Incoherent holography

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ABSTRACT

Dennis Gabor invented in-line holography in 1947, but at that time the coherent light from a laser did not yet exist and therefore the holograms he produced were of very low quality. When the laser was born in 1960 beautiful 3-D off-center holograms were for the first time produced by Emmett Leith and Juris Upatnieks. However, already as early as 1934 the inventor and artist Hans Weil patented a method to produce simple pictures that appeared floating in space, by scratching a transparent or metallic surface in certain directions. In 1995 William J. Beaty published a method for "Hand-Drawn Holograms". Then it became possible for any artist to draw his own 3-D pictures of simple objects and using his ingenuous techniques these hand drawn images will mimic many of the qualities of ordinary holograms.

Keywords: Holography, Coherence, Diffraction, Scratches.

1. INTRODUCTION

Hologram means "whole writing" stating that the total information of an image is included in the holographic image. The introductory, fundamental holographic experiments in 1947 by Dennis Gabor where hindered by the lack of a sufficiently coherent light source.[1] However as soon as the laser arrived it became possible in 1960 for Emmett Leith and Juris Upatnieks to produce perfect beautiful three-dimensional off-axis transmission holograms.[2] Using the coherent laser light for recording and reconstruction the quality of these holograms is astonishing. They are so perfect that some measurements can be made in the holographic image of the object with an accuracy of a fraction of a thousand of a millimeter. Another early development was made by Yuri Denisyuk [3] who invented the reflection or Lippmann hologram, which can be reconstructed by white light, because the hologram itself works like a interference filter that selects one single wave length. However, for ordinary imaging purposes such an accuracy is not at all needed and therefore much work has been made to lower the quality of holography by sacrificing some of its properties and thereby simplify and cheapen its recording and especially its reconstruction.. One such example is the rainbow hologram, which was presented by Steve Benton.[4] This hologram works during reconstruction like a grating spectroscope that by diffraction selects one single wavelength. However to gain this result the vertical parallax is sacrificed.

The above holograms all need coherent light for the recording, but there are also other types that can both be recorded and reconstructed without coherent light, however they usually have an intermediate step where coherent light is needed. These are the multiplex holograms where the object is photographed from many horizontal directions after which every photo is holographically recorded in the form of a thin vertical stripe. By combining these holograms a new hologram is formed that has stepwise horizontal, but usually no vertical, parallax.[5] The method can, however, also produce stepwise vertical parallax but in that case the object also has to be photographed from many vertical directions and the thin vertical holograms are broken up into small square holograms, pixels.[6] Finally both ordinary holograms and multiplex holograms can be produced by computers in which case neither coherent light nor a real object is needed for recording.

However, parallel to these developments artists have worked on simpler ways to produce virtual 3-D images. Already as early as 1934 the inventor and artist Hans Weil patented a method to produce simple pictures that appeared floating in space by scratching a metallic or transparent surface in certain directions.[7] His Patent [8] of December 1934 "Improvement in Advertising and the like Signs" describes methods of producing "directive reflections by grooving a metal surface or transparent sheet of glass"... "Each set of information becomes visible only when the surface is illuminated from particular

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direction." In modern holography this is expressed by saying that the various hologram images must be reconstructed with light from different directions. The patent also points out: "Different sets of information to be visible only from specific angles of observation, and that it is thus possible to produce stereoscopic images which have a three-dimensional effect without any need for the observer to be equipped with special glasses or the like"...It is also pointed out that "the grooves can be made extremely small, e.g. consist of the scratches caused by grazing with sandpaper or the like." The patent further states: "The reflecting groups of surface elements may represent stereoscopic pictures or moving phases so that by simultaneous or successive stereoscopic or kinematographic effects respectively can be obtained." The latter method appears to be a direct forerunner of modern multiplex holograms. Finally Hans Weil also describes a directively reflecting screen made up of squares in a similar way as the partial pixels of some modern embossed holograms [6]. Thus, the impression is that the artist Hans Weil´s invention of 1933 represents a type of incoherent holography in which the actual exposure stage is missing.

In 1995 William J. Beaty published a method for "Hand-Drawn Holograms".[9] Apart from hand-drawn holograms he proposes the following names: Giant-fringe holography, nondiffractive holograms, single-fringe holograms, scratch-o-grams, holosketches, wire-brush holograms, incoherent holograms, phonograph holograms, car-hood holograms. The last name because he got inspired to the idea when he noticed a number of glowing highlights created by the sunlight on the hood of a black station wagon. The owner of the car had obviously polished the hood with a dirty rag, and the particles of grit in the rag traced out scratches in the black paint that produced highlights in the form of hands that appeared to float in font of or behind the surface.

The technique invented by Beaty is based on drawing holograms directly by hand using a set of dividers (a compass with two points). As far as I know it has not been published in an ordinary journal but only on his web site. [9] By scribing arcs of circles on a piece of plexiglass (PMMA) he has managed to produce three-dimensional images of letters, cubes, pyramids and holes with glowing stars at the bottom. The appearance of his holograms has similarities to ordinary holograms in that they can show both an orthoscopic virtual image behind the plate and a pseudoscopic image in front. They have a parallax that is slightly limited in a way similar to that of rainbow holograms. He concludes that the hand-drawn holograms work very much like the rainbow holograms which function for many wavelengths and thus are not restricted to certain fixed separations of their grating lines.

Using Beaty´s technique, which I chose to name scratchograms, it has now become possible for any artist to draw his own pictures of simple objects that mimic many of the qualities of ordinary holograms. The method appears not to have reached the attention it deserves and therefore I will give some information about its possibilities and limitations.

2. COHERENT COMPARED TO INCOHERENT HOLOGRAPHY

In this paper we will define coherence in the following way. When light from a single source is split into two beams which are later combined these two beams will by constructive interference produce brightness, or by destructive interference produce darkness depending on their relative phases. If the path length difference between the two beams is many wave lengths only coherent light can produce fixed interference lines or points of darkness.

The most stringent interpretation of the word hologram is that it is able to reconstruct both amplitude and phase of the recorded light waves. Another, more popular, interpretation is that in a holographic plate the information about the object is evenly distributed over the whole area of the plate. The incoherent holograms to be discussed here do more or less fulfill the latter condition but not the former as the phases are not recorded.

In Fig.1 we see one of many different configurations that can be used for the recording of ordinary holograms. They are all based on the coherent interference of object beams with the reference beam. The light from each object point (O) interferes with the light from the reference point source (R) and produces a set of bright and dark curves in the form of rotational hyperboloids with (O) and (R) as focal points. Hologram plates at different positions will all be intersected by these hyperboloids and the more or less circular curves thus produced on the plates are after processing used to reconstruct the object points. Every line of intersection has such a direction, curvature and separation to its neighbor that light is thrown from (R) to (O) by reflection, diffraction and interference. Thus, the position is very well determined by these three factors, perhaps so over determined that e.g. reflections from single lines could be enough to produce at least an approximate image of the object.

3. REFLECTIONS FROM SINGLE CIRCLES

I suppose that most of you have seen on the windscreen of your car a bright line stretching out in space from the rotation axis of your wiper to the sun as described in page 86 of Ref. 10. This line is formed by incoherent diffraction from all the circular scratches caused by the wiper. Bright spots or highlights are seen where these scratches are tangent to one of a set of rotational symmetric ellipsoids having the sun as one focal point (A) and your eye as the other (B). The reason why brightness is seen at these points is that if the inside of the ellipsoid is mirror like it will reflect (and focus) light from (A) to (B). Thus, any part of a scratch on the windscreen that happens to be parallel to the intersection of that screen by one of the ellipsoids will be reflected to your eye and thus appear bright. The mentioned ellipsoids are identical to the ellipsoids of the "holo-diagram" that are used as tools to optimize holograhic recordings, to evaluate holographic interference fringes, to explain apparent distortions of wavefronts and to visualize relativistic effects.[10]

Take a piece of plexiglass and draw a circle using a pair of dividers (F of Fig.2). It is important that the separation of the legs can be adjusted by a screw and that both legs are equipped with steel points. The force on the dividers should be very low so that no noise is heard and so that the line that is formed is almost as thin as a hair.[9] It should be almost invisible and not scatter light at all angles but only reflect the light in certain directions. Look through the plexiglass, which we in the following name the plate, towards a point source of light (A), e.g. a spotlight. If the spotlight is seen exactly in the center of the drawn circular scratch the whole circle will appear bright. If the spotlight is above the circle and slightly to the left only two points of the circle will appear bright, namely one close to the top (D), where the circle is illuminated from outside, and one at the bottom (E) where it is illuminated from inside. The one on the top will appear to be behind the screen (as focused by a convex mirror) while the other will appear to be in front of the screen (as focused by a concave mirror).

Another way to understand the parallax that causes this 3-D effect is that if you move your head to the right, the view of the spotlight through the plate will move to the right and thus the point (D) will also move to the right and thus appear to be behind the plate. To the point (E) the situation will be the opposite. The larger the radius C-D the further away from the plane of the plate will the points (D) and (E) appear. If the radius is zero they will of course both appear at the surface of the plate. If a set of concentric circles around (C) are drawn, an approximately straight line will appear in space. This line passes through (D) in front of the plate, through the plate at (C) and at (E) behind the plate. (For exceptions see Ref. 10 pages 185 - 197. Thus, the image of the object point (C) will at (D) appear at the distance (d) behind the plate and at (E) and the same distance in front at (E). However, the parallax will be at maximum as we move our eye along a line perpendicular to the AE ($\beta = 90^\circ$ in Fig 2) but zero for movements parallel to AE. Thus:

$$d = R \sin \beta / \mathrm{tg}\, \alpha \qquad \text{(eq. 1)}$$

Where (d) is the apparent distance from the plate surface, R is the radius of the circle, α is the angle between the surface normal and illuminating light rays while β is the angle between AE and the line along which the parallax is studied (CG). Thus, to get not only horizontal but also vertical parallax the line AC of Fig.2 should differ from the vertical.

The result will be the same whether the plate is made of transparent materials like plexiglass or of reflective materials such as metals or black plexiglass. When the image is reconstructed in reflection the point (A) represents the reflected image of the reconstructing light source. The main observable difference is that when the reflection hologram is tilted the reconstructed image is tilted too, while in a transmisson hologram it is rather insensitive to tilts.

The described effect can be seen when a gramophone record or a CD-disk is illuminated by a point source. [11, 12] In the following we will name it an incoherent zone plate which focuses a point source into a focal line, similar to the fuction of axicons and other optical devices that produce "non diffractive beams". The corresponding coherent zone plate, the Fresnel's zone plate, focuses a light beam from a coherent point source into two focal points, one in front and one behind the plate. These points (sometimes more than two) will be positioned on the same line as the focal line of the incoherent zone plate. Thus, if you look towards the coherent Fresnel's zone plate you see two bright images of a coherent point source, one in front and one behind the plate. If you look towards the incoherent zone plate you see a bright line trough the center of the zones and directed towards the point source. Finally, if you look towards one single circular scratch you see again two bright points, one in front and one behind the plate.

4. HOW TO PRODUCE THE SCRATCHOGRAM

Now we are ready to show in a diagram how to produce a hand drawn image of the letter (L) as seen in Fig.3a. For the actual drawing of the scratchograms we use the method introduced by William Beaty [9] , while for their explanation we use diagrams based on Ref. 10 pages. 86, 185-197.

Draw the letter (L) which we name the master image on a transparent plate. Center one circle at the top of the (L), another at the corner and finally a third circle at the extreme right of the horizontal leg, all the circles with the same radius (R). Then draw lines from the image of the spotlight (A) through each of the circle centers. The points where these lines intersect the circles from outside produce a virtual image (V) of the (L) which appears behind the plate, while the inside intersections produce a conjugate image (P) which appears to be in front. They correspond to the orthoscopic respective pseudoscopic image in ordinary holography. There is no doubt that the image (P) of the hand drawn hologram is pseudoscopic as it appears inside-out, but it differs from that of ordinary holography in that it is parallel to both the master image and to the virtual image instead of being rotated by 180 degrees as seen in Fig.3b. The reason is that in Fig.3b (V) and (P) are on opposite sides of (A) while in Fig.3a they are on the same side, which also has the positive result that the image which appears to be closer to the observer also appears larger. (If the image of the lightsource (A) of Fig.3a is positioned somewhere inside all the circles, both images will become pseudoscopic and one might be the mirror image of the other. However in that case the distortions are so severe that such a configuration is of no practical use. Thus, a straight line might even be deformed into a closed loop similat to the caustic formed by the reflection from the inside of a napkin ring.

In Fig.4 we see a photo of the resulted hand-drawn hologram reconstructed by a spotlight. The master image (L) was first scratched with a sharp point. Then we fixed the separation (R) of a pair of dividers to be slightly larger than the size of the (L) which was about 20 x 30 mm. One circle was drawn at the top of the (L) then the center was stepwise moved downwards about half a millimeter at the time, making a set of circles until it reached the horizontal leg of (L). Finally we did similarly along the horizontal leg of (L). All reconstructed images were photographed using a CCD-camera and then filtered for increased contrast and reduced noise.

Figs.5 and 6 were made to show the 3-D effect of the scratchogram. The letter K was scratched with a radius of 35mm, T with a radius of 45 mm and H with a radius of 55 mm. Thus, all reconstructed letters appeared separated in depth with H furthest away. In Fig.5 we see KTH photographed from the front and easy to read. In Fig.6, however, they were photographed from the left and therefore the letters covered each and became totally illegible.

5. DRAWING A CUBE

To demonstrate the possibilities and especially the limitations of scratchography we will now make the diagram of Fig.7, which shows how to draw a three-dimensional cube half of which should appear behind, the other in front of the plate. We start by drawing the master image in the form of a square. Along each side we draw circles with a radius (R) of about one quarter of the length of the side of the square. When illuminated from the top these circles will produce two squares one will appear higher up and behind the plate and the other further down and in front. Then, at each corner draw a set of concentric circles with radii from zero to (R). The result will be lines in space stretching from each corner of the front square through the master square to the back square. One could say that we have drawn "Huygens wavelets" from each point of a cube.[12]. These spherical waves will of course intersect the plate in the form off circles with larger radii the further away the points are.

When the plate is illuminated from behind and the spotlight is seen at (A) the perceived image is constructed, as shown in the diagram of (Fig.8). Using the methods of Fig.3a, lines are drawn from (A) through each of the centers of the circles. Connecting the points of intersection of these lines by respective circle produces the sides of the cube. From Fig.8 it is seen that the image of the cube is slightly deformed because the point (A) is not at infinite distance. The closer (A) is the more deformed appears the cube.

In Fig.9 is seen a photo of the cube reconstructed from the scratchogram by a spotlight The master was made by drawing or scratching a square with a size of about 60 mm x 60 mm on a plate. Circles with a radius of about 15 mm were then drawn along each side of the square. Finally, at each corner a set of concentric circles with were drawn with radii increasing in steps of about 0,5 mm from 3 to 15 mm. The resulting reconstruction shows that there is a slight deformation corresponding to the prediction of the diagram in Fig.8. These distortions are accentuated in the diagram of Fig.10 and the photos of Fig.11 and 12 where the illumination point (A) was closer to the cube and the photos were taken from the left and right respectively. Finally in the diagram of Fig. 13and 11 the cube has totally changed shape because (A) is too close to the circles, it is even inside the master. However, by instead keeping the image of the light source (A) far from the master image the distortions are usually acceptable and hardly discernible.

6. CONCLUSION

To make ordinary holograms one usually needs a darkroom, vibration insulated table, laser, hologram plates, optical components and liquids for processing which all together is rather complicated, cumbersome and above all expensive. To make a scratchogram all that is needed is a plate of suitable material e.g. transparent or black plexiglass, a pair of dividers, inspiration and a lot of patience. Thus the method described here is very suitable to artists and retired professors and could just as well be named "Poor mans hologram". The image can be reconstructed both in transmission or in reflection. Just like ordinary holograms the scratchogram produces a three-dimensional image, like rainbow holograms it can be reconstructed by white light and unlike the rainbow hologram it can have both horizontal and vertical parallax. The angle of view is in the scratchogram limited because at some angles the distortion of the image is too severe. However, this is also true for many ordinary holograms.

Like ordinary holograms it produces two conjugate images, one of which is orthoscopic and behind the plate, while the other is pseudoscopic and in front of the plate. Unlike in ordinary holography the pseudoscopic image is not rotated by 180 degrees. If the latter image is not wanted the full circles should not be drawn but only that part which is reconstructed from the convex side.

As in most holography one image is reconstructed is by each illumination beam. Thus, the images can be multiplied by using more than one spotlight. Color scratchograms can be reconstructed by illumination from different angles with spotlights of different colors. As pointed out by William Beaty the ideas of the scratchograma could probably inspire to simplifications of ordinary computer generated holograms. They can of course also be embossed using the same, or most likely much simpler, methods as ordinary holograms. Finally, for those who do not have the patience for making the hand-drawn holograms there are of course all the possibilities of using numerically controlled machine tools, e.g. vertical milling machines, to produce the scratches needed for the scratchogram [14, 15]. In that case the hologram could even be just a byproduct in industrial machining of ordinary metal surfaces.

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REFERENCES

1. D. Gabor, "A new microscopic principle," Nature, London, 161, 777-778 (1948).
2. E. N. Leith and J. Upatnieks, "New techniques in wavefront reconstruction," J. Opt. Soc. Am. 51 1469 (1961).
3. Yu. N. Denisyuk, "Photographic reconstruction of the optical properties of an object in its own scattered radiation field," Soviet Physics-Doklady 7, Nr. 6, 543-545 (1962).
4. S. Benton,"Hologram reconstructions with extended light sources," J. Opt. Soc. Am. 59, 1545A (1969).
5. D. J. De Bitetto, "Holographic panoramic stereograms synthesized from white light recordings," Appl. Opt. Vol. 9, 1740 (1969).
6. J. H. Kulick, "Partial pixels: a three-dimensional diffractive display architecture" J. Opt. Soc. Am. A, Vol. 12, No. 1, 73-83 (1995).
7. N. H. Abramson, "The inventor Hans Weil as a pioneer of holography," Holography-Yearbook 1989/90, c/o Rita Wittig Publishing, Germany.
8. H. H. Weil, "Improvements in advertising and like signs," UK Patent No. 37208/34 (1934).
9. W. J. Beaty, 7040 22nd Ave. NW, Seattle, WA 98117, USA, "Hand-drawn holograms, " Website http://www.amasci.com/amateur/holol.html
10. N. H. Abramson, *Light in flight or the holodiagram the Columbi egg of optics*, SPIE Press Vol. PM27, page 86 (1996).
11. Jearl Walker, "What do phonographic records have in common with windshield wipers?," Scientific American, Vol. 261, No. 1, 106-109 (1989).
12. P. A. Tippler, *College Physics*, Worth Publishers, Inc, page 406 (1987)
13. J. B. Lott, "Reflections on a gramophone record," Mathematical Gazette Vol. 47, No. 360, 113-118 (1963).
14. W. J. Siemens, "Experimental production of synthetic holograms, "Appl. Opt. Vol. 7, No. 3, 535 (1968).
15. W. Plummer and L. Gardner, "A mechanically generated hologram?," Appl. Opt. Vol. 31, No. 31, 6585-6588 (1992)

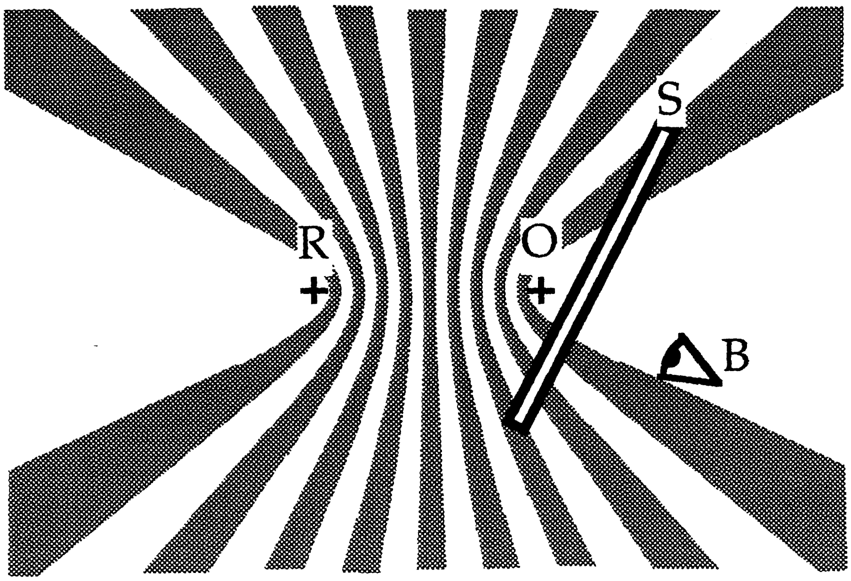
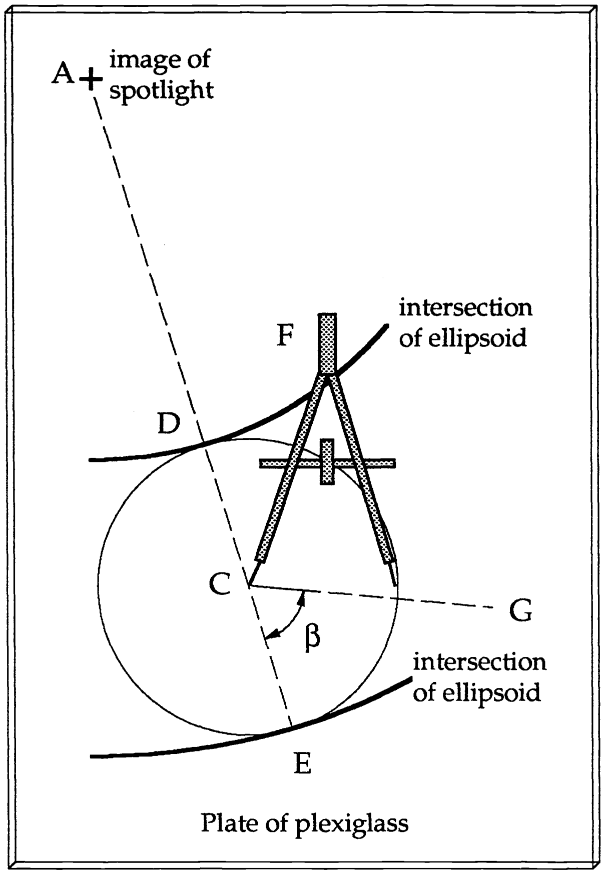


Fig.1. Example of one of many possible configurations for the recording of an ordinary hologram. (O) is one point on the object illuminated by laser light, while (R) is the point source of reference light. The mutually coherent (O) and (R) produce by interference a set of bright and dark rotational symmetric hyperboloids with (O) and (R) as focal points and OR as rotational axis. The hologram plate (S) records the intersection of these hyperboloids.



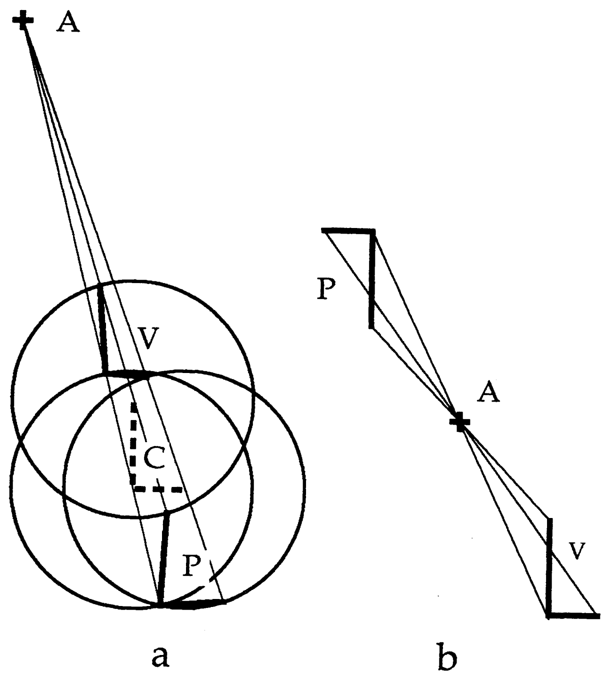
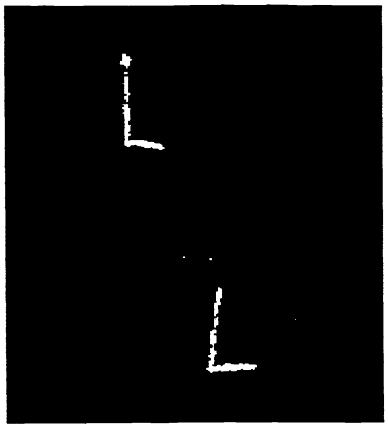
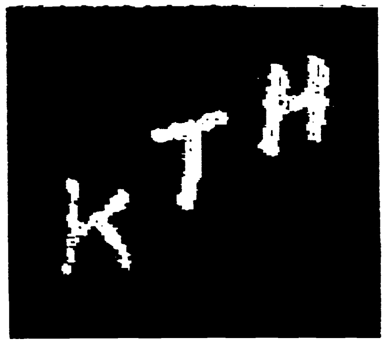


Fig.2. A pair of callipers (F) is used to scratch a circle on a plate of plexiglass. (A) is the image of a spotlight as seen through the plate. Two bright reflections are seen at the scratched circle where it is tangent to one of a set of rotational symmetric ellipsoids with (A) as one focal point and the eye of the observer as the other. As the observing eye is moved along a line CG the point (C) will be fixed to the plate while (D) will appear behind and (E) will appear in front.

Fig.3. A scratched hologram, a scratchogram, of the letter (L) is made (Fig.3a) by drawing a set of circles with constant radius. In this diagram one circle is centered at the top, another at the corner and a third to the right of the master image (L). Lines are drawn from the spotlight through each circle center. Where these lines intersect respective circle the two conjugate reconstructions of the (L) are found. The virtual image (V) appears behind, while the pseudoscopic (P) appears in front of the plate. In ordinary holography (V) and (L) are rotated in relation to each other, but in the scratchogram they are not.





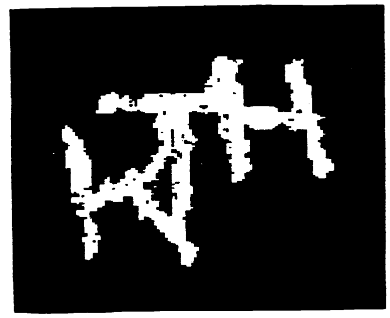


Fig.4. A photo of the reconstruction of the scratchogram made as described in the diagram of Fig.3a. The master (L) was in the middle between the two images but can not be seen. The centers of the circles are separated by about half a millimeter.

Fig.5. Reconstruction of the letters KTH, where (K) appears at about 35 mm, (T) at 45mm and (H) at 55mm behind the plate. The plate was viewed from the front.

Fig.6. When the plate of Fig.5 was viewed from the left the letters covered each other and became more or less illegible.

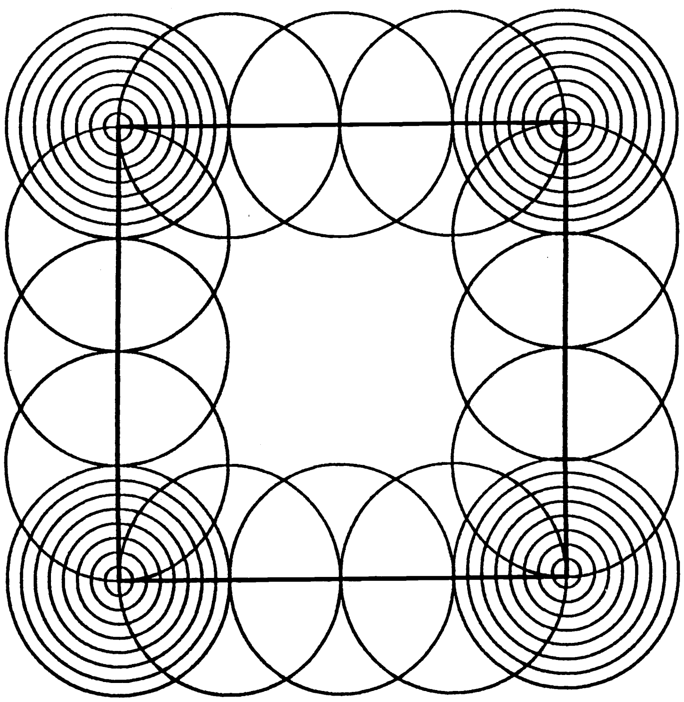


Fig.7. Drawing a cube, half of which appears behind and the other in front of the plate (V) respective (P) of Fig.3a. The circles along the sides of the square produce one square in front and one behind the plate. The sets of concentric circles at the corners of the master square produce lines that point towards the spotlight and connect those squares.

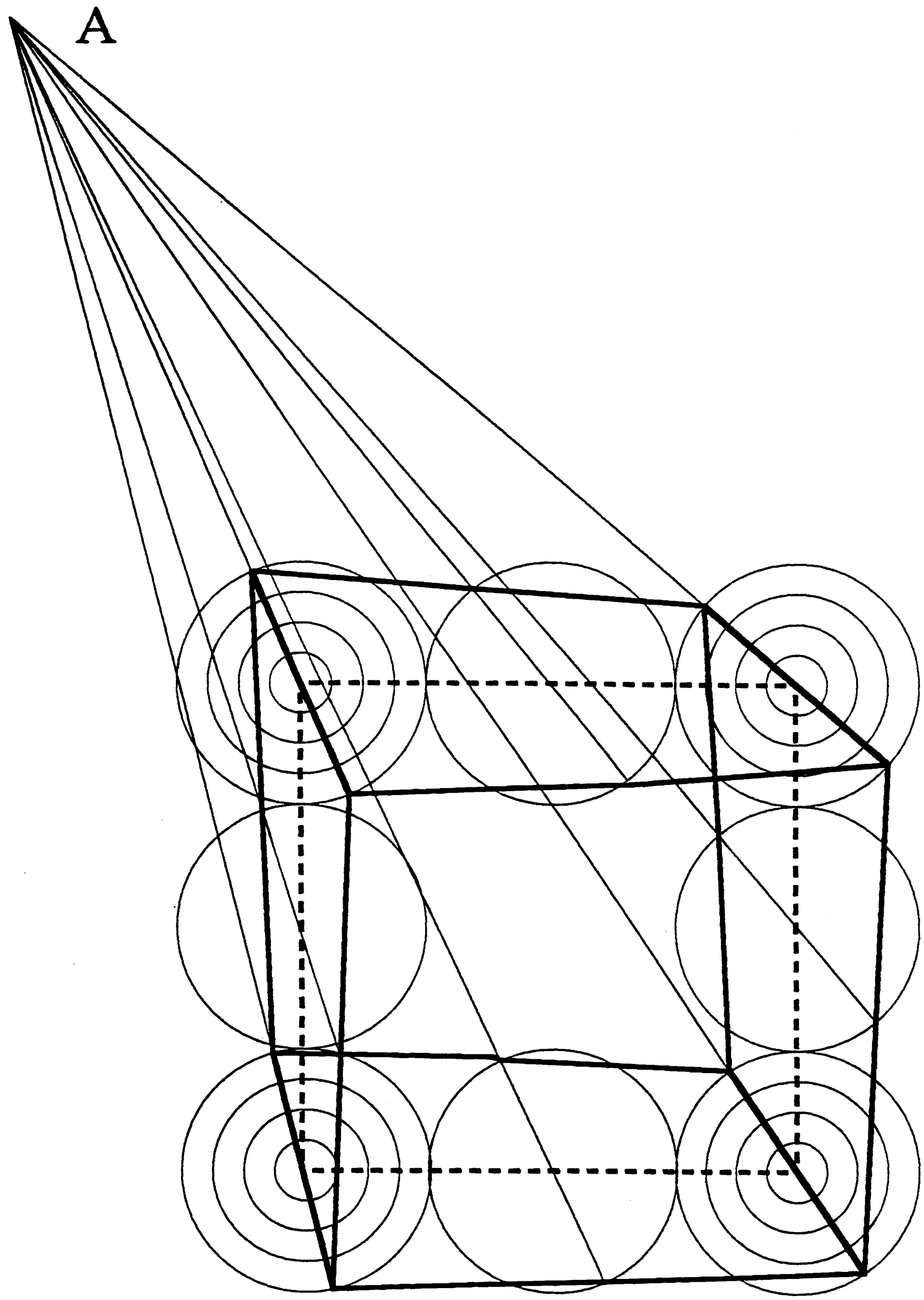


Fig.8. Using the method of Fig.3a we make a diagram of the reconstruction of Fig.7. To produce both horizontal and vertical parallax we let the reconstructing spotlight illuminated from the top and slightly from the left. A small distortion is caused by as the point (A) is in the vicinity of the circles centered at the master.

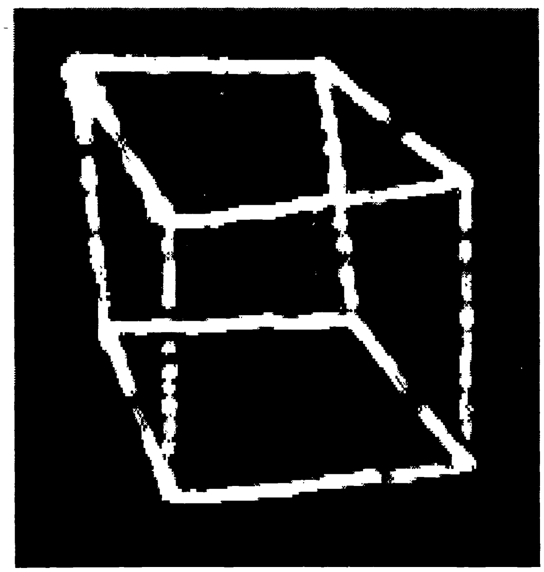


Fig.9. Photo of the reconstruction in reflection of the scratchogram described in Fig.8. The separation of the circles is about 0,5 mm. The view is slightly from the left and the reflected image of the spotlight is in the vicinity of the master, thus causing a slight distortion as shown in the diagram of Fig.8.

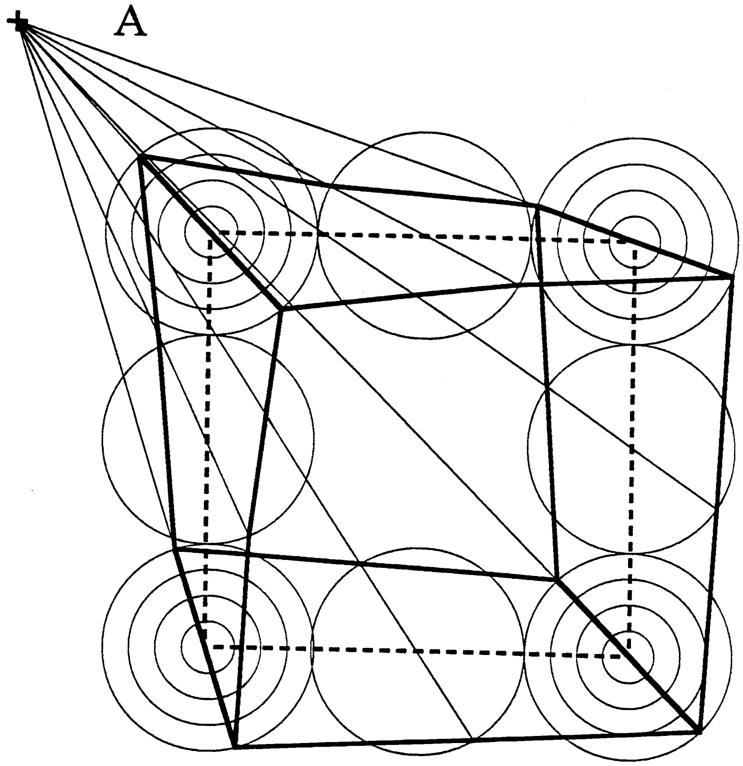


Fig.10. By positioning the reflected image of the spotlight (A) closer to the circles the distortion of the reconstructed image is increased.

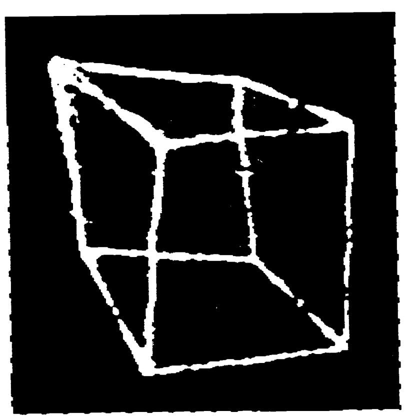


Fig.11. The distorted image as seen from the left.

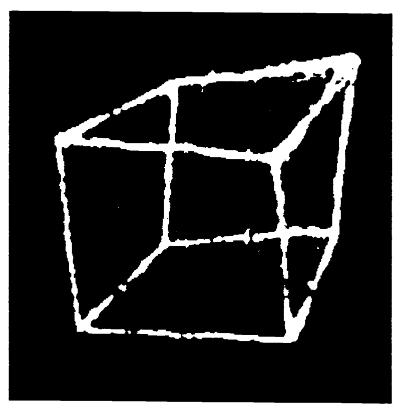


Fig.12. The same reconstruction as in Fig.11 but viewed from the right.

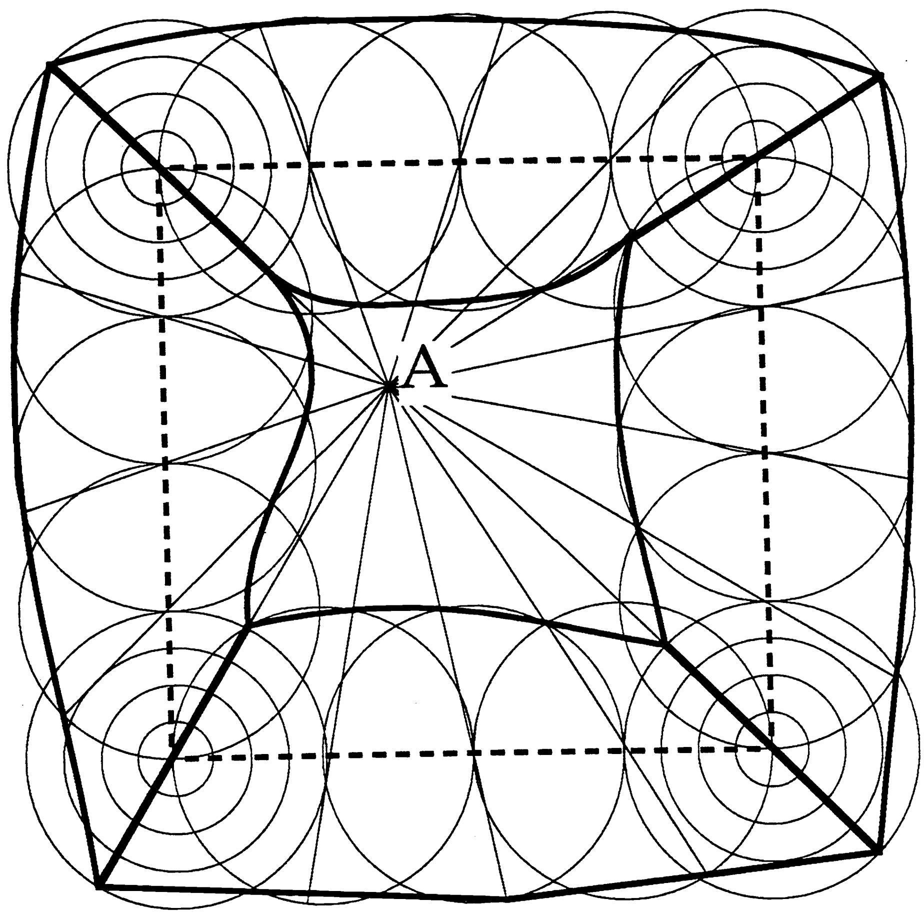


Fig.13. When the reflected image of the reconstructing spotlight is positioned inside the circles the distortion becomes unacceptable. A straight line might distort into a curve or even into a closed loop, or it might brake up into two hyperbolas.