POLAROID AND ITS APPLICATION TO AERIAL PHOTOGRAPHY AND PHOTOGRAMMETRY*

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STEREOSCOPIC photography has long needed a process whereby the two necessary pictures could be effectively superimposed without interference, loss of detail, loss of light or the introduction of eyestrain. The anaglyphic method has, until the present, been the only one whereby any superposition could be achieved. This method has had serious drawbacks and has consequently never been completely satisfactory.

My function today is to present to you a new method, the vectographic method, to analyze its characteristics and to explore its possibilities.

This method is the invention of Mr. Edwin H. Land, President of the Polaroid Corporation. I am indebted to him not only for the invention itself but for many valuable suggestions concerning the best method of presenting this material to you.

The word vectograph is supposed to tell you that a vectograph is something like a photograph. It is also supposed to suggest that it is different from a photograph of the familiar kind because it depends upon and alters the vectorial properties of the light with which it is illuminated.

In order to explain how this occurs I want to first refresh your memory by a brief resume of the pertinent characteristics of polarized light and polarizers.

The simplest way of doing this is by the familiar analogy of the rope and picket fence. Though this analogy will not stand careful analysis it is useful enough for our purpose here. Imagine a rope, one end of which is fixed to a post while the other end is held in your hand. In between the two ends the rope passes through three picket fences, the two nearest you have their pickets arranged vertically while the third has its pickets arranged horizontally. Now if you vibrate the rope in a random manner these random vibrations will be transmitted along the rope to the first picket fence. The pickets of this fence will, however, only permit the passage of the vertical vibrations. Consequently, the rope beyond this fence will only vibrate vertically. Since the second fence also has its pickets arranged vertically it will have no effect whatever on the rope, the vibrations passing through as though the fence were not there. The third fence, however, having the pickets arranged horizontally can only permit the passage of horizontal vibrations. Since the motion of the rope now contains no horizontal components of vibration none are permitted to pass through the fence. Thus the rope on the far side of the fence does not vibrate at all. For our purposes the rope corresponds to a beam of light and the fences to polarizers. The first polarizer polarizes the light in a vertical plane, that is, all the light which passes through the polarizer is vibrating in a vertical plane. The second polarizer being also oriented vertically has no effect whatever on the beam of vertically polarized light which reaches it. The third polarizer being oriented at right angles to the polarization of the light beam reaching it completely absorbs this beam permitting no light to pass through.

Now if we have two sheets of Polaroid, polarizing material, they will polarize

* Professor Rule demonstrated the preparation of vectographs during the reading of this paper at the Annual Meeting, Washington, D. C., January 24. Those prepared during the address were projected onto the screen to permit the assembly to view the results. This explanation will serve to clarify the active sense in which it is written.

the light into one plane so long as their axes of polarization are parallel and they will eliminate substantially all the light—that is, they will appear black—if their axes of polarization are at right angles.

If they are rotated from the former of these positions to the latter, the quantity of light passing through them will be gradually diminished.

You will note that we have here a method of producing a grey scale by means of polarized light. We could control the distribution of such a grey scale over any given area by differentially orienting two polarizing surfaces to make up any pattern of greys we might desire to produce. In this manner we could produce a picture composed entirely of polarized light. Because of the enormous complexity of such a procedure and because it does not lend itself to three-dimensional representation it is not the method of the three-dimensional vectograph.

In this vectograph we use an entirely different method of producing a grey scale by means of polarized light. This vectograph is prepared by forming an image in which the direction of polarization is the same everywhere but in which the polarized light is diluted with varying amounts of ordinary unpolarized light. For making this kind of vectograph, a new type of polarizer has been developed. This is a plastic sheet comprising oriented, long-chain molecules, which can be separately converted to polarizing molecules by allowing the sheet to imbibe a solution containing an additional component. These polarizing molecules retain the orientation possessed by the sheet initially. The number of polarizing molecules formed can be determined quantitatively by controlling the concentration of the solution, or the time of contact of the sheet with the solution. I have here a plastic sheet consisting of the oriented long-chain molecules. If you will examine this sheet through your Polaroid Square, you will find that at the moment it has no polarizing properties.

As you will see, it is perfectly transparent, resembling an ordinary sheet of film stock. In this beaker I have a solution of the additional component required to render the sheet a polarizer, and you will see that where I apply the solution to the sheet, it will become polarizing.

As you see, it is not too difficult tc obtain a range of intensity, depending upon the perfection of the polarizer, which we set up in the sheet.

This is an important phenomenon in the vectographic process. You now see that something like a picture can be rendered in terms not of opaque pigment but in terms of degree of polarization. All that is necessary to obtain a satisfactory picture is to introduce a precise control of both distribution and intensity. This can be achieved by any means which will supply the sheet with the polarizing component in proportion to the density of the image in the picture. The means which we are using and which I shall use this afternoon is that of the wash-off relief film with which you are undoubtedly familiar and which is nothing more than a film made directly from the photographic negative, in which the image is rendered in terms of depth of relief rather than in terms of density.

I have here a relief film made from a picture.

I will first dip the relief film to prepare the print so that it will properly absorb the missing component needed for converting the oriented molecules into oriented *polarizing* molecules.

Now we will place it in contact with this sheet, made up of the oriented molecules which, you will remember, are only waiting for the necessary addition to become polarizing molecules. I shall now project on the screen the image of this polarizing sheet, which we can now call a vectograph print. The oriented molecules are now taking up from the print more or less of the components needed to make them into polarizing molecules. In the darkest portions of the print, the necessary addition is present in the greatest quantity. In the high lights, the necessary addition is present hardly at all so that in the sheet, when we remove the relief, we should expect to find areas of high degree of polarization corresponding to the dark areas in the print, and areas of very low degree of polarization corresponding to the highlights. For the middle tones, we should expect to find areas having an intermediate degree of polarization, all depending upon the number of polarizing molecules we have formed.

Through a properly oriented viewer the vectograph presents an accurate reproduction of the original photograph in full contrast, and, under properly controlled processing conditions, with full range of light and dark through the density scale.

Since the image is set up in the molecules of the sheet, the vectograph itself is essentially as grainless as the original negative.

I see that many of you have already discovered one of the unusual properties of this type of vectograph. It can be made to disappear simply by turning the Polaroid Viewing Screen to the position in which the polarizing axis of the viewer is parallel with the polarizing axis of the vectographic sheet. The vectograph appears in full contrast when the viewing screen is turned to that position in which its polarizing axis is at right angles to that of the vectographic sheet.

Here we have the crucial phenomenon which permits us to use the vectograph as a means of three-dimensional representation. Since we can make our picture appear or disappear by simply changing the orientation of our viewer it is possible to make it visible in full contrast to one eye while completely invisible to the other. You will note that to this second eye the picture is not blacked out but, quite literally, actually does not exist at all. Since this is true we are perfectly free to present a second picture to this eye which will be invisible to the other eye simply by orienting our second picture at right angles to the first. Here is such a double picture in which the two views bear no relation at all to each other. You will note that no interference of any kind occurs between the two, each appearing in full contrast to one eye only. To obtain a three-dimensional picture it is now only necessary to make these two pictures a stereoscopic pair.

I have here a set of relief films of such a stereographic pair. I also have an unprocessed vectographic sheet in which the orientation of the incomplete molecules on one side is at right angles to the orientation of the molecules on the other. I shall go through the printing process as before, except that I shall use the two reliefs properly registered and create the two polarization images at the same time.

Now we have a single sheet on one side of which appears a vectographic left-eye image and on the other the vectographic right-eye image.

Before we proceed, I believe some further comment may be in order concerning the effect of one vectograph upon the other when two of them are superimposed. Clearly each image is complete and continuous. None of the information that is contained is in any way suppressed or modified by the existence of the other image.

Since each vectograph is in itself a partial polarizer, it is obvious that the upper vectograph in a superimposed pair must act as a partial analyzer for the vectograph beneath it and to some extent at least render visible the contrast in it. If you will remove your viewers and simply look at the projected image of the two vectographs on the screen, you will see that considerable contrast is already apparent in each picture. How, then, can we explain the fact that no conflicting contrasts are introduced when the vectographs are viewed through the polarizing viewers? We can explain it in this way: Maximum contrast will be introduced by the viewing analyzer at your eye. Since the contrast introduced by the superposition is less and since contrast cannot be added to what is by definition maximum contrast, it follows that the contrast is not altered by the presence of the second picture.

At this point I want to show you a few vectographs in order to impress on you their clarity and detail. I shall avoid a rehearsal of the attributes of previous devices for bringing about three-dimensional representation. There are certain attributes of the vectographic process, however, which may not be entirely obvious and which will repay a brief survey.

Foremost among these attributes is the ability of the three-dimensional vectograph to be made as a *single* transparency, a *single* projection slide or a *single* print.

The advantages of having the two stereoscopic images embodied in a single area are apparent. When the two pictures of the stereoscopic pair existed as two separate areas incapable of superposition, there has always been the problem of arranging apparatus for permitting the eyes to see these two pictures independently in a satisfactory fashion. We are all familiar with the Wheatstone Stereoscope and with the lens viewer.

Even when such devices produce no eyestrain, they could never be used by more than one observer at once. Previous attempts at placing one view over the other—by means of printing the two views in different colors as in the anaglyph process or by means of parallax devices making use of lenticular screens—have resulted in loss in intensity, detail and so on.

In the three-dimensional vectograph, the superposition of the two necessary stereograms is accomplished directly. There is no necessity for lenses or prisms for direct viewing, no need for a double projection system in showing projected pictures. We cut directly through the mechanical and optical difficulties that have always beset the showing of three-dimensional pictures in the past. For example, after the two vectographic components of a stereo pair have been properly superimposed and framed, there is no possibility of losing the accuracy of the adjustments. The framing problem actually disappears altogether. A simple mask applied to the vectograph brings the picture frame into the plane of the screen or the print. By using polarizing masks, which can if desired, be printed in the picture, the frame may be placed at any plane one wishes before or behind the screen or print.

In effect, a three-dimensional vectographic picture can be shown in the same forms as a two-dimensional picture, i.e., by means of the transparency, the lantern slide, the paper print, and it can be viewed in the same way and by groups of comparable size. They can be shown by means of the same equipment, e.g., a three-dimensional vectographic lantern slide may be projected as you will see here by means of a standard, ordinary lantern slide projector without special equipment or attachments. The only additional requirement is the Polaroid Viewer.

Another valuable asset of this process is the removal of the restriction of size inherent in all other methods of stereoscopic viewing except the anaglyph. Thus there is no reason why we cannot make a vectograph to any enlarged size we wish within the possibilities of enlargement inherent in the original film.

There are some possibilities of this that will particularly interest this group. The capacity for projection is a capacity for achieving great enlargement very simply. Two obvious advantages immediately present themselves. First, the ability of a large group to study a terrain together. This would certainly be a very valuable feature for training purposes of various sorts. Second, the great increase in depth measuring possibility that comes with enlargement. Thus with a lantern slide projector and a screen the ability to measure depth accurately is enormously increased.

A feature of importance in this connection is that it is possible to project two vectographs at once through the same single projector, without interference between the two. Thus it would be possible to project a vectographic wandering mark or a grid directly onto the screen together with an aerial view of any terrain and thus to measure depths with a high degree of accuracy from a very much enlarged picture.

Furthermore, it is possible to view a number of vectographs at once. This offers distinct possibilities of great interest to this group for it makes possible a mosaic three-dimensional map. I have made two of these of a limited number of views. I am showing one here made up of three pieces in which the depth is highly exaggerated. This is of the Keystone Canyon in Alaska taken by Mr. Bradford Washburn who was kind enough to loan the negatives to us.

There are two things to consider in making these maps. They are getting a proper depth register from picture to picture and the errors which occur at the edges between pictures. I shall describe my procedure in making this map. Better methods can certainly be devised but mine will serve to point out the problems.

The two views in a vectograph are superimposed. The depth of every point in the resultant stereoscopic image below or above any fixed plane, for convenience we will say the plane of the vectograph itself, is dependent upon the lateral separation between the two views.

Assuming the axes of the camera to have been vertical, or the negatives to have been rectified, there will be one horizontal plane, the two images of which will be exactly superimposed. The image of this plane will coincide with the plane of the vectograph. If we choose the plane containing the lowest point in the picture to superimpose, the entire image will rise above the vectograph. My procedure has been to choose a plane slightly above the highest point in the picture so that the image is entirely below or behind the vectograph. Though this slightly reduces the stereoscopic area it gives a somewhat more expansive view and, I think, leads to less eyestrain. The chief point that we are interested in here is that the same plane must be chosen in every picture or the pieces of our mosaic will be at different levels.

We will assume that we have four successive pictures taken with a standard 60% overlap. I first register pictures one and two so that there is a very slight positive separation between the two views of the highest point. I then choose some distinctive point near the edge of this pair, some point which, due to the overlap being in excess of 50%, will also appear in pictures two and three when they are registered. I measure the distance between the two views of this point with a pair of dividers and then register views two and three so that the same point has the same separation, being careful, of course, to avoid any rotational effect which would tilt the entire picture out of register with the first. I repeat this procedure from view to view and thus maintain a continuous ground line. When we are finished with this we have three stereos of adjacent territory overlapping at the edges. It is now necessary to trim and adjust these to one another.

As you know, any one level can be matched. Above this level a V-shaped wedge will be missing, below it an inverted V will appear twice. This mosaic was matched at the river. You can detect in the high land along the splices that the land doesn't match, due to the missing V wedges. This difficulty is inherent and cannot be entirely eliminated. In areas of comparatively small depth range this confusion at the splices is not particularly noticeable.

My procedure has been to trim the right edge of each picture within the overlap area, to then put on a pair of Polaroid spectacles, slip the second picture under the first and adjust the two stereoscopically until the fit is as satisfactory as possible. Then I mark and trim the left edges and fix all the pictures together.

For reproductive purposes it would be advantageous to match the negatives after reduction so that a single pair of wash-off reliefs could be made and as many reproductions of the entire mosaic made as desired.

Splices made in the other direction, that is, parallel to the course of the plane, will show no missing or double areas but the land at the edges may have a slight displacement from right to left as the splice is crossed. The displacement would be reduced to zero if the lines connecting the corresponding exposure points of any two adjacent courses are perpendicular to the course.

Note the possibility here of making a mosaic of an entire state, for instance, that could be hung on a wall or reproduced and mailed to interested persons. Or again consider the possibilities of an important road, say the one from Valona in Albania to the Greek border, a copy of which each Greek officer could carry in his pocket.

This brings us to characteristics of the vectograph which should be discussed. These are speed in making and capacity for rapid reproduction.

Given a pair of negatives we are able to make a pair of wash-off reliefs in about six minutes. The vectograph itself can be made from the wash-off reliefs in about four minutes—a minute for bleaching, two minutes in the ink and one minute to run through the wringer and allow the image to come to full strength. This is a total of ten minutes. Allowing time for registry and trimming the reliefs fifteen minutes should be ample time for a practiced operative. Even this could be considerably shaved. Furthermore, after the first copy each additional copy could be turned out in three minutes with only a single pair of reliefs. If two sets of reliefs were made this could be cut in half. We do not know how many copies can be made from one pair of reliefs but the number is certainly in the hundreds.

It should be noted that after the wash-offs are made the process can be done in full daylight and requires very little equipment—a tank for bleach, a tank for the ink, and a wringer. This is all. None of the reactions are critical. Neither temperature nor time need be precisely controlled.

Obviously this equipment is very mobile and could be installed in an airplane or truck. A plane equipped to photograph and to make the negatives could very easily make a complete set of vectographs and have them ready upon returning to its base. These vectographs could be quickly produced in quantity and distributed as desired. Furthermore, all that any field officer would need to use a vectograph immediately upon delivery would be a pair of Polaroid spectacles. He could place a series of vectographs of a given terrain side by side and view them all at once together with other observers. This would give him a rather good picture of a large area without the necessity of making a true mosaic.

The mathematics of the vectograph are the same as the mathematics of any form of stereograph. No new problems are presented to photogrammetry. A few considerations may, however, be of interest to you.

The vectograph is admirably suited to the use of a wandering mark and of a grid. It might be of interest to describe one simple form of wandering mark.

If the two halves of the vectograph have their central points marked, the distance between these points minus the distance between the two views of any given point will be a constant, regardless of the separation between the two halves of the vectograph, for all points at this same depth and can thus be used as a measure of this depth. The necessary formula will be $(B-S)=\frac{Bf}{d}$, where $B-S$ is the distance in question, B the base, f the focal length and d the depth of the point below the plane. We make two frames which slide in each other, each having a polarized dot for one-half of the vectograph. We set the two dots over the centers of the two pictures, setting the zero mark of a scale on the edge of the frame vertically above one dot, having the scale run toward the other dot. The distance between the second dot and the zero mark on the scale is now the fixed distance between centers of the pictures.

The wandering mark is then handled stereoscopically, the fused image of the two dots being set at the ground level of the point whose depth below the camera it is desired to know. The scale reading gives the factor $B-S$ in the formula. If the base and the focal length are known, the depth below the plane can be determined.

Such a wandering mark is extremely simple to operate, is compact and should be relatively accurate.

The advantages of the vectograph to the map-maker who uses a wandering mark are considerable. No cumbersome projecting or viewing apparatus is necessary. Furthermore, the picture is in full contrast without loss of light.

A question has also arisen concerning the use of the vectograph in the field, on the ground, for determining distances. Suppose you are in the field with two cameras on an arm with parallel axes and a reasonable base, say somewhere between four and fifteen feet. If you take photographs and turn them into vectographs immediately, unenlarged, what distance detecting possibilities exist? Some theoretical idea can be obtained.

If we assume that the eye can detect a difference in convergence angle of thirty seconds of arc and if we assume that the vectograph is going to be held a distance of 15 inches from the eyes in viewing (this is a good average viewing distance), the eye can detect a difference in distance between two points the separation of whose images differ by as little as .002 of an inch.

If we let d be the distance to any point, P, and $d+E$ the distance to the more distant point from which P can just be separated by the eye we get the following formula, $E=\frac{.002d^2}{Bf-.002d}$, where B is the base and f the focal length. For any fixed base and focal length we can set up a table of separable distances, or we can choose a base and a focal length to yield any desired degree of accuracy. This form of range finding can, of course, be greatly increased in accuracy by resort to enlargement.

It is also possible here to make a fixed grid for any fixed focal length and base and to superimpose it directly on the vectograph or to place it in the focal plane of the camera and photograph it directly onto the negative for depth reading purposes.

The vectograph does not increase the possibilities of stereoscopic photographic range finding but only increases the speed and convenience with which it can be done.

I think I have only skimmed the surface of vectographic possibilities. I am sure that many other possible uses will suggest themselves to you. The process is so new that we have not been able to fully explore all of its future applications nor even to thoroughly analyze the many that have already suggested themselves.

COMMENTS ON PROFESSOR RULE'S SPEECH

Louis J. Rumaggi
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Professor Rule has described a novel method for the preparation on a single medium of two distinct images. As he has stated, the processes heretofor adopted for producing a plastic impression from two separate perspectives either required optical devices, special training, or colored images, all of which left much to be desired.

The use of polarized light and polar viewers present the clearest and most easily read plastic images of any such devices. The quality of the images is most excellent, as it is to all intents and purposes grainless. The scale of contrast is continuous and although as artificial as black and white photography in that the contrasts of the photographic film are reproduced, it is definitely superior to lithographic reproductions with its limited numbers of available grays.

The ability to "run" or to reproduce a large number of plastic copies of each scene both quickly and with little labor and equipment should cause the method to receive favorable consideration by users of such stereoscopic views.

The strip mosaic proposed is, of course, more difficult, necessitating for most satisfactory viewing that all photographs be rectified and enlarged or reduced to a common flight altitude above a selected datum. Unless this is done there will appear objectionable flashing at lines of junction. The information (data) needed to effect such rectification and scale change for the several photos is but rarely available. Such a mosaic would not be an adequate map as the relief effect on size of objects and terrain features would still be present. Moreover, there would exist duplication of certain features and omission of others. Whether such objectionable features would destroy the value of a vectographic mosaic must be disclosed by adequate tests.

The laying of a complete relief mosaic would present further difficulties. Here the proper assignment or vectographic properties to the several photographs to achieve a continuous relief impression may be impossible except in very special situations, since the photographs of successive strips will rarely have the same spacing and more rarely be properly sited.

To sum up, this method produces the clearest image separation now possible without resort to special training or recourse to more elaborate devices.

DISCUSSION OF THE PAPER "POLAROID AND ITS APPLICATION TO AERIAL PHOTOGRAPHY AND PHOTOGRAMMETRY"

Claude H. Birdseye

Before discussing this paper, I must confess that, although I majored in Physics at Oberlin College 40 years ago, I did not study polarized light and know practically nothing about it. I do not remember whether or not Dr. Charles E. St. John told us anything about this new aspect of physics before he went to Mount Wilson Observatory, but if he did I do not remember it.

However, I had the opportunity of witnessing a demonstration of Vectograph Images nearly a year ago by Dr. Roberts and Dr. Mullen of the Polaroid Corporation. This seemed to me to be such an improvement over the double polaroid projections of stereoscopic photographs, shown at the annual meeting of the Carnegie Institution of Washington in December 1939, that I studied with some care the paper by Dr. Land published in the June 1940 issue of the *Journal of the Optical Society of America.* Although I could see, with the aid of the Polaroid Viewer, the relief in the three sets of stereoscopic pictures published with that article, I must confess that most of the description was "over my head."

Nevertheless, I discussed with Mr. T. P. Pendleton, the possibility of using polarized light in plotting relief with the Multiplex Aeroprojector. It is my recollection that Mr. Pendleton told me that the volume of polarized light that could be projected through screens was not sufficient to enable the operator to measure the relief accurately on the enlarged base plate.

However, Dr. Rule states, near the end of his paper, that the process is so new that the scientists of the Polaroid Corporation have not been able to fully explore all of its future applications. We are all interested in any new developments that can improve our present practices, and anything that the Polaroid Corporation can do to improve these practices, even to the extent of developing new stereoscopic plotting instruments, will be welcomed by all photogrammetrists.