MIL-STD-150A
CHANGE NOTICE 2
28 January 1963

MILITARY STANDARD

PHOTOGRAPHIC LENSES

TO ALL ACTIVITIES:

1. The following pages of MIL-STD-150A have been revised and supersede the pages listed:

New page	Date	Superseded page	Date
3		3	12 May 1959
4		4	12 May 1959
5		5	12 May 1959
7		7	12 May 1959
10		10	12 May 1959
17		17	12 May 1959
22		22	12 May 1959
24		24	12 May 1959
26		26	12 May 1959
27		27	12 May 1959
34		34	12 May 1959

2. The following is a cumulative list of earlier changes:

New page	Date	Superseded page	Date
29	8 June 1961	29	12 May 1959

3. Retain this notice and insert before the table of contents.

4. Holder of MIL-STD-150A will verify that page changes indicated above have been entered and will destroy the previous notice. Activities which stock these notices for issue are warned that each notice, together with its appended revised pages, is in effect a separate publication to be retained until the military standard is completely revised or canceled.

FSC 6760

3.1.2.2.1 When a lens is supplied in cells, without barrel or shutter, the locating surface of the lens mount is defined as the seating surface of the rear cell.

3.1.3 *Mechanical axis*. The mechanical axis of a lens is that continuous straight line in space perpendicular to the plane of the flange or locating surface of the lens mount and passing through the center of symmetry of the flange or locating surface.

3.1.3.1 *Flange tilt*. The flange tilt of a lens is the angle between the optical axis and the mechanical axis.

3.1.3.2 *Plane of the receiver*. The plane of the receiver is that plane in the image space in which the receiver or the film in a camera is located.

3.1.3.2.1 *Focal tilt*. The focal tilt is the angle between the plane of best definition and the plane of the receiver due to the mechanical structure between the lens flange and the receiver. It is not a true characteristic of the lens alone.

3.1.4 *Equivalent focal length*.[1] The equivalent focal length, or EFL, often referred to more simply as the focal length, determines the scale of the image produced by the lens. When a given object is at an infinite distance, images produced by distortionless lenses of the same equivalent focal length will be equal in size, and images produced by lenses of different equivalent focal lengths will vary in size directly as the respective equivalent focal lengths. The equivalent focal length is defined by the equation:

$$\mathrm{EFL} = \frac{\gamma}{\tan \beta} \qquad \beta \neq 0 \qquad (1)$$

where γ is the transverse distance from the principal focus to the center of the image in the image-space focal plane of an infinitely distant object point which lies in a direction making an angle β with the optical axis. The equivalent focal length shall be measured in accordance with 5.1.2.2.

3.1.5 *Calibrated focal length*.[2] The calibrated focal length, or CFL, is defined as an adjusted value of the equivalent focal length of a lens mounted in a camera or cone, so chosen as to distribute the distortion in the manner best suited to conditions under which the photograph is to be employed. The calibrated focal length shall be determined in accordance with 5.1.2.3. The calibration conditions shall be covered by the detailed specification.

3.1.6 *Back focal distance*. The back focal distance, or BF, is defined as the distance measured from the vertex of the back surface of the lens to the plane of best definition. The back focal distance shall be measured in accordance with 5.1.2.4.

3.1.7 *Flange focal distance*. The flange focal distance, or FD, is defined as the minimum distance from the center of symmetry of the lens flange in the plane of the flange to the plane of best definition. In a perfect lens, this distance is measured along the mechanical axis which coincides with the axis of best definition. The flange focal distance shall be measured in accordance with 5.1.2.5.

3.1.8 *Front focal distance*.[2] The front focal distance, or FF, is defined as the distance measured from the principal focus located in the front space to the vertex of the front surface. The front focal distance shall be measured in accordance with 5.1.2.6.

3.1.9 *Front vertex back focal distance*.[3] The

[1] American Standard Method of Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses, Z38.4.21 — 1948.

[2] See footnote 1.

[3] See footnote 1.

front vertex back focal distance, or FVD, is defined as the distance measured from the principal focus in the back space to the vertex of the front surface. The front vertex back focal distance shall be measured in accordance with 5.1.2.7.

3.1.10 *Telephoto ratio*. The telephoto ratio is defined as the direct ratio of the equivalent focal length to the front vertex back focal distance.

3.1.11 *Depth of focus and depth of field*. For every plane in the object space, a photographic lens produces an image plane of best definition in the image space. In front of or behind this plane of best definition is a region within which the images of the selected object plane are of satisfactory quality. The distance separating the focal planes bonding this region is the depth of focus for the selected object plane. Similarly, there exists a region in space within which objects are imaged with satisfactory quality on a selected image plane. The distance separating the planes bounding this region is the depth of field. The extent of these regions of satisfactory focus may be defined in terms of a 10 percent reduction of area weighted average resolution (AWAR) below that obtained at the best focal position.

3.2 APERTURE AND RELATED QUANTITIES.

3.2.1 *Lens speed*. Lens speed is that property of a lens which affects the image illuminance. Lens speed shall be specified in terms of the following expressions: aperture ratio, relative aperture, or T-stop.

3.2.2 *Aperture ratio*.[4] The aperture ratio is the ratio 1:N or the fraction 1/N (written in this manner with the first member of the ratio, or the numerator of the fraction, equal to 1) where N is defined by the equation:

$$N = \frac{1}{2n \sin \alpha}$$

In this formula, n is the index of refraction of the medium in which the image is formed (approximately 1, if the image is formed in the air) and α is the angle subtended at the axial point of the image by the semidiameter of the exit pupil of the lens at a given diaphragm setting. If the exit pupil is not circular, the equivalent circle having the same area as the actual exit pupil should be used. Thus, for an objective in air, the aperture ratio is equal to 2 sin α. If the aperture ratio is given without qualification, its value is that corresponding to the largest indicated diaphragm opening and an infinitely distant object. If the object is at a finite distance, the value of the aperture ratio should be qualified by a statement of the corresponding magnification. The aperture ratio is applicable for the determination of exposure time when the object is at an infinite or a finite distance. For any magnification, the exposure time is inversely proportional to the square of N. Thus, the aperture ratio is a measure of the image illuminance. (For test procedure see 5.1.2.8).

3.2.3 *Effective aperture*.[5] The effective aperture of a photographic objective for distant objects, for a given setting of the diaphragm, is an opening equivalent to a right section of the largest beam of parallel light from an axial object point that is transmitted by the lens. It is usually circular, or approximately so, and is specified by its diameter. If the section is not circular, the effective diameter shall be the diameter of a circle having the same equivalent area. (For test procedure, see 5.1.2.9.)

3.2.4 *Clear aperture*.[5] The clear aperture of each surface in a lens system is the maxi-

[4] American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z38.4.20 — 1948.

[5] See footnote 4.

mum clear opening of the surface which is actually used in forming an image in any part of the field. The mount aperture at each surface shall be at least as large as the clear aperture in order that vignetting will not exceed the computed value. The clear aperture is usually circular and specified by its diameter. It is sometimes referred to as the free aperture.

3.2.5 *Relative aperture.*[5] The relative aperture shall be defined as the ratio of the EFL to the diameter of the effective aperture. The symbol for relative aperture shall be f/ followed by a numerical value. It is written as a fraction, for example, f/2 signifies that the diameter of the effective aperture is one-half the focal length. For an object at an infinite distance, the denominator of the relative aperture and the second member, N, of the aperture ratio are identical, provided the image is formed in air and the imagery obeys the sine condition.

3.2.5.1 *f-number.*[6] The f-number shall be defined as the denominator in the expression for the relative aperture. Thus, if the relative aperture is f/2, the f-number is 2.

3.2.6 *T-stop and T-number.*[7] The T-stop is referred to as the aperture of a lens calibrated photometrically and assigned a T-number, which is the f-number of a circular opening in a fictitious lens having 100 percent transmittance, and which gives the same central image illuminance as the actual lens at the specified stop opening. Hence, for a lens with a circular aperture, the

$$\text{T-number} = \frac{\text{f-number}}{\sqrt{t}} \qquad (3)$$

where t is the transmittance. For a lens with an effective aperture of any shape and area A, the corresponding formula is:

$$\text{T-number} = \frac{f}{2}\sqrt{\frac{\pi}{At}} \qquad (4)$$

The transmittance of the lens shall be defined as the ratio of the transmitted light flux to the incident light flux. The symbol for the T-stop shall be T followed by a space and a numerical value — for example, T 2. The numeral 2 represents the T-number. (For test procedure, see 5.1.2.10.)

3.2.6.1 *Area weighted average T-number.* The T-number as defined in 3.2.6 is a comparative measure of illuminance on the axis of a lens. Since the illuminance usually varies over the field, a need may exist for determining T-numbers for off axial image points and computing an average T-number. In accordance with the basic photometric relationships involved, the general definition of T-number is given as

$$T_i = \frac{1}{2}\sqrt{\pi B/E_i} \qquad (5)$$

Since, in accordance with this definition,

$$\frac{1}{2}\sqrt{\pi B} = T_o\sqrt{E_o},$$

$$T_i = T_o\sqrt{\frac{E_o}{E_i}} \qquad (6)$$

In these expressions, T_i is the T-number for an image point in a zone i, T_o is the axial T-number, B is the object luminance, E_o is the illuminance on the axis, and E_i is the average illuminance for the zone. Compatible units should be used for quantities B, E_o, and E_i. When the illuminance is averaged over the field, weighting the average by the area of the circular zone in which the illuminance is determined, and this average is substituted for E_i in equation (6), the resulting T-number is called the area weighted average T-number, or AWAT. For circular zones which extend beyond the boundaries of the

[5] See footnote 4, page 4.

[6] See footnote 4, page 4.

[7] American Standard, Aperture Calibration of Motion Picture Lenses PH22.90 – 1953.

picture format, only the area lying within the format shall be used in determining the weighting ratios. The equations for computing AWAT are:

$$AWAT = T_o \Big/ \sqrt{\sum \frac{A_i\ E_i}{A\ E_o}} \quad (7)$$

$$\text{or } AWAT = 10\ T_o \Big/ \sqrt{\sum \frac{A_i}{A} \sigma_i} \quad (8)$$

in which A is the total area of the picture format, A_i is the area of a particular zone, and σ_i is the average relative illuminance for that zone expressed in percent.

3.2.7 *Front operating aperture.* The front operating aperture is defined as the limiting aperture at the front of the lens. It will usually be given as the maximum diameter of the entrance cone at the front vertex for the specified field of view at infinity focus.

3.2.8 *Rear operating aperture.* The rear operating aperture is defined as the limiting aperture at the rear of the lens. It will usually be given as the maximum diameter of the emergent cone at the rear vertex for the specified field of view at infinity focus.

3.3 CONSTRUCTIONAL FEATURES. Pertinent features include details of the construction of the lens. These may relate to the physical configuration, or arrangement of the individual elements, to some specified optical characteristic or to the nomenclature of the various parts. Constructional features of photographic lenses are listed with definitions and explanatory data.

3.3.1 *Optical system.*[8] The optical system includes all the parts of a photographic lens and accessory optical parts which are designed to contribute to the formation of an image on the photographic emulsion or on a screen for viewing.

[8] American Standard Nomenclature for Parts of a Photographic Lens PH3.25 — 1948.

3.3.2 *Member.*[8] A member of a photographic lens is a group of parts considered as an entity because of the proximity of its parts or because it has a distinct but not always entirely separate function.

3.3.3 *Component.*[8] A component of a photographic lens is a subdivision of a member. It may consist of two or more parts cemented together or with near and approximately matching surfaces.

3.3.4 *Element.*[8] An element of a photographic lens is a single uncompounded lens, i.e., a part constructed of a single piece. The total number of elements is a significant constructional feature of a lens.

3.3.5 *Front of photographic lens.*[8] The front of a photographic lens, in general, is the end carrying the engraving, and usually facing the longer conjugate. In lens drawings, the front generally faces left or up. A notable exception is certain lenses intended to be used in photomicrography in which the front of the lens faces the shorter conjugate.

3.3.6 *Back of photographic lens.*[8] The back of a photographic lens, in general, is the end carrying the mounting thread or other attaching means and usually facing the shorter conjugate.

3.3.7 *Name of design.* Designs of lenses in which particular configurations of elements are employed are often given names. These names are usually trade names, and the name ordinarily applied to any particular configuration is usually the trade name of the oldest design of a particular type such as "Tessar." In some cases, however, the design name may not be a trade name but may be based on some feature of the lens configuration such as "Symmetrical."

3.3.8 *Telephoto.* A telephoto lens is defined

[8] American Standard Nomenclature for Parts of a Photographic Lens PH3.25 — 1948.

as a lens for which the telephoto ratio is greater than one. (See 3.1.10.)

3.3.9 *Glass types.* A constructional feature is the type of optical glass of which each element is made.

3.4 MECHANICAL AND STRUCTURAL FEATURES.

3.4.1 *Cell.* A cell is a mechanical structure holding an element, component, or member.

3.4.2 *Barrel.* A barrel is a mechanical structure in which the lens is mounted.

3.4.3 *Cone.* A cone is defined as the mechanical structure to which a lens barrel or shutter, with lens, is attached in order to bring the image in focus in the film plane of a specific aerial camera.

3.4.4 *Lens diaphragm.* A lens diaphragm is a mechanical device for reducing the effective aperture of a lens. It may take the form of an iris or a Waterhouse stop. An iris diaphragm consist of leaves providing an opening continuously variable in size. A Waterhouse stop is a removable aperture of fixed size which fits in the lens barrel. Waterhouse stops are usually provided in a graded series of apertures.

3.4.5 *Iris diaphragm control.* Unless otherwise specified, when looking at the front of a lens or remote control knob, a counterclockwise rotation of the diaphragm control shall reduce the aperture or stop the lens down.

3.4.6 *Parfocalized.* Lenses mounted in barrels may be specified as parfocalized, i.e., the flange focal distance may be specified to close tolerances that would secure an image in satisfactory focus when the lenses are interchanged on a camera.

3.4.7 *Spanner wrench openings.* When required in order to facilitate removal of cells, elements, components, or members from a cell or barrel, there shall be two openings 180 degrees apart for application of a spanner wrench. Each opening shall either be circular in shape, or a slot with parallel sides.

3.5 FIELD OF VIEW.

The field of view of a lens is a measure of the size of the image area or conjugate object area which is satisfactorily reproduced. This field may be defined in terms of the maximum size of the negative or projection material with which the lens is to be used.[10] The angular measure for field of view is the half angle, which, unless otherwise specified, is the angle subtended at the first nodal point by the optical axis and a straight line to an object point which is imaged at the extreme corner of the negative. For a projected image, the half angle is the angle subtended at the second nodal point by the optical axis and a line to the image point conjugate with the extreme corner of the projection material. The half angle is sometimes referred to the side of the image area and in such cases it shall always be so specified. The field of view may also be designated as the total field angle which is twice the half angle. Coverage is a less precise term for field of view.

3.6 OPTICAL CHARACTERISTICS.

Optical characteristics include all properties of a lens affecting its optical performances such as image quality, distortion, transmittance, image color, and condenser characteristics. When specifying optical characteristics or individual aberrations, the definitions and nomenclature set forth herein shall be used.

3.6.1 *Image quality.* Image quality em-

[10] Format Sizes for Air Cameras, ABC AIR STD 52/1, 5 Feb. 54. The participants agreed that air camera format sizes shall be: 2¼ by 2¼ inches, 4½ by 4½ inches, 9 by 9 inches, 9 by 18 inches, 18 by 18 inches. Format Sizes for Ground Cameras, ABC AIR STD 52/8, 15 Mar. 54. Ground camera format sizes standardized shall be: 1 by 1½ inches (24 by 36 millimeters), 2¼ by 2¼ inches, 2.2 by 2.75 inches.

braces all the properties of a lens affecting the quality of the image such as resolving power, aberrations, image defects, and veiling glare. Aberrations are optical defects inherent in the lens design. Because of manufacturing variations, it often happens that the measured aberrations differ from the computed aberrations. Image defects are optical defects not inherent in the lens design and resulting entirely from manufacturing and mounting variations. This standard is primarily concerned with optical performance. Optical performance can be measured in terms of resolving power, or specific optical characteristics.

3.6.2 *Resolving power*. The resolving power of a lens is a measure of its ability to image closely spaced objects so that they are recognizable as individual objects. The resolving power shall be expressed in lines per millimeter, usually in the short conjugate plane. Resolving power is measured by photographing or observing suitable test charts at specified angular distances from the center of the field. The test charts shall consist of groups of parallel straight lines and spaces of equal width; the resolving power is the reciprocal of the center-to-center distance of the lines that are just distinguishable in the recorded image. By "just distinguishable" is meant that the observer is able to count the correct number of lines in the recorded image, over the entire length of the lines and in the correct orientation, subject to the provision that no coarser pattern shall be unresolved. The appearance of resolution in a finer pattern after failure to resolve a coarser pattern is an indication of the presence of spurious resolution. Spurious resolution is a phenomenon wherein fine lines are resolved, yet coarse lines are not. For nonaxial points, it is necessary to consider the orientation of the lines. For example, the resolving power for radial lines, or "radial resolving power" (sometimes called "sagittal resolving power"), at a given point in the image plane is the resolving power for closely spaced lines that are parallel and adjacent to the radius drawn from the center of the field to the given point. Resolving power for tangential lines, or "tangential resolving power," is the resolving power for closely spaced parallel lines that are tangent and adjacent to a circle drawn through the given point whose center lies at the center of the field. Resolving power may be specified as minimum acceptable resolving power, regardless of whether radial or tangential at specified angles from the optical axis of the lens, or it may be specified at both minimum acceptable radial and minimum acceptable tangential resolving power at specified angular distances from the optical axis. The average resolving power weighted in terms of the area of the negative, the area weighted average resolution (AWAR), provides a single value by which the resolving power for the entire field may be specified. (See 3.1.2.1.1 and 3.6.2.5.)

3.6.2.1 *Photographic resolving power*. Photographic resolving power is used in specifying and measuring performance of type I, II, III, IV, V, IX, XII, and XIII lenses and is the greatest number of lines per millimeter recorded photographically as separate lines. A target pattern is considered resolved when it meets the conditions described in 3.6.2. Photographic resolving power depends markedly on the photographic conditions employed, and on the presence of background glare from the illuminated target. When specifying photographic resolving power, it is necessary also to specify the color of light to be used, the type of photosensitive material and processing, the lens speed at which the test is made, the contrast of the target, and the magnification or focus at which the lens is tested. (See 5.1.2.12.1.)

3.6.2.2 *Visual resolving power*. Visual resolving power is used in specifying and measuring of type X lenses, and is defined as the greatest number of lines per millimeter in the image of a test target pattern that are just barely distinguishable as separate lines under adequate magnification. When specifying visual resolving power it is necessary also to specify the target contrast. (See 5.1.2.12.2.)

3.6.2.3 *Projected photographic resolving power.* Projected photographic resolving power is used in specifying and measuring the performance of type VI lenses and is defined as the greatest number of lines per millimeter, in the object plane, that are barely distinguishable as separate lines when observing under magnification a photographically recorded, projected image of a suitable test target. (See 5.1.2.12.3.) When specifying projected photographic resolving power it is necessary also to specify lens speed, focus, magnification, type of illumination, contrast of target, type photosensitive material and its processing.

3.6.2.4 *Projected visual resolving power.* Projected visual resolving power is used in specifying and measuring the performance of type VII lenses and is defined as the greatest number of lines per millimeter in the object plane that are distinguishable as separate lines in the projected image. When specifying projected visual resolving power, it is usually understood to imply a high contrast target (dark lines on light background). (See 5.1.2.12.4.)

3.6.2.5 *Area weighted average resolution.* A single average value for the resolution over the picture format may be determined for any given focal plane as the area weighted average resolution, or AWAR. To determine the AWAR, the picture format is divided into concentric annular zones whose boundaries are determined from the angles which are midway between successive test angles. For zones which extend beyond the boundaries of the picture format, only the area lying within the format shall be used in determining the weighting ratio. The resolution obtained at any given test angle is multiplied by the ratio of the area of the zone for that angle to the total area of the picture format. The AWAR is the sum of these products. To obtain a single value of the resolution for each test angle, the geometric mean of the tangential and radial resolutions shall be used. However, the computations may be simplified by the use of an arithmetic mean whenever the tangential and radial resolutions differ by less than a factor of 2 to 1. When more than one measurement is made at any given test angle, an arithmetic mean shall be determined for the tangential and another for the radial resolutions. The area weighted average resolution is defined as:

$$\text{AWAR} = \sum \frac{A_i}{A} \sqrt{R_i \, T_i} \qquad (9)$$

where A_i is the area of a particular zone, R_i is the average radial resolving power in this zone (or radial resolving power at the midpoint of the zone), T_i is the average tangential resolving power in the zone (or the tangential resolving power at the midpoint of the zone), and A is the total area of the picture format, and Σ is the summation sign, summating the values

$$\frac{A_i}{A} \sqrt{R_i \, T_i}$$

over all zones in the picture area.

3.6.3 *Astigmatism and curvature of field.* In general, a lens possesses two image surfaces: one in which lines radial to the optical axis are best defined and the other in which lines tangent to circles concentric with the axis are best defined. Noncoincidence of these two image surfaces is called astigmatism, and the separation of the two image surfaces, measured parallel to the optical axis, is called the astigmatic difference. A median surface lying between the two is called the surface of least confusion and the definition in this image surface is least affected by orientation of the object. None of the surfaces is a true plane. The departure of the surface of least confusion from a true plane is called curvature of field. Resolving power figures, specified in accordance with 3.6.2, will usually be considered as referring to a flat image and object plane. When curvature of field is specified, the magnification at which it is to be measured shall be stated. (See 5.1.2.18.) Figure 1 is plotted as an example of the astigmatic difference.

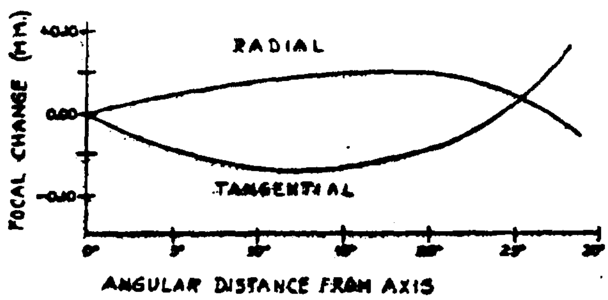

FIGURE 1. *Astigmatic Difference*

3.6.4 *Color correction.* Color correction is defined as the reduction of longitudinal and lateral chromatic aberrations. It may be specified in terms of the kind of light and color sensitivity of the photographic material to be used with the lens, e.g., the lens is color corrected for use with white light and panchromatic film of ASA speed 100. The color correction may be specified in terms of the Fraunhofer lines in the solar spectrum that are to be used in the lens calculations, e.g., C and F correction. The magnification at which the color correction is accomplished shall be designated. (See 5.1.2.14.)

3.6.4.1 *Longitudinal chromatic aberration.* Longitudinal chromatic aberration is defined as a variation in back focal distance for light of different colors or wave lengths. It is specified in terms of this focal change for light of specified colors. (See 5.1.2.14.1.) Figure 2 is plotted as an example of longitudinal chromatic aberration.

3.6.4.2 *Lateral chromatic aberration.* Lateral chromatic aberration is a variation in image scale of a lens for light of different colors or wave lengths. When required, limits on lateral chromatic aberration will be specified as the radial displacement in millimeters of the image in the first color from the image of the same point in the second color. (See 5.1.2.14.2.) Figure 3 is plotted as an example of lateral chromatic aberration.

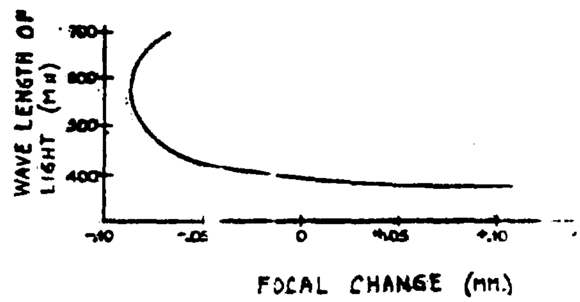

FIGURE 2. *Longitudinal Chromatic Aberration*

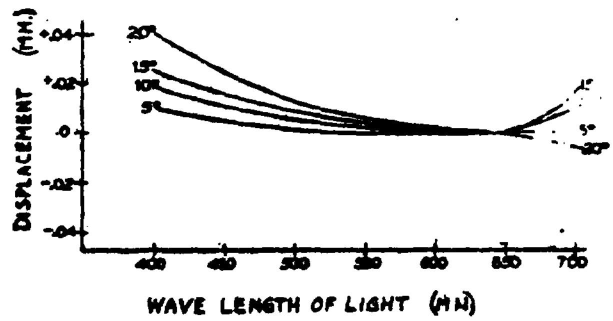

FIGURE 3. *Lateral Chromatic Aberration*

3.6.5 *Magnification.*

3.6.5.1 *Paraxial magnification.* The paraxial magnification, often referred to more simply as magnification, determines the scale of the image when the object is at a finite distance from the lens. The paraxial magnification, or PM, is defined by the following equation:

$$PM = \lim_{\gamma \to 0} \frac{\gamma'}{\gamma} \qquad (10)$$

where γ' is the radial distance from the optical axis to the image point in the image plane

3.8.1 *Material defects.*

3.8.1.1 *Bubbles.* Bubbles are air or gaseous inclusions entrapped within the glass.

3.8.1.1.1 *Seeds.* Seeds are very small bubbles

3.8.1.1.2 *Air bells.* Air bells are irregularly shaped bubbles

3.8.1.2 *Cracks.* Cracks are shallow separations or breaks in the glass.

3.8.1.3 *Feathers.* Feathers are powdered surfaces folded into the glass in the pressing process.

3.8.1.4 *Fold, or laps.* Folds, or laps, are areas in which the glass has been folded upon itself but not fused.

3.8.1.5 *Milkiness.* Milkiness is caused by cloudy or milky areas within the glass.

3.8.1.6 *Stones.* Stones are fragments of undissolved material in the glass.

3.8.1.7 *Strain.* Strain is tension within the glass caused by inadequate annealing or improper mounting. It is an area of index of refraction differing from the nominal.

3.8.1.8 *Striae.* Striae are streaks or veins in the glass with the index of refraction differing from that of the body of the glass.

3.8.1.8.1 *Reams.* Reams are fine bands of striae.

3.8.1.8.2 *Cords.* Cords are streaks of very heavy striae.

3.8.2 *Manufacturing defects.*

3.8.2.1 *Blisters.* Blisters are bubbles in a cement layer.

3.8.2.2 *Burns.* Burns are reddish stains generally ground on the central areas of elements. They are usually caused by the drying-up or glazing of a polisher.

3.8.2.3 *Cement starts.* Cement starts are spots where the components of a cemented lens have started to separate. They can be small irregular spots between the elements or run-ins at the edge, insufficient cement, or cement at the edge dissolved by a solvent.

3.8.2.3.1 *Run-ins.* Run-ins are cement separations at the edge of a cemented component.

3.8.2.4 *Chips.* Chips are areas from which glass has been broken away from the surface, edge, or bevel of an optical element.

3.8.2.5 *Cracks.* Cracks are breaks in the glass.

3.8.2.6 *Digs.* Digs are breaks of the polished surface of a round, oval, square, etc., shape including pits, holes, and surface broken bubbles.

3.8.2.6.1 *Dirt holes.* Dirt holes are digs filled with rouge.

3.8.2.7 *Dirt.* Dirt consists of dust, lint, or other foreign matter on the surface or entrapped in a cement layer.

3.8.2.8 *Grayness.* Grayness is represented by finely ground areas indicating incomplete or improper polishing.

3.8.2.9 *Mold marks.* Mold marks are marks on the surface produced by molding.

3.8.2.10 *Orange peel.* Orange peel is poorly polished surface, pock-marked with pits, having much the same surface appearance as the skin of an orange.

3.8.2.11 *Poor polish.* Poor polish pertains to polished surfaces containing minute pits of a gray or red color. They are gray grinding pits in the surface of the glass, or red grinding pints in which rouge has been so deeply embedded that it has to be removed by further polishing.

3.8.2.12 *Scratches.* Scratches are furrows or grooves in the surface of the glass caused by the removal of glass, usually made by coarse grit, fragments of glass, sharp tools, etc., rubbed over the surface.

3.8.2.13 *Smears, scum, water spots, etc.* Smears, scum, water spots, etc., are residue of evaporated or unevaporated moisture. They are usually removable by "normal" cleaning.

3.8.2.14 *Stain.* Stain is a discoloration of the glass surface, usually brown, blue, or green, caused by the deposit of foreign matter, or changes produced on the surface of the glass by chemical action of some substance with the glass.

4. GENERAL REQUIREMENTS

4.1 MARKINGS.

4.1.1 *Lens markings.* Lens markings, such as maximum aperture, focal length, field of view, and serial number shall be placed on the front of the lens cell or on the barrel if space limitations so require. The lens name and serial number shall be assigned by the manufacturer.

4.1.2 *Cell marking.* Lenses supplied in cells or constructed with removable cells shall have all cells permanently marked with at least the last three digits of the lens serial number.

4.1.3 *Maximum aperture.* All types of lenses, except types X and XI, shall be marked with their maximum aperture stated either as the relative aperture, aperture ratio or T-stop.

4.1.3.1 The symbol for relative aperture of a lens shall be f/ followed by the numerical value, for example f/2.0.[12]

4.1.3.2 The symbol for the T-stop of a lens shall be T followed by a space and then the numerical value, for example T 2.2.

4.1.3.3 *f-number.*[12] The effective diameter of the maximum aperture of the lens shall be at least 95 percent of the quotient obtained by dividing the marked focal length by the f-number corresponding to the maximum marked aperture.

4.1.4 *Iris diaphragm control marking.*

4.1.4.1 *Full stop.*[12] The standard series of diaphragm markings, or stop openings, shall be 0.7, 1.0, 1.4, 2.0, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, and 128.

4.1.4.2 *Maximum aperture value.*[12] The f-number corresponding to the maximum aperture, T-number, or aperture ratio value marked need not be selected from the above series but shall be followed by the above series of stop openings beginning with the next largest number whenever practical and progressing as far as required in the individual application; e.g., for an f/1.9 lens the diaphragm might be marked f/1.9, 2.8, 4.0, 5.6, 8, etc., if it was believed that to mark it f/1.9, 2.0, 2.8, 4.0, 5.6, etc., would confuse the marking at the f/1.9 end of the scale.

4.1.4.3 *Fractional stop values.* In addition to the numbered values, each stop may be divided into three subdivisions by dots or marks (not numbered), the dots being at "thirds of a stop," e.g., *0.7*, 0.8, 0.9, *1.0*, 1.12,

[12] American Standard Lens Aperture Markings, Z38.4.7—1950.

solving power target used on all tests shall be as follows: The target shall consist of a series of patterns decreasing in size as the $\sqrt{2}$, $\sqrt[4]{2}$, $\sqrt[6]{2}$, with a range sufficient to cover the requirements of the lens-film combination under test. The standard target element shall consist of two patterns (two sets of lines) at right angles to each other. Each pattern shall consist of three lines separated by spaces of equal width. Each line shall be five times as long as it is wide. (See Figure 7.) For types I and II lenses, targets with light lines on a dark background are preferred; for types IV, VI, VII, XII, XII lenses, targets with dark lines on a light background are preferred. The target contrast (the difference in photographic density between the lines and spaces) shall be either high, medium, or low contrast, as specified.

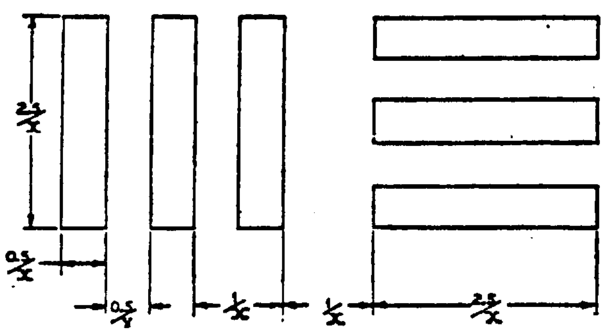

FIGURE 7. *Standard Resolving Power Test Target Element. The patterns of lines are parallel lines 2.5 x millimeters long and 0.5 x millimeters wide with space 0.5 x millimeters wide between the parallel lines, where x equals the numbers of lines per millimeter.*

5.1.1.7.1 *High contrast target.* A high contrast target is one in which the density difference between the light and dark areas is greater than 2.00.

5.1.1.7.2 *Medium contrast target.* A medium contrast target is one in which the density difference between the light and dark areas is equal to 0.80 ± 0.05.

5.1.1.7.3 *Low contrast target.* A low contrast target is one in which the density difference between the light and dark areas is equal to 0.20 ± 0.05.

5.1.2 *Test methods.*

5.1.2.1 *Plane of best definition.* The plane of best definition is usually determined by making a series of evaluations at a sufficient number of focal settings. The distance between focal settings in hundredths of millimeters shall be at least

$$\frac{\text{f-number of lens}}{\text{no. of lines/mm. expected}}$$

The detailed specification shall state the method used in determining the plane of best definition.

5.1.2.2 *Equivalent focal length.*

5.1.2.2.1 *Method 1 — Photographic method.*[14] The EFL shall be measured by placing a photographic plate in the focal plane of the image space. Unless otherwise specified, the focal plane is defined as the place of best photographic imagery for an infinity distant axial point; the focal plane may also be specified as the plane of best definition. A collimator and reticle may be conveniently used to provide an infinitely distant object point. Exposures are made with the beam of light from the collimator directed along the optical axis of the lens and a series of angles β_1, β_2, etc. On the resultant negative, measurements shall be made of the distances γ_1, γ_2, etc., from the axial images to the images corresponding to the angles β_1, β_2, etc., and the quotient $\dfrac{\gamma_1}{\tan\beta_1}$, $\dfrac{\gamma_2}{\tan\beta_2}$ etc., formed. The limiting value of this quotient as β approaches zero is the EFL. In a photographic objective free from distortion, the quotient is invariant with respect to the

[14] American Standard Methods for Designating and Measuring Focal Lengths and Focal Distances of Photographic Lenses, Z38.4.21-1948.

value of β. For many photographic purposes the distortion is negligible for points distant from the center of the useful field not more than one-fifth of its radius, and consequently, it will very often be possible to obtain a satisfactorily accurate value of the EFL by a single determination of β and γ for a point lying near the axis.

5.1.2.2.1.1 *Method 1A — Combination method.* The EFL also may be determined by adding the photographic BF to the distance from the rear vertex to the emergent nodal point. The latter distance may be determined by Method 2.

5.1.2.2.2 *Method 2 — Nodal slide method.* The lens to be tested shall be mounted on a nodal slide to rotate about the vertical axis through its second nodal point. The distance from this nodal point to the position of best axial focus for an infinitely distant object point shall be measured. This is also known as the second principal focus. (An important factor or uncertainty in using this method is the difference between the position of best focus as judged visually on the optical bench and the best focus as determined photographically by method 1.) When using this method, the criterion for determining the best axial focus should be specified. The criterion used is dependent on the type of test object or target used and may be specified in terms of either the haze position or the position of greatest concentration (see 3.6.9.1.1 and 3.6.9.1.2) or in terms of the color in and around the image.

5.1.2.3 *Calibrated focal length.* When determining the calibrated focal length, the plane of best average definition shall be chosen as the focal plane. To compute the calibrated focal length, let γ'_1, γ'_2, etc, represent the distances in the focal plane from the axial point to the images of infinitely distant object points lying in the directions making angles β_1, β_2, etc., with the optical axis of the objective. If f is the equivalent focal length in the absence of distortion, then

$$\gamma'_1 = f \tan \beta_1 \qquad (13)$$
$$\gamma'_2 = f \tan \beta_2$$

and $$\gamma'_n = f \tan \beta_n \qquad (14)$$

In the presence of distortion

$$\gamma'_1 = f \tan \beta_1 + \Delta'\gamma'_1 \qquad (15)$$
$$\gamma'_2 = f \tan \beta_2 + \Delta'\gamma'_2$$

and $$\gamma'_n = f \tan \beta_n + \Delta'\gamma'_n \qquad (16)$$

The added terms are the values of the linear distortion for values β_1, β_2, etc., respectively. The values of γ' and β are measured directly. It is evident that the individual values of the distortion defined by the above group of equations can be changed by changing the value of f. If f is the equivalent focal length, in many instances values of the distortion in the neighborhood of the axial image point will be small, and near the edge of the field the values will be large and predominantly negative or positive. Infinitely distant targets may be provided by a group of collimators or by one collimator which can be successively placed in the required angular positions. Exposures shall be made and the γ' corresponding to each angular distance from the optical axis shall be determined.

5.1.2.4 *Back focal distance.*[15] To determine the BF, the focal plane in the image space shall be determined by a visual or photographic method. The measured distance from this focal plane to the vertex of the back surface of the lens shall be the required BF.

5.1.2.5 *Flange focal distance.*[15] To determine the FD, the focal plane in the image space shall be determined by a visual or photographic method. The measurement shall be made from the plane of the locating surface or the flange to the focal plane.

5.1.2.6 *Front focal distance.*[15] To determine the FF, the focal plane in the object space shall be determined by a visual or

[15] See footnote 14, page 21.

photographic method. The measured distance from this focal plane to the vertex of the front surface of the lens shall be required FF.

5.1.2.7 *Front vertex back focal distance.* To determine the FVD, the focal plane in the image shall be determined by a visual or photographic method. The measured distance from the vertex of the front surface of the lens to the focal plane shall be the required FVD.

5.1.2.8 *Aperture ratio.* For the special case in which the object is at infinite distance (magnification = 0), N, the first member of the ratio equation (2) in 3.2.2, may be determined as the quotient obtained when the EFL is divided by the diameter of the effective aperture.

5.1.2.8.1 For the general case in which the magnification may have any value, a pinhole should be mounted at the axial point of the desired image plane, and the angle of the cone of light emerging through the pinhole from the lens should be determined by measuring the diameter of a right section of the cone at a suitable distance beyond the pinhole. The angle α can be calculated from the measurements and substituted in equation (2). If n is the index of refraction of the medium in which the angle α is measured (n = 1 for air, used in the great majority of cases), the second member of the aperture ratio is $\dfrac{1}{2n \sin \alpha}$.

When measuring the aperture ratio by the method of this paragraph, the angular subtense of the object point at the first nodal point of the photographic objective must be small as compared with the value of the angle α between the optical axis of the objective and the extreme ray proceeding to the image point.

5.1.2.9 *Effective aperture.*

5.1.2.9.1 *Method 3 — Microscope method.*[16] A traveling compound microscope is required with means for translating the microscope in a direction at right angles to its optical axis through a measured distance not less than the diameter of the maximum effective aperture to be measured. The microscope must be of low power (10X to 20X) provided with a reticle and with a working distance sufficiently long to permit the microscope to be focused on the limiting opening of the photographic objective through the front member. The photographic objective, of which the effective aperture is to be measured, shall be mounted in a convenient position to permit the traveling microscope to be directed parallel to the optical axis of the objective and focused upon the edge of the opening having the smallest apparent diameter. (The photographic objective is not to be disassembled.) This edge shall be viewed through the lens elements which are normally traversed by image-forming light before passing through the limiting opening. A microscope having a long working distance is required to avoid mechanical interference when looking through the lens elements. A microscope shall then be traversed and measurements made to determine the apparent diameter of this opening which shall be the effective aperture. In place of a traveling microscope, a suitable contour projector may be employed to measure the effective aperture. If the lens has a non-circular aperture, the measured diameter must be suitably corrected.

5.1.2.9.2 *Method 4 — Point source method.*[17] When it is not practicable to use a microscope of sufficient working distance to permit the limiting opening to be observed through the lens elements, a source of light, as small as practicable and emitting a cone sufficiently large to fill the lens, may be

[16] American Standard Methods of Designating and Measuring Apertures and Related Quantities Pertaining to Photographic Lenses, Z38.4.20-1948.

[17] American Standard Aperture Calibration of Motion Picture Lenses, PH22.90 — 1953.

placed at the second principal focus and directed toward the objective; the diameter of the emergent beam should be measured as near the front of the objective as is practicable. This method is subject to a systematic error, the value of the finite size of the source.

5.1.2.10 *T-number and transmittance.* The equipment specified in methods 5 and 6 for determining T-stops and transmittance of a lens represents workable apparatus. However, modifications are permitted provided that the basic requirements of the method and the specified accuracy are met. (See 3.2.6 and 4.1.4.4.)

5.1.2.10.1 *Method 5 — Extended source method.*[18] This method of lens calibration is based on filling the lens with light from an extended uniform source of adequate size and placing in the plane of best definition of the lens a metal plate with a hole, the diameter of which shall not exceed 3 millimeters (or 1.5 millimeters for 8-millimeter film), at its center. The light flux passing through the hole shall be measured by a photocell arrangement. This flux shall then be compared with the flux passing through a hole of the same dimensions from an open circular aperture of such a size and at such a distance from the plate that it subtends the desired angle α so that $\sin \alpha = \frac{1}{2}$ T, where T is the T-number to be measured. The greatest care is necessary to insure that the extended source is uniform. In practice, the photocell reading for each whole T-number is first determined for a series of open apertures at a fixed distance from the plate. The lens is then substituted for the open aperture with the 3-millimeter hole accurately in its focal plane and the iris of the lens closed down until the photocell meter reading produced by the lens is equal to each of the successive open hole readings. The full T-stop positions are then marked on the diaphragm ring of the lens. The intermediate thirds of stops may be found with sufficient accuracy by inserting a neutral density filter of 0.1 and 0.2 behind each open aperture in turn and noting the corresponding photocell readings or by dividing the travel of the diaphragm control into three equal parts. The extended source should be uniformly bright over its useful area to within ±3 percent. (This could be tested with a suitable telephotometer, or a small hole in an opaque screen could be moved around in front of the source and any consequent variations in photocell reading noted.) The source may be a sheet of ground glass covering a hole in a whitelined box containing several lamps mounted around the hole and shielded so that no direct light from the lamps falls on the ground glass itself. The photocell receiver may be of the phototube type with a simple d-c amplifier. Care must be taken to insure that phototube sensitivity does not change between marking readings on the open aperture and on the lens itself. To guard against this, some turret arrangement is desirable, with the lens on one side and the open aperture on the other, so that the two may be interchanged and compared quickly with each other by turning the turret. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear circular aperture is in place, subtending an angle α at the hole in the front of the photocell so that $\sin \alpha = \frac{1}{2}$N, where N is the second term in the aperture ratio of the lens to be tested. (See 3.2.2.) The value of N must be the true value, which may differ from that indicated on the barrel.

5.1.2.10.2 *Method 6 — Collimator method.*[19] In this method, light from a small

[18] See footnote 17, page 23.

[19] See footnote 17, page 23.

source (a 5-millimeter hole covered with opal glass and strongly illuminated from behind) shall be collimated by a simple lens, or an achromat if preferred, of a focal length at least three times the EFL of the lens being tested and of sufficient aperture to fill the lens being calibrated. This gives a collimated beam which will be focused by the test lens to form a small circle of light in its focal plane. This circle of light will be less than the prescribed limit of 3 millimeters diameter. Uniformity of the collimated beam can be checked by moving a small hole in an opaque screen across the beam, and noting any variations in the photocell reading. For the comparison unit, an open aperture shall be used, of diameter equal to the focal length of the lens divided by the desired T-number. This aperture shall first be mounted in front of an integrating sphere of adequate size with the usual photocell detector and the light from the collimator allowed to enter the aperture. The aperture plate shall then be replaced by the lens, the iris diaphragm closed down to give the same photocell reading, and the T-number engraved on the iris ring. The intermediate thirds of stops can be found by using 0.1 or 0.2 density filters, or by dividing the travel of the diaphragm control into three equal parts. To guard against "drift" or line-voltage variations which might occur between readings of the comparison aperture and the lens, it is convenient to leave the known standard aperture in place in front of the sphere, and to insert the lens into the beam in such a position that the small image of the source falls wholly within the standard aperture. The meter reading should then remain the same with the lens in or out of the beam. A second plate with a 3-millimeter aperture should be placed over the comparison aperture while the lens is in place to stop any stray light which may be reflected from the interior of the lens. It should be noted particularly that if this method is used, the focal length of the lens must be measured separately and a suitable set of open apertures constructed for use with it. However, by suitable devices, one single set of fixed apertures may be used for all lenses. Transmittance of a lens shall be measured at the maximum relative aperture in a direction parallel to the optical axis of the lens. Transmittance is equal to C/R where C is the calibrated photocell reading with the lens in place, and R is a similar reading when a clear diaphragm (equal to the lens effective aperture) is in place.

5.1.2.11 *Relative illumination.*

5.1.2.11.1 *Method 7 — Extended source method.* This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 5. With the lens to be measured set up in the apparatus, the photocell shall be displaced laterally to the position corresponding to the required angular positions, and the corresponding percentage of axial illuminance for each position is found from a calibration curve of the photocell meter.

5.1.2.11.2 *Method 8 — Collimator method.* This method of measuring relative illumination makes use of the same apparatus and techniques specified in method 6. With the lens to be measured set up in the apparatus, the lens shall be rotated through the desired field angles β and the photocell readings compared with the readings for the lens on axis. The percentage of light flux transmitted can then be read off a calibration curve for the photocell system and converted to desired percentage illuminance by dividing by $\cos^3 \beta$.

5.1.2.11.3 *Method 9 — Densitometric method.* This method of measuring relative illumination makes use of the same apparatus and techniques as specified in methods 5 and 6, except that a photographic plate is substituted for the photocell when the extended source is used, and for the integrating sphere when a collimator is used. In the latter case, the image produced by the lens should be in sharp focus on the emulsion plane. The exposures are made on the axis and at the required angular positions off axis. The exposure times shall be the same at all the positions. The densities of the exposed and developed images shall be measured and the relative illuminance determined using the sensitometric curve of the emulsion, obtained by exposing a calibrated step-wedge.

5.1.2.11.4 *Method 10 — Indirect computation method*. The indirect computation of illuminance distribution from dimensions of the lens are outlined in this section. The method in this case is for a lens while in the design stages, or in determining the illuminance distribution of an actual lens when no convenient photometric equipment is available.

5.1.2.11.4.1 *Distortionless lens with object at infinity*. The case where the object is at infinity is applicable to most photographic objectives encountered in aerial and ground photography. The field angle of such a lens is always expressed by the obliquity angle ϕ, in the object space. The desired relative illumination is given by:

$$R = \frac{E_\phi}{E_o} = \frac{S_\phi}{S_o} \cos^4\phi \qquad (17)$$

where E is the illuminance at the point in the image which corresponds to the obliquity angle ϕ in the object space, and E_o is the illuminance at the center of the field. $S\phi$ and S_o are, respectively, the beam section areas of the oblique and axial beams at the chosen reference plane in the object space. The area S_ϕ will in general be smaller than S_o due to vignetting, but in some unusual lenses, $S\phi$ may be somewhat greater than S_o.

5.1.2.11.4.2 *Distortionless lens with finite object distance*. The relative illumination R can be computed either in the object space or in the image space depending on which is more convenient. The illuminance at angle ϕ is given by the integral:

$$E_\phi = K\int \cos^4\phi dS = K'\int \cos^4\phi\, dS' \qquad (18)$$

where K and K' are constants independent of obliquity. The integrals are to be taken over the respective beam sections. The integrals are necessary because ϕ and ϕ' vary from point to point over the beam sections. If the aperture is small, the integral becomes unnecessary and then:

$$E\phi = KS_\phi \cos^4\phi = K'S'\phi \cos^4\phi' \qquad (19)$$

The relative illumination is then found by evaluating $E\phi$ and E_o for an oblique and axial beam and taking the ratio $R = E\phi / E_o$.

5.1.2.11.4.3 *Distorting lens with object at infinity*. This differs from the previous case because the distortion will have a considerable effect on the distribution of illuminance expressed as a function of the entering obliquity angle ϕ. In this case the relative illumination becomes:

$$R = \frac{E_\phi}{E_o} = \frac{S_\phi}{S_o} \cdot \frac{f^2 \sin\phi \cos\phi}{h' \frac{(dh')}{(d\phi)}} \qquad (20)$$

$S\phi$ and S_o are the areas of the beam sections for the oblique and axial beams at the chosen reference plane in the object space; ϕ is the obliquity angle in the object space, f is the focal length of the lens and h' is the image height. By measurements or computations on the lens, a relation can be established connecting h' with ϕ, from which the value of the derivative $dh'/d\phi$ can be found at any desired point in the field. For a distortionless lens, $h' = f \tan\phi$; in that special case equation, (20) simplifies to equation (17).

5.1.2.11.4.4 *Distorting lens with finite object distance*. The image space equations (18) or (19) hold independent of the distortion of the lens. If it is desired to use the data of the object space, equation (18) becomes:

$$E\phi = K \frac{h}{h' \frac{(dh')}{(dh)}} \int \cos^4 \phi \, dS \qquad (21)$$

where K is a constant different from that used in equation (18), h is the object height, and h′ the height of the image of that object. The derivative dh′/dh must be found by determining an algebraic relationship between h and h′. If the aperture is sufficiently small, ϕ will not vary greatly over the beam section and the equation may be reduced to the approximate form.

$$E\phi = K \frac{h}{h' \frac{(dh')}{(dh)}} S\phi \cos^4\phi \qquad (22)$$

5.1.2.11.4.5 *Monocentric lens.* In the case of a lens having a common center of curvature to all the surfaces and a concentric image surface, the relative illumination contains only one cosine, namely:

$$R = \frac{E\phi}{E_0} = \frac{S\phi}{S_0} \cos\phi \qquad (23)$$

5.1.2.12 *Resolving power.* When specifying or measuring resolving power, care should be taken to consider the following pertinent factors: methods of tests, contrast of target used, kind of and processing of photosensitive emulsion, whether filter is to be used, and magnification at which resolving power target images are read. For reading resolution, a magnification of the lowest power which permits convenient viewing will yield the highest resolution readings. (The rule based on Selwyn's experiments [20] that the numerical value of the magnification should equal the number of lines per millimeter expected to be resolved can be considered a rule of thumb.)

5.1.2.12.1 *Photographic resolving power.* When conducting photographic resolving power tests by methods 11 and 12, the photosensitive material and processing should be in accordance with table II.

5.1.2.12.1.1 *Method 11 — Collimator method.*[21] For lenses primarily intended for use on distant objects, such as types I, II, III, and V, this method should be used. The resolving power target is placed at the principal focus of a collimator and illuminated with white light. A filter of a specified color may be used and it shall be placed between the light source and the target. It is recommended that, in order to eliminate vibration effects, a flash discharge lamp be used as the light source and that the light from it be filtered if necessary to approximate white light. (See 5.1.1.4.) Exposure can be controlled by means of neutral density filters between the light source and the target. The lens to be tested shall be placed in the collimated beam from the target and a test plate or film made in a series of focal settings as described in 5.1.2.1. Unless otherwise specified, the lens shall be set at the specified maximum relative aperture. With the test plate perpendicular to the optical axis of the lens, exposure shall be made of the test target at the specified angular distance from the axis out to and including the multiple of the specified angle falling nearest the corner of the plate inside the picture format. The specified angle should be multiples of 1¼ degrees and should be spaced to provide 5 increments or more in the semi-field of the lens. The exposure time shall be the same for all angular settings and shall be the

[20] E. W. Selwyn, National Bureau of Standards C526, 219, 1954 and Photographic Journal 88B, 46, 1948.

[21] In method 11, if the resolving power is measured by rationing from the lines per millimeter of the target, EFL of the collimator, and EFL of the test lens, the value should be corrected by multiplying radial lines by the cosine of the field angle and tangential lines by the $\cos^2$ of the field angle.

TABLE II

Lens type	Photosensitive material	ASA Exposure index	Development (gamma)
I			
(70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
(5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
II			
(70-mm. format & smaller)	Panchromatic aerial	10	2.0 ± 0.10
(5-inch format & larger)	Panchromatic aerial	80	1.5 ± 0.10
III	Panchromatic aerial	50	0.8 ± 0.10
IV	Panchromatic microfilm	......	Maximum contrast
V	Panchromatic (motion picture)	50-80	0.8 ± 0.10
IX	Panchromatic (portrait)	100	0.8 ± 0.10
XII	Panchromatic microfilm	......	Maximum contrast
XIII	Panchromatic microfilm	......	Maximum contrast
XIV	Blue sensitive recording	......	1.5 ± 0.10

exposure time which gives the highest resolving power at the angular setting nearest the angle equal to one-half the half angle of view. The different angular settings may be obtained by moving the lens and test plate about an axis near the entrance pupil or by moving the collimators, or by means of a series of collimators placed in the correct angular positions. The lens may be tested with or without the filter provided with it, as required.

5.1.2.12.1.2 *Method 12 — Target range method.* For lenses primarily intended for use at finite distances, such as types IV, XII, and XIII, this method should be used. Also, it may be used, when specified, for testing other types of lenses. Properly illuminated high contrast resolving power targets shall be placed in the object space in a plane perpendicular to the optical axis of the lens to be tested and spaced at the required angular distances. The distance from the lens to the plane of the targets shall be designated. When this method is used for testing lenses at infinity focus, either formula (12) in 5.1.1.3 may be used to determine the proper distance, or some designated distance may be used. The test plate shall be adjusted perpendicular to the optical axis of the lens and exposed for maximum resolution at the target nearest the angle equal to one-half the half angle of view of the lens being tested and shall be moved in a series of focal settings as described in 5.1.2.1. The sensitized material, processing, etc., shall be in accordance with table II.

5.1.2.12.2 *Method 13 — Visual resolving power.* When visual resolving power measurements are required (such as type X lenses), they will be made exactly like the photographic resolving power tests, except that the aerial image, when it is real and easily available, will be observed visually under magnification. Method 11 or 12 in 5.1.2.12.1 will be used as specified, depending on the use of the lens. When the image formed by a viewfinder (type X lens) is a virtual image, a telescope stopped down to 5 millimeters and placed at the eye position will be used to observe the image. In this case, the resolution shall be determined in terms of a specified test chart at a specified distance. In all cases where the image is formed on a ground glass, the ground glass shall be removed to observe the aerial image, and the image shall be observed on a plane.

addition of this step enables one to measure prism angle. When measuring distortion at finite distances the plane of the targets must be parallel to the test plate. Mathematical means for adjusting the measurements may be used to eliminate error from this source. If the distortion is to be measured for an object at a finite distance, the targets shall be set up at the required distance as specified. The test procedure is the same as for the object at infinity, except that the distortion is determined on the basis of paraxial or calibrated magnification.

5.1.2.16.2 *Method 26 — Collimator bank method.* This method is intended for use with lenses mounted either in cameras or in test barrels. Method 26 is similar to method 25, except that a bank of collimators containing targets shall be used instead of a target range.

5.1.2.16.3 *Method 27 — Single collimator photographic method.* In some cases where high precision is not required, a single collimator may be used in conjunction with a test plate as in method 26. In this method, either the collimator or the lens and the test plate shall be rotated through the required field angles about the center of the entrance pupil of the lens.

5.1.2.16.4 *Method 28 — Nodal slide method.* This is a visual test method and may be used, when specified, for lenses mounted in barrels. The lens to be tested shall be properly placed on the nodal slide of an optical test bench and centered so that its optical axis is nearly coincident with the axis of the microscope. Distortion for a particular angle shall be measured by the lateral displacement of the observing microscope required to center the target at each angular setting. At each angle β, the microscope shall be displaced along its horizontal axis by the distance $f(1-\cos\beta)/\cos\beta$ away from the lens. This refocusing is not necessary if a flat field bar is used. To obtain the value of distortion, the lateral distance through which the microscope shall be displaced must be divided by the cosine of the angle at which the distortion is being measured. Because of inaccuracies present in most optical benches, it is desirable to make each measurement at the same indicated angle on each side of the axis and to average the two microscope readings obtained before computing distortion.

5.1.2.16.5 *Method 29 — Goniometer method.* This is a visual method intended for use with lenses mounted in cameras. An accurately calibrated test object on glass, usually in the form of a scale or grid, shall be placed in the plane of best definition of the lens to be tested and illuminated in a direction toward the lens to be tested. This test object must be flat, properly centered, and perpendicular to the optical axis. The lens and illuminated test object shall be placed in the goniometer so that the axis about which the angles are measured passes through the center of the entrance pupil of the lens. The telescope of the goniometer shall be pointed at successive points on the test object and the field angles determined. (The telescope shall not be refocused during the run of measurements.) From the focal length of the lens being tested and the calibration of the test object, the angles subtended by the various points on the test object can be computed. Distortion then can be computed in terms of the difference in angles on the object side and image side; this distortion in turn can be converted into the standard form. (See 5.1.2.3.) By adjusting the focus of the telescope, this method can be expanded to include some cases in which the test object is in a plane corresponding to some finite magnification. Care should be exercised to insure that the cone of light from the test lens is included in the entrance pupil of the telescope.

5.1.2.16.6 *Method 30 — Projection method.* This method is intended primarily for testing projection lenses. A test object similar to the one used in method 29 shall be placed in the object plane of the lens to be tested and projected onto a suitable screen. Measurements shall be made of the projected image of the test object. The distortion shall be computed in terms of the test object. Care should be taken to insure that the screen and test object are perpendicular to the optical axis of the lens and that the test object is flat and properly centered. The cone of light from the projection lamp shall completely fill the projection lens, and the test object shall be uniformly illuminated. The sign of distortion is reversed from theory on projection through a lens and measured at the long conjugate.

5.1.2.16.7 *Tangential distortion*. Any of the six methods for measuring radial distortion may be modified to measure tangential distortion by considering the displacement of image points perpendicular to a radius from the center of the field. The magnitude of tangential distortion varies from zero along one diameter to a maximum along an orientation 90 degrees to the diameter of zero distortion. Therefore, when required, tangential distortion shall be measured for two axial orientations of the lens, and the orientation of maximum tangential distortion computed.

5.1.2.17 *Prism effect*. To measure the prism effect in terms of a thin equivalent prism of vertex angle α, use is made of the fact that oblique rays are deviated by the prism more than, and in the same direction as, the axial ray. An assumption is made that the axial ray makes only a small angle with the normal to the surface of the prism (or the prism may be assumed to be in the minimum deviation for the axial ray). If the camera under test is used to photograph three collimators or distant targets, one axial and the other two making angles $+\beta$ and $-\beta$ with the axis, the distances from the 0 degree image to the $+\beta$ image and from the 0 degree image to the $-\beta$ image are different in the presence of a prism effect. This difference is measured on the negative. Under the assumptions made, the analytical expression for this difference is:

$$\Delta = f[\tan(\beta + \epsilon) - \tan(\beta - \epsilon) - 2\tan\epsilon_0] \qquad (26)$$

where f is the equivalent focal length of the lens, ϵ is the deviation of the ray making β with the axis (within a close approximation the deviation is the same for $+\beta$ and $-\beta$), and $\epsilon_0 = \alpha/2$ is the deviation of the axial ray. Tables for Δ can be computed for various values of f, β, and α. The measured and tabulated values of Δ are compared, and the corresponding α is evaluated.

5.1.2.18 *Spherical aberration*.

5.1.2.18.1 *Method 31 — Annual ring or Hartmann disk method*. When spherical aberration is specified in terms of change in focal position for zones of different radii, a Hartmann disk (a plate covering a front of the lens with holes at the different zones) or aperture consisting of open annular rings will be placed over the front of the lens and properly centered. Either a photographic or visual method of determining the difference in focal positions for different zones may be used. Various modifications of these methods and other methods may be employed, such as a knife-edge test or interferometric method. When measuring spherical aberration for an object at infinity, the target which is imaged by the test lens may be placed in a collimator or a distance at least 25 times the focal length of the lens to be tested.

5.1.2.18.2 *Method 32 — Stopped-aperture method*. When spherical aberration is specified in terms of the difference between the best focus at maximum aperture and at a designated reduced aperture, a nodal slide optical bench or an autocollimation method may be used to determine the difference in

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