CHAPTER V

DISCUSSION

Since it is very difficult to construct a tool having the exact curvature specified in the design, actual aberrations could be much larger than the theoretical values.

The conctructed lenses were all ground as close as possible to the specifications. All of the lenses were made by hand using an old lens grinding mechine described in the preceding section. The grinding of lens was extremely difficult since the lenses were not only small but also very fragile.

Because of the great difficulty, the actual radii of curvature were different from those specified. The comparisons are shown in the following table :

Type	The constructed radius of curvature (mm.)	The designed radius of curvature (mm.)	Errors (%)
objective	$r_1 = 77$	$r_1 = 80.14$	4
	r_2 could not be measured.	$r_2 = 22.50$	-
	$r_3 = 46$	$r_3 = 46.85$	2
eyepiece	$r_1 = \infty$ (approx.)	$r_1 = \infty$	-
	$r_2 = 16$	$r_2 = 17.58$	9
	$r_3 = 17$	$r_3 = 17.58$	4
	$r_4 = \infty$ (approx.)	$r_4 = \infty$	-

Table 5-1. Comparison between the constructed radii of curvature and the designed radii of curvature.

The dark rings of each lens surface were circular, indicating that the lens surfaces of the constructed lenses were spherical at least in the region observed.

According to the measurement, the total magnification was 49 times instead of 30 times as the design. The defect was partly due to the shorter objective focal length than the design by 21 %, and the shorter eyepiece focal length than the design by 16 %. By computation the measured values of the objective and the eyepiece focal length would give the total magnification of 45 times. It was notable that the direct measurement of the total magnification was different from the total magnification calculated from the measured focal lengths. Although the discrepancy could possibly arise from the errors in the above measurement, it could be accounted for by the 9 % error in the optical tube length which was found to be 174 mm long.

The focal lengths of the objective and the eyepiece were different from the design because of the change of the radii of curvature from the design, especially for the eyepiece.

In the case of the objective, the radii of curvature of the cemented surfaces were not measured. However, due to the small difference between the refractive indices of the two components, the variation of the curvature, c_2, would only slightly change the objective focal length.

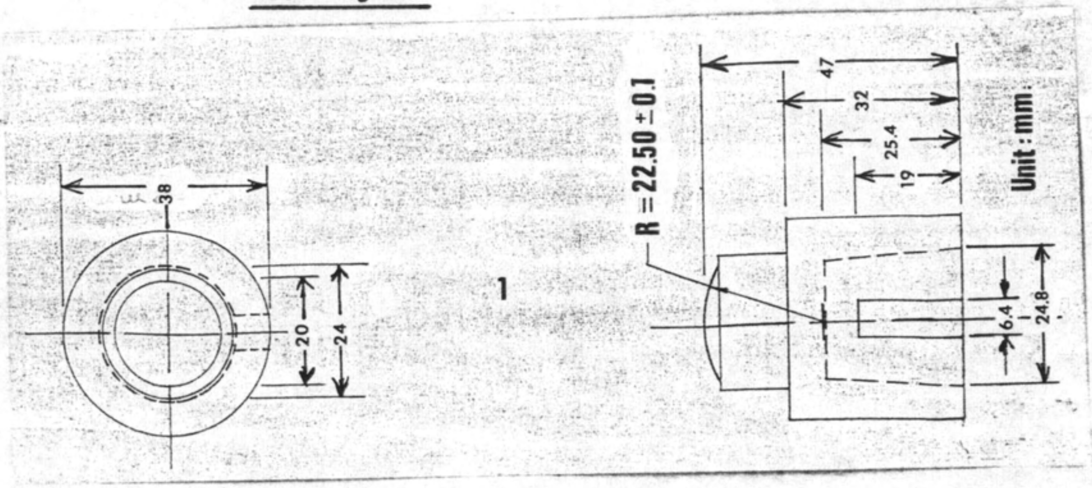
The change of the values from the design increased chromatic aberration, spherical aberration and coma which became obvious during the test. The increased aberrations would deteriorate the resolving power; the actual resolving power in monochromatic light was found to be worse than the theoretical value by 50 %. However, the final image quality was acceptable although the lenses were not coated with MgF_2. The vernier scale gave good accuracy but the mechanical parts were not quite satisfactory, the microscope could significantly wobble when traveling on the stage.

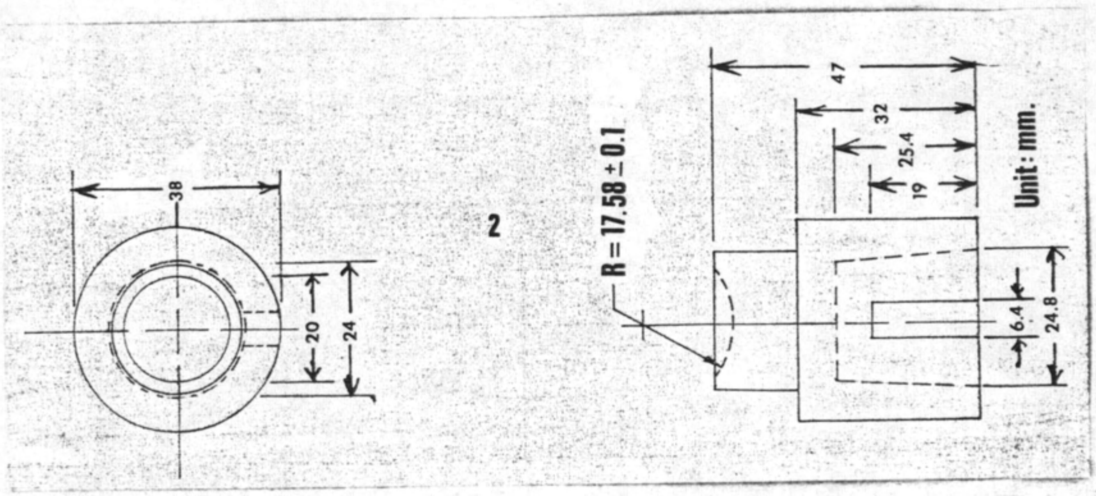
At the polishing stage, the cloth over pitch technique was used to polish the lens surface. The technique gave a smoother surface and was less time consuming. If the lens surface was not smooth, the image was blurred; and, if the lens was not centered on the optical axis, the off axis aberrations markedly increased. So that the quality of a lens depends very much on the polishing and the centering.

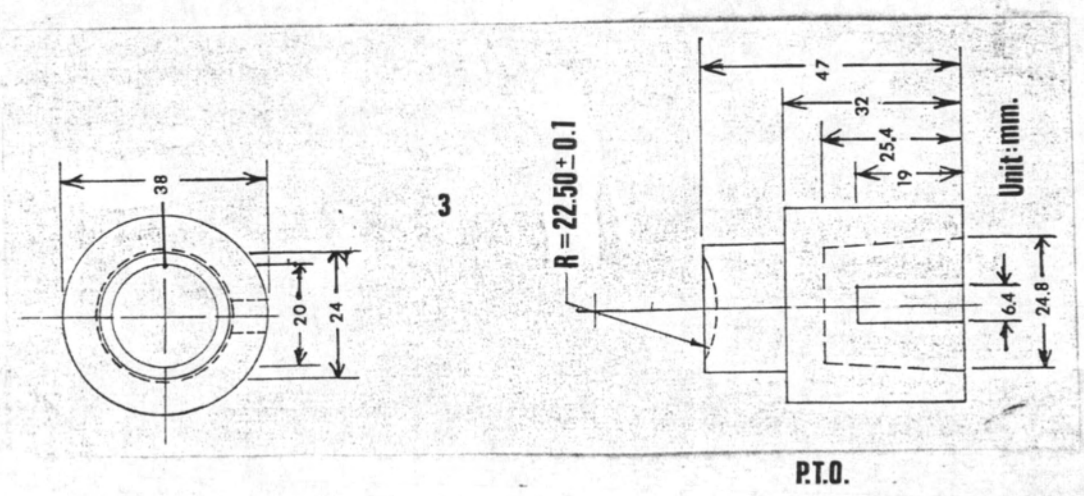
The computer programs were used for the calculation of the aberrations of the achromatic doublet and the eyepiece. This technique can also be applied to any other doublet lens design.

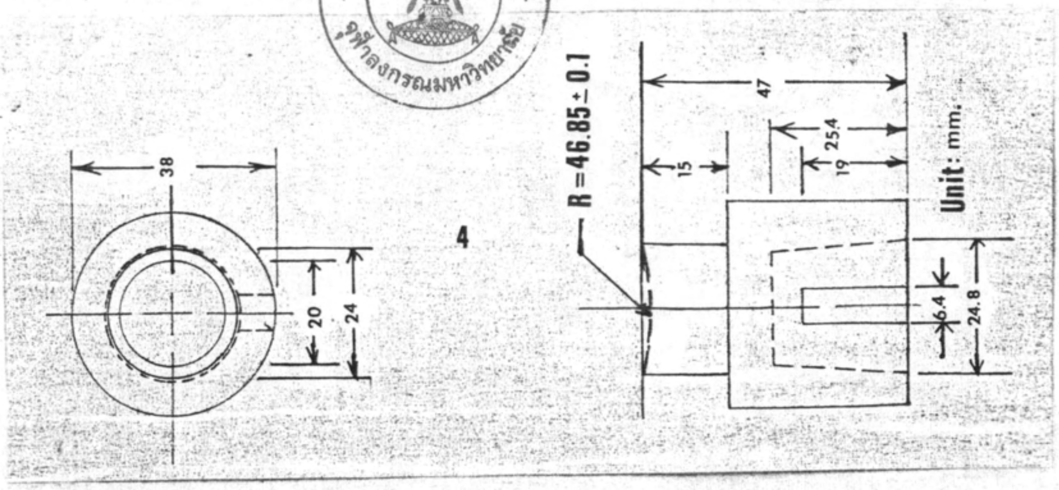
Appendix 1

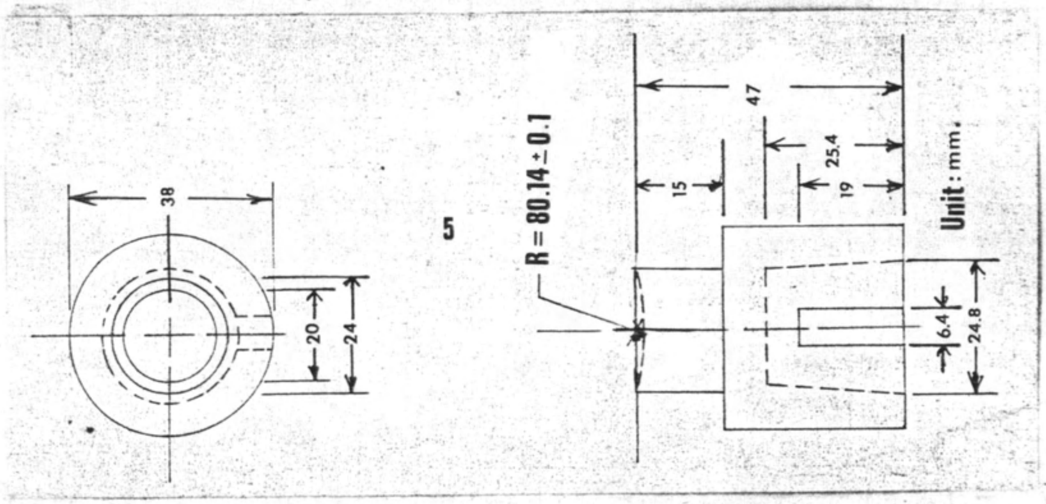
Tool Diagram

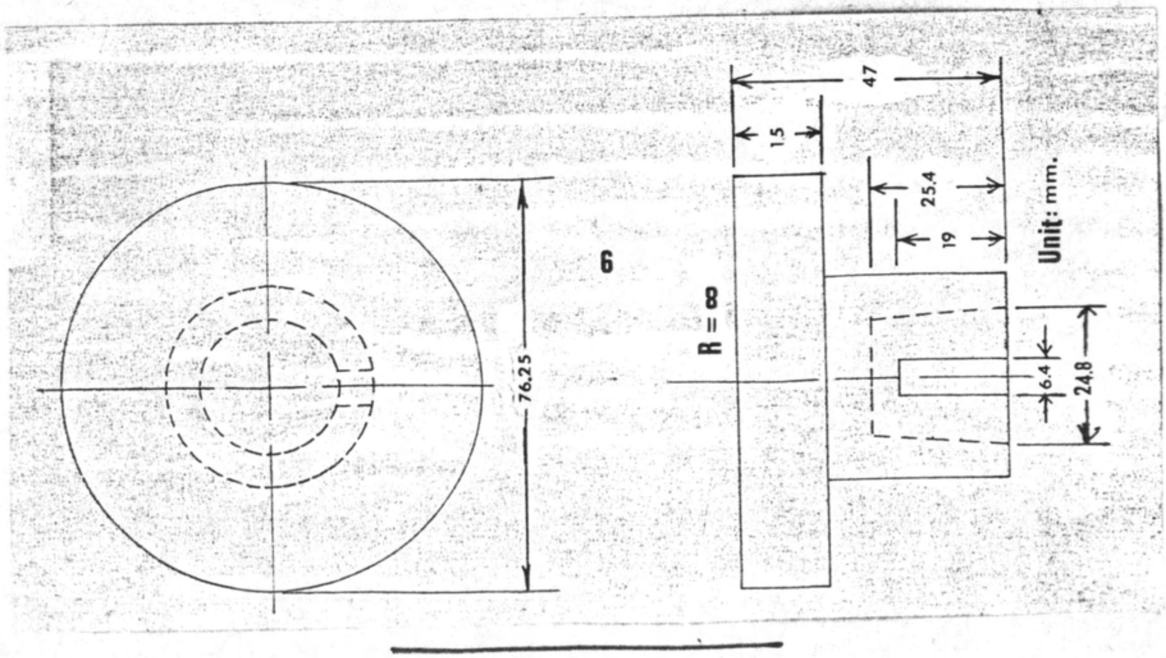






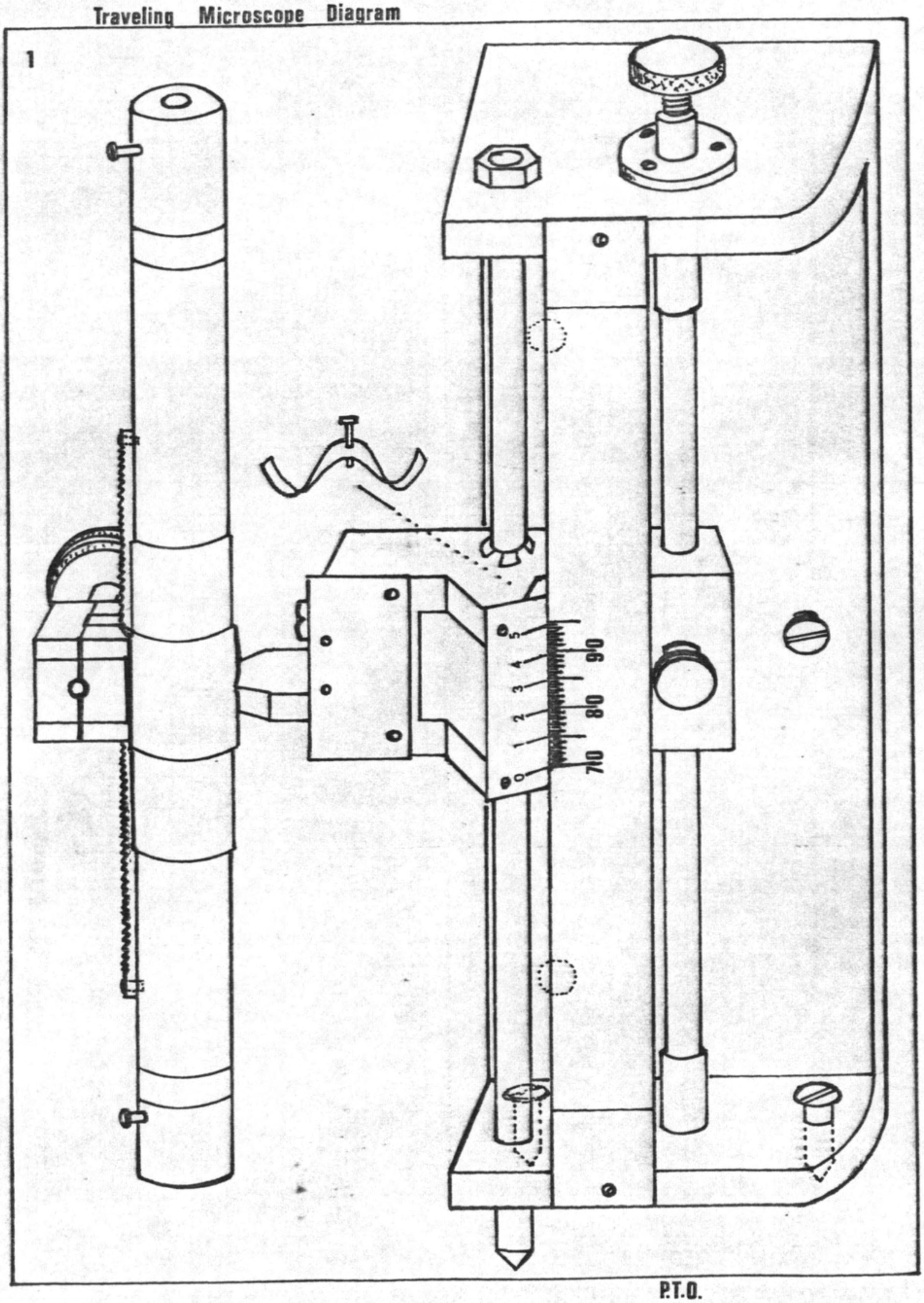

38
20
24
4
R = 46.85 ± 0.1
15
47
25.4
19
6.4
24.8
Unit : mm.


38
20
24
5
R = 80.14 ± 0.1
15
47
25.4
19
6.4
24.8
Unit : mm.


76.25
6
R = ∞
15
47
25.4
19
6.4
24.8
Unit : mm.

Appendix 2

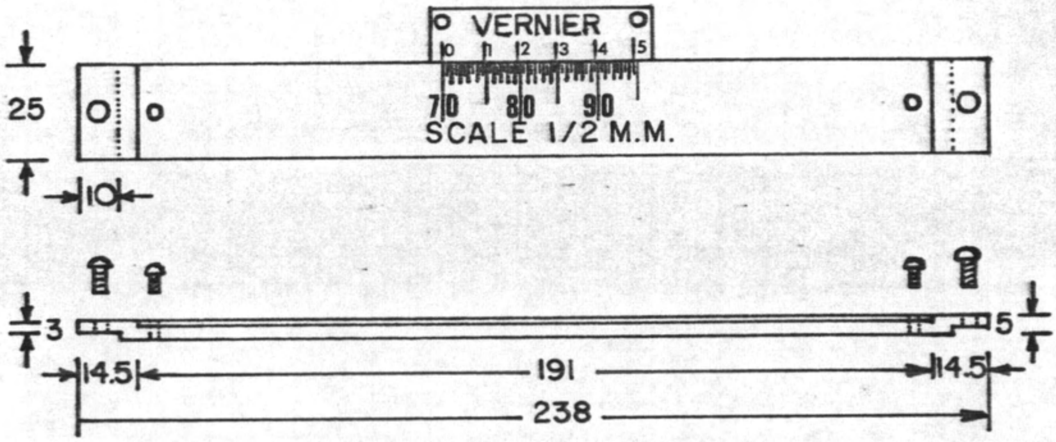
Traveling Microscope Diagram

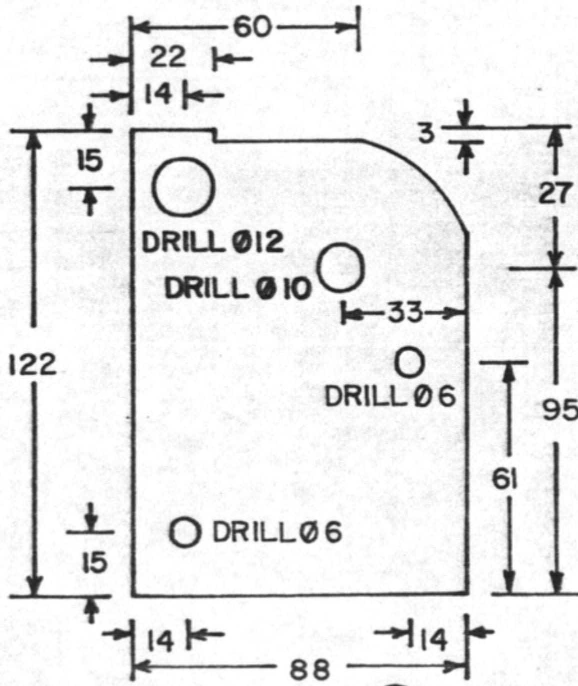


P.T.O.

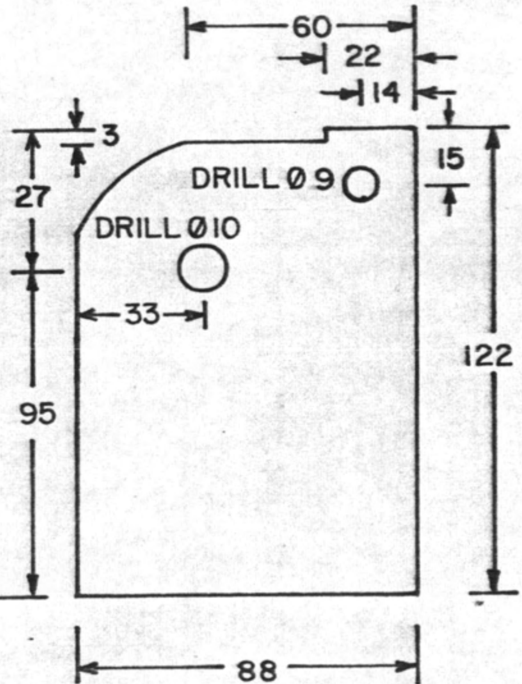
2

SCALE FOR READING AND VERNIER
SCALE 1:2



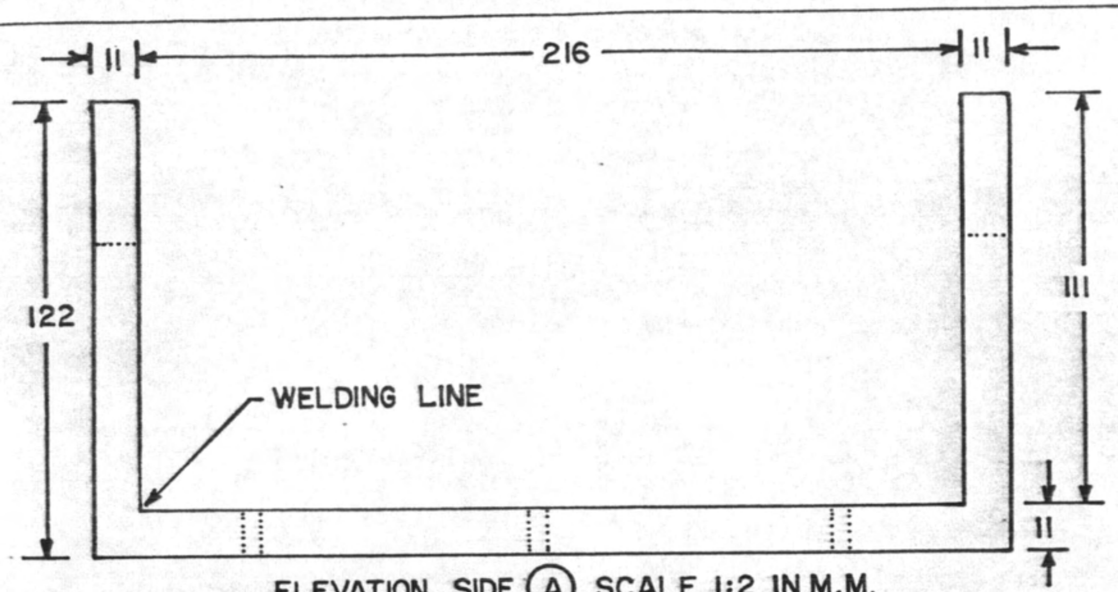


ELEVATION SIDE (B)
SCALE 1:2 IN M.M.

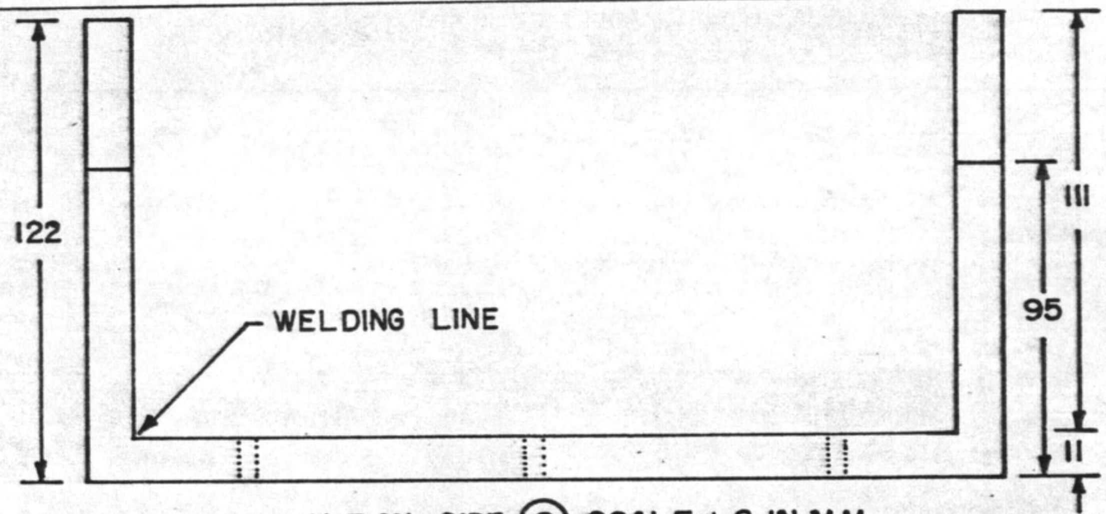


ELEVATION SIDE (D)
SCALE 1:2 IN M. M.

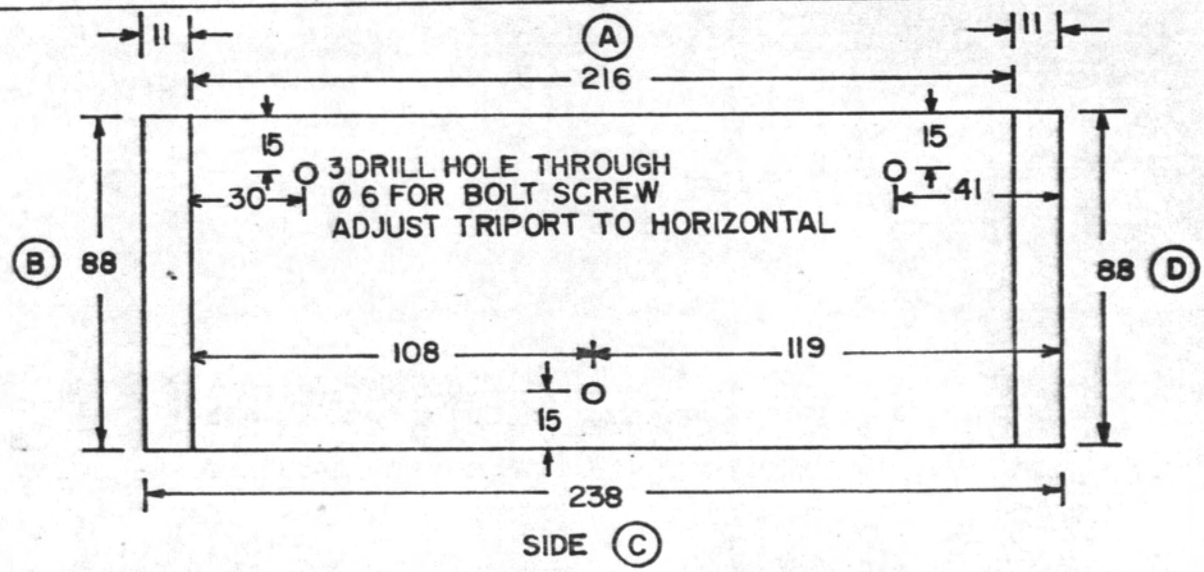
3



ELEVATION SIDE (A) SCALE 1:2 IN M.M.



ELEVATION SIDE (C) SCALE 1:2 IN M.M.

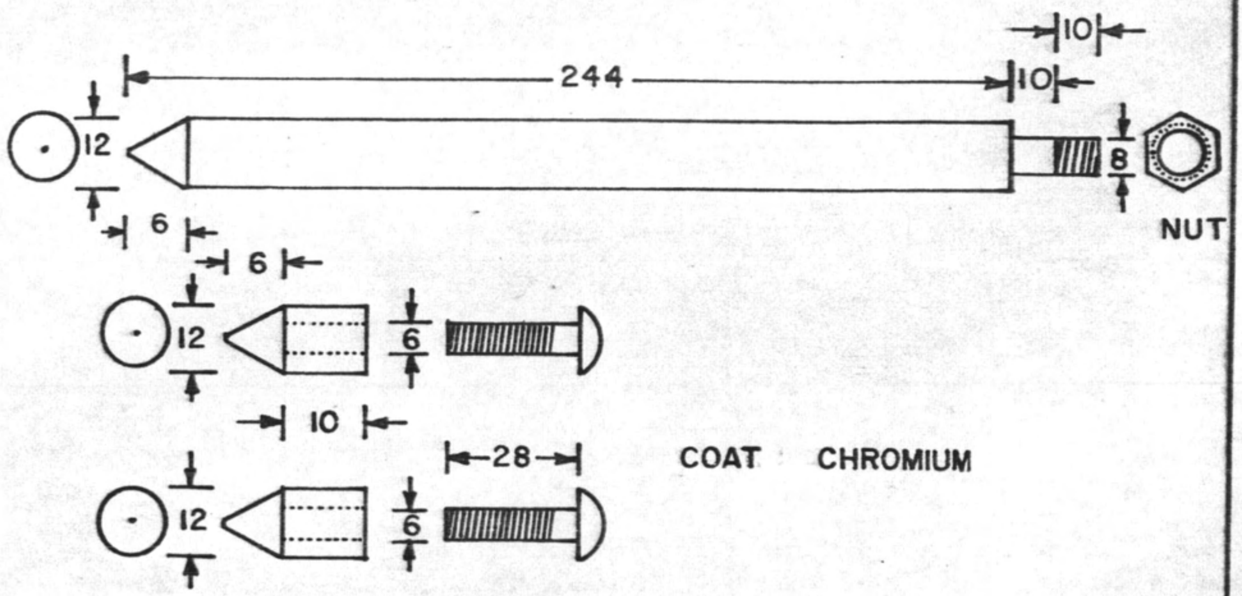


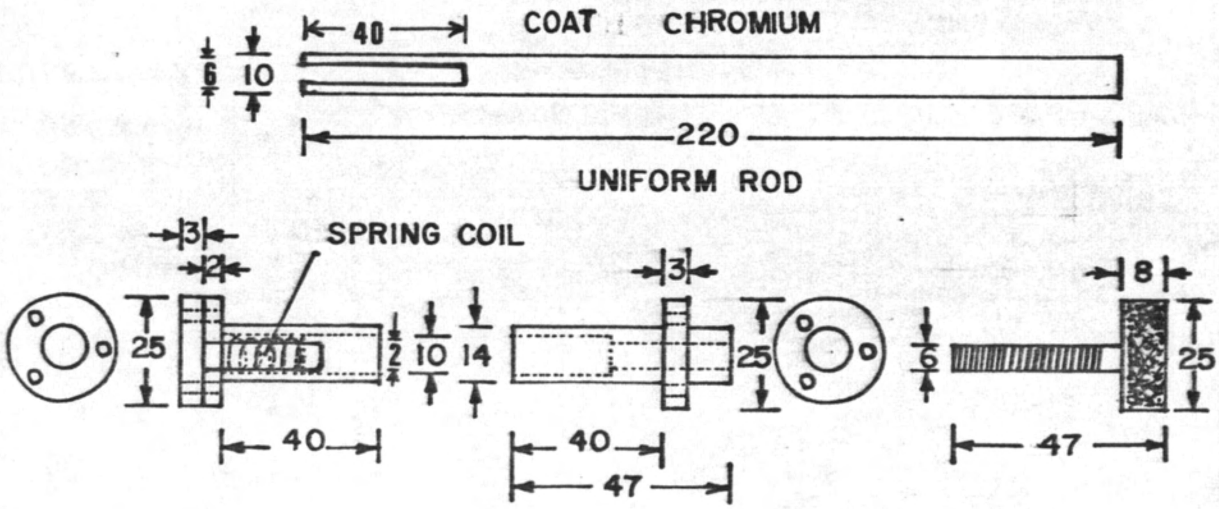
TOP VIEW IRON BASE SCALE 1:2 IN M.M.

P.T.O.

4

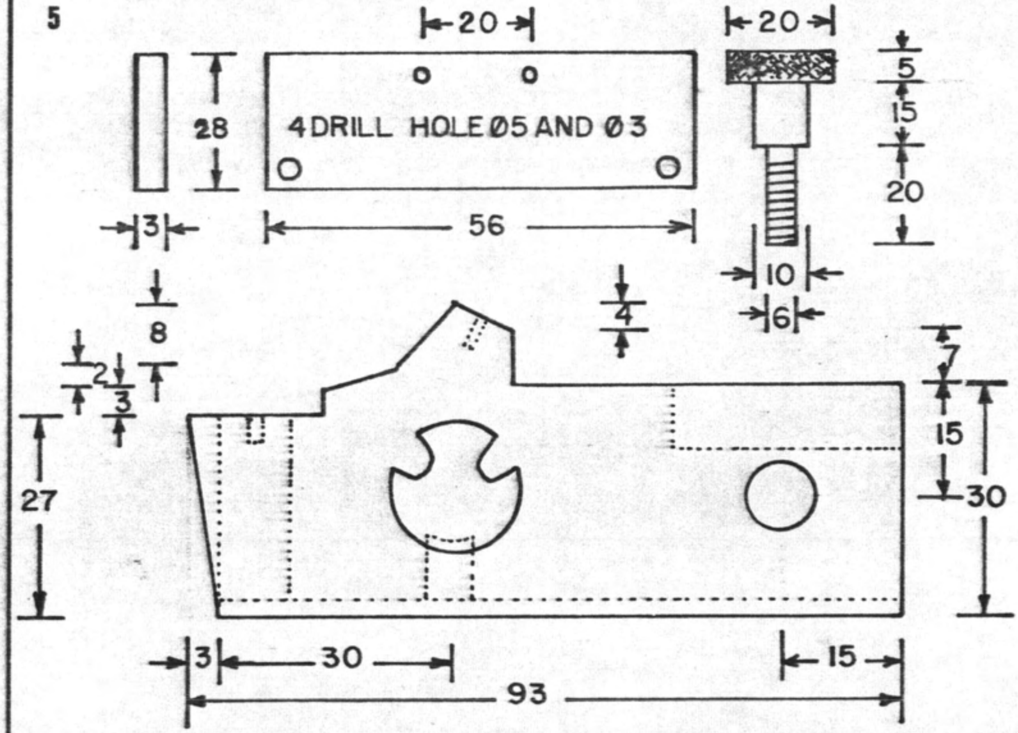
IRON ROD BEAM AND TRIPORT SCALE 1:2 IN M.M.



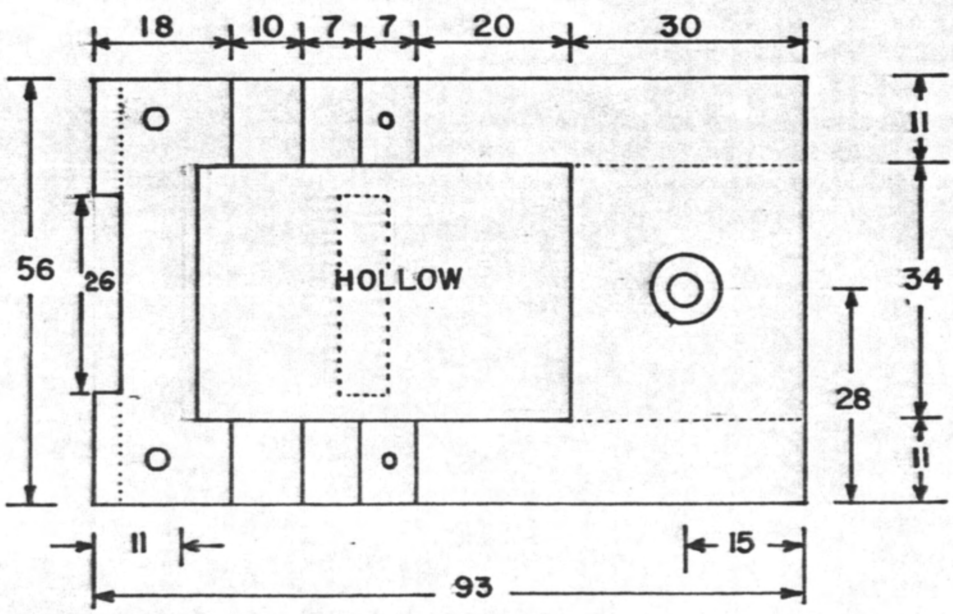


IRON ROD BEAM AND BRASS BOOT SCALE 1:2 IN M.M.

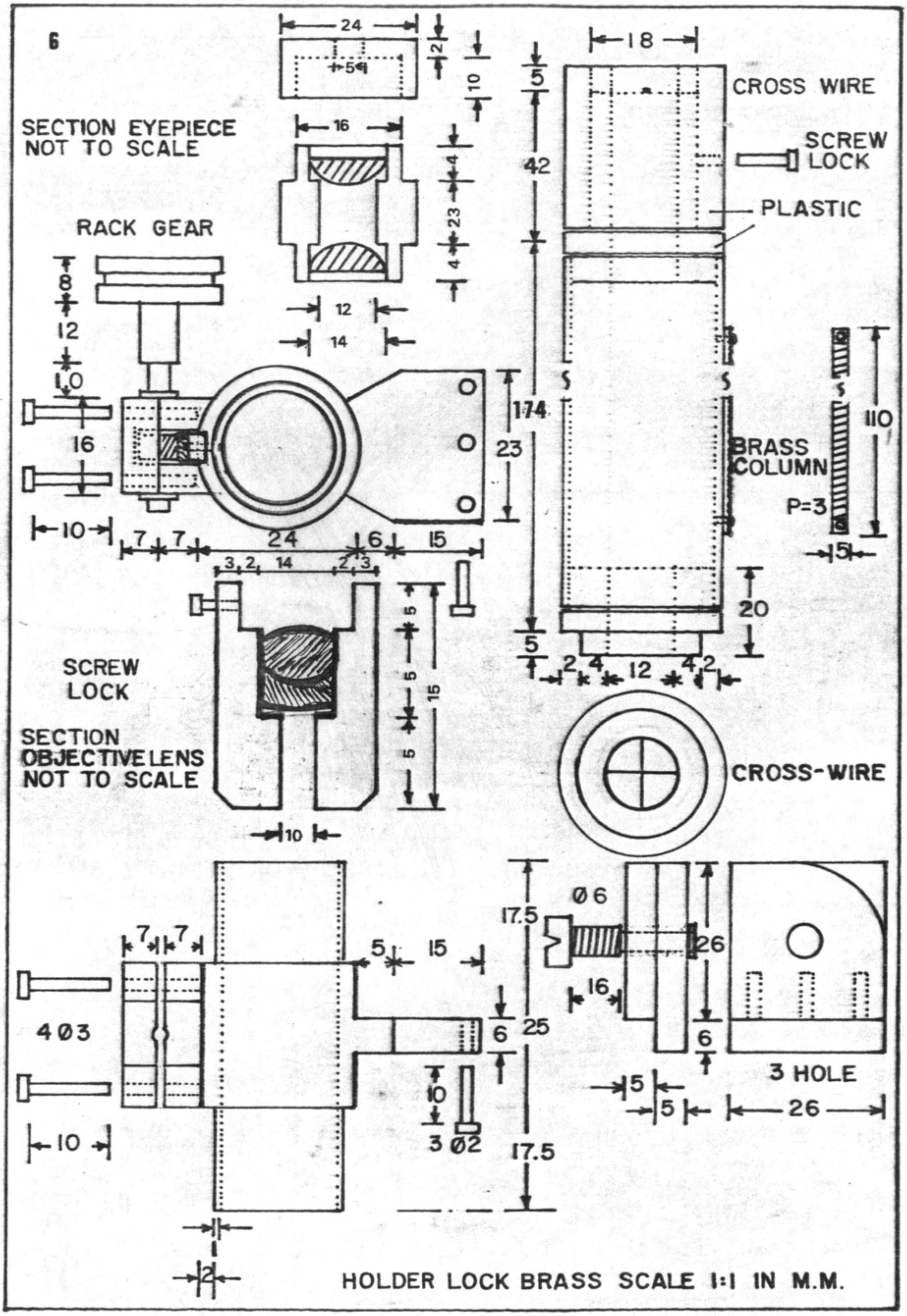
5



ELEVATION PLASTIC HOUSING SCALE 1:1 IN M.M.



TOP VIEW PLASTIC HOUSING SCALE 1:1 IN M.M.


6
SECTION EYEPIECE
NOT TO SCALE
RACK GEAR
CROSS WIRE
SCREW
LOCK
PLASTIC
BRASS
COLUMN
P=3
SCREW
LOCK
SECTION
OBJECTIVE LENS
NOT TO SCALE
CROSS-WIRE
4 Ø3
3 Ø2
Ø6
3 HOLE
HOLDER LOCK BRASS SCALE 1:1 IN M.M.

END.

Appendix 3

Program One

```
2642010  F
*JOBID,NOLIST        2642010          SIRISAK TACHATHAWEKUN
*JOBID, NOLIST       SIRISAK TACHATHAWEKUN  PHYSICS DEPARTMENT  THESIS
*JOBID, NOLIST,F14
C      RAY TRACING CALCULATIONS
C      FOR FRAUNHOFER ACHROMATIC OBJECTIVE LENS
       DIMENSION P(4),C(3),D(3),V(4),XAR(4),X(3,21),A(3,21),R(3)
       READ(2,5) P,C,D,V
     5 FORMAT(4F14.10/3F14.10/3F14.10/4F14.10)
       READ(2,10) UBA,HBA,UA,HA
    10 FORMAT(2F14.10/2F14.10)
       DO 300 K=1,2
       DO 200 J=K,21
       IF(K.EQ.1) GO TO 20
       Z=-Z
    20 SUMS1=0.0
       SUMS2=0.0
       SUMS3=0.0
       SUMS4=0.0
       SUMS5=0.0
       SUMCL=0.0
       SUMCT=0.0
       DO 100 I=1,3
       IF(I.GT.1) GO TO 30
       UB=UBA
       HB=HBA
       U=UA
       H=HA
    30 IF(I.EQ.1) GO TO 40
       U=UP
       H=HP
       UB=UBP
       HB=HBP
    40 IF(J.EQ.1) GO TO 50
       X(I,J)=X(I,1)+Z
       A(I,J)=A(I,1)+Z
       Y=X(I,J)/H
       C(I)=Y
       IF(J.GT.1) GO TO 60
    50 X(I,J)=H*C(I)
       A(I,J)=P(I)*(X(I,J)-U)
    60 AM=A(I,J)*H
       UP=X(I,J)-(A(I,J)/P(I+1))
       HP=H-(D(I)*UP)
       DEL=(UP/P(I+1))-(U/P(I))
       XB=HB*C(I)
       B=P(I)*(XB-UB)
       UBP=XB-(B/P(I+1))
       HBP=HB-(D(I)*UBP)
       S1=A(I,J)*A(I,J)*H*DEL
       SUMS1=SUMS1+S1
       S2=A(I,J)*B*H*DEL
       SUMS2=SUMS2+S2
       S3=B*B*H*DEL
       SUMS3=SUMS3+S3
       GP=(1.0/P(I+1))-(1.0/P(I))
       PP=-C(I)*GP
       HH=-P(I)*UB*H
       S4=HH*HH*PP
       SUMS4=SUMS4+S4
       S5=(B/A(I,J))*(S3+S4)
```

P.T.O.

```
      SUMS5=SUMS5+S5
      XAR(I)=(P(I)-1.0)/(P(I)*V(I))
      XAR(I+1)=(P(I+1)-1.0)/(P(I+1)*V(I+1))
      DELXAR=XAR(I+1)-XAR(I)
      CL=A(I,J)*H*DELXAR
      SUMCL=SUMCL+CL
      CT=B*H*DELXAR
      SUMCT=SUMCT+CT
      R(I)=1.0/C(I)
  100 WRITE(3,120) K,J,I,P(I),P(I+1),C(I),D(I),
     *UB,HB,XB,B,UBP,HBP,U,H,X(I,J),A(I,J),
     *AM,DEL,UP,HP,S1,S2,S3,S4,S5,DELXAR,CL,CT,R(I)
  120 FORMAT(10X,7HK      =,6X,I2,6X/10X,7HJ      =,6X,I2,6X/
     *10X,7HI      =,6X,I2,6X/10X,7HP(I)   =,F14.10/
     *10X,7HP(I+1)=,F14.10/10X,7HC(I)   =,F14.10/10X,7HD(I)   =,F14.10//
     *10X,7HUB     =,F14.10/10X,7HHB     =,F14.10/10X,7HXB     =,F14.10/
     *10X,7HB      =,F14.10/10X,7HUBP    =,F14.10/10X,7HHBP    =,F14.10//
     *10X,7HU      =,F14.10/10X,7HH      =,F14.10/10X,7HX      =,F14.10/
     *10X,7HA      =,F14.10/10X,7HAM     =,F14.10/10X,7HDEL    =,F14.10/
     *10X,7HUP     =,F14.10/10X,7HHP     =,F14.10//10X,7HS1     =,F14.10/
     *10X,7HS2     =,F14.10/10X,7HS3     =,F14.10/10X,7HS4     =,F14.10/
     *10X,7HS5     =,F14.10/10X,7HDELXAR=,F14.10/
     *10X,7HCL     =,F14.10/10X,7HCT     =,F14.10/10X,7HR(I)   =,F14.6///)
      W040=SUMS1/8.0
      W131=SUMS2/2.0
      W222=SUMS3/2.0
      W220=(SUMS3+SUMS4)/4.0
      W211=SUMS5/2.0
      WD20=SUMCL/2.0
      WD11=SUMCT
      QQ=(C(3)+C(1))/(C(3)-C(1))
      WRITE(3,150) SUMS1,SUMS2,SUMS3,SUMS4,SUMS5,SUMCL,SUMCT,
     *W040,W131,W222,W220,W211,WD20,WD11,QQ
  150 FORMAT(10X,7HSUMS1 =,F14.10/10X,7HSUMS2 =,F14.10/
     *10X,7HSUMS3 =,F14.10/10X,7HSUMS4 =,F14.10/10X,7HSUMS5 =,F14.10/
     *10X,7HSUMCL =,F14.10/10X,7HSUMCT =,F14.10//
     *10X,7HW040   =,F14.10/10X,7HW131   =,F14.10/10X,7HW222   =,F14.10/
     *10X,7HW220   =,F14.10/10X,7HW211   =,F14.10/10X,7HWD20   =,F14.10/
     *10X,7HWD11   =,F14.10/10X,7HQQ     =,F14.10//////)
      AJ=J
      Z=(A(1,1)/20.0)*AJ
  200 CONTINUE
      Z=0.0
      Z=A(1,1)/20.0
  300 CONTINUE
      STOP
      END
*DATA
1.0            1.6229          1.68881        1.0
0.0335425863   -0.0325243059   0.0
3.0            2.0             0.0
1.0            56.89           30.97          1.0
-0.028125      0.0
-0.0234375     5.0
```

Appendix 4

Program Two

```
2642010   F
*JOBID,NOLIST       2642010            SIRISAK TACHATHAWEKUN
*JOBID, NOLIST, F14
C       THE GRADUATE THESIS OF PHYSICS, CHULALONGKORN UNIVERSITY
C       OPTICAL RESEARCH WAS MADE BY MR. SIRISAK TACHATHAWEKUN
C       USING FORTRAN D SYSTEM TAPE REVISION NUMBER 5.3
C       *JOBID,NOLIST, F14
C       RAY TRACING CALCULATIONS AND BENDING METHOD
C       FOR FRAUNHOFER ACHROMATIC OBJECTIVE LENS
        DIMENSION P(4),C(3),D(3),R(3),XX(3),AA(3),X(3),A(3)
        READ(2,10) P,D,UA,HA,UBA,HBA,C
     10 FORMAT(4F14.10/3F14.10/2F14.10/2F14.10/3F14.10)
        REWIND 6
        DO 100 I=1,3
        M=I+1
        IF(I.GT.1) GO TO 20
        U=UA
        H=HA
     20 IF(I.EQ.1) GO TO 30
        U=UP
        H=HP
     30 XX(I)=H*C(I)
        AA(I)=P(I)*(XX(I)-U)
        UP=XX(I)-AA(I)/P(M)
        HP=H-D(I)*UP
    100 CONTINUE
        WRITE(6,40) XX(1),XX(2),XX(3),AA(1),AA(2),AA(3)
     40 FORMAT (6F14.10)
        DO 300 K=1,2
        DO 200 J=1,500
        AJ=J
        Z=(AA(1)/1000.0)*AJ
        IF(K.EQ.1) GO TO 50
        Z=-Z
     50 X(1)=XX(1)+Z
        A(1)=AA(1)+Z
        X(2)=XX(2)+Z
        A(2)=AA(2)+Z
        X(3)=XX(3)+Z
        A(3)=AA(3)+Z
        WRITE(6,40) X(1),A(1),X(2),A(2),X(3),A(3)
    200 CONTINUE
    300 CONTINUE
        END FILE 6
        REWIND 6
        READ(6,40) XX(1),XX(2),XX(3),AA(1),AA(2),AA(3)
        WRITE(3,60) XX(1),XX(2),XX(3),AA(1),AA(2),AA(3)
     60 FORMAT (10X,7HXX(1) =,F14.10,10X,7HXX(2) =,F14.10,
       *10X,7HXX(3) =,F14.10/10X,7HAA(1) =,F14.10,
       *10X,7HAA(2) =,F14.10,10X,7HAA(3) =,F14.10///)
        DO 500 J=1,1000
        READ(6,40) X(1),A(1),X(2),A(2),X(3),A(3)
```

P.T.O.

```
      SUMS1=0.0
      SUMS2=0.0
      SUMS3=0.0
      DO 400 I=1,3
      M=I+1
      IF(I.GT.1) GO TO 70
      U=UA
      H=HA
      UB=UBA
      HB=HBA
   70 IF(I.EQ.1) GO TO 80
      U=UP
      H=HP
      UB=UBP
      HB=HBP
   80 C(I)=X(I)/H
      R(I)=1.0/C(I)
      UP=X(I)-A(I)/P(M)
      HP=H-D(I)*UP
      DEL=(UP/P(M))-(U/P(I))
      XB=HB*C(I)
      B=P(I)*(XB-UB)
      UBP=XB-(B/P(M))
      HBP=HB-D(I)*UBP
      S1=A(I)*A(I)*H*DEL
      SUMS1=SUMS1+S1
      S2=A(I)*B*H*DEL
      SUMS2=SUMS2+S2
      S3=B*B*H*DEL
      SUMS3=SUMS3+S3
  400 CONTINUE
      W040=SUMS1/8.0
      W031=SUMS2/2.0
      W222=SUMS3/2.0
      WRITE(3,90) J,R(1),R(2),R(3),X(1),X(2),X(3),A(1),A(2),A(3),
     *SUMS1,SUMS2,SUMS3,W040,W031,W222
   90 FORMAT (10X,7H     J =,5X,I4,5X/
     *10X,7HR(1)   =,F14.6,10X,7HR(2)   =,F14.6,10X,7HR(3)   =,F14.6/
     *10X,7HX(1)   =,F14.10,10X,7HX(2)   =,F14.10,10X,7HX(3)   =,F14.10/
     *10X,7HA(1)   =,F14.10,10X,7HA(2)   =,F14.10,10X,7HA(3)   =,F14.10/
     *10X,7HSUMS1 =,F14.10,10X,7HSUMS2 =,F14.10,10X,7HSUMS3 =,F14.10/
     *10X,7HW040  =,F14.10,10X,7HW031  =,F14.10,10X,7HW222  =,F14.10///)
  500 CONTINUE
      STOP
      END
*DATA
1.0            1.6229         1.68881        1.0
3.0            2.0            0.0
-0.0234375     5.0
-0.028125      0.0
0.0335425863   -0.0325243059  0.0
```

Appendix 5

Program Three

```
2642010  F
*JOBID, NOLIST     2642010          SIRISAK TACHATHAWEKUN
*JOBID, NOLIST     THESIS RESEARCH              GRADUATE SCHOOL CHULA. U.
*JOBID, NOLIST,F20
C      RAY TRACING CALCULATIONS BY SEPARATING TWO LENSES
C      FOR RAMSDEN EYEPIECE
      DIMENSION P(5),C(4),D(4)
      READ(2,10) P,C,D,F,UA,HA
   10 FORMAT(5F14.10/4F14.10/4F14.10/3F14.10)
      REWIND 6
      DO 200 J=1,40
      AJ=J
      D(2)=(F/20.0)*AJ
      DO 100 I=1,4
      M=I+1
      IF(I.GT.1) GO TO 20
      U=UA
      H=HA
   20 IF(I.EQ.1) GO TO 30
      U=UP
      H=HP
   30 X=H*C(I)
      A=P(I)*(X-U)
      UP=X-A/P(M)
      HP=H-D(I)*UP
  100 CONTINUE
      Z=HP/UP
      W=-(6.0/2.5)*UP
      HBA=-(W*8.8072779)
      WRITE(6,40) D(2),Z,W,HBA
   40 FORMAT (F14.6,F20.6,2F14.10)
  200 CONTINUE
      END FILE 6
      REWIND 6
      DO 400 J=1,40
      READ (6,40) D(2),Z,W,HBA
      SUMS1=0.0
      SUMS2=0.0
      SUMS3=0.0
      DO 300 I=1,4
      M=I+1
      IF (I.GT.1) GO TO 50
      U=UA
      H=HA
      UB=W
      HB=HBA
   50 IF(I.EQ.1) GO TO 60
      U=UP
      H=HP
      UB=UBP
      HB=HBP
   60 X=H*C(I)
      A=P(I)*(X-U)
      UP=X-A/P(M)
      HP=H-(D(I)*UP)
      DEL=UP/P(M)-U/P(I)
      XB=HB*C(I)
      B=P(I)*(XB-UB)
      UBP=XB-B/P(M)
      HBP=HB-(D(I)*UBP)
      S1=A*A*H*DEL
      SUMS1=SUMS1+S1
      S2=A*B*H*DEL
      SUMS2=SUMS2+S2
      S3=B*B*H*DEL
      SUMS3=SUMS3+S3
  300 CONTINUE
      W040=SUMS1/8.0
      W031=SUMS2/2.0
      W222=SUMS3/2.0
      WRITE (3,70) J,D(2),Z,W,HBA,W040,W031,W222
   70 FORMAT (10X,7H     J =,I2/10X,7HD(2)  =,F14.6,
     *10X,7H     Z =,F20.6,4X,7H     W =,F14.10,
     *10X,7HHBA   =,F14.10/10X,7HW040  =,F14.10,
     *10X,7HW031  =,F14.10,10X,7HW222  =,F14.10///)
  400 CONTINUE
      STOP
      END
*DATA
1.0           1.54082       1.0           1.54082       1.0
0.0           -0.0568936630 0.0568938890  0.0
2.5           0.0           2.5           0.0
32.5          0.0           2.5
```