ENEE 408E Optical System Design

Design Projects #3, 10/7/03

Due 10/16/03

You would be well advised to go through the Code V Test Drive before completing these design projects.

For Code V problems provide the lens table, 2-D views of the lenses, spot diagrams, and MTF.

(1) A thick lens with $n = 1.5$ has $R_1 = 100mm, R_2 = -120mm$ with $d = 25mm$. Calculate the position of the principal planes and the focal length of the lens. Compare your paraxial calculations with the results from Code V. Use Code V to provide a plot of your final layout showing rays going through the focal point.

(2) Use Code V to calculate the amount of spherical aberration that results for the extreme rays traveling parallel to the axis, when the aperture (diameter) of the lens is 50mm. These are the rays that pass through the lens at the greatest distance from the axis. The magnitude of the spherical aberration is the diameter of the circle in the paraxial focal plane through which all rays pass.

(3) Design a biconvex lens with $R_1 = R_2$ and a focal length of 300mm using LAK8 glass. Do this both analytically and by using Code V. Code V can optimize the lens thickness. Choose the lens parameters so that the f/number of the lens is 4.

(4) Repeat question (3) but make the lens a plano-convex one.

(5) Repeat question (3) but optimize both surfaces of the lens for minimum aberration (sharpest image).

(6) Compare the spherical aberration for the extreme rays and the different lenses designed in questions (3), (4), and (5).

(7) Use Code V to design an achromatic doublet for wavelengths of 450nm and 650nm. Make the lens an f/4 lens with a focal length of 100mm.

(8) For each of the following imaging situations calculate:
(a) the position of the image
(b) whether the image is real or virtual
(c) linear and angular magnification
(d) draw a ray tracing diagram

(i) f=2; u=3
(ii) f=-2; u=3
(iii) f=2; u=1.5
(iv) f=-3; u=2
(v) a concave mirror with R=5; u=8
(vi) a concave mirror with R=5; u=3
(vii) a convex mirror with |R|=5; u=3

DO NOT USE CODE V FOR THIS PROBLEM.

ENEE 408E
Design Projects #3

(1) $n := 1.5$ $R1 := 0.1$ $R2 := -0.12$

$$D1 := \frac{(n-1)}{R1} \qquad D2 := \frac{1-n}{R2}$$

$D1 = 5$ $D2 = 4.166667$

$d := 0.025$

$$h1 := \frac{d}{n\cdot\left(1 + \frac{D1}{D2} - d\cdot\frac{D1}{n}\right)}$$

$h1 = 7.874016 \times 10^{-3}$ 7.87mm

$$h2 := \frac{d}{n\cdot\left(1 + \frac{D2}{D1} - d\cdot\frac{D2}{n}\right)}$$

$h2 = 9.448819 \times 10^{-3}$ 9.45mm

$$f := \left(D1 + D2 - \frac{d\cdot D1\cdot D2}{n}\right)^{-1}$$

$f = 0.113386$ 113mm

$FFL := f - h1$ $BFL := f - h2$

$FFL = 0.105512$ $BFL = 0.103937$

Note that CodeV gives EFL=113.3858mm, FFL=103.937mm BFL=103.937mm, which all agree with the calculation here

(2) Results from Radial Energy Analysis

Percentage	Diameter
10	0.08259
20	0.31435
30	0.57828
40	0.96713
50	1.26685
60	1.68509
70	2.24947
80	2.55699
90	3.34031
100	3.70443

Note that maximum spherical aberration is 3.70443mm. You can get the same result from a ray aberration plot

(3) For LAK8

$n := 1.713$ $d := 25\cdot 10^{-3}$ Chosen thickness $f := 300$

$$f = \left(2\cdot D - \frac{d\cdot D^2}{n}\right)^{-1}$$ f for a symmetrical biconvex lens

$$\begin{bmatrix} \frac{1}{(2\cdot f\cdot d)}\cdot\left[2\cdot f\cdot n + 2\cdot\left(f^2\cdot n^2 - f\cdot d\cdot n\right)^{\left(\frac{1}{2}\right)}\right] \\ \frac{1}{(2\cdot f\cdot d)}\cdot\left[2\cdot f\cdot n - 2\cdot\left(f^2\cdot n^2 - f\cdot d\cdot n\right)^{\left(\frac{1}{2}\right)}\right] \end{bmatrix}$$ Symbolic solution for D for a symmetrical bicoonvex lens

$$D := \frac{1}{(2\cdot f\cdot d)}\cdot\left[2\cdot f\cdot n + 2\cdot\left(f^2\cdot n^2 - f\cdot d\cdot n\right)^{\left(\frac{1}{2}\right)}\right]$$ Solutions for D

$$D := \frac{1}{(2\cdot f\cdot d)}\cdot\left[2\cdot f\cdot n - 2\cdot\left(f^2\cdot n^2 - f\cdot d\cdot n\right)^{\left(\frac{1}{2}\right)}\right]$$

$D = 1.666687 \times 10^{-3}$

$R := \frac{n-1}{D}$

$R = 427.794797$ This is the value to start with in CodeV

The Code V optimization gives R=419.3mm, and changes the thickness

Spherical aberration diameter is 0.68714mm after best focus

(4) For a plano convex lens D2=0 $f := 300\cdot 10^{-3}$

$f = (D1)^{-1}$

$D1 := \frac{1}{f}$

$D1 = 3.333333$

$R := \frac{n-1}{D1}$

$R = 0.2139$ This is the value to start with in Code V

Spherical aberration diameter is 0.37139 after best focus

(5) After optimization, including best focus

Spherical aberration diameter is 0.35965 mm

The answer to this question is quite sensitive to where you start in the optimization process. I found that you could optimize better by fixing the thickness. Note that this optimized lens is close to plano-convex.

(6) See answers to (3) (4) and (5) above

(7) Maximum aberration diameter is 0.01078mm

Singlet lens for 408E 0331

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	100	
> STO:	100.00000	25.000000		500000.000001	100	100	100
2:	-120.00000	103.937008			100	PIM	
IMG:	INFINITY	0.000000			100	100	

SPECIFICATION DATA

EPD	20.00000
DIM	IN
WL	587.56
REF	1
WTW	1
XAN	0.00000
YAN	0.00000
WTF	1.00000
VUY	0.00000
VLY	0.00000

REFRACTIVE INDICES

GLASS CODE	587.56
500000.000001	1.500000

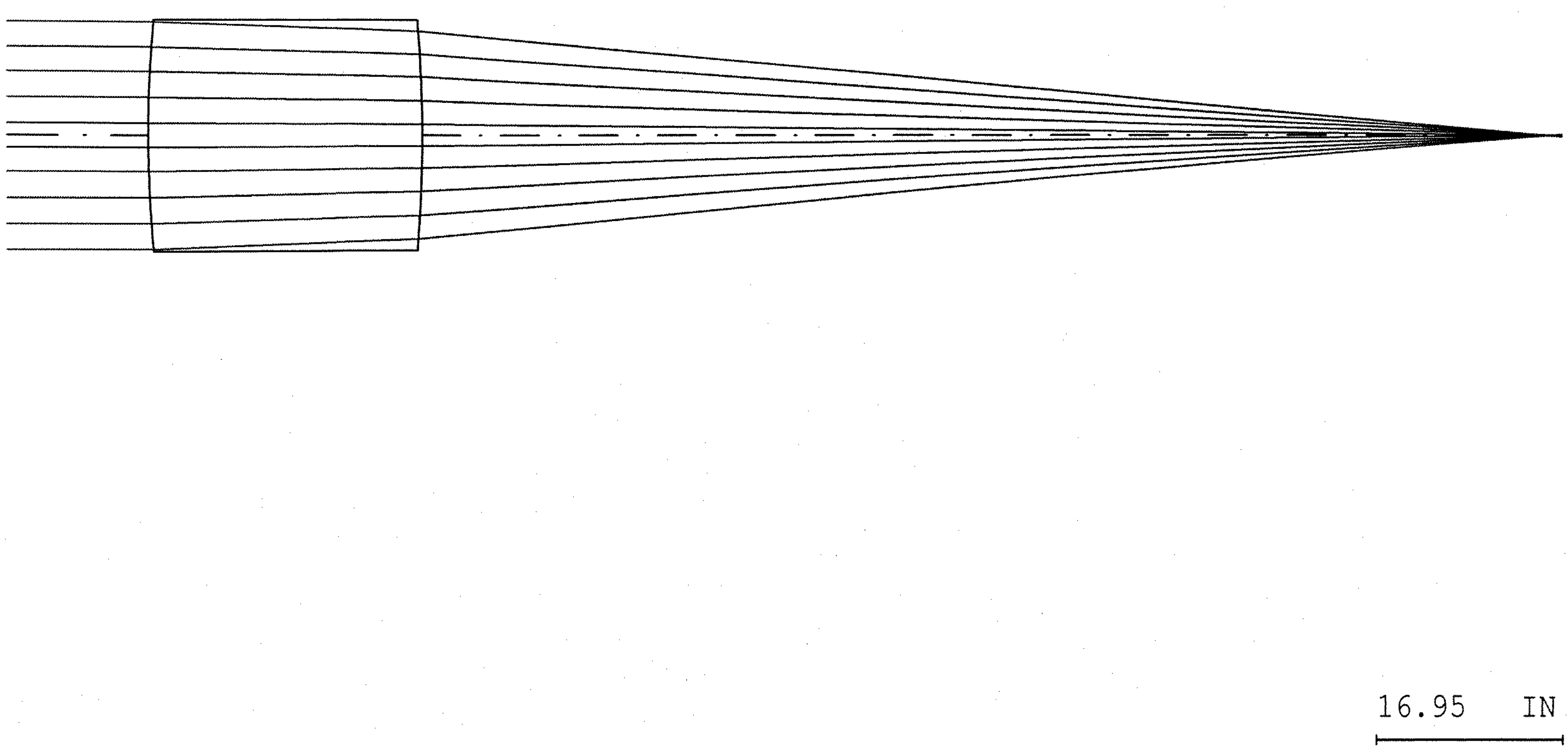
SOLVES
PIM

No pickups defined in system

INFINITE CONJUGATES

EFL	113.3858
BFL	103.9370
FFL	-105.5118
FNO	5.6693
IMG DIS	103.9370
OAL	25.0000
PARAXIAL IMAGE	
HT	0.0000
ANG	0.0000
ENTRANCE PUPIL	
DIA	20.0000
THI	0.0000
EXIT PUPIL	
DIA	21.4925
THI	-17.9104

16:17:37

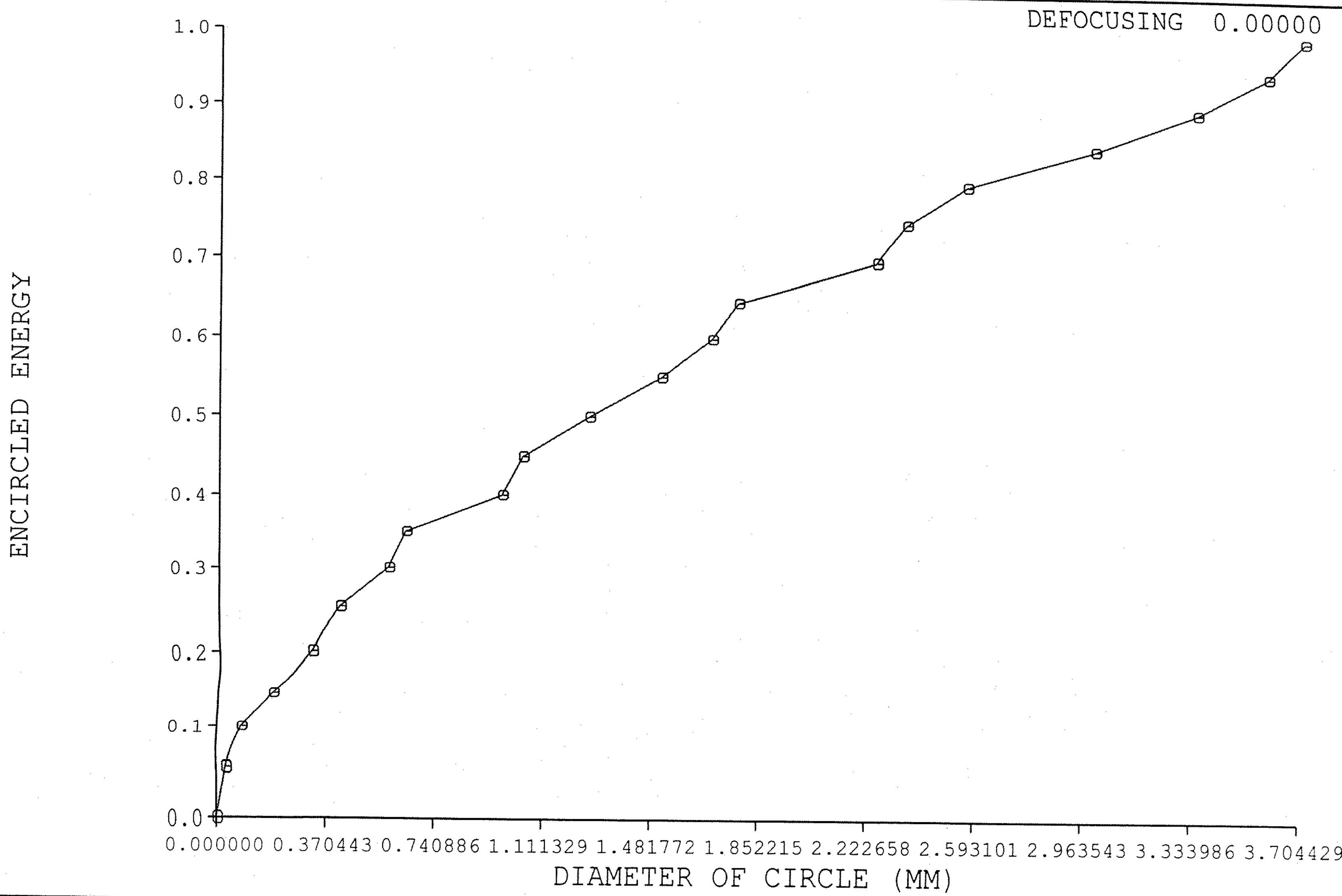


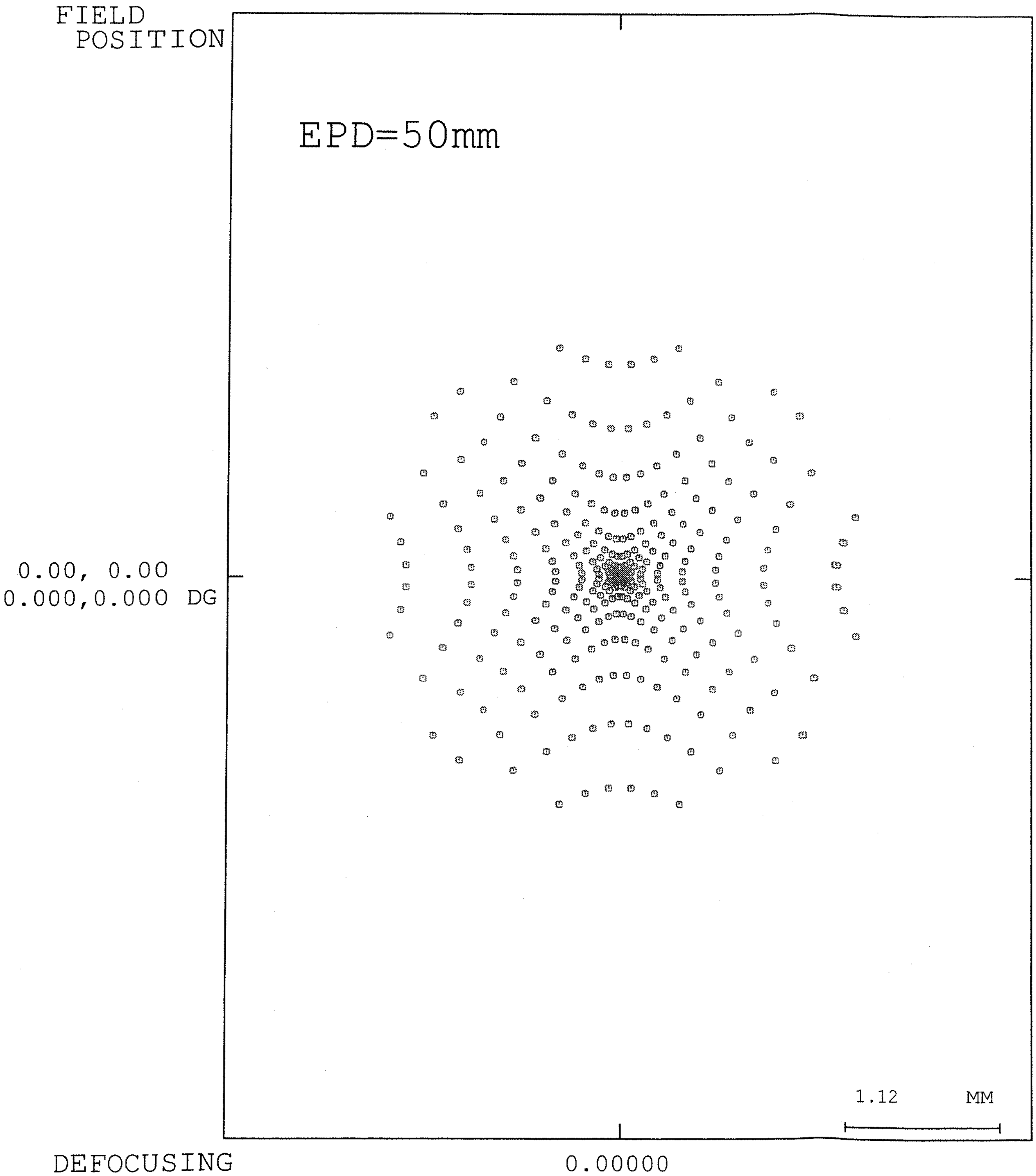
Singlet lens for 408E 0331 Scale: 0.06 17-Oct-03

Singlet lens for 408
E 0331

17-Oct-03

(0.000,0.000) DEGREES





Singlet lens for 408E 0331

16:22:25

Singlet lens for 408E 0331

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	100	
> STO:	419.30869	40.000000		LAK8_SCHOTT	0	0	
2:	-419.30869	288.088110			PIK	PIM	
IMG:	INFINITY	0.000000			100	100	

SPECIFICATION DATA

FNO	4.00000
DIM	MM
WL	587.56
REF	1
WTW	1
XAN	0.00000
YAN	0.00000
WTF	1.00000
VUY	0.00000
VLY	0.00000

REFRACTIVE INDICES

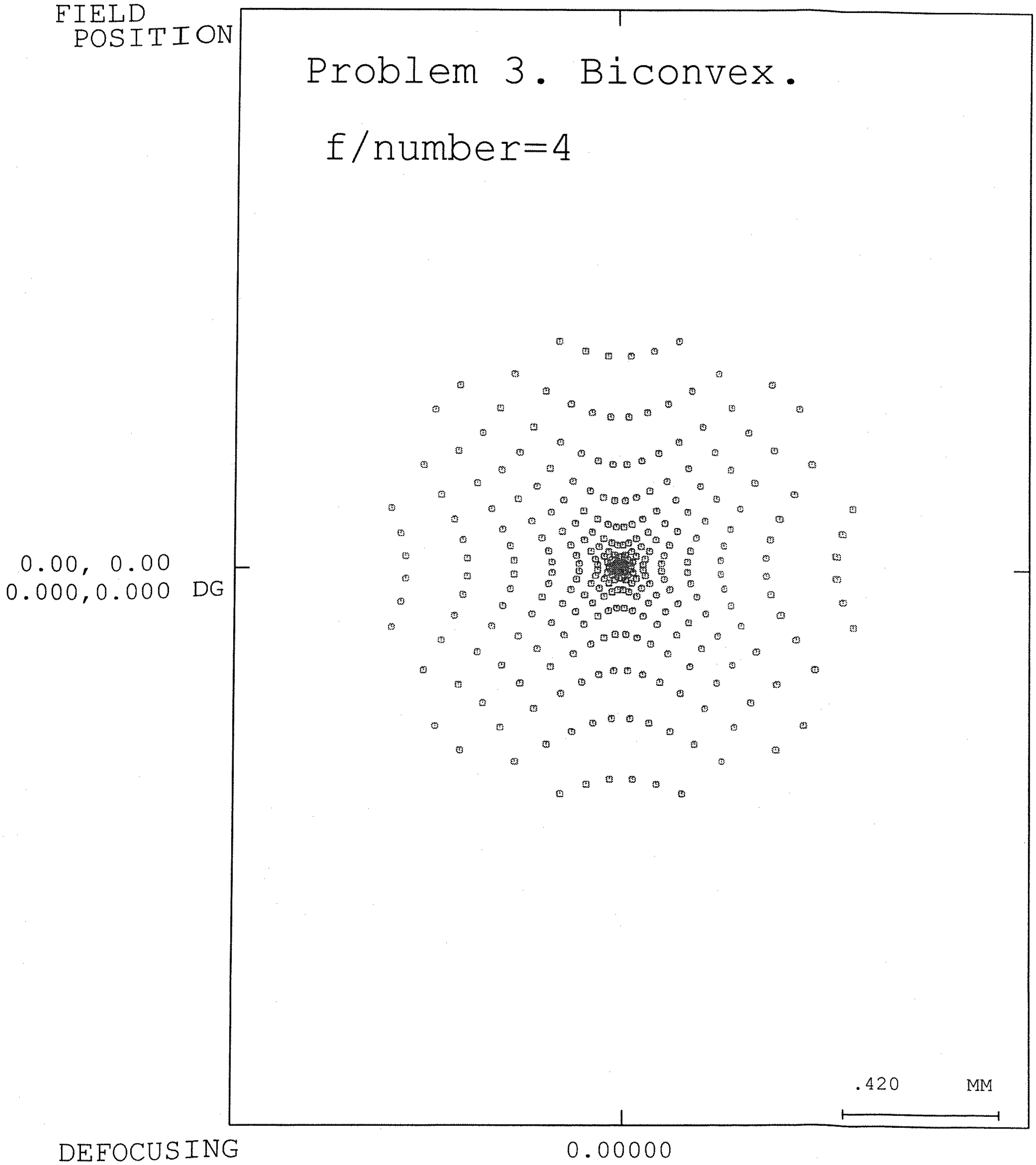
GLASS CODE	587.56
LAK8_SCHOTT	1.713003

SOLVES
PIM

PICKUPS
PIK RDY S2 Z1 RDY S1 Z1 -1.000000

INFINITE CONJUGATES

EFL	300.0000
BFL	288.0881
FFL	-288.0881
FNO	4.0000
IMG DIS	288.0881
OAL	40.0000
PARAXIAL IMAGE	
HT	0.0000
ANG	0.0000
ENTRANCE PUPIL	
DIA	75.0000
THI	0.0000
EXIT PUPIL	
DIA	78.1011
THI	-24.3163



Singlet lens for 408E 0331

16:45:48

Plano Convex Singlet lens for 408E Problem 4

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	100	
STO:	213.90095	38.000000		LAK8_SCHOTT	0	0	
2:	INFINITY	277.816737			100	PIM	
> IMG:	INFINITY	-1.522765			100	0	

SPECIFICATION DATA

FNO	4.00000
DIM	MM
WL	587.56
REF	1
WTW	1
XAN	0.00000
YAN	0.00000
WTF	1.00000
VUY	0.00000
VLY	0.00000

REFRACTIVE INDICES

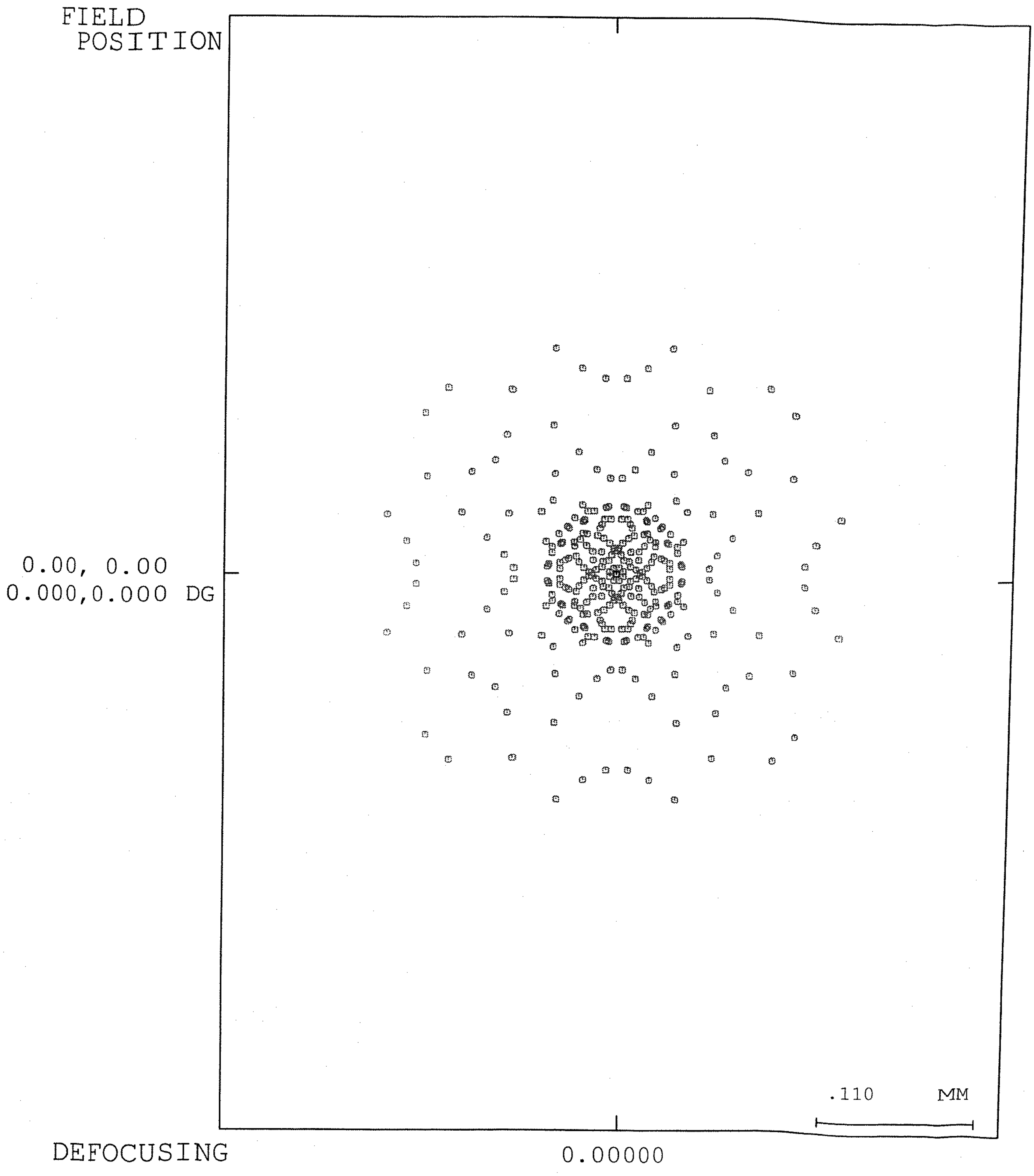
GLASS CODE	587.56
LAK8_SCHOTT	1.713003

SOLVES
PIM

No pickups defined in system

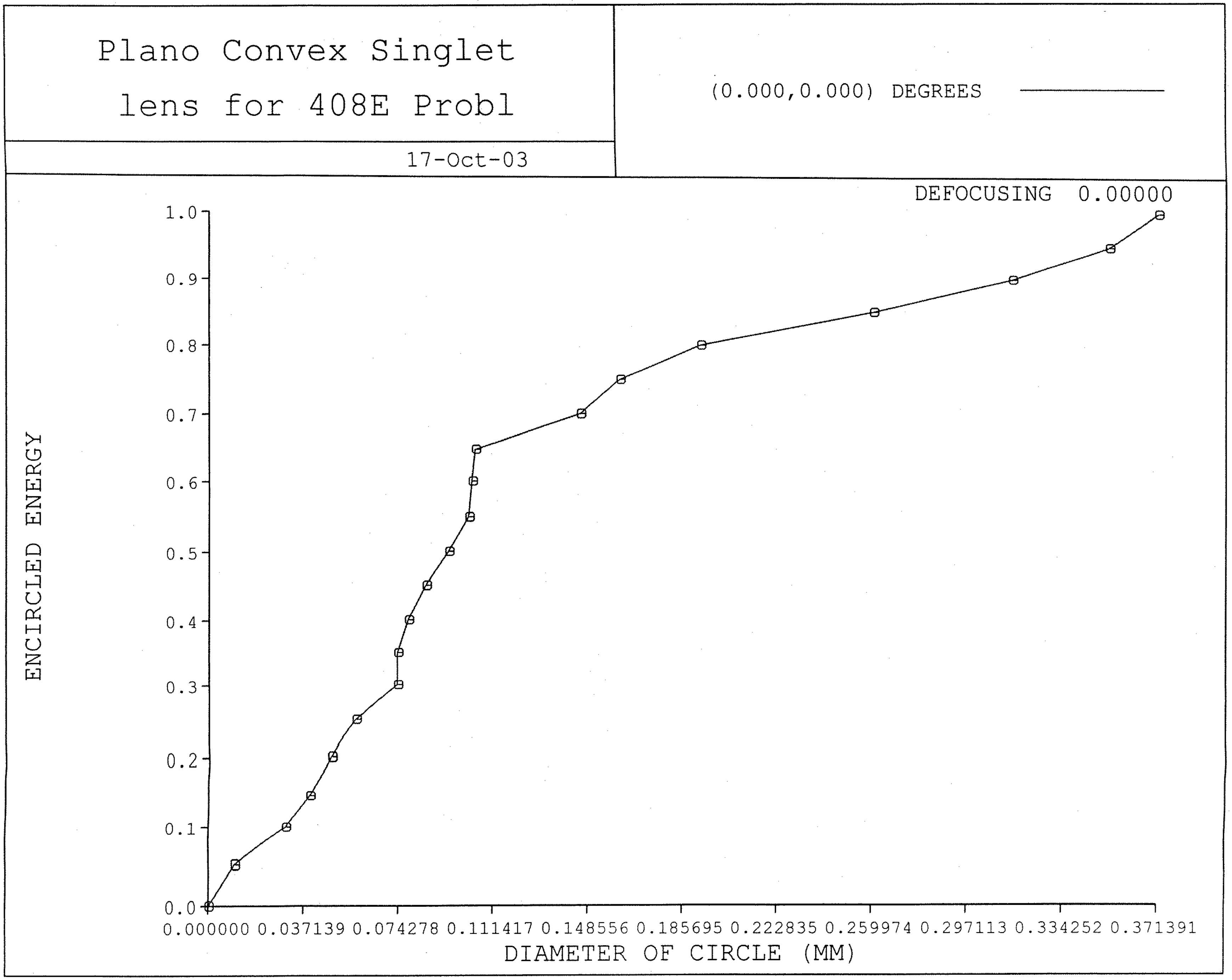
INFINITE CONJUGATES

EFL	300.0000
BFL	277.8167
FFL	-300.0000
FNO	4.0000
IMG DIS	276.2940
OAL	38.0000
PARAXIAL IMAGE	
HT	0.0000
ANG	0.0000
ENTRANCE PUPIL	
DIA	75.0000
THI	0.0000
EXIT PUPIL	
DIA	75.0000
THI	-22.1833

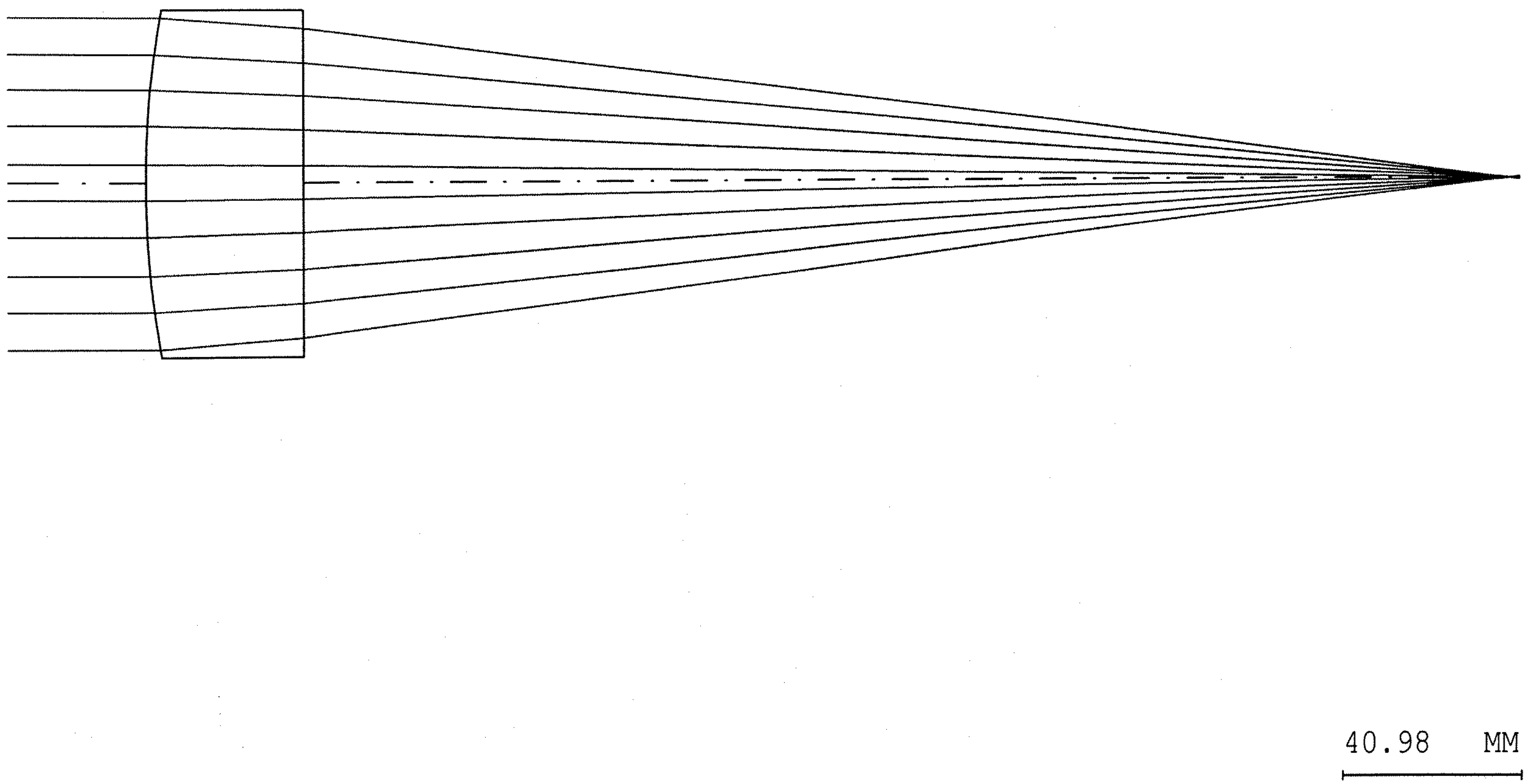


Plano Convex Singlet for 408E Problem 4

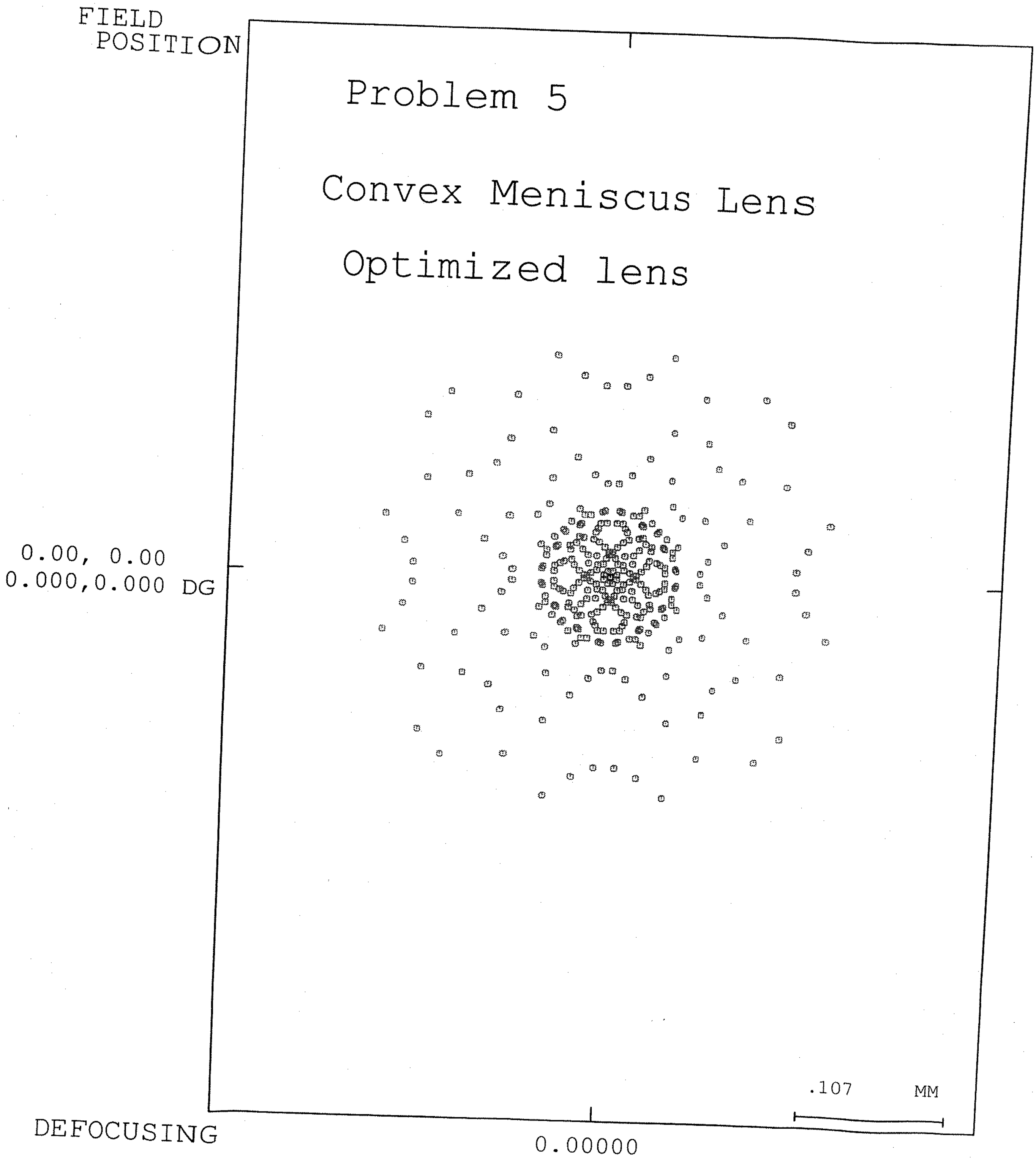
17:37:47


Plano Convex Singlet
lens for 408E Probl
17-Oct-03
(0.000,0.000) DEGREES
DEFOCUSING 0.00000
ENCIRCLED ENERGY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.000000 0.037139 0.074278 0.111417 0.148556 0.185695 0.222835 0.259974 0.297113 0.334252 0.371391
DIAMETER OF CIRCLE (MM)

16:56:03



Singlet lens for 408E Plano Convex | Scale: 0.61 | 17-Oct-03



Singlet lens for 408E Plano Convex

Optimized Singlet lens for 408E Problem 5

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	100	
STO:	209.95806	70.000000		LAK8_SCHOTT	0	0	
2:	10035.02532	258.259726			0	PIM	
> IMG:	INFINITY	-1.475736			100	0	

SPECIFICATION DATA

FNO	4.00000
DIM	MM
WL	587.56
REF	1
WTW	1
XAN	0.00000
YAN	0.00000
WTF	1.00000
VUY	0.00000
VLY	0.00000

REFRACTIVE INDICES

GLASS CODE	587.56
LAK8_SCHOTT	1.713003

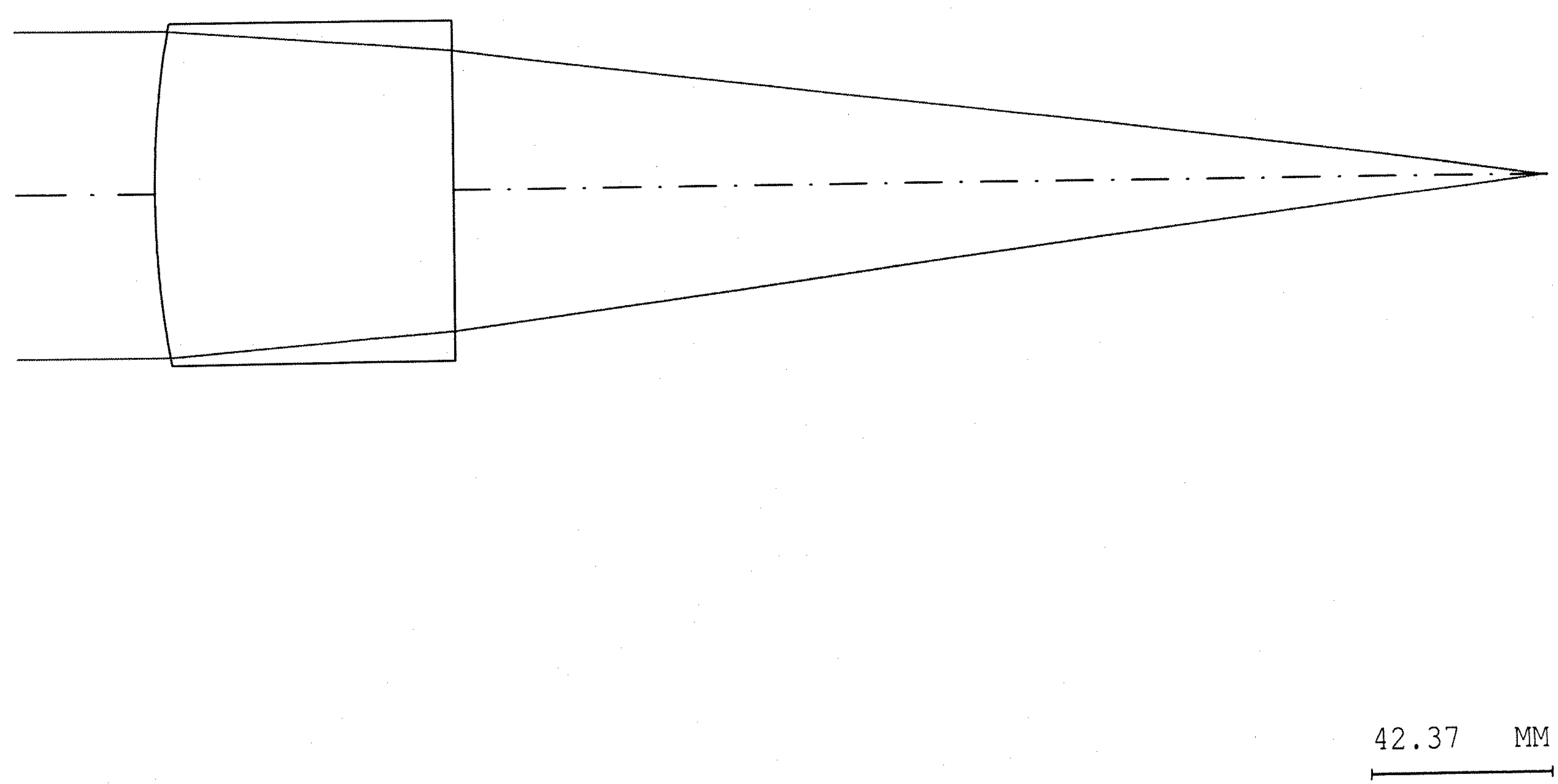
SOLVES
PIM

No pickups defined in system

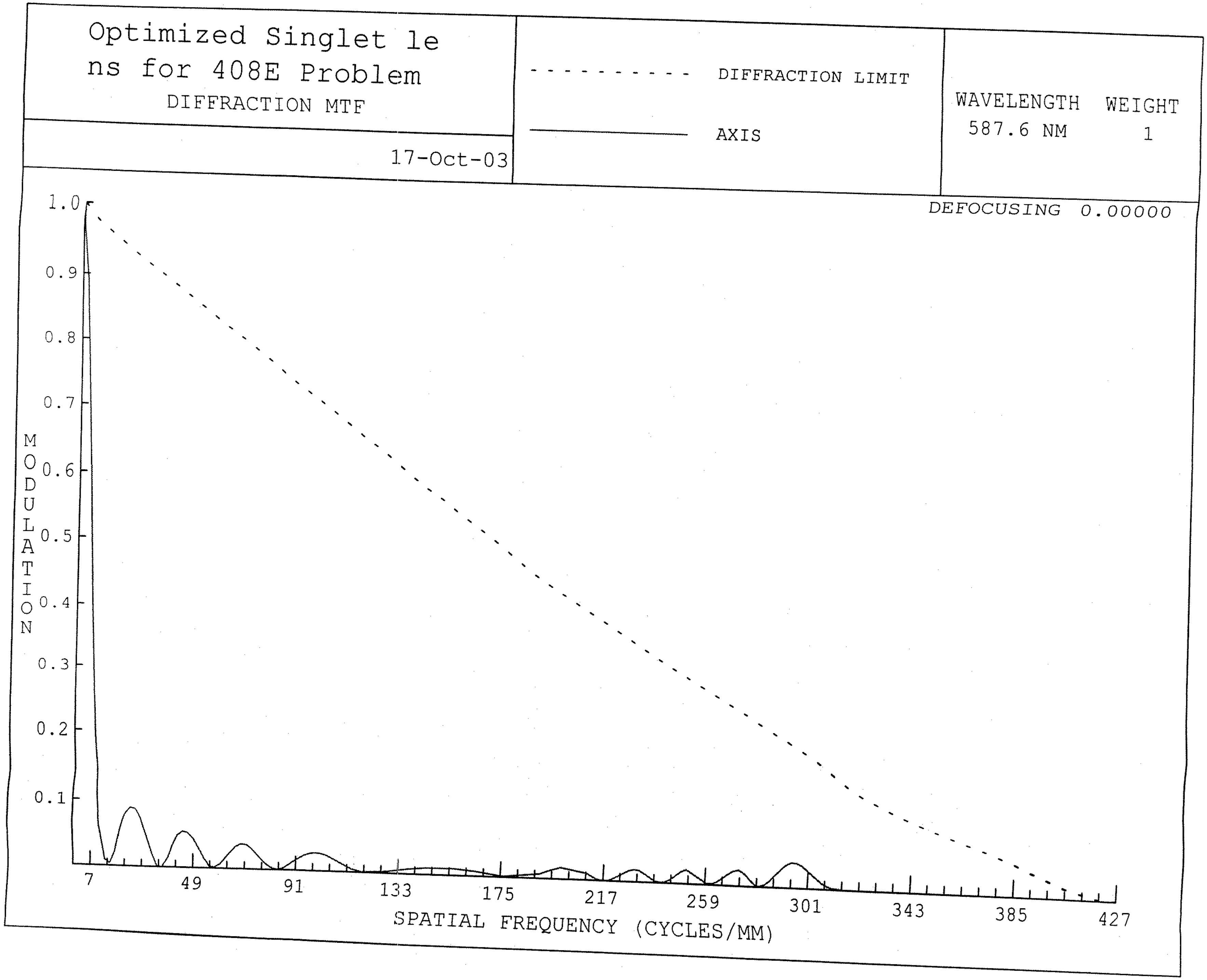
INFINITE CONJUGATES

EFL	299.8735
BFL	258.2597
FFL	-300.7441
FNO	4.0000
IMG DIS	256.7840
OAL	70.0000
PARAXIAL IMAGE	
HT	0.0000
ANG	0.0000
ENTRANCE PUPIL	
DIA	74.9684
THI	0.0000
EXIT PUPIL	
DIA	74.7513
THI	-40.7456

17:12:06



Optimized Singlet lens for 408E Problem   Scale: 0.59   17-Oct-03


Optimized Singlet le
ns for 408E Problem
DIFFRACTION MTF
17-Oct-03
DIFFRACTION LIMIT
AXIS
WAVELENGTH WEIGHT
587.6 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
7
49
91
133
175
217
259
301
343
385
427
SPATIAL FREQUENCY (CYCLES/MM)

Achromat Problem 7

	RDY	THI	RMD	GLA	CCY	THC	GLC
OBJ:	INFINITY	INFINITY			100	100	
STO:	64.03769	12.000000		SK5_SCHOTT	0	0	
2:	-50.20025	10.574239		LAF11A_SCHOTT	0	0	
3:	-173.25002	89.423447			0	PIM	
> IMG:	INFINITY	-0.002986			100	0	

SPECIFICATION DATA

FNO	4.00000	
DIM	MM	
WL	650.00	486.10
REF	2	
WTW	1	1
INI	ORA	
XAN	0.00000	
YAN	0.00000	
WTF	1.00000	
VUY	0.00000	
VLY	0.00000	

REFRACTIVE INDICES

GLASS CODE	650.00	486.10
SK5_SCHOTT	1.586426	1.595811
LAF11A_SCHOTT	1.750500	1.773841

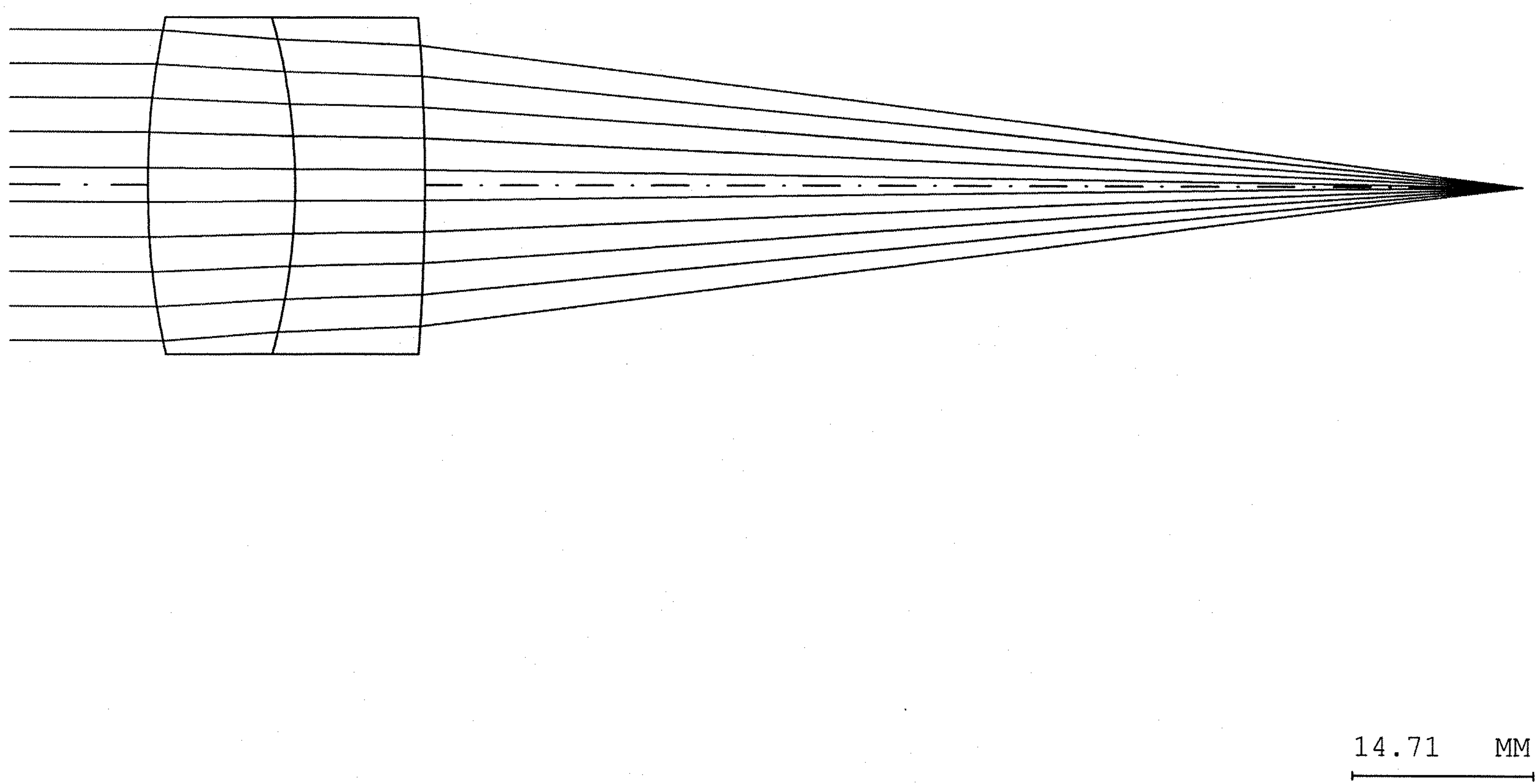
SOLVES
PIM

No pickups defined in system

INFINITE CONJUGATES

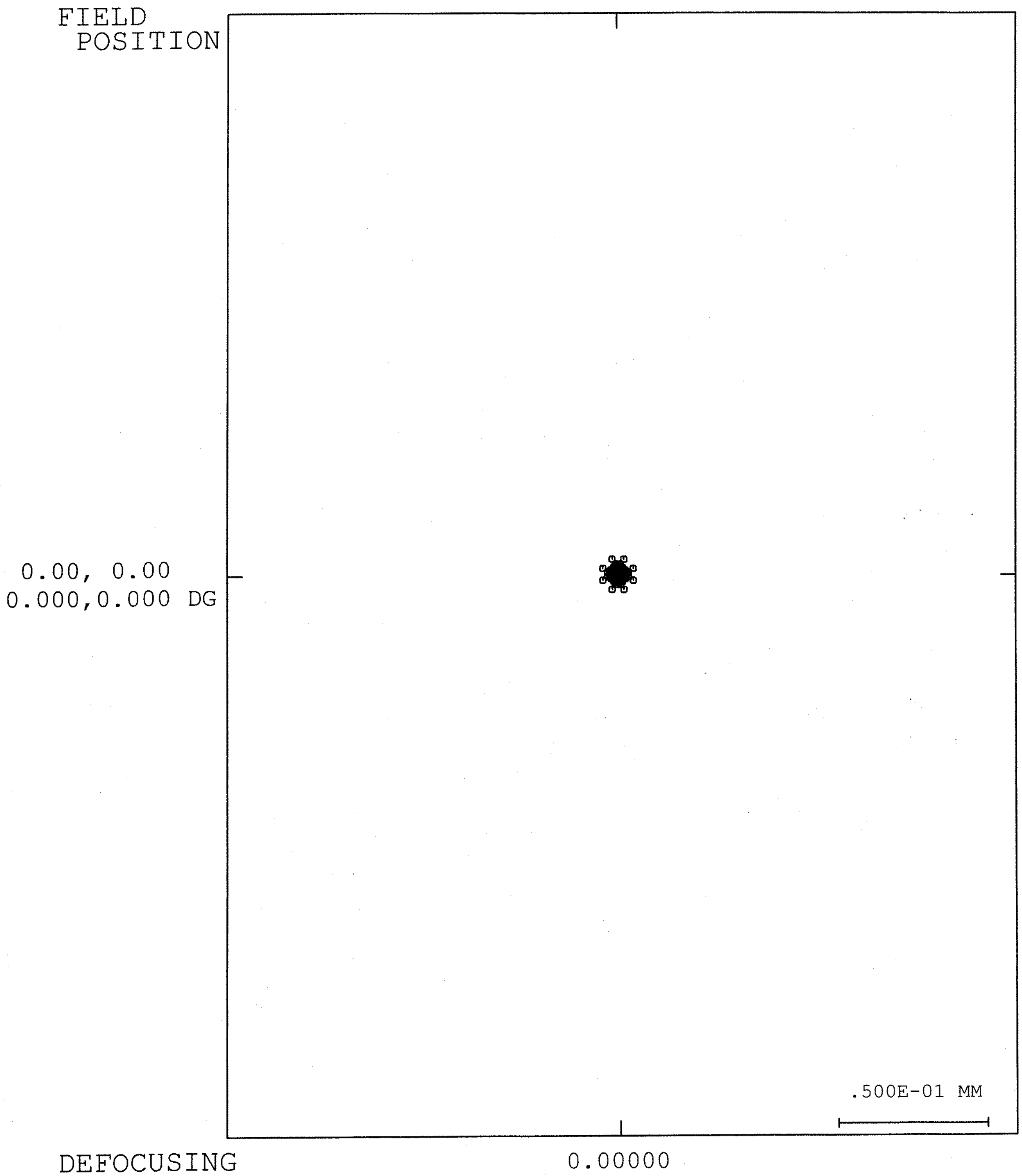
EFL	100.0000
BFL	89.4234
FFL	-96.5744
FNO	4.0000
IMG DIS	89.4205
OAL	22.5742
PARAXIAL IMAGE	
HT	0.0000
ANG	0.0000
ENTRANCE PUPIL	
DIA	25.0000
THI	0.0000
EXIT PUPIL	
DIA	25.8868
THI	-14.1237

18:04:38



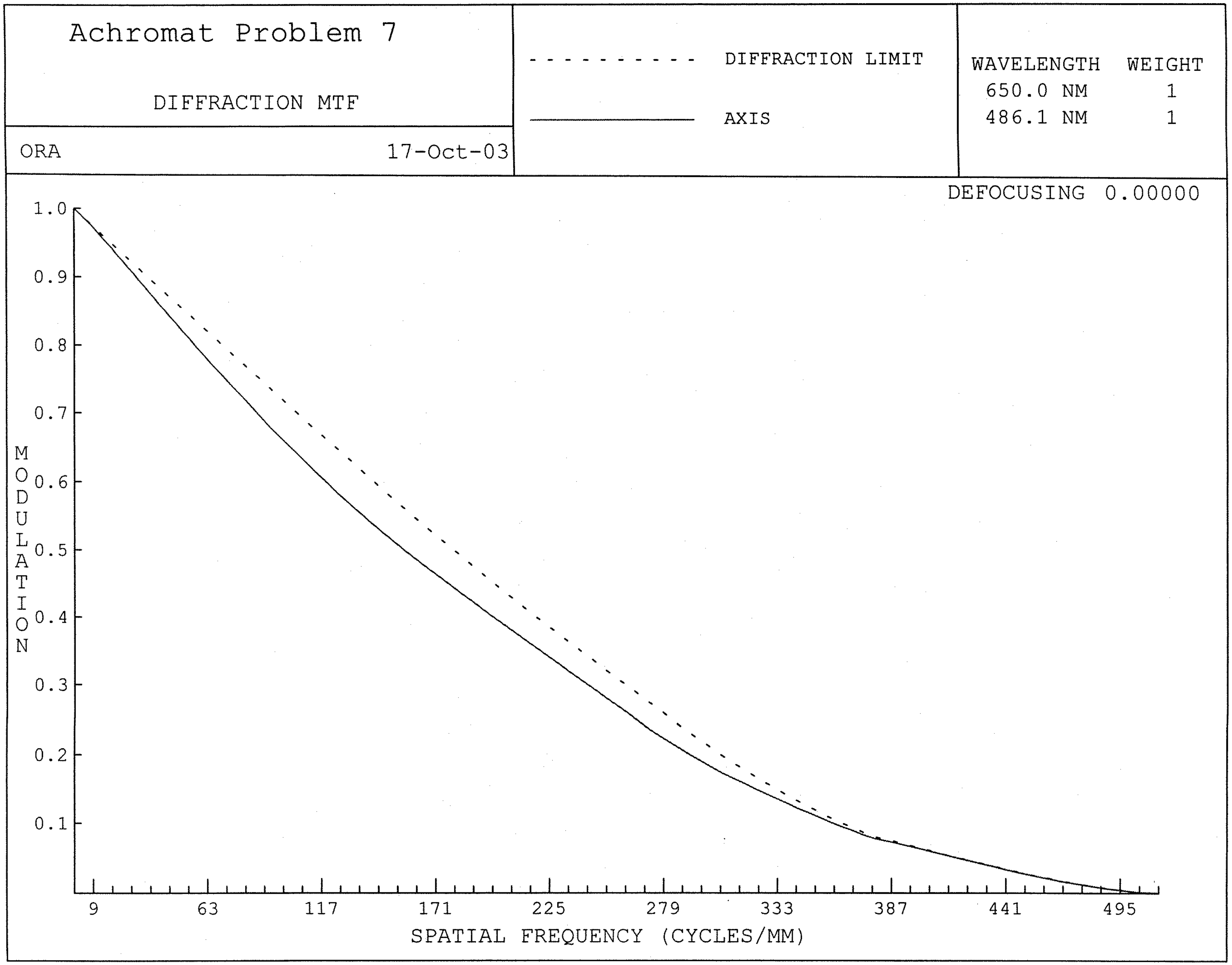
Achromat Problem 7

Scale: 1.70 ORA 17-Oct-03



Achromat Problem 7

18:04:54



Achromat Problem 7
DIFFRACTION MTF
ORA
17-Oct-03
DIFFRACTION LIMIT
AXIS
WAVELENGTH WEIGHT
650.0 NM 1
486.1 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
9
63
117
171
225
279
333
387
441
495
SPATIAL FREQUENCY (CYCLES/MM)

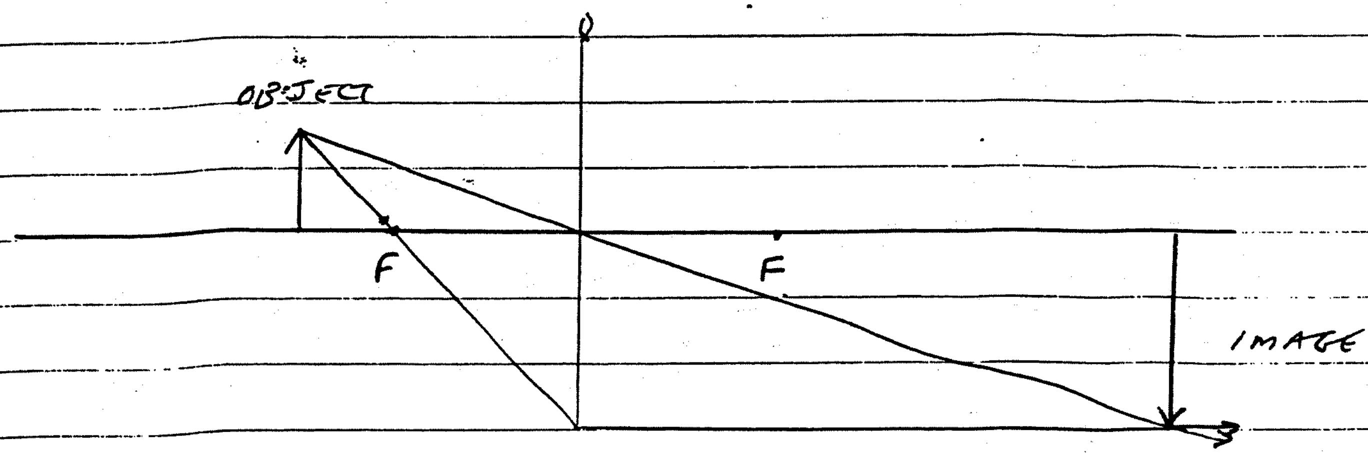
(8) (i) $f = 2$ $u = 3$ $\frac{1}{v} = \frac{1}{f} - \frac{1}{u}$

$\frac{1}{v} = \frac{1}{2} - \frac{1}{3} \Rightarrow \underline{v = 6}$

real image

linear magnification $m = \frac{v}{u} = 2$

angular magnification $m' = 1/m = \underline{0.5}$

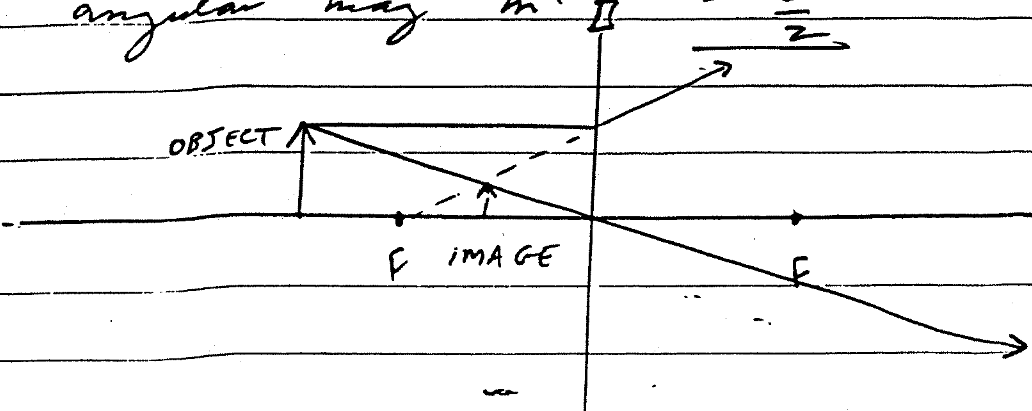


(ii) $f = -2$ $u = 3$ $\frac{1}{v} = -\frac{1}{2} - \frac{1}{3}$ $\underline{v = -\frac{6}{5}}$

virtual image

linear mag $m = v/u = \underline{-\frac{2}{5}}$

angular mag $m' = \underline{-\frac{5}{2}}$

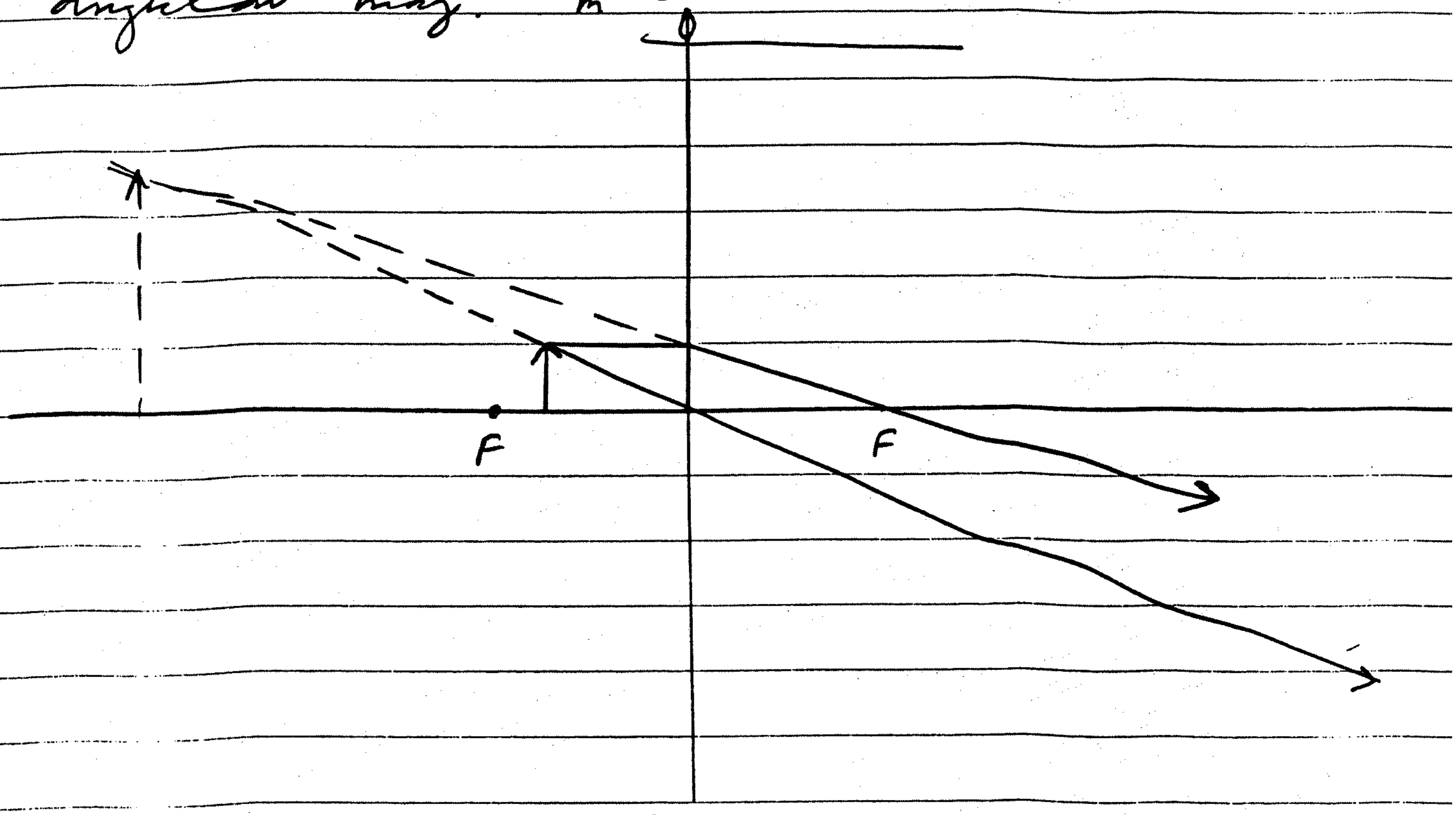


(iii) $f = 2 \quad u = 1.5 \qquad \frac{1}{v} = \frac{1}{2} - \frac{1}{1.5} \Longrightarrow v = -6$

virtual image

linear mag. $m = v/u = -4$

angular mag. $m' = -0.25$

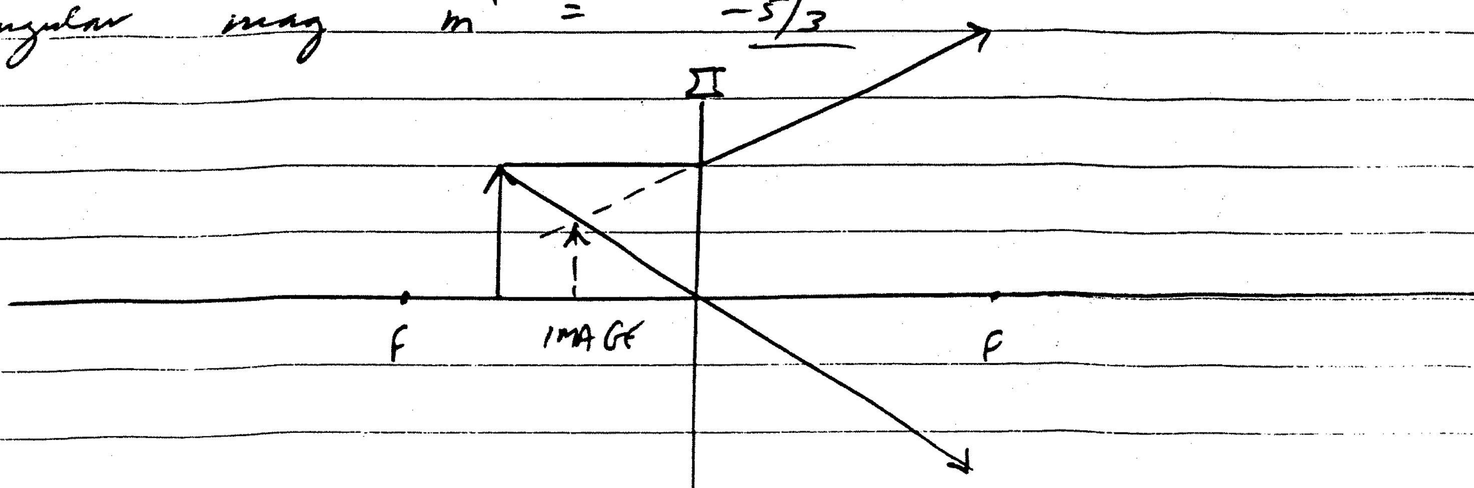


(iv) $f = -3 \quad u = 2 \qquad \frac{1}{v} = -\frac{1}{3} - \frac{1}{2} \qquad v = -\frac{6}{5}$

virtual image

linear mag. $m = v/u = -3/5$

angular mag $m' = -5/3$



(v) A concave mirror with $R = 5$; $u = 8$

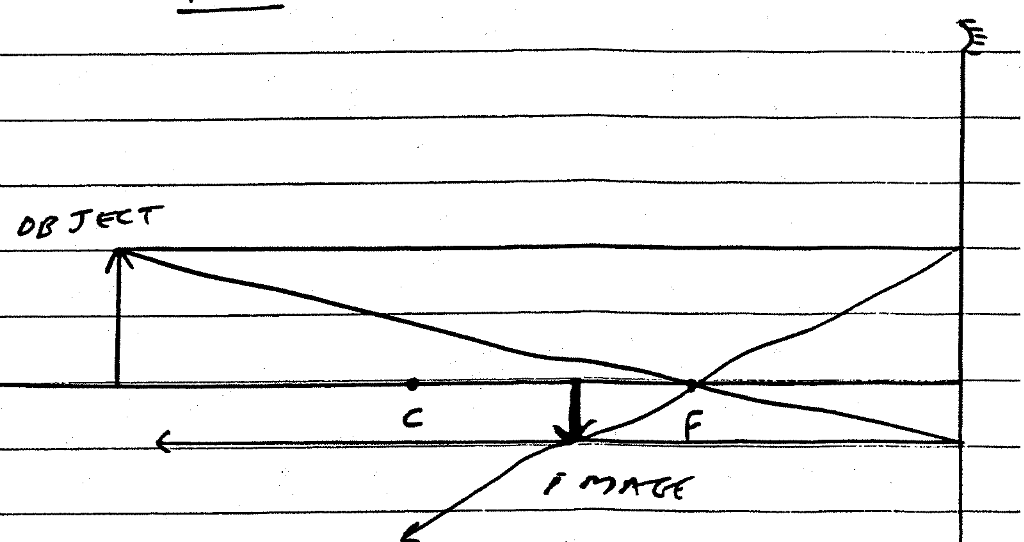
$f = R/2 = 2.5$

$\frac{1}{v} = \frac{1}{2.5} - \frac{1}{8}$ $\qquad v = \frac{40}{11}$ (3.63636)

real image

linear mag $= v/u = 5/11$

ang. mag $= 11/5$



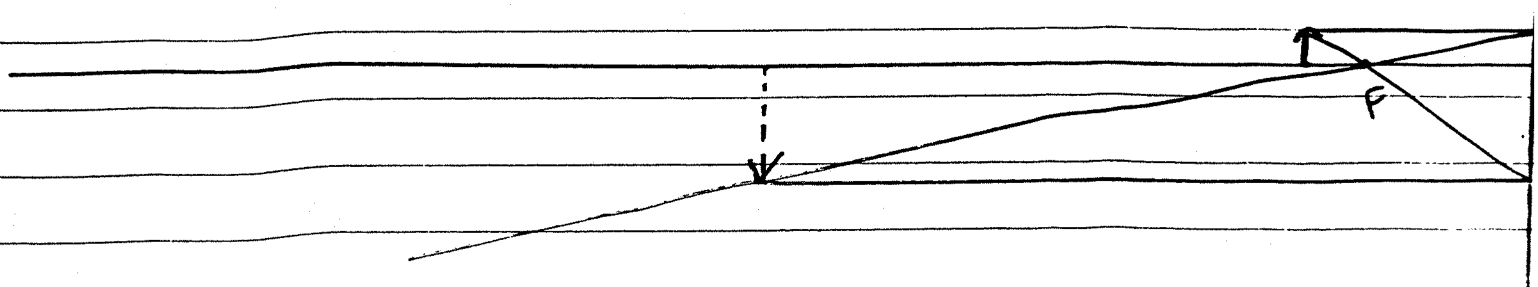
(vi) Concave mirror with $R = 5$, $u = 3$ $\qquad \frac{1}{v} = \frac{1}{2.5} - \frac{1}{3}$

$v = 15$

real image

linear mag $= v/u = 5$

ang mag $= 0.2$



(vii) A convex mirror with $|R| = 5$; $u = 3$

$f = -2.5$ $\quad \frac{1}{v} = -\frac{1}{2.5} - \frac{1}{3}$ $\quad v = -\frac{15}{11}$

virtual image

linear mag $= \frac{v}{u} = -\frac{5}{11}$

angular mag $= -\frac{11}{5}$