THE ORTHOCAMERA: ORTHOGONAL PHOTOGRAPHIC SCANNING CAMERA

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THE need during World War II for obtaining certain definite mechanical and topographical data quickly and in volume led the late *Professor H. L. Cooke* of the Palmer Physical Laboratory, Princeton University to invent and successfully develop the Ortho-camera. By completely eliminating perspective, the Orthocamera takes photographs of an entirely new type. These photographs, or orthographs, combine the geometrical characteristics of the best mechanical drawings and the familiar pictorial effects of ordinary photographs, with their simplicity and ease of interpretation.

In the usual methods of taking photographs, a camera is employed having a lens toward which the rays may be regarded as converging to a center. The photographic rays pass to the lens in the form of a cone and, due to the angularity of the rays with respect to the optical axis of the camera, there is a relative planimetric displacement of all features shown on the photograph which do not lie in any single datum plane of the object. All points of the object nearer to the camera than the datum plane are shown in the photograph as relatively displaced outward from the optical axis of the lens, while all parts of the object further from the camera than the datum plane are relatively displaced inward with respect to the axis. This is true of all photographs of solid objects taken in the ordinary way with any known form of camera; thus it is impossible to use such a photograph as an accurate plan of the object, in which all the elements thereof are required to be shown in correct orthogonal relationship.

An outstanding example of the difficulties (fully appreciated by photogrammetrists), involved in utilizing a photograph as a plan from which measurements may be taken, occurs in the case of photographs of terrain taken from airplanes, and it is desired to use the photographs as maps. Such photographs, even if taken from the highest altitudes feasible, are subject to serious distortion, particularly if they are of hilly or mountainous country; therefore, it is not feasible to use such photographs directly as maps or plans of the country. Accurate measurements cannot be taken directly. Numerous efforts have been made to correct airplane photographs so as to render them more suitable as maps, but all known methods of correction are only crude approximations, and cannot take care of the intricate irregularities of the surface photographed.

Professor Cooke devised and patented several methods of producing orthogonally corrected photographs of terrain for map preparation. The final evolved method used in the Orthocamera will be described.

The method involves utilizing a telecentric lens interposed between the camera lens proper and the object, placed so that its principal focus is coincident with the outer nodal point of the camera lens, the two lenses being arranged coaxially. If the telecentric lens is of proper design and is co-extensive in area with the object to be photographed, or with some segment thereof that is to be photographed in a single exposure, it, in effect, transmits to the camera lens only rays leaving the object in directions parallel to the axis of the lens system. The result is that the photograph of the object is, in effect, identical with one

* The text, in the main, is taken from the works of the late Prof. H. L. Cooke. Reed Research, Inc., in arrangement with the estate of Prof. Cooke, is undertaking the further development of this invention. Mr. Prickett, associate of Prof. Cooke, is consultant on this project.

photographed only by means of such parallel rays. This method substantially eliminates the effects of parallax or perspective.

The principles of the telecentric lens system may be developed by reference to Figures 1 to 4. In each of these figures T is the telecentric lens, preferably of long focus (corresponding with the lens T in Figure 1.) L is the photographic object (corresponding with objective L in Figure 1), O is an object and I is its

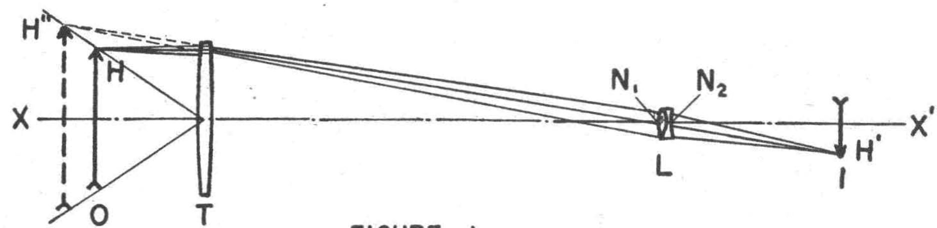

FIGURE 1

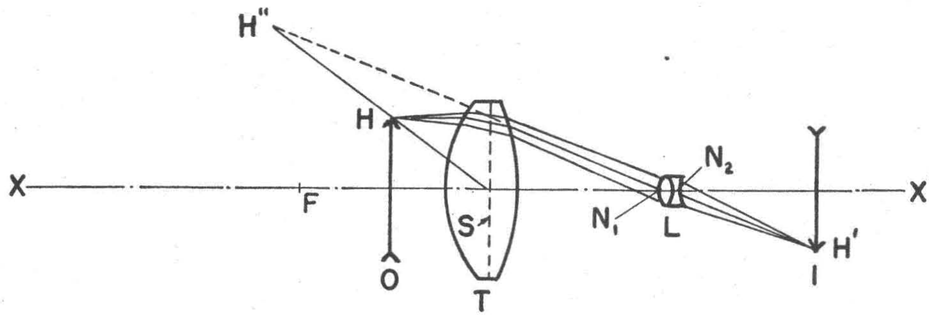

FIGURE 2

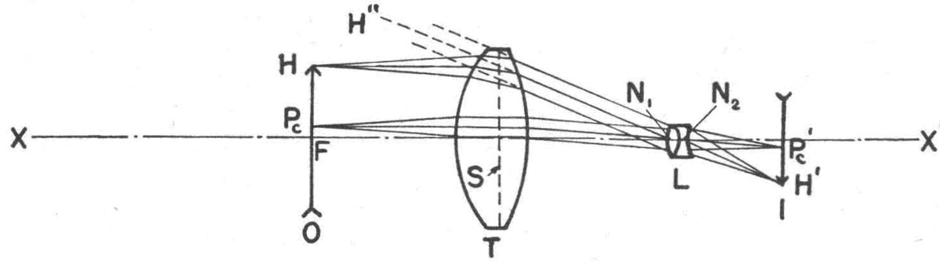

FIGURE 3

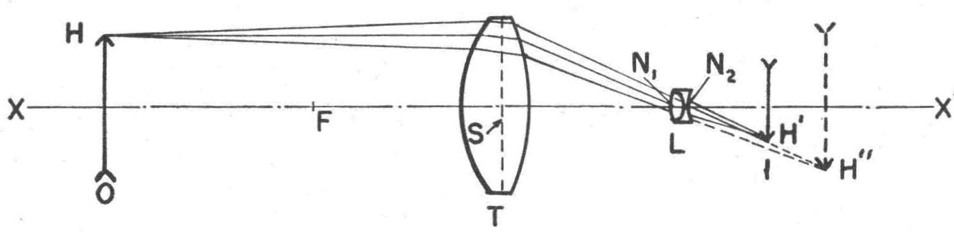

FIGURE 4

real image. These four figures represent different arrangements of the same parts. Figure 1 shows the approximate actual form of the system, while Figures 2, 3 and 4 show great exaggeration of the form and relation of the elements in order to clarify the geometrical optics of the system.

The lenses T and L are mounted with their axes coincident on the line $x-x'$, with the principal focus of the lens T coincident with the outer (object space) nodal point N_1 of objective L. When adjusted in this manner, a ray from the head H of the object O, directed parallel to $x-x'$, after traversing the lens T will be directed towards the outer nodal point N_1; after traversing the lens L, the ray will proceed along a parallel line passing through the inner (image space) nodal point N_2 to the head H' of the real image I. Rays of this sort, directed towards and away from the nodal points N_1 and N_2 respectively will be referred to as nodal rays, and these rays afford a simple means of locating the image position in the image plane I of a point in the object plane O.

It is to be noted that the two parts of the nodal rays, one part proceeding from the object O to the lens T parallel to the axis $x-x'$, and the other from the lens T to the outer nodal point N_1 intersect, when produced, (see Figure 2) in a certain surface S on, or within, the lens T.

In Figures 1 to 4, it is assumed that the projection surface S of the lens T is a plane, that this plane is parallel to the planes of the image I and object O, and normal to the axis $x-x'$. Under these circumstances the image I is an orthogonal projection of the orthogonal projection of the object O on the projection surface S of the lens T. Thus the image I is an orthogonal projection of the object O.

Up to this point it has been assumed that the object O lies in a plane normal to the axis $x-x'$. It is, however, the main purpose of this apparatus to develop a method for photographically recording orthogonal projections of irregular objects of three dimensional form. Such an object O is shown in Figure 9 in which the arrangement of lenses T and L, axis $x-x'$ and image I corresponds with that of Figure 1. A pencil of rays is shown drawn from the point P located in a recessed portion of the object O. As drawn this pencil is not interfered with by portions of the object of greater elevation (i.e., nearer to the camera) than the point P. Such a point of greater elevation is indicated at A on the object O. This is due to the fact that the diaphragm stop R of the lens L is of sufficiently small diameter to limit the conical angle of the pencil of rays from P which reach the image plane I so that this result is accomplished. In the Orthocamera the lens stop R is usually, but not necessarily, so adjusted that only pencils of rays from the object O of exceedingly small conical angle are utilized in the formation of the image I. This has the additional effect of increasing the depth of focus of the optical system, so that objects of considerable variation of contour in the direction of the axis $x-x'$ may be accommodated without noticeable loss of definition. It should be noted that if the lenses T and L are such that the effect of their aberrations can be neglected, then the entire part of the object O covered by the lens T can be photographed with a single exposure.

For this instrument it is important to be able to calculate the scale of the image I in relation to the object O. This may be accomplished in the usual manner if the position of the object O in relation to the lens T is known and also the equivalent focal lengths of the two lenses T and L.

In Figures 2, 3 and 4, F represents the principal focus of the lens T, to the left of the lens. There are three distinct methods of employing the telecentric system as shown. (1) In Figure 2 the object O is nearer the lens T than the focus F. (2) In Figure 3 the object is at the focal distance. (3) In Figure 4 the object is beyond the focal distance of the lens T. In Figure 2 the lens T forms the virtual image H'' of the object point H; in Figure 3 the virtual image of H is formed at infinity, as indicated by the dotted lines and arrow H''; in Figure 4 the virtual image of H is at H'' which represents a virtual object which is employed by the lens L in forming the real image H', the pencil of rays being convergent after passing the lens T. Inspection and consideration of Figures 2, 3 and 4 will show that the object O may be placed at any point to the left of the lens T and a real image I formed to the right of the lens L; but as the distance of the object to the left of the lens T is progressively increased, the scale of the image I progressively diminishes, becoming ultimately too small for practical purposes. It is of interest to note that with the object at the principal focus of the lens T, as indicated in Figure 3, the scale of the image I in relation to the object O is equal to the ratio of the back focus of the lens L to the distance of the projection surface S of the lens T from the outer nodal point N_1 of the lens L.

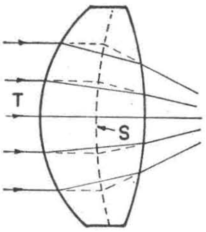

FIGURE 5

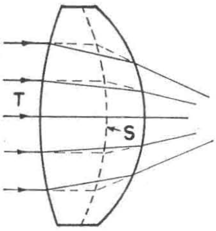

FIGURE 6

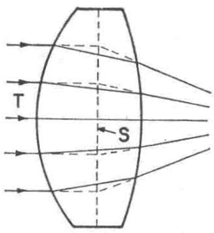

FIGURE 7

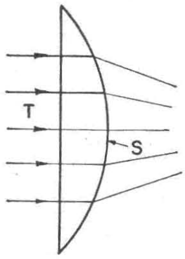

FIGURE 8

It will be apparent from the above that theoretical exactness of orthogonal projection is produced when the telecentric lens T is so designed that the projection surface S is a plane. A lens having such characteristics, or so close an approximation thereof as to be entirely suitable for the purposes of the present equipment, may be readily made by properly forming the surfaces thereof.

Reference to Figures 5, 6, 7 and 8 will make this clear. These four figures show telecentric lenses T of different and greatly exaggerated forms, with nodal rays, marked by arrow heads, transmitted by the lens. It will be seen that the surface S in which the incident and emergent portions of these nodal rays intersect when produced, may take various forms, depending on the form and distribution of the refracting surfaces of the lens T. When these surfaces are so formed and located, (Figure 7) that the surface S is substantially a plane, it is obvious that the emergent nodal rays are so located that they act as though they came from a true orthogonal projection on the surface S of the object from which the incident nodal rays originated. This surface of intersection, S, of the incident and emergent nodal rays will be referred to as the projection surface of the lens T. In practice, telecentric lenses, such as T, are usually very thin, with very slight curvature of surfaces, so that it is a simple matter to design a double convex lens of this character, having a projection surface which is a plane, to an exceedingly high order of approximation.

In the plano-convex form of lens shown in Figure 8 the parallel rays coming from the object will enter the lens normal to the plane surface thereof, and the projection surface S coincides with the convex surface of the lens. As the lens used in practice would have a relatively long focus, the curvature of the surface S would be slight. (Figure 8 shows the lens in greatly exaggerated form for the purpose of illustrating the principle). The use of such a lens will eliminate the errors due to parallax, and only slight theoretical error will be present in the ultimate projection; this is not due to parallax but to the slight deviation of the surface S from a plane. Such slight theoretical error under ordinary conditions will be of no practical importance, and will be substantially undetectable in the resultant map. As indicated above, lenses may be prepared which eliminate even this possible source of imperfection. Such lenses take the general form of the asymmetrical double convex lens shown in Figure 1.

The telecentric lens system is subject to the limitation that the size of the object which can be photographed can be no greater than the size of the telecentric lens employed. In the case of objects of considerable dimensions, this difficulty might be obviated by shifting the camera laterally, without altering the orientation of its axis, photographing different portions of this object, in succession, and then piecing these views together to form a connected whole. However, the scanning method of the Orthocamera employs continuous relative motions between the optical system, photographic plate and object in such a manner that the photographing of successive portions of the object is carried out as a continuous process and not as a step-by-step procedure. This relative motion is so effected as to cause the different portions of the photograph to appear

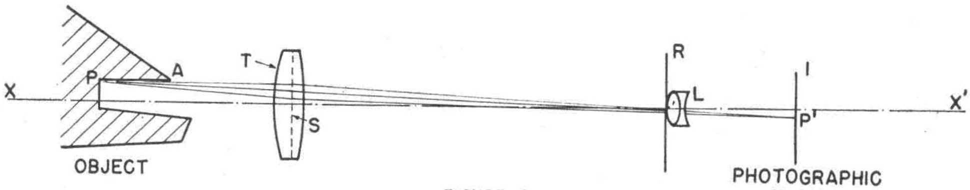

FIGURE 9

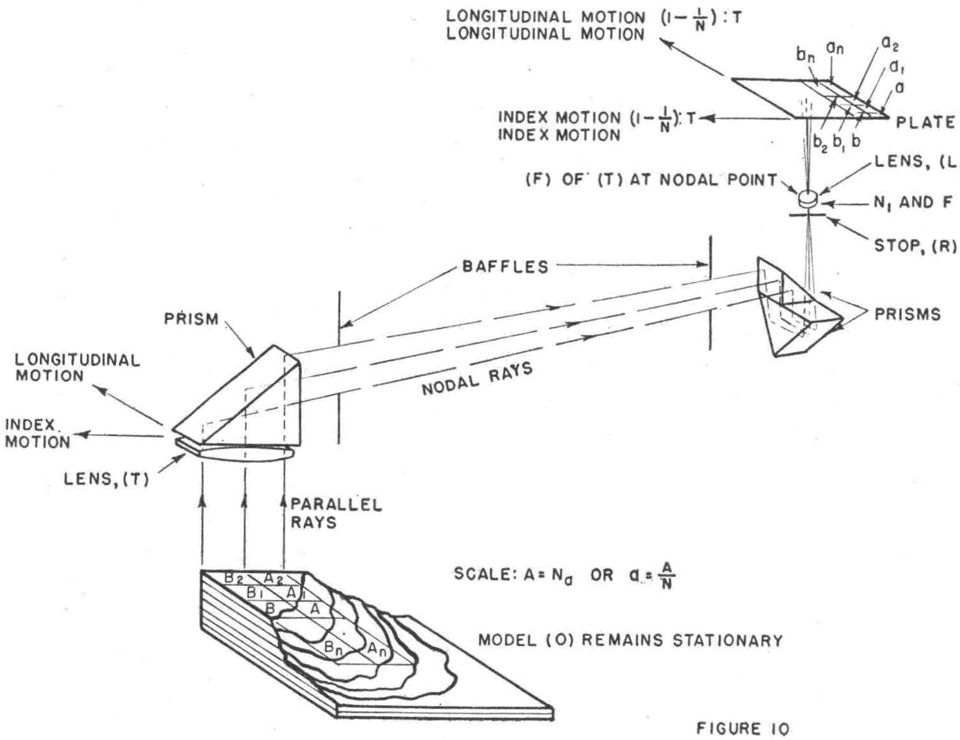

FIGURE 10

in the form of a continuous picture on the plate, requiring no piecing of picture parts to achieve a connected photographic representation of the entire object. At the same time the theoretical errors due to conical projection are avoided.

A lens system of simple design and moderate dimensions produces an orthogonal projection accurate to within the limits of experimental error. The object, photographic plate, and the camera equipped with a telecentric optical system, are maintained by coordinated motions of one or more of these elements in such relation that a point-to-point orthogonal correspondence between elements of the object photographed and corresponding elements of the plate on which the image is recorded is maintained continuously during the process of exposure. In this way it is possible to produce a continuous exposure on a single plate covering an area of much greater extent than that included in the instantaneous field of

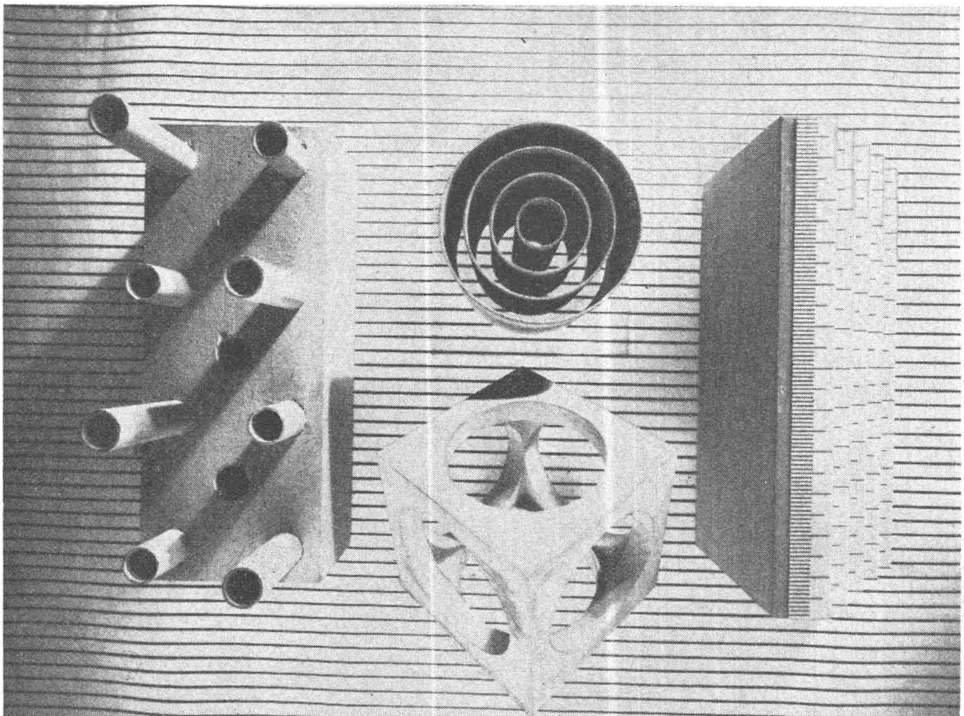

FIG. 11. Conventional Photograph.

view of the optical system employed. With parallax wholly eliminated, by employing an optical system having a very small field of view and subtending a cone of rays of very small angle at any instant, the remaining errors are due to imperfection of lenses and mechanical construction of the apparatus. As the field of view of the optical system is restricted to a small angle, the imperfections and aberrations of the lenses produce no detectable errors in the photograph. Precision fabrication of the instrument reduces the residual errors to a minimum.

In preparing an orthograph of an object, the desired scale must be produced as part of the scanning operation. If, for example, the distance "*d*" from the object to the lens is made three times the distance "*d*" from the lens to the plate, there is a reduction in the size of the image of 1:3, such ratio being designated by $1/N$. To photograph a fixed object with a scale change, it is necessary to produce relative motion between the optical system and the plate so as to maintain a point-to-point correspondence between elements of the object and the images of such elements in fixed positions with respect to the moving plate. If the scale of reduction of the image is to be $1/N$, in order to prevent movement of the image with respect to the plate with an image erecting system, the plate and optical system must be moved in the same direction through distances in the ratio $(1-1/N):1$. Without image erection, the ratio of the corresponding displacement must be $(1+1/N):1$. If $N=3$ it follows that for each displacement of the optical system the plate must be given a corresponding displacement two

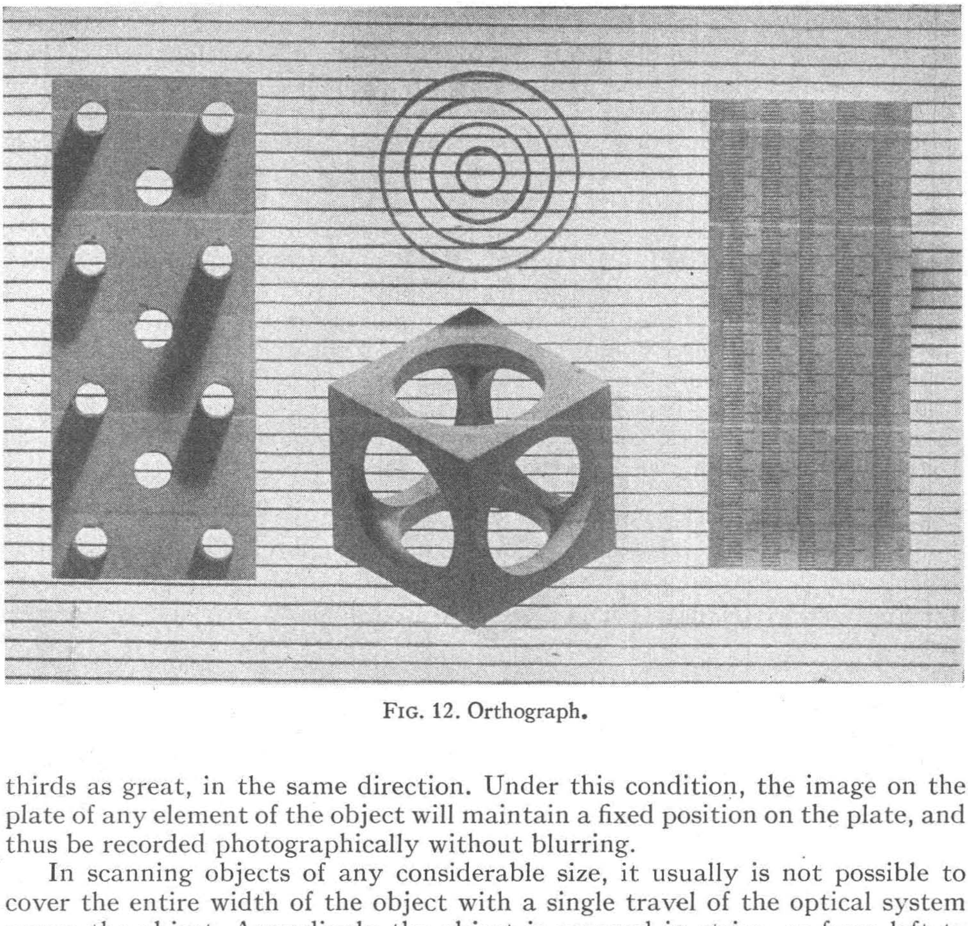

FIG. 12. Orthograph.

thirds as great, in the same direction. Under this condition, the image on the plate of any element of the object will maintain a fixed position on the plate, and thus be recorded photographically without blurring.

In scanning objects of any considerable size, it usually is not possible to cover the entire width of the object with a single travel of the optical system across the object. Accordingly the object is scanned in strips, as from left to right, moved downward a distance equal to the width of the strip and is scanned from right to left, and so on until the entire surface of the object is covered. Here again, if the reduction in scale of the photograph is to be $1:N$ and an image erecting system is employed, then in the lateral movements, left to right, and transverse displacements for scanning strips, the ratio of the speed of motion of the plate to that of the optical system must be $(1-1/N):1$. If no erecting device is employed the ratio of the corresponding motions is $(1+1/N):1$.

The use of the telecentric system described above has been referenced to the photographing of relief models of terrain to produce orthogonally corrected maps therefrom. Another important utilization of this technique has been applied to ship and machinery models. Such orthographs have the distinct advantage over the conventional photographs that, as parallactic distortion has been eliminated, the orthograph details the object to correct scale for direct measurements. Scale drawings of the machine or object may also be prepared by merely dimensioning directly on the orthograph.

An interesting adaption of the Orthocamera has been demonstrated by *Prof. Cooke.* Having had a relief model carved on laminated plaster block, the block is placed under the multiplex projectors with its culture imaged upon it while an orthograph is made. The block is then coated with a photographic emulsion, positioned under the Orthocamera, now equipped with a projector, and the orthographic plate is back scanned on to the carved relief block. The end result is a relief model with all its culture photographed in true position on its surface.

The present model of the Orthocamera is designed to cover objects up to $30'' \times 40'' \times 24''$. Larger objects can be covered in overlapping sections fitted together to form a continuous orthograph, without break or discontinuity. The negatives produced by this instrument are on precise scales of 1:5 or 1:10, depending on the settings of the controls.

It should be clearly understood that the principle on which the Orthocamera works represents an exact solution of the problem of orthographic photography, and is not in any sense a mere approximation to precise conditions.

An obvious field of usefulness for orthographs, is in the preparation of isometric representations of completed machines, for the guidance of mechanics in charge of assembly work. Form lines of curved surfaces of models, such as those of fuselages, airplane wings and propellers, ship hulls, or automobile bodies, heat exchangers and burners, can be reproduced quickly and accurately with the Orthocamera, by ruling such models in mutually perpendicular planes before orthographing.

Orthographs are destined to have important applications in both science and industry, for these revolutionary photographs of complicated machines or other objects supply the exact quantitative and detailed information previously obtainable only by the most painstaking measurements and draftsmanship.