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Winter College on Optics and Photonics
7 - 25 February 2000

1218-30

"Optical Design"

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Istituto Nazionale di Ottica Applicata
Firenze
Italy

Please note: These are preliminary notes intended for internal distribution only.

Optical design

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Istituto Nazionale di Ottica Applicata, Firenze, Italy

- Historical background
- The mainframe of optical engineering
- The work of optical design

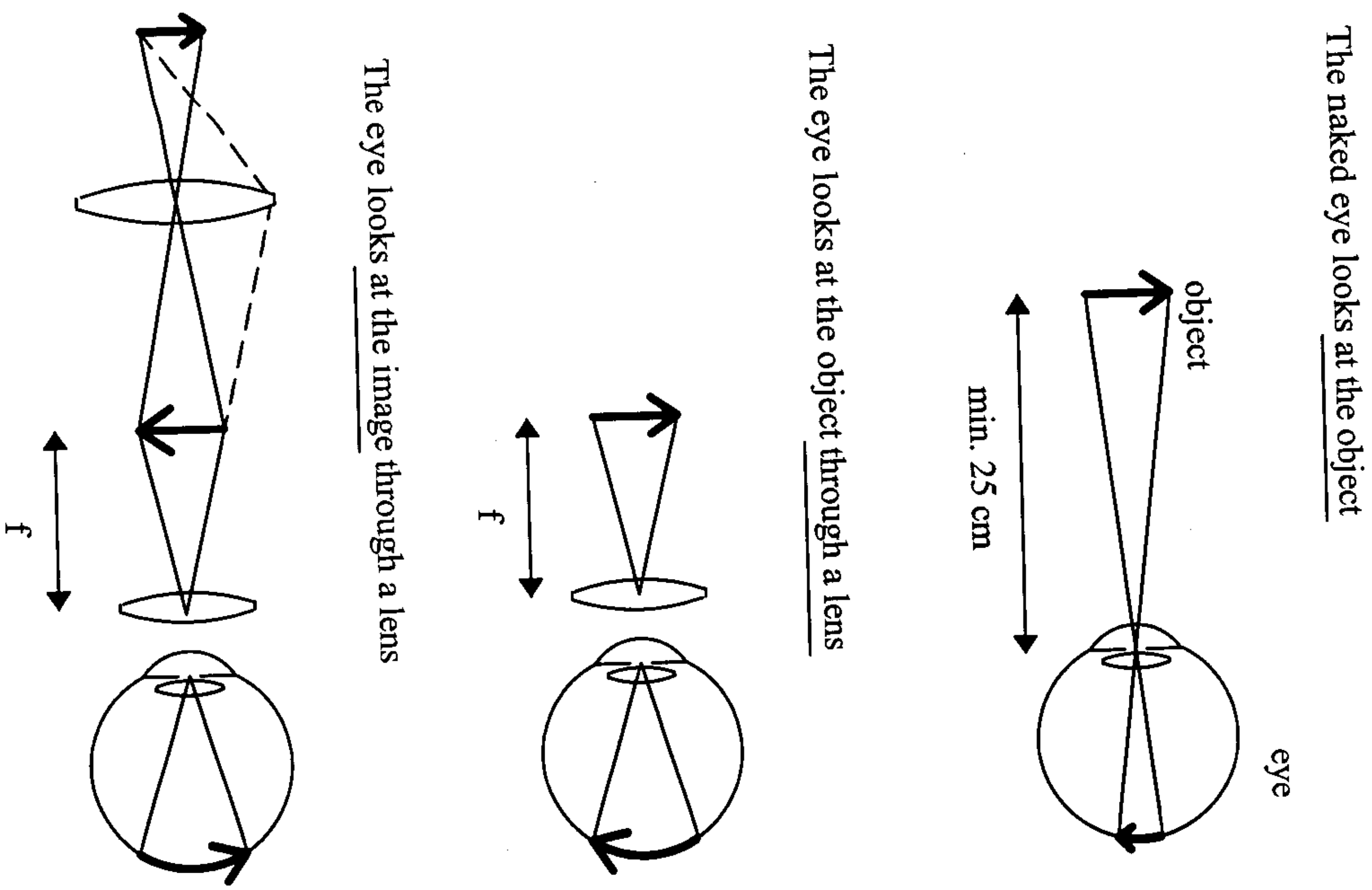
"If I were endowed with dictatorial powers, I would require everyone receiving a degree in a scientific subject to know its history and to have read the classical papers relating to it.

Historical knowledge is important because it stimulates creative thinking. The man who first struggled with an idea, trying to find a law, looked at the situation with different eyes than do we who accept the law as a matter of course. He considered alternatives to the law, and different interpretations may still be stimulating and worth thinking about."

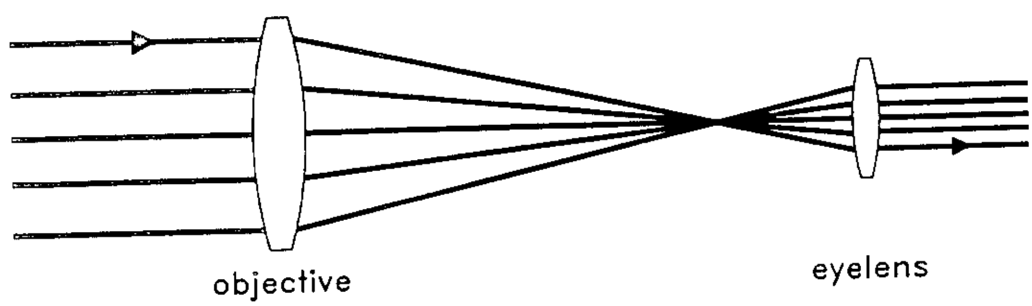
Max Herzberger

Optics from Euclid to Huygens
Appl. Opt. **5**, 1383-1393 (1966)

?	The magnifying glass
…	
~ 1285	Spectacles invented
…	
~ 1608	Hans Lippershey: telescope
~ 1608	Zacharias Janssen: compound microscope
1610	Galileo's telescope
1611	Kepler, *Dioptrice:* small angle refraction law $i \propto i'$
1615	The achievement of Sagredo: $\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$
1621	Snell: refraction law empirically discovered
~ 1628	C. Scheiner: the Keplerian telescope made
1637	Descartes, *La Dioptrique:* $n \sin i = n' \sin i'$
1647	B. Cavalieri, *Exercitationes geometricae:* lensmaker's formula $\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$
1653	Huygens, *Dioptrica:* conjugation law
~ 1660	Huygens eyepiece, with field lens
~ 1660	Campani erector, with two lenses
1668	Newton: the reflective telescope
1670	Newton, *Lectiones opticae:* spherical aberration calculated
…	
1758	J. Dollond: the achromatic telescope
…	
1839	Daguerre: photography invented
1839	Petzval: the Petzval sum
1841	Gauss: paraxial optics
1856	Seidel: the Seidel aberrations
…	
1886	Schott catalog, with 44 glasses
1893	H.D. Taylor: the 'Cooke' triplet
…	
1929	A.E. Conrady, *Applied optics and optical design*
1930	M. Berek, *Grundlagen der praktischen Optik*
1936	A. Smakula (C. Zeiss): coating lens surfaces in a vacuum patented
1962	*Military handbook 141: optical design*
1964	A. Cox, *A system of optics design*



Astronomical (Keplerian) telescope



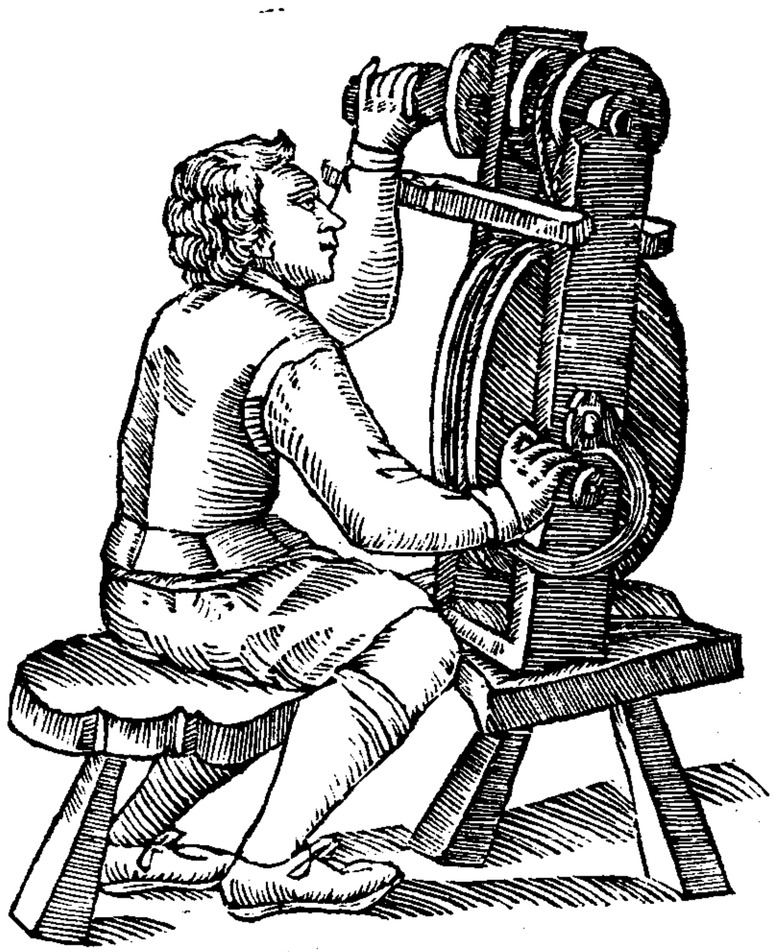


Fig. 2. - A « tornio in aria » used by early lens-makers for the production of telescopic lenses at Murano and Venice. From Conte Carlo Antonio Manzini, *L'Occhiale all'Occhio, Dioptrica Prattica*, Bologna 1660.

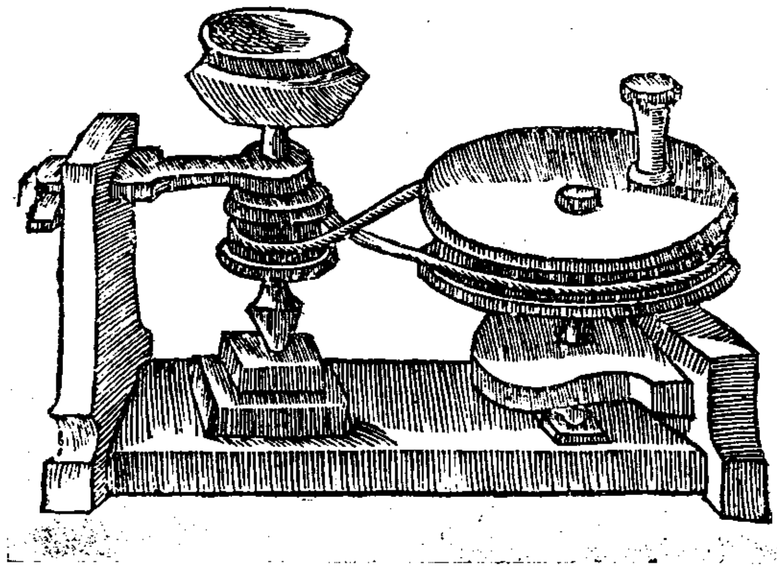
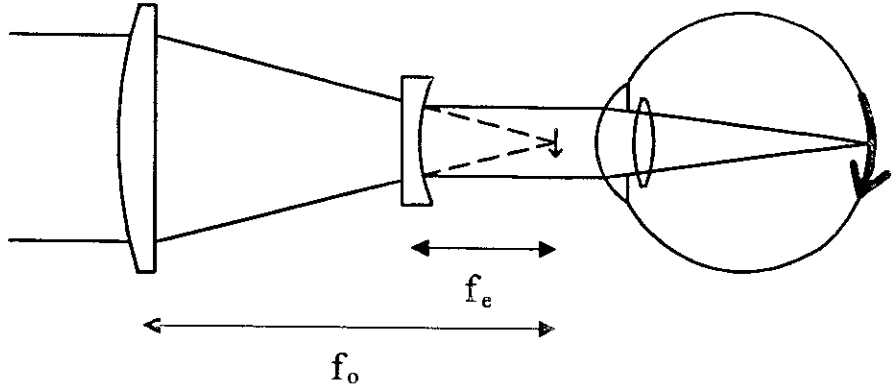
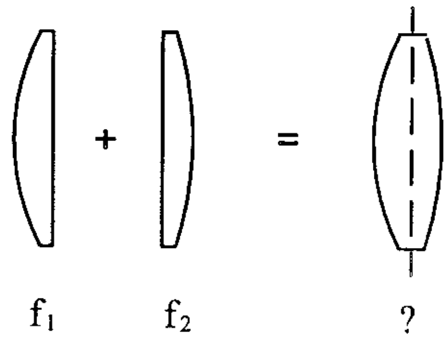


Fig. 3. - A lens-grinding lathe designed by Ippolito Francini of Florence, on which Galileo's later lenses were probably produced. From Manzini, *L'Occhiale all'Occhio...*

Lenses originally used by Galileo were plano-convex

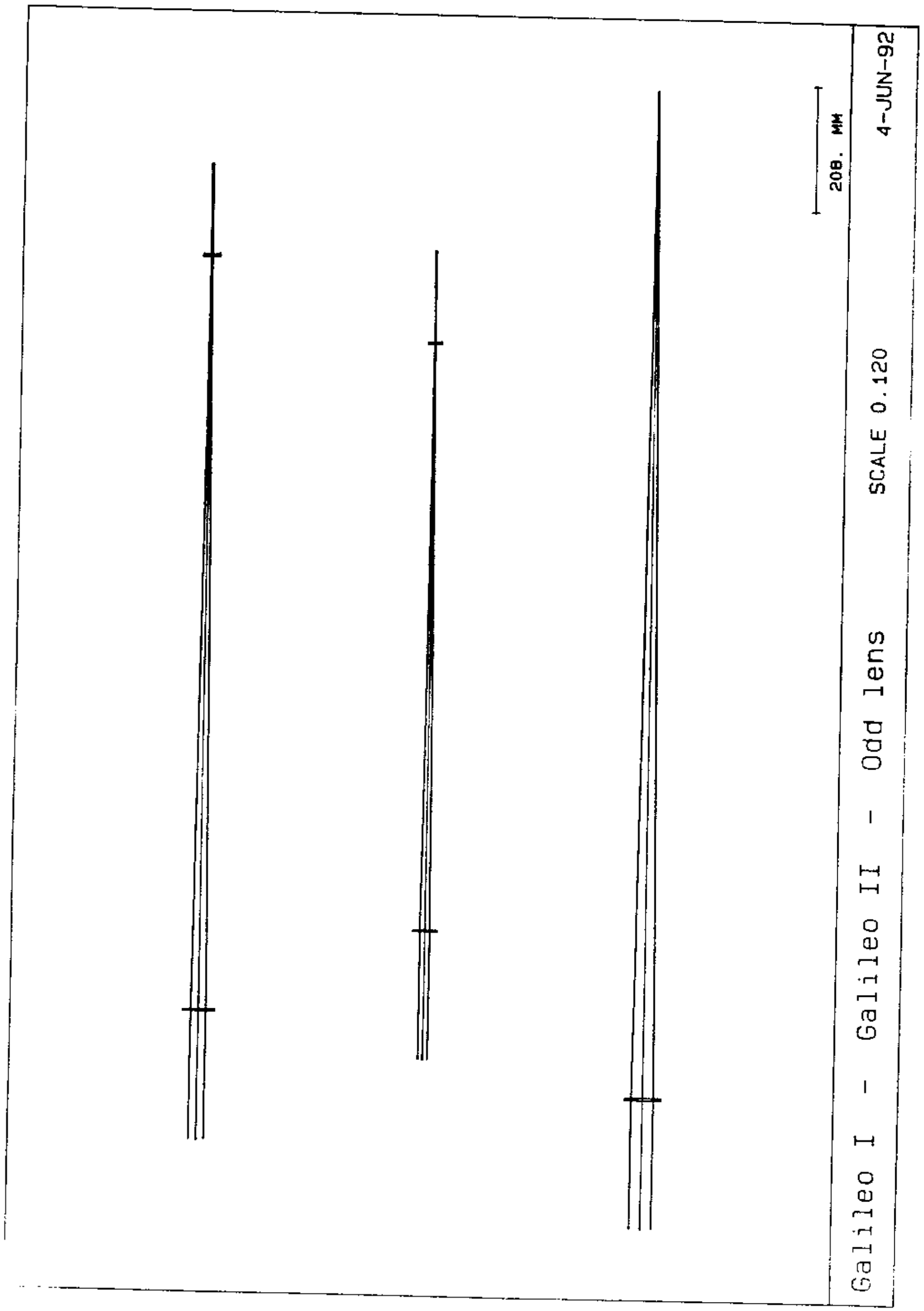


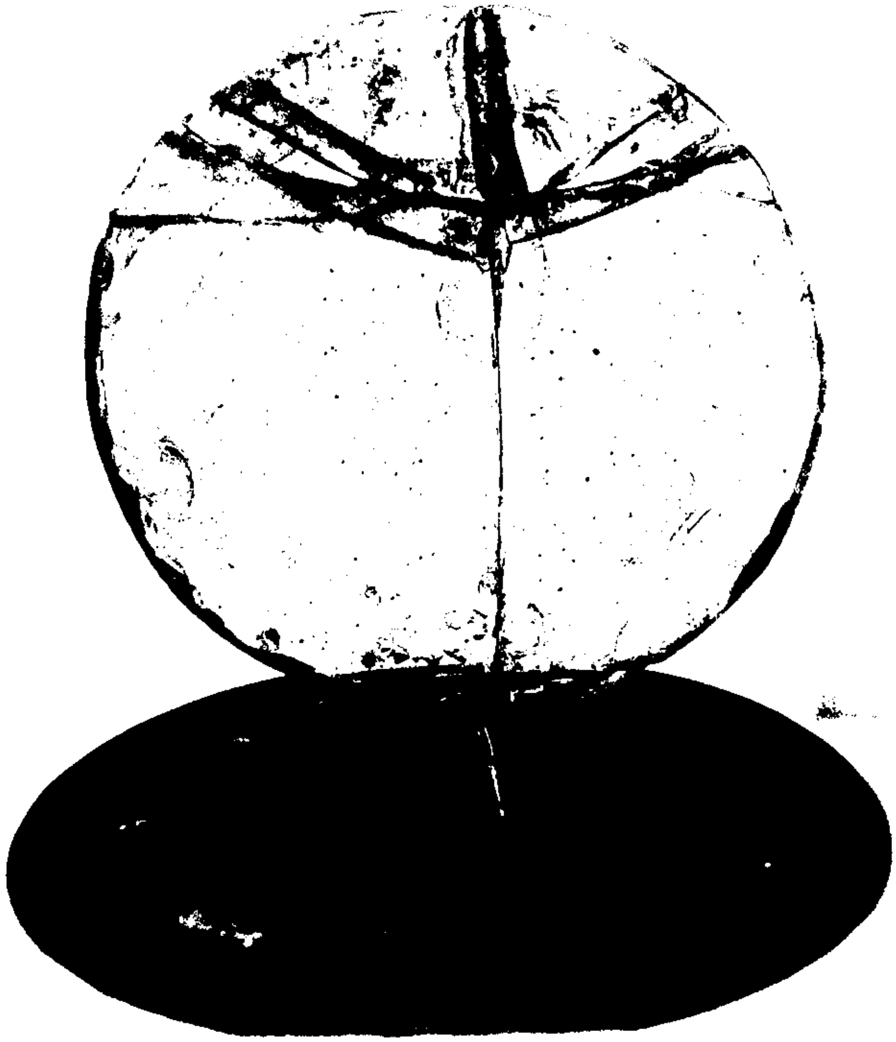
How about using a bi - convex objective ?

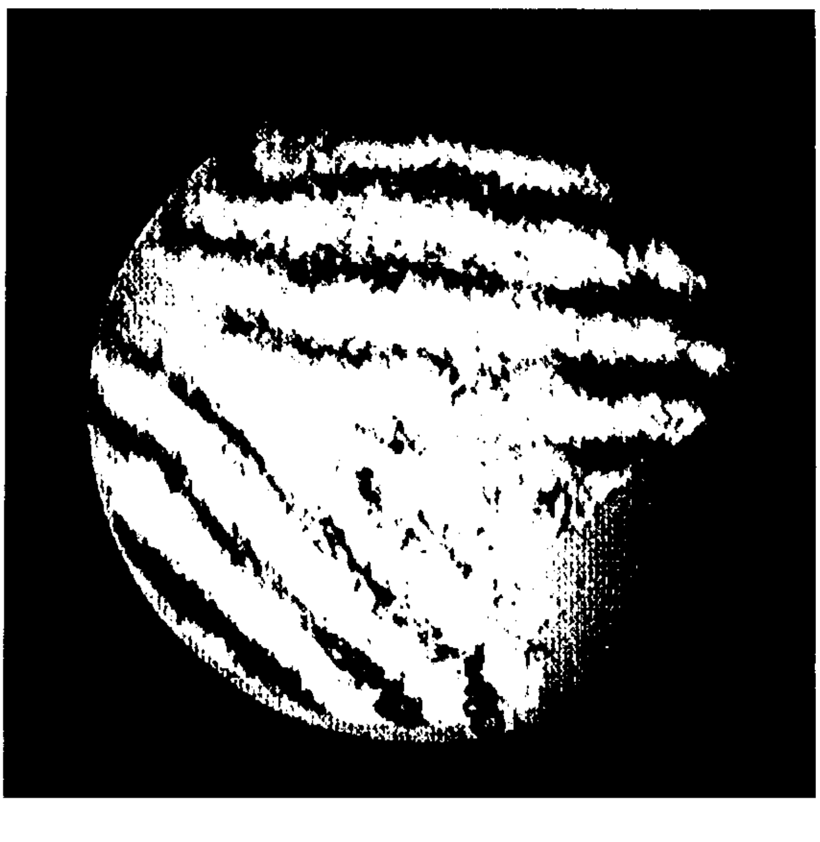


Sagredo, 1615

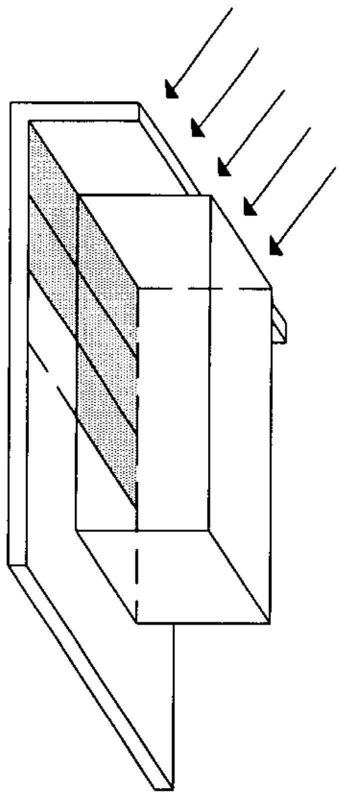
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

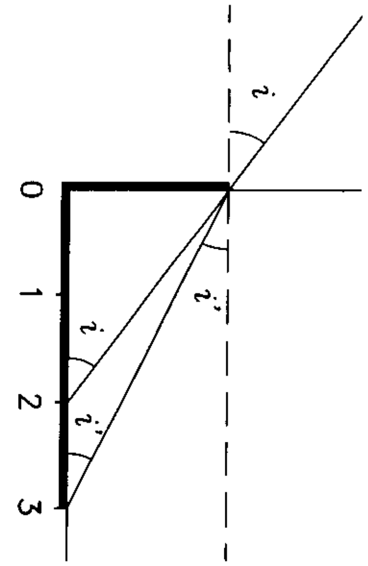






DIOPTRICE (Kepler, 1611)

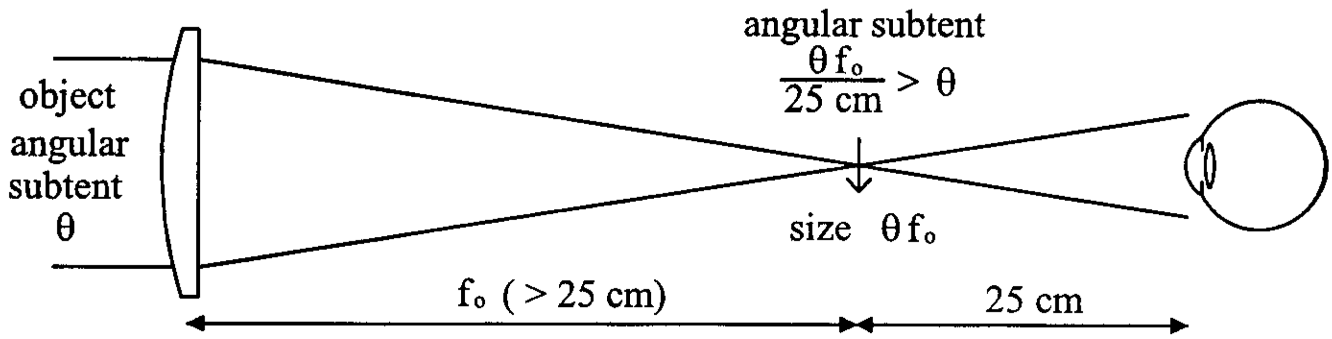


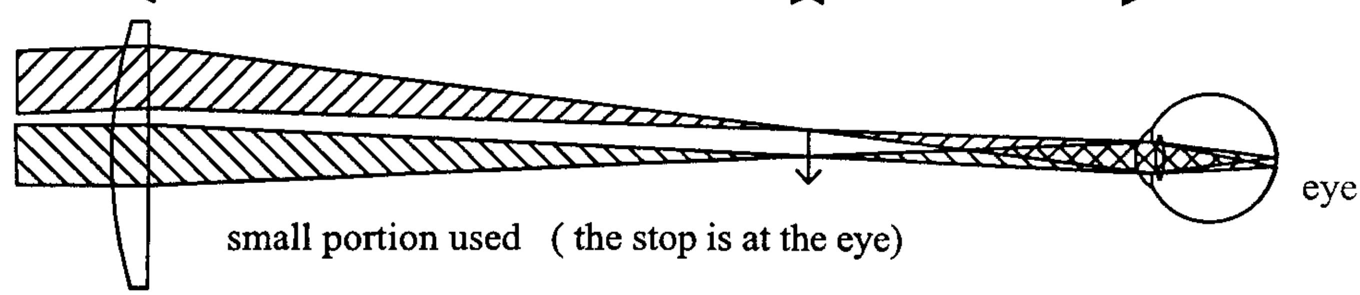


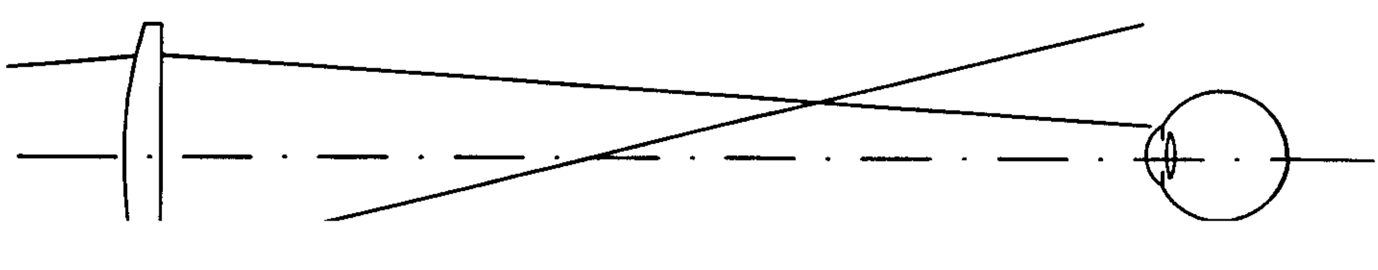
For incidence angles up to 30°

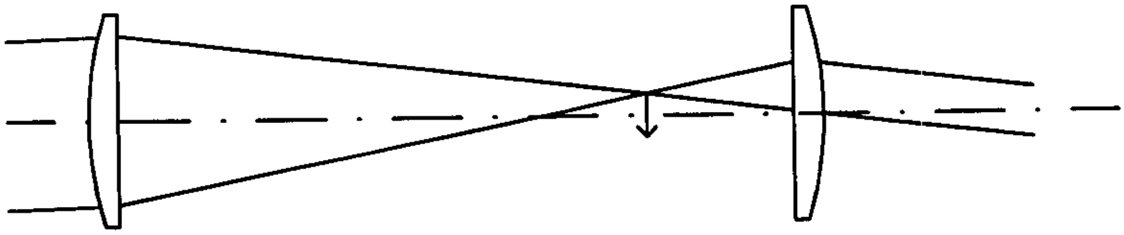
$$i = \frac{3}{2}\, i'$$

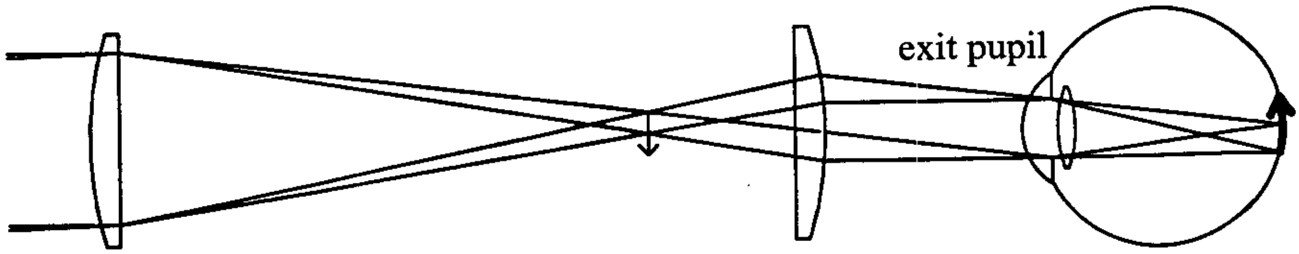
The telescope. Why is the eyelens required ?



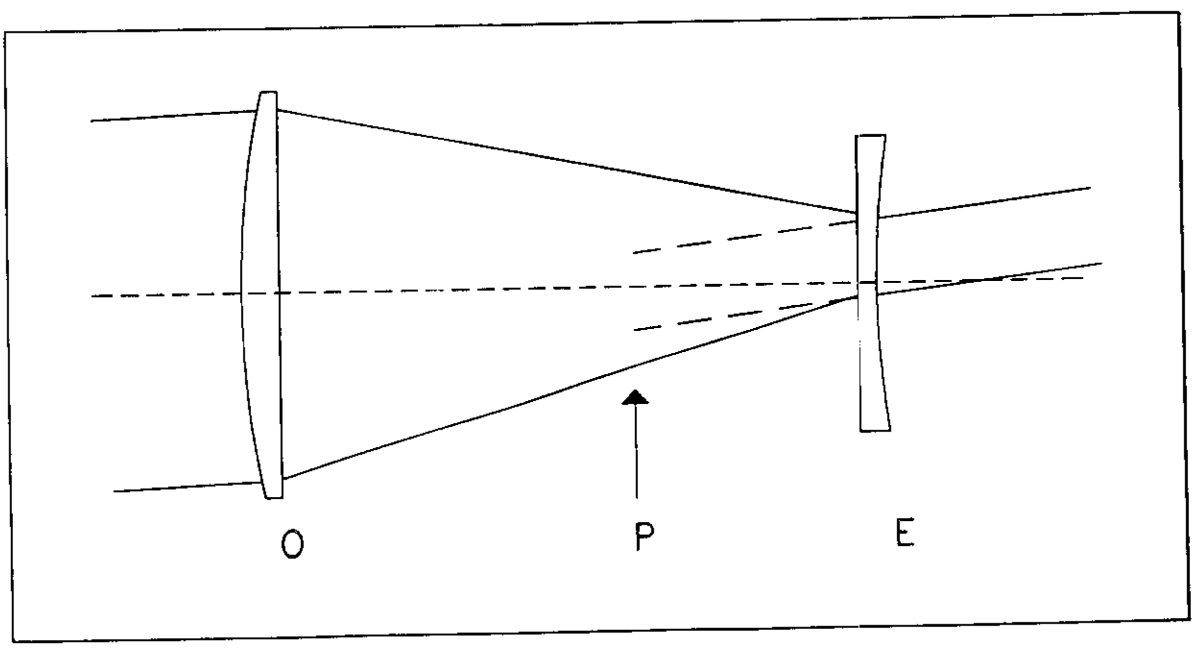




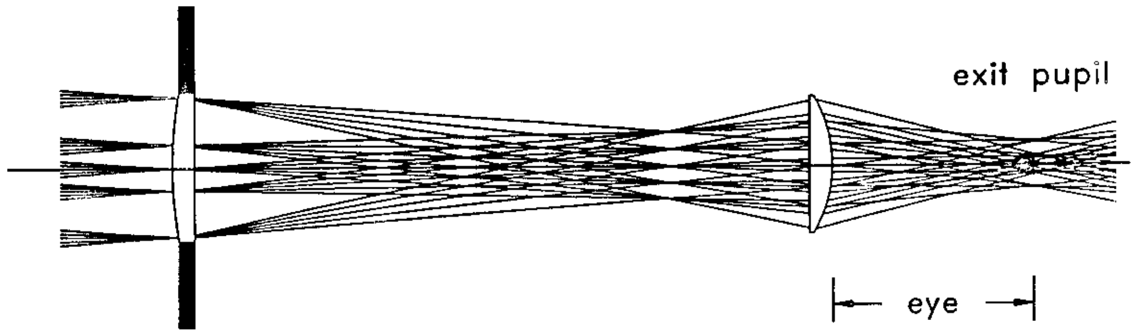




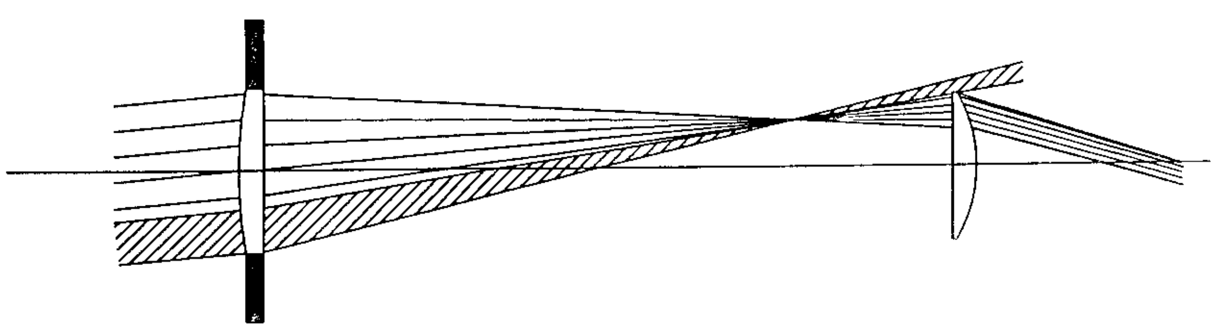
exit pupil



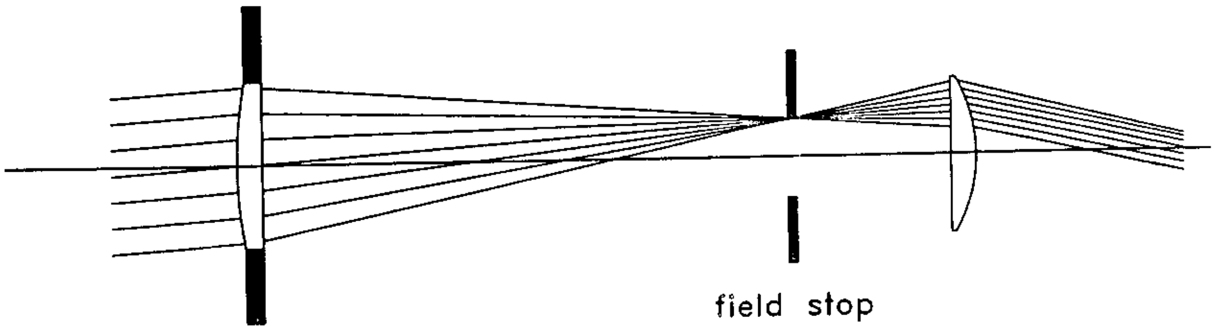
O
P
E



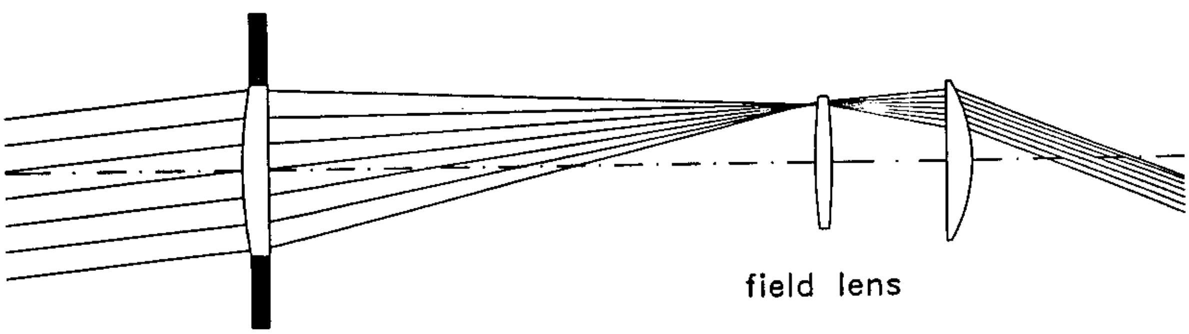
4° max. field angle



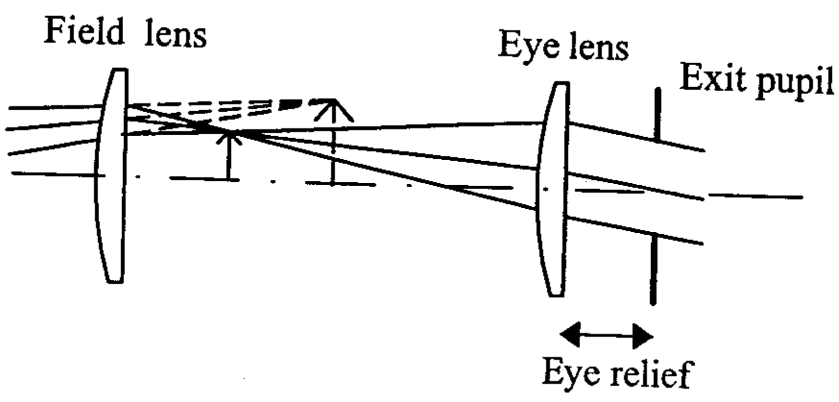
5° field angle



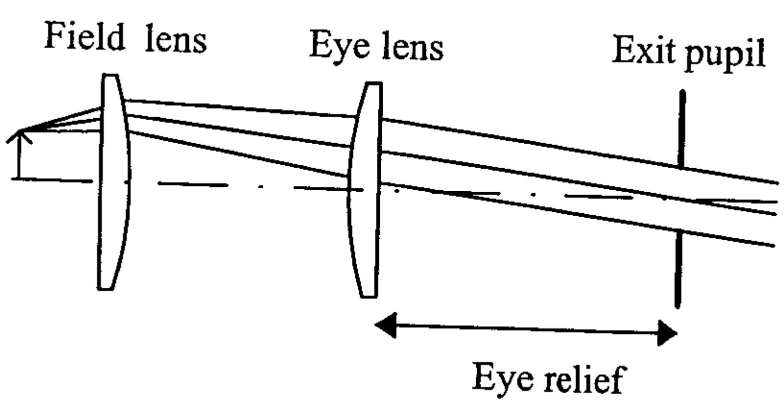
4° field angle



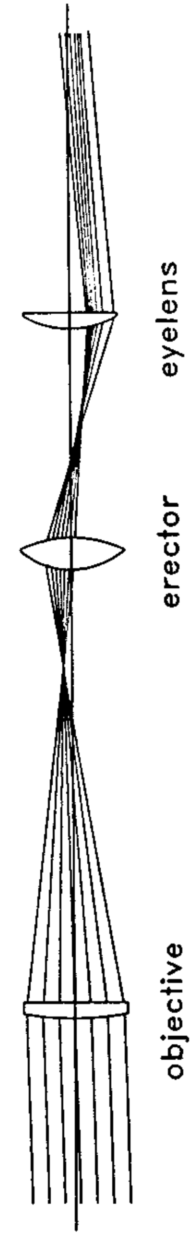
6° field angle



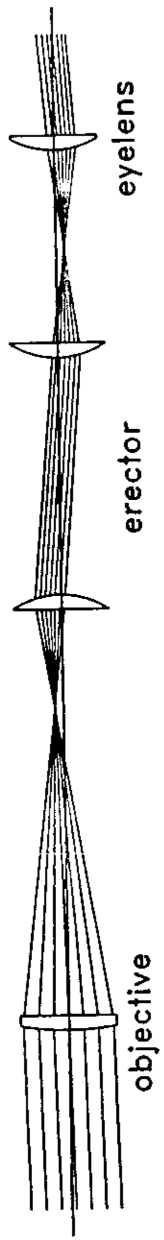
The Huygens eyepiece



The Ramsden eyepiece

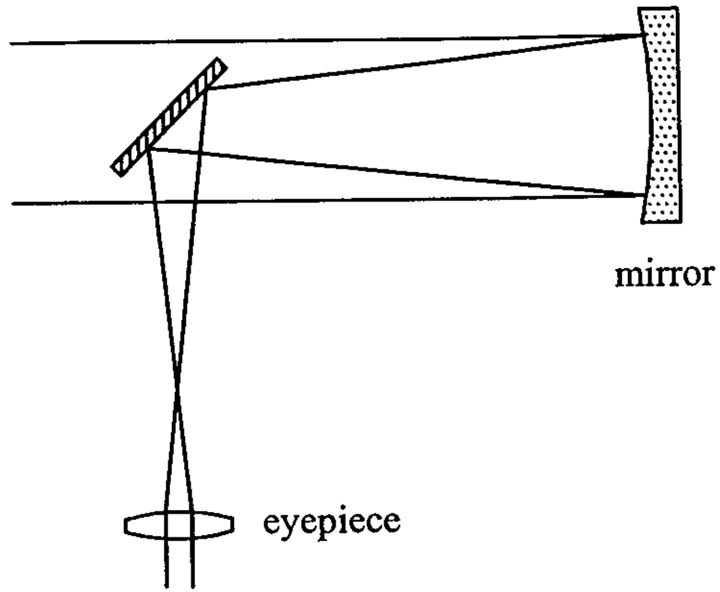


1.5° field angle

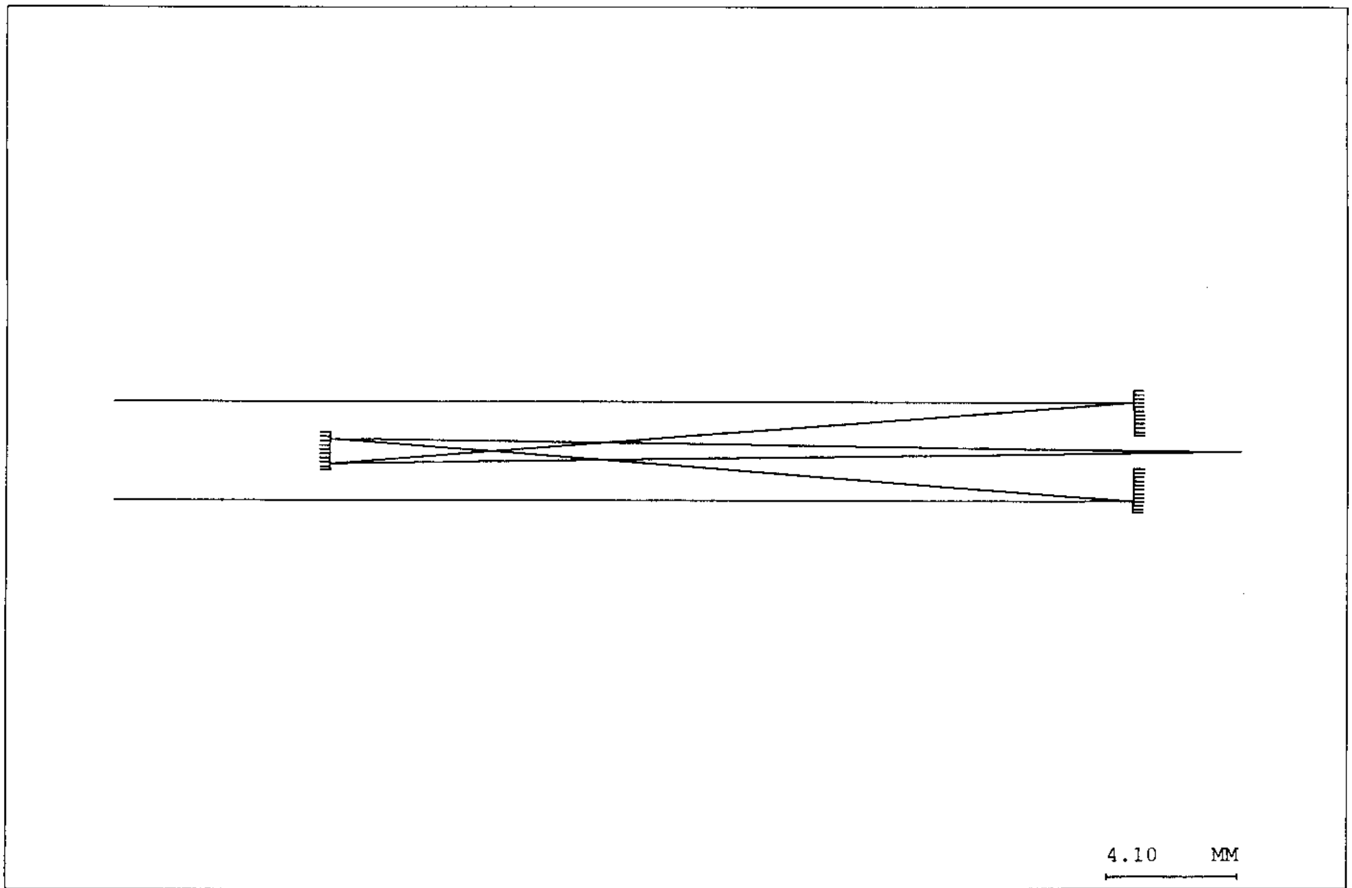


1.5° field angle

Newton: The reflective telescope (1668)

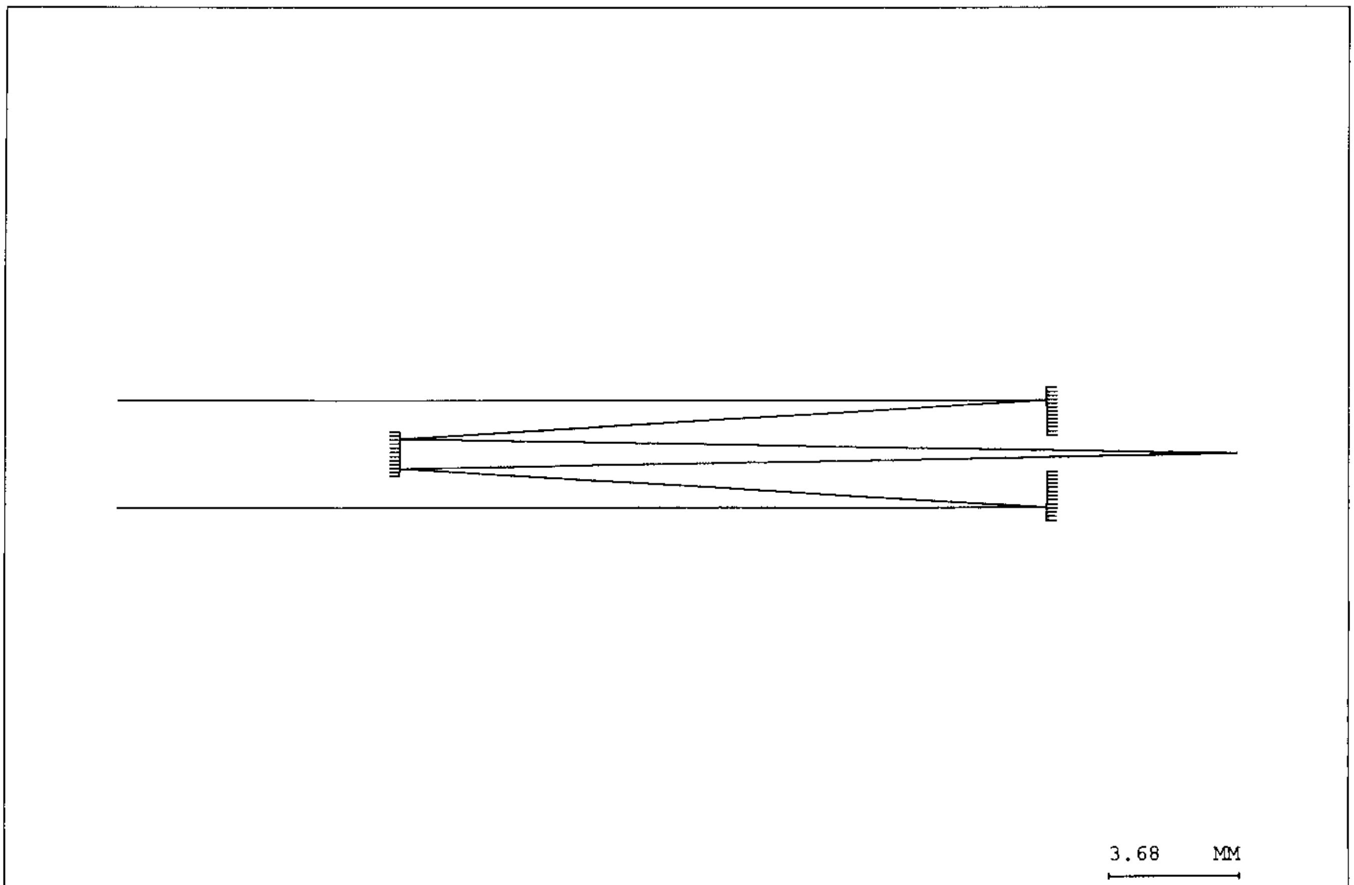


13:52:36

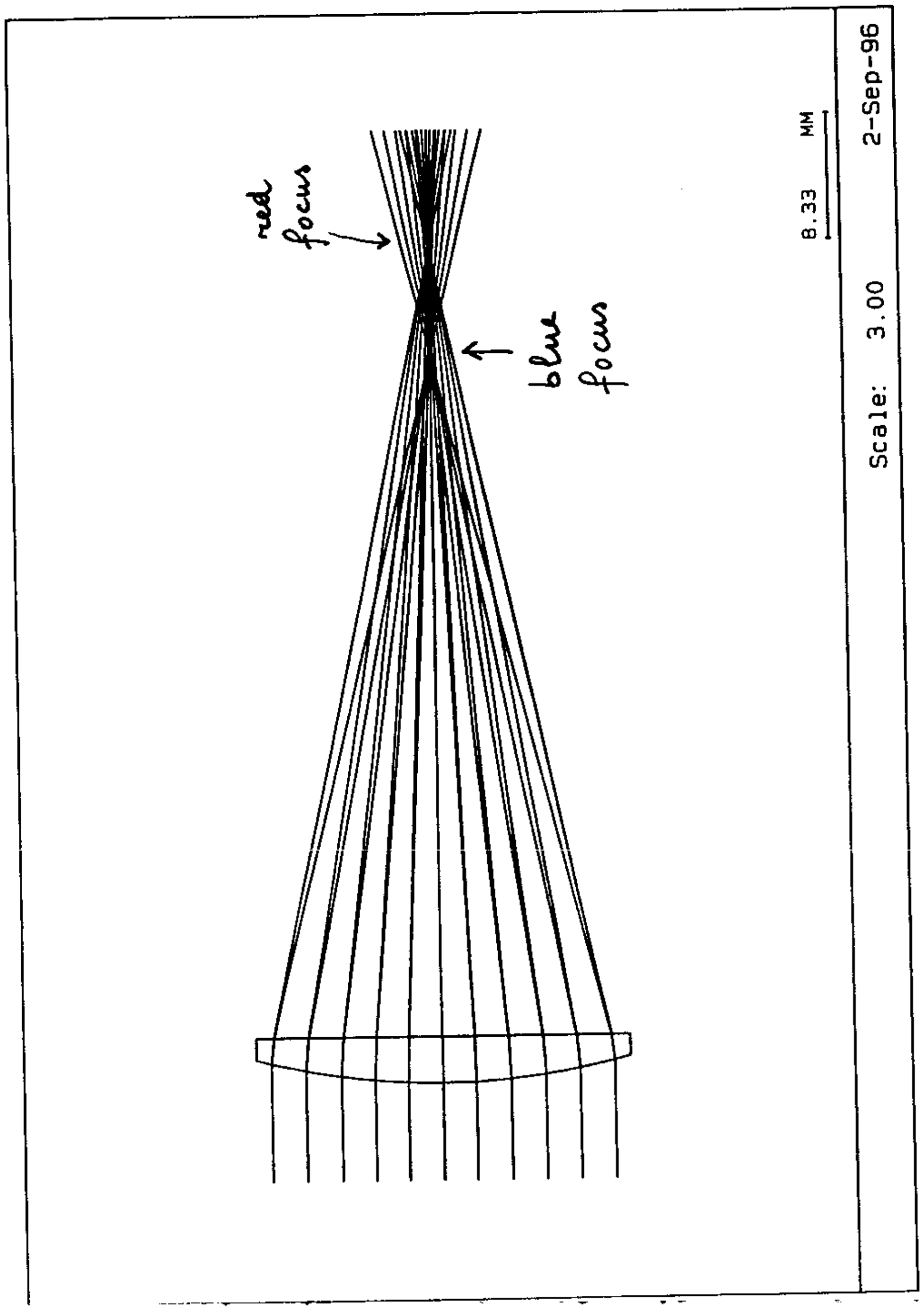


Gregorian telescope (1663) Scale: 6.10 17-Feb-00

13:48:58



Cassegrain telescope (1672) Scale: 6.80 17-Feb-00



<u>Axial color</u>

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \qquad \text{single lens}$$

$$\frac{d(1/f)}{1/f} = \frac{dn}{n-1}$$

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \qquad \text{two lenses}$$

$$\frac{d(1/f)}{1/f} = \frac{1}{f_1}\left(\frac{dn}{n-1}\right)_1 + \frac{1}{f_2}\left(\frac{dn}{n-1}\right)_2$$

If $\left(\frac{dn}{n-1}\right)_1 = \left(\frac{dn}{n-1}\right)_2$, then

$d(1/f) = 0$ is only possible for

$$f_2 = -f_1 \qquad \left(\Longrightarrow \frac{1}{f} = 0\right)$$

Otherwise:

Refer to spectral lines

λ_d	587.56 nm	Helium
λ_F	486.13 nm	Hydrogen
λ_C	656.27 nm	Hydrogen

and define the "Abbe number" V_d:

$$V_d = \frac{n_d - 1}{n_F - n_C} \qquad \left[\sim \left(\frac{dn}{n-1}\right)^{-1}\right]$$

Write $\frac{1}{f} = K, \ \frac{1}{f_1} = K_1, \ \frac{1}{f_2} = K_2 \qquad (K = K_1 + K_2).$

Axial color:

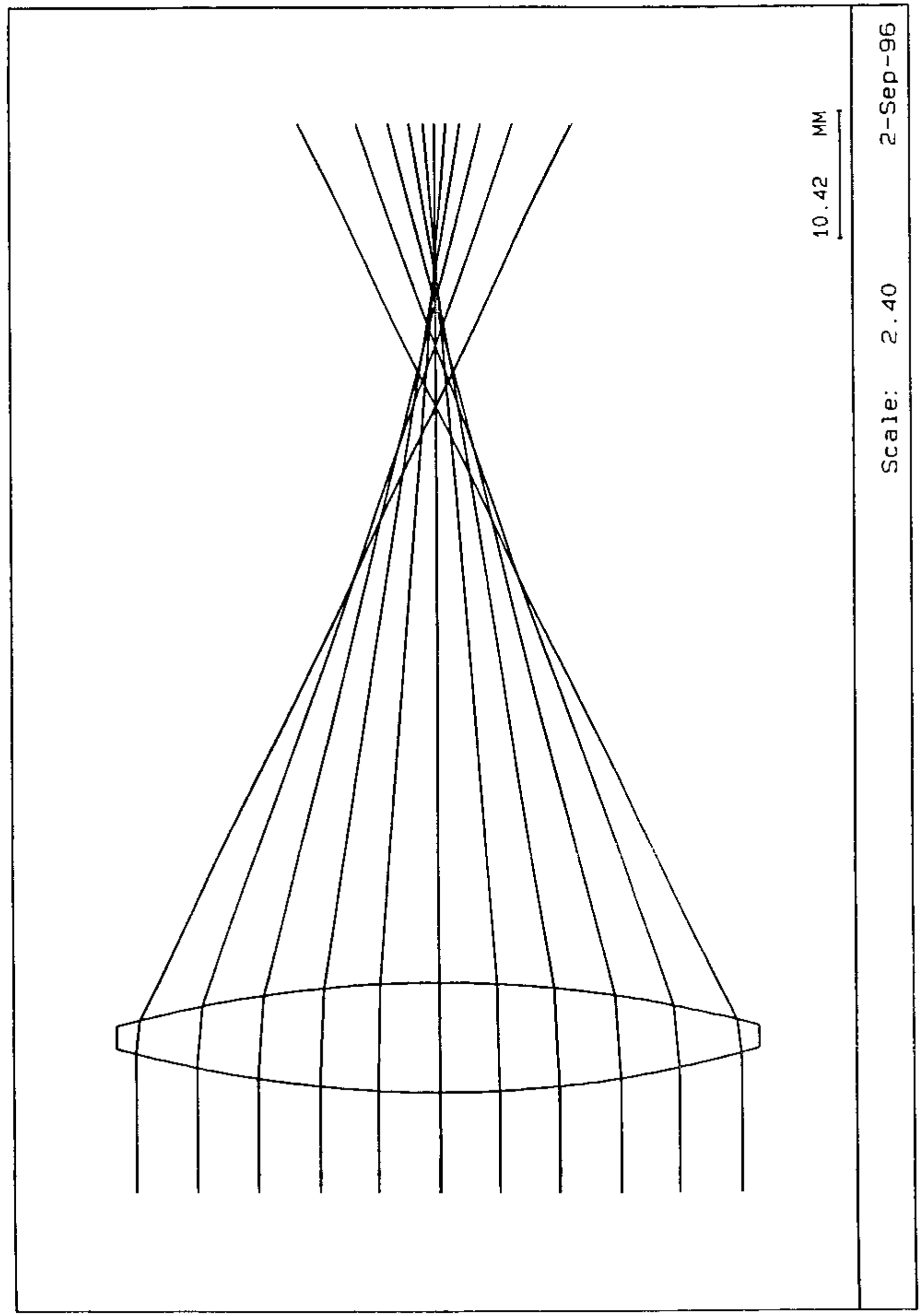
$$\frac{\Delta K}{K} = \frac{K_1}{V_1} + \frac{K_2}{V_2}$$

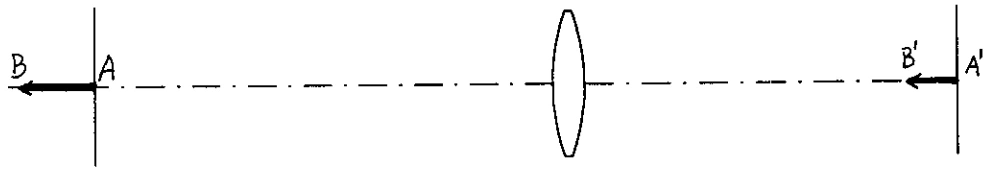
Correcting for the axial color:

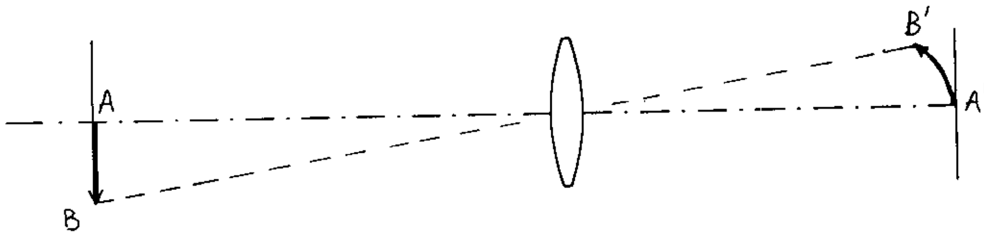
$$\Delta K = 0 \qquad \Longrightarrow \qquad K_1 = \frac{V_1}{V_1 - V_2} K, \qquad K_2 = \frac{-V_2}{V_1 - V_2} K$$

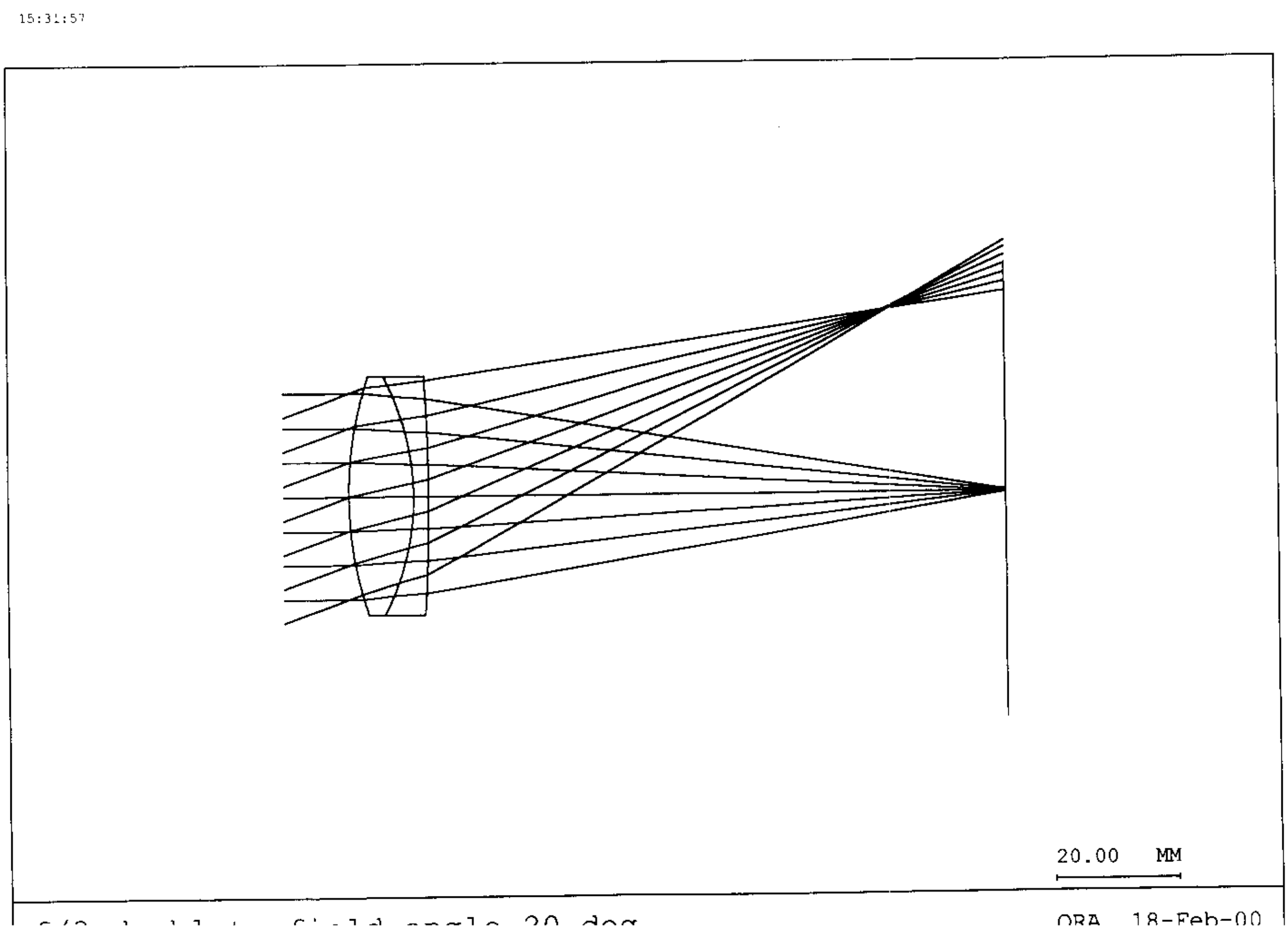
Example: $V_1 = 60$ (crown glass), $V_2 = 36$ (flint glass)

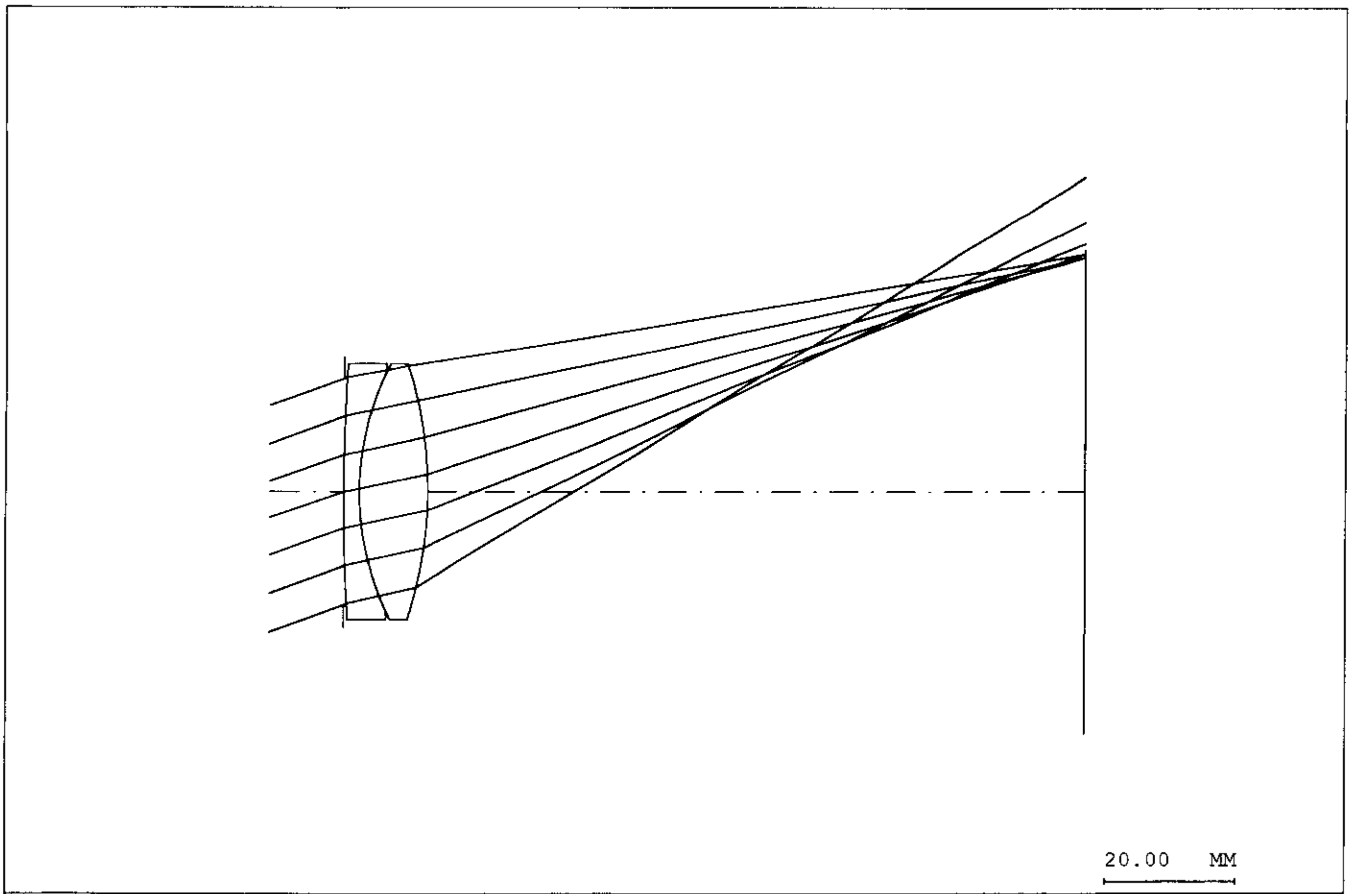
$$\Longrightarrow \qquad K_1 = 2.5\ K, \qquad K_2 = -1.5\ K$$




B
A
B'
A'

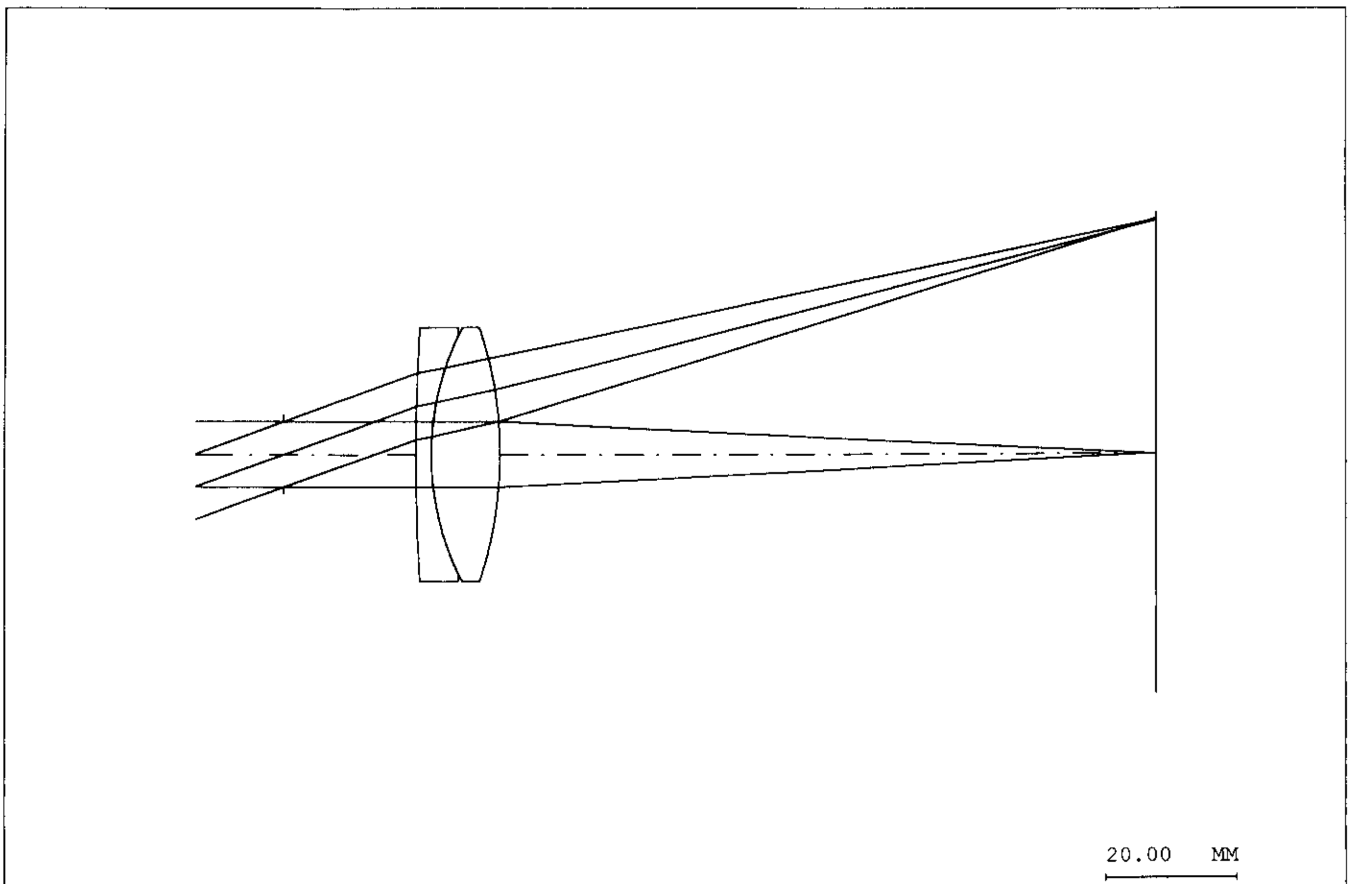

A
B
B'
A'

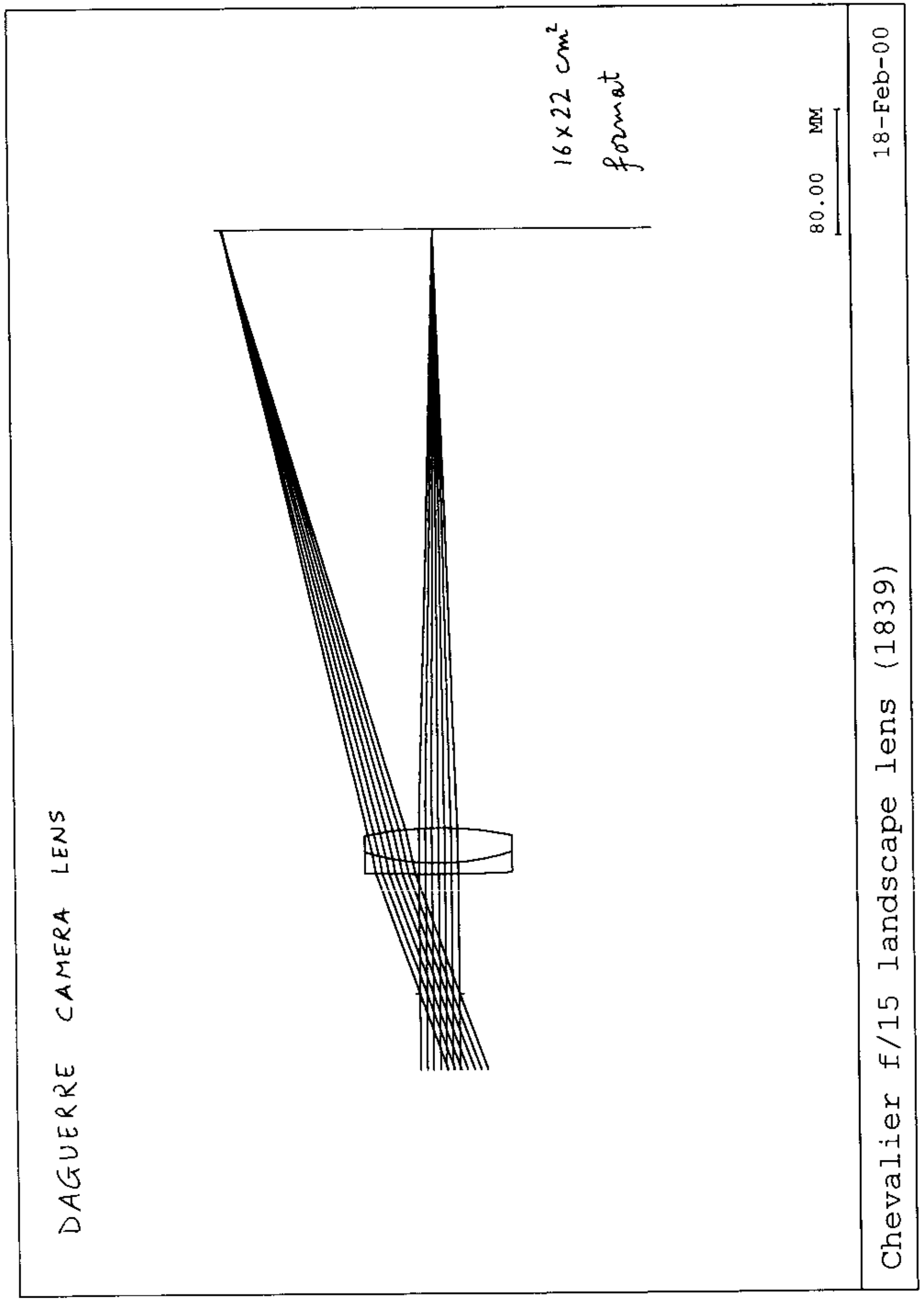

15:31:57
20.00 MM
ORA 18-Feb-00



f/3 doublet, field angle 20 deg ORA 18-Feb-00

15:24:19

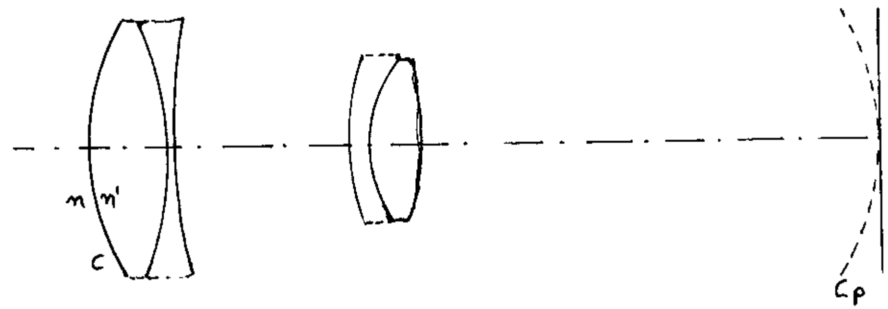




The Petzval sum

... For help with his calculations he approached the Archduke Ludwig, Director General of Artillery in the Austrian army, who ordered that "Corporals Löschner and Haim and eight gunners skilled in computing be placed at his disposal." With this somewhat unusual help, in only about six months Petzval completed the design of two objectives...

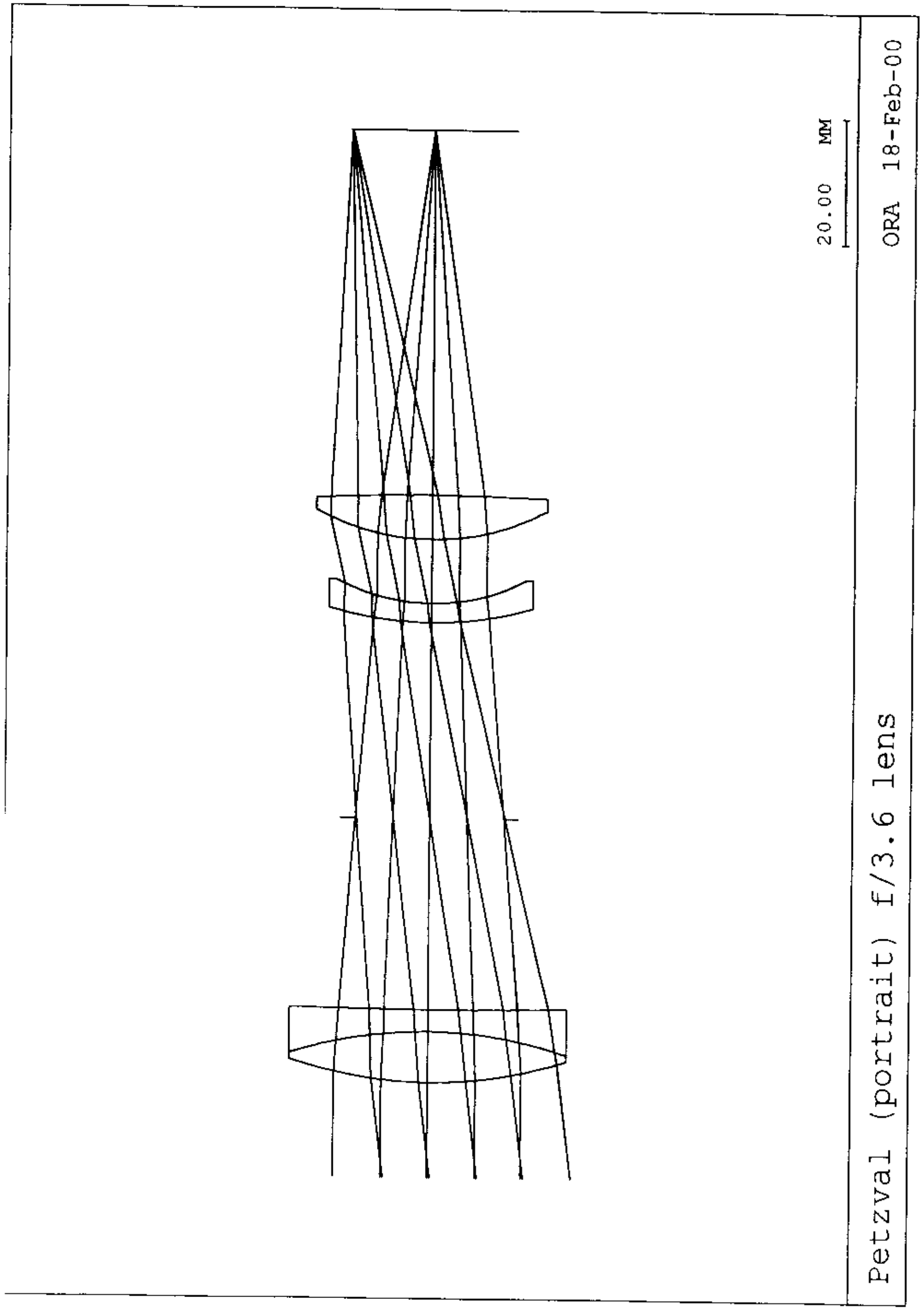
R. Kingslake, *A history of the photographic lens*, Academic Press, San Diego 1989, p. 35.



$$K = c\,(n' - n) \qquad \text{surface power} \qquad (c = \frac{1}{R})$$

$$P = \sum \frac{K}{n\,n'} \qquad \text{Petzval sum}$$

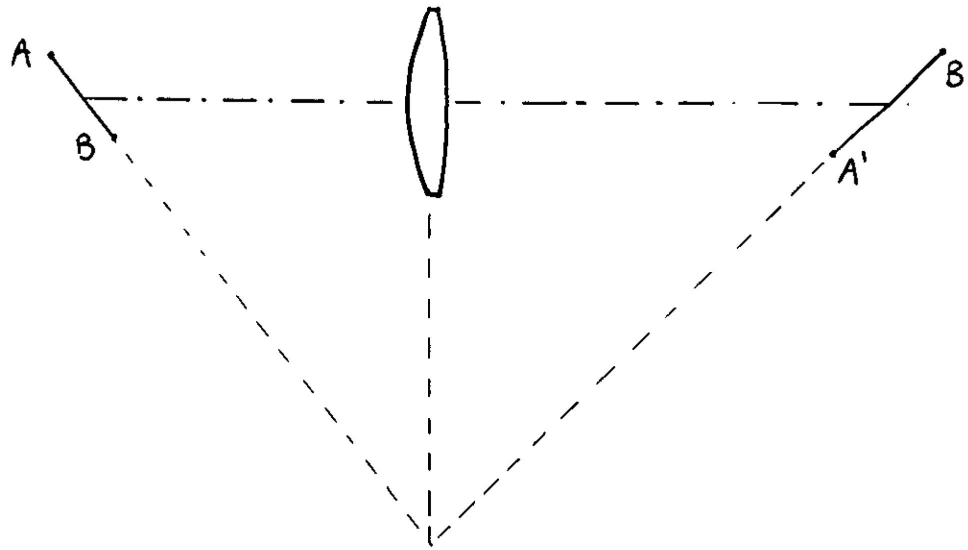
$$c_P = -P \qquad \text{Petzval curvature}$$



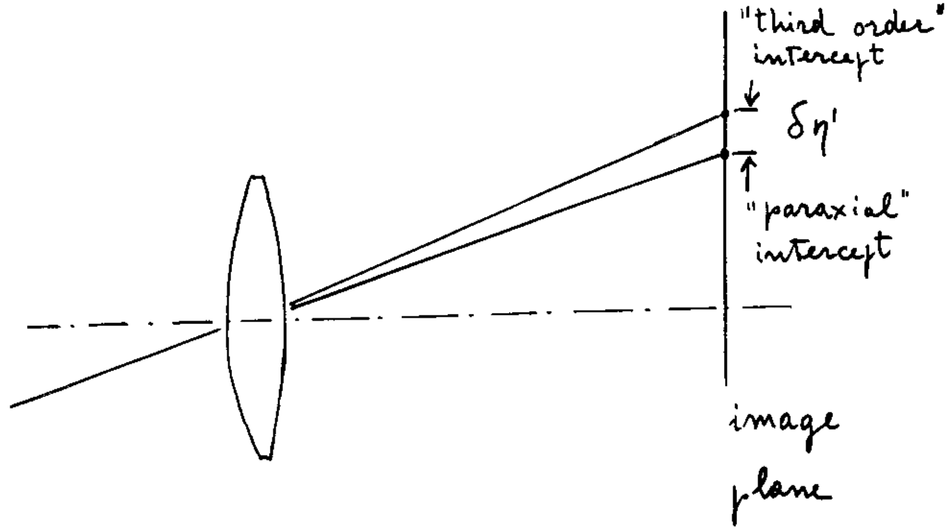
The Scheimpflug condition

"Captain Theodor Scheimpflug of the Austrian army pointed out early in the present century that if the object plane is tilted relative to the lens axis, the image plane will also be tilted in such a way that the object plane, image plane, and median plane through the lens will all meet."

R. Kingslake, *Optical system design*, Academic Press, Orlando 1983, p. 58.

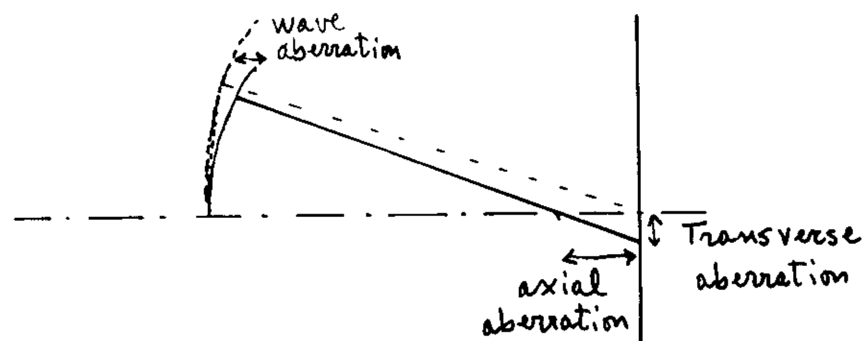


Aberrations



$\delta\eta'$ results of 5 independent terms ("aberrations").

Aberrations are made of surface contributions, linearly added.



Seidel aberrations:

Spherical aberration
Coma
Astigmatism
Field curvature
Distortion

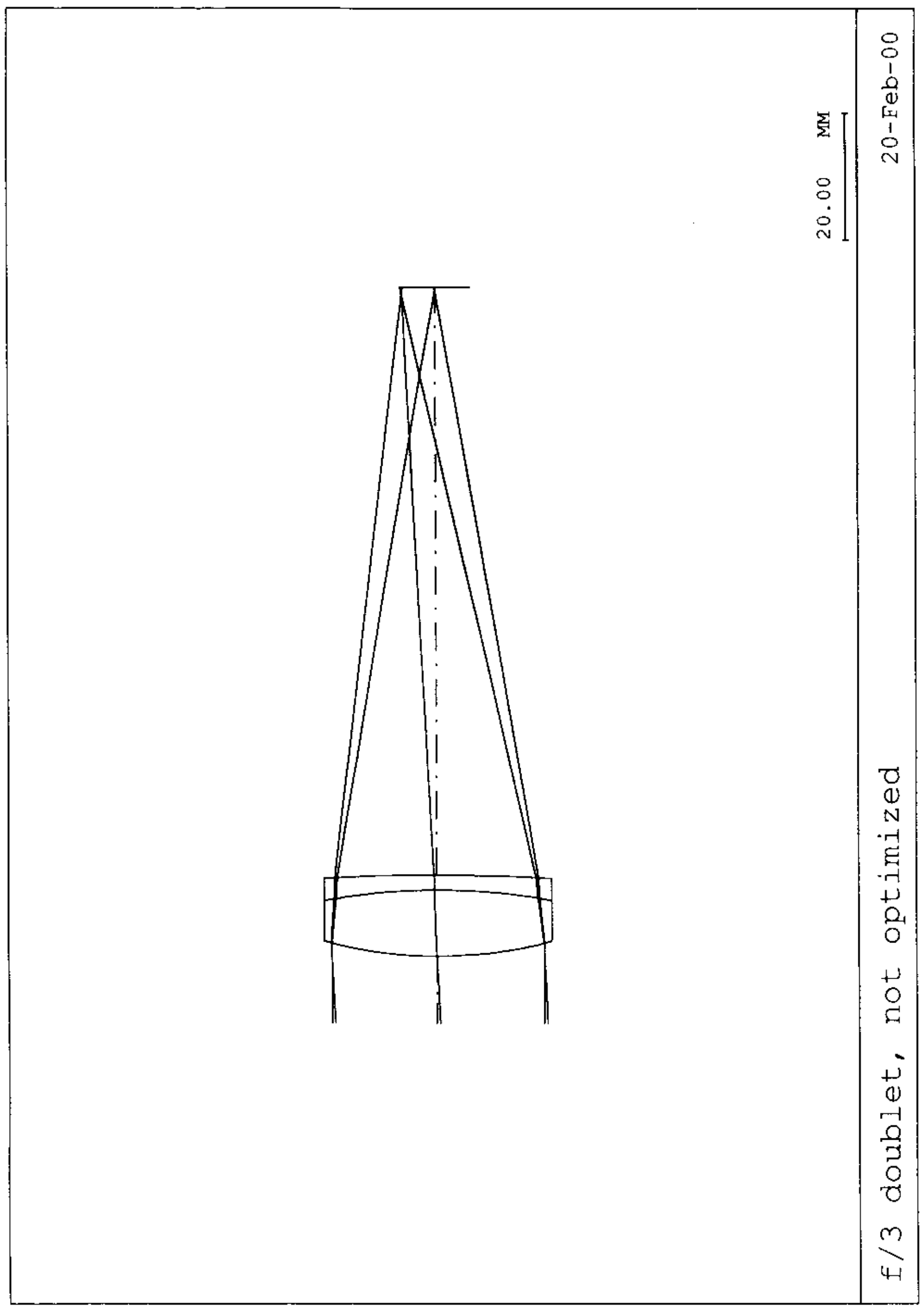
The aberrations are the result of approximations (power series expansion).

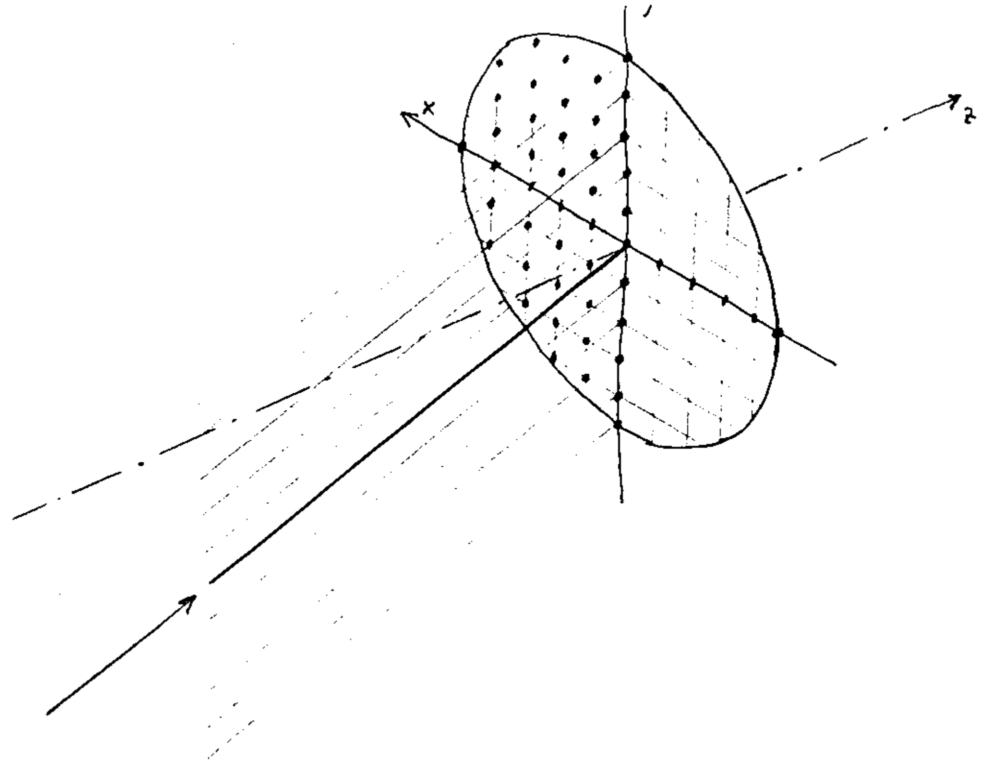
Aberrations can be approached as:

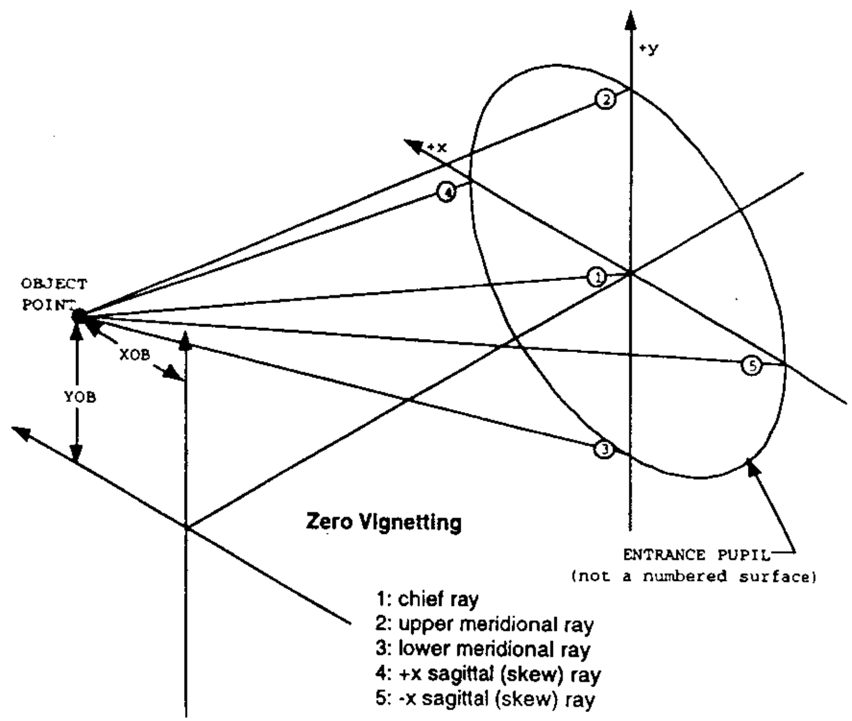
axial quantities	2nd order analysis
transverse quantities	3rd order analysis
wave quantities	4th order analysis

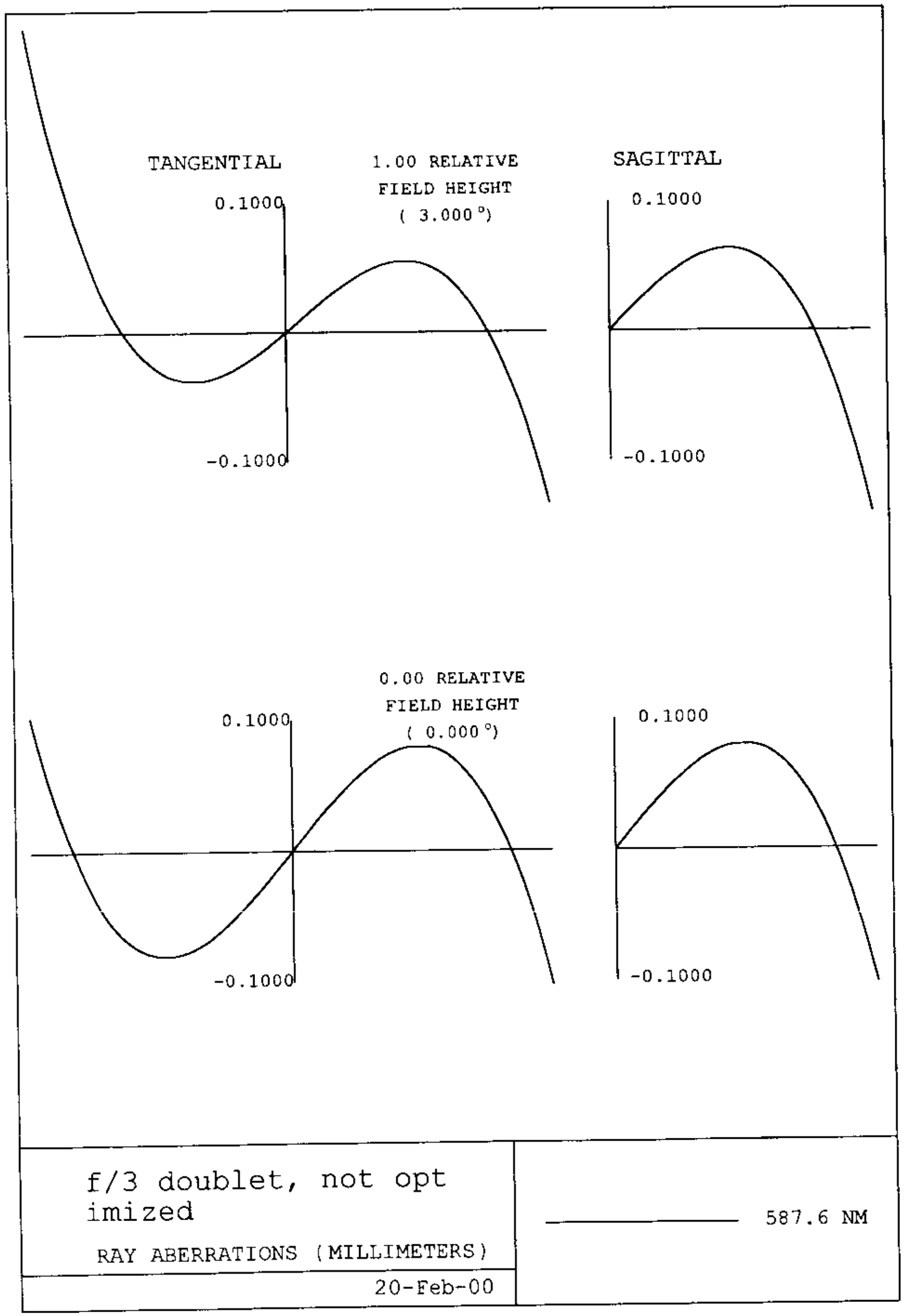
Chromatic aberrations:

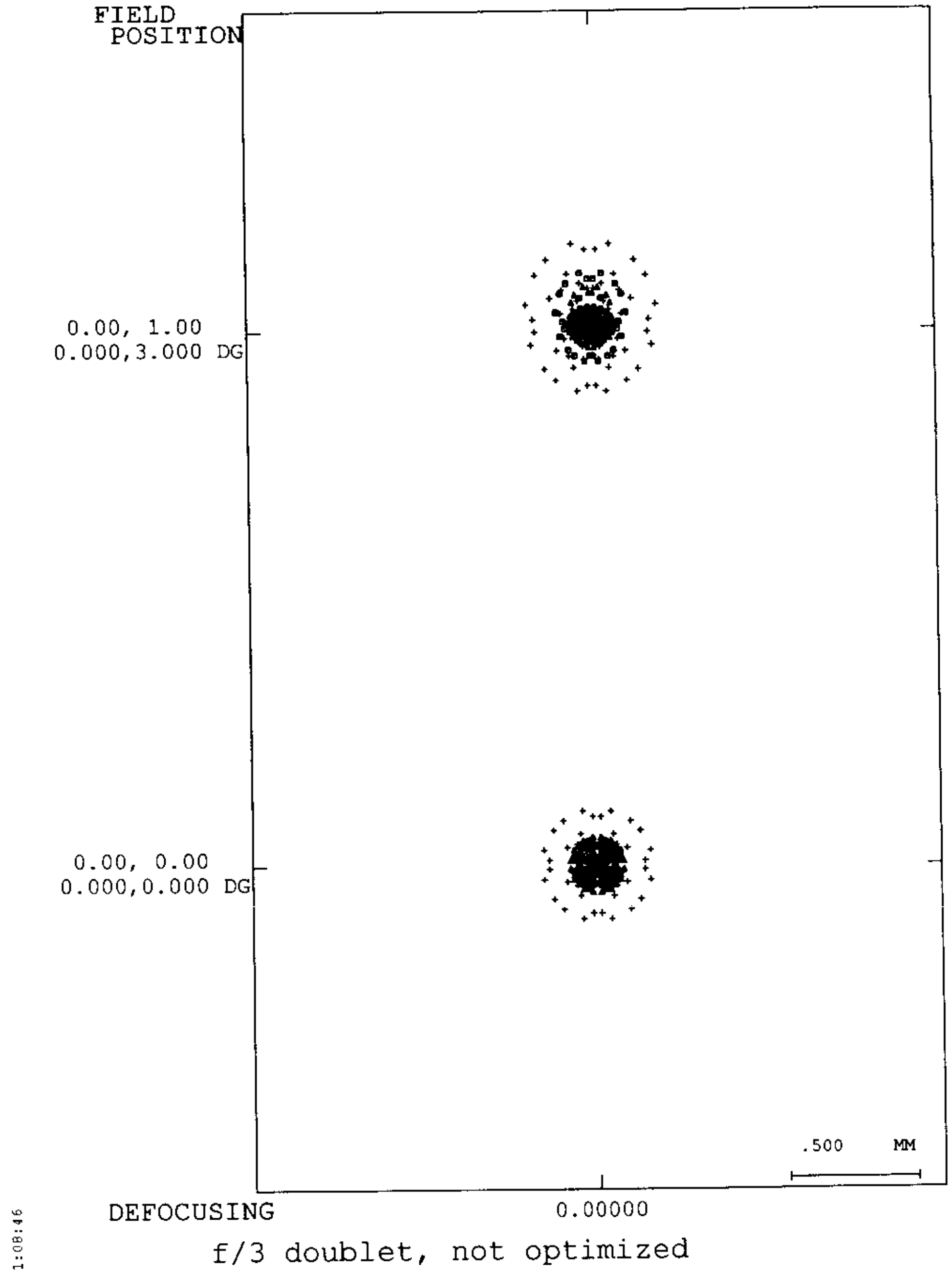
Axial color
Lateral color


20.00 MM
20-Feb-00
f/3 doublet, not optimized


x
y
z

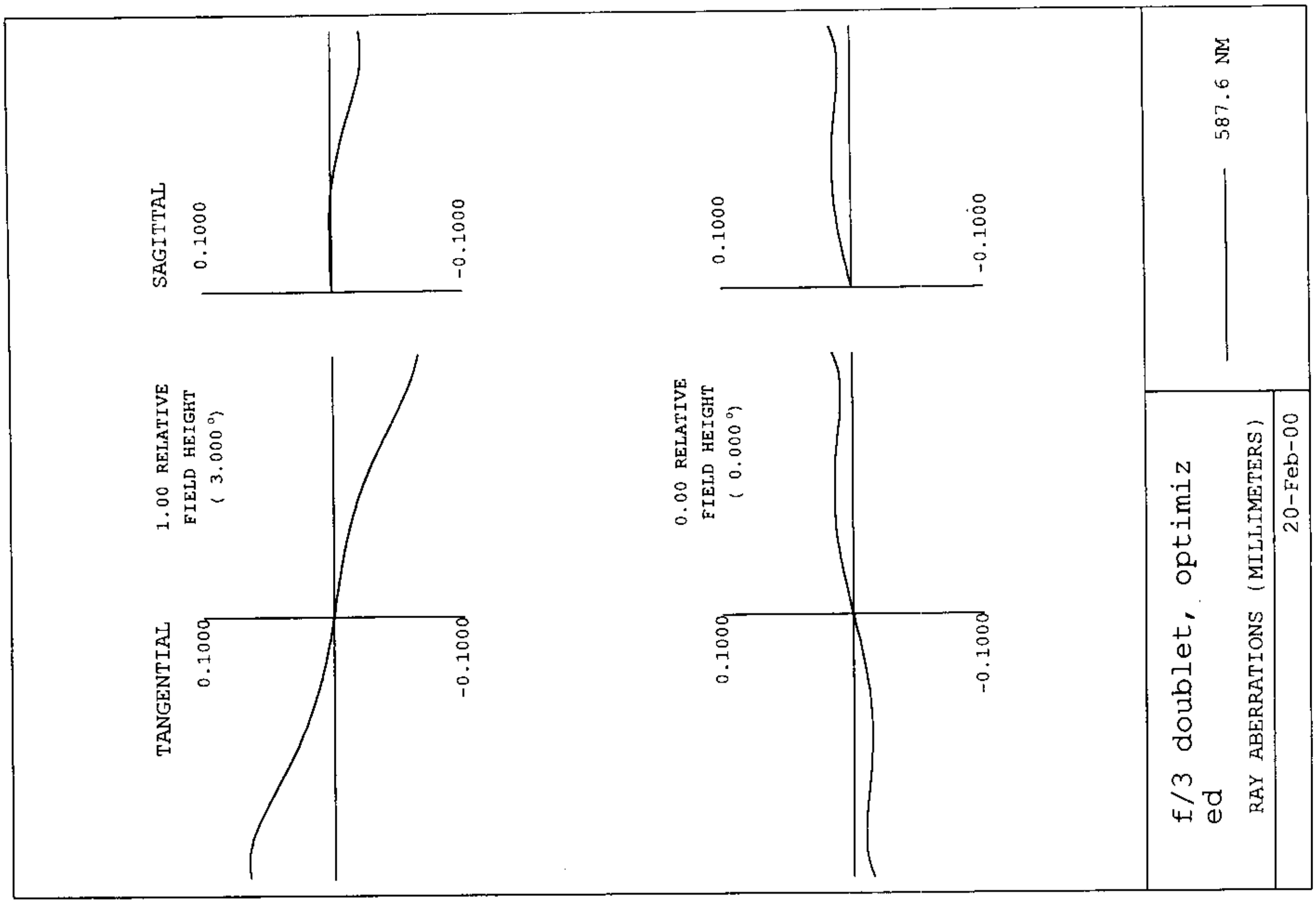

+y
+x
OBJECT POINT
XOB
YOB
ENTRANCE PUPIL
(not a numbered surface)
Zero Vignetting
1: chief ray
2: upper meridional ray
3: lower meridional ray
4: +x sagittal (skew) ray
5: -x sagittal (skew) ray


TANGENTIAL
1.00 RELATIVE
FIELD HEIGHT
(3.000°)
SAGITTAL
0.1000
-0.1000
0.00 RELATIVE
FIELD HEIGHT
(0.000°)
f/3 doublet, not opt
imized
RAY ABERRATIONS (MILLIMETERS)
20-Feb-00
587.6 NM

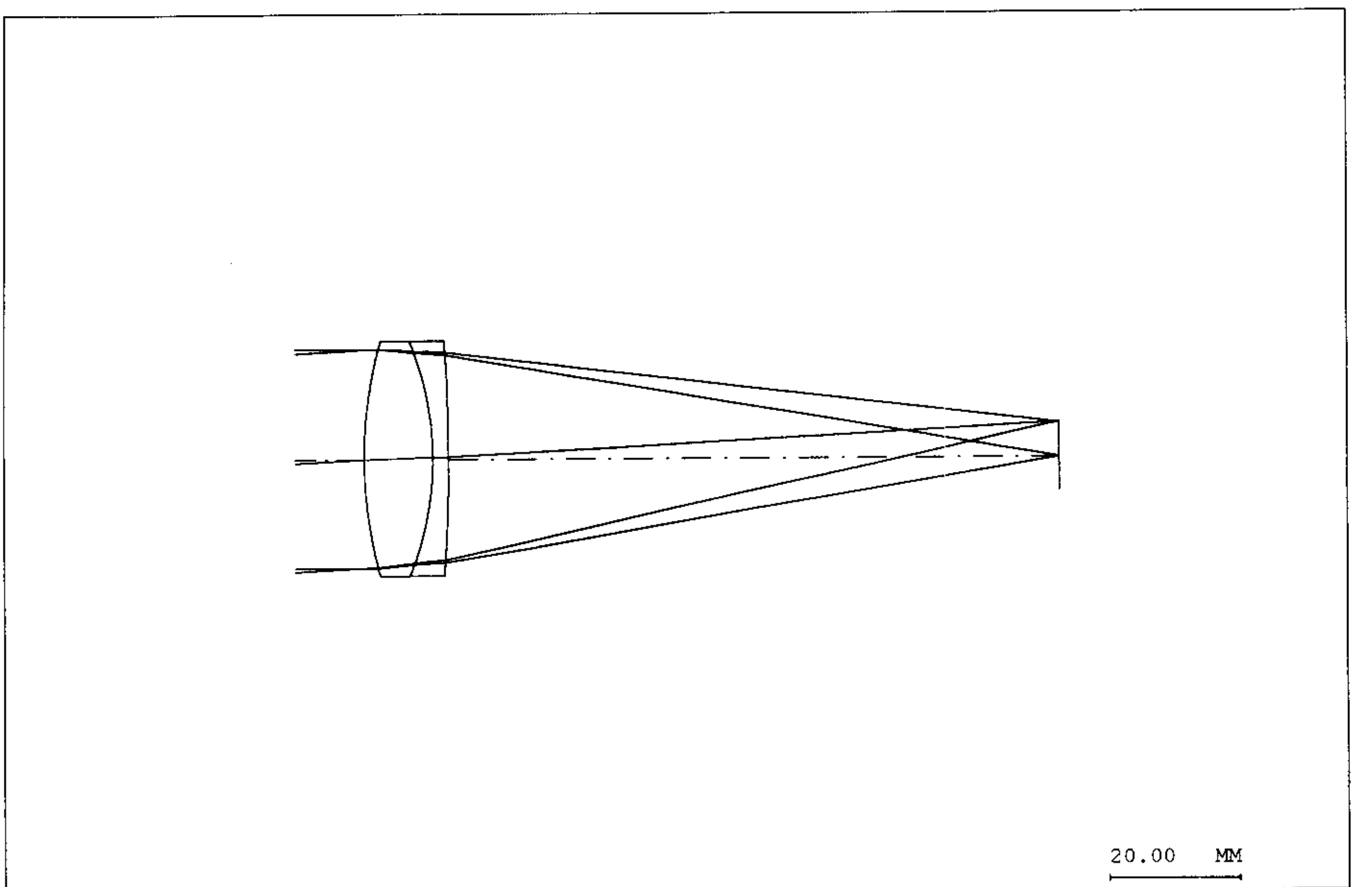

FIELD
POSITION
0.00, 1.00
0.000,3.000 DG
0.00, 0.00
0.000,0.000 DG
.500 MM
DEFOCUSING
0.00000
f/3 doublet, not optimized
11:08:46

```
f/3 doublet, not optimized

                 RDY              THI      RMD        GLA
> OBJ:        INFINITY         INFINITY
  STO:        70.50410        10.345634           BSM24_OHARA
    2:      -100.00000         2.351280           SF1_SCHOTT
    3:      -316.13853        92.451433
  IMG:        INFINITY         0.000000

SPECIFICATION DATA
   FNO        3.00000
   DIM             MM
   WL          656.30    587.60    486.10
   YAN        0.00000       3.00000

REFRACTIVE INDICES
    GLASS CODE                  656.30       587.60       486.10
   BSM24_OHARA                1.614254     1.617644     1.625478
   SF1_SCHOTT                 1.710311     1.717355     1.734628

INFINITE CONJUGATES
   EFL        100.6356
   BFL         93.9199
   FFL        -99.5022
   FNO          3.0000
   IMG DIS     92.4514
   OAL         12.6969
   PARAXIAL IMAGE
    HT          5.2741
   ANG          3.0000
   ENTRANCE PUPIL
    DIA        33.5452
    THI         0.0000
   EXIT PUPIL
    DIA        33.9273
    THI        -7.8619

      THIRD ORDER ANALYSIS   -   Wavelength =   587.6 NM

     Spherical  Tangential Tangential  Sagittal     Petzval     Distortion
     aberration coma       astigmatism astigmatism  blur

STO  -0.159901  -0.105677  -0.035834   -0.020313    -0.012553  -0.004475
  2   0.090156  -0.031530   0.004508    0.002057     0.000832  -0.000240
  3  -0.268183   0.188051  -0.047017   -0.017714    -0.003063   0.004140

SUM  -0.337928   0.050844  -0.078343   -0.035970    -0.014784  -0.000574
```

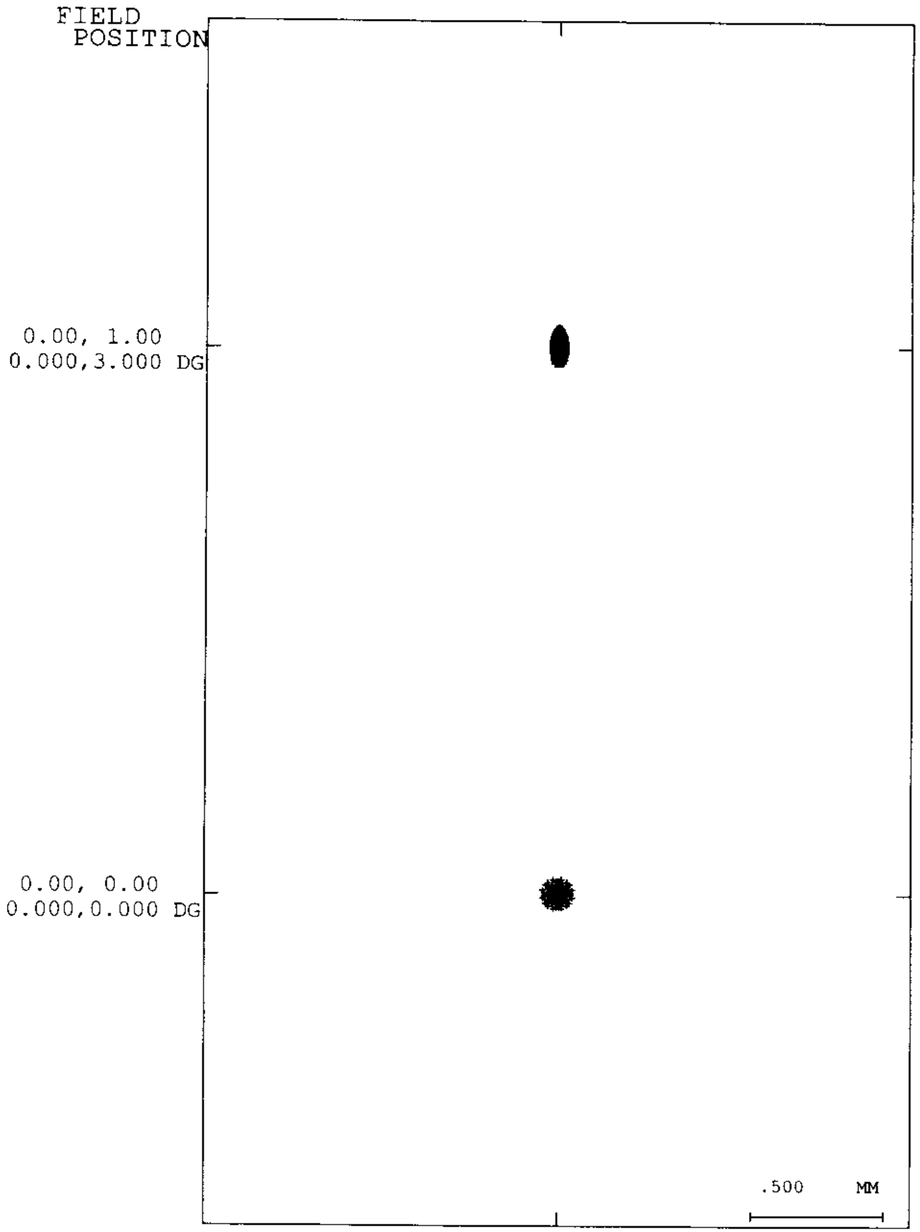
```
f/3 doublet, optimized

                 RDY              THI      RMD        GLA
> OBJ:        INFINITY         INFINITY
  STO:        66.53923        10.345634           BSM24_OHARA
    2:       -47.03954         2.351280           SF1_SCHOTT
    3:      -243.06858        92.451433
  IMG:        INFINITY         0.000000

SPECIFICATION DATA
   FNO        3.00000
   DIM             MM
   WL          656.30    587.60    486.10
   YAN        0.00000       3.00000

REFRACTIVE INDICES
    GLASS CODE                  656.30       587.60       486.10
   BSM24_OHARA                1.614254     1.617644     1.625478
   SF1_SCHOTT                 1.710311     1.717355     1.734628

INFINITE CONJUGATES
   EFL         99.6501
   BFL         92.7400
   FFL        -98.7121
   FNO          3.0000
   IMG DIS     92.4514
   OAL         12.6969
   PARAXIAL IMAGE
    HT          5.2224
   ANG          3.0000
   ENTRANCE PUPIL
    DIA        33.2167
    THI         0.0000
   EXIT PUPIL
    DIA        33.5324
    THI        -7.8571

      THIRD ORDER ANALYSIS   -   Wavelength =   587.6 NM

     Spherical  Tangential Tangential  Sagittal     Petzval     Distortion
     aberration coma       astigmatism astigmatism  blur

STO  -0.182880  -0.115195  -0.037229   -0.021104    -0.013042  -0.004431
  2   0.400384  -0.071022   0.005934    0.003134     0.001734  -0.000185
  3  -0.308837   0.202142  -0.048008   -0.018607    -0.003906   0.004060

SUM  -0.091334   0.015925  -0.079304   -0.036577    -0.015214  -0.000557
```



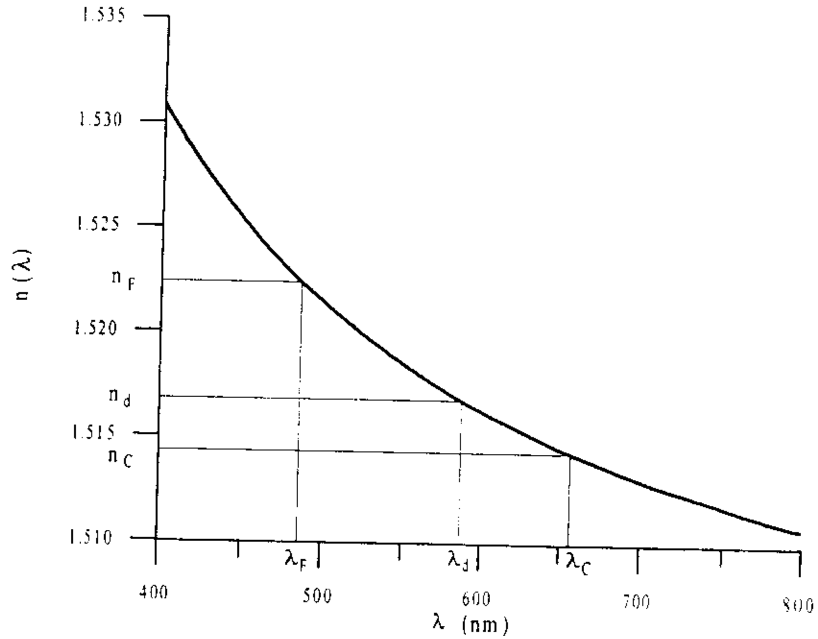
11:14:00



f/3 doublet, optimized 20-Feb-00



f/3 doublet, optimized



Sellmeier formula:

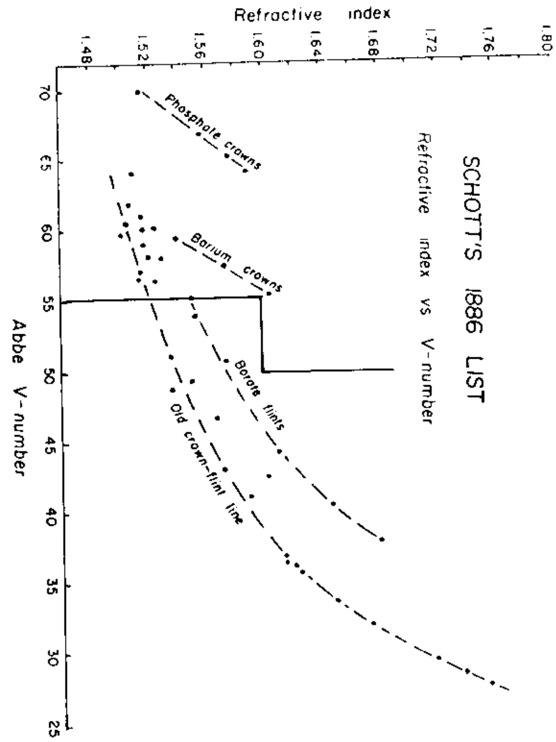
$$n^2(\lambda) - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

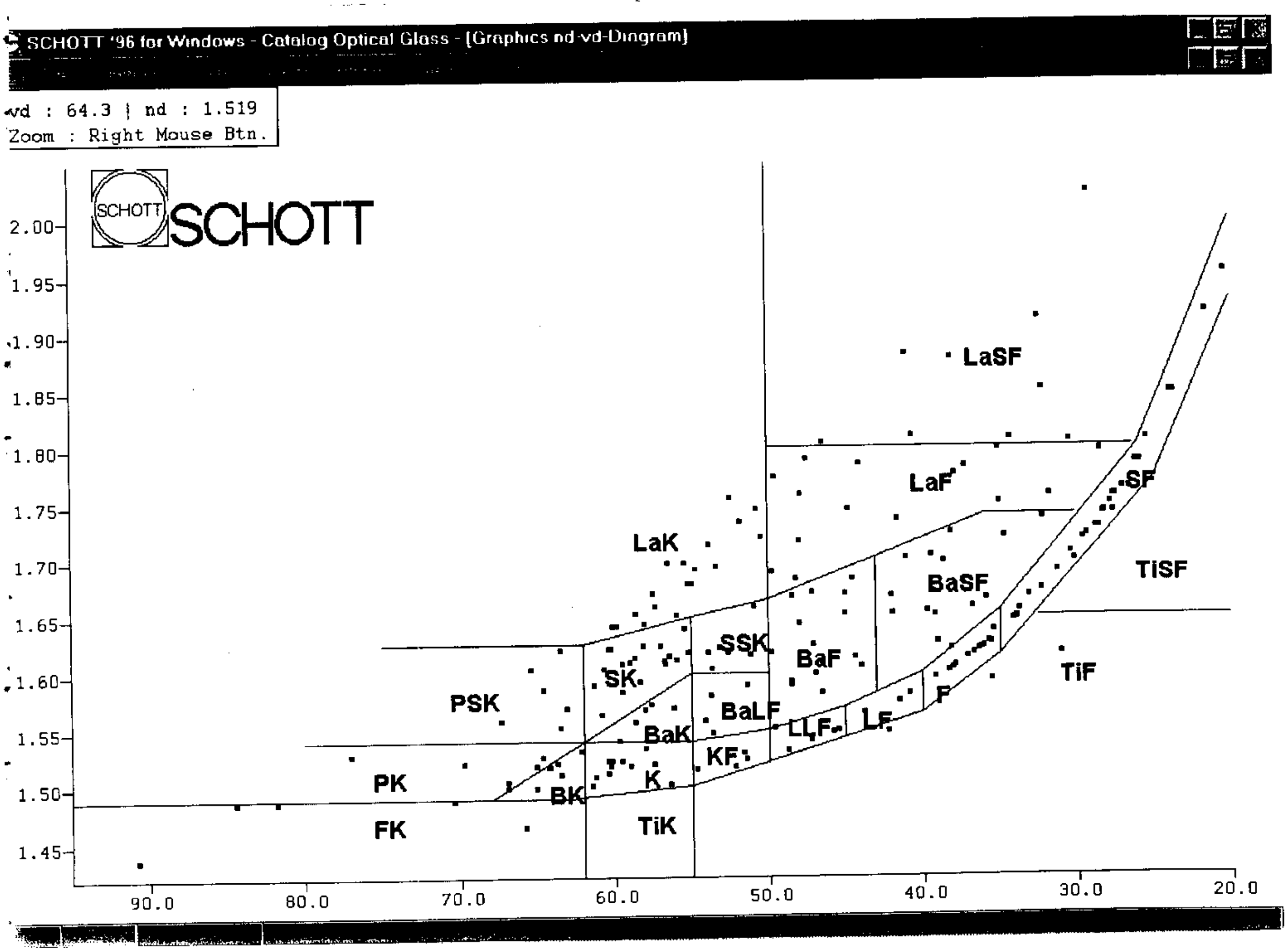
Spectral lines (wavelength λ in nm):

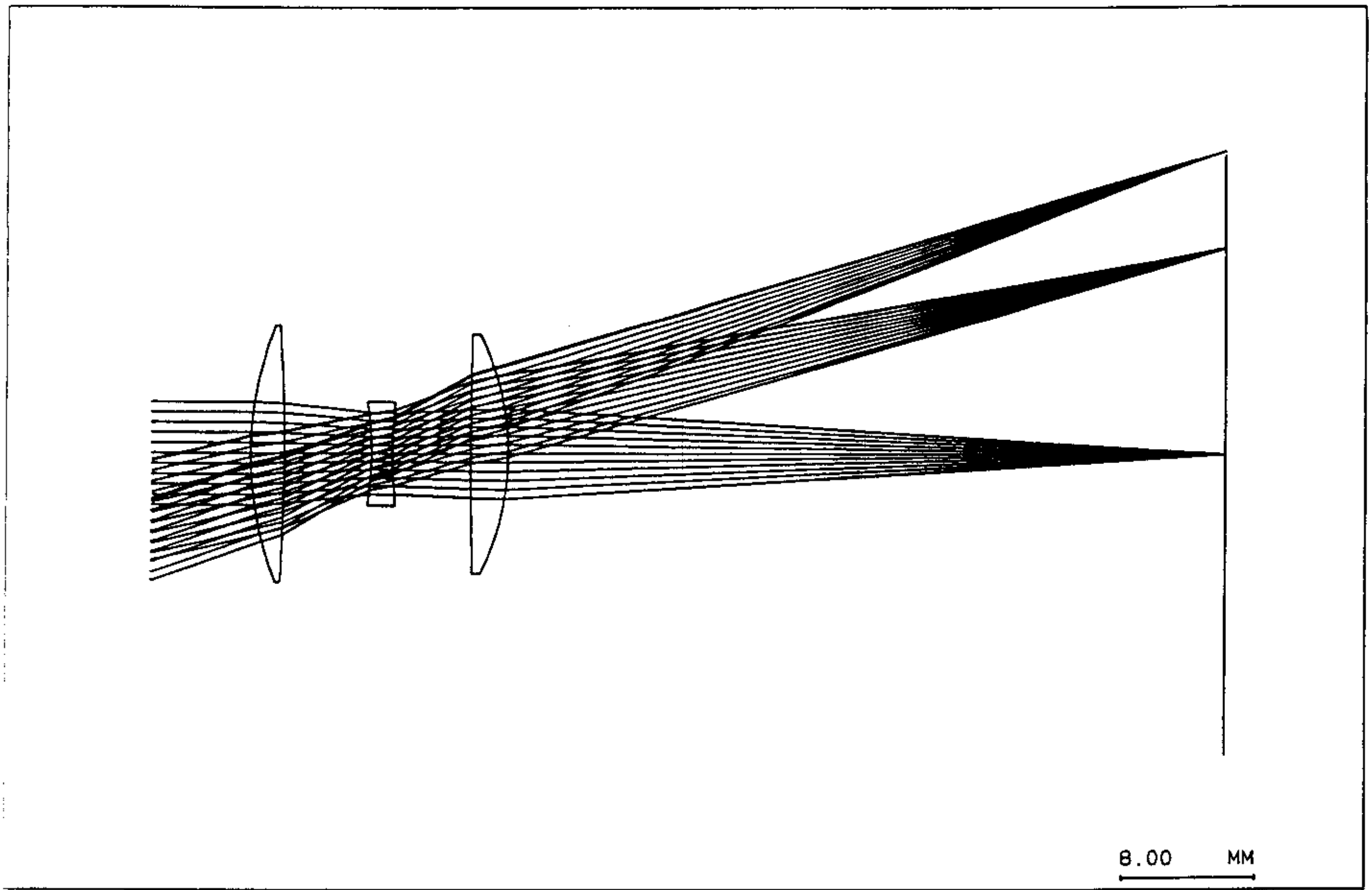
H	g	F'	F	e	d	C'	C	r
Hg	Hg	Cd	H	Hg	He	Cd	H	He
404.7	435.8	480.0	486.1	546.1	587.6	643.8	656.3	706.5

Abbe number:

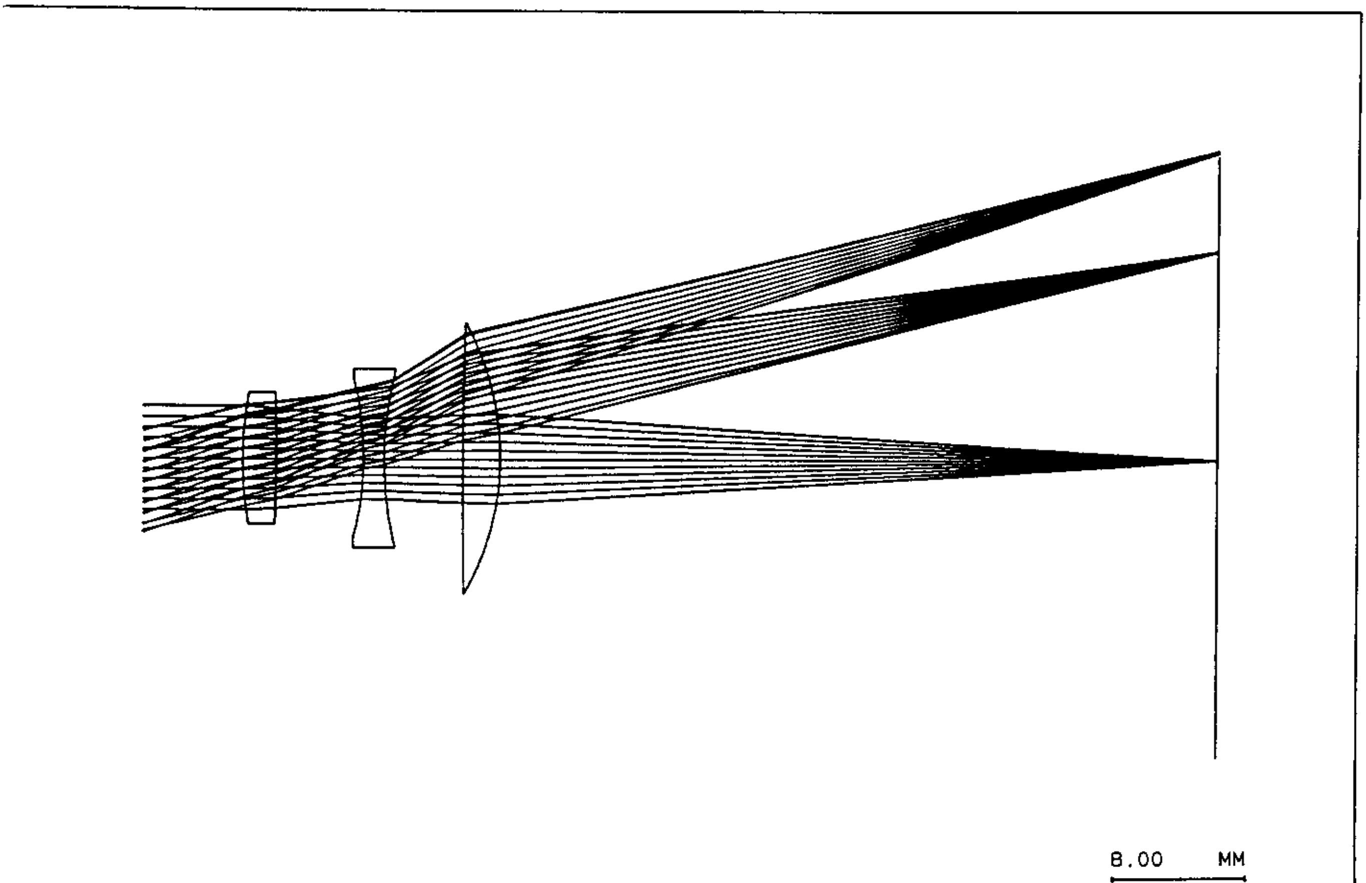
$$V_d = \frac{n_d - 1}{n_F - n_C}$$


SCHOTT'S 1886 LIST
Refractive index vs V-number
Refractive index
Abbe V-number
Phosphate crowns
Barium crowns
Borate flints
Old crown-flint line

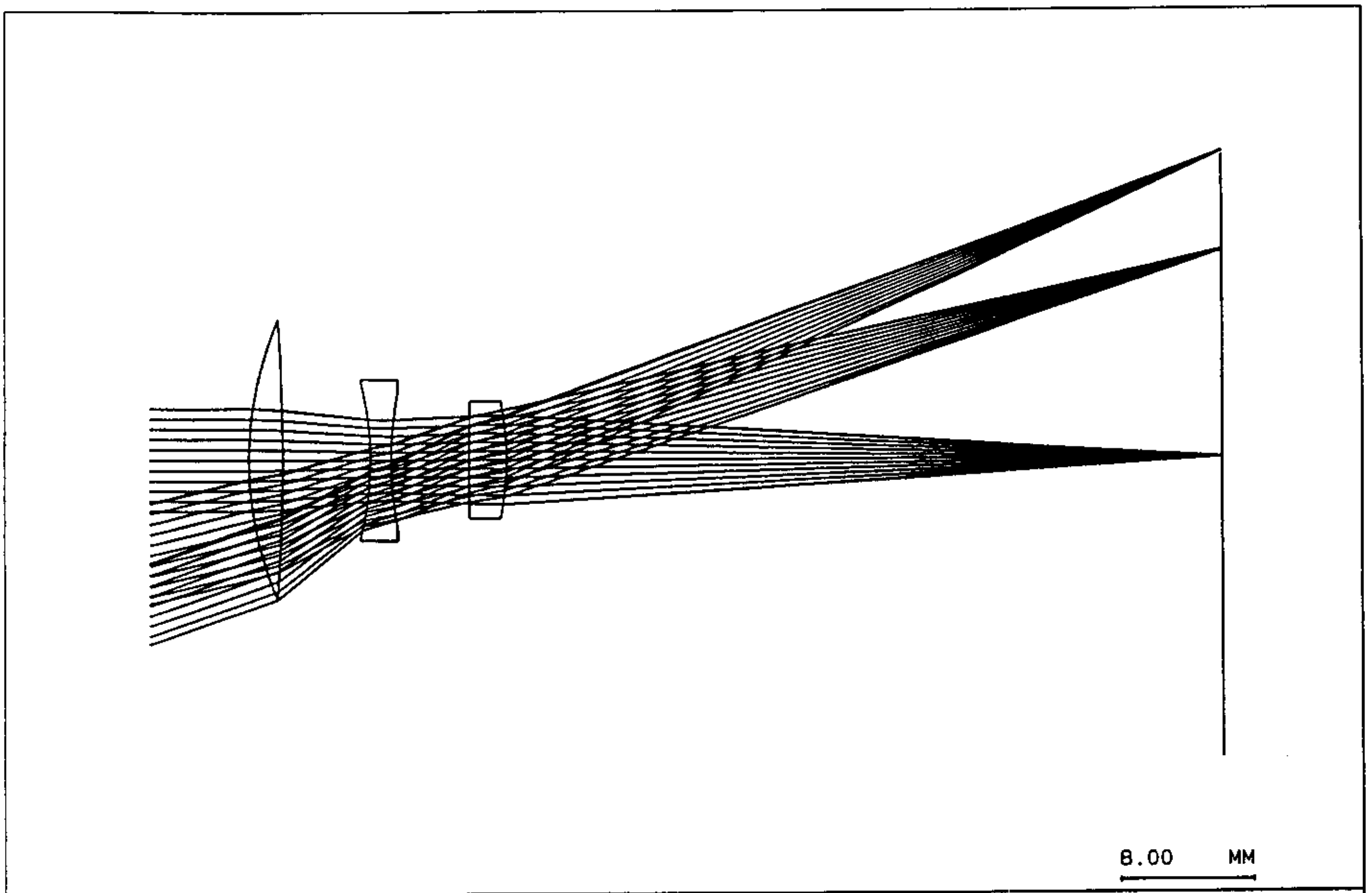

SCHOTT '96 for Windows - Catalog Optical Glass - [Graphics nd-vd-Diagram]
vd : 64.3 | nd : 1.519
Zoom : Right Mouse Btn.
SCHOTT
LaSF
LaF
LaK
BaSF
TiSF
SF
SSK
BaF
SK
PSK
TiF
BaLF
LLF
LF
F
BaK
KF
PK
BK
K
FK
TiK



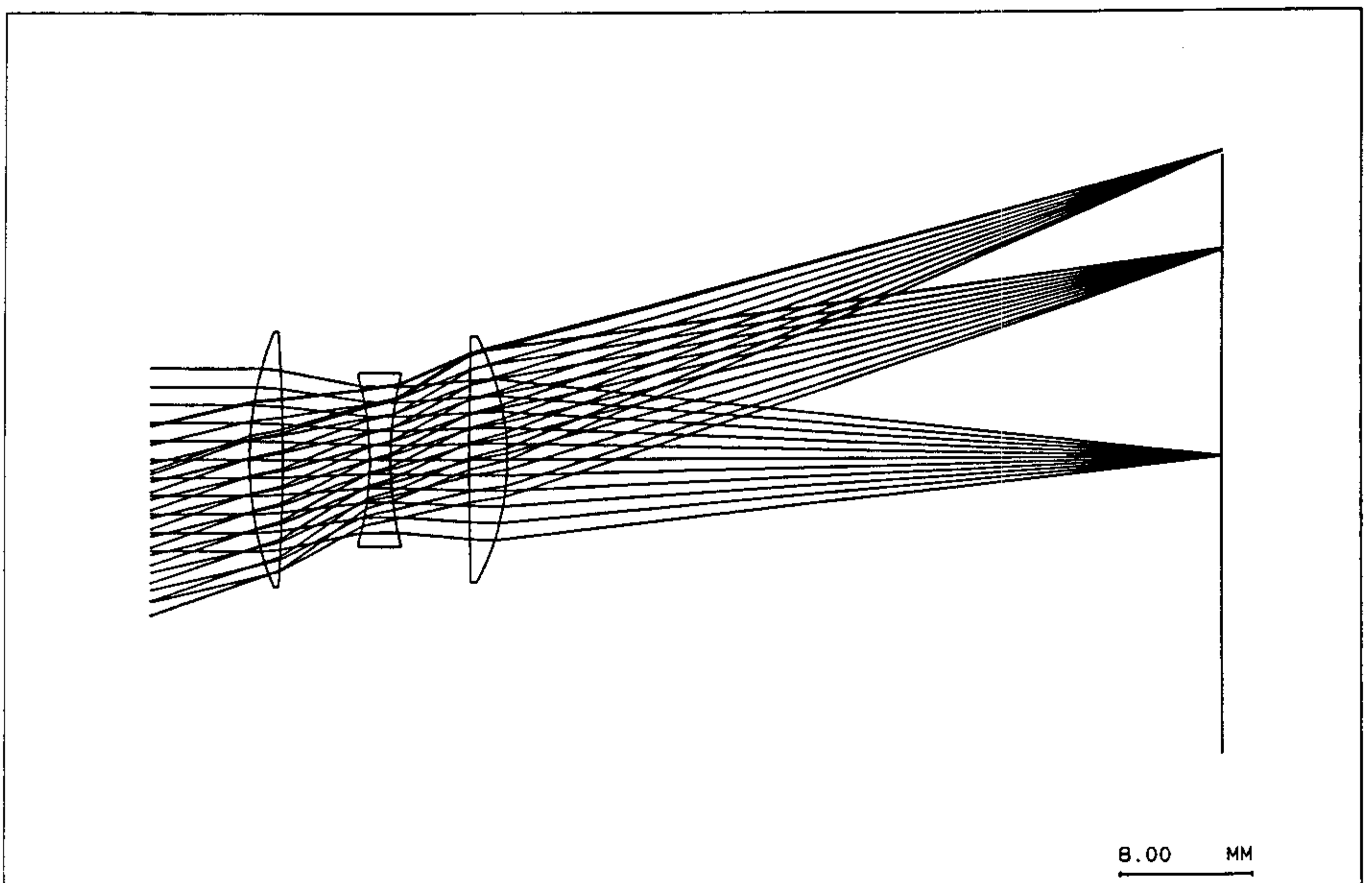
Cooke Triplet f/8 ORA 29-Oct-97



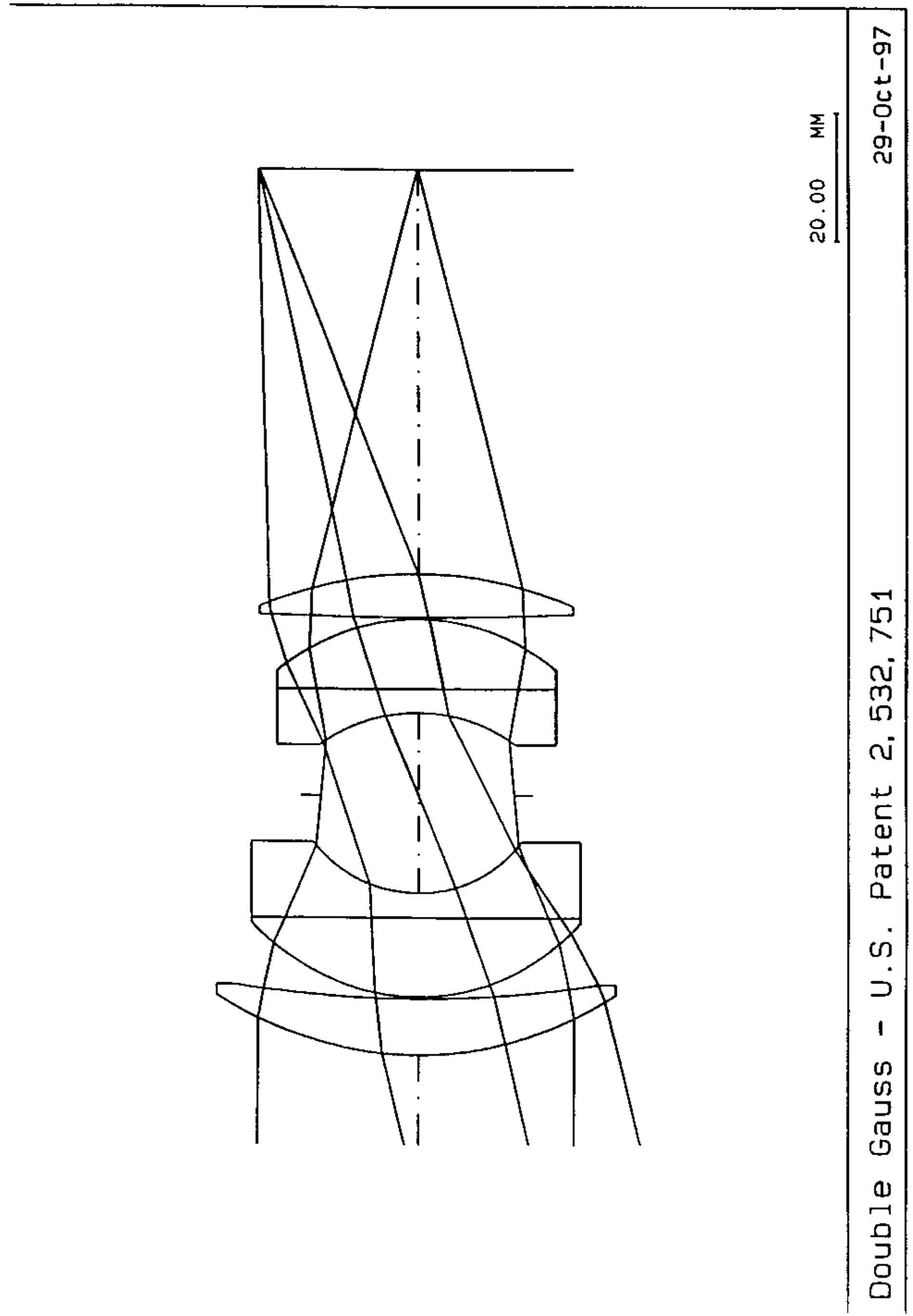
Cooke Triplet f/8 ORA 29-Oct-97



Cooke Triplet f/8 ORA 29-Oct-97



Cooke Triplet f/4.5 ORA 29-Oct-97



$r_1 =$ $e_{1.2} =$ $n =$ $n =$ $n =$ $\nu =$

$r_2 =$ $e_{2.3} =$ $n =$ $n =$ $n =$ $\nu =$

$r_3 =$ $e_{3.4} =$ $n =$ $n =$ $n =$ $\nu =$

$r_4 =$

1°	h	h				
		$1/r$				
	χ	sen χ				
	$\chi/2$	sen $\chi/2$				
		sen $\chi/2$				
		2		03010300		03010300
	x	r				
	$-VH$	VH				
	$x - VH$	$x - VH$				
	χ	h				
	$-\omega$	tag ω				
	φ	sen φ				
	χ	n				
	$-\varphi'$	$1/n'$				
	ω'_1	sen φ'				
	ζ	$1/$sen ω'				
	x_{cs}	r				
	$-e$	x_{cs}				
2°	x					
	$-r$	$1/r$				
	$x - r$	$x - r$				
	$\omega = \omega'_1$	sen ω				
	φ	sen φ				
	χ	n				
		$1/n'$				
	$-\varphi'$	sen φ'				
	ω'_2	$1/$sen ω'				
	r	r				
	x_{cs}	x_{cs}				
	$-e$					
3°	x					
	$-r$	$1/r$				
	$x - r$	$x - r$				
	$\omega = \omega'_2$	sen ω				
	φ	sen φ				
	χ	n				
		$1/n'$				
	$-\varphi'$	sen φ'				
	ω'_3	$1/$sen ω'				
	r	r				
	x_{cs}	x_{cs}				
	$-e$					
4°	x					
	$-r$	$1/r$				
	$x - r$	$x - r$				
	$\omega = \omega'_3$	sen ω				
	φ	sen φ				
	χ	n				
		$1/n'$				
	$-\varphi'$	sen φ'				
	ω'_4	$1/$sen ω'				
	r	r				
	x_{cs}	x_{cs}				
	$-e$					
	x					

SYSTEM DEVELOPMENT

Physics problem - phenomenon

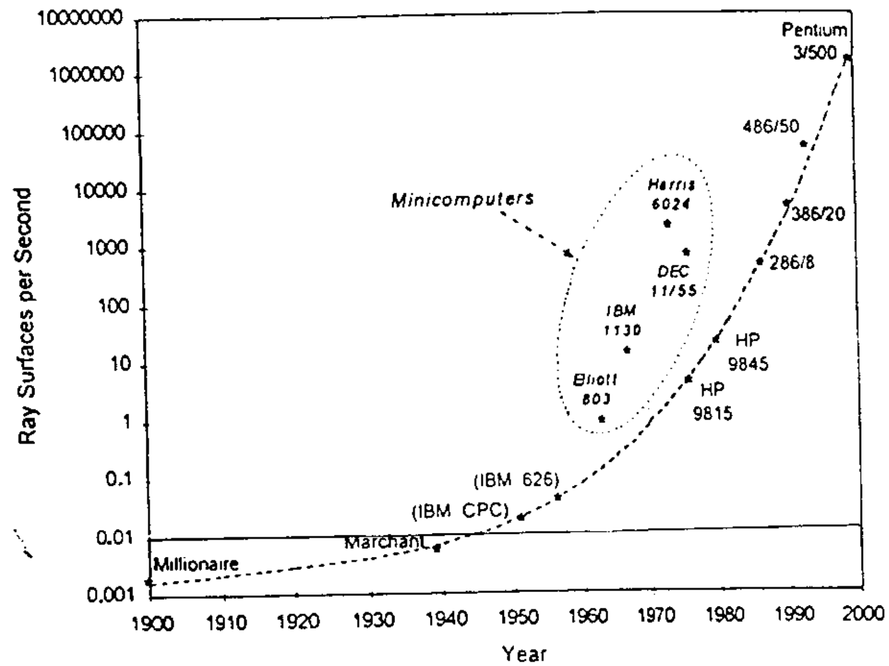
Model - specifications - constraints

Mechanics | Optics | Electronics | Informatics | ...

- Design:
  Layout
  Optimization
  Diagnostics
  Evaluation
  Tolerancing
  ...
  Drawings
- Fabrication
- Testing

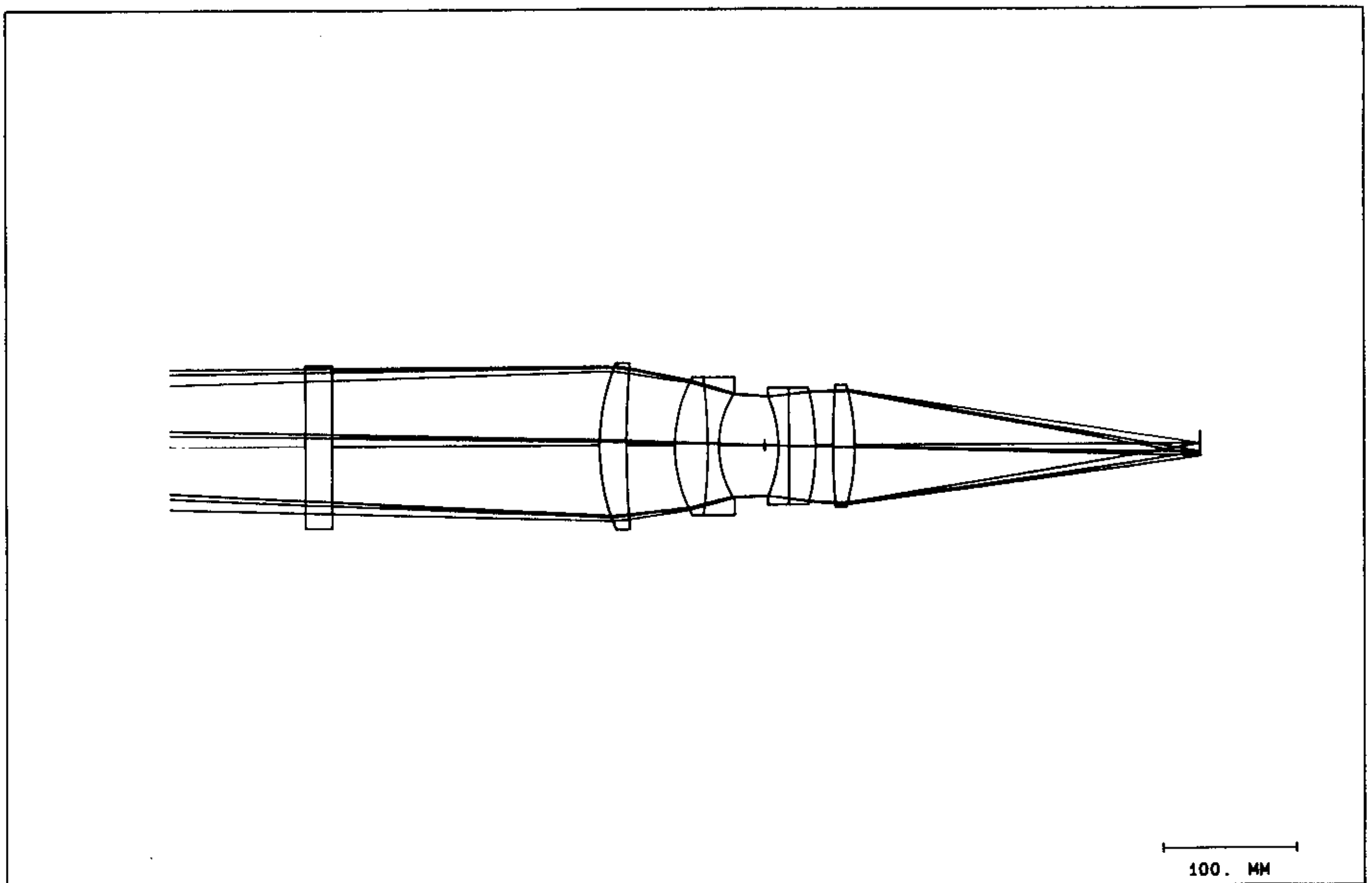
Assembly

End-to-end testing

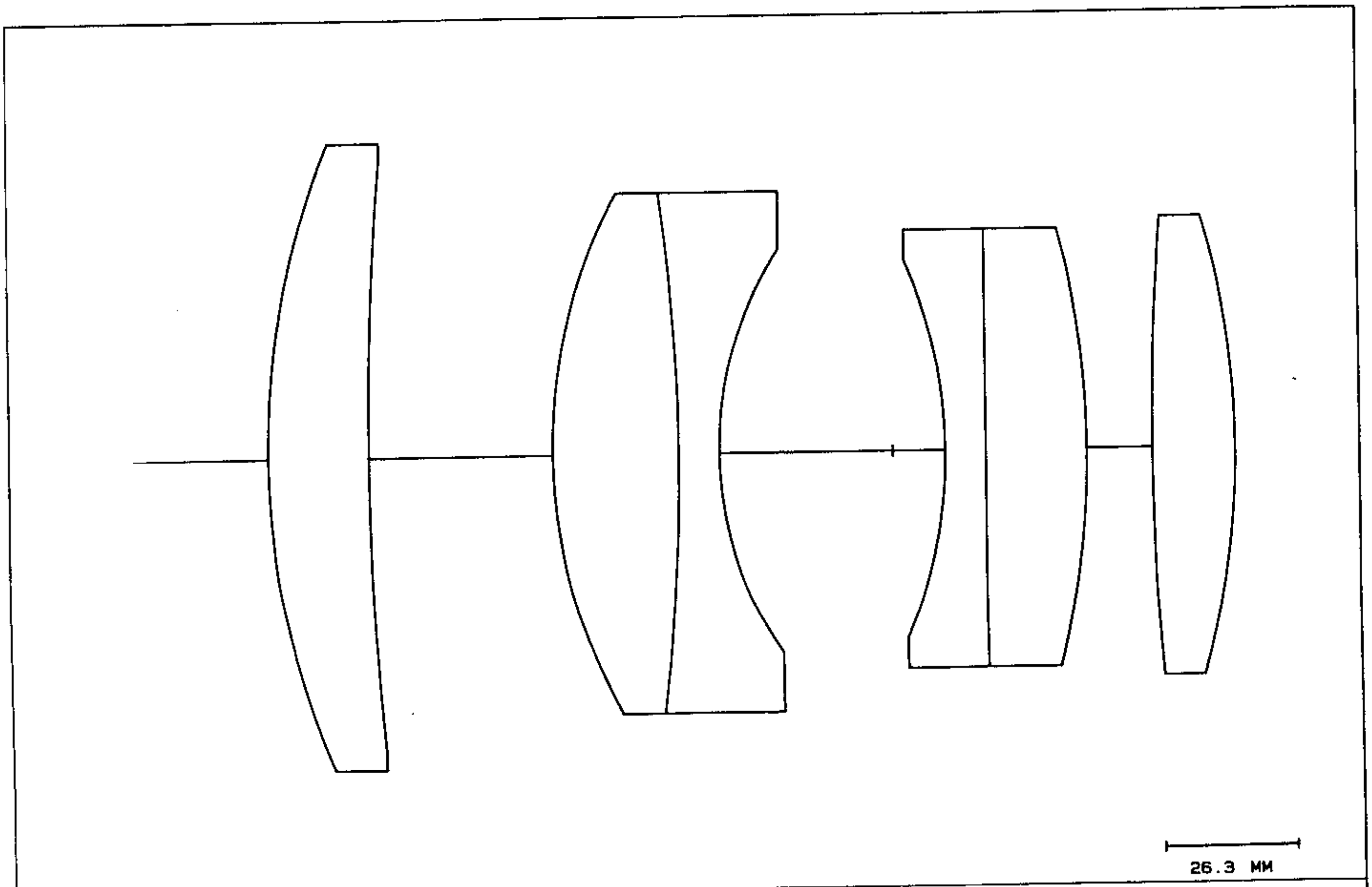


Ref.:

P. J. Rogers, "Optical design at the centenary of the Optical Society of London", *Journal of Optics A: Pure and Applied Optics* Vol. 1, pp. 769-775 (1999).



CISE LENS 14/88 SCALE 0.250 gm 26-FEB-92



CISE LENS 14/88 SCALE 0.950 gm 26-FEB-92

CISE LENS 14/88

	RDY	THI	GLA
OBJ:	1.0000E+10	1700.000000	
1:	1.0000E+10	20.000000	BK7_SCHOTT
2:	1.0000E+10	200.000000	
3:	161.85000	20.000000	SSKN5_SCHOTT
4:	644.00000	36.400000	
5:	107.83000	25.000000	SK16_SCHOTT
6:	-387.00000	8.000000	SF2_SCHOTT
7:	72.00000	34.460000	
STO:	1.0000E+10	10.330000	
9:	-93.92000	8.000000	F6_SCHOTT
10:	1.0000E+10	20.000000	SSKN8_SCHOTT
11:	-171.00000	12.930000	
12:	542.00000	16.410000	SK15_SCHOTT
13:	-163.65000	257.734210	
IMG:	1.0000E+10	0.000000	

APERTURE DATA/EDGE DEFINITIONS

CIR S1	58.884121
CIR S2	58.953342
CIR S3	60.058926
CIR S4	58.381687
CIR S5	49.634712
CIR S6	46.512066
CIR S7	39.633919
CIR S8	37.258354
CIR S9	37.114067
CIR S10	39.440716
CIR S11	41.695736
CIR S12	43.534634
CIR S13	43.763756

SPECIFICATION DATA

NAO	0.02915		
NFO	3		
FFO	-0.30000		
IFO	0.30000		
DIM	MM		
WL	1000.00	850.00	650.00
REF	2		
WTW	1	1	1
INI	gm		
XOB	0.00000	0.00000	0.00000
YOB	0.00000	35.00000	50.00000
VUY	0.00000	0.00000	0.00000
VLY	0.00000	0.00000	0.00000

REFRACTIVE INDICES

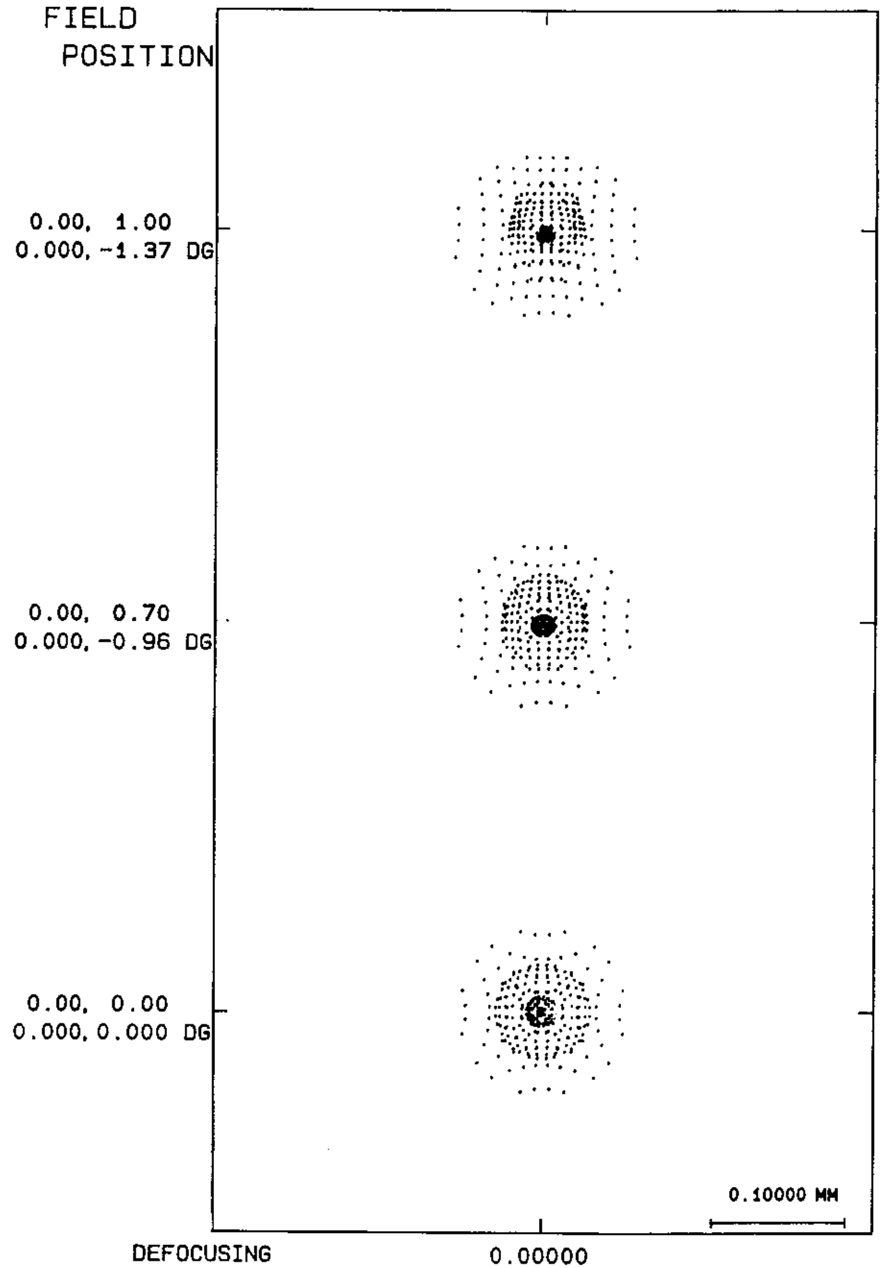
GLASS	CODE	1000.00	850.00	650.00
BK7_SCHOTT		1.507507	1.509845	1.514521
SSKN5_SCHOTT		1.644767	1.647920	1.654863
SK16_SCHOTT		1.608929	1.611717	1.617522
SF2_SCHOTT		1.628939	1.632969	1.642532
F6_SCHOTT		1.618583	1.622429	1.631494
SSKN8_SCHOTT		1.604605	1.607635	1.614292
SK15_SCHOTT		1.611248	1.614037	1.619989

INFINITE CONJUGATES

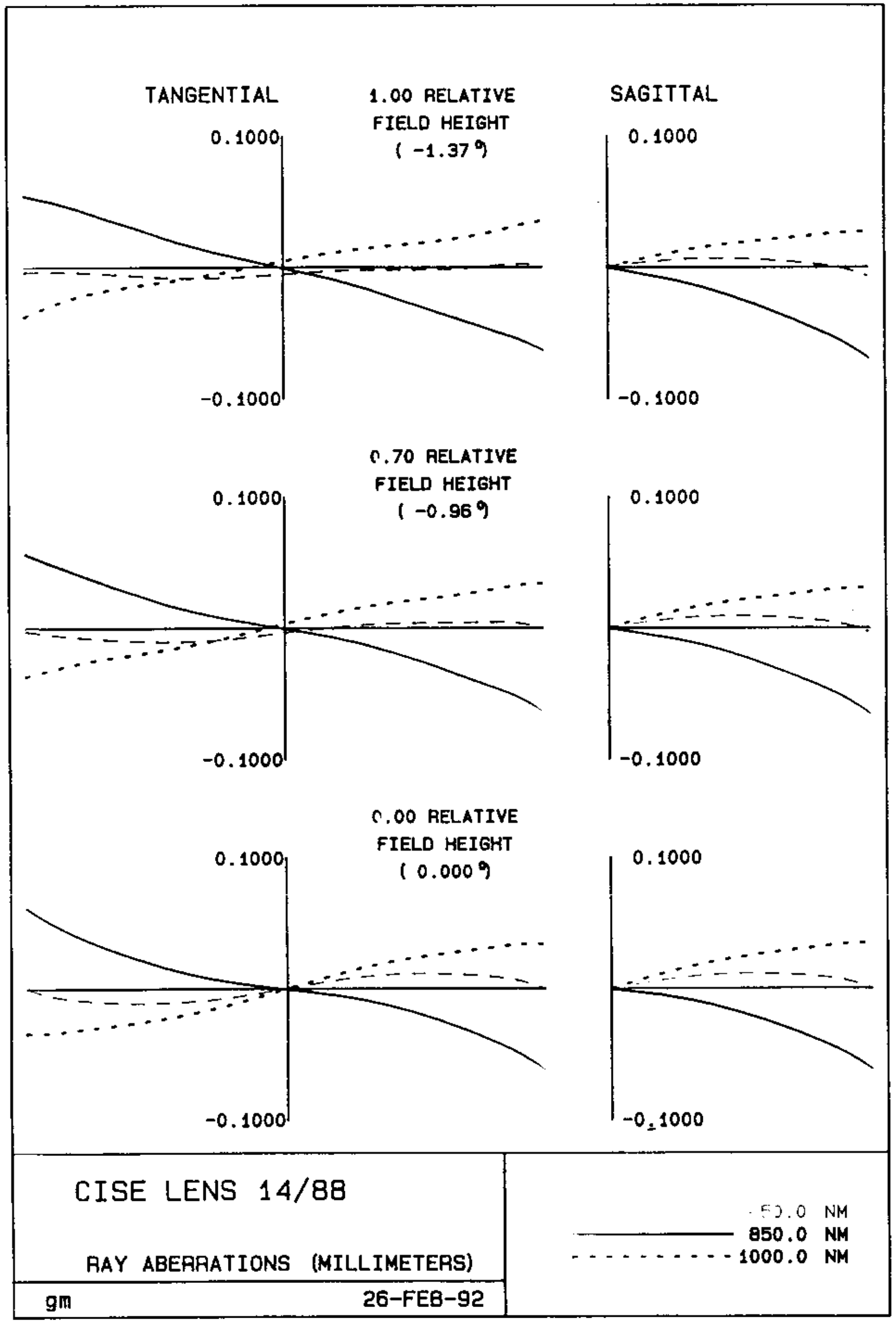
EFL	316.2355
BFL	199.3508
FFL	16.9851
FNO	2.5957

AT USED CONJUGATES

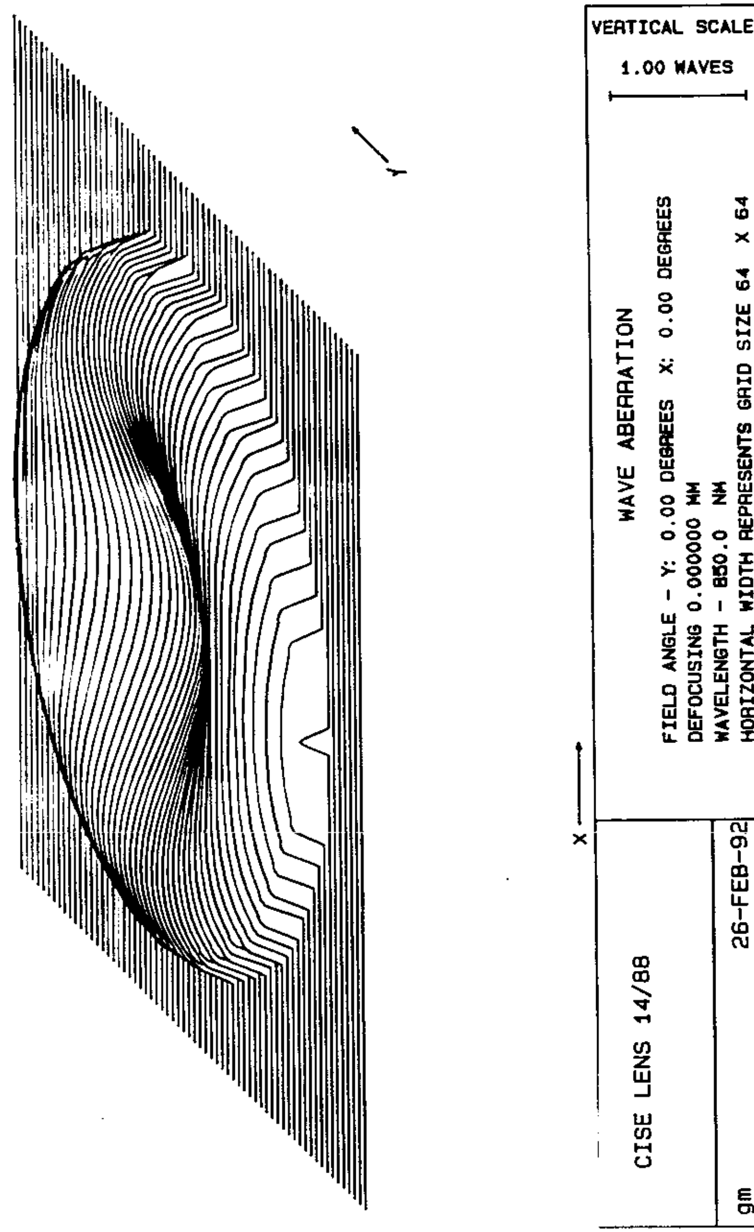
RED	0.1842
FNO	3.1592
OBJ DIS	1700.0000
TT	2369.2642
IMG DIS	257.7342
OAL	411.5300
PARAXIAL IMAGE	
HT	9.2090
THI	257.5953
ANG	1.3712
ENTRANCE PUPIL	
DIA	121.8288
THI	388.7993
EXIT PUPIL	
DIA	103.6179
THI	-69.6140



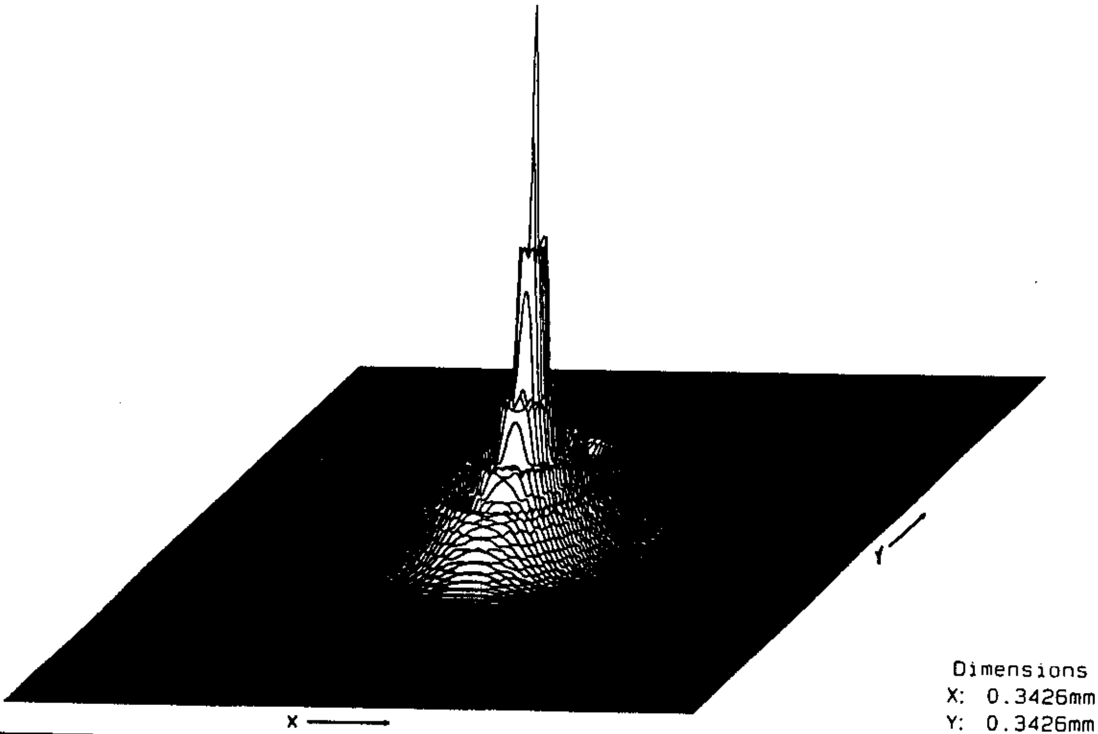
CISE LENS 14/88



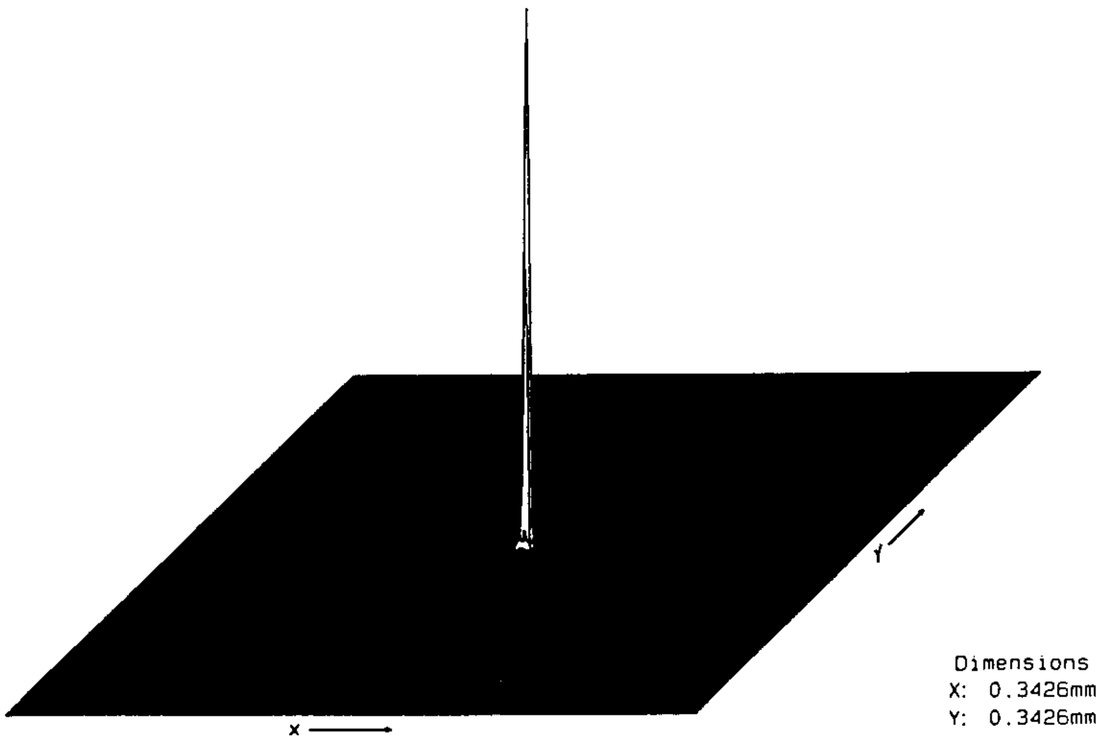
TANGENTIAL
1.00 RELATIVE FIELD HEIGHT (-1.37°)
SAGITTAL
0.1000
-0.1000
0.70 RELATIVE FIELD HEIGHT (-0.96°)
0.00 RELATIVE FIELD HEIGHT (0.000°)
CISE LENS 14/88
RAY ABERRATIONS (MILLIMETERS)
850.0 NM
1000.0 NM
gm
26-FEB-92



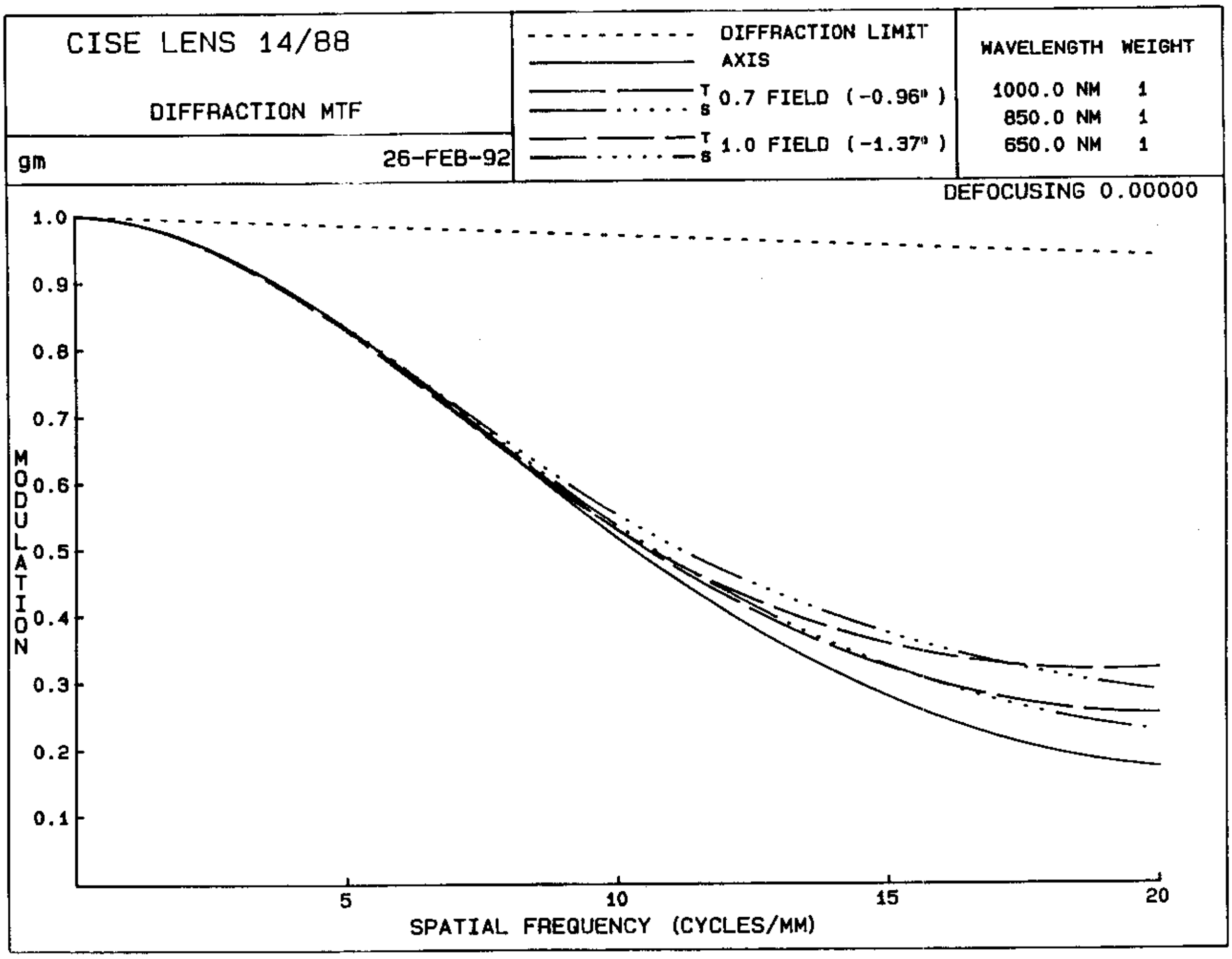
VERTICAL SCALE
1.00 WAVES
WAVE ABERRATION
FIELD ANGLE - Y: 0.00 DEGREES X: 0.00 DEGREES
DEFOCUSING 0.000000 MM
WAVELENGTH - 850.0 NM
HORIZONTAL WIDTH REPRESENTS GRID SIZE 64 X 64
X
Y
CISE LENS 14/88
26-FEB-92
gm



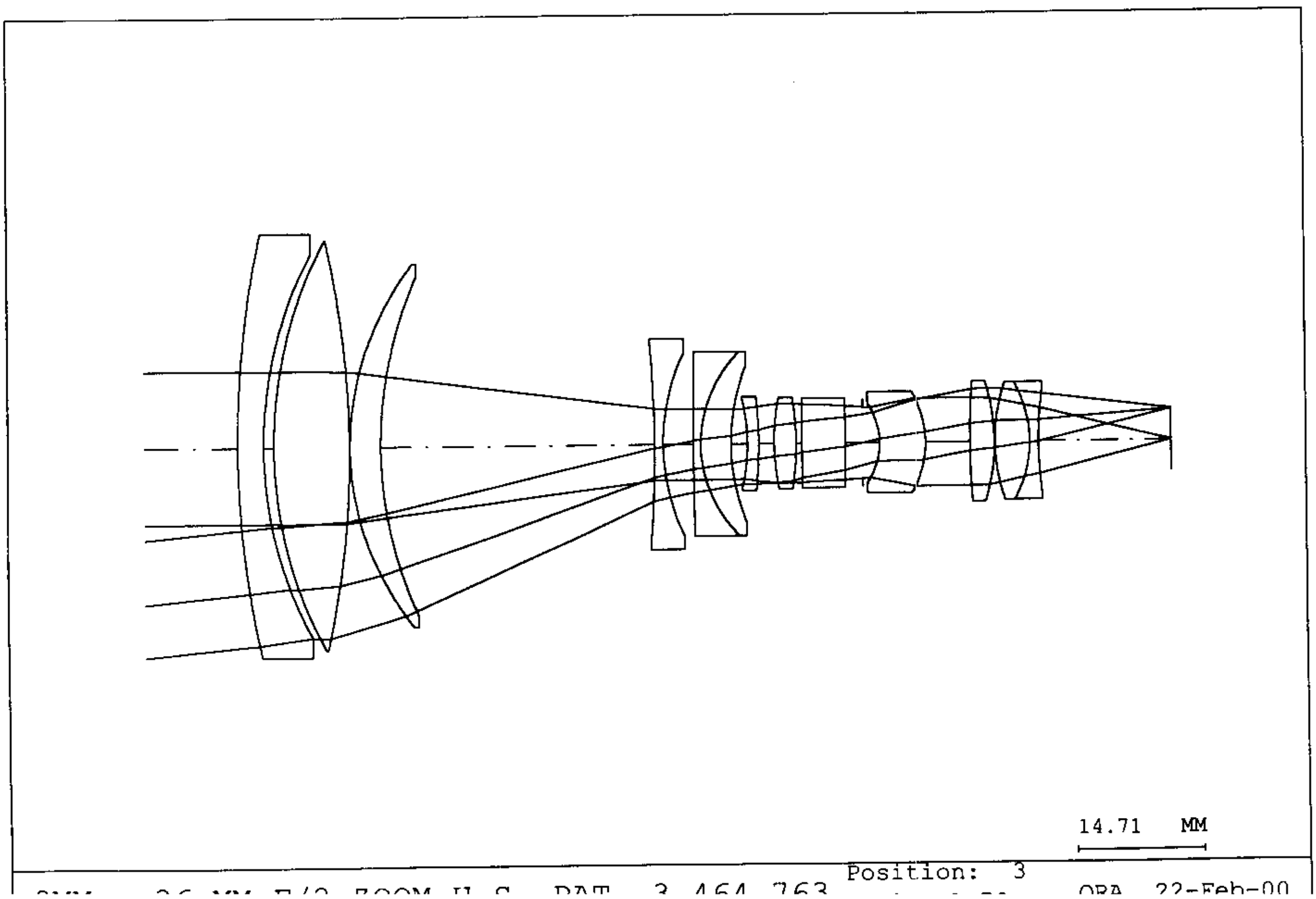
CISE LENS 14/88	DIFFRACTION INTENSITY SPREAD FUNCTION FLD (0.00, 0.00) MAX. (0.0, 0.0) DEG DEFOCUSING: 0.000000 MM	WAVELENGTH WEIGHT 850.0 NM 1
gm 21-May-96		



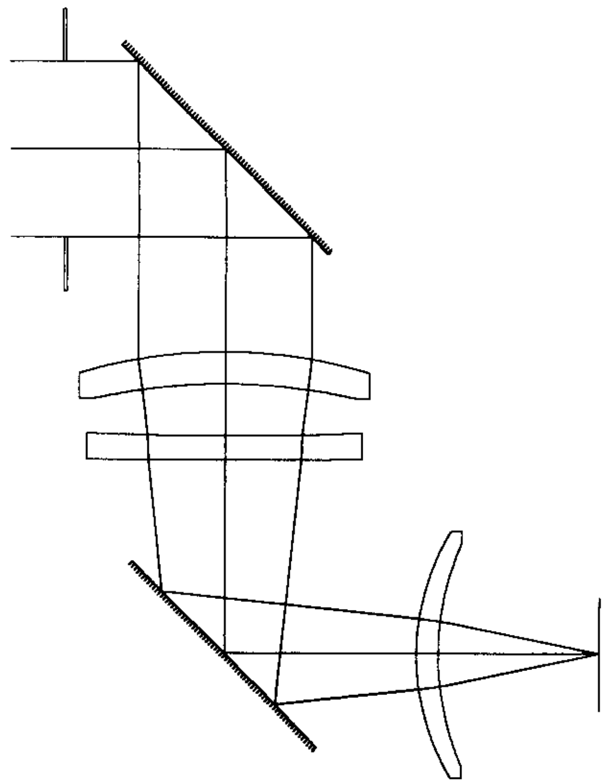
Diffraction limit	DIFFRACTION INTENSITY SPREAD FUNCTION FLD (0.00, 0.00) MAX. (0.0, 0.0) DEG	WAVELENGTH WEIGHT 850.0 NM 1

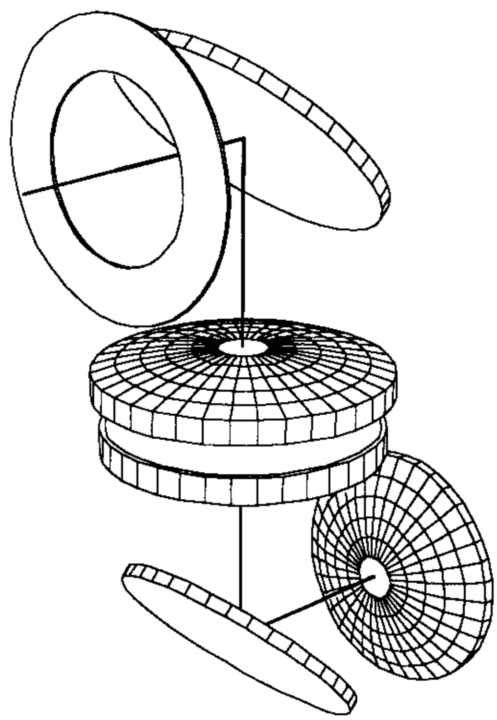

CISE LENS 14/88
DIFFRACTION MTF
gm
26-FEB-92
DIFFRACTION LIMIT
AXIS
T S 0.7 FIELD (-0.96°)
T S 1.0 FIELD (-1.37°)
WAVELENGTH WEIGHT
1000.0 NM 1
850.0 NM 1
650.0 NM 1
DEFOCUSING 0.00000
MODULATION
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
5
10
15
20
SPATIAL FREQUENCY (CYCLES/MM)

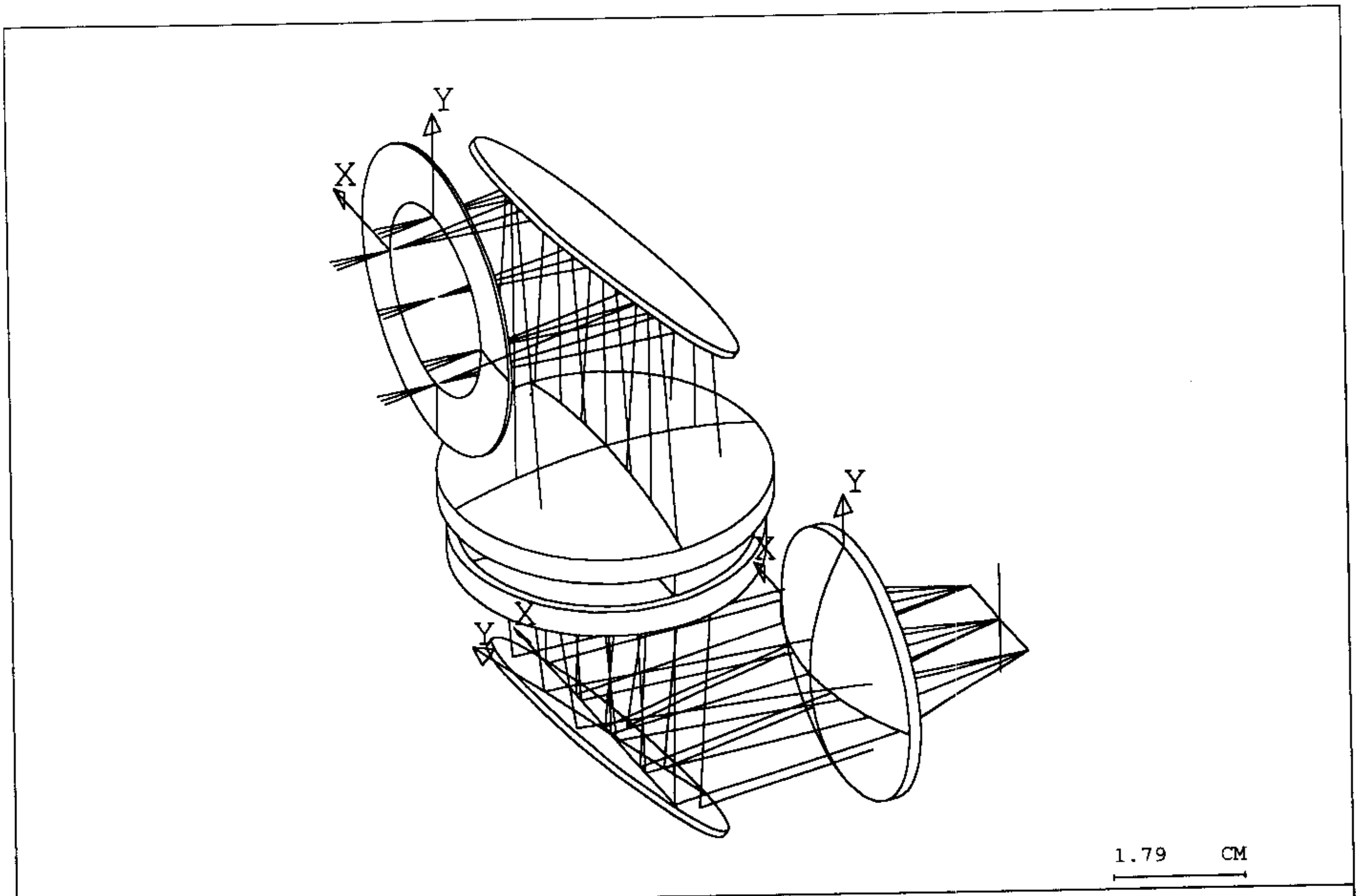
19:09:34


14.71 MM
Position: 3

19:26:12







Common mode FLIR scanner Scale: 1.40 22-Feb-00