fore, we can choose $M' = M_2'$, and make the calibrated-distortion-curves also identical. Thus one may in the process of design attempt to secure the identity either of the two characteristic or of the two calibrated-distortion-curves. There is no inherent criterion for a choice between these two alternatives. The lens designer will prefer, however, to use the characteristic-distortion-curves because they are based on the paraxial constants which have to be computed anyway when the optical system is set up and when it is modified in the course of the design. Furthermore, by using the characteristic-distortion-curves, the designer will avoid the additional computations needed for calibration.

If the designer did not succeed in obtaining the identity of two characteristic-distortion-curves, Eq. (16) will not be satisfied throughout the field (it may be, however, satisfied for some image-points). Then Eq. (17) also will not be satisfied throughout the field independently of whether both distortion-curves are calibrated, or one of them is characteristic and the other calibrated. In this case the image produced by the printer will contain some residual distortion. Then by calibrating either one of the compensating curves or the residual distortion-curve, the designer may have a better evaluation of the effective residuals, and he may distribute them favorably. But, as was reasoned before, a calibration will not permit making the compensating curves identical or to eliminate distortion completely.

References

1. Pestrecov, K., "Computation of Distortion of an 'Out-of-Focus Image'." *J. Opt. Soc. Am.*, Vol. 38, No. 7, p. 669, July 1948.
2. Southall, James P. C., "The Principles and Methods of Geometrical Optics," Macmillan Co., New York, pp. 415–417 and 555–557, 1910.
3. Hardy, Arthur C. and Perrin, Fred H., "The Principles of Optics," McGraw-Hill Book Co., Inc., New York, pp. 71–73, 1932.
4. Gardner, Irvine C., "The Significance of the Calibrated Focal Length," PHOTOGRAMMETRIC ENGINEERING, Vol. 10, No. 1, pp. 22–24, January-March 1944.
5. Lewis, James G., "A New Look at Lens Distortion," PHOTOGRAMMETRIC ENGINEERING, Vol. 22, No. 4, pp. 666–673, September, 1956.
6. Military Standard, Photographic Lenses, MIL-STD-150, p. 2, 23 October 1950.
7. Richter, Robert, "Anastigmatic Objective for Photography and Projection," U. S. Patent #2,031,792, February 25, 1936 (Application of July 25, 1934).

*The Future for Photogrammetry and Photo Interpretation**

ROBERT N. COLWELL,
University of California,
Berkeley, Calif.

ONCE Woodrow Wilson was asked if he would give a speech on a particular topic. He replied, "That depends on how long you want me to speak and how much time I'll have in which to prepare my remarks. If it's to be a 15 minute speech, I'll need nearly a week to prepare it; if it's to be a 30-minute speech, I'll need only a day or so to prepare it; but if it's to be a 60-minute speech, I'm ready to give it right now."

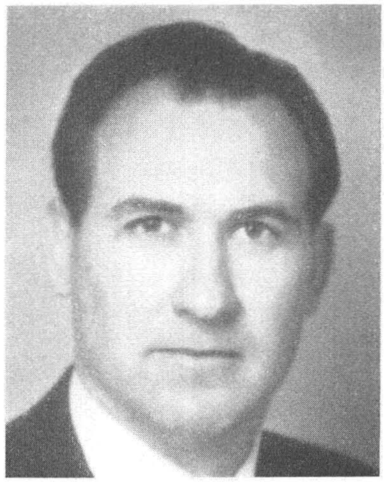
As I've been asked to give a 60-minute speech, I claim readiness to give it "right now," Woodrow Wilson style, without reference to notes or manuscript. I will be doing so, not because of any great ability to speak extemporaneously, but because most of my talk will be given from lantern slides and I never have acquired the ability to read a paper and point to features on the screen simultaneously.

Actually, I abandoned the idea of reading a paper this morning when I learned of the embarrassment which this habit caused a certain minister. As he faced his congregation he reached in his coat pocket for the carefully prepared manuscript of his sermon. Finding to his consternation that he had left it at home he said, "Friends in speaking to you this morning I must rely largely on the Lord for guidance; but I assure you that next Sun-

* Presented at the Society's 25th Annual Meeting, Hotel Shoreham, Washington, D. C. March 8 to 11, 1959.

day I shall be much better prepared." I, too, must rely largely on the Lord for guidance this morning, especially because of the nature of the topic that has been assigned to me; I certainly am not blessed with 20-20 vision when gazing into a crystal ball to predict the future.

My speech has been advertised under the alliterative title, "The Future for Photogrammetry and Photo Interpretation." Since our Society is currently celebrating its first 25 years of progress, I have been asked to speak particularly of the progress we can expect to make in photogrammetry and photo interpretation during the Society's *second* 25 years. In this uncertain world of ours, before one can make a 25-year forecast for *any* form of human endeavor, he first must face a more fundamental issue—the fate of mankind itself during that same period.



ROBERT N. COLWELL

Recently an eminent authority on this subject, Dr. Bertrand Russell, predicted that the next great war will bring about the annihilation of the human race. He seems to have an ever-increasing number of disciples, including the pessimist who says there are just three sizes of atomic bombs, "large," "larger," and "where is everybody?" Dr. Russell's predictions seem the more credible and ominous in the light of recent comments by Dr. Fred C. Schwartz, articulate authority on Communism as a threat to the free world. He reminds us that for many years the Communists' time-table has called for total world conquest by the year 1973, a scant fourteen years from now. "And thus far," he warns, "they are precisely on schedule."

If we subscribe to these dark predictions we may conclude that long before the golden anniversary of the American Society of Photogrammetry, all of her photo interpreters will have been blown sky high—trusty stereoscope and all—and her photogrammetrists, rather than sitting at the consoles of vastly improved stereo plotting machines, may themselves be mere "floating dots" in outer space.

But probably this is not the kind of prediction expected of me this morning. Surely any capable prophet of doom does not require a full 60 minutes to assure his audience that the world is fast going to hell in a handbasket. History tells us that nearly every generation has been subjected to similar predictions, based on what seemed at the time to be very sound grounds; yet somehow humanity has continued to totter along year-after-year, and most of us believe that this situation will continue for a long time to come. In fact some extremists who examine the evidence argue that the world's future never looked brighter because mankind realizes at last that he holds the key to his own annihilation, and therefore will be intelligent enough in future wars not to use absolute weapons.

In the face of these extreme and conflicting predictions, we are perhaps justified in taking a middle position. Let's assume, therefore, that 25 years hence there will still be earthmen inhabiting the Earth, and that then, as now, nations will be hotly fighting cold wars with each other, while striving to strengthen their domestic economy, not only to improve the standard of living but also to provide a maximum deterrent to attack by an enemy force. Under such circumstances photogrammetrists and photo interpreters certainly will be in great demand in both civil and military activities. But what will these workers be doing, and with what equipment and techniques will they be doing it?

In attempting to answer these questions, I feel much like one of my "timber-simple" forestry colleagues must have felt when I confronted him with a similarly perplexing series of questions. He furrowed his brow, thought hard for a moment, and then said to me in all seriousness, "Well, I don't know—but I'll tell ya!"

At this point let me prepare you for my first prediction: I am sure many of you consider that discussion of the future of photogrammetry and photo interpretation should have been programmed as two separate papers, one dealing with the future of photogrammetry, given by an expert photogrammetrist for a photogrammetric audience, and the other dealing with the future of photo interpretation, given by an expert photo interpreter for a photo interpretation audience. If a ten-minute break were scheduled between these two talks, the two audiences could pass each other on the way to or from the coffee shop, and the only person compelled to listen to both talks would be the hapless moderator.

My first prediction, then, is that the future will bring better understanding that photogrammetry and photo interpretation are not distinct fields but are closely related techniques. To illustrate this important point, let's study a typical aerial photograph (Figure 1). Let's assume that a student of photo interpretation wishes to identify objects from a study of this photograph. If he disregards the *size* of objects, believing that photo measurements are strictly for the photogrammetrist, he may very likely call the object at A a tree, the objects at B a herd of cattle, at C a tract of houses, and at D a row of telephone poles. As a hard-nosed instructor of photo interpretation, I would gleefully give this student a grade of zero, even though he had carefully taken into consideration the traditional clues of shape, shadow, tone, texture, pattern, and site.

On this photograph of known scale, a few *measurements*, together with the observations he already has made, would have told this student that the object at A is a large clump of grass, not a tree (trees are at E); the objects at B are sheep, not cattle (cattle are at F); those at C are dog kennels, not houses, (a house is at G); and the objects at D are fence posts, not telephone poles, (telephone poles are at H). Furthermore, only by measurement of parallax—another important aspect of photogrammetry—can the interpreter tell the number of stories in the house at G; and shadow measurement is the best means of determining heights of certain other objects such as the dog kennels at C. Surely then, the photo interpreter has many important uses for photogrammetry, and I believe that successful photo interpreters of the future will have greater appreciation of this fact.

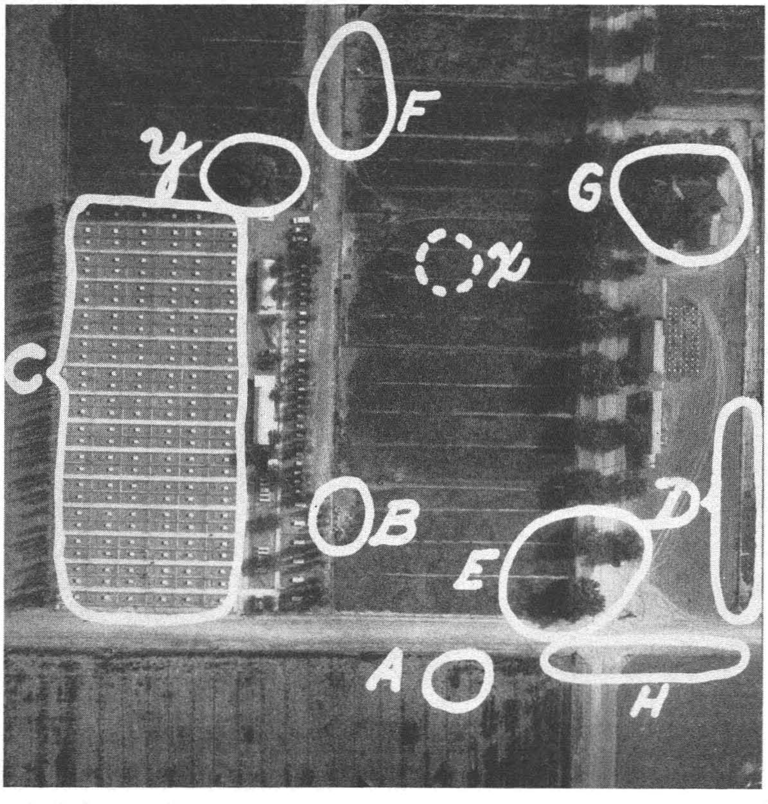


FIG. 1. Vertical photograph annotated to illustrate why photo interpreters of the future should make fuller use of photogrammetry, and why photogrammetrists of the future should make fuller use of photo interpretation. For further explanation, see text.

Similarly, the photogrammetrist must use photo interpretation at many stages in making his map. Suppose, for example, that in Figure 1 there is a ground-control point somewhere within the area encircled at X, which he must mark on his photos in order to use the point in horizontalizing a stereo model of this area in his plotting machine. When he visits this area in the field, photos in hand, the photogrammetrist practices photo interpretation in order to identify the nearby watering troughs, irrigation levees, and livestock trails that will permit him to locate the point X on his photos quickly and accurately. Back in the office, as he draws contour lines with his plotting machine, it is photo interpretation that tells this photogrammetrist whether the object at Y is a scrub-covered knoll that his "floating dot" must ride over, or a large tree crown that it must glide beneath. Finally when he returns to the field to check and complete his map, this photogrammetrist will find that photo interpretation often helps him to find certain critical features of the landscape and to plot them on his photos, so that he later can position them on the map.

The photogrammetrist, therefore, has many important uses for photo interpretation, and I believe that successful photogrammetrists of the future will have greater appreciation of this fact.

I have dwelt to this extent on the relations of photogrammetry and photo interpretation in order to justify the treatment of these subjects which follows. From now on, I will speak about aspects of the future which bear on *both photogrammetry and photo interpretation.*

The components which I propose to discuss are (1) *image quality;* (2) *human factors, i.e. characteristics of the photo user;* and (3) *equipment and techniques.* I will attempt to state where we now stand with reference to each component and then suggest ideas about its place in the future. Finally I will summarize the future of photogrammetry and photo interpretation in the light of the future we have thus predicted for each component.

Image Quality

Will the photo-images we examine 25 years hence be of significantly better quality than those we view today? If so, then I believe we must base future research and development in this field on a clearer understanding than we now have of the importance of various factors which contribute to image-quality on aerial photographs.

Our present lack of understanding in this field resembles that of two drunken British soldiers in Algiers during World War II, who were trying to find their way back to their barracks at the outskirts of town during a blackout. They bumped into a shadowy figure in a dark alley and, not realizing that he was an American general, asked him somewhat drunkenly for directions to their bivouac. Pulling himself to his full height the incensed general said, "Do you know who I am?" Hearing this, one of the limey soldiers turned to the other and said, "Now we are in a jam, chum; we don't know where we are, and he don't know who he is!"

A similar state of confusion was brought to light recently when I asked several experts what they thought should be done to improve photo-image quality. I received some very positive answers, but found surprisingly little agreement among these experts. For example, a film manufacturer said, "above all we must improve the speed and the resolving-power of the film that is used"; a fellow who is attempting to devise better camera installations in aircraft said that camera vibration is the factor which most limits image-quality; a photographer told me that we must learn how to obtain the correct exposure more consistently as this is the primary factor governing image-quality; a sensitometry expert maintained that the choice of film and filter is the all important consideration; a photo lab technician avowed that the greatest improvement would result from taking greater care in processing and printing, especially in view of the recent advances in electronic dodging methods; and a photo interpreter stoutly asserted: "It's all a matter of photographic scale; give me a scale that is large enough for me to see the necessary detail and I can interpret anything."

On considering these and other answers to my question, I concluded that many an expert suffers from a condition known as "tunnel vision." Too often, in limiting his attention to his own part in the photo reconnaissance chain, the expert loses sight of other important links that may enter into "trade-off" considerations when we try to produce the optimum photographic image.

Even those who take a somewhat broader view of factors governing photo-image quality seem to differ widely, as evidenced by the following three very positive statements published in recent issues of PHOTOGRAMMETRIC ENGINEERING:

VIEW #1. The factors controlling image quality are:

A. Angular Field	E. Altitude
B. Definition	F. Ground Speed
C. Distortion	G. Vibration
D. Character of Emulsion	H. Character of Illumination

VIEW #2. The amount of information contained in a photograph depends on four unique and distinct image properties
- A. Graininess
- B. Sharpness
- C. Resolving-Power
- D. Tone Reproduction

VIEW #3. The primary characteristics governing the quality of photographic images are:
- A. The photographic tone or color contrast between an object and its background
- B. Image sharpness characteristics
- C. Stereoscopic parallax characteristics

Such divergent views by those conducting research in this field help to explain why so little improvement of image quality has taken place during the century that man has been taking aerial photographs. (See Figure 2.)

Unfortunately time limitations preclude our making a detailed comparative analysis of these three points of view. Yet a detailed analysis is needed if we make more than bland generalizations in predicting the future of photo-image quality. Since each view deserves detailed analysis, the principles of random selection, as commonly employed, will be used in deciding which one we will discuss in detail. Ah—by random selection we have decided to discuss view #3.

In a way we have made a fortunate selection, because this opinion happens to be one advanced by a fellow who has spent most of his professional career trying to obtain a great many kinds of information from the actual interpretation of aerial photographs. Namely me. But we must remain respectful of the opinions of others, much better founded in physics and physiological optics. Also let us keep in mind that we are simply seeking a clearer understanding of the factors affecting photo-image quality, so that we can discuss in clear terms the possibilities for improving this quality.

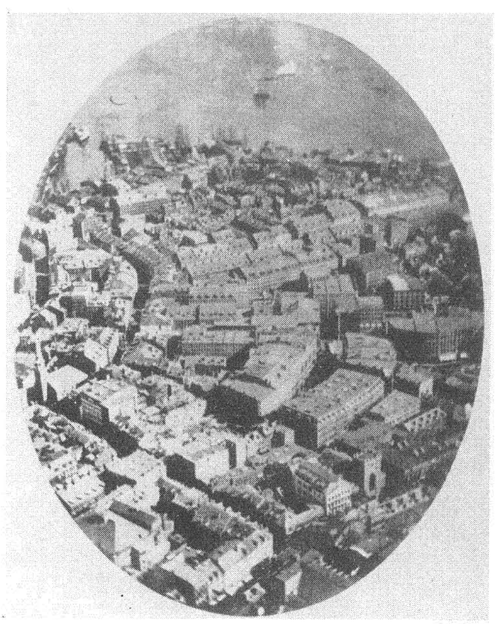


FIG. 2. Aerial photograph of the City of Boston, taken in the year 1860. Will photographic image quality improve more in the next 25 years than it has in the last 100 years?

First the terms used in view #3 will be defined by referring to Figure 3:

By photographic *tone contrast* is meant the difference in brightness between an image and its background. Thus in Figure 3, tone contrast is exemplified by the difference in brightness between points X and Y on the photograph. Similarly, in color photography, color contrast is the resultant of all hue, value, and chroma differences between the image and its background.

By *sharpness* is meant the abruptness with which the tone or color contrast appears to take place on the photograph. Thus in Figure 3 sharpness is indicated by the distance on the photograph over which the change from Tone X to Tone Y appears to take place.

Stereoscopic parallax is the displacement of the apparent position of a body with respect to a reference point or system caused by a shift in the point of observation. Thus in Figure 3 the stereoscopic parallax of the top, T, of the vertical column with respect to its base, B, is the distance dP, which is the difference between the lengths of lines BB' and TT'.

Let us briefly examine the evidence upon which this listing of characteristics has been based. When a logician or mathematician observes a certain result, and is able to demonstrate that certain conditions are both necessary and sufficient to produce that result, he is said to have defined all parameters contributing to the result. Believing that this same technique can be used to analyze the characteristics governing photo-image quality, interpretation has been made of several sets of aerial photo stereograms of the type illustrated in Figure 4-A, B, C, and D.

The area depicted in these figures was selected because it contains several objects and conditions representative of those which photo interpreters and photogrammetrists wish to study. The stereograms shown in these figures are unretouched portions of aerial photographs of the State Capitol grounds in

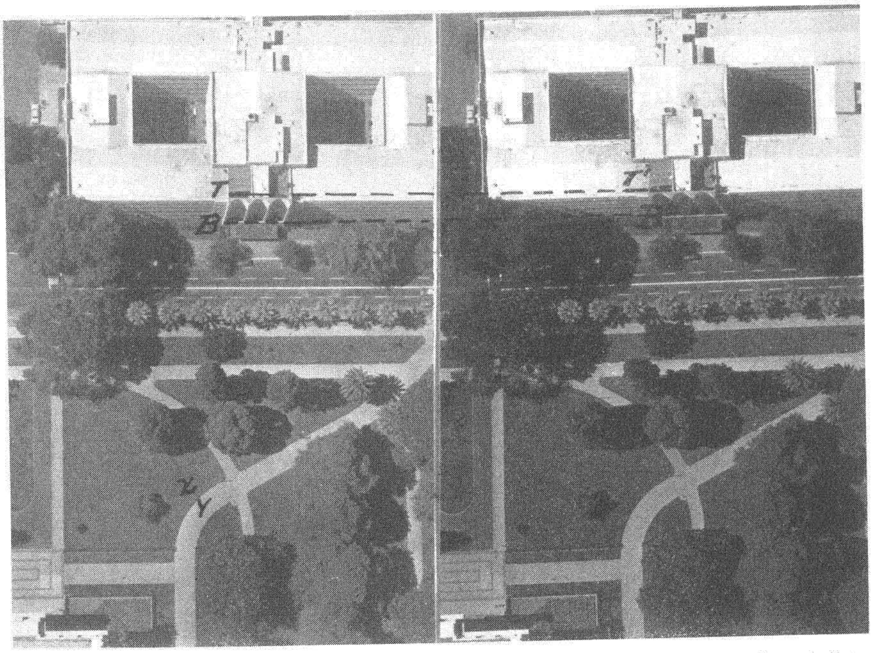


FIG. 3. Stereogram used in defining the terms "tone contrast," "sharpness" and "stereoscopic parallax." As discussed in the text these terms are considered by the author to be the three primary characteristics of photo images which aerial photographers of the future should strive to improve.

Sacramento, California. When studied comparatively, they provide evidence of the type which led me to conclude that on black-and-white photography favorable *tone*, *sharpness* and *parallax* characteristics are both necessary and sufficient for good photo-image quality. In three of the stereograms in Figure 4—(A, B, and C)—attempt was made to keep two of the characteristics favorable, while rendering only the third characteristic unfavorable, so that its effect on image quality might be judged independently of the other two characteristics. In the fourth stereogram (D) attempt was made to make all three characteristics favorable, to determine whether truly satisfactory photo-image quality is thus obtained.

Evidence that favorable tone contrast is necessary. Figure 4A is a stereogram having good sharpness and parallax characteristics, but with insufficient tone contrast for certain types of photo interpretation. For example, because of improper choice of film and filter, this stereogram is unsuitable for detecting or recognizing sidewalks against a background of green grass. (Compare bottom right quarter of this stereogram with same area in the other three stereograms.)

Evidence that favorable sharpness is necessary. Figure 4B is a stereogram having good tone contrast and parallax characteristics, but with insufficient sharpness for certain types of photo interpretation. For example, because of improper focus of the lens system, this stereogram is unsuitable for identifying palm trees. (Compare bottom left quarter of this stereogram with same area in the other three stereograms.)

Evidence that favorable parallax is necessary. Figure 4C is a stereogram having good tone and sharpness characteristics, but with insufficient parallax for certain types of photo interpretation. For example, because the camera stations were too close together, this stereogram has an inadequate stereo-base and therefore is unsuitable for distinguishing tree crowns from their shadows. (Compare top left quarter of this stereogram with same area in the other three stereograms.)

Evidence that favorable tone, sharpness and parallax are sufficient. Figure 4D is a stereogram having good tone, sharpness and parallax characteristics. I consider this to be one of the best black-and-white stereograms I have ever seen, in terms of definition and information content. Each feature mentioned in one of the three preceding stereograms as being uninterpretable is readily interpreted here, as are many other features.

The conclusion drawn from interpretation

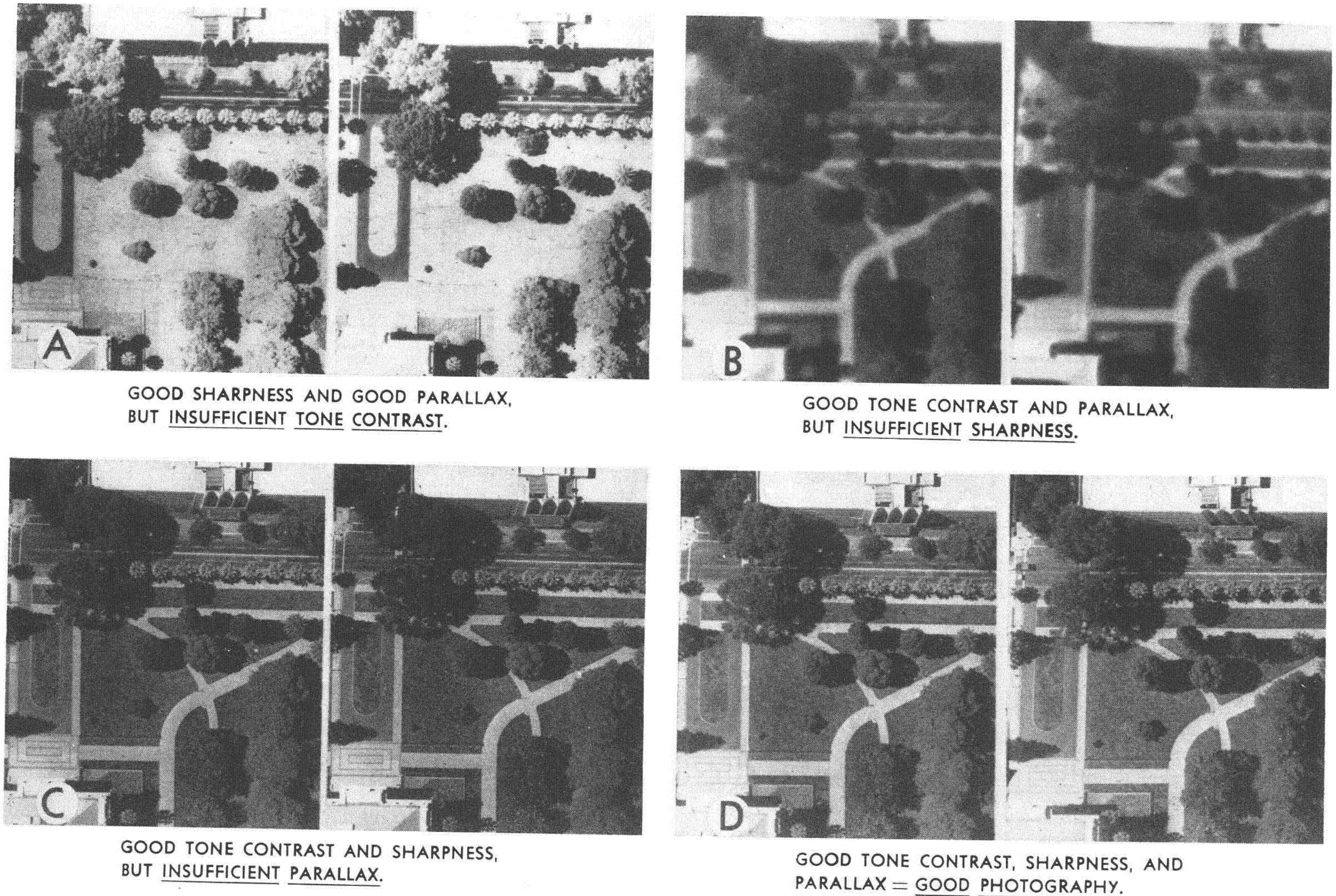


FIG. 4. Stereograms indicating that favorable tone contrast, sharpness and parallax are both necessary and sufficient for good photographic image quality.

of these four aerial photo stereograms, and many others like them, is that favorable tone, sharpness, and parallax characteristics are both necessary and sufficient for providing good photo-image quality on black-and-white photography. The quality of these photo-images could be improved still more if color photography were used.

Some investigators consider this analysis to be incomplete or oversimplified because it fails to mention certain factors which obviously affect photo-image quality. Among these factors are spectral sensitivity of the photographic film; spectral transmission by the photographic filter; image-motions caused by roll, pitch, yaw, and forward-motion of the aircraft during the exposure; camera vibration; photographic scale; amount of overlap; amount of photographic exposure; techniques and materials used in processing and printing; aberrations of the lens system; spectral reflectivity of the objects photographed; "air boil" from the photographic aircraft; and atmospheric haze disturbances.

As indicated in Table 1, I maintain that the factors above named influence image quality indirectly, through their effects on tone, sharpness and parallax (Colwell, 1954). Thus, as illustrated in Figure 4A spectral sensitivity of the film, spectral transmission by the filter, and spectral reflectivity of an object with respect to its background greatly affect tone contrast, but have little or no effect on sharpness and parallax. As illustrated in Figure 4B focus of the lens system greatly affects image sharpness but has little or no effect on tone contrast and parallax. And as illustrated in Figure 4C the length of the stereo base and its corollary—amount of forward-overlap—greatly affect stereoscopic parallax but have no effect on sharpness or tone contrast.

Assuming that this analysis gives a better understanding of the factors affecting image quality, how might it be applied to our efforts to obtain better photographic images in the future? First a special kind of "resolution target" should be constructed which would facilitate our determining what tone, sharpness, and parallax characteristics are provided by photographic equipment currently being used. To determine whether improved image quality is obtainable from a specific modification of the photographic system, we would then photograph this target with the system both before and after the modification had been made, and make a comparative interpretation of the two sets of photographs.

Figure 5 is a crude target which shows how tests of image quality might be made. It is designed to permit a quantitative determination of effects on the detection and recognition* of objects that result from improvement or degradation in tone contrast, sharpness, and parallax. The target exhibits a variety of geometric forms (cubes, pyramids, paraboloids, cylinders and cones), as well as their two-dimensional counterparts (squares and circles) of different sizes and varying tone contrasts. These objects have been placed in orderly array in Figures 5A and B to facilitate certain tests of image quality. In each grid square of Figure 5C, however, five possible positions for an object are considered available (top left, top right, lower left, lower right, and center); in most of the squares there is only one object, but a few squares have either several objects or none, in order to make for more rigorous testing. Thus Figure 5C is preferred for critical tests of detection and recognition.

The four panels on the left end of this target are included in deference to those who use other methods of analyzing image quality. Thus, to facilitate determination of "resolution" a standard Air Force high-contrast line target is included on which the block sizes vary as the sixth root of two. A grey scale is included to facilitate the measurement of tone reproduction; and two panels of black-and-white stripes are included which facilitate the measurement of "acutance" along edge gradients. Of the latter two panels, one exhibits a sharp transition along each edge gradient, and the other a gradual one, since it is based on a sine wave response curve.

The microdensitometer traces for three edge gradients, as shown in Figure 6, illustrate the danger of oversimplifying our analysis of the characteristics governing photo-image quality. Each edge gradient extends from A to B; therefore each traverses the same contrast range as the other two, and does so in the same horizontal distance on the negative. Yet according to Higgins and Jones (1952), who have used acutance to measure this characteristic, small images with the properties of the middle or S-shaped curve appear sharper and are more interpretable than those having the properties of either of the other two curves. Although this observation is not in conflict with our earlier definition that sharpness is the abruptness with

* *Detection* is merely the act of discovering the existence of an object; *recognition* is the act of discovering the true identity of the object.