linear change in the path difference must be most obvious in the direction of the shift, while in the case of astigmatism it is in the perpendicular direction. For coma and spherical aberration we should have, respectively, the highest quadratic and cubic terms in the path difference equation. In all cases other than astigmatism, the maximum change in the path difference characteristic of the given aberration at optimal shift is observed along that axis of symmetry of the interference field which is parallel to the shift. Consequently, in these cases one should tune the instruments on bands parallel to the shift. On the other hand, in investigating astigmatism, it is more convenient to tune on bands perpendicular to the shift; for astigmatism, just as for coma, one should first determine the meridional cross section of the wavefront (for example, by observing the type of interferogram obtained at various directions of the shift) and establish the optimal direction of the shift.

If the wave surface is an assemblage of different aberrations, then its investigation is obviously complicated. Nevertheless, if one distinguishes the linear, quadratic and cubic terms of the path difference in interpreting the interferogram, one can distinguish the various types of aberrations and investigate each of them separately. Thus, our results are applicable also in this complex case.

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Autostereoscopy and Integral Photography

UDC 778.39 + 778.4

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A brief description of autostereoscopic techniques for obtaining three-dimensional images is presented; the advantages and faults of integral photography are analyzed. A comparison is made between holography and integral photography, and the prospects of this latter method are indicated.

The viewing of stereo-photographs without the aid of special optics (hence the term autostereoscopy), is a long-sought goal. As of now, the recently developed holography technique produces stereo images with the largest amount of information presently possible. However, its practical utilization is difficult since it requires coherent illumination.

The concept of holography, i. e., fixation of an image by photographing the pattern of interference of waves incident on the subject and reflected by it [1], derives from the color (non-stereoscopic) photography of G. Lippmann (1894), in which interference nodes and antinodes of the light waves incident on the photographic plate and reflected by its back mirror surface are fixed within the light-sensitive layer.

Autostereoscopic methods which do not require coherent illumination, such as the parallax stereogram of Berthier (1896) [2] and the parallax panoramogram of Kanolt (1915) [3], were successful in their time, and in improved form are being used even today.

The parallax stereogram is a replica from a normal stereoscopic pair, made optically through a line pattern, i. e., through a screen of alternating vertical transparent and opaque lines. The lenses of the objective of the printing device superimpose the images of the two stereoscopic negatives on one another, but the screen subdivides them into narrow alternating strips. One must view the combined image through the same screen, set up in such a way that the right eye sees the strips belonging to the left negative and the left eye those of the right negative (Fig. 1). The image thus produced is half as bright as that obtained with the same illumination in a stereoscope, and contains less visual information, since only half of the area of each frame is viewed (and this without magnification). The stereoscopic effect is satisfactory but in order not to lose it, both the photograph and ones head must be perfectly stationary.

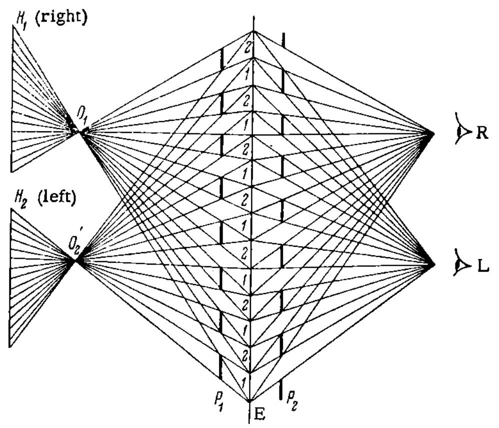

Fig. 1. Replacement of stereoscope by a line pattern screen: O_1, O_2 are projection lenses, H_1 and H_2 are the two stereoscopic negatives, P_1 and P_2 are identical line pattern screens, E is a screen or a photographic film, L and R are the eyes of the viewer, 1 and 2 are alternating strips of the left and right images.

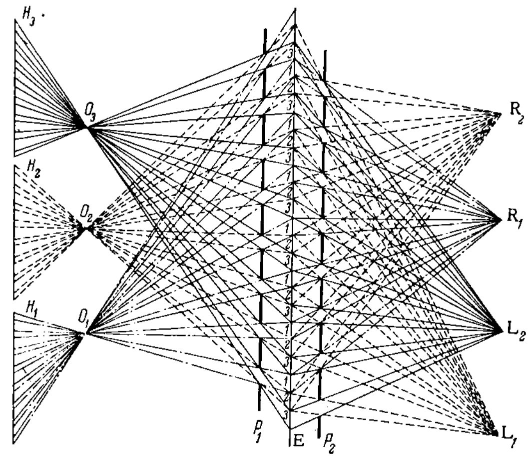

Fig. 2. Principles of a parallax panoramogram: H_1–H_3 are negatives photographed in the camera with several lenses arranged in a row: O_1 – O_3 are projection lenses; P_1, P_2 are identical line pattern screens; E is a screen or a photographic plate; L_1 and R_1, L_2 and R_2 are the positions occupied by the eyes of the viewer while shifting perpendicularly to the line direction on the pattern; 1, 2, 3, are alternating image strips.

An attempt to overcome this latter disadvantage was the parallax panoramagram [3]. The images are prepared just as in the parallax stereogram method, but from a large number of negatives (rather than two) which are reprinted through a camera with several photographic negatives arranged in a row (Fig. 2). The width of the dark lines in the patterned screen is (n-1) times as large as the width of the transparent spaces (n is the number of photographic lenses or points from which the photograph is taken). The image is n times darker than at the same illumination in the stereoscope; the amount of visual information also diminishes. However, the relief pattern is perceived more naturally than in a stereoscope because of the illusion of "scanning" the three-dimensional image by side-to-side movement of the head.

In the 1930's the line grating was replaced by embossed lens patterns, consisting of a number of thin and long cylindrical lenses. Many specialists worked on improving the technology. There was the British "lenticulated screen" process, the French method of Josse [5], the German "Diacor" [6] method and others [7]. Considerable practical success was attained in the 30's by H. E. Ives [8] who also devised the theory of the parallax panoramogram. Among present-day scientists who produced high-quality stereoscopic photographs with a screen containing an embossed cylindrical lens pattern one should mention the French investigator M. Bonnet [9]. The screens, the photographic camera and other equipment developed by Kodak in recent years have permitted many firms to mass-produce stereoscopic photographs known as xographs [10], featuring an opaque backing and a screen of cylindrical lenses. A major contribution [11] to this type of stereoscopy (the parallax stereogram and the parallax panoramogram) was made by researchers at the Soviet Motion Picture and Photography Research Institute (NIKFI), especially S. P. Ivanov, who invented a stereoscopic motion picture process [12].

The above autostereoscopic techniques do not create a sufficiently good illusion of reality, since they neglect certain characteristics of both the object space and of the stereoscopic viewing. For example, one of the great disadvantages of the parallax panoramogram is the break in the relationship between accommodation and convergence [13].

It would seem that now it would be best to return to the so-called integral photography suggested by Lippmann at approximately the same time as his color photography technique (1908).

An integral photographic plate is a surface composed of minute positive lenslets with blackened side surfaces, adjoining each other in a honeycomb pattern (known as "fly's eye") (Fig. 3a). The back surfaces of the lenslets (which are also their back focal surfaces) carry a light-sensitive emulsion. The subject is photographed, without the aid of any auxiliary optics, by the integrated plate itself, which is then photographically developed. Then the viewer, stationed on the front side of the lens pattern, views the reconstituted integral image obtained by illuminating the back (emulsion-covered) side of the plate with diffuse light (Fig. 3b). The subject appears restored to natural size in that region of space where he was originally located. The term "integral photography" derives from the writings of Lippmann, who stated that in illuminating the plate one no longer sees individual microscopic images; they are replaced by a single (integral) image, which is seen under the same angle as the original subject" [14]. The resulting images change form, just like the object itself, depending on the position of the viewer, and also change their angular dimensions with distance. A 360° panorama can be fixed on an integral cylindrical plate, and a spherical one can even accommodate all surrounding space.

Unlike other methods, integral photography creates a three-dimensional optical model of the subject which can be examined and photographed in the usual manner. The three-dimensionality of the image produced by this method is due to the fact that integral photography can reproduce very accurately the wavefront emanating from the subject [15]. This is, in turn, due to the ability of the lenslets of the integrated plate to "remember" both the directions of the incident beams of light and the parallax of the microimage fixed by each such lenslet. Figure 3c, d shows how the lenslet "remembers" each individual point on the subject. Every subject which can be represented as a set of such points is "remembered" in the same manner. The above-mentioned features make the integral image approach the qualities of the holographic image of three-dimensional objects.

Practical realization of integral photography immediately encountered considerable technical problems. Lippmann was able only to verify his concept theoretically. With the aid of 12 Stanhope magnifying glasses* [14] he proved the existence of an optical three-dimensional image in which new parts could be seen by shifting the position of the eye.

A detailed mathematical and experimental proof of Lippman's concept was produced in 1911 by Professor P. P. Sokolov of Moscow State University [16-17], who first computed the shape of the back surface of the lens element of the integral plate and established that integrated photographs "being taken without an objective lens, give upon direct examination an impression of relief characteristic of stereoscopic photography, the photographs exhibiting not only a complete relief, but a perspective varying depending on the angle at which one views the plate, that is, an approximation of reality which until now has been unattainable in any other instrument".

Estanave [18-20] made a further contribution to integral photography; he worked with units of 56 and 95 Stanhope glasses, and then later used a block of 1250 stenopic cameras**.

*A Stanhope magnifying glass is a column of glass of, for example, square cross section, spherical at one end and flat at the other.

**A stenopic camera is a small opening which gives a diffraction image of the object.

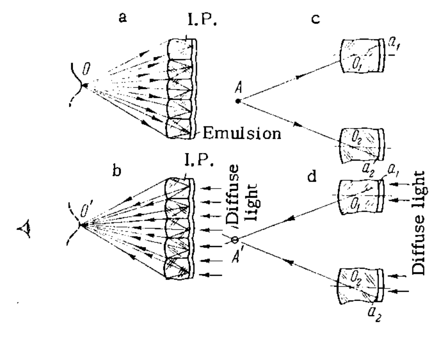

Fig. 3. Lippman's integral photography: O is the subject; O' is the reconstituted integral image of the subject; IP is the integral plate; A is a glowing point, O_1 and O_2 are the centers of projection of images of two elements (lenslets) of the integral plate; a_1 and a_2 are the images of point A fixed in the emulsion; A' is the reconstituted image of point A, which exhibits strict localization in space due to the strictly determinable position of the points O_1, a_1, and O_2, a_2.

Another technique of integral photography of small objects was realized by Gramont and Planovern (Fig. 4) [21]. An array of flat mirrors were placed in such a way that each gave an image of the subject from a slightly different point of view. By projecting the overall photographed image through the same system of camera and mirrors one produces a three-dimensional image of the subject which gives an illusion of the natural subject.

The original integral photography technique had several faults which impeded further development. Its main fault was that the reconstituted image was pseudoscopic, i. e., geometrically similar, but with an inverted relief [22]. It is interesting that this was fully eliminated by copying from an exposed integral plate onto an identical unexposed one. (This practical technique, the basis of which was given by Lippmann in his earliest work [23-24], was apparently forgotten by him, since he mentions nothing about it in any of his later papers.) The exposed integrated plate with the image of the object imprinted on it and an identical unexposed plate are arranged with their convex surfaces facing each other. The reconstituted integral image, produced by illuminating the exposed integral plate from the side of the emulsion, is recorded on the unexposed one. Copies of the integral photographs thus generated exhibit less contrast than the originals as well as lower resolution of fine details; this substantially reduces their value.

In 1967-1968, other methods of reversing the relief were proposed [25-26], but they too are fairly primitive.

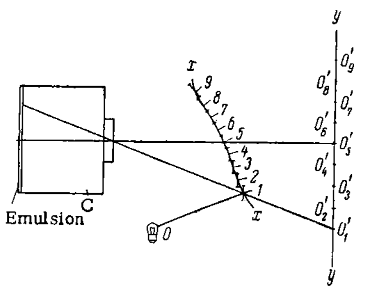

Fig. 4. Gramont and Planovern integral photographs: C is the camera; O is the subject; 1-9 are flat mirrors located on the curve XX in such a way that the subject images $O_1' - O_9'$ are located on the straight line YY, perpendicular to the axis of the camera C. The optical model is reconstituted at the site of the subject by projecting the positive through the same system of camera and mirrors.

Another fault of integral photography is [15] that for a maximum accuracy reproduction of the subject one requires infinitely small lenslets in the fly's eye pattern, but then the resolving power of each lenslet and the resolution of the reconstituted image as a whole becomes zero. This can be overcome by a compromise as to the dimensions of the fly's eye lenslet. However, at larger lenslets the discrete structure of the plate itself interferes with viewing and, what is more, the integral image itself acquires a similar structure. Correction of this fault, as well as the development of a way of reconstituting a normal, noninverted relief is a difficult, but important problem.

Comparison of holography and integral photography shows a certain similarity between them, as well as several substantial advantages of integral photography [27].

Let us cite the similarities of the two techniques:

1. Both holography and integral photography are autostereoscopic techniques, i. e., no viewing equipment is required for observing the image.
2. Both techniques require films of very high resolution.
3. Both techniques permit multiple exposure and recording of different images on the same plate, with subsequent simultaneous reconstitution of all the recorded images. This was done recently by American researchers [26].
4. The viewing images are virtually identical to that of viewing the real objects because all the psychophysiological laws and geometric conditions corresponding to the natural stereoscopic viewing are satisfied.
5. Defects in the plates do not destroy the image.
6. When part of the plate is covered, the entire image still remains visible.

Several authors [28] see the explanation of this remarkable similarity between the two techniques in the presence of the three-dimensional moiré effect*, which is obtained in reconstitution of the integral image.

Let us point out also several substantial advantages of integral photography over holography:

1. Coherent illumination is not needed at any stage of production of the integral image.
2. One can photograph specific objects which cannot be recorded holographically. More than that one can reconstruct models of three-dimensional surfaces described by mathematical equations, these models having no analogy in nature [26].
3. It is easy to work with live subjects and easy to produce color images.

To sum up, we conclude that holography and integral photography are not mutually exclusive, but supplement one another. There are areas of science and technology in which integral photography is more applicable (for example, optical methods of information readout, three-dimensional television, landscape imaging), advertising, etc.). Furthermore, combinations of integral photography and holography are possible and have already been used [29, 30].

In the USSR and abroad there is a practical interest in three-dimensional color optical images and in the theory of integral photography [13, 31].

The latest developments in screens with embossed spherical lenslets should help in intensifying theoretical and practical research.

Thus, integral photography is a promising technique, in many respects alternative to holography. It now has certain faults which appear surmountable, at which point it may become widespread in professional and amateur photographic practice.

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* The three-dimensional moiré effect appears in diffuse-light illumination of a system of two plates having a honeycomb structure. To achieve a three-dimensional moiré pattern the repetition interval of lenslets of one plate must differ only insignificantly from the interval of the other plate.

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Attenuation of Monochromatic Radiation by the Near-Ground Atmosphere

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We measured molecular absorptance of monochromatic radiation of wavelengths of 0.488, 0.633, 0.694, 0.844, 1.06, 1.15, 3.51 and 10.6 in horizontal paths in near-ground air. We showed that in certain cases (0.694 and 1.15 μ) molecular absorption is the basic factor governing the power loss in the beam during travel in the atmosphere.

Interest in data on the transmittance of the atmosphere for monochromatic radiation has grown considerably in recent years, particularly with the advent of various lasers operating in the visible, the ultraviolet and the infrared. Within any one part of the spectrum, aerosol and molecular scattering, as well as fluctuations in the intensity and angle of approach in a turbulent atmosphere are virtually independent of the degree of monochromatization of the radiation. Therefore, in studying the transmittance of the atmosphere for monochromatic radiation, one should first measure the specific transmittance function of a given layer, which is governed by selective absorption in the narrow lines of the vibrational rotational spectra of atmospheric gases. Such measurements should yield the "reduced" absorptance