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Hologrammetry: Concepts and Applications

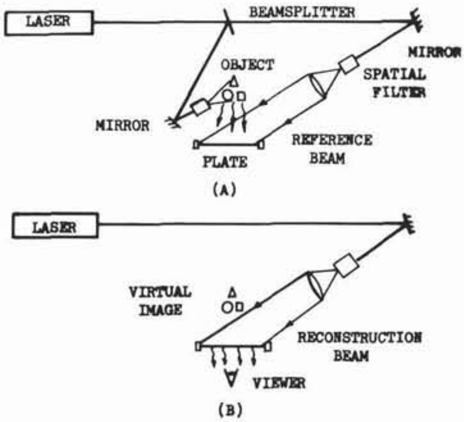


FIG. 1. *(A)* Recording Fresnel hologram; *(B)* reconstruction of Fresnel virtual image.

An advantage of the holographic stereomodel is the expected simplification and ensuing economic savings in instrumentation; although the recording equipment would be sophisticated, the mensuration and mapping devices would be greatly simplified.

ABSTRACT: *Research in holographic applications to mapping during the past several years has led to the introduction of the term* hologrammetry. *It is an interdisciplinary field combining holographic techniques for purposes of interpretation, mensuration, mapping, and display. A concise account of Fresnel and focused-image holograms, both transmission and reflection types, includes their characteristics and suitable applications. Mensuration and mapping techniques of holograms and results obtained follow. This includes targeting and digital mapping as well as graphical plotting of contours, cross-sections, etc. The use of direct holograms has been practically limited to small close-range objects. To extend the capability to topographic terrain applications from aerial photography, one must apply the concept of the holographic stereomodel. Both Fresnel and focused-image holographic stereomodels possess related advantages.*

INTRODUCTION

VARIOUS TYPES of holograms differ primarily in the geometry of the optical arrangement used to record them. A schematic diagram of recording a Fresnel Hologram is shown in Figure 1a. The reference beam interferes with the light reflected from the object at the hologram plate. After development, a duplicate of the reference beam (called the reconstruction beam) is used to illuminate the hologram and produce a virtual image of the object as depicted in Figure 1b. The geometry of this virtual image will be the same as the object's geometry provided no appreciable emulsion shrinkage occurs during development. A method has been devised to avoid emulsion shrinkage using overexposure, underdevelopment, and quick fixing and rinsing.[1]

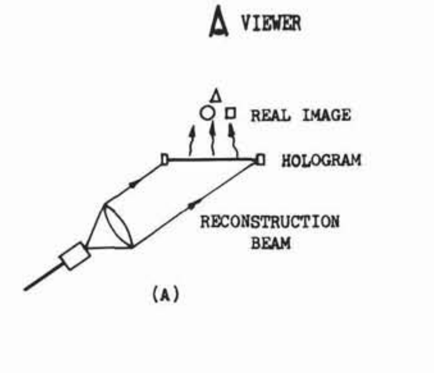


FIG. 2. Fresnel hologram: *(A)* real image, *(B)* virtual-relief (reflection) image, *(C)* real relief (reflection) image.

In addition to the virtual image, three other images may be reconstructed from a Fresnel hologram. The real image, Figure 2a, is obtained by using a reconstruction beam which is the complex conjugate of the reference beam. In case of a collimated reference beam, the complex conjugate is simply another collimated beam traveling in the opposite direction. The real image is pseudoscopically inverted, which makes it unattractive for use with three-dimensional objects. However, if used for two-dimensional objects, such as aerial photographs, it has obvious potential because it can be projected on a screen and used for display.

Two other images may be generated from a Fresnel hologram by reflection of the reconstruction beam from the emulsion of the holographic plate. They are therefore termed *relief images*. One is virtual, Figure 2b, and one is real, Figure 2c. Untreated Fresnel holograms have low reflective diffraction efficiency, but it can be increased by either aluminizing the emulsion or by bleaching.

Another type is the so-called *focused-image hologram,* the recording system of which is shown in Figure 3a. The main difference is that a lens is incorporated between the object and plate such that the object's image falls near the hologram plate. The main advantage of focused-image holograms is that they may be reconstructed with a broadband source or diffuse white light as shown in Figure 3b, as well as with a laser. Unfortunately, direct-focused image holograms of three-dimensional objects are not desirable for metric work because all object points focused off the hologram emulsion plane are distorted. However, the fact that white light is used for reconstruction makes it well-suited for display. If the object is two-dimensional, such as an aerial photograph, then focused-image holography has a good potential, as will be mentioned later on.

A third type is the volume-reflection hologram which may also be reconstructed by white light, see Figures 4a and 4b. It requires thick emulsion which, with attendant shrinkage, makes it of low geometric fidelity for three-dimensional objects. This is the reason it has not been used much in hologrammetric work.

The different types of holographic images mentioned above have been considered by

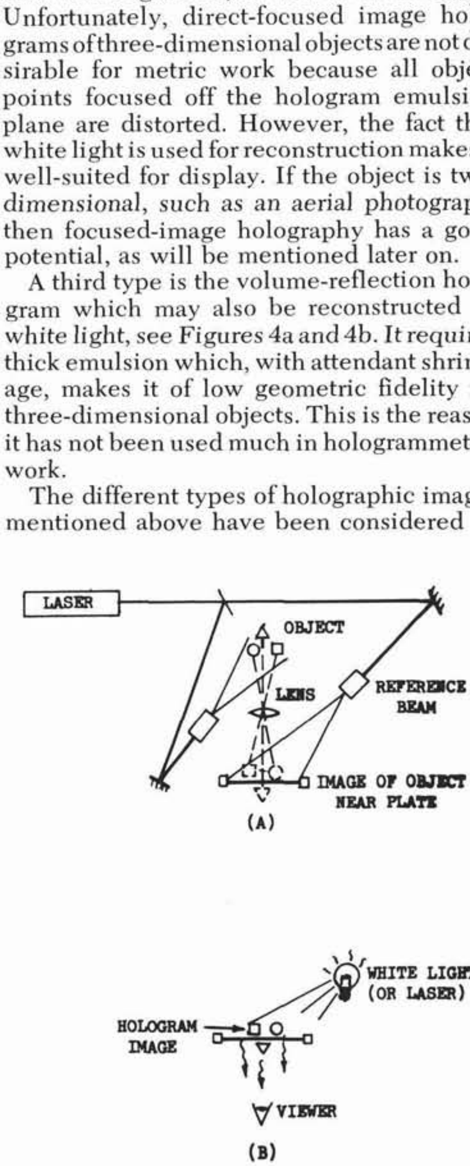
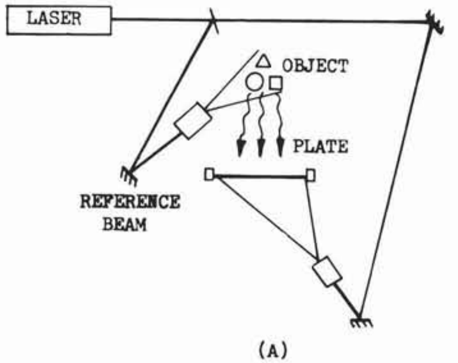


FIG. 3. Focused-image hologram: *(A) recording,* *(B)* reconstruction.



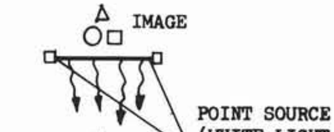


FIG. 4. Volume-reflection hologram: *(A)* recording, *(B)* reconstruction.

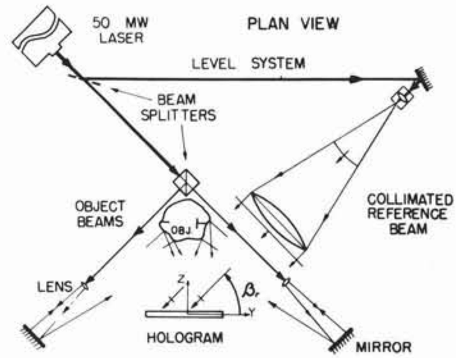


FIG. 5. Hologram recording with multiple object beams.

the photogrammetrist for purposes of mensuration and mapping as well as for display and interpretive purposes. Direct holograms of three-dimensional objects have been used as an alternative to the photogrammetric model mostly for close-range applications because the image is usually the same size as the object. Because of this, a hologram of a restituted photogrammetric model, called the holographic stereomodel, has been devised to extend the holographic capability to the wider field of topographic mapping, particularly of terrain. In the following sections direct holograms will be discussed separately from holographic stereomodels.

DIRECT HOLOGRAMS OF THREE-DIMENSIONAL OBJECTS

As was mentioned earlier, focused-image holograms of three-dimensional objects are useful mainly for display and illustrative purposes because of the absence of speckle and using white light for reconstruction. They are not however suitable for high-quality metric work because of distortions in images outside the emulsion plane. By contrast, Fresnel holograms of three-dimensional objects offer an excellent alternative to the photogrammetric model for metric work.

Compared to a photogrammetric model, a Fresnel hologram has the following characteristics: *(1)* it affords the viewer multiple perspectives within the aperture fixed by the size of the hologram plate; *(2)* parallax exists in all directions, hence no restrictions are imposed on the placement of the observer's eyes; *(3)* problems of blind spots are less severe in holographic recording because multiple object beams may be used as shown in Figure 5; *(4)* unlike photography, particularly at close range, depth of field is not a critical criterion in holography; *(5)* a holographic image is usually the same size as the recorded object whereas a photogrammetric model can be larger or smaller with proper design of the photography.

MENSURATION OF DIRECT FRESNEL HOLOGRAMS

The real image, particularly the relief type, of the Fresnel hologram has been used for display and qualitative work. On the other hand, a Fresnel virtual image is more suitable for mensuration as has been indicated in an earlier paper.[2] A self-illuminated dot is inserted in the space of the virtual image and its movements monitored by a three-axis comparator which for this research is the Autograph A7 (see Figure 6). To determine the precision of pointing at a holographic virtual image, several researchers took repeated measurements on a well-defined point. Table 1 gives the standard deviations in mm for a number of observers. The x, y plane is parallel to the hologram plate with x being parallel to the observer's eyebase (see Figure 7). Auxiliary viewing magnifications ranged from 1.0 to 2.7 whereas the distance between observer and image was 10 cm to 20 cm.

FIG. 6. Wild A7 modified for hologrammetric mensuration and mapping.

TABLE 1. PRECISION OF POINTING ON A SINGLE POINT (DIRECT HOLOGRAM).

Observer	*Standard Deviation in mm*		
	x	*y*	*z*
GHG (Ref. 3)	0.018	0.035	0.084
	0.017	0.037	0.111
MKK (Ref. 4)	0.013	0.023	0.030
	0.018	0.025	0.051
JPA (Ref. 5)	0.020	0.030	0.110
PVB (Ref. 6)	0.022	0.012	0.074
DLG (Ref. 7)	0.018	0.040	0.078
RAG (Ref. 7)	0.023	0.026	0.071

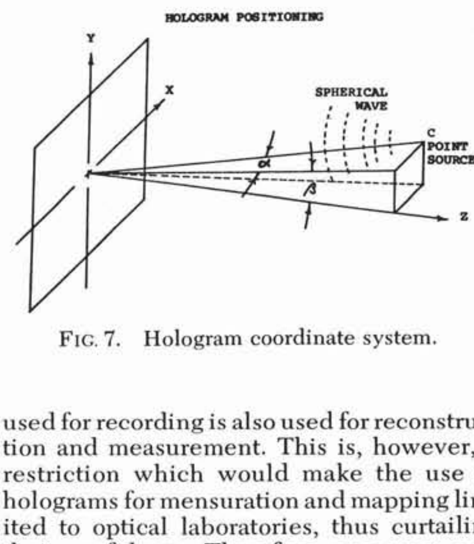


FIG. 7. Hologram coordinate system.

Many observers noted increased pointing precision using small magnifications (less than 3×) with JPA reporting 0.008, 0.013, 0.070 mm, in x, y, z, respectively, if 20× is used.[8]

Although pointing precision depends essentially on the quality of the reconstructed image, accuracy of the image necessary for metric work depends on the geometric fidelity of reconstruction. If the reconstruction geometry is different from the recording geometry, the resulting image will be distorted. This difference in geometries arises from emulsion shrinkage, and deviations between reconstruction and recording beams. Emulsion shrinkage is no longer a problem as was stated earlier.[1]

The other source of distortion would be completely eliminated if the same set-up used for recording is also used for reconstruction and measurement. This is, however, a restriction which would make the use of holograms for mensuration and mapping limited to optical laboratories, thus curtailing their usefulness. Therefore, one must consider as more common the application of reconstructing the hologram at metrology laboratories using, in general, different optical components. The main task is to determine the acceptable tolerances within which the reconstruction geometry can approximate the recording geometry.

The operation of reconstruction of a hologram has been likened to relative orientation of a stereomodel. In drawing the analogy one must be careful not to confuse these two distinctly different operations in regard to the number and type of parameters. For a hologram, Figure 7 shows that there are only *three* possible geometric elements relating the source of the reconstruction beam to a coordinate system in the hologram (whereas relative orientation is a five-parameter process).

If, as is conveniently done, the reference and reconstruction beams are collimated, only two angular elements remain. Careful experimentation showed that recovery of these two angles should be within 0.2° so that the resulting distortions are below the level of the pointing precision. In addition, simulation studies also showed that a reconstruction beam radius of 10^5 mm or larger would effectively mean a collimated beam with no significant distortions. If these tolerances are not met, Gifford's work[9] showed that eye position would influence perceived image location. In fact, each eye would see a different image for the same original object point with possible resulting y-parallax as shown in Figure 8. Error in the vertical angle would result in y and z image position shifts for vertical (y-direction) eye movement. Error in the horizontal angle, and horizontal (x-direction) eye movement, cause x and z changes. Finally, collimation errors result in a more complex pattern of changes in x, y, z with both horizontal and vertical eye movement. These conclusions are arrived at from simulation studies. Such studies indicated that certain points in the holographic image exhibit no y-parallax. For example, if α_c (reconstruction beam) is not equal to α_r (reference beam) no y-parallax exists at points having the same y-coordinates as the eyes. Reference 9 lists more instances of this nature. In addition, Reference 10 gives an example where the nature of the distortions is used to recover the recording beam geometry.

Although proper reconstruction geometry yields an image which correctly duplicates

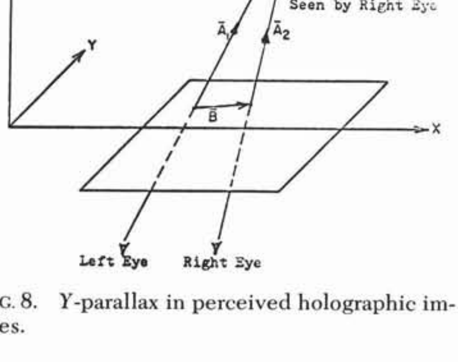


FIG. 8. Y-parallax in perceived holographic images.

the object, its position and orientation may not be correct with respect to a reference system established in the object space. Therefore, for both targeting and mapping, a transformation is necessary to obtain data from the hologram which are referenced to the desired system. If one is interested only in coordinates of selected points, as in targeting and digital mapping, the transformation may be performed computationally after the measurements are obtained from the hologram. The three coordinates of each point in the hologram $\mathbf{x}_i$ could be referred to any arbitrary system in the hologram. Then the required coordinates $\mathbf{y}_i$ may be obtained from

$$\mathbf{y}_i = k\,\mathbf{M}\,\mathbf{x}_i + \mathbf{s} \qquad (1)$$

where k is a scale factor, $\mathbf{M}$ is a 3×3 orthogonal matrix and $\mathbf{s}$ is a 3×1 translation vector. If the internal geometry of the hologram has been recovered sufficiently accurately (as explained above) k should be taken as unity and Equation 1 would express a six-parameter transformation instead of seven. If, however, one has reason to believe that there are some residual distortions in the hologram, the seven-parameter transformation would be better to use. In order to determine the parameters in the transformation, both sets of coordinates $\mathbf{x}$ and $\mathbf{y}$ must be known for a sufficient number of points. Usually more than a minimum would be available and a least-squares adjustment is then applied.

In an actual experiment to determine the accuracy of a holographic image, a test object was first measured directly. Figure 9 shows an arrangement where the object is replaced by its virtual image using a beam splitter. A self-illuminated dot (fiber optic) is moved in the virtual image and its position is monitored and recorded by a three-axis comparator. In this arrangement, a very thin (about 7 μm) pellicle beam splitter is required, otherwise distortions would occur due to refraction through the finite thickness of the beam splitter. If a regular beam splitter is used, the arrangement in Figure 10 would eliminate the distortions by placing the object on the three-axis comparator (such as a Wild A7 carriage) and leaving the fiber optic fixed.

The test object used in the experiment consists of a flat plate with 4 rows of 5 perpendicular dowels of various lengths. The entire object was painted white and discrete points, each 1.0 mm in diameter, were marked in black on top of each dowel. All measurements, except those for the photogrammetric model which are discussed later, utilized the

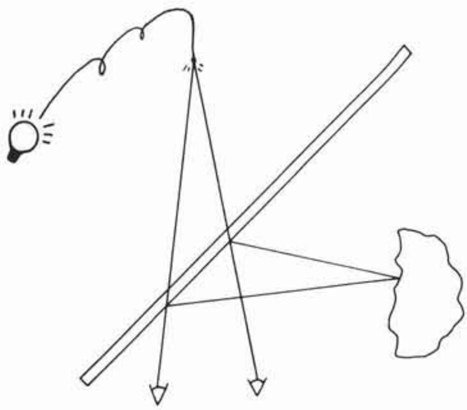


FIG. 9. Measuring the object's virtual image.

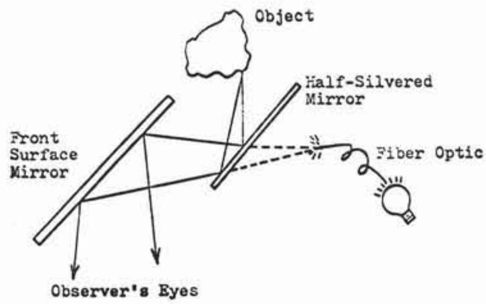


FIG. 10. Measuring the object directly.

Wild Autograph A7 as a three-axis comparator. As the divisions on the A7 are in A7 *mm*, which is scaled to be nominally 0.7 mm; as we need absolute measurements, this scale was calibrated.

In the experiment, the average distance between the observer's eyes and the object was set at about 200 mm. Three observers were selected for obtaining the measurements. Each observer used dowel Number 16 to determine his individual pointing precision by taking 20 observations. The resulting standard deviations are given in Table 2. (The x-axis is parallel to the eyebase, and z-axis away from the observer.)

In addition, correlations between XY, XZ and YZ were computed. The largest correlation was +0.200 which is not significant at the α level of 10 percent. Thus all correlations were assumed to be zero.

Each observer followed the pointing exercise with single observations at each of the 20 points. The experimental apparatus was not changed during the entire measurement process. Thus, if the measurements contained no distortions, the three observers' readings could be combined in the form of a weighted mean. However, the observers had different interpupillary distances which would yield different amounts of distortion. Therefore, a least-squares adjustment was used to determine the best values for the coordinates of the points. The resulting standard deviations for the final object coordinates were 0.023 mm, 0.040 mm and 0.080 mm in the x, y and z directions, respectively.

The six-parameter transformation was used to fit the hologram measurements to direct object measurements. From the transformation residuals, both the F test on the reference variance, and fitting a second-order regression equation on the residuals, showed no significant systematic effects. Therefore, the accuracy of measuring a hologram is at the same level as the precision of pointing.

An example of digital mapping from holograms involved the representation of the two surfaces of a dog bone-joint by a dense set of points. The research involved measuring the angular joint motion of the scapula and humerus of a German Shepherd as the animal walked a treadmill.

An external mechanical linkage with potentiometers was attached to the dog to measure accurately the skeletal movements. Knowledge of how the two bones move, combined with a knowledge of the geometry of the humeral and scapular joint surfaces, can be used to determine the relative motion of these surfaces during walking.

Although the angular motion can be directly measured, the determination of the internal surfaces of the bones at the joint is not a straightforward matter. From a photogrammetric point of view, it is conceivable that these surfaces could be photographed and the resulting stereomodels used for quantitative analysis. However, considering the size of the joint and the large variation in depth compared to the bone size, depth-of-field problems would undoubtedly have been encountered. Consequently techniques which we developed seemed to offer a more feasible solution. Holograms were made directly of the separated bone surfaces and the attached metal potentiometer-mounting blocks

TABLE 2. INDIVIDUAL POINTING STANDARD DEVIATIONS IN MM.

Observer	X	Y	Z
DLG	0.021	0.027	0.055
RAG	0.020	0.031	0.064
JES	0.017	0.050	0.086

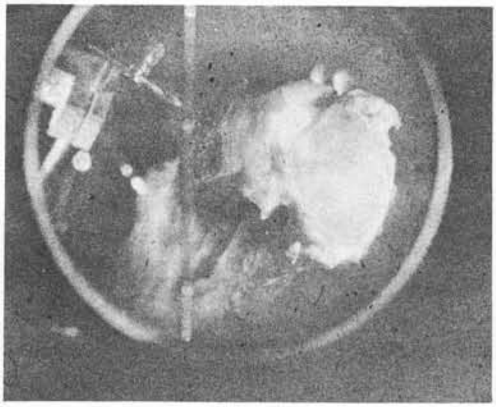


FIG. 11. Holographic virtual image of scapula and mounting block.

which were used for control. Digitized three-dimensional surface information (extracted from the holographic virtual image) was chosen to provide the greatest latitude in later data analysis.

Consideration was first given to the geometry of the control available, the accuracy of the mensuration system, and the problem of discerning a white bone surface during measurement. It was concluded that the required accuracy could be obtained if the bone surfaces were better defined by lightly spraying them with black paint. This allowed recording of the actual bone surfaces after dissection of the joint. Figure 11 shows the holographic virtual image of the scapula and mounting block. Of primary interest was an

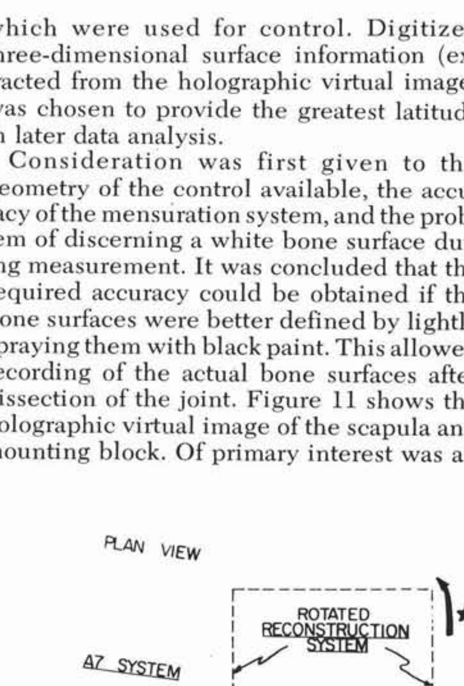


FIG. 12. Hologrammetric absolute orientation.

arthritic blister, for which coordinates were required relative to the mounting block. The coordinates of the mounting blocks were used in a seven parameter transformation, Equation 1, to arrive at the control system.

Further efforts relate to the use of a computer to match the digitized surfaces of the scapula and humerus under varying conditions of angular orientation. Thus the points of contact can be determined as they were when the dog was walking. With a computer display the reconstructed surface of a specific area, such as that of an arthritic blister, can be studied.

MAPPING DIRECT FRESNEL HOLOGRAMS

Although absolute orientation (with or without scale) can be performed computationally using Equation 1, it must be done instrumentally if one desires graphical maps from the holographic image. Such instrumental operation is quite equivalent to absolute orientation of a photogrammetric model in a plotter, except that scale change cannot be effected in the case of a hologram. This reduces the process to only three angles (comparable to common omega, common phi and azimuth in photogrammetry). Two of these (omega and phi) can be accommodated by leveling the reference beam and correspondingly the reconstruction beam. The third angle is accomplished by rotating the hologram-reference-beam assembly about a vertical axis until the hologram datum coincides with the datum required for plotting as depicted in Figure 12. Once this is accomplished, different projections of the object, such as plans, front views, and cross-sections, may be obtained by monitoring the movement of the illuminated dot when it is in apparent contact with the object's holographic image. In a like manner, contour lines can be plotted.

As an example, a toothless dental casting was sprayed black for contrast during recording. Figure 13 shows the results of a topographic map of the casting using a dual plate hologram. After plotting topographic contours, the elevations of selected points were determined from the counters on the A7. If another casting, made at a later time, were also measured at the same points, then one could quantitatively determine gum deformation with time.

The contouring of this object was especially interesting because it is a highly convoluted object. Note that the 6-mm and 8-mm contours pass beneath the others. The profile section *A-A* (Figure 13) shows why this occurs inasmuch as on the left side the higher

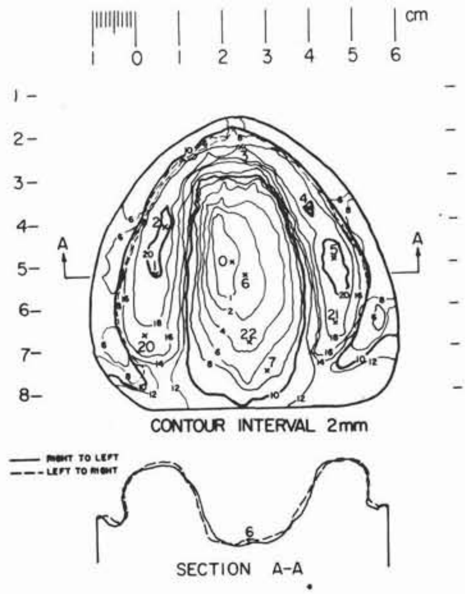


FIG. 13. Hologrammetrically compiled topography of a toothless dental casting.

position extends over the lower part.

Profiling was the most difficult task. If needed as a check, the profile was retraced starting from the opposite side. The dashed line represents the profile from the return plot.

As a final test, one observer (who possesses only one eye) attempted to point and contour the same image. Figure 14 shows effective plotting except in those regions of extremely steep slope. The observer noted that there was never any question as to the shape of the object which he could discern from the image by moving his head about. He could not have used a stereomodel at all because this would require a subjective mental impression formed while simultaneously viewing two separate perspective photographs or projections. This test at least demonstrates the pictorial value of a true three-dimensional image.

Holographic Stereomodels

A holographic stereomodel is a hologram of a restituted photogrammetric stereopair. It may be of the Fresnel or focused-image type.

Fresnel Holographic Stereomodel

Figure 15 shows a schematic of recording a pair of overlapping transparencies. After the appropriate photogrammetric operation (to be explained in a later section), the projected images will form a parallax-free stereomodel in space. A rear projection screen is used both for parallax removal and to become eventually the actual object to be recorded holographically. First, Photo 1 and Reference Beam 1 are used to expose the entire hologram plate. Then Photo 2 and Reference Beam 2 are used to expose *again* the same hologram. Thus, the hologram is actually a double-exposure hologram each of an equivalent photograph of a pair with parallel optical axes. The use of two reference beams is necessary for later image separation upon re-

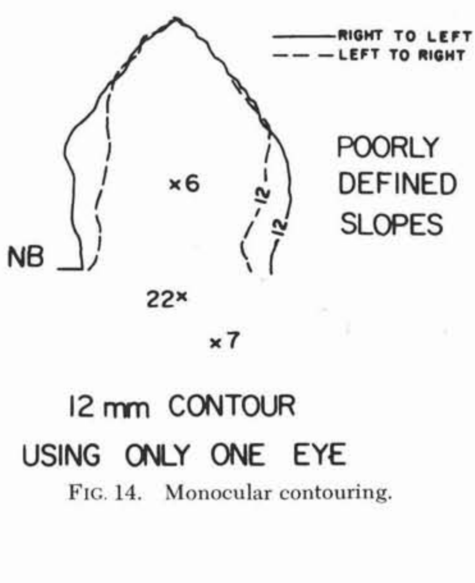


FIG. 14. Monocular contouring.

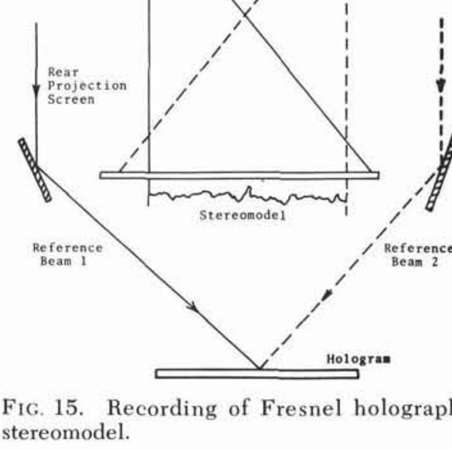


FIG. 15. Recording of Fresnel holographic stereomodel.

construction. A half-wave retarder is used to rotate the polarization of one of the two reconstruction beams by 90°, and orthogonally orientated polarizing filters are used for viewing. These filters may be rotated to effect pseudoscopic viewing for purposes of improving pointing precision. Another scheme, for viewing each photo image by a separate eye, is through selectively illuminating a different portion of the hologram for each eye.

FOCUSED-IMAGE HOLOGRAPHIC STEREOMODEL

The stereomodel is admirably suited for focused-image holography because the object recorded is a plane. Figure 16 shows that the recording arrangement for a focused image holographic stereomodel is identical to the Fresnel type except for replacing the screen by the hologram plate itself. Therefore, the screen is first used in the procedure of parallax elimination, and once the model is restituted the screen is removed, the hologram plate placed in its position and recording made as in the Fresnel case. For reconstruction and viewing, the arrangement is esentially the same as for Fresnel situation except that ordinary white light is used instead of a laser. Image separation for viewing can be done by polarization as before, or by proper arrangement such that at the selected viewing distance each image arrives at a different eye.

The focused image holographic stereomodel has the following advantages: *(1)* use of diffuse white light for reconstruction makes it a simple and less expensive operation; *(2)* removal of speckle associated with coherent illumination; *(3)* reduced reconstruction distortion since the object recorded is a plane (the photograph); *(4)* removal of rear projection screen eliminates potential distortion due to its finite thickness. However, it has some attendant disadvantages if compared to the Fresnel type, stemming from the fact that in focused-image holograms each object point generates only one image point on the hologram. Hence the hologram must be the same size as the area of the photogrammetric model. Also, because of this one-to-one correspondence, any scratch on the hologram's emulsion results in destroying information from the stored model, which is not true for the Fresnel type.

Because of the use of white light the focused-image holographic stereomodel, and particularly the reflection type, is well-suited for display and interpretive purposes. There are presently reflection focused-image holograms of terrain with high efficiency such that they can be viewed in ordinary ambient light. This is an attractive feature for display and training purposes. On the other hand, Fresnel holographic steremodels are better suited for mensuration and mapping as the use of a laser in reconstruction is no problem in the metrology laboratory; they are also usually more stable and exhibit less distortion than the focused image kind.

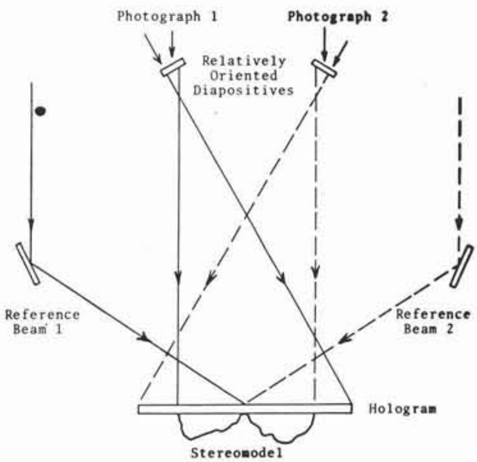


FIG. 16. Recording of focused-image holographic stereomodel.

The photogrammetric operation of model restitution which precedes holographic recording is the same for both types of holographic stereomodel. Model restitution can be effected by relative orientation, either dependent or independent, or a special form of double rectification. A brief discussion of each of these two possibilities follows.

RELATIVE ORIENTATION

Relative orientation of an overlapping pair of photographs is a five-parameter operation leading to a parallax-free model with respect to an arbitrary datum and at an arbitrary scale. Referring to Figure 15, the two transparencies are placed with respect to the projection lenses such that the emerging bundles of rays are geometrically undistorted compared to the original bundles entering the camera (i.e., recovery of interior orientation). If the photographs are illuminated the images projected on the rear projection screen will exhibit both x and y parallax. The x-parallax is removed at each selected point by moving the screen parallel it itself, whereas the y-parallax is removed at each of five points by an appropriate element of relative orientation, which may be either the dependent or independent method.

DEPENDENT RELATIVE ORIENTATION

In this procedure one photograph is fixed, a base component (b_x) is chosen to specify some arbitrary model scale, and the remaining five elements $(b_y, b_z, \omega, \phi, \kappa)$ of the second photograph used to eliminate y-parallax. The projections on the screen are regarded as two new photographs with parallel axes. Let x_f, y_f denote image coordinates on the fixed photograph. Then the corresponding coordinates on the screen are given by:

$$\begin{bmatrix} U_f \\ V_f \\ W_f \end{bmatrix} = \frac{D}{c} \begin{bmatrix} x_f \\ y_f \\ -c \end{bmatrix} \qquad (2)$$

in which c is the principal distance of the original photographs and D is the principal distance of the projected image which is equal to the distance between the projection lens and the screen. For the second (dependent) photograph the coordinates in the screen system are:

$$\begin{bmatrix} U_d \\ V_d \\ W_d \end{bmatrix} = \frac{-D - b_z}{z'} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

where

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \mathbf{M} \begin{bmatrix} x_d \\ y_d \\ -c \end{bmatrix} \qquad (3)$$

with M being the relative orientation matrix relating the system of the dependent photograph to that of the fixed one. The vector $[b_x \; b_y \; b_z]^t$ includes the base components referred to the screen coordinate system. If the newly projected images (with coordinates U_f, V_f and U_d, V_d) are treated as photographs with principal distance of D, their dependent relative orientation would yield the same b_y and b_z as the original photograph. This is an undesirable property if considering relative orientation for holographic stereomodels, which may either limit observer's position or complicate the measuring system.

INDEPENDENT RELATIVE ORIENTATION

This method makes use of two angular elements of one photograph and three angular elements of the other. Let M_1 and M_2 be the orientation matrices of the two photographs with respect to the screen coordinate system; then define the auxiliaries:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_1 = \mathbf{M}_1 \begin{bmatrix} x_1 \\ y_1 \\ -c \end{bmatrix} \quad and \quad \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_2 = \mathbf{M}_2 \begin{bmatrix} x_2 \\ y_2 \\ -c \end{bmatrix}$$

The coordinates of the projected images would then be given by

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix}_1 = \frac{-D}{z'_1} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_1 \quad and \quad \begin{bmatrix} U \\ V \\ W \end{bmatrix}_2 = \frac{-D}{z'_2} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_2 + \begin{bmatrix} b_x \\ 0 \\ 0 \end{bmatrix} \qquad (4)$$

If dependent relative orientation is performed with U_1, V_1 and U_2, V_2 as image coordinates with principal distance of D, the result would be that $b_y = b_z = \omega = \phi = \kappa = 0$. This is truly the normal situation.

DOUBLE RECTIFICATION

Rectification is a possible alternative photogrammetric procedure for producing a pair of projections related according to the normal situation and suitable for holographic recording. A rectified image represents a photograph taken from the same exposure station with a principal point located at the intersection of the projection lens optical axis with the screen, and a principal distance equal to the selected magnification times the principal distance of the original photograph. If the screen represents the object space datum, the resulting rectified photograph would be tilt-free and would represent an equivalent vertical photograph.

For recording a holographic stereomodel, one photograph may be fixed, thus making the screen parallel to its plane, and the second photograph rectified and oriented to it. The orientation operation will involve only three elements which are equivalent to b_y, b_z, and a kappa rotation. This makes it a modified form of dependent relative orientation, which is not desirable for holographic stereomodel recording.

An alternative procedure would be to consider the rectification of both photographs. However, if the two photographs are rectified to a plane parallel to the object space datum (as is normally done using control or photo-data) and they originally had b_y and b_z, the new images will still exhibit b_y and b_z if one is oriented with respect to the other (using b_y, b_z and κ). The only way to obtain projections on the screen with no b_y and b_z, is to position the screen parallel to the space vector representing the base between the photographs. This position would be taken as the easel position, and each photograph rectified to it. Then with one rotation the two photographs may be oriented to each other. This becomes equivalent to independent relative orientation but with the added feature of satisfying the Scheimpflug condition for each photograph. This condition (which states that the photograph, lens, and easel planes must all meet in one line) guarantees that the projected image is in the plane of focus of the lens. This is not strictly the case with regular orientation where the photographic plane and lens plane are parallel. Instead, the projected image (the plane of the screen) is within the depth of focus range of the projection lens. For small tilt angles, as for nominal vertical aerial photographs, this would be acceptable for Fresnel holograms. For photographs with large tilts (for example, convergent photography), double rectification becomes necessary. For focused image holographic stereomodels, double rectification may be the only acceptable procedure if they are used for precision metric work. This is because of the fact that if the photographic and lens planes are parallel to each other but inclined to the hologram plane, the projected image may not collapse on the holographic emulsion and distortions will result. This particular area needs further investigation.

All the above operations have been numerically simulated and tested. The results obtained verified all the assertions given. The operations yielding the strict normal situation are independent relative orientation and double rectification with respect to a plane parallel to the original photographic base.[10]

RECONSTRUCTION OF THE HOLOGRAPHIC STEREOMODEL

As for direct holograms of objects, proper reconstruction is a requisite to accurate mensuration of holographic stereomodels. The presence of two perspective centers and two reconstruction beams makes correct reconstruction and viewing an important operation. In direct holograms, if the reconstruction geometry is exactly the same as the recording geometry, there will be no distortions and the position of the observer would be immaterial. If, however, significant deviations occur between recording and reconstruction geometries, the amount and direction of distortions will depend on which portion of the hologram the observer is looking through. This phenomenon is just as critical for holographic stereomodels as for direct holograms, because in fact the holographic stereomodel is nothing but two superimposed holograms, one for each photograph. The problem is compounded by the fact that the position of the eyes relative to the perspective centers of the recorded images influences the geometry of the perceived model.

Simulation studies showed that, in order to eliminate the dependency of image positions on eye locations, absolute errors in both the horizontal and vertical angles of each of the two reconstruction beams must be each less than 0.2° (the same as for the direct hologram). In addition, however, because essentially two holographic images are being reconstructed, the relative error in the horizontal angles of the two reconstruction beams need to be less than 0.01° in order that y-parallax may be undetectable. Similarly, relative error in the vertical angles of only 0.01° or less can be tolerated. Finally, if one beam's collimation is in error, y-parallaxes are significant, but if compensating collimation errors occur, y-parallax becomes negligible. In the latter situation, however, scale errors result in the model. In general, if $(1/R_c - 1/R_r) < 10^{-5}$, where R_c and R_r are radii of reconstruction and recording beams, respectively, scale errors will be negligible.

A POSTERIORI PARALLAX REMOVAL

One of the advantages of the procedure used in recording the holographic stereomodel is the ability to remove residual y-parallax after the hologram is recorded, i.e., during reconstruction. Although several possible movements can be used for the purpose, a rotation of the hologram plate in its plane is both effective and tolerable. Its influence is similar to that of a b_y base component between the two photographs. Caution should be exercised, however, in employing *a posteriori* y-parallax removal because hologram plate rotation is equivalent to changing the angles of both reconstruction beams which in turn may cause unacceptable distortions.

MENSURATION OF THE HOLOGRAPHIC STEREOMODEL

It has been pointed out that certain tolerances must be met in the reconstruction of holographic stereomodels so that eye movement (i.e., looking through different parts of the hologram) causes no significant shifts in the perceived holographic image. In addition to this possibility, the position of the eye depends on, and has influence on, the type of mensuration technique used. Originally, just as in the case of direct holograms, a single self-illuminated dot was applied. However, even under perfect reconstruction geometry, the location of the observer's eyes with respect to the perspective centers of the two images recorded on the hologram affects the perceived three-dimensional positions. To investigate this influence, a complete analytical and experimental analysis was performed. Basically, if the eyes occupy the exact locations as the perspective centers, a single dot could be used for mensuration without any resulting distortions. As this is physically almost impossible, considering the complexity of the eye's geometry, one must determine allowable eye position variation.

Let e represent eye deviation from the perspective center in any one coordinate x, y, or z (keeping the base at the interocular separation). If x, y, z represent the undistorted coordinates of a point in the model, the error in any one coordinate due to e in the direction of that coordinate is $(e/c)z$, (c is the principal distance) and the other two coordinates will not change. For example, if the eyes are moved a distance e in the y-direction, the perceived y coordinate will be in error by $(e/c)z$, but x and z will be undistorted. On the basis of this, and assuming the screen is placed in the middle of a model relief of 10 percent of the flying height, the maximum z is $0.05c$ and the distortion would be $0.05e$ at a maximum. In order for this maximum distortion to be less than the pointing accuracy, e needs to be less than about 1 mm. This is obviously a very severe requirement on eye position particularly if one considers the complexity of the human eye. Therefore, an alternate more manageable mensuration technique is needed.

DOUBLE DOT MENSURATION SYSTEM

The entire problem with the single-dot scheme arose from allowing the measuring dot to move out of the plane of the images. If two dots, one on each image, are used in the plane of the holographic image (representing the plane of the screen), then eye position will not be important. However, the position of the two dots must be referenced to the perspective centers, which may increase measurement complexity.

If the two images in the holographic stereomodel are related in the strictly normal case (as, for example, with independent relative orientation), model coordinate determination is simplified. These coordinates may be obtained from:

$$X = x_{o1} + \frac{b_x (x_1 - x_{o1})}{b_x + x_1 - x_2} \qquad (5)$$

$$Y = y_o + \frac{b_x (y - y_o)}{b_x + x_1 - x_2} \qquad (6)$$

$$Z = D \left[1 - \frac{b_x}{b_x + x_1 - x_2} \right] \qquad (7)$$

where X, Y, Z are the model coordinates for any point whose coordinates are (x_1, y) and (x_2, y) on the two projected images, respectively. Note that as these two images are according to the normal case, the y-coordinates of both conjugate images are equal. The base separation between the perspective centers is b_x which is equal to $(x_{02} - x_{01})$. x_{01}, x_{02}, y_0, D are the elements of interior orientation for the two images projected on the screen.

All coordinates in Equation 5, 6 and 7 are referred to one and the same coordinate system whose X, Y axes lie in the plane of the screen and its X-axis is parallel to the new image base. It is clear from these equations that the principal points of the projected images (x_{01}, x_{02}, y_0) as well as the new principal distance, D, are necessary to accomplish accurate mensuration. These can be recovered during recording using either a mask or actual marking of the principal points, and calibrating the distance between the projection lens nodal point and the screen when independent relative orientation is accomplished.

Another factor which merits consideration is the convergence angle in viewing a holographic stereomodel. Considering as an example the case of unaided viewing, Figure 17 depicts two arrangements, one with the model behind and the other in front of the screen. (Placing the model about the screen makes the double dot system unduly complicated.) For natural viewing, the convergence

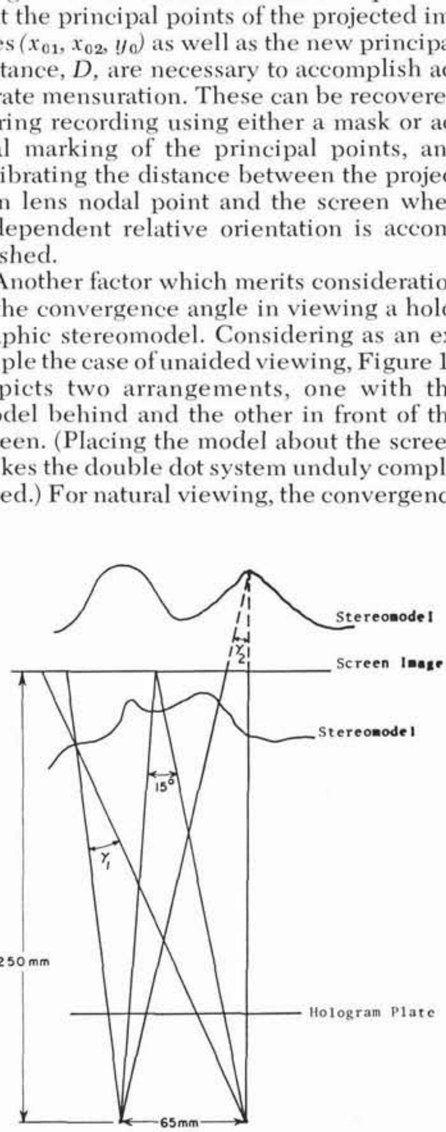


FIG. 17. Convergence angle versus model position.

angle is usually 15° or less, and therefore the model should be placed behind the screen.

EXPERIMENTAL MENSURATION OF THE FRESNEL HOLOGRAPHIC STEREOMODEL

The test object, of which the direct hologram was made, was used in the laboratory to obtain a pair of overlapping photographs on the same negative glass plate. This eliminates the necessity for relative orientation, as the plate is placed back and projected through the photographing lenses for holographic stereomodel recording. To verify the conclusions (which were obtained on the basis of simulation analysis) about single-dot mensuration the procedure of using the single dot was used on this actual holographic stereomodel. From 20 repeated observations on one well-identified point, standard deviation scaled to represent all points in the test model are $\sigma_x = 0.111$ *mm*, $\sigma_y = 0.166$ *mm*, and $\sigma_z = 0.288$ *mm*. Obviously these are considerably larger than the case of a direct hologram. Furthermore, a six-parameter transformation of the holographic stereomodel to the calibrated object points resulted in an excessive reference variance value (up to 27.34) *vs.* an *a priori* value of 1, and maximum residuals of $v_x = 0.4$ *mm*, $v_y = 1.0$ *mm* and $v_z = 3.3$ *mm*. Such values completely rule out the single-dot system.

Double-dot analysis was possible only through simulation because time was not available to build a prototype. Each image was measured separately and model coordinates computed as shown by Equations 5, 6, 7. The accuracy of the fitting of these coordinates to the object were $\sigma_x = 0.037$ *mm*, $\sigma_y = 0.037$ *mm*, $\sigma_z = 0.190$ *mm* which compare quite favorably to the results of strictly photogrammetric techniques which gave $\sigma_x = 0.030$, $\sigma_y = 0.030$, $\sigma_z = 0.115$ *mm*. There was some indication of residual systematic errors in the holographic stereomodel but more experimentation, preferably with an actual prototype, is advised before one can draw firm conclusions. However, it is obvious that pointing, mensuration, and targeting are feasible using two dots in the plane of the screen image. The coordinates of these two dots as an aggregate, as well as their physical separation (which would change from point to point in the model) would yield the Cartesian coordinates of any model points.

MAPPING THE HOLOGRAPHIC STEREOMODEL

As there is no prototype instrument with a two-dot measuring system, a photogrammetric plotter (Wild A7) was modified and a single self-illuminated dot used to plot a topographic map from a holographic stereomodel. It should be emphasized that this was done to demonstrate the feasibility of mapping from such models. As for direct holograms, the holographic stereomodel must be transformed in order to bring its sys-

FIG. 18. A stereopair containing an explosively produced crater.

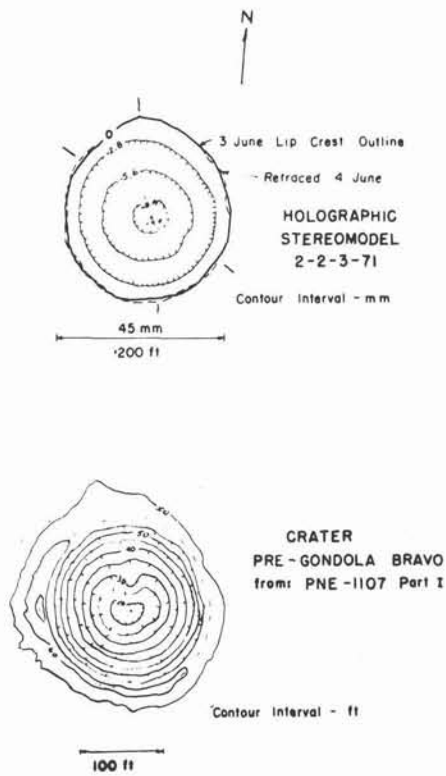


FIG. 19. Comparison of hologrammetric and photogrammetric contours of crater in Figure 18.

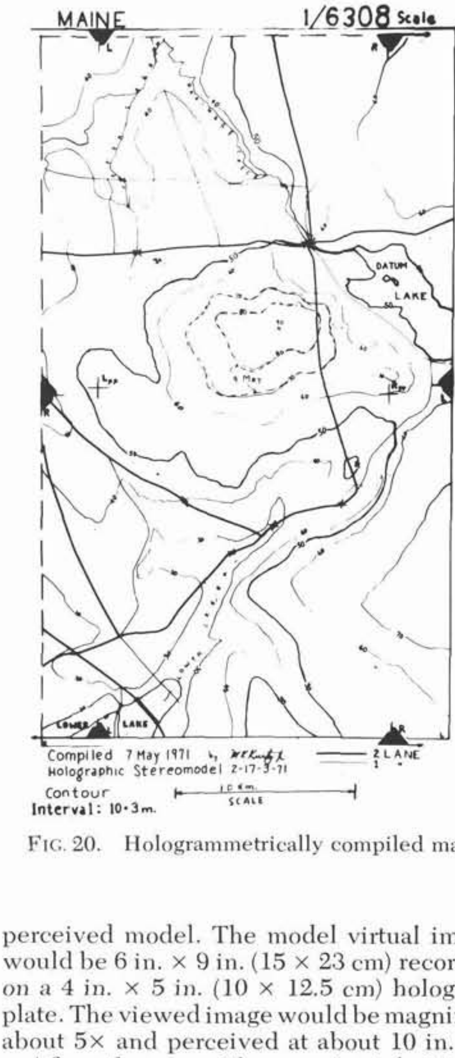


FIG. 20. Hologrammetrically compiled map.

tem parallel to the instrument datum. This makes plotting meaningful, and requires knowledge of ground control in the model to be plotted. Figure 18 shows an overlapping pair of aerial photographs which contain an explosively produced crater (Pre-Gondola Bravo). Figure 19 shows a comparison between contours plotted from the holographic stereomodel, and those produced by photogrammetric technqiues using the same photography. Figure 20 is an early result of a topographic map from a holographic stereomodel. Some contour lines (dashed lines in the figure) were plotted two days later to determine reproducibility. Taking the map of Figure 20 as a demonstration of potential, there should be little doubt that accurate maps can be obtained from holographic stereomodels using an instrument which employs the two-dot system.

In all tests performed, the holographic stereomodel was viewed either by unaided eyes or through a hand-held large magnifying lens. In the design of an actual mensuration system one would incorporate separate eyepieces and allow for magnification of the perceived model. The model virtual image would be 6 in. × 9 in. (15 × 23 cm) recorded on a 4 in. × 5 in. (10 × 12.5 cm) hologram plate. The viewed image would be magnified about 5× and perceived at about 10 in. (25 cm) from the eye, with approximately 2 in. (5 cm) diameter field of view.

These are the initial design parameters considered for a prototype mensuration and plotting equipment from the holographic stereomodel. Preliminary study indicates that, although some optical problems are yet to be solved, a special plotter for use with holographic stereomodels is a feasible proposition which is expected to be less complex than heavy photogrammetric plotters.

AUTOMATION IN HOLOGRAMMETRY

Coherent optical techniques can be applied to photogrammetric mapping systems insofar as correlating conjugate images. Balasubramanian[11] is credited with introducing the technique of coherent optical heterodyning to this field. Coincidence detection of conjugate imagery may be effected through the use of the normalized cross-correlation coefficient.[12] Such a detection performed in an automatic mode would lead to rapid extraction of contours or cross-sections.

As the author sees it, correlation may be performed either in the image space or in the model space. Operating in image space requires input imagery in a form equivalent to purely vertical photography (i.e. taken according to the normal situation) and yields *perspective* contours. Such contours would require further reduction in order to convert them to orthoscopic form. By contrast, performing correlation in model space would yield orthoscopic contours directly. In this application a holographic stereomodel is most suitable to operate with. However, due to the relatively high convergence angle between pairs of conjugate rays, some means is needed to bring them to be parallel before heterodyne detection. Several methods are potentially feasible for this purpose and are presently being evaluated.

Different aspects of automated hologrammetric systems are being actively studied at the present time. It is anticipated that a suitable system will be forthcoming. Therefore, details of automation in hologrammetry are left for a future consideration.

Conclusions

The different aspects of this paper can be considered as activities of a relatively recent interdisciplinary field called hologrammetry. It combines the techniques of photogrammetry and holography. Although consideration has been given to the application of photogremmetric methods and optical holography, the future may certainly bring other types of holography and procedures of coherent optics into this field.

Direct holograms of objects are useful recording alternatives to regular photogrammetric models. They may be used for objects measuring a few inches in each of three dimensions suitable for 1:1 scale recording. Objects of complex shapes are better suited for holographic recording where vertical plane mirrors may be placed around the object in order to record otherwise blind spots. Both measurements and mapping can be readily performed on holograms.

The holographic stereomodel (Fresnel or focused-image) stores and allows the retrieval of three-dimensional information; it is at an advanced stage of processing compared to aerial photographs. This type of display offers distinct advantages for qualitative, interpretive, and training purposes, particularly if the focused-image process is used. For quantitative uses it also affords the user access to the three-dimensional model which has heretofore been confined to the photogrammetric laboratory.

One distinct advantage of the Fresnel holographic stereomodel results from the information storage capacity of a hologram. Not only can the equivalent of one pair of photographs be stored on one hologram plate in the proper geometric relationship, but also several stereomodels could be stored on the same hologram plate (multiplexing). One possible technique of storing models is to use only two small areas of the hologram plate for each model.

Another advantage of the holographic stereomodel is the expected simplification and ensuing economic savings in instrumentation for its mensuration and mapping. Although the equipment for its recording would, by necessity, be sophisticated and extensive, mensuration and mapping are by contrast much simplified. Systems for extracting digital or graphical information from holographic stereomodels require essentially an instrument of the type used with terrestrial normal-case photographs. This kind of instrument is considerably less complex and less expensive than regular plotters and requires operators with minimal photogrammetric training. Consequently, one can envision a central well-equipped facility for the production of holographic stereomodels, serving many smaller less expensive satellite mensuration and mapping stations.

The holographic stereomodel concept also offers unique advantages for subsequent automated data processing. Its configuration makes it adaptable to interferometric correlation techniques for automatic contouring or profiling, particularly when applying heterodyne detection.

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REFERENCES AND BIBLIOGRAPHY

1. Kellie, T. F. and Stevenson, W. S., "Experimental Techniques in Real Time Holographic Interferometry", *Optical Engineering*, 12:2, 1973.
2. Mikhail, E. M., and Glaser, G. H. "Mensuration Aspects of Holograms", *Photogrammetric Engineering*, 37(3): 267-276, 1971.
3. Glaser, G. H. and Mikhail, E. M., "Study of Potential Applications of Holographic Techniques to Mapping," Interim Technical Report, December 1970. ETL-CR-70-8. (AD718084).
4. Kurtz, M. K., Balasubramanian, N., Mikhail, E. M., Stevenson, W. H., "Study of the Application of Holographic Techniques to Mapping", Final Technical Report, October 1971. ETL-CR-71-17, (AD734327).
5. Agnard, J. P., "Hologrammetrie: tolerance de L'orentation Relative des Hologrammes pour Fines de Mesures," Master of Science Thesis, Laval University, Quebec, Canada, December 1970.
6. von Berckefeldt, P., "Versche zur Herstellung, Rukonstruktion und Ausmessung von Hologrammen," *Wissenschaftliche Arbeiten* Nr. 44, der Lehrstuhle für Geodäsie, Photogrammetrie und Kartographie an der Technischen Universität Hannover, West Germany, 1970.
7. Gifford, D. L., and Mikhail, E. M., "Some Close-Range Mensuration Techniques," paper presented to the Fall Convention of the American Society of Photogrammetry, Orlando, Florida, October 1973.
8. Agnard, J. P., "Hologrammetrie de Haute Precision," presented paper to Commission V, XII International Society of Photogrammetry Congress, Ottawa, Canada, August 1972.
9. Gifford, D. L., "Perceived Holographic Image Distortion," presented paper, Coherent Optics in Mapping Seminar, Society of Photo-Optical Instrumentation Engineers (SPIE), Rochester, N.Y., March 1974.
10. Gifford, D. L. and Mikhail, E. M., "Study of the Characteristics of the Holographic Stereomodel for Application in Mensuration and Mapping," Final Technical Report Part I, July 1973, ETL-CR-73-14.
11. Balasubramanian, N., "Coherent Optics in Photogrammetry" tutorial notes, Coherent Optics in Mapping Seminar, SPIE, Rochester, N.Y., March 1974.
12. Balasubramanian, N., "Image Coincidence Detection Using Optical Correlation Techniques," Coherent Optics in Mapping Seminar, SPIE, Rochester, N. Y., March 1974.

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