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OPTIMAL FSTOP/RESOLUTION APPARATUS AND METHOD FOR SPECIFIED DEPTH-OF-FIELD

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

The present invention relates generally to determining a camera's optimal f_{stop}, and more particularly to a method and apparatus for computing the f_{stop} that provides optimal resolution for a specified depth-of-field.

(2) Description of the Prior Art

It is well known that a camera's f_{stop} controls the depth-of-field in a photographic image. The depth-of-field is the region in which objects remain focused, and objects outside the depth-of-field are not focused. For a given depth-of-field, another measure of image quality is the resolution, or image sharpness, within that depth-of-field. The depth-of-field resolution is determined by film properties (grain size), lens properties (focal length and aperture), light properties (wavelength), and depth-of-field size.

Because depth-of-field and resolution are each affected by a camera's f_{stop}, photographers often compromise depth-of-field for increased resolution, or vice-versa. U.S. Patent No. 4,785,323 details a method of selecting an aperture/shutter combination with an optimum depth-of-field to blur ratio, but maximum resolution throughout the depth-of-field is not considered. Alternately, U.S. Patent No. 4,792,823 describes a manual depth-of-field preview device in which an optimum depth-of-field is user-determined by previewing images. Again, optimum settings are not computed or considered. U.S. Patent Nos. 5,049,916 and 5,130,739 optimize photographic exposure through extra system speed, but sacrifice depth-of-field for shutter speed to minimize blur from system and object motion. These patents do not address picture sharpness or depth-of-field control. U.S. Patent No. 5,532,782 provides calculations for an f_{stop} that ensure focus for multiple objects at various distances; however, maximum sharpness or resolution is not addressed.

There is currently no method or apparatus for computing the maximum resolution or image sharpness within a predefined depth-of-field. What is needed is a method and apparatus that allow a photographer to compute f_{stop} for optimal resolution throughout a predetermined depth-of-field.

SUMMARY OF THE INVENTION

It is a general purpose and object of the present invention to provide a method and apparatus to compute f_{stop} to provide maximum image resolution or sharpness.

It is a further object to provide such computation for a predetermined depth-of-field specified by the photographer.

It is yet another object to provide such computation in an exact manner, and in an approximate manner for relative computational ease.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

These objects are accomplished with the present invention by a method and apparatus to determine f_{stop} that provides optimal image resolution for a predetermined depth-of-field. An approximate and exact method and apparatus are provided to determine the optimal resolution f_{stop}. The optimal resolution f_{stop} is a function of the lens focal length, depth-of-field in front of the object, wavelength of light, and distance of the object to the lens center. Once the optimal resolution f_{stop} is determined, the camera is adjusted to the closest discrete f_{stop}

available. When the approximate field technique is utilized, the camera must be adjusted to the discrete f_{stop} closest to, but not exceeding, the computed f_{stop}.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the invention and many of the attendant advantages thereto will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings, wherein like reference numerals refer to like parts and wherein:

FIG. 1 is a basic camera lens diagram to explain the notation;

FIG. 2 is a plot of spot size/resolution versus f_{stop} for grain size;

FIG. 3 is a plot of spot size/resolution versus f_{stop} for diffraction using a fixed wavelength of light;

FIG. 4 is a plot of spot size/resolution versus f_{stop} for a fixed depth-of-field;

FIG. 5 is a plot of spot size/resolution versus f_{stop} for a specified short-range photography scenario;

FIG. 6 is a plot of spot size/resolution versus f_{stop} for a specified mid-range photography scenario;

FIG. 7 is a plot of spot size/resolution versus f_{stop} for a specified long-range photography scenario; and

FIG. 8 is a diagram of the method and apparatus for determining the f_{stop} for optimal resolution, depending upon the choice of field technique or exact method.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, there is shown a diagram indicating a camera lens **10** and associated optical references to define the terms to be used herein. Object space **12** shall be defined as all points on the side of the lens opposite the film, while image space **14** defines all points on the side of the lens containing the film. Similarly, the object plane **16** is the plane in object space **12** containing the object of interest, parallel to the plane containing the lens **18**, and a distance o **20** from the lens. The image plane **22** is the plane in image space **14** parallel to the plane containing the lens **18**, and a distance i **24** from the lens. Points in object space **12** are mapped into image space **14** by the thin lens formula:

$$1/f = 1/o + 1/i, \qquad (1)$$

where f **26** is the lens **10** focal length equal to the distance between the plane containing the lens center **18**, and a parallel image plane **28** containing the focused image of an object at infinity in object space **12**.

As FIG. 1 shows, a point **30** on the object plane translates to a point **32** on the image plane. As objects move away from the object plane **16**, the focus of the image of those objects deteriorates; however, objects close to the object plane **16** may still provide focused images, and this is known as the depth-of-field effect. Objects within the depth-of-field, but not on the object plane **16**, project to a spot or disk on the image plane **22**. If D_f **34** is the depth-of-field in front of the object, then a point **36** at a distance D_f **34** in front of the object plane **16** projects to a point **36i** in image space such that the image plane **22** contains a spot or disk of diameter h_i **38**. Similarly, if D_r **40** is the depth-of-field to the rear of the object, then a point **42** at a distance D_r **40** to the rear of the object plane **16** also projects to a point **42i** in the image space such that the image plane **22** contains a spot or disk of diameter h_i **38**. For objects within the total depth-of-field, $D_f + D_r$ **44**, the resolution limit at the image plane **22** is therefore h_i **38**, otherwise known as the spot size, or resolution.

A point in object space **12** is therefore in focus if its image on the image plane **22** is less than h_i **38** in diameter, and a point in object space **12** is in perfect focus if its image on the image plane **22** is also a point. It then follows that two points in object space are resolvable if their image plane images are disjoint.

Image resolution is affected by several factors including film grain size, diffraction, and depth-of-field. Film grain size does not depend upon camera settings and is independent of f_{stop} that controls the camera aperture. Additionally, film grain size remains constant regardless of depth-of-field, object distance, or lens focal length.

Referring now to FIG. 2, there is shown a plot of spot size in the image plane versus f_{stop} as a function of grain size. As FIG. 2 indicates, the relationship between spot size or resolution, and f_{stop}, is constant for all f_{stop} values.

A camera aperture restricts light waves to cause interference known as diffraction, and diffraction limits image resolution. The resolution effects from diffraction depend on the light wavelength, aperture diameter (i.e., f_{stop}), and distance between the film and the lens. E. Hecht, *Optics*, 2nd Edition, provides a well known relationship between diffraction spot size and the circular aperture opening:

$$\text{Diffraction spot diameter} = 2.44 * i * \lambda / A \quad (2)$$

$$= \lambda * \{(o * f)/(o - f)\} * (f_{stop}/f) \quad (3)$$

where:

λ is the wavelength of light (angstroms);

A is the aperture diameter (meters); and

$f_{stop} = f/A$.

Referring now to FIG. 3, there is shown the basic linear relationship between spot size and f_{stop} for a constant light wavelength, λ, where o and f are held constant. As FIG. 3 indicates, for a constant wavelength, resolution from diffraction decreases (spot size increases) as f_{stop} increases.

Image resolution is also limited by the fact that all objects cannot be located in the object plane. As stated previously, objects within the depth-of-field and located on the lens axis, project onto the image plane as a disk with diameter h_i given by the well known equation:

$$h_i = (f/f_{stop})*(f/(o-f))*(d/(o-d)) \qquad (4)$$

where:

d is depth-of-field (in front of object) (meters).

The resolution due to depth-of-field therefore depends upon f_{stop}, focal length, object distance, and distance from the object plane (depth-of-field). Referring now to FIG. 4, there is shown a plot of spot size or resolution versus f_{stop} for a constant depth-of-field, with f and o held constant, indicating a hyperbolic shape. As f_{stop} increases, depth-of-field changes cause resolution to increase (spot size decreases).

Referring now to FIG. 5, there is shown a plot of film grain size, diffraction, and depth-of-field on the same plot of resolution versus f_{stop}. Because the three effects are always present, plotting on the same graph allows insight into the dominating effect. To produce the graphs in FIG. 5, light wavelength was set to 5500 angstroms as a compromise between the 4000 angstrom and 7000 angstrom values in the visible spectrum. For FIG. 5, close distance, or short-range photography was considered, and accordingly, object distance was set at 1 meter, focal length to 28 millimeters, depth-of-field to 0.1 meter, and film grain size to 4 micrometers.

Conventional f_{stop} computations suggest the f_{stop} corresponding to the intersection of the depth-of-field and grain size curves **60**. As FIG. 5 indicates, the f_{stop} at the intersection of the depth-of-field and grain size curves **60** corresponds to an f_{stop} where diffraction **62**, not depth-of-field or grain size, limits the resolution or spot size. Selecting the f_{stop} at the intersection of the depth-of-field and grain size curves **60** therefore ignores the dominating and limiting diffraction effect **62** on resolution at that f_{stop}.

The invention presented herein is to use the f_{stop} providing maximum resolution, or equivalently, the f_{stop} that minimizes the maximum of the three spot sizes. FIG. 5 shows that depth-of-field limits the resolution for f_{stop} values less than 8.5 **64,66**, while diffraction limits the resolution for f_{stop} values greater than 8.5 **64, 66**. Because depth-of-field resolution decreases as f_{stop} increases, while diffraction resolution increases as f_{stop} increases, the minimum spot size, or optimum resolution, occurs at the intersection **64** of the depth-of-field and diffraction curves. When this intersection **64** is above the film grain line as in this short-range scenario, film grain does not limit resolution more than diffraction or depth-of-field. The f_{stop} providing optimal resolution in the short-range scenario is therefore that f_{stop} corresponding to the intersection of the depth-of-field and diffraction curves **64**. As FIG. 5 shows, the invention's f_{stop} **66** is nearly one-third the conventional method f_{stop} **68**, with the invention producing a smaller spot size **70** (i.e., increased resolution) of nearly one-third the conventional method f_{stop} spot size **72**.

Referring now to FIG. 6, there is shown a plot of the three resolution factors for mid-range photography. The FIG. 6 curves used an object distance set to 100 meters, focal length to 50 millimeters, depth-of-field to 40 meters, film grain size to 4 micrometers, and light wavelength to 5500 angstroms. As FIG. 6 indicates, just as in FIG. 5, for all f_{stop} values, either diffraction or depth-of-field limits the resolution, with the intersection of the depth-of-field and diffraction curves occurring above the film grain size curve. Since film grain size is not the limiting resolution factor in the mid-range scenario, the f_{stop} providing maximum resolution remains the intersection of the diffraction and depth-of-field curves **80**. Once again, the f_{stop} generated by the conventional technique, at the intersection of the depth-of-field and grain size curves **82**, exists in a region where diffraction limits the resolution. Using the invention to determine f_{stop} as the intersection of the depth-of-field and diffraction curves **80**, the optimal f_{stop} **84** providing maximum resolution is obtained. An f_{stop} less than the optimal f_{stop} **84** is limited by depth-of-field to produce larger spot sizes than the optimal spot size **86**; and an f_{stop} greater than the optimal f_{stop} **84** is limited by diffraction to produce larger spot sizes than the optimal spot size **86**.

Referring now to FIG. 7, there is shown a plot of the three resolution factors for long-range photography. FIG. 7 curves used an object distance of 1000 meters, focal length set to 200 millimeters, depth-of-field set to 100 meters, film grain size of 4 micrometers, and light wavelength set to 5500 angstroms. As FIG. 7 indicates, the depth-of-field and diffraction curves intersect **100** below the film grain size. The invention indicates through FIG. 7 that when the depth-of-field and diffraction curves intersect **100** below the film grain size, any f_{stop} value in the region where the depth-of-field and diffraction curves are below the film grain curve, provides the maximum resolution as limited by the film grain size. As the diffraction curve crosses the film grain curve, the diffraction effect limits the resolution. The f_{stop} computed by the invention **102** therefore provides equal resolution to the f_{stop} provided by the conventional computation **104** in this long-range photography case; however, the invention provides insight into a range of f_{stop} values that achieve this optimal resolution. For this long-range photography scenario, all f_{stop} in the region where the diffraction spot size is less than the film grain spot size provide a resolution equal to the film grain spot size **106**; otherwise, diffraction limits the resolution. The f_{stop} providing maximum resolution is therefore an f_{stop} in the range in which the film grain size remains the dominating effect.

FIGS. 5, 6, and 7 illustrate the invention that stipulates for a predetermined depth-of-field, the optimal f_{stop} is the intersection of the diffraction and depth-of-field curves. If this intersection is greater than the film grain spot size, the intersection provides the optimal resolution; alternately, if the intersection is less than the film grain spot size, the invention provides a range of suitable f_{stop} values that provide maximum resolution, however that resolution is provided by the film grain spot size.

The intersection of the depth-of-field and diffraction curves requires solving equations (3) and (4) simultaneously for f_{stop}, assuming $f<<o$ and $d<<o$, setting λ=4000 angstroms, and specifying f in millimeters, thereby resulting in the following computation for the optimal f_{stop}:

$$\text{optimal } f_{stop} = f*\mathrm{sqrt}(d)/o \qquad (5)$$

where:

f is in millimeters;

o is in meters; and,

d is in meters.

Since λ ranges between 4000 and 7000 angstroms, and equation (5) was derived using λ=4000 angstroms, equation (5) provides an upper bound on the optimal f_{stop}.

When the optimal expression for f_{stop} from equation (5) is substituted into equation (4), and the same assumptions are made that $f \ll o$, $d \ll o$, λ=4000 angstroms, and specifying f in millimeters, the following expression for optimal resolution results:

$$\text{optimal resolution} = f^{*}\text{sqrt}(d)/o \text{ microns} \qquad (6)$$

where:

f is in millimeters;

o is in meters; and,

d is in meters.

Equations (5) and (6) indicate that the optimal f_{stop} and optimal resolution expressions are computationally identical. The photographer must merely compute the expression $f^{*}\text{sqrt}(d)/o$ and interpret the result as being the optimal f_{stop} or the optimal resolution in microns. If the resolution is smaller than the film grain resolution, the film grain limits the image resolution; otherwise, diffraction and depth-of-field effects limit the resolution and the invention provides the optimal resolution f_{stop} for the given depth-of-field.

Because f_{stop} settings are discrete rather than continuous, photographic equipment may not contain the exact f_{stop} provided by equation (5). Since equation (5) assumes λ=4000 angstroms and $d \ll o$, equation (5) provides an upper bound for the optimal f_{stop}; therefore, in setting photographic equipment for the optimal f_{stop} computed by equation (5), the f_{stop} closest to the computed f_{stop}, but not exceeding the computed f_{stop}, should be chosen.

Although equations (5) and (6) are accurate, reliable, and easily computed expressions for the optimal f_{stop} and optimal resolution in microns, the expressions were derived using the approximations that $f \ll o$, $d \ll o$, λ=4000 angstroms, and f units of millimeters. Expressions (5) and (6) are therefore referred to as the "field technique" or approximate method, as the computations may be simply computed. For more exact computations, the optimal f_{stop} follows, derived by solving equations (3) and (4) simultaneously for f_{stop}:

$$\textit{exact}\ \text{optimal}\ f_{stop} = f*\mathrm{sqrt}(d/(2.44*\lambda*o*(o-d))) \qquad (7)$$

where:

λ is in meters;

f is in meters;

o is in meters; and,

d is in meters.

For photographers desiring an exact computation of the optimal f_{stop} or resolution in microns, the computation described by equation (7) may be used. Because equation (7) is more complex than equations (5) or (6), it is anticipated that a computer or calculator could be programmed or utilized in solving equation (7). The computer or calculator may be integrated with the camera, or a separate device. The same devices and configurations may be utilized for the field technique; however, the field technique's relative simplicity increases the likelihood that a the optimal f_{stop} can be computed without any extraneous device.

Referring now to FIG. 8, there is shown a procedure **110** for determining the optimum f_{stop} and resolution. The general photographic procedure **112** is not altered until the f_{stop} determination is required. The general photographic procedure includes choosing a film speed **112a**, selecting a lens focal length **112b**, choosing a shutter speed **112c**, focusing the object **112d**, and obtaining values for focal length, object distance, and depth-of-field **112e**. The invention presented herein is then inserted into the general photographic procedure to provide the optimal f_{stop} for the desired depth-of-field. The photographer must first determine whether the exact or approximate f_{stop} will be computed **114**. If the approximate or field technique is being implemented, the approximate f_{stop} established by equation (5) is computed **116**, and the camera is adjusted using the f_{stop} closest to, but not exceeding, the f_{stop} provided by equation (5) **118**. This f_{stop} value is equivalent to the resolution in microns. Alternately, if the exact method is desired, the exact f_{stop} is computed using equation (7) **120**, and the camera is adjusted to the closest discrete f_{stop} **122**. Once the camera is adjusted for the computed f_{stop}, at **118** or **122**, the shutter release may be depressed **124**.

The advantage of the present invention over the prior art is that the invention provides a method and apparatus to determine an f_{stop} to provide optimal resolution for a specified depth-of-field. Within the method provided, an estimate and an exact procedure are identified depending upon the computational resources available.

What has thus been described is a method and apparatus to determine the f_{stop} that provides optimal image resolution for a predetermined depth-of-field. An approximate and exact method and apparatus are provided to determine the optimal resolution f_{stop}. The optimal resolution f_{stop} is a function of the lens focal length, depth-of-field in front of the object, wavelength of light, and distance of the object to the lens center. Once the optimal resolution f_{stop} is determined, the camera is adjusted to the closest discrete f_{stop} available. When the approximate field technique is utilized, the camera must be adjusted to the discrete f_{stop} closest to, but not exceeding, the computed f_{stop}.

Although the present invention has been described relative to a specific embodiment thereof, it is not so limited. Obviously many modifications and variations of the present invention may become apparent in light of the above teachings. For example, the computations may be performed with or without the assistance of electronics; and such electronics may or may not be integrated to the camera for automatic adjustment. The desired depth-of-field in front of the object may be approximated or measured using a range finder, etc. Although the wavelength of light range specified the visible spectrum, other spectra (e.g., infrared) are also valid in the optimal f_{stop} computations.

Many additional changes in the details, materials, steps and arrangement of parts, herein described and illustrated to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention. It is therefore understood that

the invention may be practiced otherwise than as specifically described.

Attorney Docket No. 79064

OPTIMAL FSTOP/RESOLUTION APPARATUS AND METHOD FOR SPECIFIED DEPTH-OF-FIELD

ABSTRACT OF THE DISCLOSURE

A method and apparatus to determine the f_{stop} that provides optimal image resolution for a predetermined depth-of-field. An approximate and exact method and apparatus are provided to determine the optimal resolution f_{stop}. The optimal resolution f_{stop} is a function of the lens focal length, depth-of-field in front of the object, wavelength of light, and distance of the object to the lens center. Once the optimal resolution f_{stop} is determined, the camera is adjusted to the closest discrete f_{stop} available. When the approximate field technique is utilized, the camera must be adjusted to the discrete f_{stop} closest to, but not exceeding, the computed f_{stop}.

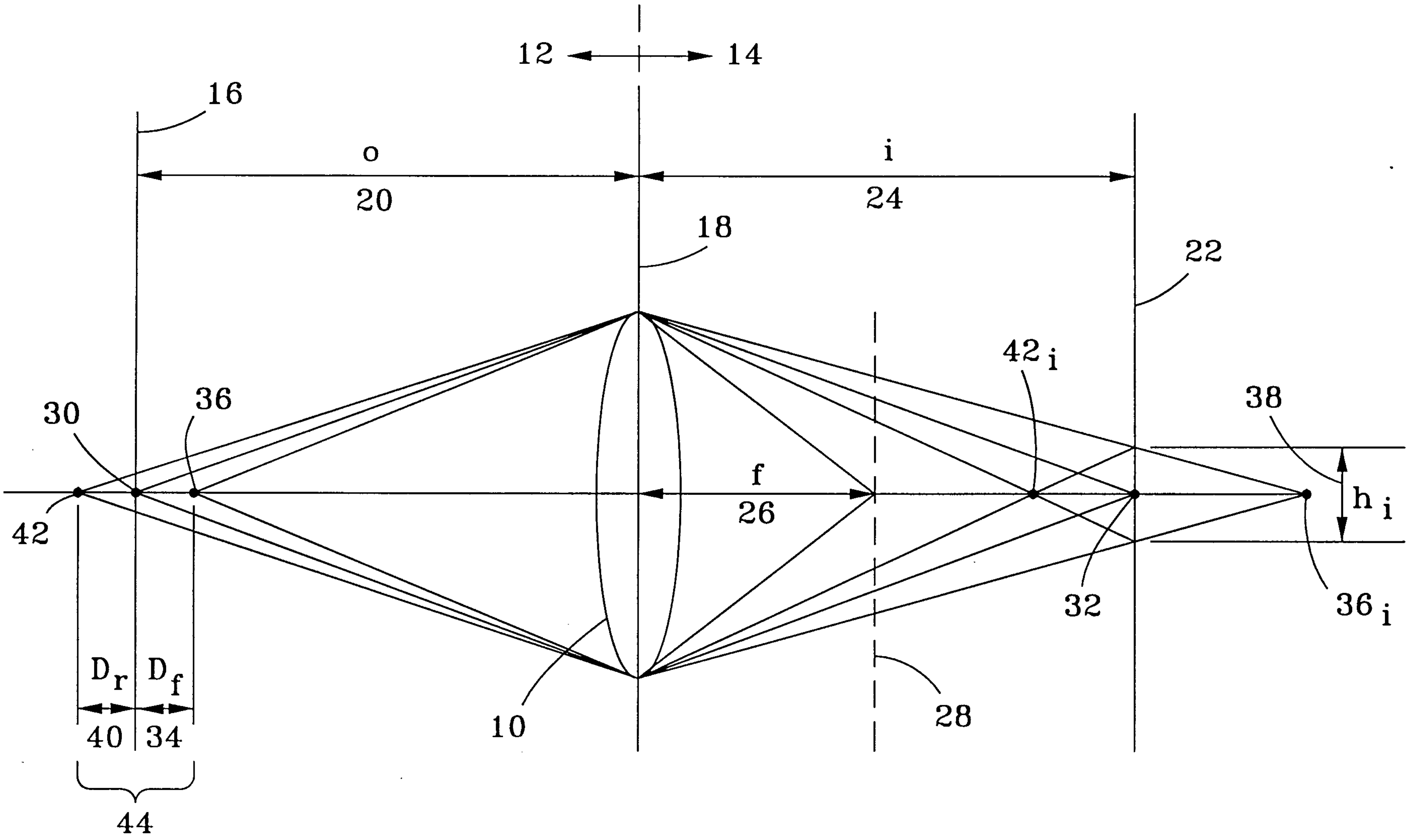
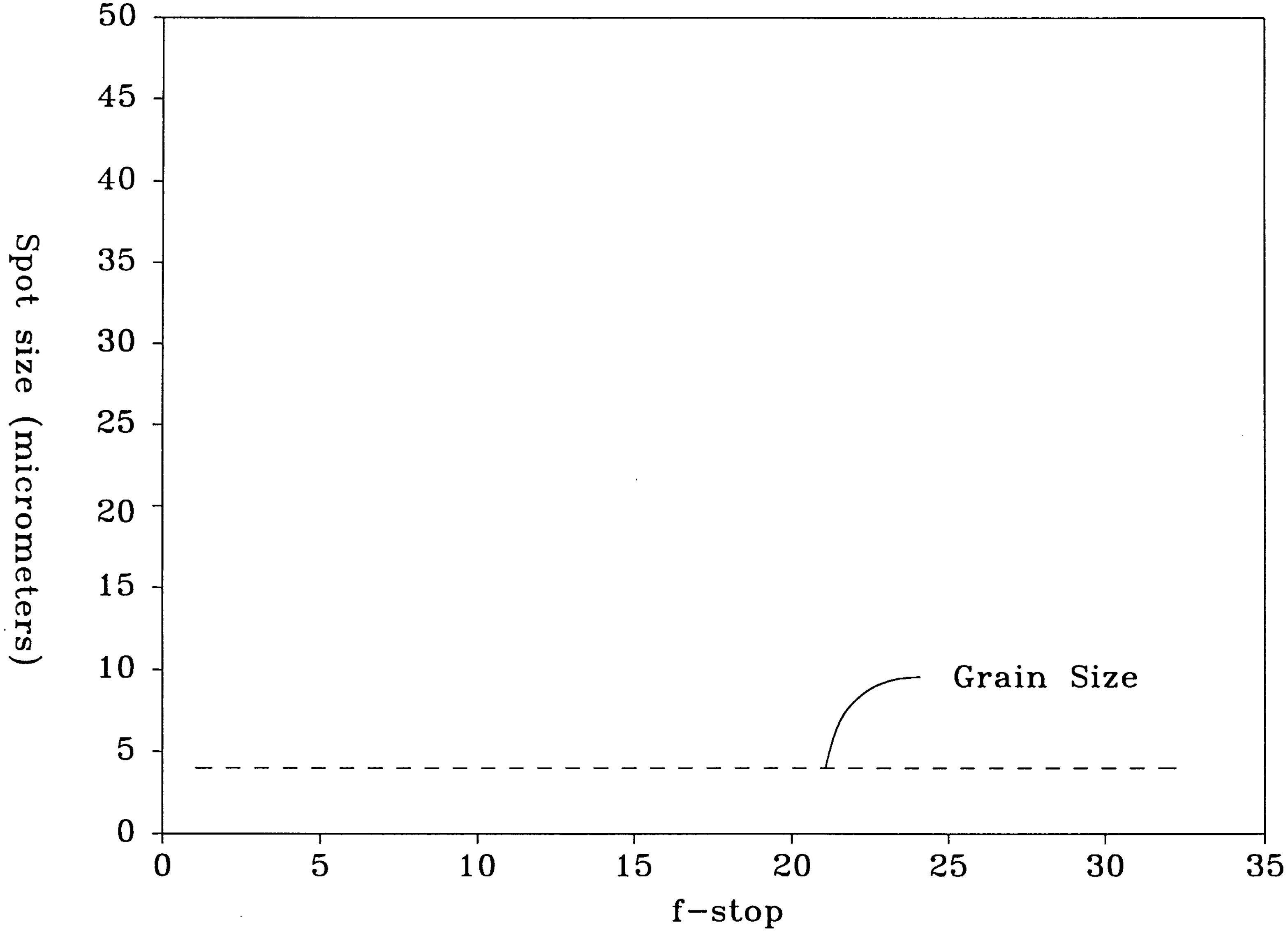

12
14
16
o
20
i
24
18
22
42$_i$
38
30
36
f
26
h$_i$
42
32
36$_i$
D$_r$
D$_f$
40
34
10
28
44

FIG. 1



50
45
40
35
30
25
20
15
10
5
0
Spot size (micrometers)
0
5
10
15
20
25
30
35
f−stop
Grain Size

FIG. 2

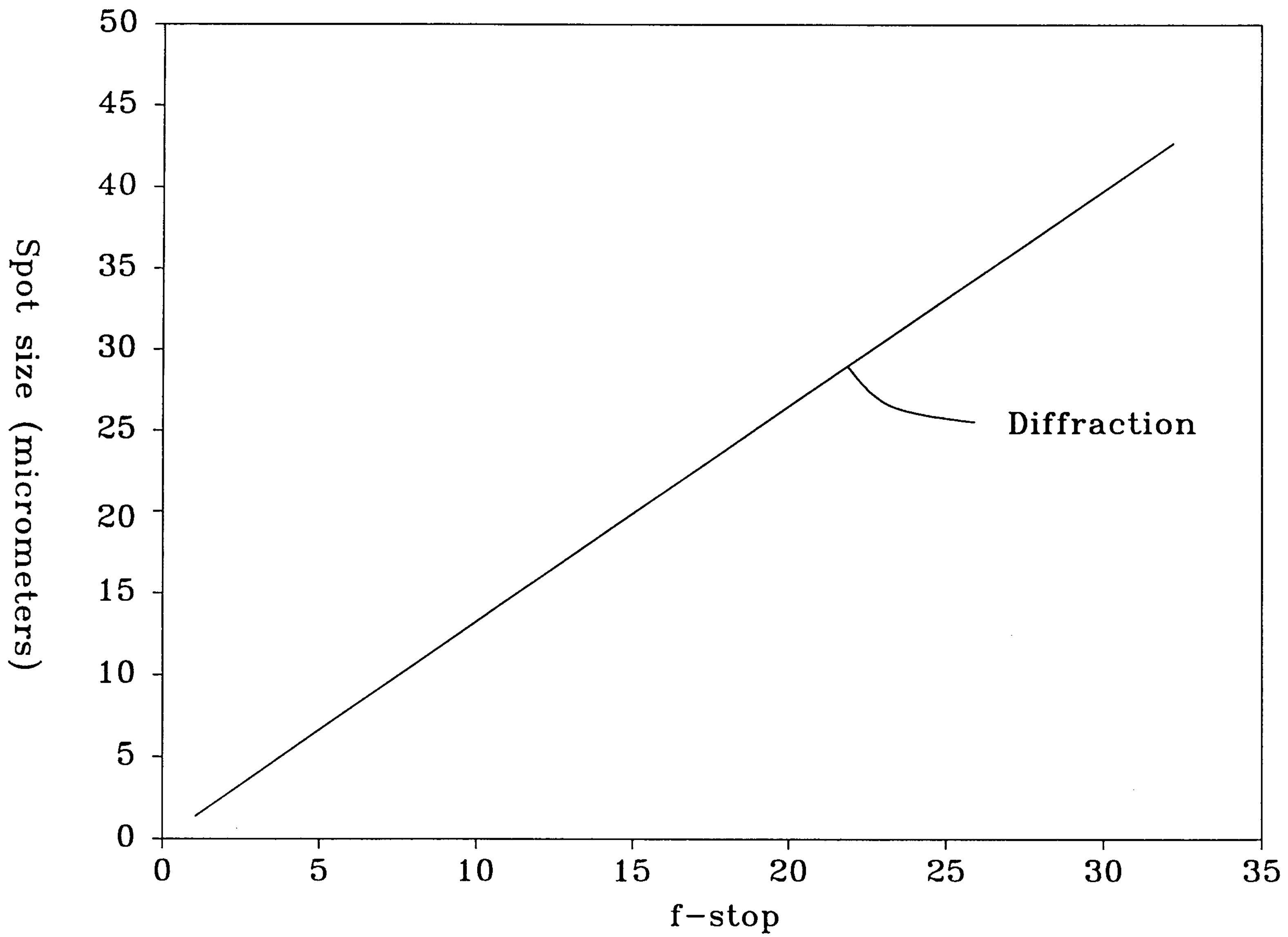

50
45
40
35
30
25
20
15
10
5
0
Spot size (micrometers)
0
5
10
15
20
25
30
35
f−stop
Diffraction

FIG. 3

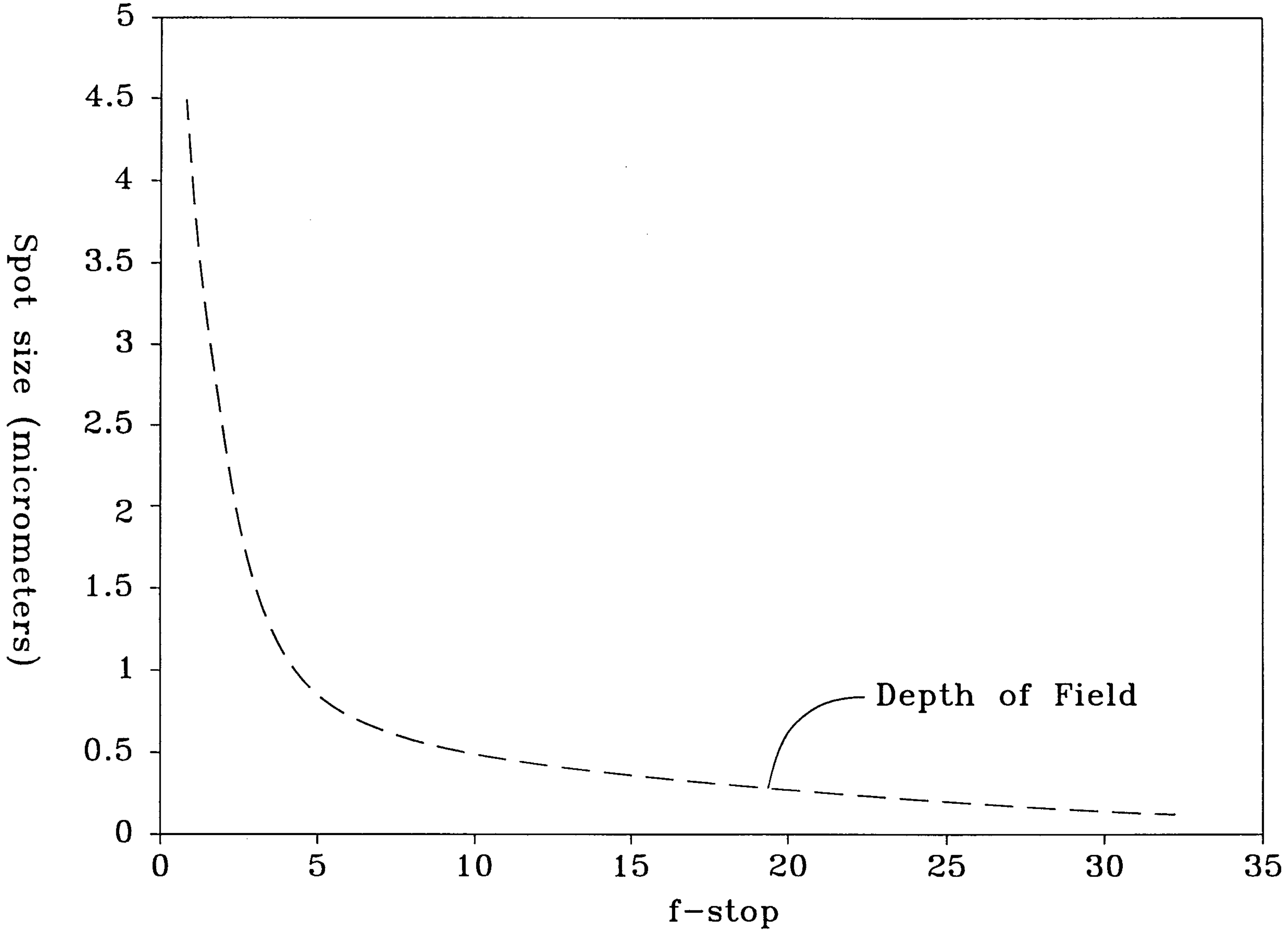

Spot size (micrometers)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
f−stop
Depth of Field

FIG. 4

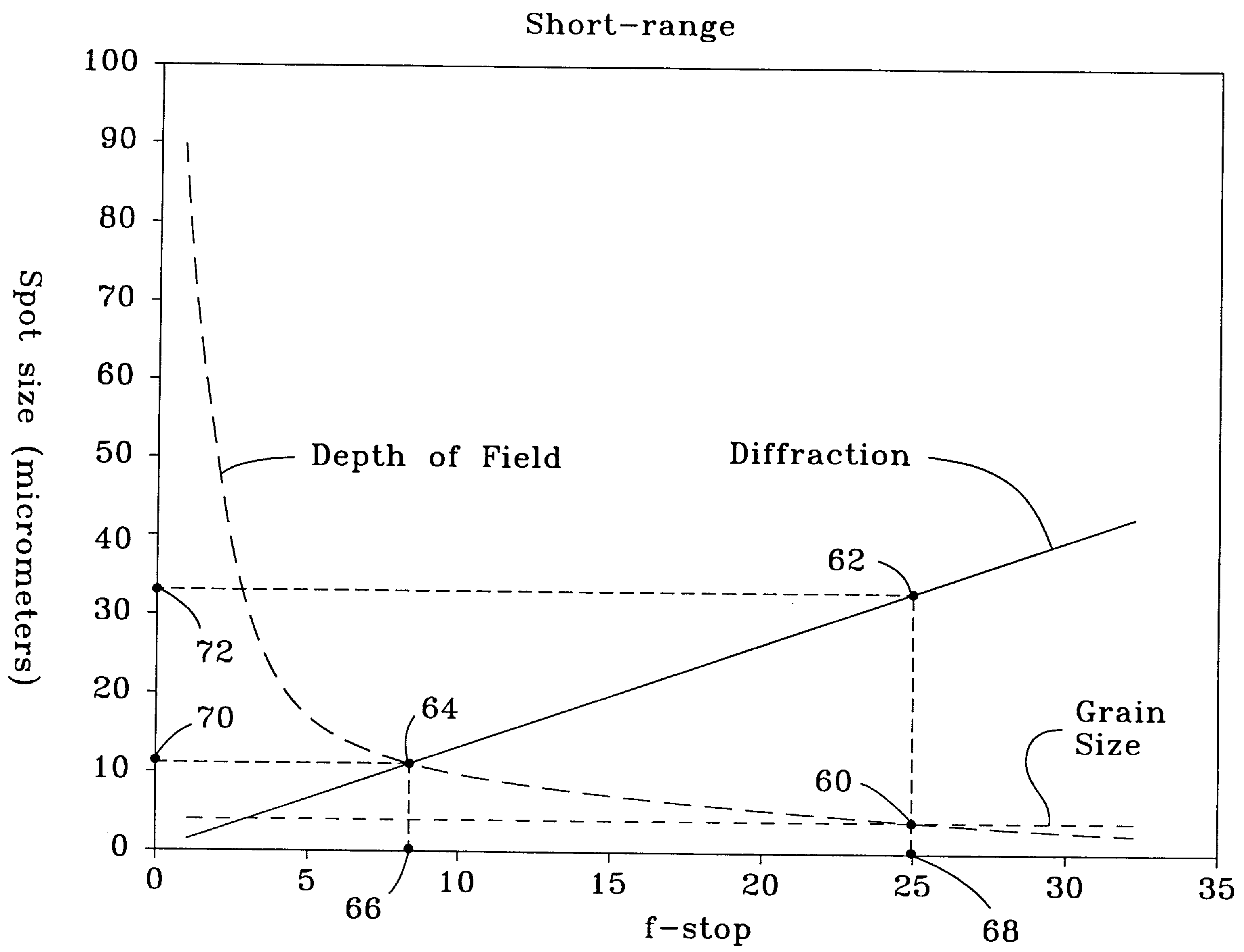

Short-range
Spot size (micrometers)
100
90
80
70
60
50
40
30
20
10
0
Depth of Field
Diffraction
62
72
70
64
Grain
Size
60
0
5
10
15
20
25
30
35
66
f-stop
68

FIG. 5

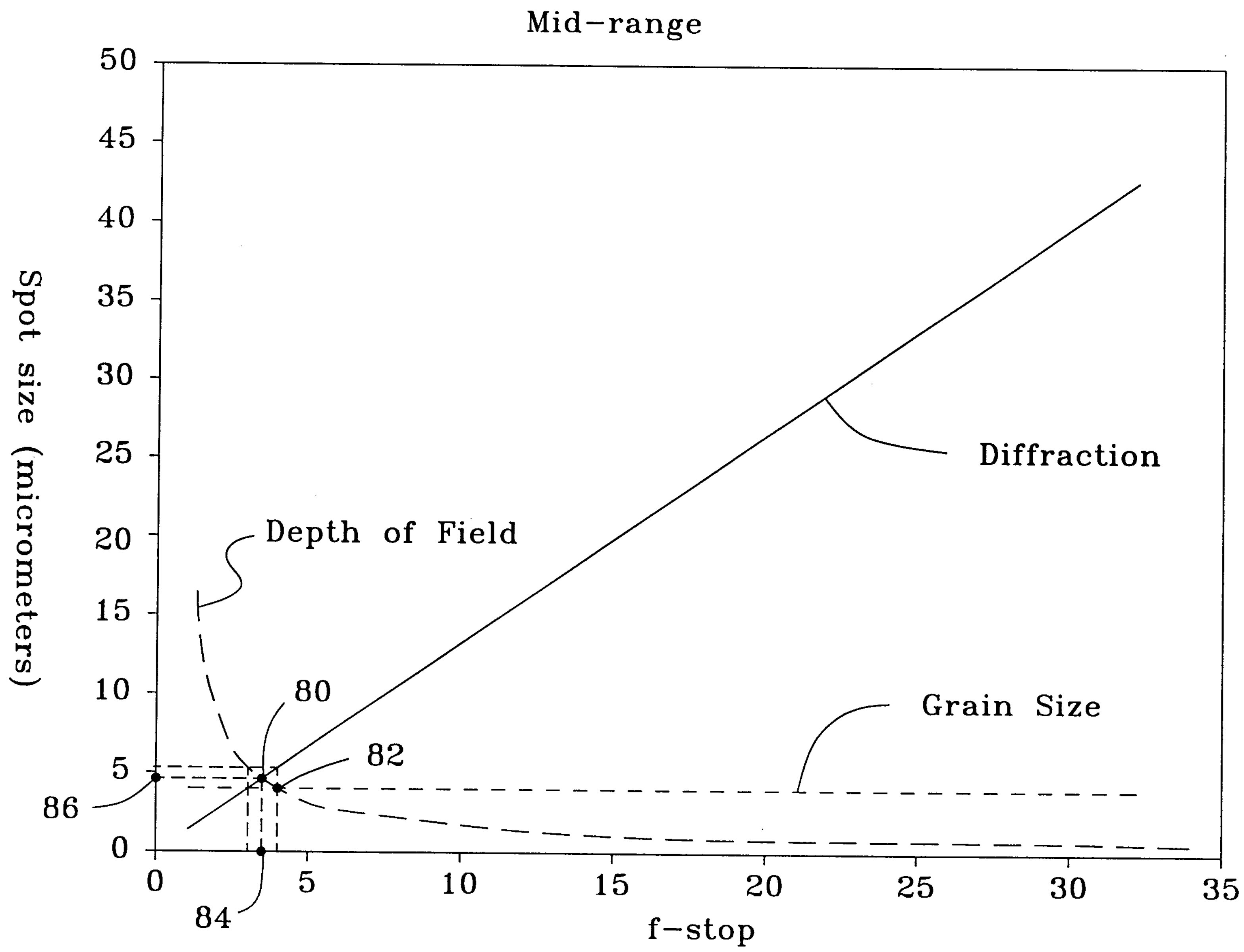

Mid-range
Spot size (micrometers)
50
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
f-stop
Diffraction
Depth of Field
Grain Size
80
82
84
86

FIG. 6

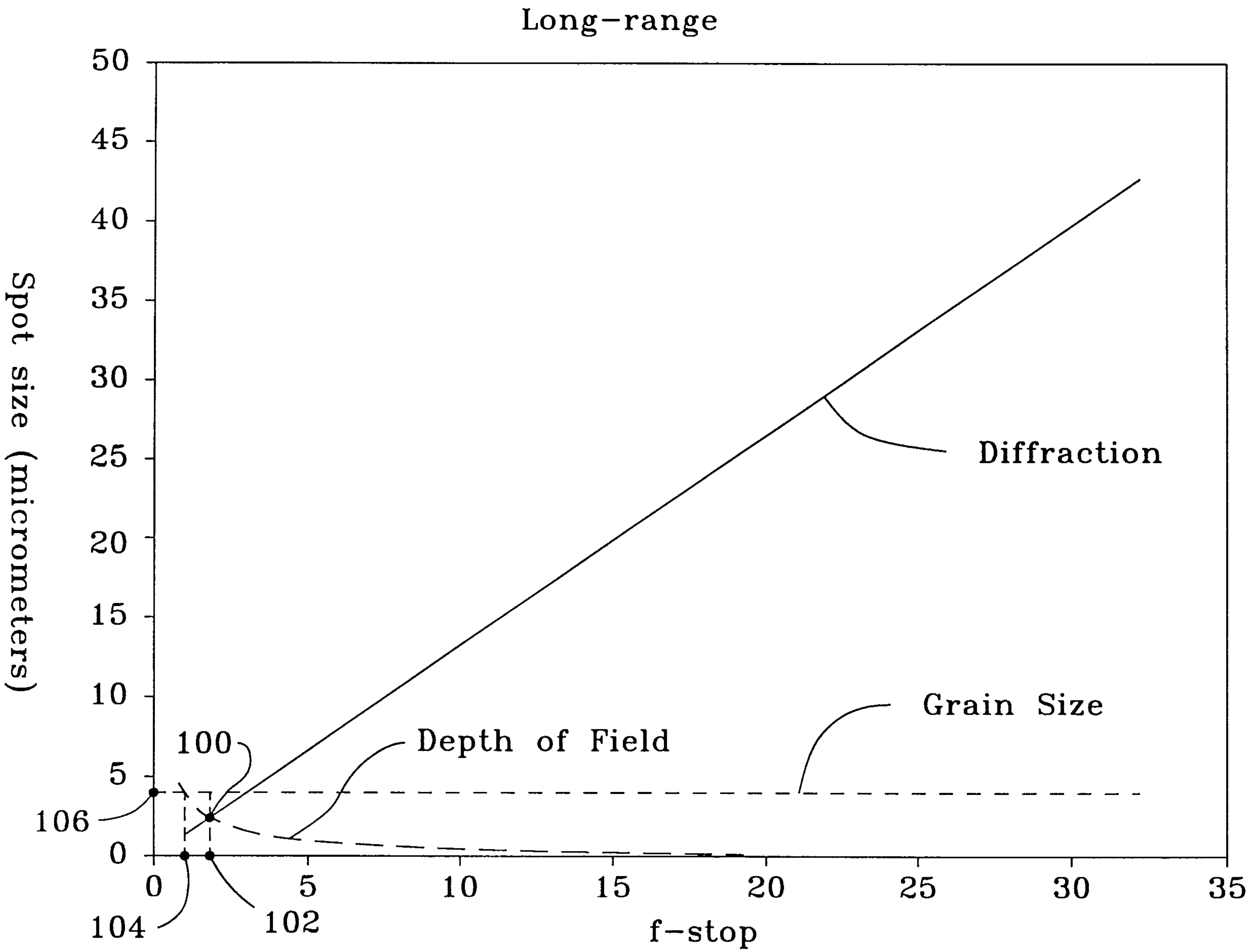

Long-range
Spot size (micrometers)
50
45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
f-stop
Diffraction
Grain Size
Depth of Field
100
102
104
106

FIG. 7

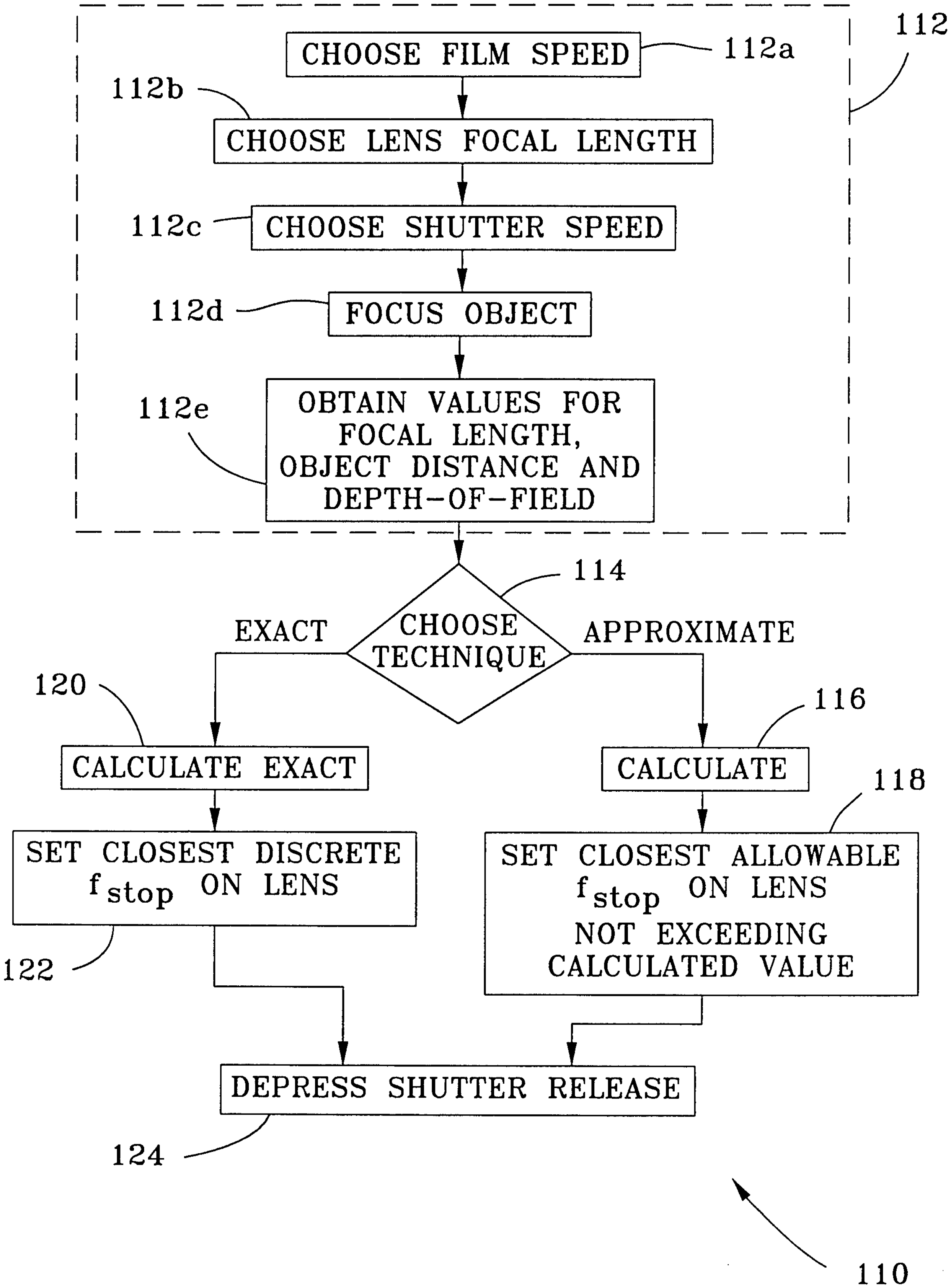

112
CHOOSE FILM SPEED
112a
112b
CHOOSE LENS FOCAL LENGTH
112c
CHOOSE SHUTTER SPEED
112d
FOCUS OBJECT
112e
OBTAIN VALUES FOR FOCAL LENGTH, OBJECT DISTANCE AND DEPTH-OF-FIELD
114
CHOOSE TECHNIQUE
EXACT
APPROXIMATE
120
CALCULATE EXACT
116
CALCULATE
118
SET CLOSEST DISCRETE f_{stop} ON LENS
122
SET CLOSEST ALLOWABLE f_{stop} ON LENS NOT EXCEEDING CALCULATED VALUE
DEPRESS SHUTTER RELEASE
124
110

FIG. 8