REVISED CSO OPTICS MEMO #4 **Oct 17, 1995**

CASSEGRAIN RELAY OPTICS FOR THE CSO CHOPPING SECONDARY

Updates

The relay optics are now in place, and the dewar mounting interface is slightly different from the original plan described in the earlier versions of this memo, both insofar as measurements have accurately determined the true location of the mounting plate relative to the optics, and also in that it has been decided that each observer will provide a mounting plate specific to his/her own instrument, which will attach directly to the inner half of the rotation stage bearing. Fig. 0 is now included in the following revised memo to delineate a MINIMUM thickness mounting plate, which will leave the final focus 7.6 inches above the mounting plate, as before. Other than this one aspect, and a few clarifications, the bulk of the memo is unchanged.

The size of the mounting plate's central hole (for the light!) is up to the individual investigator, but should not exceed a diameter of 8 inches. Small extensions ($\leq$ 1 inch) below the level of the mounting plate may clear the optics, but come with no guarantees.

The Relay Optics

The relay optics are designed to allow two dewars to be mounted simultaneously near the Cassegrain focus. To accomplish this, the relay optics will take the F/12.4 radiation from the Cassegrain focus and send it to one of two identical F/4.48 foci, by means of flat steering mirrors and two identical ellipsoidal mirrors. The particular focus in use will be selected via a turntable-mounted mirror. In short, the F/4.48 foci will be 7.965 inches above the surface of the rotation stage bearings, or 7.6 inches above the mounting plate described in Fig. 0. An image of the primary will also be located 5.6 inches before the focus, or 2 inches above the mounting plate. The focal plane plate scale is 4.6 arc seconds per mm.

These relayed foci will be easily accessible, and upward pointing. All dewars will need to be downward looking, with entrance windows on the dewar symmetry axes. Dewars can be filled with cryogens, and their liquid He pumped on, while mounted on the relay optics assembly.

The two output foci are symmetrically placed with respect to the telescope's symmetry plane (through the midpoint of the telecope's elevation axis). There being only 44 inches available between the elevation axis bearings, the two foci are located 11 inches to either side of this symmetry plane. This allows for a space of 22 inch width ('width' being along the elevation axis) for each of two dewars. DEWARS THUS CANNOT EXCEED 22 INCHES IN WIDTH. Dewars of this size can be up to 48 inches high.

An instrument rotater will be provided, to allow dewars to be rotated about their axes. If rotation of a particular dewar is NOT planned, then gadgets can extend further than 11 inches from the dewar axis, but only along the direction perpendicular to the elevation axis. If however, one plans to rotate a given dewar with the instrument rotater, then to avoid crashing electronics boxes into the telescope structure or other dewars, electronics boxes and cable connectors must also fall within 11 inches of the dewar axis. Thus, THE RADIUS, INCLUDING ALL ELECTRONICS BOXES, OF ANY DEWAR WHICH WILL BE ROTATED ON THE INSTRUMENT ROTATER CANNOT EXCEED 11 INCHES. As the rotation stage will be operating largely out of sight under computer control, and another dewar will usually be mounted on the other optical port, for safety reasons one should not plan on exceeding this 11 inch limit in some direction, under the assumption that only small rotation angles will be used.

Optical System

Figs. 1 and 2 provide 3-dimensional views of one half of the symmetric optical system. The first mirror after the secondary, M3, is mounted on a turntable, and serves to pick one of the two foci. All subsequent optics come in two identical sets, so it is only necessary to discuss one of the sets in the following. Figures 3 and 4 provide 2-dimensional side-views of the optics in more detail; however, keep in mind that M4 and M5 are not in the midplane of the telescope.

To locate and describe the mirrors more fully, consider the telescope at zenith, so that the light reaching the Cassegrain focus is travelling vertically downward. A coordinate system can then be set up which has the positive z-axis pointing downward, along the direction of the incident light, the x-axis along the telescope's elevation axis, (pointing toward the compressor side), and the y-axis pointing toward the control room. The zero of coordinates is taken at the intersection of the telescope and elevation axes, and all distances in the following are given in mm. For example, the Cassegrain focus is then located at (x,y,z) = (0,0,863.6). The coordinates of all mirror centers are given in this system in Table 1.

The first mirror after the secondary, M3, will be a square, 12 × 12 inch, flat mirror located along the telescope axis 431.8 mm (17 inches) beyond the Cassegrain focus. It will be oriented so that the reexpanding F/12.4 cone of radiation is deflected by 136°from the incident direction. M3 thus has a normal tipped by 22°from the vertical, and sits on a vertical rotation stage. Two fixed stops will be used to rotate by ± 24.6273°about the z axis, to select either of the two foci.

After reflection, the ray bundle proceeds upward at an angle of 44°to the -z axis, with y component mainly towards the control room, but skewed slightly off to the side, so that in propagating 38 inches (965.2 mm), the chief ray from an on-axis object arrives exactly 11 inches to the side of the telescope symmetry plane. A second flat mirror, M4 (square, of size 14 × 14 inches), is centered at this point, $[(x, y, z) = (-279.400, 609.496, 601.093)]$, and oriented so that the chief ray, after reflection, emerges parallel to the -y axis (i.e., directly away from the control room). The required mirror normal (out the back of the mirror) is given by the angles it makes with the three coordinate axes, $(\theta_x, \theta_y, \theta_z) =$ (99.2215°,25.4206°,113.4673°). M4 thus has the effect of redirecting the chief ray into a plane parallel to the y-z plane, the x=-279.4 mm plane (or x = -11 inch plane). All subsequent optics are in this plane (with an identical second set in the x = +279.4 plane).

After another 16 inches (406.4 mm) of travel, the light hits an off-axis ellipsoid, M5, where the chief ray is bent by 37°(angle measured within the x = -11 inch plane). The centerpoint of this ellipsoid is in the displaced y-z plane, and the coordinates of its center are (-279.4,203.096,601.093). Along the chief ray, its two focal lengths are 3500 mm and 547.508 mm. These lengths do not correspond to the object and image distances, as the Cassegrain focus is located 71 inches (1803.4 mm) before the center of the ellipse, while the final F/4.48 relayed focus is 641.987 mm (25.275 inches) beyond the ellipse, at (-279.4,715.810,214.736). The true vertex of the ellipse (Fig. 5) is located 43.513 mm behind the mirror center (along the y-axis), and 381.221 mm above it (along the z-axis), or at (-279.4,159.583,219.872). The ellipsoidal mirror is an 14″ × 15″ rectangular section, and its parameters are listed more fully in Table 2.

The ellipse also forms an image of the primary 5.6 inches before the F/4.48 focus (Fig. 6). The diameter of the image is 32mm. Since it may be desirable to have this primary image inside the dewar by up to 2 inches, the nominal dewar mounting surface will be located 7.6 inches before the final focus (Figs. 3 & 4), if the mounting plate is constructed as per Fig. 0. Dewars not making use of this primary image can be mounted further back, with a suitably modified mounting assembly.

Image Quality

Imaging was considered for the shortest wavelength, $\lambda = 0.35$ mm, for which good imaging (Strehl ratio, $S \gtrsim 0.9$) over a square 2 arc minute FOV was desired. An unobstructed FOV of 3 arc minutes at all wavelengths was also specified. As seen in Fig. 6, the best focal distance really depends on lateral position in the image plane, but as the depth of focus is large ($F^2\lambda > 7$ mm), this does affect the Strehl ratios much.

The results of the Code V calculations are shown in Fig. 7. This figure shows the Strehl ratio as a function of position in the field (the various curves) and secondary chopper throw (abscissa) for a hypothetical 2 arcmin square array. The Strehl ratio for the central pixel is shown by the solid curve, by the dashed curves for the two pixels at the end of the axis in the FOV perpendicular to the chop throw, by the dotted curves for the two pixels at the end of the axis parallel to the chop throw, and by the dash-dotted curves for the four corner pixels. For ease in deciphering, the top panel omits the corner pixels of the array.

With no chopping (array centered on both the secondary and ellipse axes), there is a degradation of Strehl ratio from 1 at the center of the square FOV, to 0.92 at the axial edges, to 0.88 at the worst corner (1.4 arcmin from the axis), because the light which reaches the edges of the array must traverse the ellipse M5 off-axis. Including also the secondary chop, the performance of the central pixel is seen to be determined entirely by chopping secondary aberrations (see memo no. 1). Off the center of the FOV, the 2 arc minute long axis perpendicular to the chop direction has excellent imaging, with $S > 0.9$ out to a ± 4 arc minute chop (dashed curves). Furthermore, the entire 2 arc minute FOV has $S > 0.87$ for chop angles smaller than ± 2 arc minutes.

Finally, by virtue of leaving the telescope's plane of symmetry, the field of view is rotated relative to a fixed z-axis by about 14°. The direction is marked near the top surface of the rotation bearing. Since this is a fixed rotation, it can be accounted for with the instrument rotater.

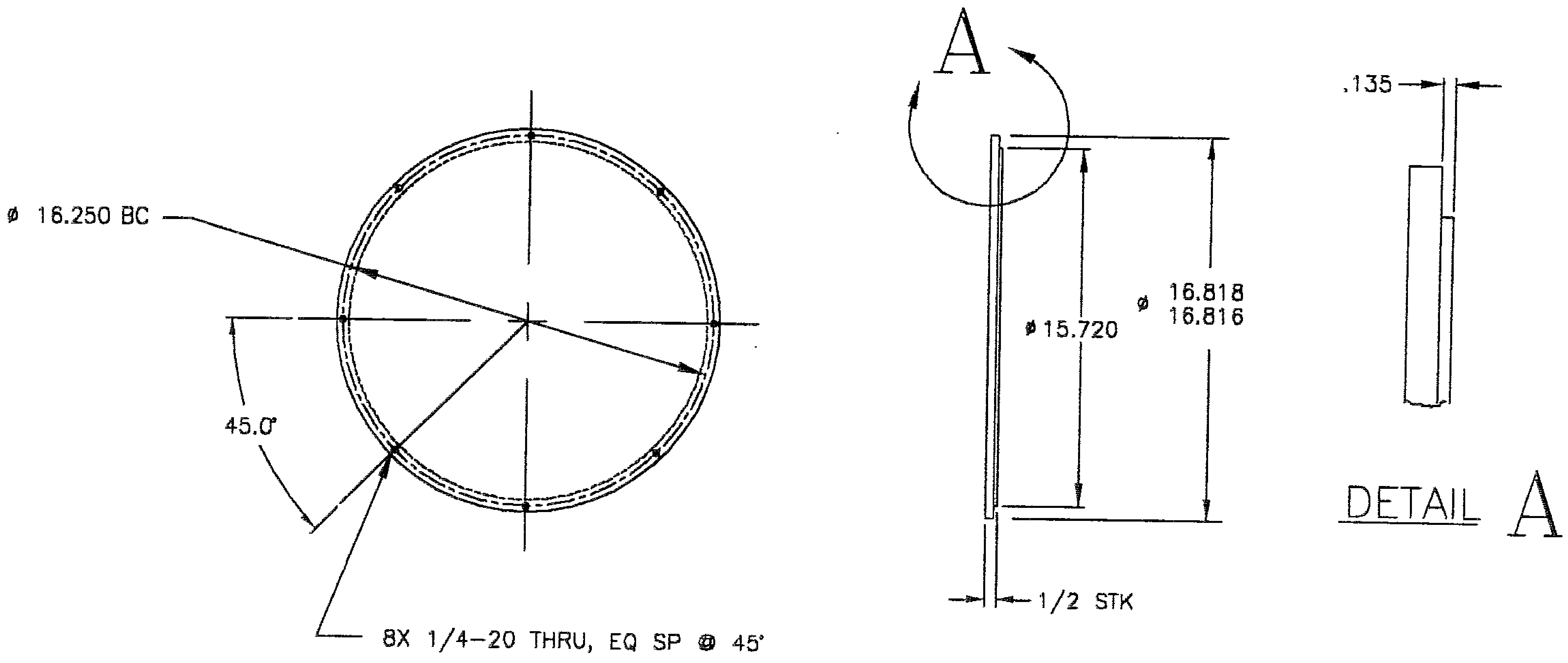
```
File: RELAY_OPTICS.RSI: coordinates along chief ray (zero at elevation axis)
Note: flip signs on x,y for description

CODE V> tit?
     Final relay optics: angles 44 and 37 degrees

CODE V> glo s3

CODE V> rsi 0 0 0 0
```

TABLE I

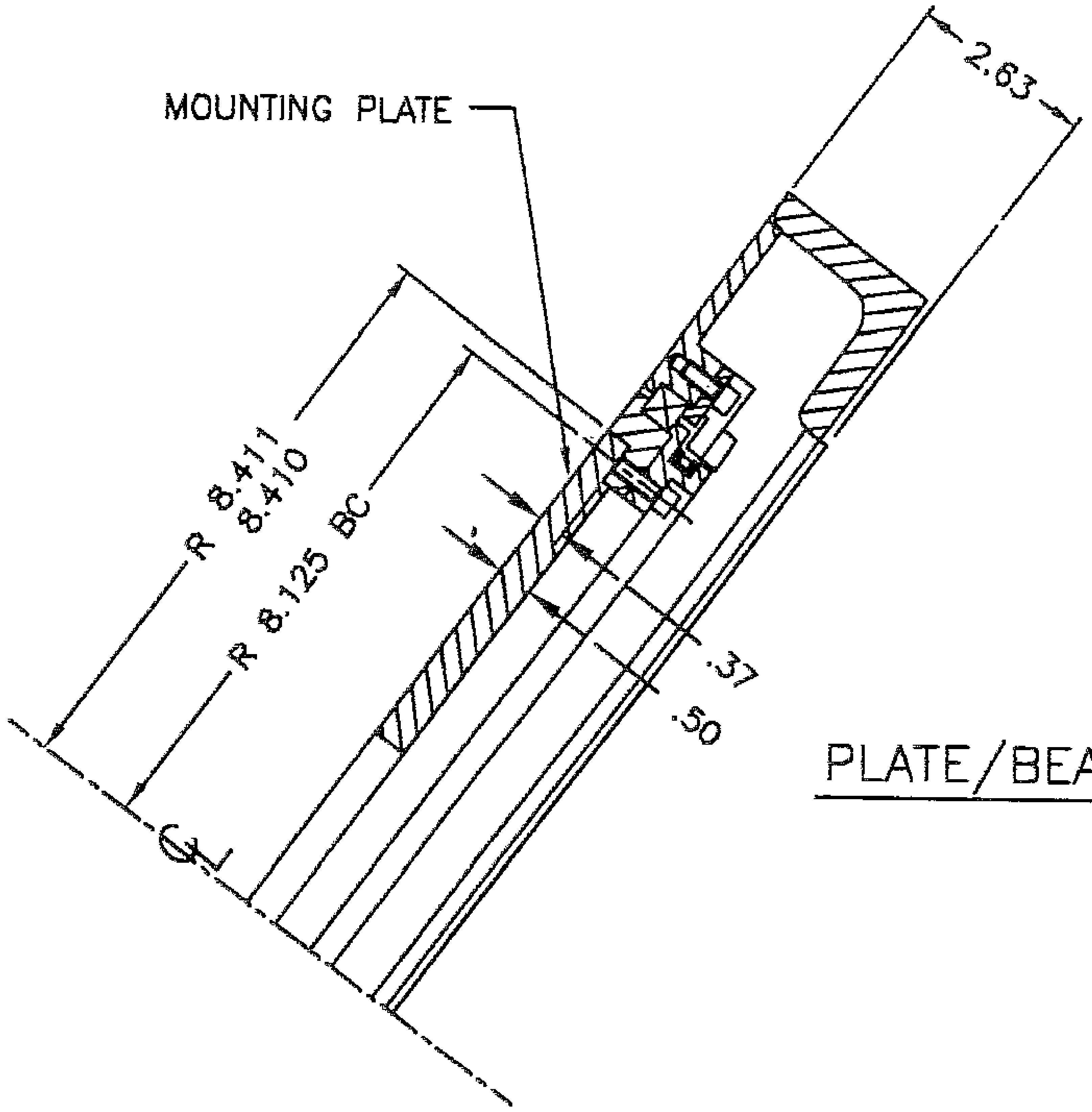
```
     Final relay optics: angles 44 and 37 degrees
     Position  1, Wavelength = ******* NM
     Global coordinates with respect to surface   3
               X            Y            Z            TANX         TANY         LENGTH
 OBJ       0.00000      0.00000    -0.100E+13      0.00000      0.00000
   1 O     0.00000      0.00000  -2328.14180      0.00000      0.00000      0.00000
 STO       0.00000      0.00000  -6217.57850      0.00000      0.00000   3889.43670
elevation axis:
   3       0.00000      0.00000      0.00000      0.00000      0.00000   6217.57850
   4       0.00000      0.00000    339.85200      0.00000      0.00000    339.85200
Cassegrain focus:
   5       0.00000      0.00000    863.60000      0.00000      0.00000    523.74800
   6       0.00000      0.00000   1295.40000      0.00000      0.00000    431.80000
M3:
   7       0.00000      0.00000   1295.40000     -0.40242      0.87785      0.00000
   8     279.39998   -609.49552    601.09322     -0.40242      0.87785    965.20000
M4:
   9     279.39998   -609.49552    601.09322      0.69577    999.00000      0.00000
  10     279.39999   -203.09552    601.09325      0.69577    999.00000    406.40000
M5: (ellipse)
  11     279.39999   -203.09589    601.09325      0.00000      1.32705     -0.00037
  12     279.39999   -358.56889    483.93606      0.00000      1.32705    194.67321
  13     279.39999   -358.56889    483.93606      0.00000      1.32705      0.00000
 IMG     279.39999   -715.80987    214.73596      0.00000      1.32705    447.31400
                          OPD =     0.000 Waves
```

TABLE 2

```
     ! FILE RELAY_INPUT.SEQ  (output of RELAY.FOR to input to Code V)
     !
     ! Deflection angle at flat tertiary m3=   44.0 DEG
3    ! Mirror M3 is tipped from z axis by         22.0 deg
     ! and rotated about z axis by    24.627283 degrees
     ! Distance between centers of m3 & m4 =  965.200 MM
     ! For the M4 toward the sidecab side of the telescope:
     ! M4 normal at following angles to x,y,z axes  99.22154  25.42064 113.46732
M4   ! M4 normal x,y,z direction cosines:  -0.1602524   0.9031807  -0.3982258
     ! Normal is out the back of the mirror, in coord. sys.
     ! with z down, y to control room, & x to compressors
     !
      WL  350000.00
      XAN   0.0000  0.0167  0.0167  0.0167  0.0000 -0.0167 -0.0167 -0.0167  0.0000
      YAN   0.0000  0.0167  0.0000 -0.0167 -0.0167 -0.0167  0.0000  0.0167  0.0167
      CDE  s6      24.627283
      THI  s7       -965.200
      ADE  s7      22.000000
      CDE  s8     -32.508041
      ADE  s9      25.420643
      CDE s10      21.920631
     ! ELLIPSE: CHIEF RAY BEND =  37.0 DEGREES
     !          L1            L2      FNUM IN    FNUM OUT
     !    1803.400     641.987      12.360       4.400
     ! TOTAL THICKNESS |S5| + |S7| + |S9| =    1803.400
     !          A+C           A-C     EPSILON  VERT.RAD.CURV.
     !     3563.961     483.547   0.7610643      -851.5574951
M5   ! INPUT SIDE FOCAL LEN  3500.000  OUTPUT SIDE   547.508
     ! VERTEX LOCATION WITH RESPECT TO MIRROR CENTER:
     !     43.513 MM BEHIND THE MIRROR CENTER IN Y, AND
     !    381.221 MM ABOVE IN Z
     ! ANGLE: INCOMING RAY TO ELLIPSE AXIS     6.140 DEG
     ! ANGLE: MIRROR NORMAL TO ELLIPSE AXIS    24.640 DEG   —   cos gives size correcti
      THI S5     431.800
      THI S7    -965.200
      THI S9     406.400
      THI S10      43.513
      RDY S11    -851.557
      K   S11 -0.57921886
      YDE S11     381.221
      ADE S11    6.140429
      ADY S11 EDG    -374.380
      ADE S12  -43.140430
      THI S13    -447.314
      YDE S13    -330.644
```

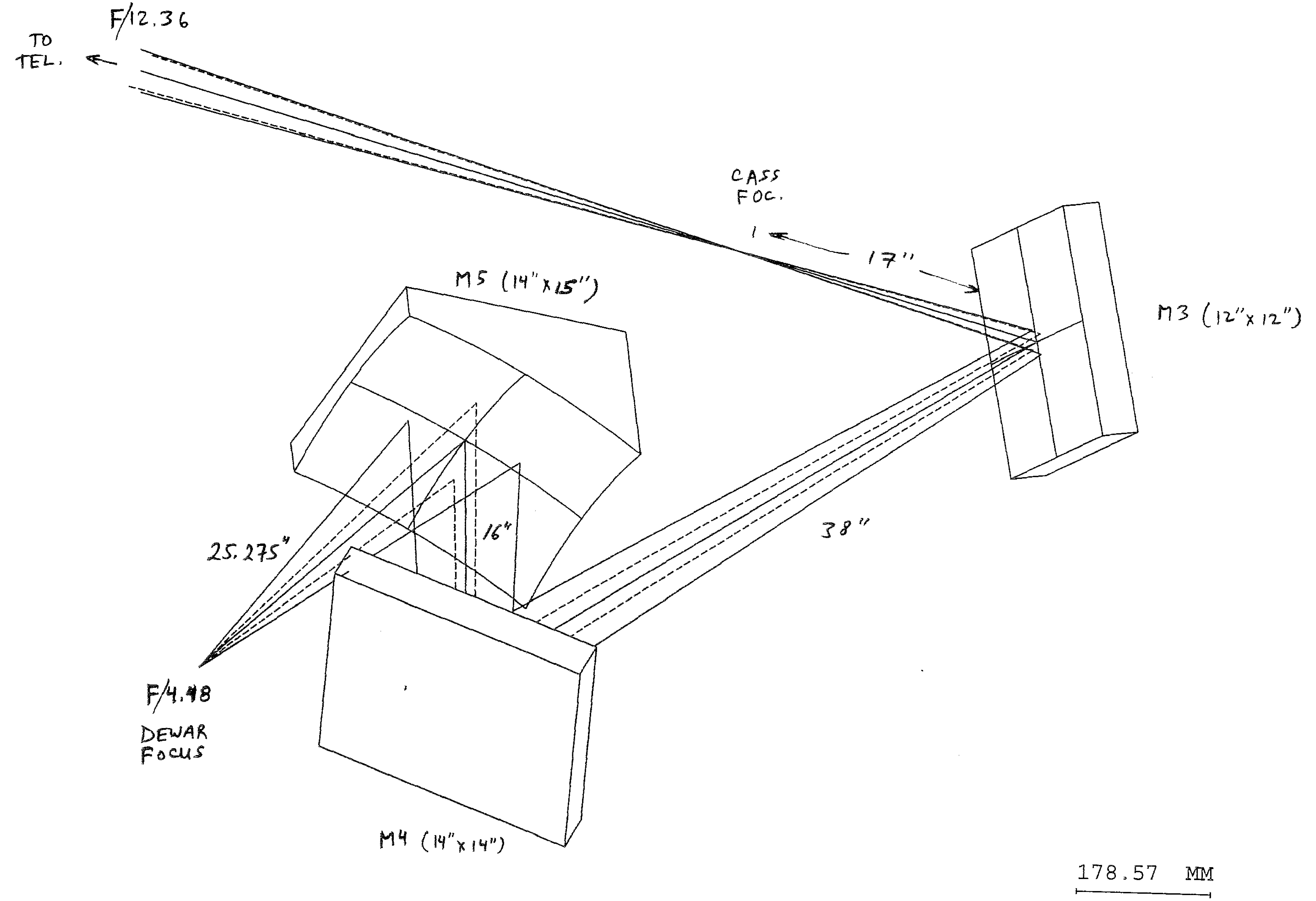


MOUNTING PLATE



PLATE/BEARING ASSEMBLY

3

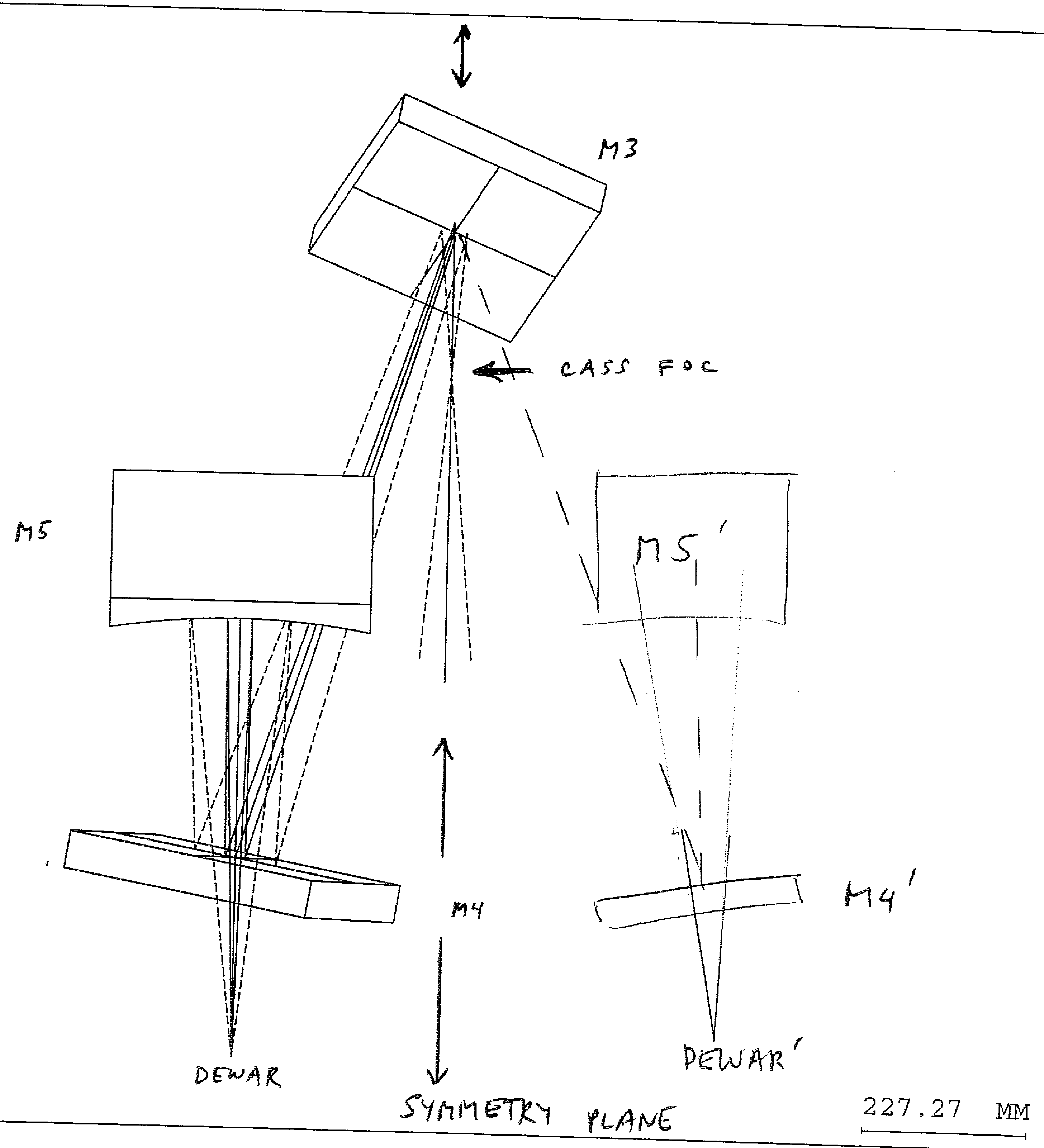


Relay optics with angles 44 and 37

Scale: 0.14

25-FEB-94

SIDE VIEW

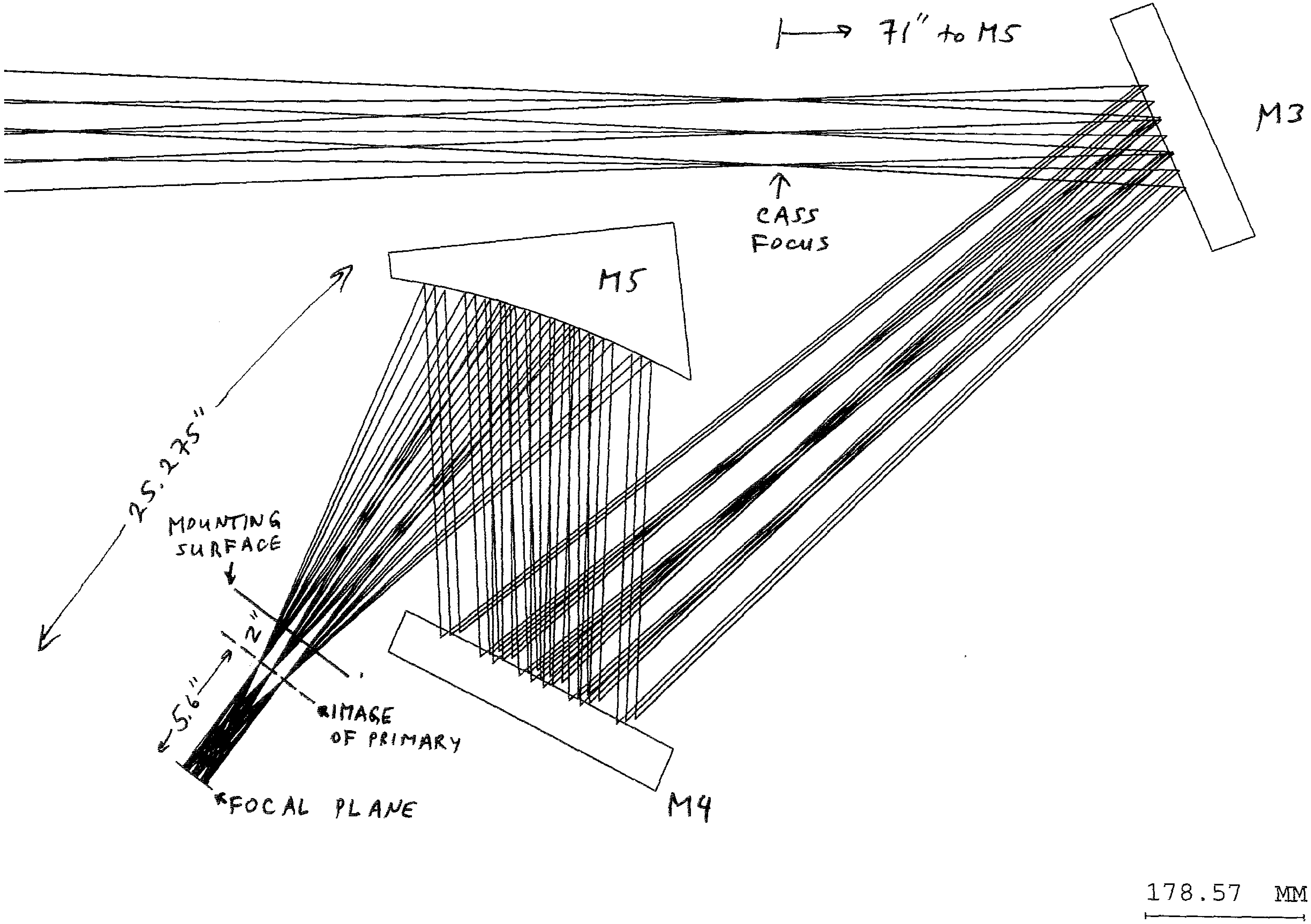


Relay optics with angles 44 and 37

Scale: 0.11

25-FEB-94

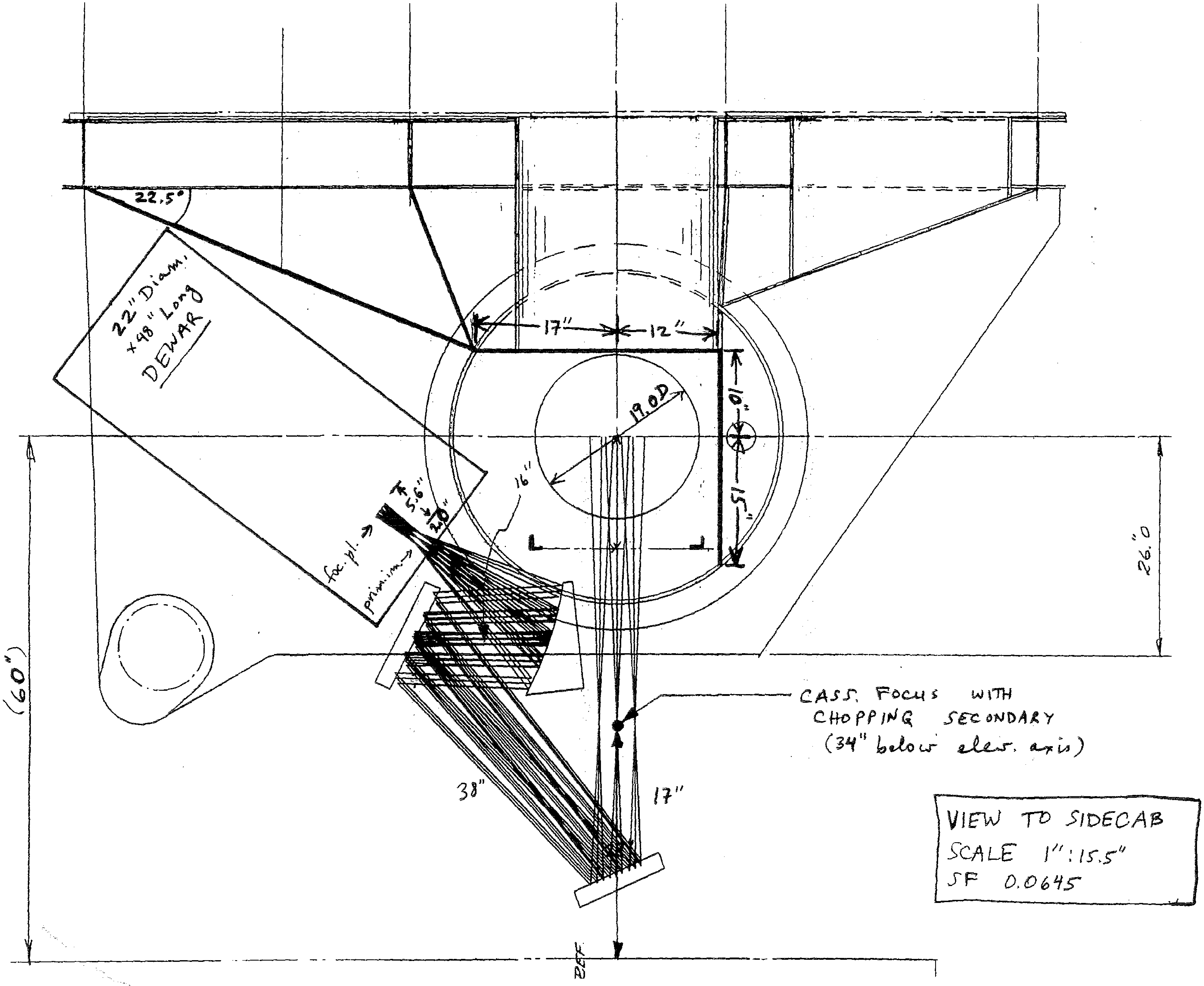
TOP VIEW



Final relay optics: angles 44 and 37 deg Scale: 0.14 25-FEB-94

SIDE VIEW

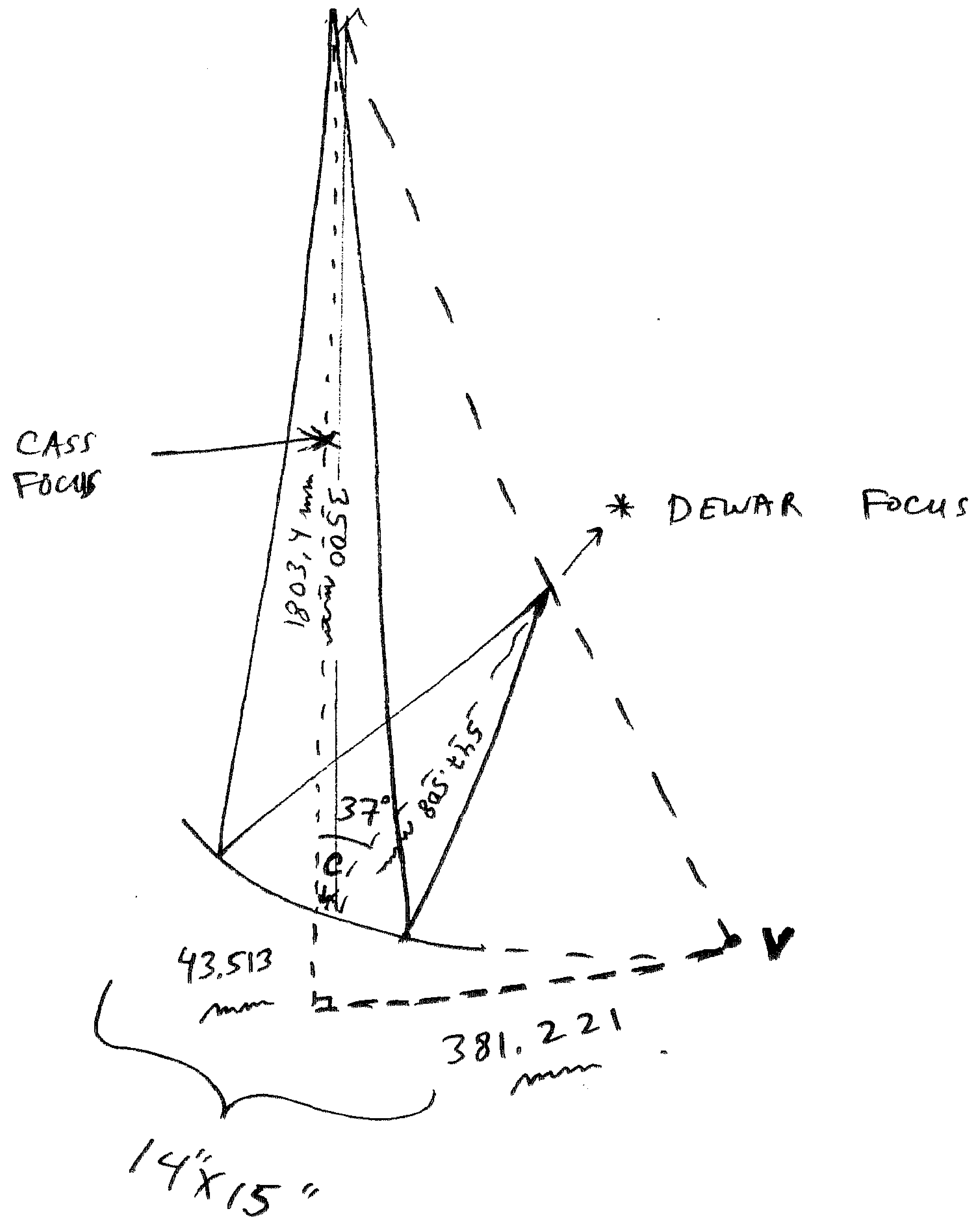
FOV = 2'



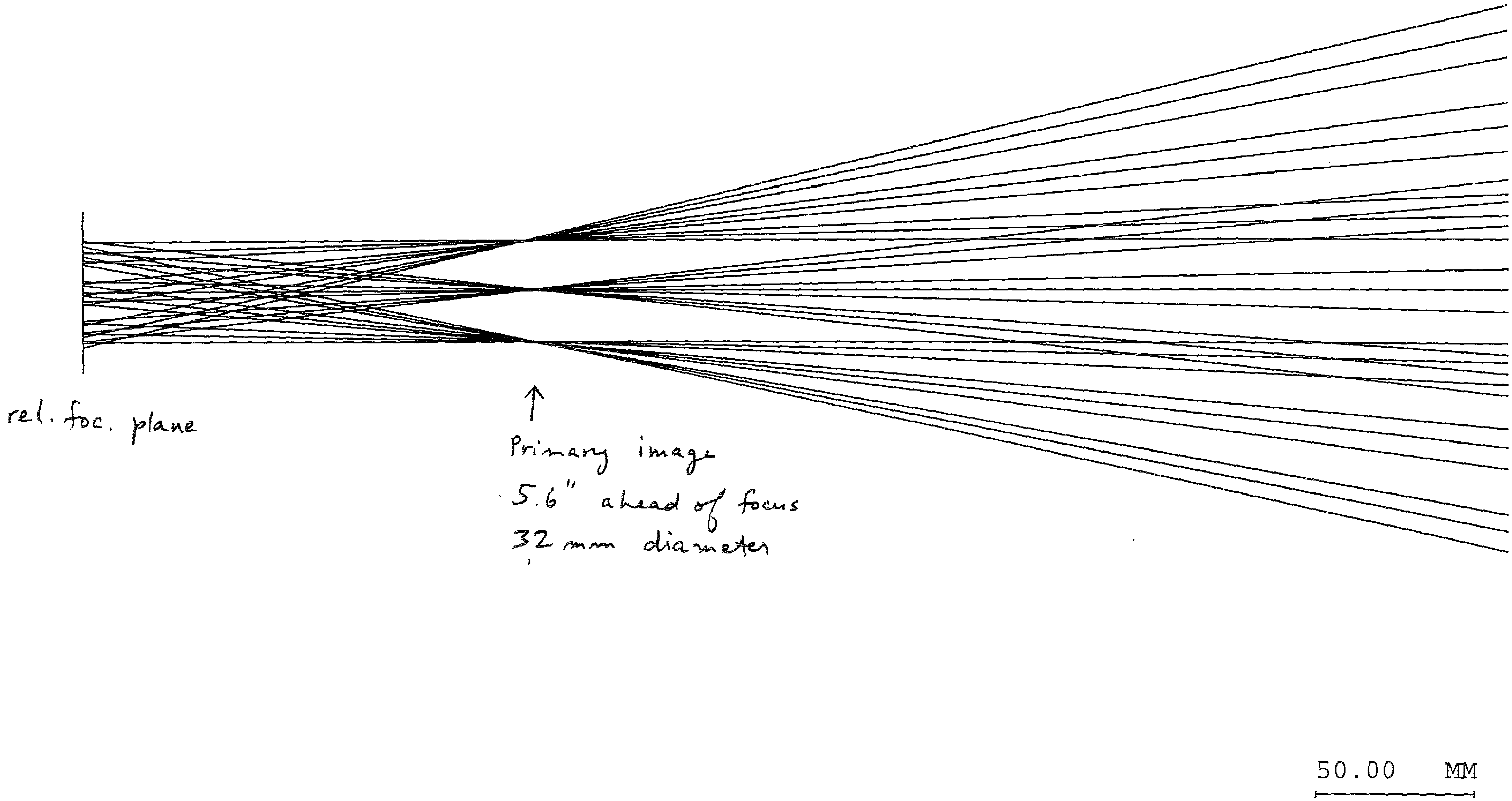
VIEW TO SIDECAB
SCALE 1":15.5"
SF 0.0645

Ellipse M5:

see table 2, M5

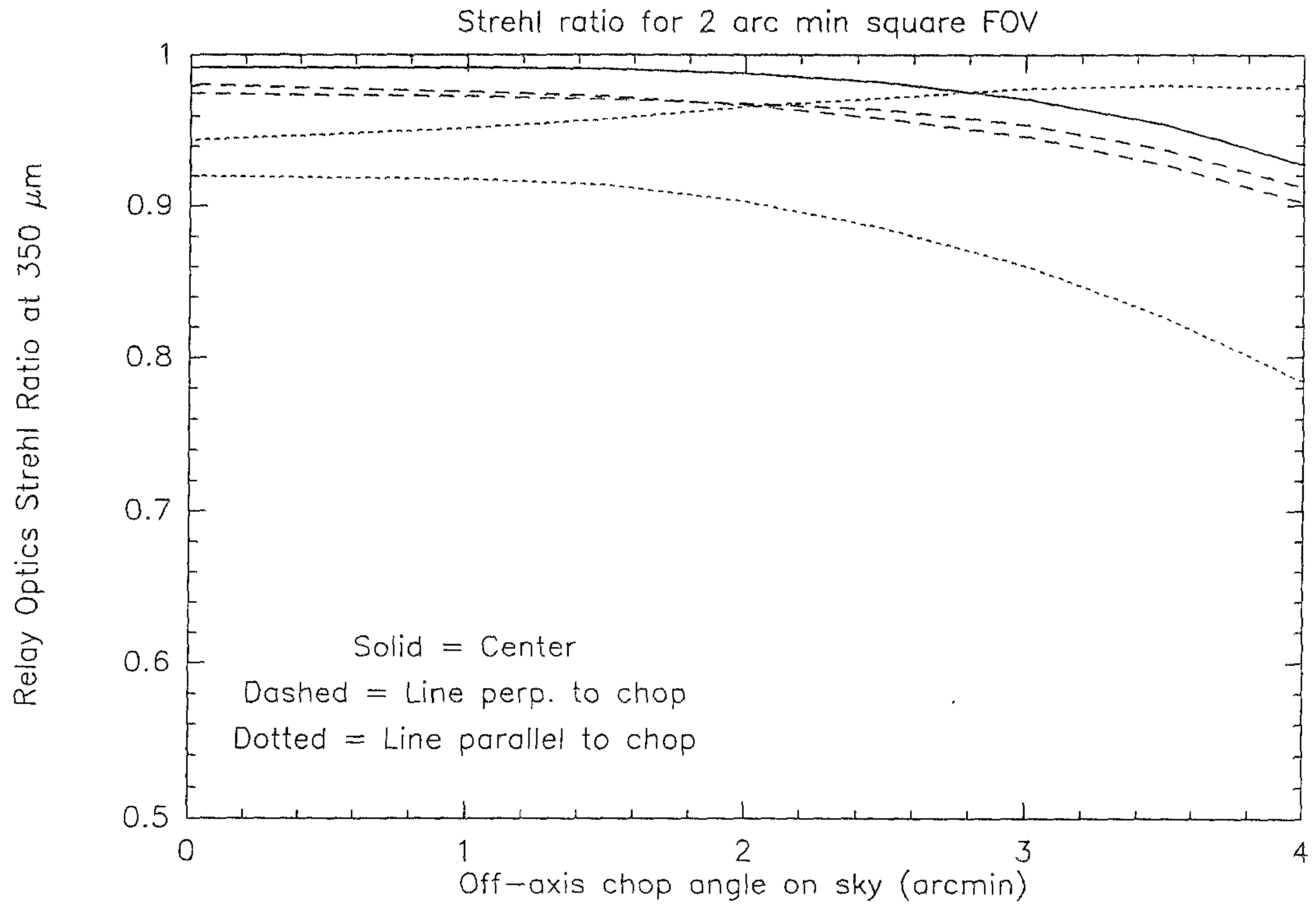


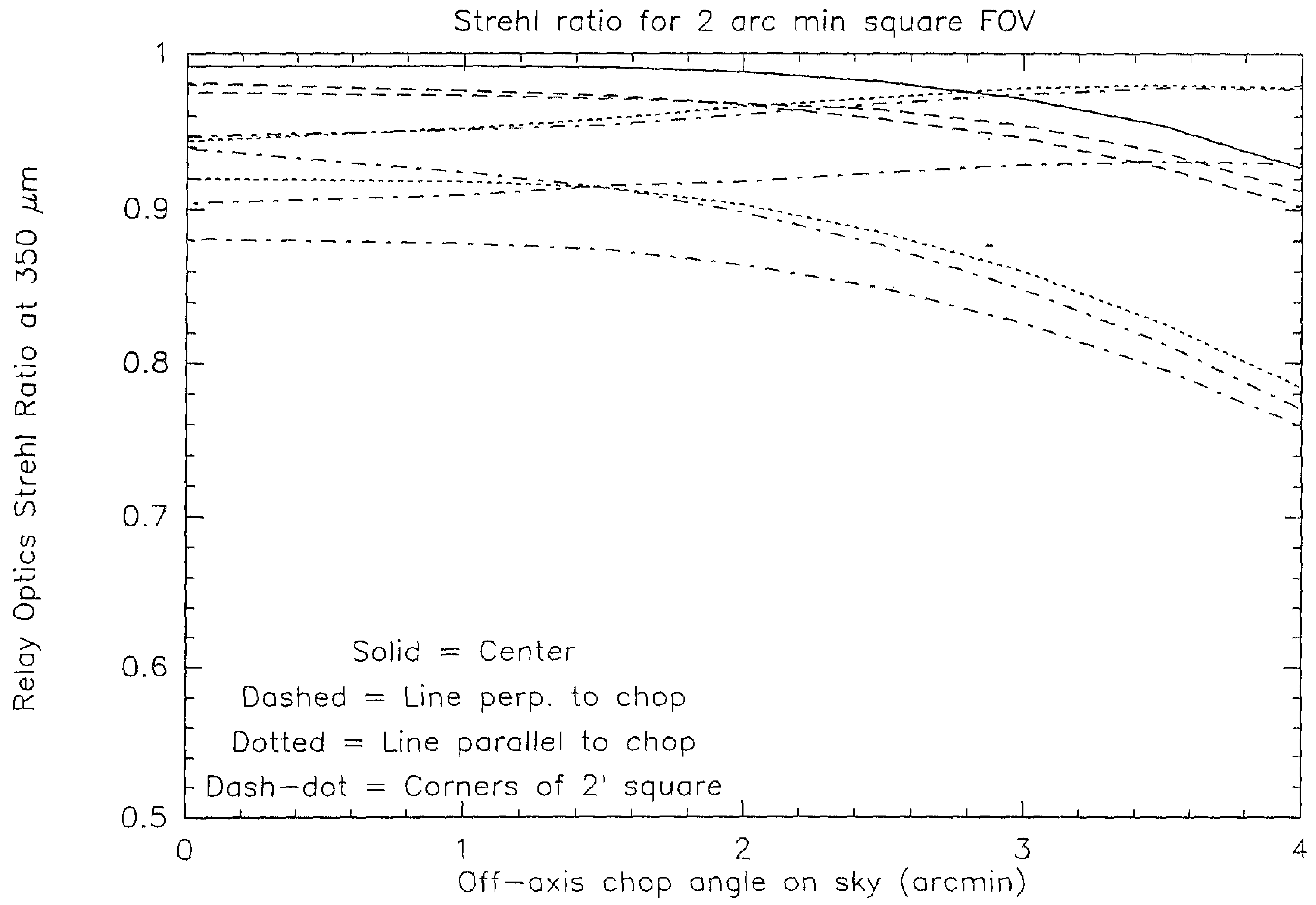
10:27:01 GS



Final relay optics: angles 44 and 37 deg

25-FEB-94


Strehl ratio for 2 arc min square FOV
Relay Optics Strehl Ratio at 350 μm
1
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
Off−axis chop angle on sky (arcmin)
Solid = Center
Dashed = Line perp. to chop
Dotted = Line parallel to chop


Strehl ratio for 2 arc min square FOV
Relay Optics Strehl Ratio at 350 μm
1
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
Off−axis chop angle on sky (arcmin)
Solid = Center
Dashed = Line perp. to chop
Dotted = Line parallel to chop
Dash−dot = Corners of 2' square