over here who really want to get closer to the photogrammetrists in other countries.

The European continent not only sends us occasional visitors like Mr. Staub, but it sends us also people of great scientific attainment who become citizens of our country and spend the rest of their lives working with us to advance science in this country. The Bausch and Lomb Optical Company, of Rochester; New York, is fortunate in having such a man, Dr. Konstantin Pestrecov, who is now in charge of photographic projection optics design of the Scientific Bureau of Bausch and Lomb. He is going to speak to us this morning.

Dr. Pestrecov was born in Russia and studied in Russia. He received several prizes for his outstanding work in spectrographic X-ray work. He came to this country in 1931 and became associated first with the Rockefeller Institute for Medical Research, and Columbia University. He eventually went to the Bausch and Lomb Optical Company, and of course we know him best for his work with that Company. During the war Dr. Pestrecov was very closely involved in the development of aerial camera lenses and multiplex equipment, and every one of us here recognizes the importance of that phase of the work. I would like to introduce to you now Dr. Pestrecov.

RESOLUTION (START)

DR. KONSTANTIN PESTRECOV: I have a secret to reveal to you about why this paper is being presented today. The reason is simple. I had to talk so often with so many people about the subject of resolution that I got tired and decided to write everything that I knew about it. I hope that the paper will be eventually published in PHOTOGRAMMETRIC ENGINEERING, and then my job will be simple. I will just distribute reprints and forget the whole matter. In the meantime, we have prepared some advanced mimeographed copies of the talk, and those who are really interested can obtain them from Mr. Reynolds at our exhibit booth. It is really to him that the major credit should be given for this paper, because he really forced me into it, and then later when he realized how difficult the job was, he did all possible to render technical assistance, with some others of my colleagues. Well, let's go to the business of resolution.*

Basic factors pertaining to photographic resolution are summarized in this paper. Extensive material now available indicates that the resolving power of a lens is a rather indeterminate quantity which may vary widely depending upon the conditions of tests. To be of real meaning, the resolution data for a given lens should always include an identification of the target and of the emulsion used.

Criteria are suggested for the establishment of resolution requirements, and formulas are discussed which predict the probable resolutions of lens-film combinations. A formula is derived indicating the minimum focal length required for recording ample detail from a specified altitude.

BASIC REQUIREMENTS OF PHOTOGRAPHIC OPTICS

In designing a lens system for photographic applications, the lens designer strives to satisfy the following two basic requirements. The first is that the system devised by him should be capable of reproducing on a photographic emulsion the variety of subjects surrounding us. The second is that the reproduction should be as faithful as it is possible to achieve within the limitation of our knowledge.

There are many factors which determine the faithfulness of reproduction. The most important of them are the freedom from distortion and the availability of a sufficient amount of detail in the image.

The problem of distortion, not being within the scope of this paper, will not be discussed here. We may note, however, that the condition of freedom from

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* Part of this material was presented on October 31, 1946, before the Rochester Convention of the Photographic Society of America, and published in PSA Journal, Vol. 13, No. 3, pp. 155–159, 1947.

distortion is relatively easily satisfied in lenses intended for general photographic purposes, as the distortion tolerances in these applications are usually very liberal. The problem does, however, assume large proportions whenever some extremely critical requirements are to be satisfied, as it is, for example, in the case of photogrammetric optics.

Lenses are available now, in which the distortion is reduced to unbelievably low values. Thus in the generally known Metrogons the distortion is less than one tenth of one percent within practically the entire field diameter of 90 degrees, and it is further drastically reduced in the multiplex reduction printers. Although extremely satisfactory results are being obtained from the utilization of the Metrogon photography in the multiplex precision mapping, the residual distortion is still a limiting factor in the procedure. To eliminate this factor, a wide angle lens with the distortion reduced practically to zero is required. Major efforts will be needed to produce such a lens without sacrificing something in the image quality, and the progress of design may be slow. Still we may hope that some day a satisfactory distortion-free lens will be produced.

Disregarding the distortion requirements, a photographic image cannot be of much use unless it reveals all the detail that may be of importance for a given purpose. The ability of an image-forming system to reproduce detail is determined by its resolving power, which may be numerically expressed by the number of the smallest elements per unit area or per unit length still resolved in the picture.

Statements are often heard that the resolving power of this or that lens is that much. We will see later that such statements have practically no meaning, unless they include specifications as to the conditions under which the resolution data were obtained. The nature of resolution phenomena makes it impossible to isolate and measure the resolving power of a lens as such. Resolution measurements always involve not only a lens but also a target and a receptor. It is an unfortunate fact, which now should be generally recognized, that, even for a given target, resolution data cannot be obtained that would be characteristic of the lens alone. Therefore, it should become the commonly accepted practice to speak of the lens-receptor resolution, and, specifically in the case of photographic imagery,—of the lens-emulsion, or lens-film resolution. Still for the purposes of this discussion it should be useful to consider first some idealized cases in which the lens resolving power may have a certain meaning as a separate entity.

IDEAL (MATHEMATICAL) LENS, AND PHYSICALLY PERFECT LENS

Let us first consider an ideal lens, even if it exists only in our imagination. The ideal lens would reproduce an infinitely small object element as an infinitely small element in the image space. Speaking mathematically, it would image a point object as a point, a line as a line, and a plane as a plane. With the imagery of this kind we could bring two object points or two lines as near to each other as we wish, and still have them reproduced as two distinct points or, respectively, as two lines in the image space. The ideal lens has an infinitely great resolving power.

As usual, nature does not give us anything ideal, and it does not permit us to realize ideal optical systems. All actual optical systems have certain imperfections. I am not speaking here about manufacturing imperfections although they are also a very important factor. I have in mind the inherent imperfections known as optical aberrations. They cannot be entirely eliminated from any system, and they impose severe limitations on the lens performance and its resolving power.

We could imagine a lens entirely free from all the aberrations and all the imperfections of manufacture; even then we find that a point-to-point imagery and, hence, an infinitely great resolving power cannot be obtained, because of the diffraction phenomena. They occur whenever light is transmitted through finite openings. Real lenses always have finite openings and, therefore, always produce diffraction effects. Diffraction phenomena interfere with the rectilinear propagation of light, they deviate it from its proper course, and redistribute light into periodic maxima and minima. These phenomena do not permit a point of light to be imaged as a point even by a physically perfect lens.

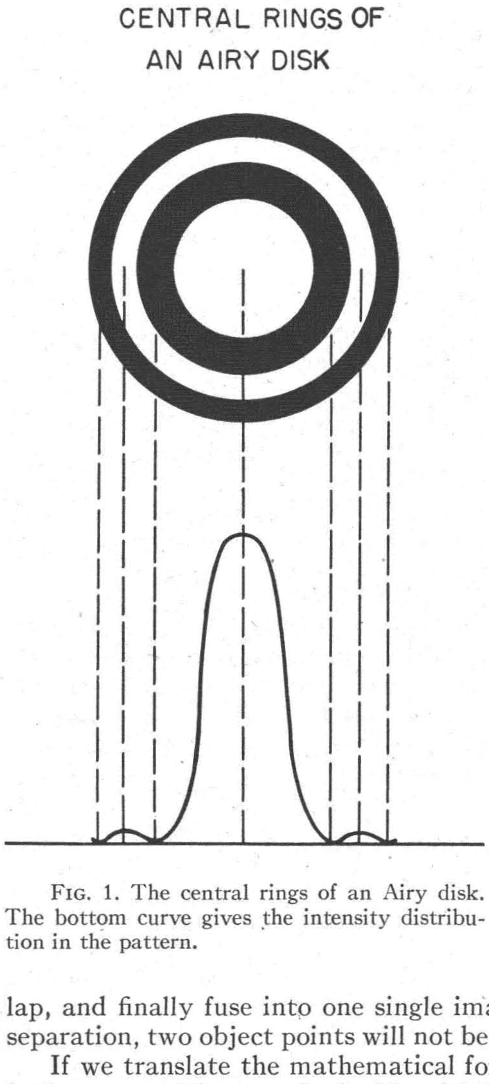

FIG. 1. The central rings of an Airy disk. The bottom curve gives the intensity distribution in the pattern.

If we could design a system free from aberrations, and make a physically perfect lens (under certain conditions some lenses may be considered as almost perfect), we still would find that the image of a point of light is not a point, but a bright disc of a measurable dimension, surrounded by an infinite number of rings. The light distribution within this pattern is such that about 84% of the available light is concentrated in the central area, 7% falls within the first bright ring and the rest is distributed among the remaining infinite number of rings. Thus, for all practical purposes we may limit ourselves to the consideration of only the central area known as the Airy (1834) disk, as represented in Figure 1.[1]

Airy found that the size of the disk depends on the wave-length of the light used and the speed (f-number) of the system. If we have two object points, a perfect lens will image them as two Airy disks. It should be obvious that as two object points are brought nearer and nearer to each other, their Airy disks will eventually touch each other, then partially overlap, and finally fuse into one single image patch. In other words, at a certain separation, two object points will not be resolved in the image space.

If we translate the mathematical formula, derived by Airy, into resolution in lines per millimeter obtainable with lenses of various f-numbers, we produce the curve represented in Figure 2. The most important fact here is that as the perfect lens is stopped down, its resolution drops rapidly. For example a wide open f/4 lens has a theoretical resolution of 350 lines per millimeter; stopped down to f/16 it resolves only 85 lines per millimeter. With actual lenses the situa-

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[1] Jacobs, Donald H., *Fundamentals of Optical Engineering*, p. 176, McGraw-Hill Book Co., 1943.

tion is significantly different. The residual aberrations in a wide open lens, especially of a longer focal length, and some unfavorable characteristics of emulsions, may drastically reduce resolving power particularly in the extra-axial regions. As the lens is stopped down some of its aberrations become smaller, and its photographic resolving power may gradually increase, until, at a certain stop, it approaches the theoretical value. This critical stop may be in the region where the theoretical resolution is inherently low.

PHOTOGRAPHIC EMULSION AND SOME OTHER FACTORS AFFECTING RESOLUTION

Our main interest is in the resolution of lenses as it may be recorded by a photographic emulsion. Here again we do not have an ideal material, as no emulsion is capable of recording a point image even if such could be produced by a lens. Dealing with photographic emulsions we also encounter phenomena analogical to aberrations in lenses, which phenomena prevent point-to-point imagery and limit the resolution possibilities to definite values. Thus, the resolving power of each emulsion is inherently determined by the emulsion characteristics.

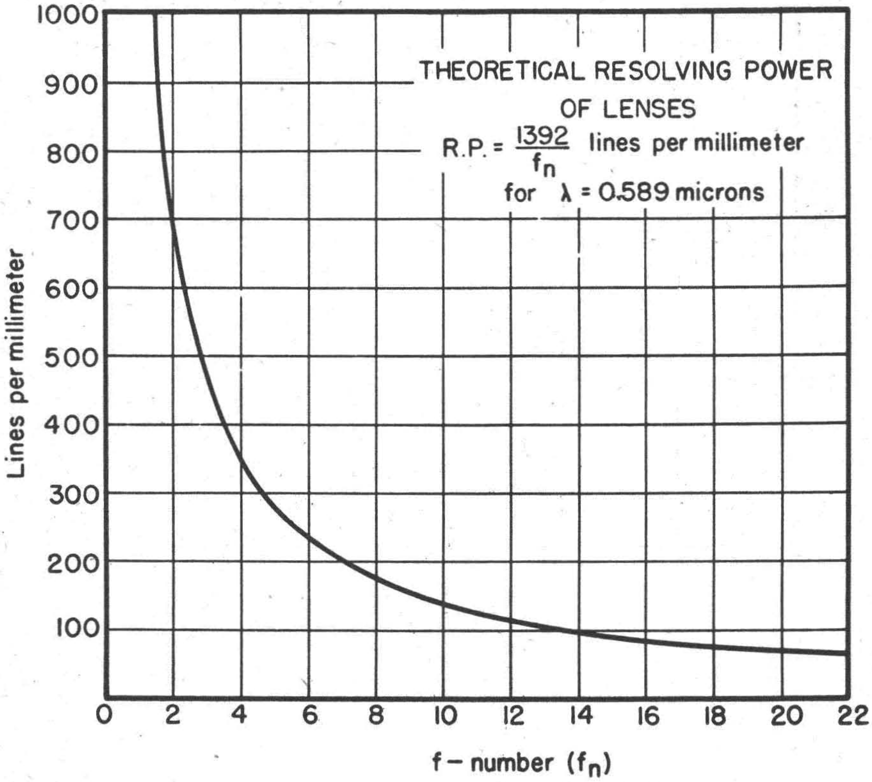

FIG. 2. Theoretical resolving power as a function of the f-number of a physically perfect lens.

Nevertheless, external factors also play a decisive part in defining the limiting resolution of a given emulsion. The most important of them are the geometry of the object and its contrast. We find, for example, that with a target consisting of a certain number of narrow lines per millimeter the resolution data differ from those obtained with a target having the same number of wider lines. We find that resolution of dark lines on a light background is different from resolution of light lines on a dark background. We find that resolution is drastically affected by detail contrast. This dependence is represented by a composite graph[2] (Fig. 3) covering a number of emulsions. The resolution data on which the graph is based were obtained by measuring the resolving powers of a series of photographic emulsions, using targets consisting of transparent lines on a dark background. The transmittance of the transparent lines practically was equal to 100% (density=0), the density of the background was varied as indicated on the graph. The contrast ratios, also indicated therein, were obtained as the ratios of the clear line transmittance and the transmittance of the background.

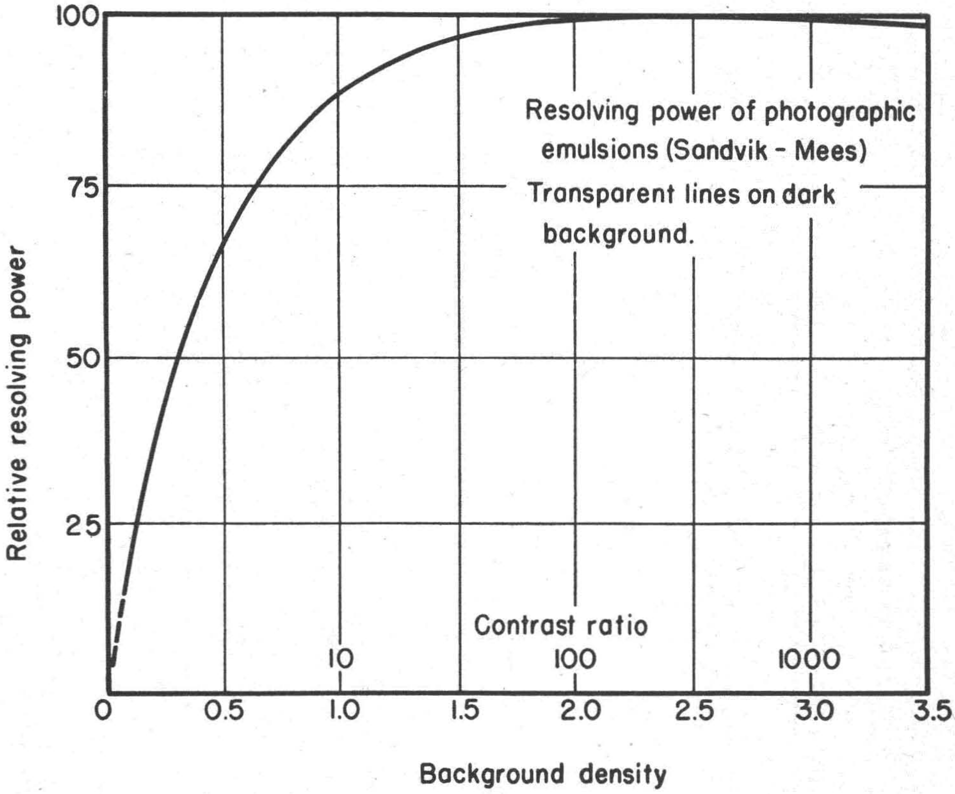

FIG. 3. Composite curve of resolving power of four emulsions, plotted as a function of the density (contrast) of the test object. The value of 100 was assigned to the maximum resolving power of each emulsion.

Each emulsion under test gave a maximum resolving power at a certain contrast ratio. This resolving power was assigned the value of 100, and the resolving powers measured at other contrasts were rated with respect to that maximum. The relative resolving power curves for the various emulsions proved to be so similar that they could be represented with a sufficient accuracy as the composite curve of Figure 3.

This curve is extremely important for a proper understanding of photo-

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[2] Mees, C. E. Kenneth, *The Theory of the Photographic Process*, p. 900, The Macmillan Co., 1942.

graphic resolution. A photographer usually deals with scenes[3] whose average contrast ratio is approximately 32:1, and even considerably higher according to the latest data by C. E. Mees. This is well within the region of the resolution maxima of photographic emulsions. Often, however, photographic situations are encountered with considerably lower contrast ratios. In aerial photography, for example, according to the British data,[4] the mean contrast ratio is about 3:1, and the typical value is as low as 1.6:1. We find from Figure 3 that for these contrast ratios the relative resolution of emulsions drops to about 60% and 35% respectively. Disregarding all other factors and assuming an ideal lens, this graph reveals one of the basic reasons why in aerial photography the maximum resolution capabilities of emulsions cannot be utilized for recording the corresponding detail available in the average low-contrast object on the ground.

Other factors of importance are: the spectral composition of the illuminant; the spectral sensitivity of the emulsion, its other physical and chemical properties; the exposures used, the developer composition, concentration and temperatures; and the development time. A good summary on the importance of all these factors may be found in the well known book by Dr. C. E. Kenneth Mees.[5]

TARGETS

Among the most important factors affecting the photographic resolution is the target itself. Despite this fact, there is no national and international agreement as yet with regard to the type of target for resolution testing.

In this country until the very recent time the Bureau of Standards target (Fig. 4) has been in common use. The main objections to it are that its geometry (i.e., the length-width ratio of the lines and their number) changes with the block, and that, when the photographic image of the target is observed under a magnifier or a microscope, it is practically impossible to count the number of lines in the finer blocks in order to ascertain that a particular block is photographically reproduced with the correct number of lines. Another objection is that the resolution intervals from one block to the adjacent are too large ($\sqrt{2}$) to permit a critical evaluation of the limiting resolution.

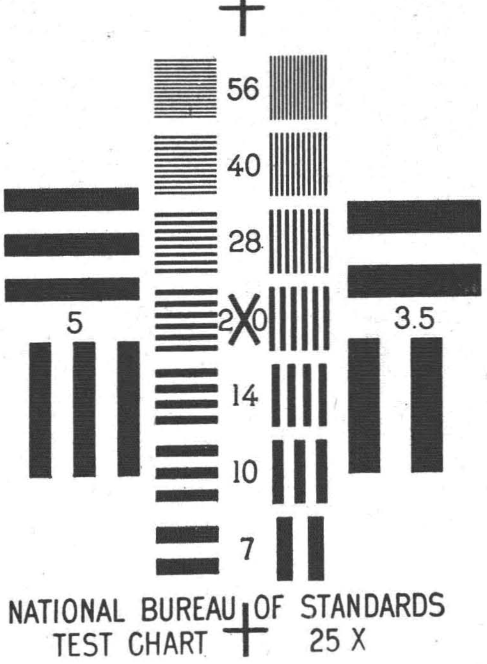

FIG. 4. Resolution target used by the National Bureau of Standards. Infinite contrast. The resolution values of the adjacent blocks are in the $\sqrt{2}$ ratio.

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[3] Hardy, Arthur C. and Perrin, Fred H., *The Principles of Optics*, p. 220, McGraw-Hill Book Co., 1932.

[4] Selwyn, E. W. H. and Tearle, J. L., "*The Performance of Aircraft Camera Lenses*," The Proceedings of The Physical Society, Vol. 58, Part 5, No. 329, p. 503, 1946.

[5] Mees, *loc. cit.*, pp. 894–906.

Meeting these objections, the United States Army Air Force has introduced[6] its own target (Fig. 5) with three lines in each block, with a constant length-width ratio, and with the resolution intervals of $\sqrt[3]{2}$.

The British have experimented with a number of targets and finally have come to favor the "Cobb-target"[7] consisting of only two lines in each block, with a constant length-width ratio and the resolution intervals nearly equal to $\sqrt[6]{2}$.

All these targets consist of vertical and horizontal lines, and they permit the evaluation of resolution in two directions only. As used in testing instruments, these targets yield the tangential and the sagittal (radial) resolution. Although the resolution data in these two preferred directions, may be of much meaning and importance for lens designers, they are not sufficient for estimating the average resolution in all the directions within a given image area.

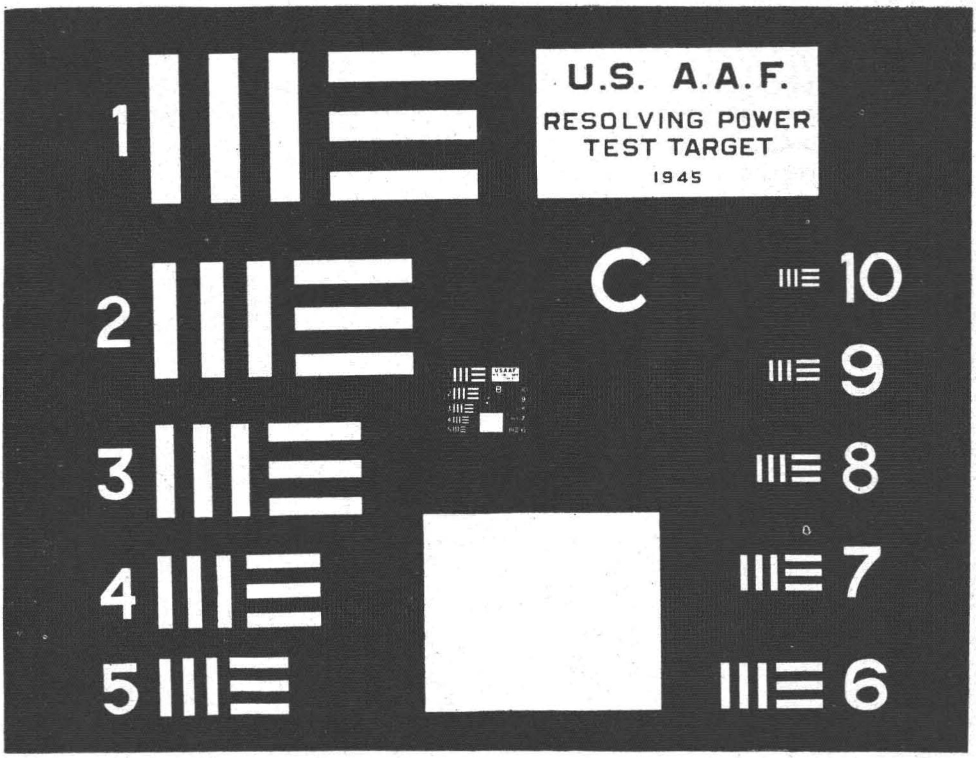

FIG. 5. Resolution target used by the U. S. Army Air Force. Infinite contrast. The resolution values of the adjacent blocks are in the $\sqrt[3]{2}$ ratio.

Actual experimentation has shown that neither the geometrical nor arith-

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[6] Kendall, C. W. and Schumacher, B. A. "*Measuring the Resolving Power of Lenses,*" Photo Technique, Vol. 3, No. 4, p. 51, 1941.

Pryor, Paul L., *Air Material Command Research on Resolution and Distortion*, PHOTOGRAMMETRIC ENGINEERING, Vol. XII, No. 4, p. 389, 1946.

[7] Cobb, Percy W. and Moss, Frank K. "*The Four Variables of The Visual Threshold,*" Journal of the Franklin Institute, Vol. 205, No. 6, p. 832, 1928.

metical mean of the tangential and the sagittal resolution provide a good estimate of the resolution integrated in all the directions, and that in the absence of integrated data the lower value of the two resolutions (tangential and sagittal) may be taken as better depicting the true situation.

Targets have been proposed that can be used for the evaluation of resolution in all directions simultaneously. The oldest of them is the "sector target" (Fig. 6) designed by P. G. Nutting.[8] This target has proved rather inconvenient for a rapid determination of the limiting resolution, and, therefore, has been practically abandoned.

The Optics Laboratory of the National Research Council of Canada has successfully used, under the direction of Dr. L. E. Howlett,[9] a target consisting of light annuluses on a dark background (Fig. 7). This target is arranged in $\sqrt[6]{2}$ steps. By correlating the resolution data obtained with the annulus target with the average resolution obtained with line targets photographed in a number of orientations throughout 360°, Dr. Howlett and his co-workers have established that the annulus target serves very well for determining the average resolution in all the directions at a given image area. This target is very convenient as it gives a single representative resolution value and it does not require any assumptions as to the relative weights of the tangential and sagittal resolutions, which assumptions are necessary when line targets are used.

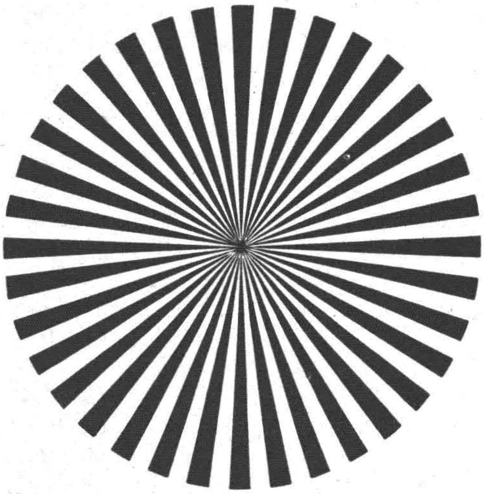

FIG. 6. Sector target, introduced by P. G. Nutting.

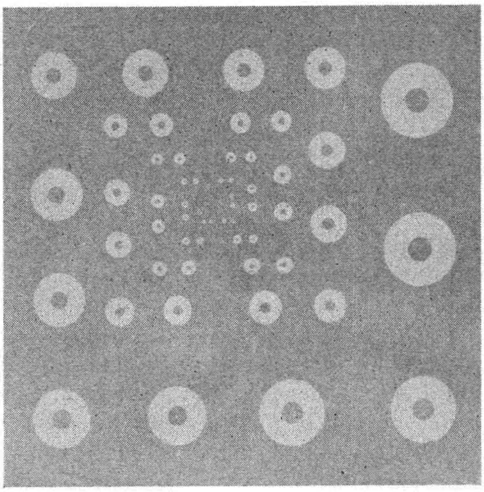

FIG. 7. Canadian annulus target of 1.6:1 contrast ratio. The resolution values of the adjacent annuluses are in the $\sqrt[6]{2}$ ratio.

There is one characteristic common to all the targets discussed above. It is that the ratio of the line-width (or the annulus width in the annulus targets) and the spacing width (the inside diameter of the annulus) is equal to one, Considering the fact that photographic resolution is drastically affected by the line-spacing ratio of the target, it is most fortunate that at the present there is at least a tacit agreement that the ratio of one should be considered as standard.

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[8] Jewell, L. E., "*A Chart Method of Testing Photographic Lenses,*" Journal of the Optical Society of America, Vols. 2–3, Nos. 3–6, p. 52, 1919.

[9] Howlett, L. E., "*Photographic Resolving Power,*" Canadian Journal of Research, Vol. 24, Sec. A, No. 4, pp. 15–40, 1946.

Another general agreement which may be mentioned for the record is that in optical practice the "resolution line" always consists of the "line itself" and the adjacent spacing. In other words, the width of a "resolution line" is equal to the sum of the widths of the line itself and of the adjacent spacing; this is also equal to the distance between the centers of two neighboring light (or dark) "lines." It should be noted, however, that this convention is not adhered to in television practice where the line itself and the spacing are each counted as distinct "resolution lines." Consequently, a resolution in lines per millimeter expressed in "television lines" is always twice as high as the same resolution expressed in "optical lines."

The question may be asked what is a line and what is a spacing in a resolution target. The answer is probably generally known, but still may be repeated here. The spacing and the target surround (background) are always similar, i.e., spacings are dark or light depending on whether the surround is dark or light. By a tacit agreement resolution targets are always produced so that the transmittance (or reflectance) of the spacings is the same as that of the surround.

The most disturbing factor in resolution measurements is the lack of agreement with regard to the contrast of test targets and relative to the emulsions to be used in resolution testing. In this country we persist in using high contrast targets and special high-contrast emulsions of extremely high resolving power. The British and Canadians have found sufficient justification for using regular commercial emulsions and targets of 1.6:1 contrast ratio (0.2 density difference between the lines and the background) at least in testing aerial lenses. Because of this discrepancy and the complexity of resolution phenomena, it is generally impossible to correlate the huge material accumulated by the British and Canadians with our own material. Still Figure 3 gives us some idea as to what the probable correlation may be. For the same emulsion and processing, and disregarding possible variations in the lens behavior with targets of different contrasts, we could expect that our resolution data with targets of high contrast should be on the average 2.5 times as high as the British and Canadian data with the targets of the extremely low (1.6) contrast, although some actual experimentation indicates that a factor smaller than 2 should be more appropriate.

It has been already mentioned that emulsion resolution is affected by line-spacing ratio and it varies depending on whether the target consists of light lines on dark background or dark lines on light background; it is usually lower for targets with light background. These differences, of course, persist and may be emphasized in lens-film resolution testing.

The length-width ratio, the general form of the target (line, sector, annulus), and the number of lines in the target block are also of great importance. No reliable correlation is possible here, as the resolution results may be affected not only by the target geometry but also by the lens, the emulsion, and focusing. Generally, however, the sector target tends to produce lower resolution, targets with greater number of lines in the block and targets with higher length-width ratio tend to produce higher resolution, and the annulus target yields significantly lower results than two- or three-line targets even of low length-width ratios.

Difficulties of Recording and Evaluating

Now we have a target, a lens, an emulsion, and certain conditions under which the resolution data are to be recorded. In order to obtain a satisfactory record, the image produced by the lens should be critically focused on the emulsion. Here we immediately encounter an extremely difficult situation, as the more critical we are, the more elusive becomes "the best focus." The situation was recently analyzed by H. H. Hopkins,[10] who clearly illustrated that no lens has unique focus but merely a spatial region of focus, different parts of which may satisfy different requirements. He stated that generally "the assumption of the worker is that the lens has a focus; it is just hard to find." Practically every lens can be focused to produce either the highest resolution at a somewhat lower detail contrast, or the highest detail contrast with a somewhat impaired resolution and "sharpness." What focus shall we choose?

The situation is difficult when we limit ourselves to the axial imagery. If we wish, however, to include the total field covered by the lens (and we cannot disregard the extra-axial regions if the purpose of testing is to obtain an over-all picture of the lens-film resolution), the situation becomes practically hopeless. The resolution of all lenses varies significantly with the image distance from the axis. At a certain focusing with a given lens and film we may obtain the highest possible resolution on the axis, but find that the peripheral or zonal resolution is low and that it can be improved by a slight refocusing with a consequent sacrifice of the axial resolution. What focusing should be preferred?

There are no definite answers to these questions, and the evaluation of the over-all resolution is necessarily based on some arbitrary decisions as to what image plane should be selected for one of the "best average resolution."

Suppose now that we have made the necessary decisions and finally obtained a photographic record representing the lens-film performance under certain conditions. We need an instrument to evaluate the record. I can discuss here the only instrument readily available, namely the human eye, helped by a magnifier or a miscroscope. The human eye is not an ideal instrument, and it has its own peculiarities.

At a recent meeting of the Optical Society of America, several papers were presented dealing with the ability of the eye to recognize detail available in the target. This work was extremely important for the war effort, and it was conducted on a large scale. The accumulated data have confirmed and expanded previously available knowledge that the resolving power of the eye is greatly influenced by the size, shape, contrast, and illumination of the target, and that there are significant variations in the ability of observers to evaluate detail.

The title of this paper is "Photographic Resolution of Lenses." Actually, we never determine the resolving power of a lens as such, but we evaluate the performance of a system consisting of a target, a lens, an emulsion, and an observer. There are no simple relationships between the components of this system.

The situation is extremely complicated, and it practically excludes the possibility of determining the "absolute quality" of a lens on the basis of resolution data.

During the war extensive work was done in this country as well as in England and Canada in order to determine the significance and value of resolution tests. The most important conclusion based on this material is that, to be of real value, resolution tests should be conducted under the conditions as near as possible to the actual conditions of use. There is, however, no agreement as to what conditions should be accepted as standard.

BASIC RESOLUTION CRITERION FOR PHOTOGRAPHIC LENSES

The question is often asked, "What should be the resolution requirements for a good photographic picture?" There is no generally valid answer to this question as the requirements should vary greatly depending upon the applica-

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[10] Hopkins, H. H., "*Light Waves and Lenses,*" Photographic Journal, Vol. 86B, No. 3, pp. 73–84, 1946.

tion. Still some criterion as to what is needed in the general-purpose photography may be found in the resolving power of the eye. Indeed, disregarding any artistic effects, a photographer usually tries to record what he observes, and, therefore, he should generally be satisfied if the detail in the picture is equivalent to that visually perceived in the object. The resolving power of the eye is about one minute of arc. Using this basis, we may establish the equivalent resolution requirements for photographic images produced with lenses of various focal lengths. The approximate formula is:

$$R_e = \frac{100}{f} \tag{1}$$

where R_e is the resolution in lines per millimeter equivalent to that of the eye, and f is the lens focal length in inches. The formula is graphically represented in Figure 8. With targets of relatively high contrast and lenses of medium focal lengths (about 5 to 10 inches) these resolution requirements are satisfied by practically every modern lens within its total angular coverage and even on commercial emulsions of relatively low resolving power. Lenses of focal lengths longer than 10 inches are capable of satisfying these requirements also with targets of low contrast. With lenses of shorter focal lengths, high contrast targets and emulsions of higher resolving power are needed if we wish to obtain a resolution equivalent to that of the eye, and even the best available lenses may be capable of meeting these requirements only within a relatively low angular coverage.

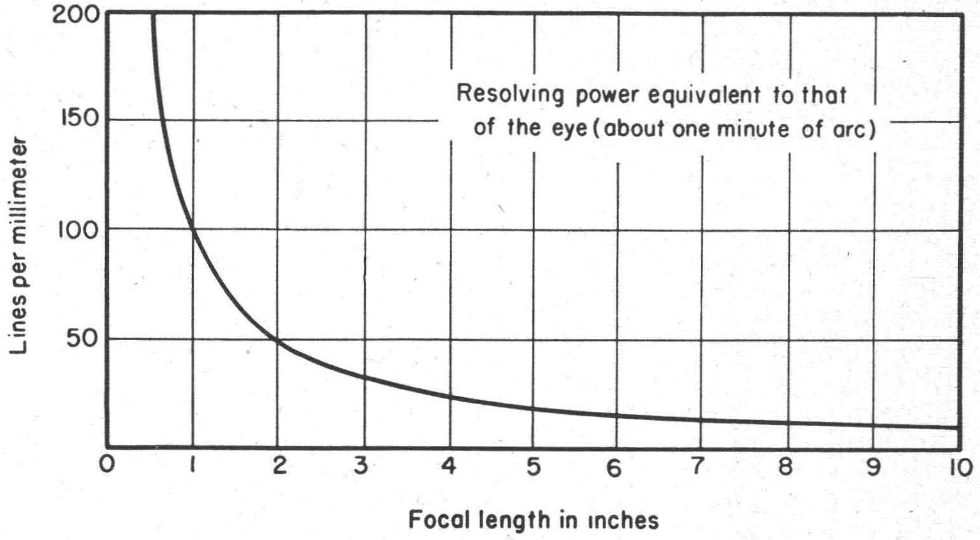

FIG. 8. Resolution in the image, sufficient to render detail equivalent to that perceived visually in the object. The curve is based on the visual resolution of about one minute of arc.

It should, however, be emphatically stated that the resolution available in a photographic image does not tell the whole story either about the lens performance or about the pictorial quality of the photograph. Resolution data do reveal certain information obtained under a special set of conditions, and they may serve well for determining the suitability of a lens for a specific application; they do not necessarily provide an entirely reliable basis for judging the "over-all quality" of a lens. We can hardly ever hope to define and measure the "over-all quality" because of the extreme complexity of all the factors involved.

Astronomers, who more than anybody else have been concerned about resolution and image quality of their optical systems, know all the enumerated facts very well, and they are not surprised when a telescope excellently suitable for recording double stars (a high resolution of a high-contrast object) does not produce a satisfactory picture of the moon (a low contrast object).

To evaluate a lens, a number of elaborate tests are needed and plenty of experience as well as a lot of common sense. In general pictorial work, the photographer should not rely exclusively on any set of analytical data, including the data on resolving power, but he should develop and use his ability to evaluate the general quality of the picture produced by a given lens. After all, if he is satisfied with the picture, it is hardly of much importance whether the peripheral resolution is 15, or 20, or any other number of lines per millimeter, especially considering the fact that a lens may yield a relatively high resolution when tested with a schematic target and a special emulsion, and still fail to produce entirely satisfactory pictures because of some deterioration in detail contrast and shape.

Photography is not only a science but also an art. Even with lenses of old designs photographers were able to produce extremely satisfactory pictures. With the excellently corrected lenses now generally available, the photographer will hardly ever find a situation where the lens becomes a factor which prevents him from producing a good picture of a high artistic or human value.

Special Resolution Requirements, Particularly for Aerial Photography

Many statements made in the preceding text cease to be valid whenever we deal with special photographic work whose primary purpose is to obtain detailed information about the object. An outstanding example of such special application is aerial photography for reconnaissance and mapping. Here it is hardly of much significance whether the photograph produces a pleasing impression and has an esthetic value as long as it reveals all the information needed. In peace and in war time, the purpose of aerial photography is to record the data available on the ground. Especially in war time, it is of paramount importance for intelligence to obtain all possible information about the enemy territory. Statements have been made[11] that during the last conflict 60–80% of all the information needed for military purposes was secured by means of aerial photography.

Such information cannot be obtained unless the photograph reveals abundance of detail. Since lens-film resolution is the primary factor determining photographic detail, the main emphasis in aerial photography should be put on the resolution requirements, disregarding some special cases, not under discussion here, in which distortion requirements may be of relatively greater importance.

Accepting these statements as the basis for further discussion, we immediately find an answer to some of the difficult questions asked previously. Shall we prefer the highest resolution with a lower detail contrast, or a high detail contrast with impaired resolution? Shall we focus a lens to obtain the maximum axial resolution, or choose a compromise focus with an improved zonal and peripheral resolution? How to judge the "over-all quality" of a lens? The

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[11] Dunham, Theodore, "*Present Problems in Aerial Photography*" Paper delivered at the opening of the Boston University Optical Research Laboratory, December 13, 1946.

answer is obvious: for aerial photography the best lens and the best focusing are those that yield the highest average resolution within the specified image area on a given emulsion.

How high should this resolution be? As high as possible! In this respect, there is really no limit to our wishes, particularly when we deal with military applications as then even one per cent of additional information may mean victory instead of defeat. Still we should realize that aerial photography never can reveal everything that is available on the ground, and, consequently, we should formulate some reasonable, even if somewhat optimistic, resolution criterion. An attempt to formulate a criterion for the general-purpose photography has been made earlier in the text. It was based on the limiting angular resolution of the eye. Considering the fact that lenses of longer focal lengths are capable of higher than one-minute resolution, that all our modern instrumentation essentially serves us for obtaining more data than are directly perceived by our senses, and that we are primarily interested in physical detail on the ground and not in the angle it subtends from a certain altitude, the one-minute resolution criterion should be superseded by a more specific and perhaps a stricter requirement.

During the war the general public was quite impressed by the ability of aerial lenses to record railroad ties from relatively high altitudes. I doubt that recording of railroad ties is of much civil or military value. Still, railroad ties are the only target on the ground which is almost generally available and which is very similar to the line targets used in photographic laboratories for resolution testing. Considering also the fact that, when photographed from high altitudes, they represent a rather fine detail, it may be reasonable to accept railroad ties as a "natural" test target on the ground and to use their dimensions for the establishment of a resolution criterion for aerial photography.

The average width and spacing of railroad ties are each about 10 inches. Consequently they form a ground target with "resolution lines" 20 inches wide, i.e., a target with 0.002 line per millimeter. In order to resolve this target on a photograph taken from an altitude of H feet with a lens of the focal length of f inches, we need a lens-film resolution (R_n in lines per millimeter) as given by the following formula:

$$R_n = 0.024 \frac{H}{f} \cdot \tag{2}$$

We should emphasize that this formula, represented graphically in Figure 9, only gives us the idea as to what lens-film resolution would be needed if we are to obtain a distinct photographic record of railroad ties; it does not, however, reveal any information as to what resolution may be actually obtained with a given lens and a given emulsion.

It may be of interest to note, that on the basis of about one minute resolution limit, and disregarding any factors (such as the extremely low target contrast) affecting visibility of ground detail, the maximum altitude from which the eye still can resolve railroad ties, is somewhat greater than 5,000 feet. This is perhaps an optimistic estimate of the visibility with an average eye under average atmospheric conditions. It does give us, however, a relative measure of merit for aerial photography. A photograph taken from 5,000 feet and revealing railroad ties contains as much detail as can be perceived visually from this altitude. A photograph with railroad ties resolved from a higher altitude is "better than the eye"; it contains more detail than is available visually—in direct proportion to the ratio of the actual flight altitude to 5,000 feet.

ESTIMATES OF PROBABLE LENS-FILM RESOLUTION

For a proper utilization of aerial photography and for the development of new photogrammetric procedures, a knowledge of actual resolution that can be obtained under certain conditions is considerably more important than any abstract resolution criteria. As a matter of fact, it would be useless to set any resolution requirements unless some confidence exists that they actually can be met in practice.

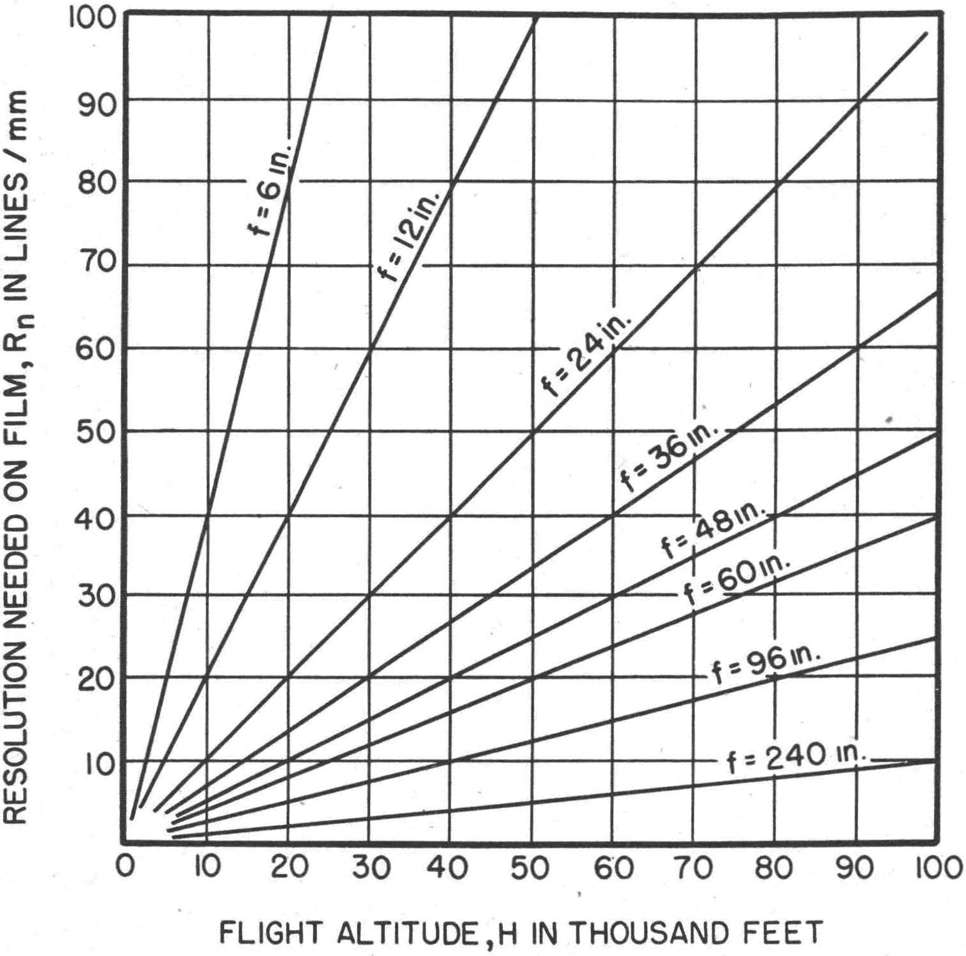

FIG. 9. Resolution needed on film for resolving railroad ties on the ground. The needed resolution is plotted as a function of flight altitude for lenses of different focal lengths.

During the war the problem of lens performance acquired immediate importance, and extensive efforts were made to find satisfactory answers to the following two basic questions. The first: what lens is the best suited for a given purpose? The second: what resolution is to be expected from a lens and an emulsion of some known characteristics?

Large research groups were set up in this country as well as in England and Canada who concentrated their activities on the problems of aerial photography.

The results of this research are now being slowly made generally available. Unfortunately, there is as yet no over-all summary of the American work, although the results of some investigations have been published,[12] and a number of reports have been already released (on microfilm) through the U. S. Department of Commerce. It takes some time to obtain copies of these reports, and my order for those that may be of great interest in this discussion has not yet been filled. This is why I have to rely almost exclusively on the well summarized Canadian[13] and British[14] work.

Considering the relative simplicity of visual resolution tests, serious attempts have been made to obtain quantitative correlation between visual and photographic resolution of lenses. All these attempts have failed. This does not mean that all visual tests on photographic lenses have no value and should be entirely discarded. On the contrary, they have been, and will remain, most useful for optical designers and inspectors.

Optical designers utilize visual measurements of aberrations to verify the computed results and ascertain the proper execution of a sample. As long as the computation of aberrations remains the primary tool of lens design, visual measurements will continue to be the main source of analytical information of direct importance to the designer. Since the information of this kind cannot be obtained from data on photographic resolution, their main value for the optical designer lies in the fact that they serve as a stamp of final approval or disapproval for the designer's ideas as to what distribution of residual aberrations should be considered the most favorable for securing a satisfactory photographic resolution.

In optical inspection, visual observations of lens performance characteristics, including its resolution, serve excellently for maintaining a certain standard of quality. I venture to state that, as soon as a certain empirical correlation is established between the visual and photographic performance of a given formula, actual inspection of production lots may be based entirely on visual tests, unless some extremely critical photographic requirements are to be met. In the latter case there may be no other recourse but to use the cumbersome photographic testing in order to secure the best result.

The fundamental causes, responsible for the lack of a simple relationship between visual and photographic resolution of lenses, are found in the radically different characteristics of the human eye and photographic emulsions. As compared with common panchromatic emulsions, the contrast sensitivity of the eye is many times higher, while its spectral sensitivity is confined to a narrower band with the maximum in the green-yellow region. Hence, while observing a deteriorated aerial image of a resolution pattern, the eye may disregard unfavorable effects of deep blue and red light, and, by picking up very small brightness differences, resolve the pattern, which cannot be resolved on a photographic emulsion. Generally, the eye conveys very optimistic information with regard to the resolution capabilities of a lens, and it is apt to minimize the detrimental effects of the residual monochromatic and chromatic aberrations. This is why with well corrected lenses visual observations almost generally yield considerably higher resolution values than those that can be obtained even on special emulsions of extremely high resolving power. Particularly on the axis and with the targets of higher contrast, visual resolution even of relatively fast lenses

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[12] Washer, Francis E., "*Region of Usable Imagery in Airplane-Camera Lenses*," Journal of Research of the National Bureau of Standards, Vol. 34, No. 2, RP 1636, pp. 175–197, 1945.

[13] Howlett, *loc. cit.*, pp. 15–40.

[14] Selwyn and Tearle, *loc. cit.*, pp. 493–524.

usually reaches the theoretical limits determined by the curve of Figure 2, and the curve is closely followed as the lens is stopped down. Yet photographic resolution of a wide open lens practically never approaches the theoretical limit, and for relatively fast lenses it increases as the lens is stopped down, reaching a maximum at a certain stop. According to the British data this critical stop usually lies somewhere between *f*/8 and *f*/22.

The British have conducted extensive investigations in order to utilize visual resolution data and some theoretical relationships for determining the photographic resolution. Finally they gave up, and they came out in favor of an empirical approach. By surveying a large number of lenses (of British, American and German makes), whose focal lengths ranged from 5 to 49 inches and *f*-numbers from 2.9 to 7.0, they were able to discover certain regularities in the photographic performances of lenses, and finally to derive the following formula[15] expressing the probable average resolution for a lens-emulsion combination.

$$R_p = \left(\frac{207}{fG}\right)^{1/2}\left(\frac{\text{F. No.}}{\tan^2\alpha}\right)^{0.3} \tag{3}$$

where: R_p is the probable resolution in lines per millimeter averaged within a given image area;

f is the focal length of the lens in inches;

F. No. is the *f*-number, i.e., the quotient of the focal length divided by the entrance pupil diameter of the lens;

α is the half-angular field in degrees, corresponding to the given image area;

G is a "granularity factor" characteristic of the given emulsion for a given image density.

The G values at a density of 1.0 are listed in the following table.

TABLE 1. GRANULARITY VALUES, G, AT A DENSITY OF 1.0

Emulsion (film):	Aero Super XX	Panatomic X	Microfilm
G-value:	1.6	1.2	0.3

This is apparently the only formula available in optical literature that permits a relatively good estimate of the resolution obtainable with a given lens and emulsion. It should be emphasized, however, that this formula was derived from an analysis of the British experimental data with the Cobb type target of 1.6:1 contrast ratio. It may not be universally valid for other targets and other emulsions. As a matter of fact for targets of high contrast the previously mentioned correlation factor (i.e., the ratio of the resolution obtainable with a high-contrast target to that obtainable with the low-contrast target) somewhat smaller than 2 seems to be indicated. Even this correlation may be misleading because it implies that a lens-film combination giving, with a low-contrast target, a higher resolution than another combination, should give a higher resolution also with a high-contrast target. Actually, however, it was demonstrated by some British experiments that relative rating of lenses even with the same emulsion may be reversed as the target form or contrast is changed.

The most interesting fact is that the British formula does not contain any factors (besides the focal length, the *f*-number and the field angle) pertaining to the lens design, its "quality," or the manufacturer. This may be surprising to

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[15] Selwyn and Tearle: *Loc. cit.*, p. 523.

those who are never satisfied with a lens from a given manufacturer and suspect that somebody else, particularly "abroad," should be able to offer a better lens.

The implication of the British formula is that in our era the design staffs of all well established optical manufacturers have nearly the same ideas as to how a good lens should be designed and that in their work they are capable of attaining about an equal degree of perfection. There is nothing astonishing in this, considering the fact that optical design is not a secret magic but a generally known science, and that the perfection of a formula mainly reflects the amount of time and the intensity of effort allocated to its development. This does not mean that the capabilities and intuitions of all optical scientists are equal, or that all lenses are equally good. Indeed, even allowing for some uncertainties of the experimentation, the British have found, on the basis of their criteria, that some lenses should be judged as somewhat better than others. The value of the British formula is not that it reveals an ultimate limit of photographic performance but that it establishes a certain reference standard for photographic optics of this time.

In this connection it may be of interest to refer to a report (OSRD 3629) on "Tests of Aerial Camera Lenses" issued by the Mount Wilson Observatory in March, 1944. I have not received this report as yet, and have to quote from an abstract.[16] The pertinent quotation is: "All of the lenses tested have a resolution for high contrast targets which greatly exceeds that of ordinary emulsions used in aerial photography. Lens design and manufacture is so well advanced that, among the factors which limit the resolution obtained in aerial photography, the design of the lens is of secondary importance." This is perhaps a too optimistic statement. Nevertheless, it is highly indicative of the actual situation.

Considering the fact that the most frequently used aerial emulsion is Aero Super XX, that the common aerial negative size is 9 in.×9 in., and that 90° coverage may be of particular interest to photogrammetrists, the basic resolution formula may be broken into the following two more convenient formulas. Probable resolution in lines/mm on Aero Super XX:

For 9″ × 9″ coverage: $R_p = 3.75\ (\text{F. No.})^{0.3} f^{0.1}$ (4)

For 90° coverage: $R_p = 11.37\ (\text{F. No.})^{0.3} f^{-0.5}.$ (5)

These formulas indicate the probable resolution on Aero Super XX film, obtainable with lenses of various focal lengths and at various speeds (f-numbers). As useful as they are, they do not provide direct information often needed in aerial photography as to what lens would reveal more ground detail from a given flight altitude.

To answer this question we may utilize the following relationship between the resolution (R_r) actually recorded in the negative and the corresponding resolution R_g on the ground,

$$R_g = \frac{R_r f}{H} \tag{6}$$

where all the quantities should be expressed in congruent units.

We notice that for a given flight altitude, the ground resolution is directly proportional to $R_r f$. That is why the British and Canadians frequently use this product, under the name of "ground resolution," to denote the relative merit of

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[16] U. S. Department of Commerce, "*Bibliography of Scientific and Industrial Reports*," Vol. 2, No. 3, PB 28542, p. 218, 1946.

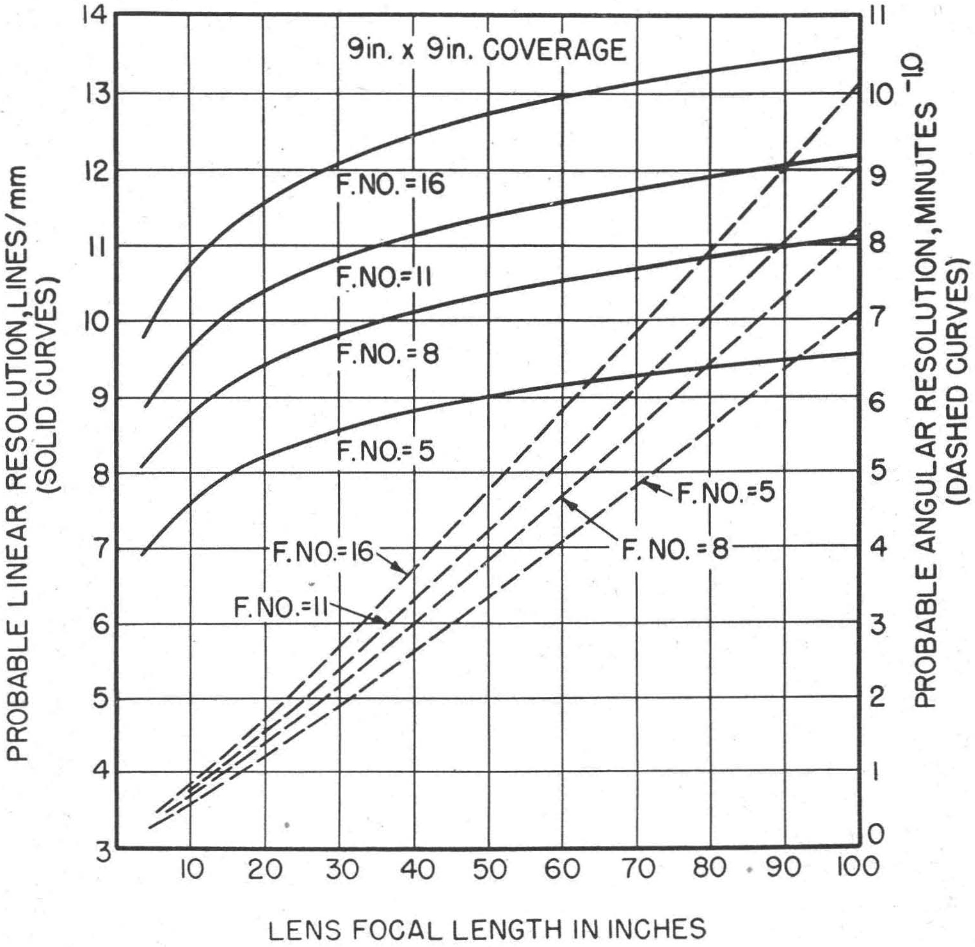

FIG. 10. Probable average resolution within 9 in. ×9 in. coverage on Aero Super XX film. Computed from the British formula for the Cobb target of 1.6:1 contrast ratio.

a lens for aerial photography. Actually, this product is nothing else but the reciprocal value of the resolution angle, equivalent to the linear resolution recorded on the film. It will be denoted in this paper by A, and used under the name of angular resolution.

Now, by using obvious transformations, we may write the following expressions for the probable angular resolution A_P

Probable angular resolution in minutes$^{-1.0}$ on Aero Super XX:

For 9″ × 9″ coverage: $A_p = 0.028\ (\text{F. No.})^{0.3} f^{1.1}$ (7)

For 90° coverage: $A_p = 0.084\ (\text{F. No.})^{0.3} f^{0.5}$. (8)

A graphical representation of these two and of the two preceding resolution formulas is given in Figure 10 and Figure 11. It should be emphasized here that these formulas do not represent an unimpeachable law of physics, but only reflect a certain statistical deduction made by the British from a relatively limited experimental material. The fact that the focal lengths investigated by the British ranged only up to 49″, hardly makes reasonable our extending the curves up to 100″. The only justification for this extension is that it may indicate the correct trend and that it may establish some reference values to be verified by future experimentation.

It may be noted that within a somewhat more limited experimentation (a smaller number of lenses of focal lengths from 6 to 40″ and f-numbers from 4 to 8), and using somewhat different procedures, the Canadians obtained results very similar to the British. Although they have not derived an explicit resolution formula and their representation of the experimental data is significantly different from the British, they arrived at essentially the same standard of the present quality. Thus for *f*/6.3 lenses (6″ to 40″) and 9″×9″ coverage on Aero Super XX, they indicated a resolution standard of about 9.5 lines/mm with

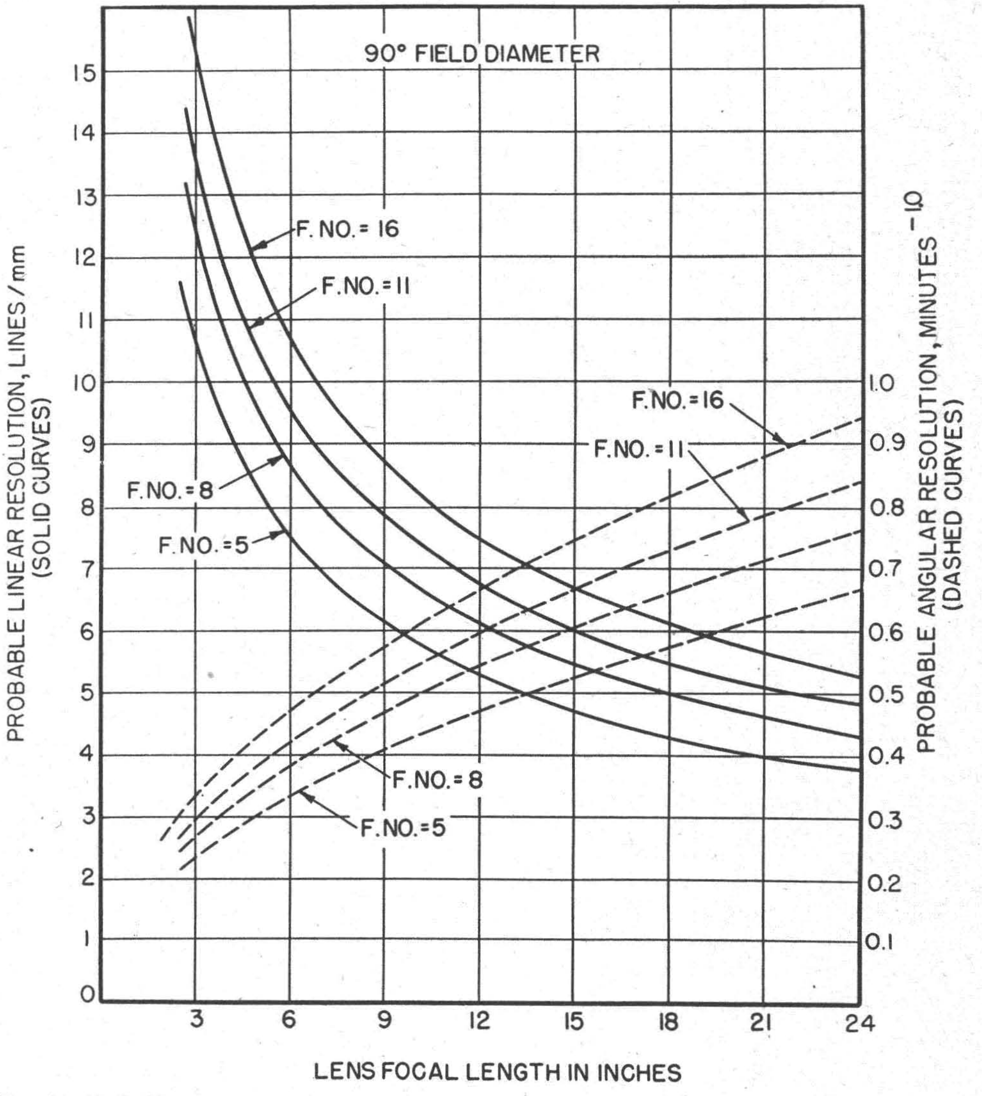

FIG. 11. Probable average resolution within 90° coverage on Aero Super XX film. Computed from the British formula for the Cobb target of 1.6:1 contrast ratio.

the Cobb target and of about 7.5 lines/mm with the annulus target. These values are not too far from the mean value of 8.6 lines/mm that is obtained, for the same region of focal lengths, from the British formula. The Canadians have suggested also an improved standard nearly 1.5 times higher than the present.

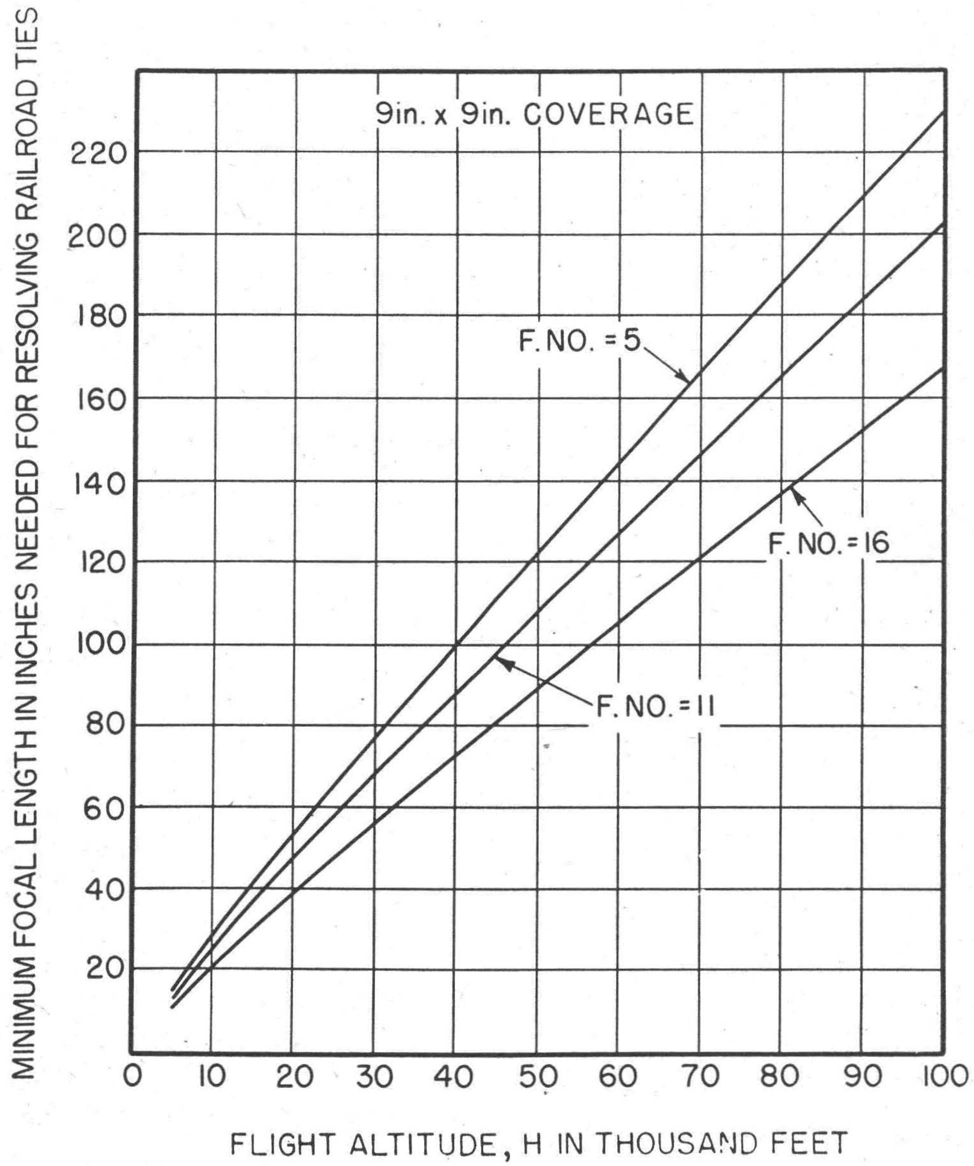

FIG. 12. Minimum focal length needed for resolving railroad ties within 9 in.×9 in. coverage on Aero Super XX film. The curves are derived by combining the British formula with the "railroad-tie" criterion.

Figure 10 and particularly Figure 11 dramatically reveal why lenses of longer focal length are more suitable for high altitude photography. Indeed, while for 9″×9″ coverage the linear resolution in lines/mm on the film becomes almost stationary for longer focal lengths, the angular resolution (i.e., the lens-film capability to resolve ground detail) rapidly increases with the focal length. For the 90° coverage, the angular resolution also increases with the focal length, despite the rapid decrease of the linear resolution.

These results should not be interpreted too optimistically for any photogrammetric procedures involving additional optical processing (photographic copying, reducing, enlarging, projecting, etc.), as it may significantly impair or even nullify the initial gains secured on the aerial negative.

Using the formulas predicting the probable lens-film resolution and combining them with the formulas, such as the "visual resolution" formula (1) or the "railroad-tie resolution" formula (2), which specify our resolution requirements, we may derive relationships that would indicate what lenses should be most suitable for a given purpose.

For example, if we are interested to find with what focal length we can secure ample detail on 9″×9″ aerial negatives taken from a certain altitude, we will combine formulas (2) and (4). Indeed, if the desirable resolution is R_n and the probable resolution is R_P, satisfactory results will be obtained if R_P is equal to or greater than R_n. Hence:

$$3.75\,(\text{F. No.})^{0.3}f^{0.1} \geqq 0.024\,\frac{H}{f}\,.$$

From which:

$$f \geqq 0.011\,(\text{F. No.})^{-0.27}H^{0.91} \tag{9}$$

where: f is the lens focal length in inches;
F. No. is the lens f-number;
H is the flight altitude in feet.

The sign of equality in formula (9) obviously identifies the minimum focal length needed to resolve railroad ties from an altitude H. This relationship is represented in Figure 12. It establishes rather stringent requirements and indicates that lenses of longer focal lengths are needed even for relatively low flight altitudes. We should realize, of course, that the basic requirement (the resolution of railroad ties) is rather strict in itself, and that for some photogrammetric applications abundance of detail may be to a certain extent sacrificed, particularly if some other advantages are to be gained by utilizing lenses of shorter focal lengths than those indicated in Figure 12.

The British data and the formulas derived from them are based on laboratory experimentation; they should be taken with some reservations when applied to actual aerial photography. There are many factors (camera vibrations, relative motion of the aircraft with respect to the ground, atmospheric haze, etc.) which tend to reduce the laboratory estimates of the attainable resolution. Some available data indicate that under average conditions of aerial photography only 60% of the laboratory resolution can be secured, while under more favorable conditions the laboratory limits may be reached.

Further extensive experimentation in the laboratory and in the air is needed to verify any deductions that may be indicated in this paper, particularly those that pertain to photography with lenses of longer focal lengths and to photography from high altitudes.

None of the statements and formulas discussed in this paper have an absolute validity. The purpose of this representation was to summarize the most important facts pertaining to photographic resolution and to establish a tentative (and perhaps relatively reliable) basis which may provide at least some answers to some questions of interest to photographers and to photogrammetrists. Only future work will reveal whether or not the establishment of this basis was of any real value.

RESOLUTION (END)

President Sanders: I am sure that every one of us feels, as I do, a considerable indebtedness to Dr. Pestrecov for the material that he has presented here today. It has truly been educational, and I think it is the type of information that we can use to good advantage. It is the kind of subject that could have been extremely difficult and dry, but Dr. Pestrecov's ability to ring in a little humor at the right time has certainly made it extremely palatable. We thank you Dr. Pestrecov.

You all know that the isolationist theory is a thing of the past in a political sense. In this Society we have never been isolationists in a scientific sense. As a matter of fact, we have in our membership a man who is a real ambassador of scientific good will wherever mapping and surveying are involved. The efficacy of this peripatetic individual is aided by his unusual linguistic ability, of which we have been permitted to take advantage on many occasions.

Our speaker, Dr. Andre Simonpietri, is Special Adviser on Cartographic Matters to the Department of State. He is also traveling Secretary of the Commission on Cartography for the Pan American Institute of Geography and History. In this capacity he has attended three Pan American consultations, one here in Washington, one in Rio de Janeiro, Brazil, and one in Caracas, Venezuela. In each of those he was a person of considerable importance and was depended on greatly. In my attendance at one of them I was extremely proud to see a representative of our Society taking such an active part in such a widespread function.

Dr. Simonpietri was educated here in the United States and in Europe. He is a member of many professional societies outside of the United States, in such countries as Mexico, Peru, Uruguay, Bolivia, Ecuador, and probably others with which I am not familiar. So you see, Dr. Simonpietri is excellently equipped to speak to us today on his subject, The Future of Mapping in the Americas. Dr. Simonpietri.

Dr. Andre Simonpietri: Thank you, Mr. President.

Ladies and Gentlemen: The title of this talk was suggested by President FitzGerald, the idea being to attempt to fill in with the general idea of mapping in the Americas, since we had heard from Mexico through General Quintanilla and Mr. Vaca and from Canada through Mr. Carroll, and to carry the international phase of it a bit farther than North America, we had a paper from Venezuela and the very interesting talk of Mr. Staub of Switzerland. So, when this was suggested to me, it seemed to me quite a good idea.

I asked him, "What particular phase of mapping. Photogrammetry?"

"No, just mapping in general."

North America has been covered. That leaves Central and South America. I did a bit of mathematical calculation on that, and I figured there were roughly five or six different types of maps and mapping operations that you could talk about—geodetic operations, topographic maps, aeronautical charts, hydrographic charts, and special use maps, geological or soil conservation, whatever you want to call them. There are about five different phases of each of those about which you could talk. That makes twenty-five. There are at least twenty countries involved. That makes five hundred. There are about five agencies in each country interested in this subject. That makes twenty-five hundred. Taking a minute to cover each particular point, we would be here quite a