COMPUTATION BOOK

NAME	Number
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Course

Used from December 1965, to July 2, 1968.

HARVARD COOPERATIVE SOCIETY
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6 December 1965

Tests of Minicard FE-5142 film extended to red-sensitive range.

This film was tested to determine it's resolution capability and its suitability for recording holograms. By recording the interference pattern of one collimated beam and one spherical wavefront, spacial frequencies up to 2600 lines/mm were recorded. It seems that higher spacial frequencies could be recorded. The exposure times were about 1/10 sec. and the film exibited characteristics of being extremely high-contrast.

Several holograms were made with an angle of about 30° between the reference and signal beams. Reconstructions were obtained, but the intensity of the image was low and the scattered light level was high. Holograms were made under identical conditions on 649F emulsion on glass plates and film. The images on glass plates were very clear and sharp, and exposure time of 3 minutes was required. Images on the film were of lower intensity, in spots did not reconstruct due to vibration of film, and required exposures times of 10 min., compared to 1 min. for the minicard film. The minicard film behaved as a low contrast film at these exposure levels. The 649F emulsions were developed for 6 min. in Kodak D-19 developer, the minicard for 4 min. in the same developer. The reciprocity law apparently does not hold for the minicard film at low light levels. The films were sandwitched between two glass plates during the exposure, but apparently some vibration was present.

Juris Upatnieks, 6 Dec. 1965

6 December 1965

Reasons for some of the imperfections in enlargements of microscope slides using hologram tech

The enlargements of microscope slides made in summer of 1964 and shown on page 50+51 of the previous notebook show several defects. Two of these are the superposition of a grating-like structure, the other is a coarser background brightness variation. The same original fly's wing was examined in laser light under both high and low magnification. Under high magnification the grating-like structure was clearly visible. Apparently it is caused by reflection from one or two of the four surfaces (the fly's wing was mounted between two glass plates). Under lower magnification, the coarser structure was also visible. This might also be caused by interference from multiple reflections, or it might be caused by highly irregular glass surface. Anyhow, these two defects are caused by the manner of mounting the specimen and not by the hologram process itself.

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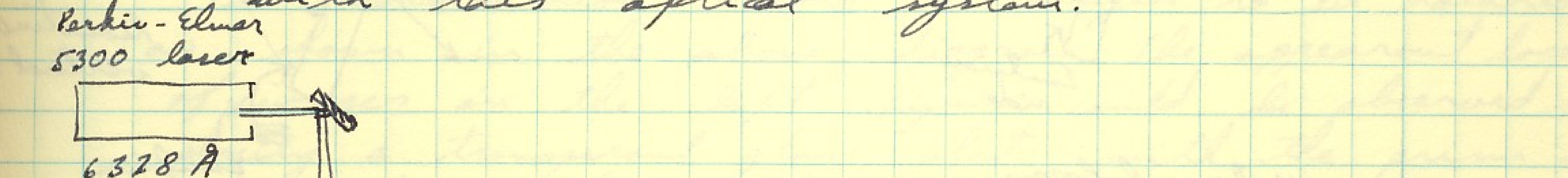
8 December 1965

Experimental verification of the cause of forward images in holograms made with reference beam from the back.

Holograms made with the reference beam from the other side of the photographic plate exibited some unexpected properties. These were that images also reconstruct if the hologram is illuminated in the ordinary manner, with light illuminating the plate from one side and the observer viewing it from the other. Two such images are visible, one on either side of the reference beam. An explanation proposed Leith and others suggested that internal reflections of the signal and reference beams cause these other two images.

To verify this idea, a hologram was made with this optical system:



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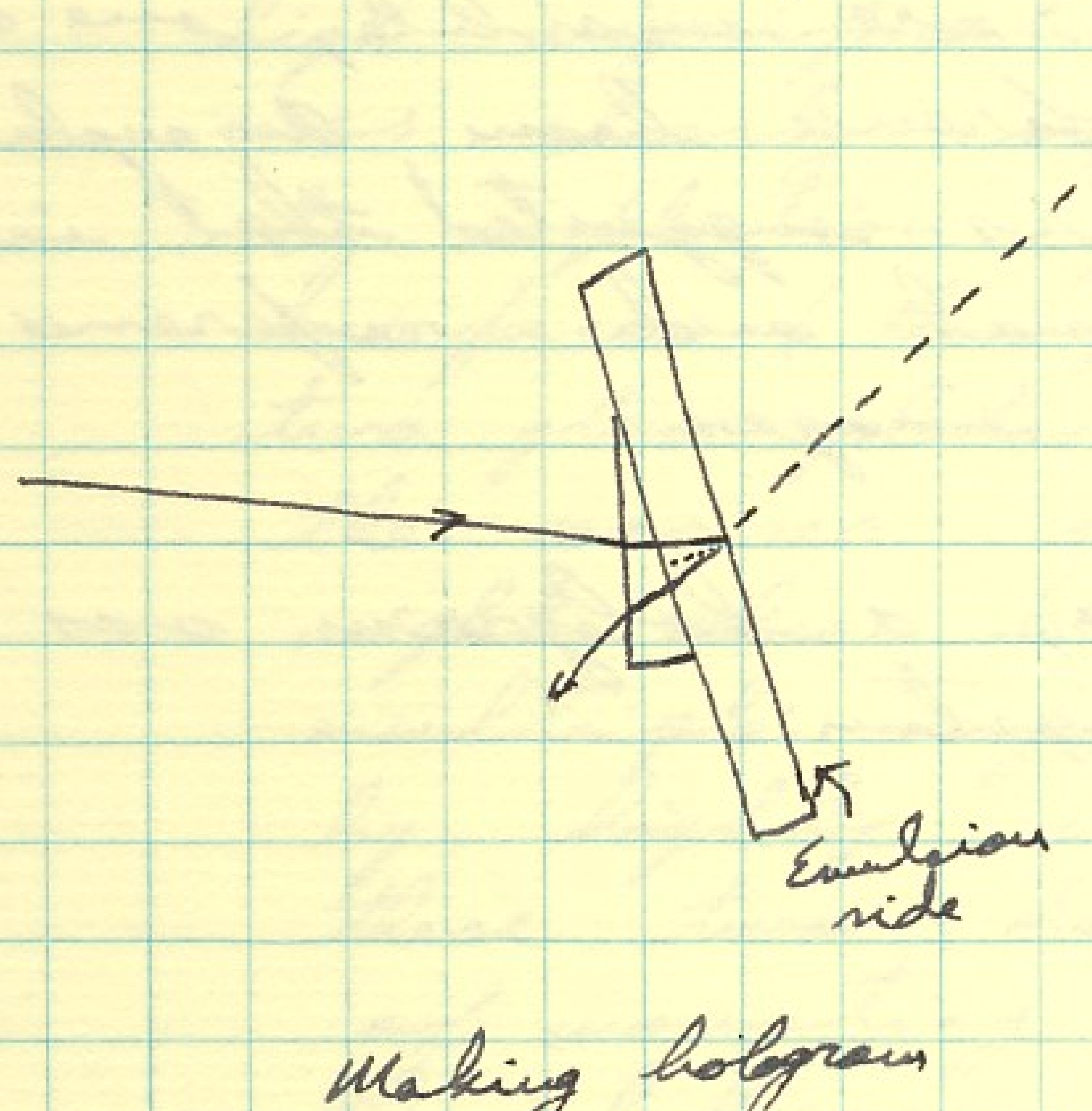
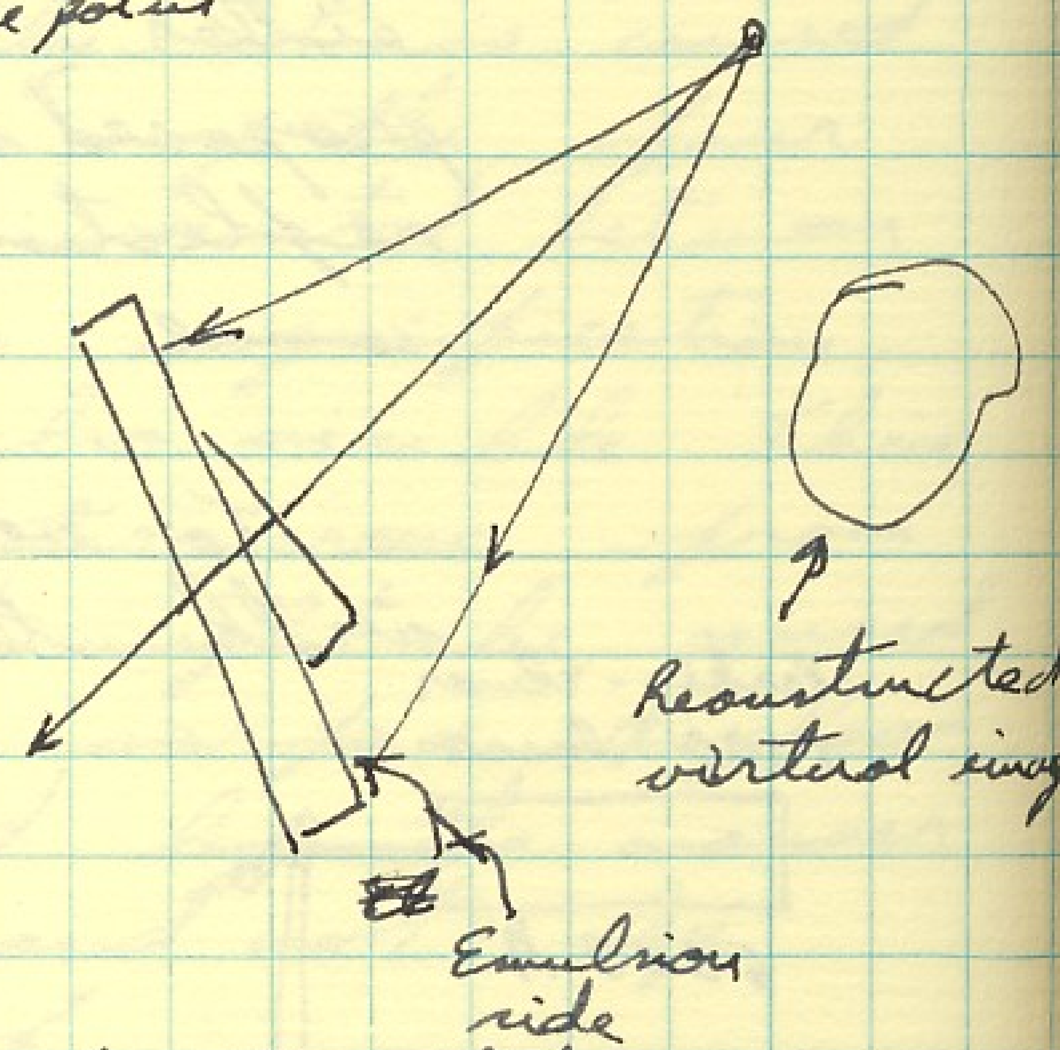
The intensity of reference beam was 30×10^{-4} and of signal beam 18×10^{-4} measured with S.&M light meter. Exposure time was 70 sec. and the plate was slightly overexposed. A 9° prism was placed on the glass side of the plate with ~~and~~ Xylene liquid between the surfaces to eliminate surface reflections.

If internal reflection at the emulsion side of the reference beam is cause of one image, then the source should appear to be near the object and reconstruction should be possible:





Reconstructing hologram.
With prism in place, image should appear to reconstruct in same place

In reconstruction, the image appeared to come from the same location when the prism was in place, thus verifying that this image indeed comes from the reflected reference beam.

The other image could come from internal reflection of the signal beam. The following diagrams apply to this case:

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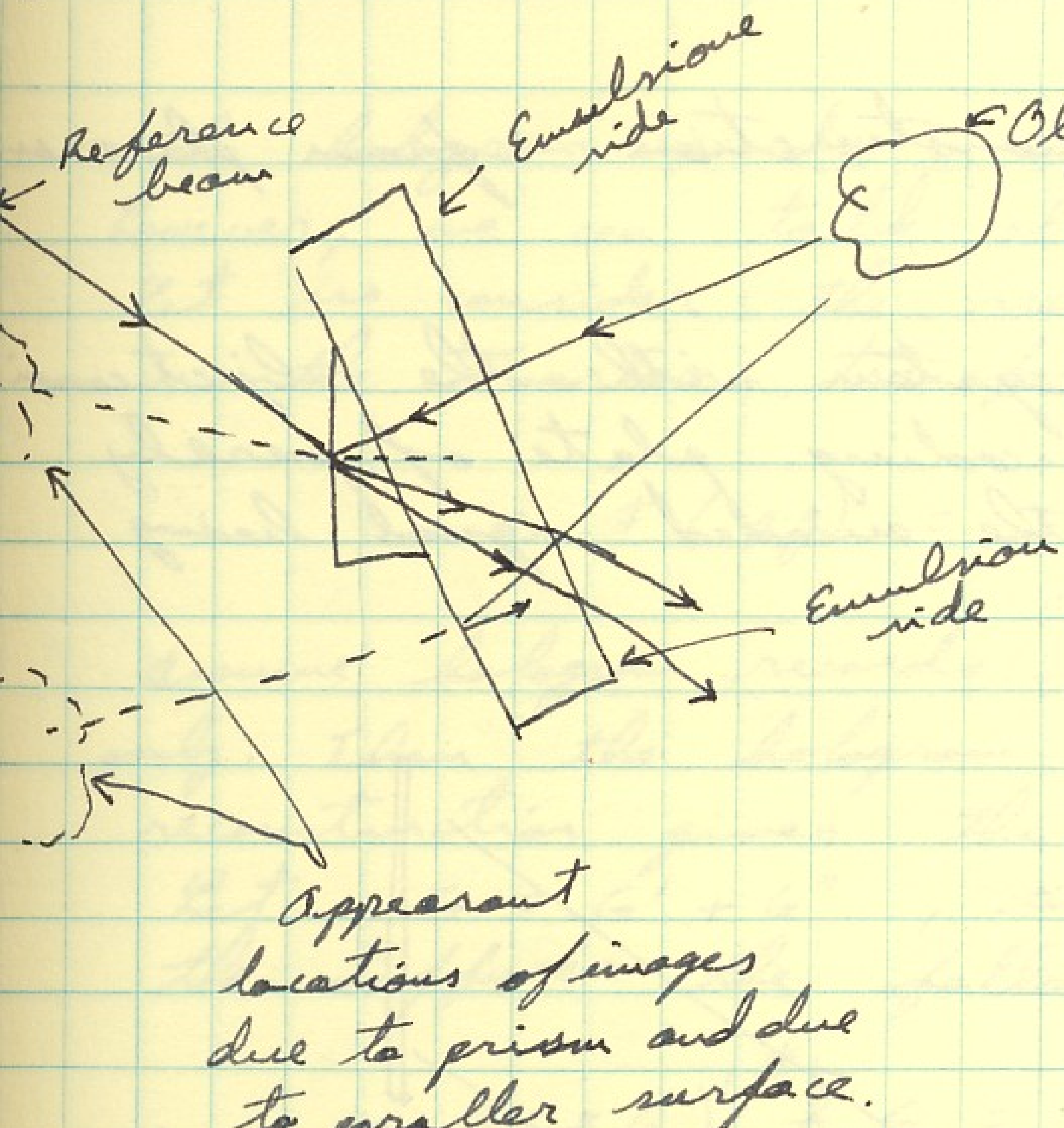

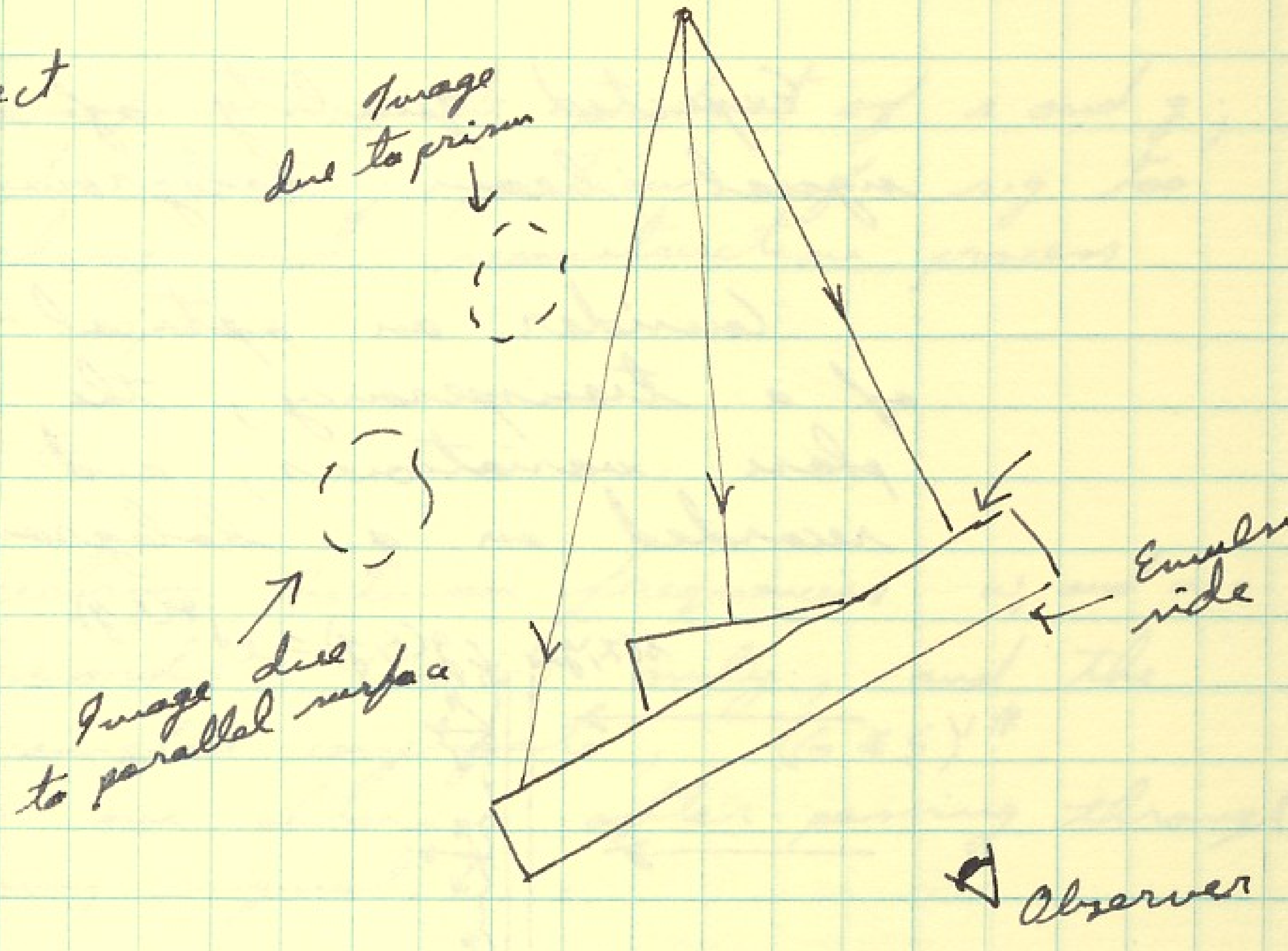

Making of hologram

Reconstruction

The reconstruction showed the images to be located as shown in the above diagram. The appearant location of images in the left figure could be observed by placing a transperant glass plate with the prism in same place where the hologram was made.

Observations of the reconstructed hologram are in good agreement with the above predicted location of images.

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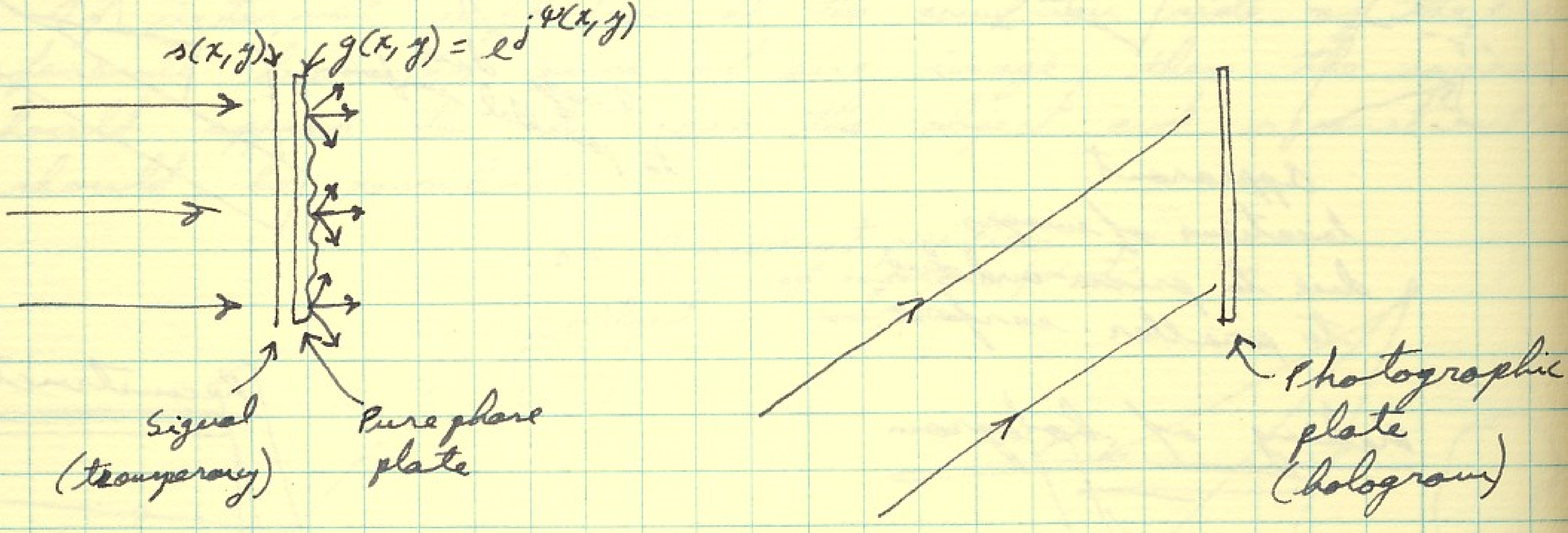
24 December 1965

Expected quality of reconstruction from phase-encoded signal beam holograms.

Consider an optical system with the object consisting of a transparency, the encoding plate of purely phase variations, and the encoded signal being recorded on a hologram:



$$s(x,y) = a(x,y)\, e^{j\theta(x,y)}$$
$$g(x,y) = e^{j\psi(x,y)}$$

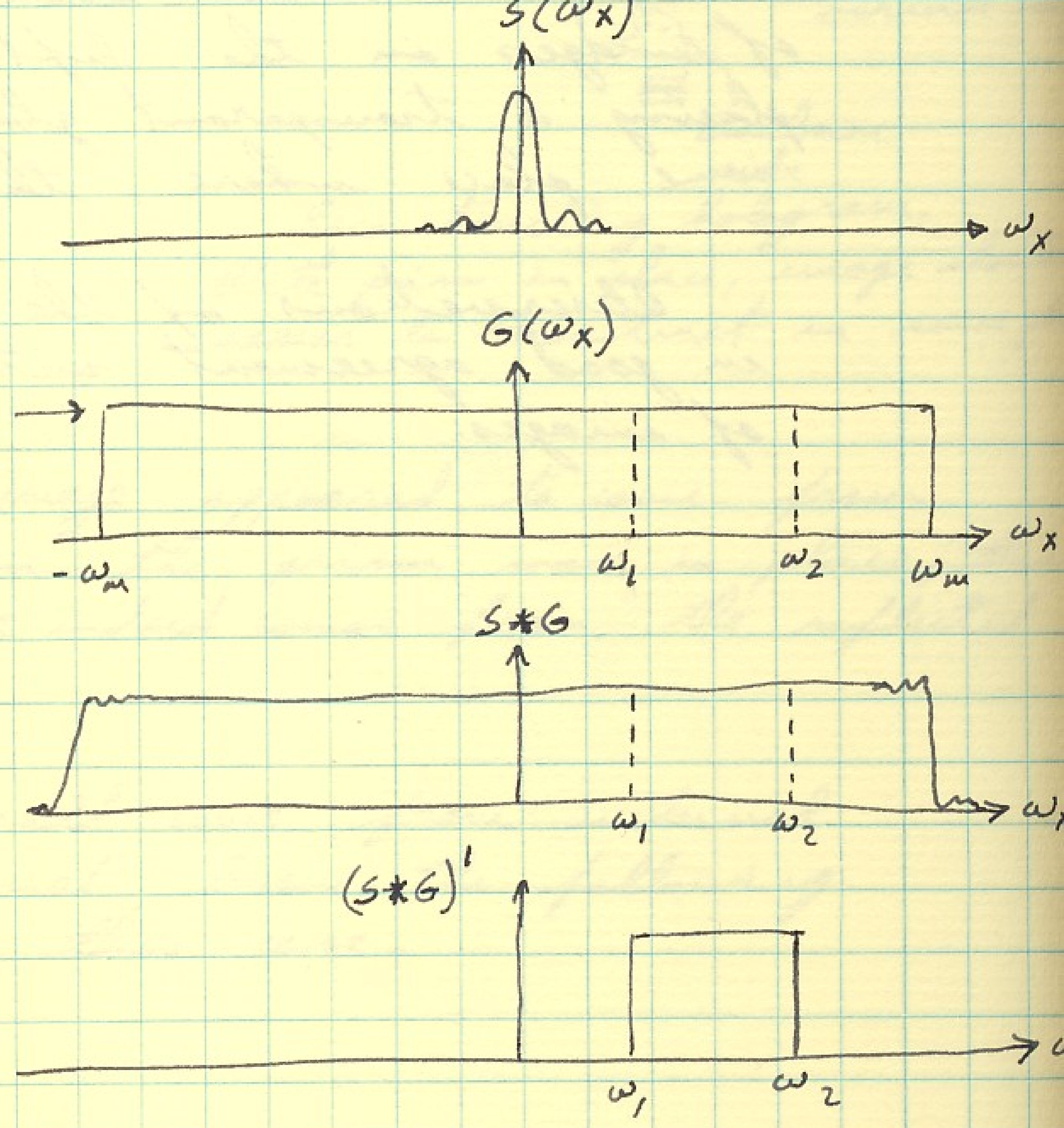
$$\mathcal{F}(s) = S(\omega_x, \omega_y)$$
$$\mathcal{F}(g) = G(\omega_x, \omega_y)$$

(Note: spectrum of G is actually amplitude-varying)

$$G = \begin{cases} G' & \omega_1 \le \omega \le \omega_2 \\ G'' & \text{elsewhere} \end{cases}$$

Let $(S*G)' = S'*G'$

where S' is actual portion of S recorded on a hologram



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The hologram records a transform of the product of s and g; however, we can talk about recording portions of s.g too. Let us consider the recording and reconstruction process in the Fourier transform plane.

$$\mathcal{F}(s \cdot g) = S * G$$

Assume hologram records spectrum between frequencies ω_1 and ω_2 only. Then the hologram records $(S*G)'$ only, and the reconstruction gives the complex conjugate, $(G*S)'^*$.
Let $G = G' + G''$, then one obtains after passing through the differer the following signal:

$$(S*G)'^* * G = (S'^* * G'^*) * (G' + G'')$$

$$= S'^* * (G'^* * G') + S'^* * (G'^* * G'')$$

(↑ G'^*)

$$= S'^* + S'^* * (G'^* * G'')$$

since $G'^* * G'$ gives a delta function correlation

The other signal $S'^* * (G'^* * G'')$ does not correlate to a delta function and therefore amount to noise, which we shal call N. The reconstructed signal is then of the form

$$\mathcal{F}^{-1}[(S*G)'^* * G] = s' + n$$

The signal to noise ratio, assuming $s' = s$, is then

$$\frac{s}{n} = \frac{\frac{\omega_2 - \omega_1}{2\omega_m}}{1 - \frac{\omega_2 - \omega_1}{2\omega_m}} = \frac{\omega_2 - \omega_1}{2\omega_m + \omega_1 - \omega_2}$$

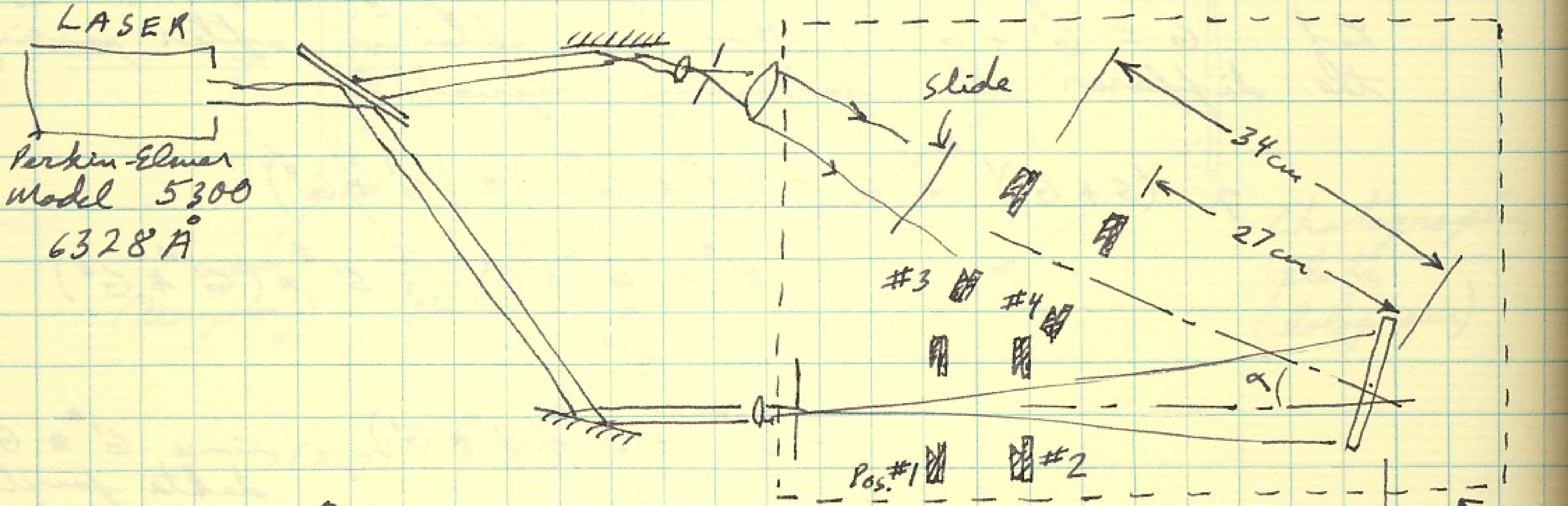
Thus the reconstruction will be noisy if $2\omega_m$ is much greater than $\omega_2 - \omega_1$. Presumably, s' should be nearly as good as s if the bandwidth of s is considerably less than $\omega_2 - \omega_1$.

Juris Upatnieks, 24 December 19[illegible]

28 December 1965

Experiments with phase-encoded reference beam

Experiments were done with the permanently assembled optical system for making phase-encoded holograms. The fixed mounting of the hologram was replaced by a mount with vertical, horizontal, and rotational adjustment since it was found that the hologram could not be replaced with sufficient accuracy. The optical system used was the following:



$\alpha = 23°$

f_s (at 6328 Å) $\approx$ 640 l/mm

Two holograms were made on 23 December 1965 with diffusers in the reference beam in position #2.

	S.M. light meter reading	Diffuser	Exp. time	Micron. settings for recon.
Hologram #1	7×10^{-2} ref.	"A" in pos. #2	8 sec. (exp. good)	Horiz.: 5.3+ and 0.3 Vert.: 0.2 and 0.7
Hologram #2	6×10^{-3} ref.	"D" in pos. #2	85 sec. (exp. good)	Horiz.: 5.3+ and 0.5 Vert.: 0.2 and 0.7

Both holograms gave readable reconstructions when properly adjusted. Diffuser "A" is a piece of etched glass with narrow-band dispersion; diffuser "D" is opal glass with appearantly equal dispersions in all directions. The estimated maximum spacial frequency

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content of the reference beam with diffuser "D" was 250 l/mm, and that for diffuser "A" lower. The reconstructed images were recorded on film:

Film recordings (sheet #15, 27 Dec. 1965):

#5 Reconstruction from hologram #1 with diffuser "A". Exp. times: 1, 3, 12, 30 sec. (attenuator in light beam).

#6 Reconstruction from hologram #2 with diffuser "D". Exp. times: 3, 12, 30, 90 sec.

To make the reconstruction completly disappear, hologram #1 had to be misaligned by about 40μ either up or sideways; hologram #2 had to misaligned by about 20μ.

Difficulties were encountered in aligning the holograms: usually only a band of letters could be reconstructed at a time instead of the whole image. It was found that rotation of the hologram around vertical axis would correct this. The rotation appearantly corrects for a horizontal scale error, which in turn might be caused by shrinkage of the emulsion when drying. Different part of the hologram reconstruct with different brightness, appearantly also caused by shrinkage of emulsion.

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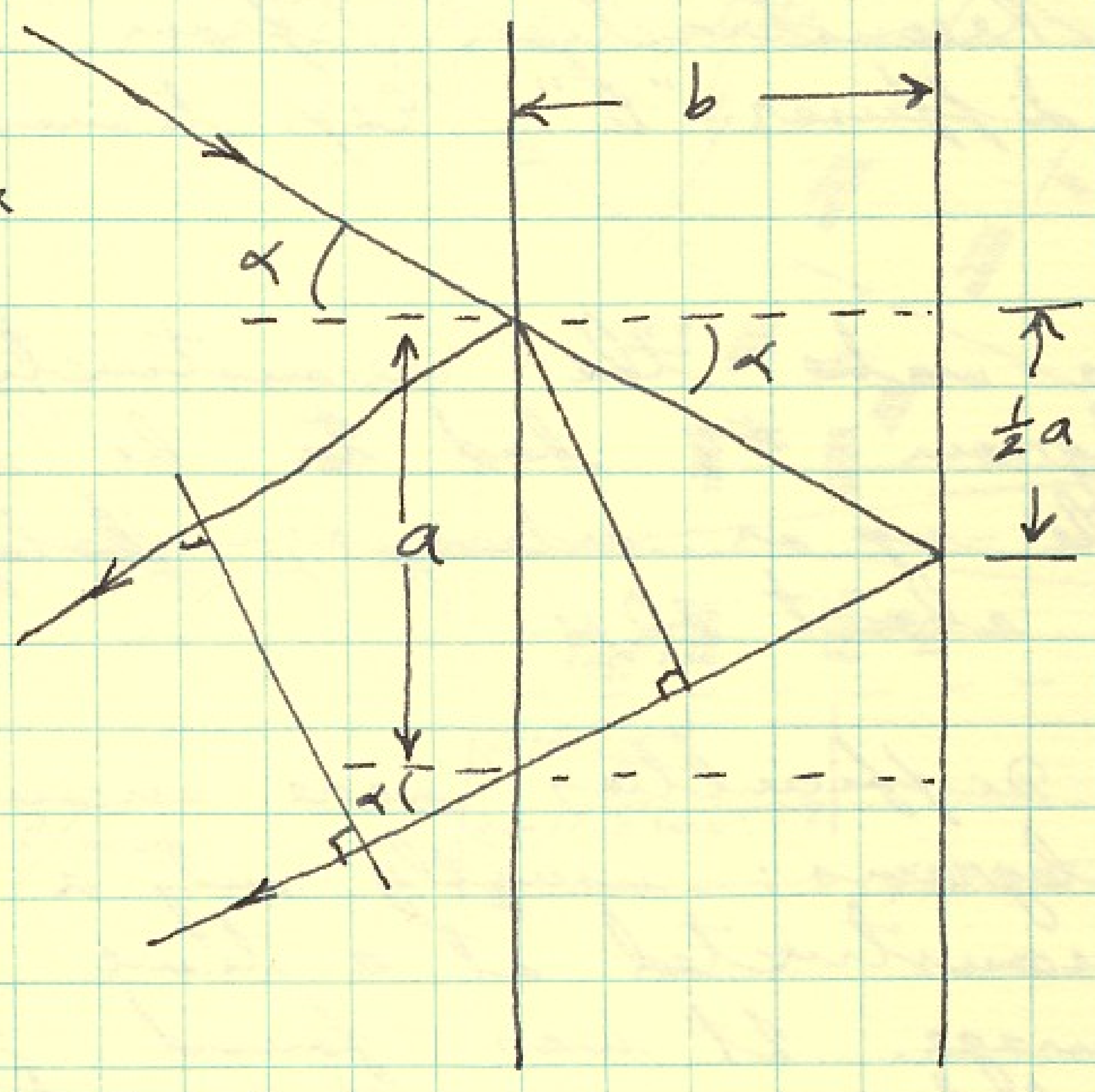
4 January 1966

change in wavelength at which hologram reconstructs due to changes in angle of incidence

To calculate the effect of changing the angle of incidence of light on a hologram, it is sufficient to consider two reflective layers within the emulsion. The layers are produced by interference in the hologram making process.

α = angle of incidence
b = spacing between layers
D = total path difference



$$D = 2\frac{b}{\cos\alpha} - a\sin\alpha$$

$$a = 2b\tan\alpha$$

$$D = \frac{2b}{\cos} - \frac{2b\sin^2\alpha}{\cos\alpha} = \frac{2b}{\cos\alpha}(1-\sin^2\alpha)$$

$$D = 2b\cos\alpha$$

Therefore, path length decreases with increasing angle of incidence, and the hologram with reconstruct at shorter wavelengths.

Juris Upatnieks, 4 January 1966

6 January 1966

Holograms with phase-encoded signal beam.

Several holograms were made with the fixed assembly, and using etched glass and opal glass having different dispersion characteristics. The data on holograms are as follows (all holograms were made on 5 January 1966):

Hologram #	Intensity of light	Type of diff. & pos.	Exp. time	Remarks
#1	35×10^{-3} ref. 38×10^{-3} signal	Diff. "A" in pos. #3	10 sec.	Exp. O.K. but dark
#2	11×10^{-3} ref. 10×10^{-3} sign.	Diff. "B" in pos. #3 Diff. "C" in pos. #4	40 sec.	Exp. O.K. but dark
#3	2.5×10^{-4} ref. 2.5×10^{-4} sign.	Diff. "D" in pos. #4	3½ min.	Exp. good

Holograms #1 & #2 diffracted intense light, hologram #3 somewhat less.

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7 January 1966

Reconstruction from holograms with phase-encoded signal beam.

Hologram #1 above was reconstructed and image photographed on PAN-X film, developed in the usual manner. Two different size areas of the hologram were used. The larger area, or aperture, produced much better signal to noise ratio than the small aperture.

Juris Upatnieks, 7 January 196

7 January 1966

Film recordings show (sheet #16, 6 Jan. 1966):

#1 Reconstruction from hologram #1 of 5 Jan. 66. 25 mm diameter aperture at hologram, 152 mm Baltar lens used to focus light, set at f-5.6. Exposure times: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{50}$, $\frac{1}{25}$ sec.; $\frac{1}{250}$ sec. best exp.

#2 Reconstruction from hologram #1 of 5 Jan '66. 10 mm ~~ap~~ diameter aperture at hologram, 152 mm Baltar lens used to focus light, set at f-14. Exposure times: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$ sec.; best exp.: $\frac{1}{100}$ sec.

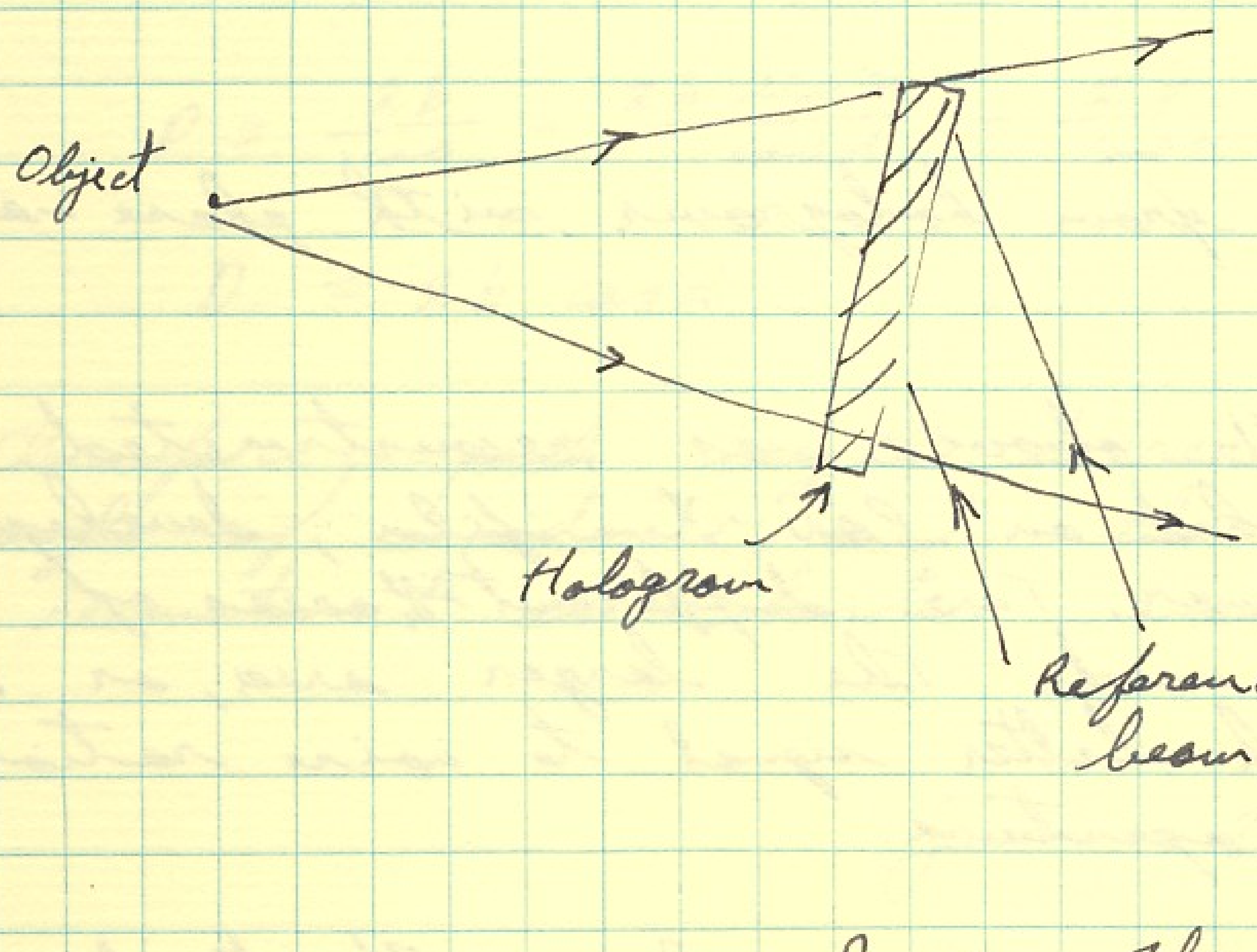
Attempts were made to reconstruct holograms #2 and #3 of 5 Jan. 66, but image could not be obtained. Apparently something was misaligned in the system.

Juris Upatnieks, 7 January 1966

7 January 1966.

On the reconstruction of hologram with reference beam from the back side

Consider the hologram of a single point:



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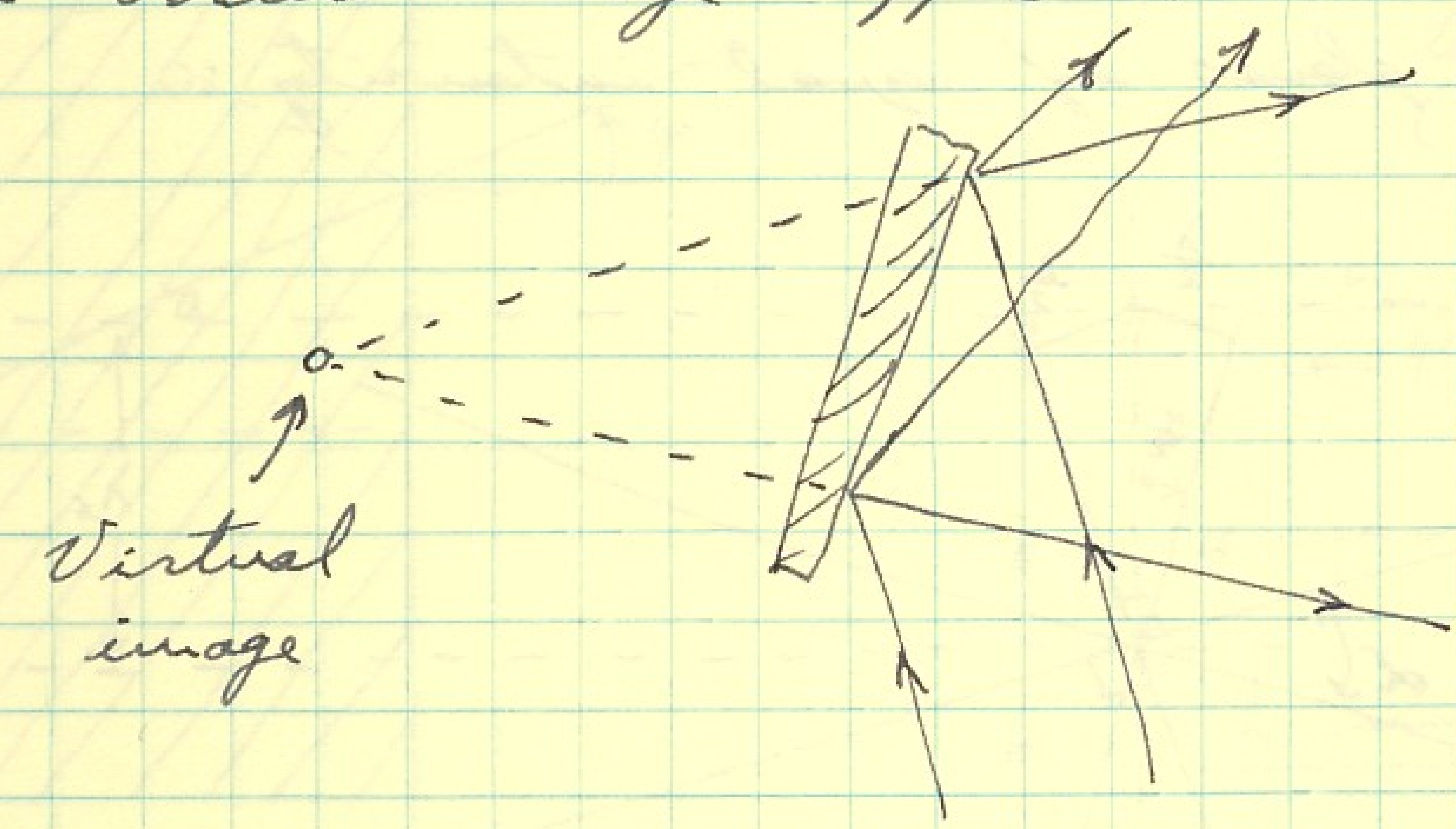
The fringes form in the three-dimensional recording medium as indicated in the diagram. On reconstruction, the virtual image appears:



One should note that the reconstruction is caused by reflection off the three-dimensional interference pattern, rather than by diffraction. Since all wavelengths of light are reflected in the same manner, the image should reconstruct with white light, without any decrease in the quality of the image. The multiple layers of reflecting surfaces in the recording medium, however, act as an interference filter, and thus the reconstructed image appears to be monochromatic. Actually, a band of frequencies are selected by the "filter".

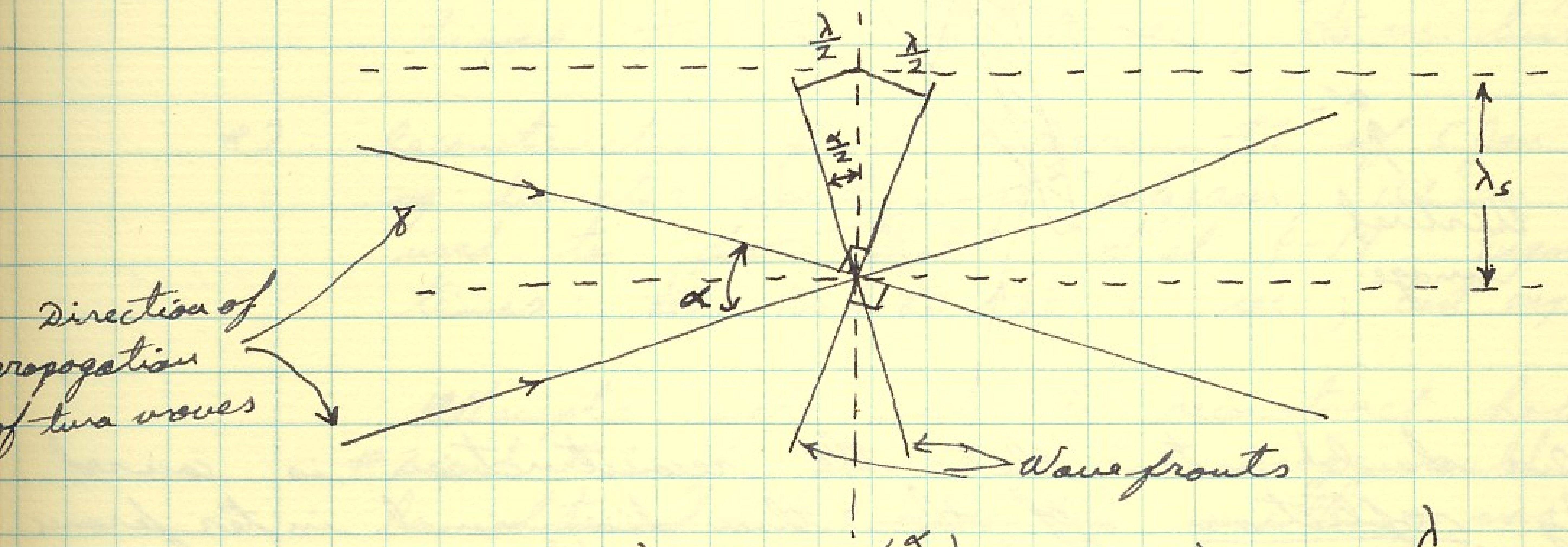
The image reconstructed in white light should be just as sharp as one reconstructed in monochromatic light.

Juris Upatnieks, 22 January 196

10 February 1966

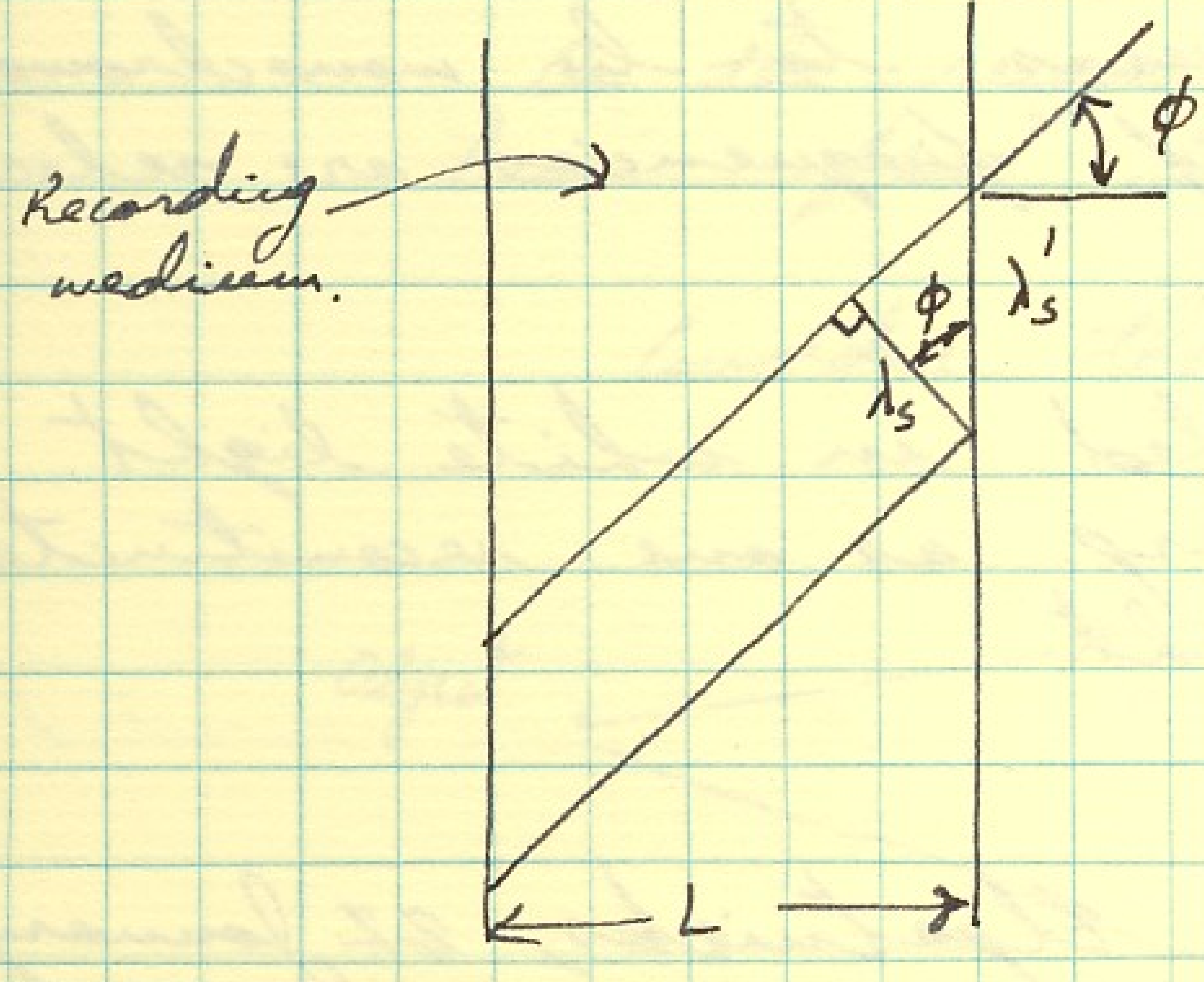
Recording of fringes in 3-dimensional medium, from geometrical considerations.

Spacing of planes of equal intensity:



$$\frac{\lambda}{2\lambda_s} = \sin\left(\frac{\alpha}{2}\right) \quad \text{or} \quad \lambda_s = \frac{\lambda}{2\sin\left(\frac{1}{2}\alpha\right)}$$

where λ is the wavelength of light inside the recording medium; λ_s is the spacing between planes of equal intensity, also spacial wavelength.



$$\lambda_s' = \frac{\lambda_s}{\cos\phi}$$

$$\lambda_s' = \frac{\lambda}{2\cos\phi\,\sin\left(\frac{1}{2}\alpha\right)}$$

λ_s' = spacial wavelength measured along the surface of the recording medium.

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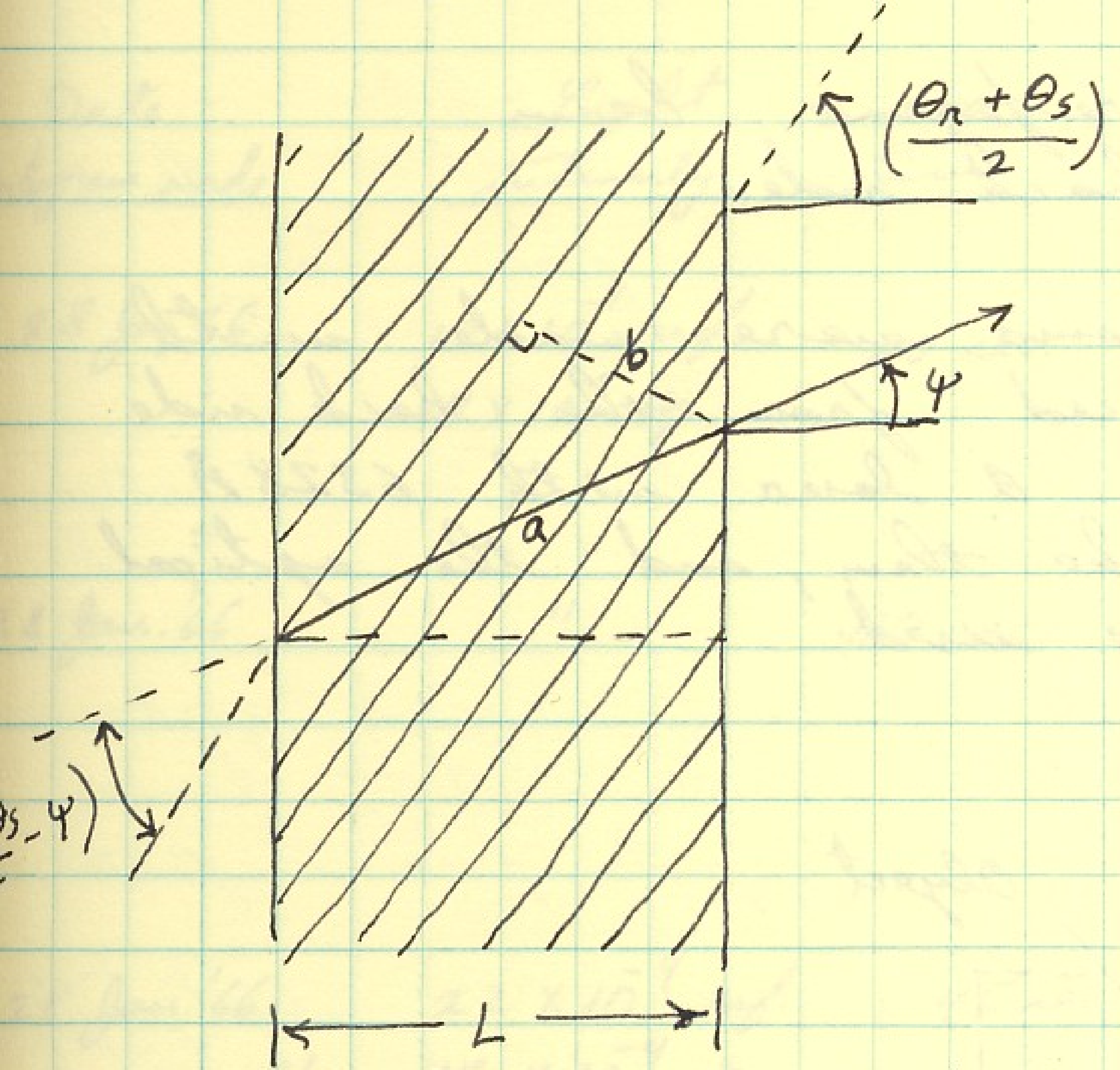
10 February 1966



θ_r = angle of reference beam to ⊥ of recording medium

θ_s = angle of signal beam to ⊥ of recording medium (signal being one plane wavefront)

$$a = \frac{L}{\cos\psi}$$

$$b = a \sin\left(\frac{\theta_r+\theta_s}{2} - \psi\right)$$

$$b = \frac{L \sin\left(\frac{\theta_r+\theta_s}{2} - \psi\right)}{\cos\psi}$$

Let N = # of planes intersected by diffracted ray in direction ψ, of wavelength λ'

Then $N = \frac{b}{\lambda_s}$; for ~~path~~ phase to change by 2π, wavelength change must be

$$\Delta\lambda = \lambda' - \lambda = \frac{\lambda'}{N} = \frac{\lambda_s \lambda'}{b}$$

Let $\alpha = \theta_r - \theta_s$, then

$$\Delta\lambda = \frac{\lambda\lambda' \cos\psi}{2L \sin\left(\frac{\theta_r-\theta_s}{2}\right) \sin\left(\frac{\theta_r+\theta_s}{2} - \psi\right)}$$

If $\psi = \theta_s + \Delta\psi$ and $\Delta\psi$ is small, and if $\lambda \approx \lambda'$, then

$$\boxed{\Delta\lambda = \frac{\lambda^2 \cos\theta_s}{2L \sin^2 \frac{1}{2}(\theta_r - \theta_s)}}$$

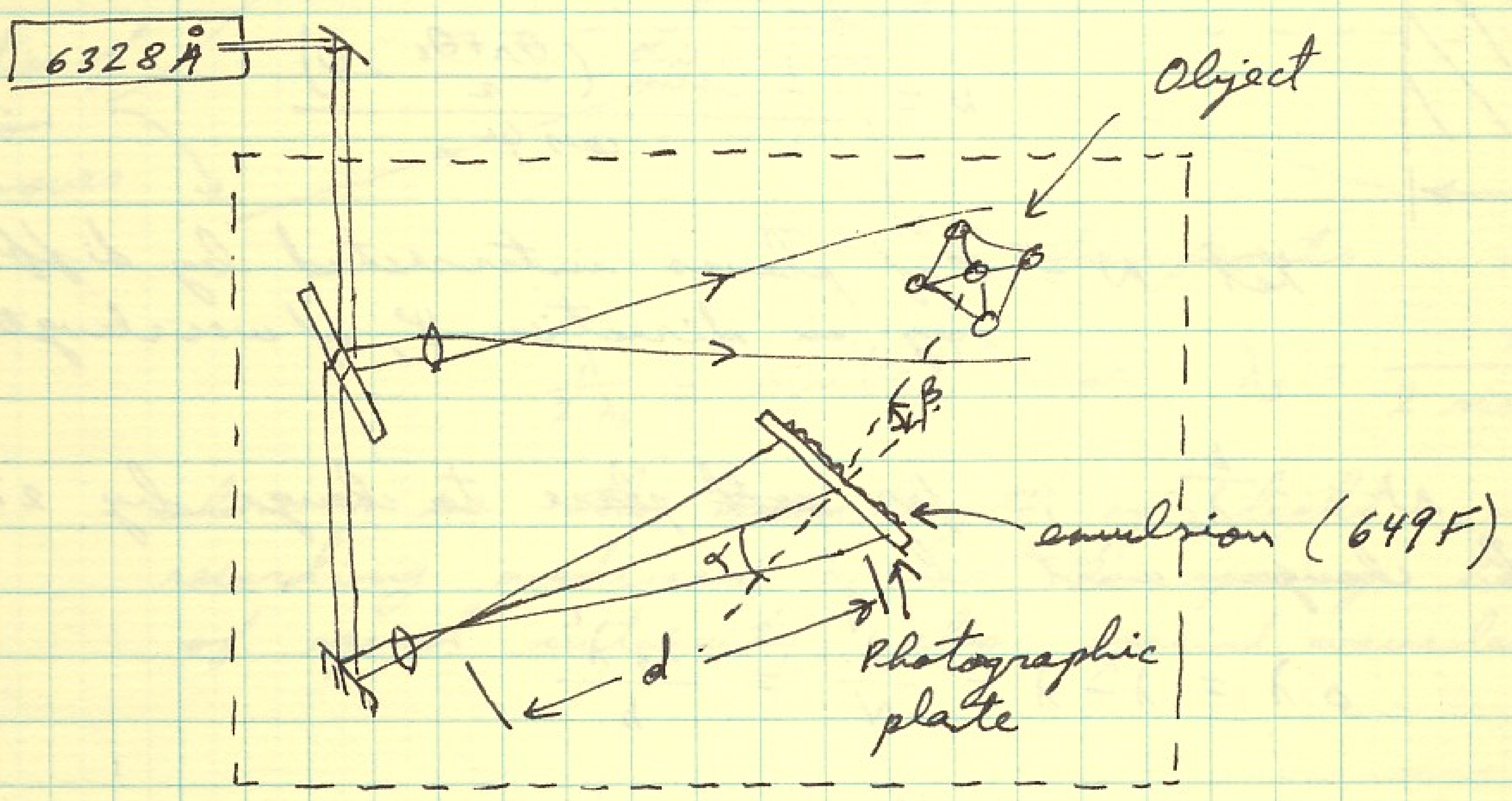
Juris Upatnieks, 10 February 1966

22 February 1966

Holograms made with reference beam introduced from the back side.

A number of holograms were made with the reference beam introduced from the back side of the photographic plate. A laser with 6328Å light was used to make them, and the optical system shown below was used:

Perkin-Elmer model 5300 laser



The following holograms were made:

Date hologram made	Light intensity	Exp. time	Development	Remarks
25 Jan.'66	28×10^{-4} ref. 11×10^{-4} sig.	190 sec.	Standart (6 min. D-19, then fixed)	Exposure too dark, part reconstruct well
26 Jan '66	same	190 sec.	Standart, then bleached	Very weak reconstructi
27 Jan '66	11×10^{-4} ref. 10×10^{-4} sig.	160 sec.	Standart	Exposure dark (3% trans reconstruction is fair

Juris Upatnieks, 22 February 1966

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Date [ho]logram made		Light intensity	Exp. time	Development	Remarks
28 Jan '66		12×10^{-4} ref. 14×10^{-4} sig.	110 sec.	Standard	Exposure good. Reconstructio[n] poor, apparantly caused by vibration of plate
[2]8 Jan. '66		"	110 sec.	Develop. standard, no fixing	Same as above. Previous pooly reconstru[cted] plates appear to have vibrated.
28 Jan '66	#1	22×10^{-4} ref. 18×10^{-4} sig.	45 sec.	Standard, no fixing	Exp. light, reconstr. weak
"	#2	"	90 sec.	Standard, no fixing	Exp. dark, plate vibrating, reconstr. good around edges
31 Jan. '66		17×10^{-4} ref. 16×10^{-4} sig.	90 sec.	Standart, no fixing	Exp. good (10% transm.), reconstruction very good
[1] Feb. '66	#1	16×10^{-4} ref. 14×10^{-4} sig.	100 sec.	Standart, no fixing, plate bleached	Exp. good, dark Reconstruction very good.
"	#2	18×10^{-4} ref. 16×10^{-4} sig.	70 sec.	Standard, no fixing	Exp. good, 16% transmissio[n] Reconstruction very good.
"	#3	15×10^{-4} ref. 6×10^{-4} sig.	150 sec.	"	Subject: train, moved during exp. Reconstr. poor. 5% transmission
"	#4	18×10^{-4} ref. 7×10^{-4} sig.	130 sec.	"	Subject: train, reconstruct[ed] well. 7% transm.
[2] Feb. '66	#1	19×10^{-4} ref. 10×10^{-4} sig.	100 sec.	"	$\alpha = 32°$, $d = 95$ cm. Exp. good, reconstruction weak
	#2	20×10^{-4} ref. 8×10^{-4} sig.	125 sec.	standart, no fixing, bleached.	Reconstruction good, exp. good.

NOTE: on all above holograms, $\alpha = 15°$, $\beta = 4°$, $d = 95$ cm
Light meter calibration: $25 \times 10^{-2} = 0.07$ watts/cm^2
Required exp. for 25% is 1000 ergs/cm^2

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22 Feb. 1966

22 February 1966

Vibration of the $\frac{1}{8}$" thick photographic plate was a major problem and apparently affects the brightness of the reconstructed image even when the image appears to be good. Shrinkage of the developed emulsion is reduced considerably if the plate is not fixed. Fixed plates reconstructed from bluish-green to violet colors, the unfixed ones from orange to dark green. Good reconstruction were obtained using either mercury arc or zirkonium arc light sources without filters. Better, cleaner images were obtained with an interference filter.

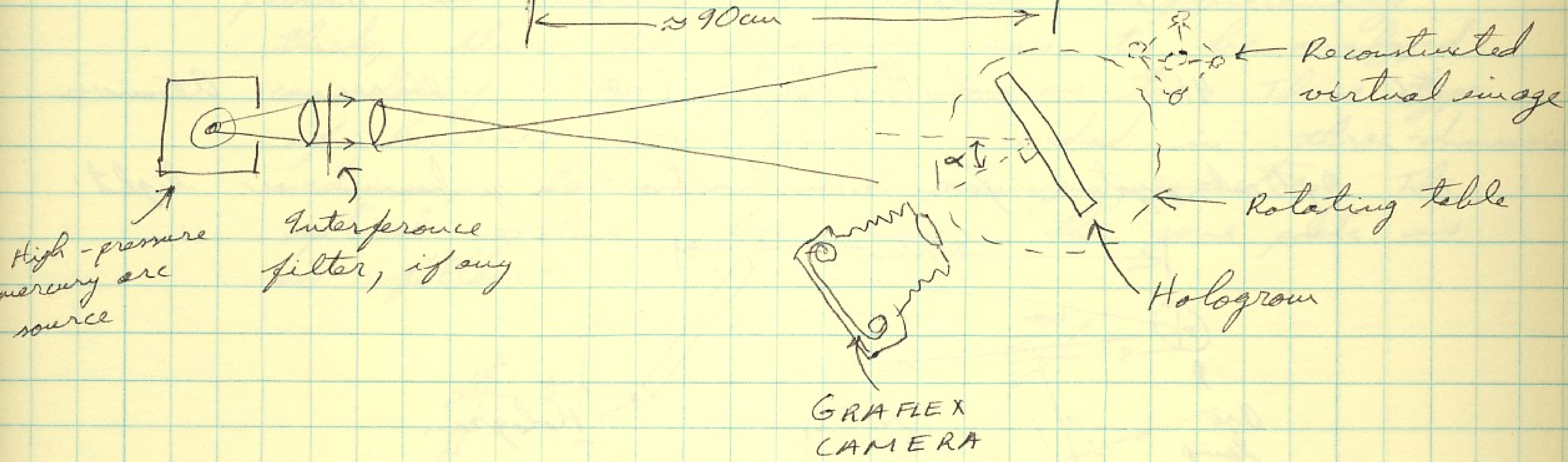
Since all the images recorded on a photographic plate reconstruct simulteneously, obviously images on both sides of the plate will also reconstruct simulteneously. Thus, for example, image over 360° field of view can be recorded on one plate if the reference beam is brought in from above or below (360° measured in horizontal plane).

Juris Upatnieks, 22 February 196

24 February 1966

Reconstruction of images from holograms made with the reference beam from the back side.

Reconstructions were made with the following optical system using high-pressure mercury arc source of light:



The hologram was rotated to give best reconstruction for each color of light, and the camera was adjusted each time to get the best view.

Reconstructions made on 31 January 1966: (from hogr. of 31 Jan.'6

Negative J.U. ~~Print~~ #	angle α	filter	f-no. of lens	exp. time	subject
#1	44°	yellow (579 mμ, 80 Å ½ B.W)	f-8	10 sec.	Atomium
#3	44°	~~yello~~ none	f-8	4 sec.	Atomium
#6	67°	green (546 mμ, 80 Å ½ B.W.)	f-8	25 sec.	Atomium
#8	67°	none	f-8	10 sec.	Atomium

Reconstructions made on 1 Feb. 1966: (from hologram #4 of 1 Feb.'66)

#1	37°	yellow - (579 mμ, 80 Å ½ B.W.)	f-8	10 sec.	Train
#2	37°	no filter	f-8	5 sec.	Train
#4		green (546 mμ, 80 Å ½ B.W.)	f-8	10 sec.	Train
#3		no filter	f-8	20 sec.	Train

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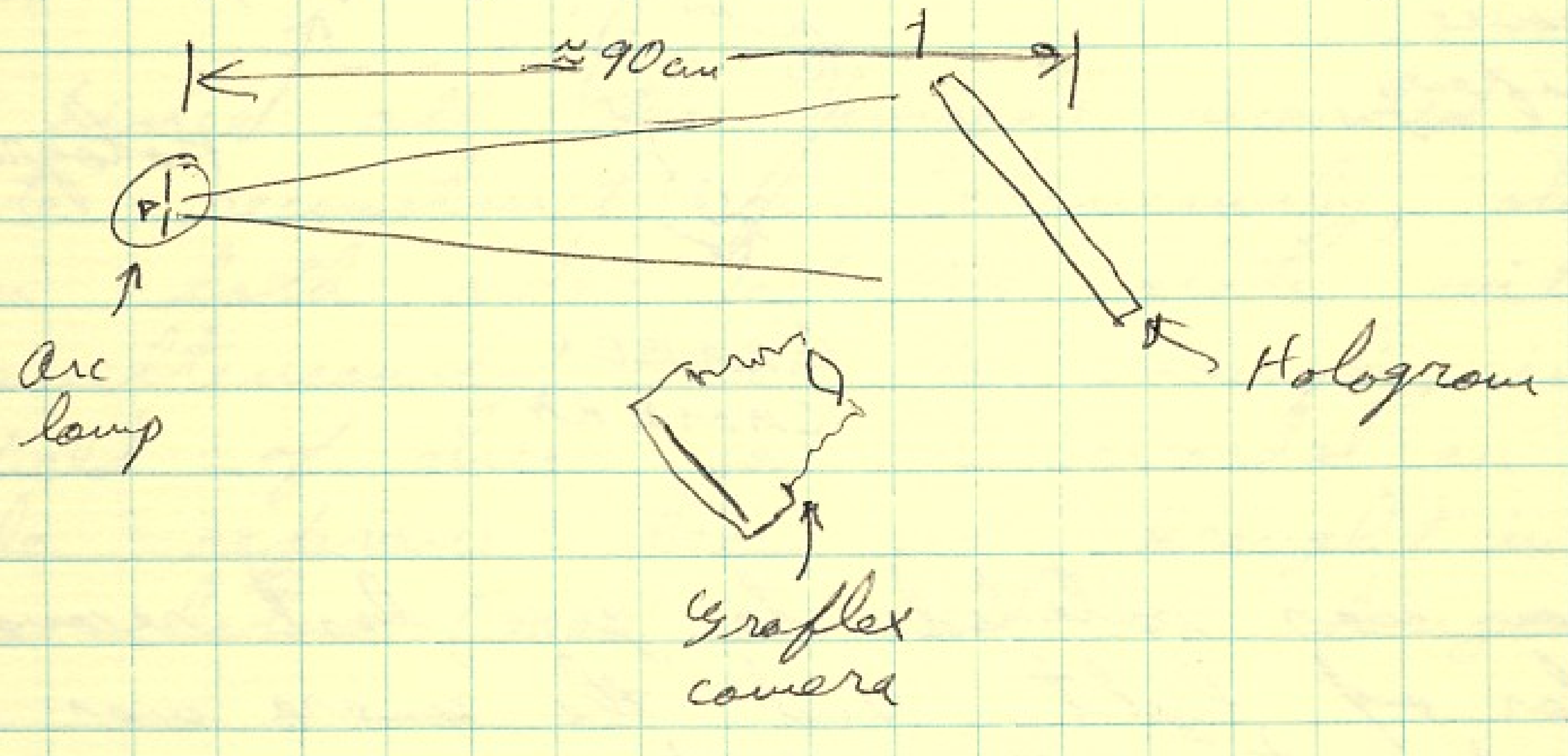
Reconstructions made with zirkonium arc light source, on #1 ~~Jan.~~ Feb. 1966; (hologram made 31 Jan. '66)
J.U. (24 Feb. '66)

Negative #	angle α	filter	f-no. of lens	Exp. time	Subject
#5	27°	none, reconstruction appeared in orange color	f-8	20 sec.	Atomium
#6	41°	yellow (579 mμ, 80Å ½ B.W.)	f-8	40 sec.	Atomium

Optical system for reconstruction in zirkonium arc light:



Reconstruction made in sunlight, in 1st week of Feb. 1966:

#1	—	no filter, reconstruction orange	f-8	1/100 sec.	Atomium
#2	—	none	f-11	1/100 sec.	Atomium

Reconstructions made from hologram of 31 Jan. 1966

Holograms reconstructed with zirkonium arc, on 16 Feb. 1966, from hologram of 31 Jan. 1966:

	apparent color of image	filter	f-no. of lens	Subject
#1	green	none	f-8	Atomium
#2	green	5460 Å, 80 Å ½ B.W.	f-8	"
#3	yellow	none	f-8	"
#4	yellow	5790 Å, 80 Å ½ B.W.	f-8	"
#5	orange	none	f-8	"

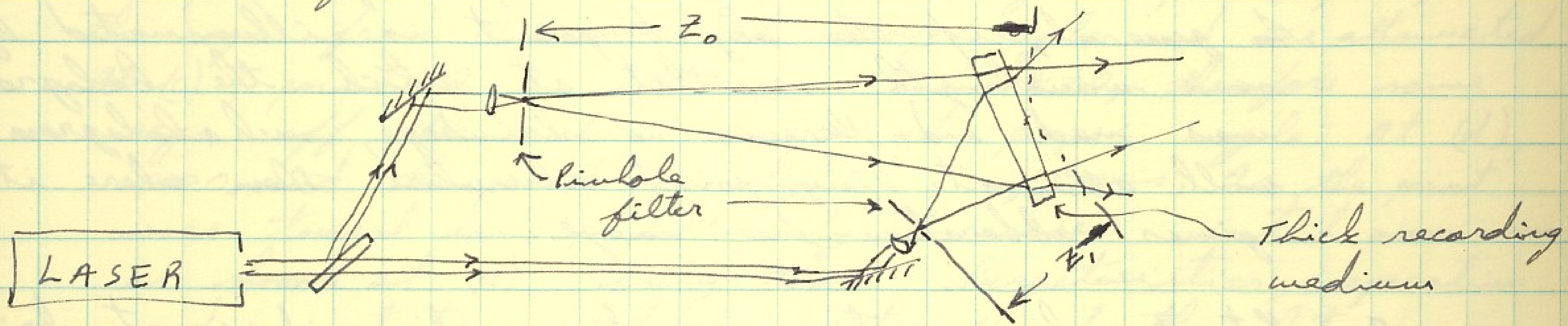
These photographs were recorded on color positive film:

Juris Upatnieks, 24 Feb. 1966

1 March 1966

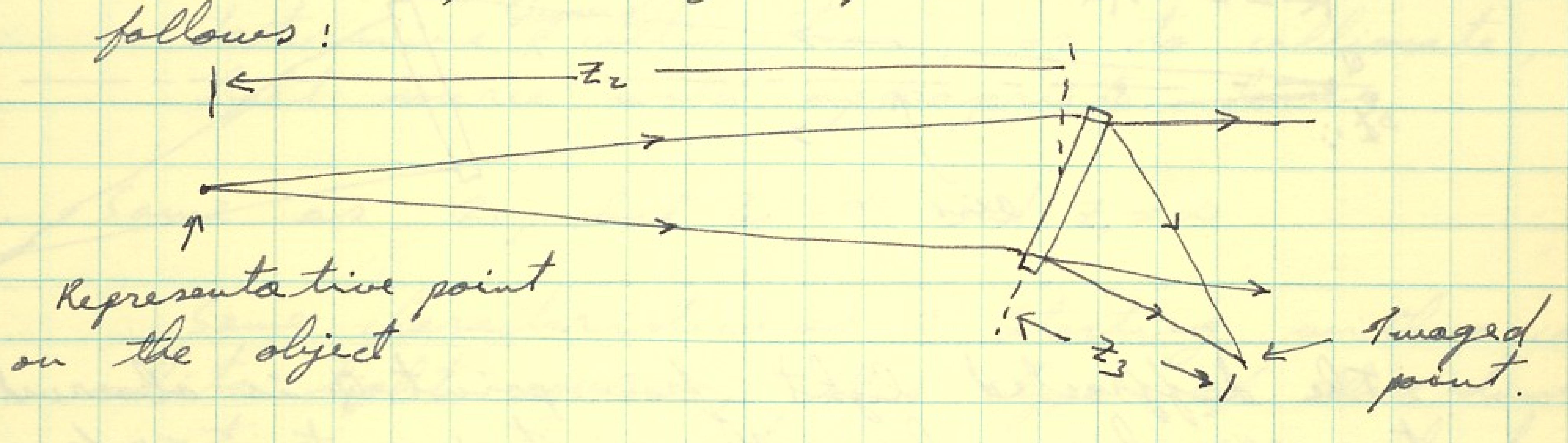
Characteristics and uses of three-dimensional Fresnel zone plates.

If a plane wavefront and a spherical wavefront interfere, the resulting interference pattern in one plane is a Fresnel zone plate. If this pattern is recorded in medium sufficiently thick, then the recording has to be analyzed considering the third dimension too. This type of Fresnel zone plate, recorded in three-dimension medium, has some interesting properties. The optical system for making the zone plate is as follows:



Usually z_0 is made near infinity by inserting another lens between the recording medium the pinhole, or z_0 can be negative. Orientation of the recording medium can vary.

In use, the zone plate would be used as follows:



Consider the following special cases:

1. Let z_0 be negative, and let $z_2 = -z_0$
   In this case the hologram (Fresnel zone plate) will reconstruct the image point without abberations and at the wavelength at which the plate was made.

Juris Upatnieks, 1 March 1966

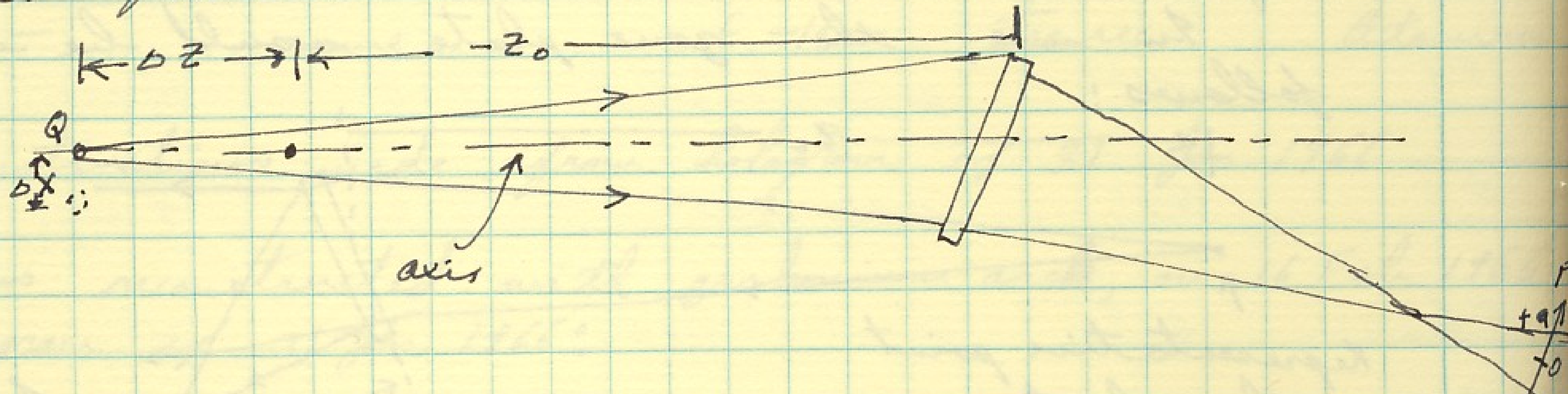
1 March 1966

If the recording medium is thick, the zone plate will act as a filter and image a limited B.W. of wavelengths, the width of band depending on thickness of recording medium. Any point on axis but in front or behind $z_2 = -z_0$, will reconstruct but with smaller effective aperture of the zone plate, thus attenuating the aberrations ordinarily present in this case. If these points are not monochromatic, each part of zone plate will reconstruct (focus) a different color. The abberations for these colors might be smaller.

If a point is moved off axis, again abberations will increase but brightness of imaged point decrease. In general, if the object point is illuminated by same wavelength as that at which the hologram was made and there is no shrinkage, such a hologram will attenuate any point elsewhere than where it gives abberation-free image.

2. Let z_0 be negative, recording medium does not shrink, and same wavelength of light is used

This type of zone plate could be used as a range and direction finder. The optical system is as follows:



The diffracted light from point Q is observed at some plane where the point is not in focus, for example at P. For various positions of point Q the following light distributions would be obtained:

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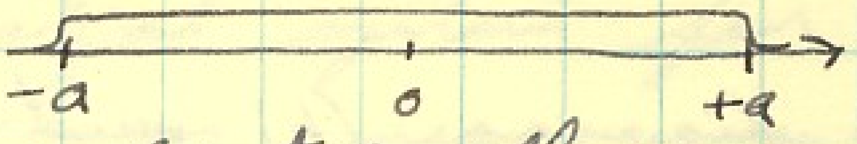
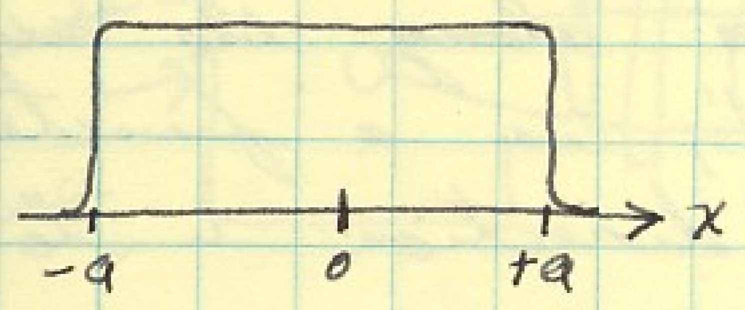


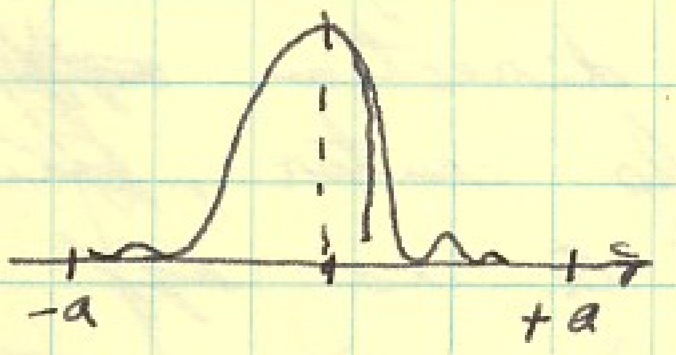
Point Q with $\Delta z = 0$, slightly off axis

(d)



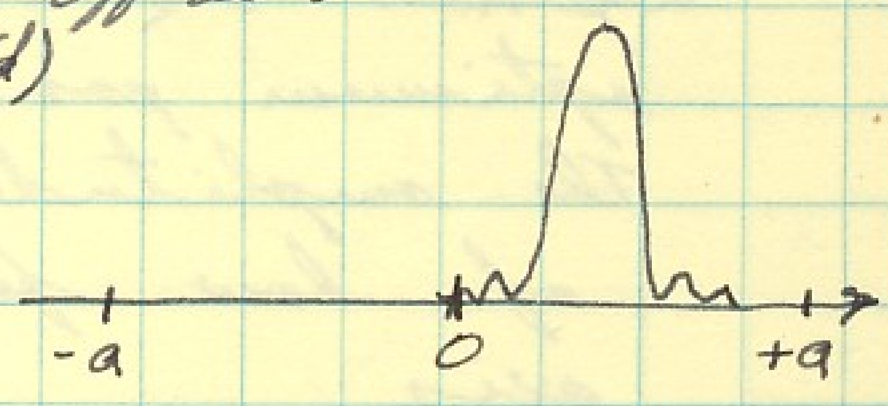
Point Q with $\Delta z = 0$, on axis

(a)



Point Q with $\Delta z \neq 0$, on axis

(b)



Point Q off axis, $\Delta z \neq 0$

(c)

At (a) above, all area is uniformly bright. At (b), $\Delta z \neq 0$ but point is on axis. Near the edges of the plate, the rays from Q arrive at wrong angle and are attenuated. At (c), point Q is off axis and $\Delta z \neq 0$, therefore some rays off the center arrive at proper angle. At (d), $\Delta z = 0$ and the point is slightly off axis. As the point moves toward axis, intensity increases until maximum as ~~shown~~ at (a). Using these characteristics, reperation and orientation between points Q and the plate can be accuratly determined.

3. Same as 2., but $z_0 = \infty$, no restrictions ~~of~~ on z_1. This plate has similar characteristics to that above. Since case (a) is obtained when point Q is at infinity, this could be used to determine degree of collimation, or to collimate, a light source with appropriate lenses.

4. Same as 2., but $z_0 = \infty$ and $z_1 = \infty$

Same characteristics as 2. Starting with a collimated, white light source, this type of three-dimensional grating can be used as a very narrow-band interference filter. If the source is extended in size, in <u>one</u> dimension it can pick out a narrow line without the help of a slit. This should give a sharper and less expensive filter than conventional interference filters.

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In figures (b) and (c), the width of the peaks depends on how far the point is away from its optimum position in direction ~~off axis~~ along the axis. The amplitude at the center, point "O", is a function of how far point Q is off in direction ⊥ to the axis.

A number of such interference patterns can be superimposed, resulting in a superposition of previously described characteristics.

Juris Upatnieks, 1 March 1966

4 March 1966

Emulsion thickness measurements.

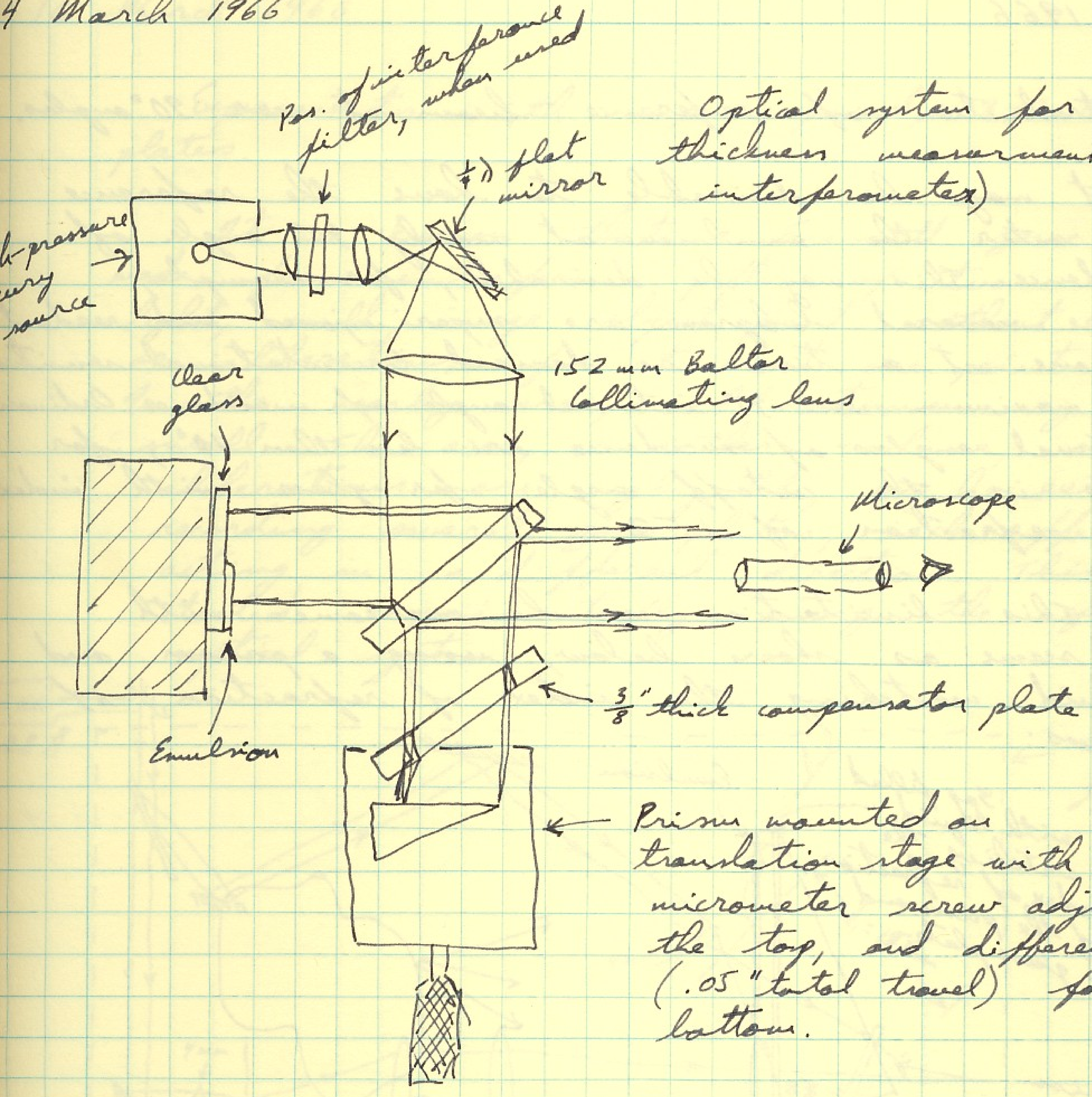
Emulsion thickness, and its change due to processing, has great effect on the reconstructed image when a hologram is made with a large angle between the reference and signal beams. In order to predict the behavior of such a hologram, emulsion thickness must be known. The diagram on the next page shows the optical system for measuring the emulsion thickness.

The measurements so far have been somewhat inconsistent. Thickness of the 4×5×⅛ plate with 649 F emulsion has been measured to be between 13.4 and 15.8 μ, depending on plate and processing. Thickness may depend on processing, humidity of air, exposure, and variations in production. Further tests will be made.

Juris Upatnieks, 4 March 1966

4 March 1966

Optical system for emulsion thickness measurement (Michelson interferometer)



All of the above components were mounted on a 24×24×4 in surface plate.

Measurements were made as follows: a reference fringe was found on the clear side by observing white-light fringes, then interference filter was inserted, stage moved and fringes counted untill clear (good contrast) fringes were observed on the other side, and finally filter was removed and reference fringe moved to same location. Thickness "h" is then equal to:
$h = \frac{N}{2}(\lambda)$, where N is number of fringes and λ is the wavelength of light with filter in place.

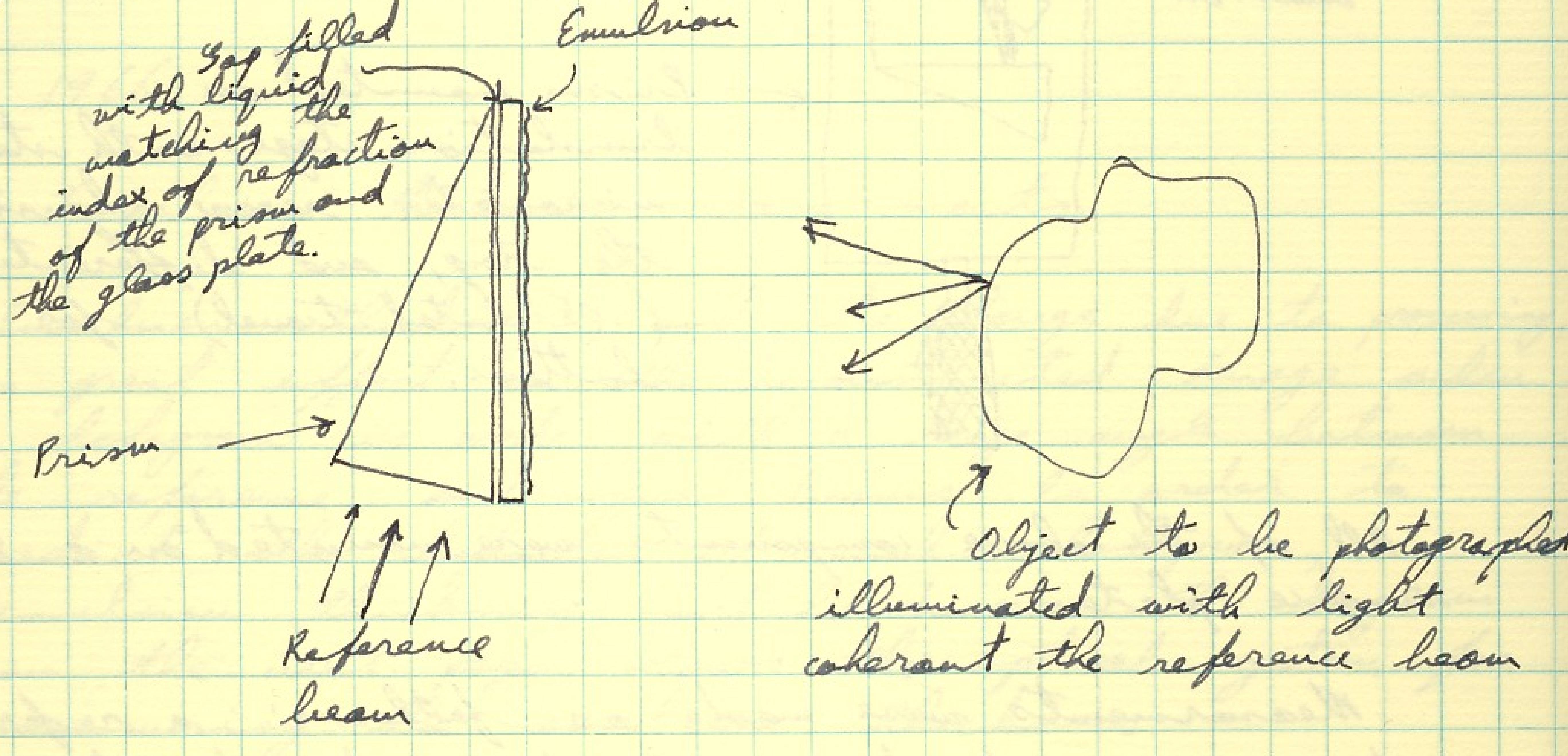
Juris Upatnieks, 4 March 1966.

8 March 1966

Introduction of reference beam at near 90° angles.

It may be desirable to have the reference beam enter the emulsion at nearly 90° angle of incidence. This may be desirable, for example, where several hologram are superimposed and readout of one at a time is desired. Orientational sensitivi- is maximum near 90° internal angle of incidence. Ordinarily internal angles of incidence are less than 40°, for this is the cutoff angle for glass with index of refraction of 1.52.

This limitation can be overcome with the scene as shown below, using a prism and liquid matching the index of refraction of glass:



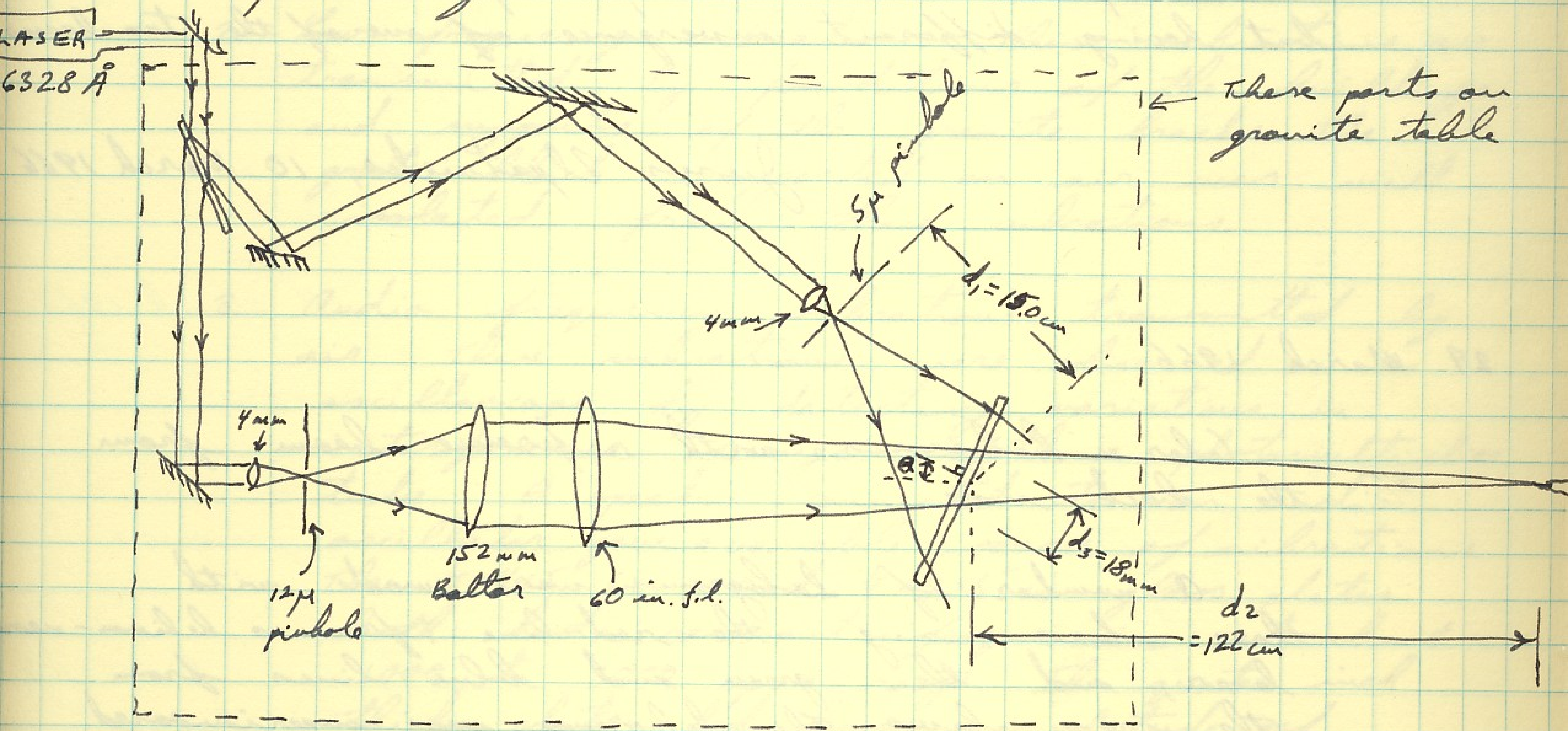
With this arrangement, the unavailable region of internal angles between 41° and 139° can be reached. The emulsion may be toward the prism also, and the object may be on the other, or both, sides of the plate-prism combination.

Juris Upatnieks, 8 March 1966

10 March 1966

Experiments with superimposed, 3-D Fresnel zone plates.

It is known that a Fresnell zone plate, made from interference pattern of two beams of light, will image object point without distortion or abberations for at least one point in space. In the nearby area, abberations may be small. The area, or rather volume, over which abberations are negligable, can be extended by recording several zone plates, each effectively acting in a differant direction. This idea was tested experimentally using the following optical system:



A plate was made with 3 Fresnel zone plates superimposed, on 8 March 1966:

37×10^{-2} converging beam
45×10^{-2} diverging beam

Exp.: 3 times @ .20 sec. each
$\Theta = 15°, 20°, 25°$

Processing:
Developed 6 min in D-19, washed ½
no fixing.

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10 March 1966

To test the quality of the plate, the converging beam was blocked and point focus of the imaged diverging beam was observed. The zone plate gave diffraction limited point image for the exact three angles of $\theta = 15°, 20°$, and $25°$; for $\frac{1}{2}°$ either way from these angles, the point image was still nearly perfect; for other angles, astigmatism became quite large. Suppre[ssion] of the unwanted zone plate image was good at the exact values of θ. At halfway points, $17.5°$ and 22.5 interference patterns between the waves diffract[ed] by each zone plate could be observed. The interference pattern had a complex pattern, indicating large aberrat[ions].

Zone plates could be superimposed on same axis but having different convergance of one of the two beams

Juris Upatnieks, 10 March 1966.

29 March 1966

Color holograms with reference beam from the back side.

A number of holograms were made with three colors using the red line from a helium-neon laser, and the green and blue lines from the argon laser. The holograms were superimposed in sequence on a single photographic plate. The first successful hologram with all three colors was made on about March 14, 1966. The quality, however, has not been very good since the intensity of reconstructed image has been quite low compared to the scattered light off the surface of the glass plate.

Juris Upatnieks, 29 March 1966

29 March 1966

Other difficulties were encountered, causing inconsistent results. On several occations two of the colors have reconstructed, while the third has been absend. The reconstructions have had varying intensities for identically exposed holograms. A search for causes of these results have led to a recongnition of the following problems:

1. Short coherence length of green and blue laser lines. The coherence length can be increased by decreasing the power output, and its affect by selecting subjects that are not large.

2. Low frequency vibrations. These vibrations are transmitted by foundations of the buildings and supports of the granite blocks. The granite block supported on air was well isolated from these vibrations.

3. Audio frequency vibrations transmitted by air. These vibrations were observed on an oscilloscope by detecting variations in interferance fringes with a photomultiplier tube. A speaker connected to an audio oscillator gave a variable source of vibrations. The $\frac{1}{8}$ x 4 x 5 in. and $\frac{1}{4}$ x 4 x 5 in glass plates both had resonant frequencies at about 1000 to 3000 cps. range. The quater inch thick plate had lower amplitude of vibration. The fans ~~for~~ of the argon laser caused caused considerable vibration. An enclosure will be made to reduce audio vibration intensity.

It appears that vibrations are the cause of poor quality reconstructions. Optical system used for making holograms is shown on the next page.

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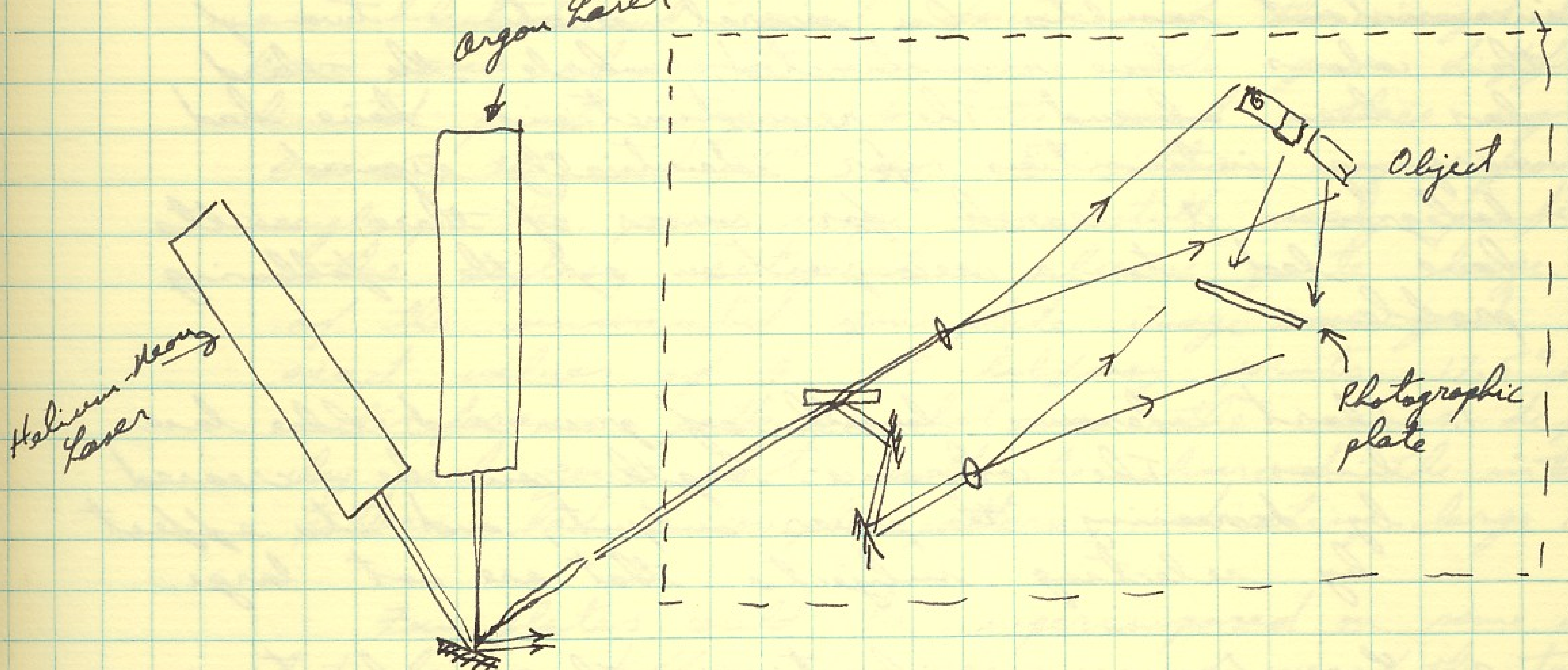

Mirror adjusted to bring one or the other laser beam into the system.

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14 April 1966

Reconstruction of holograms with low-pressure mercury arc source.

Excellent reconstructions of holograms have been obtained with the green (5461 Å) line of a low pressure mercury arc source, GE-100W lamp. To visual appearance, the reconstruction is as good as with a laser, and nearly as bright as 4×5 in. hologram illuminated with 8 mW laser. The brightness is achieved by using a large-size pinhole, which does not degrade the image quality seriously since the eye inherently

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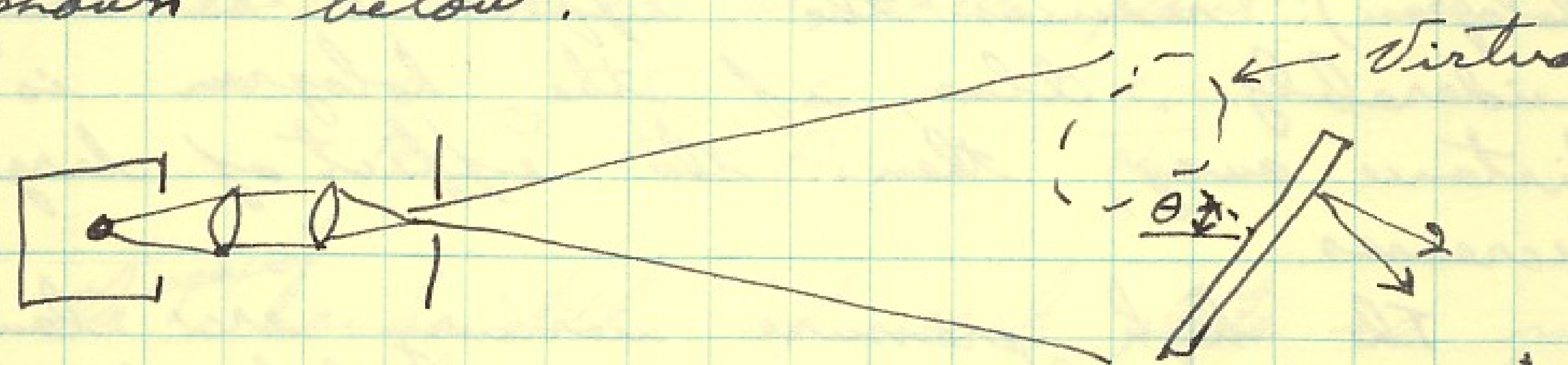
has low resolving power to begin with, about 1 min. of an arc or 3×10^{-4} radians. Reasonably good images can also be seen with the yellow mercury line if the offset angle is not large, under, say 30°. At higher angles the double yellow line causes double images to appear. Mercury arc lamp, as well as other similar incoherent light sources, are especially well suited for hologram reconstruction since they have most of the energy concentrated at a few spectral lines, and each line is quite narrow. Ordinary, front reference beam holograms, can be viewed if a filter is used to reject the other mercury lines; holograms with reference beam from the back side can be also viewed without the filter, and give extremely sharp image. Holograms with reference beam from the front but with large offset can be used without a filter since the hologram itself acts as a filter. By rotating the hologram, reconstructions can be observed in the green, yellow, or violet lines of the source.

Here are calculations on the expected degradation of image quality when viewed with mercury-arc source. A typical arrangement for viewing holograms is shown below:



a = pinhole size
θ = angle between illuminating beam and ⊥ to the plate

From coherence-length (Δl) measurements of the lamp, $\Delta l \approx 4000\lambda$, and using coherence-length eq. $\Delta l = \frac{(\lambda_0)^2}{\Delta\lambda}$, we can calculate $\Delta\lambda$ to be:

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$$\Delta\lambda = \frac{(\lambda_0)^2}{\Delta l} = \frac{(5461)^2}{4000\,(5461)} = 1.4\ \text{Å}$$

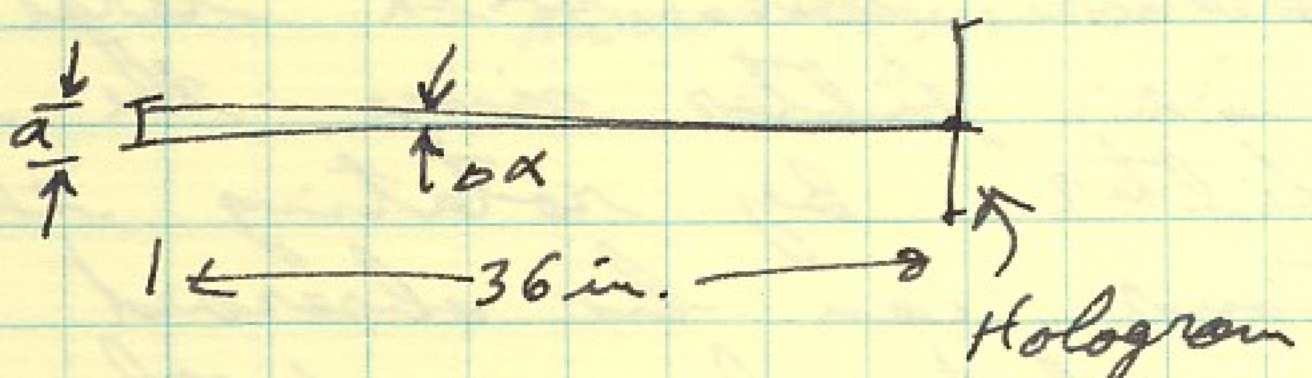
From the grating eq. $\lambda_s(\sin\theta_1 - \sin\theta_2) = \lambda_\ell$, and letting $\theta_2 = 0$, $\theta_1 = 45°$, $\lambda_\ell = 5461\ \text{Å}$, we can calculate $\Delta\theta_1$:

$$\lambda_s \sin(\theta_1 + \Delta\theta_1) = \lambda_s(\sin\theta_1 \cos\Delta\theta_1 + \cos\theta_1 \sin\Delta\theta_1)$$

$$\approx \lambda_s(\sin\theta_1 + \Delta\theta\cos\theta_1) = \lambda_\ell + \Delta\lambda_\ell$$

$$\Delta\theta \approx \frac{\Delta\lambda_\ell}{\lambda_s\cos\theta_1} = \frac{1.4}{5461\,(.707)} \approx 3.6 \times 10^{-4}\ \text{rad.}$$

This is approximatly the same as the resolution limit of the eye. Assuming $a = \frac{1}{8}$ in., and distance to hologram to be 36 in., the angle of the source at the hologram is:



$$\Delta\alpha = \frac{1}{8 \times 36\ \sout{ft}} = 3.5 \times 10^{-3}\ \text{rad}$$

Thus $\Delta\alpha$ is about ten times larger than the resolution limit of the eye. The degradation of the image is not as great as it may appear, since the inherent graininess of coherent light (when making a hologram) reduces the effective resolving ability considerably. Also, if the hologram is viewed some distance away, then the effect of large light source size decreases.

The high pressure mercury arc lamp has $\Delta l \approx 70\,\lambda$, or $\Delta\lambda \approx 80\ \text{Å}$. This means that line width is 50 times that of the low-pressure mercury lamp, and would be less suitable for viewing holograms.

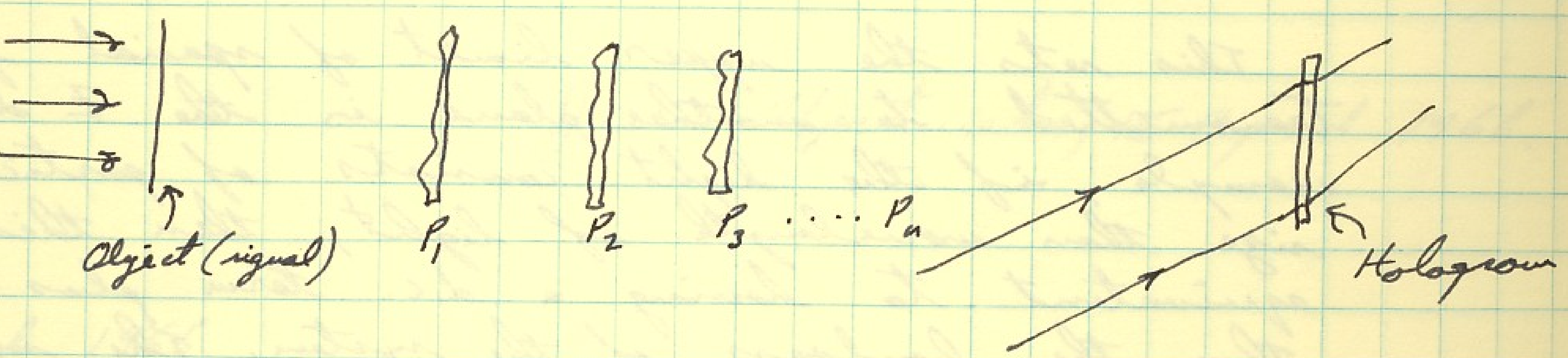
Juris Upatnieks, 14 April 1966.

15 April 1966

On reconstruction through diffuse media.

On p. 6 of this notebook the conditions under which good reconstructions of the image can be expected were discussed. Several additional considerations will be mentioned here.

First of all, if several successive etched or ground glass plates are used between the object and the hologram plane, then whatever ~~is~~ comes from the previous scatterer plate must be considered as the signal for the next one. Consider the diagram below:



The signal at P_1 is the object, at P_2 the light distribution after it has passed through P_1, at P_3 whatever arrives there, etc. The computation for signal to noise ration must be carried out at each plane, and the overall system performance $\frac{S}{N}$ is then the product of the signal to noise ratios at each plane:

(1) $$\frac{S}{N} \approx \frac{S_1}{N_1} \cdot \frac{S_2}{N_2} \cdot \dots \cdot \frac{S_n}{N_n}$$

If the spacial bandwidth of each plate is small, then addition of other planes may improve the final $\frac{S}{N}$ ratio since any noise generated by the hologram misalignment would be scattered over a wider angle by the other planes. If the spacial bandwidth is wide, then degradation can be expected. The reason for this degradation is that convolution takes place of the signal arriving at a plane, and the spectrum of the diffuse glass itself. Thus, bandwidth of the convolution may exceed the upper limit of spacial frequencies that can be transmitted by an optical system.

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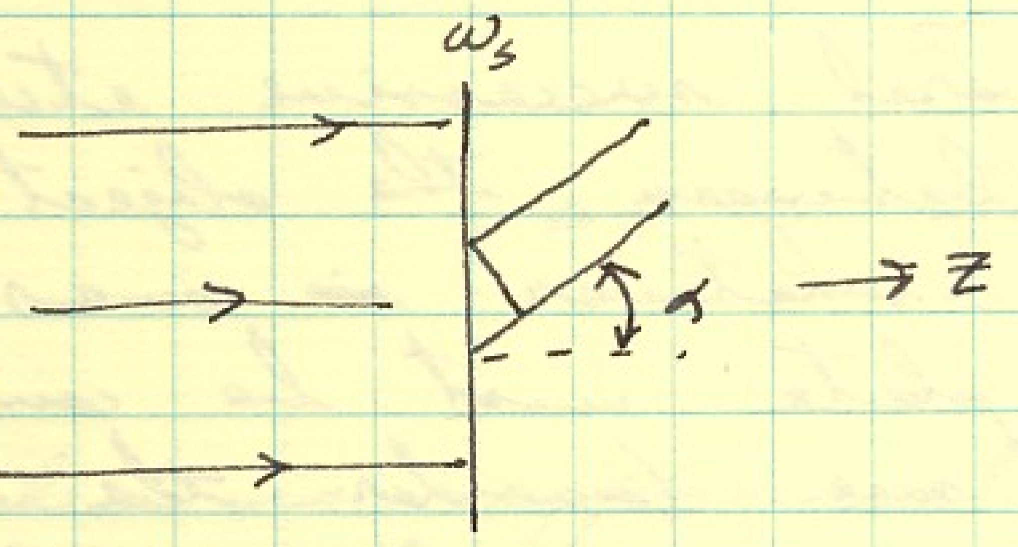
If we consider the diagram below, then the maximum spacial frequency f_m that can be transmitted by an optical system is

(2) $$f_m = \frac{1}{\lambda_\ell}$$ where λ_ℓ is the wavelength of light

(3)



$$\lambda_s \sin\alpha = \lambda_\ell$$

or $$\frac{1}{\lambda_s} = f_s = \frac{\sin\alpha}{\lambda_\ell} \qquad -\frac{\pi}{2} < \alpha < \frac{\pi}{2}$$

This sets the upper limit of spacial frequencies transmitted to another plane in the Z direction. For example, if the light consists of particles of smaller size than wavelength of light, then this would be equivalent to having a d.c. term plus pulses narrower than the bandpass of the system. The system would allow only a limited band of frequencies to pass, and receiving of pulses in their indentical shape would be impossible. Thus, this type of a system is not reversible. If an optical system is not reversible, then reconstruction of the object through such a system is not possible (noise level would be very high with respect to the signal).

For some systems, the overall system $\frac{S}{N}$ could be represented by the expression

$$\frac{S}{N} \approx \left(\frac{S_1}{N_1}\right)^n$$ J.U.

where n is the number of diffusers. A three-dimensionally distributed scatterer could also be represented by such an expression.

An interesting phenomena takes place if we consider a square wave plane grating:

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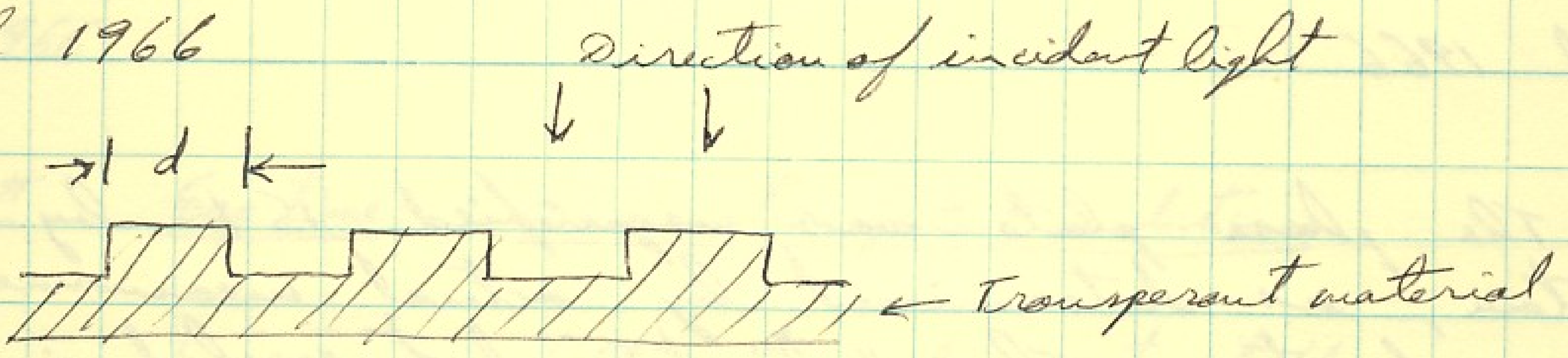

If the thickness is such that phase retardation is exactly π for a wavelength λ_0, then there is no d.c. term in the spectrum of this grating. Next, if d is made such that $d < \lambda_0$, then there is no transmitted or reflected diffracted light. Thus, such a grating must act as a perfect mirror for λ_0, but not for other wavelengths. If the phase retardation is $n\pi$, then this type of a grating represents narrow stop filter.

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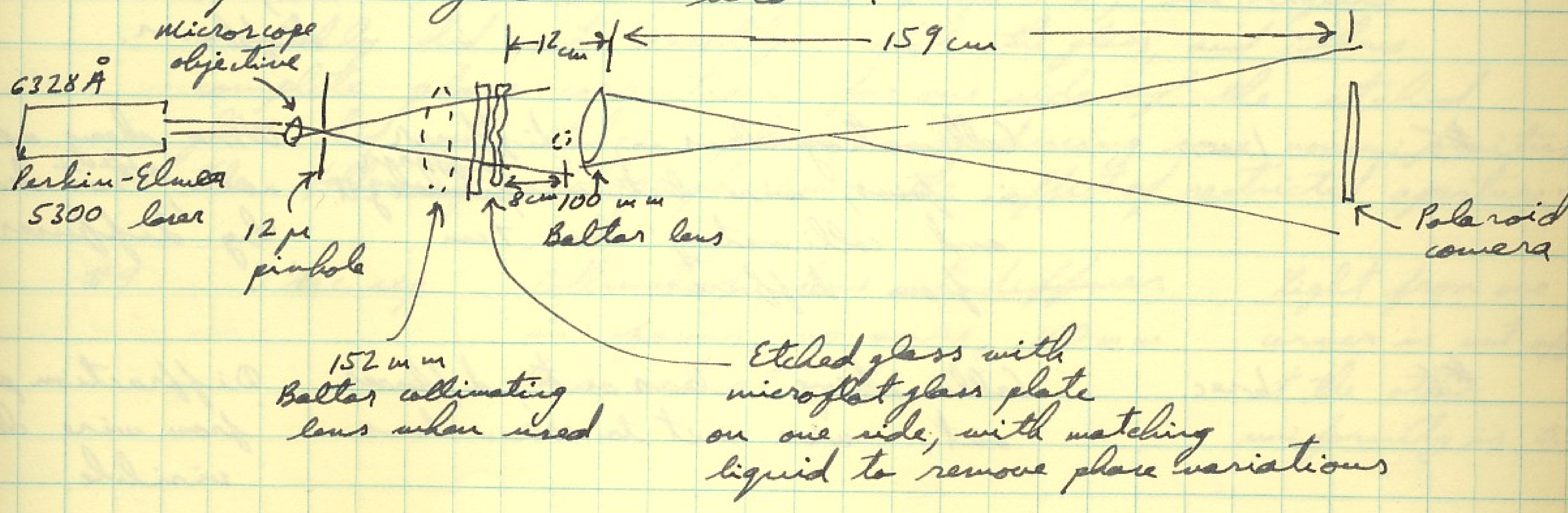
19 April 1966

Experimental verification of the technique for improving 2-dimensional holograms.

On pages 132 and 133 of computation book # 768, the method of using pure phase modulation of two-dimensional objects was described. Experiments were performed to verify these ideas with the optical system below:



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The phase plate was magnified 15X by the optical system, as determined by actual measurement of magnification. The "object" photographed in this case was the clear field (without transparency) of the ground glass. The experiments were performed on 18 April 1966. The following photographs were taken:

Photograph #:	Exp. time	Description of test conditions	Remarks
#1	1 sec.	Collimating lens out, no diffuser, no wire	Pattern of circles comes from dust and other imperfecti[ons] of the 100 mm lens
#2	1 sec.	Collimating lens out, diffuser in focus, no wire	Good focus is over part of photograph; Small spots were on microflat glass surfaces.
#3	1 sec.	Collimating lens out, diffuser in but film 170½ cm from lens (11½ cm out of focus), no wire	Typical grain of diffuser, magnified 15X by lens
#4	1 sec.	Collimating lens in, diffuser in focus, no wire	Visible pattern is fro[m] collimating lens. Phase encoding does n[ot] change effect of du[st] etc., that are before diffuser.
#5	1 sec.	Collimating lens in, diffuser in focus, wire between ~~pinhole~~ diffuser J.U. and collimating lens 7 cm from diffuser.	Wire shows up as noise, effect not decreased by diffuser.
#6	1 sec.	Collimating lens out, diffuser out, wire next to 100 mm lens	Diffraction pattern from wire clearly visible.

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Photograph #	Exp. time	Description of test conditions	Remarks
#7	1 sec.	Collimating lens out, diffuser in focus, wire next to 100 mm lens	Some moire appearant, but effect not very disturbing
#8	1 sec.	Collimating lens out, film $170\frac{1}{2}$ cm from lens ($11\frac{1}{2}$ cm out of focus), wire next to the 100 mm lens	Additional moire is almost completely lost in the moire from diffuser itself

These tests clearly indicate that the effect of imperfection in a coherent optical system can be greatly reduced by phase-modulating a transparency. It is also important that the phase plate is precisely in focus, that the illuminating beam of the phase plate is uniform, and that the transparency is in the same plane as the phase plate (right next to it or in the imaged position of the phase plate). If these conditions are not met, then inferior results will be obtained. It is important also that the optical system images all of the scattered light, or records it in the case of a hologram. Restriction of aperture may result in moire. In the experiment performed, the liquid probably did not exactly match the glass, and thus complete phase correction for one side of the etched glass did not take place, introducing some nonuniformities. The following photograph shows the effect of restricted aperture:

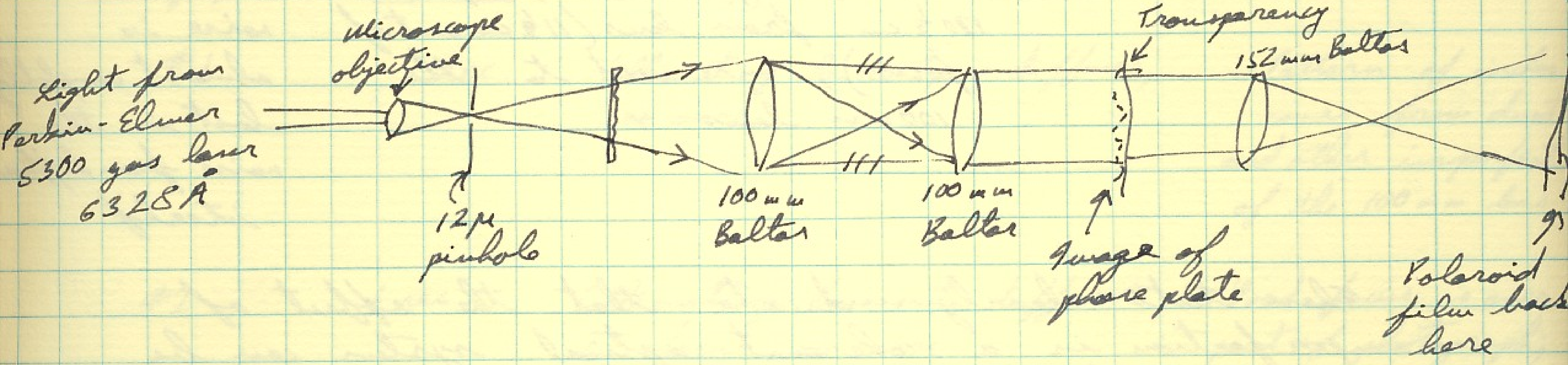
Photograph #	Exp. time	Description of test conditions	Remarks
#9	2 sec. exp.	Collimating lens out, diffuser in focus, no wire, 100 mm lens set at f-5.6	Light from one corner is cut off, at the other uniformity is O.K.

Juris Upatnieks, 19 April 1966

27 April 1966

Experiments with phase-encoded transparencies.

Experiments to further test imaging of phase-modulated transparency were made, similar to those on pp. 35-37 of this notebook. Actual transparencies were imaged in this case through an optical system consisting of several lenses. The system used is shown below:



The following photographs were taken on 20 April 1966:

Photograph #	Exp. time	Description of test conditions	Remarks
Subject: Portrait			
#2	½ sec.	Diffuser + transparency in focus	Image good at ca
#3	⅕ sec.	Diffuser out, transparency out	Diffraction pattern from dust + dirt visible all over
#4	½ sec.	Diffuser out of focus, transparency in focus.	Grain from diffuser visible
Subject: Portrait, higher magnification			
#5	2 sec. exp.	Diff. in focus, transp. in focus.	Some intensity variations from phase plate are vis
#6	1 sec.	Diffuser out of focus, transp. in focus.	Diffraction pattern from dirt obscure image.
#7	2 sec.	Diffuser out of focus, transp. in focus.	Image has grainy appearance

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Photograph #	Exp.	Description of test conditions	Remarks
Subject: monograph, dark letters on transparent background.			
#8	1½ sec.	Diffuser & slide in focus.	Some variation in intensity are visible.
#9	1½ sec.	Differ out of focus, slide in focus	Grain very pronounced and annoying.
#10	$\frac{1}{5}$ sec.	Diffuser out, slide in focus, made 21 April 1966	Diffraction patterns form background.

The size of the portrait was ~~#~~ 1 cm across the head (width). The monograph was approximatly same in length. It appears that some residual amplitude modulation was present even when diffuser was in focus. This is probably because both sides of the diffuser plate were etched and the liquid used to smoth one side did not match exactly the glass.

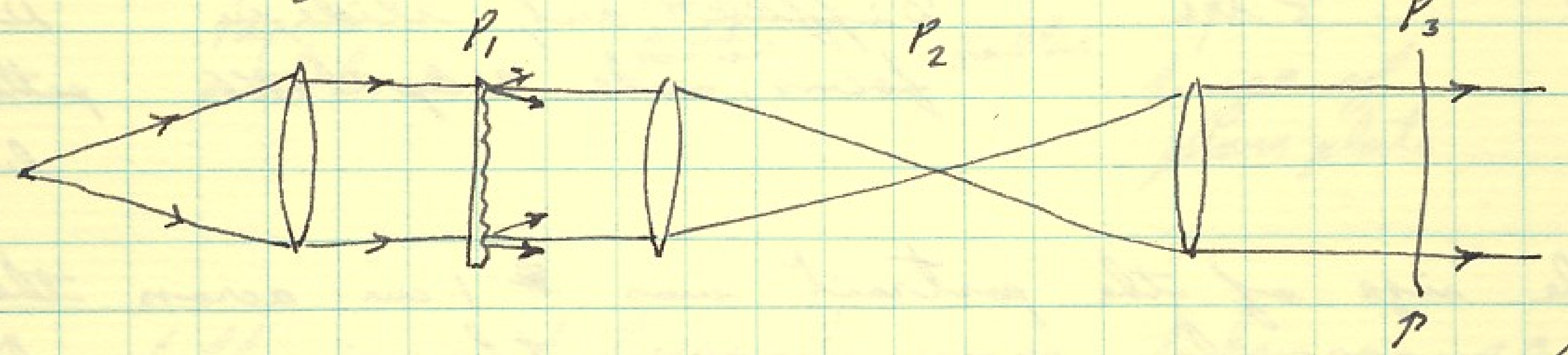
Juris Upatnieks, 27 April 1966.

25 May 1966

Graininess in coherent optical systems

Imaging of diffusely reflecting or transmitting surfaces nearly always produces an image that is grainy in appearance. From experiments it is known that a larger aperture (f-number) optical system will ~~result~~ give finer grain pattern, and thus be less objectionable. The cause of this grainy appearance will be discussed here.

For simplicity of analysis, consider this optical system:



The signal in this case is a pure phase function, $s(\xi,\eta) = a_0\, e^{j\phi(\xi,\eta)}$. The transfer function of the optical system (this particular one or any other) is $g(x-\xi, y-\eta)$. The output of the system at plane P_3 is then given by

$$i(x,y) = s * g = \iint_{-\infty}^{+\infty} s(\xi,\eta)\, g(x-\xi, y-\eta)\, d\xi\, d\eta$$

$$= a_0 \iint_{-\infty}^{+\infty} e^{j\phi(\xi,\eta)}\, g(x-\xi, y-\eta)\, d\xi\, d\eta$$

This integral shows that the output intensity, $i \cdot i^*$, depends on the averaging, or integration, or the vector $e^{j\phi(\xi,\eta)}$ over the area of the transfer function. If the phase of $s(\xi,\eta)$ does not vary a great deal over the area of integration, then $i(x,y)$ remains constant and grainy appearance is absent. If ~~a~~ the phase varies considerably over the area of integration,

Juris Upatnieks, 25 May 1966

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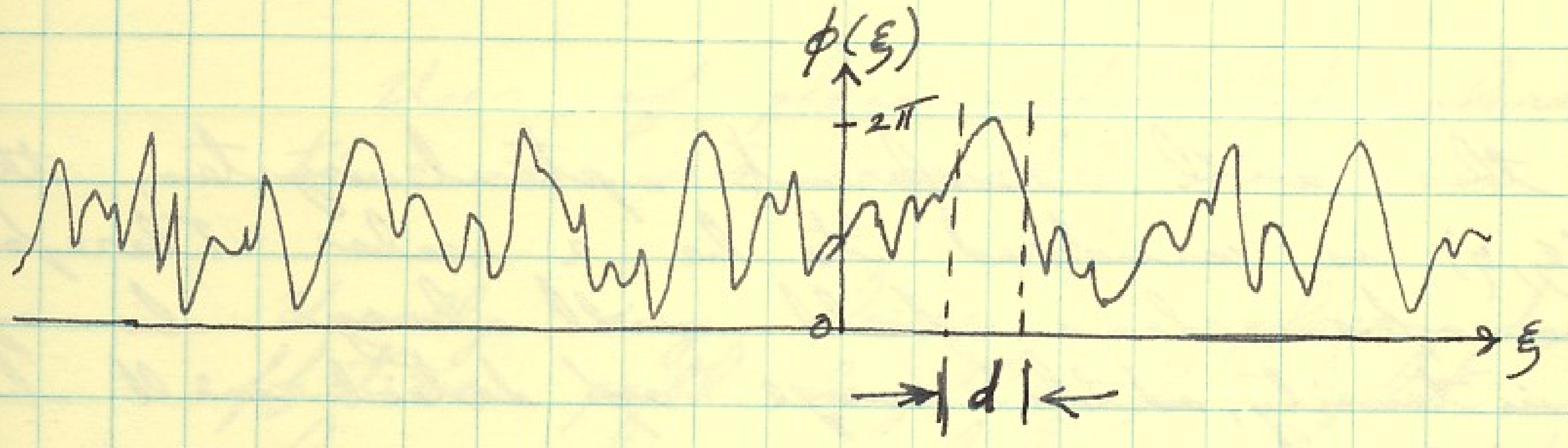


One-dimension phase variations of etched glass. Amplitude $= a_0$

then $i(x,y)$ can be expected to vary too and thus amplitude variations exist at the output even if they were absent at the input. This is the case for finely ground glass, and for diffusely reflecting surface, since in both of these cases only phase variations exist at the surface.

Mathematically, we can distinguish two cases:

Case 1: Phase variation small over area of integration. Then the approximation

$$g(x-\xi, y-\eta) = \delta(x-\xi, y-\eta)$$

can be made. The output then is

$$i(x,y) = \iint_{-\infty}^{\infty} e^{j\phi(\xi,\eta)}\, \delta(x-\xi, y-\eta)\, d\xi\, d\eta = e^{j\phi(x,y)}$$

Case 2: Phase variations are large over area of integration. For a one-dimensional case, see graph above. If the effective width of integration is d, and maximum spacial frequency content of $\phi(\xi,\eta)$ is f_m, then phase variations are significant in producing amplitude variations at the output if $f_m \geq \frac{1}{d}$. For diffraction-limited optical system, the transfer function is a Bessel function

$$g(x-\xi, y-\eta) = k_1 J\left[k_2(x-\xi), k_3(y-\eta)\right]$$

For other optical systems, the transfer function might be more complex.

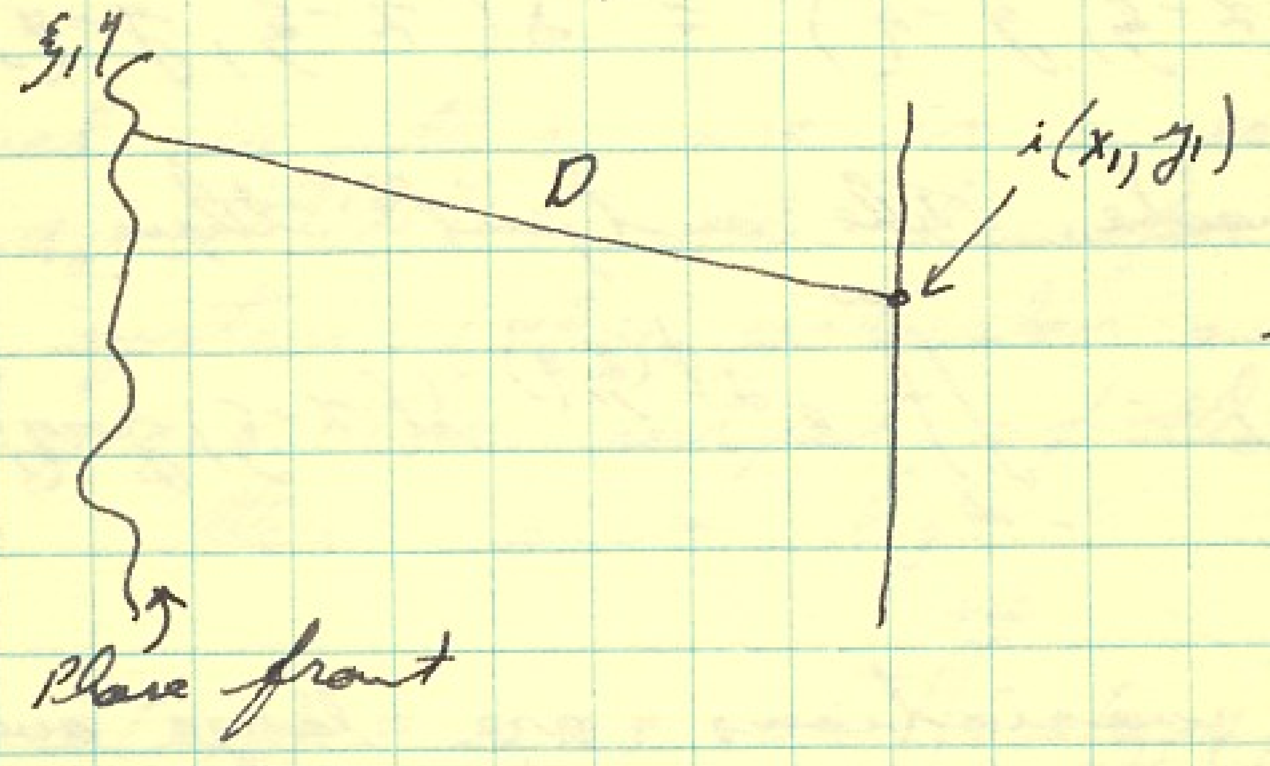
Juris Upatnieks, 25 May 1966

25 May 1966

Comparing this with incoherent optical system, the signal $s(\xi, \eta)$ is considered to be a scalar. Therefore, the image of a clear field will always be of uniform intensity, and the image of detail will be slightly less sharp.

In order to image a phase-varying field with constant amplitude faithfully, the spacial frequency content of the signal must be less than the bandwith of spacial frequencies that the optical system can reproduce. This is true whether the imaging is done by lenses, holograms, or by the lens of the eye.

For the case where the phase-varying plane is out of focus, we can first find the signal at the plane which is imaged:



$$i(x,y) = a_0 \iint \frac{e^{i\phi(\xi,\eta)}}{D(\xi,\eta)}\, d\xi\, d\eta$$

It is known that this integral gives always amplitude and phase varying signal. The image ~~of~~ is then similar, or grainy in appearance.

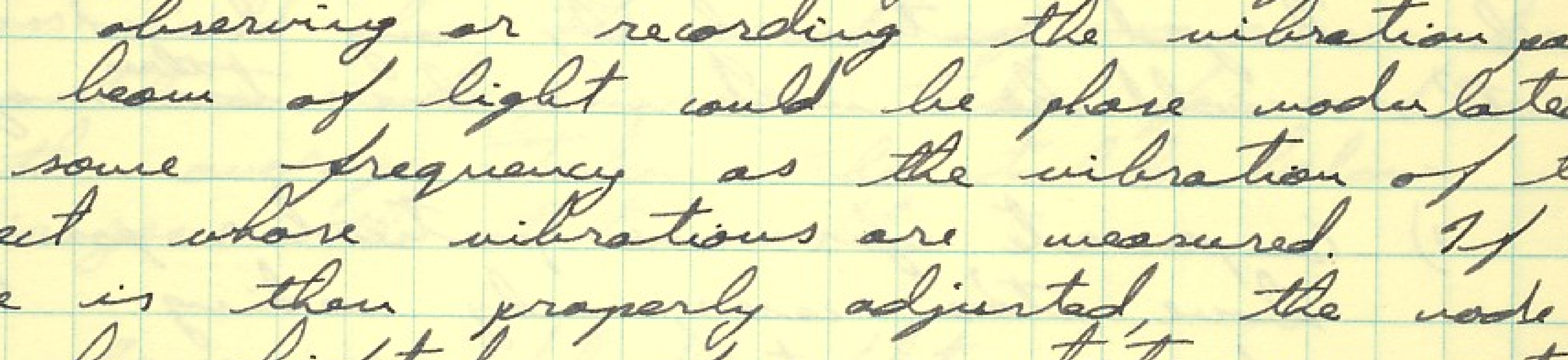
Juris Upatnieks, 25 May 1966

3 June 1966

Uses of phase-modulated coherent light with time as one variable.

Usually any change in phase due to changes in effective path length of light is undesirable when making holograms. A deliberate phase change as a function of time can be introduced in, for example, the reference beam to achieve special effects.

One use would be in conjunction with vibration measurments using the hologram technique. When observing or recording the vibration pattern, one beam of light could be phase modulated at the same frequency as the vibration of the object whose vibrations are measured. If the phase is then properly adjusted, the node point can be shifted from a stationary part of the object to one which is moving. This may be especially desirable if the amplitude of vibration is many wavelengths so that the contrast of the fringes becomes very weak. The reference point can then be shifted, and if the phase modulation is calibrated, then accurate measurment is still possible. This digram illustrates one possible arrangement:



Note: Mirror ① or ② is moved at same rate as object is vibrating, and both are phase locked (exited by same source of energy)

Juris Upatnieks, 3 June 1966

3 June 1966

Another application would be to change the path length of the referance beam by the same amount as the path length of the signal is changing due to vibration of the object. A detector would have to be installed to determine the motion of the object, and this signal could then be fed into a servo amplifier that in turn would change the referance beam path length. This scene would work for the whole object only if it vibrated as a whole.

If a laser would be available where λ could be changed continuously by any desired amount, then this could be used in there ~~two~~ three ways:

1) Compensate for one particular point in the above two cases, by making $\frac{\Delta L}{\lambda} = N =$ constant for some point.

2) Determine the $\Delta L = 0$ point by making λ be a function of time. Fringes then could be observed only where path length defferance is zero, or $\Delta L = 0$.

3) Make both both ΔL and λ functions of time, then if one is known, the other can be found from relation $\frac{\Delta L}{\lambda} =$ constant.

Juris Upatnieks, 3 ~~July~~ June 19[illegible]

7 June 1966

Emulsion thickness measurement of the 649F emulsion on 4×5×1/8 in. glass plates.

A series of measurements were made using the optical system shown on p. 25. In order to reduce the effect of emulsion thickness variations from plate to plate, one plate was cut in several pieces and each peace processed in a different way. It was found, however, that even emulsion on one plate may vary as much as 2μ. Thus, the test results are difficult to interpret. Small variations in thickness could be the result of uneven emulsion coating. Three readings were taken for each case and the average taken. The table below summirizes the test results.

Plate identification	Processing and handling of plates	1 hr. after	24 hrs. after		
I - A	Exposed, developed, washed	16.1 μ	15.8 μ		
I - B	Unexposed, developed, washed	15.4 μ	15.1 μ		
I - C	Exposed, developed, fixed, washed	15.7 μ	15.2 μ		
I - D	Unexposed, developed, fixed, washed	15.5 μ	13.3 μ		
II - A	Unexposed, developed, washed	17.3 μ	16.9 μ	(fixed) 14.6 μ	14.2 μ
II - B	Unexposed, developed, stop-bath, washed	15.5 μ	?	(fixed) 13.7 μ	13.7 μ
II - C	Unexposed, developed, fixed, washed	13.7 μ	13.7 μ		
II - D	Unexposed, developed, stop-bath, hardener, fixed, washed	13.7 μ	13.4 μ		
		1 hr. after	4 hrs. after	24 hrs. after	
III - A	Unexposed, washed	14.8 μ	15.3 μ	15.4 μ	
III - B	Unexposed, washed, hardener	15.1 μ	15.0 μ	15.4 μ	

Plates in the III series appear to differ in thickness in time. Perhaps slightly different place was measured on each plate. The error in measurement is about ±0.3 μ.

Juris Upatnieks, 7 June 1966

7 June 1966

Perhaps because of the relatively large variations in emulsion thickness across the plate, conclusions are difficult to make. It appears that the following statements are true:

1. Exposed, processed emulsion is thicker than unexposed plate by about one λ maximum.

2. Fixing shrinks the emulsion 12% to 18%

3. Emulsion processed with hardener shrinks by about 0.3μ more than one processed without it. This conclusion is supported by observations of back-illuminated holograms.

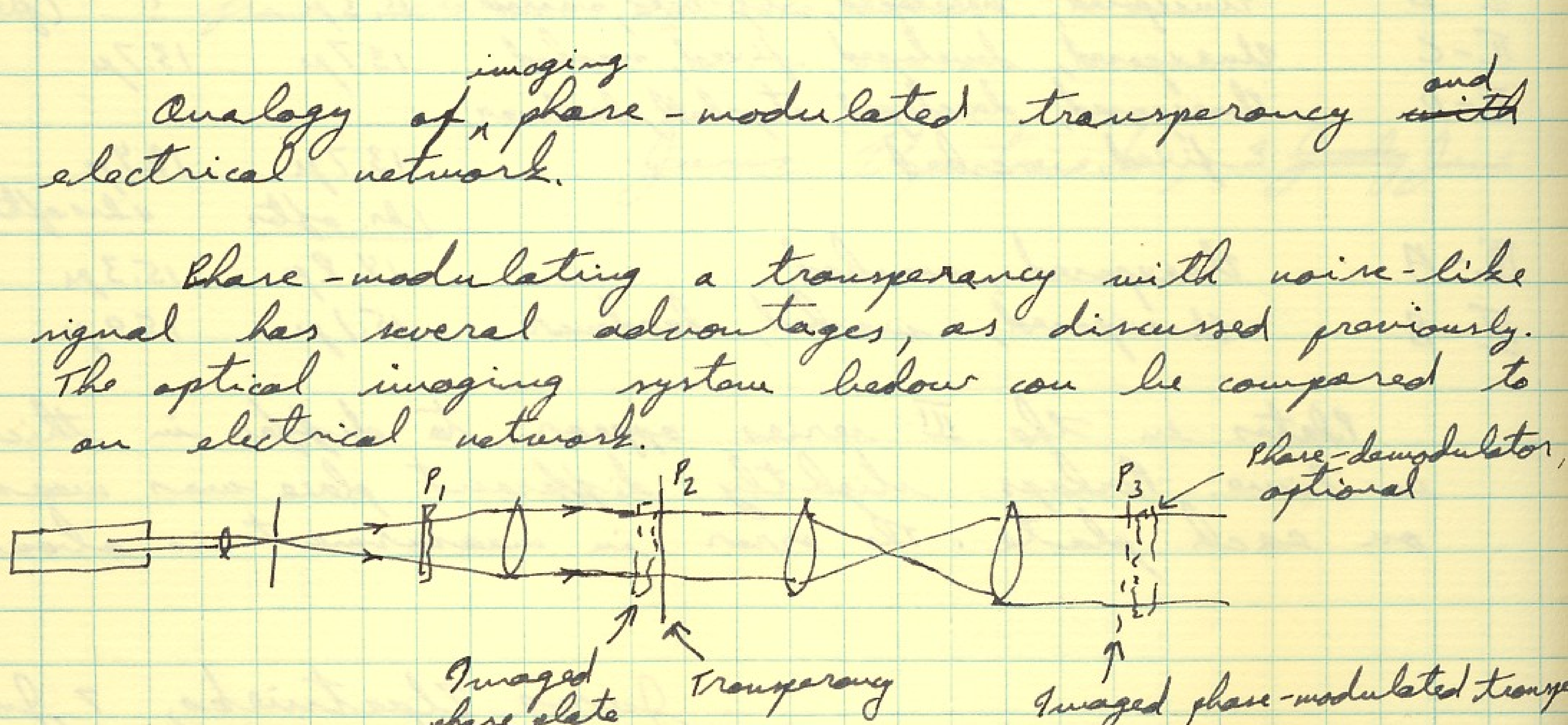
Due to the many factors affecting the actual optical path length in the emulsion, it seems that conclusions drawn from measurement of light wavelength and constructive interference should be more reliable.

Juris Upatnieks, 7 June 1966.

1 August 1966

Analogy of imaging phase-modulated transparency and electrical network.

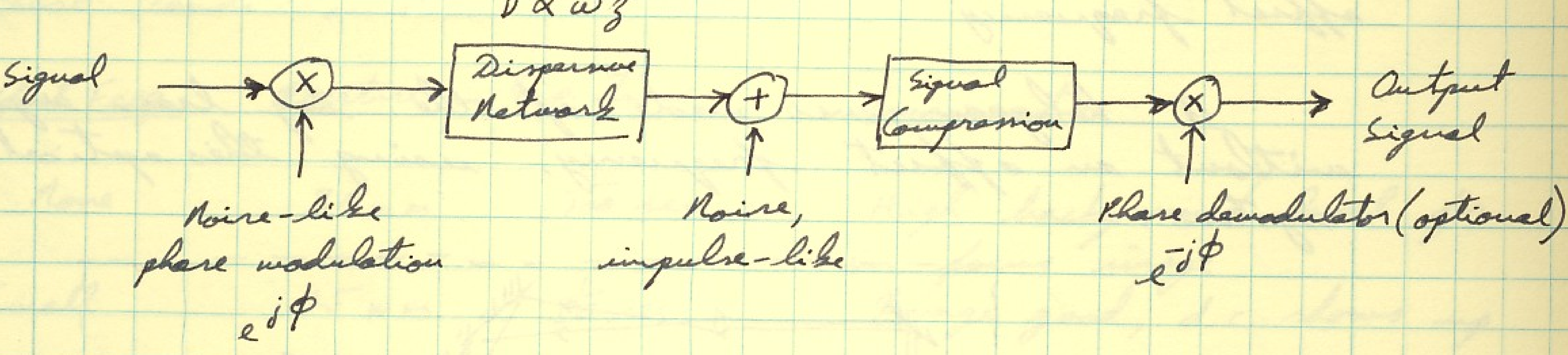
Phase-modulating a transparency with noise-like signal has several advantages, as discussed previously. The optical imaging system below can be compared to an electrical network.



Juris Upatnieks, 1 August 1966

1 August 1966.

The equivalent electrical network would be as follows:



The signal of a transparency usually consists of a large d.c. term and some high-frequency terms: $s(x,y) = a_0 + s_1(x,y)$. The dispersive network in our optical system is simply free space, and dispersion D is proportional to spacial frequency content of the signal and the distance z from the object (or image) plane: $D \propto \omega z$. D may be thought of as being the distance over which the wave from a signal in the transparency is spread out when it encounters noise (dust, imperfections in a lens or mirror, etc.). Signals of high spacial frequency are dispersed over a large area, and thus for all practical purposes is not affected by defects in the imaging system. In the compression network (focusing), the signal is compressed to focus while the noise is dispersed, thus improving the apparent signal-to-noise ratio. The d.c. term does not get dispersed, and thus is greatly affected by imperfections.

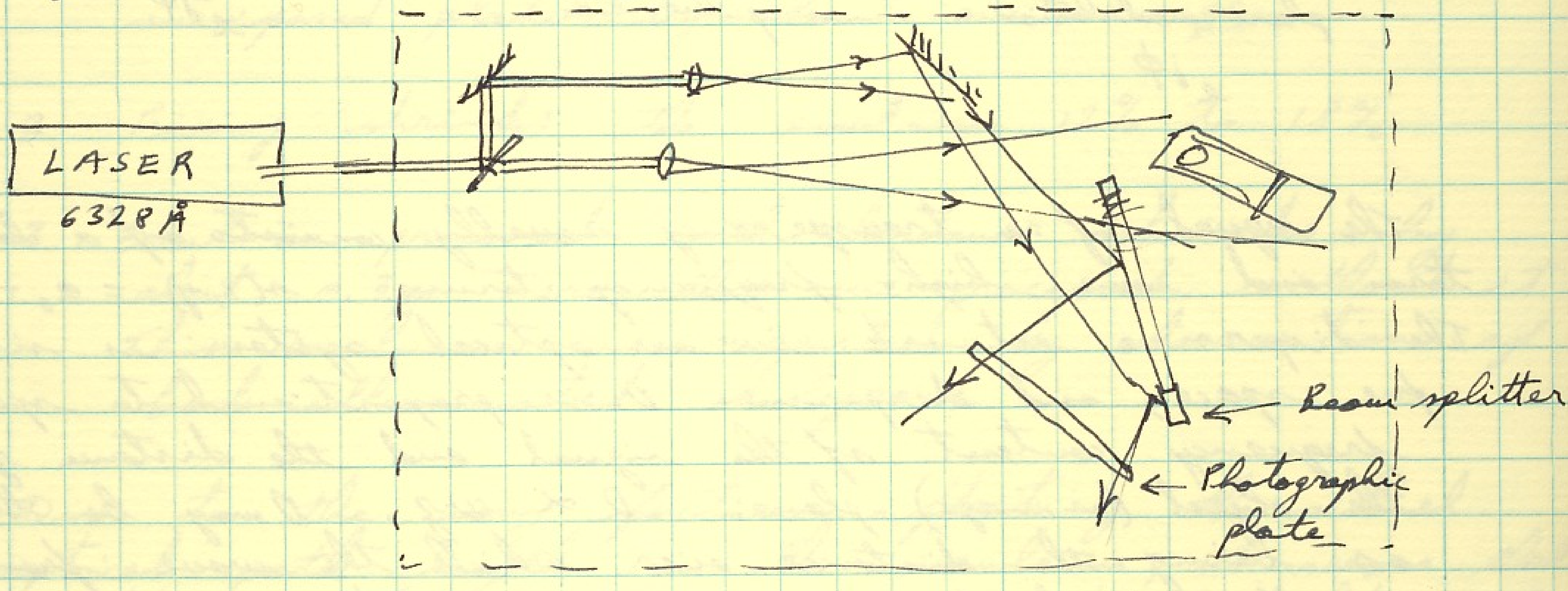
The purpose of the phase-modulation is to disperse the d.c. term, a_0, also. In this way the a_0 term is imaged with a smaller effect from defects, ~~and~~ the noise is spread out over a larger area, and the interference with the a_0 term produces a slight noise-like background. Finally, if the phase of the transparency is important, then a phase plate with a conjugate phase can be placed at the image plane and thus demodulate the signal.

Juris Upatnieks, 2 August 1966.

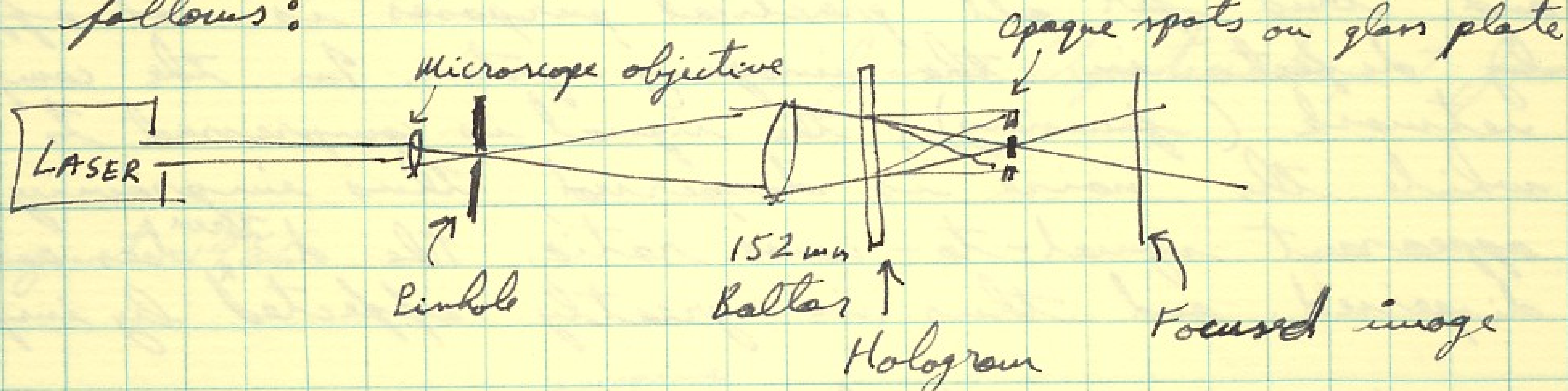
August 5, 1966

Three-dimensional hologram with and without offset frequency.

A hologram was made of the toy train engine without an offset frequency, using this optical system:



The image was reconstructed with a lens as follows:



The d.c. term, and the two bright sideband spots, were removed by spacial filtering. The sideband spots were caused by interference of the reference reflecting off the front surface of the beam splitter and the back surface. The reconstructions were recorded on polaroid film. ~~One~~ One images with large (about 30 mm) aperture ~~were~~ was recognizable, but had hight background level of light and consequently poor contrast; another with same aperture but off to one side, thus effectively having a small offset frequency, was much better. The image with a small, 4 mm, aperture, was very bad without the offset.

Juris Upatnieks, 5 August 1966

5 August 1966.

The four photographs, taken on 29 July 1966, were made under these conditions:

	Offset Freq.	Aperture	Exp. time	Comments
#1	None	30 mm	1/100 sec.	High background level for in-focus image
#2	Small	25 mm	1/50 sec.	Image good, d.c. shows up
#3	None	4 mm	2/5 sec.	Image very poor, conjugate image partly in focus and superimposed on in-focus image
#4	Small	4 mm	1/2 sec.	Image good.

Conclusion: images without offset frequency are poor even for three-dimensional diffuse objects.

Juris Upatnieks, 5 August 1966.

5 October 1966 Read + understood by me on Oct 5 1966
B P Hildebrand

Holograms made with light having short coherence length and limited spacial coherence.

A problem frequently encountered with ordinary coherent light sources is that they have a very limited coherence length and limited spacial coherence. Limited coherence length restricts the number of fringes that one can obtain, and this is very serious with the offset-frequency technique since a fine fringe spacing is required. The source size limits the highest spacial frequency that can be recorded, affects the spacial coherence

Juris Upatnieks, 5 October 1966

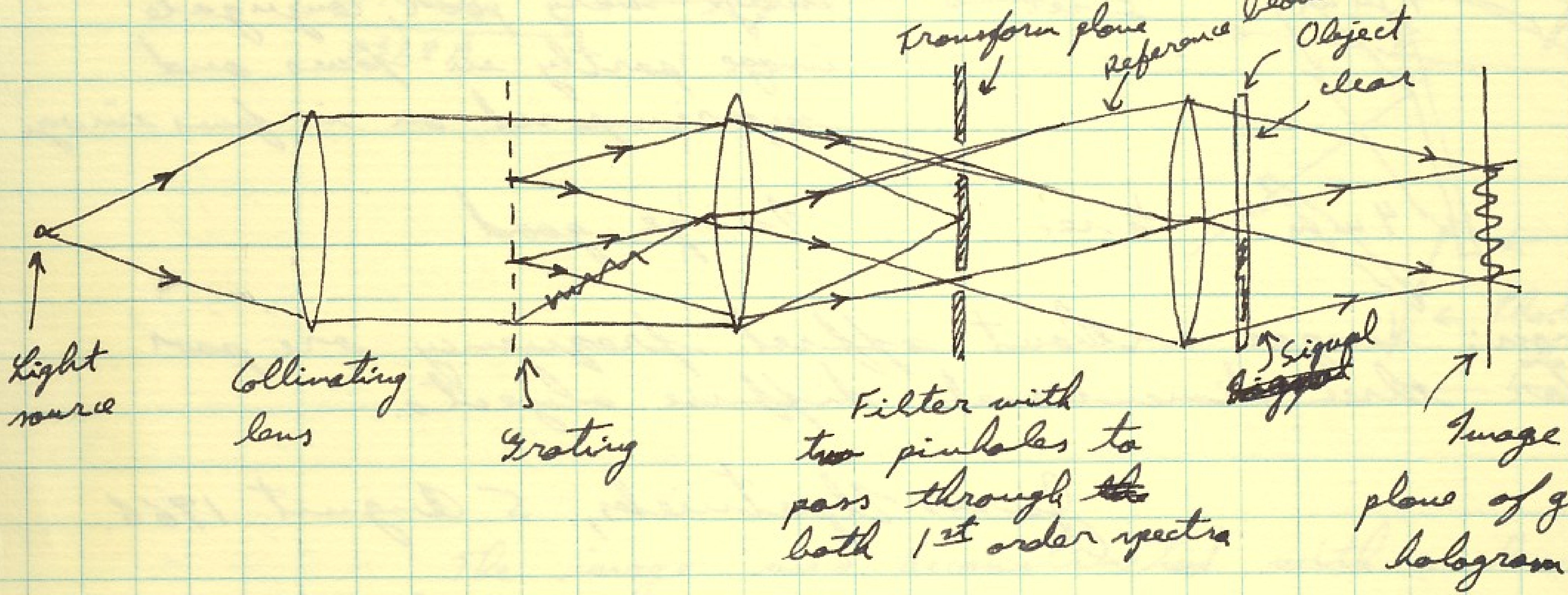
Read and understood by me on ~~Aug~~ Oct 5, 1966, K. A. Haines

Read + understood by me on Oct 5 1966

5 October 1966 B P Hildebrand

of the light beam, and is also a serious limitation on the offset-frequency technique of holography.

A technique is proposed here that will greatly extend the object (transparency) size of which a hologram can be made with ~~limited~~ partially coherent light, and also improve the resolution of the reconstructed image ~~made~~ from such a hologram. A hologram would be made with the optical system shown below:



The light source is assumed to be partially coherent, such as obtained with a mercury-arc lamp with an interference filter and a pinhole. The grating has constant spacial frequency and should have high diffraction efficiency. The two first-order sidebands are the filtered out at the transform plane to two partially coherent light sources. The grating, with the d.c. term removed, is imaged and the hologram is made at this plane. The transparency is placed in one beam and a compensating plate in the other. The transparency could be placed anywhere between the transform plane and the hologram plane, just as long only one beam passes through the transparency.

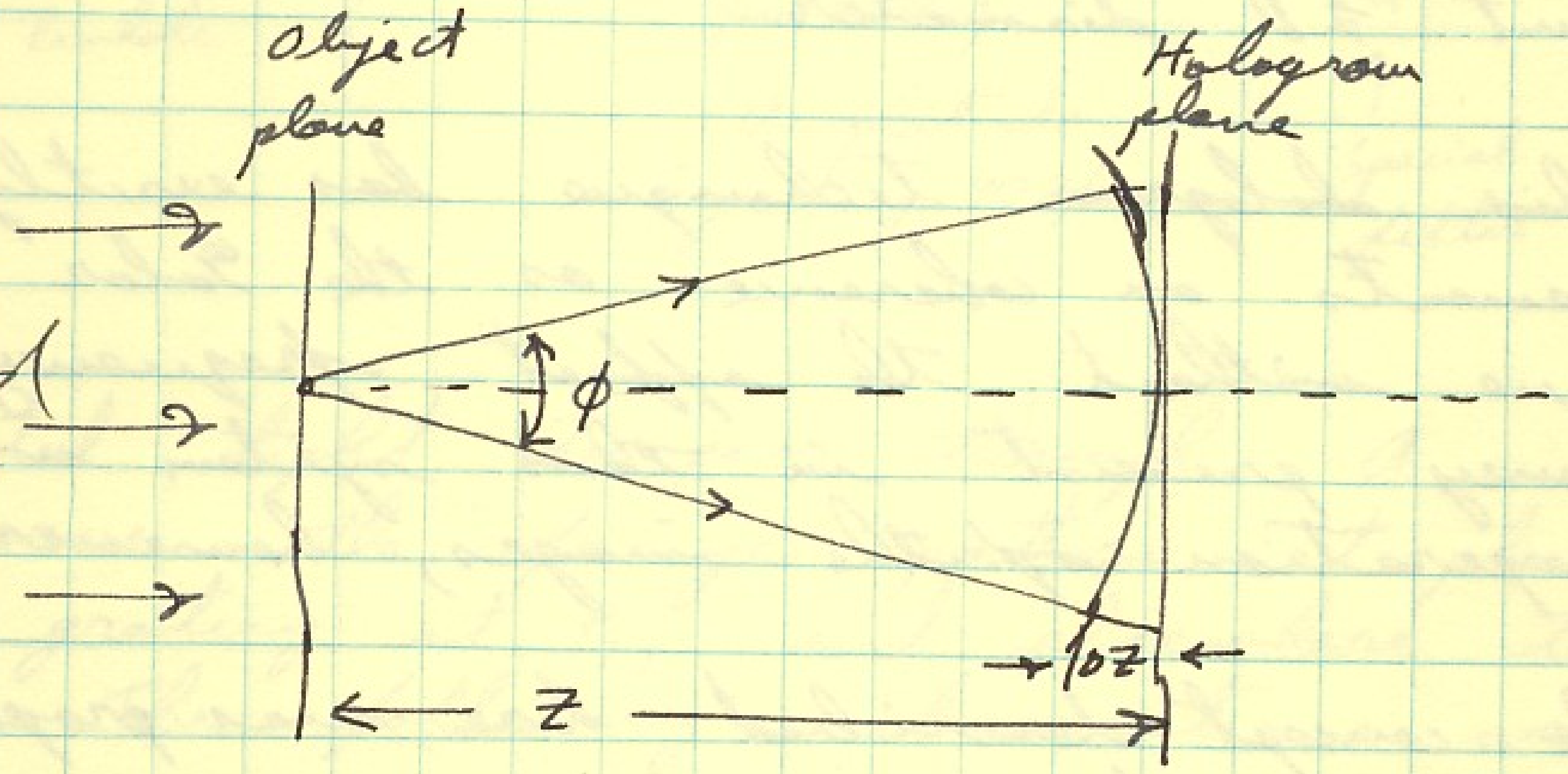
Since the grating is imaged on the hologram plate, no coherence or monochromaticity is required to make the grating, or a hologram of two plain beams. Some coherence

Juris Upatnieks, 5 October 1966

Read + understood by me on Oct 5/1966, K. A. Haines

5 October 1966

and monochromaticity is required to record the interference pattern between the light scattered by the object and the reference beam. To estimate coherence requirements, consider the diagram below:



Read & understood by me on Oct 5 1966
B. P. Hildebrand

To record light scattered over angle ϕ by ~~the~~ a point on the object, two requirements must be met. First, the relation

$$\Delta z < \Delta l \quad \text{must hold,}$$

where Δl is the coherence length of the light source. For a low-pressure mercury arc lamp, $\Delta l \approx 1.2$ mm, or about 2000 fringes could be recorded. The second requirement that must hold is

$$\frac{a\,z}{F} < \frac{\lambda}{2\phi}$$

where F is the focal length of the collimating lens, a is the diameter of the pinhole source, and λ is the wavelength of light. Also, the lenses must be capable of accuratly imaging the grating.

To obtain the greatest area possible for the object, each of the two point sources at the transform plane should fill half the aperture of the last lens. If lens diameter is D, then the frequency of the grating should be

$$f_s = \frac{D}{4\lambda\,(\text{focal length})} = \frac{1}{4\lambda\,(\text{f-no of lens})}$$

Juris Upatnieks, 5 October 1966

Read and understood by me on Oct. 5/1966, K. A. Haines

5 October 1966.

For a f-5.6 lens system, the grating should have about 70 l/mm, or 100 l/mm for a f-4 system. The useful area ~~#~~for the object will be a circular of about ½D diameter.

This hologram technique has exactly the same requirements on coherence as the color hologram technique without the offset frequency. The offset frequency present in this system will insure the separation of the images, however.

The concept described here was proposed by Emmett N. Leith.

Juris Upatnieks, 5 October 1966

Read + understood by me on Oct 5/1966
B P Hildebrand

Read + understood by me on Oct 5/1966, K. A. Haines

11 November 1966

Production of interference fringes with light lacking time coherence.

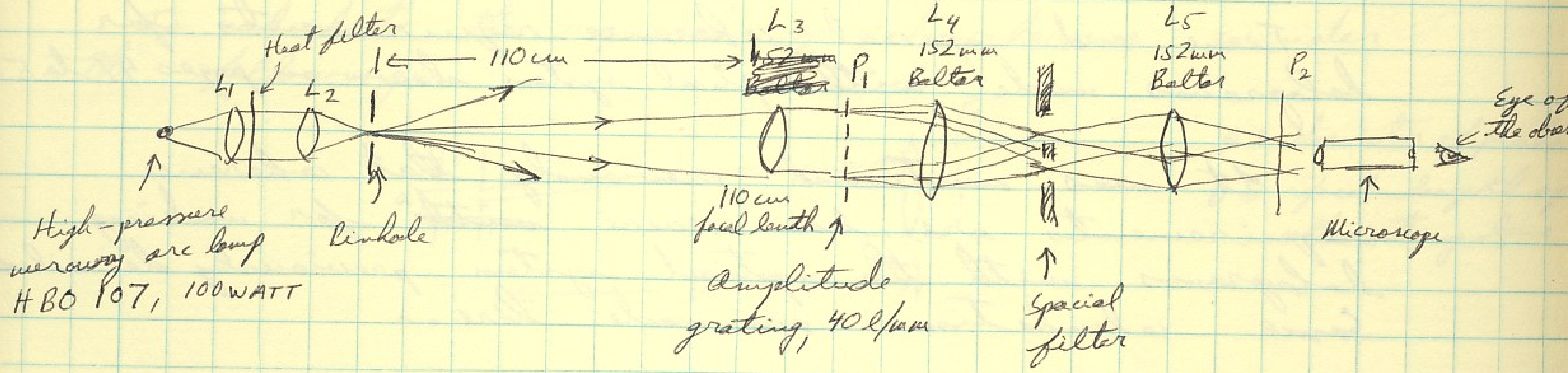
White light interference fringes were produced with the optical system shown here. A high-pressure mercury arc lamp was used as a light source, focused to a pinhole, and collimated by lens L_3. No color filters were used. A grating was placed at P_1, the first ~~two~~ order sidebands were selected ~~filtered out~~ by a spacial filter, and the interference pattern was observed to the right of lens L_5. The spacial filter allowed all of the 1st sideband

Read and understood by me, Kenneth A. Haines on Nov. 11, 1966.

Observed Experiment
Read & Understood Text Charles B. Jacobson
Nov 11, 1966

Juris Upatnieks, 11 November 1966

11 November 1966



diffracted light to pass through. A microscope was used to observe the fringes pattern at plane P_2, image plane of the grating at P_1, and elsewhere to the right of L5. The following observations were made:

1. With a 50μ pinhole in place, white light interference fringes were observed at plane P_2 and everywhere up to the lens L_5 where the two beams of light overlapped. There was no seperation of colors across the plane of observation anywhere. A slight loss of contrast was observed as one moved away from the plane P_2.

2. With the pinhole removed, the effective source size was about 3 mm diameter. Good contrast fringes were observed at plane P_2 and no shift in color or loss of contrast was abserved over the area of overlaping beams. As the microscope was focused to other planes increasingly further away from P_2, the contrast of the fringes decreased.

From the above observations we can conclude that interference fringes can be produced with white light over an area limited only by the aperture of the lens. Furthermore, only spacial coherence is required to produce fringes at other planes than P_2, time coherence is not required.

Juris Upatnieks, 11 November 1966

Observed Experiment
Read & Understood Text
Charles B. Jacobson
November 11, 1966

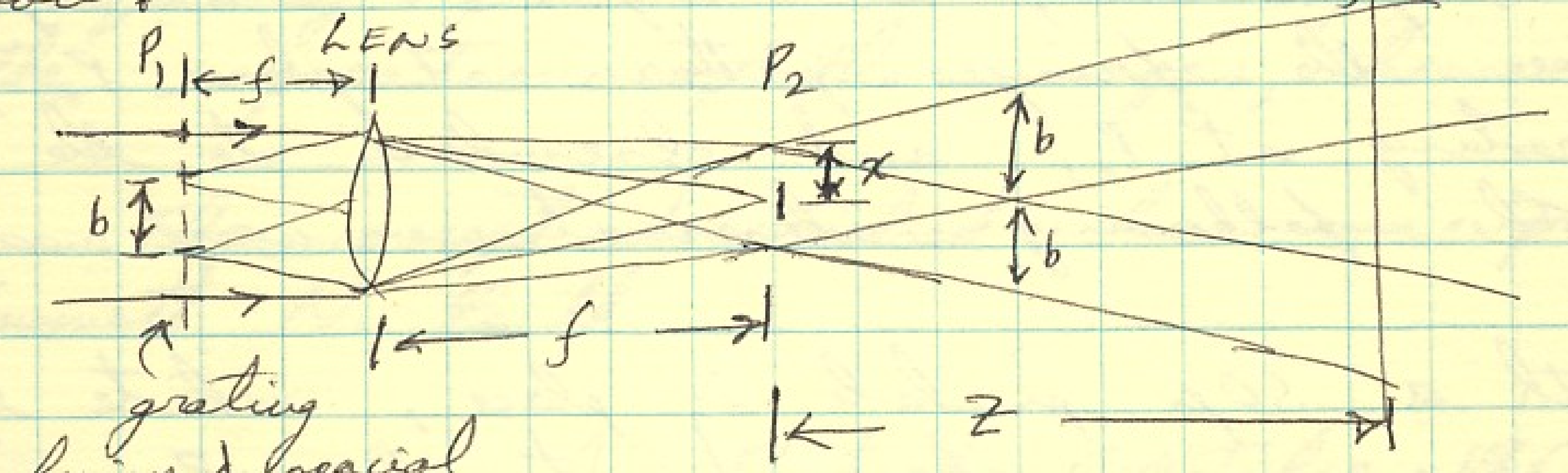
... and understood by me, Kenneth A. Haines on Nov. 11, 1966.
Experiment was observed by me, Kenneth A. Haines on Nov. 11, 1966.

November 16, 1966

Time and spacial coherence requirements for holograms made with optical system shown on pages 49 to 52.

It was mentioned previously that coherence requirements are less severe ~~with~~ for making holograms with the optical system previously described. Some calculations are made here.

The two coherent sources are obtained as shown below:



Consider collimated white light impinging on the grating having spacial frequency λ_s. At P_2 the spectra of light will be displayed distance x from the optical axis, and x is given by

$$x = f\left(\frac{\lambda_\ell}{\lambda_s}\right)$$

where λ_ℓ is the wavelength of light. At plane P_3 distance z from the two point sources an interference pattern will be formed having spacial frequency λ_s':

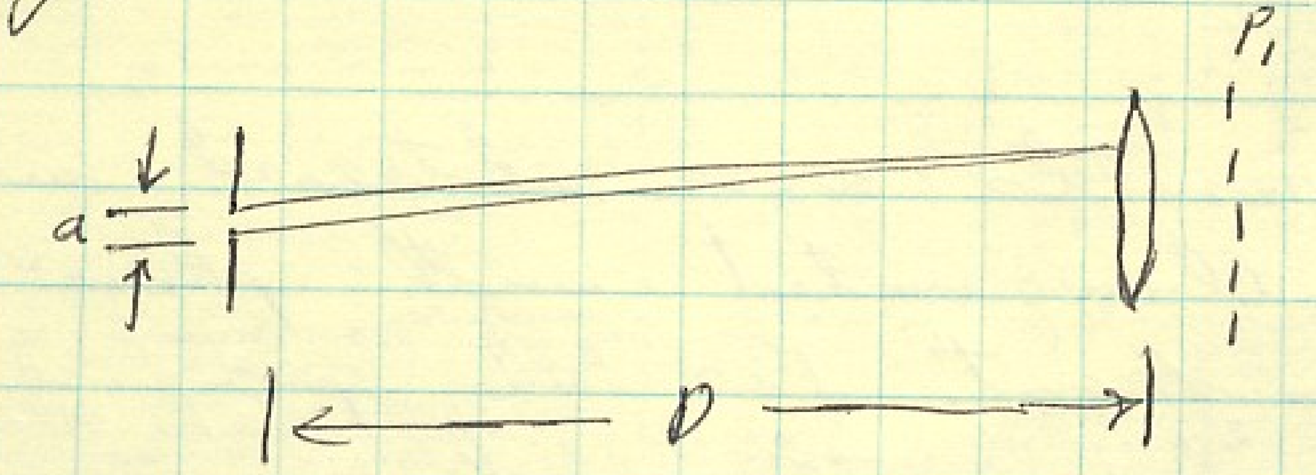
$$\lambda_s' = \frac{z\lambda_\ell}{2x} = \frac{z\lambda_\ell}{2f\left(\frac{\lambda_\ell}{\lambda_s}\right)} = \frac{1}{2}\lambda_s\left(\frac{z}{f}\right)$$

Since λ_s' is independent of wavelength of light, white light fringes will form everywhere in space where the two beams overlap. Thus, <u>time coherence is not required for forming interference fringes</u>, or the carrier frequency for ~~the~~ a hologram. It is assumed here that spacial coherence exists at plane P_1, ~~or~~ that is, light originates from a point source.

Juris Upatnieks, 16 November 1966

16 November 1966.

To calculate the required spacial coherence, consider the following:



a = diameter of pinhole

D = focal length of collimating lens

We can find coherence at plane P_1 above from finding spacial frequency at P_1 that would result from two perfect point sources at each edge of the slit (or pinhole). This ~~frequency,~~ wavelength λ_{so}, is given by

$$\lambda_{so} = \lambda_e \left(\frac{D}{a}\right)$$

For example, for $a = 25 \times 10^{-3}$ mm and $D = 10^3$ mm, $\lambda_{so} = 20$ mm for $\lambda_e = \ldots$
Fringe visibility (as given in Born + Wolf, p. 267) is the following:

0.9 for $\frac{1}{4}\lambda_{so}$

0.4 for $\frac{1}{2}\lambda_{so}$

0.1 for $\frac{3}{4}\lambda_{so}$

Thus, light waves from two points $\frac{1}{4}\lambda_{so}$ apart in plane P_1 will give fringe visibility 0.9, etc. for other values.

We can calculate the spacial coherence requirement, Δl, at plane P_3 (fig. p. 54). At P_3 the wavefronts from P_1 are magnified by a factor $\left(\frac{z}{f}\right)$. Then

$$\Delta l = b\left(\frac{f}{z}\right) \quad \text{for} \quad z \geq f$$

and this Δl is the required special coherence at plane P_1. If we put a lens after P_2 and image the grating at plane P_3, then each point from ~~at~~ plane P_1 interferes with itself, no spacial coherence is required, and $\Delta l = 0$. Therefore, by imaging a grating, neither time nor spacial coherence is required. Consequently, the carrier frequency can be obtained without any coherence at all.

Juris Upatnieks, 16 November 1966

17 November 1966

Experiments with phase-modulated wavefronts and imaging.

Improved results were obtained with imaging of transparencies illuminated with phase-modulated constan[t] amplitude wavefront. For the purpose of comparison, images illuminated with a plain wavefront and with the diffuser out-of-focus were also made. The experiments were performed in September 1966. The optical system shown below was used:

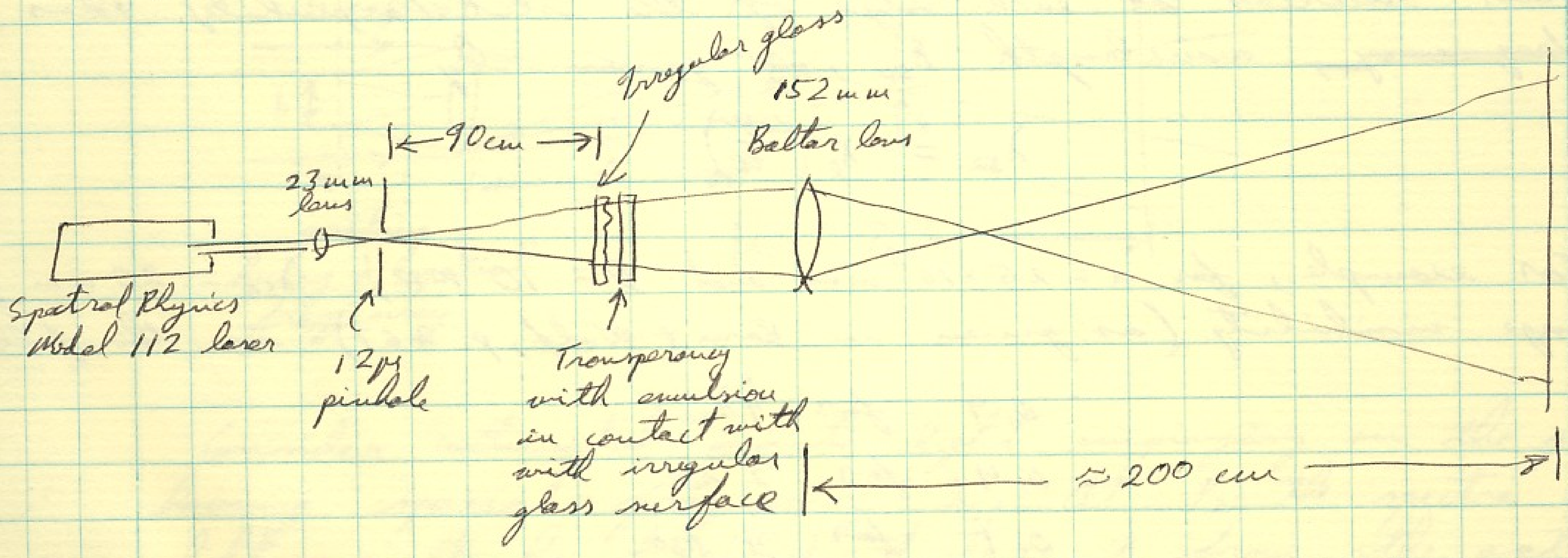


Image with a plane wavefront illumination, with irregular glass remov[ed] from the system. Als[o] X14 magnification. This image has hig[h] resolution but many diffraction patterns on the surface of the lens. Graininess is not visible.

Juris Upatnieks, 17 November 1966.

17 November 1966

Image of the transparen illuminated with phase-modulated wave fro The image is grain-f at the center, but has grain elsewhere. Due to field curvature of lens it was impossib to focus the who image at one time. Moving the film would bring another area in focus. Magnification x14.

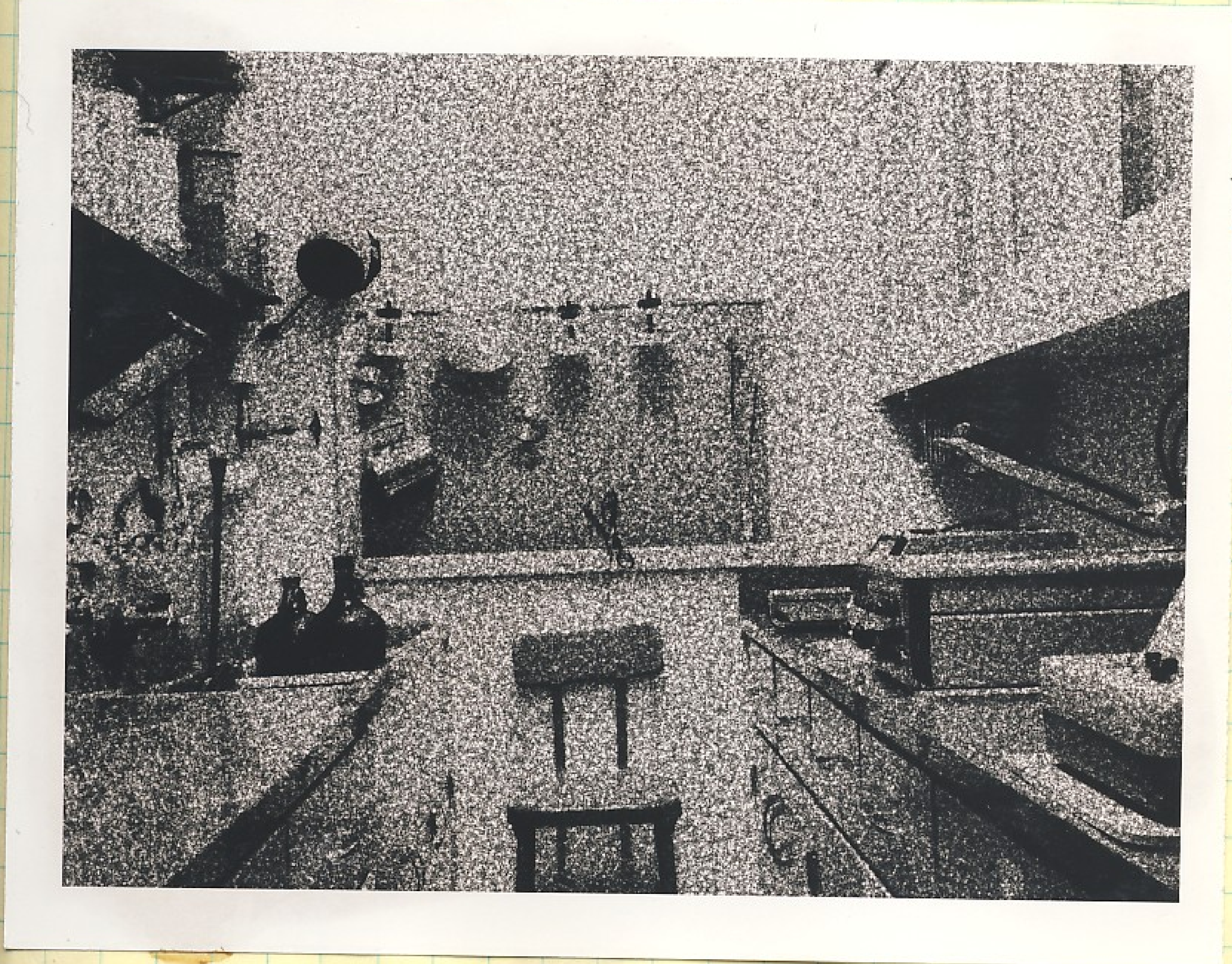
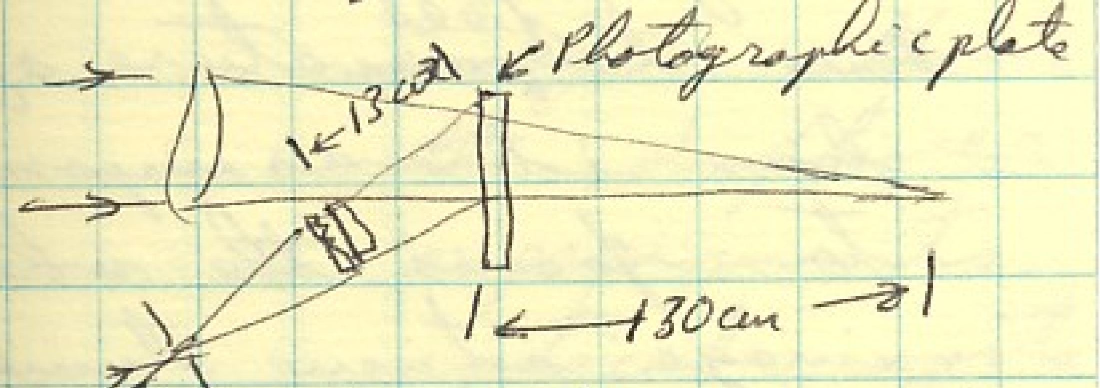


Image of the transparenc with diffuser (irregular glass) moved 4mm away from the transparency. The irregular glass thus ~~lens~~ acts as diffuse screen, illumin the transparency with light having both random phase and amplitude variations. The image thus becomes very grainy in appearance.

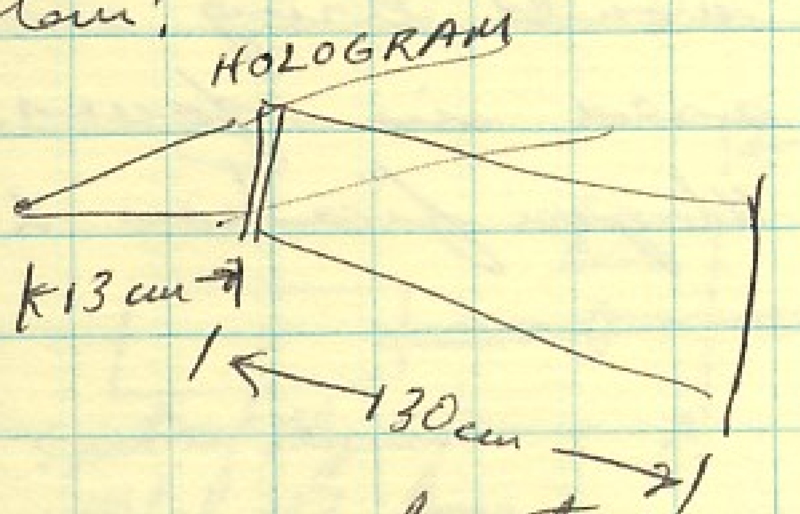
Juris Upatnieks, 17 November 1966.

17 November 1966

Hologram reconstruction of a transparency illuminated with the same phase-modulated wavefront. Magnification about X10. Hologram made as follows:



Reconstructed using this system:



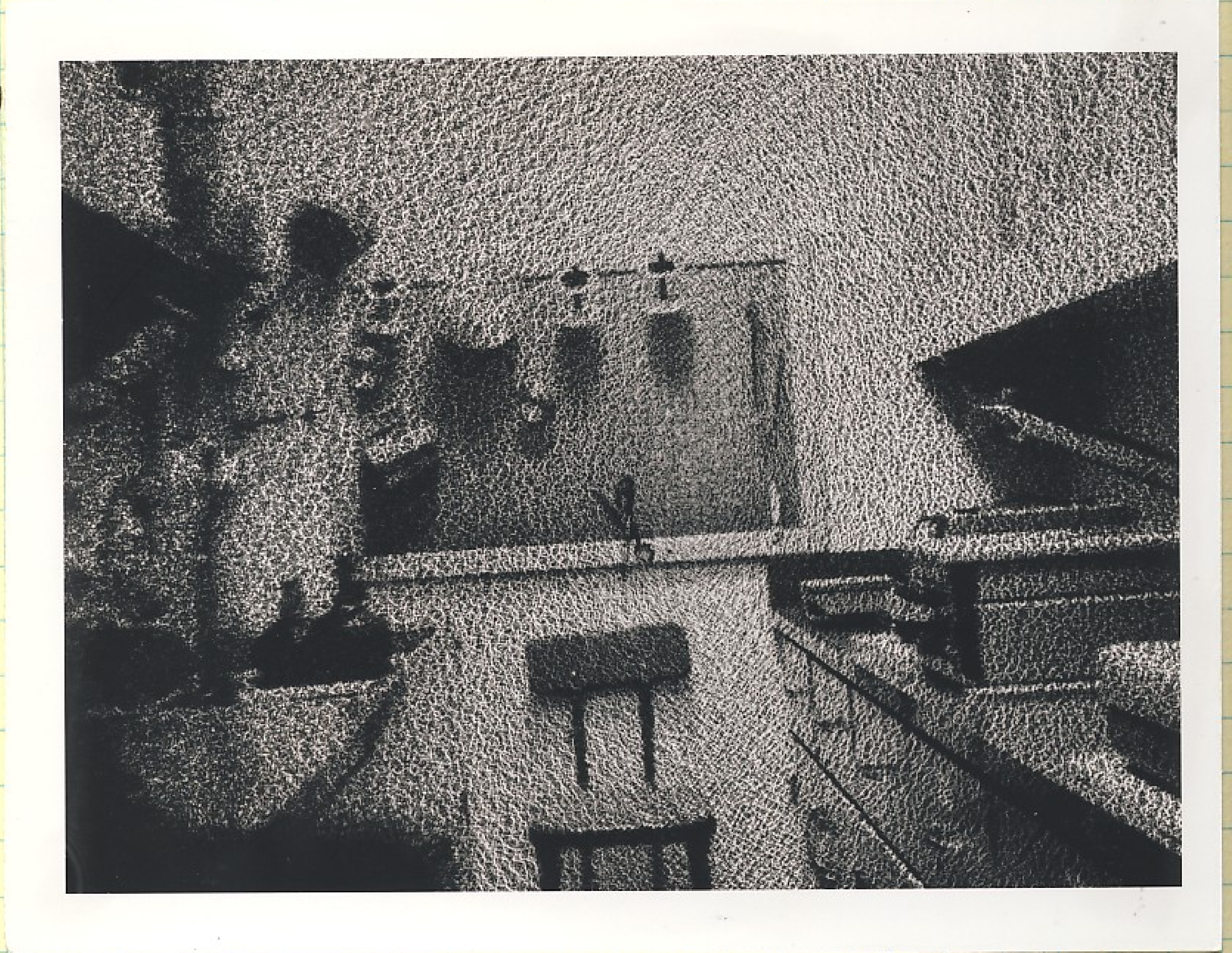
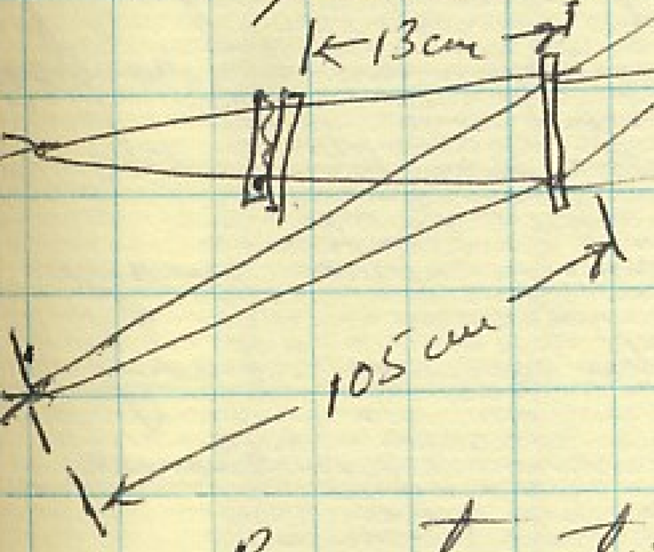
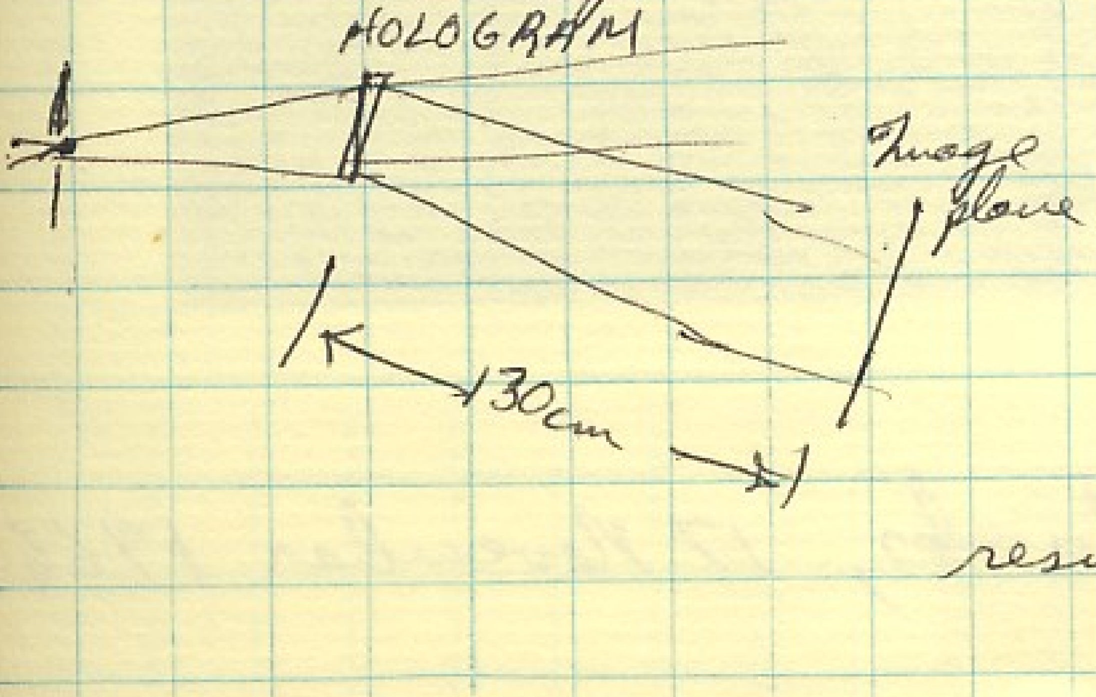


Image poor due to abberations from magnification, except at a small area in the center. This demonstrates ~~it~~ the use of phase-modulated wavefronts for testing imaging systems.

Hologram reconstruction of a transparency illuminated with a phase-modulated wavefront. Magnification about X10. Hologram made as follows:



Reconstruction made with this system:



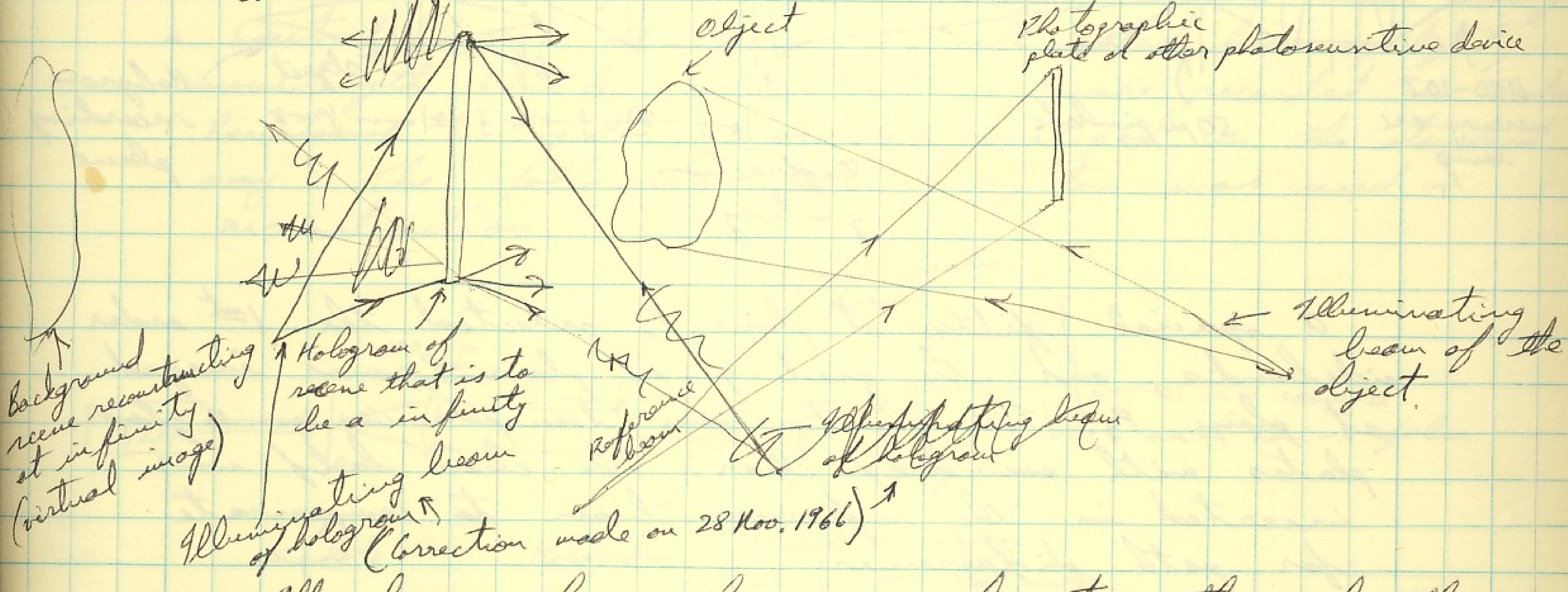
This reconstruction has much better overall quality, indicating that smaller abberations result from holograms made with the system shown

Juris Upatnieks, 17 Nov. 1966

18 November 1966

Technique for obtaining a background scene that appear to be ~~for J.U. 18 Nov 66 hologram~~ located at infinity in a hologram.

It may be desirable in a hologram scene to have a background that appears to be at infinity. For example, in a hologram used as a training device, it may be necessary to have a horizon or other objects to have the appearance of being far away. One way to achieve this effect is to first make a hologram of a two-dimensional diffuse surface with the desired scene painted on it. The diffuse surface may be transmitting or reflecting. A hologram would be made of this scene and then reconstructed as a background for a second hologram scene. A possible arrangement is shown here:



All beams shown here are coherent with each other. Since the background scene was two dimensional distortion when it is enlarged should be negligible. The background scene is made to appear at infinity by enlarging in the reconstruction process.

Juris Upatnieks, 18 November 1966

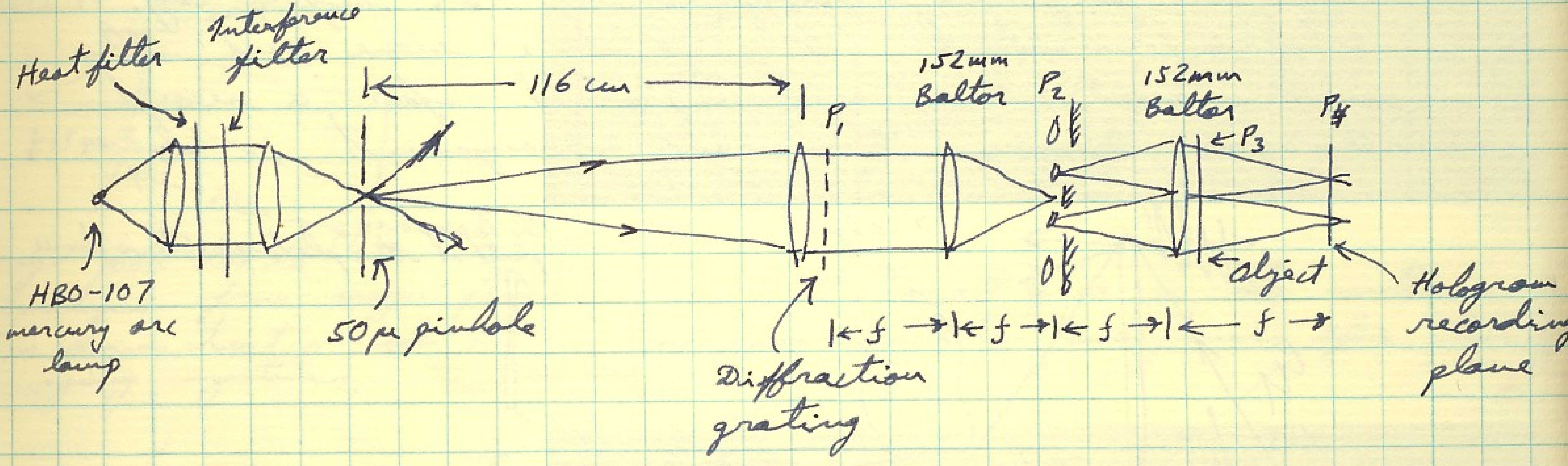
Read + understood by me on Nov 28/66
B.P. Hildebrand

Read & understood on Nov. 29 1966
B. Jacobson

23 November 1966

Experiments with holograms using partially coherent light sources.

Hologram of the carrier-frequency type were made using a HBO-107 super-pressure mercury arc lamp as a light source. An interferance filter was used to select the green line (5461 Å) of the spectrum, and SO-243 film for recording the hologram. The film was developed for 8 min. in Kodak D-19 developer. The following optical system was used:



A spacial filter at plane P_2 selected the 1st order sidebands, and the grating at plane P_1 was imaged at plane P_4. The objects were transparancies on glass plates with one-half clear. The clear half was inserted in the reference beam to compensate for path differences.

The spacial coherence at P_1, using the $\frac{1}{2}\ \lambda_{50}$ criteria, is over an area of 13 mm diameter. The hologram at P_4 records the object with about 50 l/mm resolution.

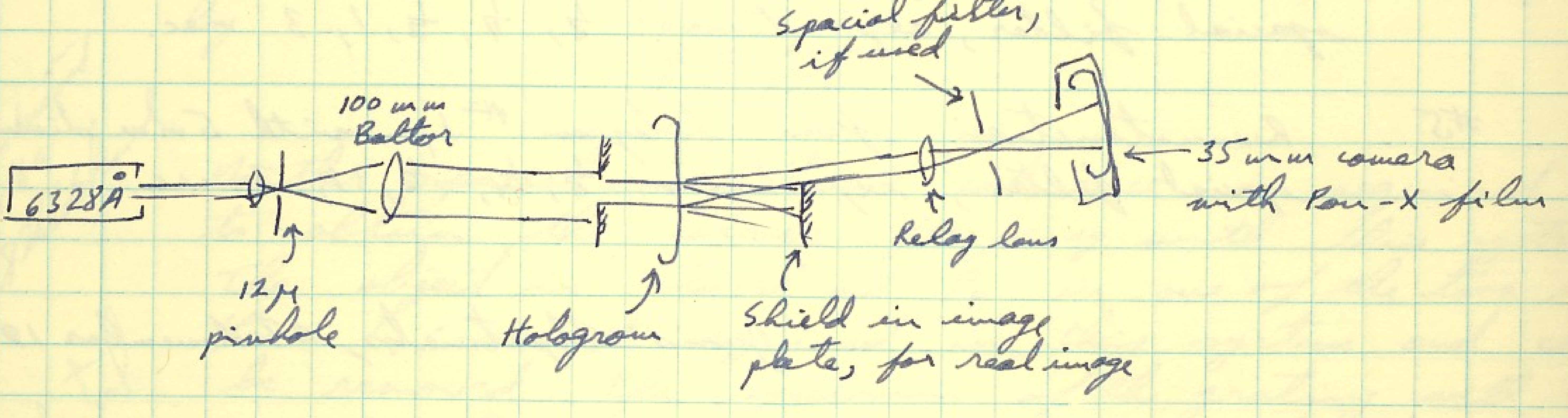
The following hologram were made: (on 70 mm SO-243 film)

Juris Upatnieks, 23 November 1966

23 November 1966

	Date exp. made:	Exp. times	Object	Interference filter	Carrier freq.	Comments
#1	16 Nov. 1966	3 & 5 min.	Large letters	green	80 l/mm	
#2	16 Nov. 1966	10, 20, 40 sec.	Large letters	none (white light)	80 l/mm	
#3	18 Nov. 1966	10 & 20 min.	Small letters	green	80 l/mm	
#4	21 Nov. 1966	10 & 20 min.	Large letters	green	200 l/mm	
#5	21 Nov. 1966	10 & 20 min.	Continuous tone transparency (photo lab.)	green	200 l/mm	Both underexp

Reconstruction of the above holograms were made using a Spectral Physics 112 laser, in collimated beam of light, wavelength 6328Å. Reconstructions were recorded on Kodak Panatomic-X film, and it was developed in the standard way. The following optical system was used in reconstruction:



Film recordings show (sheet #16, 21 Nov. 1966):

#3 Reconstruction from hologram #3, no spacial filter, exposure times: 1/15, 1/8, 1/4, 1/2, 1 sec.

#4 Reconstruction from hologram #1, no spacial filter, exp. times: 1/30, 1/15, 1/8, 1/4, 1/2, 1 sec.

Juris Upatnieks, 23 November 1966

23 November 1966

#5 Reconstruction from hologram #4, 5 mm diameter spacial filter, exp. times: $\frac{1}{15}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3 sec.

#6 Reconstruction from hologram #4, no spacial filter, exp. times: $\frac{1}{15}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3 sec.

(Sheet #17, 21 Nov. 1966):

#1 Reconstruction from hologram #5, with 3 mm diameter spacial filter, exp. times: $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3, 10 sec.

#2 Reconstruction from hologram #~~1~~5, no spacial filter, exp. times: $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3 sec.

(Sheet #17, 22 Nov. 1966):

#3 Reconstruction from hologram #2, 7 mm diameter filter exp. times: $\frac{1}{30}$, $\frac{1}{15}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1 sec.

#4 Reconstruction from hologram #3, with 5 mm diameter spacial filter, exp. times: $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3 sec.

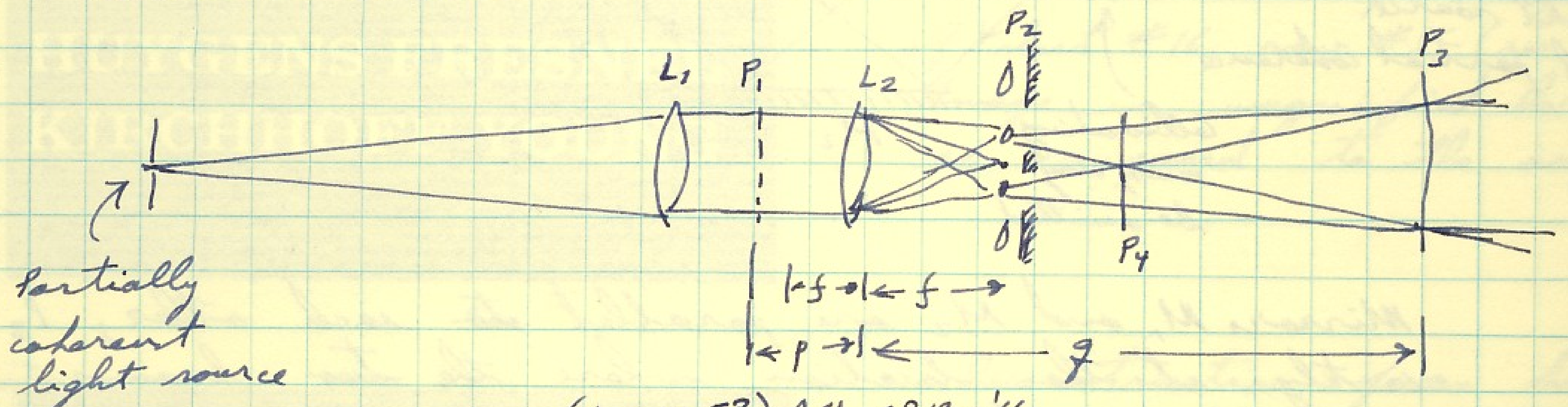
#5 Reconstruction from hologram #1, with 5 mm diameter spacial filter, exp. times: $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, 3 sec.

Juris Upatnieks, 23 November 1966

23 November 1966

Other techniques of obtaining carrier frequency with small coherence requirements.

A simplified optical system for obtaining fringes (carrier frequency) for holograms is shown below:



(L_5, p. 53) J.U., 28 Nov. '66.

The second lens ^can be removed if the diffraction grating is placed a distance greater than f from lens L_2. In that case the image of grating at P_1 will appear at plane P_3, distance q from the lens. Location of P_3 can be found from the lens formula, and is given by

$$q = \frac{pf}{p-f}$$

Neither spacial nor time coherence is required to obtain the carrier frequency with this system. The object is placed at P_4 in one of the two beams. Lens L_1 is not required in this system and can be removed. The spectrum of the grating will then appear to the right of plane P_2, and the spacial filter would have to be relocated accordingly.

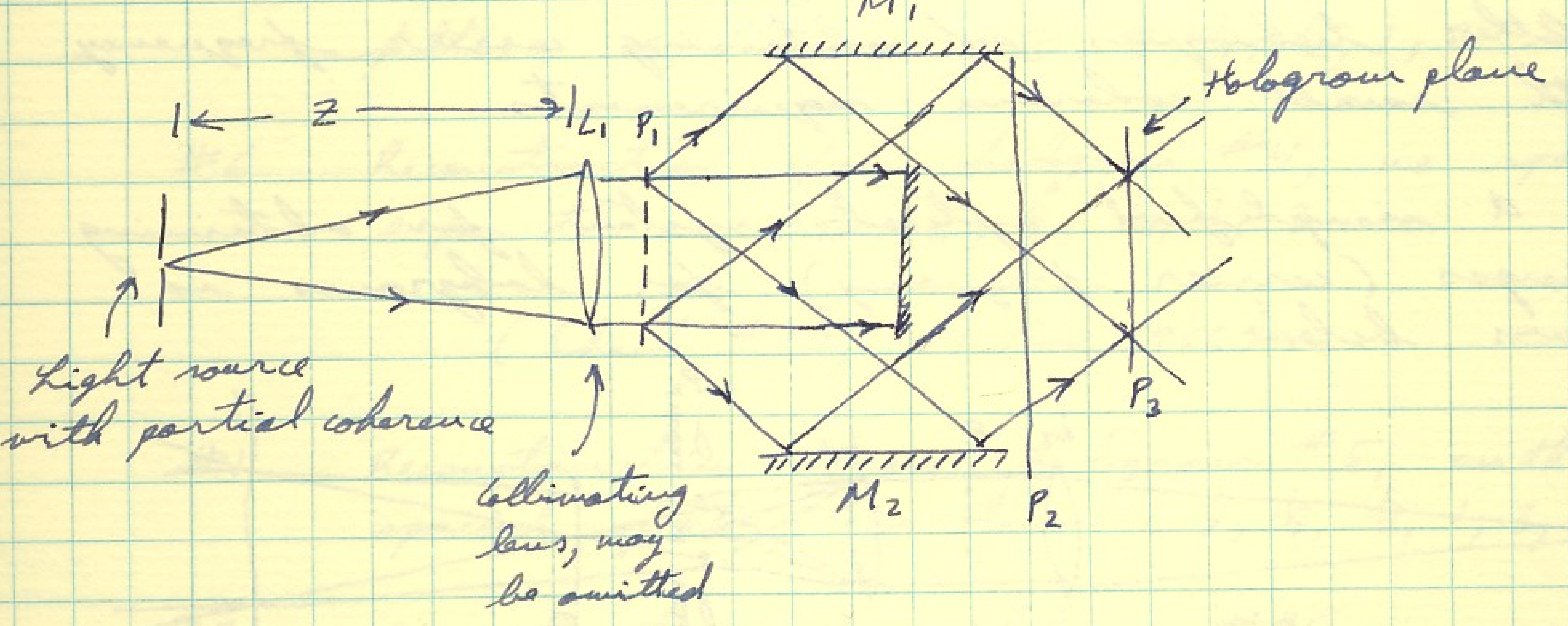
Another technique of obtaining fringes is shown in the diagram on the next page. For this system some time and spacial coherence is required, but the requirements are small. This system can operate entirely without lenses.

Read + understood on Nov 28/66 B.J. Hildebrand

Read & Understood on Nov 29, 1966 [illegible]

Juris Upatnieks, 23 November 1966

23 November 1966



Mirrors M_1 and M_2 are parallel ~~to~~ each other, P_3 is exactly at the location where the ~~two~~ beams completly overlap, and grating at plane P_1 has sufficiently high spacial frequency so that the two 1st order diffracted beams are completly separated from the undifracted beam and any higher order diffracted beams.

For a given wavelength λ_e of light, a plane P_3 exists at which light diffracted from any point in plane P_1 coincides with itself. Furthermore, since P_1, P_3, M_1 and M_2 form the sides of a parallelogram, the optical path length from any point in P_1 to P_3 is the same. Since the wavefronts coincide at P_3, no spacial coherence is required.

If the light is not monochromatic, then at plane P_3 can be found for only one wavelength λ_0 for which no shearing of the wavefronts exists. Thus, for light lacking time coherence, some spacial coherence must exist at plane P_1 in order to form the carrier-frequency at plane P_3. The requirements on spacial coherence are small if the bandwith of the source is, say, 100 Å. The lens L_1 can be omitted if distance Z is much larger than diameter of L_1.

Juris Upatnieks, 23 November 1966

Read + understood on Nov 28/66 BP Hildebrand

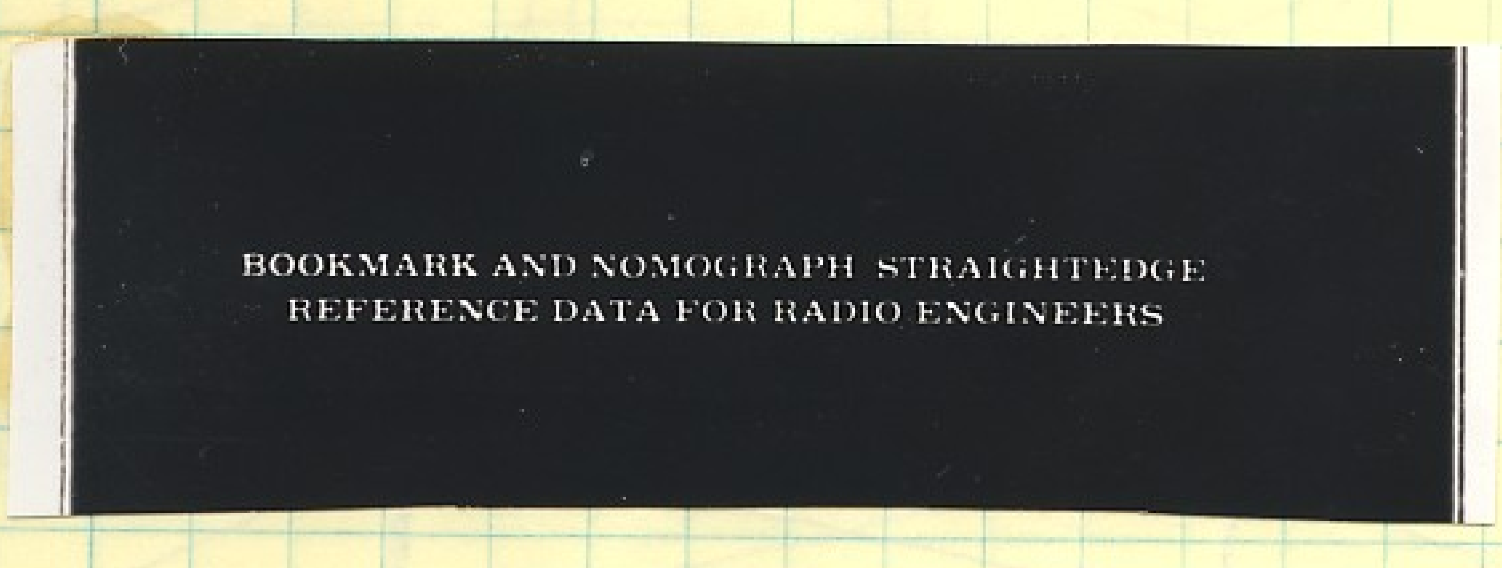
Read & understood on Nov 29 1966 C B Jacobson

2 December 1966

Reconstructions from holograms made with mercury-arc lamp.

Both images below are reconstructions from holograms made on SO-243 Kodak film using super-high-pressure mercury-arc

Reconstruction from hologram #4, 21 Nov. 66. Print from negative of sheet #16, row #5 (see p. 62). Image is magnified here X3. as compared to the original.



Reconstruction from hologram #3, 18 Nov. 66. Print from negative of sheet #017, row #4, (see p. 62). Image magnified X3. diameters compared to original.

lamp HBO-107. This arc lamp has coherence length of about 60λ in the green line. The experimental optical set-up allowed recording of up to 50 l/mm resolution for fringe visibility of 0.4. The fine lettering contains some detail in excess of this limit, and thus appears to be lost. Some of the horizontal lines have nearly dissapeared. Spacial filters were used in reconstruction to reduce the noise level in the image. The reconstructions were made with a laser, 6328Å wavelength.

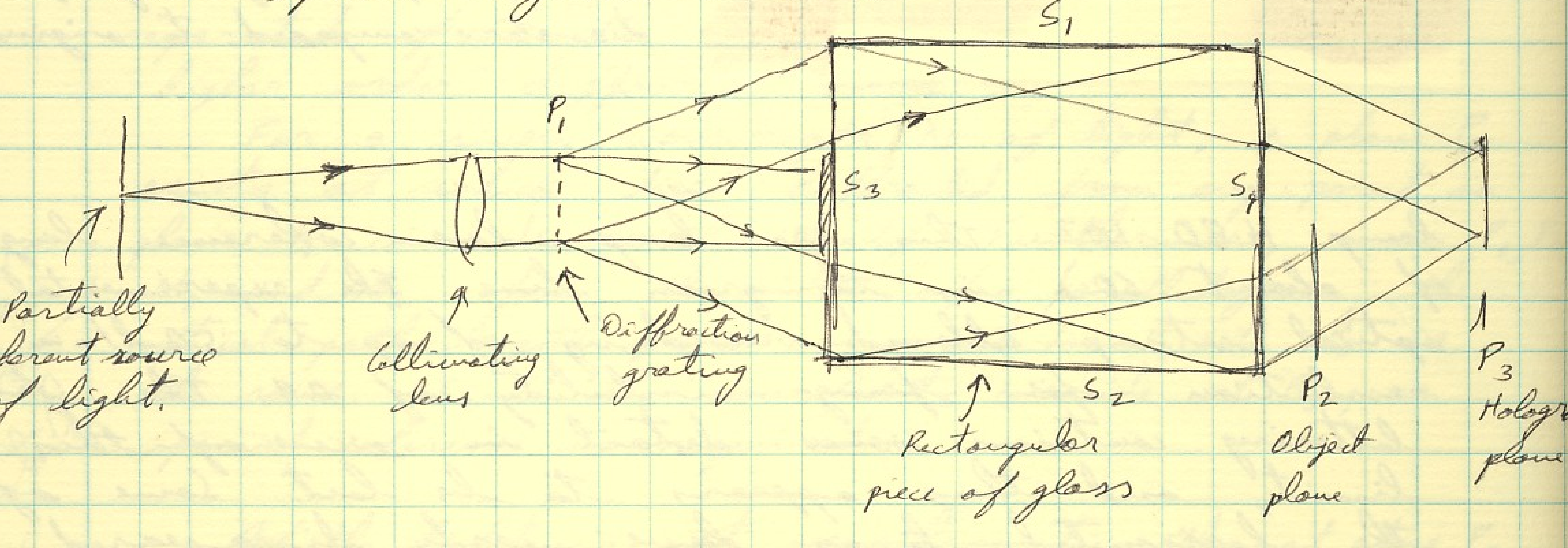
Juris Upatnieks, 2 December 196

14 December, 1966

Improoved techniques of obtaining carrier frequency with limited coherence.

The optical system on p. 64 has three adjustments which must be made in order to obtain fringes with minimum coherence requirements. These requirements are: 1) Mirrors M_1 and M_2 must be parallel to each other; 2) The grating at P_1 must be perpendicular to M_1 and M_2 and incident light beam parallel to M_1 and M_3; 3) Plane P_3 must be at a location where the two wavefronts overal and coincide exactly. The first two requirements are severe and must be met very precisely. The third requirement is trivial.

The first requirement, that of having mirrors M_1 and M_2 parallel, can be easily met by using the optical system below:



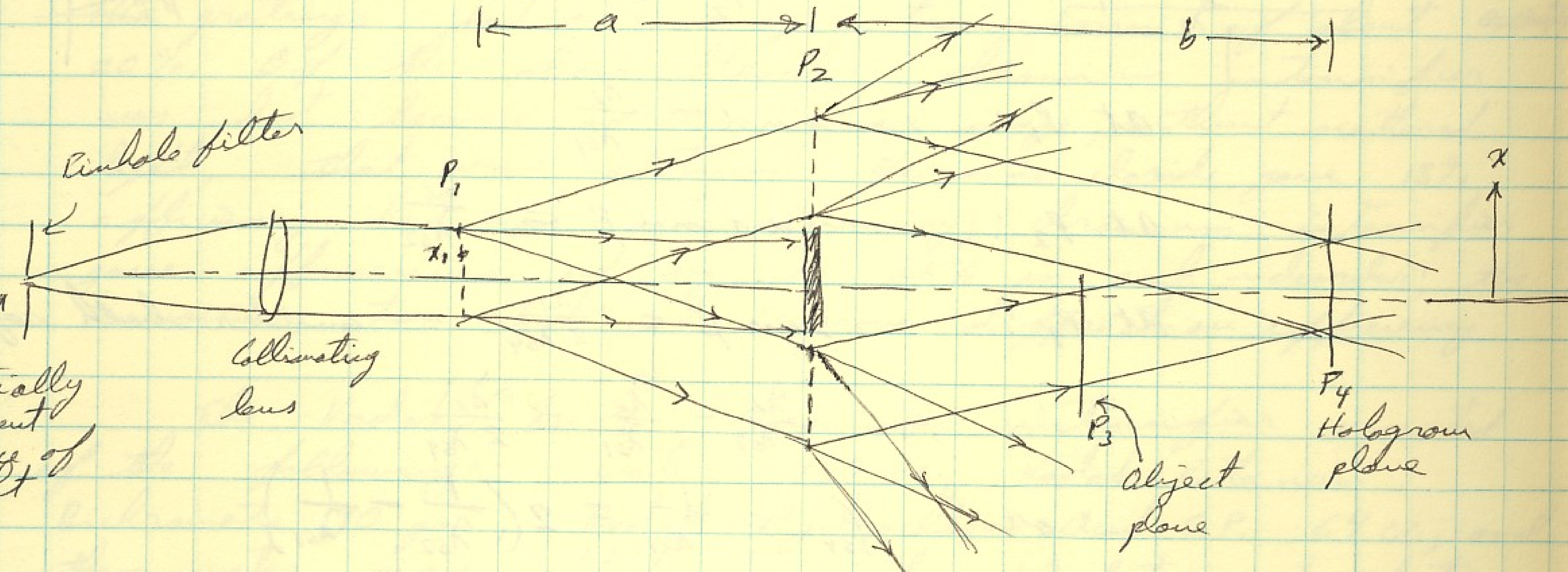
The glass block, of optical grade glass, has sides S_1 and S_2, and sides S_3 and S_4 parallel and optically flat. Thus the alignment of the reflecting surfaces S_1 and S_2 could be done in manufacturing of the glass block, thus simplifying the optical alignment problem. The rotational alignment is the only other critical alignment, and propably could be done by observing fringe contrast at plane P_3 while rotating the glass block. Object

Juris Upatnieks, 14 December 1966

14 December 1966

would be placed in one beam only at plane P_2, and a material of equal thickness would be placed in the other beam to compensate for differences in path length. The dispersion of different wavelengths of light would be somewhat higher than that for the optical system on p. 64.

Another arrangement which would compensate for dispersion of light is shown below:



For a given ray of light originating at plane P_1 distance x_1 from the optical axis, the position at plane P_2 is x_2 and is given by

$$x_2 = x_1 \pm a \frac{\lambda_e}{\lambda_{s1}}$$

λ_e = wavelength of light

λ_{s1} = spacial wavelength of grating at plane P_1

At plane P_4 this ray is at x_4:

$$x_4 = x_1 \pm (a+b)\frac{\lambda_e}{\lambda_{s1}} \mp b\frac{\lambda_e}{\lambda_{s2}}$$

$$= x_1 \pm \lambda_e \left(\frac{a+b}{\lambda_{s1}} - \frac{b}{\lambda_{s2}} \right)$$

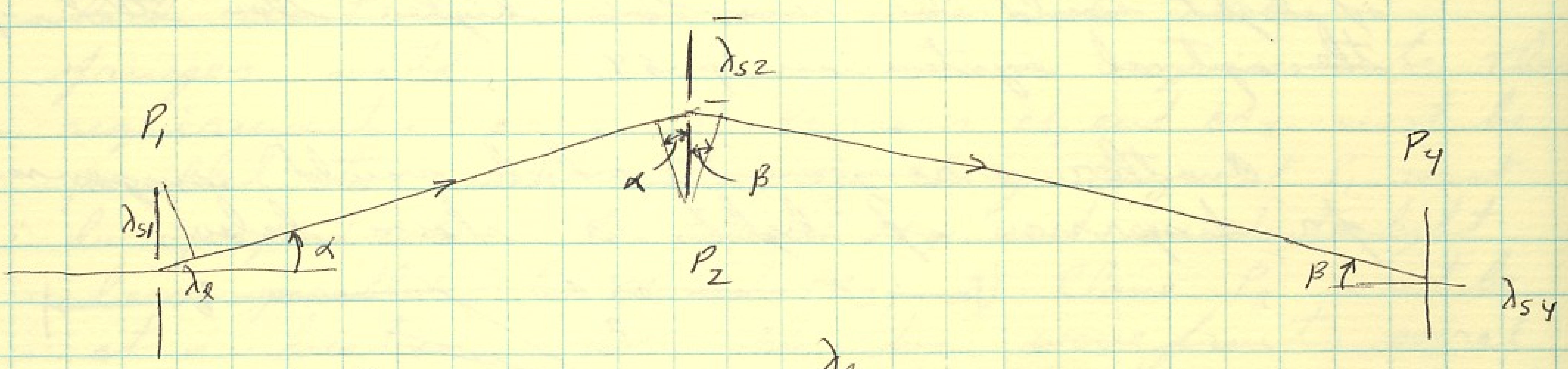
Since the quantity $\left(\frac{a+b}{\lambda_{s1}} - \frac{b}{\lambda_{s2}}\right)$ can be made to equal zero by proper choice of parameters, the rays emanating from any point x_1 meet at a point x_4 and this position is independ of the wavelength of light. Therefore, no ~~t~~ spacial coherence is required to obtain the carrier frequency.

Note: Source must be small if no lenses are used in each of the two beams to image grating. Juris Upatnieks, 19 Jan. 1967

Juris Upatnieks, 14 December 19

14 December 1966.

To calculate the spacial frequency at plane P_4, consider the ray diagram below:



at P_1: $\sin\alpha = \dfrac{\lambda_e}{\lambda_{s1}}$

at P_2: $\sin\alpha + \sin\beta = \dfrac{\lambda_e}{\lambda_{s2}}$

at P_4: $\sin\beta = \dfrac{\lambda_e}{2\lambda_{s4}}$ consider both rays

$$\therefore \quad \frac{\lambda_e}{\lambda_{s2}} - \frac{\lambda_e}{\lambda_{s1}} = \frac{\lambda_e}{2\lambda_{s4}}$$

$$\text{or} \quad f_{s4} = \frac{1}{\lambda_{s4}} = 2\left(\frac{1}{\lambda_{s2}} - \frac{1}{\lambda_{s1}}\right)$$

Since f_{s4} is independent of the wavelength of light, no time coherence is required to produce interference fringes at plane P_4. Therefore, this system will produce a carrier frequency even in white light. The example considered here assumes identical gratings at plane P_2. This assumption is not necessary, as white-light fringes can be produced with each of the two gratings at plane P_2 with different spacial frequencies and a appropriate choise of plane P_4.

Phase of fringe patterns for each wavelength may vary in that there and thus, wash-out or loss of contrast may occur. 20 Dec. 1966 Juris Upatnieks

Juris Upatnieks, 14 December 19

20 December 1966

Experiments with bleaching of sinusoidal gratings

A number of experiments were conducted with gratings having spacial frequencies of 50 to 250 l/mm, made by recording the interference pattern of two plane waves. The following bleaches were tried: mercuric cloride, Farmer's reducer solution "2" (sodium thiosulfate 16 oz, water 64 oz), chromium intensifier Kodak's formula "In-4", and Kodak modified Belitzski reducer formula R-8. The gratings had an average transmission of about ~~20%~~ 20%. Of the above bleaches, chromium intensifier was best because of the clear image, without scattered light, that was obtained. Mercuric cloride gave 13% efficiency but was extremely noisy; chromium intensifier gave efficiencies of up to 25% in each sideorder; the remaining two did not improve diffraction efficiency.

The Kodak "In-4" chromium intensifier consisted of the following: water 750 cc, Kodak Potasium Bichromate 90 gm, Kodak Hydrochloric Acid C.P. 64 cc, and then water was added to make 1.0 liter of solution.

Overexposed plates gave better diffraction efficiencies. The following experiment was performed with different exposures

Exposure time	d.c. intensity	1st sideorder intensity	2nd sideorder intensity
1 sec. (20% transm.)	85%	3% + 3%	—
2 sec.	33%	20% + 20%	4% + 3.5%
5 sec.	21%	24% + 25%	5.7% + 5%
7 sec.	21%	24% + 26%	5.5% + 5.5%
10 sec.	35%	24% + 26%	3.5% + 4%
15 sec.	26%	23 + 24%	4.5% + 4.5%

The gratings were recorded on 649F emulsion on 4×5×1/8" glass plates. A repetition of the 5 to 10 sec. exposures at a later time gave only 13% efficiency in the 1st order, and the reasons for this change are being investigated.

Juris Upatnieks, 20 December 1966

20 December 1966

The bleaching process can be repeated several times to increase diffraction efficiency. A test with gratings having average transmission of 20% was made:

	d.c.	1st order	2nd order
a) Bleached once, presoaked in water	85%	5%	—
b) Bleached twice, presoaked in water	28%	25 & 27%	4.5% & 5%
c) Bleached three times, " " "	1.5%	20% & 22%	17% & 17

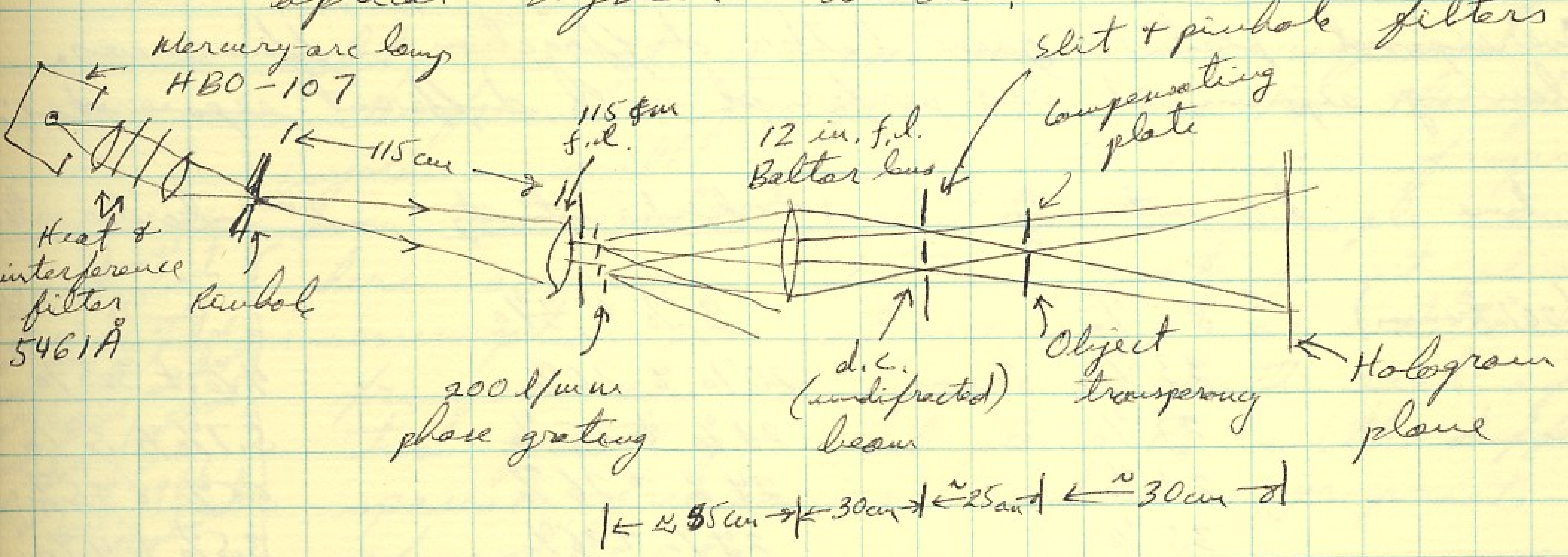
Measurements were made with laser light, 6328 Å, and a photomultiplier detector.

Juris Upatnieks, 20 December 1966.

19 January 1967

Experiments with holograms made with super-high-pressure mercury arc lamp.

Several holograms were made with the optical system below:



With the above system vibration of the steel rail caused poor holograms occationaly. Considerable abberations at the frequency plane were observed, probably introduced by either the lens or nonuniformities in the grating, or both. The light beam after filters

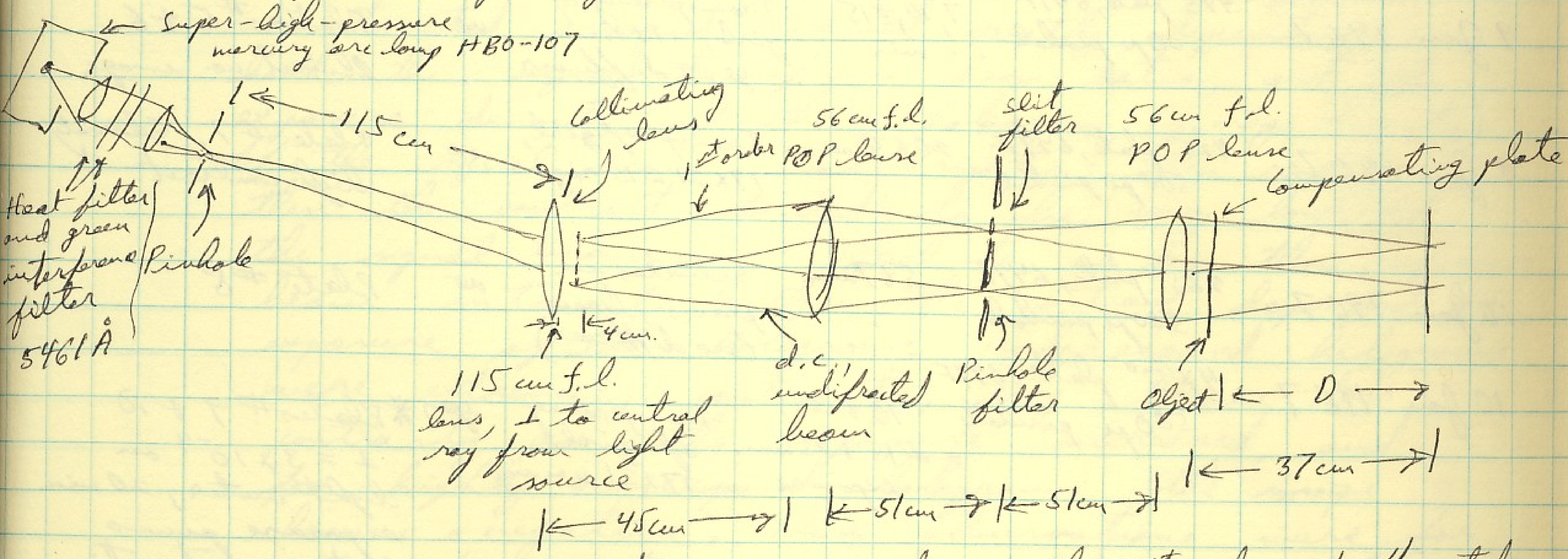
Juris Upatnieks, 19 January 1967

19 January 1967

in the Fourier transform plane was clean and uniform except for some low-frequency patterns from the diffraction gratings. Holograms were recorded on SO-243 film, 70 mm wide, and was processed in the standard way. Signal beam was about 2 to 3 times stronger than ref. beam without attenuation. Green interference filter was used.

Date exp. made	Size of source pinhole	Exp. times	Object	Signal beam attenuated?	Remarks
28 Dec. 1966	50μ	4 & 10 min.	Fine letters 2 rows	no	
28 Dec. 1966	50μ	2 & 5 min	Transparency of girl	no	
28 Dec. 1966	50μ	4 & 10 min.	Coarse letters, 2 rows	no	
29 Dec. 1966	25μ	15 & 30 min.	Fine letters, 2 rows	no	
29 Dec. 1966	50μ	2, 4, & 10 min.	Transparency of girl	no	

To avoid vibration and to improve image, high-quality lenses from P.O.P. processor were used to image the grating and the system was set up on the granite bench. The P.O.P. lenses have 56 cm focal length and an 8 in. aperture. The following system was used:



200 l/mm l/mm grating was used, with 1st order diffracted light being about $\frac{1}{2}$ to $\frac{1}{3}$ as intense as the d.c. term.

Juris Upatnieks, 19 January 1967

19 January 1967

The following holograms were made:

Date exp. made	Film Pinhole size at source	Exposure time	Object	Signal beam attenuated?		Remarks
9 Jan. 1967	50-243 50 μ	1, 2, 4 min.	Diffuse glass transparency of girl, 30 x 38 mm	no		
12 Jan. 1967	50-243 50 μ	2, 5, 10 min.	Diffuse glass & transp. of girl 30 x 38 mm	yes	*	5 min. exp. best. Diffraction eff. appears to be low
12 Jan. 1967	50-243 25 μ	8, 20 min.	"	yes		Reconstructed spectrum same as with 50 μ pinhole
12 Jan. 1967	50-243 25 μ	8 & 20 min.	Long sentence, 33 μ wide lines	no		No more detail than on hologram with 50 μ pinhole
12 Jan 1967	50-243 50 μ	1, 2, 4, 10 min.	"	no	*	Excellent signal to noise. Some letters have abberations
13 Jan. 1967	50-243 25 μ	20 & 40 min.	Diffuse glass with two figures ahead, 13 & 31 cm from hologram	yes		
13 Jan 1967	50-243 50 μ	4, 10, & 20 min.	"	yes	*	Good reconstructions, max spacial signal freq ± 35 l/mm.
7 Jan. 1967	4x5" plate, 649F 500 μ	10 & 15 min.	Transparency of girl, 17 x 21 mm size	no		Contrast extremely high; #4 plate
9 Jan. 1967	4x5" plate, 649F 500 μ pinhole	7, 10, & 15 min	Transparency of girl, 17 x 21 mm size, & diffuser	no		Plates #5 & 6. Almost no image
9 Jan 1967	4x5" plate, 649F 500 μ pinhole	20 & 30 min.	Transp. of girl, 17 x 21 mm size	no		Plate #7. Extremely high contrast
10 Jan 1967	4x5" plate, 649F 500 μ pinhole	5 & 7 min.	Silhuetes in plain beam (no diffuser)	no		Plate #8
10 Jan 1967	4 x 5" plate, 649F 500 μ pinhole	10 & 20, and 15 & 25 min. exposure	Transparency of girl, 17 x 21 mm size	yes	*	Plates # 9 & 10 $I = 3 \times 10^{-4}$ on light meter, 20 min. exposure gives best reconstruction

Juris Upatnieks, 19 January 1967

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Holograms on several 4 x 5 in glass plates with 649F emulsion were made with the optical system on p. 70:

Date of exposure	Pinhole size & emulsion	Exposure time	Object	Signal beam attenuated?	Remarks
3 Jan. 1967	500μ	10, 20, + 30 min.	Transparency of girl, 17 x 21 mm size	no	Plates #1 & 2 $I = 11 \times 10^{-4}$ on light meter Contrast very poor, poor image quality
4 Jan. 1967	500μ	15 & 20 min.	Transparency of girl, 17x21mm size	yes	Plate #3, $I = 2 \times 10^{-4}$

(* indicates this hologram used for making prints of reconstructions)

The reconstructions of the 33μ letters showed considerable abberations in some parts. It appears that these abberations are caused either by the imaging lenses of the grating, or perhaphs the grating itself has abberations. Otherwise the reconstructions appear to be of high quality.

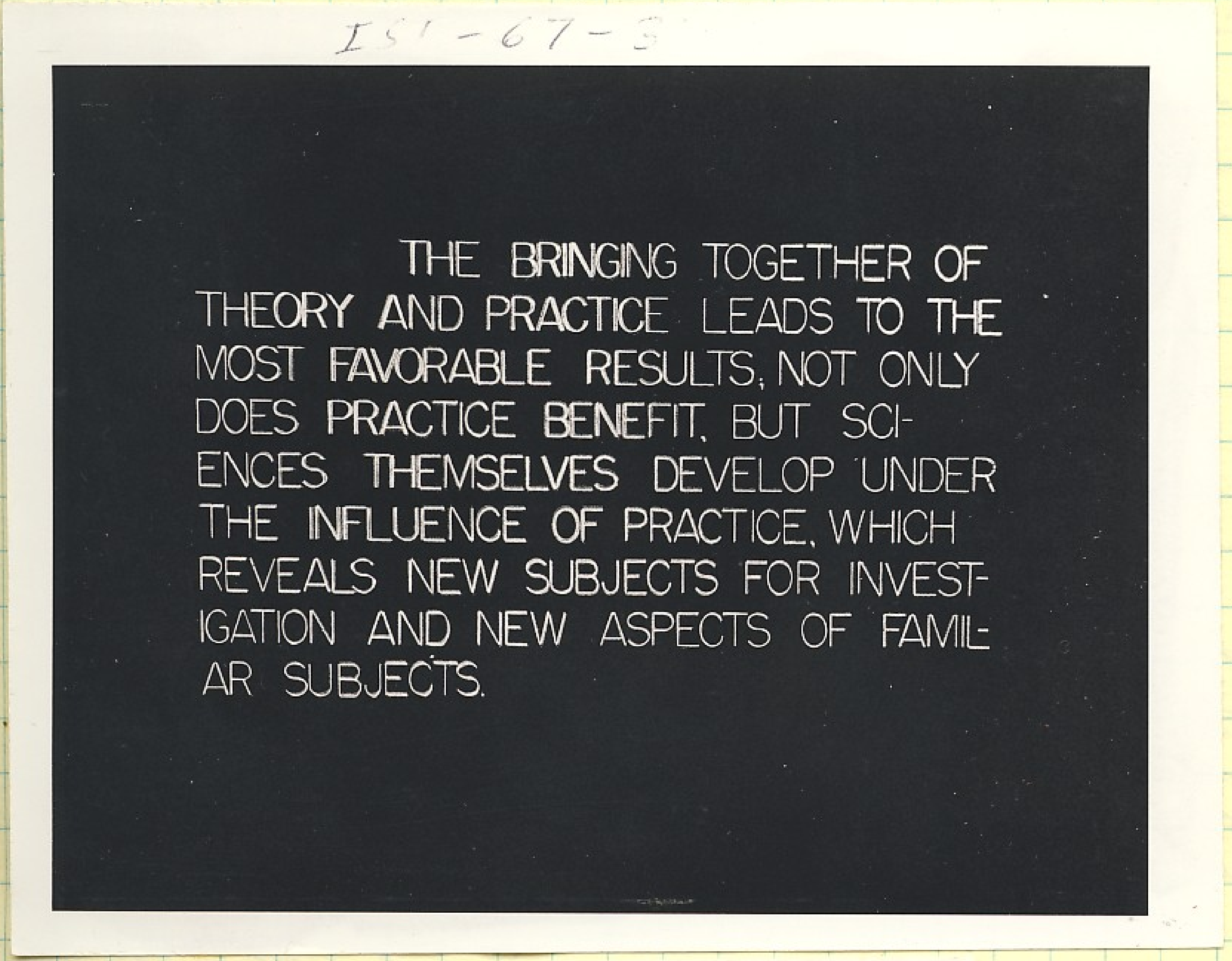
It was observed that the contrast of the reconstructed imaged varied greatly depending on both the signal-to-reference beam ratio, and the exposure density of the hologram (average density). If the signal beam was brighter than reference, then the contrast tended to be very low. If the signal beam was equal to or less than reference beam intensity, then the contrast depended on exposure of the hologram: underexposed holograms were extremely contrasty, they became less contrasty as the exposure increased, and for highly overexposed holograms the image became a negative. These observations were for only for continuous tone holograms illuminated with ~~dis~~ plane wavefronts.

Juris Upatnieks, 19 January 1967

26 January 1967

Reconstructions with laser from holograms made with super-pressure HBO-107 mercury-arc lamp

IST-67-30



Reconstruction from hologram made on 12 Jan 1967 on SO-243 film, 50μ pinhole, 4 min. exposure. Reconstructed in 6328 Å laser light with filter at the Fourier transform plane of the reconstructed image to reduce scattered light level.

IST-67-31

Reconstruction from a hologram made on 10 Jan. 1967 on 4×5×⅛ in glass plate with 649F emulsion, 500μ pinhole, 20 min. exposure. Original size of transparency was 21×17 mm. Reconstructed in 6328 Å laser light with filter at the Fourier transform plane of reconstructed image to reduce scattered light level.

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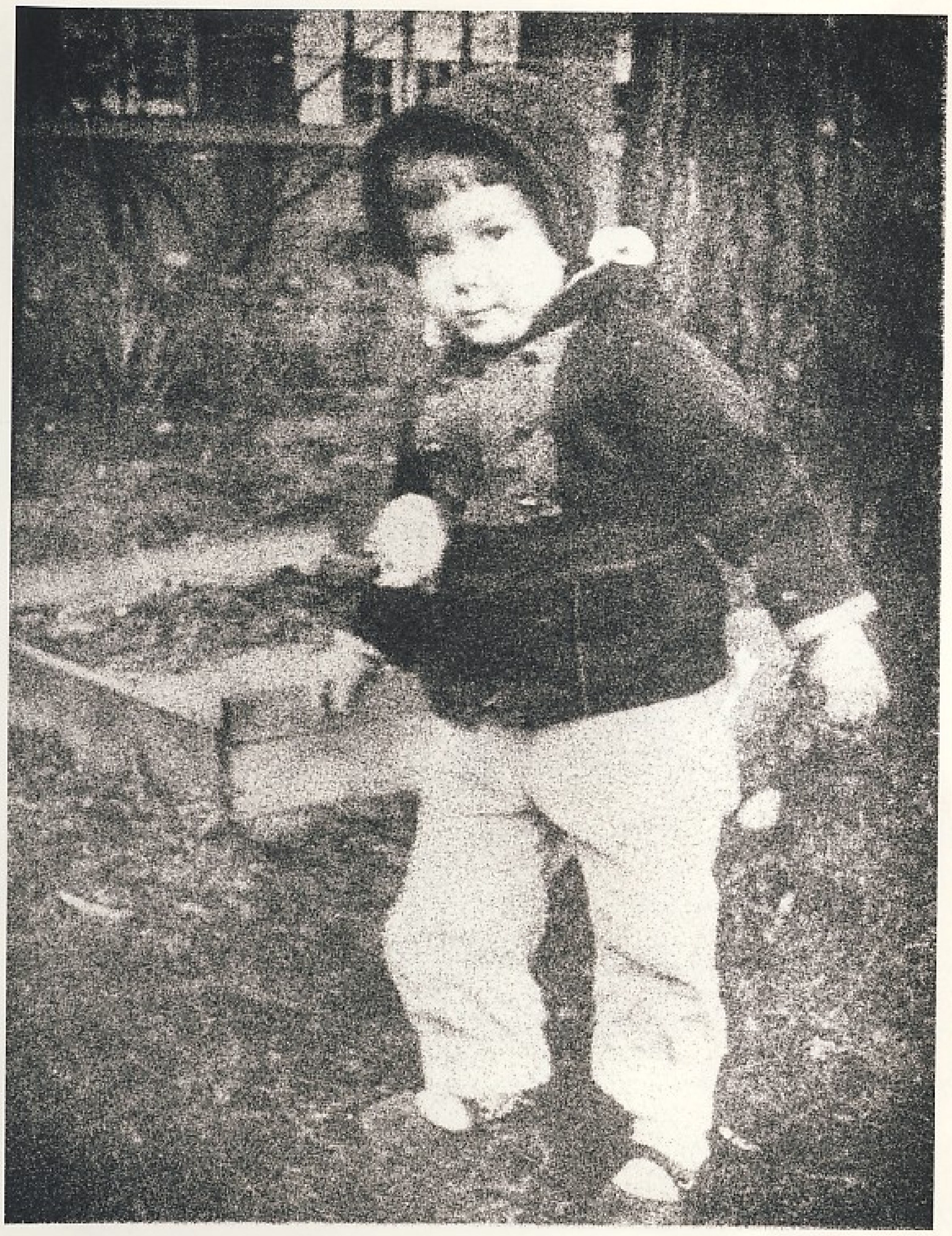
IST-67-32

IST - 67 - 32



Left: Reconstruction from a hologram made on 12 Jan. 1967 on SO-243 film, 50μ pinhole, 5 min. exp., with transparency illuminated with diffuse light. Original size of transparency was 30 x 38 mm, and spacial filter was used in reconstruction with 6328 Å laser light.

Below:

Reconstructions from one hologram made on 13 Jan. 19[illegible] of two figures 22 mm in height, recorded on SO-243 film, with diffuse light, 10 min. exposure. Reconstructed in 6328 Å laser light. The film was placed at the point (plane) where each figure came to focus

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26 January 1967

IST - 67 - 34

IST - 67 - 33

27 January 1967

A number of reconstruction were made in the original optical system in which the holograms were made. The main reason was to find out if change in wavelength made any difference in the abberations observed in hologram of the long sentence and having 33μ wide lines. Also, it seemed necessary to show that good reconstructions could be obtained without a laser. Both the hologram of the long sentence and of the girl were reconstructed with spacial filter allowing wavelength from orange to green to pass through, and the reconstructed objects appeared to reconstruct white and without any obvious color dispersion. The lack of color dispersion is caused by the fact that the original dispersed reference beam was used, and the signal was relatively coarse. The white-light reconstruction was not recorded.

The film recordings show (Sheet #18, 19 Jan. 1967, #6):

#6 Reconstruction of hologram made on 10 Jan '67 of girl illuminated with plane wavefront. Reconstructed in original reference beam, spacial filter, 500μ pinhole

(Sheet #18, 19 January 1967):

#1 Reconstruction in original reference beam, mercury-arc lamp, using 500 μ pinhole. Hologram: of long sentence, 33μ wide lines, made on 12 Jan. 1967 on SO-243 film. Plus-X film.

#2 Same as #1, focus readjusted, plus-X film.

(Sheet #18, 24 Jan. 1967):

#3 Reconstruction from hologram of 23 Jan. 67 in original reference beam, 500μ pinhole, ~~virtual~~ real image used & no spacial filter. Exp.: 5, 10, 20, 40 sec., 1½, 3 min.

#4 Reconstructed from hologram made on 23 Jan. 1967, reconstructed in original reference beam, 400μ pinhole, virtual image used. Exp.: 30, 50, 80, 140 sec.

Juris Upatnieks, 27 January 1967

27 January 1967

(Sheet #018, 25 Jan. 1967):

#5 Reconstructed from hologram made on 23 Jan. 1967, 250 μ pinhole, in original reference beam, virtual image used, spacial filter. Exp.: ~~30~~, 50, 80, 140 sec.

#6 Same as #5 but 125 μ pinhole used. Exp.: ~~30, 50, 80, 140 sec.~~ 1, 2, 5 min.

(Sheet #019, 25 Jan. 1967):

#1 Same as #5 above, 125 μ pinhole, camera slightly tilted, exp. 1, 2, 5 min.

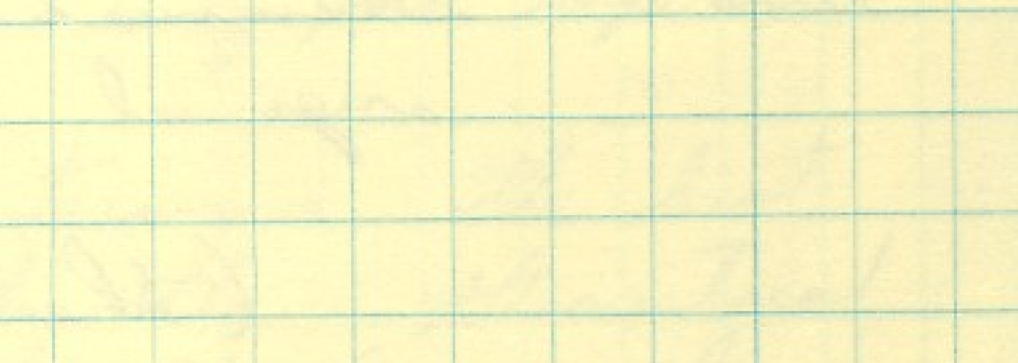
Juris Upatnieks, 27 January 1967

15 February 1967

Experiments with holography using mercury-arc lamp, HBO-107.

Holograms were made with a scatter plate instead of a grating in optical system show on p. 71. The following holograms were made:

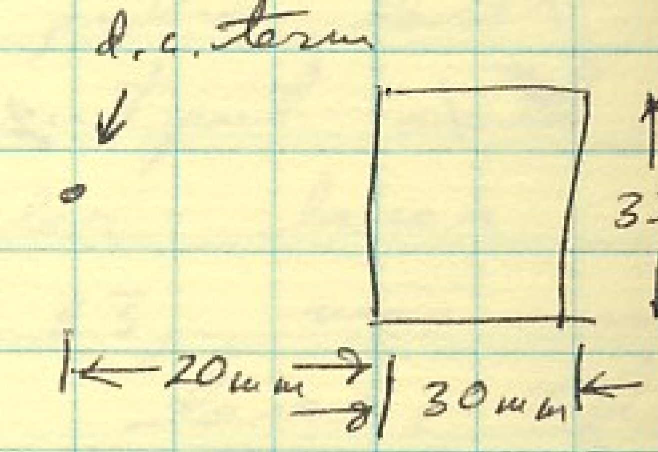
Date of exp.	Size of source	Exp. times	Object	Signal beam attenuated?	Remarks
31 Jan. 1967	250 μ	1, 1½, 2 min.	Transp. of grid, 30×33 mm size	none	Spacial filter in transform plane:



Only part of the transform reconstructed.

Juris Upatnieks, 15 February 1967

15 February 1967

Date of exp.	Size of source	Exp. times	Object	Remarks
2 Feb. 1967	250μ	1, 1½, 2 min.	Transparency of girl 30x33 mm size	Filter in transform plane:  Only part of the spacial spectrum at the transform plane reconstructed.
2 Feb. 1967	250μ	1 & 1½ min.	Same as above, but object in transform plane	Same filter as above, transparency in the filter aperture. Only part of the image reconstructed, indicating lack of coherence over some parts of the aperture.

Juris Upatnieks, 15 February 1967

16 February 1967

Experiments with holograms made using mercury-arc lamp HBO-107.

Exposure made on	Source, filter	Exposure	Remarks
23 Jan 1967	500μ pinhole, 649F emulsion	20 min. & 30 min.	Hologram made with POP lenses, a 200 l/mm grating, with the long sentence as the object. Plate #11. Object in 1st sideorder, no attenuator used.

A number of reconstructions were made from various holograms that are of significant importance.

Juris Upatnieks, 16 February 196

16 February 1967

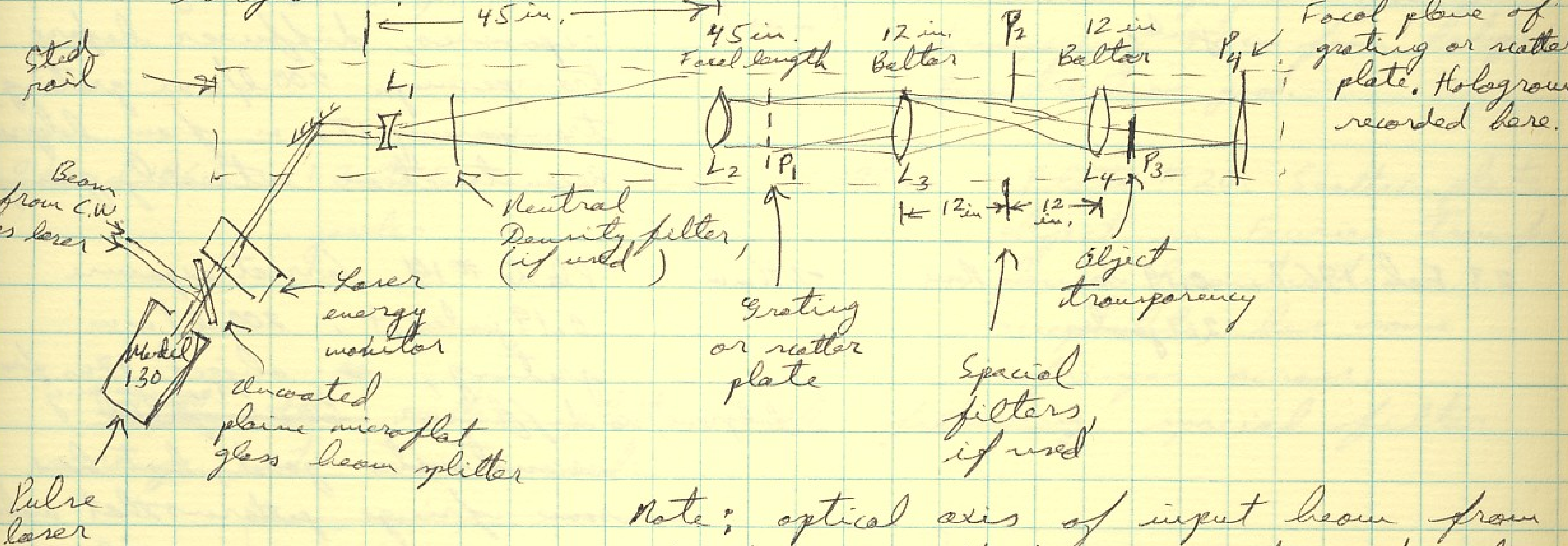
Negative #	Date made	Remarks
#1	24 Jan. 1967	Reconstructed from hologram made on 23 Jan. 1967 with laser light. Image has better overall appearance, although lines are not as sharp.
#2	6 Feb. 1967	Reconstructed from hologram made on 2 Feb. 1967 with diffuse scatter plate and transparency of girl 40 cm from hologram. Reconstructed with 6328 Å laser light.
#3	6 Feb. 1967	Fourier transform of the same hologram from which #2 was made.
#4	6 Feb. 1967	Reconstruction from a hologram made on 2 Feb. 1967 with a scatter plate and object transparency in the Fourier transform plane.
#5	6 Feb. 1967	Same as #4, but image magnified.

Juris Upatnieks, 8 March 1967

8 March 1967

Holograms made with ruby pulse laser

Holograms were made with Optics Technology pulse laser, model 130, having 6943 Å wavelength output with maximum of 5 joules/pulse energy. Lear Siegler laser energy ~~motistor~~ monitor MI-2, series no. 33, was used to measure the output energy of the laser. The optical system shown below was used to make holograms:



Note: optical axis of input beam from L_1 to L_2 offset so as to make the zero order and one 1st order diffraction by a 200 l/mm grating centered on the optical axis of lenses L_3 & L_4.

The holograms were recorded on either 649F emulsion on 4 x 5 x $\frac{1}{8}$ in. glass plates, or on 70 mm wide SO-243 film. The output of the laser was measured for each pulse as there was no consistency between input and output energy of the pulse. No Q-switching was used. Some exposures on 649 F emulsion were obtained by multiple exposures. It was found that the speed of the Polaroid 55 P/N film has about the same sensitivity as the 649F emulsion. The SO-243 is extremely sensitive and required considerable attenuation even at minimum energy output from the laser, at about 0.1 joules.

Juris Upatnieks, 8 March 1967.

8 March 1967

The object for all of the following holograms was a 21 × 17 mm size transparency of the girl

4x5 in plates:

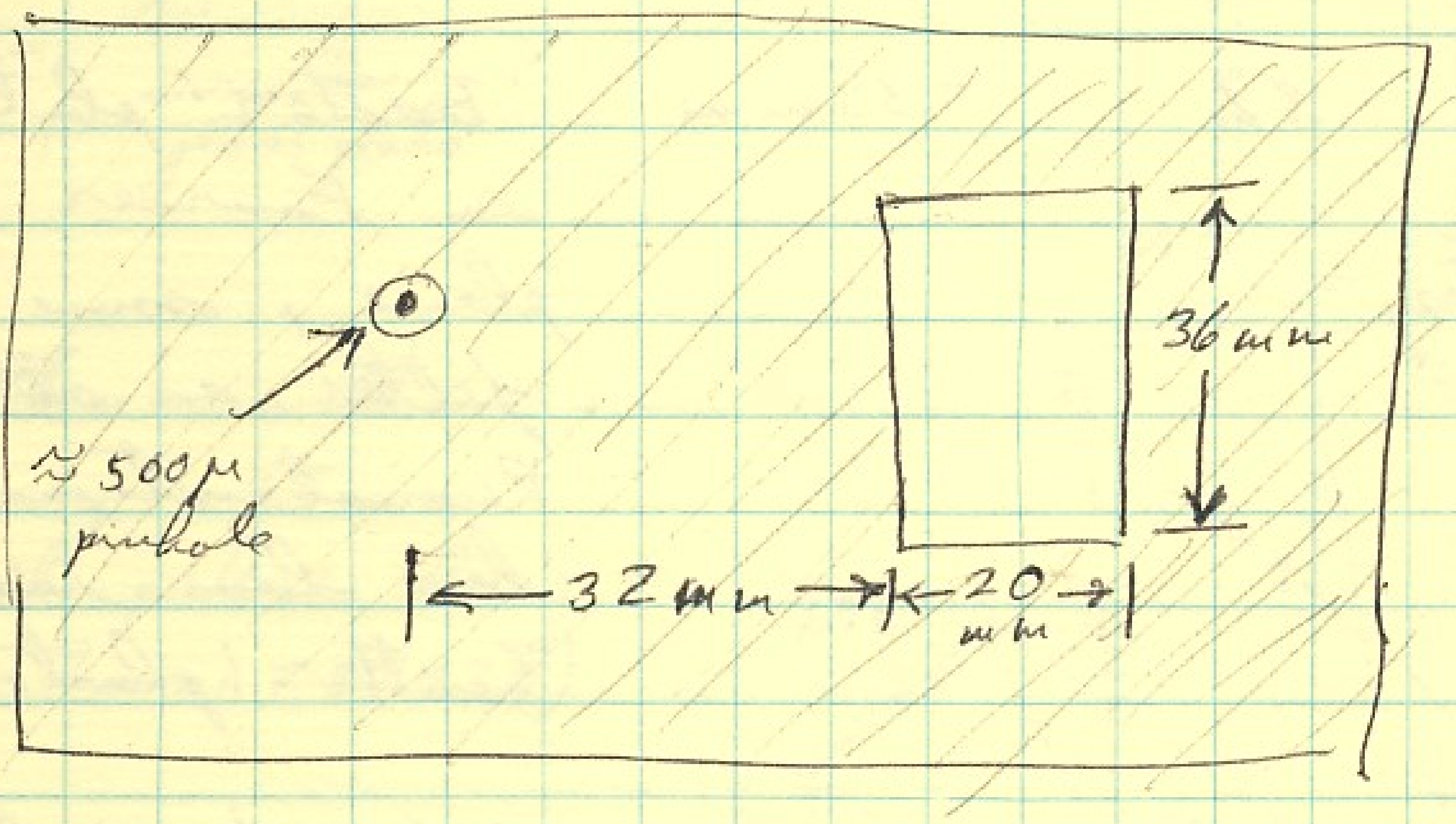
Date of exposure	Exposure	Attenuator	Focal L. of L_1	Remarks
17 Feb. 1967	0.15 to 4.6 joules	22% transm. in ref. beam.	−69 mm	Plate #12. All underexposed. 4.6 joule exposure has low density. (4.6 j output from 2 × 2500 j input).
20 Feb. 1967	0.1 to 3.6 joules	22% T	(−296 mm)	Plate #13. Several good exposures, diffuser before transparency. 200 l/mm grating, transparency 17 mm from hologram. Reconstruction extremely grainy.
23 Feb. 1967	0.19 to 2.7 joules	None	−296 mm	Plate #14. Correct exposure 0.19 joules +, 200 l/mm grating, ~~o~~ object 17 mm from hologram, no diffuser. ~~Clear field~~ Transparency reconstructs good, but has some fringe patterns that make appearance very poor.
23 Feb. 1967	0.015 to 1.27 joules. Correct exp. about 0.3 joules	None	−296 mm	Plate #15. Diffuser in d.c. order, no object. Reconstruction shows that spacial frequencies of up to 10 l/mm are recorded. This indicates lazer has poor spacial coherence
27 Feb. 1967	0.7 to 1.95 joules. Best exp. 1.95 joules	None	−150 mm	Plate #16. Wide angle diffuser in d.c. order, transparency, 200 l/mm grating. Reconstruction extremely poor, grainy, with scattered bright spots.
1 March 1967	Exp. 0.2 to 5.7 joules. Best exp. 5 joules	None		Plate #17. Transparency in Fourier transform plane. Scatter plate instead of grating. Reconstruction not sharp.

Juris Upatnieks, 8 March 1967.

8 March 1967

Date of exp.	Exposure	attenuator	l_1	Remarks
1 March 1967	0.2 to 4.3 joules, some on top of each other	None	-150 mm	Plate #18. Mostly multiple exposures with plate shifted between exposures. Poor reconstructions. Scatter plate.
2 March 1967	1.5 to 6.2 joules Best exp. 4 joules	None	-296 mm	Plate #19. Scatter plate instead of grating. Object transparency 17 cm from hologram. Reconstruction good.
2 March 1967	1.2 to 5.7 joules	None	-296 mm	Plate #20. Scatter plate, object in Fourier transform plane. Reconstruction acceptable, has some fringes across.

With the scatter plate, the following spacial filter arrangement was used:



Good images (reconstructions) can be made with the scatter plate and the object in either the transform plane or near the hologram. Spectrum over the whole filter aperture was recorded and the problems encountered with the Hg-arc were not evident. With the Hg-arc lamp only a small part of the spacial spectrum could be recorded at a time. Since pulse laser has excellent time coherence, no spread due to lack of monochromaticity is encountered. The image is degraded by lack of spacial coherence only. It is interesting to

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note that granularity is dependent only on the aperture at the transform plane and not by the spacial coherence of the source. The resolution is directly related to spacial coherence. Thus, granularity and resolution are independent of each other with a scatter plate arrangement. With a grating as the beam splitter, resolution and granularity both are directly related to the spacial coherence.

Several holograms were made on SO-243 film:

Date of exp.	Exposure	Attenuator	Focal length of L_1	Remarks
15 Feb. 1967	0.04 to 0.24 joules	3% T	-35 mm	Hologram of transparency 17 cm from hologram, 200 l/mm grating, no diffuser. Reconstruction poor; image lost in intense ~~diffra~~ fringe patterns.
6 March 1967 #1	0.11 to 0.68 joules Best exp. 0.45 joules	3%	-35 mm	Scatter plate, transparency in Fourier transform plane, same spacial filter as on p. 83. Reconstruction good but has low resolution. Scatter plate.
6 March 1967 #2	0.24 to 1.23 joules Best exp. 0.62 joules	3%	-35 mm	Scatter plate, object transparency 17 cm from hologram, same spacial filter as on p. 83. Reconstruction excellent: small grain and very good resolution.
6 March 1967 #3	0.075 to 0.45 joules Best exp. 0.11 joules	3%	-35 mm	200 l/mm grating, low-angle scatter plate 1 cm from object transparency, ~~the~~ transparency 15 cm from hologram. Reconstructe good, a little grainy

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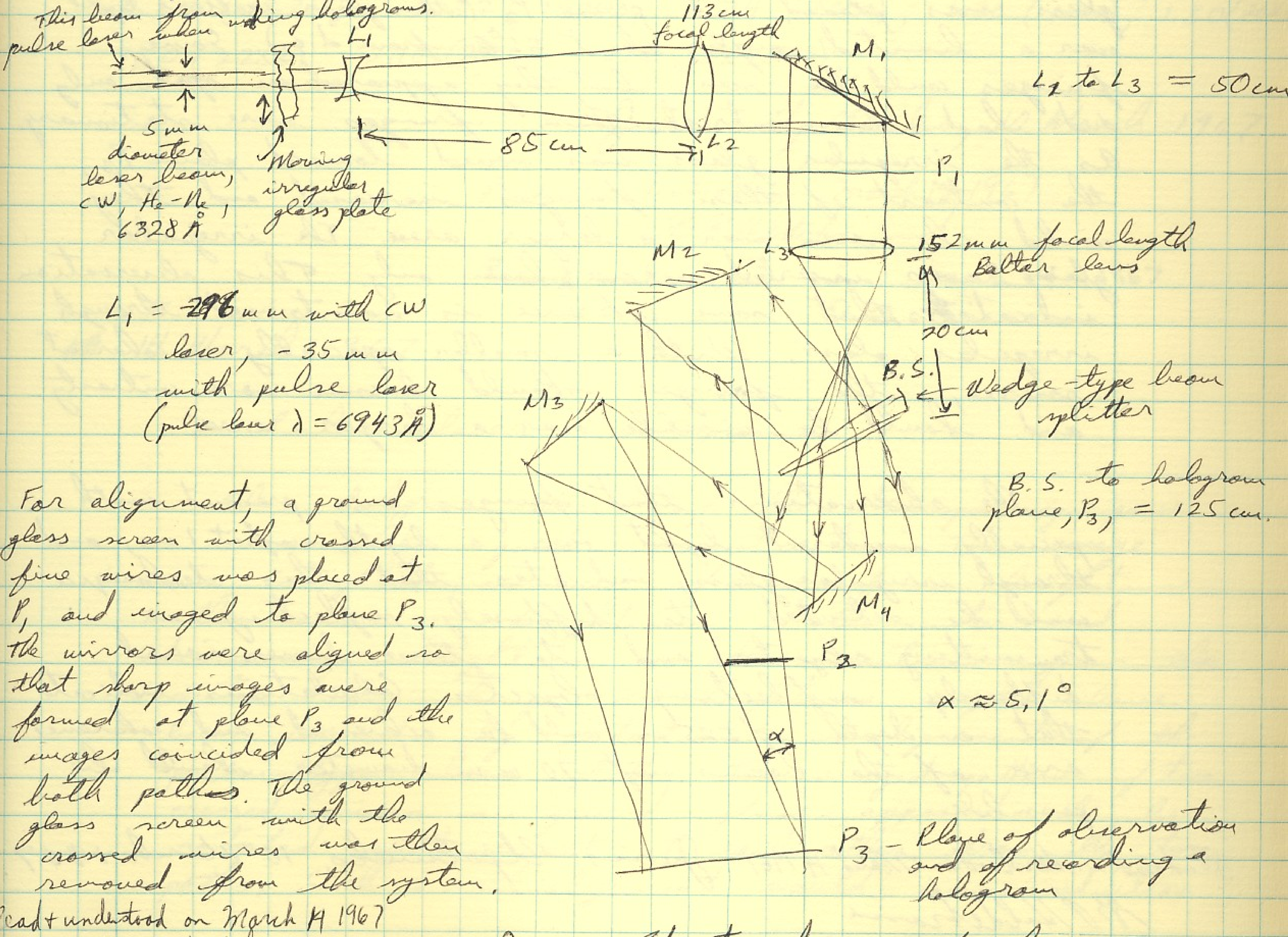
Pulse laser holograms.

A pulse laser is known to have excellent time coherence and poor spacial coherence. For the optical system on p. 81, with $L_1 = -296$ mm, the apparent source size was calculated to be about 500 μ diameter. Good holograms can be made with it using the imaged grating or scatter-plate technique, but the useful aperture is severely limited by the aperture of the lens. The objects are limited to those that can be viewed in transmission or in silhouette.

In order to examine possibilities of obtaining larger apertures and perhaps going to 3-dimensional objects, the following optical system was set up:



$L_1 = -296$ mm with CW laser, -35 mm with pulse laser (pulse laser $\lambda = 6943$ Å)

For alignment, a ground glass screen with crossed fine wires was placed at P_1 and imaged to plane P_3. The mirrors were aligned so that sharp images were formed at plane P_3 and the images coincided from both paths. The ground glass screen with the crossed wires was then removed from the system.

Read + understood on March 14 1967
B R Hildebrand

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Read & understood on March 14, 1967 A. A. Friesem

10 March 1967

With the ~~gro~~ irregular glass plate moving, CW laser, and the system adjusted properly, stationary high-contrast fringes were observed at plane P_3. The fringes were visible with a source 5.0 mm diameter that was monochromatic and spacially incoherent. Fringes could be observed across the whole field, about 12 cm in width, and about 1 cm out of focus either direction from plane P_3. Stationary fringes at in-focus plane P_3 could be seen with the ground glass in place at plane P_1. The fringes had same appearance when the moving irregular glass screen was removed from the beam.

With the system adjusted as before and the ground glass removed from plane P_1, an irregular glass was placed at plane P_2 (this glass scatters light over a limited angle, about $\pm 5°$ from d.c.). Some fringes could be seen, but they appeared in spots only and had low contrast. These fringes were stationary. As the irregular glass was moved toward plane P_3, the contrast of these fringes increased and they could be seen over a larger area. The irregular glass was inserted in one beam only. This observation indicates that some coherence is maintained through irregular glass. With a smaller spacially incoherent source, the fringes should become more contrasty and should be visible over a larger area.

The observations that fringes were present with spacially incoherent light over a depth of ± 1 cm, and through irregular glass, indicates that this technique could be extended to diffusely reflecting or transmitting objects and to three-dimensional diffusely reflecting objects. Calculations indicate that a depth of ± 25 cm could be achieved, and coherence area of the beams of 70 mm diameter should be possible.

Read and understood on March 14 1967 Juris Upatnieks, 10 March 1967

B P Hildebrand

Read & understood on March 14, 1967
A. A. Friesem

10 March 1967

Holograms were made with the optical system as shown, $L_1 = -35$ mm, Optics Technology pulse laser model 130, at 6943 Å = λ. The object transparency was at P_2 with irregular glass plate 10 mm behind it, and P_2 about 45 cm from P_3. SO-243 film was used, and moving irregular glass was removed from the front of L_1.

The following exposure were made, with number in parenthesis indicating input energy to laser: 0.23 joules (1225 joules), 0.12 (1100), 0.42 (1400), 0.85 (1600), 1.22 (1800), 1.40 (2020), 1.70 (2250), 1.90 (2500), 3.2 (2 x 2400).

The transparency was then removed, mirror M_3 was replaced by ~~th~~ a toy train, and the following exposures were made (reference beam was not attenuated): 0.26 joules (1225 joules), 0.13 (1225), 0.32 (1400), 0.74 (1600), 1.20 (1800), 1.30 (20–), 1.50 (2250), 2.10 (2500), 3.8 (2 x 2500).

Juris Upatnieks, 10 March 1967

Read & understood on March 14 1967
B.P. Hildebrand.

Read & understood on March 14, 1967
A.A. Friesem

14 March 1967

Pulse laser holograms.

The hologram above of the transparency gave a reasonably good reconstruction. The image was weighted, or was of nonuniform brightness with maximum brightness at the center and decreasing brightness in all directions from the center. This change in brightness might have been caused by rotational misalignment of the prism-type beam splitter. The imaged pattern of two crossed wires on ground glass appeared to be rotated with respect to each other from the two paths. Such a misalignment would cause reduction

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of fringe contrast as one moved in a radial direction away from the point of coincidence of the two images. With better alignment this difficulty could be avoided. The 0.12 joule exposure was the best, slightly too dark.

The other hologram of the toy train did not reconstruct any image. The cause may be the extremely high reference beam relative to the signal beam, and the poor spacial coherence since the train was far away from the hologram and close to the beam splitter.

Holograms were made with the same optical system as shown on p. 85 except L_3 was replaced by a 50 mm f.l. lens. Exposures ranging from 0.1 to 3.9 joules were made with the irregular glass as a diffuser, and 30X33 mm size transparency as the object. Another set of exposures were made with sand-blasted glass as the diffuser and the same object. The shorter focal length of L_3 in the optical system should increase spacial coherence by a factor of 3 and decrease intensity by a factor of 9. Images through both paths were carefully adjusted to make them coincide.

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22 March 1967

Experiments with pulse laser holograms

Good reconstructions were made from the holograms above, made on 14 March 1967. The best exposures were in the range 0.5 to 0.9 joules. When the virtual image was observed, the whole transparency could be seen from any part of the hologram. This indicates that

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spacial and time coherence was maintained between every point of the reference beam and the object (transparency). The reconstructions are very sharp with fine detail visible, and granularity is very fine. Some coarse nonuniformities across the image are evident. These are caused from the irregular pattern in the beam illuminating the diffuser, and the diffuser being so close to the transparency, about 1 cm. With this system it should be possible to make holograms of 3-dimensional objects. The reconstructions were made on 17 March 1967, and were recorded on Polaroid type 55 P/N film.

The SO-229 film was tested for sensitivity at 6328Å. With a light meter reading of 14×10^{-3}, 25 sec. exposure, and neutral density wedge step with 60% transmission, exposure density of about 20% was achieved. This indicates that SO-229 is about 6 times faster 649F on glass plates. SO-229 was developed for 6 min. in D-19.

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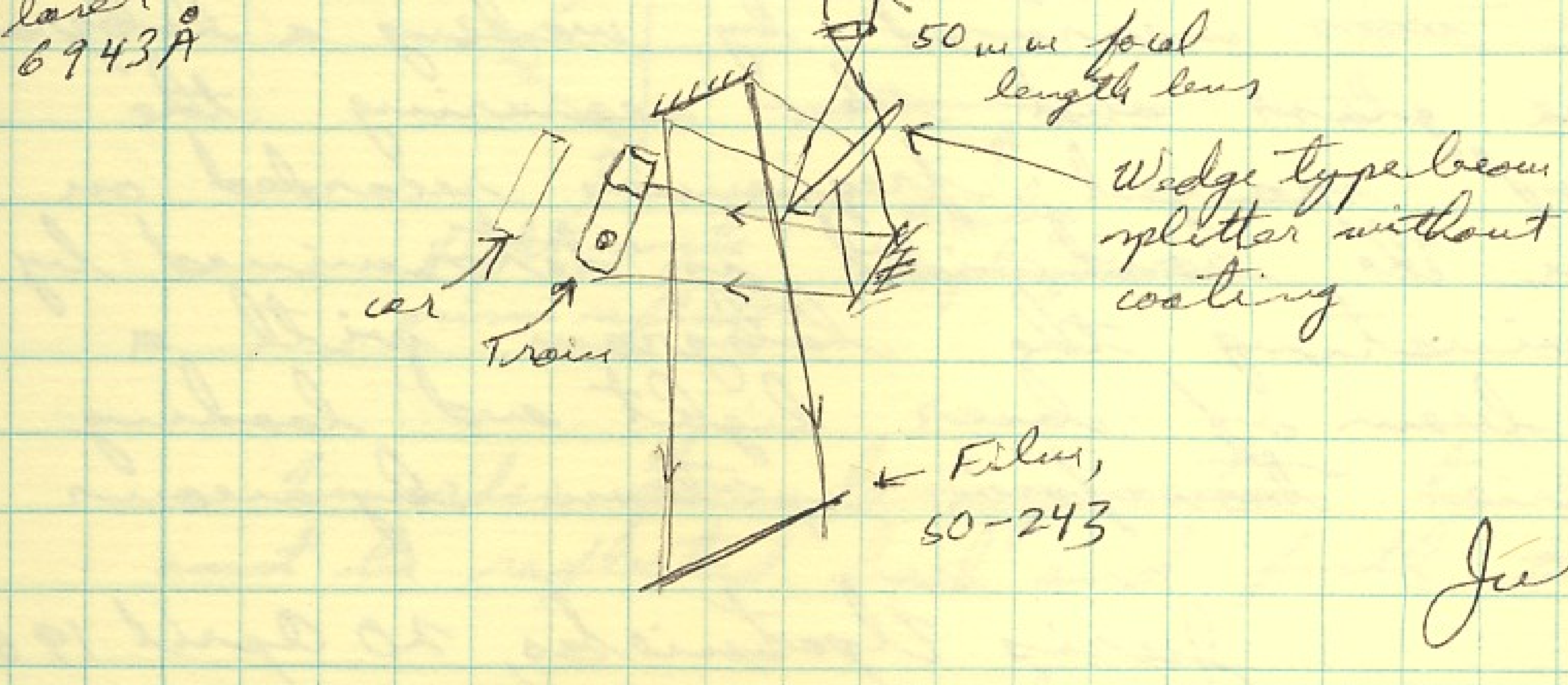
4 April 1967

Experiments with pulse laser holograms.

A pulse laser hologram was made with the following optical system of a three-dimensional object:



The distances are same as for the optical system on p. 85.

The hologram was made on 24 March 1967.

Exposures: 2.16 joules (one pulse), 4.0 joules (2 pulses), & 5.3 joules (3 pulses).

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The 4 joule exposure was the best one. Reconstruction were made on 3 April 1967, and were rather noisy. Only the central part of the train was reconstructed and the signal to noise ratio was low. However, a three-dimensional object was photographed and reconstructed. Apparently sufficient spacial coherence is maintained only at the center of the ~~image~~ object field. Several pulses are required to obtain sufficient exposure, which sometimes cause interference effects at the object or on the film. It appears that the spacial coherence must be improved without the loss of energy to make good three-dimensional holograms.

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20 April 1967

Spacial coherence of ruby pulse laser, Optronics Technology Model 130.

A number of experiments have been performed during the last month to determine if the spacial coherence of the pulse laser could be improved. The poor spacial coherence is the result of the high gain of the ruby laser and the short resonant cavity. Many modes besides the ones on the optical axis are supported by the laser, resulting in wide divergence of the output beam. The coherence was measured by making a hologram of a diffuse glass and then measuring the bandwidth of spacial frequencies recorded on the hologram. The bandwidth is determined by ~~mean~~ illuminating the hologram with a collimated beam of laser light and looking at the Fourier transform spectrum by means of a lens.

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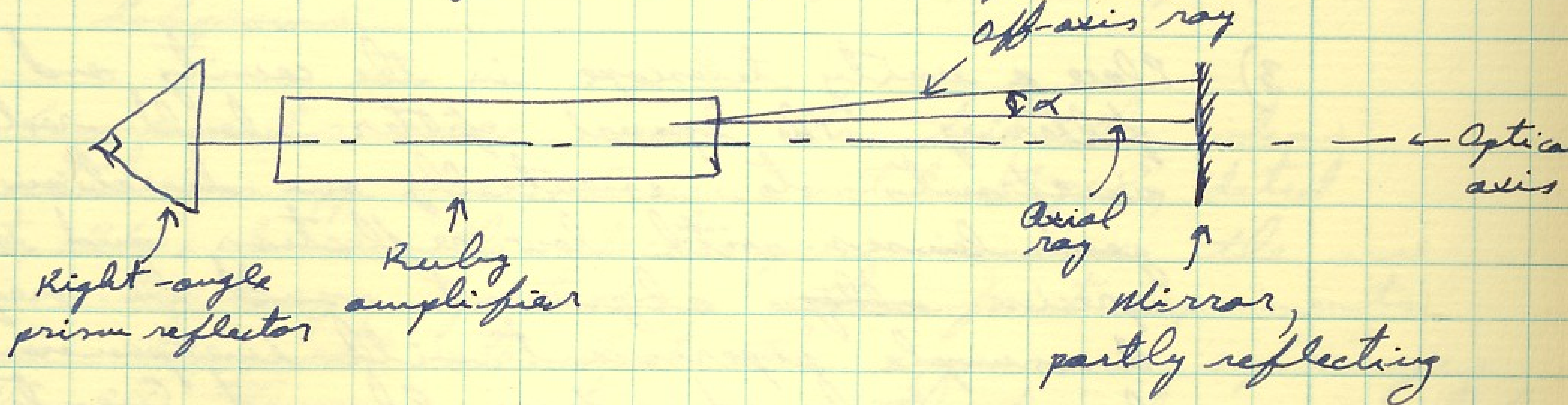
With the laser cavity in its original arrangement, the divergence of the beam was measured to be 0.0017 radians or about 0.1°; with the cavity extended from its original length of 33 cm to 118 cm, the divergence was measured to be 0.06° or 0.001 radians. With a 300 mm focal length lens, this corresponds to 500 μ diameter light source in the first case, and 300 μ diameter light source in the second. To obtain good holograms of three-dimensional object, the source size should be about 1 μ, or a few wavelengths in diameter. It should be noted that the coherence measurements are of questionable accuracy due to difficulties in performing the experiments.

Apparently spacial coherence is improved by increasing cavity length and there is no loss in output power. Improvement in coherence can be expected since the modes would have to be closer to the axis of the cavity to reflect back and fourth between the mirrors. Assuming that equivalent source size decreases by same ratio as increase in cavity length, then 33 meter cavity length would be required to get a 5 μ diameter source, or 165 meter for a 1 μ source. It cannot be expected that this relation remains true for very long cavity lengths, since diffraction affects and density variations in air become important.

In general, the problem of transverse mode selection is illustrated by the following diagram:



In order for lasing action to take place, a wavefront must be reflected back and forth through the ruby

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in such a way that gain exceeds losses until a maximum value is reached. Assuming a perfect cavity with perfect alignment, the rays parallel to the optical axis satisfy the above condition. Rays at small angles may travel through the cavity several times until they begin to hit the restricting apertures of the cavity and are attenuated.

Using this simple model, transverse modes should be reduced under the following conditions:

1) The length of the cavity is increased. An off-axis ray can travel fewer times through the ruby. Experimentally there seems to be no ~~de~~ decrease in output energy with increasing cavity length, but ~~there~~ there is improvement in spacial coherence.

2) Restrict the aperture of the cavity. Reason for improvement is same as in (1). Coherence measurements have not been made, but energy output measurement are the following:

Output energy	Input energy	Shape of aperture	Ratio of original power to power with apert.	Ratio of original to restricted aper
2.2 joules	2500 joules	none (3/8" diam)	1	1
1.9 joules	"	○ 11/32"	1.16	1.19
0.7 joules	"	○ ○ 5/32"	3.1	2.9

3) Place a unity telescope in the cavity and use spacial filtering. The spacial filter should restrict the wavefronts to essentially one direction. Very good lenses with low reflection and extremely precise ~~allign~~ alignment would be required. A simple experiment with inexpensive single-element lenses purchased from Edmund Scientific was conducted with the following results:

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Output energy	Input energy	Lenses, if any	Pinhole, if any	
0.9 joules	1600 joules	none	none	
0.3 "	1600 "	Two 156 mm single-element lenses	none	Alignment not exact
0.07 joules	1600 joules	none	0.31 mm	Pinhole approximately centered, much larger than focus of He-Ne laser beam.

It seems that a unity telescope would offer the best possibility of achieving good spacial coherence without excessive loss in output energy. This scheme depends on the quality of components and exactness of alignment which might be difficult to achieve. Even if everything was perfect, the ruby itself has considerable nonuniformity (½λ) in transmission according to Alekseff) which would make it impossible to pass a given wavefront many times through the same pinhole as it traverses the cavity. A ½λ change in optical path length across the ruby is very severe as compared to the standards of optical flats or interferometers.

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22 June 1967

Experiments with reducing spatial frequencies in holograms.

Experiments were made to test the ideas described on pp. 140 – 145 in notebook #768, dated 21 Oct. 1965. Since the technique involves the use of restricting apertures, the first experiments were designed to test the appearance of images through these apertures without reducing spatial frequencies. The experimental system is shown

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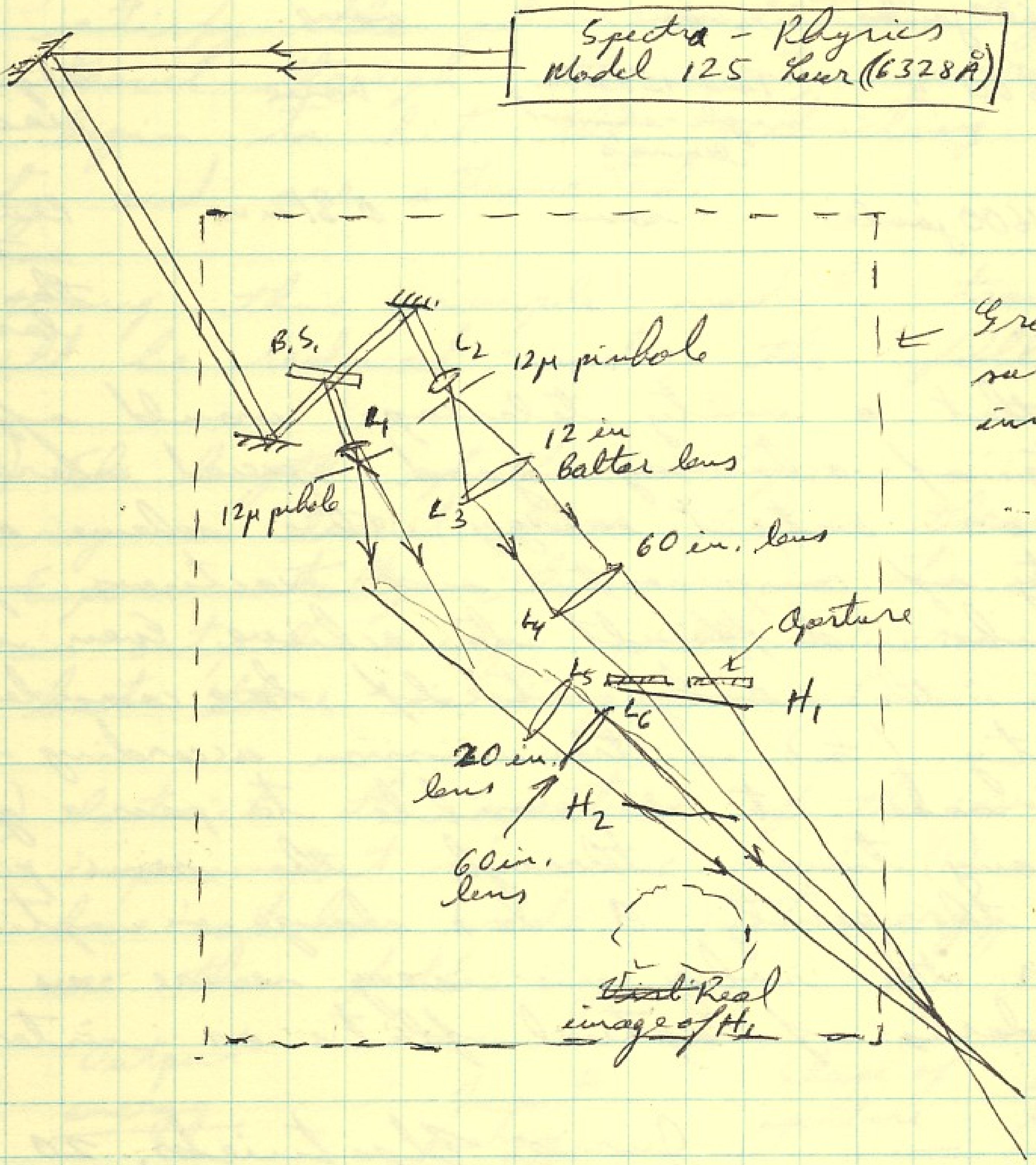
below.



Hologram H_2 made from hologram H_1.

The real image of hologram H_1 one was restructed behind the the position where hologram H_2 would be made. Due to lack to proper lenses, it was not possible to reconstruct H_1 at one-to-one scale, and the real image was somewhat magnified. ~~Ap~~ Apertures of various shapes were placed directly in front of H_1. The reference beam was introduced as shown in order to facilitate reconstruction of hologram H_2, since one simply has to illuminate H_2 with a diverging beam of light. For the hologram where the aperture was a single rectangle, lens L_2 was changed so that the laser beam was concentrated on this aperture. The reconstructed image was quite bright in the later cases.

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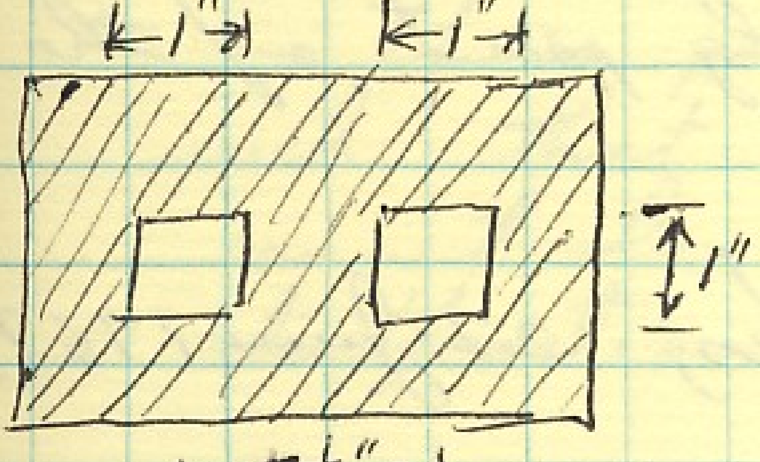
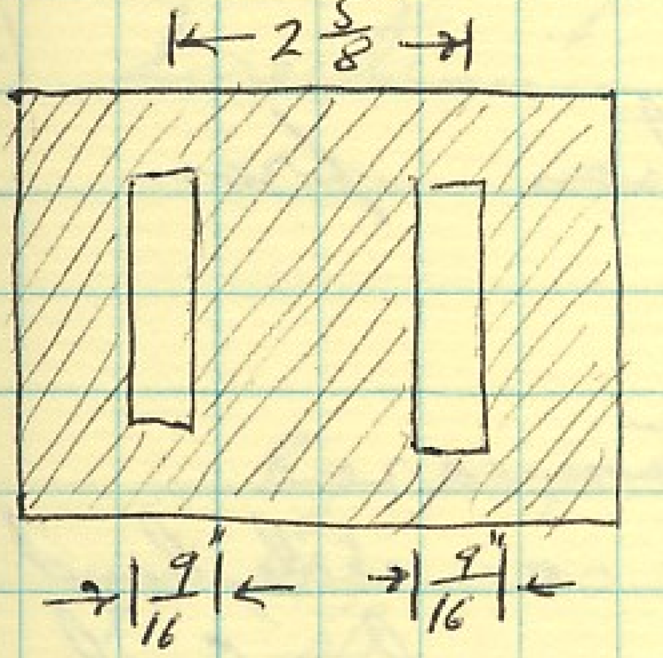
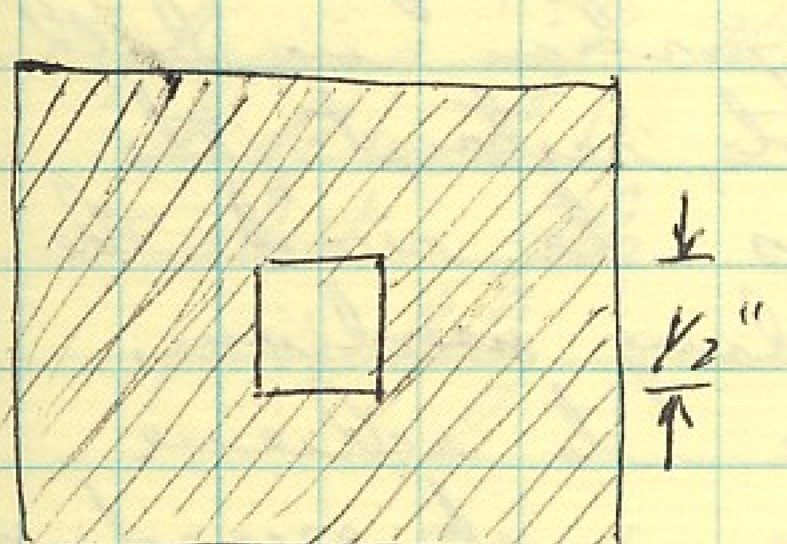
Hologram H_1 was adjusted while the reconstructed real image was observed with a magnifier. The hologram could be adjusted so that the real image appeared quite sharp and well resolved.

The following holograms were made from a 4×5 in. Life hologram as H_1:

Aperture	Light intensity	Exposure	Comments
	Signal: 30×10^{-4} Ref: 80×10^{-4} 110×10^{-4}	70 to 120 sec. Best exp. was 70 sec.	Correctly exposed hologram reconstructed a very neat and bright image. It could be easily seen in Hg-ar lamp with a 1mm diamet pinhole and 100cm away. (Hologram made on 14 June '6
	Signal: 14×10^{-4} Ref.: 90×10^{-4} 104×10^{-4}	75 & 85 sec. Best exp. 75 sec.	Exposure somewhat dark. Reconstructio good, and good parallax visible in up and down direction. (Exp. made 15 Ju
	Signal: 7×10^{-3} max. Ref.: 18×10^{-3} " 25×10^{-3}	20 and 30 sec. 20 sec. exp. best.	Due to the smal aperture the signal is highly nonunifo over the hologram pl H_2. Hence signal to reference ratio must large. Nonlinearities create "halo" around imag Extremely bright reconstruction. (Exp. made on 15 June '67)

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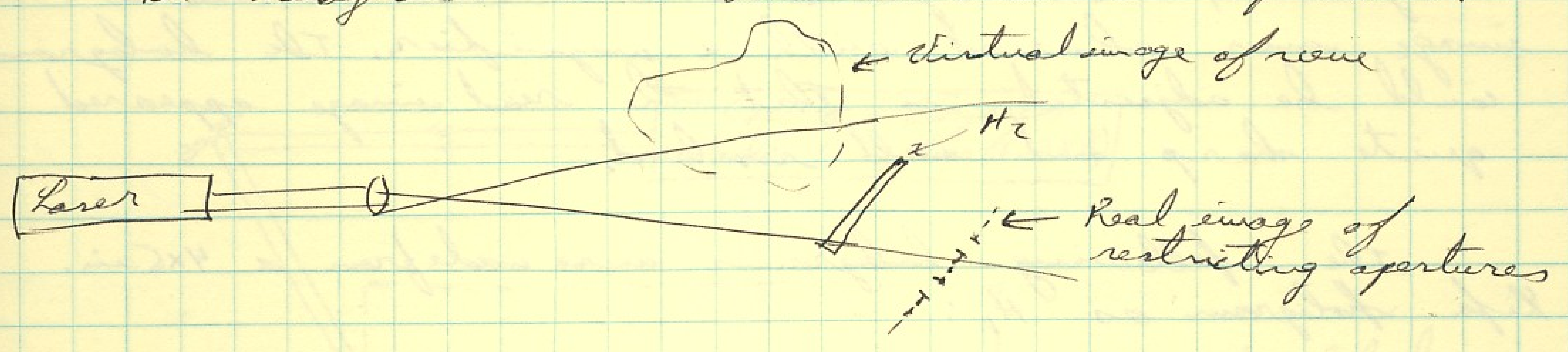
The holograms were reconstructed as follows:



When the eye was placed at the position of the real image of the aperture, the whole scene could be seen at once. At other planes only part of the scene could be seen at one time.

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Efficient single-sideband diffraction from two-dimensional grating.

Bleached gratings ~~of~~ or Fresnel zone plates are known to diffract more light into a sideband that ones having intensity variations only. Such gratings tend to diffract a large portion in both 1st orders, 2nd orders, etc. One way to restrict the diffraction to only one 1st side order is to record the gratings in three-dimensional recording medium. Another technique is described here to achieve the same result with a two-dimensional recording medium.

Consider the diffraction by a plane grating on the next page. The conditions for diffraction in the β_{r+} direction are that the condition

$$d\,(\sin\beta_i + \sin\beta_{r+}) = \lambda \qquad (1)$$

are satisfied.

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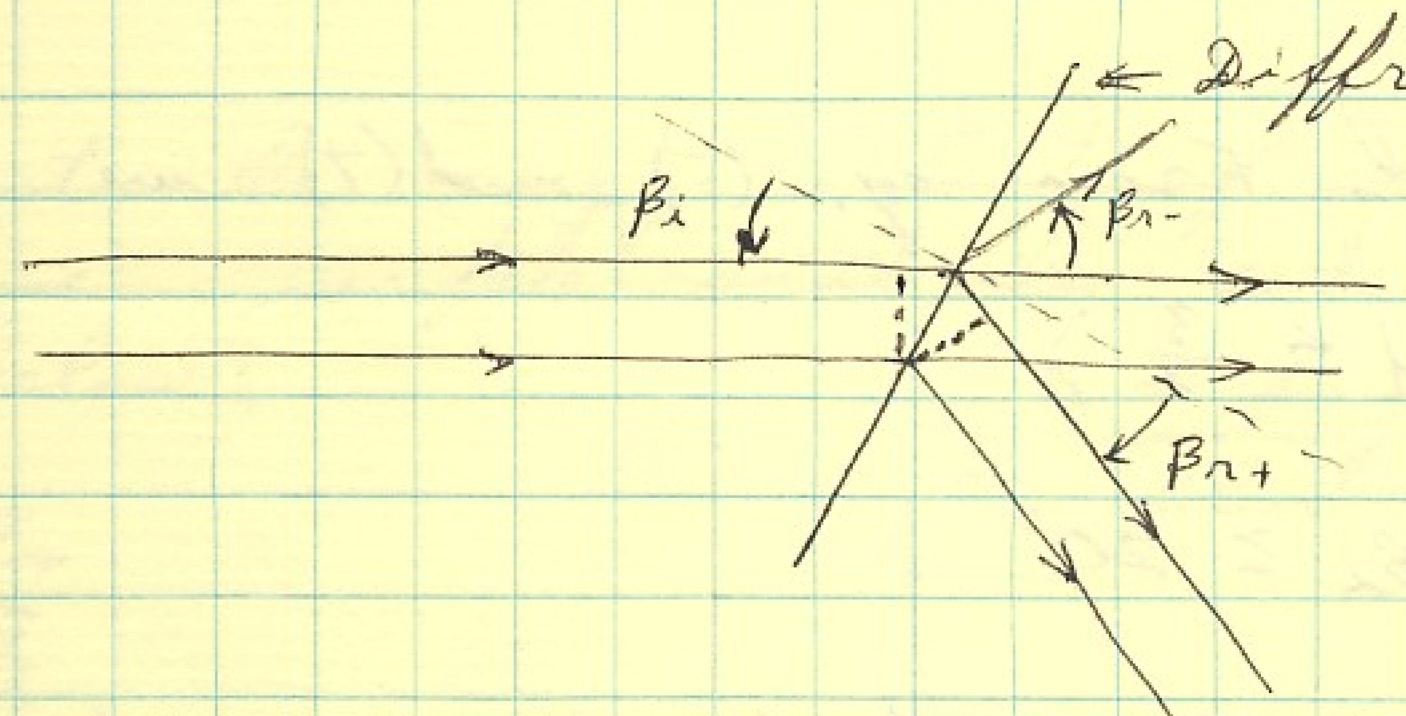

For the diffraction in β_{r-} direction the conditions are

$$d(\sin\beta_{r-} - \sin\beta_i) = \lambda \qquad (2)$$

It is possible choose the parameters β_i, β_{r+} and d such that equation (1) will be satisfied and equation (2) cannot be satisfied. The conditions for 2nd order diffraction in the β_{r+} direction are

$$d(\sin\beta_i + \sin\beta_{r+}) = 2\lambda \qquad (3)$$

and in general for higher order diffractions in the (+) or (−) direction the relationship is

$$d\{(\sin\beta_i \pm \sin\beta_{r+})\} = n\lambda, \quad n = 0, \pm1, \pm2, \ldots \qquad (4)$$

By proper selection of β_i and d it is possible that eq. (4) is satisfied only for $n = 0$ and $n = +1$. Diffraction in the zero order direction can be eliminated by proper phasing of the grating. The light energy then must be either diffracted into the +1 order or be reflected. It appears that the light energy would go mostly in the +1 order, possibly with a 90% efficiency.

As a special case, consider $\beta_i = \beta_{r+}$, and then

$$2d\sin\beta_i = \lambda \qquad (5)$$

To eliminate −1 order the relation

$$d(1 - \sin\beta_i) \geq \lambda \qquad (6)$$

or

$$\sin\beta_i \leq 1 - \frac{\lambda}{d} \qquad (7)$$

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must be satisfied. From eq. (5) and (7) we find that

$$d \leq \frac{3}{2} \lambda \qquad (8)$$

or

$$\beta_i \geq 20^\circ$$

For this choice of β_i and d the -1 and higher negative orders are also suppressed.

Such bleached (or phased) gratings and Fresnel zone plates could be useful as high-efficiency optical elements.

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11 August 1967

Production of phase plates having random phase distribution.

The image quality of transparencies and similar objects can be improved if they are illuminated with a constant-amplitude, random-phase wavefront. Such wavefronts are produced by passing a plane wavefront through transparent material one side of which is irregular. Such an irregular surface can be made by recording an interference pattern and bleaching it.

One desirable quality of an irregular random phase plate is that it contains equal amounts of energy in all spatial frequencies used. Another one is that the pattern is random which can be easily achieved by recording interference pattern from a ground glass screen.

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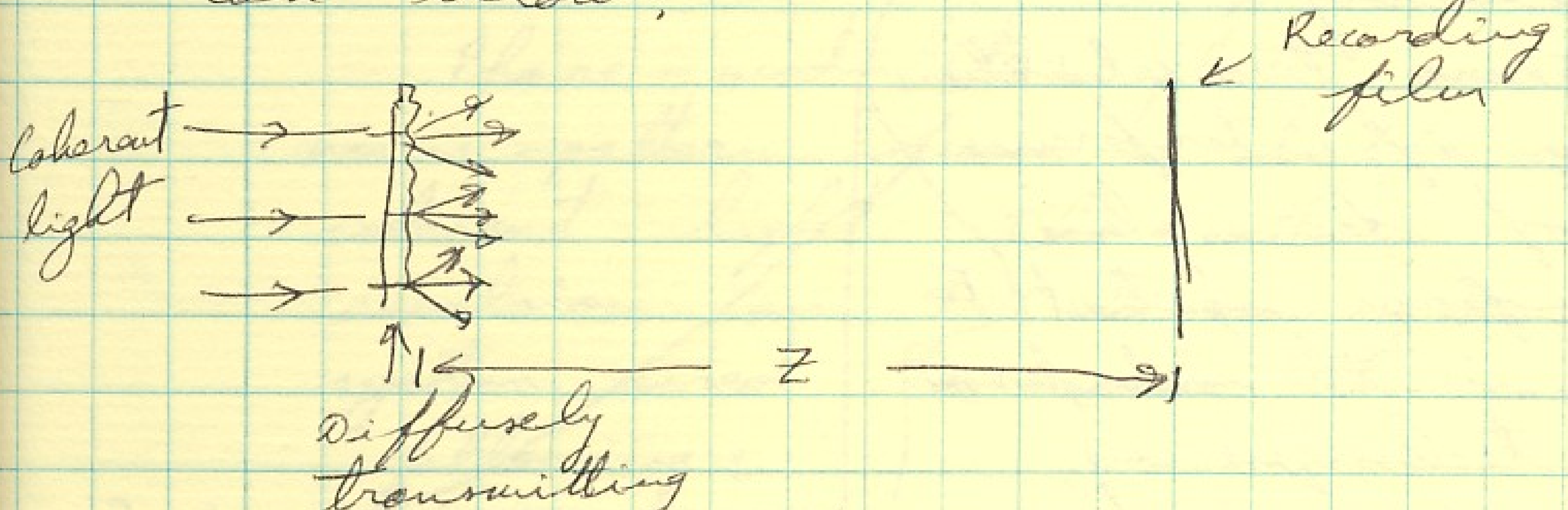
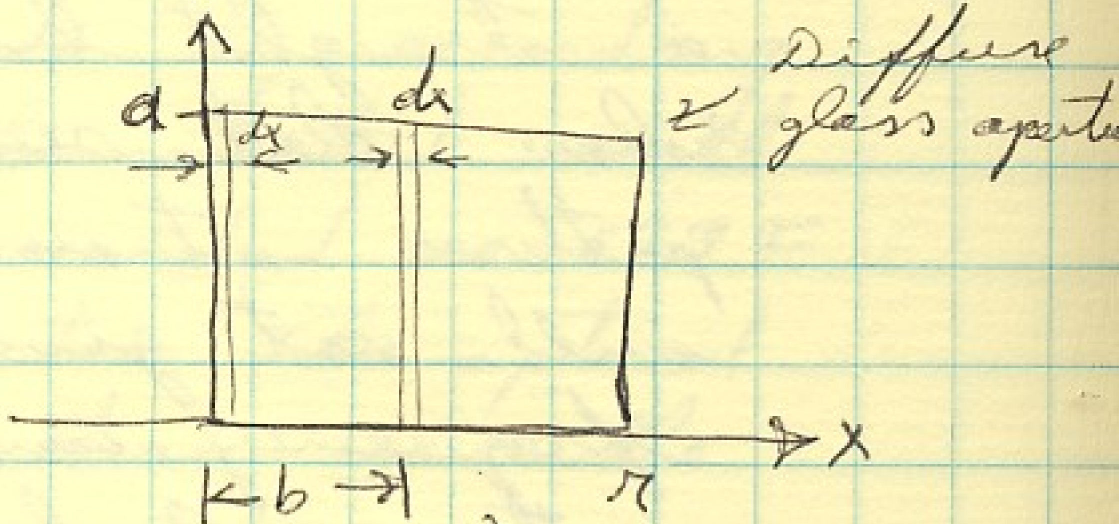
First, the energy content of an interference pattern from a diffuse surface will be calculated. Consider the case below:



(a)



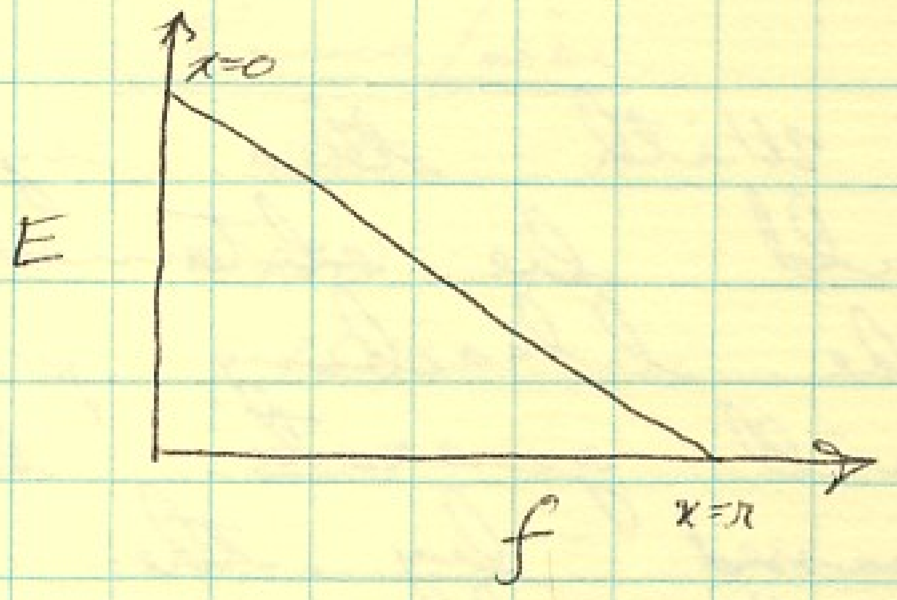
(b)

Let f = spatial frequency

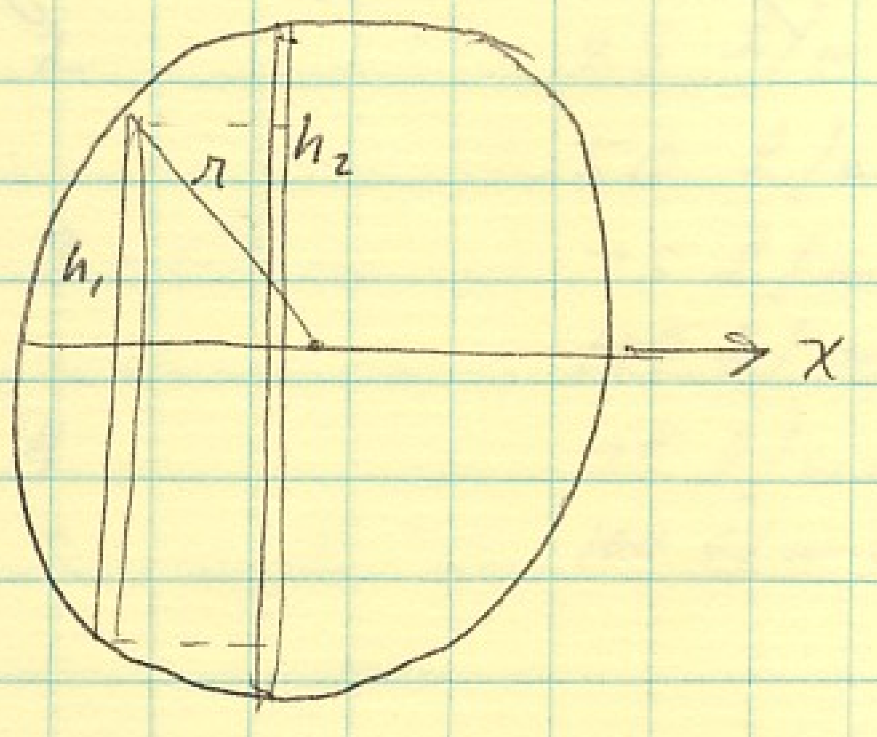
On the screen distance z from diffuse glass plate interference pattern is formed having spatial frequency $f \approx \frac{b}{\lambda z}$. At (b) we consider the area of small strips dx wide and separated by b, and assume that only points on a line parallel to x-axis interfere to produce a frequency component in that direction. Furthermore, assume that energy is proportional to the number of dx lines distance b apart. Energy E can then be calculated to be

$$E \propto \int_0^{r-b} a\,dx = ax\Big|_0^{r-b} = a(r-b)$$

A plot of this as a function of b is shown at right:



A similar calculation can be made for a circular aperture:



$$h_1(x) = \sqrt{r^2 - x^2} = r\sqrt{1-\left(\frac{x}{r}\right)^2}$$

$$E \propto 4\int_{b/2}^{r} h_1(x)\,dx = 4\int_{b/2}^{r} \sqrt{r^2-x^2}\,dx$$

$$= 2\left[x\sqrt{r^2-x^2} + r^2 \sin^{-1}\left(\frac{x}{r}\right)\right]_{b/2}^{r}$$

$$E = k r^2 \left[\pi - \sqrt{1-\left(\frac{b}{2r}\right)^2} - 2\sin^{-1}\left(\frac{b}{2r}\right)\right]$$

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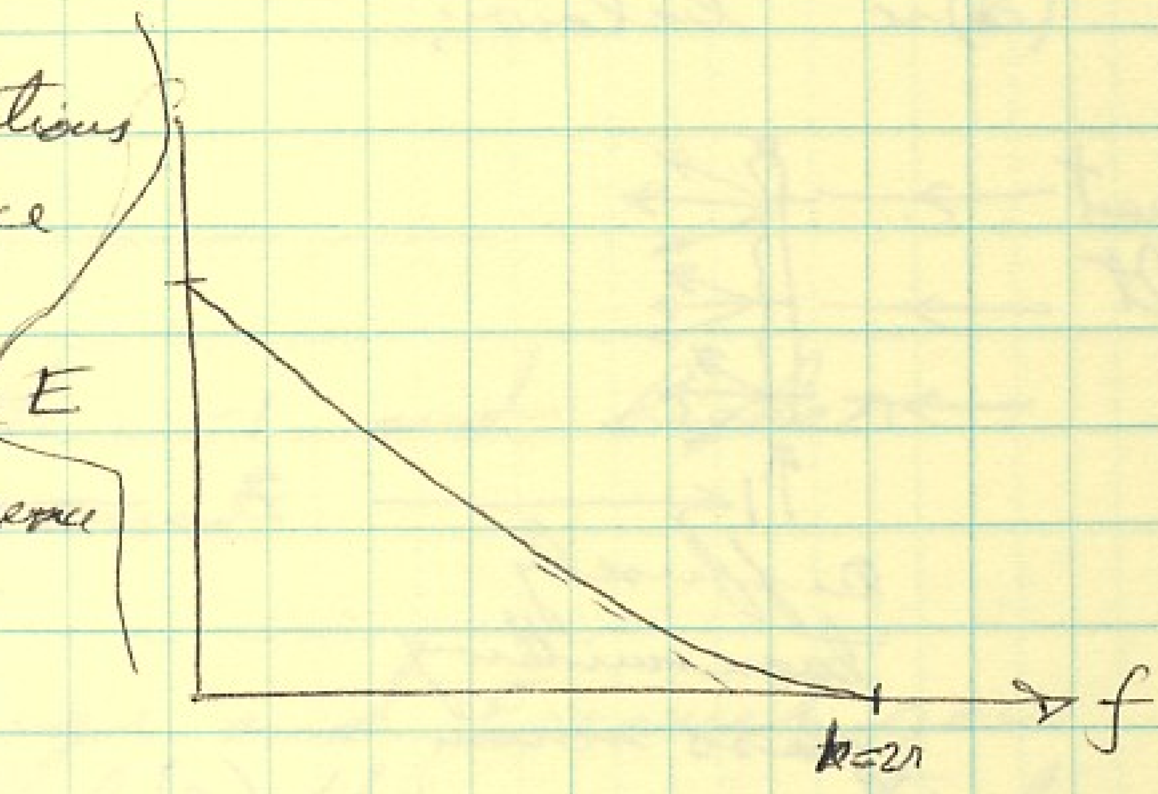
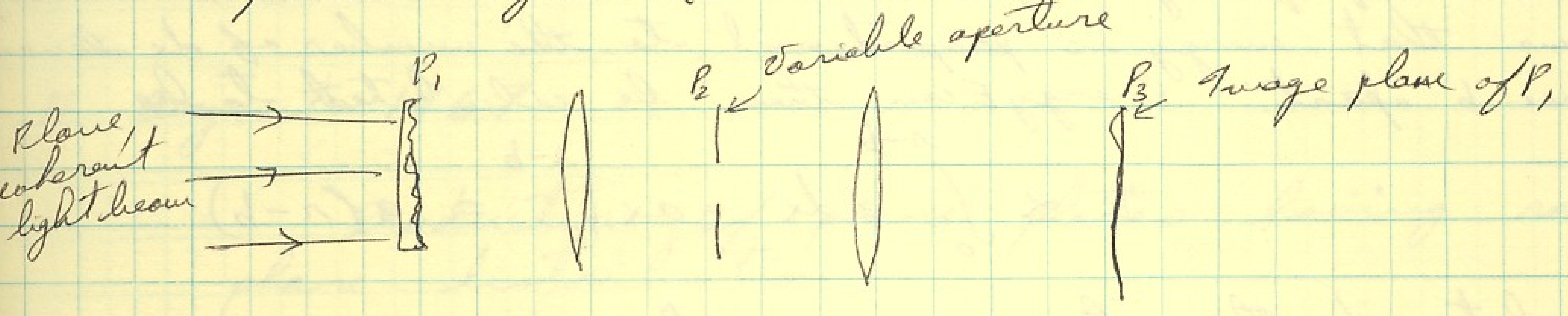
The plot for the circular case is very similar to the rectangular case (in one dimension) except that the curve is not exactly a a straight line. These two calculations show that recording of interference pattern at an out-of-focus plane will not give uniform spatial frequency content in the interference pattern. A better technique is to image the diffuse surface and place a spatial filter in the transform plane. In this case the spatial frequency content of the interference pattern should be uniform (equal energy for all ~~patterns~~ frequencies) since a diffuse surface has such distribution before filtering. The diagram below shows the optical system:





With this system any desired frequency range could be obtained by adjusting the aperture. The bleaching process is non-linear and thus will generate higher spatial frequencies than passed by the aperture. The result should be better, however, than by recording patterns at an out-of-focus plane.

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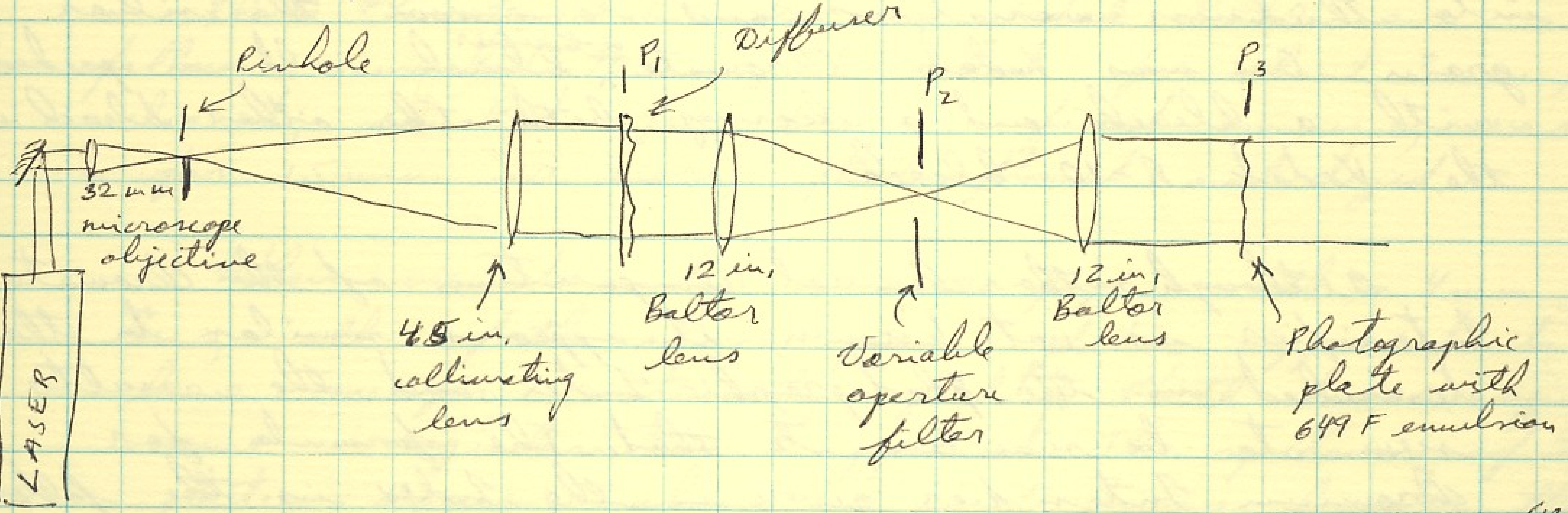
Experiments with production of phase-modulator plates by bleaching.

Phase-modulator plates were made by recording moire-pattern from a diffuser illuminated with coherent light. The pattern was recorded on 649 F emulsion on 4 x 5 x 1/8 in. glass plates. The optical system used to make the moire pattern was the following:



The pass-band of the spatial filter for the 305 mm (12 in) focal length lenses was calculated to be the following:

Lines/mm	Aperture diam.	Lines/mm	Aperture diam.
16 l/mm	3,05 mm	80	15,3 mm
25	4.8	100	19,0
40	7.6	160	30,5
60	11,5	200	38

The following plates were exposed:

Plate #	Spatial freq. of aperture	Density	Transmission
1	25 l/mm	1,3	6%
	50 l/mm	2.2	0,7%
2	25 l/mm	1,3	5%
	50 l/mm	2,2	0,7%
3	75 l/mm	2,2	0,7%
	100 l/mm	2,2	0,7%
4	75 l/mm	2,0	1%
	100 l/mm	2,0	1%

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Plate #	Spatial freq. (oper.)	Density	Transmission
5	25 l/mm on both	2.6 and 3.8	0.26% and ~~3.8~~ 0.016%
6	25 l/mm on both	" "	0.26% and 0.016%

All plates were developed in D-19 for 5 min, and fixed.

Two bleaches were used to convert intensity variations into thickness variations and to remove the silver grain. One was Kodak Chromate Intensifier bleach sold in packets with a bleach and a clearing bath. The other bleach was the Kodak R-10 bleach.

Although the chemical composition of the Chromate Intensifier is not known, it appears similar to that described in the photographic Index and the results seem to be similar to that. The formula for Chromium Intensifier given in the Index is the following:

Water	750.0 cc
Kodak Pottasium Bichromate	~~[illegible]~~ 90.0 gms
Kodak Hydrochloric Acid, C.P.	64.0 cc
Add water to make	1.0 liters

The formulas for Kodak R-10 bleach are as follows:

Solution A

Distilled water	500 ml
Ammonium Bichromate	20 gms
Concentrated Sulfuric Acid	14 ml
Distilled water to make	1.0 liters

Solution B

Sodium Chloride	45 gms
Distilled Water to make	1.0 liters

For use, mix one part sol. A, one part sol. B, and 10 parts of water

Juris Upatnieks, 22 August 1967

22 August 1967

Plates #1 and #2 were bleached in the Chromate Intensifier in the following manner: the plate was placed in chromate bleach until the image disappeared, for about 3 min.; it was then washed and placed in the clearing bath, washed again, and then fixed, and washed. Plate #1 was bleached three times, with development Dektol developer after the first two bleachings, and fixed after the last one.

Plate #5 was bleached in Kodak R-10 as follows: washed 10 min., bleached for about 3 min., until cleared; washed for 4 min., fixed 8 min., washed for 15 min. or more, photo-flowed and dryed.

When viewed under a microscope with a 4mm f.l. lens, all of the above plane plates appeared to have unifor intensity fields. With lower magnificatio some irregularities appeared. The spectrum of the plates appear about 4 or 5 times broader than that recorded. Also, when slightly defocused, the pattern has low spatial frequency which increases as defocusing is increased. The plates appear to have too high frequency content for want applications. The problem appearantly is that the slopes of the irregularities are too steep. ~~to~~ Better plates should have finer high-frequency irregularit and less low frequency irregularities.

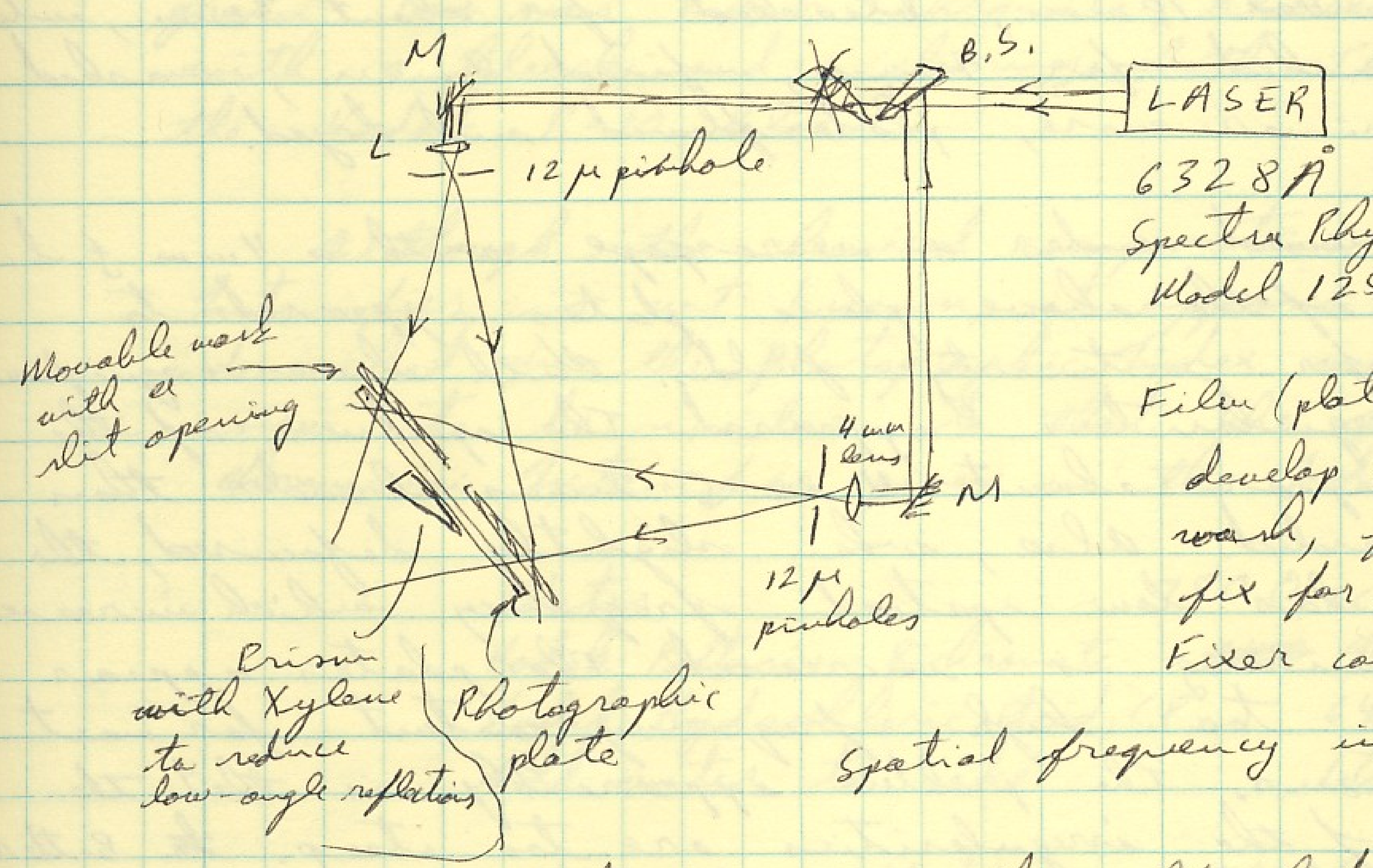
One way to improove the results might be to place a spatial filter with ring-like aperture This should reduce low-frequency components.

Juris Upatnieks, 22 Aug. 196

August 24, 1967

Experiments with producing high-efficiency diffraction gratings by bleaching recorded interference patterns.

A number of gratings were made by recording the interference patterns of two beams of light on 649F emulsion supported by 4×5×1/8 in. glass plates. The plates were then bleached and diffraction efficiency was measured. The optical system used to make the plates is shown below:



6328 Å
Spectra Physics
Model 125

Film (plate) development:

develop D-19 for 5 or 6 min., wash, fix in Kodak Rapid fix for 5-10 min., wash. Fixer contains hardener.

Spatial frequency in emulsion ≈ 2230 l/mm

The gratings were then bleached in various bleaches. Some of the bleaches used had the following chemical content:

1. Mercuric Cloride bleach:

a)	Kodak Potassium Bromide	22.5 gms
b)	Mercury Cloride	22.5 gms
c)	Water to make	1.0 liters

This solution loses potency with time and has undesirable side effect, such as coloring. The bleach used was rather old an fresh solution might give better results.

Juris Upatnieks, 24 August 1967

August 24, 1967

2. Chromium Intensifier, Kodak In-4

a) Water 750.0 cc
b) Kodak Potassium Bichromate 90.0 gms
c) Hydrochloric acid, C.P. 64.0 cc
d) Add water to make 1000 cc

3. Kodak Bleach Bath R-10

Sol. A

a) Distilled water 500 ml
b) Ammonium bichromate 20 gms
c) Concentrate sulfuric acid 14 ml
d) Distilled water to make 1000 cc

Sol. B

a) Sodium chloride 45 gms
b) Distilled water 1000 cc

For use, mix 1 par sol. A, 1 sol. B, and 10 parts of water.

The test results (measurement of efficiency of diffraction), are the following:

	Max. % eff	% Transmission	Min. % Transm.
Mercuric chloride bleach, dry plate	*30%	47%	10½%
Chromate bleach, dry plate	*25%	64%	24%
Chromate bleach, wet plate	*39%	64%	
Kodak R-10 bleach bath, dry plate	41%	57%	14%
Kodak R-10 bleach bath, wet plate	49%	49%	4.9%

*These readings may be somewhat high due to nonlinear meter response

↑ at angle of diffraction

In all of the cases above, the plates were not fixed after bleaching. If the plates are fixed after bleaching, the transmission increases to nearly that of clear glass but the diffraction efficiency falls to a few percent or less than one percent. The major disadvantage of omitting the fixing is that the emulsion remains somewhat dark and absorbs light. The color is usually yellowish or brownish. In case of the chromate bleach, the commercially available Chromium Intensifier

Juris Upatnieks, 24 August 1967

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was used and it contained a clearing bath. The clearing bath turned the brownish color into slightly white deposit throughout the emulsion without affecting the efficiency of diffraction. The average transmission was slightly better with the clearing bath. The chemical composition of the clearing bath is not known. It was observed that the wet emulsions were unstable and turned darker with ti

Another fact appears from the measured efficiencies: That diffraction efficiency is dependent on the thickness of the emulsion. By leaving the emulsion wet (it was wetted and covered with clear glass), the thickness can be increased by a factor of three. By controlling the acidity of the water and by avoiding use of a hardener, this increase could be as high as X 18 (from table in the book The Theory of Photographic Process). The last column on the previous page suggests that any further increas would be small since usually less than 14% is transmitted through the plate at the angle of diffraction. A rather large increase should be possible if the absorbtion of the emulsion can be decreased without lowering the index of refraction change within the emulsion.

Of the losses, 10% consist of reflection at the 1st surface of the glass. If all the light was diffracted without absorbtion, then an efficiency of 80% could be achieved. By coating the surfaces a still further improvement should be possible. In the above experiments, the $\vec{E}$ is parallel to the plane of incidence, and the angle between the two beams was $\approx 90°$.

The experimental work was done Carl Leonard.

Juris Upatnieks, 24 August 1967

20 September 1967

Experiments with bleaching of recorded interference patterns.

Experiments and investigation of the bleaching ~~path~~ reactions was continued. Spatial emphasis was placed on the investigation of the chemical reactions that take place during bleaching process.

The probable chemical reactions of the chromate bleaches are probably the following:

Kodak R-10 bleach without NaCl

$$6Ag + (NH_4)_2Cr_2O_7 + 7H_2SO_4 = 3Ag_2SO_4 + Cr_2(SO_4)_3\downarrow + (NH_4)_2SO_4 + 7H_2O$$

(Ag_2SO_4 sol.; $Cr_2(SO_4)_3$ probably insol.; $(NH_4)_2SO_4$ sol.)

with NaCl the reaction might be

$$6Ag + 6NaCl + (NH_4)_2Cr_2O_7 + 7H_2SO_4 = 6AgCl\downarrow + Cr_2(SO_4)_3\downarrow + 3Na_2SO_4 + (NH_4)_2SO_4 + 7H_2O$$

($AgCl$ insol., $n = 2.07$; $Cr_2(SO_4)_3$ probably insol.; Na_2SO_4 sol.; $(NH_4)_2SO_4$ sol.)

Kodak R-9 bleach

$$6Ag + K_2Cr_2O_7 + 7H_2SO_4 = 3Ag_2SO_4 + Cr_2(SO_4)_3\downarrow + K_2SO_4 + 7H_2O$$

(Ag_2SO_4 sol.; K_2SO_4 sol.)

Kodak In-4 chromium bleach

$$Ag + K_2Cr_2O_7 + 14HCl = 8AgCl\downarrow + 2CrCl_3\downarrow + K_2Cl + 7H_2O$$

($AgCl$ insol.; $CrCl_3$ insol.; K_2Cl sol.)

another chromate bleach variation

$$6Ag + (NH_4)_2Cr_2O_7 + 14HCl = 6AgCl\downarrow + 2CrCl_3\downarrow + 2(NH_4)Cl + 7H_2O$$

($AgCl$ insol.; $CrCl_3$ insol.; $(NH_4)Cl$ sol.)

Juris Upatnieks, 20 Sept. 1967

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The packaged Kodak chromium intensifier states that it contains $KCrO_3Cl$ as the bleaching agent. If we assume that H_2SO_4 is used as the acid, then the reaction should be

$$6Ag + 2KCrO_3Cl + 6H_2SO_4 \overset{?}{=} 2AgCl\downarrow + Cr_2(SO_4)_3\downarrow + K_2SO_4$$

$$+ 6H_2O \; \cancel{+ Cl_2} \; + 2\underset{sol.}{Ag_2SO_4}$$

The chemicals probably include some other compounds which react with SO_4. ~~and remove it.~~ The question of what is contained in the clearing bath is not known. It is possible that the yellowish color is caused by some residual sulfur compound and that the clearing bath reacts with it or dissolves it from the solution. The clearing bath does not change the ~~ap~~ efficiency appreciably and tends to leave a whitish resi

In the above reactions the index of refraction is apparently caused by the following compounds remaining in the emulsion:

Compound	Index of refraction	Color in crystaline form
$Cr_2(SO_4)_3$	?	violet or red
$AgCl$	2.071	white
$CrCl_3$	?	violet

The above bleach baths are all used as intensifiers. Intensification is achieved by developing the bleached plates causing the following reaction:

$$AgCl + Cr_2(SO_4)_3 + \text{developer} = Ag + Cr + \text{other sol. compoun}$$

Besides the original silver, chromate is also deposited in the emulsion.

Juris Upatnieks, 20 Sept. 1967

21 Sept. 1967

Other chemical compounds for bleaching photographic plates.

The following reactions may take place and increase the index of refraction. The reactions with a (✓) have been tried and bleaching action was observed.

1. $Ag + 3H_2O + KI + K_3Fe(CN)_6 = AgI\downarrow + K_4Fe(CN)_6 \cdot 3H_2O$

2. $Ag + 3H_2O + KBr + K_3Fe(CN)_6 = AgBr\downarrow + K_4Fe(CN)_6 \cdot 3H_2O$ ✓

3. $Ag + 3H_2O + KCl + K_3Fe(CN)_6 = AgCl\downarrow + K_4Fe(CN)_6 \cdot 3H_2O$

4. $CuBr_2 + Ag + H_2O_2 = \begin{cases} AgBr\downarrow + CuO\downarrow + H_2O \\ AgBr\downarrow + Cu_2O\downarrow + H_2O \end{cases}$ ✓ } One of these should be true. Appearance: yellowish or light brown

5. $CuBr_2 + Ag + H_2O = \begin{cases} AgBr\downarrow + Cu\downarrow \\ AgBr\downarrow + CuBr\downarrow \\ AgBr\downarrow + Cu_2O\downarrow + Cu(OH)_2\downarrow \end{cases}$ ✓ } Appearance light pink

6. $Ag + 4K_3Fe(CN)_6 = 3K_4Fe(CN)_6 + Ag_4Fe(CN)_6\downarrow$ ✓

7. a) $Ag + K_2Cr_2O_7 + 14HCl = 6AgCl\downarrow + 2KCl + 2CrCl_3\downarrow + 7H_2O$

b) $2AgCl + 2CrCl_3 + NaOH = 8NaCl + Cr_2O_3\downarrow + H_2O + Ag_2O$?

or $2AgCl + 2CrCl_3 + 8NH_4OH = 8NH_4Cl + Cr_2O_3\downarrow + 4H_2O + Ag_2O$ (↑ sol. in NH_4OH)

In order for the bleaching action to take place with the desired increase in index of refraction, two conditions must be met by the bleach: the chemical reaction takes place only in presence of silver and

Juris Upatnieks, 21 Sept. 1967

21 Sept 1967

and one of the products (or more than one) must be insoluble and have higher index of refraction than the emulsion. These conditions are met by all of the above equations. The color of the crystal refers to its bulk form, not dispersed in fine form in the emulsion, and it may have different appearance in fine suspended state. The following table lists the optical properties of the deposited compounds as given by the Handbook of Chemistry and Physics:

Compound	Index of refraction	color
AgI	2.21	yellow
$AgBr$	2.253	pale yellow
$AgCl$	2.071	white
CuO	2.63 ~~2.116~~	black ~~white~~
Cu_2O	2.705	red
$CuBr$	2.116	white
$Cu(OH)_2$	?	blue
$Ag_4Fe(CN)_6$	?	white
$CrCl_3$	?	violet
Cr_2O_3	2.551	green
Ag_2O	?	brown-black
Ag_2O_2	?	gray-black

Other compounds having high index of refraction are listed below:

mol.	n	mol.	n
HgI_2	2.75, 2.45	AlC_3	2.7 (@ 700 mμ)
SrS	2.11	SbI_3	2.78
$TlCl$	2.25	BaO	1.98
TlI	2.78	BaS	2.16
SnI_4	2.106	CdO	2.49
		CaS	2.137

Juris Upatnieks, 21 September 1967

26 September 1967

Effect of phase-modulated wavefront on the appearance of the image.

One use of a phase-modulated wavefront would be to illuminate essentially two-dimensional microscopic specimens. Since phase-modulation of the image increases the spatial bandwidth of object, either better optical system must be used or else some degradation in the image quality can be expected.

If the signal is $s(x,y)$ and the phase ~~signal~~ wavefront is $v(x,y)$, then the resulting spectrum is $S*V$, where the capital letters the Fourier transforms of the inputs s and v. If S is near the diffraction limited bandpass of the optical system, then $S*V$ is likely to exceed this limit. For the case where $v(x,y)$ is well imaged by itself, some interesting results may be obtained when $S*V$ is present. For example, if $s(x,y)$ is a pure phase object, then $s(x,y)\,v(x,y)$ may give intensity variations where the product exceeds the bandpass. Since $v(x,y)$ is pure phase and is random in character, the intensity variations also will be random. If the inputs are of the form $s(x,y) = e^{j\alpha(x,y)}$ and $v(x,y) = e^{j\phi(x,y)}$, then intensity variations should exist whenever

$$\frac{d^2\phi(x,y)}{dx\,dy} + \frac{d^2\alpha(x,y)}{dx\,dy} \geq k\,\omega_{max}$$

where ω_{max} is the bandlimit of the optical system and k is the appropriate ~~c~~ constant. By varying the aperture at the transform plane ω_x max may be varied. Alternatly, $\phi(x,y)$ or additional random phase may be introduced in the reconstruction process, varying with time perhaps, and thus ~~high~~ phase lines of high spatial frequency content may be converted into intensity varying lines at the image plane.

Juris Upatnieks, Sept. 26, 1967

October 17, 1967 — witnessed by Jerry Zelenka Oct 18, 1967

Improvement of the brightness of multiple image holograms.

The idea of superimposing several holograms on the same plate is well known and has been demonstrated experimentally. The exposures are usually made so that the total exposure of the plate is same as for a single hologram. For example, if object intensity is I and T is time required to reach optimum density of the hologram, then assuming all objects to have same intensity the exposure for each hologram would be $I\left(\frac{T}{N}\right)$. Consequently, the brightness of each image is approximately $\frac{1}{N}$ as compared to a single exposure.

The brightness of each superimposed hologram can be increased by the following method. An exposure level is experimentally found which would give approximately linear recording or noise free reconstruction when bleached (density changed into index of refraction change). Experiments have shown that such bleached hologram has approximately the same diffraction efficiency as an optimum unbleached hologram. The multiple-image hologram is then made by exposing the film for each image for the same time as for a single-image hologram. Thus, the total exposure is ITN, or N times the normal exposure. Since after bleaching all density is changed into index-of-refraction changes, no light is lost due to absorbtion by the density of the exposed film. Furthermore, the index-of-refraction changes for each individual hologram remains the same provided that linear portion of the D&H curve is not exceeded. For the 649F emulsion a density of 3 to 4 can easily be reached and it should be possible to place several holograms on one plate without decreasing the brightness of each.

Juris Upatnieks, 17 October 196[7]

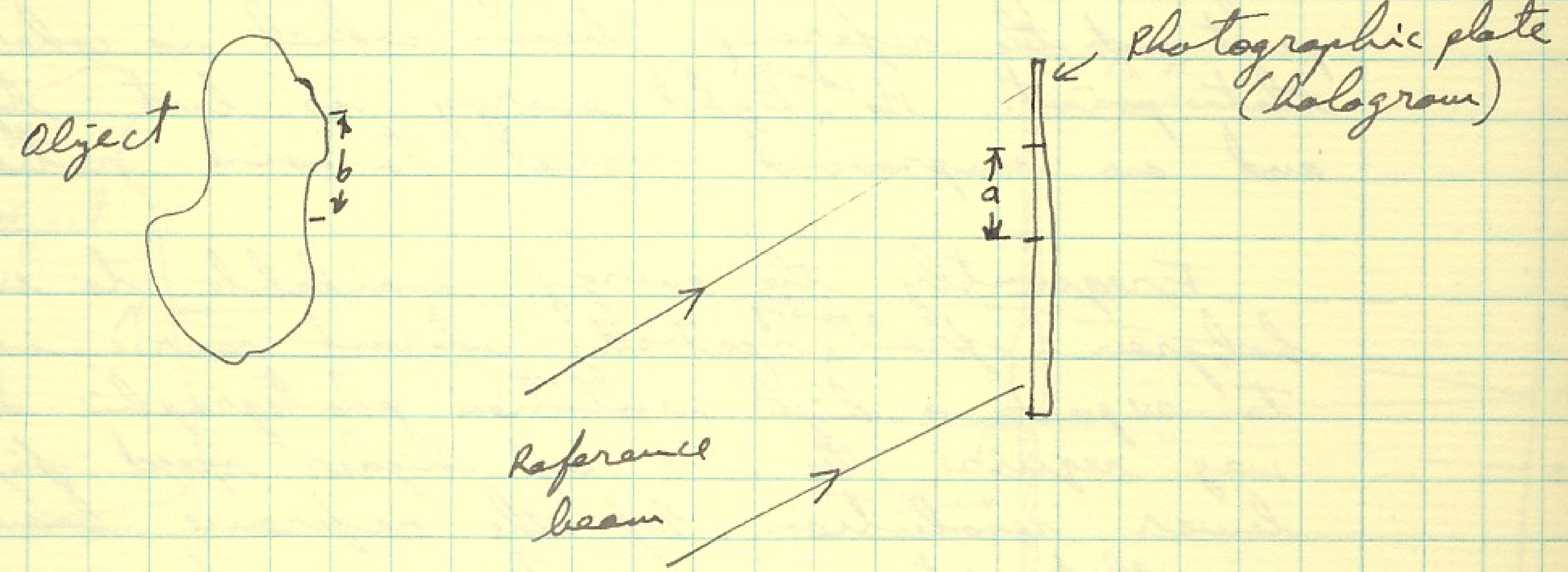
Read and understood by O. Friesem Oct. 20, 1967

October 18, 1967

witnessed by
Jerry Zelenka Oct 18, 1967

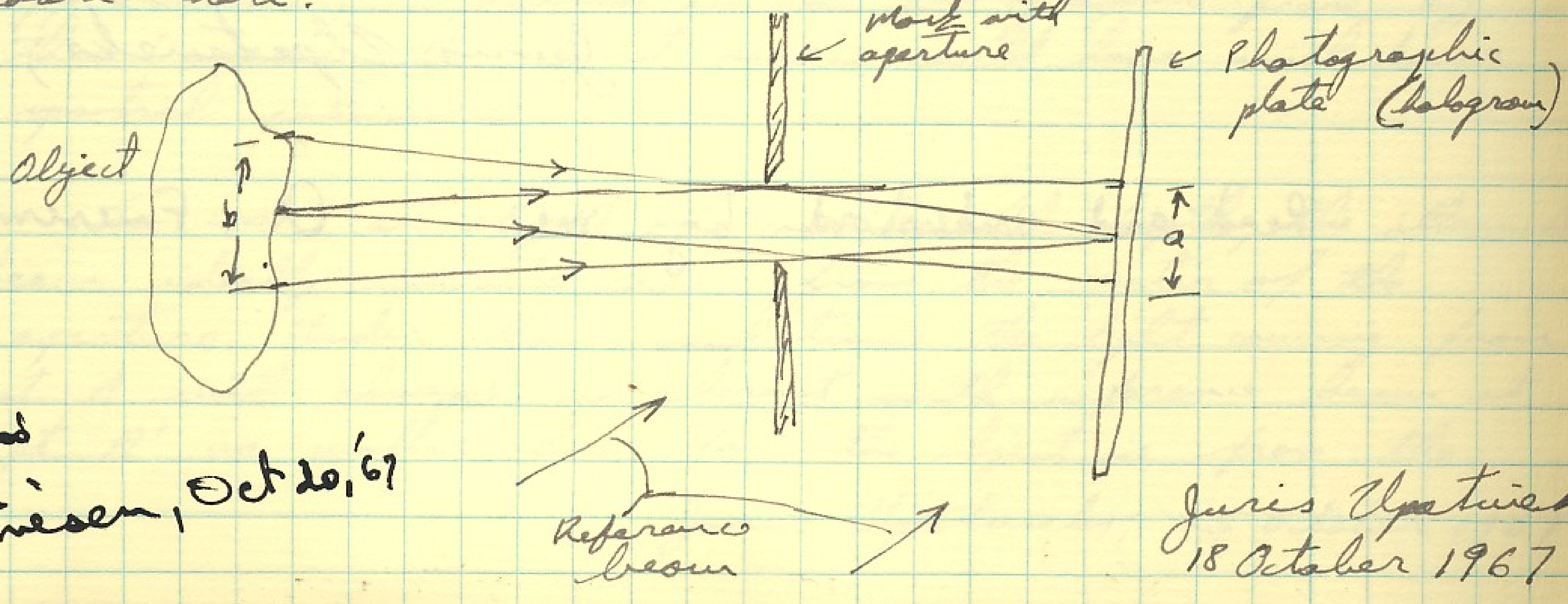
Holograms of three-dimensional objects with light sources having limited spatial coherence.

If holograms are made with light sources having poor spatial coherence, the hologram reconstructions are rather poor due to a large bias buildup. This is illustrated in the figure below:



If the reference beam has coherence over an area having diameter "a" and if the object has coherence over area of diameter "b", then light arriving from area "b" will be recorded over hologram area "a" and the rest of the light, being incoherent, will simply raise the uniform bias level of the hologram and consequently decrease the signal-to-noise ratio. The net result is that only part of the object can be seen from any point of the hologram.

The incoherent light can be eliminated from the hologram by inserting a restricting aperture between the object and the hologram recording plane, as shown here:



Read & understood by me A. Friesen, Oct 20, '67

Juris Upatnieks
18 October 1967

witnessed by
October 18, 1967 Jerry Zelenka Oct 18, 1967

By positioning the mask as shown in the figure, only those rays incoherent with the reference beam are obstructed and the coherent rays are allowed to reach the photographic plate. It is assumed here that the reference beam is positioned in such a way that the rays passing through the aperture ~~meet~~ from a given point on the object meet with a corresponding part of the reference beam which is coherent with that point. No coherent light energy is lost by this technique and an improoved signal-to-noise ratio will result.

Frequently the energy available to expose the hologram from a partly spatially coherent source is too low to expose a high-resolution photographic emulsion. This may require the use of higher speed film with lower resolution. If the reference beam is positioned so that it appears to come from a point close to the aperture of the mask, then the spatial frequencies can be made arbitrarily low choosing the proper mask-to-hologram distance. Also, the signal to noise ratio can be easily increased by several orders of magnitude using this technique since the mask in the reconstruction step will remove most of the scattered light from the object plane. If one desires to view the virtual image and see the whole scene at once, ~~it~~ a second hologram can be made from this one in a manner described earlier.

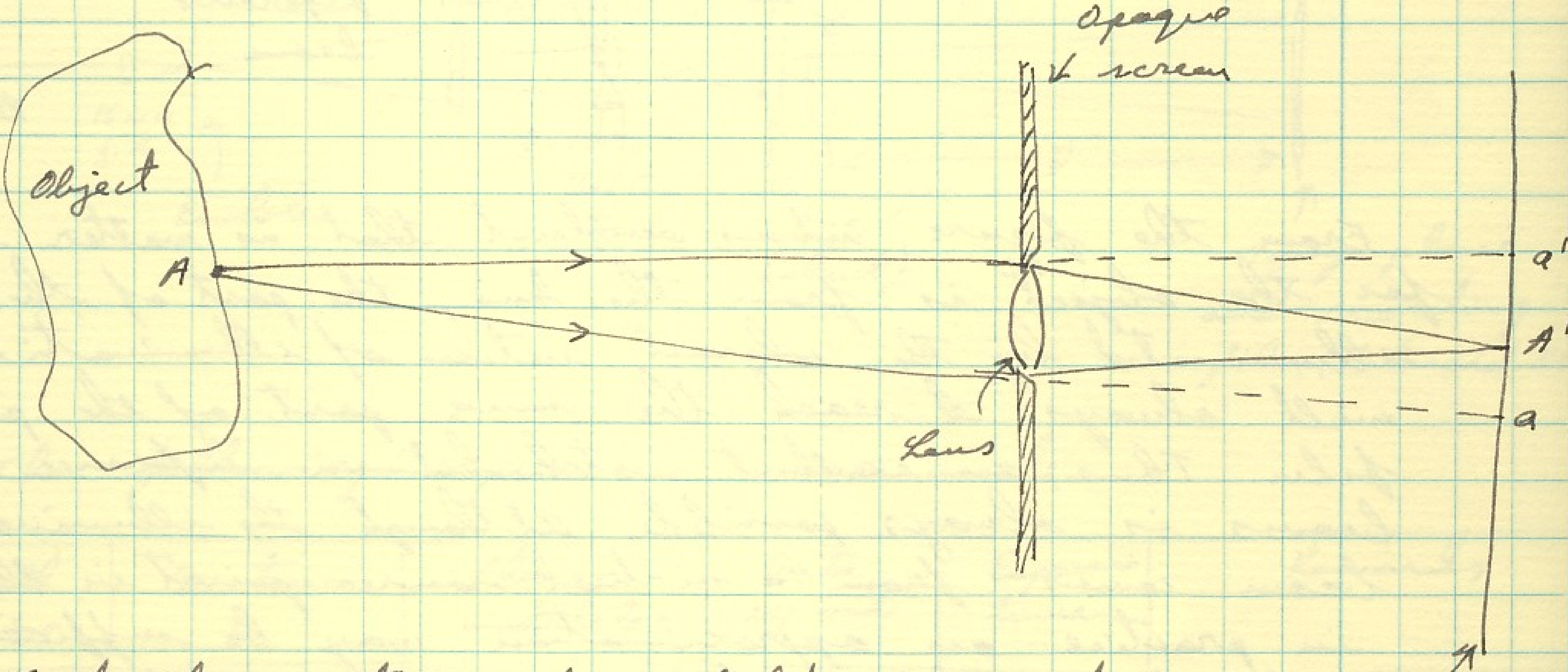
Juris Upatnieks, 18 October 1967

Read and understood by me A. Friesem Oct 20, '67

25 October 1967

Holograms made through restricting apertures.

The characteristics of holograms made with a restricting aperture in front of it has been described before. A relaxation of spatial coherence requirements can be achieved if a focusing element is placed at the aperture. Consider the figure below.



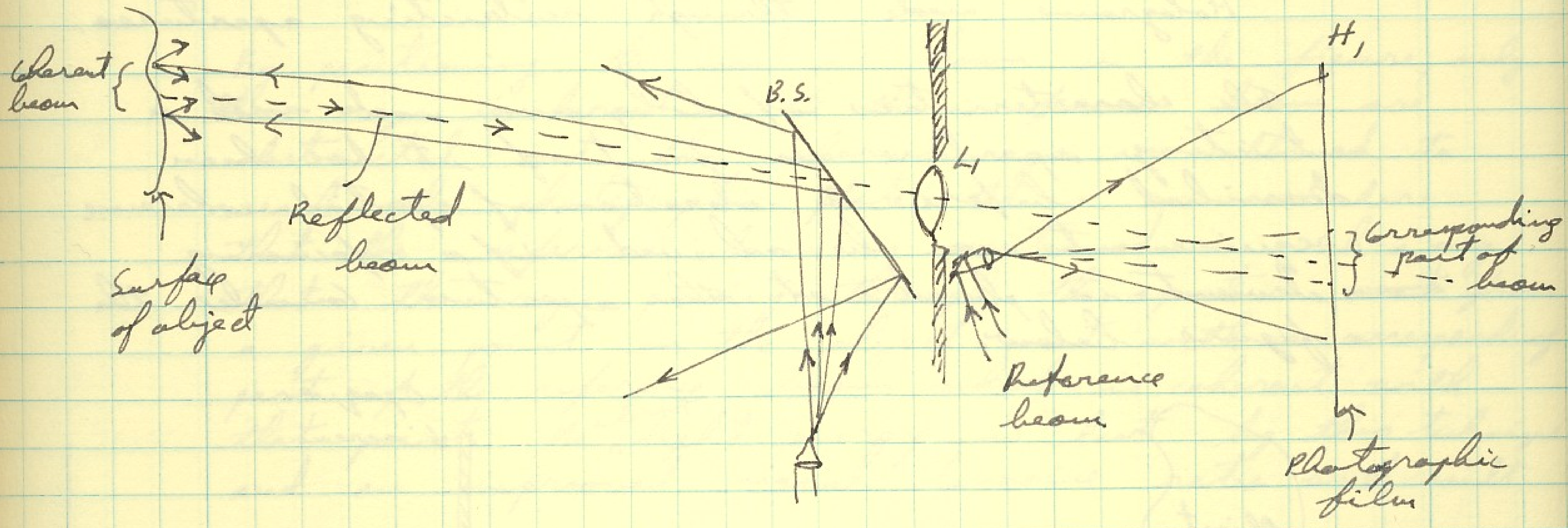
With the aperture alone, light from a pt. A on the object passes through aperture and falls an area a-a' on the hologram. If a partially coherent light source is used (good time coherence but ~~poor~~ poor spatial coherence), the the reference beam may manipulated that the area a-a' is illuminated by reference beam coherent with the light falling on pt. A. We may think of the aperture acting as a pinhole lens. The area a'-a can be reduced to a very small size by placing a lens at the aperture so that the image is approximatly focused on the photographic plate. By this means the light source could have much lower spatial coherence.

To cover an object of considerable depth, the illuminating beam ideally should come from the center of the aperture. Under these conditions the light coming from pt. A will always be coherent with reference beam at pt. A' no matter how far the object is from the

Juris Upatnieks, 25 October 1967

25 October 1967

aperture. This is illustrated below:



From the figure it is evident that no matter how far the object is from the lens, the part of the object illuminated by the coherent section of illuminating beam will always ~~to~~ reach the same part of the photographic film. Thus, an excellent match between reference and signal beams is always possible. Although the illuminating beam comes from a virtual source point in the lens, in practice an approximation may be sufficient, that of placing the point source to one side, near the aperture. The second hologram would be made by reconstructing hologram H_1 through the same lens. By this technique the effect of the lens L_1 would be completly removed and one could see the whole image at once from the position of the lens aperture. All the abberations introduced by the lens will also be removed.

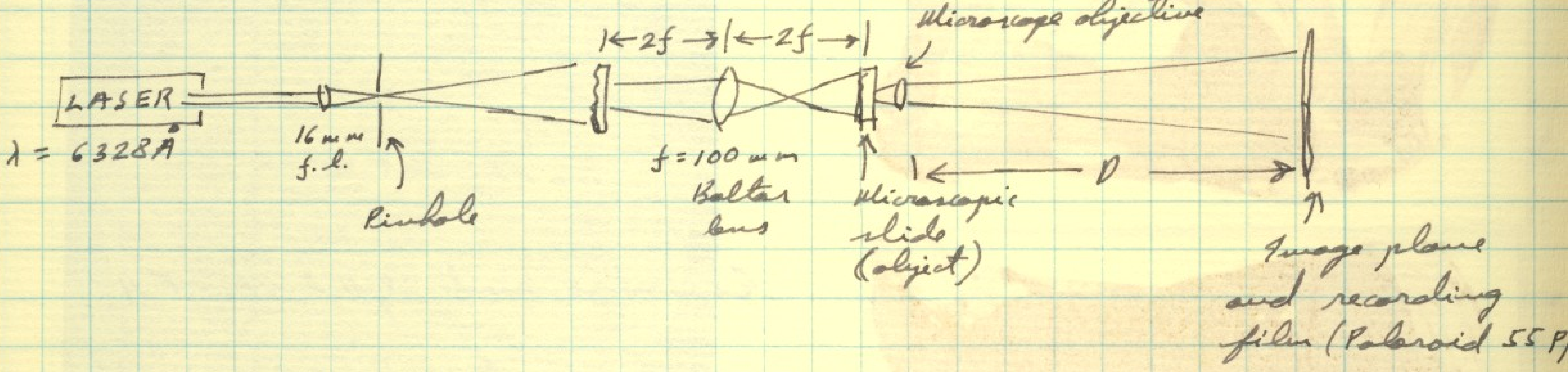
If we have a highly coherent light source, then a random phase plate may be placed in the aperture. By this means the object can be encoded in making hologram H_1 and decoded in making hologram H_2.

Juris Upatnieks, 25 October 1967.

31 October 1967

Experiments with phase-modulated wavefront illumination in microscopy.

Some experiments were performed to determine the quality of images one can obtain with coherent light and phase-modulated wavefront illumination. The following optical system was used:



The following exposures were made:

Negative #	Focal length of objective	Distance D	Phase-modulator	Date exp. made	Exposure time	Remarks
1	8 mm	65 cm	Plate #10, 8.5 l/mm	28 Oct. '67	1 sec.	Obj. Polystichum, overexpo
2	8 mm	65 cm	Plate #10, 8.5 l/mm	" " "	7/10 sec.	" " , ~~exp.~~ pos. light
3	"	"	" "	" " "	1/5 sec.	" " , pos. dark
4	"	65 cm	none	" " "	1/2 sec.	" " , exp. good
5	"	"	Plate #1, 25 l/mm	" " "	1 sec.	" " , pos. slightly da
6	4 mm	"	Plate #10, 8.5 l/mm	" " "	2 sec.	" " , exp. O.K.
7	"	"	none	" " "	2 sec.	" " , exp. O.K.
8	8 mm	"	Plate #10, 8.5 l/mm	" " "	2 sec.	no object, ~~or 100 mm lens~~ exp. O.K., no lens (1)
9	"	"	none	" " "	2 sec.	" " , exp. O.K. (1)
10	"	"	Plate #11, 16 l/mm	" " "	5/2 sec.	" " , exp. O.K.
1	8 mm	65 cm	Irregular glass plate	30 Oct 1967	3 sec.	no object or 100 mm lens
2	4 mm	"	" " "	30 Oct. 1967	5 sec.	" " " "
3	"	"	none	" " "	5 sec.	" " " "
4	"	"	ground glass	" " "	12 sec.	" " " "
5	"	"	none	" " "	15 sec.	Obj. snake skin, exp. O.K.

(1) For these exposures the 100 mm lens was removed and phase plate was moved to object position. This was done also for photographs 1-5 made on 30 Oct. 1967.

Juris Upatnieks, 30 October 1967

31 October 1967

Imaging through a microscope:

Exposure made 28 Oct. '67, #2

Magnification: X80
Objective: 8 mm f.l., N.A. = 0.50
Phase-modulated wavefront illumination.

Exposure made 28 Oct. '67, #4

Magnification: X80
Objective: 8 mm f.l., N.A. = 0.50
Plane wavefront illumination

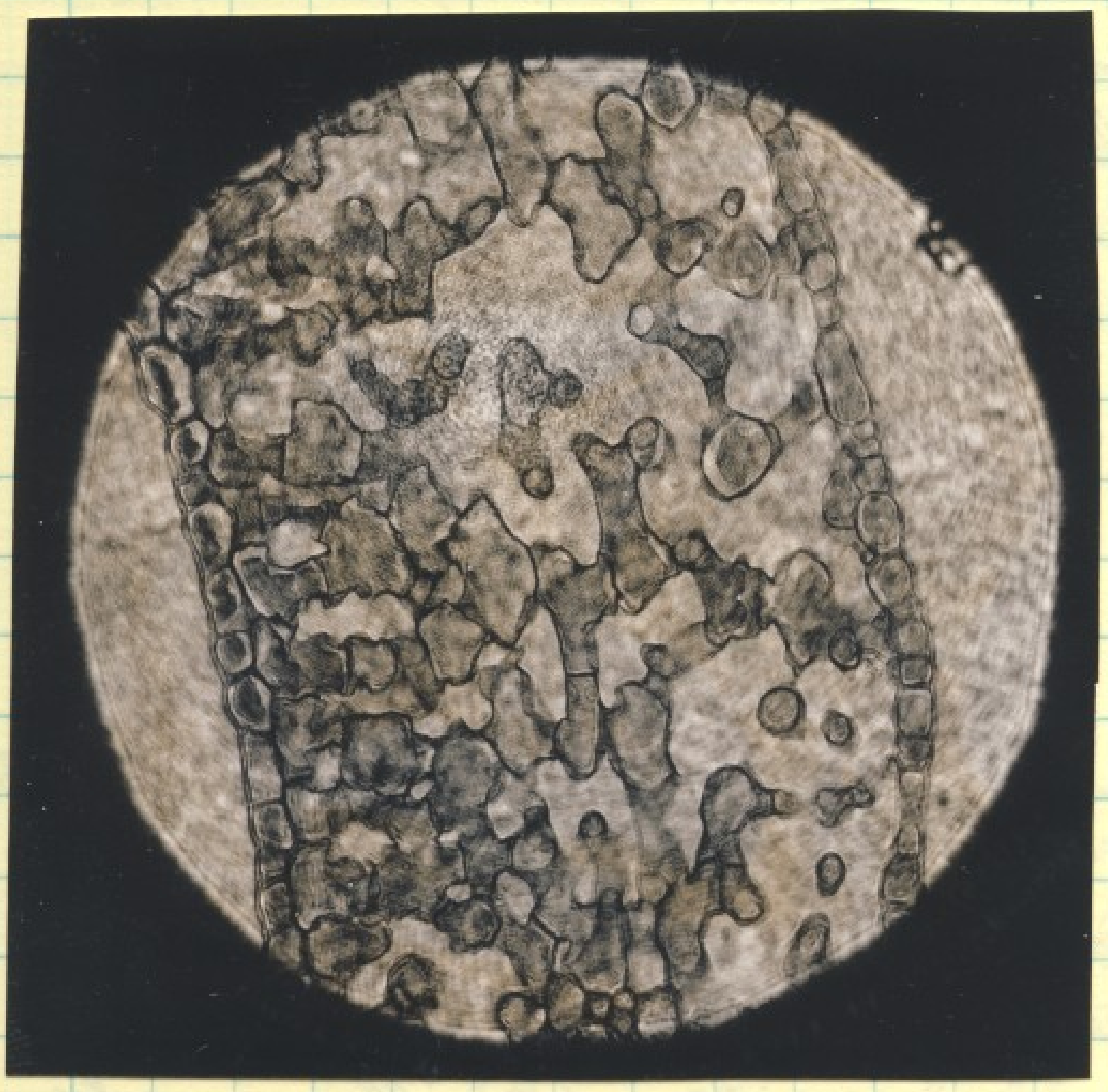
Exposure made 28 Oct. 1967, #5

Magnification: X80
Objective: 8 mm f.l., N.A. = 0.50
Diffuse wavefront illumination.

Juris Upatnieks, 31 October 1967

31 October 1967

The pictures with plane wavefront illumination show that the noise level is quite hight. The phase-modulation converts this noise into random pattern, but it is still quite appearant and distracting.

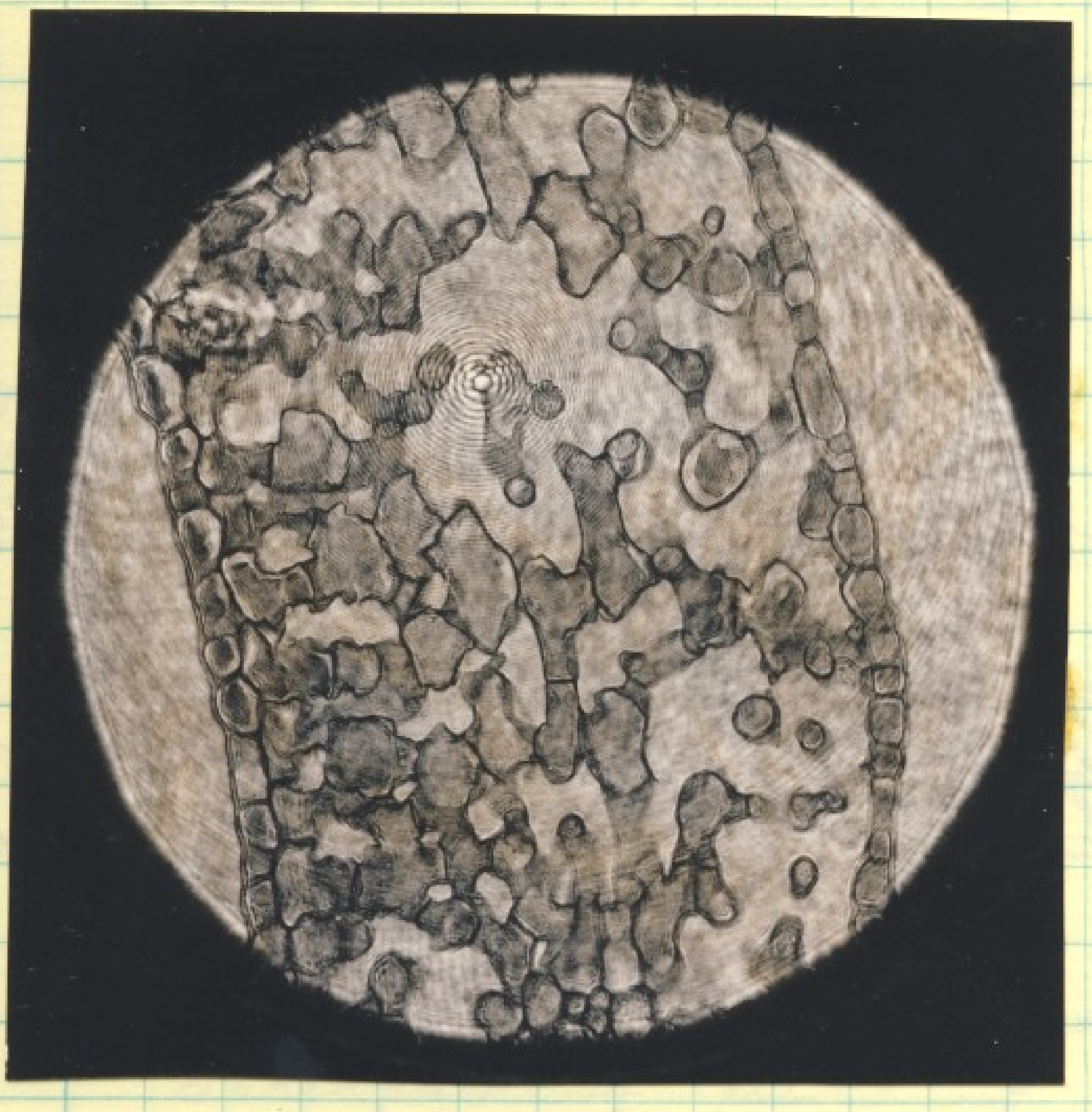


Exposure made 28 October 1967, #6

Magnification; X160

Objective: 4mm f.l., N.A.=0.65
Phase-modulated wavefront illumination.

Note that the ring structure below appears as an irregular intensity pattern here. The object is no longer completly washed in places by ring patterns.



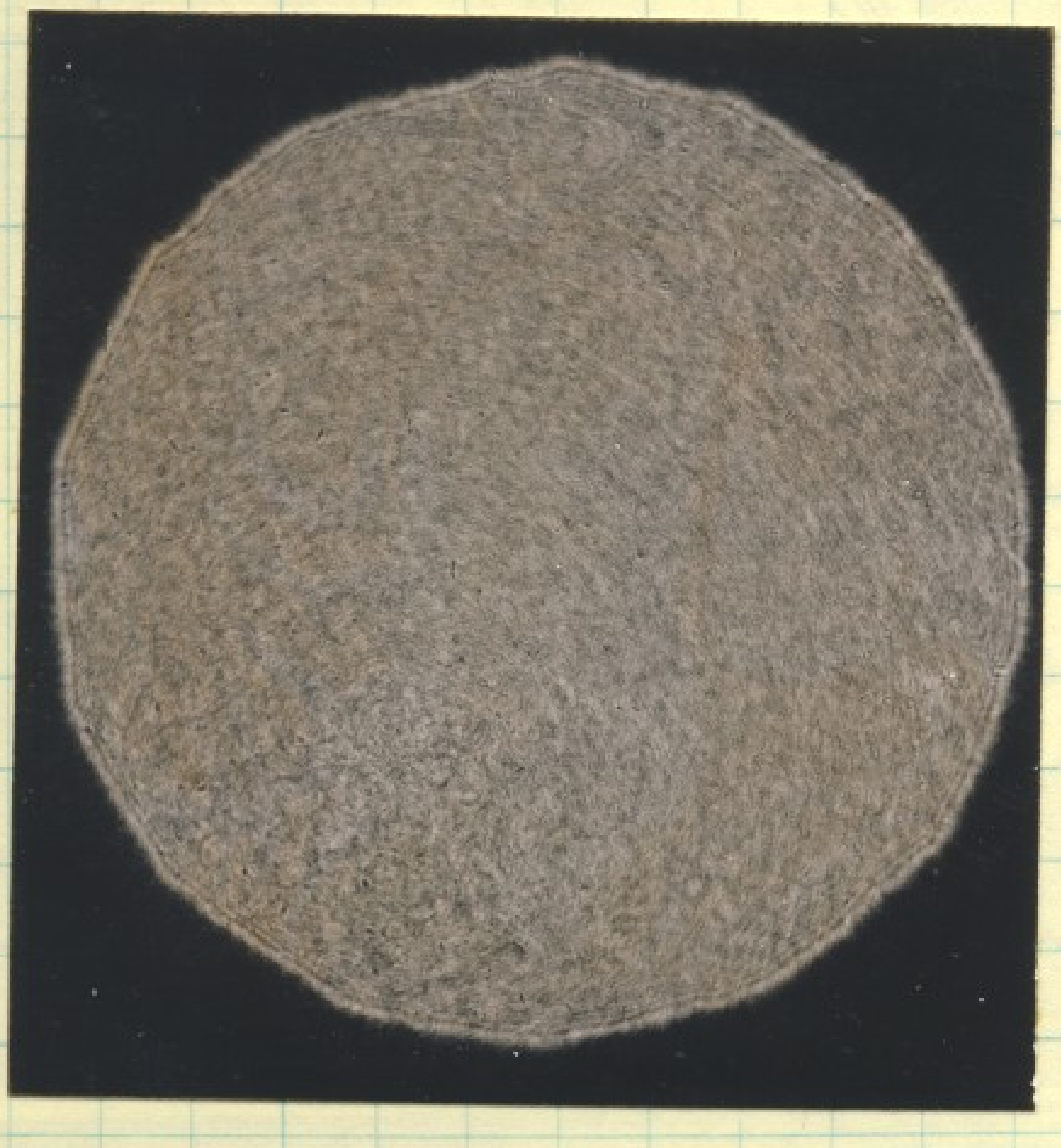
Exposure mad 28 Oct. 1967, #7

Magnification: X160
Objective: 4mm f.l., N.A.=0.65
Plane wavefront illumination

The concentric rings are probly from glass-air surface reflections.

Juris Upatnieks, 31 October 1967

31 October 1967

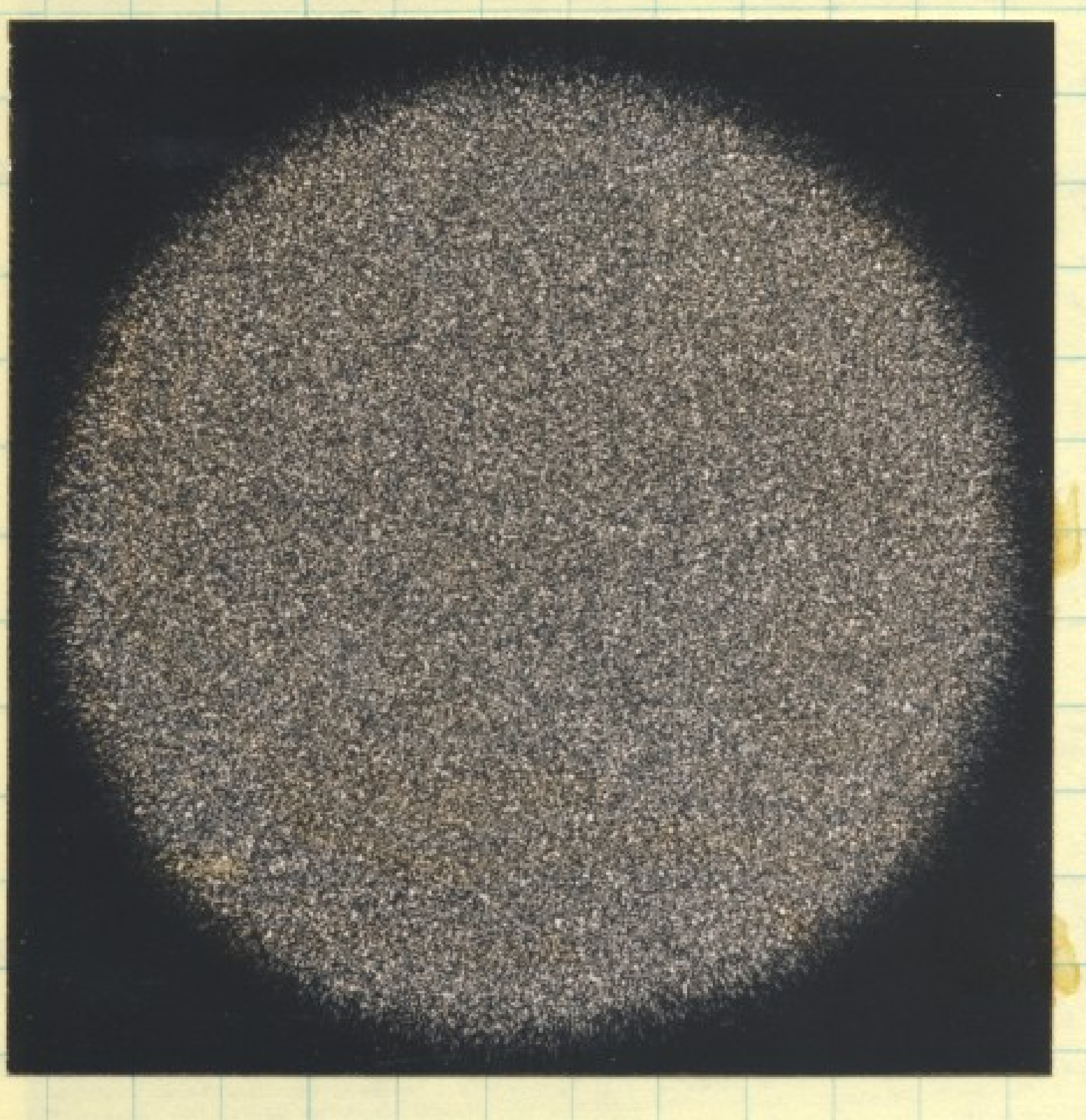


Exposure made on 30 October 1967, # 2

Magnification: X 160
Objective: 4 mm f.l., N.A. = 0.65
Phase-modulated wavefront illumination

Exposure made on 30 October 1967, # 3

Magnification: X160
Objective: 4 mm f.l., N.A. = 0.65
Plane wavefront illumination



Exposure made on 30 October 1967, #4

Magnification: X160
Objective: 4 mm f.l., N.A. = 0.65
Diffuse illumination wavefront

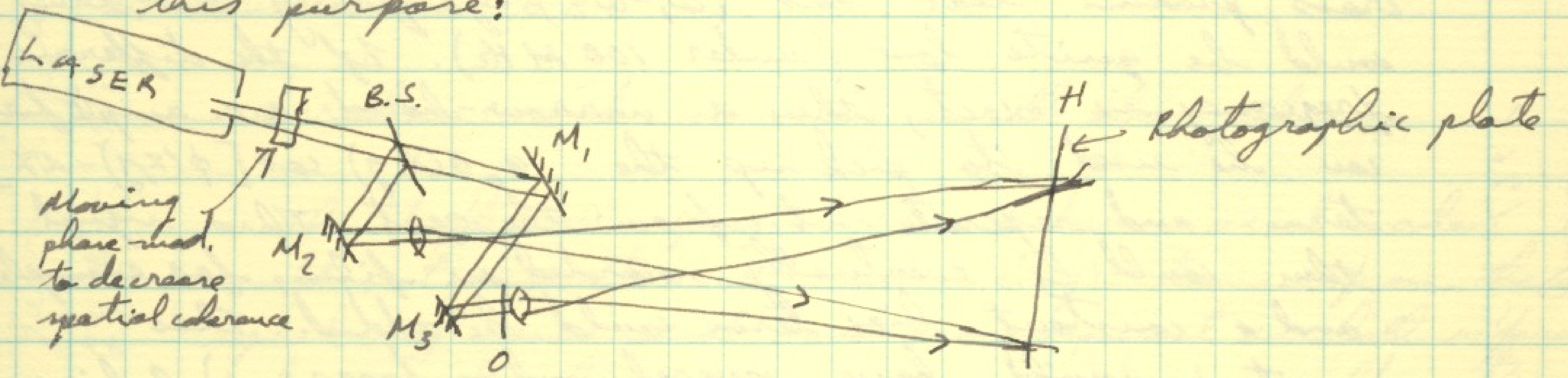
Juris Upatnieks, 30 October 1967

2 November 1967

Reduction of noise level due to scattered light by use of partially coherent light.

The microscopic images on the previous pages show that the noise level is rather high due to various optical elements in the imaging system. The use of phase-mod. wavefront breaks the noise into random pattern, but the level remains just as high. Some improvement in signal-to-noise ratio could be achieved by the use of partially coherent light if two conditions are satisfied: 1) the image is nearly in focus, and 2) the imaging system (lenses) can be considered to be space invariant, that is, they have the ideal properties of a perfect lens. If these properties are satisfied, then a light source with partial spatial coherence could be used and the techniques of superimposing corresponding parts of the same wavefront at the hologram plane could be employed. Since the light, both in signal and reference beams, would be coherent over only a small area dA, then light scattered by defects of the imaging system would be incoherent with other areas except area dA. Thus, if the noise is scattered over a large area compared to dA, considerable reduction in noise level would be possible.

An optical system as shown below could be used for this purpose:



The optical system would be carefully adjusted so that corresponding parts of the wavefront would match exactly at the hologram plane. Object O would be positioned to come to focus at plane H. Coarseness of moving phase plate would determine degree of spatial coherence. Because of decreased coherence this system would be affected less by noise in lenses & other parts. A phase-mod. still could be used behind the object.

Juris Upatnieks, 2 November 1967

21 November 1967

Removing of intermodulation terms in a hologram electronically (by filtering in time domain).

If a hologram pattern is to be read off by a scanning device, such as a photomultiplier tube or a TV-image pickup tube, then it could be advantageous to use two light frequencies that are ~~of~~ slightly different. The resulting a.c. signal could be filtered and separated from the intermodulation terms usually present in a hologram, ~~too~~ and the bandwidth requirement could be reduced by one-half. Consider the signals

$$u_0 = a_0 \cos(\alpha x - j\omega_1 t) \qquad \text{reference signal}$$

$$u = a(x,y) \cos[\phi(x,y) - \omega_2 t] \qquad \text{information bearing signal}$$

The average intensity of this signal is then proportional to $\langle (u_0+u)^2 \rangle$, or

$$\langle (u_0+u)^2 \rangle = \tfrac{1}{2} a_0^2 + \tfrac{1}{2} a^2(x,y)$$

$$+ \langle a_0 a(x,y) \cos[\phi(x,y) - \alpha x + (\omega_1-\omega_2)t] \rangle$$

Before averaging, the other coefficients had frequencies of approximately 2ω associated with them except the cross product that has $(\omega_1-\omega_2)$ frequency and thus could be quite low (under 100 MHz). If the difference frequency is exact, then a narrow-band a.c. amplifier can be used to pick up the $a_0 a(x,y) \cos[\phi(x,y) - \alpha x]$ term and separate it from the rest. This signal then could be eventually recorded on film, for example, and a constant bias term could be added. This system would have several advantages: 1) a bias term could be introduced which could be constant and therefore independent of $a^2(x,y)$, and, since narrow-band amplifiers tend to be relatively noise-free, the relative values of a_0 and $a(x,y)$ would not greatly affect the image quality; 2) ~~&~~ since the intermodulation terms

Juris Upatnieks, 21 November 1967

Read and understood O. D. Friesen 29 Nov. '67

Read and understood, Jerry S. Zelenka 29 Nov. 1967

21 November 1967

terms are removed from the cross-product term, the spatial carrier frequency could be reduced by one-half thus decreasing the required bandwidth for transmission of the hologram signal ; 3) Since the difference frequency for many lasers is of the order 80 – 200 MHz, the signal could be directly amplified for transmission and thus simplify required electronic circuitry.

Ideally the object should be illuminated with light waves having frequency ω_2 and the reference signal should have frequency ω_1, such that the difference $(\omega_1 - \omega_2)$ is approximately constant. This might be difficult to achieve in practice, but fortunately lasers ordinarily have several axial modes where ~~difference~~ frequencies are separated by multiples of $(\omega_j - \omega_i)$, where i and j are two adjacent modes. The sum of all the adjacent difference frequencies then could be used as the $(\omega_1 - \omega_2)$ frequency. Phase locking may be required, but that can be easily achieved in practice.

Some arbitrary difference frequency could be generated by modulating one of the beams or else changing the path to generate a doppler shift in frequencies. Juris Upatnieks, 21 November 1967.

Read & understood A. A. Friesem 29 Nov. '67

29 November 1967

Corrections and comments on the above idea.

The difference frequencies between axial modes would not separate a_0^2 and $a^2(x,y)$ terms from the desired signal if some axial modes are present in both reference and signal beams, since a_0^2 and $a^2(x,y)$ would contain the same difference frequencies. If a laser is operating in, say, two transverse modes, then these transverse modes can be separated by spatial filtering and one mode could be used for a reference and the other for illuminating the object. The difference frequencies between transverse and axial modes generally are not the same.

Juris Upatnieks, 29 November 1967

Read and Understood Jerry S. Zelenka 29 Nov. 1967

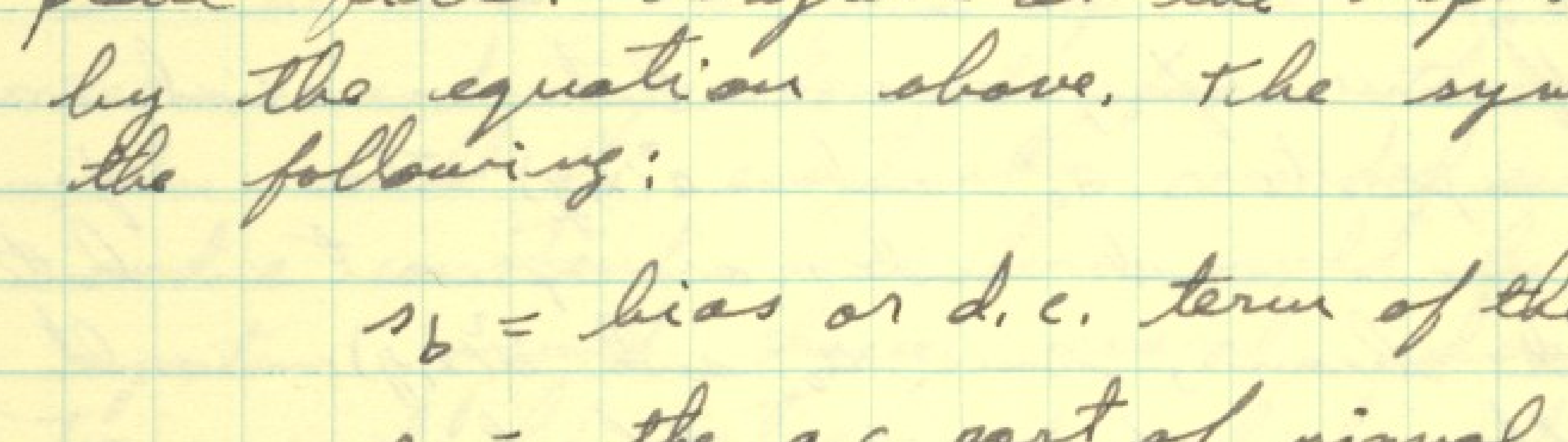
11 January, 1968

Recovery of high-quality images from holograms made with half-plane filtering.

A technique for making and reconstructing holograms using half-plane filtering was described by Lohmann [Optica Acta (Paris) 3, 97 (1956)] and was described from communications theory point of view later [Leith and Upatnieks, J. Opt. Soc. Amer. 52, 1123 (Oct.'62)]. The hologram obtained was described in the later paper as:

$$\chi\chi^* = s_b^2 + s_b(s_r * f * g) + s_b(s_r * f * g)^* + |s_r * f * g|^2$$

A high quality image can be recovered from such hologram if spatial filtering is used with a lens half o which is positive and half of which is a negative lens. This type of filtering operation was described a paper "Requirements for Hologram Construction", Leith, Kozma, and Upatnieks, Proceedings - Spring Joint Computer Conference, 1966, in connection with a hologram produced in a different way. The optical system ~~of~~ was as follows; but now we place a half-~~f~~



plane filter hologram at the input which is described by the equation above. The symbols above mean the following:

s_b = bias or d. c. term of the signal

s_r = the a.c. part of signal

f = dispersion function

$g = \frac{1}{2}\delta(x) + \frac{i}{\pi x}$ = Hilbert transform of a half-plane filter

Juris Upatnieks, 11 January 1968

11 January 1968

The 2nd and 3rd terms in the first equation contain one half of the spatial frequency spectrum of the signal. By proper choice of the lens L_2 we can multiply each half of the spectrum in the reconstruction process f^* and f, and we get the imaged signal s_i which is

$$s_i = s_b^2 + s_b(s_r * f * g) * f^* + s_b(s_r * f * g)^* * f + \cdots$$

$$= s_b^2 + s_b(s_r * g) * f * f^* + s_b(s_r * g)^* * f^* * f + \cdots$$

$$= s_b^2 + s_b(s_r * g) + s_b(s_r * g)^* + \cdots$$

Substituting $g = \frac{1}{2}\delta(x) + \frac{i}{\pi x}$, we get

$$s_i = s_b^2 + s_b s_r * \left(\tfrac{1}{2}\delta(x) + \tfrac{i}{\pi x}\right) + s_b s_r^* * \left(\tfrac{1}{2}\delta(x) - \tfrac{i}{\pi x}\right) + \cdots$$

$$= s_b^2 + s_b\left(\tfrac{1}{2}s_r + \tfrac{1}{2}s_r^*\right) + s_b(s_r - s_r^*) * \left(\tfrac{i}{\pi x}\right) + \cdots$$

If s_r is a real signal, then

$$\boxed{s_i = s_b^2 + s_b s_r} + \text{intermodulation terms}$$

Thus we have recovered the signal as though the complete spectrum of the signal was recorded, and yet we have eliminated the conjugate image term. Above s_b is a constant and therefore not important. The recovered image with half-plane filtering in both construction and reconstruction contained the term $-\frac{1}{2} s_b s_r * \left(\frac{i}{\pi x}\right)$ which was quite annoying. In this case it is completely eliminated. The noise term $|s_r * f * g|$ could be made small by increasing the bias term.

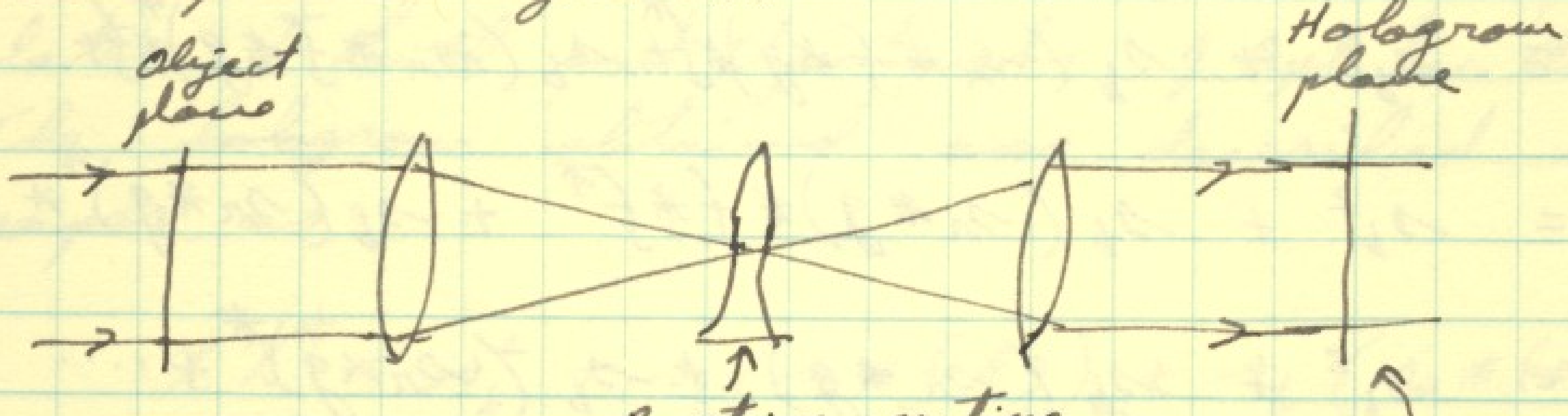
It should be noted that the elimination of the extraneous term occurs only if the input signal s_r is real.

Juris Upatnieks, 11 January 1968

18 January 1968

Recording and reconstruction of phase object using positive-negative lens in transform plane.

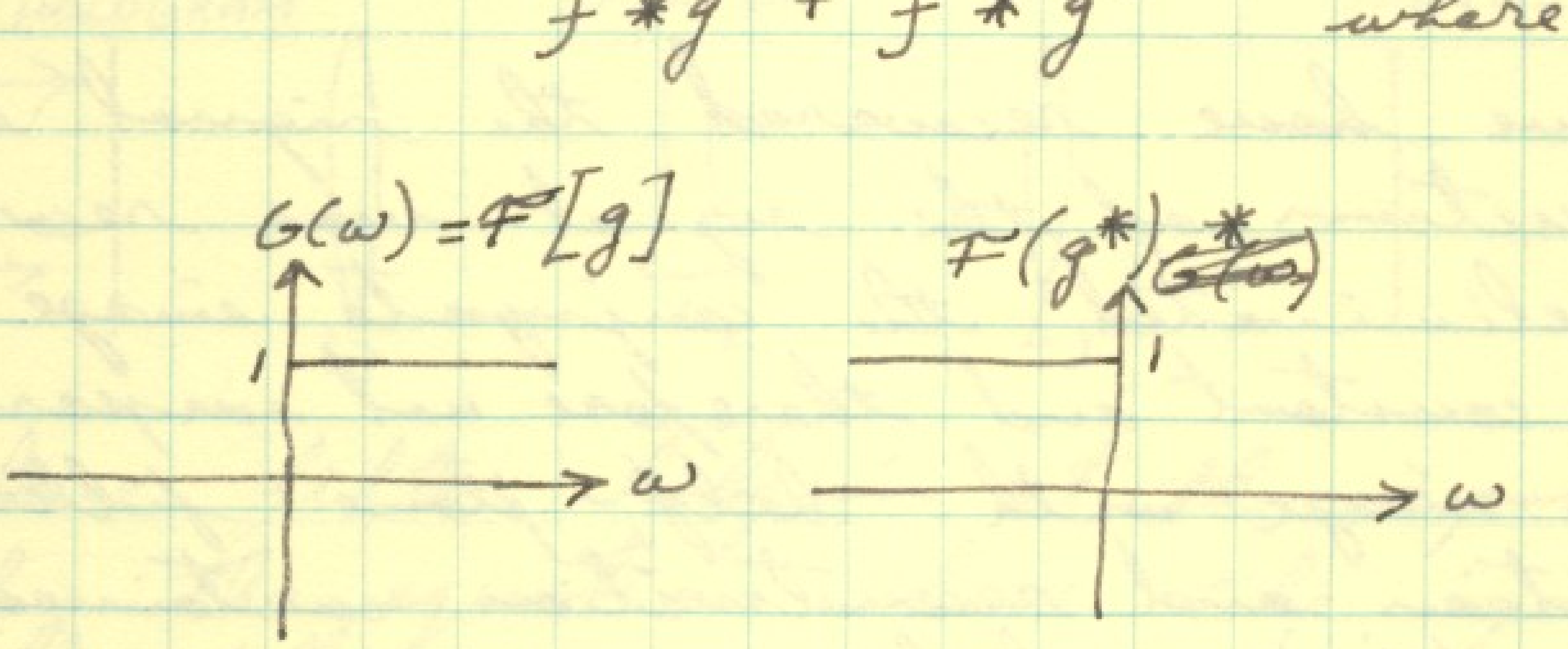
In the paper "Requirements for Hologram Reconstruction", Proc. Spring Joint Computer Conf. 1966, describes a technique of making holograms with this optical system:



The question will be considered here as to what is reconstructed if the input signal is complex, that is, if it is a phase object.

The effect of the filter on the signal at the hologram plane can be described by

(1) $$f * g + f^* * g^*$$ where $f \propto e^{jk(x^2+y^2)}$ is the dispersion factor, g is the half-plane filter



In the reconstruction process the lens in filter plane is reversed and the action of the filter can be described by

(2) $$f * g^* + f^* * g$$

The * indicates conjugate and $*$ indicates convolution.

Juris Upatnieks, 18 January 1968

18 January 1968

Some of the properties of the Hilbert transform, and of function f, are listed here:

$$g * g = g \qquad f * f^* = 1$$

$$g * g^* = 0 \qquad f * f = 2f$$

$$g^* * g^* = g^*$$

Let the signal be $s = s_b + s_r$, where s_b is the average transmitted term, the d.c. term, and s_r is the a.c. signal, a complex number. At the hologram plane we get a signal X which is

$$X = s_b + s_r * f * g + s_r * (f * g)^* \qquad (3)$$

The film records

$$XX^* = s_b^2 + s_b(s_r * f * g) + s_b(s_r * f^* * g^*) + s_b(s_r * f * g)^*$$
$$+ s_b(s_r * f^* * g^*)^* + |s_r * f * g|^2 + |s_r * f^* * g^*|^2 \qquad (4)$$

The recorded hologram signal is reconstructed through the filter expressed by eq (2), and using above Hilbert transform relations and filter relations, we get

$$XX^* * [f * g^* + f^* * g] = s_b^2 + s_b s_r * g + s_b s_r * g^* + s_b s_r^* * g^*$$
$$+ s_b s_r^* * g + \text{intermodulation terms} \qquad (5)$$

$$= s_b^2 + s_b s_r * (g + g^*) + s_b s_r^* * (g^* + g) + \text{intermod. terms}$$

$$= s_b^2 + s_b s_r + s_b s_r^* + \text{interm. terms}$$

since $g + g^* = \delta(x)$

$$= s_b^2 + s_b \operatorname{Re} s_r + \text{intermodulation terms}$$

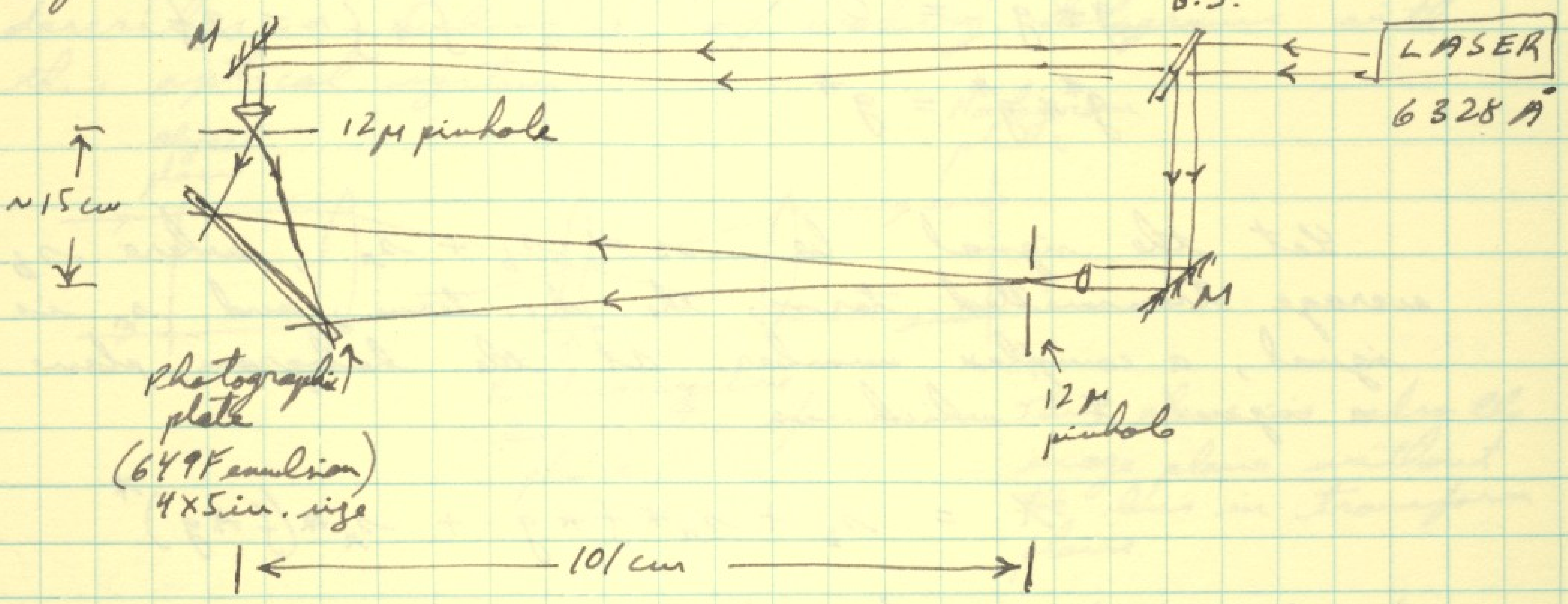
∴ The hologram reconstructs the real part of the original signal.

Juris Upatnieks, 18 January 1968

1 February 1968

Imaging with Fresnell lens made by recording interference pattern between two beams and bleaching it.

Zone plates were made with the optical system below:



The recorded interference pattern was then bleached in modified R-10 bleach to improve diffraction efficiency, and then it was used to image a transparency consisting of transparent ~~background~~ letters on opaque background. The transparency was illumintrated with incoherent (spatially) laser light obtained by moving a diffusing screen in the laser beam. To obtain the conjugate of one beam for best resolution, a lens was used to image the transparency 101 cm in front of the hologram, as shown below:

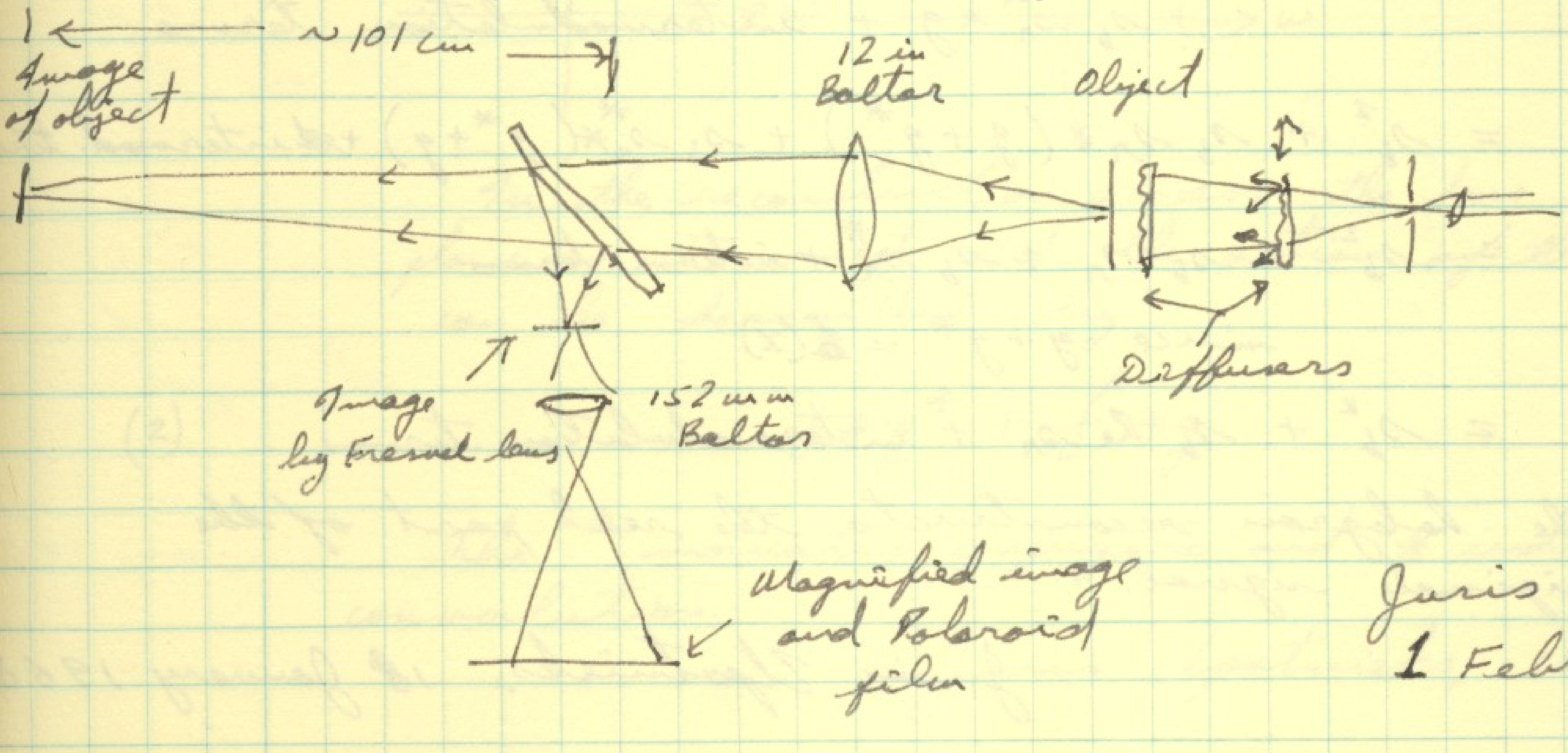


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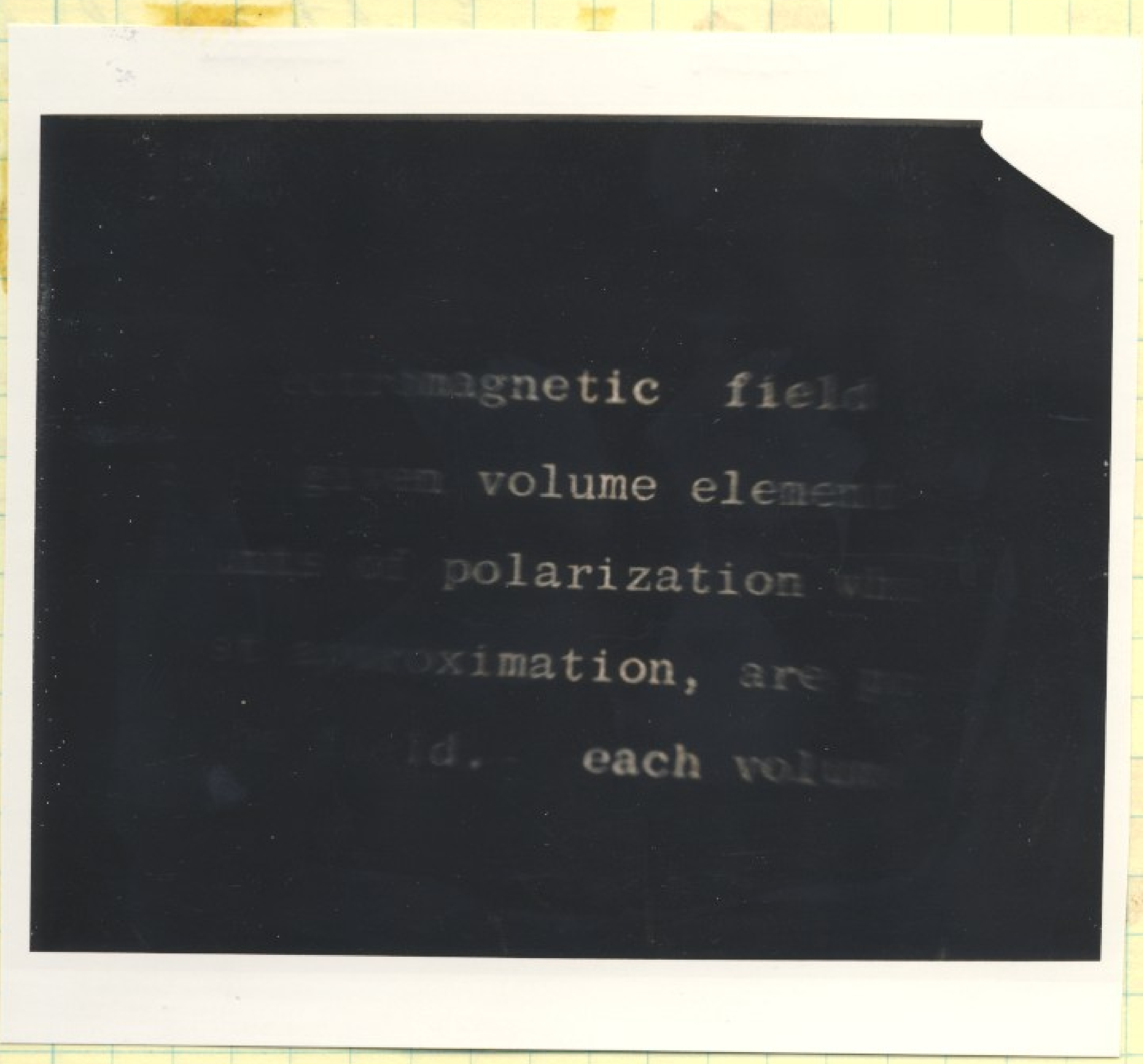
Image with a single zone plate, made on 18 December 1967. 40 mm aperture, focal length $\sim$ 30 cm, f-8, 4 sec. exposure. Half-power points are approximately $\pm 2\frac{1}{2}^\circ$ from the center. Note that abberations increase quickly in directions away from best focus.



This image is same as above but with a 10 mm aperture, or f-32. Exposure made on 18 December 1968.

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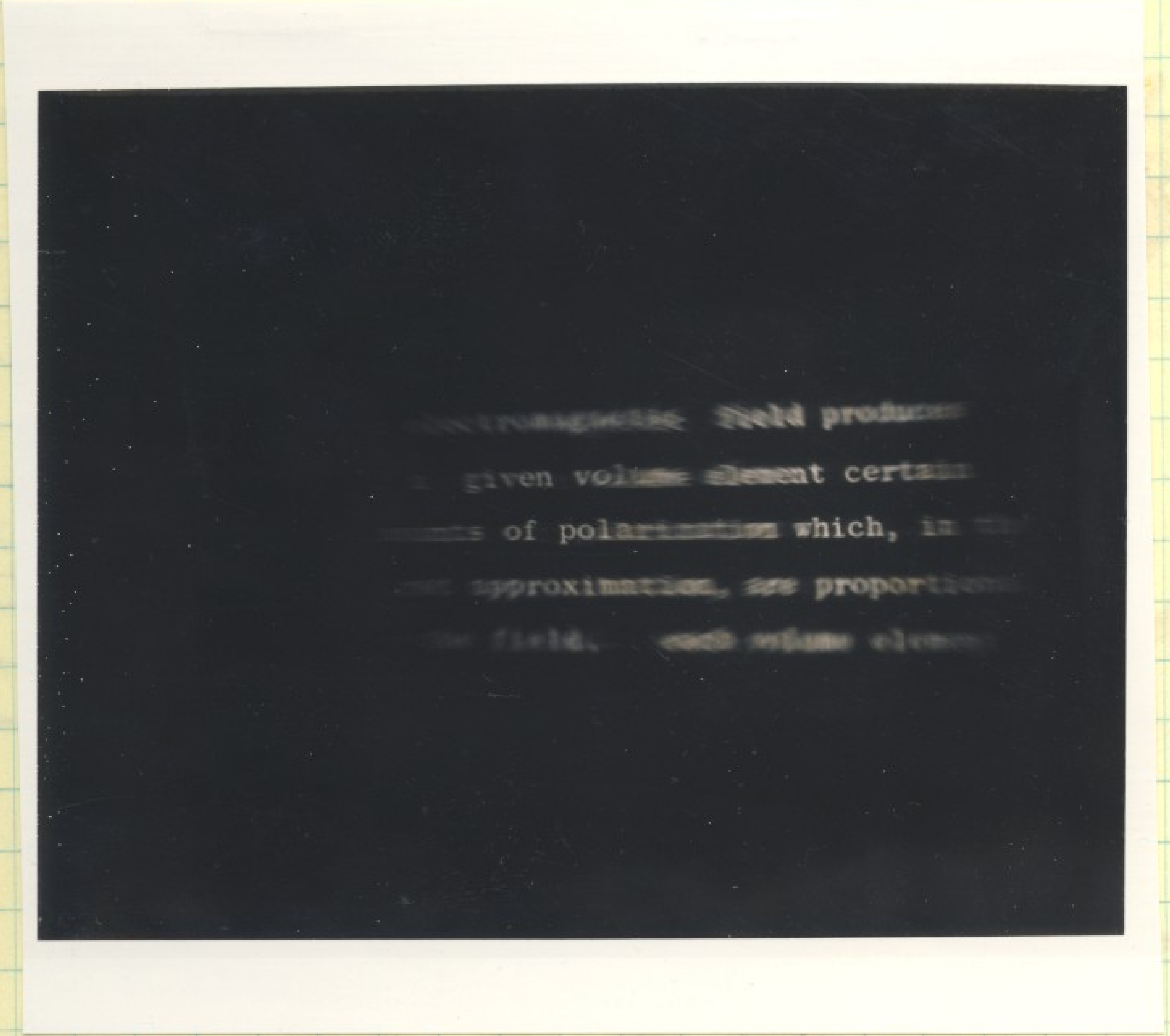

Image with a double zone plate, having 2½° separation between them. Exposure made on 4 January 1968, aperture 10 mm, focal length ~11.5 cm, f-11, exposure time 100 sec. The two areas at which each zone plate gives a sharp image is clearly visible.

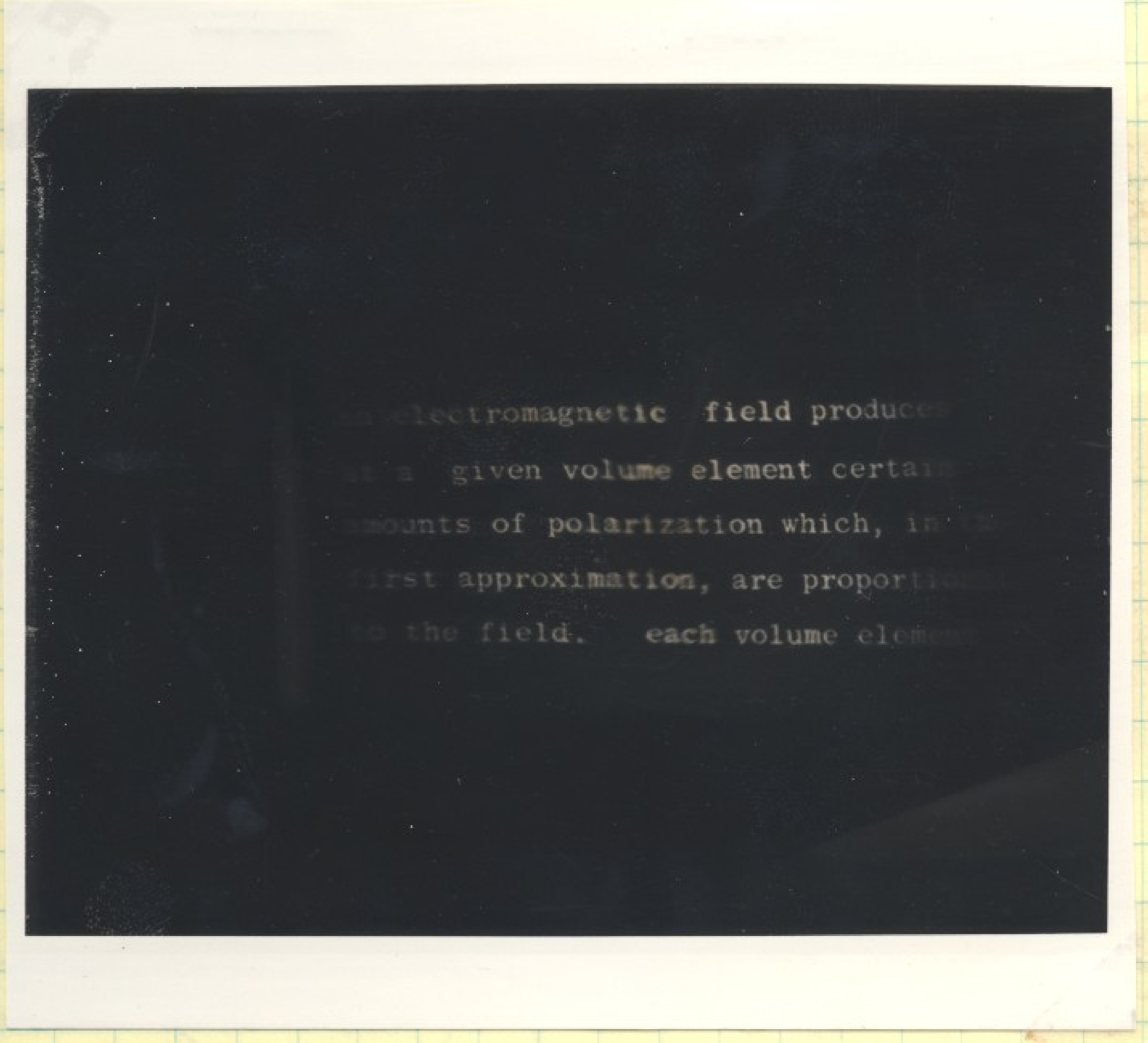

Image with same double zone plate as above, made on 4 January 1968. Exposure was 15 min., aperture 3 mm, aperture f-35. Note that image is good over the whole field of view, thus demonstrating that improved imaging can be obtained with multiple zone plates.

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1 February 1968

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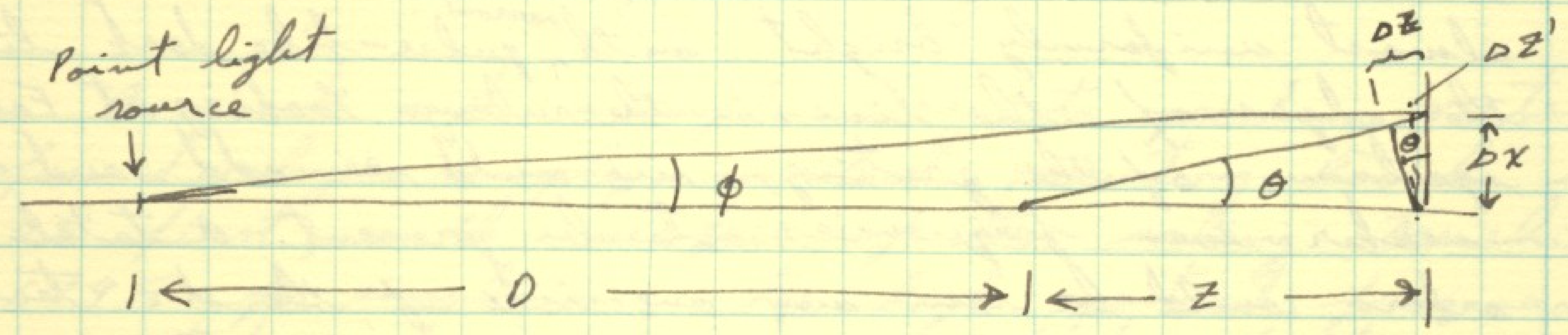
Calculation of the distance at which a periodic structure repeats, or "focuses" by itself.

Consider the diagram below:



The object (goal) is to find Z for which the object, such a grating, appears to be in focus. The following relations are evident from the geometry:

$$\sin \theta_n = n \frac{\lambda}{d_0} = n \lambda f_0 = ~~\frac{\Delta Z}{\Delta X}~~ \approx \frac{\Delta X}{Z}$$

J. U. 17 May '68

where $n = 0, 1, 2, \ldots$, f_0 is fundamental spatial frequency, λ is the wavelength of light, and d_0 is spatial period. We must find Z such that $\Delta Z - \Delta Z' = N\lambda$, where $N = 0, 1, 2, 3, \ldots$.

$$\sin \phi = \frac{\Delta X}{D + Z} \quad \text{and} \quad \Delta Z' = ~~\Delta X \sin \phi~~ = \frac{(\Delta X)^2}{D+Z}\left(\frac{1}{2}\right.$$

J. U. 17 May '68

Also $$\Delta Z = \frac{(\Delta X)^2}{2Z}$$

From which we get $$\Delta Z - \Delta Z' = (\Delta X)^2 \left[\frac{1}{Z} - \frac{1}{D+Z}\right]$$

$$\Delta Z - \Delta Z' = N\lambda = (n \lambda f_0 Z)^2 \left[\frac{D}{2Z(D+Z)}\right]$$

Factor of 2 added 17 May 68 J.U.

From which we get

$$\boxed{Z = \frac{2N}{(nf_0)^2 \lambda - \left(\frac{N}{D}\right)}}$$

We see that for collimated beam $D \to \infty$ and $Z = \frac{2N}{(nf_0)^2 \lambda}$

To test this equation, an experiment was set up with a

Juris Upatnieks, 1 February 1968

1 February 1968

Ronchi ruling (grating) having fundamental spatial frequency of 3.2 lines/mm and this was inserted in a diverging laser beam. The pattern repeated itself at distances as predicted by the equation on the previous page. It was also observed that at distances at which $\Delta z - \Delta z' = \frac{1}{2}\lambda$ the field became almost uniformly bright with narrow pulse-like dark lines at the edges of the lines in the ruling. Looking at Fourier spectrum of the grating, one could see odd and also weaker even frequencies to be present. A total of 70 orders could be seen on one side of the d.c. term.

Juris Upatnieks, 1 February 1968.

23 April 1968

The production of phase gratings.

For the purpose of testing the concepts of self-imaging gratings and their use to produce uniform amplitude fields, phase gratings had to be constructed with spatial frequencies in the range 3 to 10 lines/mm. It was decided to produce these by bleaching photographically recorded gratings, using the standard Kodak R-10 bleach. A number of techniques were tried.

The Mach-Zehnder interferometer was set up to form low-frequency interference patterns using collimated light. The bleached grating was very noisy due to phase errors introduced by bleaching scattered light patterns from dust and bubbles in the glass. This effect could be reduced by using spatially incoherent light and employing some

Juris Upatnieks, 23 April 1968.

23 April 1968

wavefront matching system. Another way would be to use an unbleached grating and image it using incoherent light and filtering in the transform plane. These techniques seemed somewhat cumbersome and were not tried experimentally.

A good and simple way to produce gratings was found by simply contact printing Ronchi rulings. At first, with surface of the ruling touching the 649F ~~f~~ emulsion, too high spatial frequencies were created and uniform amplitude field could not be attained. This was so because the bleached pattern was essentially a phase step function. Improved results were obtained by spacing the ruling 1/8 to 1/32 in. away from the emulsion and using a broad diffuse light source for illumination (an enlarger with lenses removed and at max. height). The most suitable grating was obtained with 1/32 in. spacing and exposure to give a density of D = 1.0 before bleaching.

To get better dispersion of moire effects, a crossed grating is desirable. Difficulty was encountered at first because the crossed grating seemed to have abberations and each orientation would come to focus at a different plane. Using a cylindrical lens correction could be made for one "in-focus" plane, but not for all. It was found that this was caused by the two gratings not being exactly perpendicular to each other. Finally, two separate one-dimensional gratings were used and alignment was done by observing some focal plane, with the more distant planes being more sensitive to misalignment. We also observed that if two gratings are positioned at 60° angle, then uniform field intensity occurs every other "focal" plane of a single grating, and for a 45° angle it is every third plane.

Juris Upatnieks, 23 April 1968

25 April 1968

The following phase gratings were made during the months February through April 1968. In all cases the standard Kodak R-10 bleach was used to bleach the recorded interference or intensity pattern.

Plate #	Description
#1	Contact print of Ronchi rulings, 4, 6, 8, and 10 l/mm. Exposure very light and phase modulation small
#2	Same as above, contact print, higher density and greater phase modulation
#3	Interference pattern of 10 l/mm and 5 l/mm made with Mach-Zehnder interferometer. Gratings have high noise level. Made 6 Feb. 1968.
#4	Same as #2, different print.
#5	Contact print of 4, 6, 8, and 10 l/mm Ronchi Rulings, 0.01 in. spacer to give reduced spatial resolution. Made 6 Feb. 1968.
#6	Same as #5 but with 1/8" spacing. Print illuminated with enlarger lamp, lens removed and enlarger lamp at top position.
#7	Contact double print 4, 6, 8, and 10 l/mm Ronchi rulings, gratings crossed. 1/8" in. spacer.
#8	Contact print of Ronchi ruling, 4 lines/mm, 1/8 in. spacer, one-dimensional grating
#9	Same as #8, $\frac{1}{16}$ in. spacing, exposed for $D = 2.0$
#10	Contact print of Ronchi ruling, 8 l/mm, crossed grating. Made 29 March 1968. $\frac{1}{32}$ in. spacing, exposed for D=
#11	Contact print of Ronchi ruling, 8 l/mm crossed grating, exposed for $T = 8\%$, $\frac{1}{32}$ in. spacing

Juris Upatnieks, 25 April 1968

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Plate #	Description
# 12	Contact print of Ronchi ruling, 8 l/mm, $\frac{1}{32}$ in. spacing, exposed for a density of D = 2.6. Made 1 April 1968
# 13	Contact print same as above, exposed for D = 2.7 Made April 1, 1968.
# 14	Contact print of Ronchi ruling, 8 l/mm, $\frac{1}{16}$ in. spacing, exposed for density of D = 1.93.
# 15	Same as # 14 but with 1/32 in. spacing, exposed for a density of D = .

Juris Upatnieks, 25 April 1968.

25 April 1968

Experiments with self-imaging phase plates (gratings) to improve two-dimensional image quality.

The idea of using phase modulated wavefronts to illuminate transparencies was described and carried out in practice before. The disadvantage of using random phase plates was that any noise introduced before the phase plate was not eliminated in the output. Also, the transparency had to be in contact with phase plate or a lens relay system had to be used.

As suggested by E. N. Leith, both of the above difficulties could be eliminated using a self-imaging phase plates, such as regular phase gratings. With these phase-modulator plates uniform amplitude fields can be obtained at regular intervals away from the modulator (see p. 131.)

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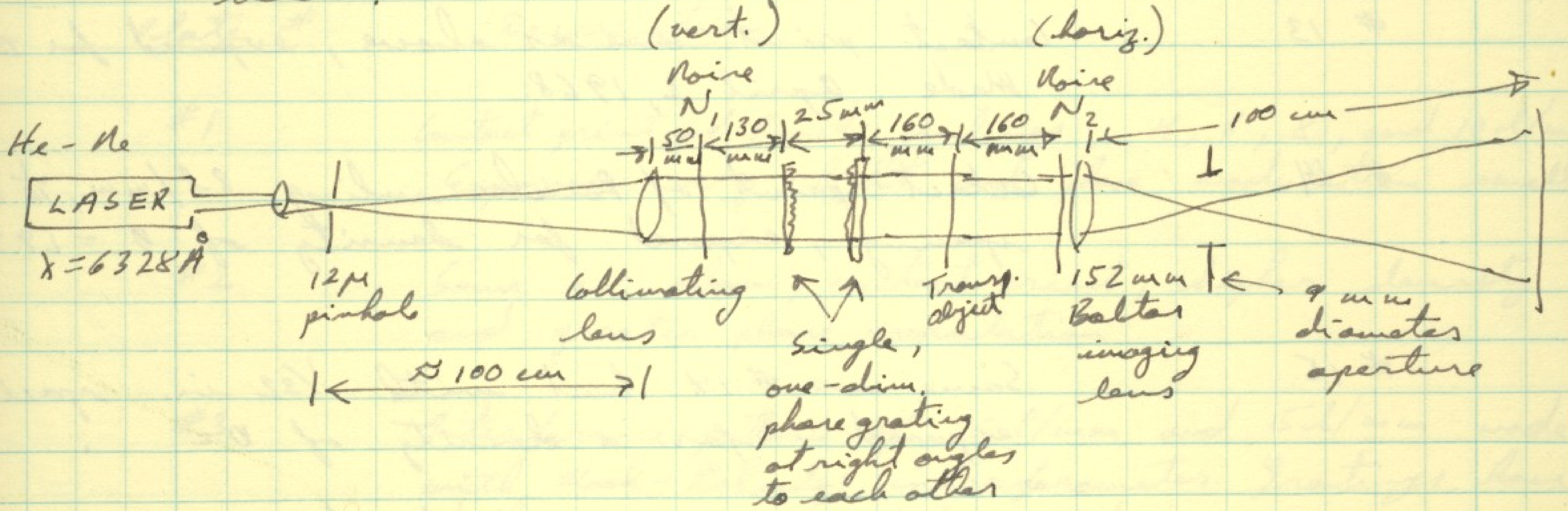
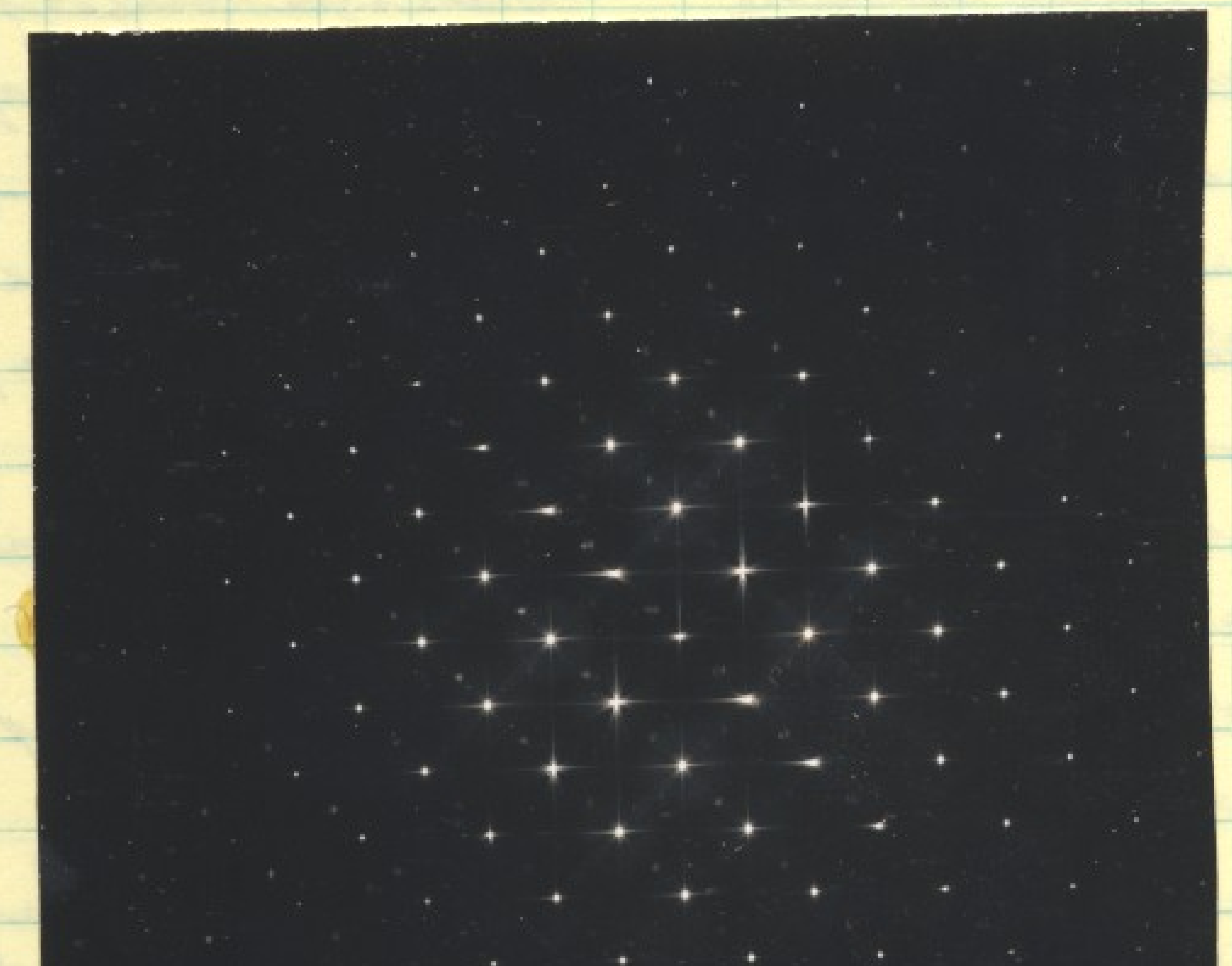
This way any moire introduced before the transparency or after it gets suppressed. To demonstrate this characteristic the experiments were performed with the optical system shown below:



Two seperate one-dimensional grating were used because these could be aligned more exactly to obtain better abberation-free imaging of the uniform amplitude field at regular intervals. The aperture was inserted after the imaging lens to limit the bandwidth of the diffuse illumination. The spectrum of the crossed gratings is shown below:



The spacing between points represents 8ℓ/mm spatial frequency. Exp. time was $\frac{1}{10}$ sec., and good recording could also be made with 1/50 sec. exp. Photograph made on 30 April 1968.

Juris Upatnieks
25 April 1968

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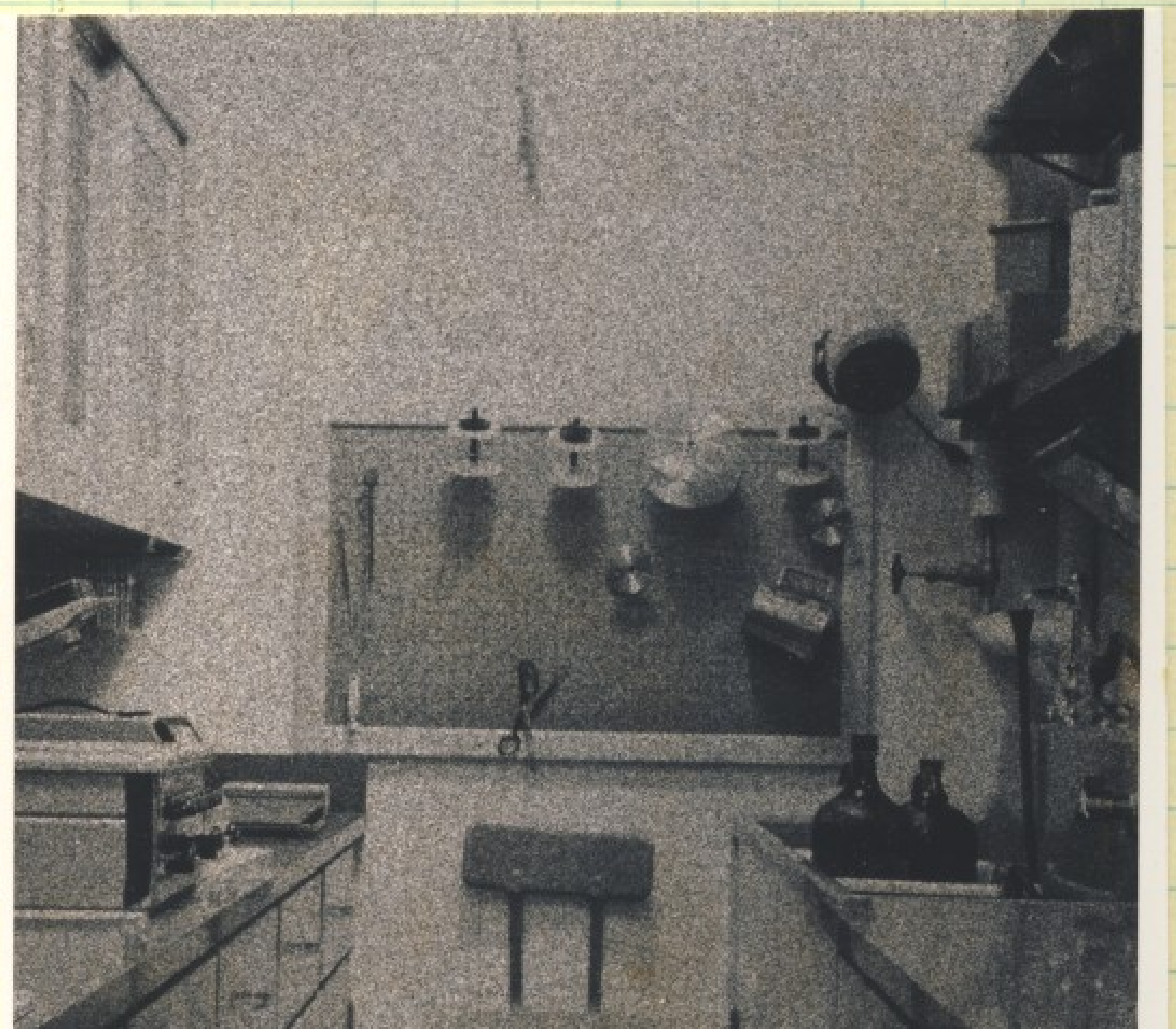
Plane wavefront illumination
(Experiment conducted on 3 April '68)

Phase-modulated wavefront from two crossed phase gratings, 160 mm away from closest phase grating
(Experiment conducted on 3 April 1968)

Random phase-modulated wavefront illumination.
Phase-mod. in contact with transp.
(Experiment conducted on 3 April 1968)



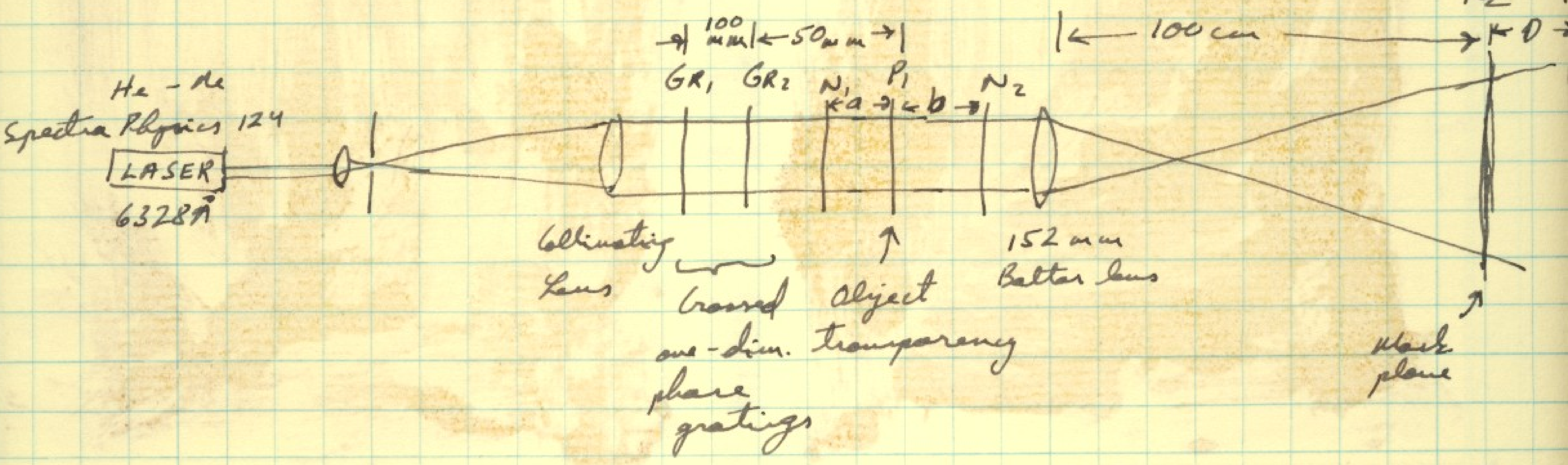
Diffuse-wavefront illumination with 9 mm diam. restricting aperture at Fourier transform plane.
(Experiment conducted on 3 April 1968)

Juris Upatnieks, 25 April 1968.

29 April 1968

Experiments with filters at the output (image) plane of an optical system.

A number of experiments were performed with masks (filters) at the image plane of an optical system shown below:

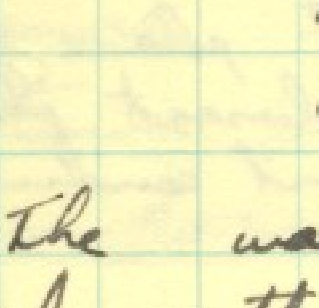


N_1 and N_2 is noise consisting of a fine wire (about #

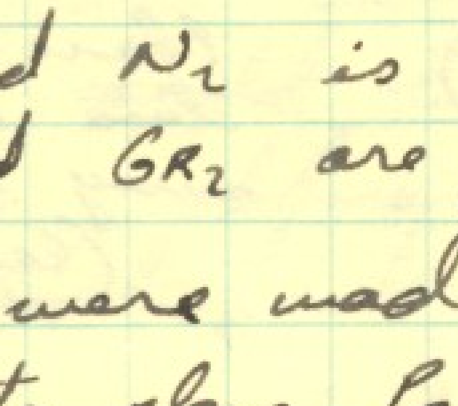
GR_1 and GR_2 are gratings #14 & #15, 8 l/mm

The masks were made by imaging the desired crossed grid pattern to plane P_2 and recording it on 649 F emulsion on 4×5×1/8 glass plates. The plates were then developed in Kodak D-8 developer (2 parts H_2O to 1 part of D-8). By controlling the exposure time pattern consisting of dark lines or black dots could be obtained. The patterns were the contact printed on similar glass plates with Kodak 649F emulsion and were developed in Kodak D-8 (1 part of H_2O and 2 parts D-8). The developed and fixed plates had brownish appearance. The resulting patterns were these:

Crossed grid



Dot pattern



Mask dimensions:

Dot diameter: 0.174 mm
Dot or line spacing: 0.70 mm
Line width: 0.13 mm

When used, again the mask was placed in plane P_2 and the recording film distance D behind it.

Juris Upatnieks, 29 April 1968.

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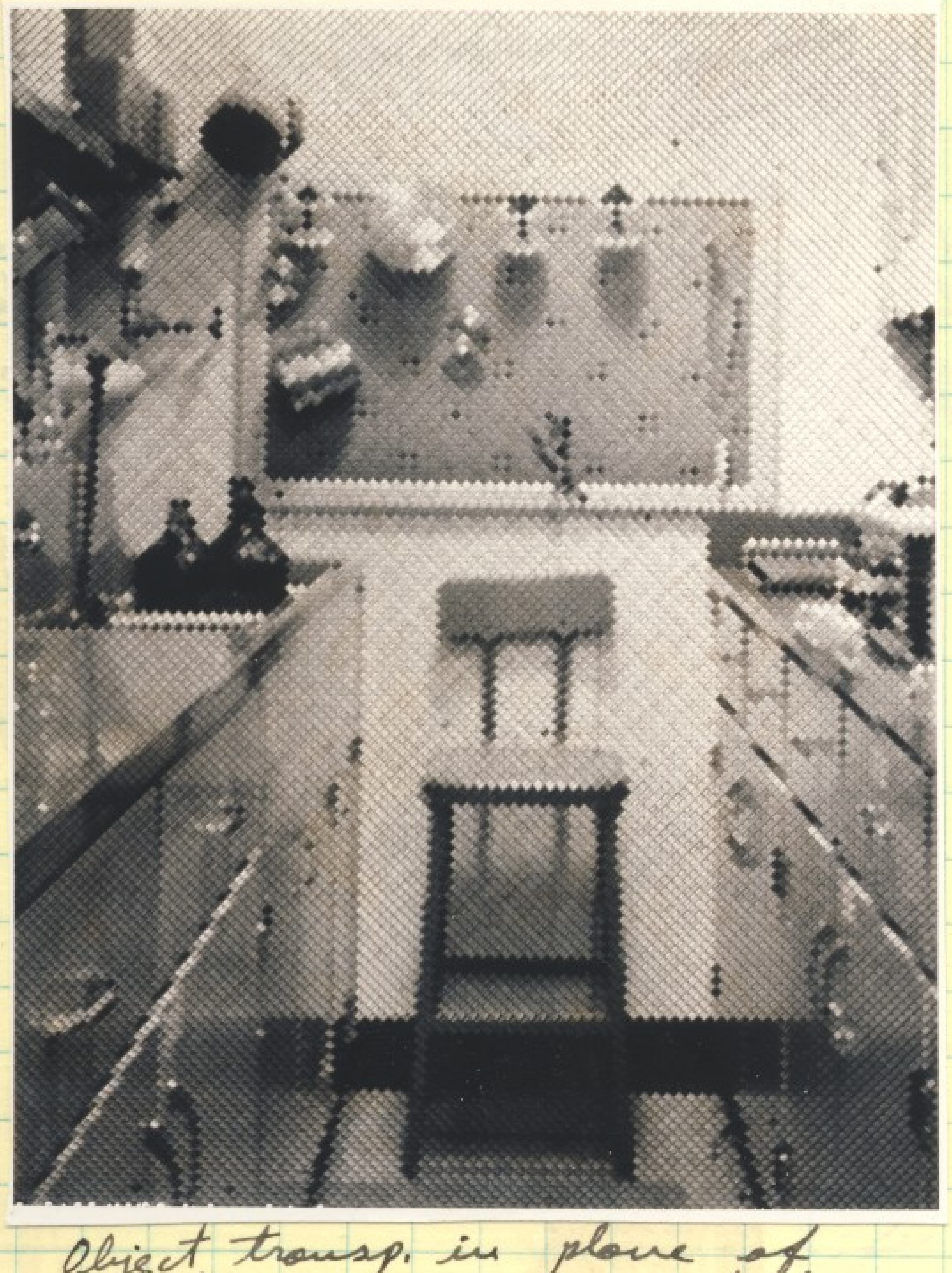
The alignment of the mask was quite critical. When properly aligned, a uniformly bright field emerged from the mask. The effect of air currents was visible as darkened waves passing across the field, similar in appearance to those when Mach-Zehnder interferometer is set for zero fringe frequency and one path is disturbed.

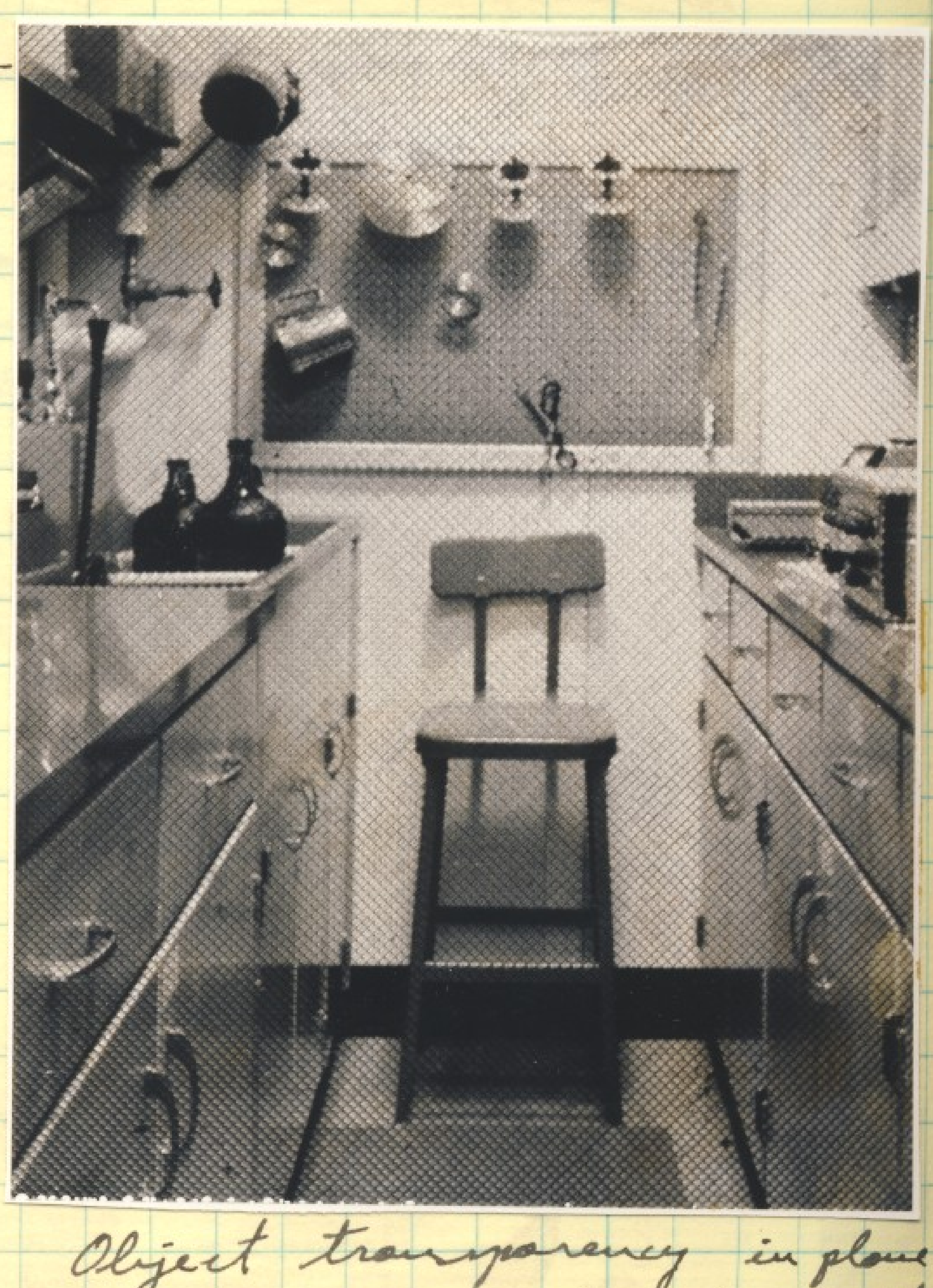
The two photographs below show the effect of placing the object transparency in plane of the grid pattern and uniform amplitude field:

#1



Object transp. in plane of grid pattern, recorded with D = 100 mm. No noise added to the system. 1/12 sec. exposure. Experiment performed on 23 April '68. Grid mask in place.

#2



Object transparency in plane of uniform amplitude field, image recorded with D=100 m[illegible] No noise added, grid mask in place, 1/12 sec. exposure. Experim[illegible] performed on 23 April 1968.

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\#3

Image made with D = 130 mm, dot pattern mask in place, object transparency in uniform amplitude field. $\frac{1}{5}$ sec. exposure. Experiment performed on 24 April 1968.

\#4

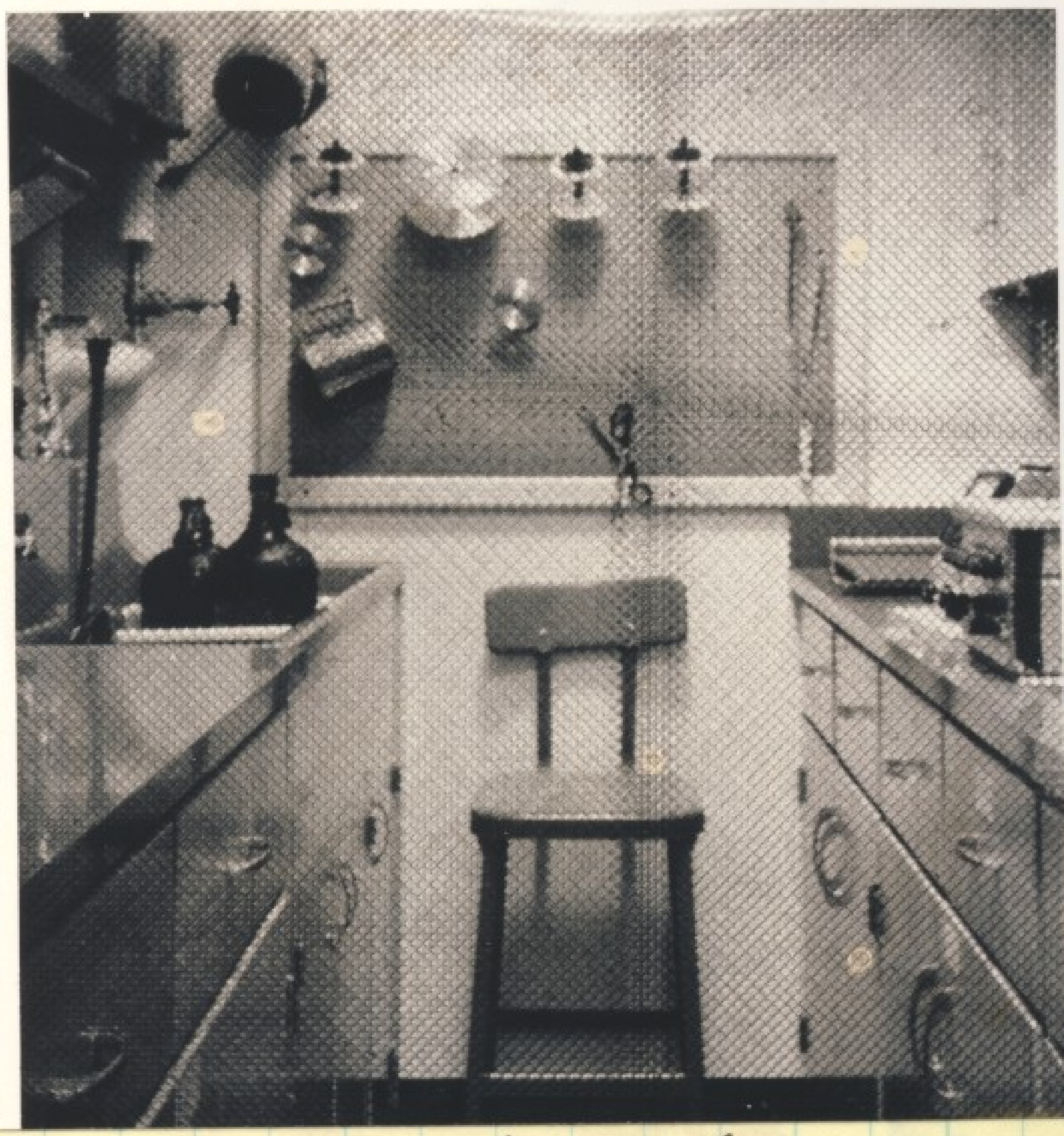


Image made with D = 130 mm, grid mask in place, object transp. in uniform amplitude field. $\frac{1}{25}$ sec. exp. Exper. performed on 23 April '68

\#5

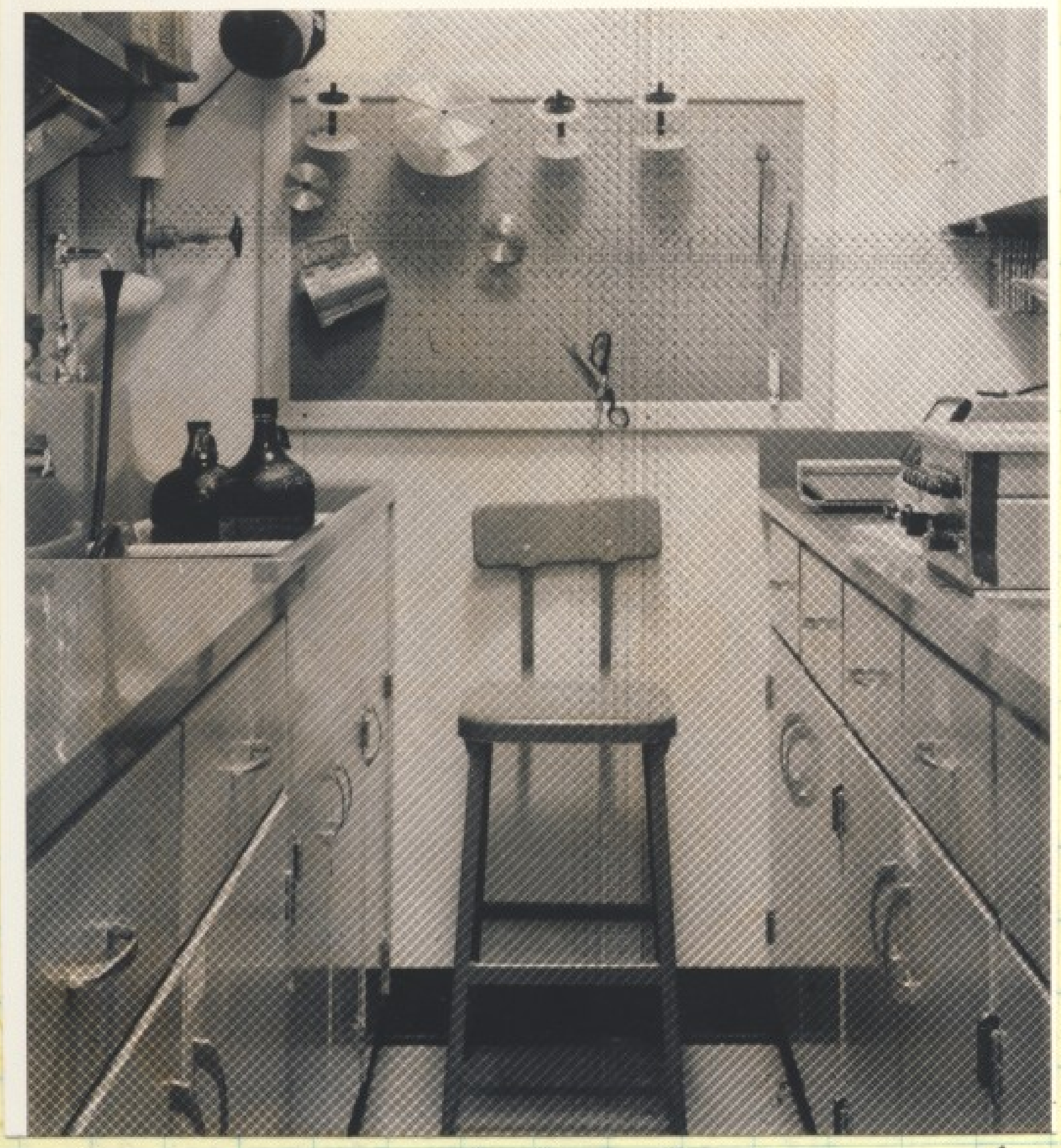


Image recorded at focus of object, no mask. Object at plane of fine grid pattern. 1/50 sec. exposure time. Experiment performed on 24 April 1968.

\#6

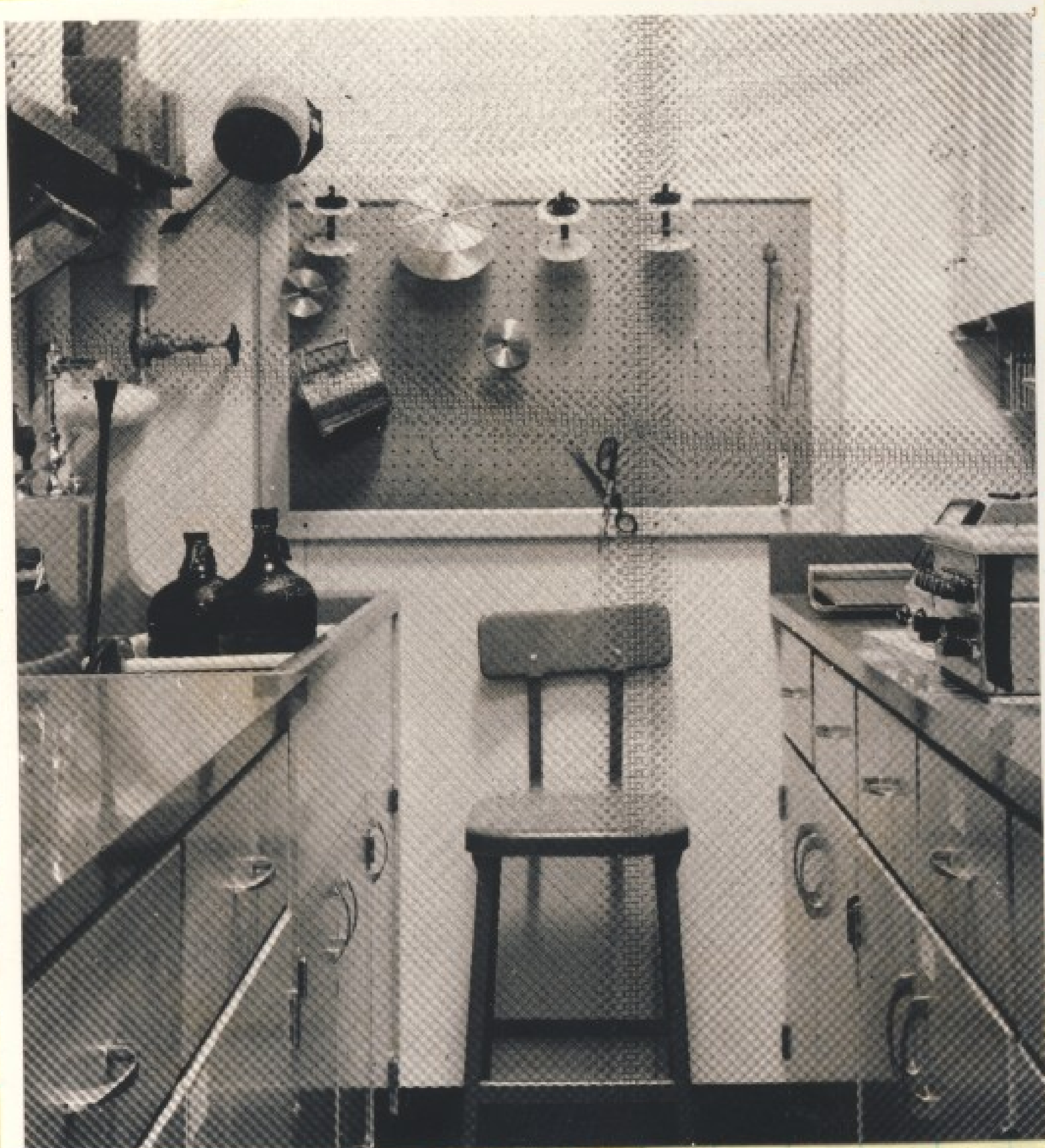


Image recorded at focus of object, no mask. Object in uniform field plane. 1/50 sec. exposure time. Experiment performed 23 April '68

Juris Upatnieks, 29 April 1968.

29 April 1968.

For all of the experiments with results #1 to #6, two crossed phase gratings were used. For #1 and #2 no extra noise was used besides the natural dust on lenses; for #3 to #6, noise was added with a = b = 30 mm, except for #5 a = 50 mm and b = 30 mm. The vertical pattern is from noise before the transparency and horizontal is from noise behind (in front) the transparency. It seems that #5 looks better than #3 or #4. The appearance of both #3 and #4 would probably be improoved if a mask was used also at the input.

Juris Upatnieks, 29 April 1968.

2 May 1968

The use of phase grating to improove images in spatial filtering systems.

The previous experiments show that improoved image quality can be obtained with wavefronts having uniform amplitude and periodic phase structures. At the Fourier transform plane a rectangular array of spots appear due to the crossed phase gratings. Let us call this $H(x_1, y_1)$ and the transform of the transparency $S(x_1, y_1)$. If the transparency is illuminated by light coming from a crossed phase grating, then the resulting spectra is $H * S$. If H is a two-dimensional array of delta functions, then convolution with S results in a well-separated redundant spectra of the signal (if the frequency of grating is properly choosen). Thus a redundant spatial filter could be constructed to perform some operation on the input signal multiplied by the periodic phase structure. The output of such filtered signal should be improoved just like the unfiltered image is.

Juris Upatnieks, 2 May 1968.

17 May 1968

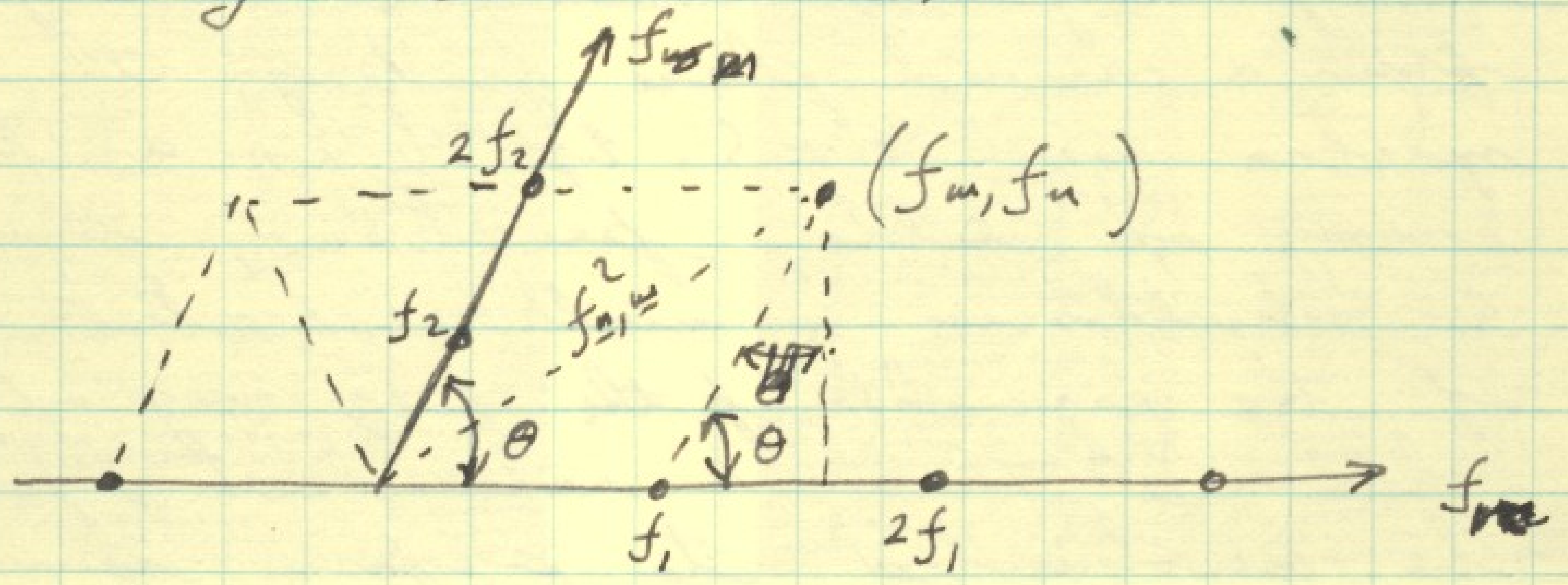
Self - Imaging Phase Plates.

On page 131 of this notebook the distances at which a grating images itself was calculated for both collimated and diverging spherical wavefronts. The distance Z for the N's plane and n's harmonic was given as

$$Z_N = \frac{2N}{\lambda (n f_0)^2} \quad \text{for } \Delta Z = 2\pi m,\ m = 0, \ldots$$

Experimental observations have shown that uniform amplitude wavefronts appear not only for $\Delta Z = 2\pi m$, or phase shift of multiple of 2π radians, but also for $\Delta Z = \pi m$, or phase shifts of half wavelength for odd multiples of fundamental frequency and full wavelength shifts for even multiples of fundamental frequency. This is true for both single phase gratings and for crossed gratings at right angles to each other.

The distance Z_n will now be calculated for crossed gratings not at right angles to each other and having different spacial frequencies. We shall assume that uniform amplitude will be observed if all the Fourier transform components are shifted by a multiple of 2π radians. The following geometry will be used:



(1) $$f_{n,m}^2 = (n f_1 \pm m f_2 \cos\theta)^2 + (m f_2 \sin\theta)^2$$

Juris Upatnieks, 17 May 1968

17 May 1968

(2) $$f_{n,m}^2 = \sout{f_1^2 (n} \; n^2 f_1^2 \pm 2nm f_1 f_2 \cos\theta + m^2 f_2 \cos^2\theta + m^2 f_2 \sin^2\theta$$

(3) $$f_{n,m}^2 = n^2 f_1^2 + m^2 f_2^2 \pm 2nm f_1 f_2 \cos\theta$$

A uniform amplitude field will result whenever each of the three terms of eq. (3) will be shifted by a multiple of 2π radians in phase with respect to each other and the $f_{0,0}$ term. For the case where $f_1 = f_2$, we can simplify to

(4) $$f_{n,m}^2 = f^2 \left[n^2 + m^2 \pm 2nm \cos\theta \right]$$

where f is the fundamental frequency components of the gratings. We find the smallest z for separation between planes as follows: let $z_0 = \frac{2}{\lambda f^2}$ which is the separation required for the $f_{1,0}$ or $f_{0,1}$ frequency. Assume that 2π shift required for intermodulation terms. Then z_1 is given by

(5) $$\boxed{z_1 = \frac{2 z_0}{2\cos\theta} = \frac{z_0}{\cos\theta}}$$ where $\frac{1}{\cos\theta}$ must be an even number

This relation has been verified experimentally. The following is a list of observed z_1 and angles θ:

θ	$\cos\theta$	z_1
60°	1/2	$2z_0$
70.6°	1/3	$3z_0$
48.2°	2/3	$3z_0$
78.5°	1/5	$5z_0$
66.4°	2/5	$5z_0$
53.1°	3/5	$5z_0$
36.9°	4/5	$5z_0$

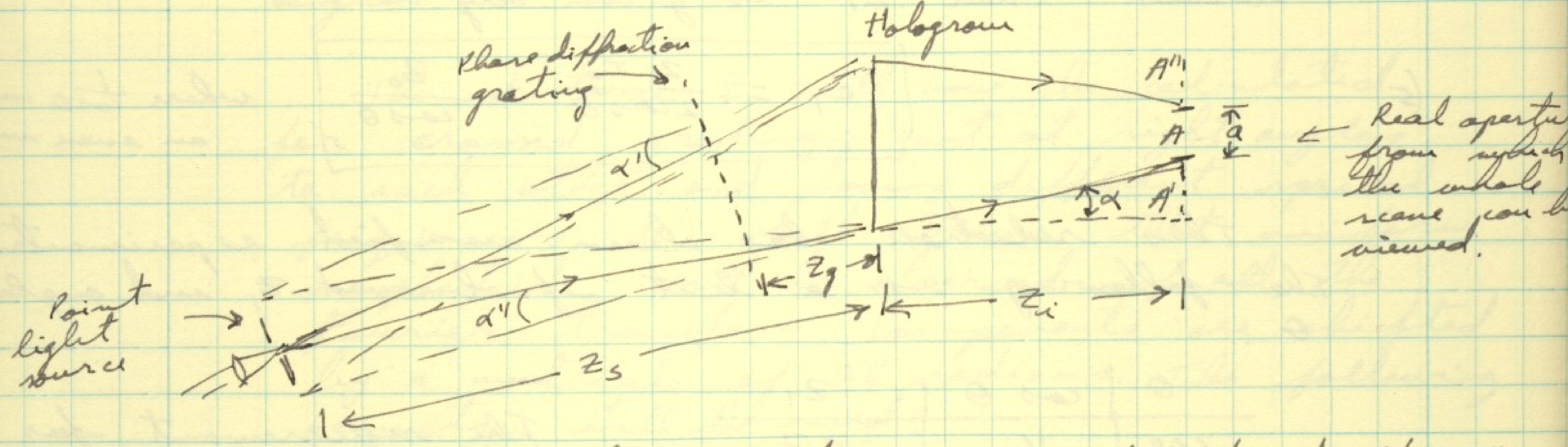
The requirement for different minimum phase shifts for each grating frequencies ($f_{n,0}$ and $f_{0,m}$) ~~is not~~ and the intermod. frequencies $f_{n,m}$ ($n \neq 0$, $m \neq 0$) is not clear at this time.

Juris Upatnieks, 17 May 1968.

21 May 1968

Increasing the visibility of holograms made with restricted viewing aperture.

Holograms were previously described which had a real aperture from which the whole scene could be viewed. This aperture is usually considered much smaller ~~and~~ than the hologram itself and thus restricts the direction from which a hologram can be viewed. We can alleviate this restriction somewhat by producing similar images side by side, that is, repeating the same scene and perspective over many times. This type of image could be obtained by illuminating the hologram with several beams of light, or artenatly, producing the equivalent by placing a diffraction grating between the illuminating source and the hologram. Consider the geometry below:



We would to have aperture A reproduced at A', A'' and so on. This would require that incident light beam appears to come from sources such that angles α', α'', etc. are formed. For $z_g = 0$ we find that spatial frequency f of the grating should be

$$f = \frac{a}{z_i \lambda} = \frac{\alpha}{\lambda} = \frac{\alpha'}{\lambda}$$

This equation should hold for any z_g except that narrower spread from the source is required if z_g is small.

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If a similar spread is desirable in the other dimension, then another grating may be oriented to produce images of the aperture in that direction. A crossed phase grating would accomplish this.

Separation of apertures may also be achieved by using several wavelengths of light. In that case $\Delta\lambda = \lambda_1 - \lambda_2 = \frac{\alpha}{f_h}$, where f_h is the carrier frequency of the hologram and λ_1 and λ_2 are the wavelengths used in reconstruction.

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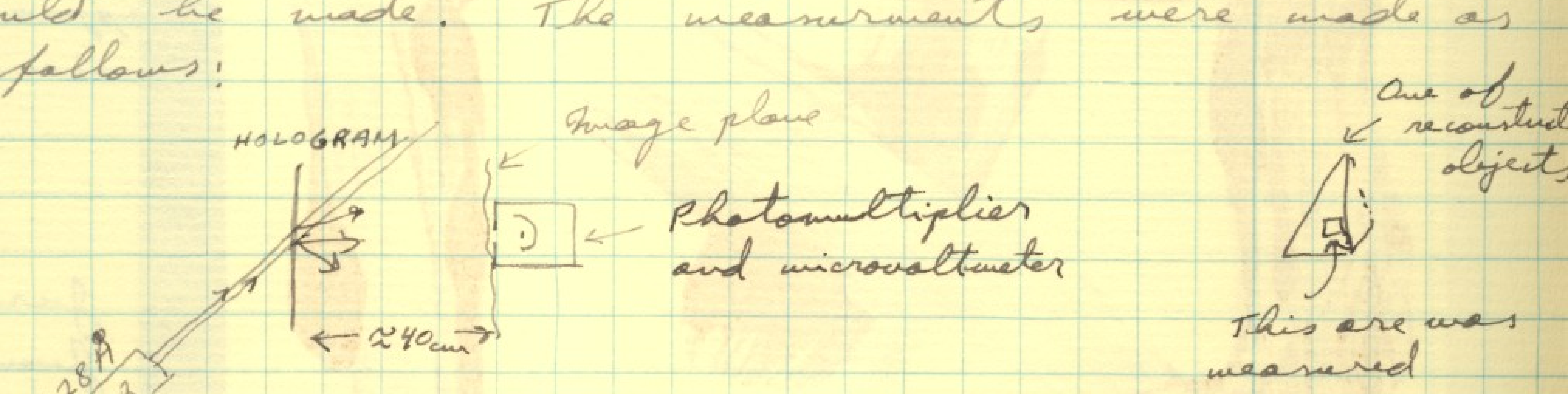
21 June 1968

Bleaching of Holograms.

Several holograms have been bleached which have given much brighter reconstructions with only slight increase in noise level. We have used $K_3Fe(CN)_6$ bleach, modified Kodak R-10 bleach with KBr, and combination bleach of HgCl and modified R-10 bleach. Several "Life" holograms were bleached in $K_3Fe(CN)_6$ and since many similar holograms are available, comparison of brightness could be made. The measurements were made as follows:



The measurements were made about 40cm from the hologram and slight adjustments in distance from the hologram were made so that

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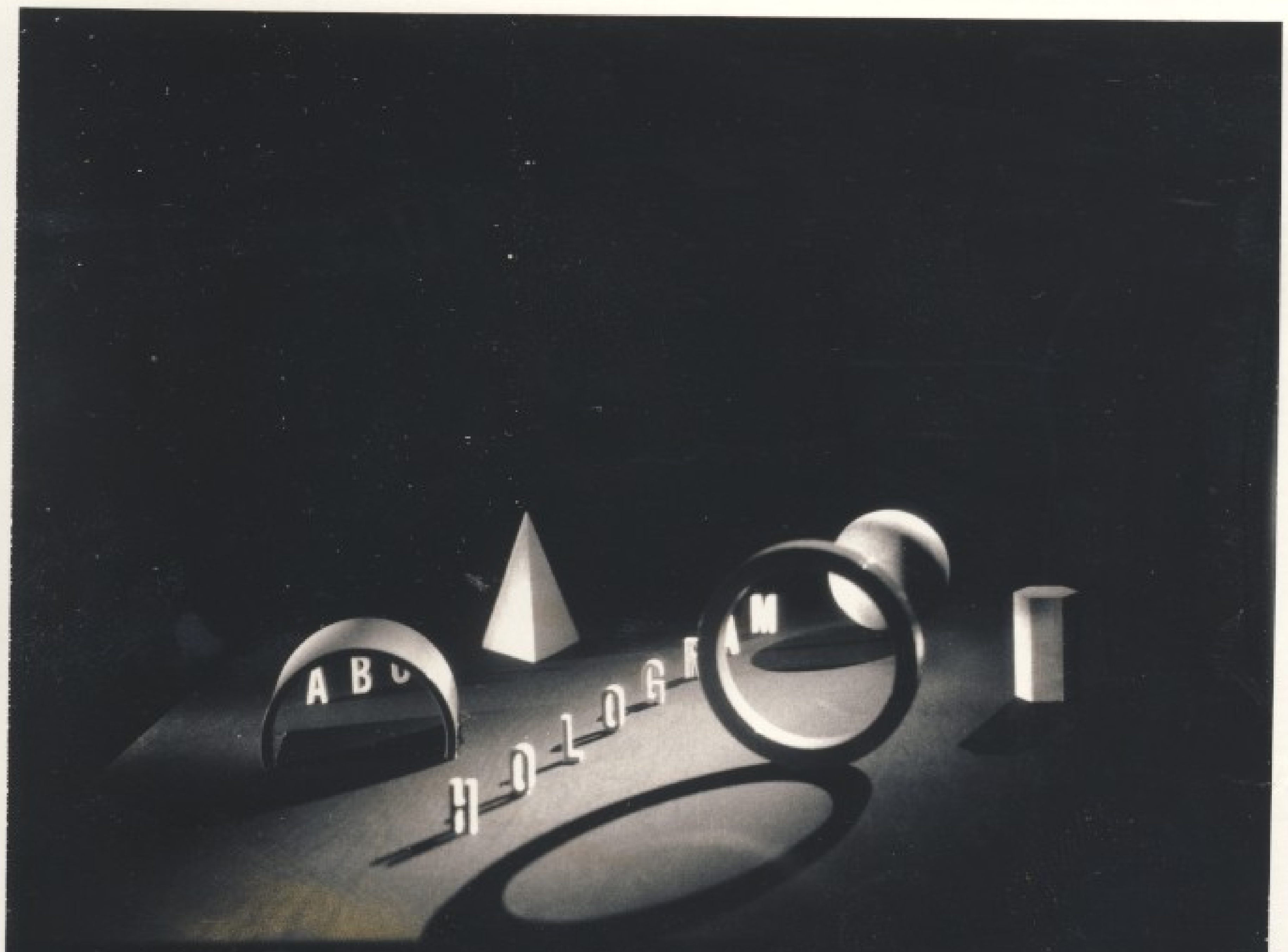
the object size would be constant in each case. The density of unbleached hologram was ≃ D = 0.8 to 1.0, of bleached hologram same before bleaching, and of third hologram, also bleached, 1.2 to 1.5. The measured brightnesses were as follows:

	Microvoltmeter reading	Brightness r to unbleache
Unbleached hologram:	6.2 mV	1:1
Bleached, light, hologram:	20.0 mV	3.2 : 1
Bleached, denser, hologram:	40.5 mV	6.5 : 1

The last hologram, with density of 1.2 to 1.5 and bleached, was brightest of all but was rather noisy. The lighter bleached one was three times brighter and did not have any degrading noise effects. From graphs of diffraction efficiency vs. transmittance before bleaching of plaine gratings, the light hologram corresponds to efficiency of about 10% and the denser to about 15%. Due to the unequal beams and some scattered incoherent light, the overall efficiency of bleached holograms should be lower.



This photograph shows virtual image reconstructi of bleached lower density hologram. The image appears sharp and noise-free.

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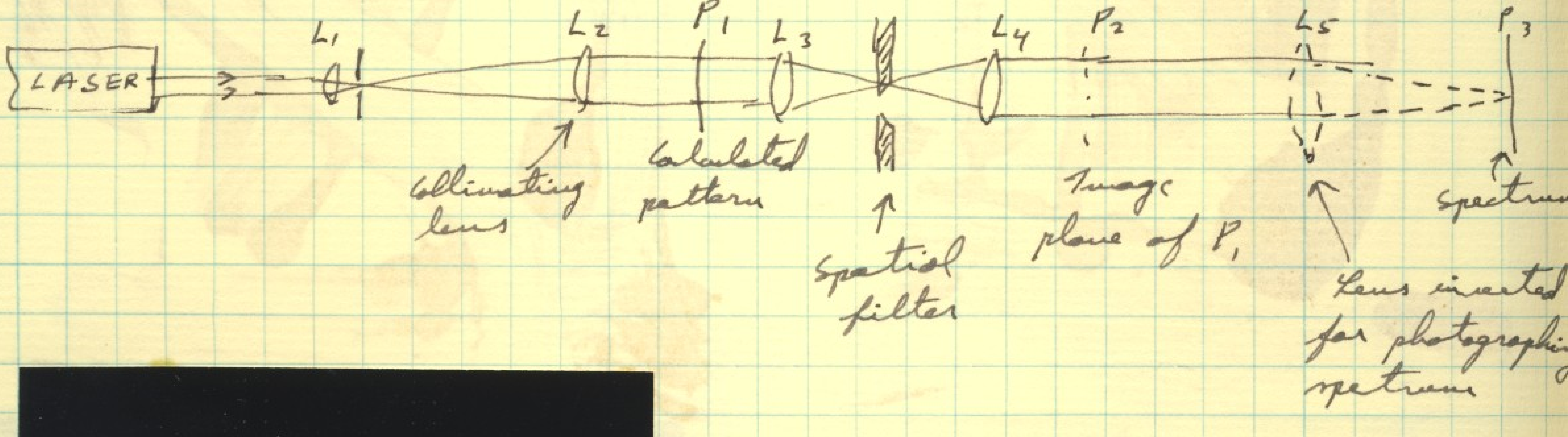
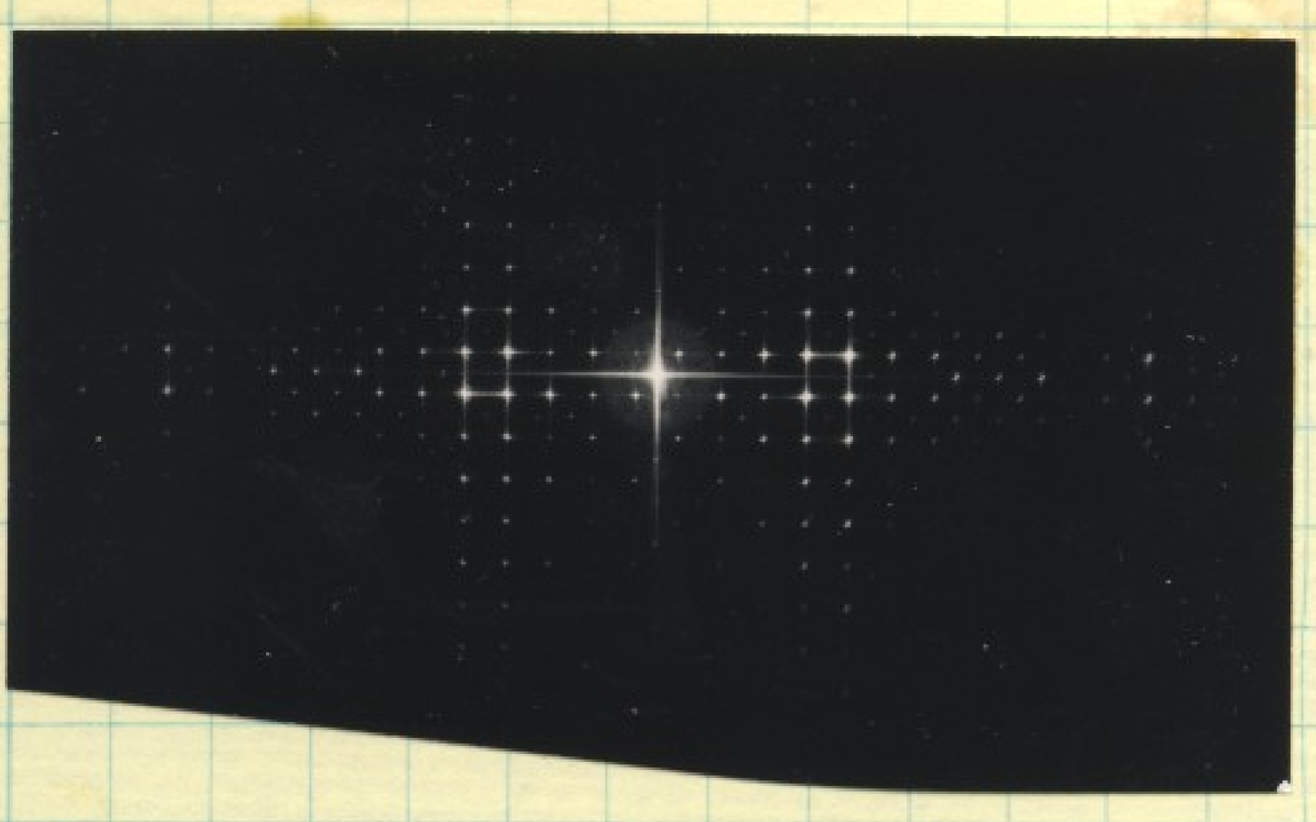
June 21, 1968.

25 June 1968

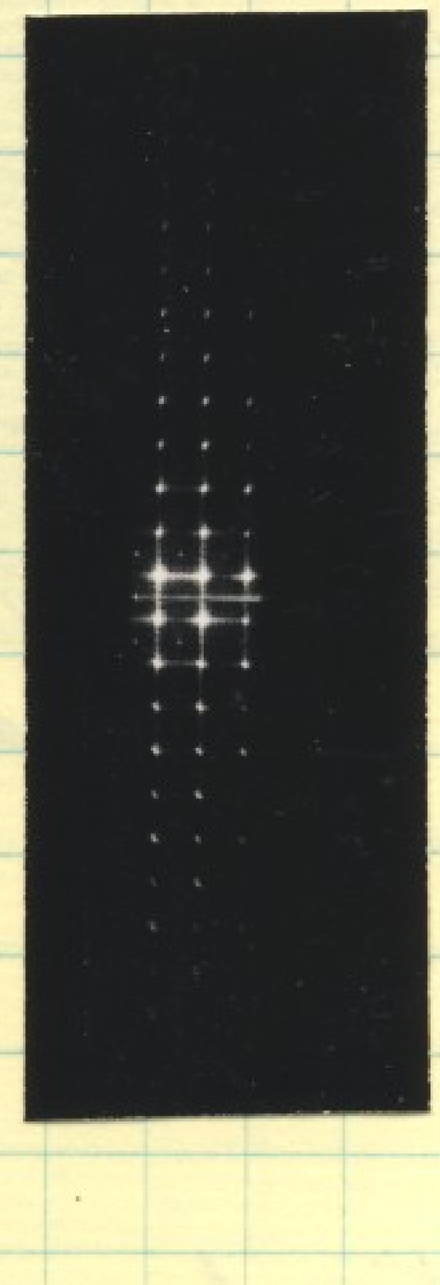
Experiments with pseudo-random phase plates (pattern calculated).

Experiments were conducted during the month of May and beginning of June with the calculated phase plate of Emmett N. Leith. The following photographs show the experimental results and the diagram below shows the schematic of the optical system:





Spectrum of calculated pseudo-random phase plate, without filtering. Exposure made 22 May 1968. 1/25 sec. exposure.



Spectrum of filtered pseudo-random phase plate. The ~~f~~ photographs on the next page were made with a filter passing the spectrum shown here. 1/5 sec. exposure. Photograph made on 29 May 1968.

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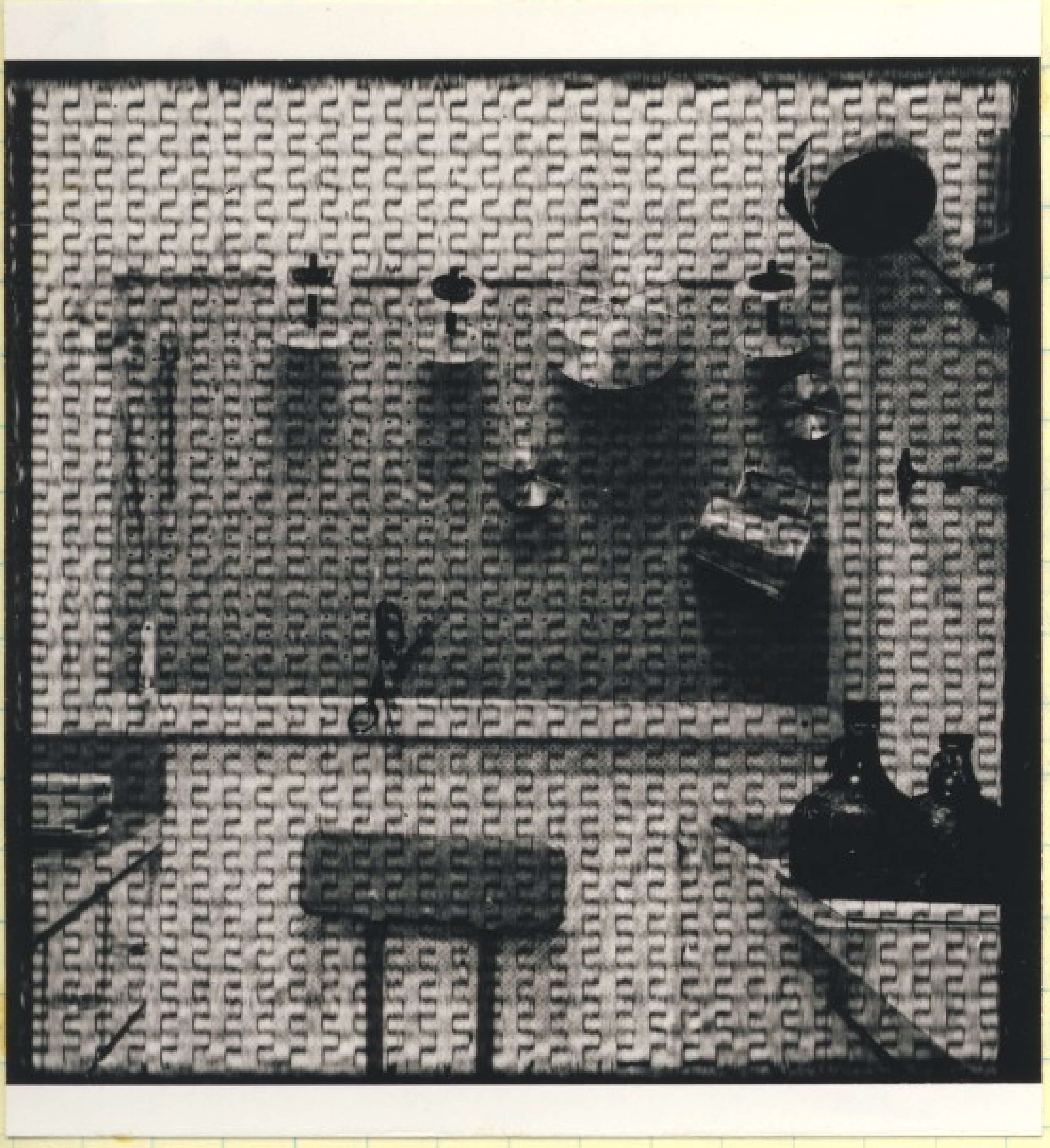
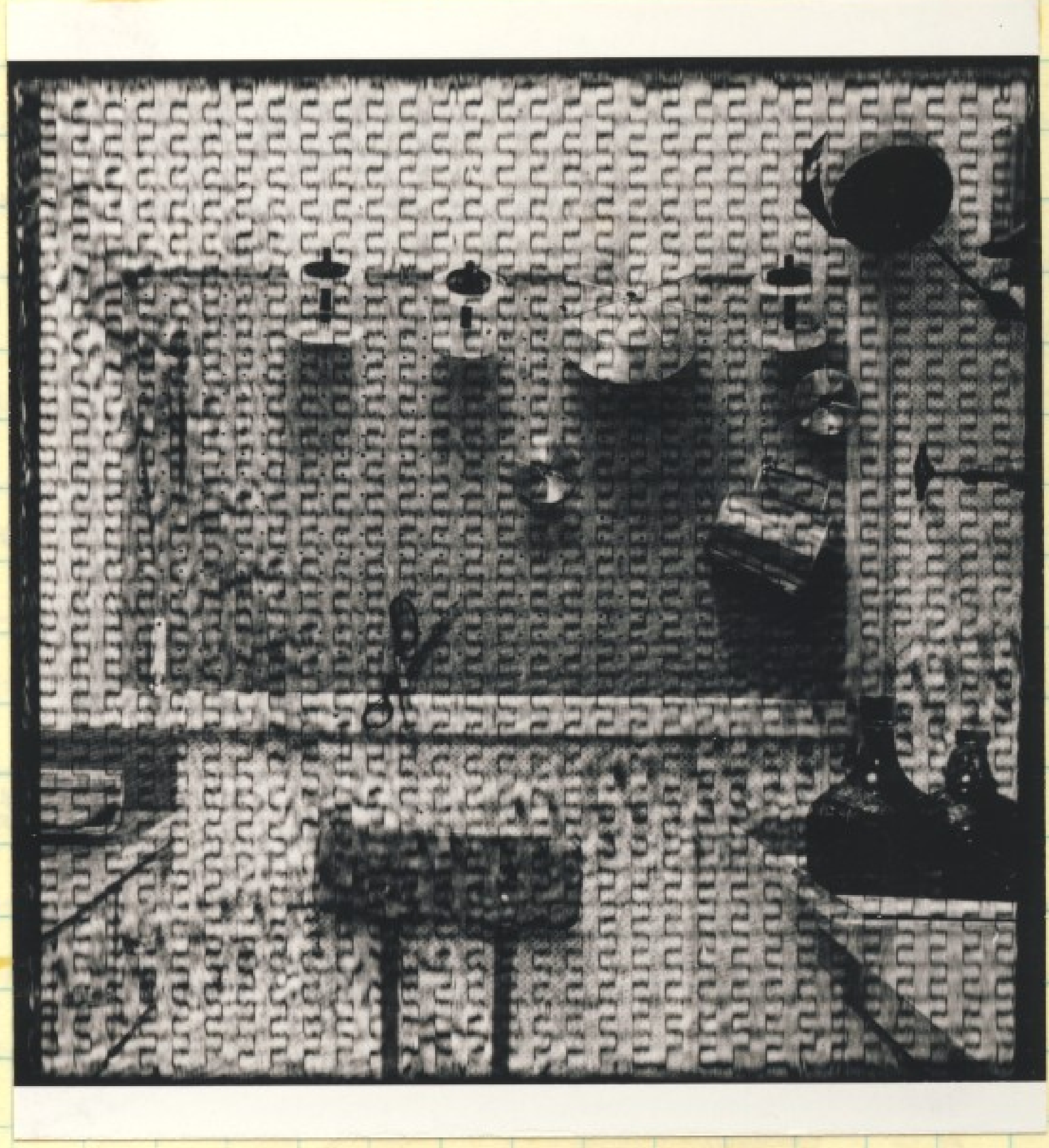
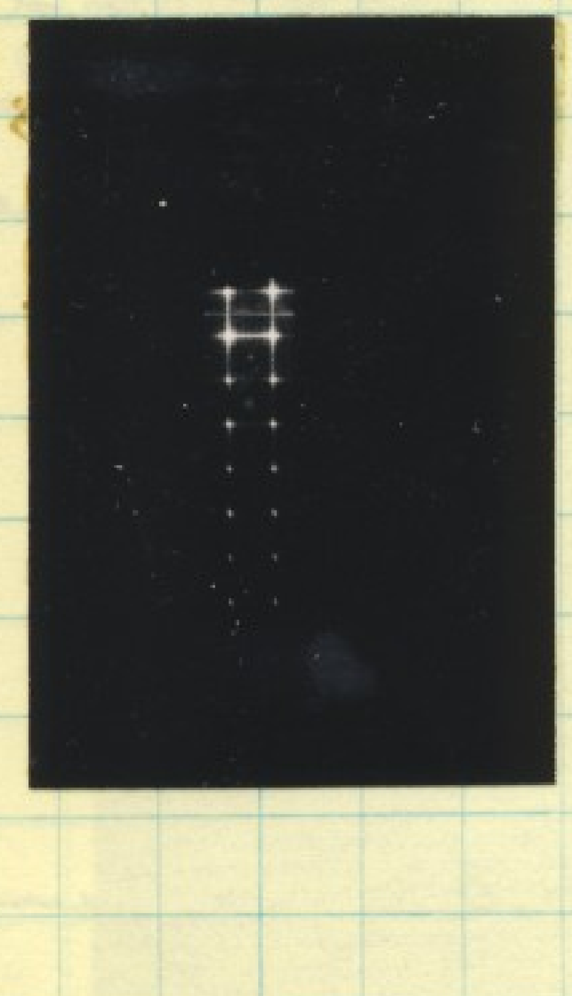




Photograph of an imaged transparency illuminated with spectrum shown on previous page. No noise was added. Imaging was done with a 100 mm Baltar lens. Transparency at plane P_2. Photograph made on 24 May 1968.

Same as at left except noise added before and after transparency. Photograph made 24 May 1968.



Filtered spectrum of pseudo-random phase plate. This spectrum was allowed to pass and form a wavefront to obtain the clear fields shown on the following page. Photograph made on 30 May 1968.

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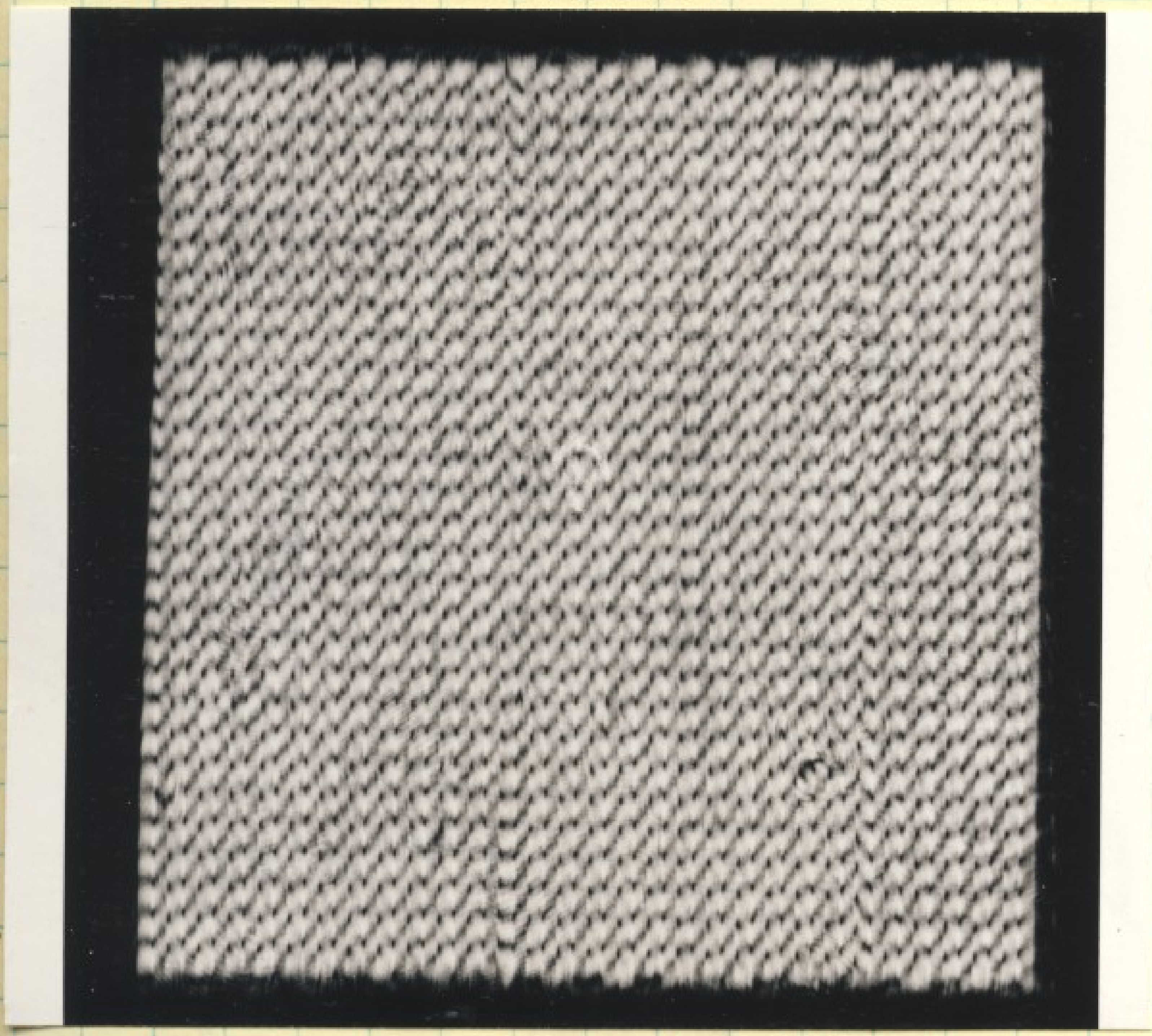
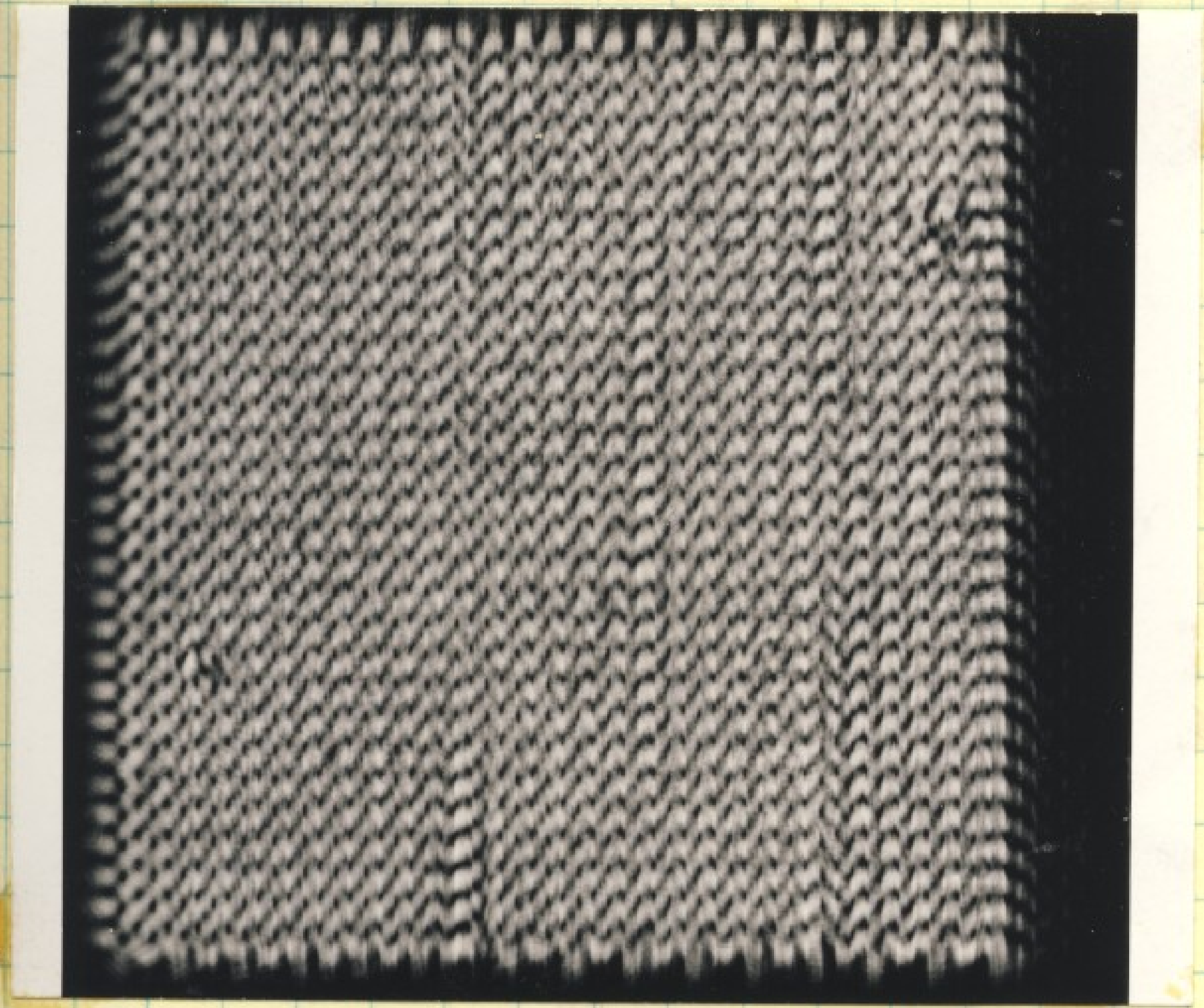


Clear field at plane P_2 obtained with the spectrum on the previous page. Photograph taken on 30 May 1968.



Clear field 19 cm from plane P_2 ~~taken~~ obtained with the spectrum on the previous page. Distance of 19 cm corresponds to phase shift of $\pi/4$ radians. Photograph taken on 30 May 1968.

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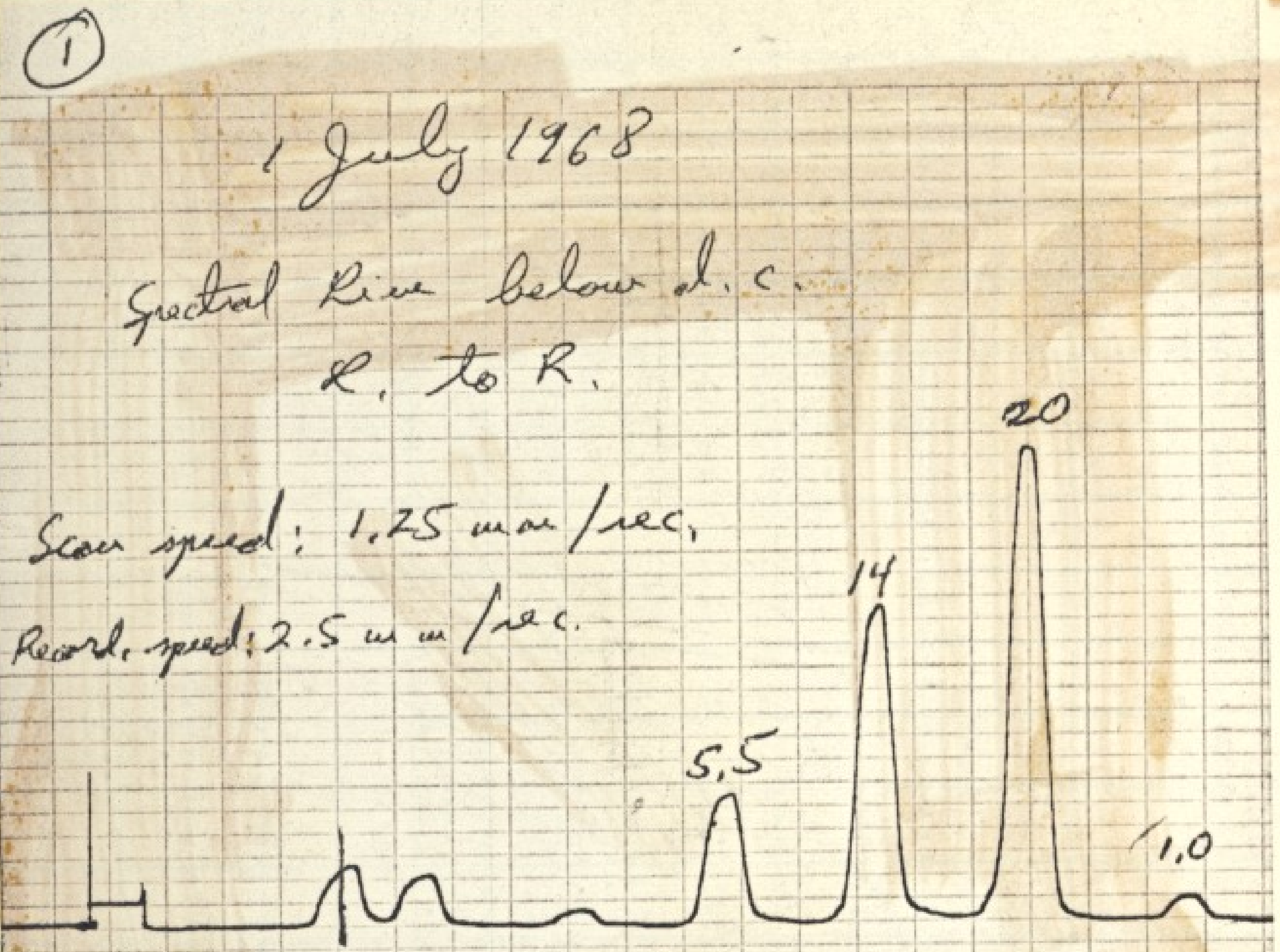
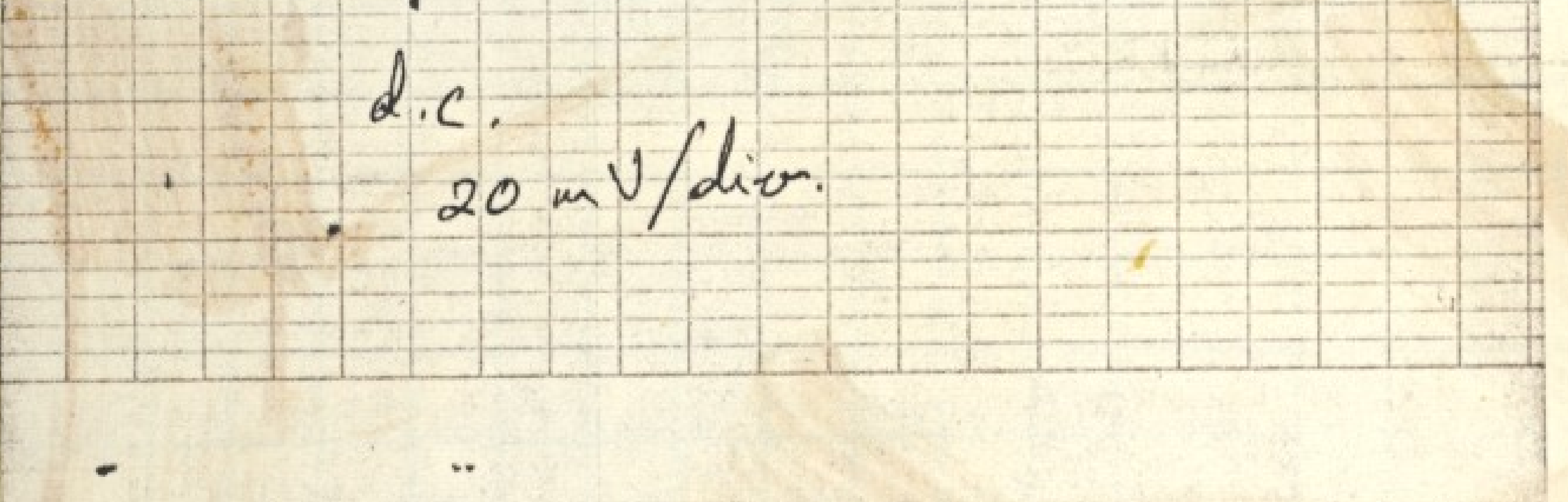
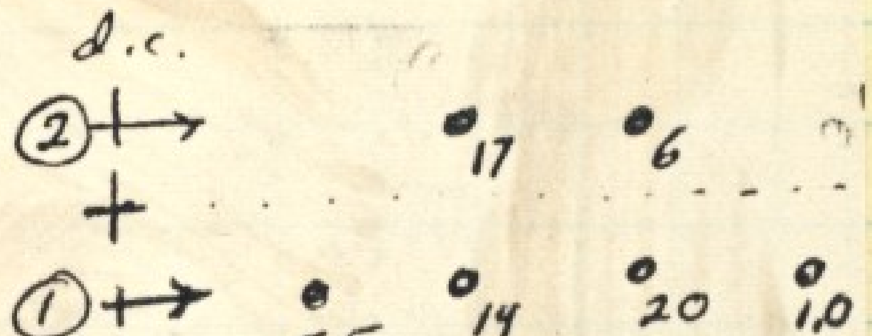
2 July 1968

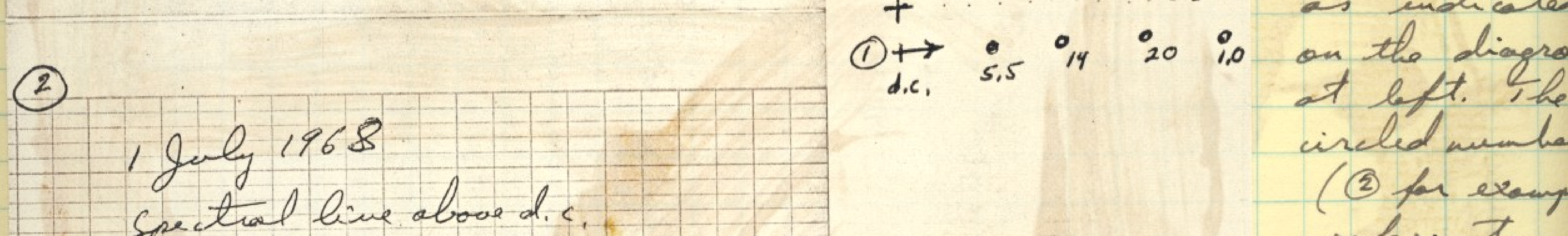
Measurments of intensities of pseudo-random, calculated, phase plate.







The graph on the left and on the followi[ng] page shows the measured inte[nsities] of the spectrum of pseudo-ran[dom] phase plate. The measurements were made with the optical sys[tem] shown below. The photo-multip[lier] was driven at a constant speed and scanned across the spectrum as indicated on the diagram at left. The circled numbers (② for example) refer to the graph number. The complete photog[raph of the] spectrum is shown on page 147 of this notebook.



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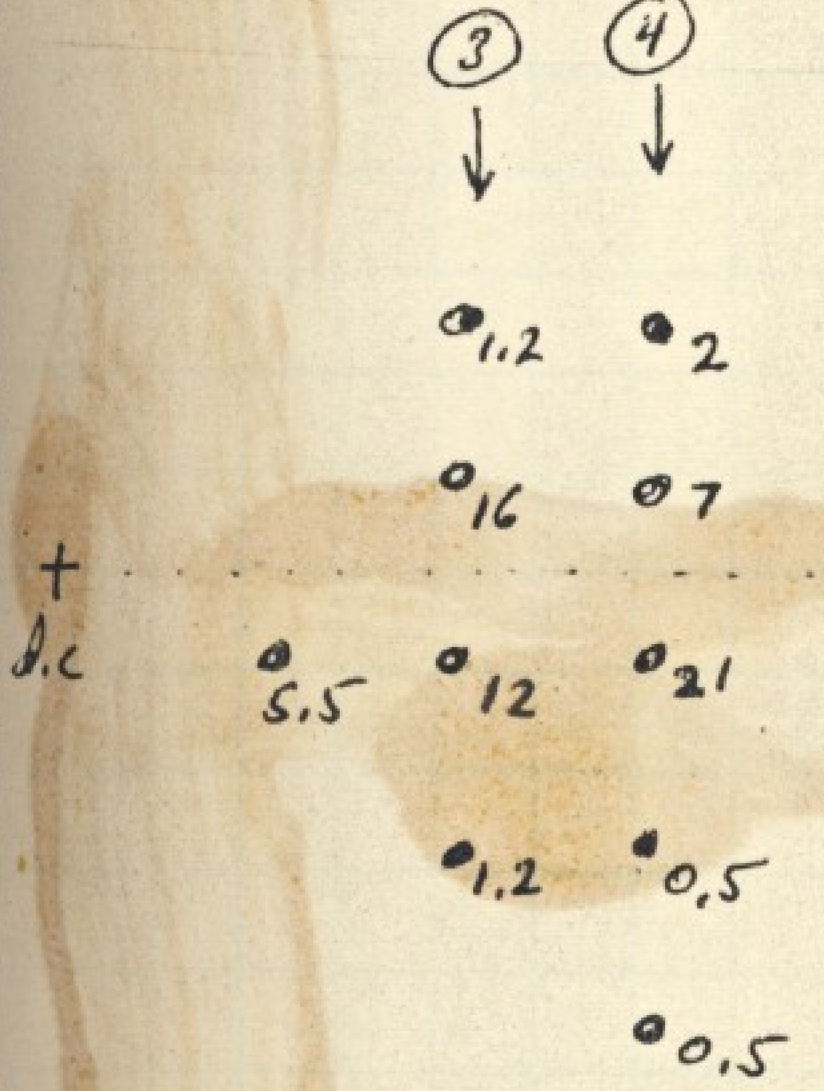

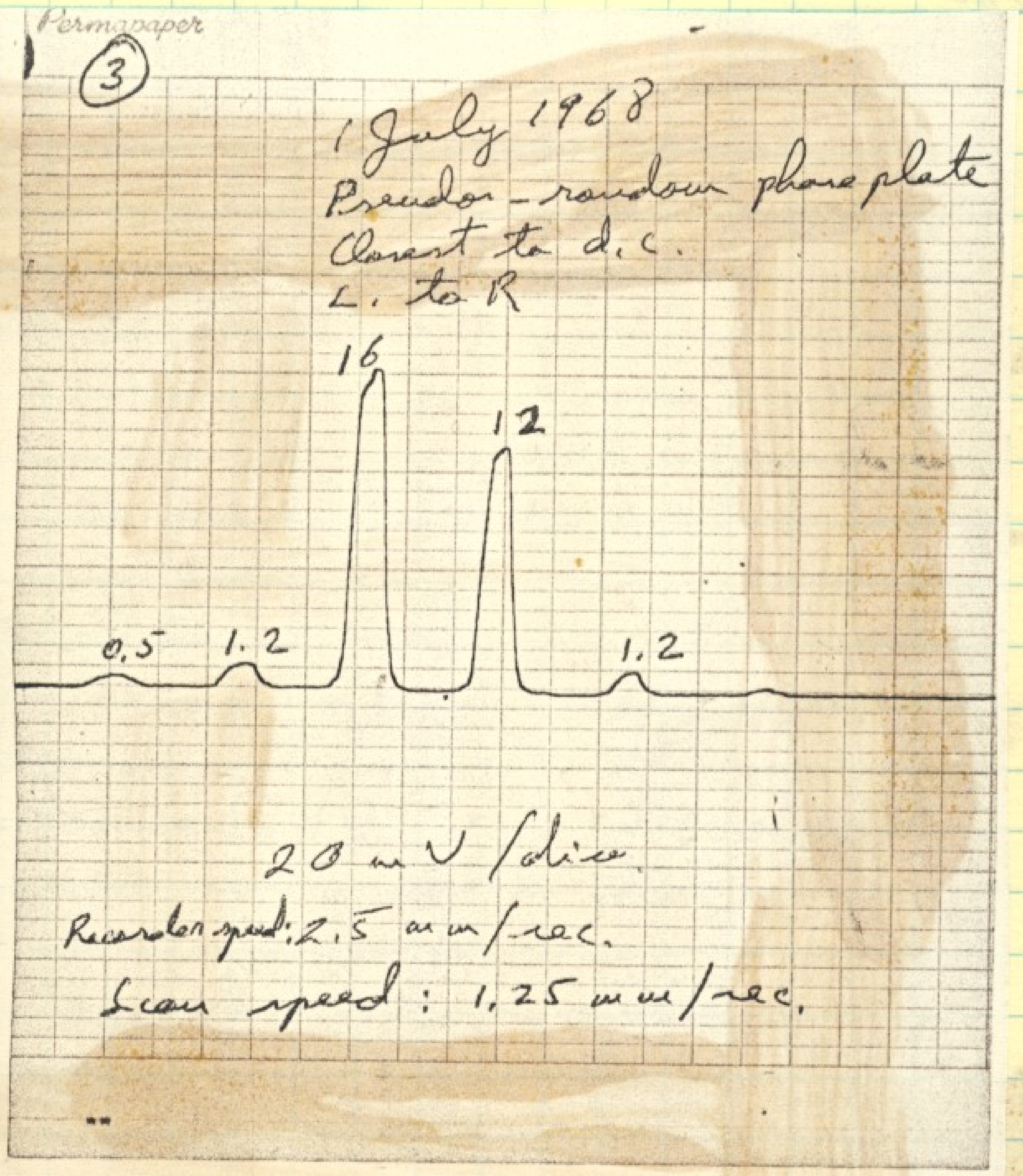

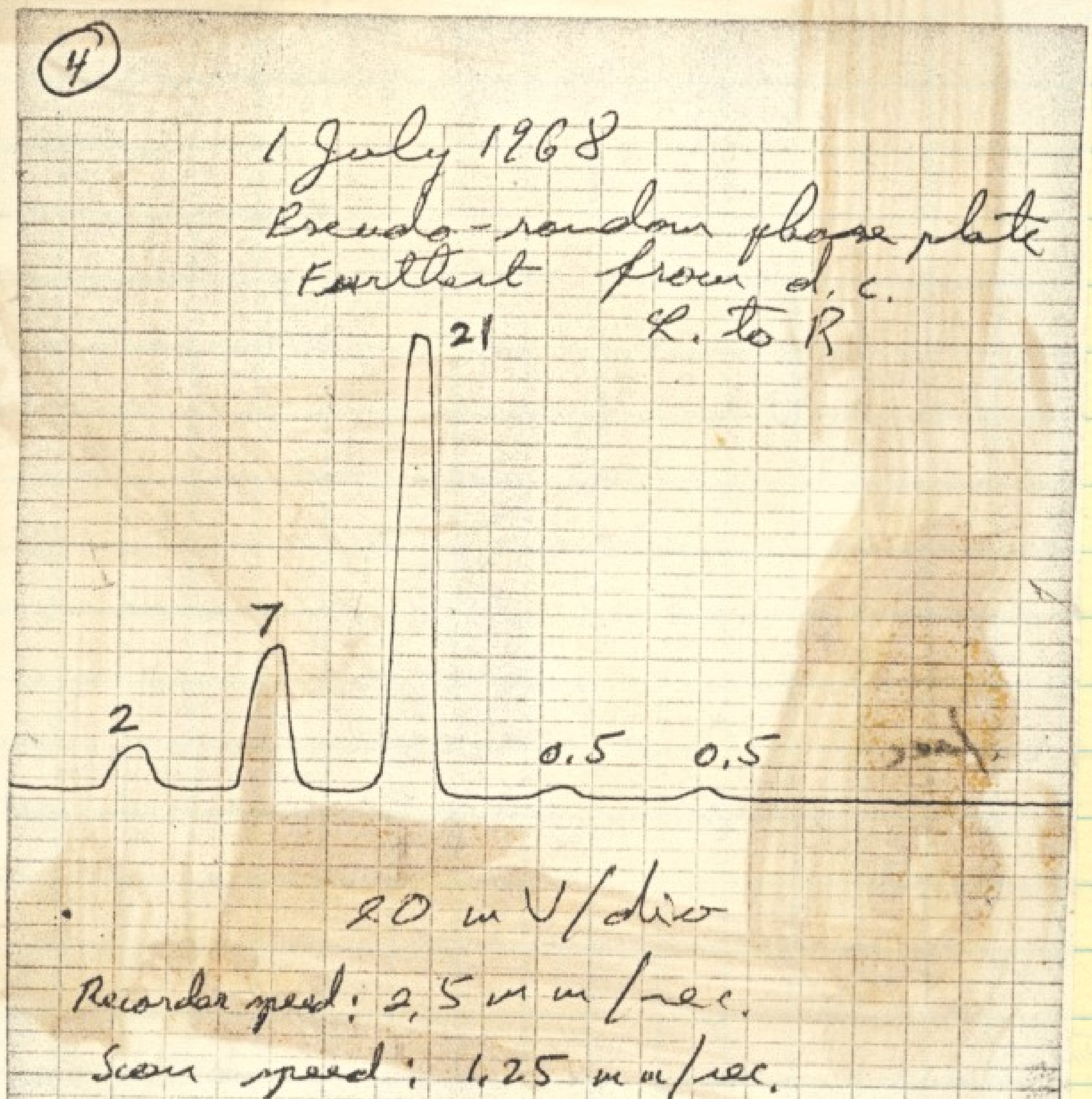

These two scans, ③ and ④, are in direction perpendicular to ① and ②. Slight difference in measured values is probably caused by changing laser output.

The graph on the following page shows scan across image plane of the pseudo-random phase plate with one filtered sideband.

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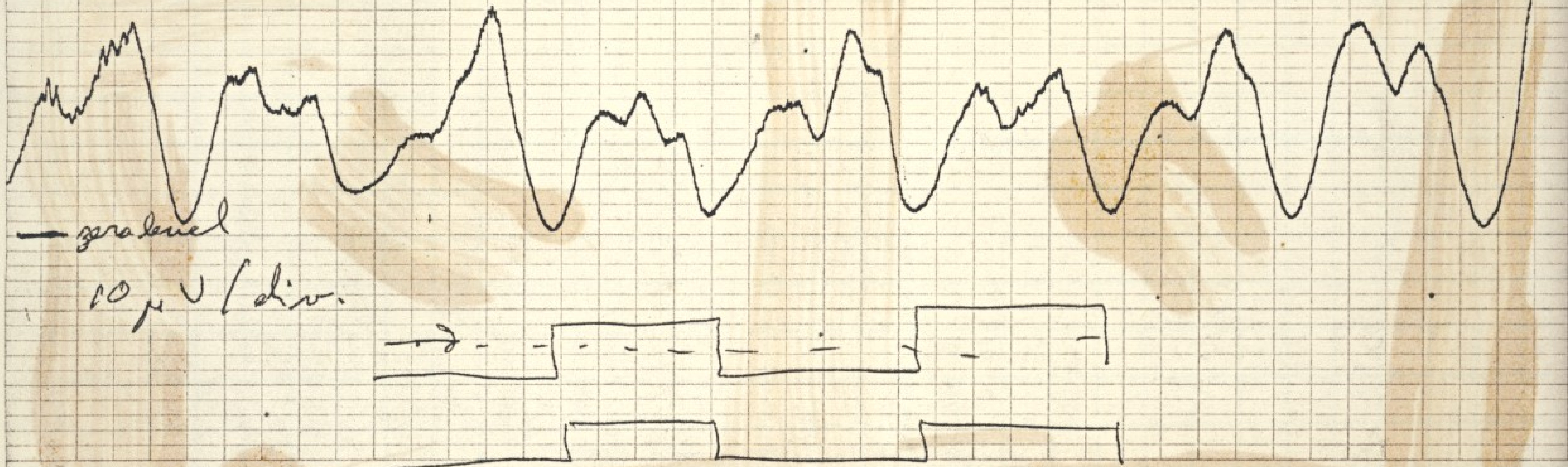
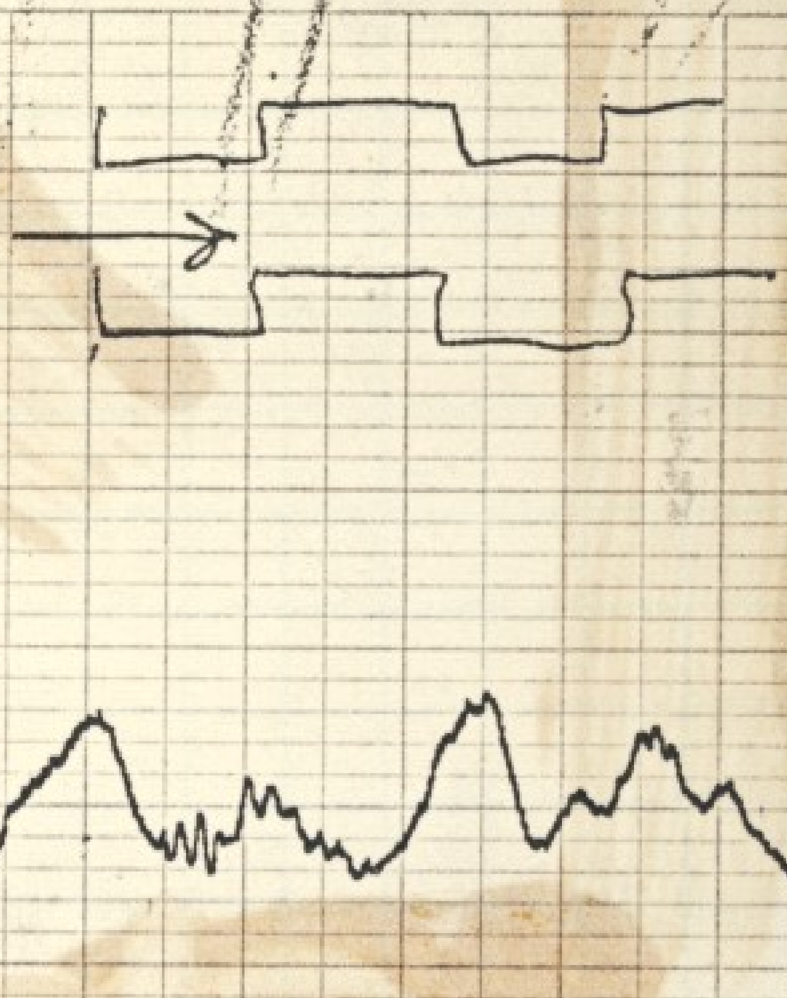
2 July 1968

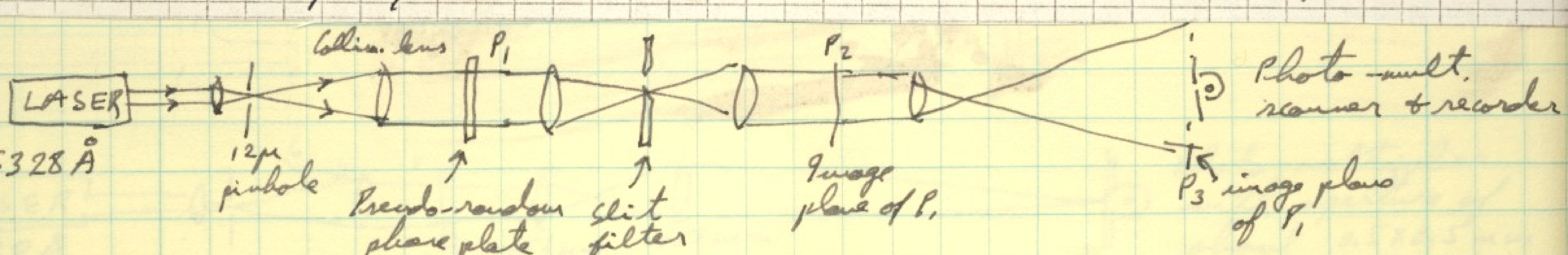
1 July 1968
Filtered pseudo-random phase plate
In focal plane
Chart speed: 2.5 mm/sec.
Scan speed: 1.25 mm/sec.



SANBORN Recording Permapaper

1 July 1968
Filtered random phase pattern
filtered, in focal plane
Chart speed: 2.5 mm/sec.
Scan Speed: 1.25 mm/sec.





Juris Upatnieks, 2 July 1968