 2, S2+S3+S5 BY 3, S1+S3+S5 BY 4
?1
DO YOU WANT THE PRIMARY PARABOLIC ?
?NO
CAN BOTH SURFACES BE ASPHERIC ?
?YES
SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2+S3 ARE
CONIC CON.1  CONIC CON.2  ASPHERIC CON.2
-0.996807    -3.96336      0
S1          S2          S3          S4          S5
-1.62981E-9  -6.46552E-4  6.46552E-4  9.50000E-4  -1.60552E-4
DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?
?YES
HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5
?2
WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6
?1
DO YOU WANT THE PRIMARY PARABOLIC ?
?NO

```

Fig. 7. Sample Design Run, Continued.

CAN BOTH SURFACES BE ASPHERIC ?

?NO

SEIDEL ABERRATIONS FOR SPHERICAL PRIMARY AND MIN S1+S2 ARE

CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2

0	5.74569	0		
S1	S2	S3	S4	S5
6.35776E-3	-6.35776E-3	-2.67241E-4	9.50000E-4	-3.06759E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?YES

HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?YES

SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2 ARE

CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2

-1	-4.14655	0		
S1	S2	S3	S4	S5
5.38793E-4	-5.38793E-4	6.63793E-4	9.50000E-4	-1.57793E-4

(9) DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?YES

HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1    CONIC CON. 2    ASPHERIC CON. 2

-1.09259	-5.0625	0		
S1	S2	S3	S4	S5
6.98492E-10	1.74623E-10	7.50000E-4	9.50000E-4	-1.44000E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H,F,M,L,D) CHANGED ?

?NO

THE TOTAL SURFACE DEPTH AT THE EDGE OF THE PRIMARY IS    -1.87476

THE ASPHERIC DEPTH AT THE EDGE OF THE PRIMARY IS            2.88825E-3

THE TOTAL SURFACE DEPTH AT THE EDGE OF THE SECONDARY IS    -0.368812

THE ASPHERIC DEPTH AT THE EDGE OF THE SECONDARY IS            1.15943E-3

THE INSIDE RADIUS OF THE PRIMARY IS                            2.94155

(10) THE VERTEX THICKNESS OF THE PRIMARY IS                        5

THE VERTEX THICKNESS OF THE SECONDARY IS                      1.47079

THE CENTER OF MASS AS MEASURED FROM THE REAR OF THE PRIMARY ALONG THE  
OPTIC AXIS IS                                                        8.72019

DENOTE THE UNITS ON THE INPUT VALUES: INCHES BY 2.54, MILLIMETERS BY 0.1  
CENTIMETERS BY 1, METERS BY 100

?1

THE TOTAL HEIGHT IN GRAMS IS 79435.3

THE MOMENT OF INERTIA (IN GM.(UNITS)\*\*2)FOR THE SYSTEM IS

1.21153E+8

DO YOU WANT TO RUN THIS CASSEGRAIN ON ACOSS ?

?YES

(11) GIVE THE LENS A NAME

?SAMPLE

TYPE THE COMMAND \_\_\_\_\_MONITOR\_\_\_\_\_

THEN TYPE THE COMMAND ----TOCDC ACOSS.CDC-----

AND THE ACOSS OUTPUT WILL BE PLACED IN THE DEC 10 FILE AS OUTPUT

Fig. 7. Sample Design Run, Continued.

TYPE OUTPUT  
ACCOSY LICENSED FOR USE AT U OF A. TUCSON PD 04/28/75

```

--LENS
--LI, SAMPLE
--SAY, 50
--SCY, -100000000
--TH, 1.00000E+10
--AIR
--AIR
--COBS, 14.7078
--ASTOP EN
--REFS
--CV, -0.0015
--CC, -1.09259
--TH, -235.294
--REFL
--CV, -0.0034
--CC, -5.0625
--ASPH, 0
--TH, 294.118
--REFL
--PY, 0
--AIR
--EOS

--OCVY

```

(12)

EFL	BF	F/NBR	LENGTH	OID	T-MAG
1000.0024	.0000	10.00	294.1180*****		-.000000

--PXTY ALL

PXT IN YZ PLANE AT WAVL 1

SURF	PY	PCY	PUY	PUCY
0	0.00000	-.10000E+09	.00000	.01000
1	50.00000	0.00000	.00000	.01000
2	50.00000	0.00000	.15000	-.01000
3	14.70590	2.35294	-.05000	.02600
4	.00004	10.00001	-.05000	.02600
5	.00000	10.00003	-.05000	.02600

--MAB3 ALL

MONOCHROMATIC ABERRATIONS AT WAVL 1

SURF	SA3	CHA3	AST3	DIS3	PT23
1	0.000000	0.000000	0.000000	0.000000	0.000000
2	.003986	.016875	-.000750	0.000000	.000750
3	-.003986	-.016875	.000000	.000144	-.001700
4	0.000000	0.000000	0.000000	0.000000	0.000000
TOTALS	-.000002	-.000000	-.0007500	.001440	-.0009500

Fig. 7. Sample Design Run, Continued.

```
--LENO  
LENS SAMPLE  
SAY 5.0000000E+01  
SCY -1.0000000E+00 0.  
TH 1.0000000E+10  
AIR  
TH 0.  
AIR  
(12) CC -1.0925900E+00  
REFS  
ASTOP EN  
CV -1.5000000E-03  
COBS 1.4707000E+01 0.  
TH -2.3529400E+02  
REFL  
ASPH 0. 0. 0. 0.  
CC -5.0625000E+00  
CV -3.4000000E-03  
TH 2.9411800E+02  
REFL  
PY 0.  
AIR  
EOS  
C .....END OF LENS DECK.....  
--EXIT
```

Fig. 7. Sample Design Run, Continued.

9. Thinking we might do better with a smaller L we change L from 1.0 to 0.8 and repeat steps 6, 7, 8 and decide that the combination of two aspherics and minimum S1 and S2 is better.

10. The program lists the total surface depths, the aspheric depths, the inside radius of the primary, the vertex mirror thicknesses, the center of mass (using a density of 2.5 gm/cm<sup>3</sup>), the total weight in grams, and the moment of inertia.

11. The program creates a lens deck with the last system's parameters and puts it on file so we can run this mirror system on the ACCOS 5 program by typing the commands "MONITOR", and then "TOCD ACCOS5.CDC". The program then tells us where we will find the output from ACCOS5, when it has run.

12. The output from the ACCOS5 run is listed for comparison with the Seidel aberrations. The two lists of aberrations are related by the following equations:

$$SA3 = \frac{S1}{2nu}$$

$$CMA3 = \frac{3 S2}{2nu} = \text{Tangential Coma}$$

$$AST3 = \frac{S3}{2nu}$$

$$PTZ3 = \frac{S4}{2nu}$$

$$DIS3 = \frac{S5}{2nu}$$

where u is the final marginal ray angle with the optic axis (for this sample lens u = (PUY) = - 0.05).

Comments on Programming

To use this program, the first thing that must be done is to enter the program into the Dec 10 file directory. To do this, obtain the card deck of the program, type the following cards, and read them into the CDC 6400 card reader in this sequence:

\$JOB - name (ppn)

\$PASSWORD - password

\$DECK - name, ext

[ the card deck of the program

\$EOD

where: name, is the name desired to call the job;

ppn, is the billing number on the Dec 10;

password, is the password for the ppn;

name, ext., is the name wanted to call the file.

Once the program is on file and has been logged into the Dec 10, the following statements should be typed (to number the program statements): "SOS name, ext"; and "\*EN". Then Basic should be entered, and the program into Basic by typing: "R\_BASIC", and then "OLD FILE NAME--name. ext".

Now the following changes must be made in the program:

In statement 5840:

ZDR0            charged to the name wanted to call the job

9702762X. charged to the billing number for the CDC 6400.

In statement 5900:

6XXX,XXXXX charged to the billing number on the Dec 10.

AAAAAA charged to your password for the Dec 10  
billing number.

Secondary mirror misalignment considerations, both axial and lateral, were not included in the program. To include these considerations, the best reference would be Wetherell and Rimmer (1972, pp. 2823-2826). All the equations they present in this article can be converted for use in this program by using the following substitutions:

$$m = M, F = \frac{F}{H}, F_p = \frac{F}{HM}, D_p = H,$$

$$\beta = \frac{M(1-L)}{1+ML}, \epsilon = \frac{R}{H}, \eta = \frac{F(1-L)}{H(1+ML)}$$

Since the program is in Basic any or all of the effects of misalignment mentioned by Wetherell and Rimmer can be monitored by the program by including the appropriate equations (with the above substitutions) in the program. A listing of the program is included in Appendix A.

## CHAPTER 5

### THE EFFECTS OF PARAMETER L ON AN APLANAT

To observe the effect of L on the obstruction ratio, the value of S3, the value of S4, the primary aspheric constant (A4), and the secondary aspheric constant (A3) for a two mirror aplanatic system, the following arbitrary system was run on the program: aperture height (50 cm), image height (10 cm), effective focal length (1000 cm), magnification of secondary (5), and L (from 0.1 to 1.4). The run is listed in Appendix B, and the values for Table 3 were taken from there.

Table 3. Properties of Aplanat vs. L.

<u>L</u>	<u>e</u>	<u>S3 (10<sup>-4</sup>)</u>	<u>S4 (10<sup>-4</sup>)</u>	<u>A4</u>	<u>A3</u>
0.1	0.6800	3.625	2.5	-1.160	-2.719
0.2	0.5200	4.750	7.5	-1.080	-2.563
0.4	0.3600	7.000	17.5	-1.040	-2.484
0.6	0.2800	9.250	27.5	-1.027	-2.458
0.8	0.2320	11.500	37.5	-1.020	-2.445
1.0	0.2000	13.750	47.5	-1.016	-2.438
1.2	0.1761	16.000	57.5	-1.013	-2.432
1.4	0.1600	18.250	67.5	-1.011	-2.429

Plotting  $e$  vs.  $L$  for this system in Fig. 8, we see the ratio  $e$  decreases rapidly as  $L$  increases. An equation for  $e$  in terms of  $L$  is:

$$\frac{\frac{H}{1 + ML} + \frac{LD}{1 + ML}}{H} .$$

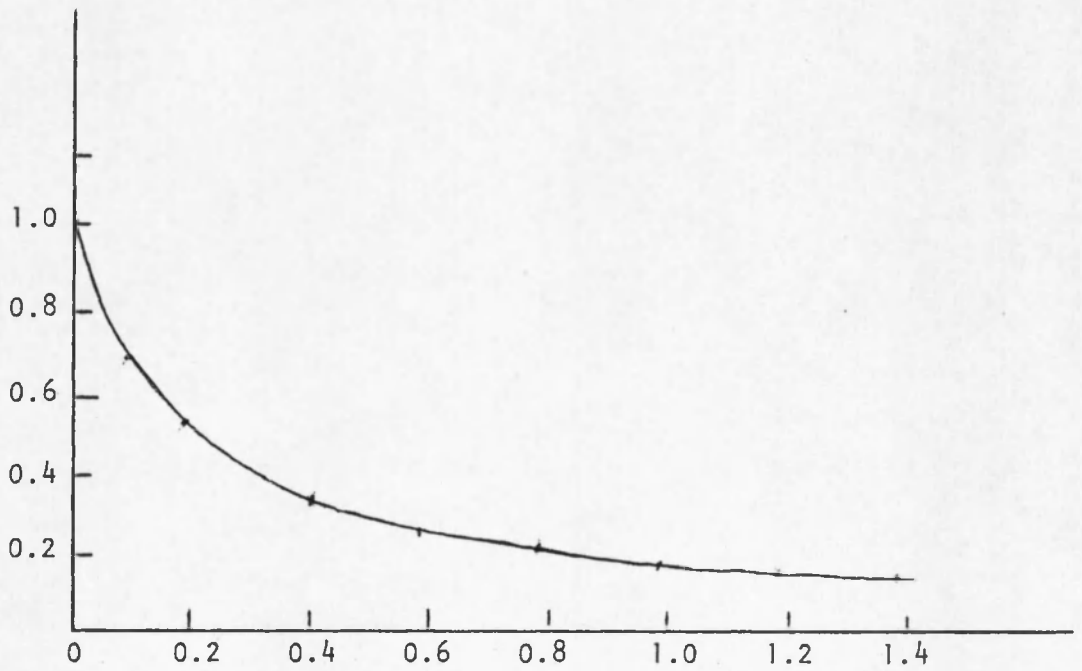


Fig. 8.  $e$  vs.  $L$ .

From the plot we see that  $e$  becomes reasonable when  $L$  becomes greater than 0.4.

Plotting  $S_3$  vs.  $L$  for this system in Fig. 9, we see that  $S_3$  increases linearly as  $L$  increases. Projecting the plot for the value of  $L$  where  $S_3 = 0$  (an astigmatic aplanat), we find  $L = -0.22$ .

Which means that we would have a virtual image if we used this value for  $L$  to make the system astigmatic. Checking this value for  $L$  with the relation for astigmatic aplanats  $[L = 1/(\frac{1}{2}-M)]$  we find agreement.

Plotting  $S_4$  vs.  $L$  for this system in Fig. 10, we see that  $S_4$  also increases linearly as  $L$  increases. Finding that  $S_4 = 0$  when  $L = 0.05$  we can again check this value with the relation for a zero Petzval curvature  $[L = 1 / (M^2 - M)]$ , and find agreement. Therefore, from this graph we can determine that for this system, the lowest value of  $S_4$  will be given by the lowest value of  $L$  we can use.

Plotting  $A_4$  vs.  $L$  for this system in Fig. 11, we see that  $A_4$  approaches -1.01 nonlinearly as  $L$  increases.  $A_4$  also decreases very rapidly as  $L$  approaches zero.

Plotting  $A_3$  vs.  $L$  for the system in Figure 12, we notice that  $A_3$  approaches -2.42 as  $L$  increases, and then decreases very rapidly as  $L$  approaches zero.

In summary we can say that the general effect of  $L$ , increasing from 0 to 1.4, on this system is to increase the Seidel aberrations linearly and reduce the obstruction ratio. Each conic constant has

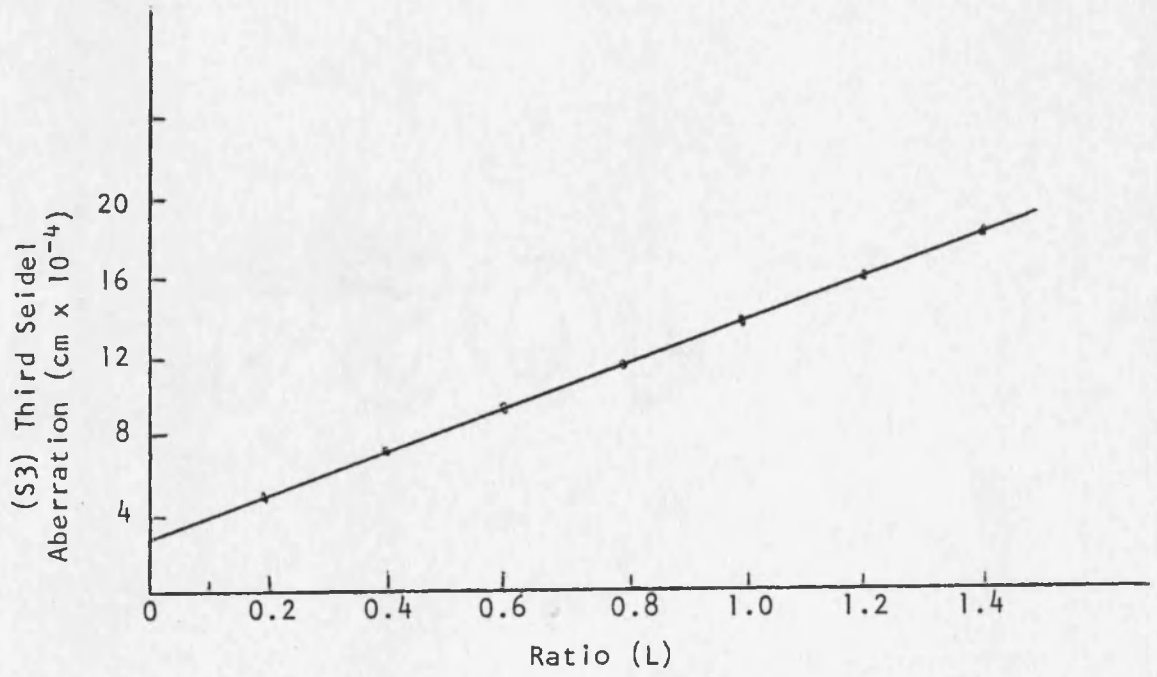


Fig. 9. S3 vs. L.

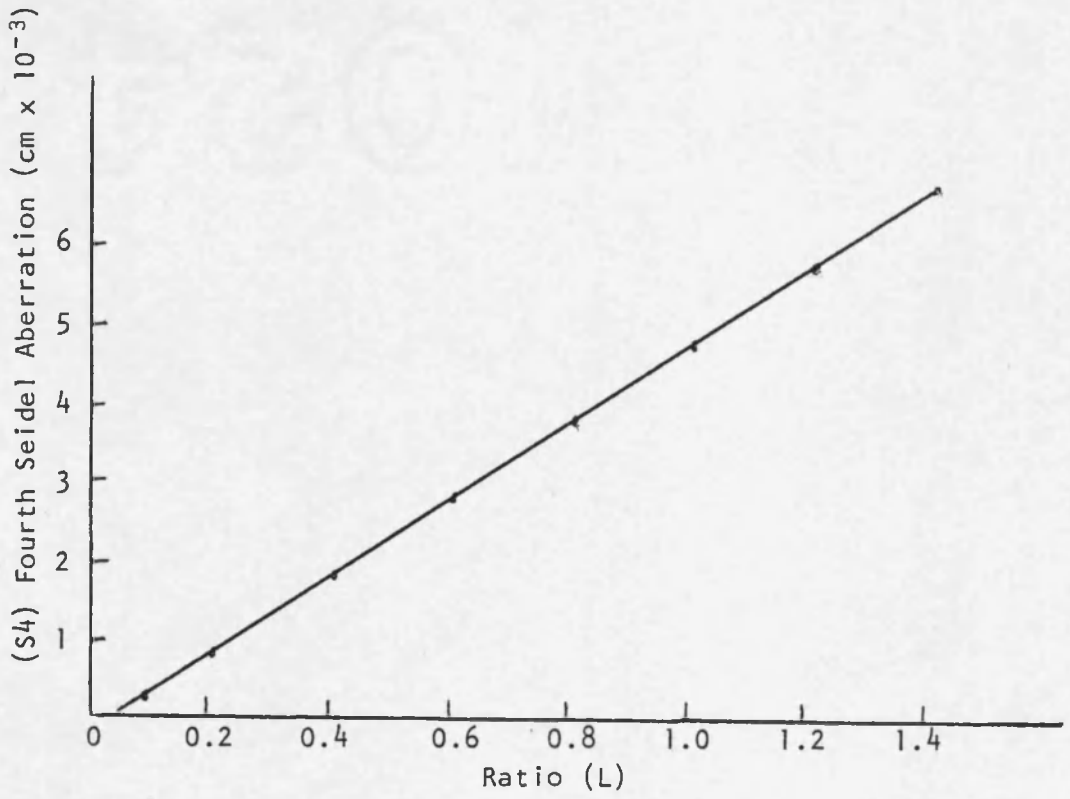


Fig. 10.  $A_4$  vs.  $L$ .

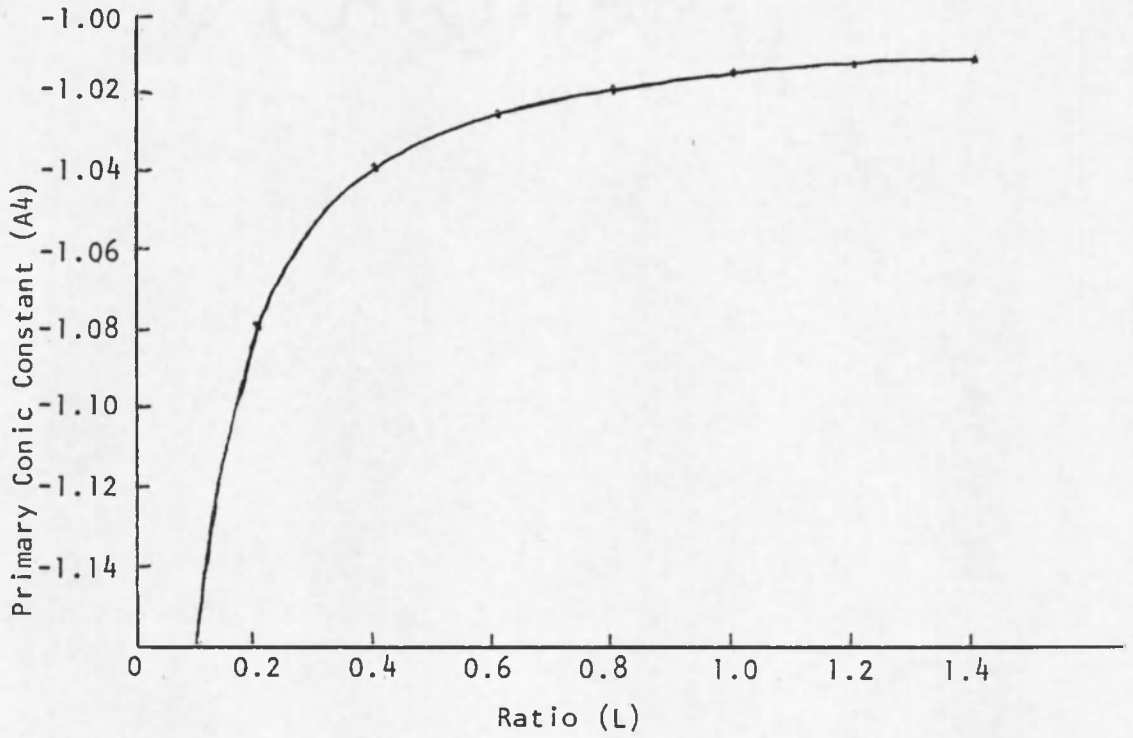
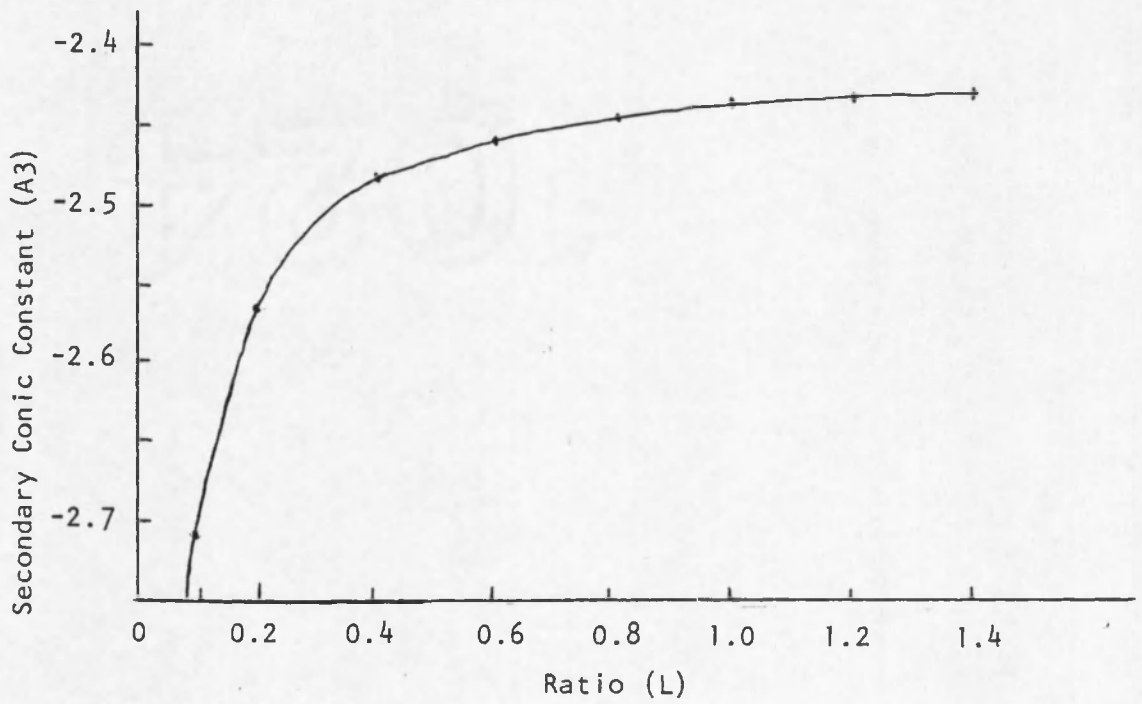


Fig. 11.  $A_4$  vs.  $L$ .

Fig. 10.  $A_4$  vs.  $L$ .Fig. 12.  $A_3$  vs.  $L$ .

a large amount of change as  $L$  goes from 0 to 0.5, but then they each tend to converge to their final values as  $L$  approaches 1.4.

To present a better idea of the systems represented in these plots, diagrams of three systems considered appear in Fig. 13 ( $l = .1$ ), Fig. 14 ( $l = .6$ ), and Fig. 15 ( $l = 1.4$ ).

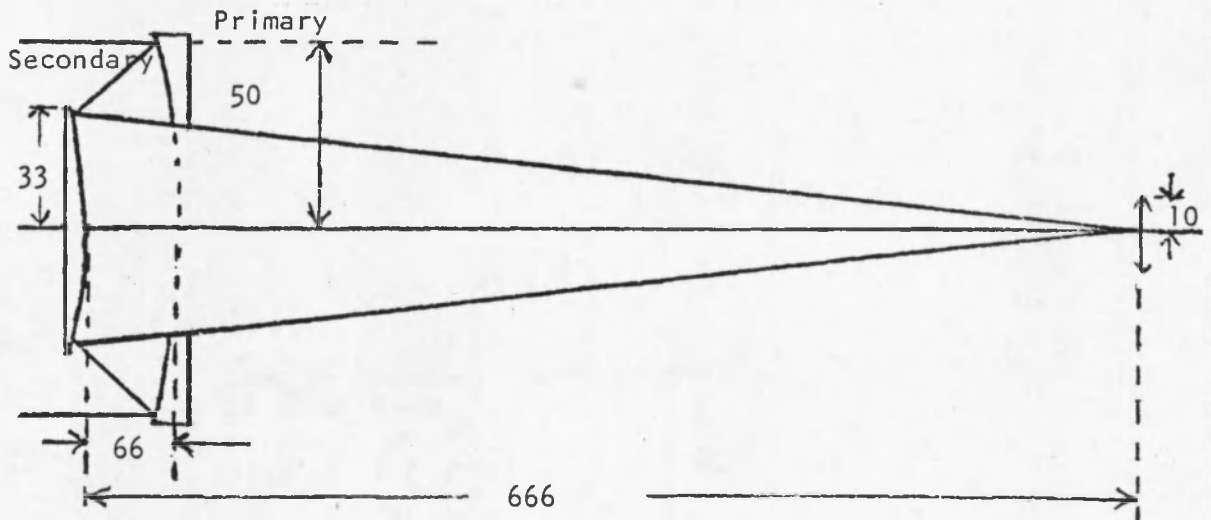


Fig. 13. System for  $L = .1$ .

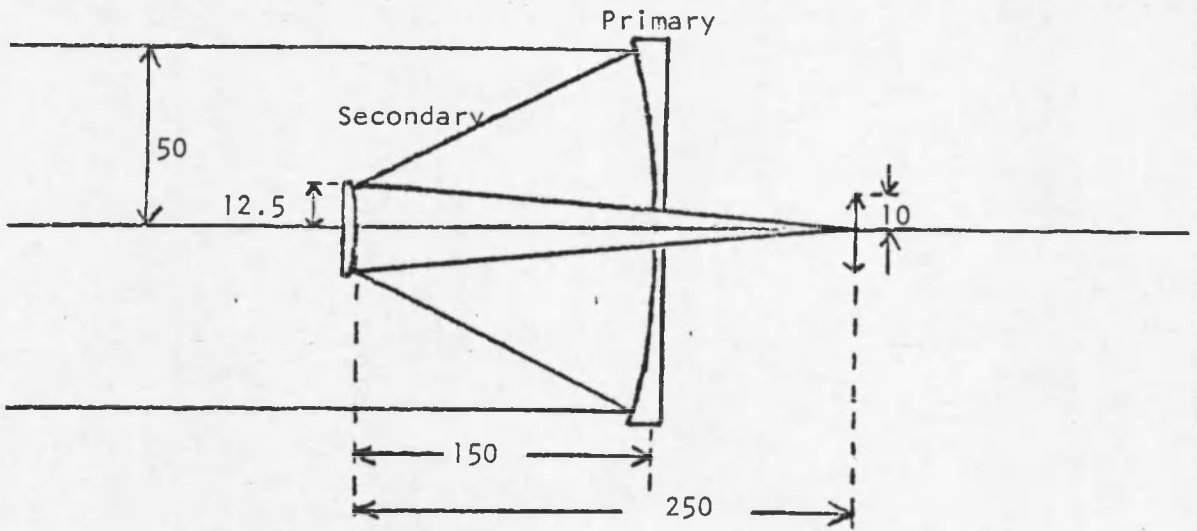


Fig. 14. System for  $L = 0.6$ .

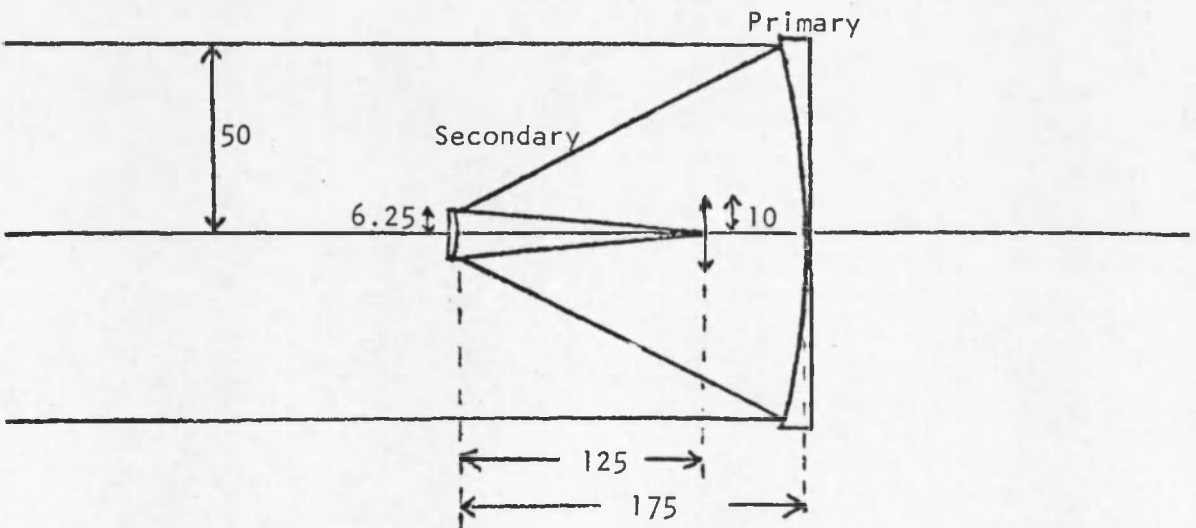


Fig. 15. System for  $L = 1.4$ .

## CHAPTER 6

### CONCLUSIONS

The program is limited to two mirror systems and so is primarily for the designer who is designing this type of system. The writer believes the program can be a valuable tool to this designer who is looking for a usable set of starting parameters for input to an involved design program, which allows all the parameters to vary. It is intended to place the starting design close enough to the minimum solution desired, that the more involved program can more quickly find the best minimum. As is stated by Jamieson (1971, p. 94) (referring to the design programs now available) "Normally the final system is similar to the initial system in terms of the distribution of powers so that the step taken in parameter space is normally small." So by placing the original design or starting parameters close to the solution, a more efficient use of the involved program may be realized. To this end, the writer believes the program can claim some success.

The listing of the physical parameters of the system (such as the center of mass, thicknesses, etc.) at the end of the program is provided to give the designer a more detailed description of the resultant system. A description of the approximations made in these calculations is listed in Appendix C. These physical parameters will obviously change when the more involved program changes the system, but the changes will be small.

## APPENDIX A

### PROGRAM LISTING

This is a list of the program as it will look after the procedure in the Comments on Programming section has been followed. It is included as a reference for those who wish to make changes in the program.

```

10 PRINT"THE UNITS ON THE FOLLOWING CALCULATED VALUES WILL BE THE°
20 PRINT"SAME AS THE UNITS ON YOUR INPUT VALUES°
30 PRINT"WHAT IS THE APERTURE HEIGHT?"
40 LET J=A3=A4=A9=0
50 INPUT H
60 PRINT"WHAT IS THE IMAGE HEIGHT?"
70 INPUT D
80 PRINT"WHAT IS THE FOCAL LENGTH?"
90 INPUT F
100 PRINT"WHAT IS THE MAGNIFICATION OF THE SECONDARY ?°
110 INPUT M
120 PRINT"WHAT IS THE RATIO OF THE MIRROR SEPARATION TO°
130 PRINT"THE IMAGE DISTANCE FROM THE SECONDARY°
140 INPUT L
150 PRINT"H", "F", "M", "L", "D°
160 PRINT H, F, M, L, D
170 LET W=H*D/F
180 LET S4=(W*W/F)*(-1-M*(1-M)*L)
190 LET P1=-M*W/S4
200 LET K1=M/F
210 LET K2=(1-M)*(1+M*L)/(F)
220 LET H1=H
230 LET D1=L*F/(1+M*L)
240 LET D2=F/(1+M*L)
250 LET R=ABS(H/(1+M*L))+ABS(L*D/(1+M*L))
260 LET C2=K2/2
270 LET C1=-K1/2
280 LET F1=1/(K1*M*2)
290 LET Q7=0
300 LET Q4=1
310 IF M=1 THEN 340
320 LET F2=-1/(K2*2*R)
330 IF M<>1 THEN 390
340 LET F2=0
350 LET Q5=D*L/H
360 LET Q6=16*M**4/(1+M*L)**4
370 LET Q4=0
380 LET Q7=1
390 PRINT"1ST POWER", "2ND POWER", "SEPARATION", "B FOCAL DIST°
400 PRINT K1, K2, D1, D2
410 PRINT"CURVATURE 1°", "CURVATURE 2°", "PRIMARY F#°", "SECONDARY F#°
420 PRINT C1, C2, F1, F2
430 PRINT "RADIUS OF SECONDARY°
440 PRINT R
450 PRINT"S4", "PETZVAL RADIUS°
460 PRINT S4, P1
470 PRINT"IS THE PETZVAL RADIUS TOO SMALL ?°
480 INPUT O$
490 IF O$="NO" THEN 530
500 PRINT"TO INCREASE PETZVAL RADIUS : INCREASE FOCAL LENGTH, DECREASE°
510 PRINT"THE MAGNIFICATION OF THE SECONDARY, OR DECREASE L°
520 GO TO 80
530 GOSUB 4950
540 PRINT "THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE°
550 LET B=2*W**3/(H*H)
560 PRINT "S1", "S2", "S3", "S4", "S5°
570 IF M<>1 THEN 650
580 LET S1=(H**4/(4*F**3))*M**3
590 LET S2=(H*M*W/(2*F*F))*(-1)

```

```

600 LET S3=(N*W/F)*(1)
610 LET S4=(N*W/F)*(-1)
620 LET S5=0
630 LET K=0
640 GO TO 710
650 LET K=(1-M)**3/(1+M*L)
660 LET S1=(H**4/(4*F**3))*(M**3+K*((1+M)/(1-M))**2)
670 LET S2=(H**4/(2*F**2))*(-1+(L/2)*K*((1+M)/(1-M))**2)
680 LET S3=(N*W/F)*(1-(1-M)*L+(L/2)**2*K*((1+M)/(1-M))**2)
690 LET S4=(N*W/F)*(-1-M*(1-M)*L)
700 LET S5=B*(L*(1-M)-(L/2)**2*(1-M)*(3-M)+(L/2)**3*K*((1+M)/(1-M))**2)
710 LET A1=A5=.5
720 LET A2=A6=1
730 IF J=1 THEN 750
740 PRINT S1, S2, S3, S4, S5
750 PRINT "HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5"
760 INPUT P
770 IF P=4 THEN 3210
780 IF P=3 THEN 3610
790 IF P=2 THEN 1550
800 PRINT "WHICH ONE MINIMIZED ? DENOTE S1 BY 1, S2 BY 2, S3 BY 3, S5 BY 5"
810 INPUT P
820 PRINT "DO YOU WANT THE PRIMARY PARABOLIC ?"
830 INPUT O$
840 IF O$="NO" THEN 1010
850 LET A4=-1
860 IF P=5 THEN 990
870 IF P=3 THEN 970
880 IF P=2 THEN 950
890 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1 ARE"
900 LET E1=S1+(H**4/(4*F**3))*(-M**3+K*A5)+Q7*Q6*A5
910 LET E2=S1+(H**4/(4*F**3))*(-M**3+K*A6)+Q7*A6*Q6
920 LET A3=A5-(E1*(A5-A6))/(E1-E2)
930 GOSUB 4860
940 GO TO 5300
950 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S2 ARE"
960 GO TO 1270
970 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S3 ARE"
980 GO TO 1370
990 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S5 ARE"
1000 GO TO 1470
1010 IF P=5 THEN 1450
1020 IF P=3 THEN 1350
1030 IF P=2 THEN 1250
1040 PRINT "DENOTE WHICH SURFACE ASPHERIC: PRIMARY BY 1, SECONDARY BY 2"
1050 INPUT P
1060 IF P=2 THEN 1150
1070 LET B1=S1+(H**4/(4*F**3))*(M**3*A1)
1080 LET B2=S1+(H**4/(4*F**3))*(M**3*A2)
1090 LET A4=A1-(B1*(A1-A2))/(B1-B2)
1100 LET S1=S1+(H**4/(4*F**3))*(M**3*A4)
1110 PRINT "SEIDEL ABERRATIONS FOR A SPHERICAL SECONDARY AND MIN S1 ARE"
1120 PRINT "S1", "S2", "S3", "S4", "S5", "PRIMARY CONIC CONSTANT"
1130 PRINT S1, S2, S3, S4, S5, A4
1140 GO TO 5300
1150 LET A4=0
1160 PRINT "SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1 ARE"
1170 IF M<1 THEN 1200
1180 LET A9=-S1/Q6
1190 GO TO 1230
1200 LET B1=S1+(H**4/(4*F**3))*K*A1
1210 LET B2=S1+(H**4/(4*F**3))*K*A2
1220 LET A3=A1-(B1*(A1-A2))/(B1-B2)
1230 GOSUB 4860
1240 GO TO 5300
1250 LET A4=0

```

```

1260 PRINT "SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S2 ARE"
1270 IF M<>1 THEN 1300
1280 LET A9=-S2/(Q5*Q6)
1290 GO TO 1330
1300 LET B1=S2+(L/2)*K*A1*H*H*N/(2*F*F)
1310 LET B2=S2+(L/2)*K*A2*H*H*N/(2*F*F)
1320 LET A3=A1-(B1*(A1-A2))/(B1-B2)
1330 GOSUB 4860
1340 GO TO 5300
1350 LET A4=0
1360 PRINT "SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S3 ARE"
1370 IF M<>1 THEN 1400
1380 LET A9=-S3/(Q5**2*Q6)
1390 GO TO 1430
1400 LET B1=S3+(L/2)**2*K*A1*N*N/F
1410 LET B2=S3+(L/2)**2*K*A2*N*N/F
1420 LET A3=A1-(B1*(A1-A2))/(B1-B2)
1430 GOSUB 4860
1440 GO TO 5300
1450 PRINT "SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S5 ARE"
1460 LET A4=0
1470 IF M<>1 THEN 1500
1480 LET A9=0
1490 GO TO 1530
1500 LET B1=S5+(2*N**3/(H*H))*(L/2)**3*K*A1
1510 LET B2=S5 +(2*N**3/(H*H))*(L/2)**3*K*A2
1520 LET A3=A1-(B1*(A1-A2))/(B1-B2)
1530 GOSUB 4860
1540 GO TO 5300
1550 PRINT "WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3"
1560 PRINT "S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6"
1570 LET A1=A5=.5
1580 LET A2=A6=1
1590 INPUT P
1600 IF P=3 THEN 2580
1610 IF P=2 THEN 2200
1620 IF P=1 THEN 1820
1630 PRINT "DO YOU WANT THE PRIMARY PARABOLIC ?"
1640 INPUT O$
1650 IF O$="NO" THEN 1710
1660 LET A4=-1
1670 IF P=4 THEN 1760
1680 IF P=5 THEN 1780
1690 IF P=6 THEN 1800
1700 GO TO 5300
1710 LET A4=0
1720 IF P=4 THEN 2940
1730 IF P=5 THEN 3030
1740 IF P=6 THEN 3120
1750 GO TO 5300
1760 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S2+S3 ARE"
1770 GO TO 2950
1780 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S2+S5 ARE"
1790 GO TO 3040
1800 PRINT "SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S3+S5 ARE"
1810 GO TO 3130
1820 PRINT "DO YOU WANT THE PRIMARY PARABOLIC ?"
1830 INPUT O$
1840 IF O$="YES" THEN 2000
1850 PRINT "CAN BOTH SURFACES BE ASPHERIC ?"
1860 INPUT O$
1870 IF O$="NO" THEN 2100
1880 PRINT "SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE"
1890 IF M<>1 THEN 1920
1900 LET A9=-S2/(Q5*Q6)
1910 GO TO 1950

```

```

1920 LET E1=S2+(L/2)*K*A5*H*H*W/(2*F*F)
1930 LET E2=S2+(L/2)*K*A6*H*H*W/(2*F*F)
1940 LET A3=A5-(E1*(A5-A6))/(E1-E2)
1950 LET B1=S1+(H**4/(4*F**3))*(M**3*A1+K*A3)+Q6*Q7*A9
1960 LET B2=S1+(H**4/(4*F**3))*(M**3*A2+K*A3)+Q6*Q7*A9
1970 LET A4=A1-(B1*(A1-A2))/(B1-B2)
1980 GOSUB 4860
1990 GO TO 5300
2000 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2 ARE"
2010 LET A4=-1
2020 LET E1=S1+S2+A5*((L/2)*K*H*H*W/(2*F*F)+(H**4/(4*F**3))*K)-(H**4/
(4*F**3))*M**3
2030 LET E1=S1+S2+A6*((L/2)*K*H*H*W/(2*F*F)+(H**4/(4*F**3))*K)-(H**4/
(4*F**3))*M**3
2040 IF MC>1 THEN 2070
2050 LET A9=-S2/(Q6*(1+Q5))
2060 GO TO 2080
2070 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2080 GOSUB 4860
2090 GO TO 5300
2100 PRINT "SEIDEL ABERRATIONS FOR SPHERICAL PRIMARY AND MIN S1+S2 ARE"
2110 LET A4=0
2120 LET E1=S1+S2+A5*((L/2)*K*H*H*W/(2*F*F)+(H**4/(4*F**3))*K)
2130 LET E2=S1+S2+A6*((L/2)*K*H*H*W/(2*F*F)+(H**4/(4*F**3))*K)
2140 IF MC>1 THEN 2170
2150 LET A9=(-S1-S2)/(Q6*(1+Q5))
2160 GO TO 2180
2170 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2180 GOSUB 4860
2190 GO TO 5300
2200 PRINT"DO YOU WANT THE PRIMARY PARABOLIC ?"
2210 INPUT O$
2220 IF O$="NO" THEN 2330
2230 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S3 ARE"
2240 LET A4=-1
2250 LET E1=S1+S3+A5*((L/2)**2*K*W*W/F+(H**4/(4*F**3))*K)-(H**4/(4*F**3))
*M**3
2260 LET E2=S1+S3+A6*((L/2)**2*K*W*W/F+(H**4/(4*F**3))*K)-(H**4/(4*F**3))
*M**3
2270 IF MC>1 THEN 2300
2280 LET A9=-S3/(Q6*(1+Q5**2))
2290 GO TO 2310
2300 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2310 GOSUB 4860
2320 GO TO 5300
2330 PRINT"CAN BOTH SURFACES BE ASPHERIC ?"
2340 INPUT O$
2350 IF O$="NO" THEN 2480
2360 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S3 ARE"
2370 LET E1=S3+(L/2)**2*K*A5*W*W/F
2380 LET E2=S3+(L/2)**2*K*A6*W*W/F
2390 IF MC>1 THEN 2420
2400 LET A9=-S3/(Q5**2*Q6)
2410 GO TO 2430
2420 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2430 LET B1=S1+(H**4/(4*F**3))*(M**3*A1+K*A3)+Q6*A9*Q7
2440 LET B2=S1+(H**4/(4*F**3))*(M**3*A2+K*A3)+Q6*A9*Q7
2450 LET A4=A1-(B1*(A5-A6))/(B1-B2)
2460 GOSUB 4860
2470 GO TO 5300
2480 PRINT"SEIDEL ABERRATIONS FOR SPHERICAL PRIMARY AND MIN S1+S3 ARE"
2490 LET A4=0
2500 LET E1=S1+S3+A5*((L/2)**2*K*W*W/F+(H**4/(4*F**3))*K)
2510 LET E2=S1+S3+A6*((L/2)**2*K*W*W/F+(H**4/(4*F**3))*K)
2520 IF MC>1 THEN 2550

```

```

2530 LET A9=(-S1-S3)/(Q6*(1+Q5**2))
2540 GO TO 2560
2550 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2560 GOSUB 4860
2570 GO TO 5300
2580 PRINT"DO YOU WANT THE PRIMARY PARABOLIC ?"
2590 INPUT Q$
2600 IF Q$="YES" THEN 2860
2610 PRINT"CAN BOTH SURFACES BE ASPHERIC ?"
2620 INPUT Q$
2630 IF Q$="NO" THEN 2760
2640 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S5 ARE"
2650 LET B1=S5+B*(L/2)**3*K*A1
2660 LET B2=S5+B*(L/2)**3*K*A2
2670 IF M<>1 THEN 2700
2680 LET A9=0
2690 GO TO 2710
2700 LET A3=A1-(B1*(A1-A2))/(B1-B2)
2710 LET E1=S1+(H**4/(4*F**3))*(M**3*A5+K*A3)+Q6*A9*Q7
2720 LET E2=S1+(H**4/(4*F**3))*(M**3*A6+K*A3)+Q6*A9*Q7
2730 LET A4=A5-(E1*(A5-A6))/(E1-E2)
2740 GOSUB 4860
2750 GO TO 5300
2760 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1+S5 ARE"
2770 LET A4=0
2780 LET E1=S1+S5+A5*(B*(L/2)**3*K+K*H**4/(4*F**3))
2790 LET E2=S1+S5+A6*(B*(L/2)**3*K+K*H**4/(4*F**3))
2800 IF M<>1 THEN 2830
2810 LET A9=-S1/(Q6*(1+Q5**3))
2820 GO TO 2840
2830 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2840 GOSUB 4860
2850 GO TO 5300
2860 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S5 ARE"
2870 LET A4=-1
2880 LET E1=S1+S5-(H**4/(4*F**3))*M**3+A5*(B*(L/2)**3*K+(H**4/(4*F**3))*K)
2890 LET E2=S1+S5-(H**4/(4*F**3))*M**3+A6*(B*(L/2)**3*K+(H**4/(4*F**3))*K)
2900 IF M=1 THEN 2920
2910 LET A3=A5-(E1*(A5-A6))/(E1-E2)
2920 GOSUB 4860
2930 GO TO 5300
2940 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S2+S3 ARE"
2950 LET B1=S2+S3+A5*((L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F)
2960 LET B2=S2+S3+A6*((L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F)
2970 IF M<>1 THEN 3000
2980 LET A9=(-S2-S3)/(Q6*(Q5+Q5**2))
2990 GO TO 3010
3000 LET A3=A5-(B1*(A5-A6))/(B1-B2)
3010 GOSUB 4860
3020 GO TO 5300
3030 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S2+S5 ARE"
3040 LET B1=S2+S5+A5*((L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
3050 LET B2=S2+S5+A6*((L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
3060 IF M<>1 THEN 3090
3070 LET A9=(-S2-S5)/(Q6*(Q5+Q5**3))
3080 GO TO 3100
3090 LET A3=A5-(B1*(A5-A6))/(B1-B2)
3100 GOSUB 4860
3110 GO TO 5300
3120 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S3+S5 ARE"
3130 LET B1=S3+S5+A5*((L/2)**2*K*W*W/F+B*(L/2)**3*K)
3140 LET B2=S3+S5+A6*((L/2)**2*K*W*W/F+B*(L/2)**3*K)
3150 IF M<>1 THEN 3180
3160 LET A9=(-S3)/(Q6*(Q5**2+Q5**3))
3170 GO TO 3190

```

```

3180 LET A3=A5-(B1*(A5-A6))/(B1-B2)
3190 GOSUB 4860
3200 GO TO 5300
3210 PRINT"DO YOU WANT THE PRIMARY PARABOLIC ?"
3220 INPUT O$
3230 IF O$="YES" THEN 3510
3240 PRINT"CAN BOTH SURFACES BE ASPHERIC ?"
3250 INPUT O$
3260 IF O$="NO" THEN 3400
3270 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2+S3+S5 ARE"
3280 LET G=(L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F+B*(L/2)**3*K
3290 LET G3=S2+S3+S5+G*A5
3300 LET G4=S2+S3+S5+G*A6
3310 IF M<1 THEN 3340
3320 LET A9=(-S2-S3)/(Q6*(Q5+Q5**2+Q5**3))
3330 GO TO 3350
3340 LET A3=A5-(G3*(A5-A6))/(G3-G4)
3350 LET J1=S1+(H**4/(4*F**3))*(M**3*A5+K*A3)+Q6*A9*Q7
3360 LET J2=S1+(H**4/(4*F**3))*(M**3*A6+K*A3)+Q6*A9*Q7
3370 LET A4=A5-(J1*(A5-A6))/(J1-J2)
3380 GOSUB 4860
3390 GO TO 5300
3400 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1+S2+S3+S5"
3410 LET G=(L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F+B*(L/2)**3*K+
K*(H**4/(4*F**3))
3420 LET A4=0
3430 LET E1=S1+S2+S3+S5+A5*G
3440 LET E2=S1+S2+S3+S5+A6*G
3450 IF M<1 THEN 3480
3460 LET A9=(-S1-S2-S3)/(Q6*(1+Q5+Q5**2+Q5**3))
3470 GO TO 3490
3480 LET A3=A5-(E1*(A5-A6))/(E1-E2)
3490 GOSUB 4860
3500 GO TO 5300
3510 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2+S3+S5"
3520 LET G=(L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F+B*(L/2)**3*K+
K*(H**4/(4*F**3))
3530 LET A4=-1
3540 LET E1=S1+S2+S3+S5-(H**4/(4*F**3))*M**3+A5*G
3550 LET E2=S1+S2+S3+S5-(H**4/(4*F**3))*M**3+A6*G
3560 LET A9=(-S2-S3)/(Q6*(1+Q5+Q5**2+Q5**3))
3570 GO TO 3590
3580 A3=A5-(E1*(A5-A6))/(E1-E2)
3590 GOSUB 4860
3600 GO TO 5300
3610 PRINT"WHICH THREE ABERRATIONS MINIMIZED? DENOTE S1+S2+S3 BY 1,"
3620 PRINT"S1+S2+S5 BY 2, S2+S3+S5 BY 3, S1+S3+S5 BY 4"
3630 INPUT P
3640 PRINT"DO YOU WANT THE PRIMARY PARABOLIC ?"
3650 INPUT O$
3660 IF P=3 THEN 4330
3670 IF O$="YES" THEN 3890
3680 PRINT"CAN BOTH SURFACES BE ASPHERIC ?"
3690 INPUT O$
3700 IF O$="NO" THEN 3750
3710 IF P=4 THEN 4480
3720 IF P=2 THEN 4210
3730 IF P=1 THEN 4090
3740 GO TO 5300
3750 IF P=4 THEN 4730
3760 IF P=2 THEN 4600
3770 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1+S2+S3 ARE"
3780 LET A4=0
3790 LET E1=S1+S2+S3+A1*(K*H**4/(4*F**3)+(L/2)*K*H*H*W/(2*F*F)+
(L/2)**2*K*W*W/F)

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```

3800 LET E2=S1+S2+S3+A2*((K*H**4/(4*F**3)+(L/2)*K*H*H*W/(2*F*F)+
(L/2)**2*K*W*W/F)
3810 IF MC>1 THEN 3850
3820 LET A9=(-S1-S2-S3)/(Q6*(1+Q5+Q5**2))
3830 IF Q$="NO" THEN 3870
3840 LET A9=(-S2-S3)/(Q6*(1+Q5+Q5**2))
3850 IF Q$="YES" THEN 4050
3860 LET A3=A1-E1*(A1-A2)/(E1-E2)
3870 GOSUB 4860
3880 GO TO 5300
3890 LET A4=-1
3900 IF P=4 THEN 3930
3910 IF P=2 THEN 3980
3920 IF P=1 THEN 4030
3930 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S3+S5 ARE"
3940 GO TO 4750
3950 LET E1=E1-(H**4/(4*F**3))*M**3
3960 LET E2=E2-(H**4/(4*F**3))*M**3
3970 GO TO 4020
3980 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2+S5 ARE"
3990 GO TO 4620
4000 LET E1=E1-(H**4/(4*F**3))*M**3
4010 LET E2=E2-(H**4/(4*F**3))*M**3
4020 GO TO 4690
4030 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S1+S2+S3 ARE"
4040 GO TO 3790
4050 LET E1=E1-(H**4/(4*F**3))*M**3
4060 LET E2=E2-(H**4/(4*F**3))*M**3
4070 IF M=1 THEN 3870
4080 GO TO 3860
4090 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2+S3 ARE"
4100 LET B1=S2+S3+A1*((L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F)
4110 LET B2=S2+S3+A2*((L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F)
4120 IF MC>1 THEN 4150
4130 LET A9=(-S2-S3)/(Q6*(Q5+Q5**2))
4140 GO TO 4160
4150 LET A3=A1-(B1*(A1-A2))/(B1-B2)
4160 LET E1=S1+(H**4/(4*F**3))*(M**3*A5+K*A3)+Q6*A9*Q7
4170 LET E2=S1+(H**4/(4*F**3))*(M**3*A6+K*A3)+Q6*A9*Q7
4180 LET A4=A5-(E1*(A5-A6))/(E1-E2)
4190 GOSUB 4860
4200 GO TO 5300
4210 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2+S5 ARE"
4220 LET B1=S2+S5+A5*((L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
4230 LET B2=S2+S5+A6*((L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
4240 IF MC>1 THEN 4270
4250 LET A9=-S2/(Q6*(Q5+Q5**3))
4260 GO TO 4280
4270 LET A3=A5-(B1*(A5-A6))/(B1-B2)
4280 LET E1=S1+(H**4/(4*F**3))*(M**3*A1+K*A3)+Q6*A9*Q7
4290 LET E2=S1+(H**4/(4*F**3))*(M**3*A2+K*A3)+Q6*A9*Q7
4300 LET A4=A1-(E1*(A1-A2))/(E1-E2)
4310 GOSUB 4860
4320 GO TO 5300
4330 LET A4=-1
4340 IF Q$="YES" THEN 4380
4350 LET A4=0
4360 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S2+S3+S5 ARE"
4370 GO TO 4390
4380 PRINT"SEIDEL ABERRATIONS FOR A PARABOLIC PRIMARY AND MIN S2+S3+S5 ARE"
4390 LET G=(L/2)*K*H*H*W/(2*F*F)+(L/2)**2*K*W*W/F+B*(L/2)**3*K
4400 LET G1=S2+S3+S5+G*A5
4410 LET G2=S2+S3+S5+G*A6
4420 IF MC>1 THEN 4450

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4430 LET A9=(-S2-S3)/(Q6*(Q5+Q5**2+Q5**3))
4440 GO TO 4460
4450 LET A3=A5-(G1*(A5-A6))/(G1-G2)
4460 GOSUB 4860
4470 GO TO 5300
4480 PRINT"SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S3+S5 ARE"
4490 LET B1=S3+S5+A5*((L/2)**2*K*N*N/W/F+B*(L/2)**3*K)
4500 LET B2=S3+S5+A6*((L/2)**2*K*N*N/W/F+B*(L/2)**3*K)
4510 IF M<>1 THEN 4540
4520 LET A9=-S3/(Q6*(Q5**2+Q5**3))
4530 GO TO 4550
4540 LET A3=A5-(B1*(A5-A6))/(B1-B2)
4550 LET E1=S1+(H**4/(4*F**3))*(M**3*A1+K*A3)+Q6*A9*Q7
4560 LET E2=S1+(H**4/(4*F**3))*(M**3*A2+K*A3)+Q6*A9*Q7
4570 LET A4=A5-(E1*(A5-A6))/(E1-E2)
4580 GOSUB 4860
4590 GO TO 5300
4600 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1+S2+S5 ARE"
4610 LET A4=0
4620 LET E1=S1+S2+S5+A5*(K*H**4/(4*F**3)+(L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
4630 LET E2=S1+S2+S5+A6*(K*H**4/(4*F**3)+(L/2)*K*H*H*W/(2*F*F)+B*(L/2)**3*K)
4640 IF M<>1 THEN 4680
4650 LET A9=(-S1-S2)/(Q6*(1+Q5+Q5**3))
4660 IF Q#="NO" THEN 4710
4670 LET A9=-S2/(Q6*(1+Q5+Q5**3))
4680 IF Q#="YES" THEN 4000
4690 IF M=1 THEN 4710
4700 LET A3=A5-(E1*(A5-A6))/(E1-E2)
4710 GOSUB 4860
4720 GO TO 5300
4730 PRINT"SEIDEL ABERRATIONS FOR A SPHERICAL PRIMARY AND MIN S1+S3+S5 ARE"
4740 LET A4=0
4750 LET E1=S1+S3+S5+A5*(K*H**4/(4*F**3)+(L/2)**2*K*N*N/W/F+B*(L/2)**3*K)
4760 LET E2=S1+S3+S5+A6*(K*H**4/(4*F**3)+(L/2)**2*K*N*N/W/F+B*(L/2)**3*K)
4770 IF M<>1 THEN 4810
4780 LET A9=(-S1-S3)/(Q6*(1+Q5**2+Q5**3))
4790 IF Q#="NO" THEN 4840
4800 LET A9=-S3/(Q6*(1+Q5**2+Q5**3))
4810 IF Q#="YES" THEN 3950
4820 IF M=1 THEN 4840
4830 LET A3=A5-(E1*(A5-A6))/(E1-E2)
4840 GOSUB 4860
4850 GO TO 5300
4860 LET S1=S1+(H**4/(4*F**3))*(M**3*A4+K*A3)+Q6*A9*Q7
4870 PRINT"CONIC CON. 1", "CONIC CON. 2", "ASPHERIC CON. 2"
4880 PRINT A4, A3, A9
4890 PRINT"S1", "S2", "S3", "S4", "S5"
4900 LET S2=S2+(H*H*W/(2*F*F))*(L/2)*K*A3+Q5*Q6*A9
4910 LET S3=S3+(W*W/F)*(L/2)**2*K*A3+Q5**2*Q6*A9
4920 LET S5=S5+B*(L/2)**3*K*A3+Q5**3*Q6*A9
4930 PRINT S1, S2, S3, S4, S5
4940 RETURN
4950 DIM Y(25), U(25), Z(25), V(25)
4960 FOR I=1 TO 5
4970 LET C(I)=T(I)=0
4980 LET N(I)=1
4990 NEXT I
5000 LET Z(1)=-D*1E10/F
5010 LET Z(2)=Y(1)=0
5020 LET T(1)=1E10
5030 LET Y(2)=H
5040 PRINT "SURF", "CURVATURE", "INDEX", "THICKNESS"
5050 FOR I=1 TO 5

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5060 LET C(3)=C1
5070 LET C(4)=C2
5080 LET T(2)=0
5090 LET N(3)=-1
5100 LET T(3)=-D1
5110 LET T(4)=D2
5120 PRINT I-1, C(I), N(I), T(I)
5130 NEXT I
5140 PRINT "SURF", "AXIAL Y", "AXIAL U", "CHIEF Y", "CHIEF U"
5150 LET U(1)=Y(2)/T(1)
5160 LET V(1)=(Z(2)-Z(1))/T(1)
5170 PRINT 0, Y(1), U(1), Z(1), V(1)
5180 FOR I=1 TO 5
5190 IF N(I+1)=0 THEN 5210
5200 LET X=N(I)/N(I+1)
5210 LET Y(I+1)=Y(I)+T(I)*U(I)
5220 LET Z(I+1)=Z(I)+T(I)*V(I)
5230 IF N(I+1)=0 THEN 5280
5240 LET U(I+1)=X*U(I)-(1-X)*Y(I+1)*C(I+1)
5250 LET V(I+1)=X*V(I)-(1-X)*Z(I+1)*C(I+1)
5260 PRINT I, Y(I+1), U(I+1), Z(I+1), V(I+1)
5270 NEXT I
5280 PRINT I, Y(I+1), U(I), Z(I+1), V(I)
5290 RETURN
5300 PRINT "DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?"
5310 INPUT 0$
5320 IF 0$="NO" THEN 5360
5330 LET A4=A3=A9=0
5340 LET J=1
5350 GO TO 570
5360 PRINT "DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?"
5370 INPUT 0$
5380 IF 0$="YES" THEN 30
5390 LET E1=C1*H*H/(1+SQR(1-(1+A4)*C1*H*H))
5400 PRINT "THE TOTAL SURFACE DEPTH AT THE EDGE OF THE PRIMARY IS", E1
5410 LET E2=E1-C1*H*H/(1+SQR(1-C1*H*H))
5420 PRINT "THE ASPHERIC DEPTH AT THE EDGE OF THE PRIMARY IS", E2
5430 IF C2=0 THEN 5490
5440 LET E3=C2*R*R/(1+SQR(1-(1+A3)*C2*C2*R*R))
5450 PRINT "THE TOTAL SURFACE DEPTH AT THE EDGE OF THE SECONDARY IS", E3
5460 LET E4=E3-C2*R*R/(1+SQR(1-C2*C2*R*R))
5470 PRINT "THE ASPHERIC DEPTH AT THE EDGE OF THE SECONDARY IS", E4
5480 GO TO 5510
5490 LET E5=A9*R**4
5500 PRINT "THE TOTAL SURFACE DEPTH AT THE EDGE OF THE SECONDARY IS", E5
5510 LET J1=2.5
5520 LET U=D+((D2-D1)*(R-D))/D2
5530 PRINT "THE INSIDE RADIUS OF THE PRIMARY IS", U
5540 PRINT "THE VERTEX THICKNESS OF THE PRIMARY IS", H/10
5550 PRINT "THE VERTEX THICKNESS OF THE SECONDARY IS", R/10
5560 LET V1=(C1*H**4*3.141593/4)*(1+9*H*H*C1*C1*(1+A4)/16+9*H**4*C1**4*(1+A4)**2/32)
5570 LET V2=3.141593*H**3/10
5580 LET V3=(C1*U**4*3.141593/4)*(1+9*U*U*C1*C1*(1+A4)/16+9*H**4*C1**4*(1+A4)**2/32)
5590 LET V4=3.141593*U**3/10
5600 LET V5=(C2*R**4*3.141593/4)*(1+9*R*R*C2*C2*(1+A3)/16+9*R**4*C2**4*(1+A3)**2/32)
5610 LET P2=-3*E1/8
5620 LET P3=-5*E3/8
5630 LET P8=(V2-V4)*H/20+(P2+H/10)*(V1-V3)+(D1+H/10+P3)*V5
5640 LET P1=P8+(D1+H/10+E3+R/20)*3.141593*R**3/10
5650 LET P4=P1/(V1+V2-V3-V4+V5)

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5660 PRINT"THE CENTER OF MASS AS MEASURED FROM THE REAR OF THE"
5670 PRINT"PRIMARY ALONG THE OPTIC AXIS IS ",P4
5680 PRINT"DENOTE THE UNITS ON THE INPUT VALUES: INCHES BY 2.54,"
5690 PRINT"MILLIMETERS BY 0.1,CENTIMETERS BY 1, METERS BY 100"
5700 INPUT Z
5710 LET P5=J1*Z**3*(V1+V2-V3-V4+V5)
5720 PRINT "THE TOTAL WEIGHT IN GRAMS IS",P5
5730 LET P9=(V2-V4)*(P4-H/20)**2+(V1-V3)*(P4-H/10-P2)**2+
V5*(D1+P3+H/10-P4)**2
5740 LET P6=P9+(3.141593*R**3/10)*(D1+H/10+E3+R/20-P4)**2
5750 LET P7=P6*J1*Z**3
5760 PRINT"THE MOMENT OF INERTIA (IN GM.(UNITS)**2)FOR THE SYSTEM IS",P7
5770 PRINT"DO YOU WANT TO RUN THIS CASSEGRAIN ON ACOS5 ?"
5780 INPUT O#
5790 IF O#="NO" THEN 6270
5800 PRINT"GIVE THE LENS A NAME"
5810 INPUT A#
5820 FILE#1,"ACOS5.CDC"
5830 SCRATCH#1
5840 PRINT#1,"ZDR0,BN9702762X,CN76000,T12,RS12."
5850 PRINT#1,"ATTACH(MACRO,MACROP1,ID=MITCH)"
5860 PRINT#1,"ATTACH(LENLIB,LENLIBP1,ID=MITCH)"
5870 PRINT#1,"ATTACH(ACOSLIB,ACOSLIB,ID=MITCH)"
5880 PRINT#1,"LIBRARY(ACOSLIB)"
5890 PRINT#1,"ROOT."
5900 PRINT#1,"CALL TODEC(JOB=ZDR0,PPN=$6XXX,XXXXX$,PW=AAAA)"
5910 PRINT#1,"KILL."
5920 PRINT#1,CHR$(26)
5930 PRINT#1,"CSS NOSAVE"
5940 PRINT#1,"TRAP ON"
5950 PRINT#1,"CSS ECHO"
5960 PRINT#1,"LENS"
5970 PRINT#1,"LI,";A#
5980 PRINT#1,"SAY,";H
5990 PRINT#1,"SCY,";Z<1)
6000 PRINT#1,"TH,";T<1)
6010 PRINT#1,"AIR"
6020 PRINT#1,"AIR"
6030 PRINT#1,"COBS,";R
6040 PRINT#1,"ASTOP EN"
6050 PRINT#1,"REFS"
6060 PRINT#1,"CV,";C1
6070 PRINT#1,"CC,";A4
6080 PRINT#1,"TH,";-D1
6090 PRINT#1,"REFL"
6100 PRINT#1,"CV,";C2
6110 PRINT#1,"CC,";A3
6120 PRINT#1,"ASPH,";A9
6130 PRINT#1,"TH,";D2
6140 PRINT#1,"REFL"
6150 PRINT#1,"PY,";0
6160 PRINT#1,"AIR"
6170 PRINT#1,"EOS"
6180 PRINT#1,"OCDY"
6190 PRINT#1,"PXTY ALL"
6200 PRINT#1,"MAB3 ALL"
6210 PRINT#1,"LENQ"
6220 PRINT#1,"EXIT"
6230 PRINT#1,CHR$(26)
6240 PRINT"TYPE THE COMMAND_____MONITOR_____"
6250 PRINT"THEN TYPE THE COMMAND -----TQDC ACOS5.CDC-----"
6260 PRINT"AND THE ACOS5 OUTPUT WILL BE PLACED IN THE DEC 10 FILE AS OUTPUT"
6270 END

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## APPENDIX B

### SECOND DESIGN RUN

This is the run which was used to obtain the values for Table 3. It is included for those who may be interested in the behavior of other aplanat properties as  $L$  is changed.

THE UNITS ON THE FOLLOWING CALCULATED VALUES WILL BE THE SAME AS THE UNITS ON YOUR INPUT VALUES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY

? .1

H	F	M	L	D
50	1000	5	0.1	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.006	66.6667	666.667	
CURVATURE 1	CURVATURE 2	PRIMARY FB	SECONDARY FB	
-0.0025	-0.003	2	2.45098	
RADIUS OF SECONDARY				
34				

S4 PETZVAL RADIUS

0.00025 -1000.

IS THE PETZVAL RADIUS TOO SMALL ?

?NO

SURF	CURVATURE	INDEX	THICKNESS		
0	0	1	1.00000E+10		
1	0	1	0		
2	-0.0025	-1	-66.6667		
3	-0.003	1	666.667		
4	0	1	0		
SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U	
0	0	5.00000E-9	-100000000	0.01	
1	50.	5.00000E-9	0	0.01	
2	50.	0.25	0	-0.01	
3	33.3333	-5.00000E-2	0.666667	0.014	
4	3.81470E-6	-5.00000E-2	10	0.014	
5	3.81470E-6	-5.00000E-2	10	0.014	

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
4.53125E-2	-0.003625	2.90000E-4	0.00025	-4.32000E-5

HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2
-1.16	-2.71875	0

S1	S2	S3	S4	S5
-4.65661E-9	2.91038E-11	3.62500E-4	0.00025	-4.17500E-5

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?

?YES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY

? .2

H	F	M	L	D
50	1000	5	0.2	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.008	100	500	
CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.004	2	2.40385	
RADIUS OF SECONDARY				
26				

S4 PETZVAL RADIUS

7.50000E-4 -333.333

IS THE PETZVAL RADIUS TOO SMALL ?

?NO

SURF	CURVATURE	INDEX	THICKNESS		
0	0	1	1.00000E+10		
1	0	1	0		
2	-0.0025	-1	-100		
3	-0.004	1	500		
4	0	1	0		
SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U	
0	0	5.00000E-9	-100000000	0.01	
1	50.	5.00000E-9	0	0.01	
2	50.	0.25	0	-0.01	
3	25.	-5.00000E-2	1	1.00000E-2	
4	5.00679E-6	-5.00000E-2	10.	1.00000E-2	
5	5.00679E-6	-5.00000E-2	10.	1.00000E-2	

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
8.28125E-2	-0.005125	2.70000E-4	7.50000E-4	-9.52000E-5

HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2			
-1.08	-2.5625	0			
S1	S2	S3	S4	S5	
-1.86265E-9	-2.91038E-10	4.75000E-4	7.50000E-4	-8.70000E-5	

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H,F,M,L,D) CHANGED ?

?YES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO  
THE IMAGE DISTANCE FROM THE SECONDARY

? 4

H	F	M	L	D
50	1000	5	0.4	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.012	133.333	333.333	
CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.006	2	2.31481	
RADIUS OF SECONDARY				

18

S4 PETZVAL RADIUS

0.00175 -142.857

IS THE PETZVAL RADIUS TOO SMALL ?

?NO

SURF	CURVATURE	INDEX	THICKNESS		
0	0	1	1.00000E+10		
1	0	1	0		
2	-0.0025	-1	-133.333		
3	-0.006	1	333.333		
4	0	1	0		
SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U	
0	0	5.00000E-9	-100000000	0.01	
1	50.	5.00000E-9	0	0.01	
2	50.	0.25	0	-0.01	
3	16.6667	-5.00000E-2	1.33333	0.026	
4	4.29153E-6	-5.00000E-2	10	0.026	
5	4.29153E-6	-5.00000E-2	10	0.026	

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
0.120313	-0.006625	1.70000E-4	0.00175	-2.30400E-4

HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2
-1.04	-2.48438	0

S1	S2	S3	S4	S5
0	5.82077E-11	7.00000E-4	0.00175	-0.000188

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?

?YES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO  
THE IMAGE DISTANCE FROM THE SECONDARY

? 6

H	F	M	L	D
50	1000	5	0.6	10

1ST POWER      2ND POWER      SEPARATION      B FOCAL DIST  
 0.005          -0.016          150            250  
 CURVATURE 1    CURVATURE 2    PRIMARY F#     SECONDARY F#  
 -0.0025        -0.008          2              2.23214  
 RADIUS OF SECONDARY

14  
 S4              PETZVAL RADIUS  
 0.00275        -90.9091

IS THE PETZVAL RADIUS TOO SMALL ?

?NO

SURF	CURVATURE	INDEX	THICKNESS
0	0	1	1.00000E+10
1	0	1	0
2	-0.0025	-1	-150
3	-0.008	1	250
4	0	1	0

SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U
0	0	5.00000E-9	-100000000	0.01
1	50.	5.00000E-9	0	0.01
2	50.	0.25	0	-0.01
3	12.5	-5.00000E-2	1.5	3.40000E-2
4	5.36442E-6	-5.00000E-2	10.	3.40000E-2
5	5.36442E-6	-5.00000E-2	10.	3.40000E-2

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
0.139063	-0.007375	4.00000E-5	0.00275	-4.09200E-4

HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
 S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2	S4	S5
-1.02667	-2.45833	0		
S1	S2	S3	S4	S5
1.30385E-8	-1.16415E-10	9.25000E-4	0.00275	-3.03000E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?

?YES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO  
 THE IMAGE DISTANCE FROM THE SECONDARY

? .8

H	F	M	L	D
50	1000	5	0.8	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.02	160	200	
CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.01	2	2.15517	
RADIUS OF SECONDARY				
11.6				

```

S4          PETZVAL RADIUS
0.00375     -66.6667
IS THE PETZVAL RADIUS TOO SMALL ?
?NO
SURF        CURVATURE      INDEX      THICKNESS
0           0              1          1.00000E+10
1           0              1          0
2           -0.0025        -1         -160
3           -0.01         1          200
4           0              1          0
SURF        AXIAL Y        AXIAL U    CHIEF Y    CHIEF U
0           0              5.00000E-9 -100000000 0.01
1           50.            5.00000E-9 0          0.01
2           50.            0.25       0          -0.01
3           10.            -5.00000E-2 1.6        4.20000E-2
4           5.24521E-6     -5.00000E-2 10.        4.20000E-2
5           5.24521E-6     -5.00000E-2 10.        4.20000E-2
THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE
S1          S2          S3          S4          S5
0.150312   -7.82500E-3   -1.02000E-4 0.00375    -6.32320E-4
HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5
??
WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6
?1
DO YOU WANT THE PRIMARY PARABOLIC ?
?NO
CAN BOTH SURFACES BE ASPHERIC ?
?YES
SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE
CONIC CON.1  CONIC CON.2  ASPHERIC CON.2
-1.02        -2.44531        0
S1          S2          S3          S4          S5
-1.11759E-8 -4.65661E-10   1.15000E-3   0.00375    -4.32000E-4
DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?
?NO
DO YOU WANT ANY OF THE STARTING VALUES (H,F,M,L,D) CHANGED ?
?YES
WHAT IS THE APERTURE HEIGHT?
?50
WHAT IS THE IMAGE HEIGHT?
?10
WHAT IS THE FOCAL LENGTH?
?1000
WHAT IS THE MAGNIFICATION OF THE SECONDARY ?
?5
WHAT IS THE RATIO OF THE MIRROR SEPARATION TO
THE IMAGE DISTANCE FROM THE SECONDARY
?1
H          F          M          L          D
50        1000        5          1          10
1ST POWER  2ND POWER  SEPARATION  B FOCAL DIST
0.005     -0.024     166.667    166.667
CURVATURE 1  CURVATURE 2  PRIMARY F#  SECONDARY F#
-0.0025    -0.012     2          2.00333
RADIUS OF SECONDARY
10
S4          PETZVAL RADIUS
0.00475     -52.6316
IS THE PETZVAL RADIUS TOO SMALL ?
?NO

```

SURF	CURVATURE	INDEX	THICKNESS		
0	0	1	1.00000E+10		
1	0	1	0		
2	-0.0025	-1	-166.667		
3	-0.012	1	166.667		
4	0	1	0		
SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U	
0	0	5.00000E-9	-100000000	0.01	
1	50.	5.00000E-9	0	0.01	
2	50.	0.25	0	-0.01	
3	0.33333	-5.00000E-2	1.66667	0.05	
4	5.96046E-6	-5.00000E-2	10.	0.05	
5	5.96046E-6	-5.00000E-2	10.	0.05	

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
0.157812	-0.008125	-0.00025	0.00475	-0.0009

HOW MANY ABERRATIONS MINIMIZED : S1, S2, S3, S5

?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6

?1

DO YOU WANT THE PRIMARY PARABOLIC ?

?NO

CAN BOTH SURFACES BE ASPHERIC ?

?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2
-1.016	-2.4375	0

S1	S2	S3	S4	S5
0	4.65661E-10	1.37500E-3	0.00475	-5.75000E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?

?NO

DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?

?YES

WHAT IS THE APERTURE HEIGHT?

?50

WHAT IS THE IMAGE HEIGHT?

?10

WHAT IS THE FOCAL LENGTH?

?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?

?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO  
THE IMAGE DISTANCE FROM THE SECONDARY

?1.2

H	F	M	L	D
50	1000	5	1.2	10
1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST	
0.005	-0.028	171.429	142.857	
CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#	
-0.0025	-0.014	2	2.01613	
RADIUS OF SECONDARY				
0.85714				

S4 PETZVAL RADIUS

0.00575 -43.4783

IS THE PETZVAL RADIUS TOO SMALL ?

?NO

SURF	CURVATURE	INDEX	THICKNESS
0	0	1	1.00000E+10
1	0	1	0
2	-0.0025	-1	-171.429
3	-0.014	1	142.857
4	0	1	0

SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U
0	0	5.00000E-9	-100000000	0.01
1	50.	5.00000E-9	0	0.01
2	50.	0.25	0	-0.01
3	7.14286	-5.00000E-2	1.71429	0.058
4	4.47035E-6	-5.00000E-2	10.	0.058
5	4.47035E-6	-5.00000E-2	10.	0.058

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
0.16317	-8.33929E-3	-4.01429E-4	0.00575	-1.21234E-3

HOW MANY ABERRATIONS MINIMIZED :S1,S2,S3,S5  
?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6  
?1

DO YOU WANT THE PRIMARY PARABOLIC ?  
?NO

CAN BOTH SURFACES BE ASPHERIC ?  
?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2
-1.01333	-2.43229	0

S1	S2	S3	S4	S5
0	-4.65661E-10	1.60000E-3	0.00575	-7.32000E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
?NO

DO YOU WANT ANY OF THE STARTING VALUES (H,F,M,L,D) CHANGED ?  
?YES

WHAT IS THE APERTURE HEIGHT?  
?50

WHAT IS THE IMAGE HEIGHT?  
?10

WHAT IS THE FOCAL LENGTH?  
?1000

WHAT IS THE MAGNIFICATION OF THE SECONDARY ?  
?5

WHAT IS THE RATIO OF THE MIRROR SEPARATION TO THE IMAGE DISTANCE FROM THE SECONDARY?  
?1.4

H	F	M	L	D
50	1000	5	1.4	10

1ST POWER	2ND POWER	SEPARATION	B FOCAL DIST
0.005	-3.20000E-2	175	125.

CURVATURE 1	CURVATURE 2	PRIMARY F#	SECONDARY F#
-0.0025	-1.60000E-2	2	1.95312

RADIUS OF SECONDARY  
8.

S4	PETZVAL RADIUS
6.75000E-3	-37.037

IS THE PETZVAL RADIUS TOO SMALL ?  
?NO

SURF	CURVATURE	INDEX	THICKNESS
0	0	1	1.00000E+10
1	0	1	0
2	-0.0025	-1	-175
3	-1.60000E-2	1	125.
4	0	1	0

SURF	AXIAL Y	AXIAL U	CHIEF Y	CHIEF U
0	0	5.00000E-9	-100000000	0.01
1	50.	5.00000E-9	0	0.01
2	50.	0.25	0	-0.01
3	6.25	-5.00000E-2	1.75	0.066
4	4.76837E-6	-5.00000E-2	10	0.066
5	4.76837E-6	-5.00000E-2	10	0.066

THE SEIDEL ABERRATIONS FOR BOTH SURFACES SPHERICAL ARE

S1	S2	S3	S4	S5
0.167188	-0.0085	-5.55000E-4	6.75000E-3	-1.56940E-3

HOW MANY ABERRATIONS MINIMIZED :S1, S2, S3, S5  
?2

WHICH TWO MINIMIZED? DENOTE S1+S2 BY 1, S1+S3 BY 2, S1+S5 BY 3  
S2+S3 BY 4, S2+S5 BY 5, S3+S5 BY 6  
?1

DO YOU WANT THE PRIMARY PARABOLIC ?  
?NO

CAN BOTH SURFACES BE ASPHERIC ?  
?YES

SEIDEL ABERRATIONS FOR TWO ASPHERICS AND MIN S1+S2 ARE

CONIC CON. 1	CONIC CON. 2	ASPHERIC CON. 2
-1.01143	-2.42857	0

S1	S2	S3	S4	S5
0	5.82077E-10	1.82500E-3	6.75000E-3	-9.03000E-4

DO YOU WANT A DIFFERENT COMBINATION OF ABERRATIONS MINIMIZED ?  
?NO

DO YOU WANT ANY OF THE STARTING VALUES (H, F, M, L, D) CHANGED ?  
?NO

THE TOTAL SURFACE DEPTH AT THE EDGE OF THE PRIMARY IS -3.12486  
THE ASPHERIC DEPTH AT THE EDGE OF THE PRIMARY IS 1.24428E-2  
THE TOTAL SURFACE DEPTH AT THE EDGE OF THE SECONDARY IS -0.509039  
THE ASPHERIC DEPTH AT THE EDGE OF THE SECONDARY IS 5.07589E-3  
THE INSIDE RADIUS OF THE PRIMARY IS 10.8  
THE VERTEX THICKNESS OF THE PRIMARY IS 5  
THE VERTEX THICKNESS OF THE SECONDARY IS 0.8  
THE CENTER OF MASS AS MEASURED FROM THE REAR OF THE  
PRIMARY ALONG THE OPTIC AXIS IS 1.55733  
DENOTE THE UNITS ON THE INPUT VALUES: INCHES BY 2.54,  
MILLIMETERS BY 0.1, CENTIMETERS BY 1, METERS BY 100  
?1

THE TOTAL WEIGHT IN GRAMS IS 66448.6  
THE MOMENT OF INERTIA (IN GM. (UNITS)\*\*2) FOR THE SYSTEM IS  
8.16476E+6

DO YOU WANT TO RUN THIS CASSEGRAIN ON ACOSS ?  
?NO

## APPENDIX C

### CALCULATION OF PHYSICAL PARAMETERS

In Fig. 16, the upper boundary is given by:

$$z = \frac{1}{(1+K)c} \left[ 1 - (1 - (1+K)c^2(x^2 + y^2))^{\frac{1}{2}} \right] \quad (12)$$

where  $K$  is the conic constant, and  $c$  is the curvature. The lower boundary is:  $z = 0$ , and the side boundary is:  $x^2 + y^2 = H^2$

The volume is then

$$V = 4 \int_0^H \int_0^{(H^2-y^2)^{\frac{1}{2}}} z \, dx \, dy$$

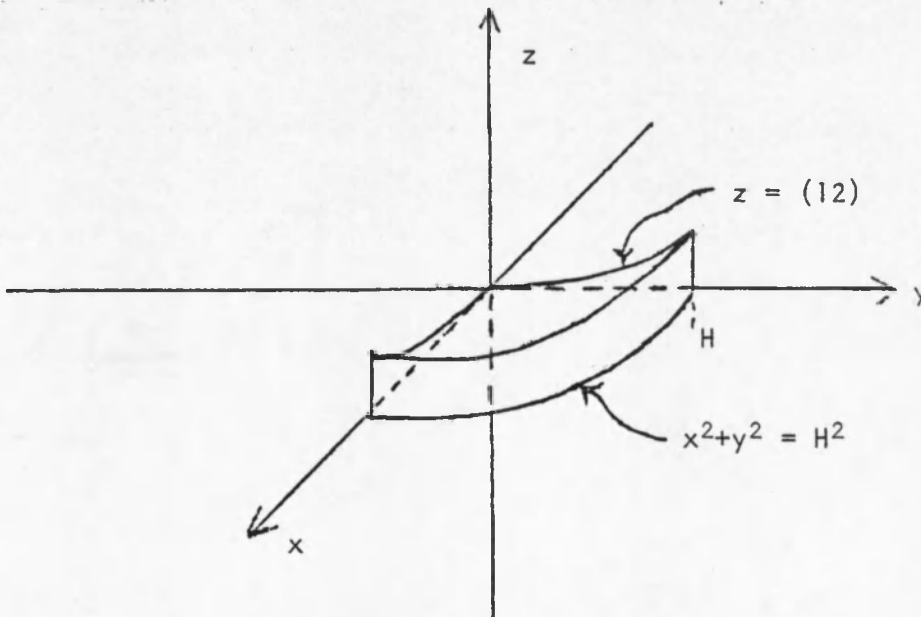


Fig. 16. Volume under Aspheric.

Using the expansion in  $z$ :

$$(1 - x)^{\frac{1}{2}} = 1 - \frac{x}{2} - \frac{x^2}{8} + \frac{3x^3}{48} + \dots$$

we get:

$$V = 4 \int_0^H \int_0^{\sqrt{H^2 - y^2}} \left[ \frac{c(x^2 + y^2)}{2} + \frac{(1+K)c^3(x^2 + y^2)^2}{8} + \frac{3(1+K)^2 c^5 (x^2 + y^2)^3}{48} \right] dx dy$$

Evaluating this integral using the substitutions:  $y = H \sin \theta$ ,  $dy = H \cos \theta d\theta$ ,  $(H^2 - y^2)^{\frac{1}{2}} = H \cos \theta$ , various trigonometric multiangle identities, and the indefinite integral tables involving  $(a^2 - x^2)^{\frac{1}{2}}$  we end up with:

$$V = \frac{cH^4\pi}{4} + \frac{9H^6(1+K)c^3\pi}{64} + \frac{9(1+K)^2c^5H^8\pi}{128}$$

### Centroid Approximations

The vertex thickness of the mirror is its height divided by ten. The centroid of the aspheric portion of the primary mirror is located (3/8) of the total surface depth (E1) from the vertex of the surface. The centroid of the aspheric portion of the secondary mirror is located (5/8) of the total surface depth (E3) from the vertex of the surface. See Fig. 16 for an explanation of the quantities used in statement 5650 of the program (the center of mass calculation). See Fig. 17 for the sign convention for the total and aspheric depths.

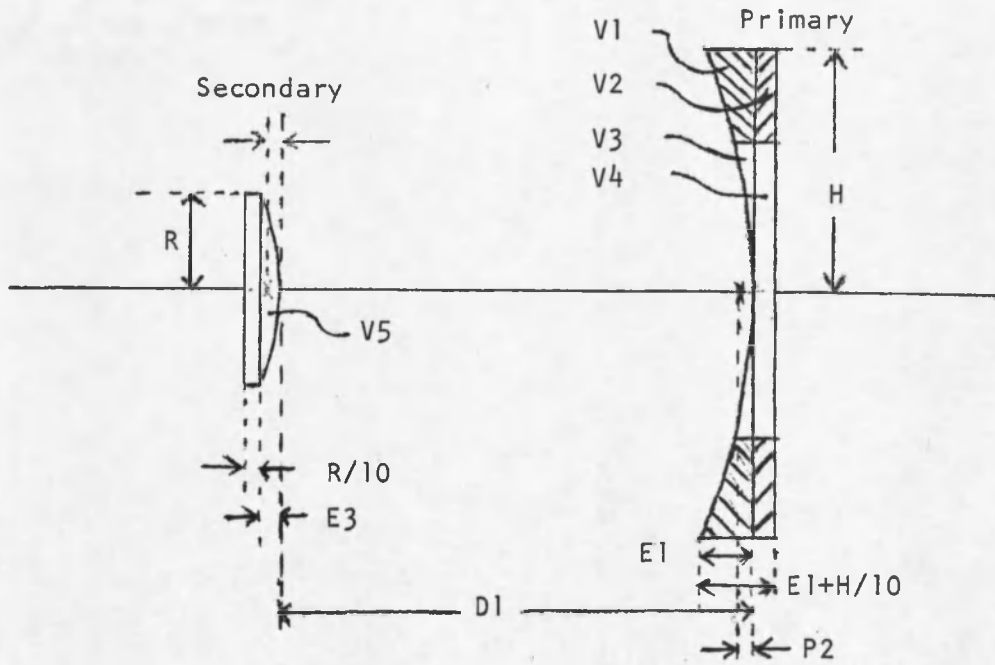


Fig. 17. Physical Dimensions.

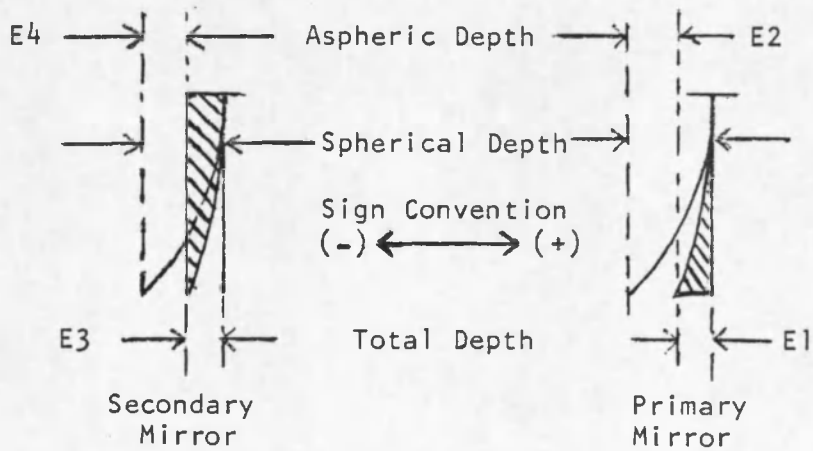


Fig. 18. Aspheric Depths.

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