

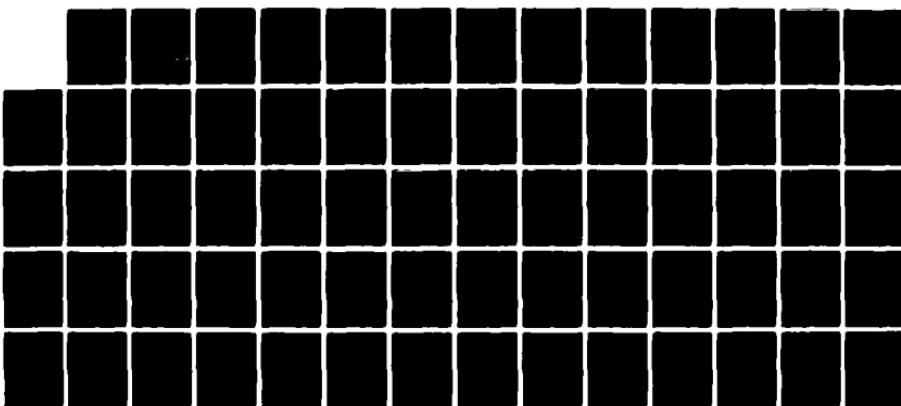
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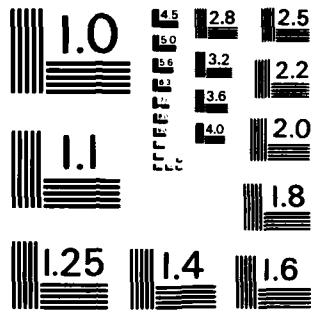
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Real Time Optical Interferometric Image  
Addition and Subtraction by Wave Polarization

by

Hua-Kuang Liu

Prepared for

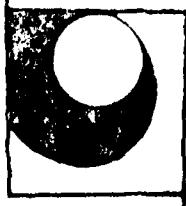
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REAL-TIME OPTICAL INTERFEROMETRIC IMAGE ADDITION  
AND SUBTRACTION BY WAVE POLARIZATION

ABSTRACT

A real-time coherent optical interferometric image addition and subtraction system based on a technique similar to an earlier work by Kunstmann and Spitschan<sup>6</sup> is extensively investigated. Theoretical analysis of the system has been compared with experimental data obtained. Distortion and resolution power of the system with respect to the size and positions of the input images have been analyzed in detail.

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# REAL-TIME OPTICAL INTERFEROMETRIC IMAGE ADDITION AND SUBTRACTION BY WAVE POLARIZATION

## 1. Introduction

Optical image addition and subtraction by holography<sup>1,2</sup> and interferometry<sup>3,4</sup> have been investigated by various researchers. In most of the interferometric methods, complex amplitudes of two images from different light paths of an interferometer are recombined by a grating or by an ordinary holographic beam splitter. By introducing a phase difference of  $\pi$  into one of the paths, the subtraction between the two images can be achieved. However, in the method used by Kunstmann and Spitschan,<sup>5</sup> an analyzer was used to produce opposite phases for the two spatially separated images, and a Wollaston prism was used for the recombination of the two images. The method is comparatively simpler and offers the following advantages. It is easier to change the phase difference between the imaging paths of the two images since this can be achieved by simply rotating the analyzer. The imaging paths of the two images are relatively closer to each other than those in the latter using a Mich-Zehnder interferometer.<sup>4</sup> Hence the method is less vulnerable to environmental vibrations. Furthermore, no holographic beam splitter or gratings are required. The birefringent Wollaston prism is commercially available. However, although Kunstmann and Spitschan<sup>5</sup> reported that subtraction has been performed in an area of 3mm by 3 mm in their experiment, no theoretical analysis of their experimental results with regard to the various optical components such as the lens and Wollaston prism have been given. For example, they have not taken the aberrations of the Wollaston prism and the precision of the coincidence of the two images into

consideration. The spherical aberration of the Wollaston prism in their system may introduce errors in the subtraction and addition and the light efficiency in the system is low. For this reason, we have investigated an improved system. The details of the theory, experimental results, and experimental data analysis of the improved system are described in the following sections.

## II. Theoretical Discussion

The basic principle of the technique of performing real-time image subtraction and addition using polarization modulation can be illustrated with the assistance of Fig. 1. Besides ordinary polarizers, a special polarization element used is called a Wollaston prism.

In Fig. 1, S is a coherent point light source, C is a collimator,  $S_1$  and  $S_2$  are two transparencies with their amplitude transmittances  $S_1(x_1, y_1)$  and  $S_2(x_1, y_1)$  representing respectively the two input signals being processed. The center of  $S_1$  is located at  $(-x_0, 0)$  and that of  $S_2$  is at  $(+x_0, 0)$  in the input plane  $I_1$ , and both of them are inclined at an angle  $\alpha$  to the z-axis as shown in Fig. 1. The input plane  $I_1$  is located at the front focal plane of the lens  $L_1$  and the output plane of the system is at the back focal plane of lens  $L_2$ . P is a polarizer and AN is an analyzer.  $P_1$  and  $P_2$  are two modulation polarizers located in front of the input transparencies  $S_1$  and  $S_2$  respectively. The unit-vectors along the directions of the principal transmittance of P,  $P_1$ ,  $P_2$ , and AN, represented by  $P$ ,  $P_1$ ,  $P_2$ , and A respectively, are shown in Fig. 2. W is a Wollaston prism which is located at the vicinity of the back focal plane of  $L_1$  and the front focal plane of  $L_2$  and has its two optical axes parallel to  $P_1$  and  $P_2$  respectively.

For simplicity, we shall assume that the two lenses  $L_1$  and  $L_2$  have the same focal length f and have perfect image formation properties with

the input plane  $I_1$  and output plane  $I_2$  as a pair of conjugate planes. Since the spherical waves radiated by the points at the plane  $I_1$  are transformed into plane waves by lens  $L_1$ , the Wollaston prism though can introduce distortions but will not induce any other monochromatic aberrations for objects at plane  $I_1$ .

The complex, vectorial amplitude distribution of the illuminating light at  $I_1$  may be represented by  $P$ . As a result of the polarization modulation of  $S_1$  and  $S_2$ , the amplitude distribution  $I_1$  immediately behind the input plane is

$$I_1 = \frac{1}{2} [S_1(x_1+x_0, y_1) P_1 + S_2(x_1-x_0, y_1) P_2] \quad (1)$$

If there is no Wollaston prism in the system, the different polarization states of  $S_1$  and  $S_2$  would not affect their image locations, and the two images would still be separated at the output plane  $I_2$ . However, when the prism is in place, the situation is different. The Wollaston prism will deflect the light beams passing through it according to the polarization state. As can be seen in Appendix A, the values of the angle of deflection for beams polarized along  $P_1$  and  $P_2$  are both approximately equal to:

$$\phi = \tan A / n_0 - n_e \quad (2)$$

where  $A$  is the apex angle of the Wollaston prism defined in the Appendix,  $n_0$  and  $n_e$  are the refractive indexes of the prism corresponding to the ordinary and extraordinary beams respectively. However, the directions of the deflections of these two beams are opposite to each other. Thus, if we adjust the distance  $x_0$  to make the angle of inclination  $\phi$  be equal to the angle  $\epsilon$ , the centers of the images of  $S_1$  and  $S_2$  can both be shifted to be on the z-axis in the output plane and hence the two images will

coincide, limited by distortions, with each other (see Appendix A). Apart from an approximately uniform amplitude attenuation and constant phase retardation (see (7A)), the output from a complex constant, the output amplitude,  $|S_1(x_2, y_2)|$ , the  $S_1$  field if  $\hat{P}_1$  without an analyzer  $\hat{A}$  being placed in front of  $\hat{P}_2$  can therefore be written as:

$$\hat{S} = \frac{i^2}{2} [S_1(x_2, y_2) \hat{P}_1 + S_2(x_2, y_2) \hat{P}_2] \quad .$$

When  $\hat{AN}$  is placed in front of  $\hat{P}_2$  as shown in Fig. 1; due to the relationship among  $\hat{P}_1$ ,  $\hat{P}_2$ ,  $\hat{A}$  and  $\hat{N}$  (Fig. 2), the output becomes

$$\hat{S} = \frac{1}{2} [S_1(x_2, y_2) - S_2(x_2, y_2)] \hat{A} \quad . \quad (3)$$

The image subtraction between  $S_1$  and  $S_2$  can thus be achieved.

Moreover, the flexibility of the proposed system can be seen by the fact that broader image processing capabilities can be attained by simple manipulation of the relative angular positions of  $P$  and  $A$ . First, we notice that the negative sign in Eq. (3) is caused by a "crossed W" geometry, i.e.,  $\hat{P}_1$  and  $\hat{P}_2$  shown in Fig. 2. If we rotate  $\hat{A}$  by  $30^\circ$ , a "parallel W" geometry is obtained and the output then becomes

$$\hat{S} = \frac{1}{2} [S_1(x_2, y_2) + S_2(x_2, y_2)] \hat{A} \quad . \quad (4)$$

and hence image addition can be achieved. Secondly, if a linear combination of the two images is desired, we can simply rotate  $AN$  (or  $P$ ) to obtain the following output,

$$\hat{S} = \frac{i^2}{2} [S_1(x_2, y_2) \cos\beta \mp S_2(x_2, y_2) \sin\beta] \hat{A} \quad . \quad (5)$$

where  $\beta$  is the angle between  $\hat{A}$  and  $\hat{P}_1$  and the "-" and "+" signs correspond

to the geometries shown in Fig. 3(a) and Fig. 3(b), respectively.

The simple and convenient technique for the linear combination of these images has its practical importance. For example, in image subtraction, the two transparencies usually do not have the same transmittance over the supposed-to-be identical portion of the two images due to the differences in emulsions or the exposure and development conditions. Thus, in order to carry out a true subtraction, a "weighted" subtraction or a linear combination is required for the removal of the pseudo-differences.

### III. Experimental Results

#### A. The experimental set-up

The experimental system is basically constructed according to the diagram shown in Figure 1 with slight modifications. A 50 mW He-Ne laser was used as the light source, the polarizer P is placed in the raw laser beam before the collimating lens C. The polarized beam, after being expanded through a pin-hole spatial filter, was collimated by a 6-inch aperture 20-inch focal-length telescopic lens C. It was found that the polarizers  $P_1$  and  $P_2$  were not required. In that case, each input image produces two spatially separated images at the output plane, and the useless one can be easily blocked. The rest of the system remained the same except that the imaging lens  $L_2$  was inserted between the analyzer AN and the final cut-out image  $I_2$ . Five different lenses have been used at the position of  $L_1$  for the purpose of finding out the influence of the Fourier transform on the effect of subtraction. The important characteristics of the lenses are listed in Table 1. The Wollaston prism is made of calcite, with its front surface area of 10mm by 10mm, total thickness of 6 mm, and the split angle of 5° (the sheet angle  $A = .245 \text{ rad.}$ ).

### 3. Interference fringes resulted from the subtraction of two open spaces.

During the experimental process, the lenses listed in Table I were used by one radiated at  $I_1$  of Fig. 1 and the output image at  $I_2$  of the same figure was observed clearly. When there was 10 specified images being placed at  $I_1$  plane, the subtraction was performed between two open spaces at  $I_2$  and  $I_3$  of Fig. 1. It has been found that the two possible air-axis extent,  $t_1$  and  $t_2$ , of  $I_1$  to  $I_2$ , it has been found that the two possible air-axis extent,  $t_1$  and  $t_2$ , of  $I_1$  to  $I_2$ . When the Fourier transform lens has a significant influence on the result of subtraction. The subtraction between the two open spaces yields no interference fringes which will be analyzed in the next Section. When the Fourier transform lens is placed with one of its two surfaces facing toward the light source (say Orientation 1) broader interference fringes can be obtained than when the surface is placed facing away from the light source (say Orientation 2). The phenomenon, common to all the lenses listed in Table I, is further illustrated in Figs. 4-9. Figures 4 and 5 present the photographic recordings of the interference fringes where the Fourier transform lens  $L_f$  was placed along Orientation 1 and 2 respectively. The various parts in these Figures indicate the different position of the Wollaston prism along the optical axis. When the Wollaston prism was placed at position a, the dark fringe has a maximum area in the interference fringe pattern. It can be seen that this is true for figures 4 and 5 likewise, the a-fits of Figures 6-9 are photographic recordings of

the interference frames where  $L_{11}$ ,  $L_{12}$ ,  $L_{13}$  and  $L_4$  were placed with orientation 1 and the Wollaston prism was so positioned that the dark fringe is maximized. The b-sarts of the same figures correspond to the sequence when these lenses were placed along Orientation 2 in the system but with the Wollaston prism arbitrarily positioned. It has been found that along Orientation 2, no matter how one adjust the position of the Wollaston prism, there was no way to obtain a greater dark fringe area than those obtained with the lens along Orientation 1.

It is important to note that the dark fringes caused by the destructive interference of the areas in the two open spaces at the input image plane are the useable areas for the performance of the subtraction. Therefore, we have attempted to maximize the dark fringes in the interference fringe pattern created by  $L_1$  through  $L_4$  each along the two possible axial orientations. The results of computations of the maximum x- and y-dimensions of the dark areas from one of the photographs of Figures 4 through 6 to the best accuracy as one can estimate are listed in Table II. Although the maximum area does not equal to XY for each of the cases listed in Table II, it seems that  $L_1$ , placed along Orientation 1 would yield the maximum area for subtraction in comparison with the other lenses.

### C. Results of subtraction between two specific input images -- a penny and a metal washer.

Since  $L_{11}$  placed along Orientation 1 has yielded the maximum area of the dark fringe, it was chosen for the Fourier transform lens. Two

input plane  $I_1$ , a penny and a metal washer, are placed respectively at  $t_1$  and  $t_2$  at the input plane  $I_1$ , of Fig. 1. A uniform transparent glass plate was placed at  $I_3$  to support the penny and washer. The two objects are attached to the glass plate by double-stick tape. The diameter of the penny is approximately 19 mm (1/4"). The metal washer has an outer diameter of approximately 9.52 mm (3/8") and a hole in the center of a diameter of about 4.76 mm (3/16"). The photographic recordings showing the subtraction results are presented in Fig. 11. The approximate center-to-center distances between the penny and washer are 70 mm (2 3/4"), 63.5 mm (2 1/2") and 60 mm (2 3/8") for a, b, and c part of the graphic in Fig. 11 respectively. These photographs have illustrated the partial overlapping, just complete overlapping, and the total overlapping of the washer and the penny in the output plane as a result of the subtraction of the original objects that are placed apart. The dark areas of the subtraction of the washer vividly demonstrate the subtraction phenomenon. The thin hair-like peeling between the upper parts of the penny and the washer is an indication of the resolution of the subtraction. The irregular traces of marks in the lower portion of the penny are caused by the glue left by the penny on the glass plate. It can be seen from the three parts in Figure 11 that the residue glue did not change its position when the penny was moved. The glue mark is also an indication of the resolution of the system.

#### IV. Data Analysis

In order to understand the subtraction system thoroughly, the interference fringe patterns as shown in Figs. 4-10 require a theoretical interpretation and the degree of accuracy of the subtraction results needs to be analyzed. We shall discuss these two aspects of the system as follows.

### A. Interpretation of the interference fringes

The theoretical model that we propose to interpret the interference fringe pattern assumes that all optical components used in our system are optically perfect, i.e., the lenses are free of aberrations. The reason that the fringes appear at the output plane is mainly due to the fact that two different "observed" light rays which enter the two different object points and reaching a certain output point in the output plane should have a different optical path length. In fact, the effect of the diffraction and aberrations in the lens, the systematic errors in the system, the position of the third or the depth of field, the quality of the optics, the presence of noise in the pattern at the output plane, could violate the idealized situation based on the light-ray concept. The light-ray concept is based on the approximation of geometrical optics, since we assume that the correction of light diffraction may be negligible in the present case. More details of the model are presented below with the help of some illustrations.

A part of the image processing system of Fig. 1 is shown in more fine details in Fig. 12. Point  $p_3$  is a certain point with coordinates  $(x_3, y_3)$  on the output plane. Based on the principle of geometrical optics, it is not difficult to find the locations of the two input plane points  $p_1$  and  $p_2$  that correspond to the output point  $p_3$ . Since in the idealized case under the assumption that the system is free of aberrations and diffraction,  $p_1$  (or  $p_2$ ) and  $p_3$  are a pair of conjugated object/image points. The optical path between  $p_1$  (or  $p_2$ ) and  $p_3$  can be evaluated along any ray passing through both of them. To be specific, we choose the rays originating from  $p_1$  and  $p_2$  that are parallel to the optical axis before they reach the Fourier transform lens. Hence the two rays would intercept at the back focal point of the lens.

In the actual illustration of the vicinity of the Wollaston prism at point  $p_3$ , Fig. 13, is drawn for the optical paths of the rays that pass through the Wollaston prism. From Fig. 13, it can be seen that the path length difference between  $P_{1,p_3}$  and  $P_{2,p_3}$  is equal to the path length difference between (SOD-EM) and (ESOU-EM). Based on this path length difference, we have calculated on a digital computer the interference fringe patterns. Other pertinent data used in the calculations include the wavelength  $\lambda = 632.8$  nm; the thickness of the Wollaston prism  $d = 6.0$  mm; the apex angle of the Wollaston prism  $A = 0.245$  radians; the ordinary refractive index  $n_0 = 1.6584^*$ ; the extraordinary refractive index  $n_e = 1.4764^*$ . The focal lengths of the Fourier lens and the focusing lens are both equal to  $f = 750$  mm; the ranges of the position of the point  $(x_3, y_3)$  are  $-100$  mm  $\leq x_3 \leq 100$  mm;  $y_3 = -166.7 \leq y_3 \leq +166.7$ ; the location of  $x_3$  varies with  $dx_3 = 2$  mm and  $dy_3 = 3.33$  mm; and finally, the distance  $r$  between the front surface of the Wollaston prism and the back focal point  $F$  of the Fourier transform lens is taken as a parameter which varies from 1.76 mm to 2.09 mm with a step increment of 0.06 mm to account for the micros adjustment of the Wollaston prism in the system.

The results of the calculations are plotted by the computer and shown in Fig. 14 where the interference fringes are represented by dots and B's. The dots denote that the absolute value of a fraction of the path length difference introduced by the Wollaston prism at  $p_3$  is less than  $\lambda/4$  or greater than  $3\lambda/4$  and the letter B denotes that the absolute

\* These indices are for wavelength  $\lambda = 589.3$  nm; for  $\lambda = 632.8$  nm the calculated patterns would be slightly different.

value of the path length difference is between  $\frac{1}{4}$  and  $\frac{3}{4}$ . Thus, if the analyzer (in Fig. 1) does not introduce any additional phase difference, the distance for the "bright" image and the PB's standard one (dark image) at the analyzer  $\beta$  in Fig. 1 introduces an additional phase difference. The corresponding will be given. The computer program listed in Appendix B.

Finally, we can see from Fig. 14 that around  $\beta = 1.17$  in the case of the prism A, at minimum and the relatively uniform area of the interference fringe is at its maximum. The maximum dark area is best for performing image subtraction. The theoretically predicted phenomenon has been fully qualitatively verified by the experimental results. Any quantitative difference between the computed and experimental data probably is caused by the imperfection of the Wollaston prism and the aberrations of lenses. The phenomenon that the fringe patterns are different for a certain lens at the two different orientations can also be explained by the fact that the aberration is dependent on the orientation.

#### 3. The distortion at the output plane.

Since the fact that the angular deflection of the light ray in the Wollaston prism varies with the incident angle at the front surface of the prism, the images superposed at the output plane cannot totally coincide with each other. Both images suffer from different amount of distortions. The resolution power of the subtraction technique is limited by these distortions. In the following, we estimate how serious the distortion is and try to find out the optimum positions of placing the two input images where the distortions can be minimized. For simplicity, the calculation is done only for one-dimensional case. We assume that the Wollaston prism has the same parameters as those in the A part of this

Section and that both the Fourier lens and the imaging lens have the same focal length  $f = 1$  (arbitrary unit), then the magnification of the whole system is 1.

The calculation is based on the configuration as shown in Fig. 15. First we choose a point  $C_3$  on the output image and then trace back along the geometrical optical paths to two corresponding points  $C_1$  and  $C_2$  on the two input transparencies. We shall call the points  $C_1$ ,  $C_2$ , and  $C_3$  the centers of the respective images. Likewise, for any point  $P_3$  on the output, the corresponding input image points  $P_1$  and  $P_2$  on the input can also be found. We further let  $H_1 = \vec{C}_1 P_1$ ,  $H_2 = \vec{C}_2 P_2$ , and  $H_3 = \vec{C}_3 P_3$ , where the positive sign is chosen if the vector is parallel to the positive  $x$ -axis. If there is no distortion,  $H_1 + H_2 = H_3$ . The differences  $H_2 - H_1$  and  $H_3 - H_2$  can be used to measure the amount of distortion and the difference  $H_1 - H_2$  can be used to determine the resolution of subtraction. For example, according to our calculated results, if the point at the intersection of the output plane and the optical axis is chosen as  $C_3$ , then  $C_1$  and  $C_2$  will have their  $x$ -coordinate value of -0.500 and 0.547, respectively, where all units are considered to be the same as that of the focal length. An output image point  $P_3$  with  $H_3 = 0.100$  has its corresponding object points  $P_1$  with  $H_1 = 0.1030$  and  $P_2$  with  $H_2 = 0.1161$ . In this case, the difference  $H_1 - H_2 = 0.0031$  is the minimum resolvable distance when the image height is around 0.1. The overall resolution data are illustrated further by two additional figures. Figure 16 is a plot of  $H_2 - H_1$  versus  $H_3$  when  $C_3$  is located on the axis. It can be seen that, for the same value of  $|H_3|$  and  $|H_3| > 0.01$ , the difference  $H_2 - H_1$  is much greater for positive  $H_3$  than for negative  $H_3$ . Thus, in order to minimize distortion and simultaneously maximize the size of the image to be subtracted one has to choose an optimum set of centers of images ( $C_1$ ,  $C_2$ ,  $C_3$ )

For example, if the maximum tolerable difference ( $H_2 - H_1$ ) is 0.001 and we place the upper end point of each of the input images 0.04 above its center ( $\lambda_3 = 0$ ), the total height of the image can be subtracted would be  $0.04 - (-0.05) = 0.19$ . If instead, when the middle point of the image is placed at the 'center', the total height of the image that can be subtracted within the tolerance is then reduced to  $0.04 - (-0.04) = 0.08$ .

Figure 17 shows a different case in which the point  $C_3$  is not located at the optical axis but at  $\lambda_3 = -0.050$ . Then it can be seen that the values of  $H_2 - H_1$  are almost distributed symmetrically around the center ( $H_3 = 0.1$ ). When the maximum tolerable  $|H_2 - H_1|$  is 0.001 and the middle points of the two input transversalies are placed at the centers  $C_1$  and  $C_2$ , the total height of the image is limited to  $(\lambda_3 - \lambda) + (-0.08) = 0.16$ . Note that in this case the distortion around the center changes very slowly and have negligible values. It is also interesting to find out the relative distortion as defined by  $10^{-3} \frac{|H_2 - H_1|}{H_3}$  excluding  $H_3 = 0$ . Two additional figures corresponding to the above-described two cases are plotted and shown in Figures 18 and 19 respectively. We can see that for the first case ( $C_3$  located on  $x$ -axis) the relative distortion is greater at the vicinity of the center than at the lower part of the image. For the second case ( $C_3$  at  $\lambda_3 = -0.05$ ), the minimum relative distortion appears at the vicinity of the center. The total height for the first case within the tolerance of  $|H_2 - H_1| = 1$  is about  $(-0.04) - (-0.16) = 0.12$  while the total height for the second case is about  $0.06 - 0.04 = 0.14$ . The computer programs for the calculations are listed in Appendix C and D respectively.

### V. CONCLUSIONS

We have presented the principle, experimental data, and data analysis of a real-time image subtraction technique by using the properties of wave polarization. The theoretical analysis predicts that interference fringes should be produced in the system and the experimental data demonstrated the phenomenon. The dark (or destructive interference) portion of the fringes can be used for performing image subtractions. The maximum area that can be used for subtraction in this system constructed is about  $26 \text{ mm} \times 18 \text{ mm}$ , which is almost one and half order of magnitude greater than that reported earlier by transistors or spittcher. In addition, in the present system, the distortion is less and the light efficiency is higher in comparison with their systems. A detailed calculation of the distortion of the images and its aberrations also has revealed the optimum positions where the input beam should be placed at the input plane when the tolerance of the drift angle of distortion error is set. From the experimental data, it seems that the Fourier lens with the smallest D/F yields the greatest double subtraction area. This is expected since in general lenses with greater f-number have less aberrations.

With regard to future work, it seems that two feasible ideas should be investigated. One is to incorporate the subtraction technique in an electro-optical system that includes the use of a Hughes liquid crystal light valve (LCL) for real-time image subtraction in a continuous mode. The other is to apply the Wollaston prism for performing real-time pseudocolor image subtraction or additions. Both of these ideas could lead to important practical applications.

## APPENDIX A

## THE FUNCTION OF A WOLLASTON PRISM

Based on the nature of a Wollaston prism, light beam traveling through the prism will gain an amount of path-length according to the beam's orientation of polarization. To illustrate the effect, a x-z plane cross-section of a Wollaston prism which consists of two triangle prisms is shown in Fig. A1. Each triangle has the apex  $A = \tan^{-1} (\frac{c}{h})$ , where  $c$  is the thickness and  $h$  is the height of the prism. The two triangle prisms are made of the same kind of birefringent crystal but have different optic axes. For our purpose, if the crystal is a "negative" one, such as the calcite, the optic axis of the left half, as shown by " $P_2$ " in Fig. A1, is parallel to  $x$ -axis (or  $P_1$ ) and that of the right half (by " $P_1$ ") is parallel to  $y$ -axis (or  $P_2$ ). Thus, for the light beam polarized along  $P_2$ , the path length increment  $\Delta_1(x)$  is approximately,

$$\begin{aligned}\Delta_1(x) &= (\frac{c}{2} + x \tan A)(n_o - 1) + (\frac{c}{2} - x \tan A)(n_e - 1) \\ &= [(n_o + n_e)/2 - 1] + x(n_o - n_e) \tan A .\end{aligned}\quad (A1)$$

Similarly, for the light beam polarized along  $P_1$ , the increment  $\Delta_2(x)$  can be written as

$$\Delta_2(x) = x[(n_p + n_e)/2 - 1] + x(n_o - n_e) \tan A .\quad (A2)$$

Based on the assumptions represented by equations (A1) and (A2), two important conclusions can be deduced. First, any plane wave after

traveling through a Wollaston prism will be deflected by an angle  $\alpha$ , which is approximately equal to  $(n_o - n_e) \tan A$ . Because we have  $n_o > n_e$  for a negative crystal,  $\alpha$  has a positive value, i.e., all plane waves coming from the points of  $S_1$  will be deflected downward by an angle  $\alpha$  since they are polarized along  $P_1$ . The image of  $S_1$  at the output plane will then also be moved downward. It will be centered on the  $-z$ -axis, if we make  $\beta = \alpha$ . Since all light waves from  $S_2$  are polarized along  $P_2$ , the image of  $S_2$  will move upward and coincide with the image of  $S_1$ .

Furthermore, the amplitude distribution at the Wollaston prism will not affect the calculated path length difference, yet, due to the focusing effect of  $L_1$ , a Wollaston prism of relatively small aperture can be used.

## ANSWER

## CLASSIFICATION

1	AL2=AL1+AL3	6	AL2=AL1+AL3	6
2	CHAMPIONSHIP	22	CHAMPIONSHIP	22
3	WAWAWAWA	23	WAWAWAWA	23
4	TRIANGLE	24	TRIANGLE	24
5	AT+244	25	AT+244	25
6	1234567890	26	1234567890	26
7	PERIODIC	27	PERIODIC	27
8	PERIODIC	28	PERIODIC	28
9	PERIODIC	29	PERIODIC	29
10	PERIODIC	30	PERIODIC	30
11	PERIODIC	31	PERIODIC	31
12	PERIODIC	32	PERIODIC	32
13	PERIODIC	33	PERIODIC	33
14	PERIODIC	34	PERIODIC	34
15	PERIODIC	35	PERIODIC	35
16	PERIODIC	36	PERIODIC	36
17	PERIODIC	37	PERIODIC	37
18	PERIODIC	38	PERIODIC	38
19	PERIODIC	39	PERIODIC	39
20	AL2=AL1+AL3	40	AL2=AL1+AL3	40
21	AL2=AL1+AL3	41	AL2=AL1+AL3	41
22	AL2=AL1+AL3	42	AL2=AL1+AL3	42
23	AL2=AL1+AL3	43	AL2=AL1+AL3	43
24	AL2=AL1+AL3	44	AL2=AL1+AL3	44
25	AL2=AL1+AL3	45	AL2=AL1+AL3	45
26	AL2=AL1+AL3	46	AL2=AL1+AL3	46
27	AL2=AL1+AL3	47	AL2=AL1+AL3	47
28	AL2=AL1+AL3	48	AL2=AL1+AL3	48
29	AL2=AL1+AL3	49	AL2=AL1+AL3	49
30	AL2=AL1+AL3	50	AL2=AL1+AL3	50
31	AL2=AL1+AL3	51	AL2=AL1+AL3	51
32	AL2=AL1+AL3	52	AL2=AL1+AL3	52
33	AL2=AL1+AL3	53	AL2=AL1+AL3	53
34	AL2=AL1+AL3	54	AL2=AL1+AL3	54
35	AL2=AL1+AL3	55	AL2=AL1+AL3	55
36	AL2=AL1+AL3	56	AL2=AL1+AL3	56
37	AL2=AL1+AL3	57	AL2=AL1+AL3	57
38	AL2=AL1+AL3	58	AL2=AL1+AL3	58
39	AL2=AL1+AL3	59	AL2=AL1+AL3	59
40	AL2=AL1+AL3	60	AL2=AL1+AL3	60
41	AL2=AL1+AL3	61	AL2=AL1+AL3	61
42	AL2=AL1+AL3	62	AL2=AL1+AL3	62
43	AL2=AL1+AL3	63	AL2=AL1+AL3	63
44	AL2=AL1+AL3	64	AL2=AL1+AL3	64
45	AL2=AL1+AL3	65	AL2=AL1+AL3	65
46	AL2=AL1+AL3	66	AL2=AL1+AL3	66
47	AL2=AL1+AL3	67	AL2=AL1+AL3	67
48	AL2=AL1+AL3	68	AL2=AL1+AL3	68
49	AL2=AL1+AL3	69	AL2=AL1+AL3	69
50	AL2=AL1+AL3	70	AL2=AL1+AL3	70
51	AL2=AL1+AL3	71	AL2=AL1+AL3	71
52	AL2=AL1+AL3	72	AL2=AL1+AL3	72
53	AL2=AL1+AL3	73	AL2=AL1+AL3	73
54	AL2=AL1+AL3	74	AL2=AL1+AL3	74
55	AL2=AL1+AL3	75	AL2=AL1+AL3	75
56	AL2=AL1+AL3	76	AL2=AL1+AL3	76
57	AL2=AL1+AL3	77	AL2=AL1+AL3	77
58	AL2=AL1+AL3	78	AL2=AL1+AL3	78
59	AL2=AL1+AL3	79	AL2=AL1+AL3	79
60	AL2=AL1+AL3	80	AL2=AL1+AL3	80
61	AL2=AL1+AL3	81	AL2=AL1+AL3	81
62	AL2=AL1+AL3	82	AL2=AL1+AL3	82
63	AL2=AL1+AL3	83	AL2=AL1+AL3	83
64	AL2=AL1+AL3	84	AL2=AL1+AL3	84
65	AL2=AL1+AL3	85	AL2=AL1+AL3	85
66	AL2=AL1+AL3	86	AL2=AL1+AL3	86
67	AL2=AL1+AL3	87	AL2=AL1+AL3	87
68	AL2=AL1+AL3	88	AL2=AL1+AL3	88
69	AL2=AL1+AL3	89	AL2=AL1+AL3	89
70	AL2=AL1+AL3	90	AL2=AL1+AL3	90

## APPENDIX E

```

      1000+1243900,167
      REAL,HC,LF,1501000,F10.2)
      CHARACTER(1),A100)
      I0=10,J0=1,I00
      100  READ(I0,J0)
      DO 50  J=1,I00
      50  DO 100  K=1,I00
      100  J=J0-0*(K-1)
      CALL  HIC3(K,J)
      HIC3=0.0
      DO 200  L=1,I00
      200  HIC3=HIC3+(L-1)*D(L)
      HIC3=(L-1)/I000
      WRITE(I0,K)
      WRITE(J0,L)
      400  FORMAT(7/19X,'151',19X,'11',19X,'2',19X,'3',14X,'4',14X,'5',14X,'6',
      & 510E-13,301)  M2=117/19X,601*1*10(-1))  I178*(-1)
      I0=200*E16,51
      CALL  HIC3(K,J)
      HIC3=1.0/HIC3
      DO 300  L=1,I00
      300  HIC3=HIC3+(L-1)*D(L)
      HIC3=(L-1)/I000
      WRITE(I0,K)
      WRITE(J0,L)
      500  FORMAT(7/19X,'151',19X,'11',19X,'2',19X,'3',14X,'4',14X,'5',14X,'6',
      & 510E-13,301)  M2=117/19X,601*1*10(-1))  I178*(-1)
      I0=200*E16,51
      CALL  HIC3(K,J)
      HIC3=1.0/HIC3
      DO 600  L=1,I00
      600  HIC3=HIC3+(L-1)*D(L)
      HIC3=(L-1)/I000
      WRITE(I0,K)
      WRITE(J0,L)
      700  FORMAT(7/19X,'151',19X,'11',19X,'2',19X,'3',14X,'4',14X,'5',14X,'6',
      & 510E-13,301)  M2=117/19X,601*1*10(-1))  I178*(-1)
      I0=200*E16,51
      CALL  HIC3(K,J)
      HIC3=1.0/HIC3
      DO 800  L=1,I00
      800  HIC3=HIC3+(L-1)*D(L)
      HIC3=(L-1)/I000
      WRITE(I0,K)
      WRITE(J0,L)
      900
      END

```

```

SUBROUTINE HIC3(K,M)
REAL,E12,F10.2)
M=.249
510E1.0009
R1E2.0004
D3=(K-1)*.01
+13E4*(M/100)
+1E-13*7172
+1.0E11*(K-1)*(F12-F13)
+1.0E10*(K-1)*(F12-F13)
+1.0E10*(K-1)*(F11-F12)+ASIN(SINC13/F12)+1/E11)
+1.0E10*(K-1)*(F11-F12)+ASIN(SINC13/F12)+1/E11)
C1=C1+C3
C2=C2+C3
      END
      END

```

#### APPENDIX D

## REFERENCES

1. D. L. Hall, G. W. Stroke, R. Restrick, A. Funkheuser, and J. Bryant, Phys. Letters, 18, 111 (1965).
2. P. B. Levy, M. A. Kondratenko, and J. F. Bryant, Appl. Opt., 10, 171 (1971).
3. S. H. Lee, S. K. Lee, and A. G. Milnes, J. Opt. Soc. Am., 63, 111 (1973).
4. K. Matsumura, N. Takeya, T. Tsujiuchi, and M. Shinoda, Opt. Commun., 2, 425 (1971).
5. P. Kinetzmann and H. J. Spitschan, Opt. Commun., 4, 166 (1971).
6. J. C. Ebersole, Opt. Eng., 14, 436 (1975).

Table I. Characteristics of the five lenses used in the telescope  
in Figure 1.

Lens No.	Focal length f (cm)	Diameter of Aperture D (cm)	$\theta$
I <sub>I</sub>	48.26	9.525	0.197
I <sub>II</sub>	76.20	10.16	0.132
I <sub>III</sub>	75.40	5.00	0.2
IV	35.00	5.08	0.161
V	25.00	2.54	0.161

TABLE II. Maximum obtainable  $x$  and  $y$  dimensions (denoted by  $\gamma$  and  $\delta$  respectively and in units of nm) of the dark fringes with two forces placed along a certain axial orientation.

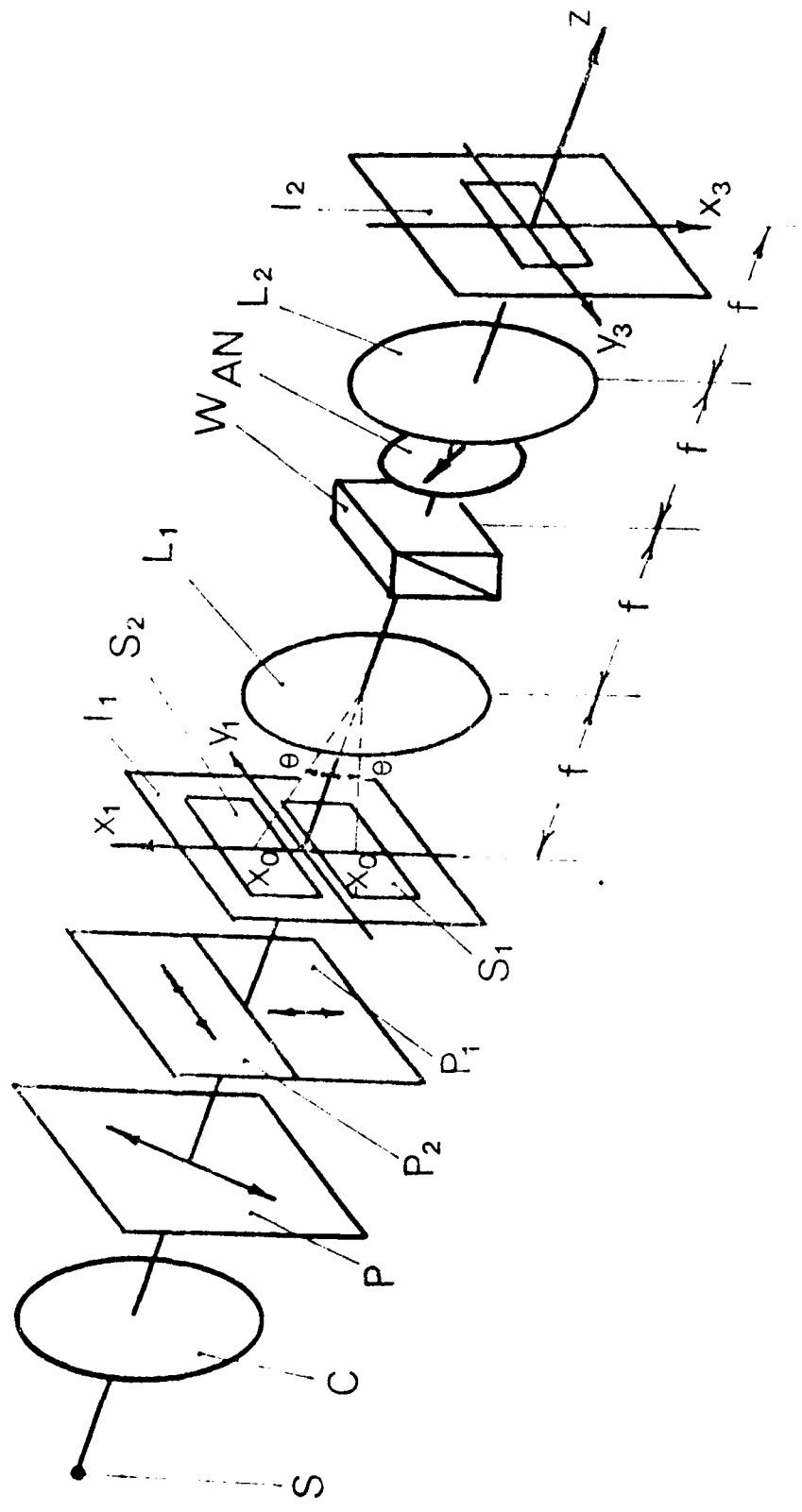
Lens #	Diff.	Orientation	$\gamma$	$\delta$
I	0.000	1	10.4	8.1
		2	11.9	24.75
II	0.000	1	17.2	23.1
		2	12.7	14.7
III	0.000	1	17.0	6.1
		2	11.0	11.5

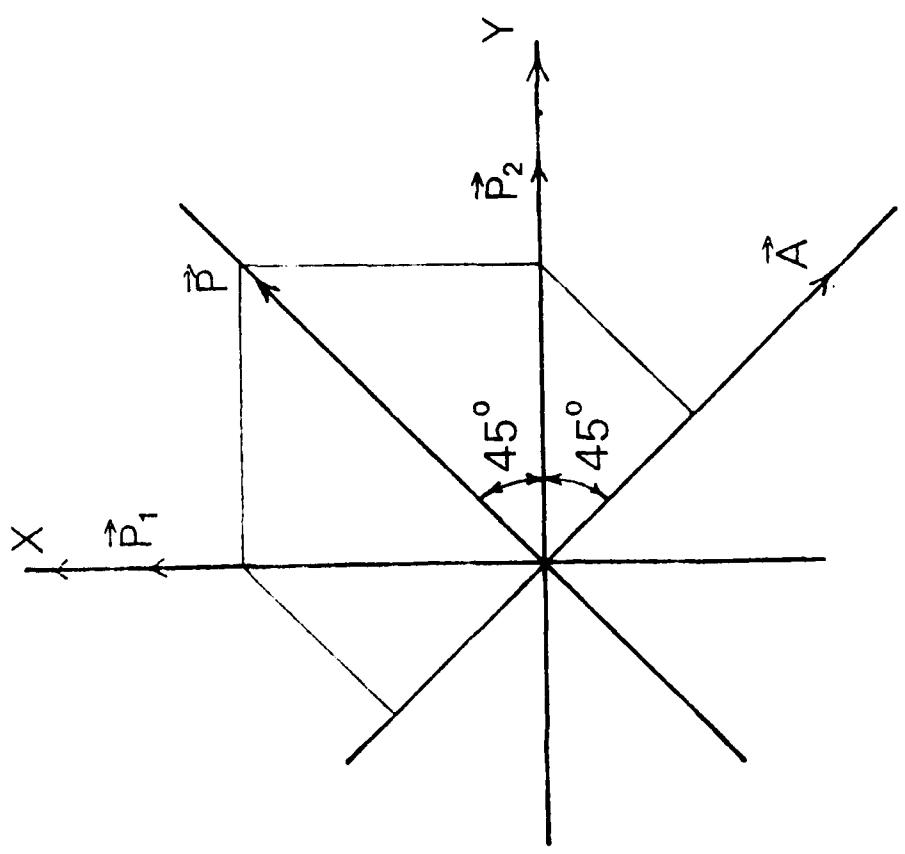
## FIGURE CAPTIONS

1. A diagram of the polarization modulation white-light fringe generation system.
2. Principal transmittance unit-vectors of the polarizers  $P$ ,  $P_1$ ,  $P_2$  and the analyzer  $M$ .
3. Principal transmittance unit-vectors of  $P$ ,  $P_1$ ,  $P_2$  and  $A$  for the linear combination of two images.
4. Photographs of interference fringes with  $L_I$  along Orientation 1 and the Wollaston prism at positions a and b.
5. Photographs of interference fringes with  $L_I$  along Orientation 2 and the Wollaston prism at positions a, b, c, and d.
6. Photographs of interference fringes with (a)  $L_{II}$  along orientation 1 and (b)  $L_{II}$  along orientation 2.
7. Photographs of interference fringes with  $L_{III}$  along Orientation 1 (Orientation 2 is the same as in Fig. 6).
8. Photographs of interference fringes with  $L_{IV}$  along Orientation 1 (a) and (b) along Orientation 2.
9. Photographs of interference fringes with  $L_V$  along Orientation 1 (a) and Orientation 2 (b).
10. Photographs of output interference fringes with  $L_I$  placed along Orientation 1 and the Wollaston prism placed at four different positions a, b, c, and d along the axis. No specific images were placed at the input plane of the system.
11. Photographs of the subtraction between a penny and a metal washer with the distance of separation between the two images varied.  $L_{II}$  was placed in the system along Orientation 1 and the Wollaston prism was placed at position a as shown in Fig. 10.
12. Light rays originating from points  $p_1$  and  $p_2$  at the input plane reaching the point  $p_3$  at the output plane through the Wollaston prism.
13. The detailed paths of the light rays passing through the Wollaston prism.

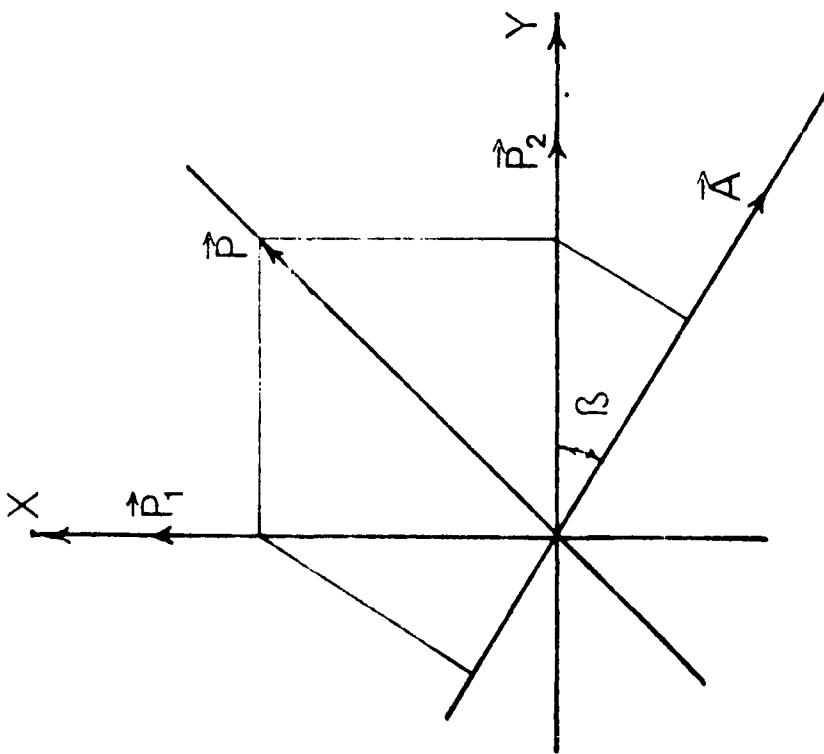
## FIGURE CAPTIONS (Cont'd)

14. Theoretically computed interference fringe patterns versus the on-axis position of the Wollaston prism.
15. Relative positions of  $p_1$  and  $p_2$  at the input plane and  $p_3$  at the output plane for the computation of image distortion.
16. A plot of  $H_2 - H_1$  versus  $H_3$  with  $C_3$  located on-axis.
17. A plot of  $|H_2 - H_1|$ , versus  $H_3$  with  $C_3$  located off-axis.
18. A plot of  $\log (|H_2 - H_1|/H_3)$  with  $C_3$  located on-axis.
19. A plot of  $\log (|H_2 - H_1|/H_3)$  with  $C_3$  located off-axis.
41. A x-y plane cross-sectional view of a Wollaston prism.

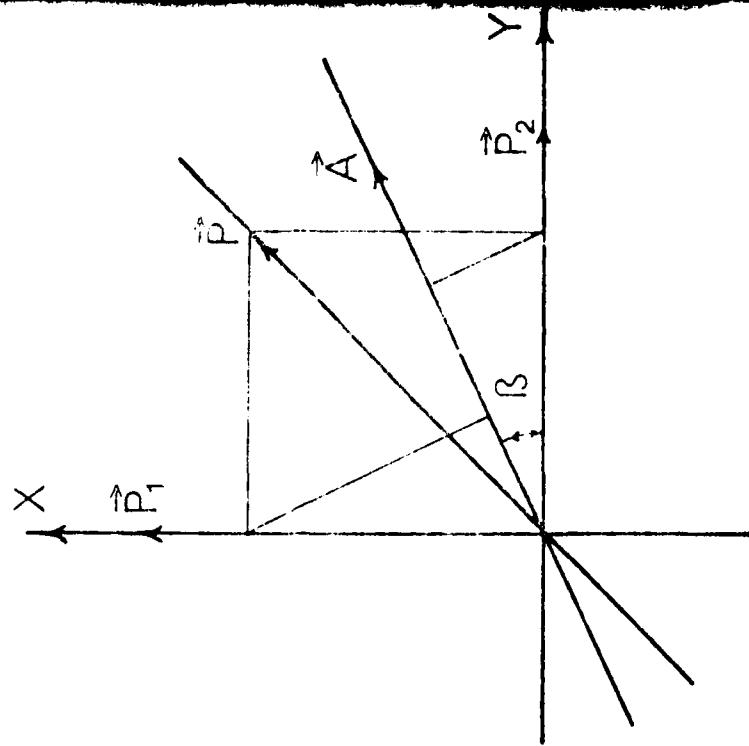


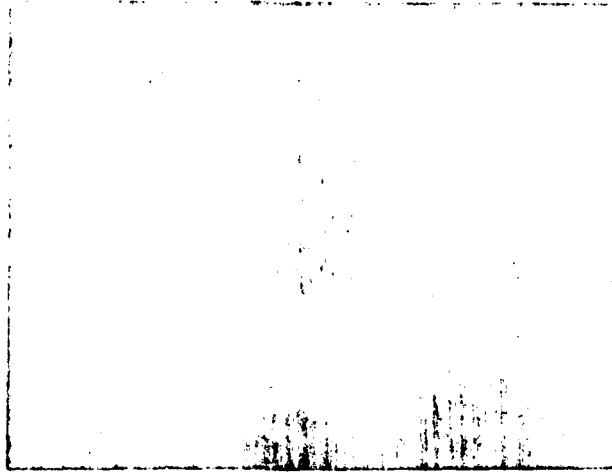


( a )

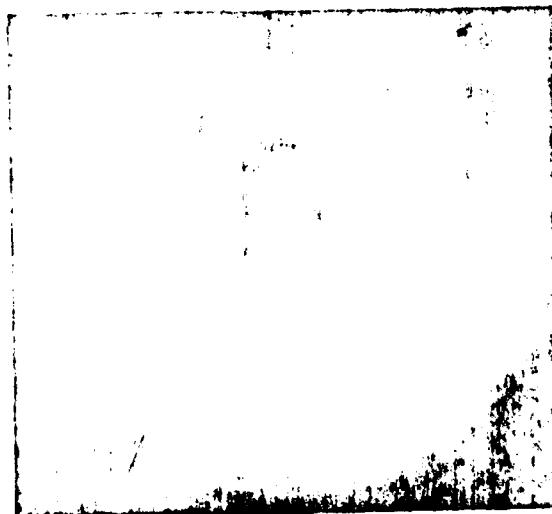


( b )

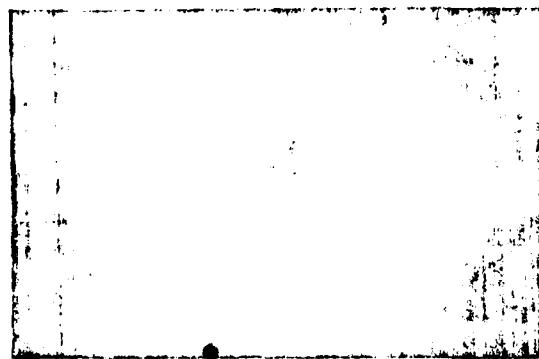




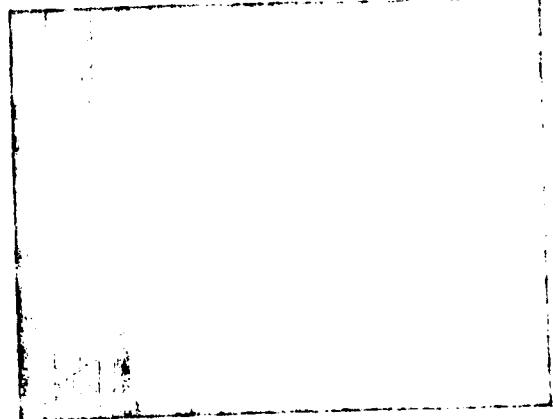
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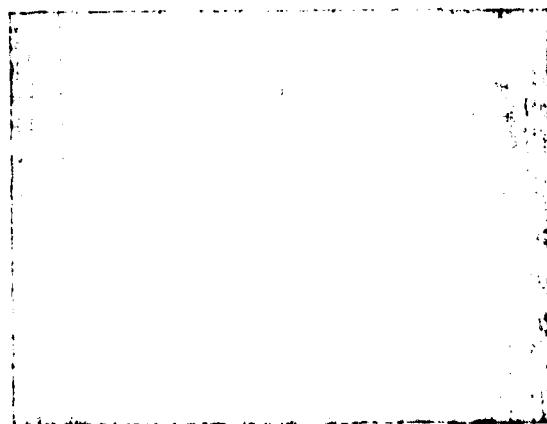
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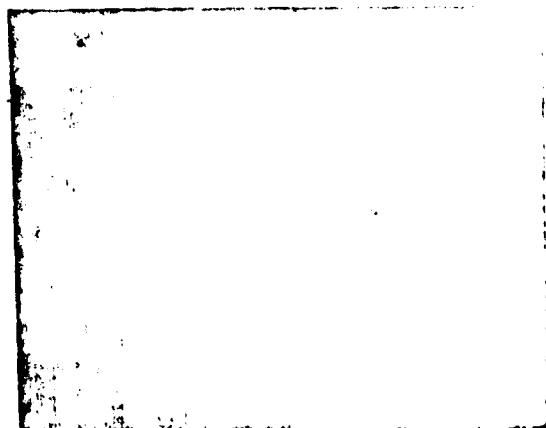
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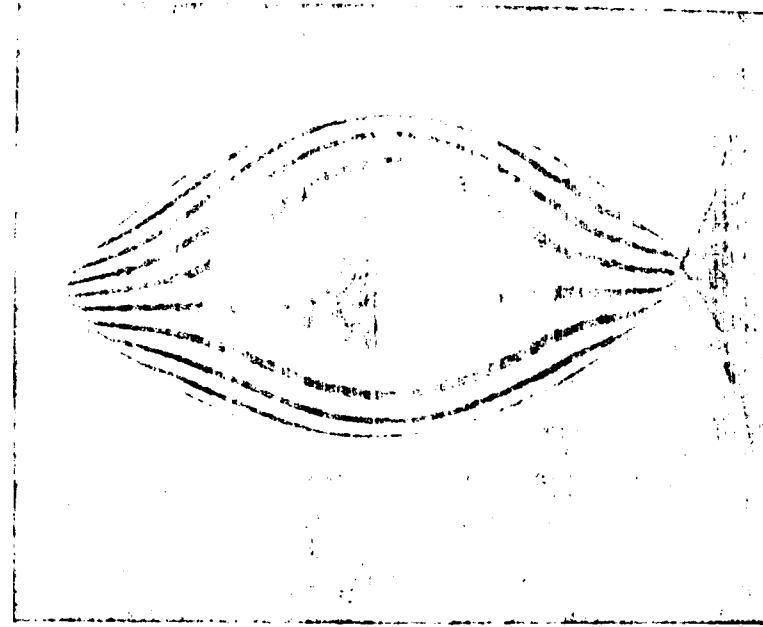
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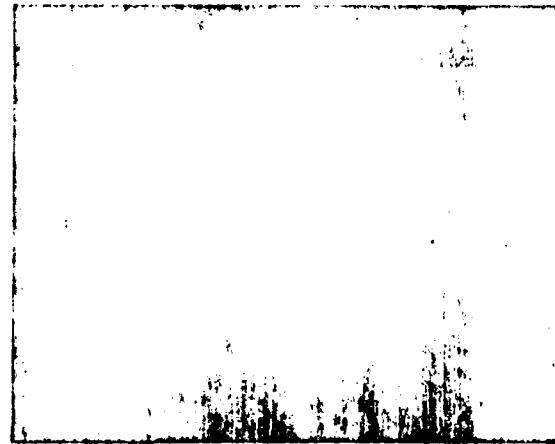
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d



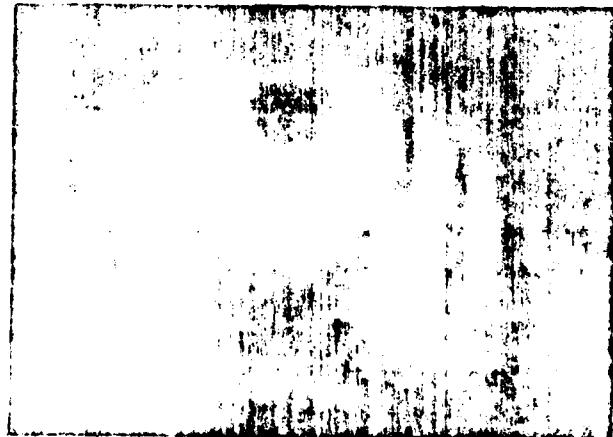
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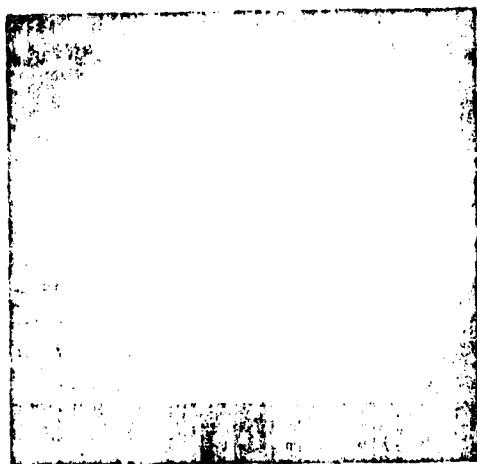
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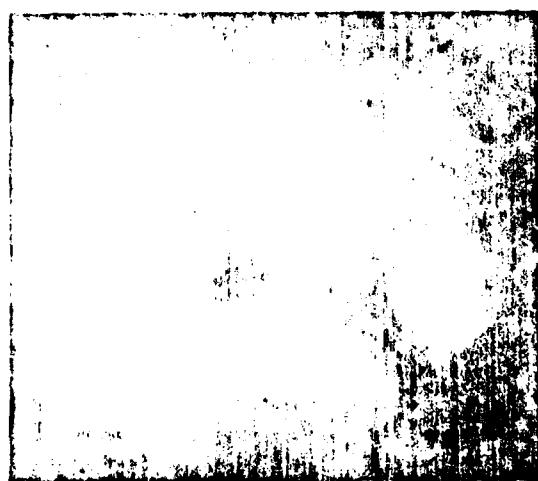
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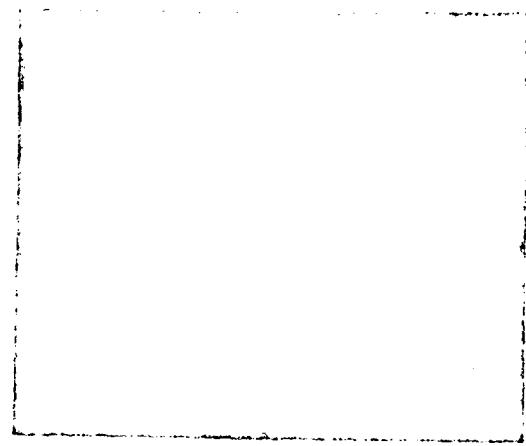
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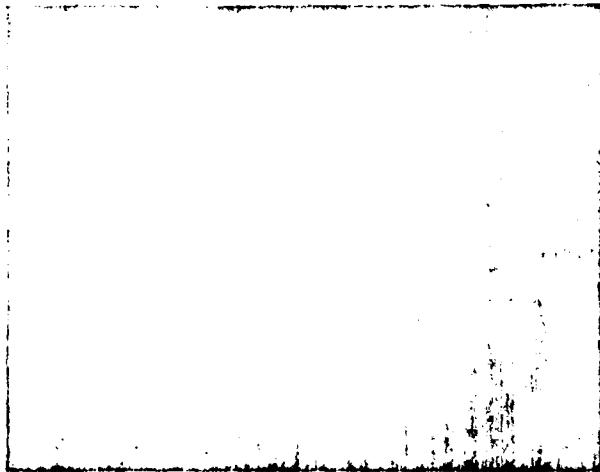
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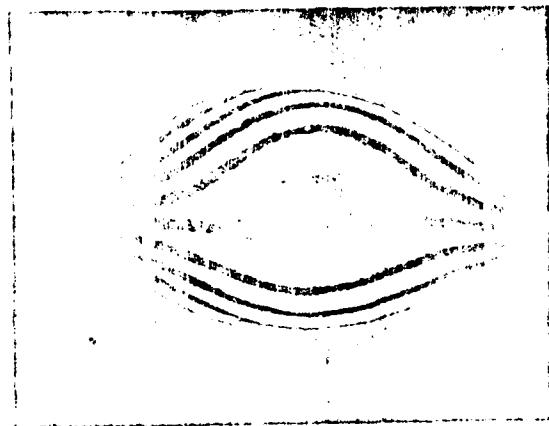
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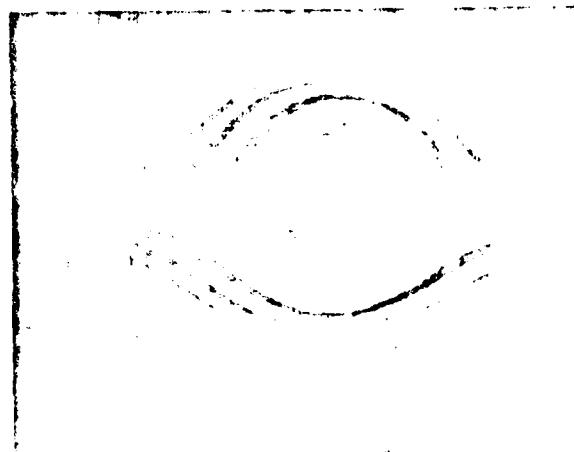
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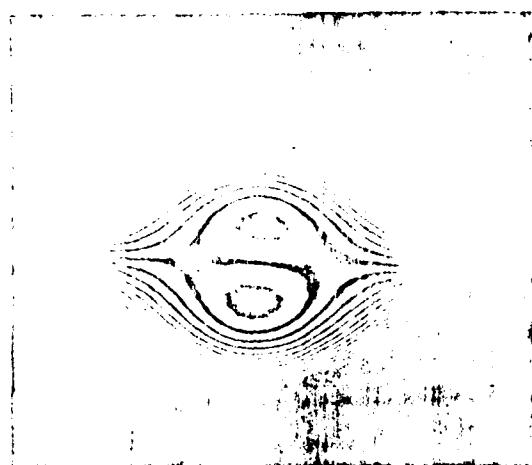
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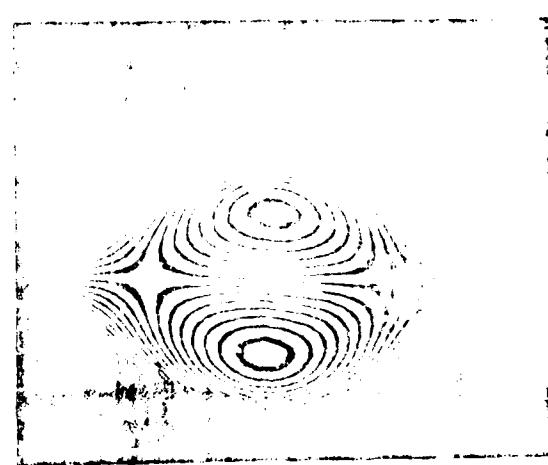
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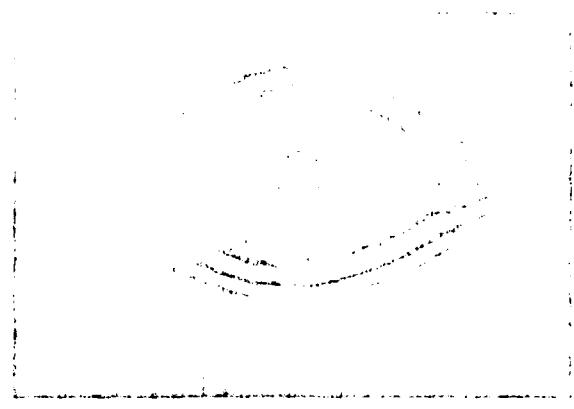
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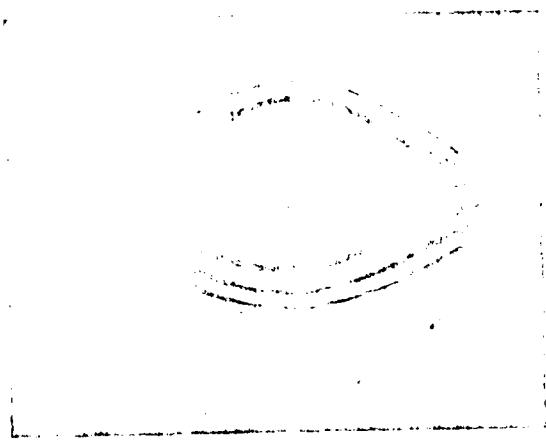
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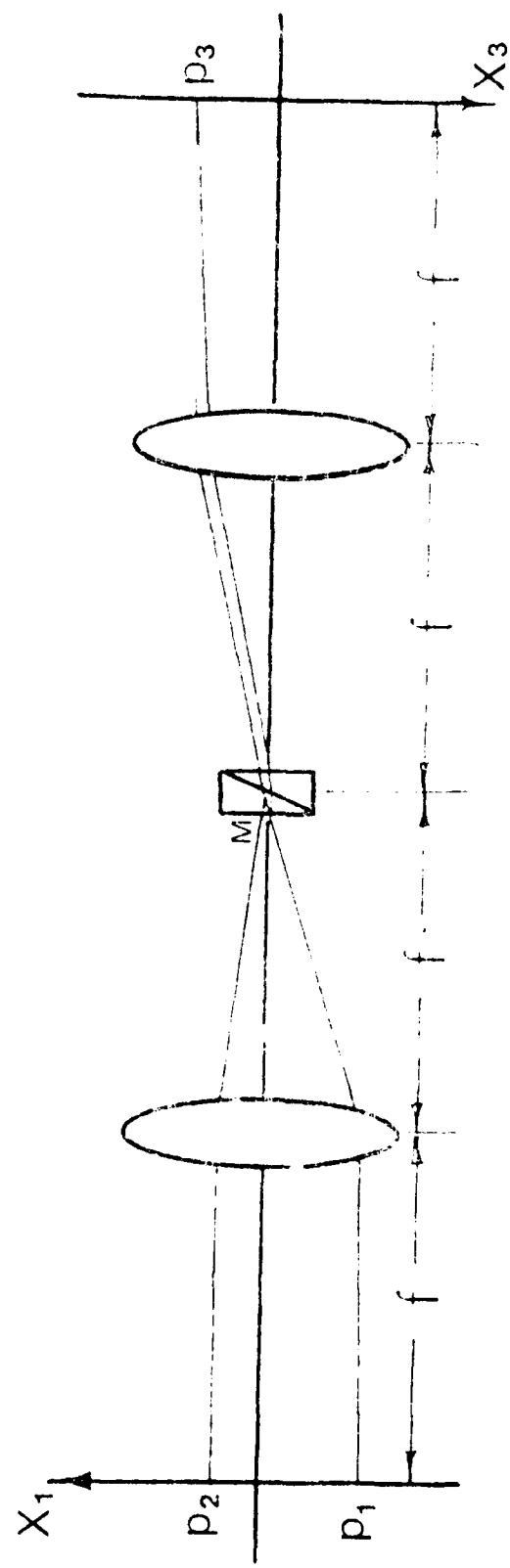
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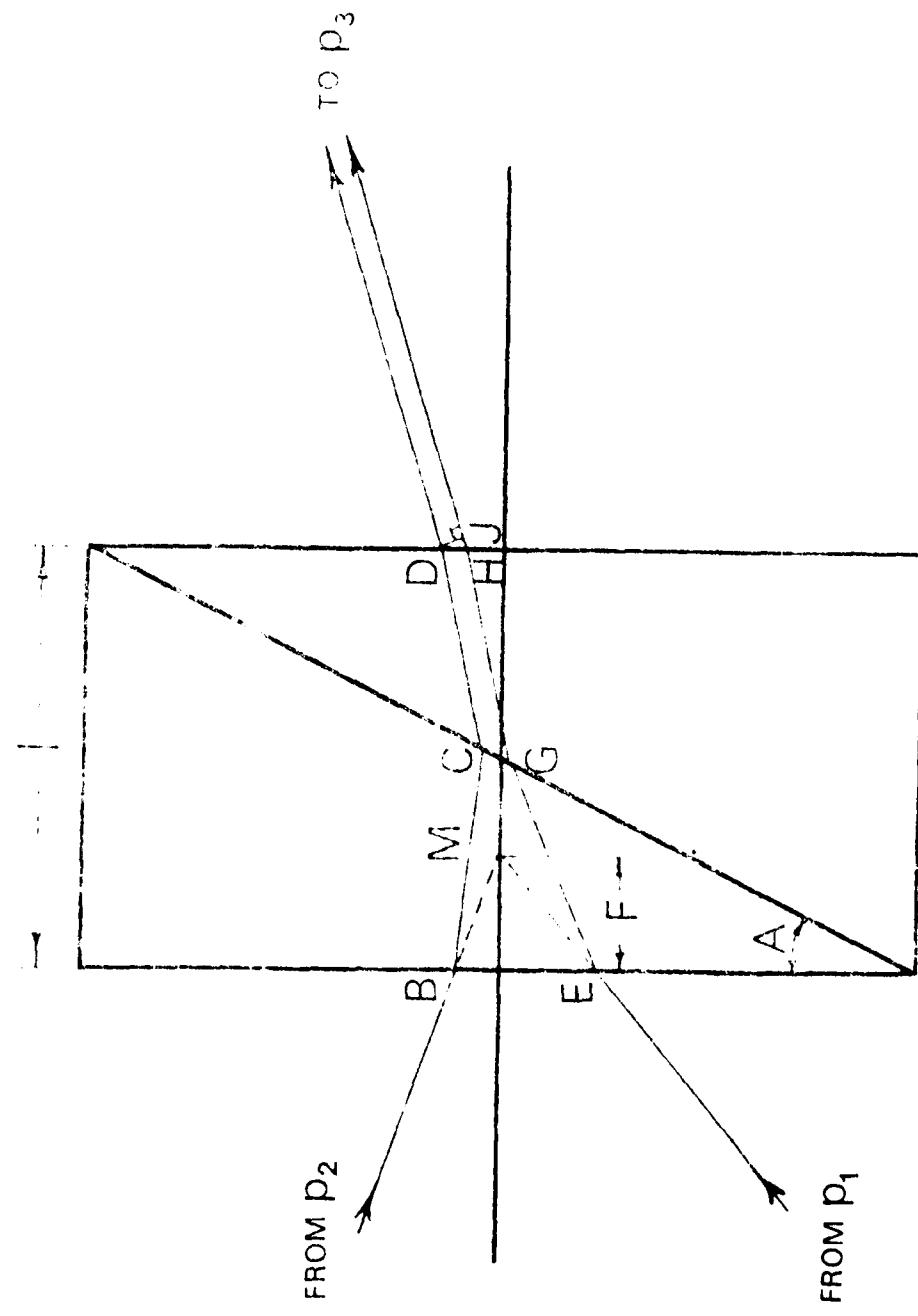


b



c





the same time, the author has been able to identify the following species:

- 1. *Leucosia fuscata* (L.)
- 2. *Leucosia fuscata* (L.)
- 3. *Leucosia fuscata* (L.)
- 4. *Leucosia fuscata* (L.)
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1. **What is the primary purpose of the study?**  
The primary purpose of the study is to evaluate the effectiveness of a new treatment for depression compared to a placebo. The study will also examine the safety profile of the new treatment.

2. **Who is eligible to participate in the study?**  
Eligible participants are adults aged 18-65 years old who have been diagnosed with major depressive disorder. Participants must be willing to take part in weekly visits and follow-up assessments.

3. **What are the inclusion criteria for the study?**  
Inclusion criteria include:

- A diagnosis of Major Depressive Disorder (MDD) as determined by a licensed psychiatrist.
- A minimum score of 18 on the Hamilton Rating Scale for Depression (HRSD).
- A minimum age of 18 years old.
- A willingness to commit to the study protocol.

4. **What are the exclusion criteria for the study?**  
Exclusion criteria include:

- A history of suicidal behavior or thoughts.
- A history of substance abuse or dependence.
- A history of significant medical conditions that would interfere with participation.
- A history of non-compliance with previous treatments.

5. **How long will the study last?**  
The study will last approximately 12 weeks, consisting of an initial screening period, a 6-week treatment phase, and a 6-week follow-up phase.

6. **What are the treatment options available in the study?**  
Participants will be randomly assigned to one of two groups:  

- Group A: New Treatment (active drug)
- Group B: Placebo

7. **What are the side effects associated with the new treatment?**  
Common side effects of the new treatment may include:

- Nausea
- Headache
- Drowsiness
- Dry mouth
- Constipation

8. **Will participants receive feedback on their progress?**  
Yes, participants will receive regular feedback on their progress through weekly visits and follow-up assessments.

9. **What are the potential risks involved in the study?**  
Potential risks include:

- Adverse reactions to the new treatment.
- Discontinuation of the new treatment due to side effects.
- Non-compliance with study protocol.

10. **How will participant privacy be protected?**  
Participant privacy will be protected through the use of anonymous identification and strict adherence to study protocols.

11. **What are the compensation and reimbursement details?**  
Participants will receive compensation for their time and effort, including travel expenses and meal allowances. Reimbursement for medical expenses related to the study will also be provided.

12. **What are the contact information for the study team?**  
Contact information for the study team includes:

- Principal Investigator: Dr. John Doe, MD
- Study Coordinator: Ms. Jane Smith, RN
- Study Office: (555) 123-4567
- Email: study@researchcenter.com







and the first stage of the process. The second stage is the period of transition from the initial state to the final state. This stage is characterized by a gradual increase in the rate of growth, followed by a period of relative stability. The third stage is the period of decline, during which the rate of growth slows down and eventually stops. The fourth stage is the period of regeneration, during which the system begins to recover and return to its initial state. The fifth stage is the period of reorganization, during which the system undergoes significant changes in its structure and function. The sixth stage is the period of finalization, during which the system reaches a new equilibrium state. The seventh stage is the period of stabilization, during which the system remains in a stable state for a long time. The eighth stage is the period of dissolution, during which the system gradually disappears or becomes irrelevant. The ninth stage is the period of rebirth, during which the system is reborn and begins a new cycle of growth and development.

The model of social development proposed by Kondratieff is based on the assumption that the economic system is a complex adaptive system that follows certain underlying patterns of behavior. These patterns are reflected in the cyclical nature of the system's development. The model also suggests that the system's behavior is influenced by various factors, such as technological advancements, political changes, and social movements. The model is particularly useful for understanding the long-term trends in the economy and for predicting future developments. It has been applied to a wide range of fields, including economics, politics, and social science. The model has also been used to analyze historical events and to predict future trends. The model is a valuable tool for anyone interested in understanding the dynamics of social development and for anyone looking to make informed decisions about the future.

the 1960's, the U.S. spent about \$10 billion on research and development of space flight technologies, mostly in the military aerospace field. This investment has led to many important technological advances, particularly in the areas of navigation, communications, and materials science. The space program has also contributed to the development of new industries, such as satellite manufacturing, and has helped to stimulate interest in science and technology among young people.

The space program has had a significant impact on society, both directly and indirectly. Directly, it has provided jobs and economic opportunities for many people, particularly in the aerospace industry. Indirectly, it has helped to improve our understanding of the universe and our place in it. The space program has also inspired many people to pursue careers in science and technology, and has helped to stimulate interest in education and learning.

The space program has also had a significant impact on our culture, particularly through the media. The first satellite, Sputnik, was launched in 1957, and its orbit around Earth became a symbol of the Cold War era. The Apollo moon landing in 1969 was a major event that captured the imagination of people all over the world.

The space program has also had a significant impact on our economy, particularly through the development of new technologies and industries. The space program has helped to stimulate interest in science and technology, and has helped to stimulate interest in education and learning.

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the other person's point of view. This is what I mean by "reflecting on dialogue". In this way, the teacher can become more aware of his/her own ways of interacting with students, and can begin to make changes in his/her teaching style. This process of self-reflection is crucial for effective teaching, as it allows the teacher to continuously improve their practice and better serve their students.

Another important aspect of reflection on dialogue is the ability to listen actively and attentively. This means listening not just to the words being spoken, but also to the tone of voice, the body language, and the overall atmosphere of the conversation. By doing this, the teacher can gain a deeper understanding of the student's thoughts and feelings, and respond more effectively to them. This active listening is essential for creating a positive learning environment where students feel safe to express themselves and ask questions.

Reflection on dialogue also involves the ability to observe and analyze the interaction between the teacher and the student. This can be done through various methods, such as video recording or audio tape recording, and then reviewing the tape to identify specific moments of effective communication or areas for improvement. This analysis can help the teacher to identify patterns of behavior and make conscious decisions about how to approach different situations in the future.

In conclusion, reflection on dialogue is a valuable tool for teachers to enhance their effectiveness in the classroom. It requires a commitment to self-improvement and a willingness to listen and learn from others. By reflecting on dialogue, teachers can develop a deeper understanding of their students' needs and create a more supportive and engaging learning environment.

відомості про діяльність підпілля в революційних рівнях. Але це не є відповідь на питання, яким чи якими засобами було отримано ці відомості. Іншими словами, відповідь на це питання може бути лише в тих випадках, коли буде встановлено, що відомості про діяльність підпілля в революційних рівнях отримані засобами, які відповідають засобам, якими відомості про діяльність підпілля в революційних рівнях надаються. Але це питання є питанням, яке виникає лише в тих випадках, коли буде встановлено, що відомості про діяльність підпілля в революційних рівнях отримані засобами, якими відомості про діяльність підпілля в революційних рівнях надаються.

Але це питання є питанням, яке виникає лише в тих випадках, коли буде встановлено, що відомості про діяльність підпілля в революційних рівнях отримані засобами, якими відомості про діяльність підпілля в революційних рівнях надаються. Але це питання є питанням, яке виникає лише в тих випадках, коли буде встановлено, що відомості про діяльність підпілля в революційних рівнях отримані засобами, якими відомості про діяльність підпілля в революційних рівнях надаються.

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1. The first step in the process of creating a new language is to identify the basic elements of communication. This involves defining the symbols used to represent different concepts and ideas. In the case of the proposed language, the symbols are based on the International Phonetic Alphabet (IPA), which provides a standard set of phonetic symbols for representing the sounds of all the world's languages. The IPA symbols are chosen because they are widely used and well-known, making it easier for people from different linguistic backgrounds to learn and use the new language.

2. Once the basic symbols have been established, the next step is to define the rules for combining them into words and sentences. This involves creating a grammar that specifies how different symbols can be put together to form meaningful units of language. In the proposed language, the grammar is designed to be as simple and intuitive as possible, making it easy for people to learn and use the language effectively.

3. The third step in the process of creating a new language is to develop a vocabulary. This involves identifying the words and phrases that are most commonly used in the language and creating a dictionary that defines them. In the proposed language, the vocabulary is based on the most common words and phrases used in English, as well as other major world languages. This makes it easier for people to learn and use the language, as they can draw on their existing knowledge of other languages to help them understand the new one.

4. The final step in the process of creating a new language is to test and refine it. This involves using the language in real-world situations to see how well it works and make any necessary changes or improvements. In the proposed language, this involves testing the grammar, vocabulary, and overall structure of the language to ensure that it is effective and easy to use.

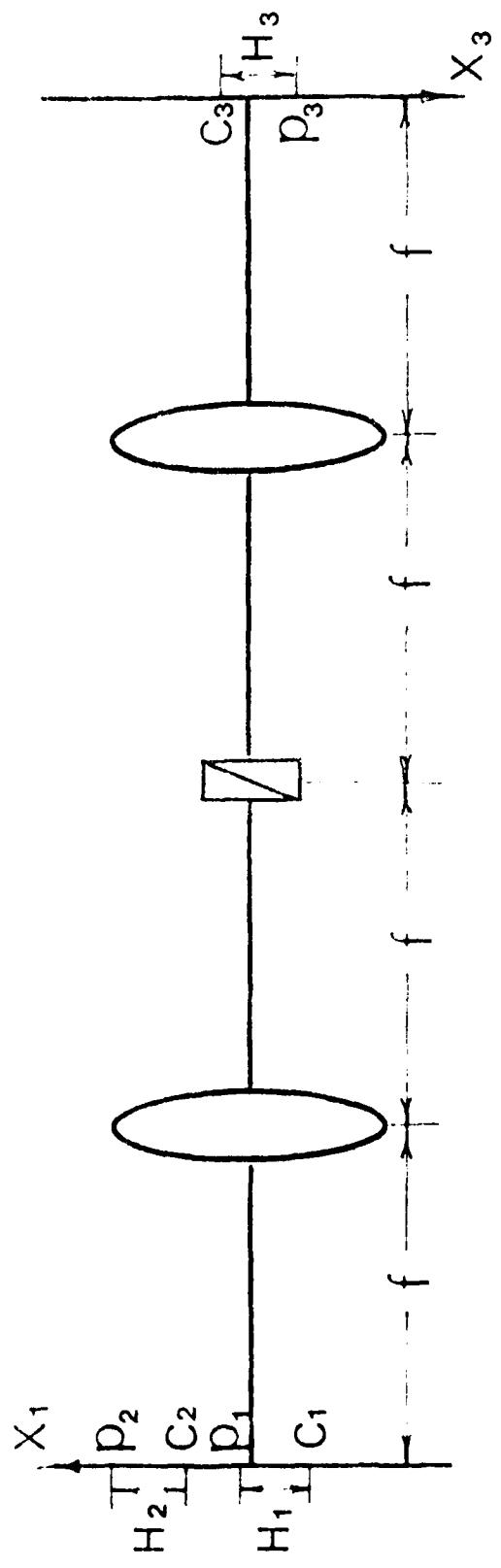
Overall, the process of creating a new language involves a careful consideration of the basic elements of communication and the rules for combining them into meaningful units of language. By following this approach, it is possible to create a language that is both effective and easy to learn and use.

the most important thing  
is to have a good  
relationship with your  
clients. You should  
try to understand their  
needs and provide them  
with the best service  
possible. This will help  
you build a strong  
client base and ensure  
that you are successful  
in your business. It's  
also important to stay  
up-to-date with the latest  
trends and technologies  
in your industry. This  
will help you stay ahead  
of the competition and  
keep your business  
thriving. Finally, it's  
important to have a  
positive attitude and  
be willing to work hard.  
With these tips, you  
can start your own  
business and achieve  
success.

Businesses are a great  
way to make money and  
achieve success. They  
can provide a sense of  
independence and allow  
you to work from home.  
However, starting a  
business can be a  
challenging process. It  
requires a lot of hard  
work, dedication, and  
perseverance. But if you  
have a clear vision and  
a plan in place, you  
can achieve success.  
One of the most  
important things to  
remember is to stay  
positive and focused.  
Don't let setbacks  
discourage you. Instead,  
use them as learning  
opportunities. Another  
key to success is to  
network with other  
business owners and  
professionals. This  
can help you find  
new clients, partners,  
and opportunities.  
Finally, it's important  
to keep your business  
up-to-date with the  
latest trends and  
technologies. This  
will help you stay  
competitive and succeed  
in the long run.



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## CONTINUATION OF THE PREVIOUS PAGE

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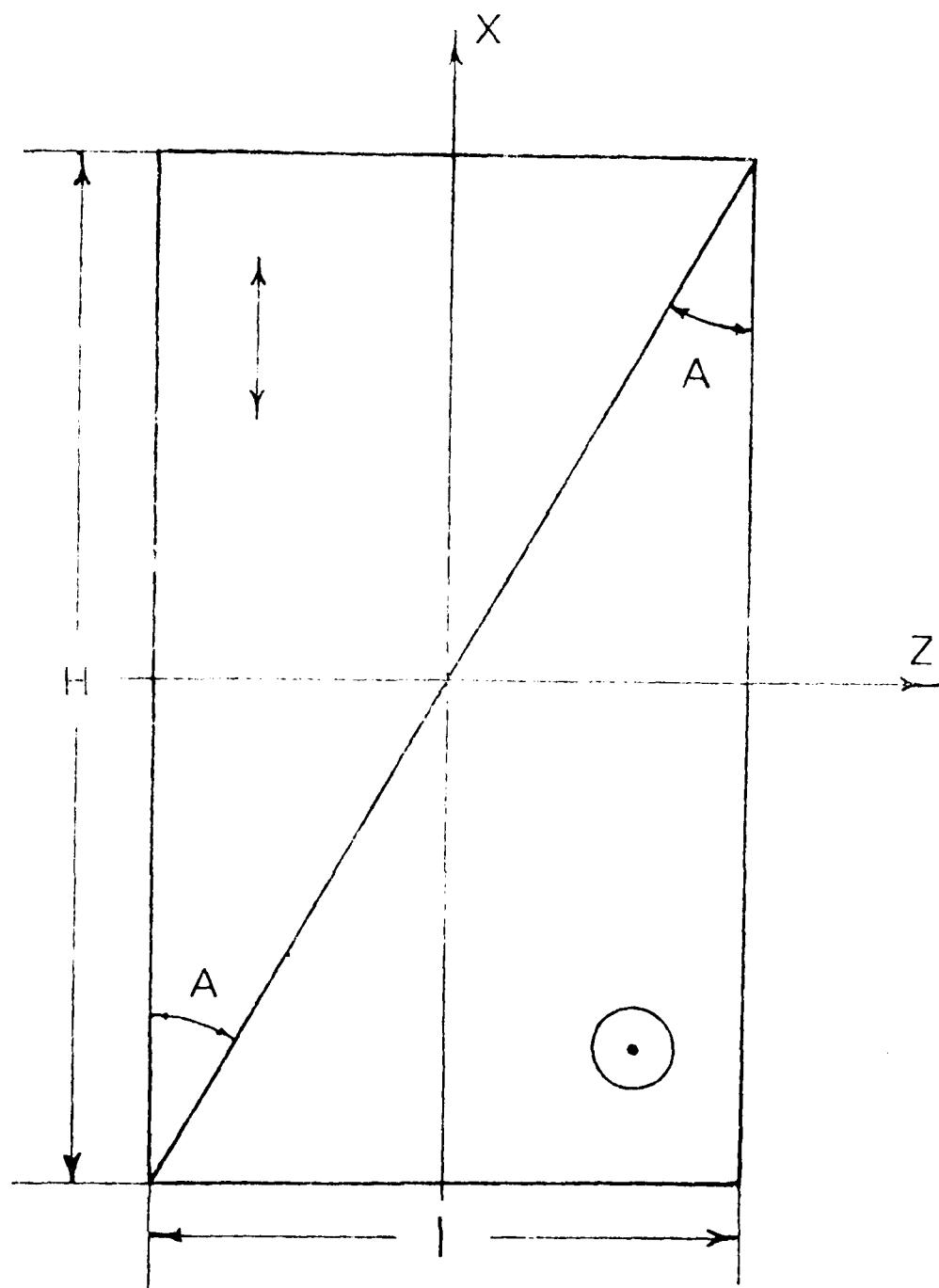


Fig. 2.1