CALIBRATION OF SURVEY CAMERAS AND LENS TESTING*

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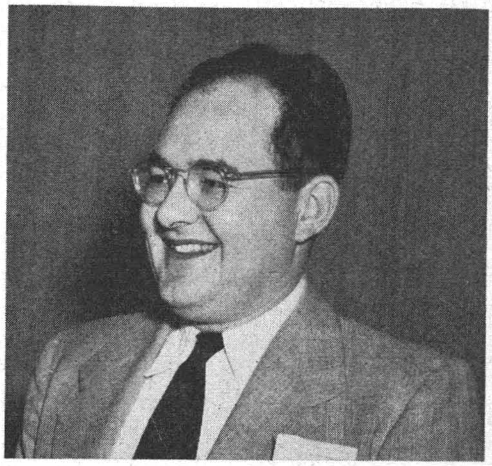
MY ROLE is to present a survey of camera calibration and lens resolution test procedures as related to the field of photogrammetry. The tone of this paper is dictated by the fact that it is to serve as an introduction for the panel forum that has for its topic, "Cameras, Lenses and Calibration." At that time, papers and discussions will cover many phases of this topic.

It is most appropriate to consider these subjects in forum discussion at this time. The Sixth Congress of Photogrammetry in 1948 passed resolutions directing Captain Reading to draft a proposal for International Photogrammetric Lens Tests for consideration for adoption by the Seventh Congress to be held in 1952. The products of this forum can and should aid in this formulation.



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As a result of conferences and correspondence, Captain Reading has been able to list several points for which he has found general agreement, these points to serve as a test format. Two of them merit mention here:

a. The test should reveal any differences in lens performances that are of significance in photogrammetry. (This might well be extended in the case of calibration to include the performance of the lens-cone combination.)
b. All the conditions of the tests should duplicate those used for photogrammetric photography as nearly as possible.

These, then, certainly establish a clear and logical objective. The philosophy is applicable to any test program—testing in terms of the performance under the conditions (usually simulated) of operation.

The purpose of an aerial photographic survey is to gather information about the terrain and about ground objects in a distortionless perspective. Camera calibration, as generally considered, relates to two aspects. First, in terms of the quantity of information or the number of details the system can record: this is generally taken to be some function of the resolution passed by the lens emulsion system. This aspect is of primary interest in reconnaissance photography. Second, in terms of the accuracy with which the position and the separation between ground points can be determined: this is generally taken to be some function of the distortion characteristic of the lens-cone-emulsion combination in conjunction with the dimensional stability of the photographic materials and, indeed, the accuracy of the camera calibration itself. This aspect is of primary interest in photogrammetric photography.

* Paper read at Seventeenth Annual Meeting of the Society, Hôtel Shoreham, Washington, D. C., January 10 to 12, 1951.

The experimental work referred to in the paper has been conducted at the Boston University Optical Research Laboratory under contract with the Wright Field Photographic Laboratory of the Air Research and Development Command.

The most direct method for the calibration of the lens, camera, and photographic material combination is to photograph with the lens in the camera, using the photographic material that is to be employed in practice.* In this method the photograph might be of a grid or a star field with points of known angular separations. This target, located some considerable distance from the lens, must cover the field of the camera. (Resolution targets should also be located over the field.) Although this method offers the simplicity of the direct approach, the very dimensions involved preclude its general laboratory usage. However, Sewell[1] has described a method that operates on the basis of this direct philosophy, and is employed by the Corps of Engineers as a field calibration method. And indeed similar methods are employed in many countries as field methods. Merritt[2] has treated methods and problems of field calibration in the preceding paper and no further elaboration is required here.

There are several installations where calibration has been reduced to laboratory procedure. Probably the newest and most elaborate instrument now in use is the new calibrator at the National Bureau of Standards. This calibration instrument contains twenty-five collimators which, in effect, locate a grid reference marker and a resolution target at infinity, for the axial bundle as well as for every 7.5 degree position along the plate diagonals. This equipment has been completely described by Washer and Case.[3] A similar calibration instrument described in PHOTOGRAMMETRIC ENGINEERING, Vol. XVI, No. 5, pp. 686–695, is now nearly ready for operation at the Fairchild Camera and Instrument Corporation. The expressed purpose of this new commercial installation is to relieve the National Bureau of Standards from the routine task of calibration of field instruments, so that it may revert to the role of establishing and maintaining the standards of calibration without performing the routine mass calibration functions.

Some modifications of the above methods do exist, which consist primarily of moving the camera through fixed angles with a single-target or single collimator, or moving a single collimator through a series of fixed angular positions.

It now seems in order to review the tasks in calibration. They include the determination of the focal-length of the objective, the location of the principal point with respect to an indicated position, the distortion of the image over the field, and the resolution of the lens-film combination.

The field position of a point on a photograph is referenced by the fiducial marks. The coordinate position of the intersection of the fiducial markers, and the relation of the lines joining opposite pairs of markers to a normal XY coordinate system, is thus of importance. In essence, it serves to reference the calibrated characteristics to the picture. The method of evaluating this aspect, the basic coordinate system of the picture format, is straightforward.

The equivalent focal-length is determined by comparator measures of the distance on the emulsion between the images of pairs of grid points lying near the optical axis, and separated by known and small angles. The equivalent focal-length is taken to be the distance measured on the plate divided by the tangent of the angle between the points. Similar treatment of pairs of grid points over the field results in the evaluation of the focal-length at the different field angles. Differences in focal-length from one field position to another result in a changing scale over the picture format. This manifests itself by radial displacement of image points from ideal positions. The radial displacement of the observed image point from the ideal image point is termed the radial distortion at that

* An excellent statement involving the philosophies of calibration is that by Howlett appearing in PHOTOGRAMMETRIC ENGINEERING, Vol. XVI, No. 1, pp. 41–46.

point. In practice these distortion values are adjusted, so that the maximum positive (displacement away from the center) and maximum negative distortions are made equal. The focal-length that is so chosen to provide this convenience is termed the "calibrated focal-length of the mapping camera." This concept is now in general use, although it is recognized that a weighting of the positive and negative radial distortions in terms of plate area might be more compatible with practice.

Those displacements of the image in a direction normal to the radial displacements are termed tangential distortions. These are attributed to the failure of the optical system to present in practice its theoretical symmetry about the optic axis. These are therefore asymmetric. These distortions are observed and evaluated by such devices as taking a picture, rotating the photographic plate through 180° with respect to a symmetric target array, and taking a second picture on the same plate.

The principal point has been defined in several ways. The one most generally accepted today is that point where rays perpendicular to the emulsion surface in the object space form an image on the emulsion. Roelofs[4] has recently proposed adoption of a calibrated principal point. This concept is based on the argument that as the calibrated focal-length is employed to adjust the magnitude of the radial distortion, so a calibrated principal point can be employed to adjust for the symmetry (or to minimize asymmetry) of the distortion pattern. Inasmuch as the argument is presented entirely from a realistic, operational viewpoint, the suggestion appears to merit the most careful attention.

We now come to the resolution aspects of the camera calibration task. There are many excellent types of resolution targets in use today—employing different shapes, orientations and groupings of objects—different contrasts of pattern. Each target has its proponents who present sound and logical reason for its use. In all cases an advantage of rating lens performance in terms of a resolution score as determined from a target lies in the simplicity of the method of assessment.* However, a disadvantage of using a resolution score, as determined from any target image, for an assessment of the ability of a lens to perform an operation, lies in the fact that the task presented to the lens is in general not similar to the task as presented in practice. In the case of aerial photography, the lens is called upon to view details of various shapes, sizes, and orientations, occurring at regular intervals, random intervals, and as isolated detail units, each distributed over a range of contrasts. No target attempts to consider all these factors and one must, in his choice of target at the present time, attempt to achieve the best approximation to practice by a judicious weighing of these factors.

It is perhaps in order to view the task presented to the lens-emulsion system in practice, and to see how the system solves this task.

Consider the laboratory test of a "perfect" lens. A picture was made on Super-XX emulsion of a high-contrast three-line resolution target. Figure 1 shows the relative contrast measured on the negative as a function of the image spacing. Contrast here used is $(T_B - T_L)/T_L$ where T_B is the transmission through the background, T_L the transmission through the line image. Figure 2 is essentially the reciprocal plot taken from Figure 1. It shows the relative contrast that would be required in the object space $(R_L - R_B)/R_B$ (where R_L is line reflectivity; R_B background reflectivity) as a function of the imaged line-

* In view of present test proposals, a word of caution seems in order. The use of multiple contrast targets may well tend to confuse the issue of judging relative performances, unless the relative values of the various contrasts are properly weighted in advance.

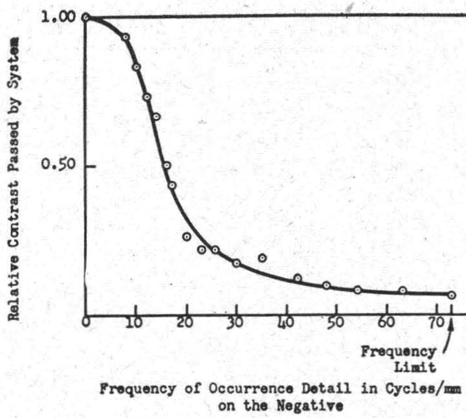

FIG. 1. Relative contrast measured on the negative as a function of the image spacing.

space dimension to just allow the detection of the lines and spaces throughout the range of the target; i.e., each unit of the pattern would be recorded at the visual contrast threshold.* This is seen qualitatively if we consider that the smallest unit (73 lines/mm. in this case) was just resolved, i.e., its contrast was reduced just to the visual detection threshold by the lens emulsion system. Therefore, any lower contrast on the target would have prevented the detection of this unit as a resolved unit, or conversely, the required relative contrast in the target is the contrast which was used. As one goes toward larger lines and spacings, more and more of the inherent contrast is preserved in the image (or less and less is lost), and therefore a lower contrast in the target would permit detection. At the limit on the large end where there is, in this example, negligible contrast reduction, the target need be only at the visual contrast threshold.

Now among the limitations of our example are that it is one of detail occurring at regular frequency (the case of both isolated and random detail is, however, quite similar to that of detail occurring at regular frequency) and that it does not consider a coordinate of exposure level. Bearing in mind these limitations, we will now consider the case of aerial photography. Assume a ground target, made up of details occurring over a range of sizes which occur at regular spacings, and at each size occurring over a range of contrasts. For a series of photographs, let us assume that the probability of any object size from zero to infinity occurring is the same as for any other size, and a relative contrast, from zero to one is as probable as any other relative contrast for any object dimension. This means that the camera is capable of exploring a portion of a detail universe, limited by the angular limit of the system on one hand, and the resolution limit of the system on the other. This is shown in Figure 3 which presents the contrast threshold curve of the system over the range of the system. In a random detail universe, it is clear that the probability of finding detail, near the resolution limit of the system of sufficient contrast to record above the threshold, is indeed small.

* In the case of photography, the visual contrast threshold is modified by a granularity factor, and is therefore itself a function of image size. Grain plays a more prominent role in the obscuration of detail as the detail image becomes smaller, until at the limit, a detail of the size of a single grain cannot be detected except by statistical methods. This in itself suggests some function of the ratio detail size to grain size (i.e., signal: noise) as playing a significant role in aerial and indeed other types of photography.

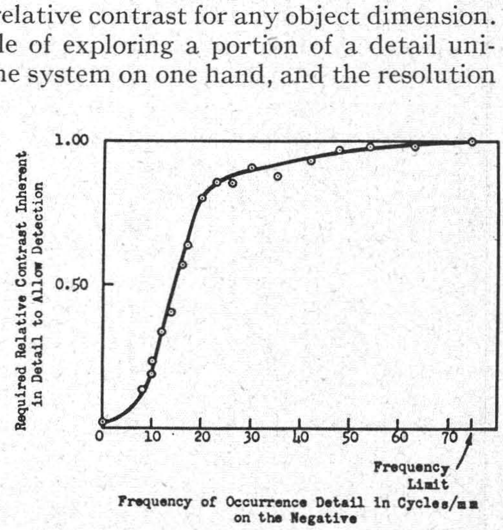

FIG. 2. The relative contrast that would be required in the object space as a function of the image line-space dimension to just allow the detection of lines and spaces.

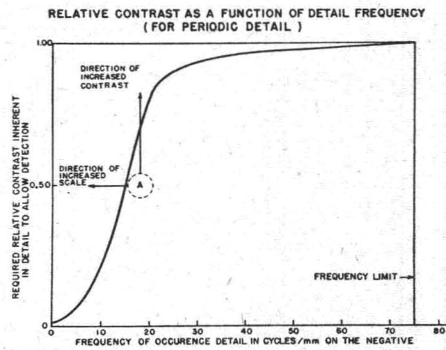

FIG. 3. The contrast threshold curve.

The case of a photograph of quality, that is not quite adequate for a particular job, implies that some details important for the task at hand are submerged below the threshold of the system. Such details are marked "A" in the figure. There are, however, two methods that may be employed to bring them above the threshold. The most common method is to increase the scale of the photography. This translates the details to the left in the diagram, and so moves them above the threshold. The other is to decrease the relative loss of contrast by the lens-emulsion combination, through processing techniques, or use of better lenses, or better focussing. These techniques translate the details up and over the threshold. In any case, the important point appears to be the procurement of sufficient contrast in the image, at any given image size.

For field usage, there is good evidence that the focal setting that provides maximum resolution score in the laboratory on the operational emulsion, is not the setting that gives the best results in actual flight operation. In the task of picture taking, we are interested in the maximum energy that can be packed into a detail unit of the minimum size recorded in the operational performance, that is, the minimum flare condition for the smallest image encountered in practice. Aerial cameras should be focussed with this in mind.

To illustrate, Figure 4 shows laboratory results obtained employing the 6-inch Metrogon lens and Super-XX emulsion. Contrast recorded on the emulsion is plotted as a function of focal settings with detail size, that is selected units of a resolution pattern, as a parameter. A consideration of the shift of the maximum contrast setting for the different image sizes is important. It shows the limitations encountered when setting or judging performance, or focussing for operational performance by a peak resolution setting obtained in the laboratory. In operation, the aerial camera generally achieves some fifty or sixty per cent of laboratory resolution performance. The fact that in many instances aerial haze tends to reduce the object contrast to near marginal conditions lends further import to this view of the contrast reduction by the system.

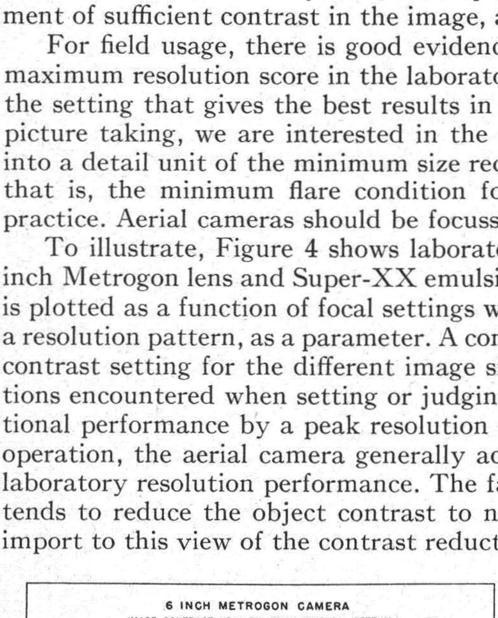

FIG. 4. Image contrast variation with focal length with a 6-inch Metrogon lens and a Super-XX emulsion.

The emphasis that has been placed on the significance of a resolution score in the judgment of relative performance of aerial equipment is probably unjustified, if only because it has tended to obscure other equally important factors. For example, it was assumed that the ability to recognize objects in photographs would serve as a measure of one aspect of photographic quality. Laboratory tests have been made, consistent with this assumption, to evaluate the probability of identifying small squares in a field composed of squares and circles of equal areas.

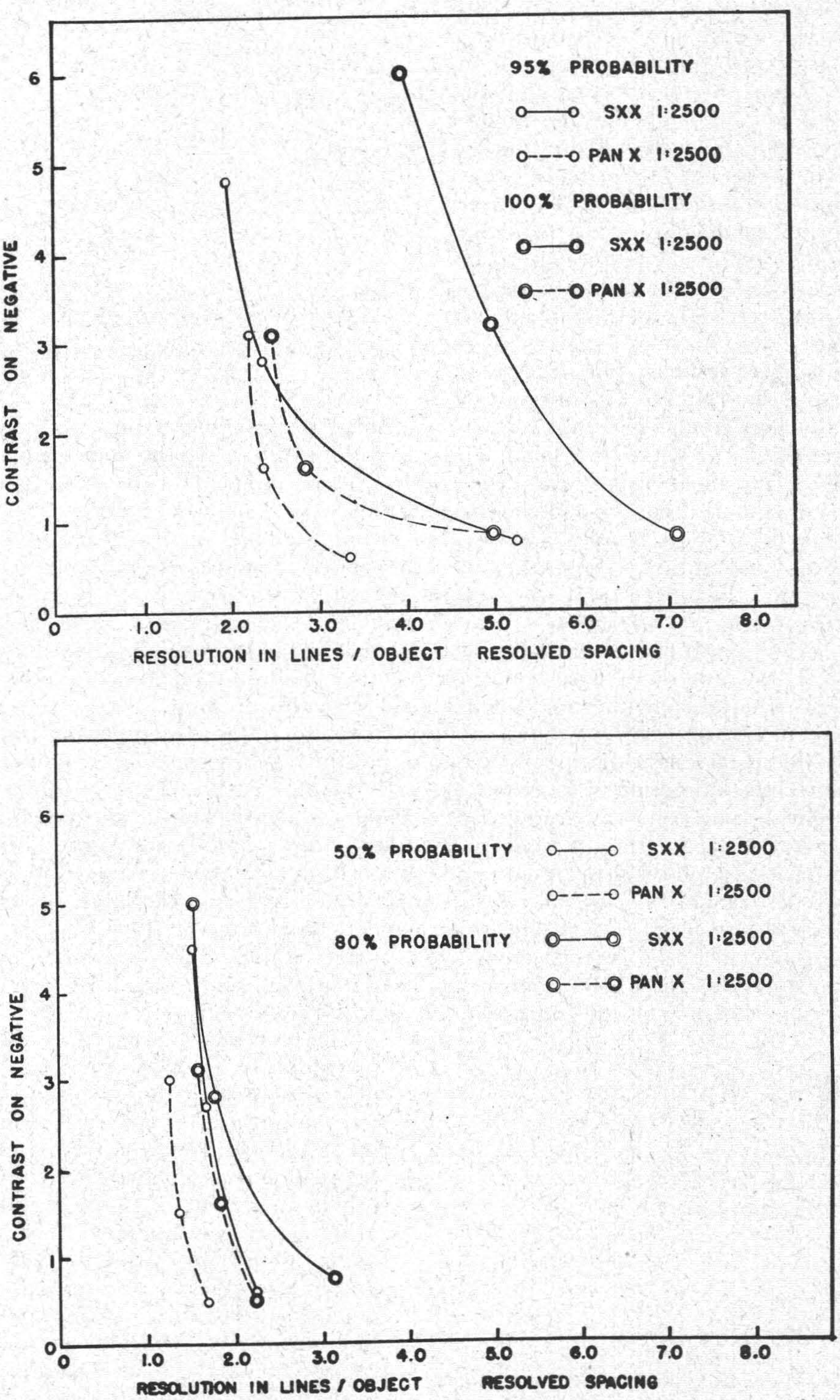

FIG. 5. Contrast as a function of resolution on Pan-X and Super-XX emulsions.

Photographs were made under various scale, resolution and contrast conditions. The comparative results on Pan-X and Super-XX emulsions are shown in Figure 5. This figure plots the contrast in the negative image for a given probability of recognition of detail as a function of resolution, where the resolution is expressed in terms of the detail itself. For example, if 3 lines/object is required to provide the desired recognizability, then 12 lines/mm. is the required resolution if the scale selected is such as to record this object at a dimension of $\frac{1}{4}$ mm. These results point out the magnitude of the importance of granularity in the recognition of photographed detail. The same probability of recognition is obtained on Pan-X emulsion at a combined lower contrast and lower resolution than on Super-XX. This, and similar evidence, has led Katz to suggest that more care and attention must be given to the processing of aerial negatives to minimize the granularity, if more information is desired from the picture. It is of particular interest to note that the difference between emulsions is greater at the lower contrasts, the significant region for aerial photography.

To conclude: The task most commonly encountered in aerial photography is not that of rendering as separate and distinct two small objects located near together, but this is the task encountered in a resolution test. In practice, the problem is generally to separate two areas by rendering the boundary between them detectable. The areas involved vary in size and shape, and relatively few and not necessarily the most important areas for an interpretation job are near the size limit of the system. The ability to detect these boundaries (edges, as Dr. Howlett would say) is entirely a function of the contrast-edge gradient and granularity. (There is obviously a close relationship between resolution and the above function.)

Due to atmospheric haze the object space is dominated by low contrast. It is held that to achieve maximum information, the loss of contrast, introduced by the lens-camera-emulsion system, must be held to a minimum when integrated over that detail universe which the system explores in practice. Thus the contrast reduction function of a lens emulsion system would appear to have a more direct relation to the judgement of the relative field performance of two lenses than does a resolution number, provided that the judgement is to be based on the number of units of detail that the lens will record, and provided that there is a near-random distribution of significant details—both as to size and contrast.

It should be pointed out here that the new resolution target introduced by Dr. Gardner[5] has the unique property of simply assessing this contrast reduction function for the lens emulsion system.

Our major weakness today in the assessment of performance is our lack of knowledge of our target characteristics. Dr. Howlett's work on the statistics of contrast distributions, as observed from the air, is the first step in this direction. When the statistics of targets, such as the distribution of shapes, sizes and contrasts, are at hand, then the formulation of the test of the relative performances of lens-emulsion systems can be placed on an absolute basis.

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