RESOLUTION, DISTORTION AND CALIBRATION OF AIR SURVEY EQUIPMENT*

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INTRODUCTION

A GREAT deal has been said and written about image quality, measurement of distortion and calibration of lenses for air survey operations. However, the lack of uniformity of opinion justifies further discussion of matters of such far reaching importance. It is hoped to present here an approach to the problem which not only is consistently logical but takes full account of the physical phenomena and the practical requirements of the problem. Apologies would be due for the simplicity of the basic thoughts if it were not that so many arguments never could arise if these simple thoughts were generally comprehended and applied. Once the correct fundamentals are accepted, satisfactory detailed arrangements for testing and calibrating automatically suggest themselves.

The function of the aerial photograph is to record details in such a way that they can be identified, and a reconstruction made of the original geometrical relationships between them. The degree to which both of these purposes can be accomplished depends upon a number of things of which the lens is only one. It is most unfortunate that all too often it is stated or inferred in discussions that many of these things can be treated individually when, in fact, they are far from independent. It is not sufficient to say that the lens must be good, and that the photographic material must be good, since there is not absolute standard of quality for one without consideration of the other. It is true that certain assessments which are really dependent on several components can nearly be made on an individual basis, but, unless it is fully realized that only circumstances have made this possible, many serious pitfalls are ahead for the careless thinker. At the same time, there are some characteristics, although not many, that can be judged alone. For instance, the emulsion support should be dimensionally stable, and this quality can be judged against an absoluted standard which permits no dimensional instability under any circumstances.

THE IMPORTANT PHYSICAL CONSIDERATIONS

To understand the problems confronting us, we must review some of the important characteristics of lenses and emulsions as well as other factors contributing to the over-all situation.

Many of our difficulties arise from an inability to design a perfect lens. A perfect lens would reproduce accurately in the focal plane both the detail and the geometry of everything in the object space. Theoretically, the geometry of the details recorded in the focal plane could be correctly maintained, but diffraction would provide a physical limit to the completeness of the record of details, even under the best circumstances. However, in photographic objectives, the limitation of diffraction is not important at the commonly used apertures. The residual aberrations are the dominant consideration. These will work both to destroy detail and the accuracy of geometrical relationships between details. It is not at all necessary to understand the complexities of optical design, in order to make an intelligent appraisal of the nature of the disturbing circumstances. The residual aberrations result from the inability of the designer to make every ray entering the front of the lens, go to exactly the right place in

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the focal plane. What happens when a point source is imaged in the focal plane by a photographic objective is a convenient illustration of the disturbing physical conditions. Ideally we would like such a source to be reproduced exactly in the image space with a correct angular relationship to the optical axis of the system. Unhappily, instead of an Airy disc which is the limiting concentration of energy for a perfect lens we have a larger blob of light having an irregular shape, because of the residual aberrations. Moreover, the size and shape of the blob depends on its position in the field. In general, it will be smaller and more symmetrical at positions closer to the axis, than at positions in the outer parts of the field. The blob will not occupy the correct position with respect to the axis of the lens. The blob has a variety of colours, because it is impossible to bring rays of different colours to exactly the same point. If we had a row of such point sources in the object space, we would have a line image in the focal plane, and from what we have said about the appearance of a point source image, we can easily imagine the appearance of the image of a line made up of a number of such points. One can go further and deduce in general terms the appearance of the edge of an opaque object.

RESOLUTION AND DISTORTION DEFINED FOR PHOTOGRAMMETRIC PURPOSES

We are now in a position to consider resolution and distortion.

So far we have thought of only the distribution of the physical energy made by the lens in the image space. We have found that this distribution of physical energy differs from what it would be for a perfect lens, because of the particular aberrations which have been left by the designer. If we are interested in using the lens to secure technical information, we become very much concerned with how many points or edges can be recorded over the usable area of the photograph. This depends on how closely two such points or edges can be brought together without being so mixed that they cannot be detected as two entities. With the thought of detection, we have introduced the factor which enables us to talk of resolution. In other words, before resolution has meaning, some form of detecting device must be introduced to interpret the physical energy distribution in the image space. The closeness with which two edges or point source images may approach and still appear as two, when both the edges and the point sources are malformed and malcoloured as a result of residual aberrations, must depend upon the physical characteristics of the device used for detecting the energy and the energy distribution in the images. It will *also* depend on the orientation of the points or edges with respect to each other in the field, and the disturbing influence of nearby points or edges. The eye, a photocell, a thermocouple, or a photographic emulsion will not give the same answer on the smallest distance at which two entities can be discerned because their sensitivities to different colours are different. Indeed, different emulsions will give different answers if they have different types of sensitivities. The different contrast sensitivities possessed by two detectors to the same colour will also introduce a difference of interpretation. Resolution is thus a function of at least the lens and the receiving device in the focal plane. Actually, there are other factors which must also be considered such as the colour of source, the shape of the target, and the contrast of the target. It is not difficult to see that if the colour of the light used to form the images were changed, the resolution numbers would also change. These concepts are simple and certainly not open to successful contradiction, but their omission from consideration in discussions of methods of lens assessment has resulted in a great deal of confusion, uncertainty, and disagreement.

Having come thus far with the thought of resolution, it is a simple matter to apply similar logic to measuring the optical distortion characteristics of a piece of equipment. If we have in the object space a number of point sources at infinity which have known angular relationships between them, we can determine the extent of distortion by making measurements on the images of the point sources in the image plane. Again, as with resolution, we have introduced the necessity of having a detecting device, and again the characteristics of the detecting device are going to affect the numerical values of our measurements. Because the images of the point sources are not points but a series of differing asymmetric concentrations of light across the field, their position has become indeterminant within certain limits until the characteristics of the detecting device have been defined. It is not unreasonable to define the location of the images as the place where the centre of gravity of the energy appears to be. However, the position of the apparent centre of gravity depends entirely upon the type of sensitive device used for observing the images. The eye will not necessarily consider the centre of gravity as being at the same place as that selected by a photocell or a photographic emulsion. Different photographic emulsions can give different measures of the distortion under appropriate circumstances. This means that the only safe way of measuring the distortion of a system is to use the energy receiver with which the lens is to be combined in practice, and to reproduce also any other attendant circumstances that might affect the final values. You will note that we have been careful to talk about the distortion of the system rather than the lens, since the distortion which is of importance to photogrammetrists is the one which would be measured under the circumstances equivalent to those prevailing in survey operations. In some cases, the difference between the distortion of the system as appropriately measured and the distortion as measured by some other arrangement, such as a visual method, may be very small and within the acceptable error of measurement so far as the photogrammetry is concerned. This is sufficient to justify the convenience, if any, of the latter method. Nevertheless when such practices are adopted, it must be fully realized that they are logical and acceptable only because, within the accuracy required, they are equivalent to the distortion measured under the exact conditions of use. Until recently, the potential discrepancies may not have been so important to photogrammetrists, but with the present tendency to ask that the final distortion be limited to a few microns, they become of very considerable potential importance. It behooves us therefore to be sure that, in all our testing and assessing, we are striving to measure the quantities in which the photogrammetrist is concerned and not some other characteristic of the system, no matter how interesting the other may be for other purposes.

LABORATORY PROCEDURES FOR MEASURING RESOLUTION AND DISTORTION

The foregoing discussion has shown that the numerical values of resolution and distortion are not inherent characteristics of a lens. Instead they depend not only on the lens but on a number of other factors. It therefore follows clearly that the laboratory procedures set up for determining these two important constants must follow very closely the conditions under which the two constants are involved in practice. However, once the fundamental concept of multi-dependence has been understood and accepted, the detailed procedure for testing and measurement is not likely to be contentious, since it must duplicate adequately the practical condition.

We will now consider the making of the two individual measurements—resolution and distortion.

Most aerial survey operations follow a fairly well established pattern. The photography is done under mean-noon sunlight with a minus-blue filter and Aero Super XX with a particular method of processing. The details on the ground as seen from the air are of low contrast. It can be safely assumed that all pieces of detail are of equal value irrespective of position in the field of view, size, or orientation. The details in the object space are at infinity as far as the lens is concerned. These conditions can be immediately applied in the testing procedure without much risk of argument, except perhaps in the decision as to the type and contrast of target to be used.

In our own laboratory, we have adopted an annulus target for the measurements, because we feel it is the best conventionalization so far suggested of the air task which confronts the lens-emulsion combination. It is a matter of satisfaction, but not of justification, that it is more convenient to use than other types. The case for this type of target has been adequately presented elsewhere (1, 2) and this discussion will not be burdened by its repetition.

English workers suggested a log contrast ratio for the target and its background of .2. Because it seemed reasonable until statistical evidence to the contrary was available, we have so far used this ratio in our work. However, it was important to undertake a statistical survey from the air of the contrast existing between adjoining pieces of detail having a size approximately equivalent to the limit of resolution attained by the average type of equipment. This investigation has been undertaken and P. D. Carman of our laboratory will shortly be reporting the results. Although the final numbers have not yet been established, it is already quite evident that a log contrast ratio of .2 is considerably on the high side. Some sound arguments can be advanced for the use of two targets having different contrasts, if the complexity of such a procedure can be justified by the usefulness of the results. Nevertheless, the higher of the two contrasts should certainly be far lower than that of the high contrast targets which now enjoy such extensive use.

The premise made that all details are of equal importance, irrespective of position, size, and orientation, conveniently establishes a criterion for locating the focal plane. If the premise is reasonable, the focal plane is the one perpendicular to the optical axis of the lens over which the resolving power averaged for area is greatest for the field of view chosen.

We will now turn and examine the effect of the physical characteristics of the optical image, the photographic emulsion and other factors on the determination of distortion and the calibration of the camera.

To be safe, the distortion measurements must be made under mean-noon sunlight modified by a minus-blue filter in the plane of best average resolving power on Aero Super XX processed in the way used in practice. Under certain circumstances, this procedure can be modified without loss of accuracy, but the acceptability of a substitute method must always be justified by its exact equivalence to the rigidly accurate duplication of practical conditions. It is not adequate to justify a substitute set of circumstances by saying that they lead to more reproducible numbers, since there is no merit in reproducibility of values if the values obtained are not a measure of the physical quantity or condition which is of importance. This seems axiomatic, but it is by no means so accepted either in distortion or resolution measurements. It is all too common, for instance, to hear the case argued against low contrast resolution measurements on the basis that it is easier to read and reproduce the high contrast ones. The same argument is used to justify erroneously one form of resolution target in place of another.

SOME COMMENTS ON DISTORTION AND CALIBRATION

It may be of interest to interject here some comments on the term "distortion." The free use of this word in matters which concern photogrammetry is somewhat to be regretted since it has a specific meaning in lens design, and there might be less confusion of thought if its application were so restricted. The substitution of some such phrase as "image displacement" to meet other circumstances has considerable justification. The distortion of which designers talk is a residual aberration in perfectly centred spherical optical systems. It is always radial in distribution. Unfortunately, it is extremely difficult to centre optical systems with the accuracy which is desirable for the more refined photogrammetric operations. As a result of inadequacy of centring, there results a tangential displacement of images in the focal plane. This phenomenon has come to be known as tangential distortion. No great objection can be taken to this expression if its use is insisted upon, but it is regrettable if its use results in the spread of a notion that tangential distortion comes from bad lens design, when in point of fact it results from inadequate workmanship.

The presence of decentring errors in lenses has led to the introduction of time-consuming complexities into calibrating procedures which are unjustifiable because they lead to no useful result. To understand this situation, it is worthwhile to review some considerations which govern the calibration requirements. The photogrammetrist bases his geometry on the principal point. For a perfect lens, this is defined as the point at which the optic axis meets the focal plane, or equivalently the point where the perpendicular from the rear node of the lens meets the focal plane. However, as soon as the lens ceases to be a perfectly centred system, the principal point loses meaning. There is no point on which the geometry of the focal plane is radially symmetrical. Although a point can be chosen for which the distortion of geometry over the field is a minimum, it necessitates an elaborate procedure. For present good quality lenses, the improvement of symmetry attained is very small, in comparison with the great amount of time and work involved. It is far more logical therefore to insist that the lens be centred to an accuracy such that the decentration can be ignored, and the principal point determined by the simple autocollimation procedures which are completely accurate for a centred system. Unfortunately, a certain merit has become attached to the determination of where the principal point would have been had the lens been perfectly centred. The justification of such a procedure has so far escaped us because it is not even the best point of symmetry (3). It is our strong opinion that the lens should be calibrated by simple autocollimation procedures, and a vigorous effort made to reduce the amount of decentration present in photogrammetric lenses. Once a lens possesses any degree of decentration, nothing can be done to produce with it the geometry that would have been produced by a perfectly centred lens except by recentring. Acceptance of compromises always tends to take the emphasis off the really necessitous thing which in this case is the devising of means for more accurately centring and mounting.

The influence of the photographic process on the measurement of distortion is important in all methods of plotting from aerial photographs, but it is somewhat more important in the multiplex process in which an additional lens-emulsion process is involved by the making of a diapositive reduction from the original negative. It can be readily seen from the foregoing that the distortion present in the final multiplex projection is a function of three distortions; that of the original camera system determined photographically, that of the diapositive printer determined photographically, and that of the projection system determined visually. Although it may be a matter of regret to the lens designer, the effective distortion in the final projection of the multiplex system cannot at the present time be predicted by combining the visually measured distortion of the photographic objective, the diapositive printing lens and the projection lens. Inadequate recognition of the influence of the two photographic steps on the distortion has led to a great deal of confused thinking. Unfortunately, the error is nurtured by a long-established tradition that the distortion of the lens is an absolute entity, and that, for attaining over-all accuracy of multiplex equipment it is sufficient if the three visual lens distortions balance when measured with the highest accuracy. Nothing could be farther from the truth. Because the multiplex process includes one more lens-emulsion step than most other mapping procedures, lack of appreciation of the foregoing will handicap the attainment of the highest accuracy of geometry.

CONCLUSION

The salient point of this discussion is the necessity of recognizing that distortion and resolution are not intrinsic properties of lenses, but are complex functions of a variety of variables of which the lens is one, and that consequently laboratory procedures for assessment of distortion and resolution and methods for calibrating photogrammetric equipment must take full cognizance of this fact or their usefulness is absent or limited. The procedures must conventionalize the practical conditions of operation.

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