FIRST-ORDER LENS THEORY

SNELL'S LAW:

$$\sin I' = \frac{N}{N'} \sin I$$

FIRST-ORDER APPROXIMATION:

$$\sin I \doteq I + \frac{I^3}{3!} + \frac{I^5}{5!} + \cdots$$

FIRST-ORDER TERM (PERFECT SYS.) — THIRD-ORDER (ABERRATIONS)

SINGLE RAYS-

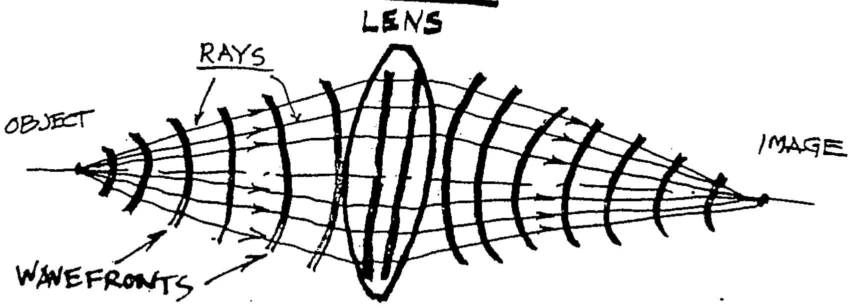


Figure 8

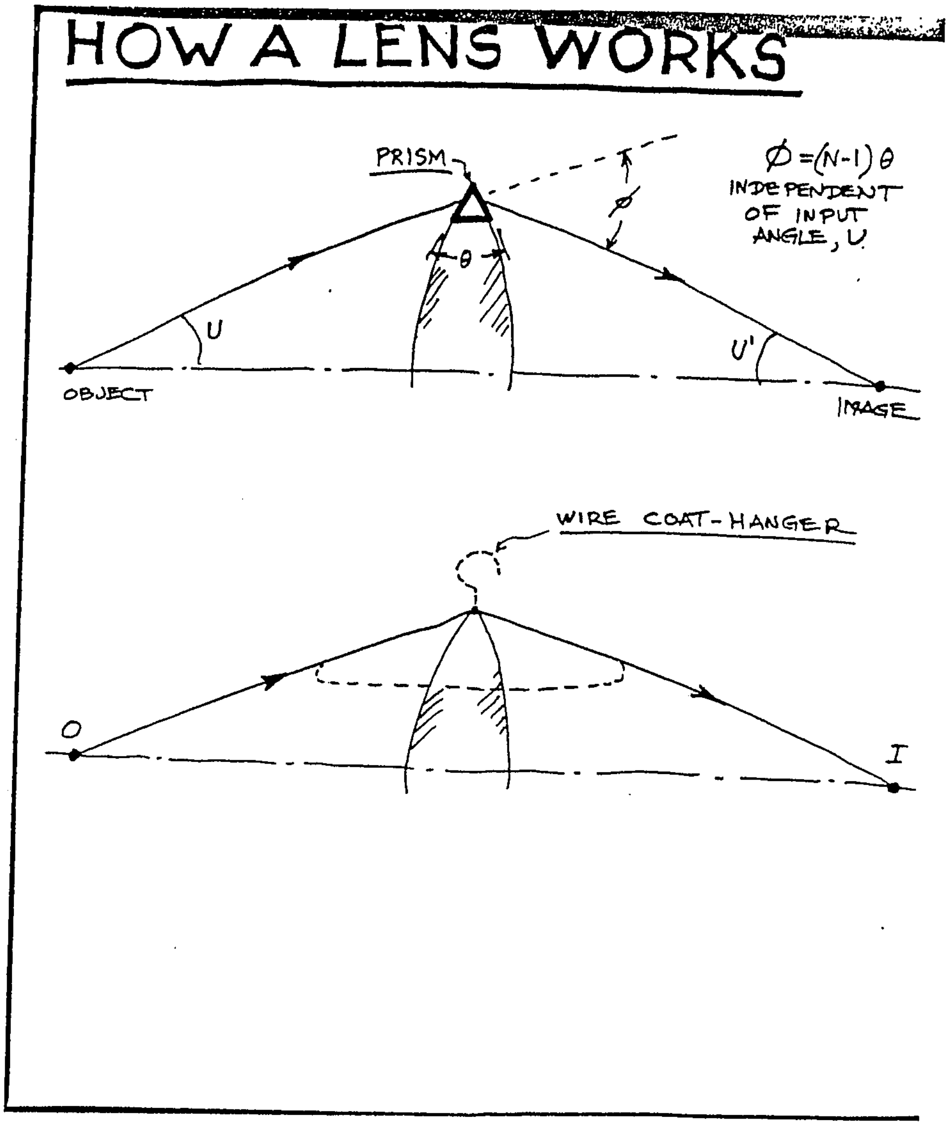
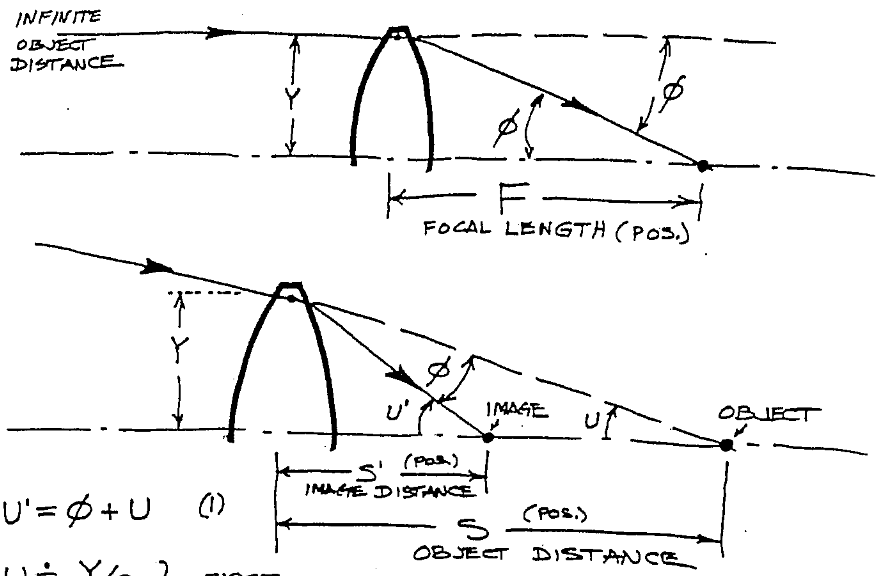

HOW A LENS WORKS
PRISM
θ
Ø
Ø =(N-1) θ
INDEPENDENT
OF INPUT
ANGLE, U
U
U'
OBJECT
IMAGE
WIRE COAT-HANGER
O
I

Figure 9

THIN-LENS EQUATION



$U' = \phi + U$ (1)

$U \doteq Y/S$
$U' \doteq Y/S'$
FIRST-ORDER APPROX.

SUBST. IN (1):

$$\frac{Y}{S'} = \frac{Y}{F} + \frac{Y}{S}$$

SMITH:
P.21
EQ. 2.4

$$\frac{1}{S'} = \frac{1}{F} + \frac{1}{S}$$

Figure 10

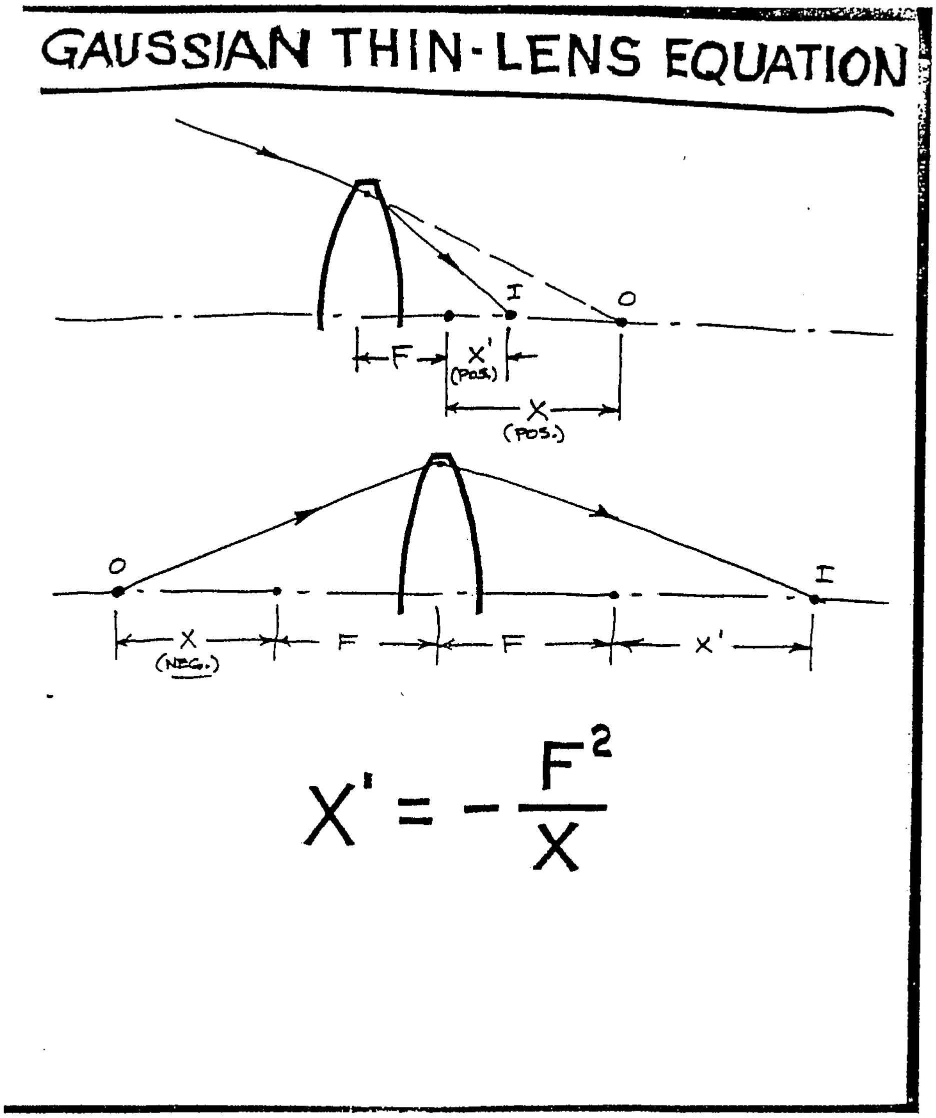

GAUSSIAN THIN-LENS EQUATION
I
O
F
X'
(POS.)
X
(POS.)
O
I
X
(NEG.)
F
F
X'
$X' = -\frac{F^2}{X}$

Figure 11

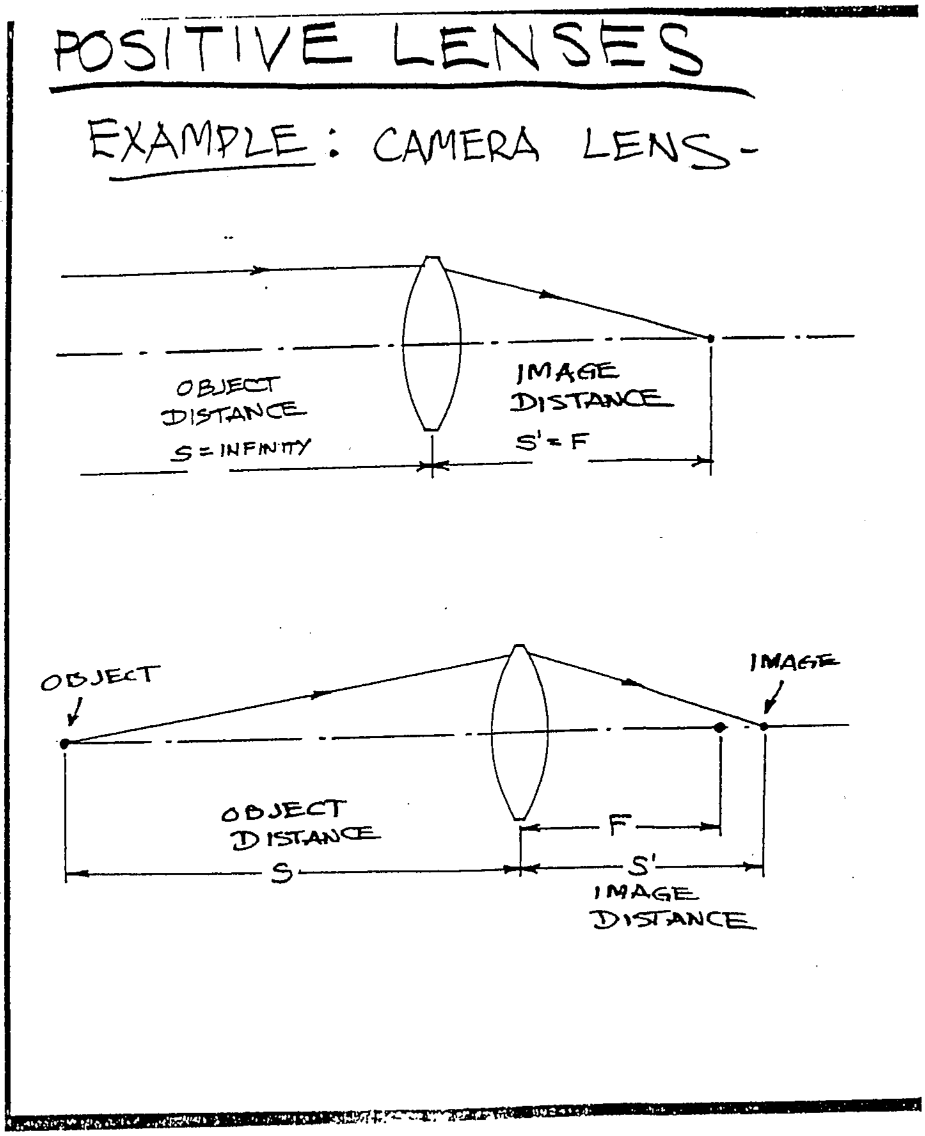

POSITIVE LENSES
EXAMPLE: CAMERA LENS-
OBJECT
DISTANCE
S = INFINITY
IMAGE
DISTANCE
S' = F
OBJECT
IMAGE
OBJECT
DISTANCE
S
F
S'
IMAGE
DISTANCE

Figure 12

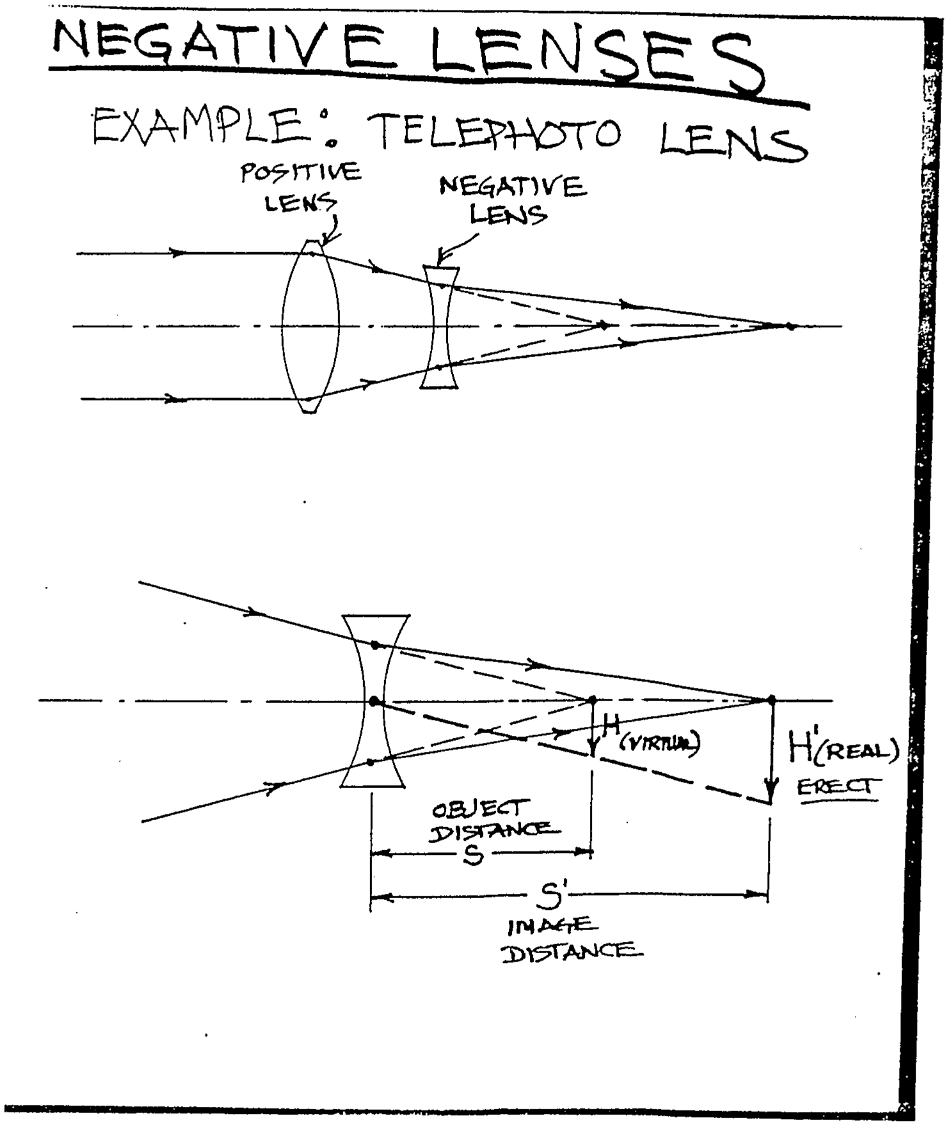
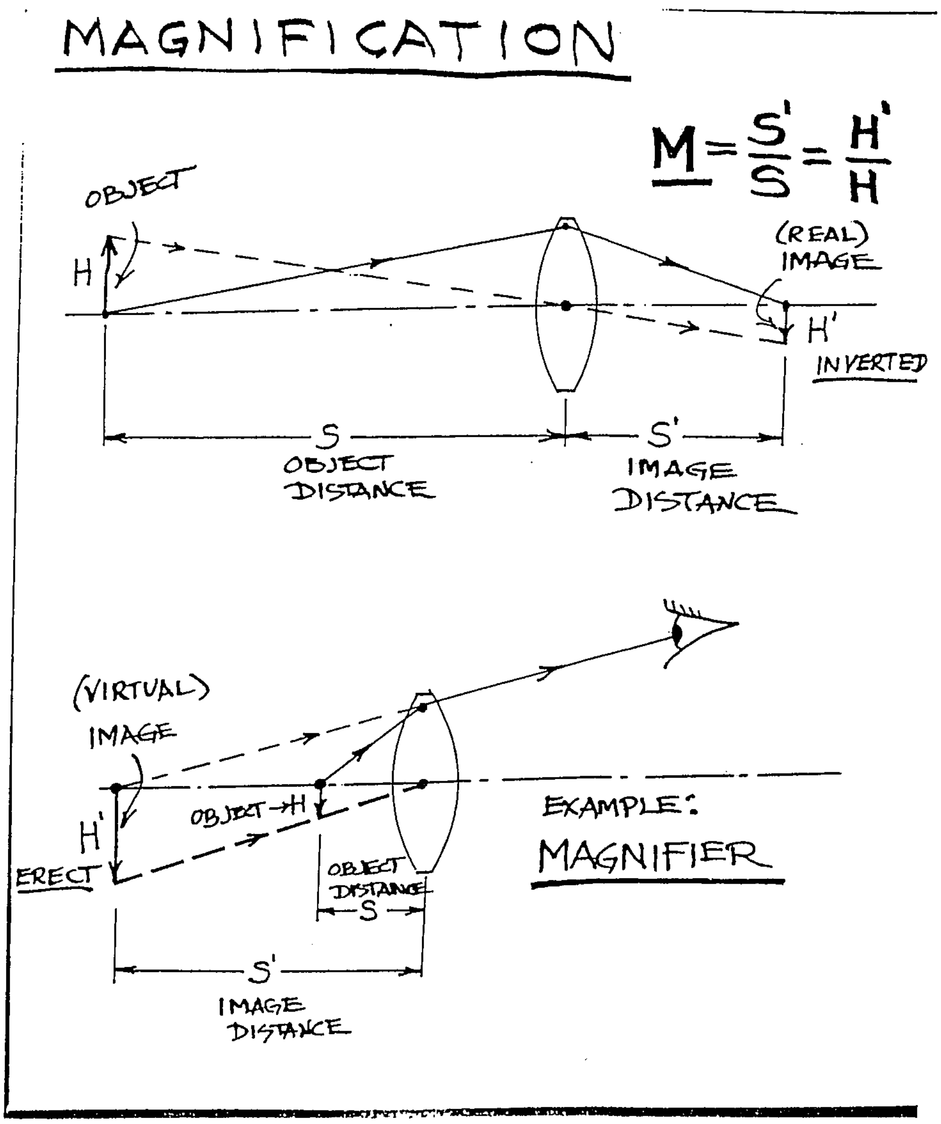

NEGATIVE LENSES
EXAMPLE: TELEPHOTO LENS
POSITIVE LENS
NEGATIVE LENS
H (VIRTUAL)
H' (REAL)
ERECT
OBJECT DISTANCE
S
S'
IMAGE DISTANCE

Figure 13



MAGNIFICATION
M = S'/S = H'/H
OBJECT
H
(REAL)
IMAGE
H'
INVERTED
S
OBJECT
DISTANCE
S'
IMAGE
DISTANCE
(VIRTUAL)
IMAGE
H'
ERECT
OBJECT→H
OBJECT
DISTANCE
S
S'
IMAGE
DISTANCE
EXAMPLE:
MAGNIFIER

Figure 14

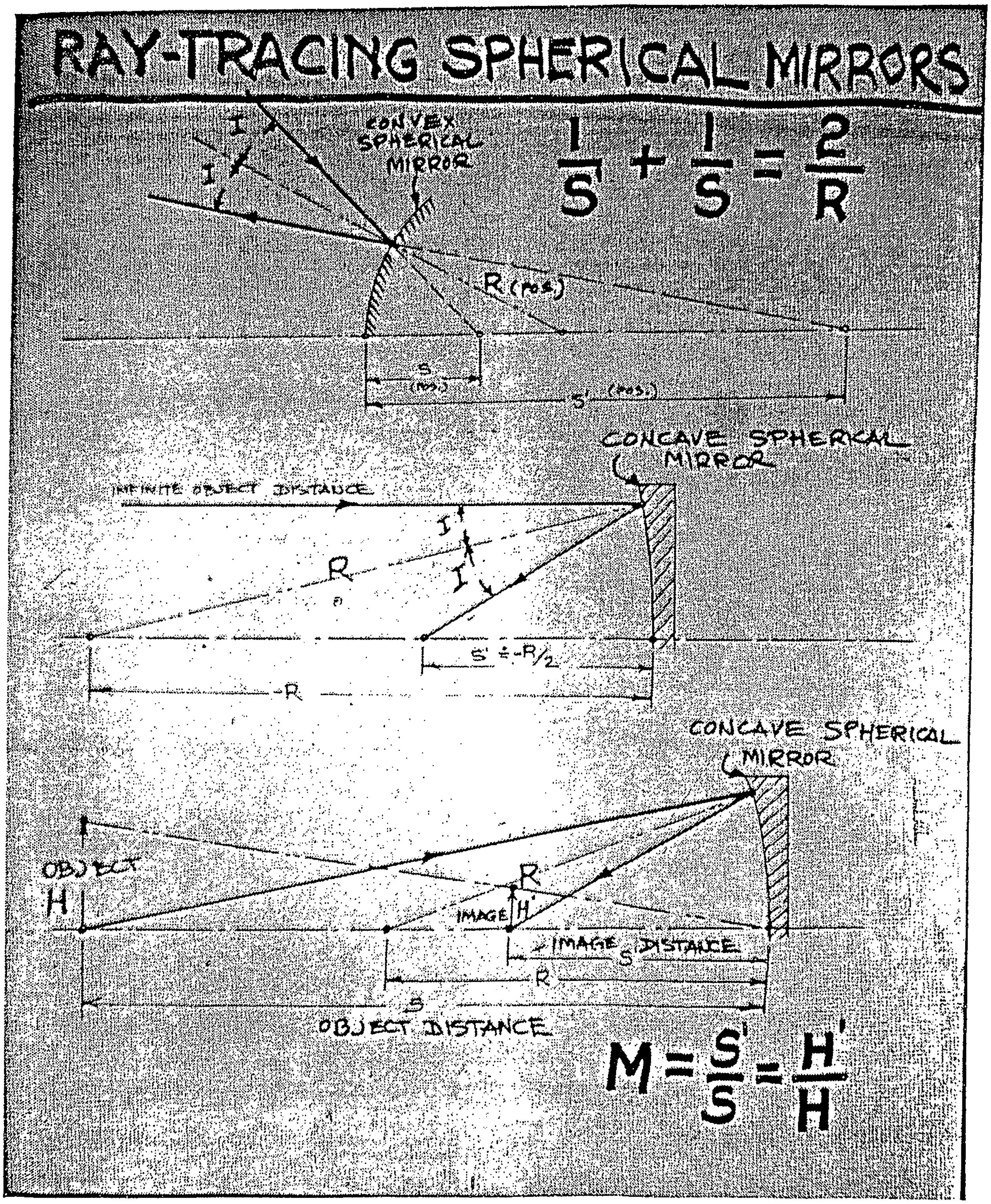
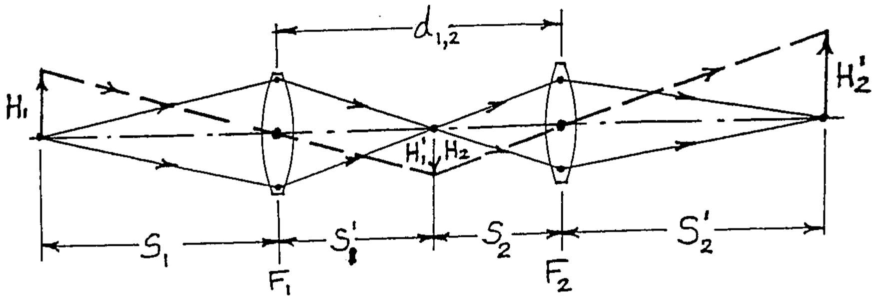

RAY-TRACING SPHERICAL MIRRORS
$\frac{1}{S'} + \frac{1}{S} = \frac{2}{R}$
CONVEX SPHERICAL MIRROR
I
I
R (POS.)
S (POS.)
S' (POS.)
CONCAVE SPHERICAL MIRROR
INFINITE OBJECT DISTANCE
I
I
R
S' ≐ -R/2
-R
CONCAVE SPHERICAL MIRROR
OBJECT
H
R
IMAGE
H'
IMAGE DISTANCE
S'
R
S
OBJECT DISTANCE
$M = \frac{S'}{S} = \frac{H'}{H}$

Figure 15

FIRST-ORDER RAY-TRACING OF MULTIPLE ELEMENTS

$$\frac{1}{S'} = \frac{1}{F} + \frac{1}{S} \qquad M = \frac{H'}{H} = \frac{S'}{S}$$



$$S_2 = S_1' - d_{1,2}$$

$$H_2 = H_1' \; ; \; \left(\frac{S_1'}{S_1} \times \frac{S_2'}{S_2}\right) H_1 = H_2'$$

Figure 16

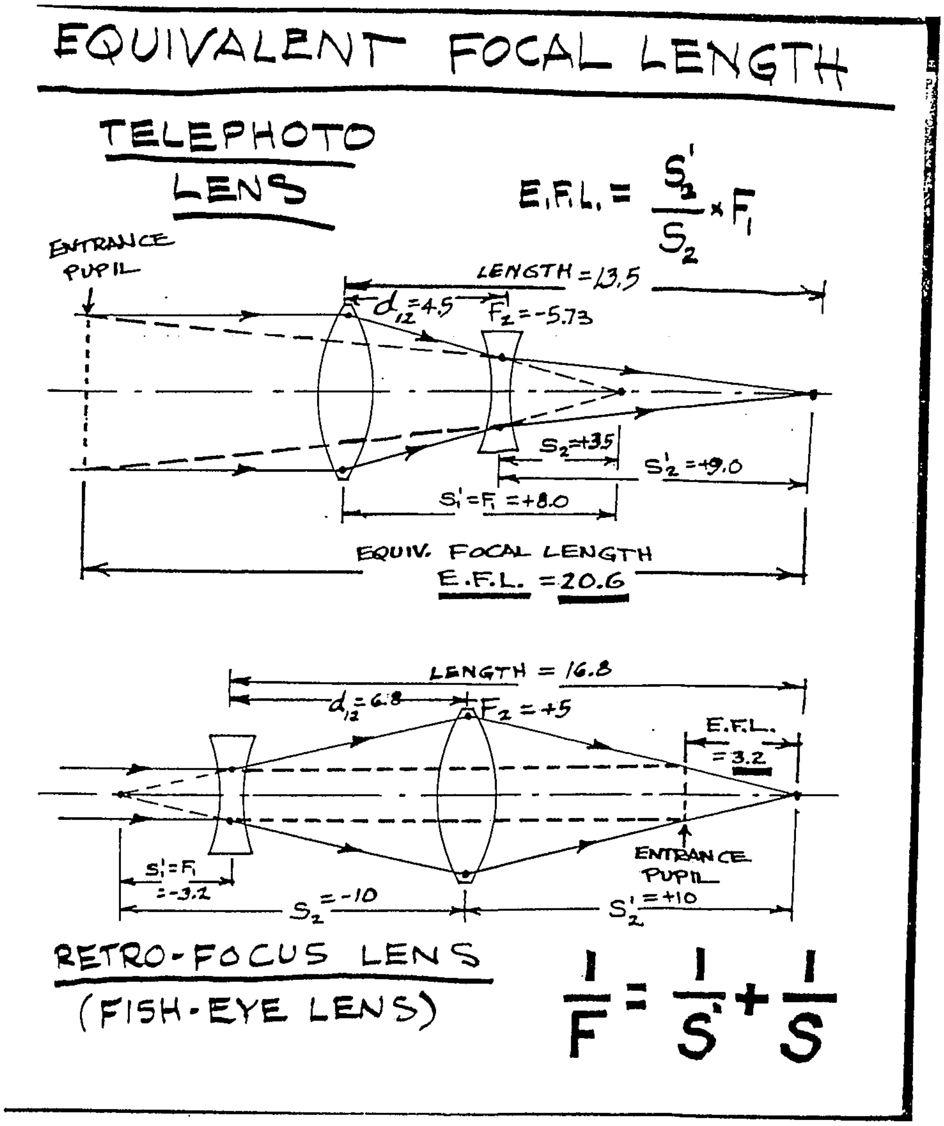

EQUIVALENT FOCAL LENGTH
TELEPHOTO LENS
E.F.L. = S'2/S2 × F1
ENTRANCE PUPIL
LENGTH = 13.5
d12 = 4.5
F2 = -5.73
S2 = +3.5
S'2 = +9.0
S'1 = F1 = +8.0
EQUIV. FOCAL LENGTH
E.F.L. = 20.6
LENGTH = 16.8
d12 = 6.8
F2 = +5
E.F.L. = 3.2
ENTRANCE PUPIL
S'1 = F1 = -3.2
S2 = -10
S'2 = +10
RETRO-FOCUS LENS
(FISH-EYE LENS)
1/F = 1/S' + 1/S

Figure 17

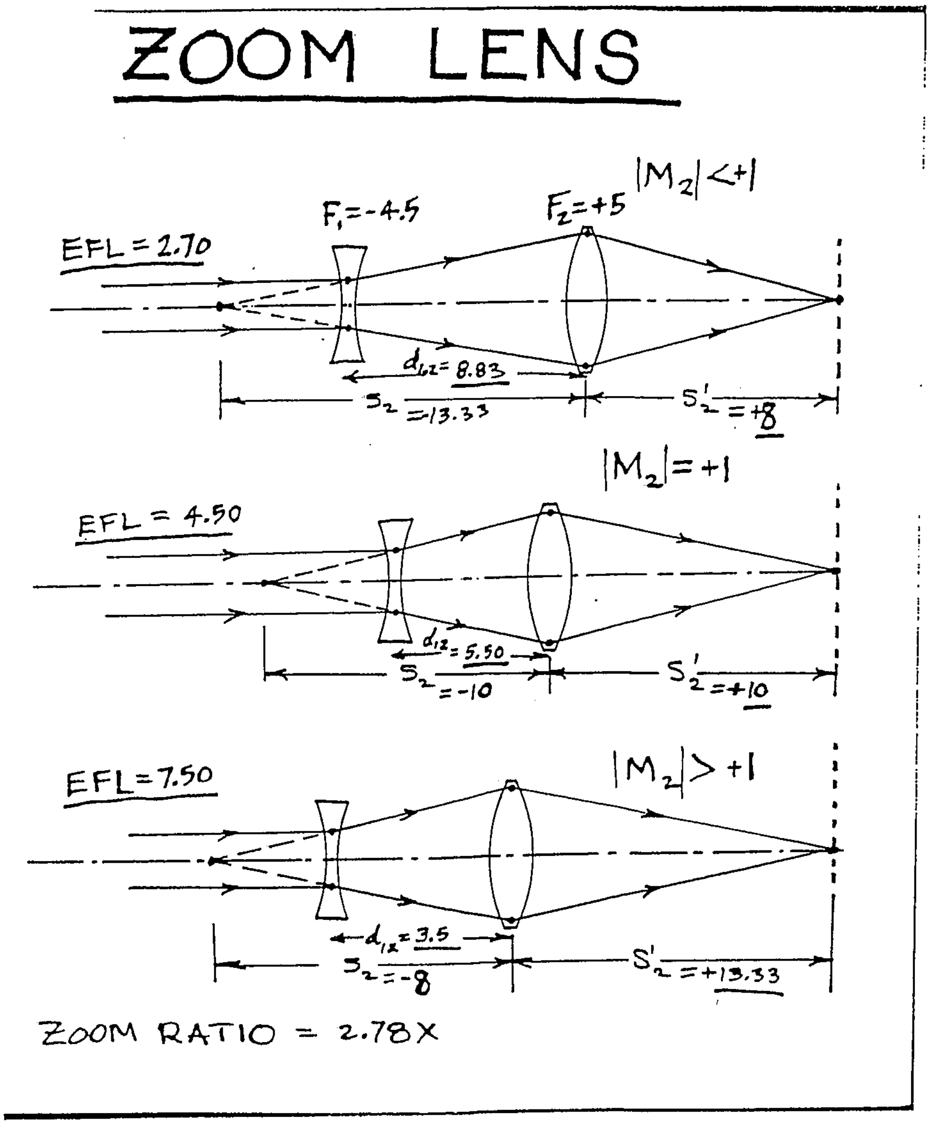

ZOOM LENS
EFL = 2.70
F1 = -4.5
F2 = +5
|M2| < +1
d12 = 8.83
S2 = -13.33
S'2 = +8
|M2| = +1
EFL = 4.50
d12 = 5.50
S2 = -10
S'2 = +10
EFL = 7.50
|M2| > +1
d12 = 3.5
S2 = -8
S'2 = +13.33
ZOOM RATIO = 2.78X

Figure 18

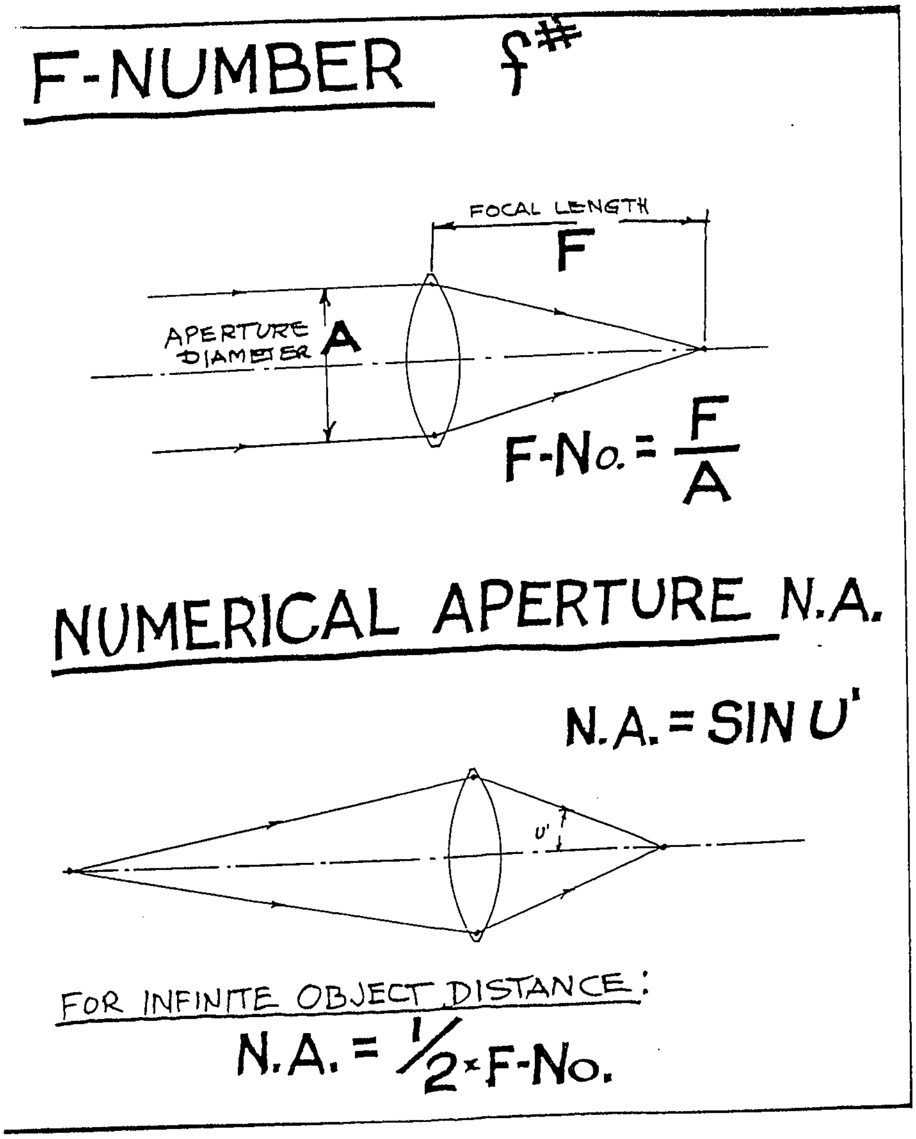

F-NUMBER f#
FOCAL LENGTH
F
APERTURE DIAMETER A
F-No. = F/A
NUMERICAL APERTURE N.A.
N.A. = SIN U'
U'
FOR INFINITE OBJECT DISTANCE:
N.A. = 1/2×F-No.

Figure 19

OFF-AXIS RAYS

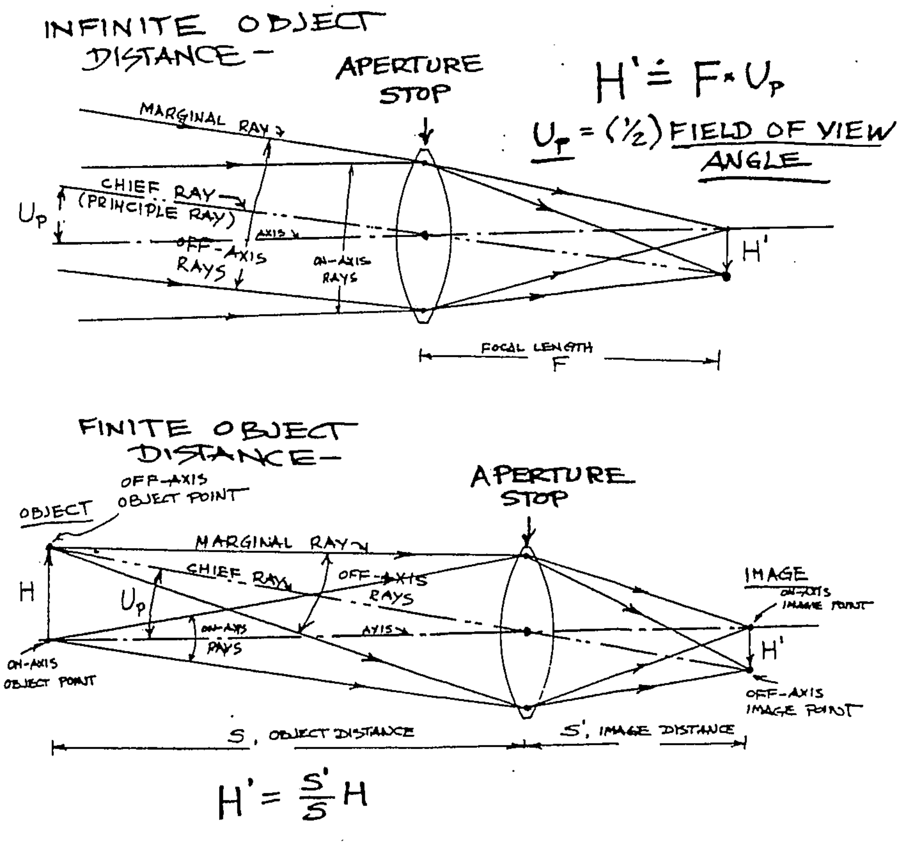


Figure 20

ENTRANCE PUPIL

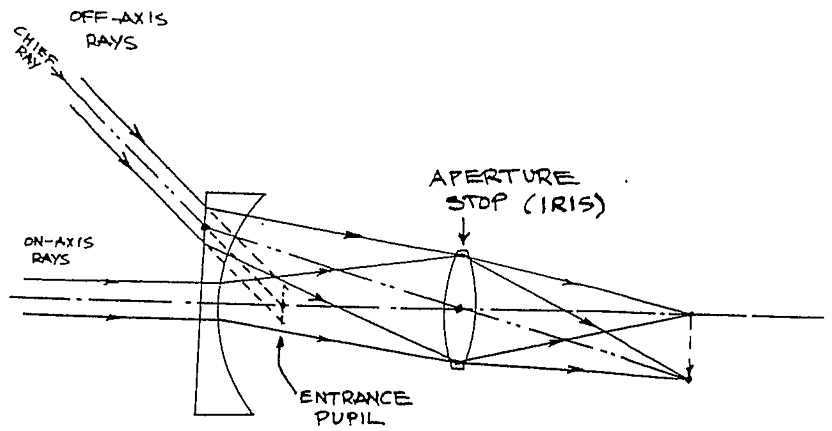


Figure 21

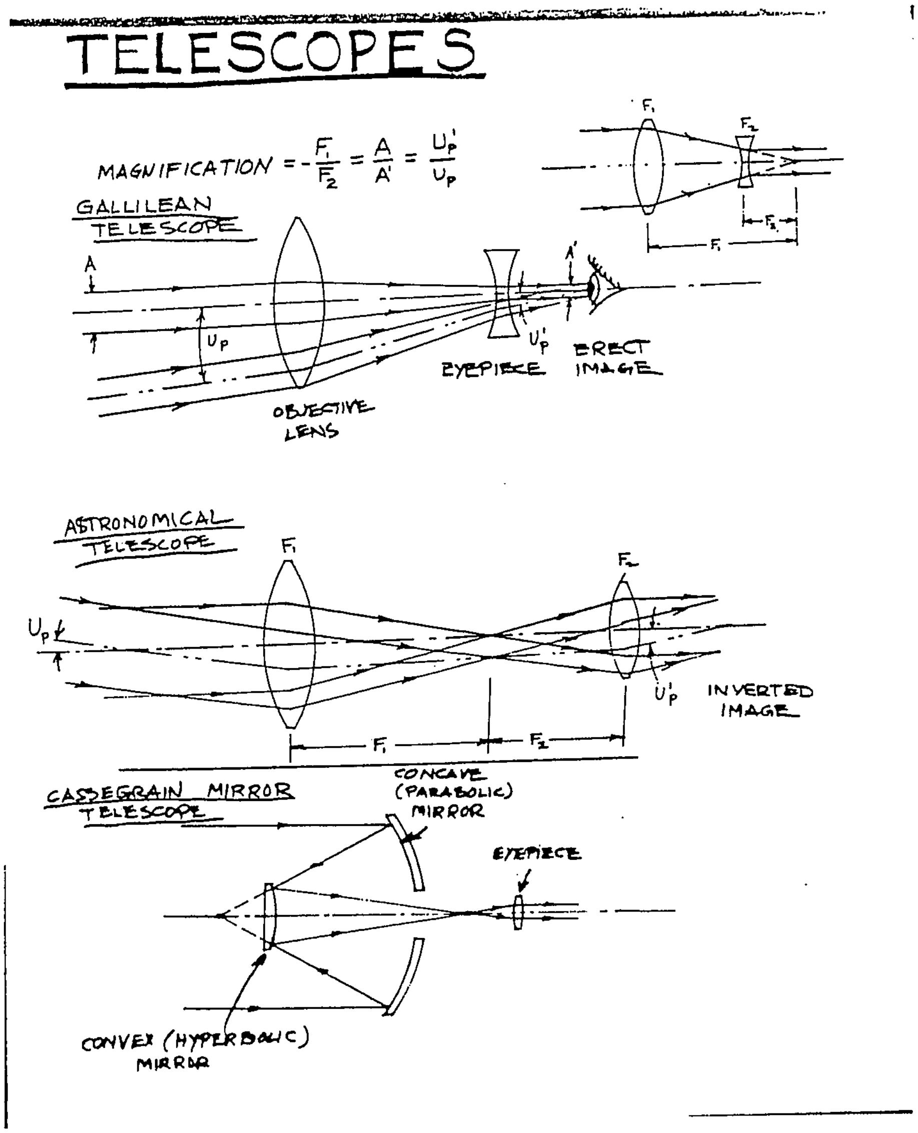
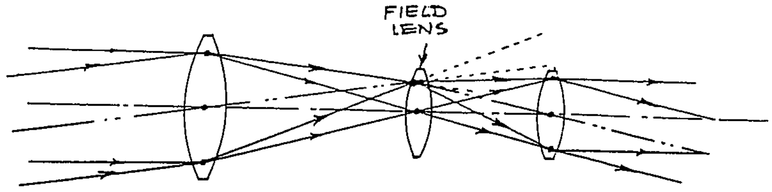
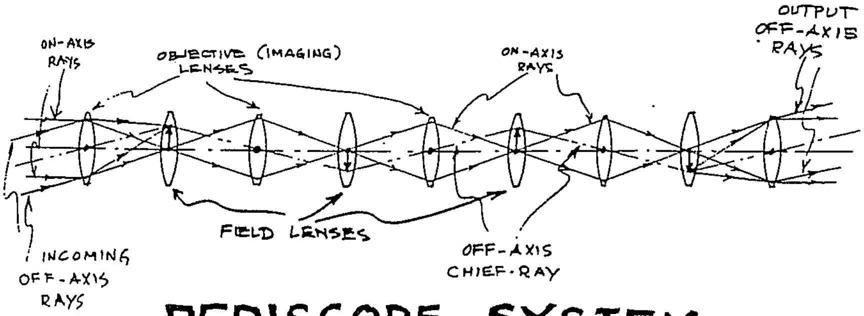

TELESCOPES
MAGNIFICATION = $-\frac{F_1}{F_2} = \frac{A}{A'} = \frac{U_p'}{U_p}$
GALLILEAN TELESCOPE
A
U_p
A'
U_p'
EYEPIECE
ERECT IMAGE
OBJECTIVE LENS
F_1
F_2
ASTRONOMICAL TELESCOPE
U_p
U_p'
INVERTED IMAGE
CASSEGRAIN MIRROR TELESCOPE
CONCAVE (PARABOLIC) MIRROR
EYEPIECE
CONVEX (HYPERBOLIC) MIRROR

Figure 22

FIELD LENSES



TELESCOPE WITH FIELD LENS



PERISCOPE SYSTEM

Figure 22A

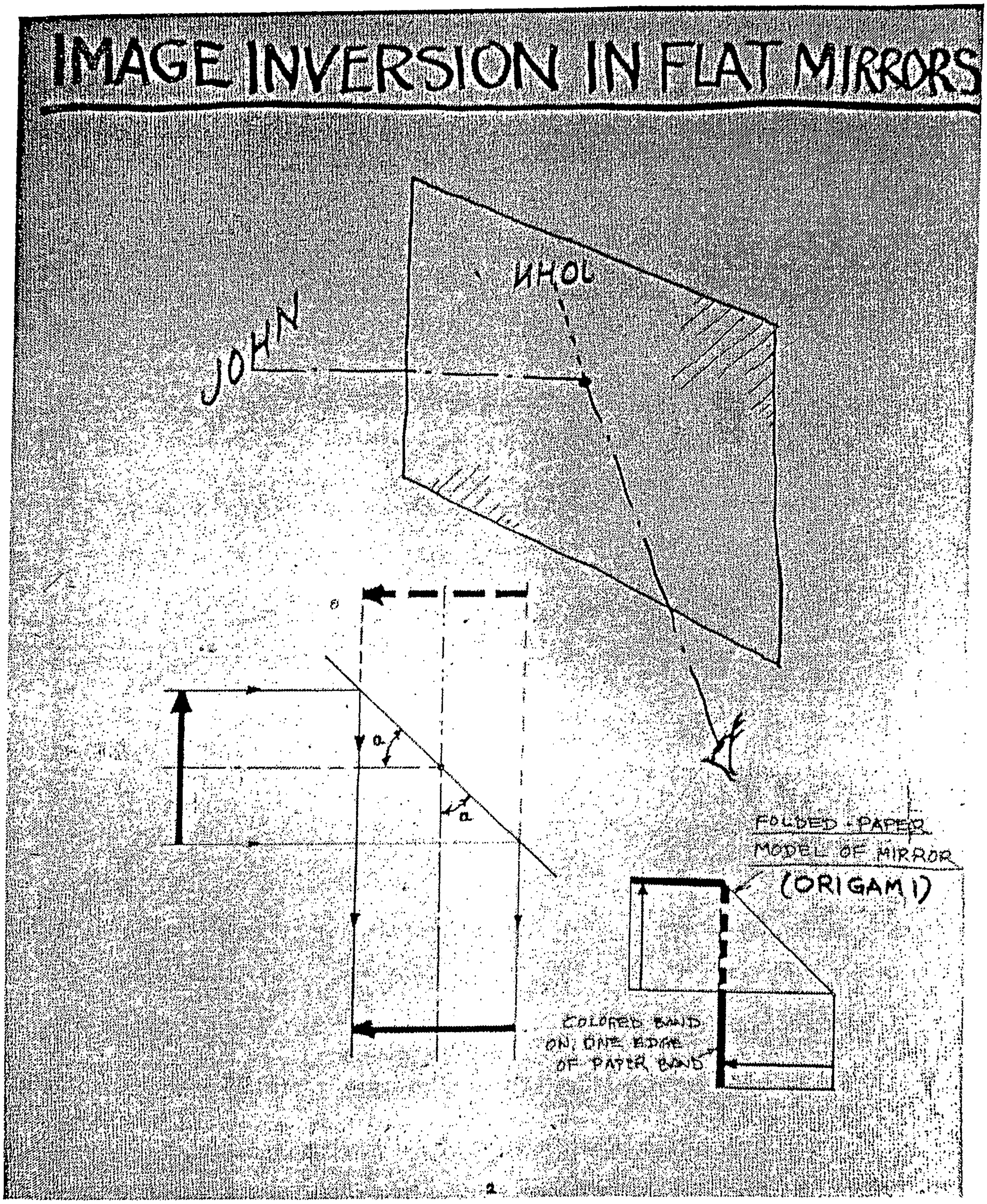


IMAGE INVERSION IN FLAT MIRRORS
JOHN
a
a
FOLDED - PAPER
MODEL OF MIRROR
(ORIGAMI)
COLORED BAND
ON ONE EDGE
OF PAPER BAND

Figure 23

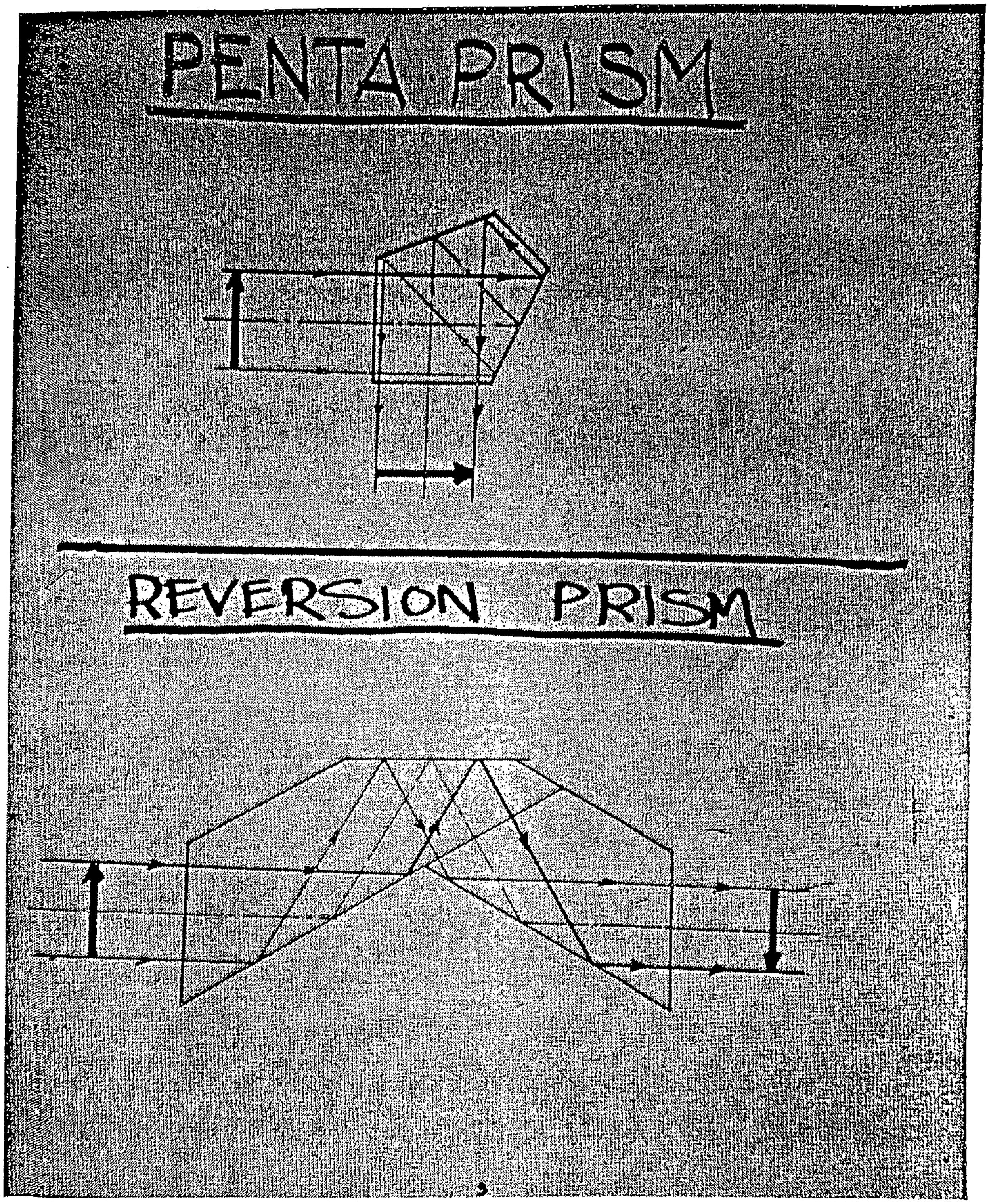


Figure 24

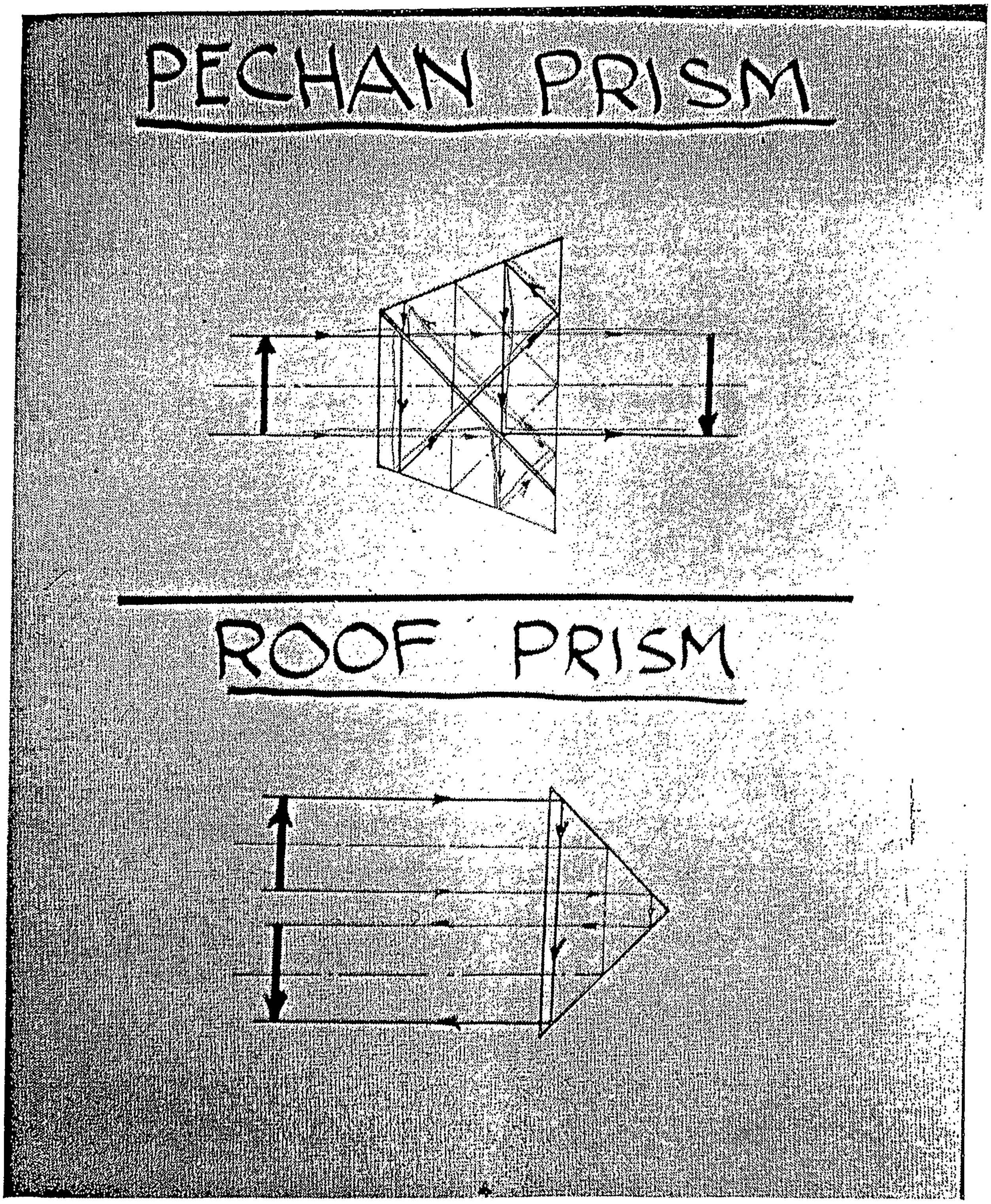


Figure 25

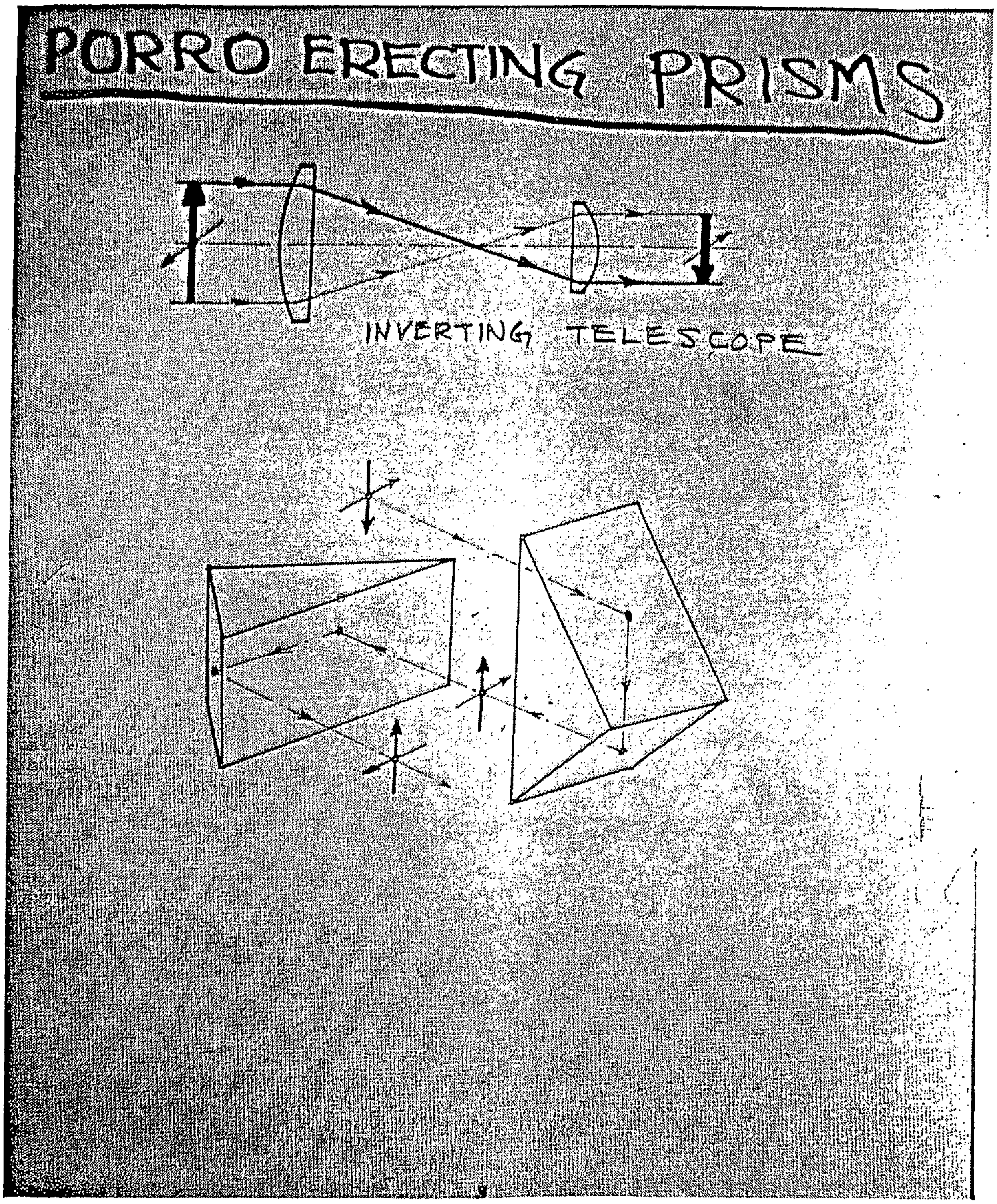


Figure 26

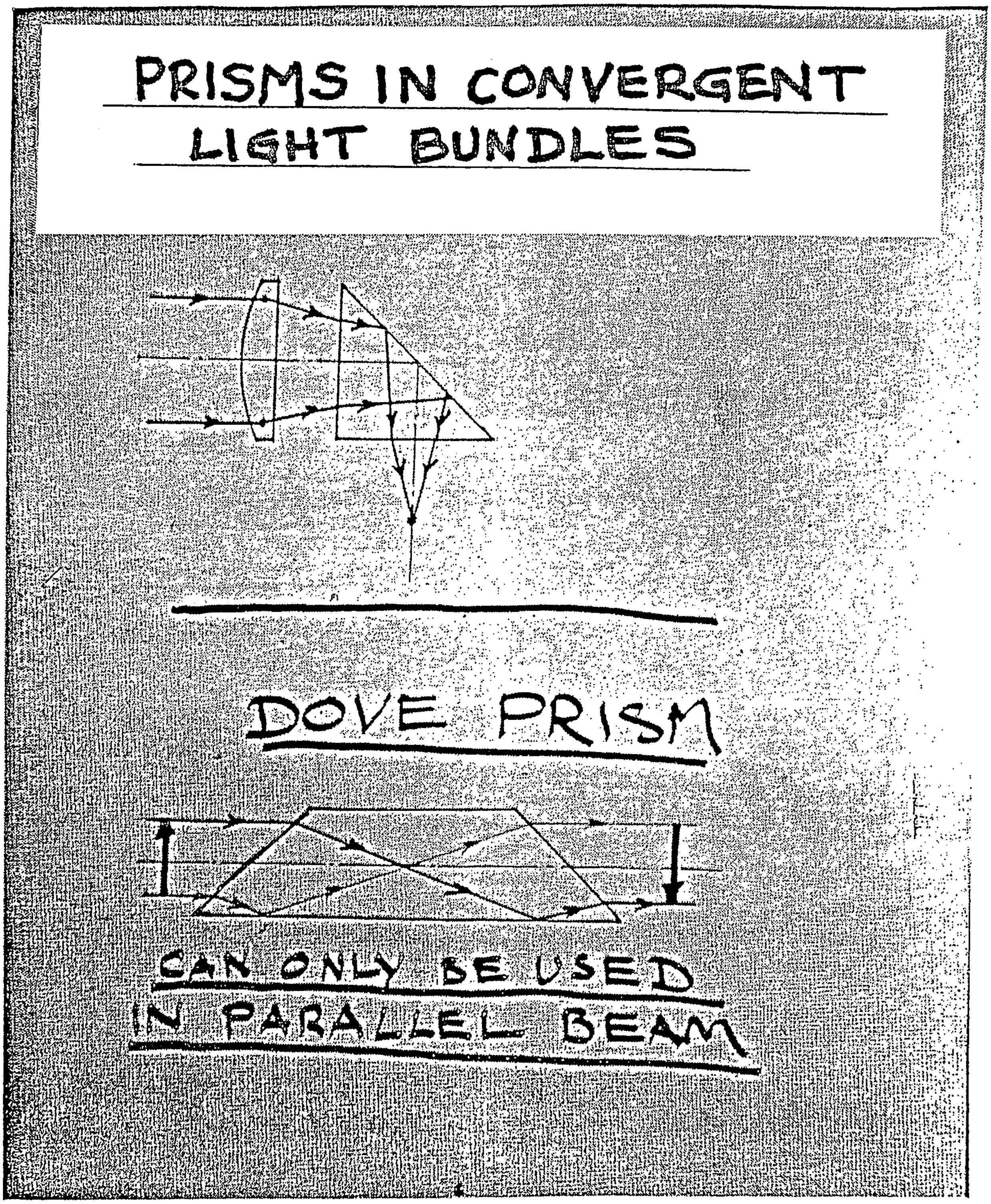

PRISMS IN CONVERGENT
LIGHT BUNDLES
DOVE PRISM
CAN ONLY BE USED
IN PARALLEL BEAM

Figure 27

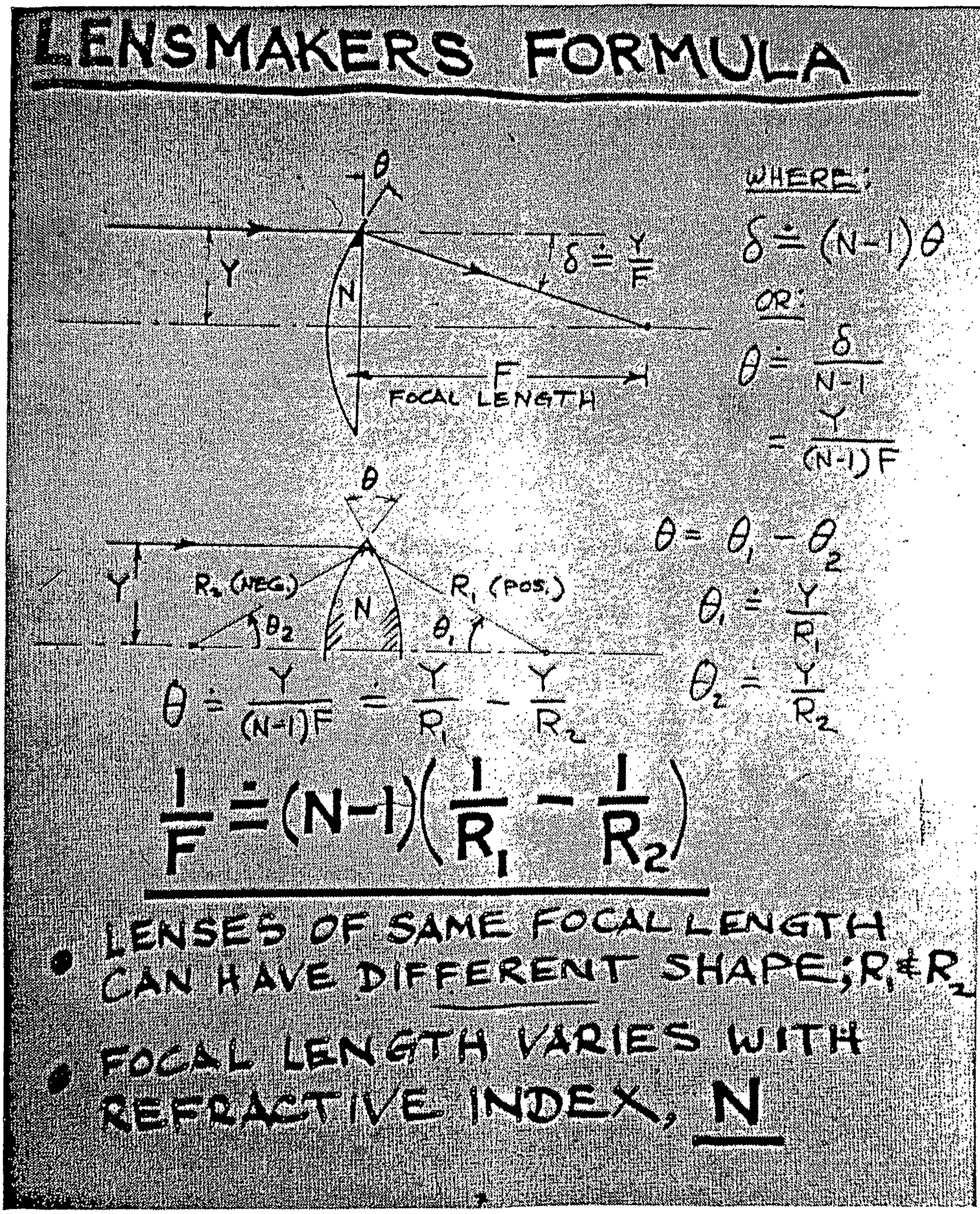

LENSMAKERS FORMULA
WHERE:
δ ≐ (N-1)θ
OR:
θ ≐ δ/(N-1)
= Y/((N-1)F)
δ ≐ Y/F
Y
N
F
FOCAL LENGTH
θ
θ = θ1 − θ2
θ1 ≐ Y/R1
θ2 ≐ Y/R2
R2 (NEG.)
R1 (POS.)
θ2
θ1
θ ≐ Y/((N-1)F) ≐ Y/R1 − Y/R2
1/F ≐ (N-1)(1/R1 − 1/R2)
LENSES OF SAME FOCAL LENGTH CAN HAVE DIFFERENT SHAPE; R1 & R2
FOCAL LENGTH VARIES WITH REFRACTIVE INDEX, N

Figure 28

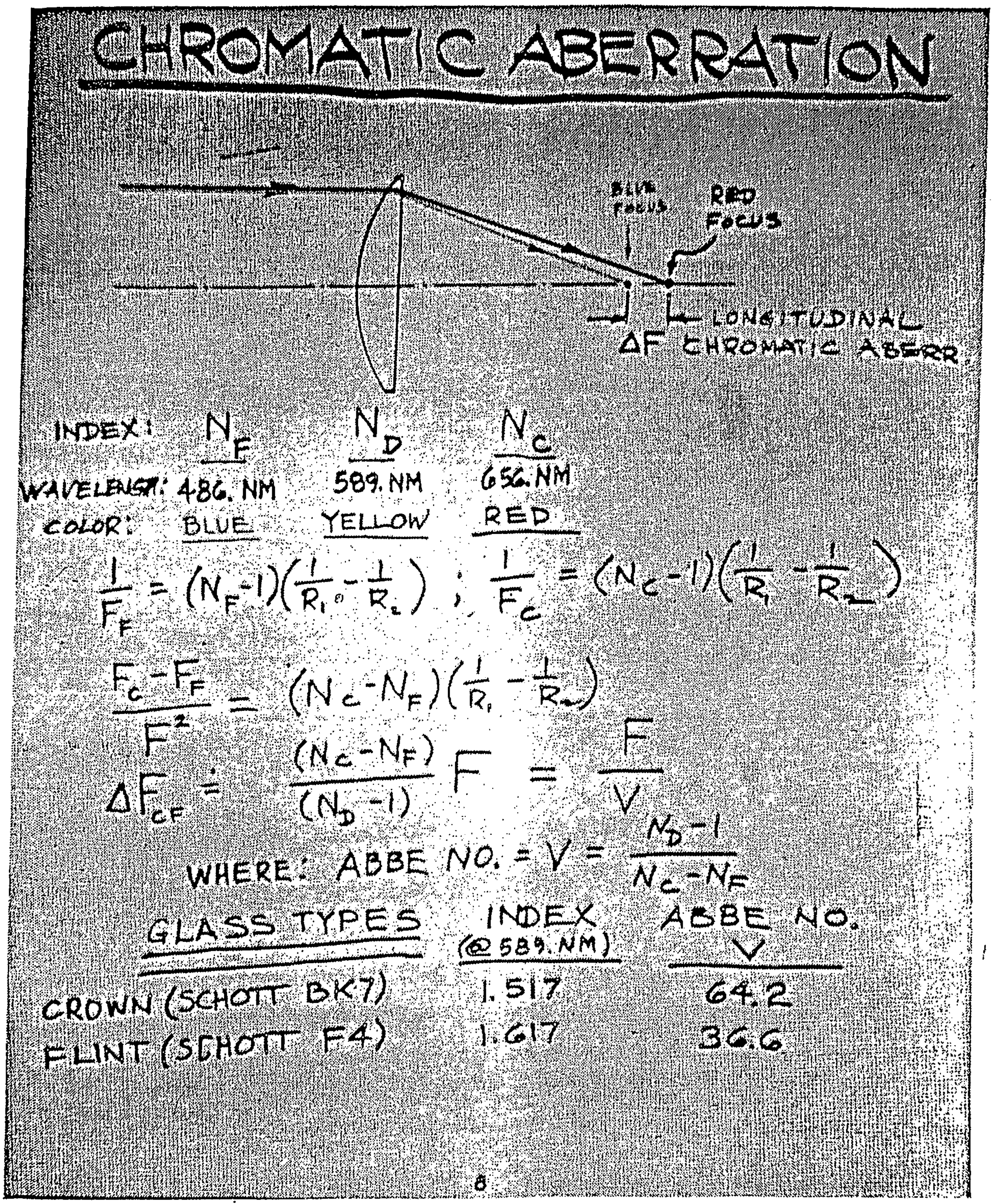

CHROMATIC ABERRATION
BLUE FOCUS
RED FOCUS
LONGITUDINAL
ΔF CHROMATIC ABERR
INDEX: N_F N_D N_C
WAVELENGTH: 486. NM 589. NM 656. NM
COLOR: BLUE YELLOW RED
$\frac{1}{F_F} = (N_F - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$; $\frac{1}{F_C} = (N_C - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$
$\frac{F_C - F_F}{F^2} = (N_C - N_F)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$
$\Delta F_{CF} \doteq \frac{(N_C - N_F)}{(N_D - 1)} F = \frac{F}{V}$
WHERE: ABBE NO. = $V = \frac{N_D - 1}{N_C - N_F}$
GLASS TYPES
INDEX (@ 589. NM)
ABBE NO. V
CROWN (SCHOTT BK7) 1.517 64.2
FLINT (SCHOTT F4) 1.617 36.6
8

Figure 29

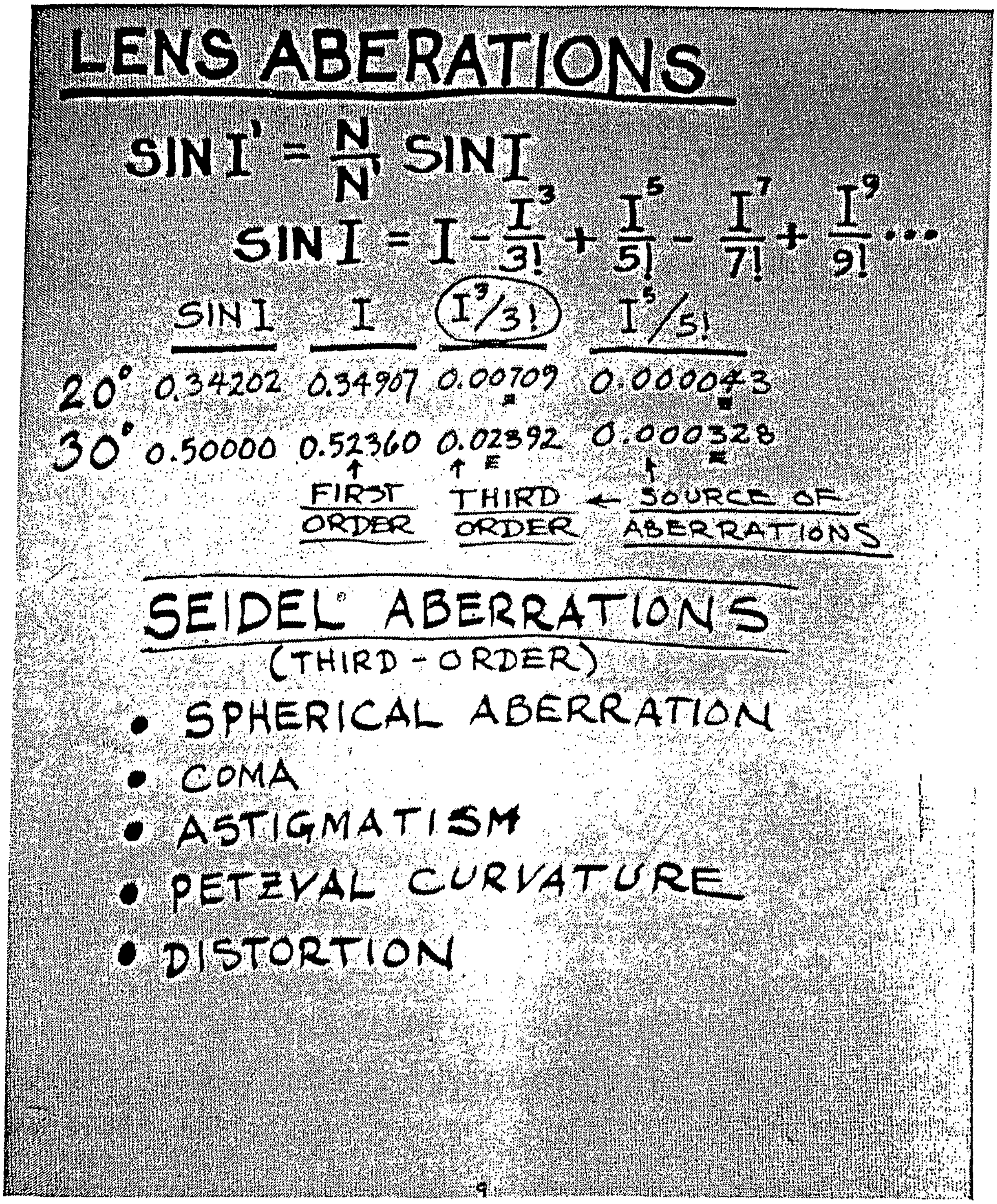

LENS ABERATIONS
SIN I' = N/N' SIN I
SIN I = I - I^3/3! + I^5/5! - I^7/7! + I^9/9! ...
SIN I | I | I^3/3! | I^5/5!
20° 0.34202 0.34907 0.00709 0.000043
30° 0.50000 0.52360 0.02392 0.000328
FIRST ORDER
THIRD ORDER
SOURCE OF ABERRATIONS
SEIDEL ABERRATIONS
(THIRD-ORDER)
• SPHERICAL ABERRATION
• COMA
• ASTIGMATISM
• PETZVAL CURVATURE
• DISTORTION

Figure 30

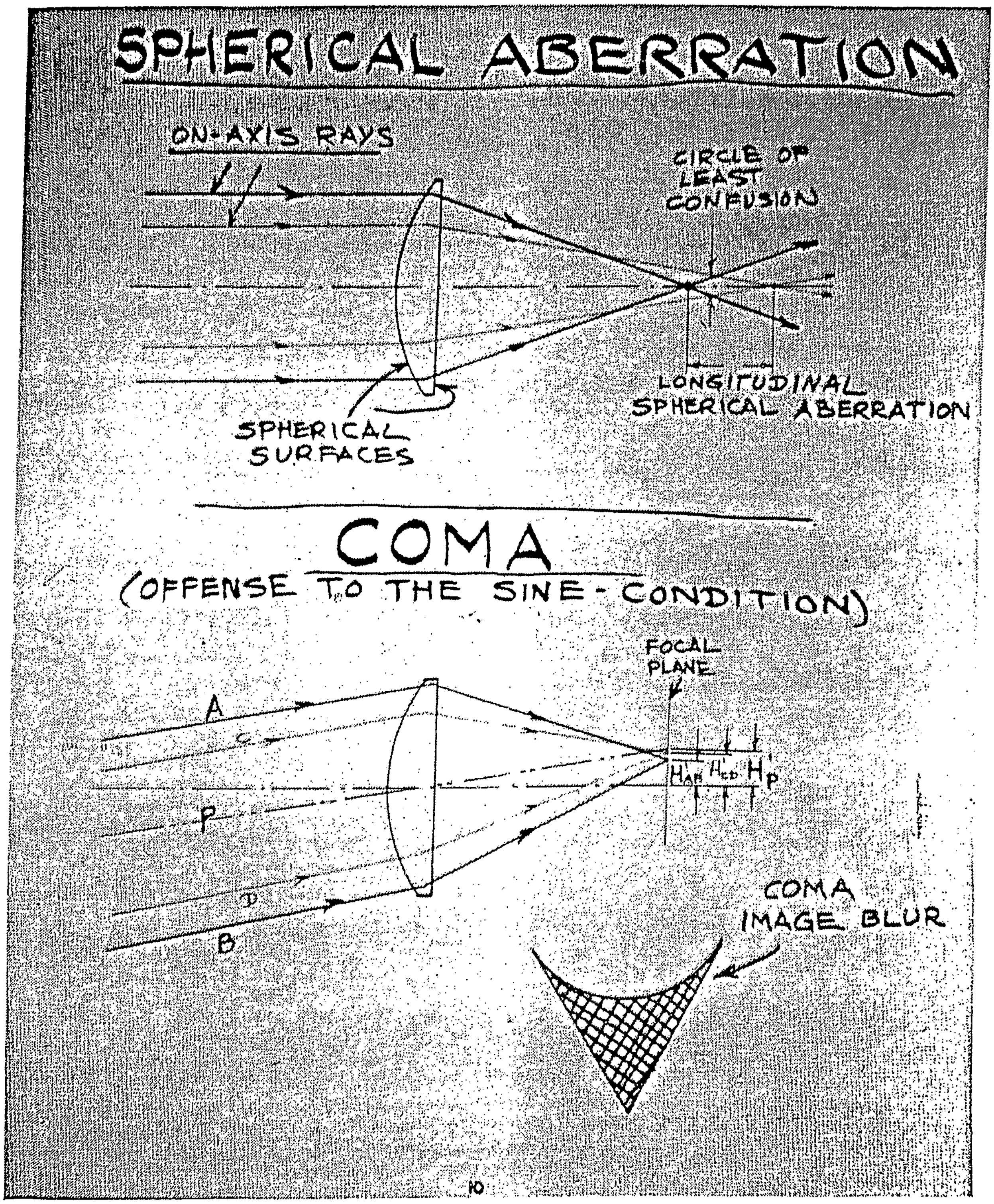

SPHERICAL ABERRATION
ON-AXIS RAYS
CIRCLE OF LEAST CONFUSION
LONGITUDINAL SPHERICAL ABERRATION
SPHERICAL SURFACES
COMA
(OFFENSE TO THE SINE-CONDITION)
FOCAL PLANE
A
C
P
D
B
COMA IMAGE BLUR
10

Figure 31

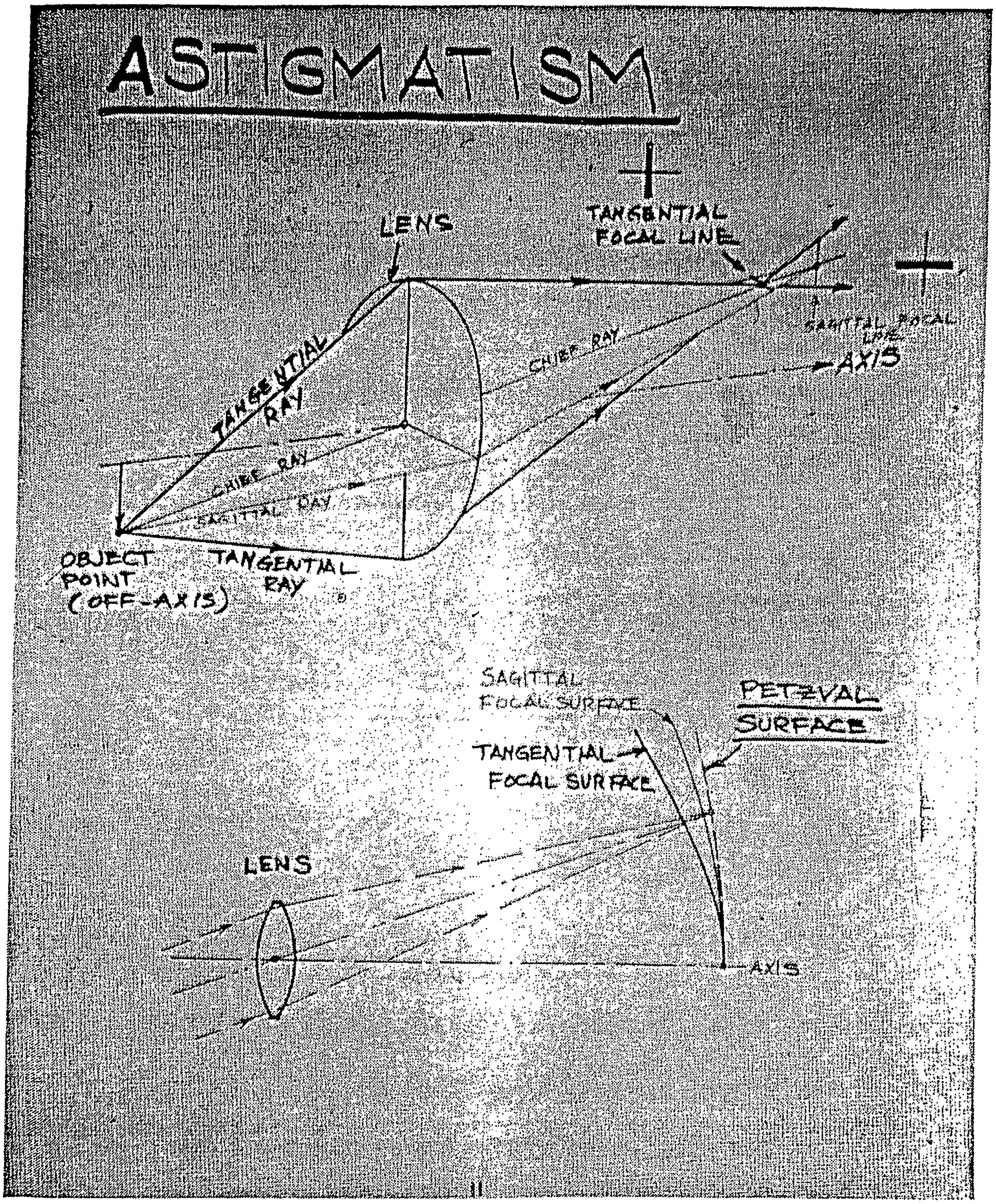

ASTIGMATISM
LENS
TANGENTIAL FOCAL LINE
SAGITTAL FOCAL LINE
AXIS
CHIEF RAY
TANGENTIAL RAY
CHIEF RAY
SAGITTAL RAY
OBJECT POINT (OFF-AXIS)
TANGENTIAL RAY
SAGITTAL FOCAL SURFACE
PETZVAL SURFACE
TANGENTIAL FOCAL SURFACE
LENS
AXIS

Figure 32

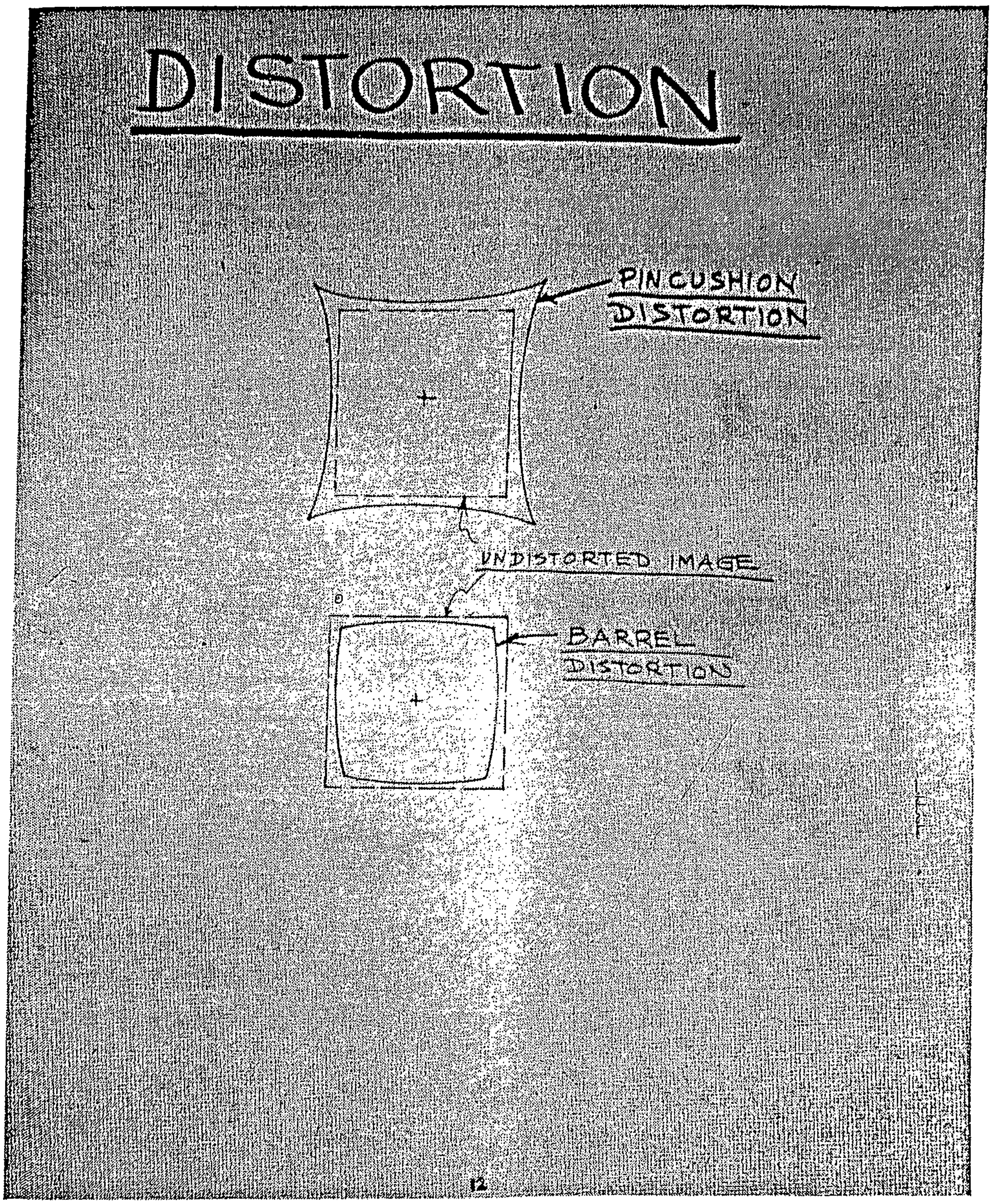

DISTORTION
PINCUSHION
DISTORTION
UNDISTORTED IMAGE
BARREL
DISTORTION
12

Figure 33

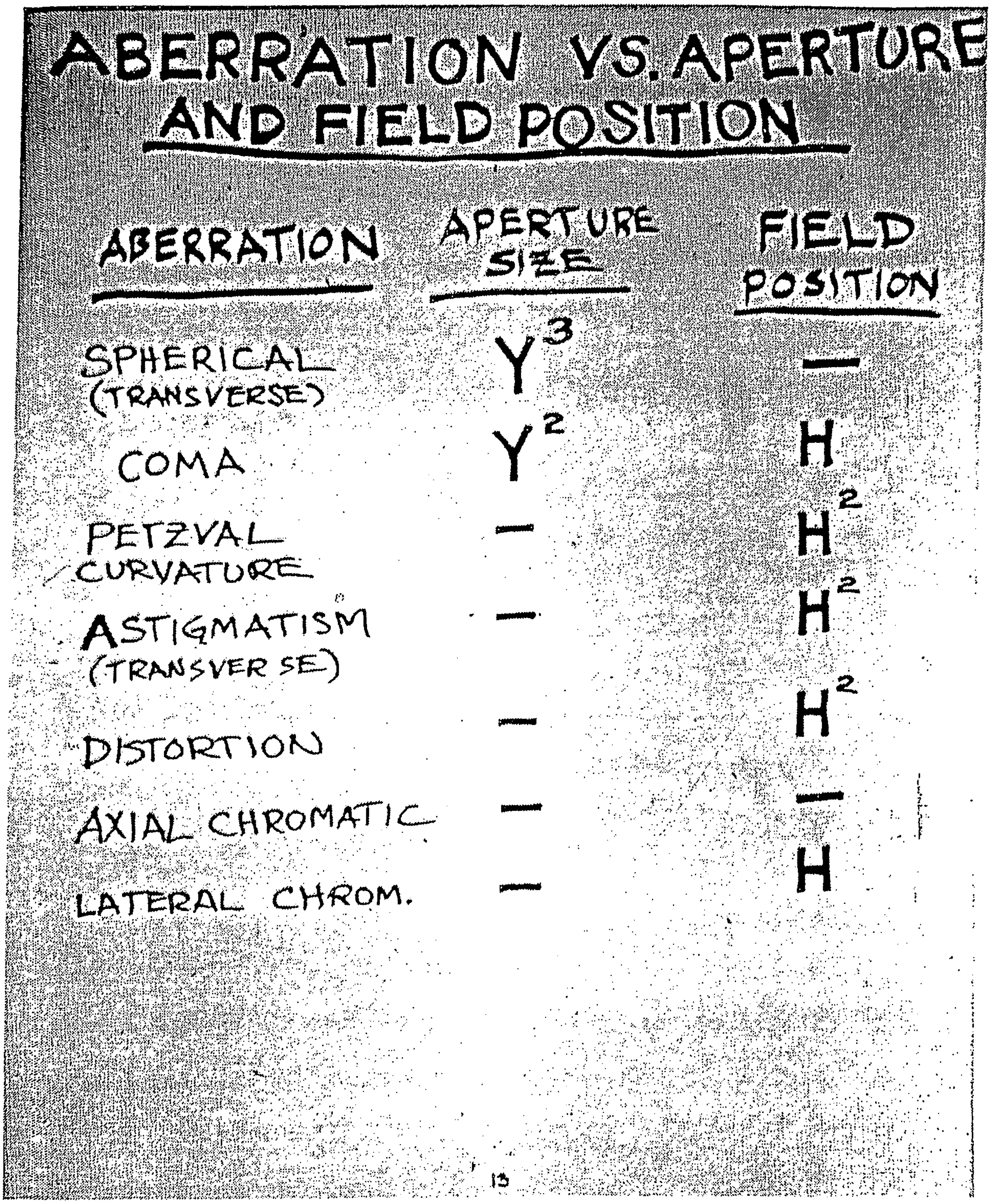
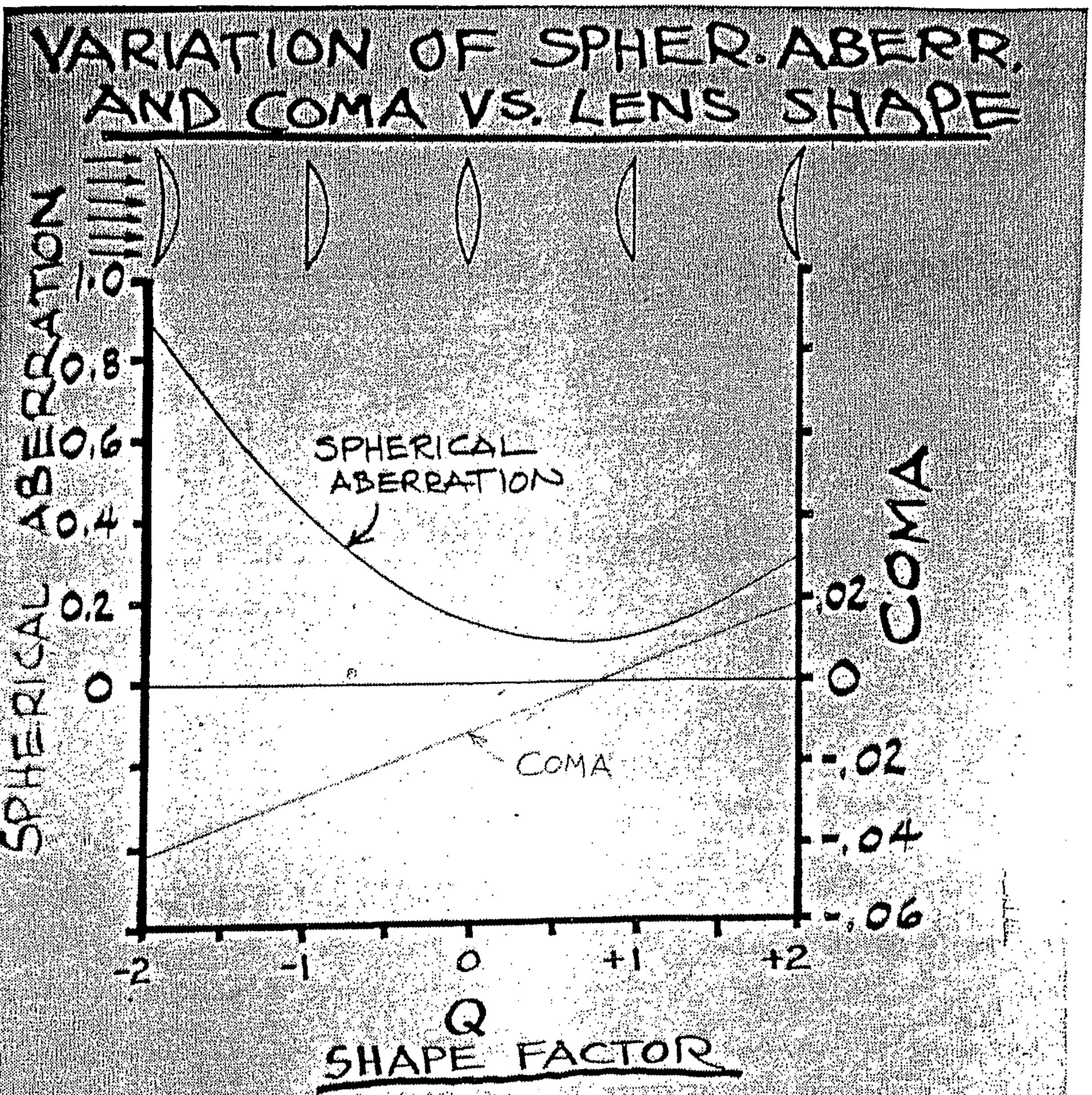

ABERRATION VS. APERTURE AND FIELD POSITION
ABERRATION
APERTURE SIZE
FIELD POSITION
SPHERICAL (TRANSVERSE)
Y3
—
COMA
Y2
H
PETZVAL CURVATURE
—
H2
ASTIGMATISM (TRANSVERSE)
—
H2
DISTORTION
—
H2
AXIAL CHROMATIC
—
—
LATERAL CHROM.
—
H
13

Figure 34



$$Q = \frac{R_2 + R_1}{R_2 - R_1}$$

Figure 35

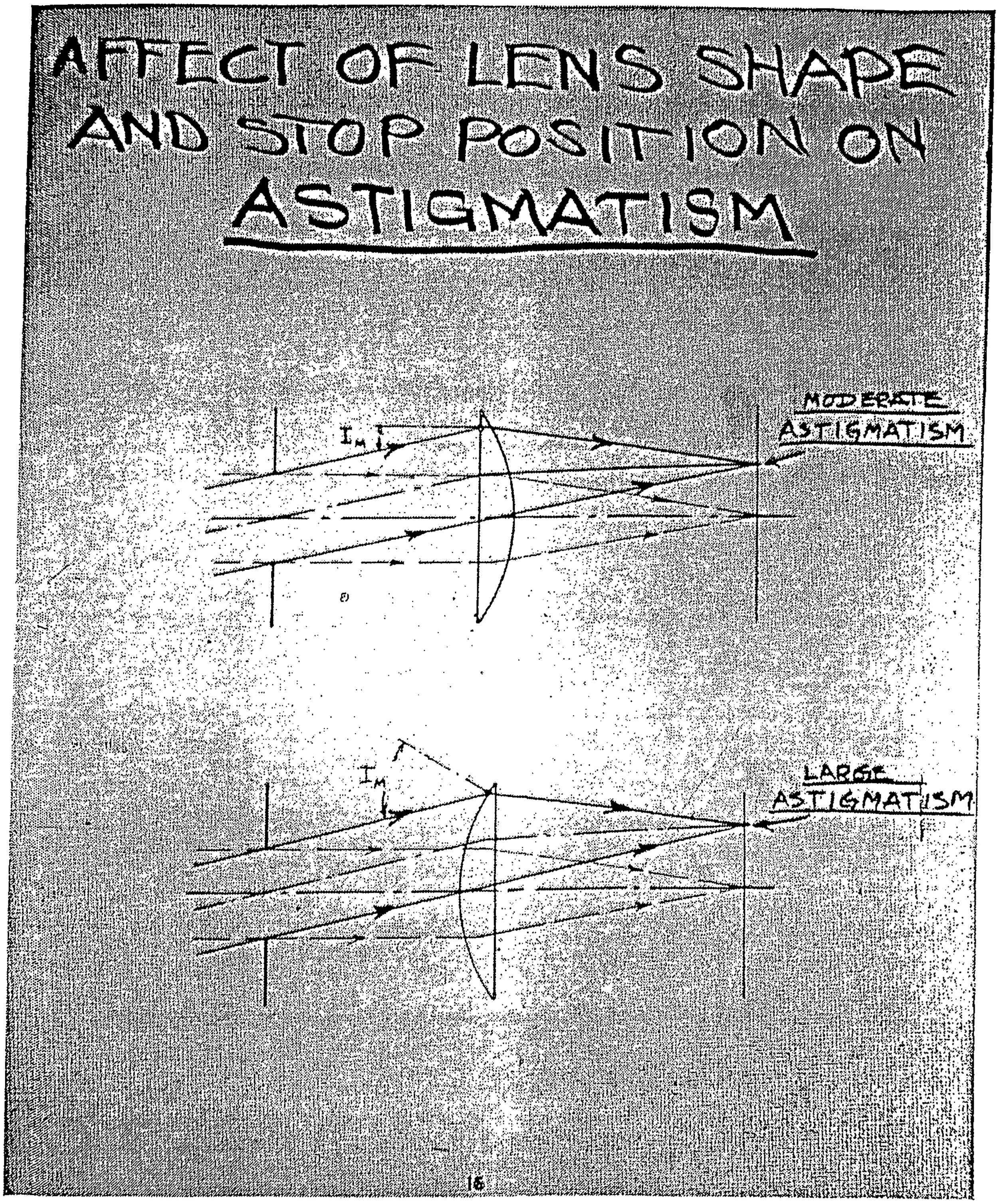

AFFECT OF LENS SHAPE AND STOP POSITION ON ASTIGMATISM
MODERATE ASTIGMATISM
LARGE ASTIGMATISM
16

Figure 36

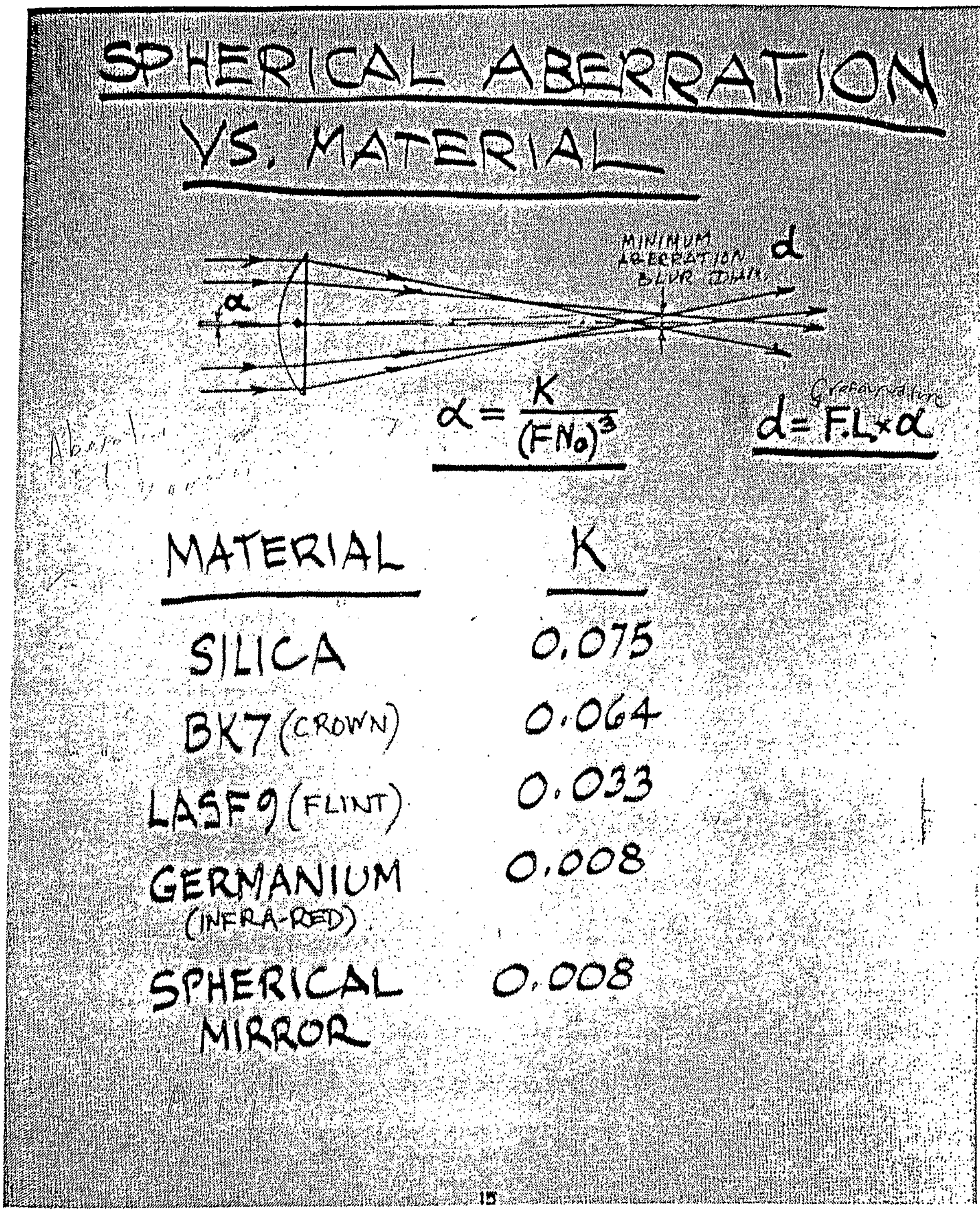

SPHERICAL ABERRATION
VS. MATERIAL
MINIMUM ABERRATION BLUR DIAM.
d
α
α = K / (F No)³
d = F.L. × α
MATERIAL
K
SILICA
0.075
BK7 (CROWN)
0.064
LASF9 (FLINT)
0.033
GERMANIUM (INFRA-RED)
0.008
SPHERICAL MIRROR
0.008
15

Figure 37

WWW.LAMBDARES.COM/OSLO

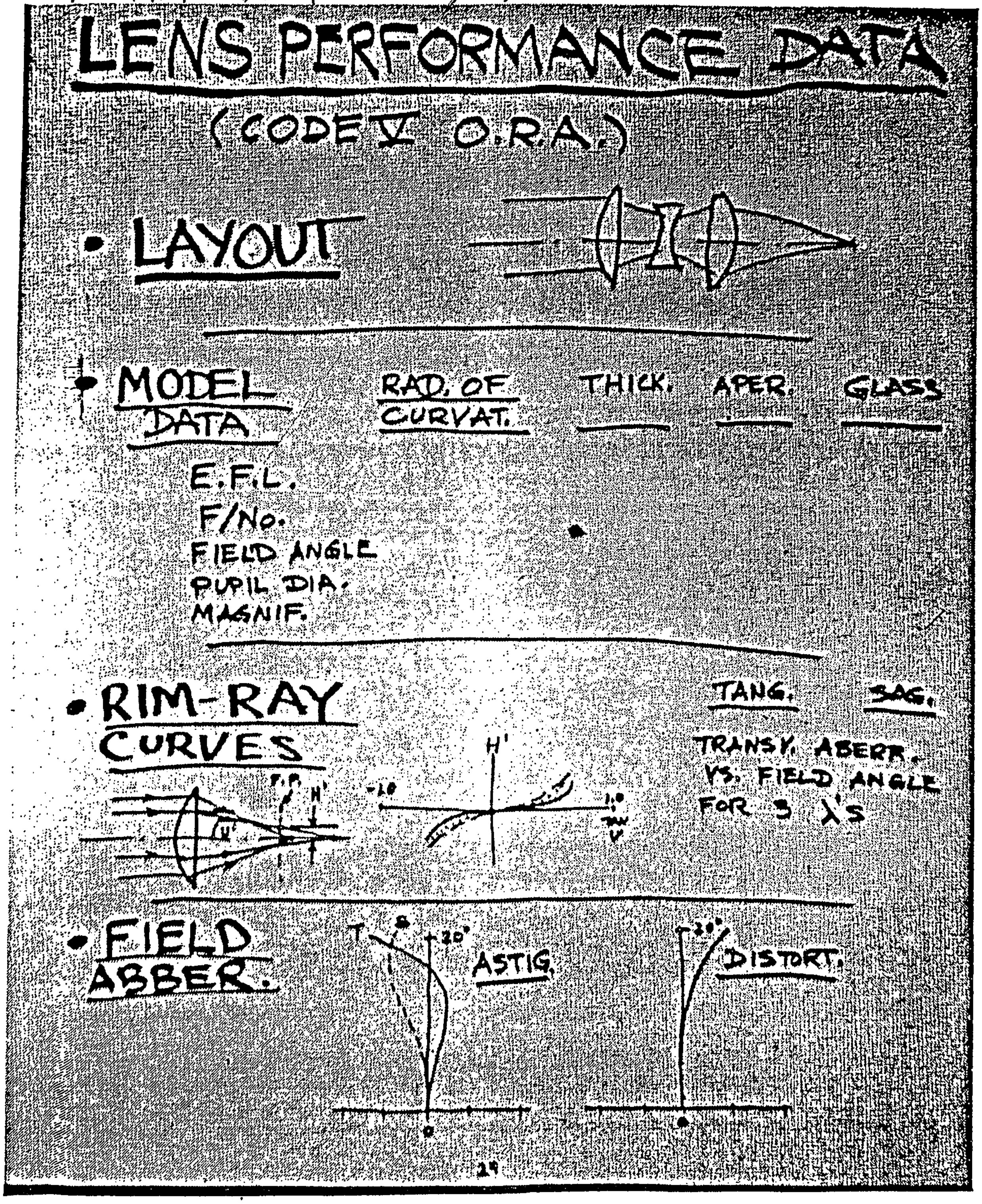


Figure 38

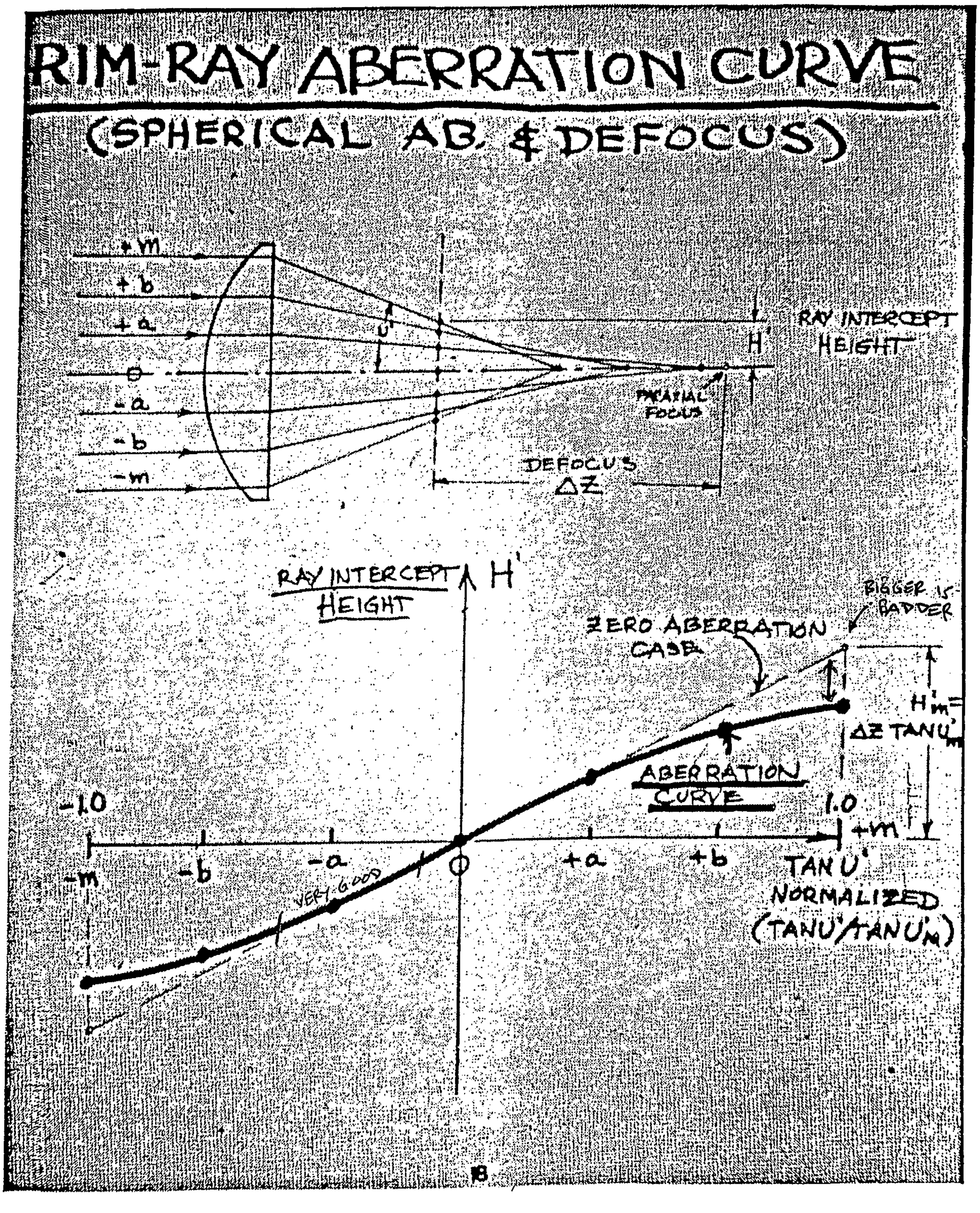

RIM-RAY ABERRATION CURVE
(SPHERICAL AB. & DEFOCUS)
+m
+b
+a
0
-a
-b
-m
U'
H'
RAY INTERCEPT HEIGHT
PARAXIAL FOCUS
DEFOCUS ΔZ
RAY INTERCEPT HEIGHT
H'
BIGGER IS BADDER
ZERO ABERRATION CASE
H'm = ΔZ TANU'm
ABERRATION CURVE
-1.0
1.0
-m
-b
-a
0
+a
+b
+m
VERY GOOD
TAN U' NORMALIZED (TANU'/TANU'M)
18

Figure 39

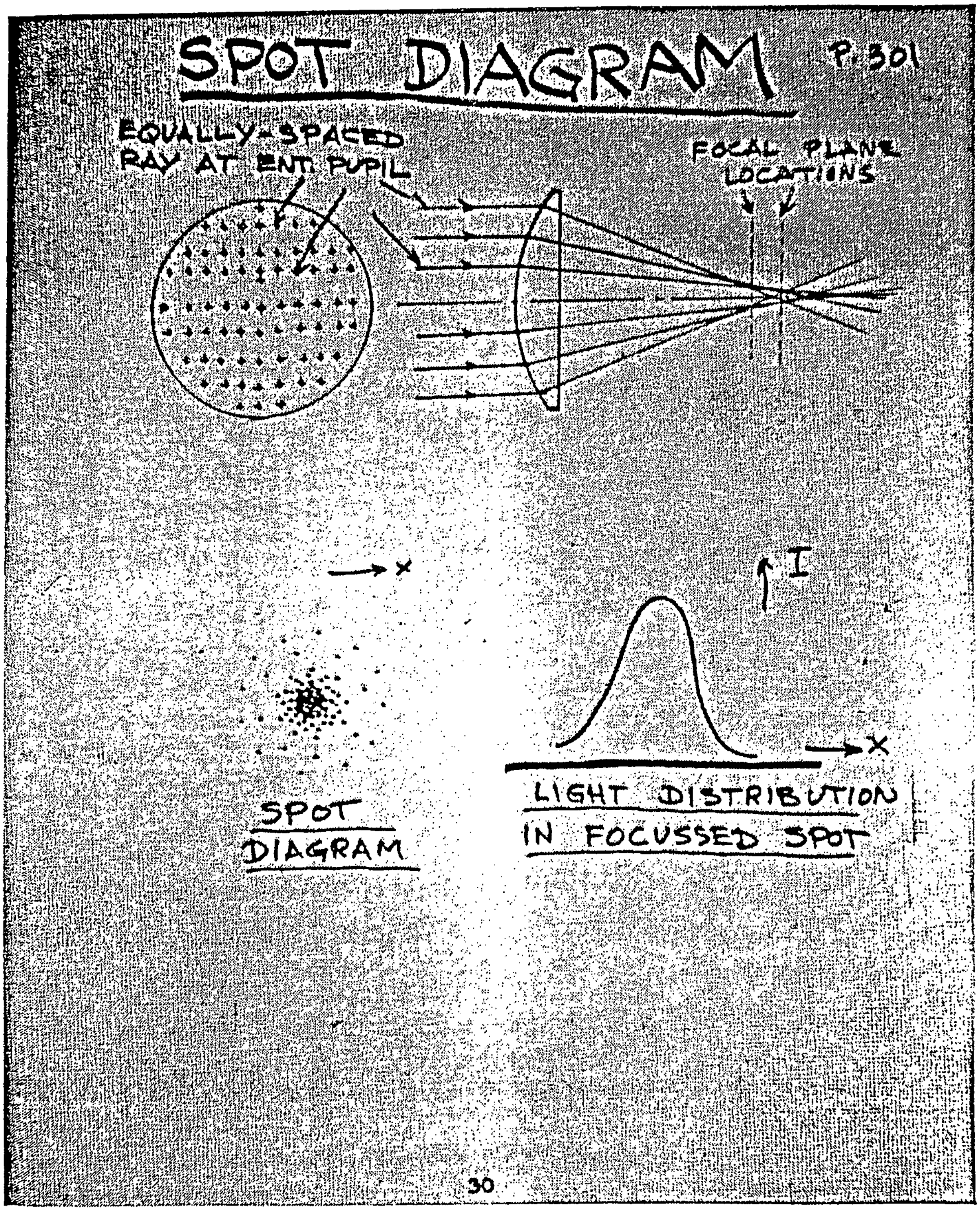

SPOT DIAGRAM
P. 301
EQUALLY-SPACED
RAY AT ENT. PUPIL
FOCAL PLANE
LOCATIONS
x
I
x
SPOT
DIAGRAM
LIGHT DISTRIBUTION
IN FOCUSSED SPOT
30

Figure 40

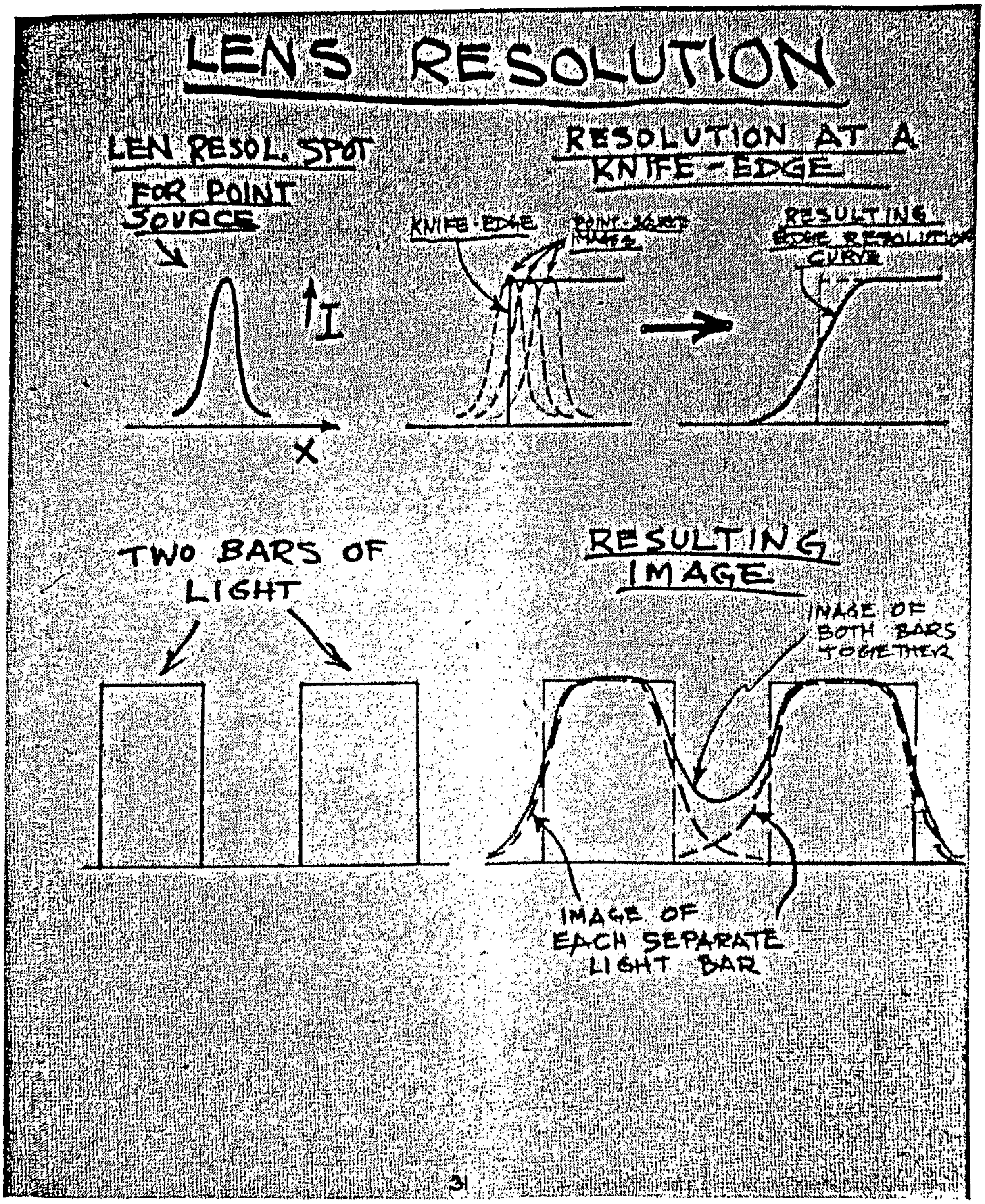

LENS RESOLUTION
LEN RESOL. SPOT
FOR POINT
SOURCE
I
X
RESOLUTION AT A
KNIFE-EDGE
KNIFE-EDGE
RESULTING
EDGE RESOLUTION
CURVE
TWO BARS OF
LIGHT
RESULTING
IMAGE
IMAGE OF
BOTH BARS
TOGETHER
IMAGE OF
EACH SEPARATE
LIGHT BAR
31

Figure 41

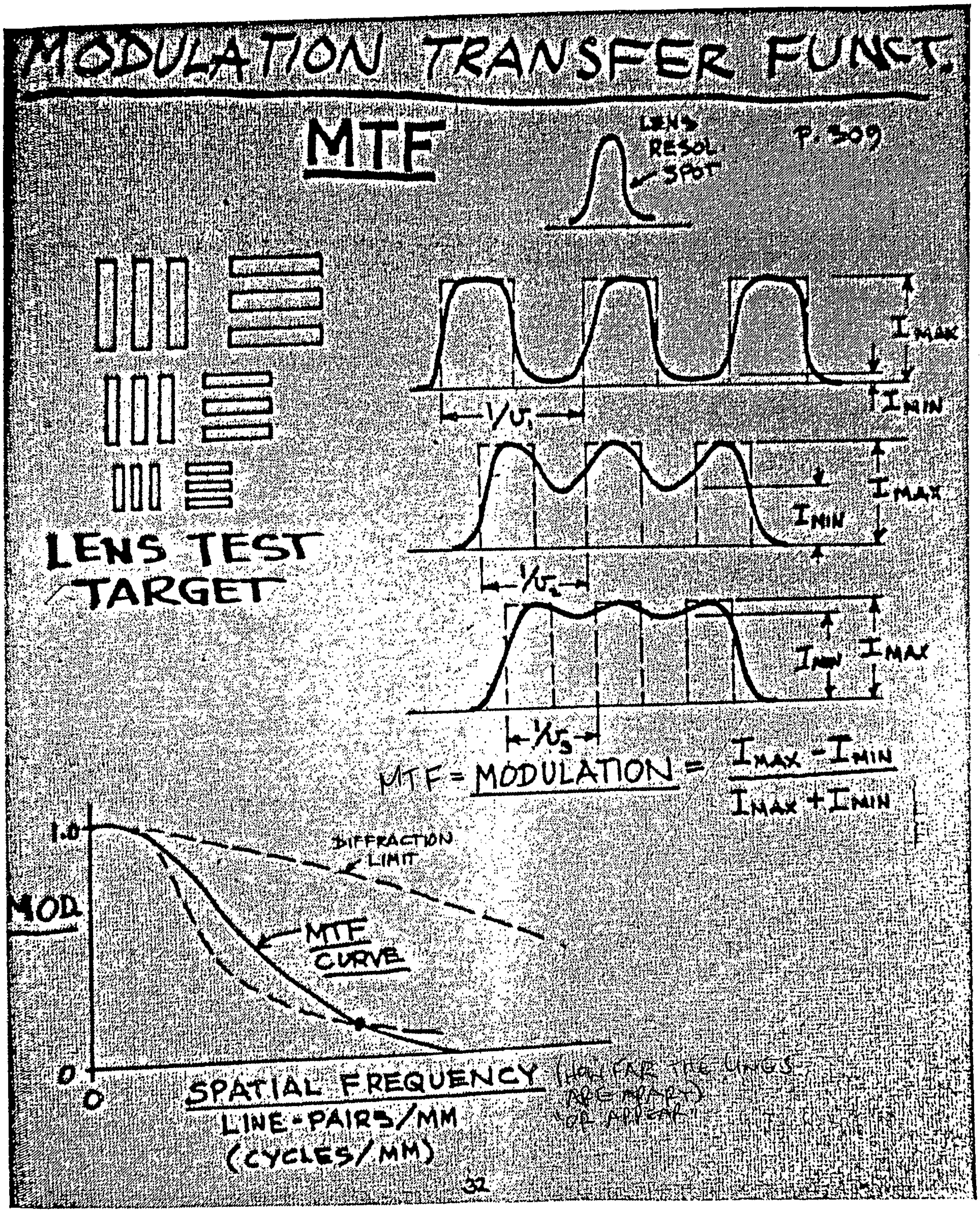

MODULATION TRANSFER FUNCT.
MTF
LENS RESOL. SPOT
P. 309
LENS TEST TARGET
IMAX
IMIN
1/υ1
1/υ2
1/υ3
MTF = MODULATION = IMAX - IMIN / IMAX + IMIN
1.0
MOD.
DIFFRACTION LIMIT
MTF CURVE
0
SPATIAL FREQUENCY
LINE-PAIRS/MM
(CYCLES/MM)
32

Figure 42

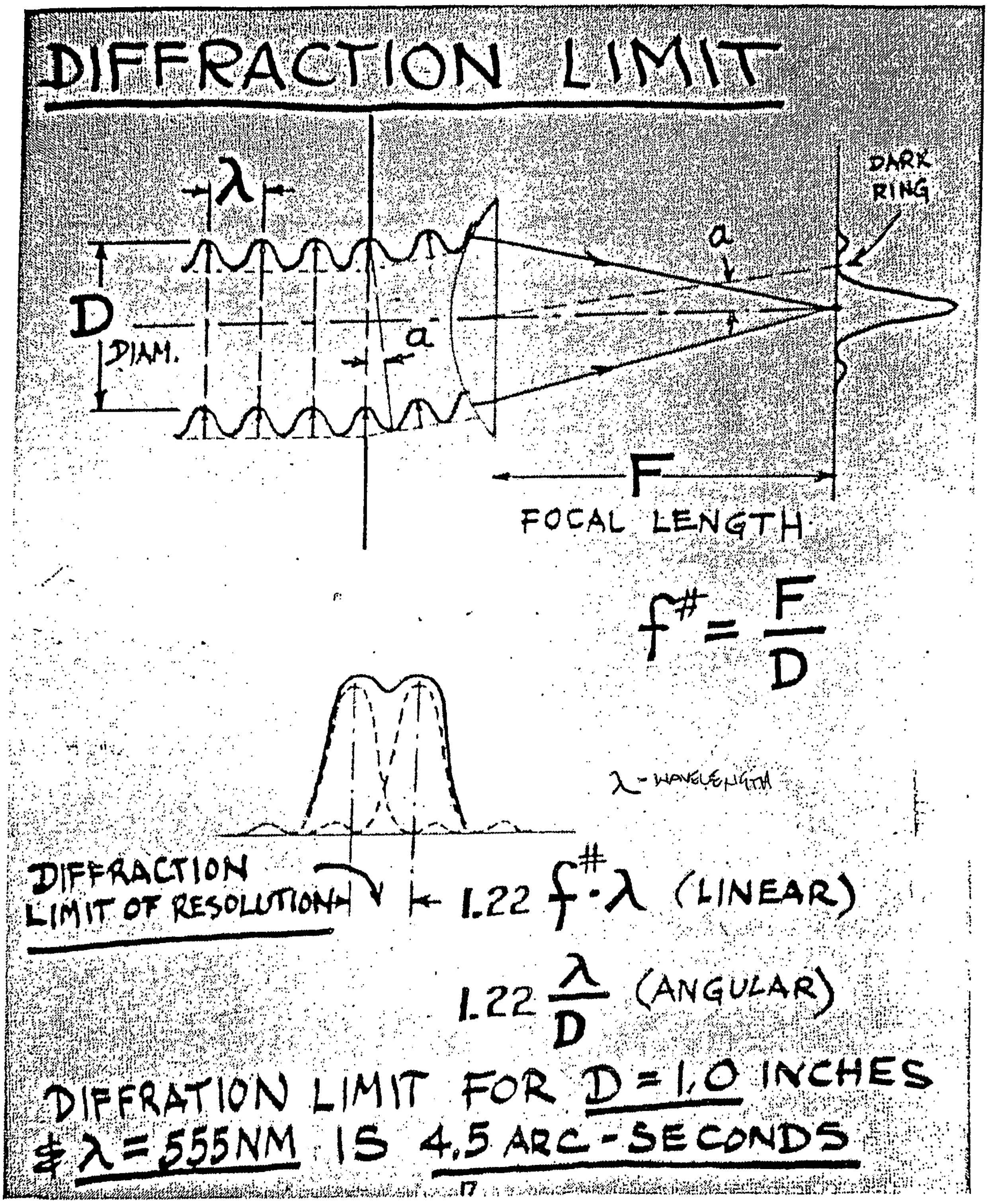

DIFFRACTION LIMIT
λ
DARK RING
a
D
DIAM.
a
F
FOCAL LENGTH
f# = F/D
λ - WAVELENGTH
DIFFRACTION LIMIT OF RESOLUTION
1.22 f#·λ (LINEAR)
1.22 λ/D (ANGULAR)
DIFFRATION LIMIT FOR D=1.0 INCHES
& λ=555NM IS 4.5 ARC-SECONDS
17

Figure 43

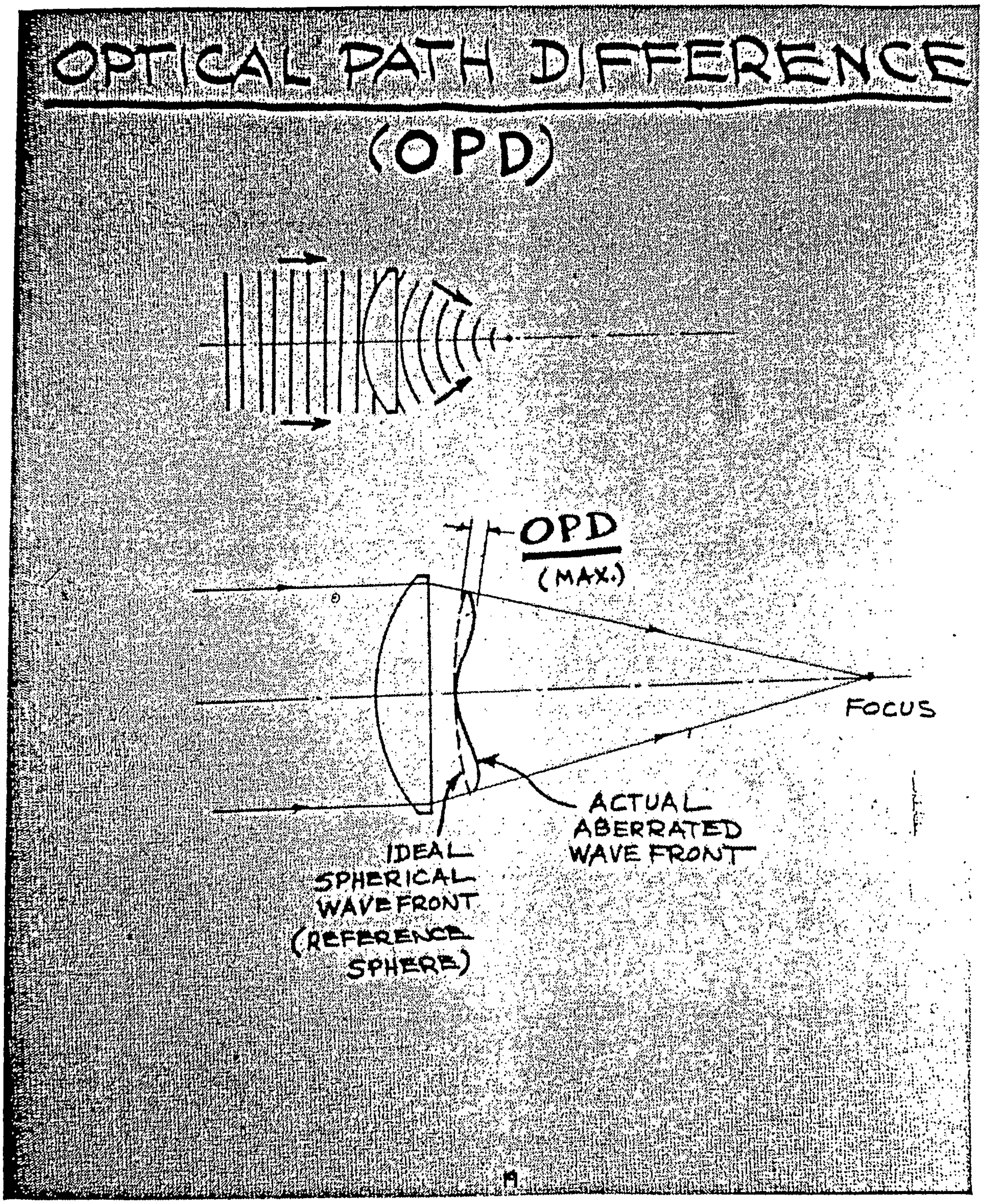

OPTICAL PATH DIFFERENCE
(OPD)
OPD
(MAX.)
FOCUS
ACTUAL
ABERRATED
WAVE FRONT
IDEAL
SPHERICAL
WAVE FRONT
(REFERENCE
SPHERE)

Figure 44

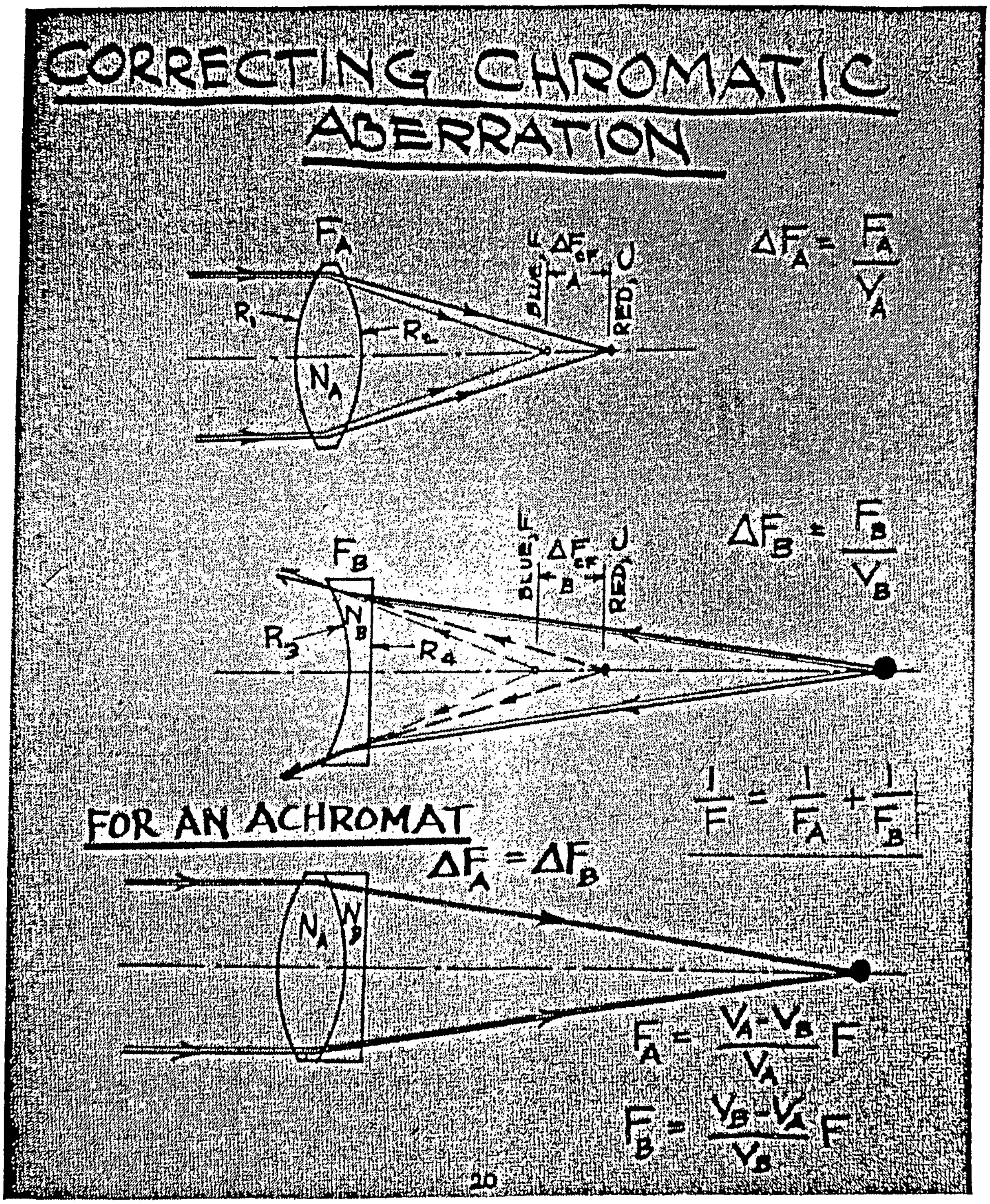

CORRECTING CHROMATIC ABERRATION
F_A
R_1
R_2
N_A
BLUE
RED
ΔF_{CF} A
$\Delta F_A = \frac{F_A}{V_A}$
F_B
R_3
R_4
N_B
BLUE
RED
ΔF_{CF} B
$\Delta F_B = \frac{F_B}{V_B}$
FOR AN ACHROMAT
$\Delta F_A = \Delta F_B$
$\frac{1}{F} = \frac{1}{F_A} + \frac{1}{F_B}$
N_A
N_B
$F_A = \frac{V_A - V_B}{V_A} F$
$F_B = \frac{V_B - V_A}{V_B} F$
20

Figure 45

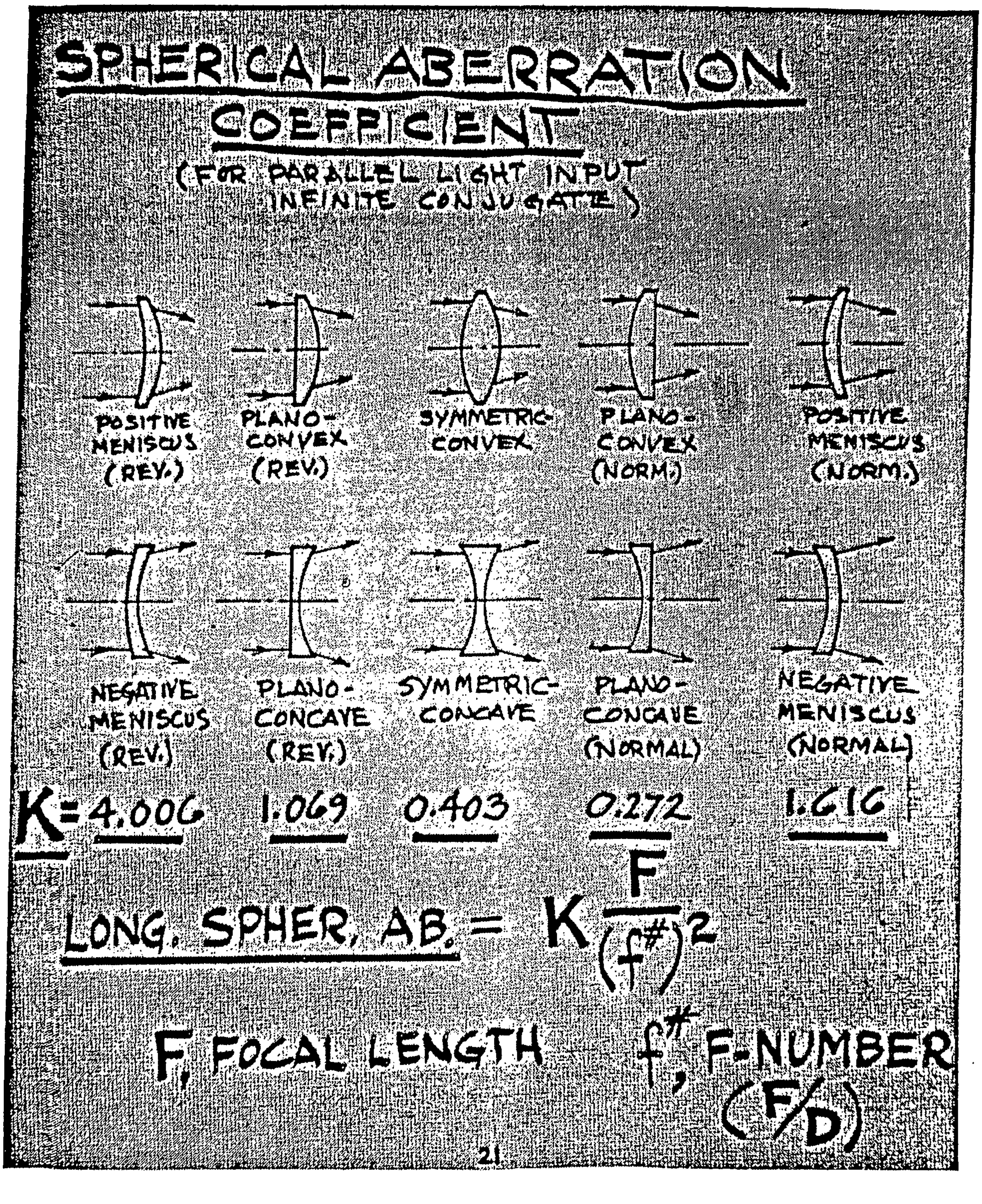

SPHERICAL ABERRATION
COEFFICIENT
(FOR PARALLEL LIGHT INPUT
INFINITE CONJUGATE)
POSITIVE MENISCUS (REV.)
PLANO-CONVEX (REV.)
SYMMETRIC-CONVEX
PLANO-CONVEX (NORM.)
POSITIVE MENISCUS (NORM.)
NEGATIVE MENISCUS (REV.)
PLANO-CONCAVE (REV.)
SYMMETRIC-CONCAVE
PLANO-CONCAVE (NORMAL)
NEGATIVE MENISCUS (NORMAL)
K= 4.006 1.069 0.403 0.272 1.616
LONG. SPHER. AB. = K F/(f#)²
F, FOCAL LENGTH f#, F-NUMBER (F/D)
21

Figure 46

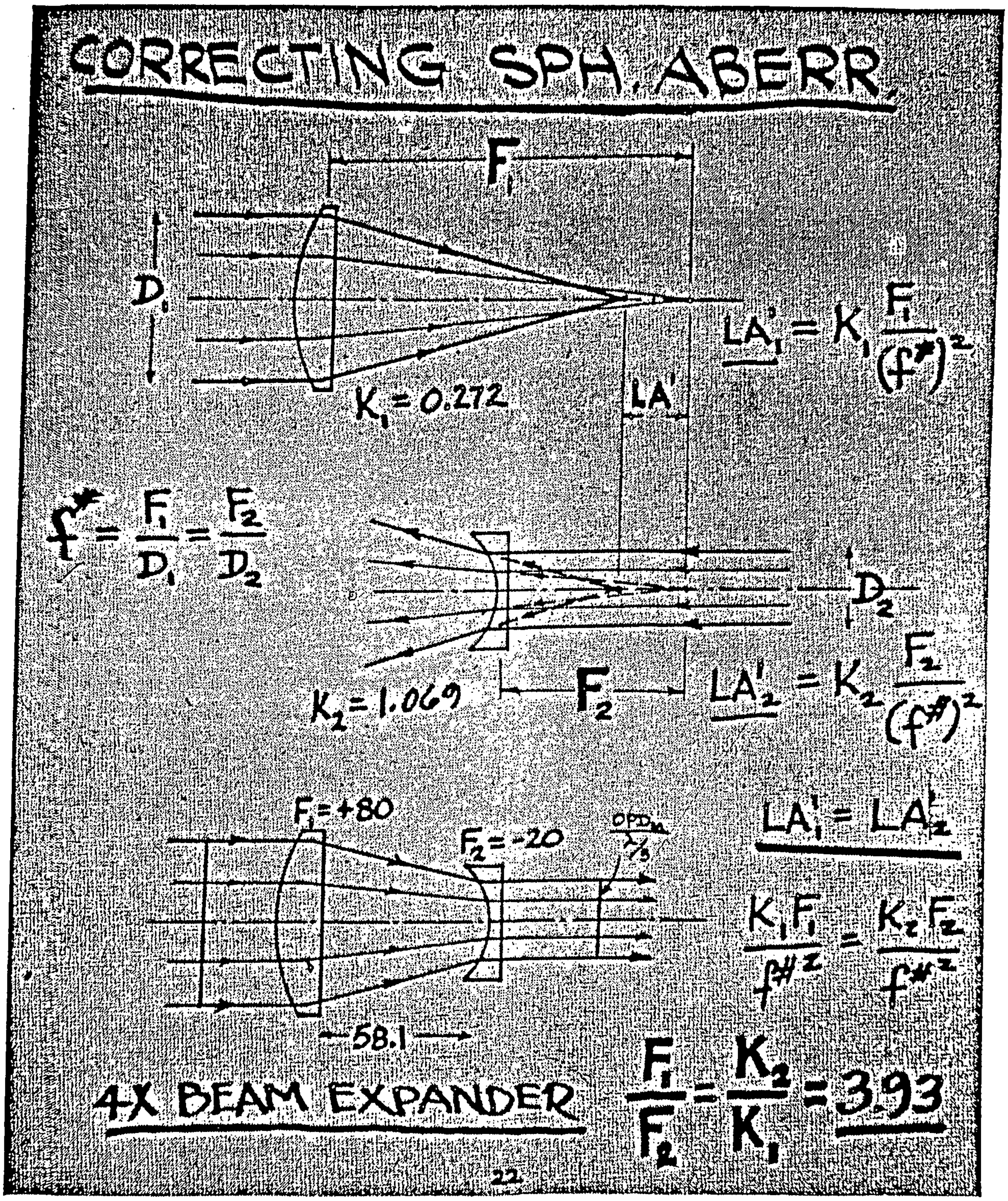

CORRECTING SPH. ABERR.
F1
D1
LA'1 = K1 F1/(f#)^2
K1 = 0.272
LA'
f# = F1/D1 = F2/D2
D2
K2 = 1.069
F2
LA'2 = K2 F2/(f#)^2
F1 = +80
F2 = -20
LA'1 = LA'2
K1F1/f#2 = K2F2/f#2
58.1
4X BEAM EXPANDER
F1/F2 = K2/K1 = 3.93
22

Figure 47

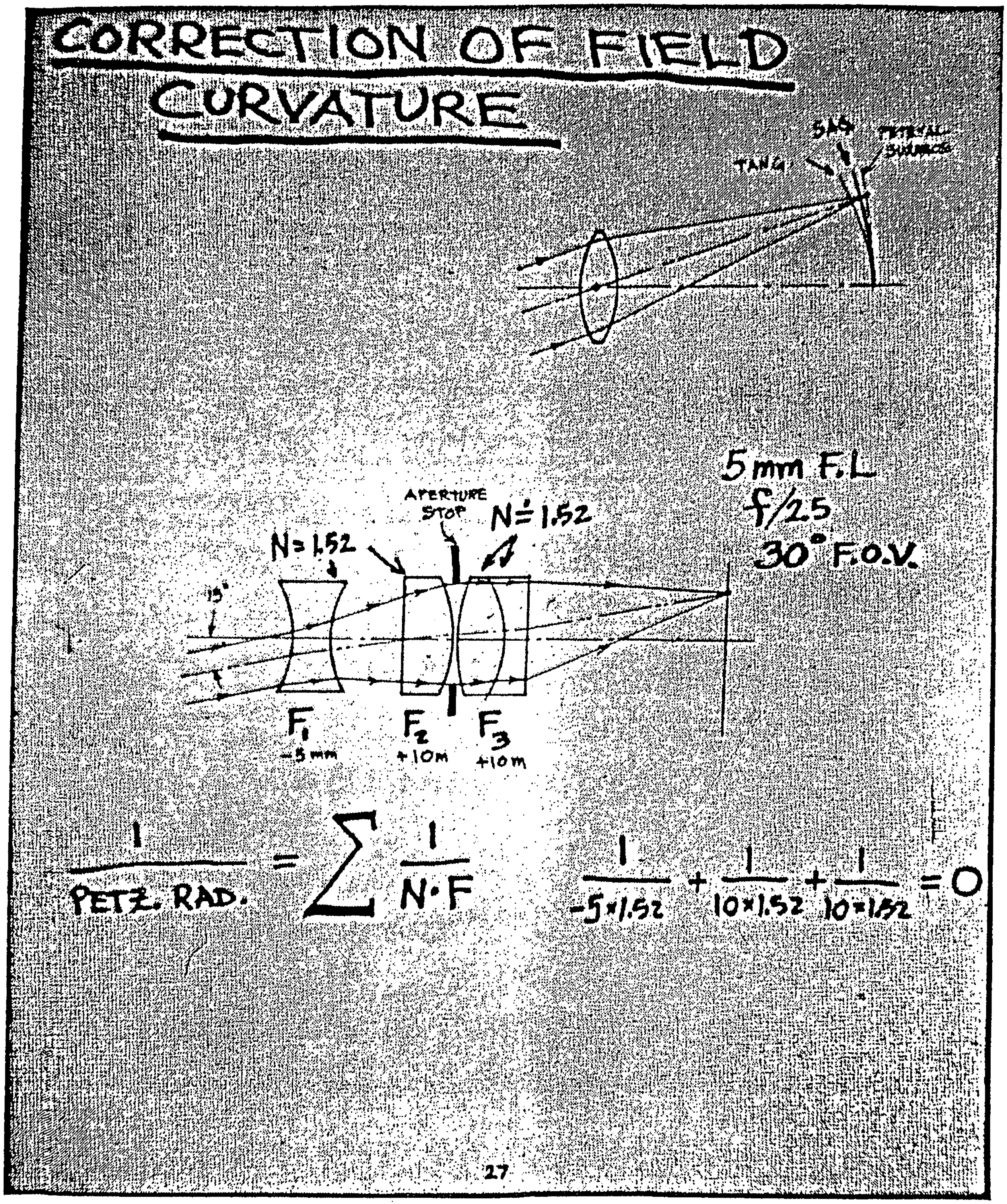

CORRECTION OF FIELD CURVATURE
SAG
TANG
5 mm F.L
f/2.5
30° F.O.V.
APERTURE STOP
N = 1.52
N ≐ 1.52
15°
F1
-5 mm
F2
+10m
F3
+10m
1 / PETZ. RAD. = Σ 1 / N·F
1/(-5×1.52) + 1/(10×1.52) + 1/(10×1.52) = 0
27

Figure 48

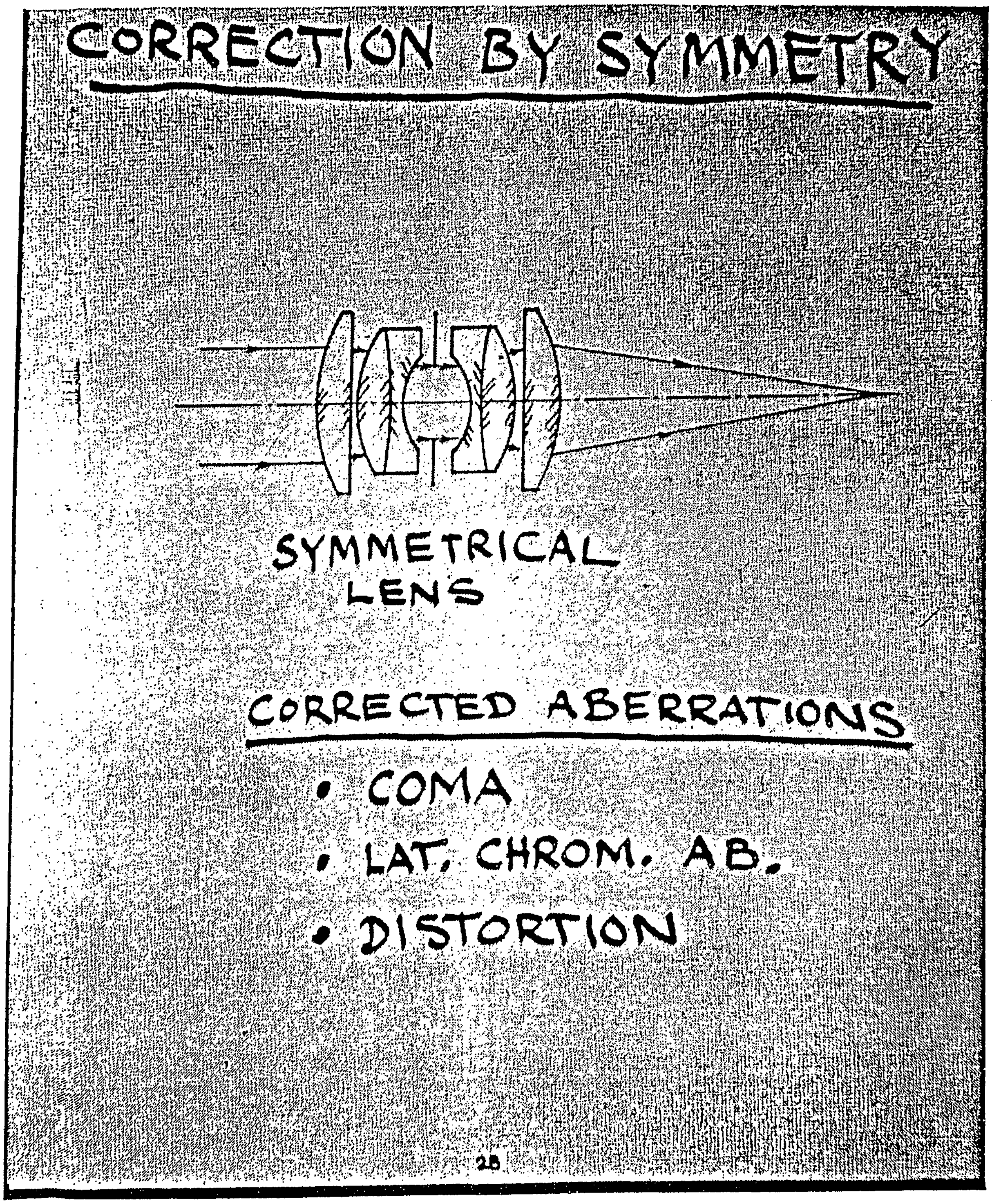

CORRECTION BY SYMMETRY
SYMMETRICAL
LENS
CORRECTED ABERRATIONS
• COMA
• LAT. CHROM. AB.
• DISTORTION
28

Figure 49