COMPUTATION BOOK

NAME: Juris Upatnieks
[redacted]

Number: 768

Course

~~JAN 15 59~~

Used from ~~Jan~~ January 16 1963, to November 17, 1965.

HARVARD COOPERATIVE SOCIETY
1400 Mass. Ave., Cambridge, Mass.
40 Mass. Ave., Cambridge, Mass.

January 16, 1963

Hologram construction using carrier frequency, produced by two beams and using a prism.

From previous experience with laser and hologram construction, the following was observed:

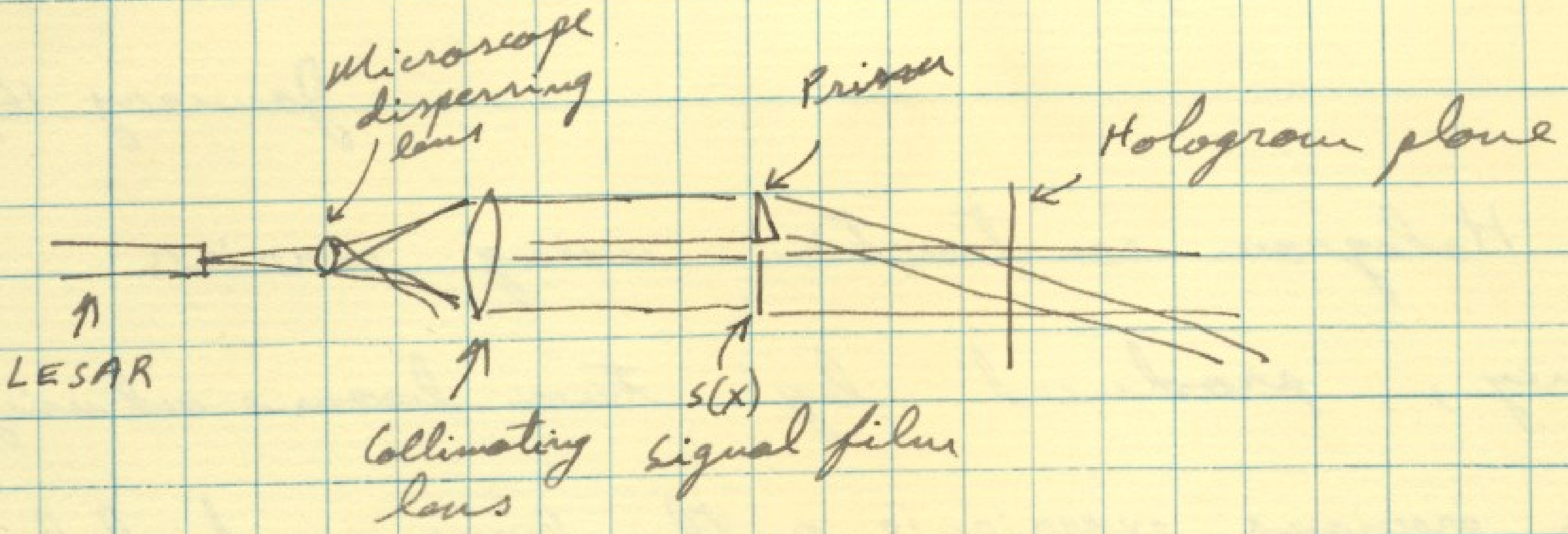
1. Coherence length is longer than path difference encountered in any experiments up to this time.

2. Noise level is very high in reconstructed continuous tone pictures and as a result of this fine detail is generally lost. Some course of noise are:
    - a. Dust particles on any surface - due to excellent coherence of the beam particles on <u>any</u> surface add consireably to noise level.
    - b. Grease or fingerprints on surfaces - these in general give phase modulation and their effect becomes more appearent with distance from the surface. Grease usually gives fine, regular noise pattern that looks like hering-bool. Fingerprints in general look like curved interference lines.
    - c. Non-uniform thicknes of film - even clear film produces interference pattern and it becomes more pronounced with distance from film.
    - d. Laser output - either laser itself or the microscope objective in front of it produces noisy output. Pinhole filter should reduce the higher frequencies of this noise.

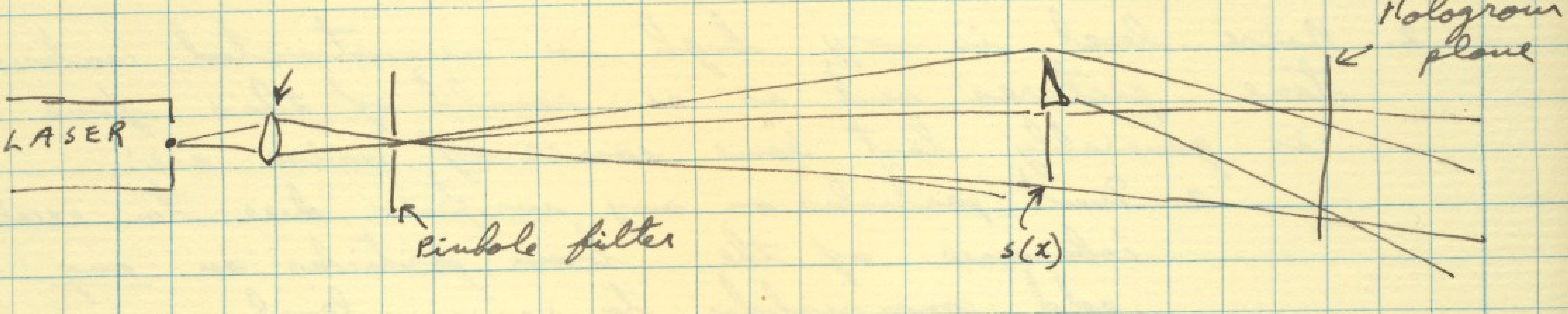
3. Carrier frequency of about 60 l/mm has given best results, but 150 l/mm have been used.

Optical system for making hologram:

signed 21 May 1964 Juris Upatnieks



To reduce noise level, the system above was modified:



Proposed ways to reduce noise level in holograms:

1. Laser output - use pinhole filter to remove high-frequency noise
2. Grease and dust on lenses - eliminate all lenses and mirrors using only a slightly diverging beam
3. Prism - use clean prism. Surface of prism may be coated to reduce multiple surface reflections.
4. Signal film - use fine grain emulsion on flat film or glass plate. Film may be placed in clean liquid gate to reduce phase modulation

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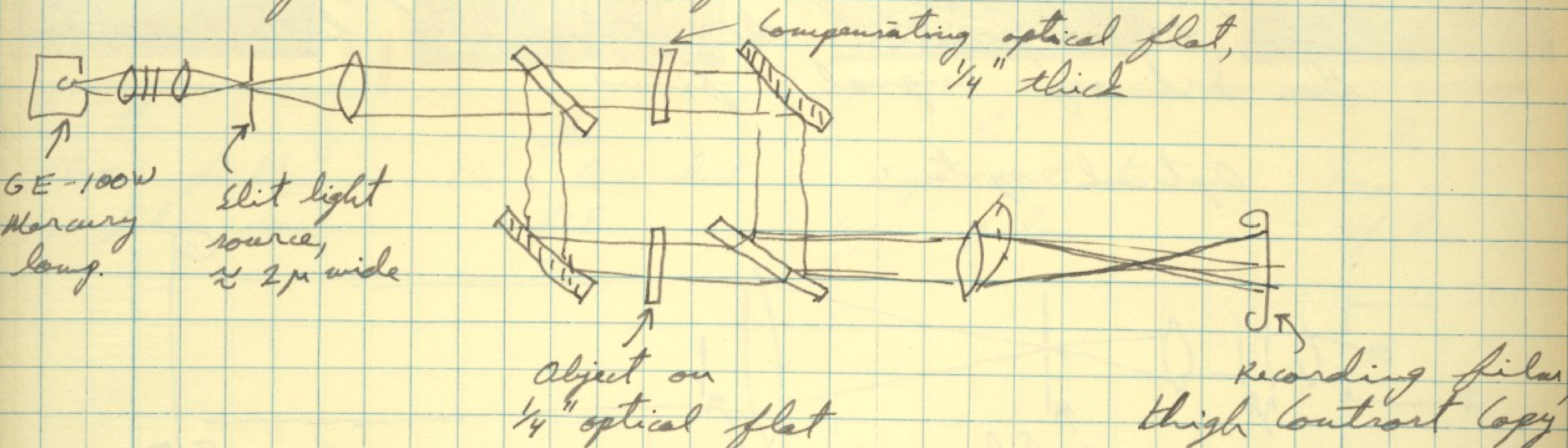
January 23, 196

Observation from one-dimensional hologram reconstruction.

A hologram was made using black letters on transparent background as the object, and obtaining 2-beam interference using Mach-Zander interferometer. The optical system for making the hologram was as follows:



In the reconstruction, the following was observed.

1. Low density hologram; object reconstructed properly, dark letters on illuminated background.

2. High density hologram; at the side where object reconstructed properly, out-of focus image appears. At the other side, light letters on dark background appear in focus.

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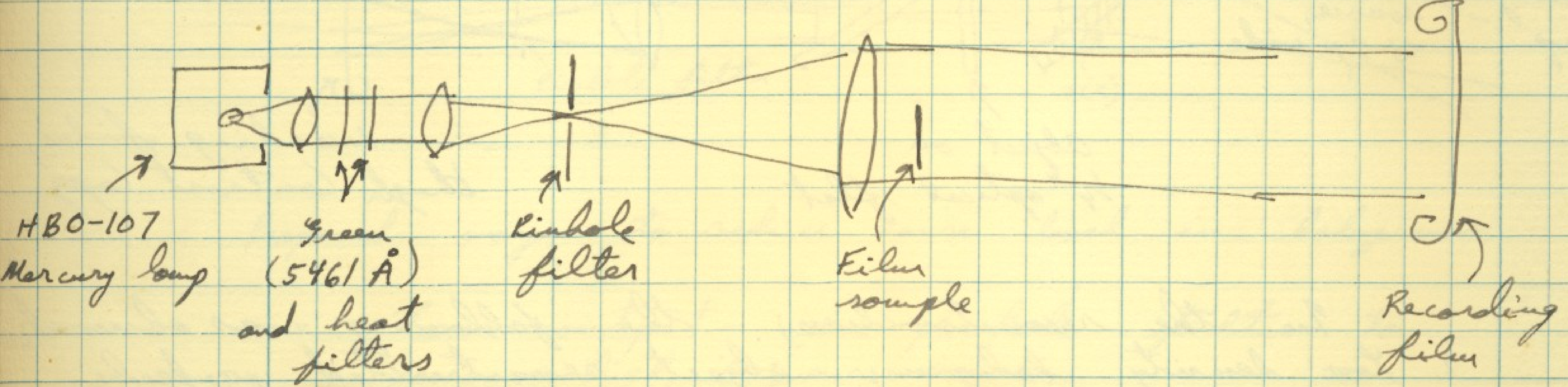
January 29, 1963

Test of the effect of non-uniform film thickness on clear field intensity distribution.

Several samples of different films were inserted into a colimated, coherent light beam. Observations were then made approximatly 3½ ft. from the film. The films were unexposed and developed in ordinary manner. No special precautions were taken preserve the film in better condition than ordinary signal films.

Optical system:



Recording film: High-Contrast Copy film, developed for 7 min. in D-19 developer. Test was made on Jan. 17, 1

NOTE: high-contract copy film has the effect of amplifying the intensity variations — direct observation showed same pattern but less intense.

Liquid used: Lugtoil

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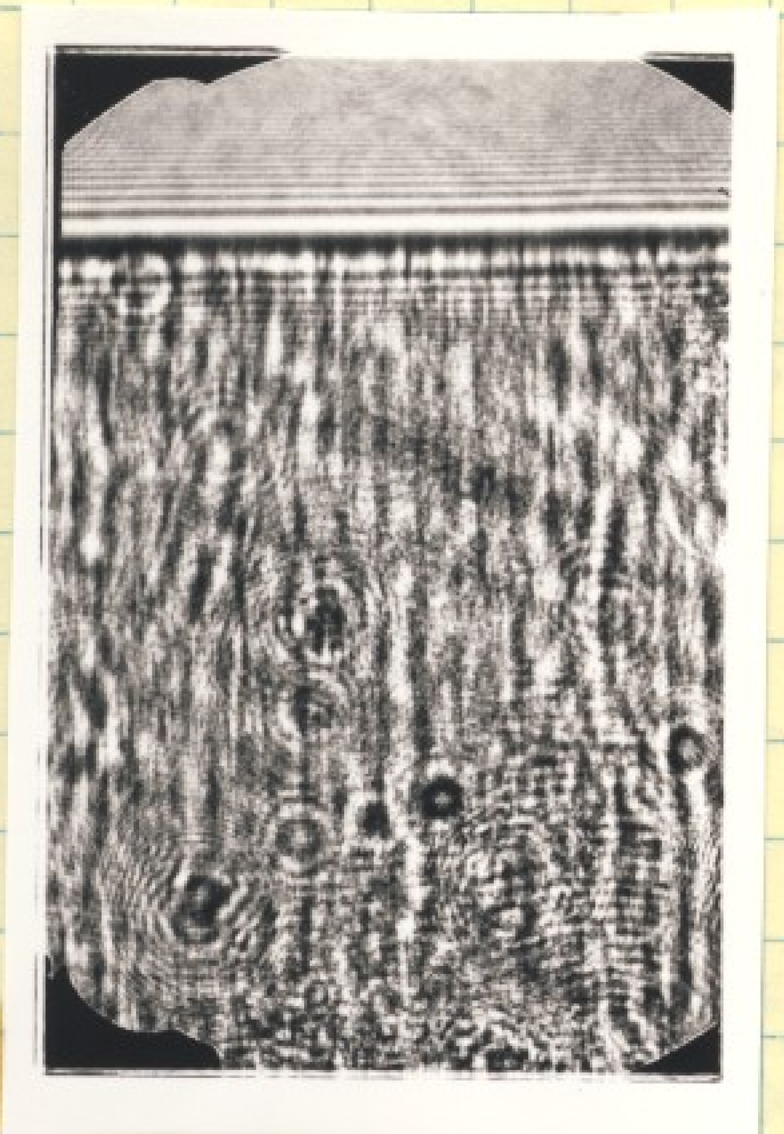
29 January 1963

NO LIQUID GATE

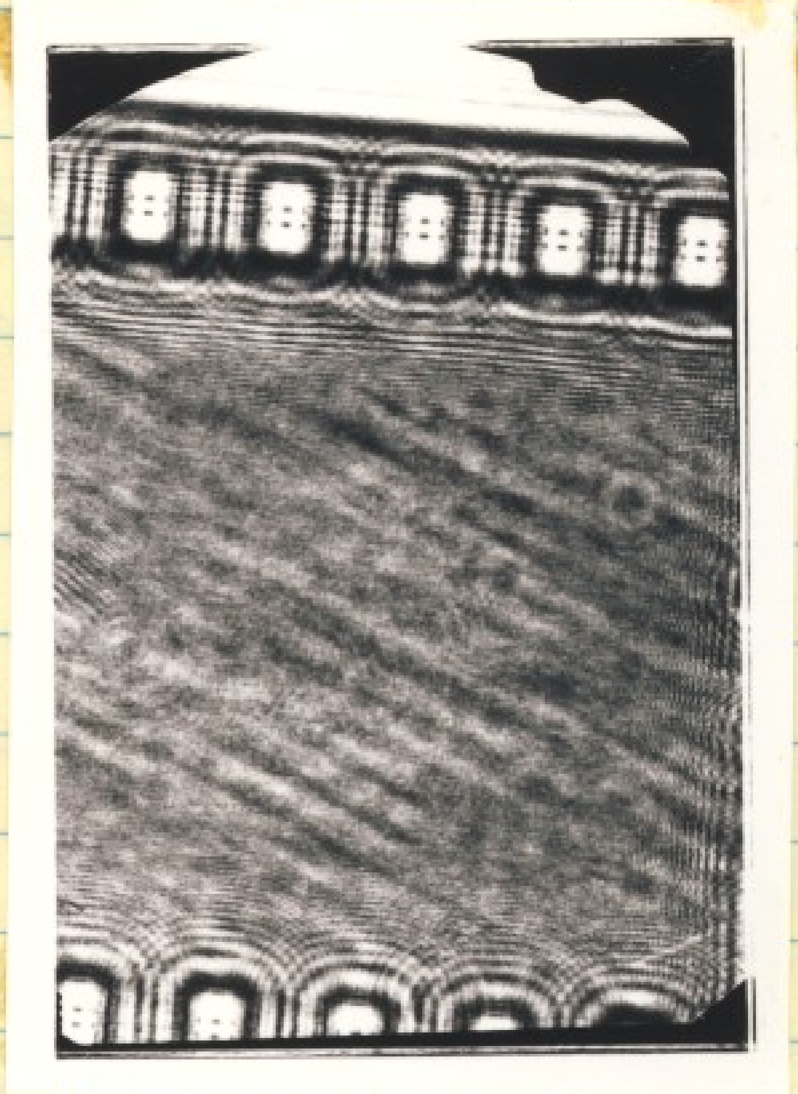
A.

Clear field,
no film in.



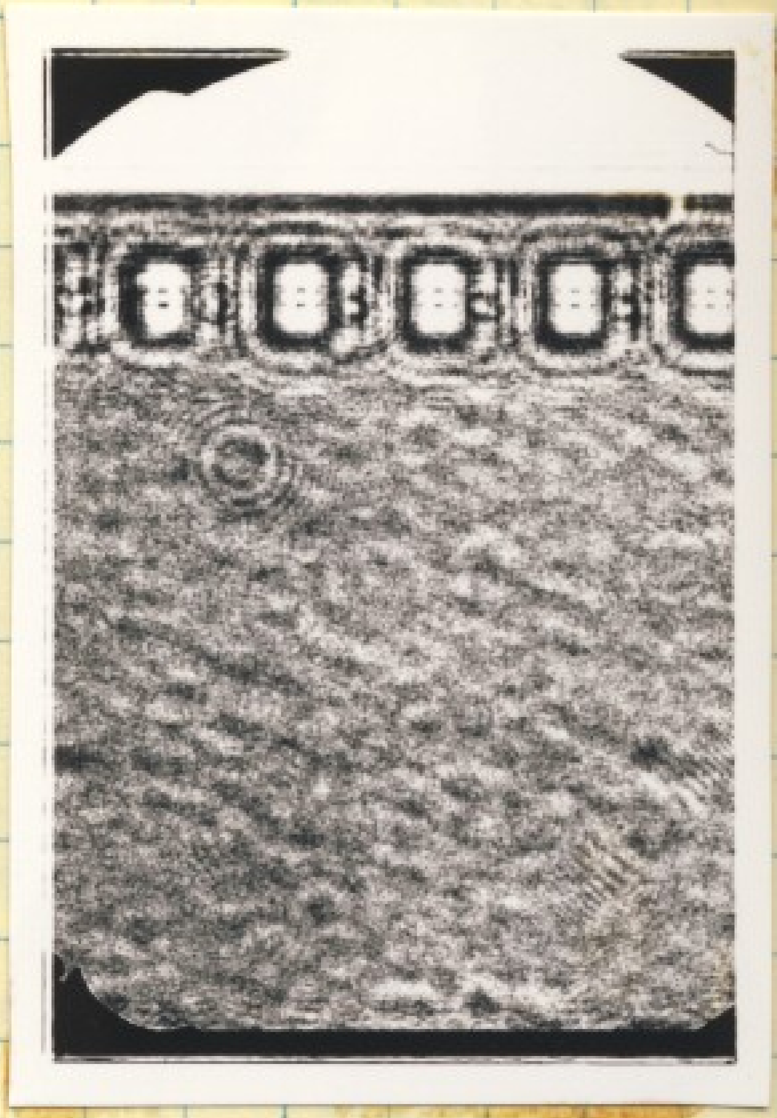
B.

Clear base sheet
film



C

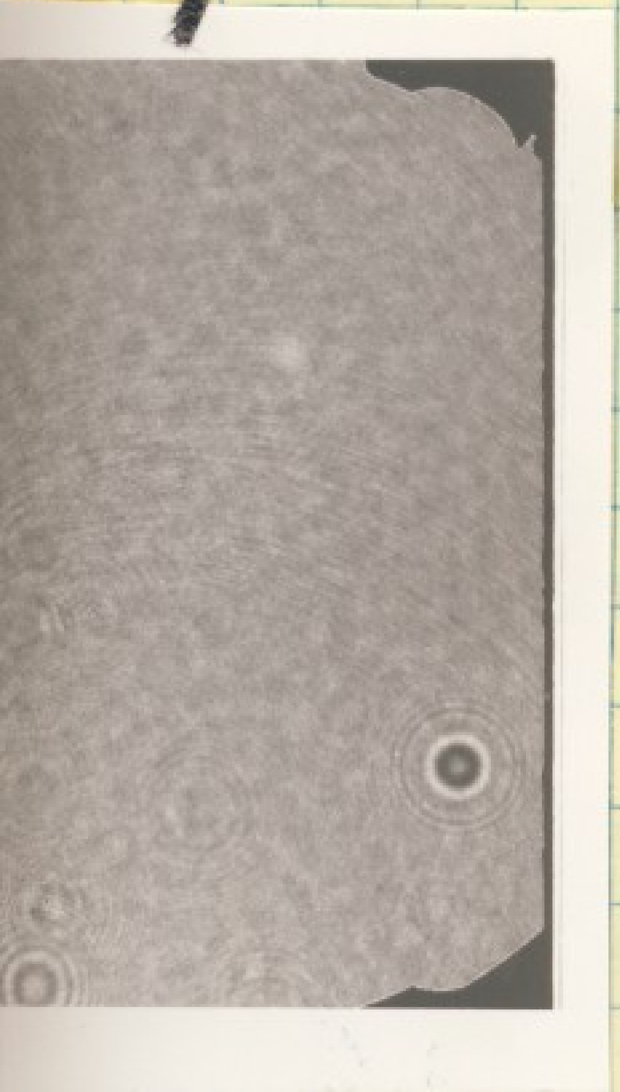
High-contrast
copy film



D

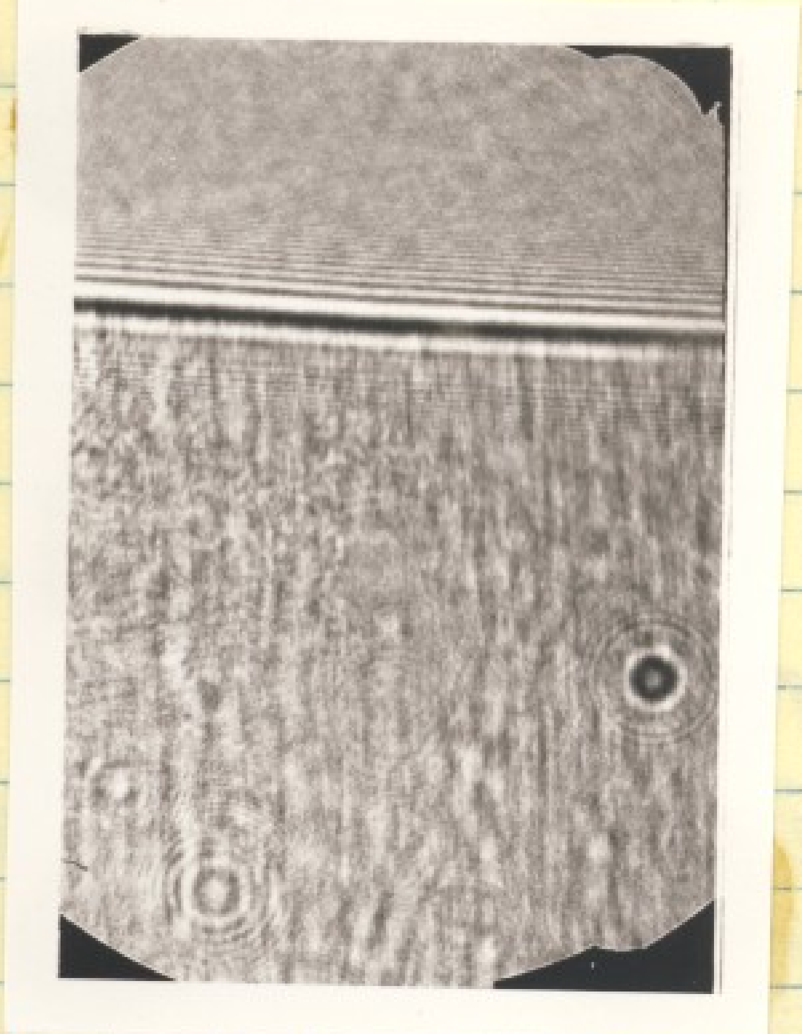
PAN - X
film

IN LIQUID GATE



E

lear field,
film in

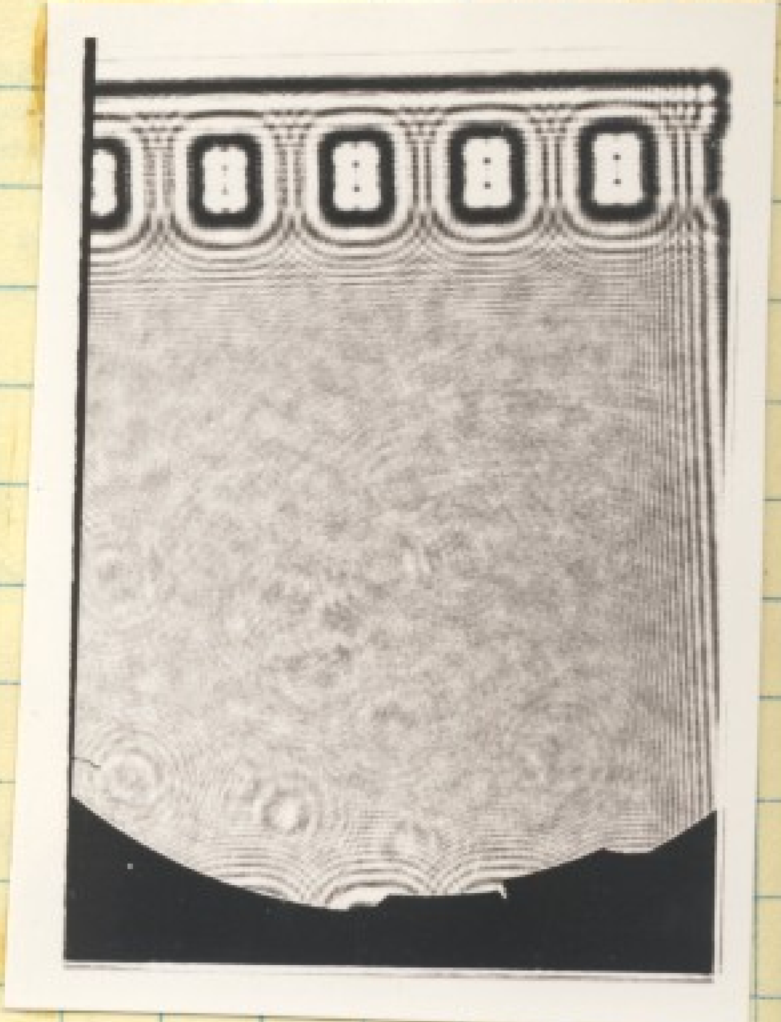


F

Clear base heet
film

G

High-contrast
copy film



H

PAN - X
film

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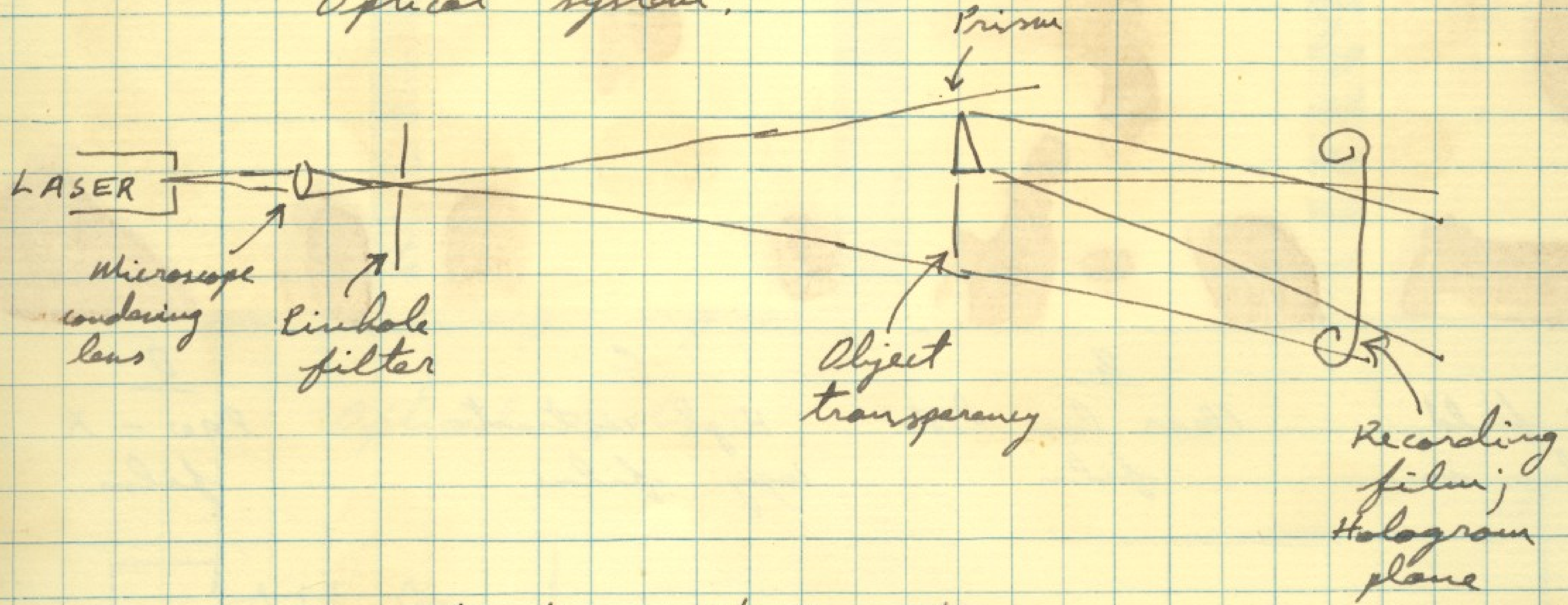
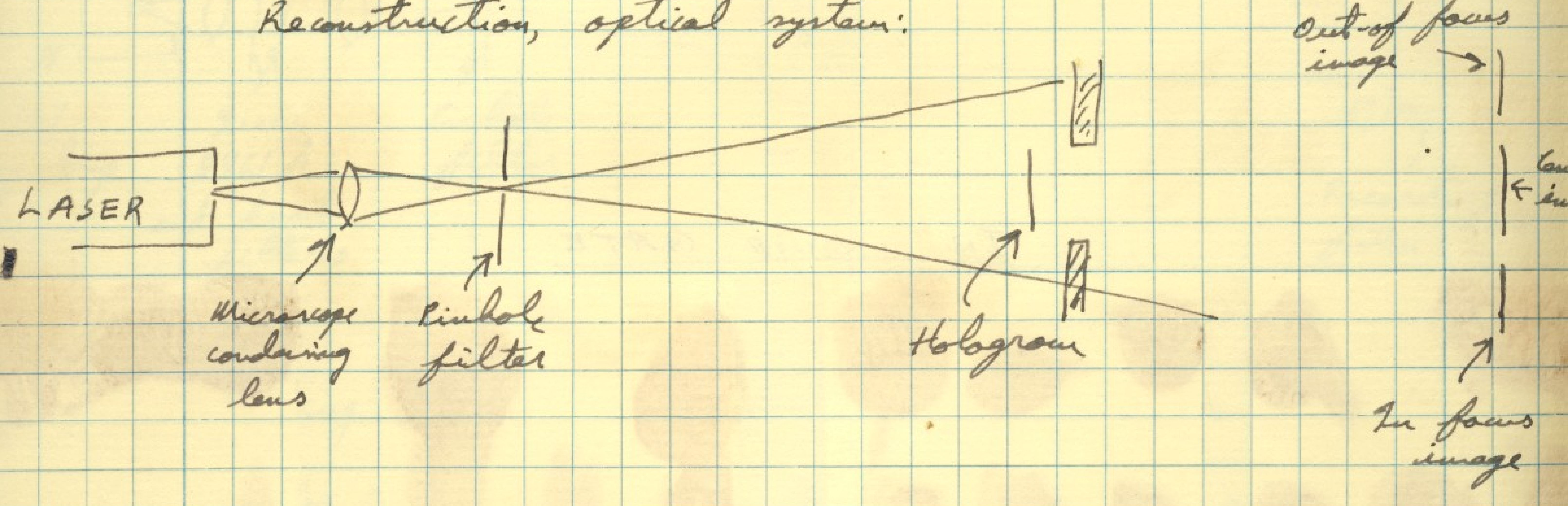
January 29, 1963

Originals and reconstructions from holograms made with carrier frequency.

Optical system:



Reconstruction, optical system:



Hologram recording film: High-contrast copy, developed as recommended by manufacturer.

Light wavelength: 6328 Å

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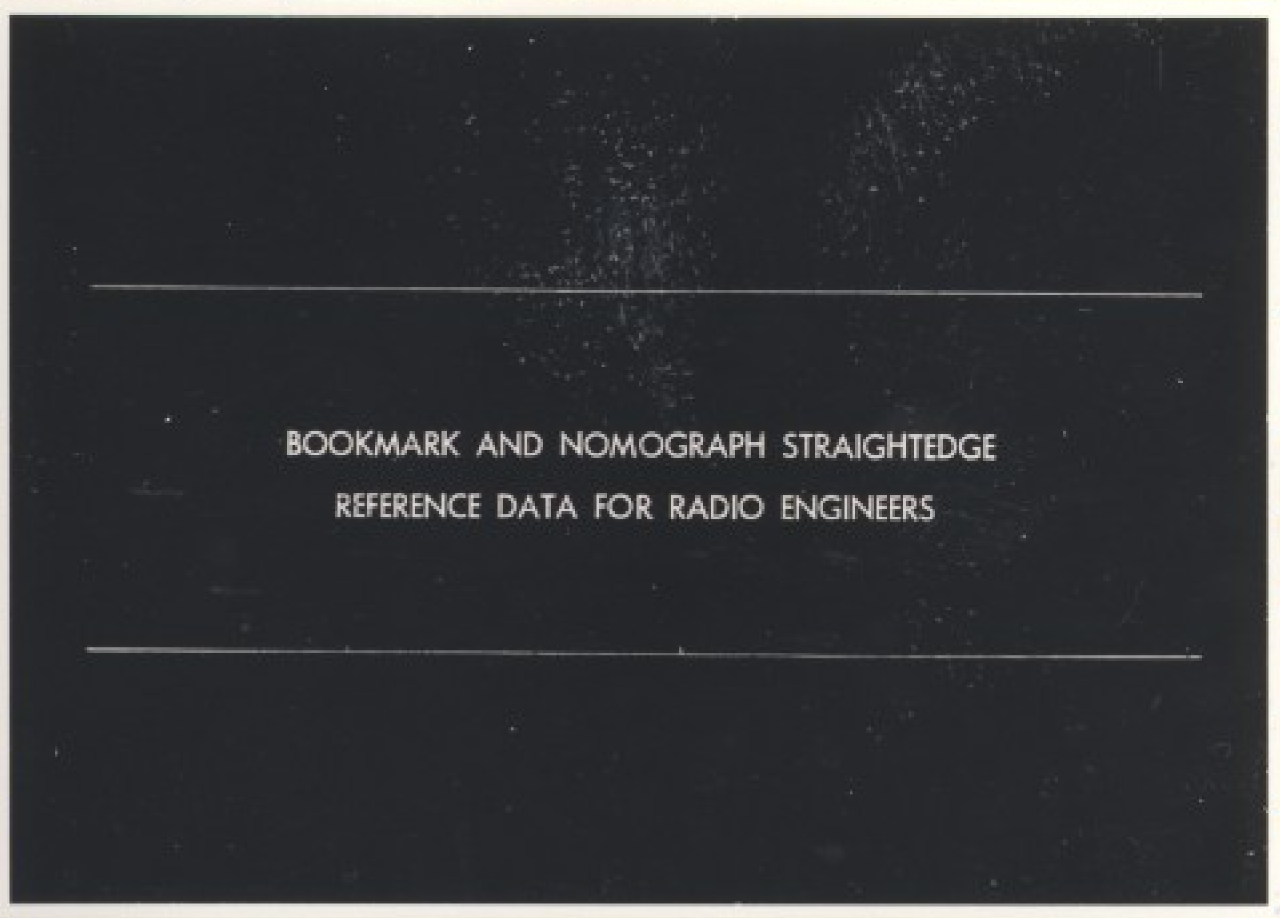
29 January 1963

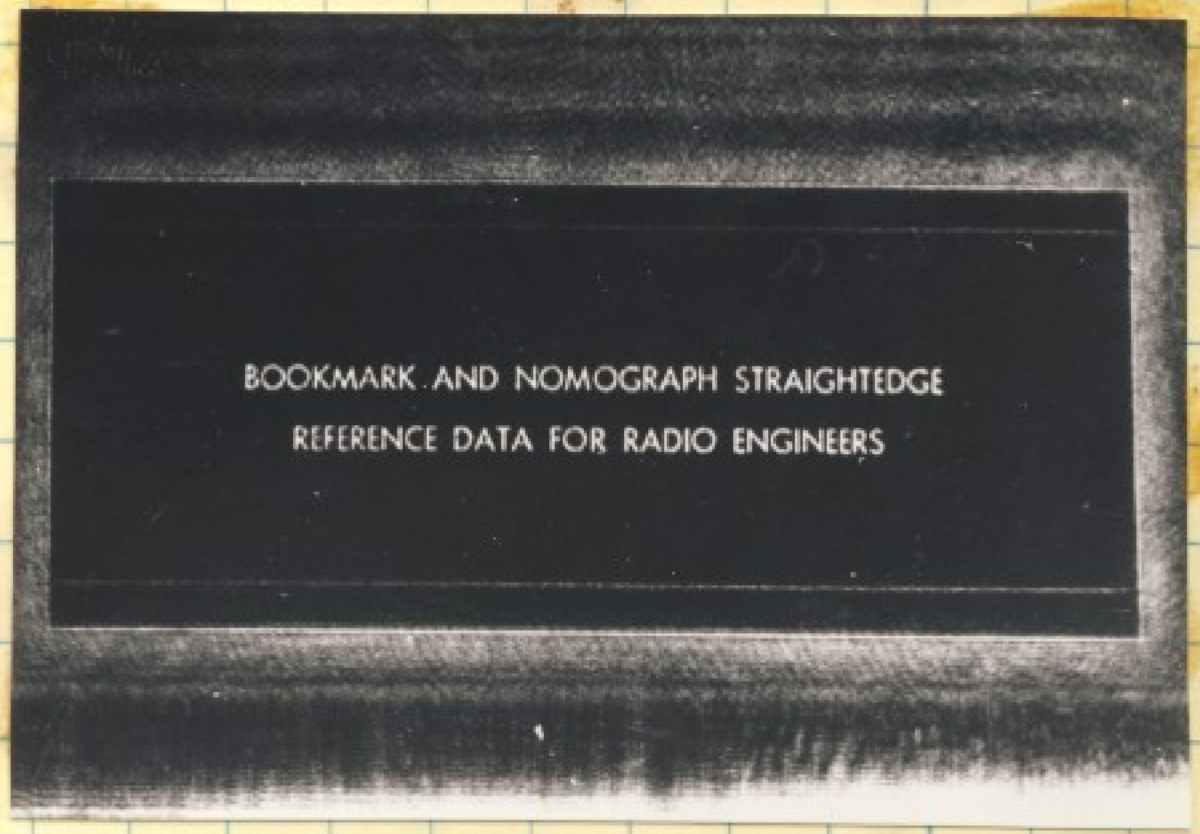
ORIGINAL



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

Hologram and reconstruction made in 1st week of Jan. '63

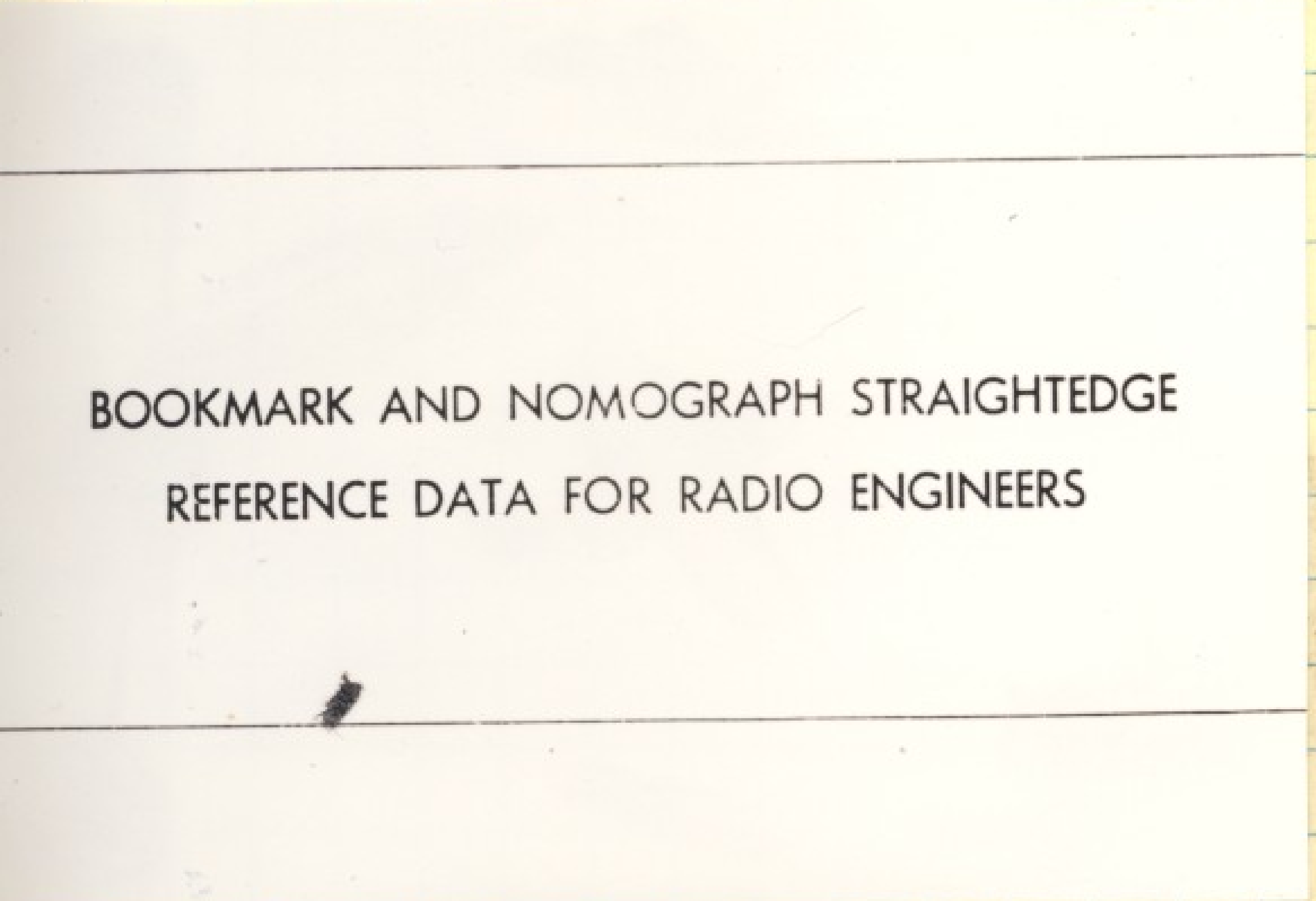
RECONSTRUCTION



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

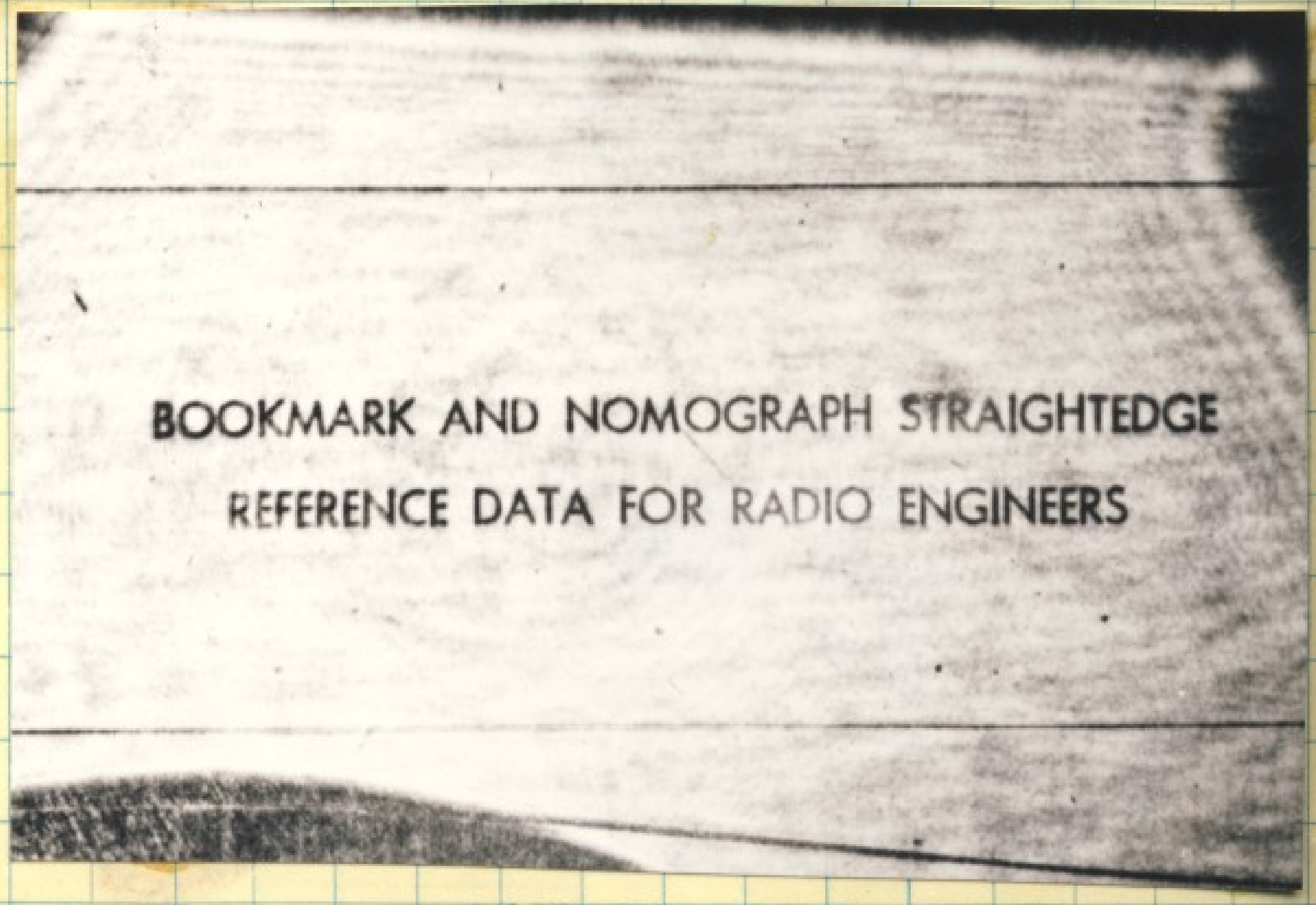
Noise in this reconstruction appears low because lines are too fine to distinguish them.

ORIGINAL



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

RECONSTRUCTION



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

Noise here appears quite strong in the backgroun
Edge effect can be seen at the top.

ORIGINAL

RECONSTRUCTION

In this case one lens and one mirror was used in the optical system. Original negative was quite dense. Reconstruction was recorded on polaroid paper. Hologram + reconstruct made in last week in Dec. 1962.

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29 January 1963

ORIGINAL

RECONSTRUCTION

Original was recorded
on PAN-X film. In recon
liquid gate was used. Li
at right are from grea
liquid gate. These were
made in 1st week of Jan

ORIGINAL

RECONSTRUCTION

Original on sheet film,
clear base. Reconstruction
shows low-frequency no
most of which is caused
non-uniform film thic
Spot at right is from pr
These were made in mid-Jan

ORIGINAL

RECONSTRUCTION

Same as above, b
in reconstruction p
was placed in liqu
gate. Edge effect
clearly visible an
could be reduced
using larger apertu

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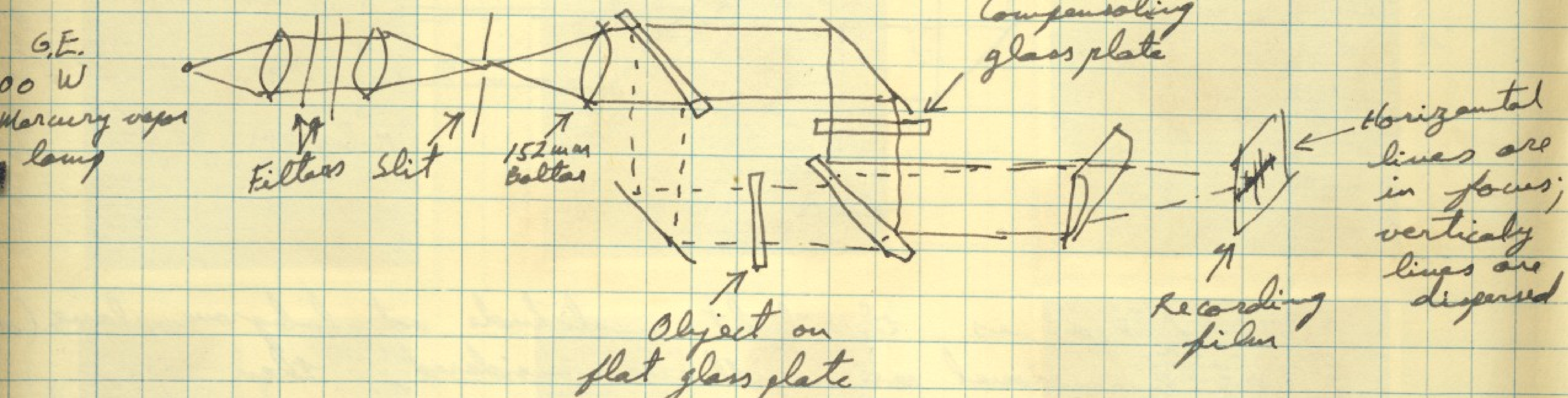
7 February 1963

1. Two-dimensional, continuous-tone holograms. The holograms made on Jan. 24, '63 appear to give the best reconstruction. This is probably because the exposure time was better than other times, and this improved signal to noise ratio. Exposure time appearantly has great effect on quality of reproduction (reconstuction).

At intermediate density of hologram there appears to be in focus and out-of focus image at the same time at one side.

2. One-dimensional hologram constuction with carrier frequency using Mach-Zender interferometer.

Optical system:



With this optical system good reconstruction were made from an object that consisted of transparent letters on opaque background. However, only a few letters could be reconstructed from many. Towarg both ends letters become very dim and were out-of-focus.

Possible causes:

a) Cylindrical lens aperture insufficient

b) Thickness variations of cylindrical lens make the focal plane of horizontal lines to be curved; therefore, only one portion at a time can be focust; hologram is not recorded where image is out of focus horizontaly.

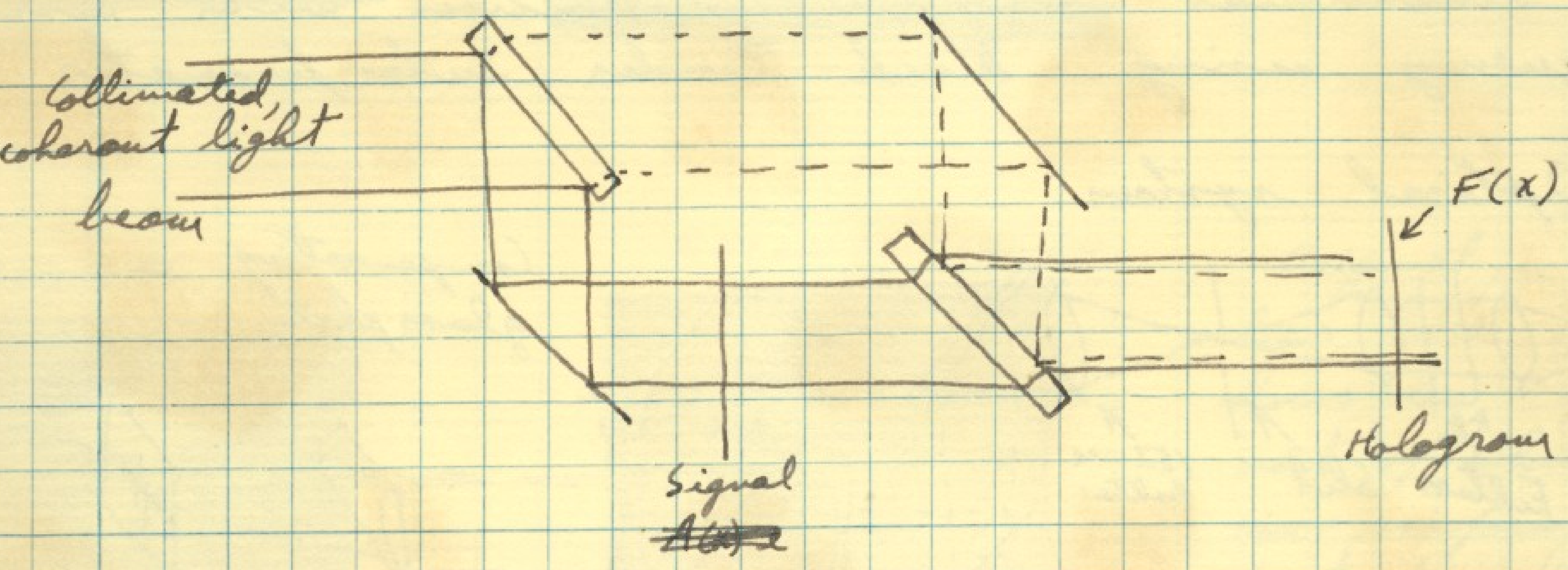
ned 21 May 1964
Juris Upatnieks

26 March 1963

Effect of film recording characteristic nonlinearity on hologram reconstruction.

During reconstruction of holograms from frames of different average density the effect shown on page 11 was observed. A possible explanation of this effect is derived.

The holograms in this case were made using Mach-Zender Interferometer, as shown below:



If F(x) is the light amplitude at hologram plane (o one-dimensional case will be considered), then the signal at this plane is:

$$F(x) = 1 + e^{j\omega x} + A(x)e^{j\phi(x)}$$

where a) 1 is the average D.C. term
b) $e^{j\omega x}$ is the carrier "
c) $A(x)$ is signal amplitude and $\phi(x)$ is its phase

Since the film records the absolute value square

$$|F(x)|^2 = \left(1 + e^{j\omega x} + A(x)e^{j\phi(x)}\right)\left(1 + e^{-j\omega x} + A(x)e^{-j\phi}\right.$$

$$= 2 + A^2(x) + 2\cos\omega x + 2A(x)\cos\phi(x) + 2A(x)\cos[\phi$$

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2ND ORDER REAL IMAGE

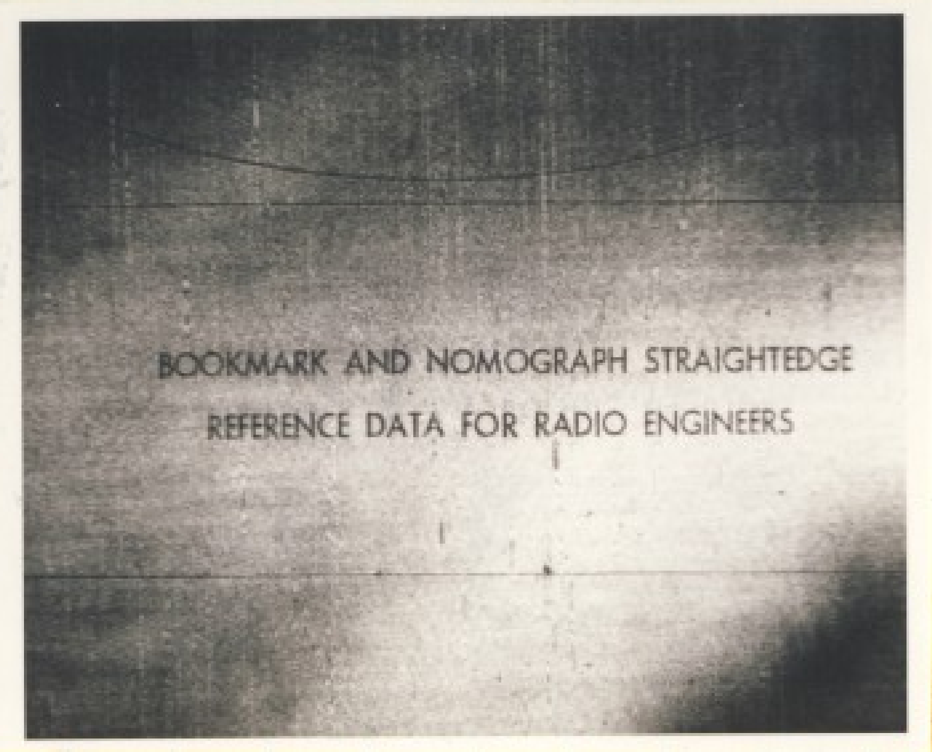
1ST ORDER REAL IMAGE

CENTRAL IMAGE

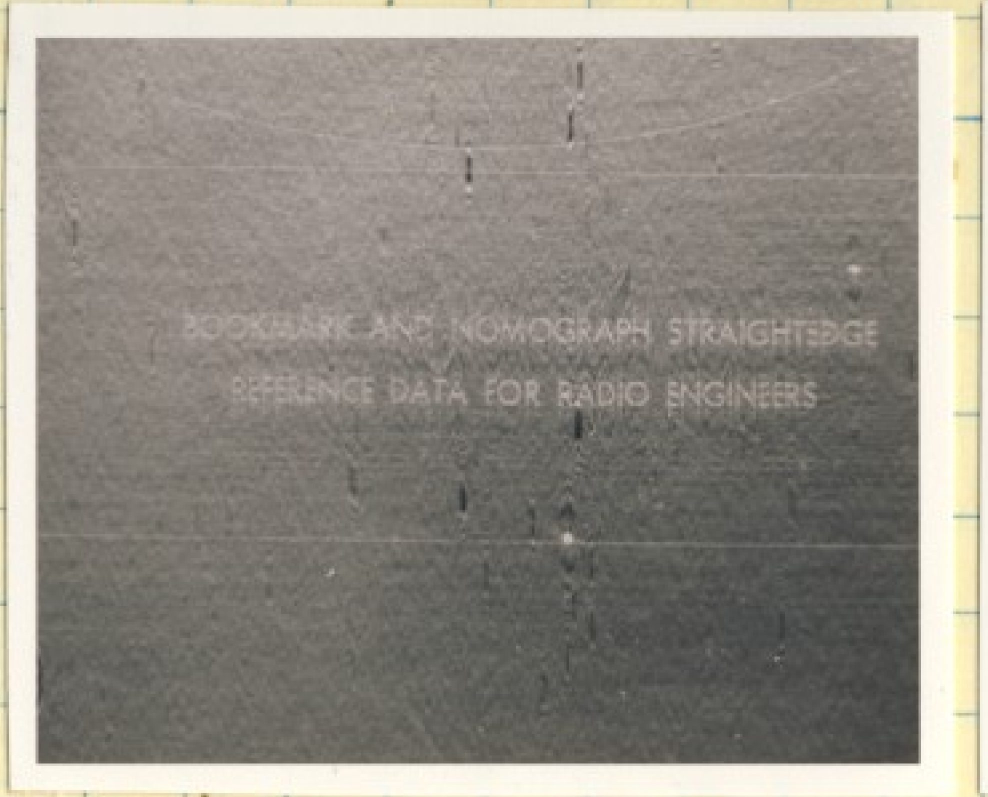
1ST ORDER VIRTUAL IMAGE

2ND ORDER VIRTUAL IMAGE

LIGH EXP.



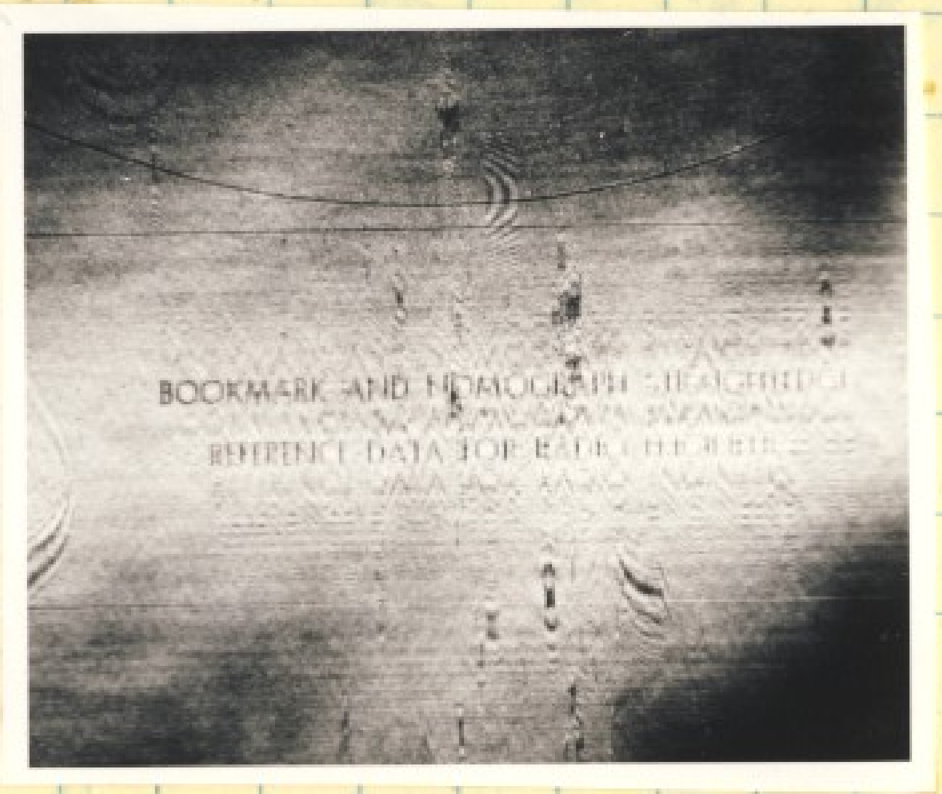
1.



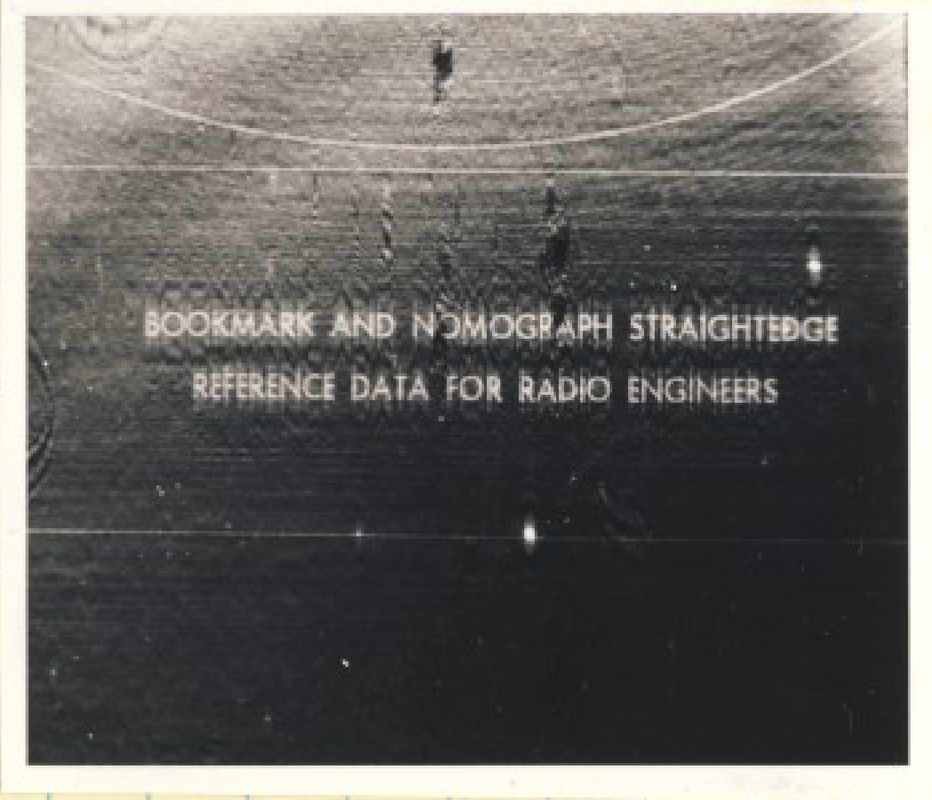
2.

3.

MEDIUM EXP.



4.



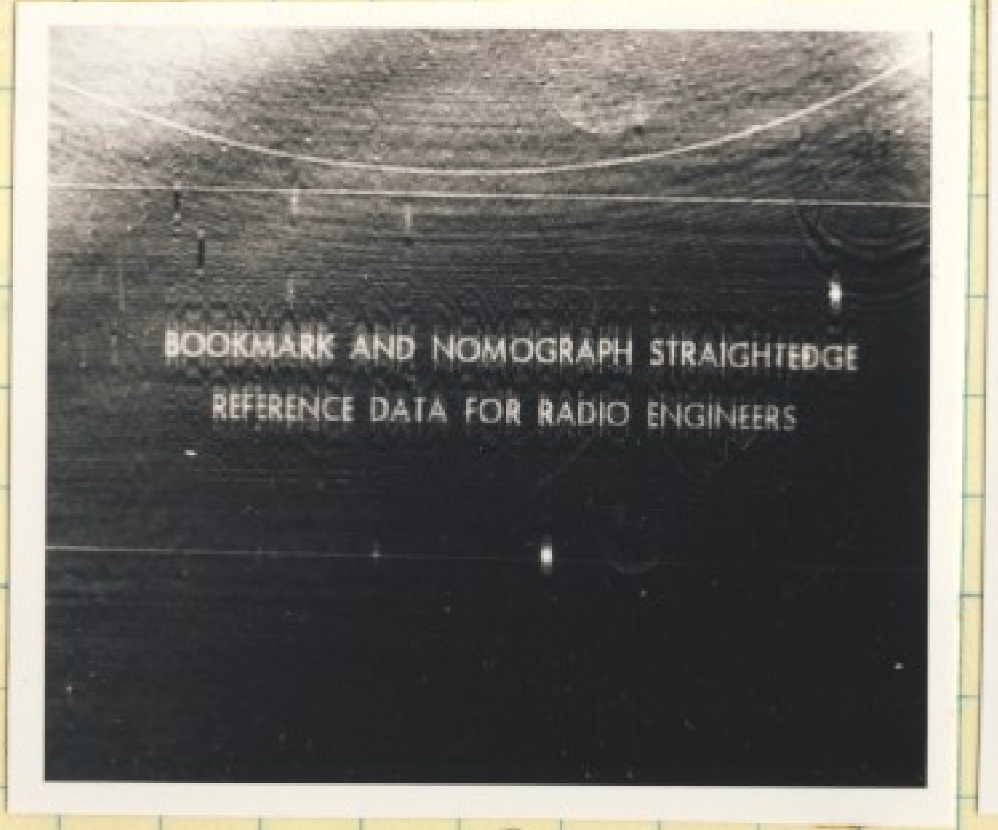
5.

6.

HEAVY EXP.

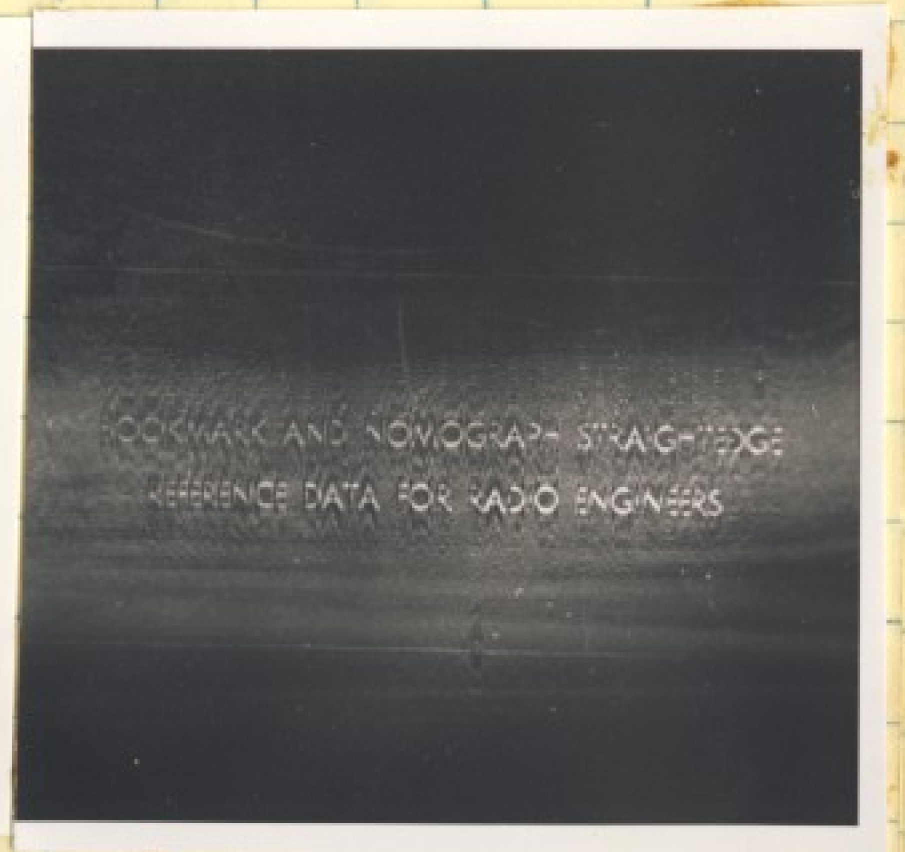
7.

8.



9.

10.



11.

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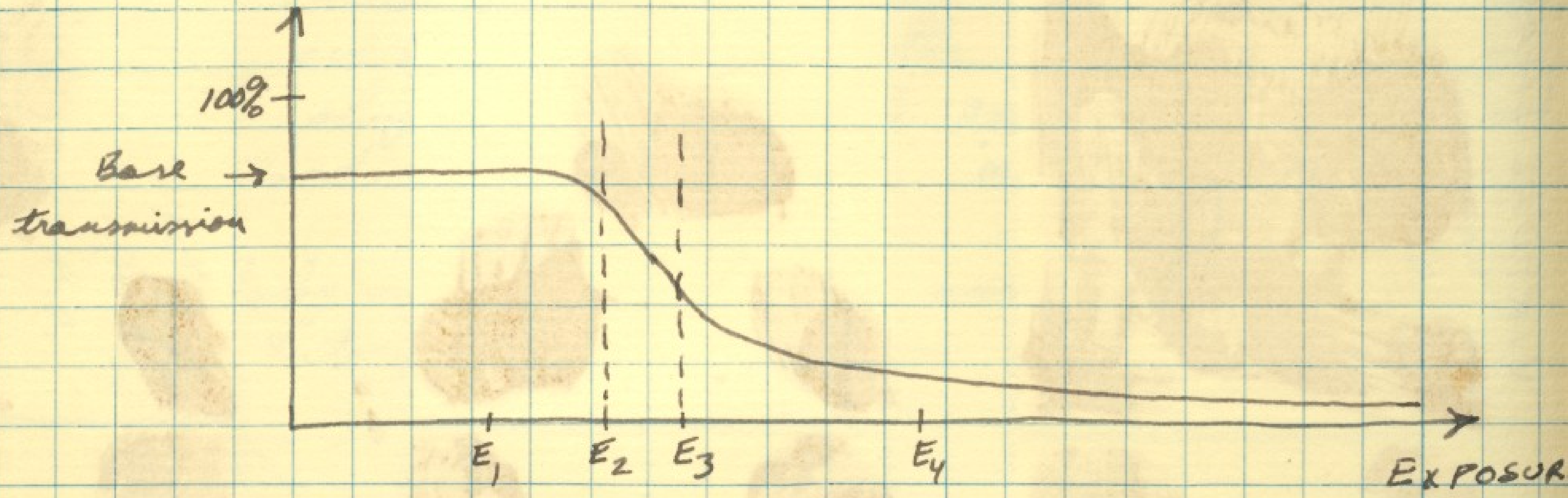
This signal, $F(x)$, is linearly recorded if film is not exposed too much. When the range of intensities exceeds the linear portion of the film, higher order terms are likely to appear: $|F(x)|^2$, $|F(x)|^4$, $|F(x)|^6$, etc.

The transmission vs. exposure curve has the general shape ~~of~~ as shown:



Between pts. E_2 and E_3 the recording is linear, beyond E_3 it has the shape similar to the curve $T = Ae^{-aE})$, or $A(1-e^{-ky})$. This can be expressed as a series:

$$Ae^{-ky} = A\left[1 - ky + \frac{(ky)^2}{2!} - \frac{(ky)^3}{3!} + \cdots\cdots\right]$$

Since the exact shape of the curve is not known, it can be assumed that the curve has the power series of

$$F(y) = A_0 - A_1 y + A_2 y^2 - A_3 y^3 + \cdots\cdots$$

where A_i are constants and may or may not equal to zero. Now let $y = |F(x)|^2$ and then $T(x)$, transmission of hologr at pt. x, is

$$T(x) = A_0 - A_1|F(x)|^2 + A_2|F(x)|^4 - A_3|F(x)|^6 + \cdot\cdot$$

Each term can be found separatly; and to simplify $A^2(x)$ term are assumed to be negligable.

$$|F(x)|^2 = 2 + 2\cos\omega x + 2A(x)\cos\phi(x) + 2A(x)\cos[\phi(x)-$$

$$|F(x)|^4 = 6 + 12A(x)\cos\phi(x)$$
$$+ 8\cos\omega x + 12A(x)\cos(\phi(x)-\omega x) + 4A(x)\cos[\phi(x)+$$
$$+ 2\cos 2\omega x + 4A(x)\cos[\phi(x) - 2\omega x]$$

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$$
\begin{aligned}
|F(x)|^6 = {} & 20 + 60A(x)\cos\phi(x) \\
& + 30\cos\omega x + 60A(x)\cos[\phi(x)-\omega x] + 30\cos[\phi(x)+\omega x] \\
& + 12\cos 2\omega x + 30A(x)\cos[\phi(x)-2\omega x] + 6\cos[\phi(x)+2\omega x] \\
& + 2\cos 3\omega x + 6A(x)\cos[\phi(x)-3\omega x]
\end{aligned}
$$

By approximating the curve by the first four terms, we get

$$
\begin{aligned}
T(x) = {} & (A_0 - 2A_1 + 6A_2 - 20A_3) + (-2A_1 + 12A_2 - 60A_3)A(x)\cos\phi(x) \\
& + (-2A_1 + 8A_2 - 30A_3)\cos\omega x + (-2A_1 + 12A_2 - 60A_3)A(x)\cos[\phi(x)-\omega x] \\
& \qquad + (4A_2 - 30A_3)A(x)\cos[\phi(x)+\omega x] \\
& + (2A_2 - 12A_3)\cos 2\omega x + (4A_2 - 30A_3)A(x)\cos[\phi(x)-2\omega x] \\
& \qquad + 6A_3\cos[\phi(x)+2\omega x] \\
& - 2A_3\cos 3\omega x - 6A_3 A(x)[\phi(x)-3\omega x]
\end{aligned}
$$

$$
\begin{aligned}
T(x) = {} & B_0 + B_1 A(x)\cos\phi(x) \\
& + B_2\cos\omega x + B_3 A(x)\cos[\phi(x)-\omega x] + B_4 A(x)\cos[\phi(x)+\omega \\
& + B_5\cos 2\omega x + B_6 A(x)\cos[\phi(x)-2\omega x] + B_7 A(x)\cos[\phi(x)+2\omega \\
& + B_8\cos 3\omega x - B_9 A(x)[\phi(x)-3\omega x]
\end{aligned}
$$

Here we clearly see that the term $[\phi(x)+\omega x]$ appears in the nonlinear case and the (+) sign indicates this term would come to focus in the opposite sideband. From the magnitude of the coefficients, it appears that for $\{\phi(x)-\omega x\}$ term to go to zero, $\phi(x)$ coefficient must also go to zero. This is not the case, however, as can be seen from the pictures. It might be that B_1 & B_3 become small compared to the compressed signal at reconstruction of B_4. Phase modulation likewise

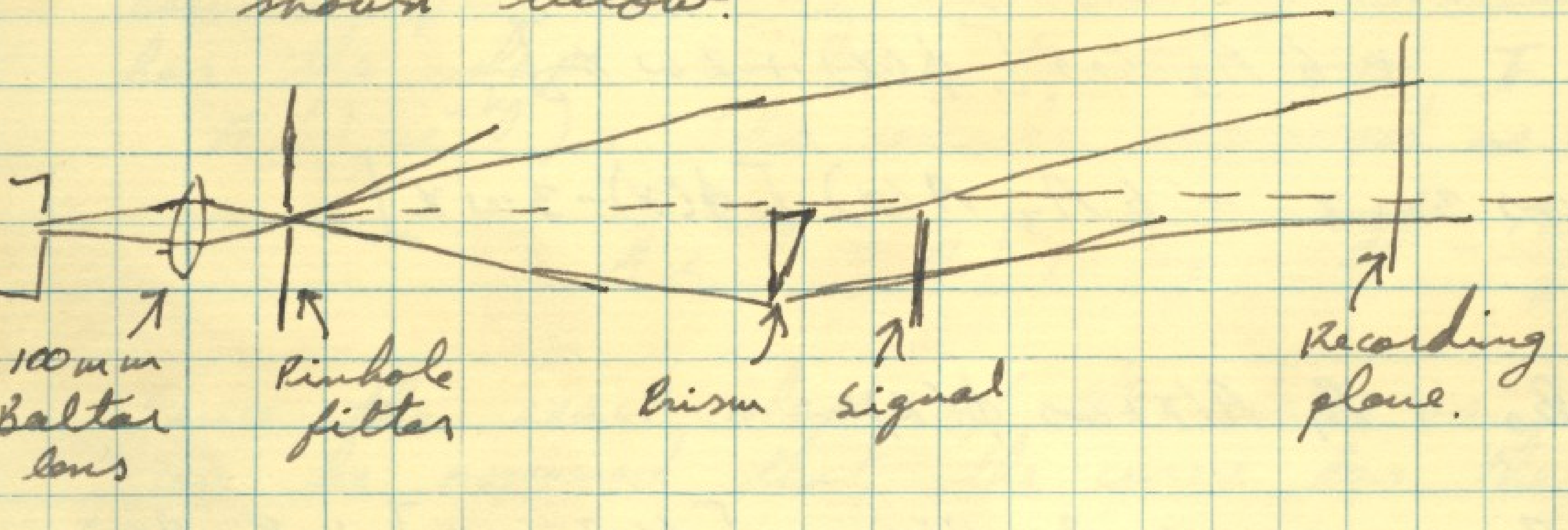
Signed 21 May 1964, Juris Upatnieks

is present and may have some effect. Placing the film in liquid gate, however, did not change the appearance of any of these pictures shown on p. 11. Close examination of pictures #4 & 6, and #7 & 11 indi that as image in one side-band begins to disap it comes into stronger focus at the other side.

1 April 1963

Two-dimensional holograms with carrier frequen

During March of '63 another attempt was made to improve the quality of reconstructed images from holograms. The setup using prism and object on a micro-flat glass plate with extremely high resolution was used. The optical system is shown below.



A carrier frequency of about 120 lines/mm was used and the object (signal) was moved to within ≃ 70 cm of the recording plane. Hologram was made on microflat glass plates with 649F emulsion on it. Examination of flatness of plates indicated that central region was flat, but emulsion thickness varied over many λ near the edge of the glass.

Reconstructions were made in the same optical system as above except the prism was removed and reconstructed images were recorded on polaroid film or paper. Reconstructions of continuous tone pictures were better than any before and both grainy appearance and low-frequency noise were far below previous level. Letter type sign

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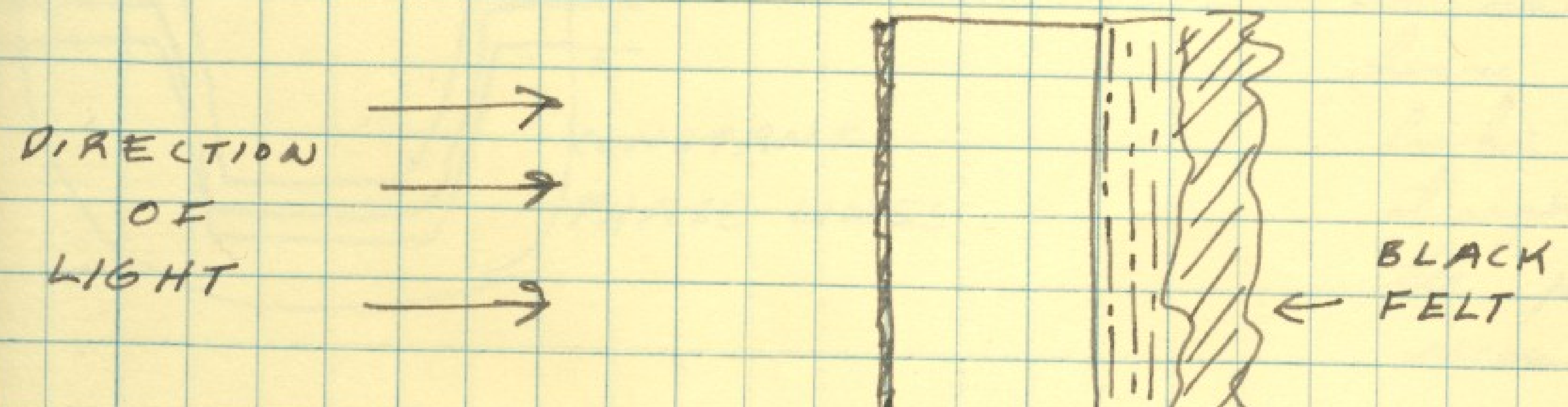
were also used and reconstructions were better than any before. Liquid gate was used in reconstruction.

Several problems, though not serious, still remain:

1) Grainy appearance of reconstruction - this was observed only using some magnification of reconstruction. This noise is caused by very fine dot-like irregularities scattered over the surface of emulsion. Emulsion 649F has less than other films. This effect may be reduced by using liquid gate.

2) Low-frequency noise in the background. It is not certain wether this is caused by defects in hologram or the original signal. Liquid gate should also reduce this effect.

3) Low-frequency amplitude modulation of hologram due to multiple reflections from surfaces of glass plate. The interference of light from transmitted beam and reflected beam produce visible, distinct, fringes. These do not seem to have any effect on reconstruction. This effect could be reduced by placing a black felt against the back surface of the plate and wetting it with liquid whose index of refraction is close to that of the glass plate. This was tried with an exposed



glass plate (clear) and the reflected fringes were found to be of much lower intensity.

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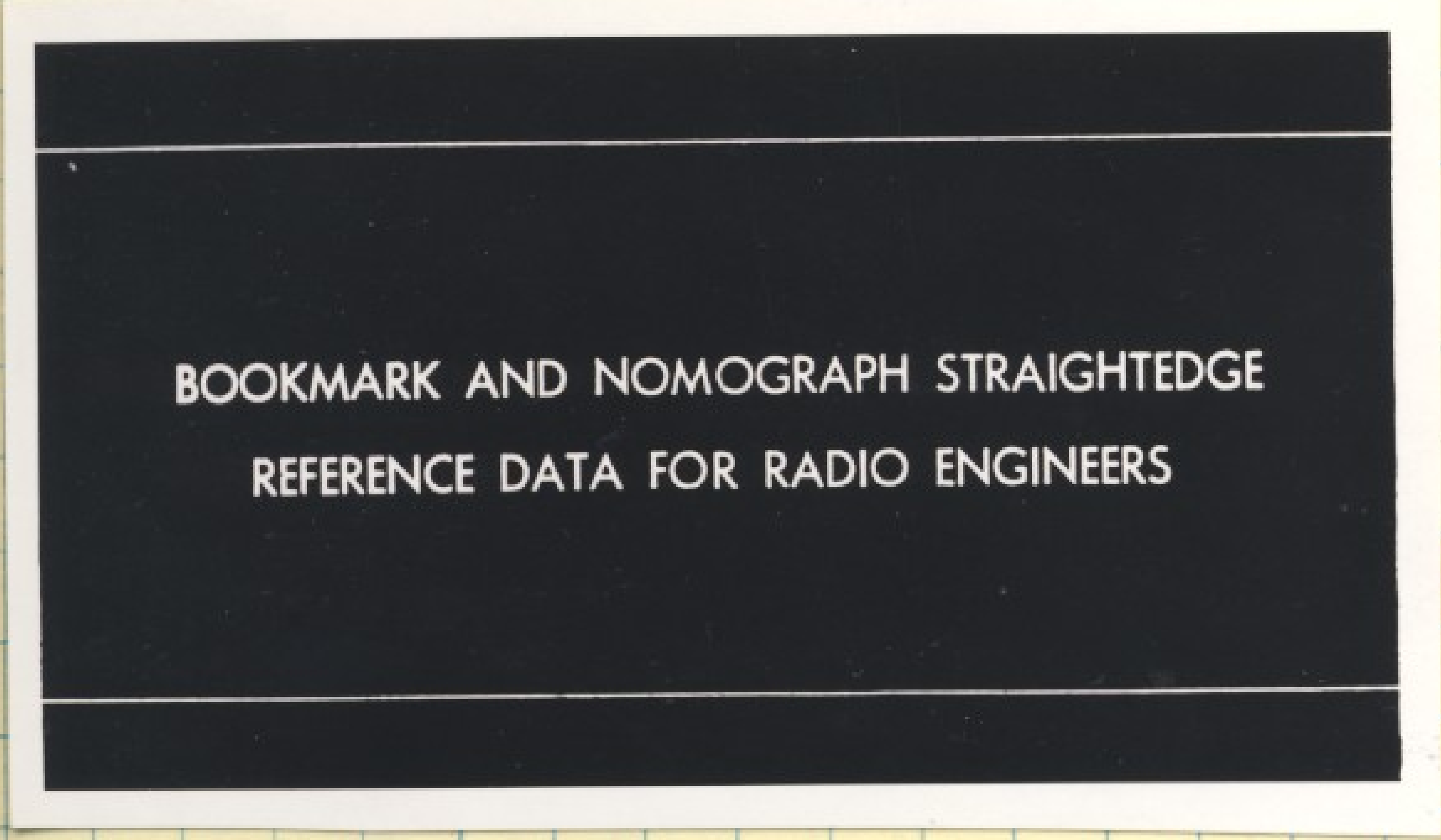
Reconstruction

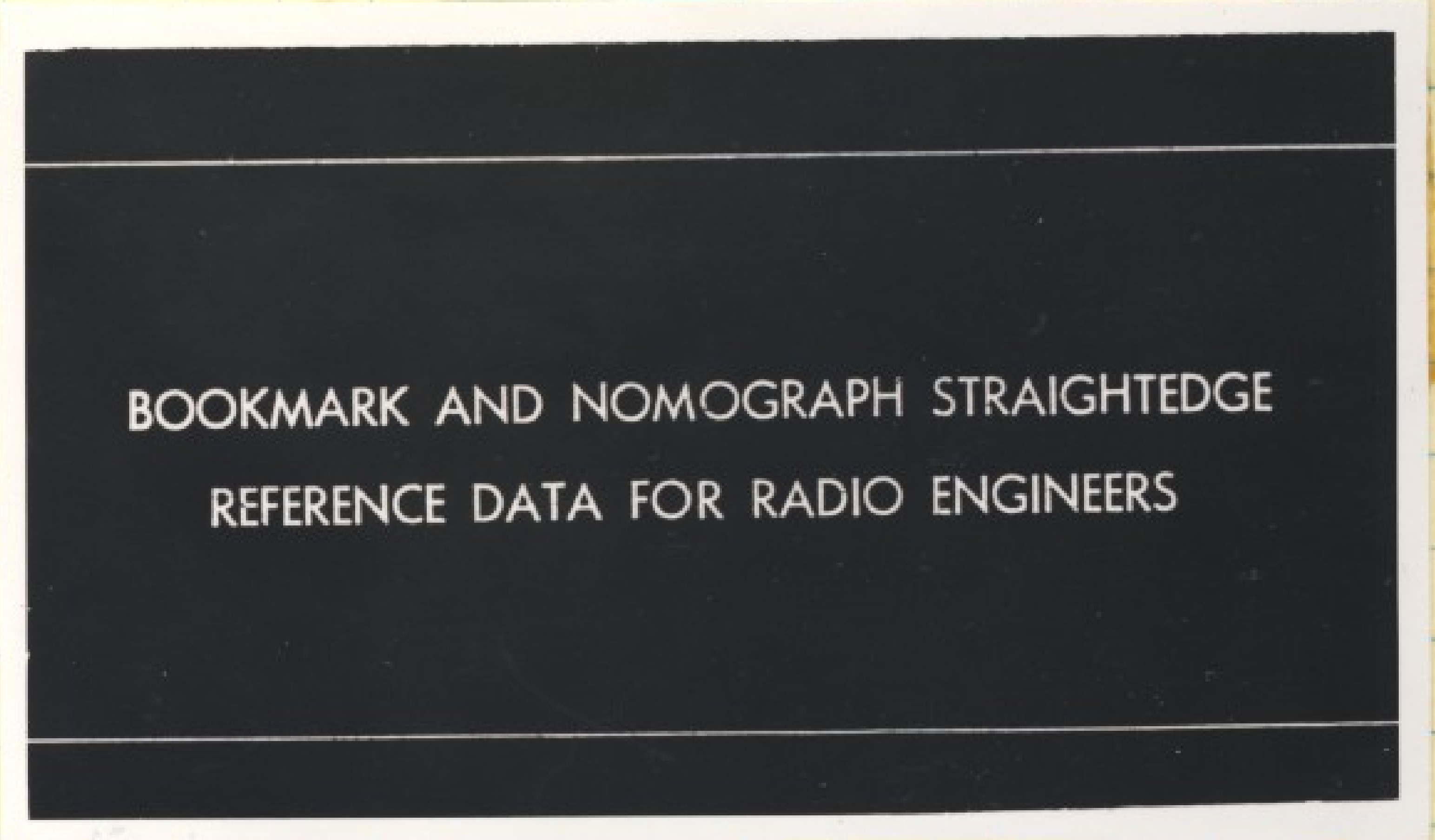
Hologram of monograph

Original of monograph



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

Reconstructed monograph



BOOKMARK AND NOMOGRAPH STRAIGHTEDGE
REFERENCE DATA FOR RADIO ENGINEERS

These holograms and reconstructions were made during March 1963.

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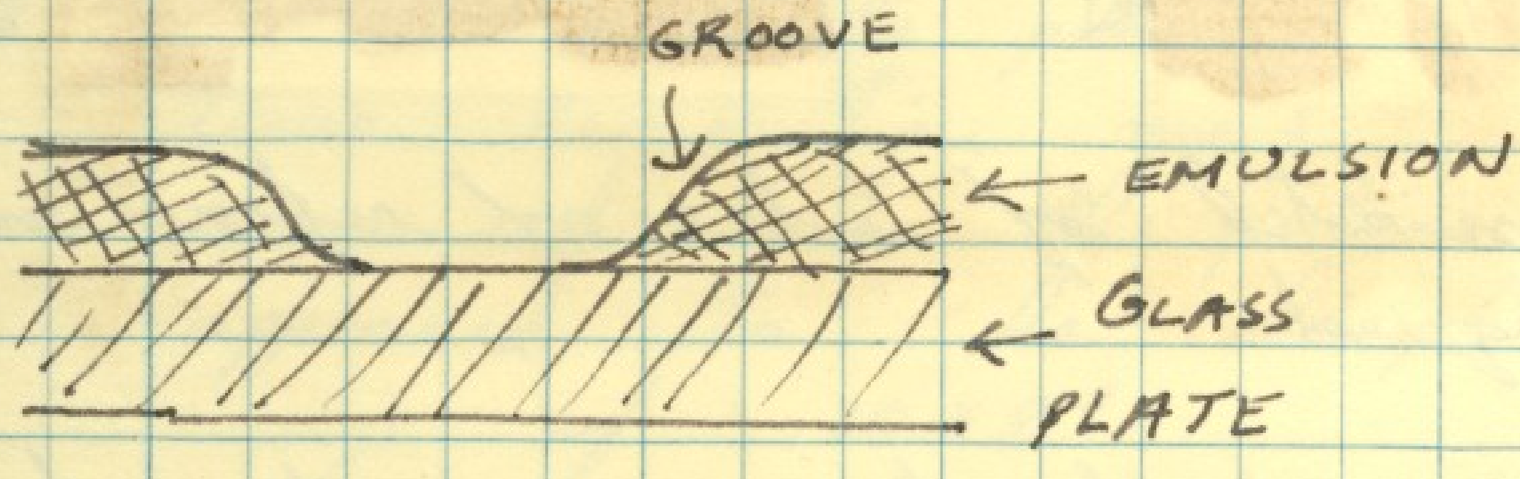
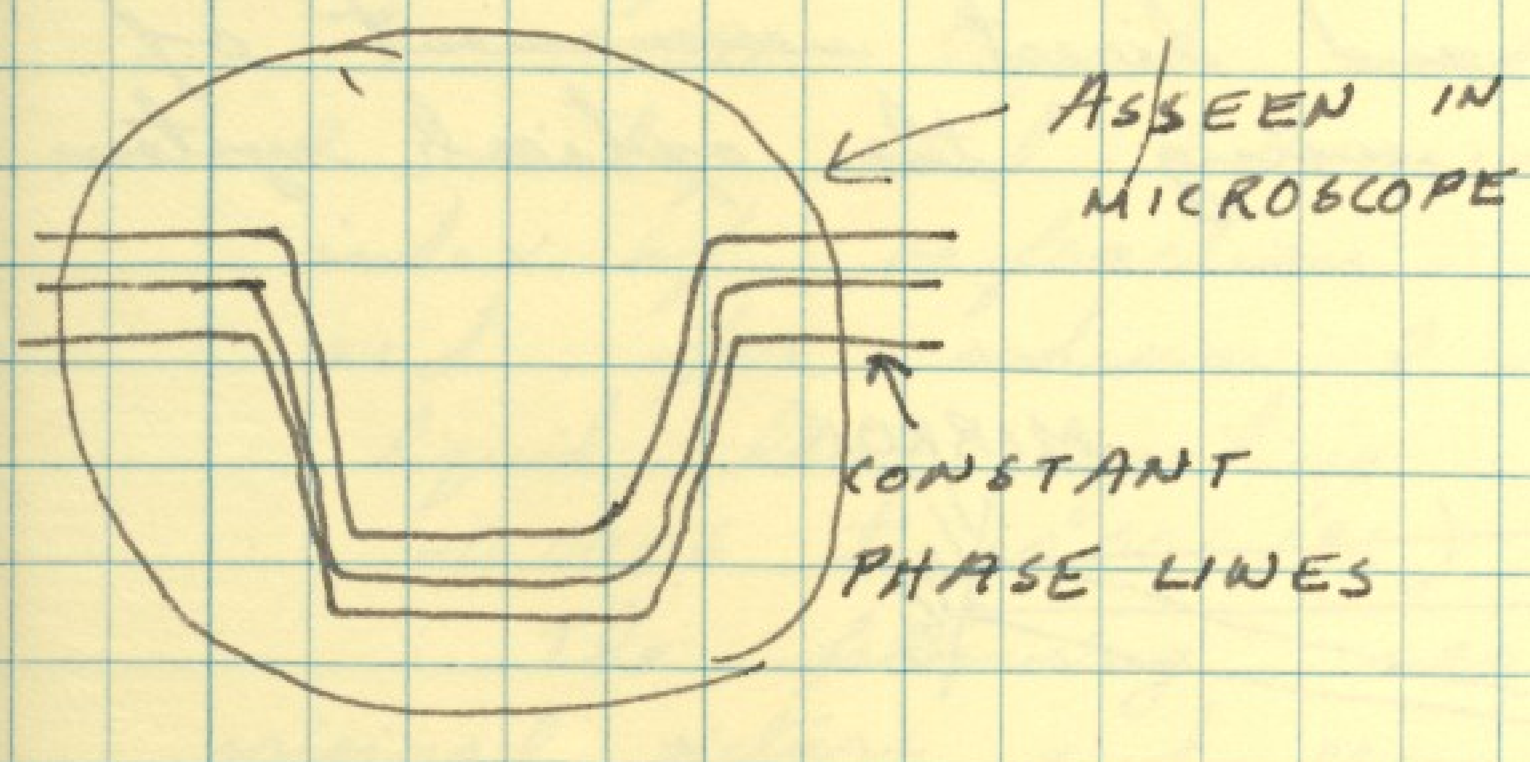
10 April 1963

Determination of the affect of liquid gate on reducing phase error in holograms.

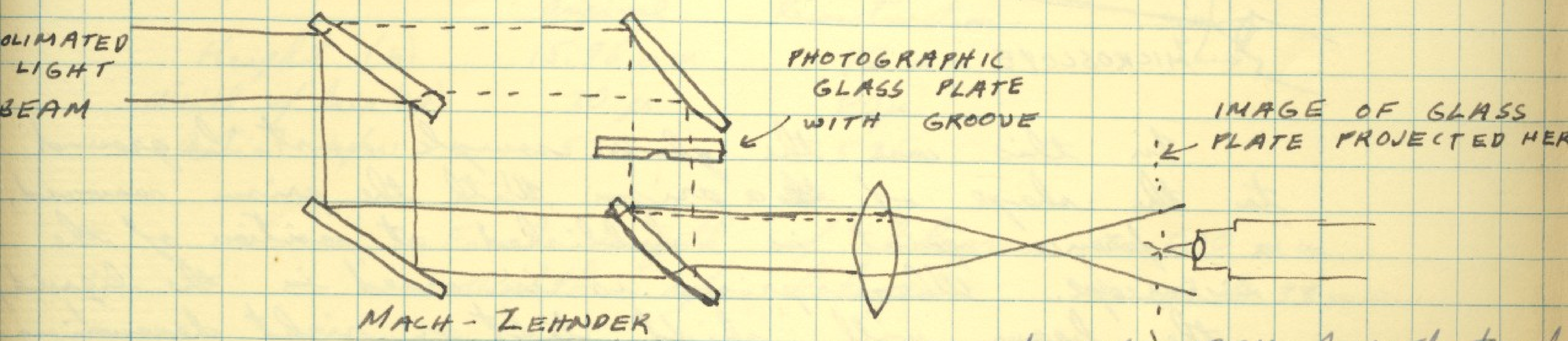
It has been frequently observed that when a hologram is placed in a liquid gate the resolution of the reconstructed image is improved. Usually the index of refraction of emulsion is assumed, and that of the liquid is measured at sodium D-line. When films and plates are used at 6328 Å red light, exact indexes of refraction are not known.

To test directly improvement in phase error, a sample glass plate was taken and exposed with varying intensity light. The plate was then developed, fixed, and etched with H_2O_2 solution, diluted. This ~~result~~ gave smooth groves at places where the plate was exposed. A cross section is shown below, and also the resulting interference pattern in Mach-Zehnder interferometer:





To observe variations in thickness (light path), the glass plate is placed in the optical system shown below. The microscope looks at projected plate and straigh wavefront and compares the phase of the two recombined light beams.



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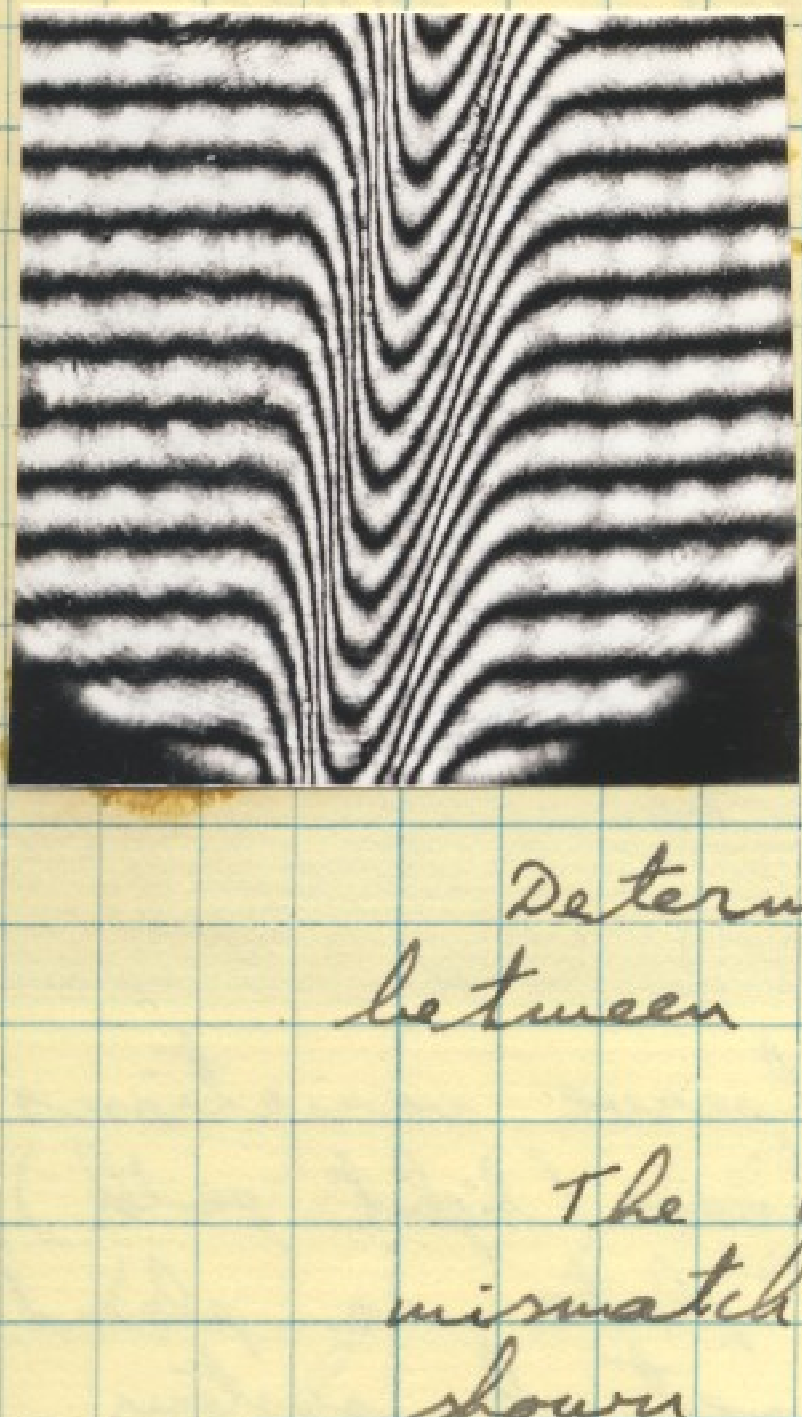
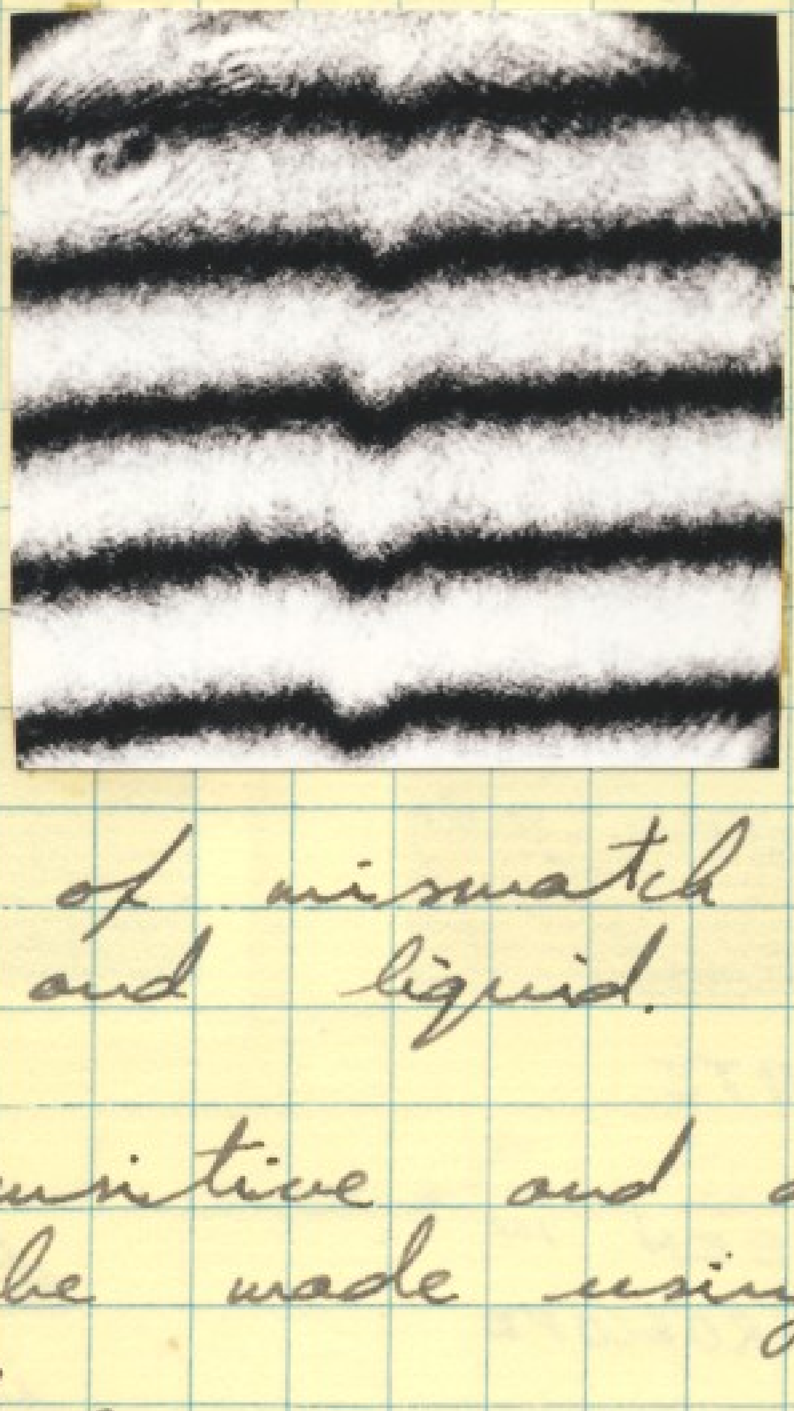
Each line represents constant phase line across the aperture. By counting the number of lines the curv paths depart from straight, the path difference can be found in terms of λ. If the surface is now placed in liquid gate, the path difference will decre and new, reduced, path difference can be found. For perfect match of liquid and emulsion there will be only straight lines, and if liquid is changed from less to more dense than emulsion, bulge i the lines will be in the opposite direction. The most outstanding feature of this technique i that both magnitude and "direction" of mismatch can be determined directly.

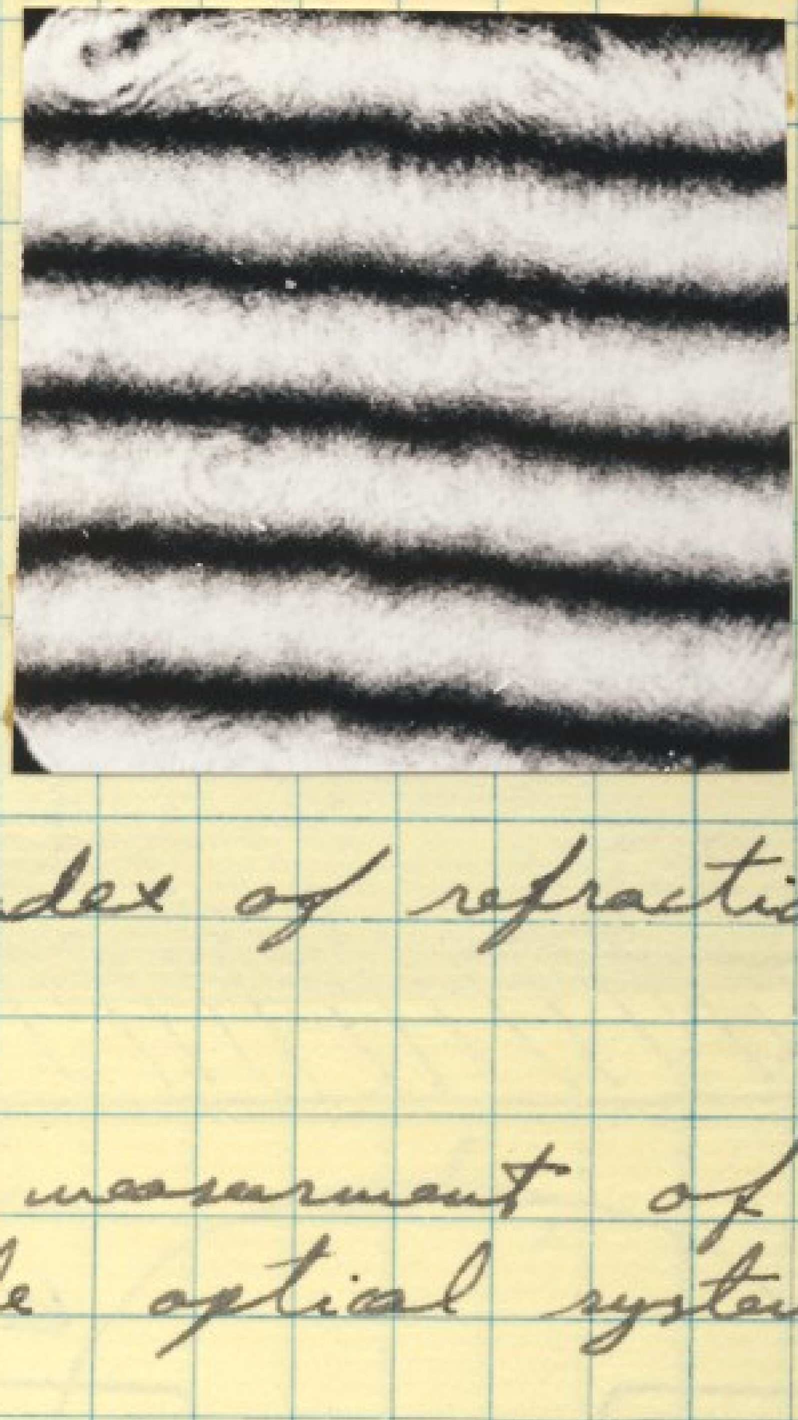
Pictures by R. GREEN
MARCH '63



Dry plate & groove



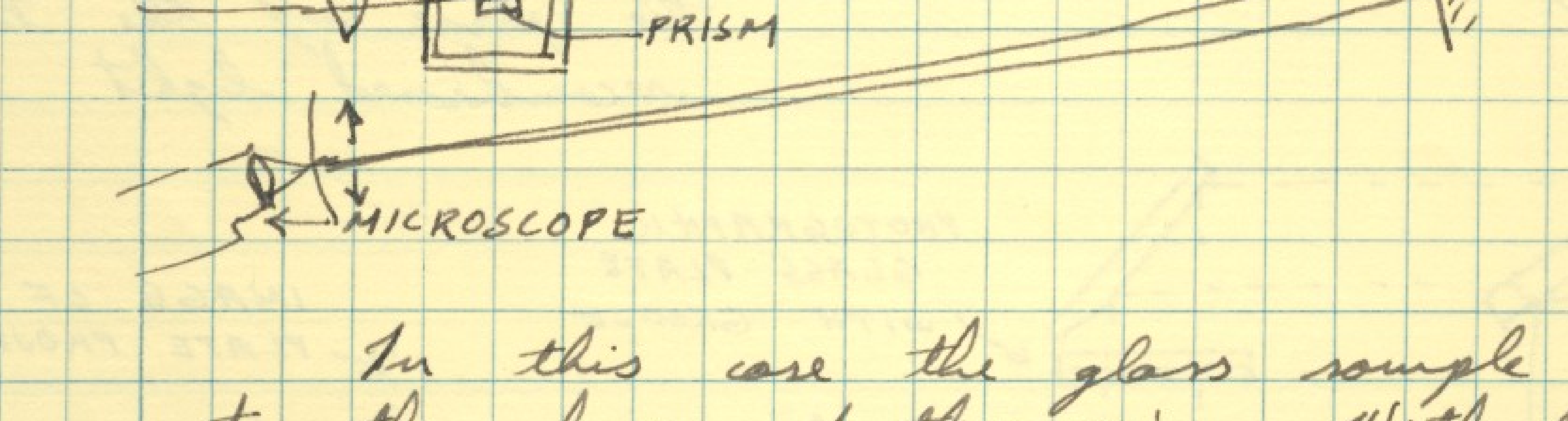
Pure liquid #1



Mixture of two liquids,
best mat

Determination of mismatch of index of refraction between glass and liquid.

The most sensitive and direct measurement of mismatch could be made using the optical system shown below:



In this case the glass sample must be ground to the shape of ~~the~~ a prism. With the prism removed, a reference point is established at position of the microscope. When prism is immersed in the liquid the beam will shift left or right depending

Signed 21 May 1964, Juris Upatnieks

on wether glass or liquid is more dense. Reference point can also be provided by light passing around the prism. When the two points coincide, the indexes of refraction are matched. Relative indexes of refraction can be calculated from the geometry of the system and the angle of the prism.

25 April 1963

Reconstruction, April '63

The same hologram from which the picture on p. 16 was reconstructed, was used to obtain the picture at right. A very well matching liquid (mixture of two) was found and used in liquid gate. Background noise was considerably lower than the previous time. Resolution was increased and the picture appeared to be sharp even when enlarged to a size of 10"×8".

The liquid used was ETHYL-BENZOYL-ACETATE, 8.3 ml, and "AROCLOR 1232", 1.7 ml. The measured index of refraction of this liquid, measured at 26.6°C and for sodium D line, was 1.5394. This liquid has negative temperature coefficiant (approx. -0.0006 to -0.001/°C).

The following measurments were made on the original picture and reconstructed one:

	Original	Reconstruction
Height (h)	15.96 mm	42 mm
Width of hair (w)	30 μ	80μ
Ratio h/w	530	525

Focal length of hologram ≃ 800 mm
Width of hologram ≃ 30 to 33mm

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The numerical value of $\frac{h}{w}$ indicates that resolution was not lost in the hologram process. The width of the dispersed signal can be calculated as follows:

$$a = \frac{2\lambda d}{2x_0} \quad \text{where}$$

$\lambda = 6328\ \text{Å}$ = wavelength of ligh
$d = 800\ \text{mm}$ = focal length of hologram
$2x_0 = 30\mu$ = width of hair (assu
unity magnification).
a = width of hologram of hai

$$a = \frac{2 \times 6.328 \times 10^{-4} \times 800}{0.03}\ \text{mm}$$

$$a = 34\ \text{mm}$$

$$\text{Compression ratio} = \frac{a}{w} \approx \frac{34}{.033}$$

$$\approx \underline{\underline{1000:1}}$$

Since "a" was calculated to be 34 mm and width of hologram is about 33 mm, indicates that the theoretical limit of resolution was reached in this case. A small error in measuring w would make large error in the calculated compression ratio. Also the definition of $(2x_0)$, the resolved element, is somewhat arbitrary.

The effectiveness of liquid in reducing background noise indicates that there is some emulsion thickness varians across the glass plate of the hologram. Observation of the <u>reflected</u> light from a hologram shows the two sideband images too. This indicates that there is sufficient phase modulation in emulsion to give a reconstructed image. Some effect, however, might ~~to~~ result by varians in absorbed light by emulsion.

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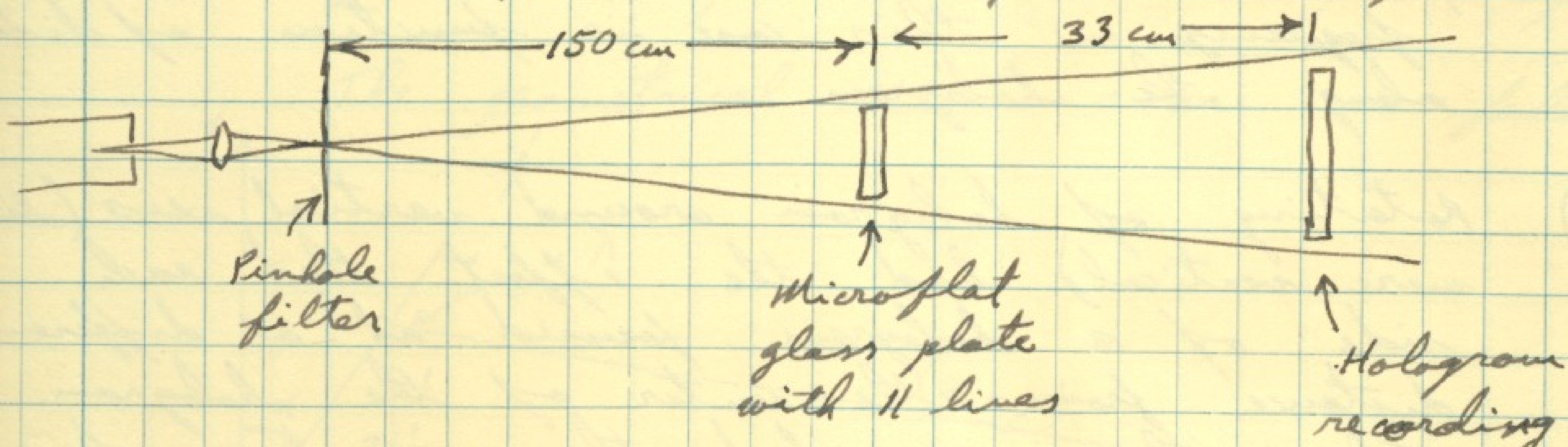
15 May 1963

Pulse Compression Tests

Pulse compression tests were made using two parallel lines photographed on a microflat glass plate with 649F emulsion. This plate was inserted in diverging, filtered laser beam and another microflat plate was used to record the hologram. Since high dispersion and compression ratios were expected, carrier frequency was not used.

The experimental setup was as follows:



Light wave length: 6328 Å
Hologram plate emulsion: 649F
ide"D" { Line width : 7.6 μ ($f = \frac{1}{.0076} = 130\ \ell/\text{mm}$)
Distance between lines: 0.59 mm
Corrected focal length = 42 cm

Calculated size of hologram $a = \frac{2\lambda f}{2X_0} = \frac{2 \times 6.33 \times 10^{-4} \times 420}{7.6 \times 10^{-3}} = 68\text{mm}$

Since the approximate effective plate width was 62 mm, "a" is taken as 62 mm. The reconstruction was photographed and measurements were made on the film.

Measured line width = 0.166
Measured line separation = 12.282

$$\frac{12.282}{0.166} = 74$$

Calculated dispersion ratio $= \frac{62}{7.6 \times 10^{-3}} = 8200$

Calculated compression ratio $= 8200 \times \left(\frac{.59}{.0076}\right)^{-1} 74$

$= 8200\ \frac{74}{78} = 8000$

∴ the compression ratio was 8000:1, with same assumptions and limitations as discussed on pg. 20.

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Some observations were made of the reconstructio process which are of interest:

1) There was no trace of the virtual image as background for the reconstruction. Since the compression ratio was 8000:1, the virtual image (that is, energy from it) would be reduced to 1/16,000 on the average.

2) Covering part of the hologram had same affects as ordinarly observed in filtering in frequency plane. This would be expected since spacial frequency in this case is function of distanc along the hologram.

3) Rotating of hologram around vertical axis (lines were vertical) had the effect that each side of a hologram focused at a different distance from the center of the hologram. Thus the image had the appearance of poor focus if hologram was rotated and no filter was inserted. ~~too~~ This fact indicates that poor focusing may be expected from all points except on axis if a Fresnel zone plate is used instead of a lens.

4) Covering half the hologram ~~to~~ had the familial effect of half-plane filter. The dark line next to the focused line in general is sharper than the focused line.

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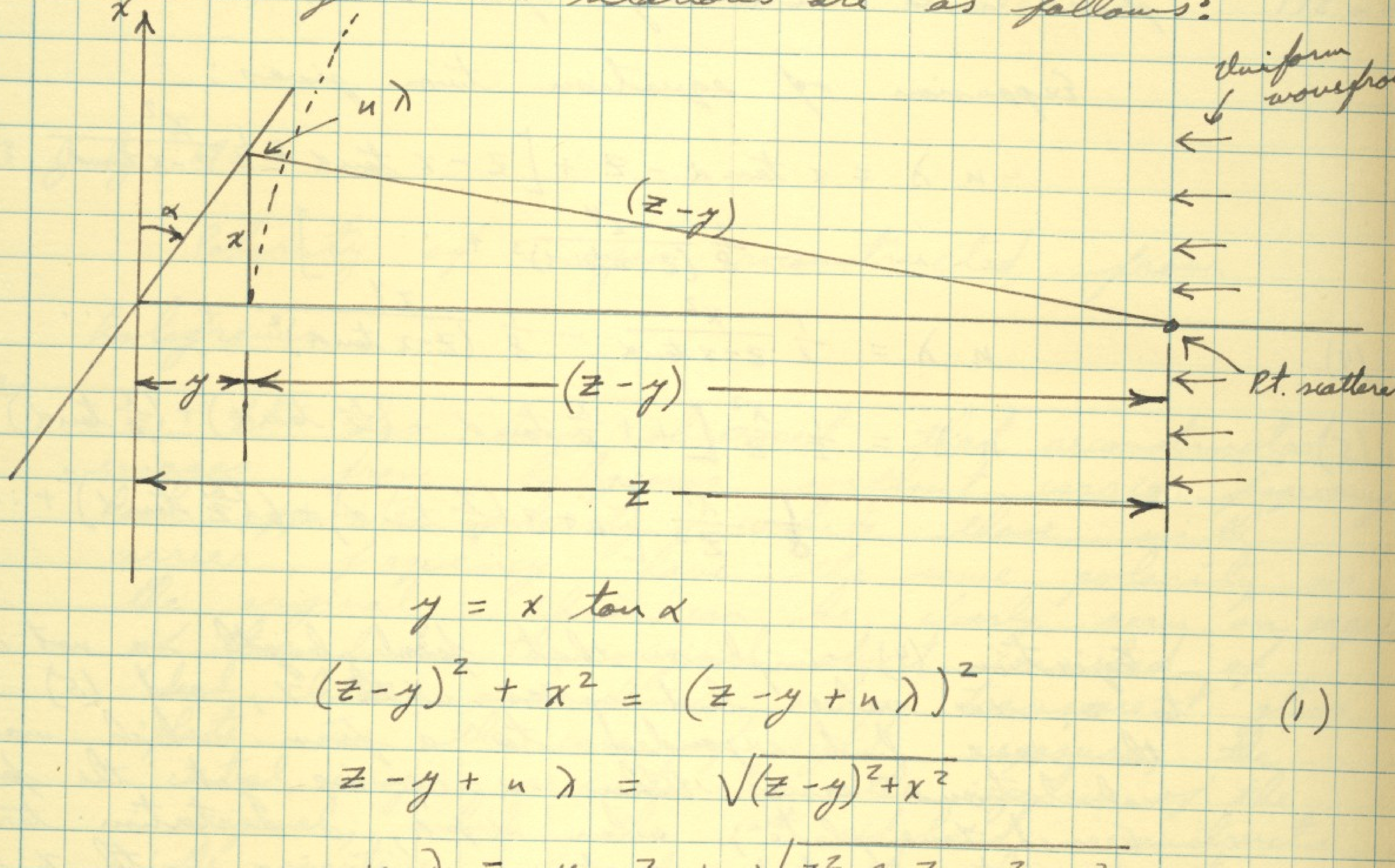
4 June 1963.

Analysis of the errors introduced by rotating holograms (Fresnel zone plates).

The approach to this problem is to calculate the dispersed signal pattern as it would appear on a tilted recording plate and to compare it with the dispersed signal on a plate that is not tilted. To simplify this analysis, the signal was taken as consisting of a single pulse, or scatterer, and an expression was found of the phase difference between diffracted light and uniform wavefront at the surface of the plate.

The geometrical relations are as follows:



$$y = x \tan\alpha$$

$$(z-y)^2 + x^2 = (z-y+n\lambda)^2 \qquad (1)$$

$$z - y + n\lambda = \sqrt{(z-y)^2+x^2}$$

$$n\lambda = y - z + \sqrt{z^2 - 2yz + y^2 + x^2}$$

$$= x\tan\alpha - z + \sqrt{z^2 - 2xz\tan\alpha + x^2(1+\tan^2\alpha)}$$

$$= x\tan\alpha - z + z\sqrt{1+\frac{1}{z^2}\left[x^2(1+\tan^2\alpha)-2xz\right.}$$

so $$n\lambda = x\tan\alpha - z + z\sqrt{1+\left[\left(\frac{x}{z}\right)^2(1+\tan^2\alpha)-2x\tan\alpha\right]}$$

or $$n\lambda = x\tan\alpha - z + \sqrt{z^2+\left[x^2(1+\tan^2\alpha)-2xz\tan\alpha\right]}$$

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Expansion of equation (3) gives, for the first two terms:

(3a) $$n\lambda = x\tan\alpha - Z + Z + \frac{1}{2}\frac{x^2}{Z}(1+\tan^2\alpha) - x\tan\alpha + \cdots$$
$$= \frac{1}{2}\frac{x^2}{Z}(1+\tan^2\alpha)$$

For this expansion the result is the familiar Fresnel zone plate whose focal length Z is now changed to
$$Z' = \frac{Z}{1+\tan^2\alpha}$$

This agrees with observations made from zone planes with relativly few lines, (about 100 or less).

Expansion of equation two gives:
$$n\lambda = x\tan\alpha - Z + \left[Z - x\tan\alpha + \frac{1}{2}\frac{x^2}{Z - x\tan\alpha} - \frac{1}{8}\frac{x^4}{(Z-x\tan\alpha)^3} + \cdots\right]$$

(4) $$n\lambda = \frac{1}{2}\frac{x^2}{Z - x\tan\alpha} - \frac{1}{8}\frac{x^4}{(Z-x\tan\alpha)^2} + \cdots$$

(5) $$n\lambda = \frac{1}{2}\frac{x^2}{Z}\left[1 + \frac{x}{Z}\tan\alpha + \left(\frac{x}{Z}\tan\alpha\right)^2 + \left(\frac{x}{Z}\tan\alpha\right)^3 + \cdots\right] - \frac{1}{8}\frac{x^4}{Z^3}\left[1 + 3\left(\frac{x}{Z}\tan\alpha\right) + 6\left(\frac{x}{Z}\tan\alpha\right)^2 + \cdots\right]$$

Equation (4) implies that focal length is not changed to a new value but varies with x, and (5) is the same but expanded to a form which makes calculations easier. When $\alpha = 0$, we get the familiar Fresnel zone plate; when $\alpha \neq 0$, a distortion term proportional to $\tan\alpha$ enters, increasing with x (or lower f-number).

Equation (3a) reduces to the form of (5) is enough terms are taken. From this it can be concluded that as a rough approximation the focal length of the zone plate changes as it is rotated, but actually the focal length changes continuously with x.

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A test was made to check equation (39) experimentally. It was found that there appeared to be two images, one ~~a~~ slightly seperated from the other and each produced by one-half of the hologram. The calculated and computed results were as follows:

Tilt of hologram	Calculated focal length	Measured focal length Near image	 Far image
0°	400 mm	400 mm	400 mm
11°	385 mm	377 mm	382 mm
22°	345 mm	321 mm	329 mm
5.5°	≈ 393 mm	398 mm	396 mm
45°	200 mm	188 mm	198 m

3 July 1963

Polarity of images reconstructed from holograms.

It has been observed that reconstructed images from holograms without carrier frequency have opposite polarity, while those with carrier frequency have the same polarity as the original. This can be clearly seen on page of this book. The original object consisted of dark letters and lines on a transparent glass plate. For the case of light exposure, the central image reconstructs the negative of the original, while the 1st sideband reconstructs the positive. Considering the characteristics of the film and the process, this phenomena can be explained.

In the recording process the bright areas are recorded as dark, and dim ones as being bright, that is, a negative is obtaine Considering the fact that transmitted averag light, the D.C. ~~level~~ of the film, does not change polarity as it passes through th

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film, this can be considered as reference signa
Since dark becomes light in the negative, this
simply means that the modulation or A.C.
signal has ~~been~~ changed π radians in phase
with respect to the referance signal. Therefore
it is to be expected that the reconstructed
image from a negative of the hologram would
give a negative reconstruction. It is likewise
expected that if a contact print of a hologra
would be made, the reconstruction would be
positive.

For the case of the sideband the
situation is different. Since in this case
the D.C. level is obtained by modulating
the referance signal, both the deflected (sid
D.C.) and the A.C. signal change phase. Thus
the sideband image should always reconstruct
as a positive. Taking a contact print of
the hologram would change the central image
but not the sideband (sideband would still be
positive). This principle has not been tested
experimentally yet.

For the case of non-linear recording (over-
exposure) shown ~~on~~ pg. 11, the reconstruction
appears to be negative in the sideband.
This cannot be as easily explained, although
it appears that in the nonlinear case the
D.C. signal is suppressed more than the
A.C. signal. Thus the amplitude might be
much higher than D.C. level and appearanc
would be than of a negive whether
the signals are in or out of phase.

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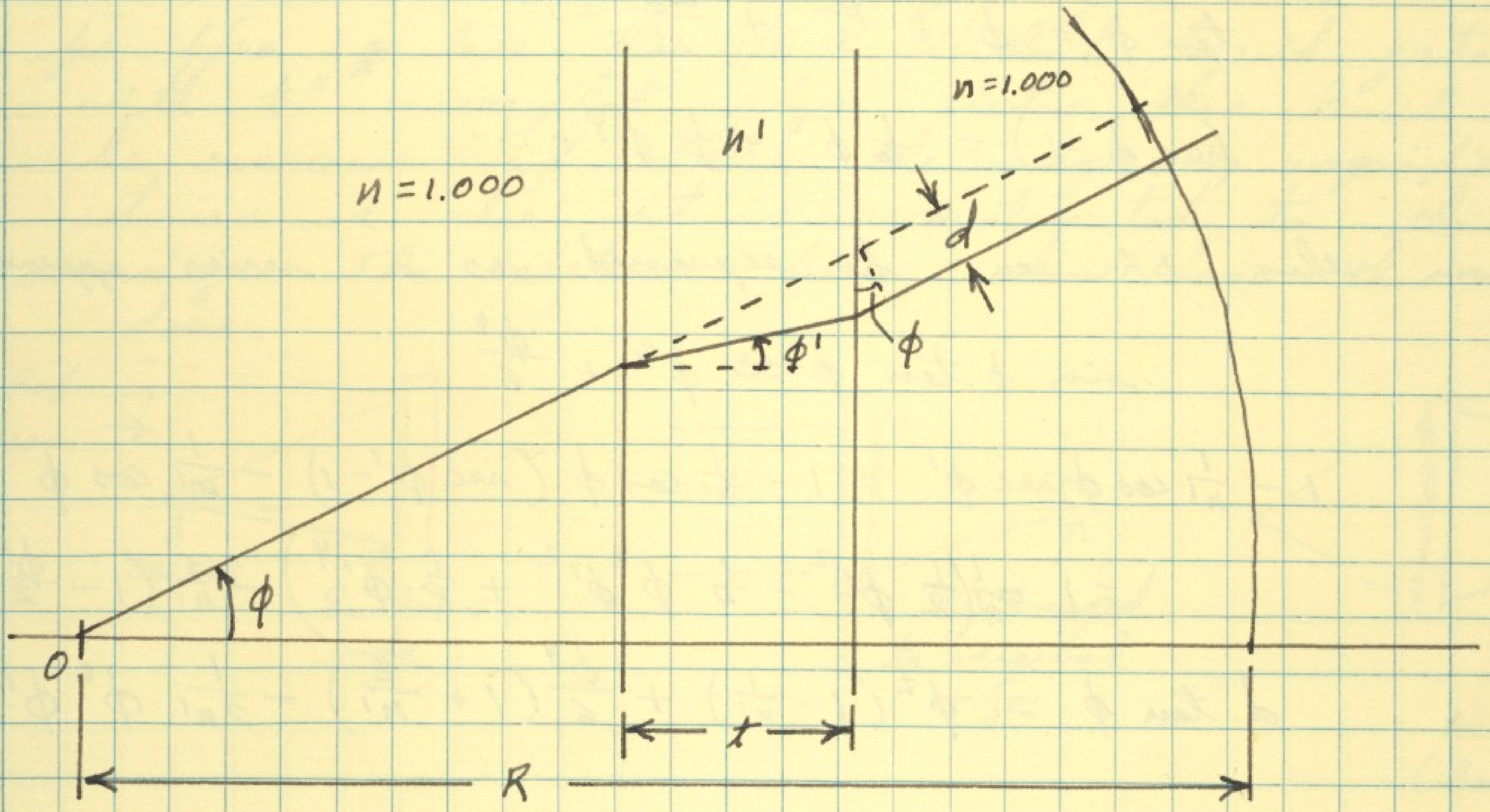
12 September 1963

Effect of microflat glass plate on the resolution limit of a hologram, or projected image.

It is a well known fact that introducing an optical flat in a system introduces abberations. In work with holograms thick microflat photographic plates are frequently used, and liquid gates may be used. The amount of error (deviation from perfect sherical wave) is calculated here.



R = radius of perfect spherical wavefront
R_0' = optical path length of radius at $\phi = 0$
R' = " " " " " at $\phi \neq 0$

$$d = t\,\cancel{\tan}\,\phi\left[1 - \frac{n\cos\phi}{n'\cos\phi'}\right]$$

from Jenkins & White "Fund. of Optics" p. 19

$$R_0' = R + t(n' - n)$$

$$R' = R - t\sec\phi + n't\sec\phi' + d\tan\phi$$

$$R' = R - t\sec\phi + n't\sec\phi' + t\sin\phi\tan\phi\left[1 - \frac{\cos\phi}{n'\cos\phi'}\right]$$

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$$\Delta R = R' - R'_0$$

$$\Delta R = t \sin\phi \tan\phi \left[1 - \frac{\cos\phi}{n'\cos\phi'}\right] + n't(\sec\phi' - 1) - nt(\sec$$

$$\Delta R = t\left\{ \sin\phi \tan\phi \left[1 - \frac{\cos\phi}{n'\cos\phi'}\right] + n'(\sec\phi' - 1) - (\sec\phi -\right.$$

From power series expansion

$$\sin\phi = \phi - \frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \cdots$$

$$\cos\phi = 1 - \frac{\phi^2}{2!} + \frac{\phi^4}{4!} - \cdots$$

$$\tan\phi = \phi + \frac{\phi^3}{3} + \frac{2\phi^5}{15} + \cdots$$

$$(\sec\phi - 1) = \frac{1}{2}\phi^2 + \frac{1}{8}\phi^4 + \cdots$$

From this ΔR can be expressed as a series approximation

$$\sin\phi \tan\phi \approx \phi^2 + \frac{\phi^4}{6}$$

$$1 - \frac{1}{n'}\cos\phi \sec\phi' = 1 - \frac{1}{n'}\cos\phi(\sec\phi' - 1) - \frac{1}{n'}\cos\phi$$

$$= 1 - \frac{1}{n'}\left(\frac{1}{2}\phi'^2 - \frac{1}{4}\phi^2\phi'^2 + \frac{1}{8}\phi'^4\right) - \frac{1}{n'}\left(1 - \frac{\phi^2}{2} + \frac{\phi^4}{24} \cdots\right)$$

$$d \tan\phi = \phi^2\left(1 - \frac{1}{n'}\right) + \frac{\phi^4}{6}\left(1 + \frac{2}{n'}\right) - \frac{1}{2n'}\phi^2\phi'^2$$

$$\Delta R = t\left\{ \phi^2\left(1 - \frac{1}{n'} - \frac{1}{2}\right) + \frac{n'}{2}\phi'^2 + \phi^4\left(\frac{1}{6} + \frac{1}{3n'} - \frac{1}{8}\right) \right.$$
$$\left. + \phi'^4\frac{n'}{8} - \frac{1}{2n'}\phi^2\phi'^2 \right\}$$

All the ϕ^2 and ϕ'^2 are spherical terms and their effect is to change the focal length, therefore they are not important. The ϕ^4 terms are spherical abberation terms and the total error due to them is δ.

$$\delta = t\left\{ \phi^4\left(\frac{1}{6} + \frac{1}{3n'} - \frac{1}{8}\right) + \phi'^4\frac{n'}{8} - \frac{1}{2n'}\phi^2\phi'^2 \right\}$$

for $n' = 1.5$ and $\phi' = \frac{2}{3}\phi$,

$$\delta \approx t\frac{\phi^4}{8}$$

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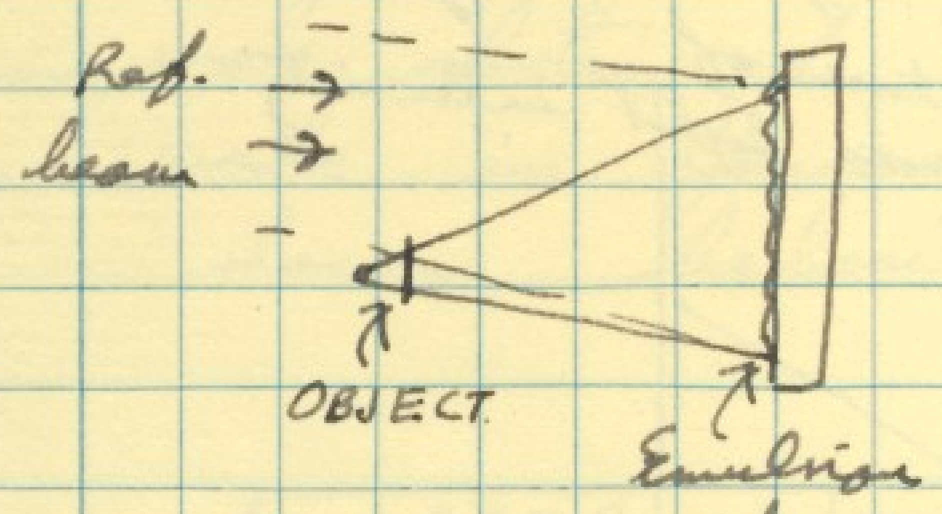
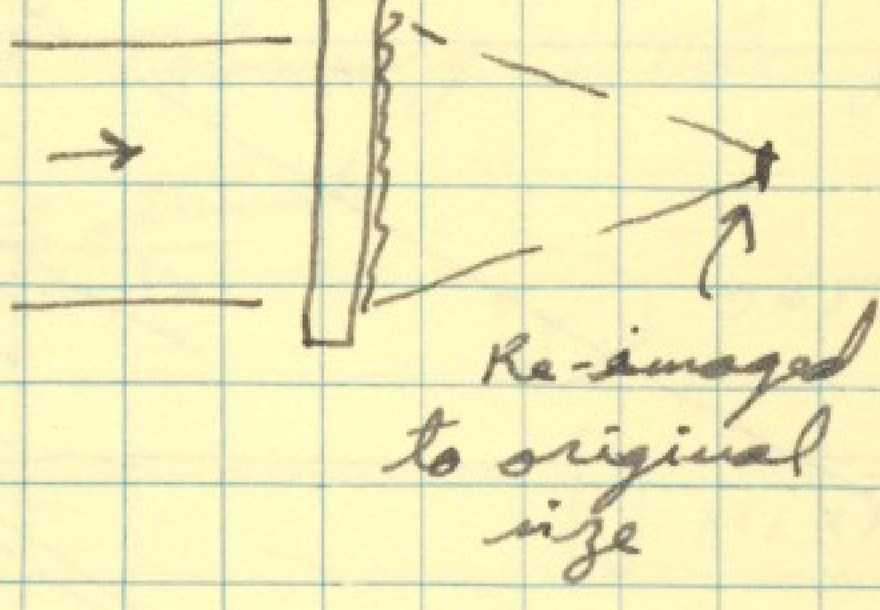
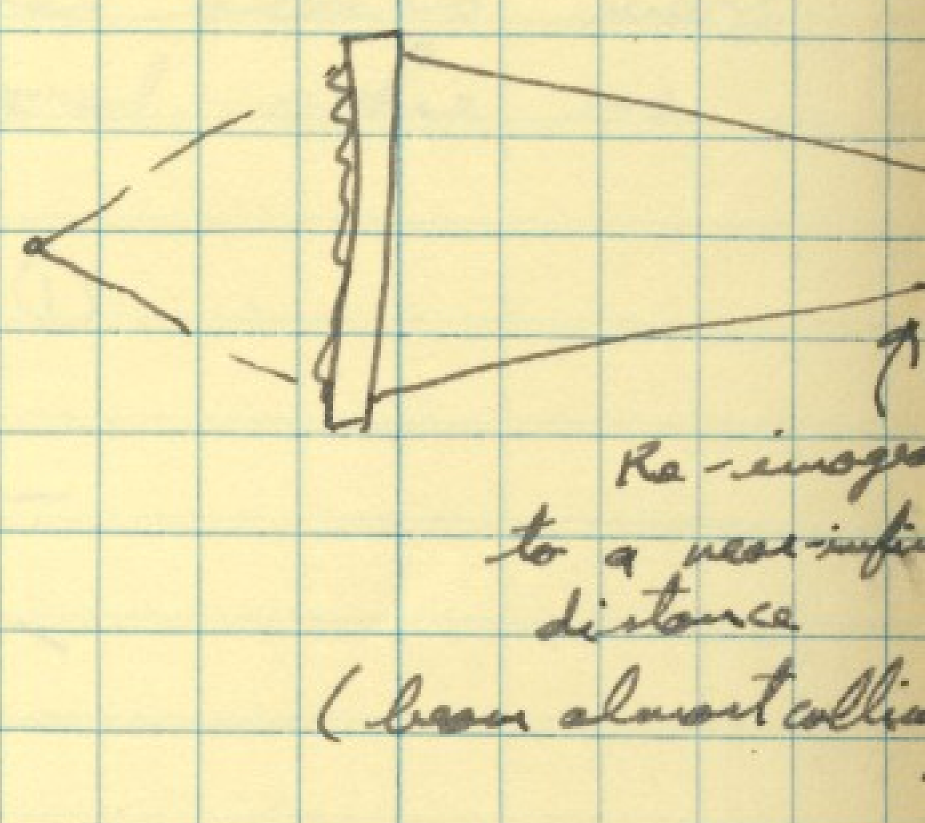
Table of allowable thickness "t"

ϕ in degrees	ϕ rad.	Corresp. f/no.	$\frac{\delta}{t}$	t for $\delta < \frac{\lambda}{4}$
3°	.0524	9.5	9×10^{-7}	170 mm
4°	.0700	7.6	3×10^{-6}	52 mm
5°	.0873	5.7	7×10^{-6}	22 mm ← ~1 in.
10°	.175	2.8	1.2×10^{-4}	1.3 mm
20°	.350	1.37	1.9×10^{-3}	.08 mm
30°	.524	0.86	9×10^{-3}	—

This table shows that liquid gate cannot be used for f/no less than f/6. Without liquid gate and with $\frac{1}{4}$" microflat glass plates this limit could be overcome if either the image is magnified many times or else it is reconstructed to the original size. The sketches below show how this can be done.





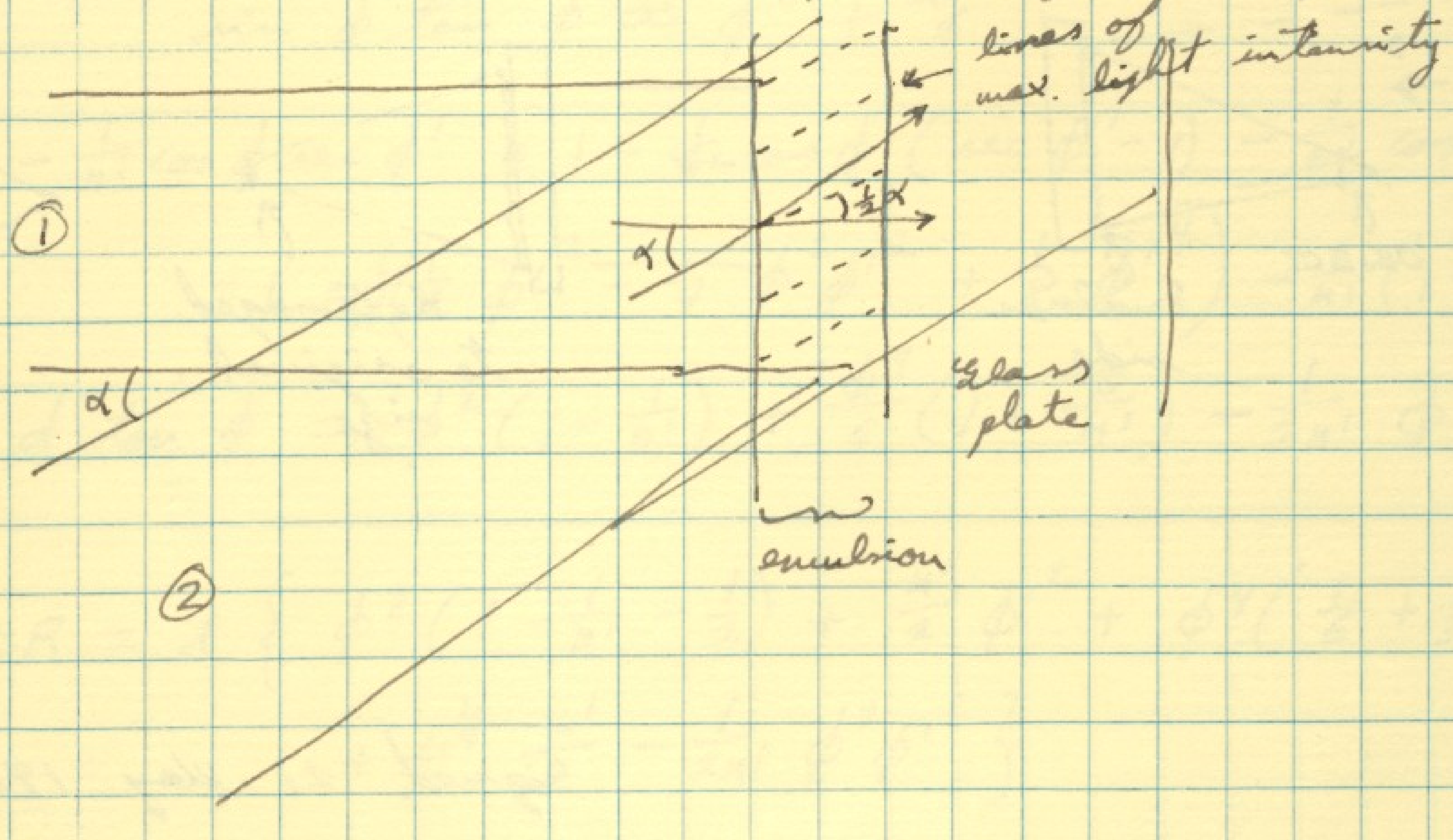


Signed 21 May 1964 Juris Upatniek

21 October 1963

During some experiments with holograms whose offset frequency was in the range of 400 to 600 l/mm it was observed that one sideband was much stronger than the other. With the usual ~~a~~ assumption that the effect of developed photographic film is to amplitude modulate the incident beam, both sidebands must be of equal strength. Unequal strength of sidebands indicates that this assumption is not valid for high offset frequencies.

The suppressed sideband effect can be explained if one assumes that the emulsion has some thickness d ~~and~~ that silver grains are distributed throughout it. Consider the following setup:



The two beams are at angle α with respect to each other and the path along which phase is constant is at $\frac{1}{2}\alpha$ through the emulsion. If this plate is developed and placed ⊥ to beam ①, ~~the~~ and if lines of, say, max. density act as reflectors, then max. light will be diffracted at an angle of α, at which maximum should occur also from the consideration of spacial frequency. A lower intensi sideband should occur at the other sideband. From considerations of hologram process, the maximum sideband should be the same which has self-focusing characteristi if object is placed in beam ②.

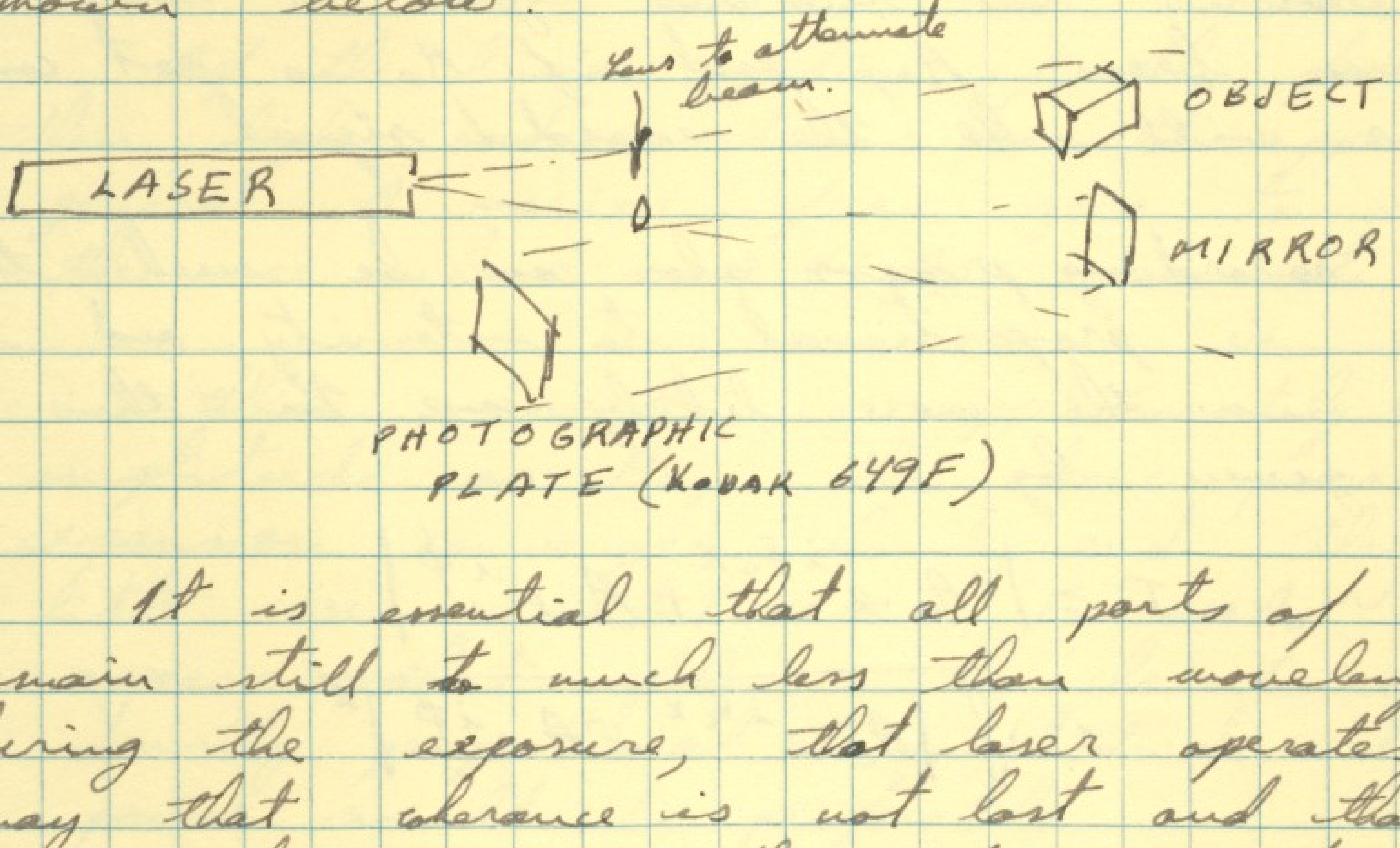
Signed 21 May 1964 Juris Upatnieks

20 February 1964

Three-Dimensional Holograms.

The technique used for making holograms of transparencies illuminated with uniform wavefront was extended to photography of three-dimensional objects that have diffuse reflection characteristics and transparencies that are illuminated with diffuse light. The transparencies have slightly grainy appearance, but small defects in emulsion do not show up as concentric circles, or Fresnel zone plates. Three dimensional objects are equally well photographed and there are not any new concepts in this.

Photography of three-dimensional objects was begun at the beginning of December 1963. First high-quality hologram showing excellent 3-D properties and paralax was obtained around December 22. Several others were made in January and February. The general scheme is shown below:



It is essential that all parts of the setup remain still to much less than wavelength of light during the exposure, that laser operates in such a way that coherence is not lost and that it has long coherence length. Coherence of about 10 in. is the maximum attained until now but the useful length is less. Depending on cavity adjustment, coherence between different parts of the beam may be lost. Insufficient coherence has been the main obstacle to successful experiments until now.

Signed 21 May 1964 Juris Upatnieks

14 April 1964

On some effects of recording holograms and the film characteristics.

In the December 1963 issue of JOSA in the paper "Wavefront Reconstruction with Continuous-tone Objects" the recording process is described to be given by

$$T = T_0 - kI$$

where T, T_0, and I are all amplitudes, or square ro of intensity, and I is given by

$$I = \left| A_0 e^{i\varepsilon_c x} + A e^{i\phi} \right|^2 = A_0^2 + A^2 + 2AA_0 \cos(\varepsilon_c$$

Here it is assumed that film density is ~~inversely~~ proportional to the square of the intensity of light falling on the emulsion. In this case the reference beam can be any value > 0, and good recording of signal can be expected. It is also obvious that recorded signal is modulated by reference beam A_0, and if A_0 is not constant, neither will be the recorded signal.

The recording process also can be such that fil density is proportional to intensity, and this perhaps is the more likely case. In this case I is given by

$$I = \left| A_0 e^{i\varepsilon_c x} + A e^{i\phi} \right|$$

$$= \sqrt{\left| A_0 e^{i\varepsilon_c x} + A e^{i\phi} \right|^2}$$

If $A \gg A_0$, then

$$I = A + \frac{1}{2}\frac{A_0^2}{A} + A_0 \cos(\varepsilon_c x - \phi) + \cdots$$

and it is obvious that modulated signal is independent of signal amplitude and depends only on reference beam amplitude.

Signed 21 May 1964 Juris Upatnie

For the other case where

$A_0 >> A$, I is given by

$$I = A_0 + \frac{1}{2}\frac{A^2}{A_0} + A\cos(\varepsilon_0 x - \phi) + \cdots\cdots$$

where higher order terms are small and can be neglected. In this case, variations in amplitude of reference beam do not affect the recorded signal amplitude, and appears to be the usual case. Experimentally reference beam sometimes has varied in intensity ~~fo~~ in ratio 2:1 over the area of emulsion, and defects in mirrors have caused Fresnel patterns. In no case has there been an observable difference in the brightness of reconstructed image.

Equation (4) on p. 1378 of JOSA Dec. 1963 can then be rewritten as

$$T = T_0 - kA_0 - \frac{1}{2}k\frac{A^2}{A_0} - kA\cos(\varepsilon_0 x - \phi) - \cdots\cdots$$

If the linear portion of the film is exceeded, then higher order terms would appear. Since in general A varies from zero to some maximum, the case where max. $A << A_0$ seems to be preferable.

When max. A is approximatly of same amplitude as A_0, the above power series expansion converges slowly and therefore is of litle use in that case. For ~~max~~ $A_0 \sim A$ max. it appears that film with characteristics of having density proportional to amplitude to the fourth power would be preferable.

Signed 21 May 1964 Juris Upatnieks

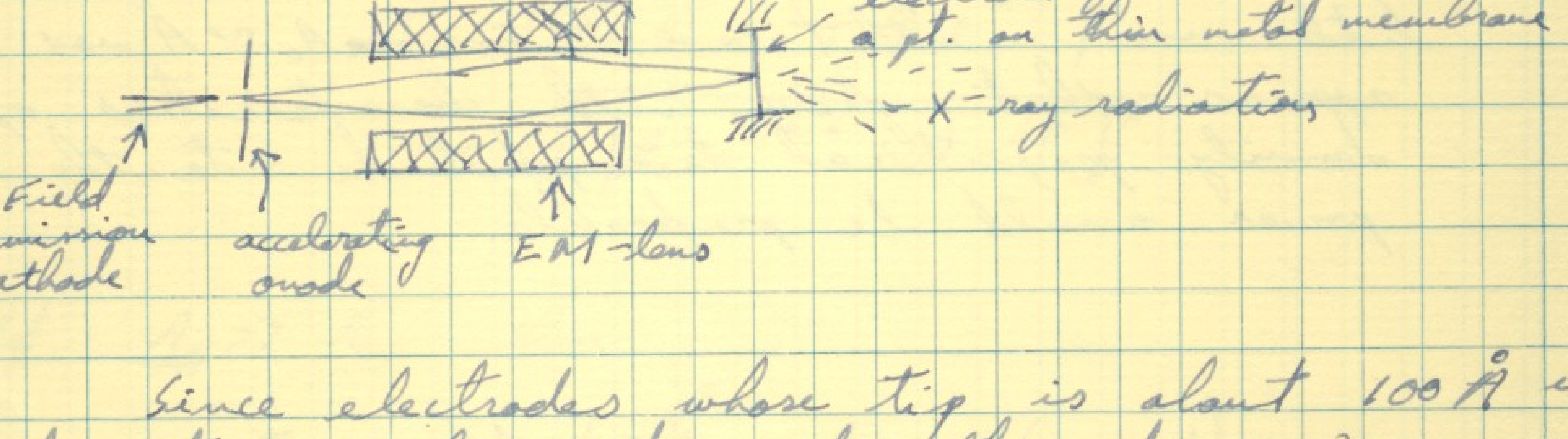
12 May 1964

Some calculations for X-ray holograms

The purpose of making holograms using X-ray radiation are two: first, to study transmission or scattering characteristics of materials in X-ray region, and secondly, to obtain improved resolution over that with light rays. By using X-rays with wavelength λ_x of about 1Å or less, it should be possible to determine position of atoms and molecules in material.

In order to increase resolution beyond that possible in visible light, improvement in resolutio must be carried out in the first step of magnification, that is, in making the hologra The desired or minimum magnification in first step, M_1, should be at least $= \frac{\lambda_e}{\lambda_x}$, since this is the theoretical possible improvement in resolution.

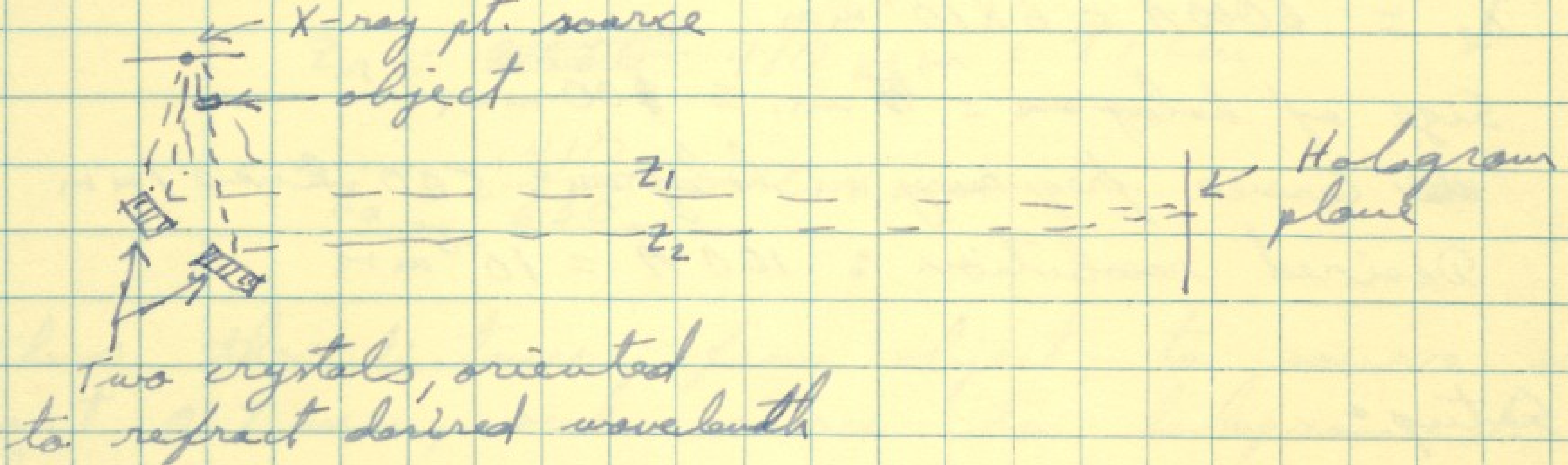
The X-ray source must be small, of the order of λ_x, and monochromatic. The source could be X-ray laser, or a very fine pt. of X-ray source which is made monochromatic. One method of making small X-ray sources, as described in literature, is the following:



Since electrodes whose tip is about 100 Å in diameter can be made and this dimension possibly could be reduced, an X-ray source of 100 Å or less should be possible to obtain with the present state of art. This source is not monochromatic.

Juris Upatnieks, May 12, 19

To make the beam monochromatic, Bragg type diffraction can be used, with a seperate crystal for the main beam, which contains object to be viewed, and the reference beam. The arrangement would be as follows:



The crystals can be oriented to ~~to~~ give maximum refractio at the desired wavelength. The two paths, z_1 and z_2 from source to hologram, can be made equal by positioning crystals properly. If X-ray source is one pt., and a pt. on hologram another, then these two points are the focii of an ellipse and the crystals must be on the arc of the ellipse to made $z_1 = z_2$. Crystals can be oriented so that λ_X at top of hologra is same from both, and at bottom again although slightly different. This change in λ_X would ~~would~~ be caused by differences in θ, where θ is angle of inciden on crystal over the width of the beam. λ_X can be maintained constant by bending crystal properly.

The use of crystals in this manner accomplishes two things simulteneously:

1) The crystals act as reflectors and reduce the size of flat surface required, as would be necessary for Lloyd's mirror. Thus it should be much easier to maintain flatness of about λ_X over the surface.

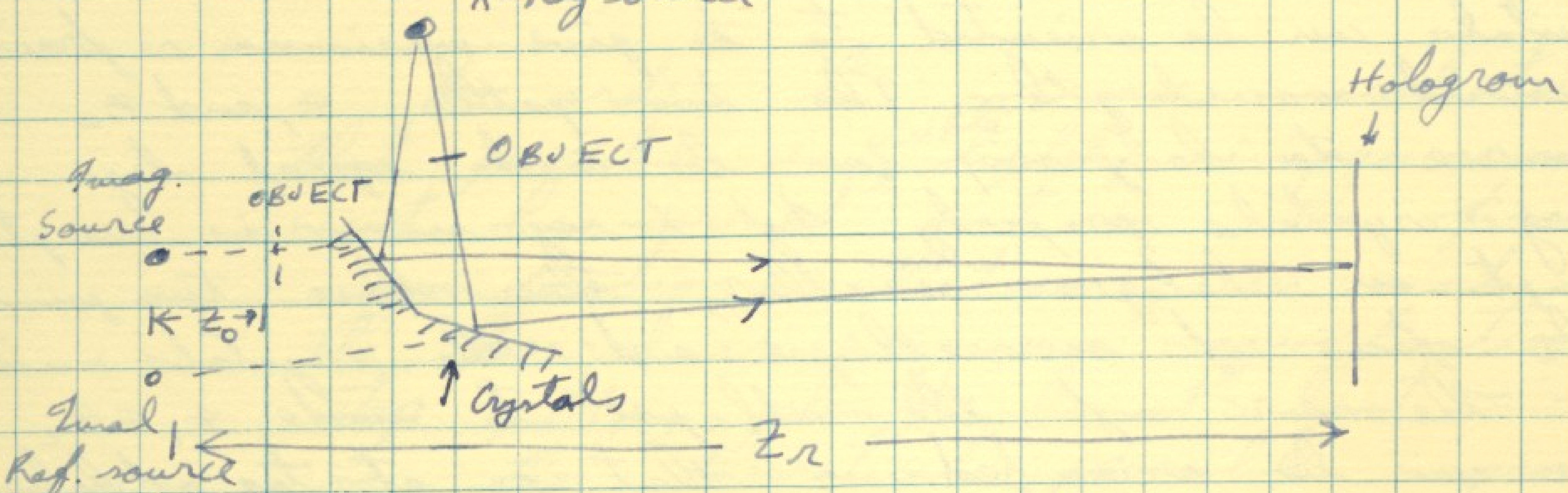
2) It makes the refracted beam monochromatic. A second set of crystals could be used to improve monochromacity.

Juris Upatnieks, May 12, 19

Sample calculations for a particular setup for making X-ray holograms:

$\lambda_x = 10\,\text{Å} = 10^{-6}$ mm
$\lambda_e = 6000\,\text{Å} = 6 \times 10^{-4}$ mm
Size of hologram = 4 in. = 100 mm
Carrier frequency on hologram: 500 lines/mm
Desired resolution: $100\,\text{Å} = 10^{-5}$ mm

Setup:



$$M_1 = \frac{\lambda_e}{\lambda_x} = \frac{6 \times 10^{-4}}{10^{-6}} = 600$$

$$M_1 = \frac{z_0}{z_r} = 600 \qquad z_0 = 600\, z_r$$

f_m = modulation spacial frequency

$$f_m = \frac{1}{\lambda_{res.}} \times \frac{1}{600} = 10^5 \times \frac{1}{600} = 170 \sim 200 \text{ l/}$$

$f_c + f_m = 500 + 200 = 700$ lines/mm

$f_c - f_m = 500 - 200 = 300$ lines/mm

To record f_m,

$$f_m = \frac{x}{\lambda_x}\left(\frac{1}{z_r - z_0} - \frac{1}{z_r}\right) \sim \frac{x\, z_0}{\lambda\, z_r^2} \qquad \text{if } z_r \gg z_0$$

$x = \frac{1}{2}$ aperture hologram

Juris Upatnieks May 12, 1964

$$z_r^2 = x \frac{z_0}{\lambda \times f_m} = 50 \frac{z_0}{10^{-6} \times 200} = 2.5 \times 10^5 z_0$$

$$z_r = 100 \sqrt{25 z_0} = 100 \sqrt{25 \times \frac{1}{600} z_r}$$

$$z_r^2 = 4.1 \times 10^{-2} \times 10^4$$

$$z_r = \cancel{3 \times 10^5}\ 410\ \text{mm} = 41\ \text{cm}$$

$$z_0 = \frac{410}{630} = 0.7\ \text{mm}$$

Thus the distance from object to source should be about 0.7 mm, and source to hologram distance should be 41. cm.

Let φ be the angle subtended by the x-ray source of the hologram. Then $\phi = 2X/z_r$

$$\phi = \frac{100\ \text{mm}}{410\ \text{mm}} = 0.25\ \text{radians} \sim 14.5^\circ$$

Thus a solid angle of 14.5° is required to illuminate the hologram in the reference beam. The beam illuminating the object can be narrower if only part of the object is observed.

Size of the crystal 3 cm away would have to be $30 \times \phi = 30 \times .25 = 0.75$ cm or 7.5 mm.

Note: the above is based on discussions with Emmett N. Leith and the following articles:

"A Lensless Modified Gabor Microscope" by E.N. Leith, 7 Aug. 1963 a memo to file.

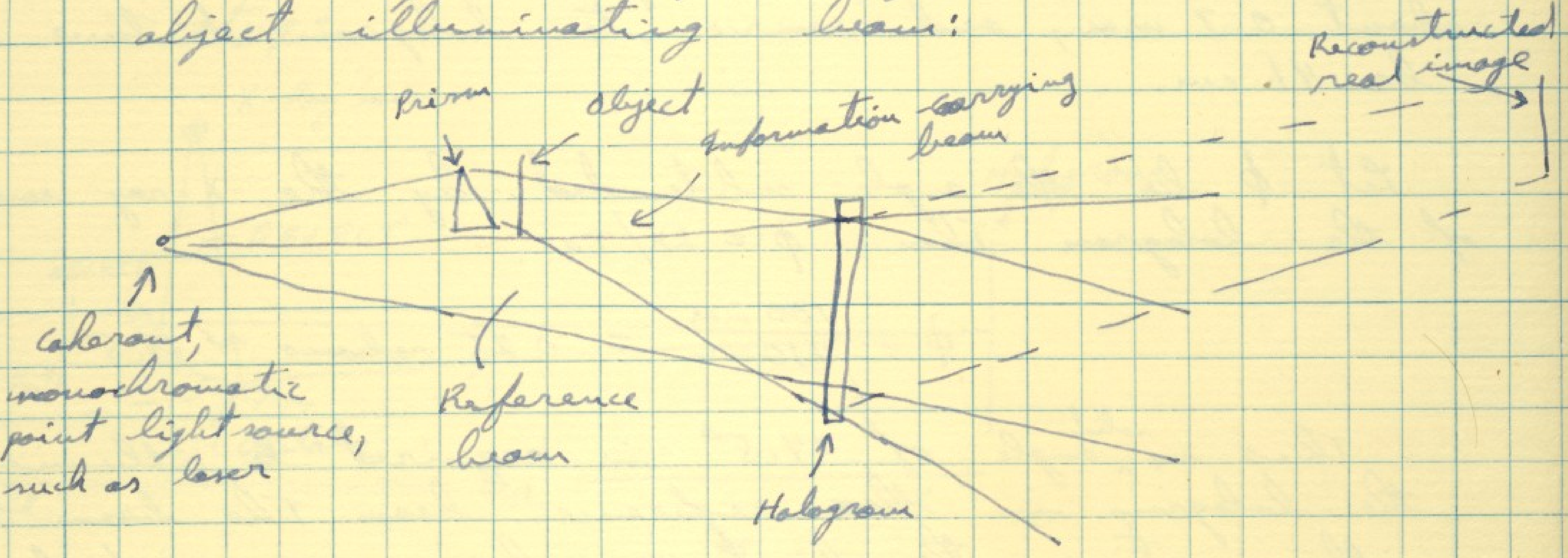
"A Communication Theory of Reconstructed Wavefronts", by E.N. Leith and Juris Upatnieks, 10 April 1961, a memo to file.

Juris Upatnieks, May 14, 1964

20 May 1964

A continuously operating lensless microscope.

In this system the hologram is used as an intermediate step for enlarging small objects and displaying them on a screen or viewing them using an eyepiece. The optical system is shown below, and as in other cases incorporates a coherent light source, a reference beam, and an object illuminating beam:



The prism is only an example of providing illumination for the object and other schemes, such as mirrors, may be used. The object in this case is shown as transparent, or one whose shaddow is of interest, but it also might be one which is examined under reflected light using systems described elsewhere. The recording medium, indicated as the hologram in the drawing, is a photosensitive thin coating on a base, such as a flat glass plate.

The recording medium must have the following characteristics: the coating is thin, of the order of 1μ or less; it turns dark in proportion to the intensity of incident light, that is, its density increases with increasing intensity and the effect is not cummulative (density does not depend on time); and the density pattern has short persistency characteristic, that is, the density pattern quickly follows changes in intensity pattern.

Signed 20 May 1964 Juris Upatnieks

Read & Understood 21 May 1964 A. Friesem

Read & Understood 21 May 1964 K. Haines

The hologram plate is positioned so that the center surface of the plate is parallel to the wavefront of the reference beam. This is necessary for optimum reconstruction (quality) will be obtained for both virtual and real images without rotating the hologram.

Since the hologram ~~receives~~ instanteneously receives intensity variations and correspondingly changes density, the reference beam will instaneously reconstruct the real image, enlarged, and separated from other terms. By adjusting object-to-source and hologram-to-source distances, any desired magnification can be obtained. The reconstructed image will follow changes in object. This reconstruction can be viewed on a screen or with an eyepiece. There is no need to turn off the object beam or to develop plate.

This is based on memo by E.N. Leith of 7 Aug 1963 and 12 Feb. 1964.

Signed 20 May 1964 Juris Upatniek

Read and understood 21 May 1964 A. Friesem

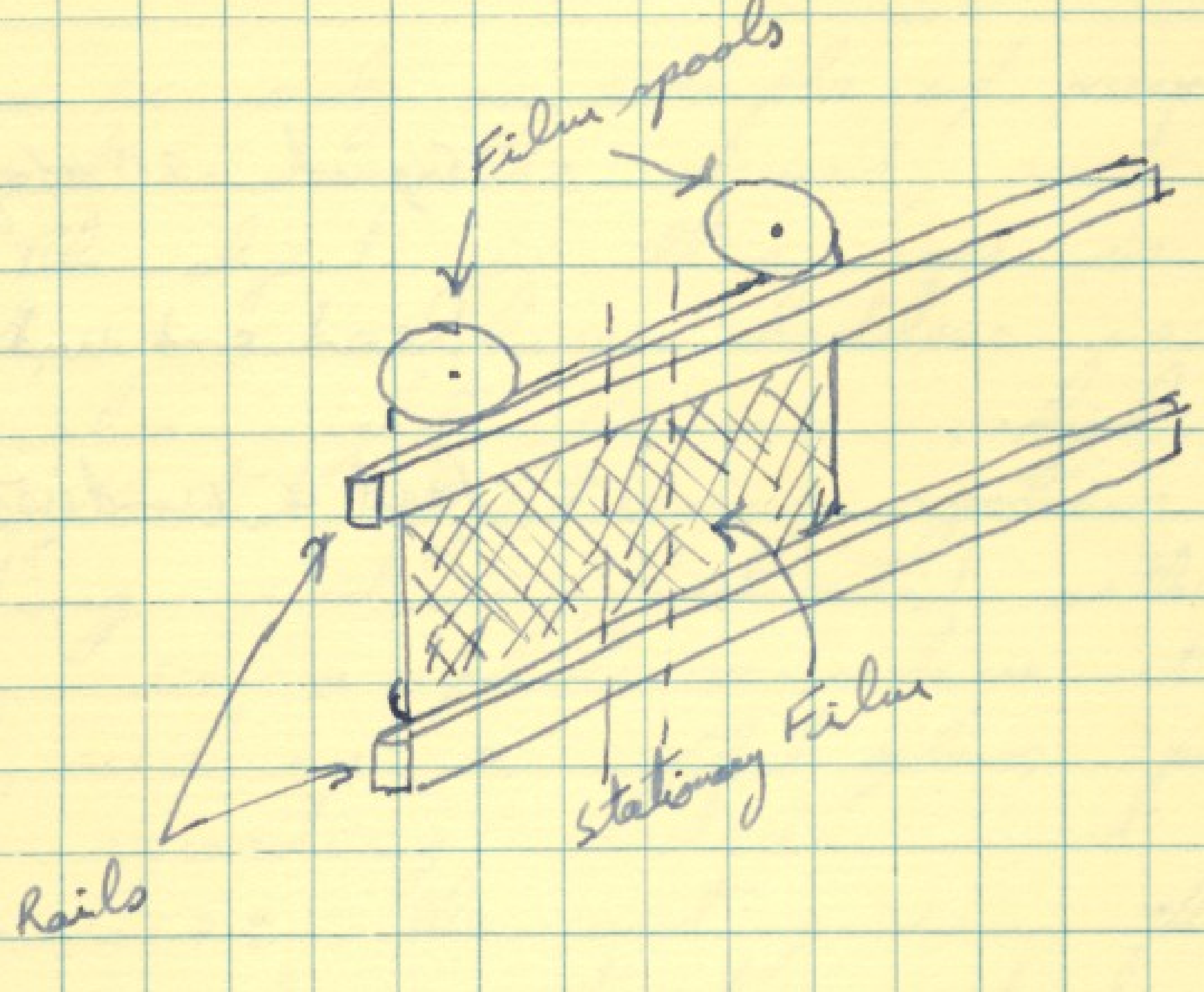
Read & understood 21 May, 1964 R. Hallin

27 May 1964

A technique for making continuous, long holograms.

In a discussion with E.N. Leith this month (May 1964), Mr. Leith proposed using holograms to simulate motion. This motion would be similar to that observing scenes from a moving vehicle, such as a car, train, or an airplane. The motion is simulated by moving a 3-D hologram past an illuminating light source and observing the reconstructed image. An illusion is created identical to the one that one gets when viewing ~~ride of~~ a a scene through the ride of a moving train. To make this simulation realistic, long continuous holograms are desirable.

One way to make such an extended continuous hologram is shown in the sketch below.



Two rails are used as tracks on which a camera rolls along on the film spools. The film spools are enclosed in an ~~light~~ box to keep light from exposing the film. A slit moving with the camera exposes a narrow area of the film. Since the film is pressed directly on the rails, it remains stationary to a high

Juris Upatnieks (May 27, 196

degree of accuracy, which is a necessity to make holograms. Amount of exposure is limited by width of slit and the speed at which the camera moves along. The length of film that can be exposed is limited by capacity of the spools, length of rail, and the area covered by the reference beam.

The basic idea here is that film is taken from a reel, held stationary during exposure, and again taken up into another reel. The film can be stored in spools that are not pressing against the rails, and for the "film spools" shown in the drawing rollers can be substituted. Provisions would be made to press the film tightly against rails at the area opposite the slit. The requirements on light source and reference beam are same as for three-dimensiona hologram described elsewhere.

The rail can be curved to any desired shape to simulate nonlinear motion.

Juris Upatnieks (May 27, 1964)

11 June 1964

A technique for making contact prints from holograms having high offset frequency.

Up to now good contact prints have been obtained from holograms having offset frequency less than about 150 lines/mm. With higher offset frequency the prints usually are more noisy, of less intensity, and frequently have dark areas which do not diffract light. The causes of deterioration are probably the following

1) Emulsion of contact plate is not perfectly flat and against the hologram.

2) Due to the thickness of emulsion, poor shaddows appear from fringes. In general, contact printing does not reproduce volume, or depth, changes in intensity.

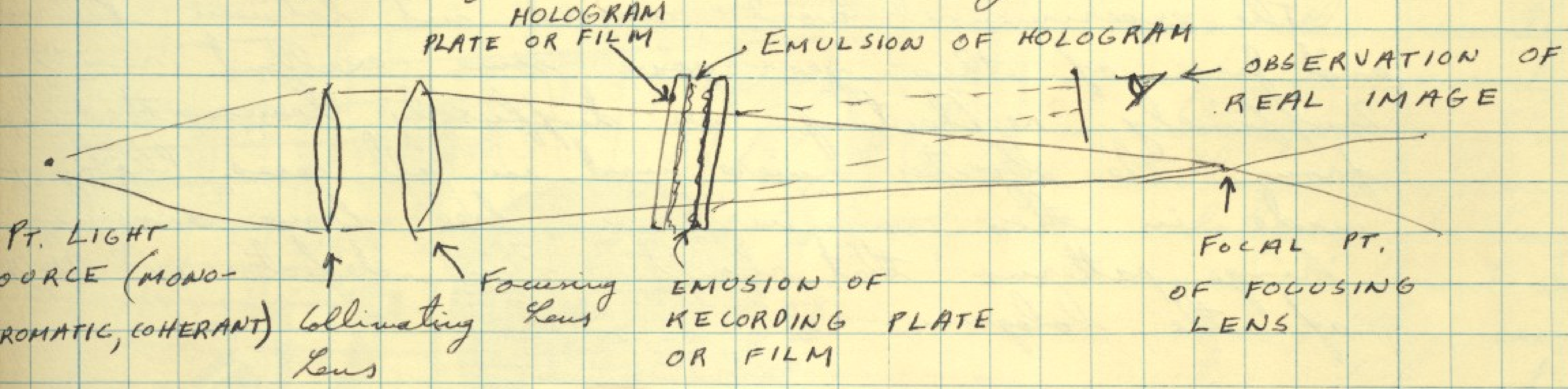
3) Orientation of plate probably does not give maximum diffraction of light.

To correct these deficiencies, it is proposed that the plate is oriented is such a way as to give optimum quality of reconstruction ~~from~~ of real image. The light which illuminates the hologram then will tend to reconstruct the original wavefronts. These wavefronts will interfere with the average transmitted wave and produce a new hologram. Since the emulsion is thick, the virtual image will not be reconstructed if offset frequency is sufficient high.

Juris Upatnieks (11 June 1964)

1 June 1964

The optical system which could be used for this type of contact printing is shown below.



The hologram is illuminated with a wavefront whose radius of curvature is same as that of the original reference beam, and whose phase is a complex conjugate of the reference beam. In the illustration above, it is assumed that reference beam was diverging. The hologram is adjusted to give a good reconstructed image of same size as the original. When all adjustments have been made, unexposed emulsion is placed in contact with the hologram and exposed.

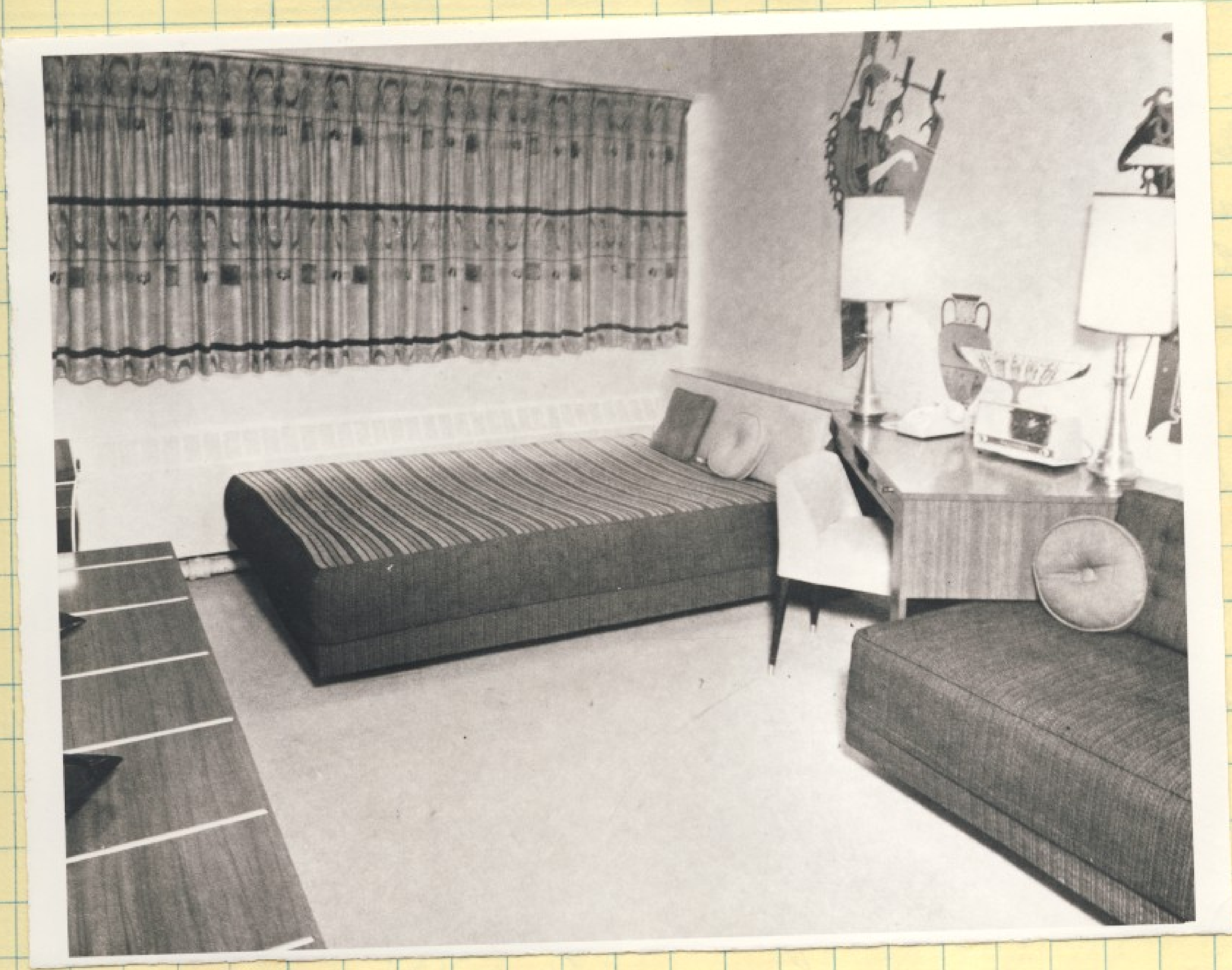
It may be that such exact adjustments may not be necessary in practice, but they would insure best results.

Juris Upatnieks (11 June 1964).

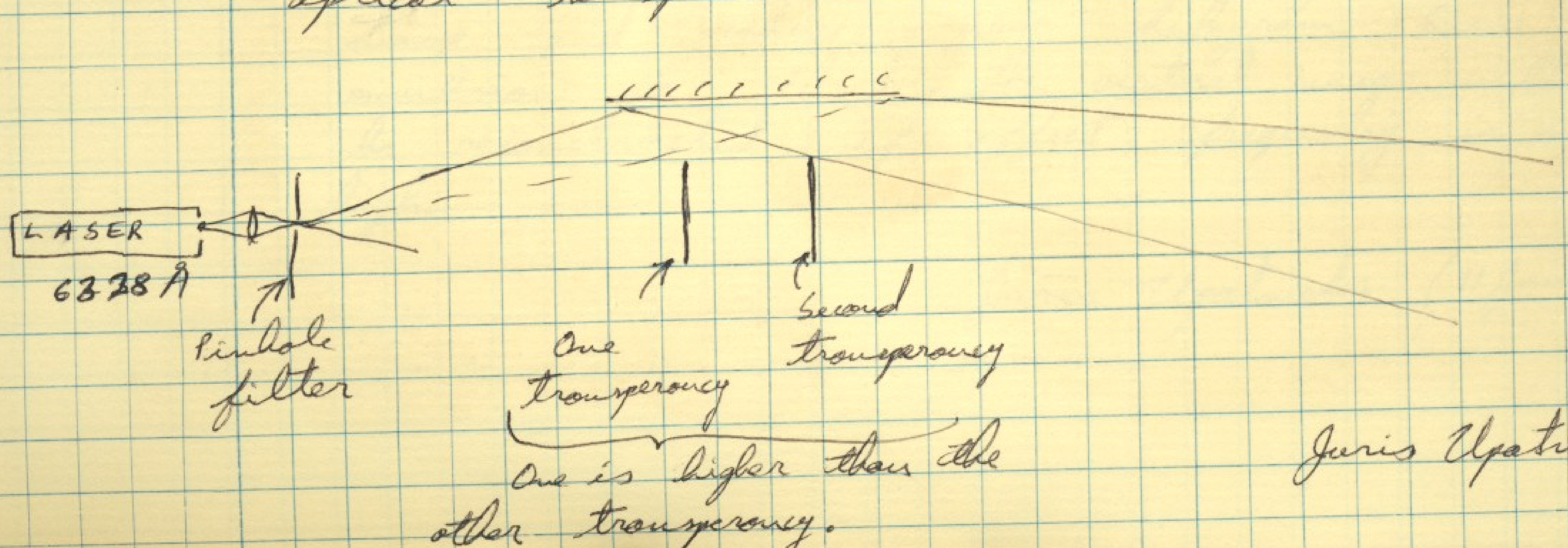
18 June 1964

Experimental results from work with hologram

The experimental work carried out between February and June of this year gave some exellent results. Diffusely reflecting or diffusely transmitted light from the objects were used in all cases. Photographs made in this manner are free from annoying fringe patterns that result from defects in the emu of the hologram



Hologram made in March 1964. This is one of the reconstructions from a hologram on which two transperancies were recorded. The seperation is made in the reconstruction process. Both transperancies were illuminated with diffused laser light. Note the absence of any diffraction pattern visible in earlier holograms reconstructions. The following optical setup was used:



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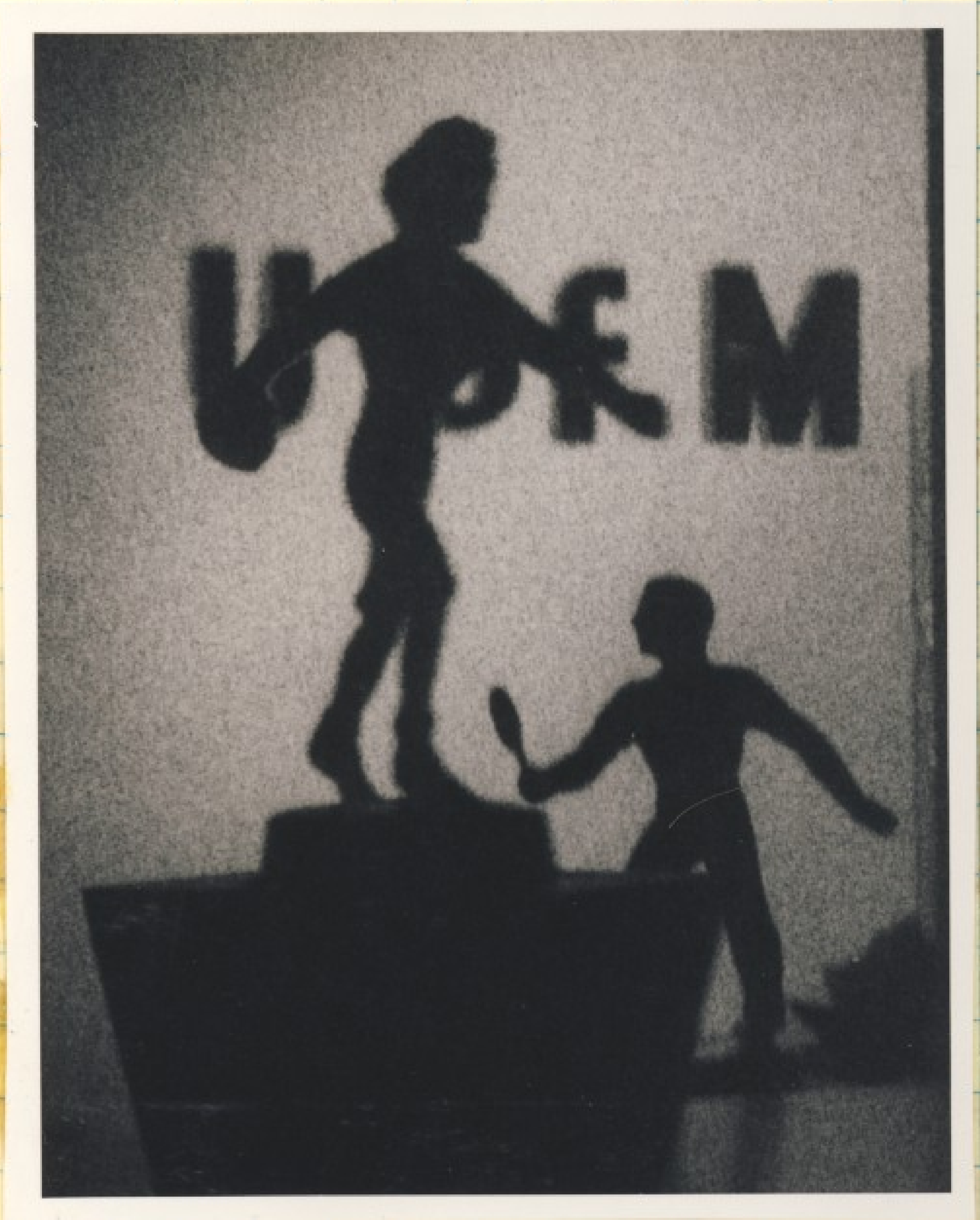
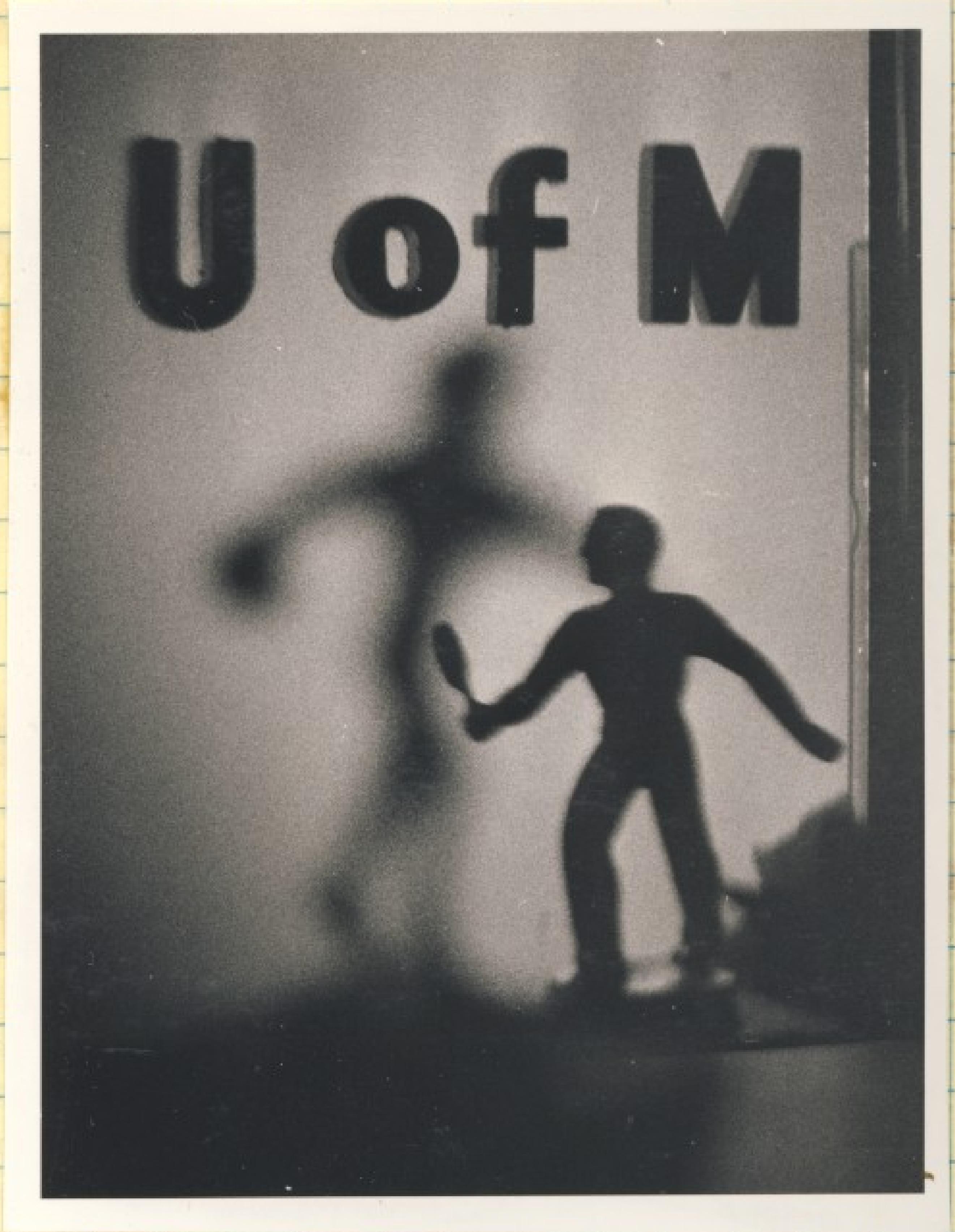
18 June 1964

Hologram made in March 1964. This is the reconstruction of the second transparancy. Since the seperation from hologram to transperancy was different each time, they came to focus at different planes when reconstucting.

18 June 1964

Hologram made in March, 1964. The four pictures below were made from the same hologram and illustrate so of the three-dimensional properties of holograms. The origi





Juris Upatnieks (18 June 1964)

18 June 1964

scene consists of an illuminated opal glass plate with the letters "U of M" on it. In front, about 3 inches, is one figure, and another one some 20 inches from it. Only the silhouttes of the figures are visible, and some reflection from the base on which they are standing. The reconstructions were made in converging beam of light, without lenses between hologram and recording plane. The two top photographs show paralax present: these two pictures were made using a small aperture, but each time a differant part of the hologram. Note that each picture has a differant perspective, or point of view. Graininess is visible because of very small aperture used here.

The lower two pictures were taken using a larger aperture, ~~the~~ same part of hologram, but recording film was moved. On left, the figure in foreground is in focus; on the right, the film was moved to a position where the letters come in good focus. These two pictures illustrate the depth of focus effect.

Hologram made in May 1964. This hologram was made from a transperancy illuminated with diffuse laser light. Only one transperancy was used. In reconstruction, a converging light beam was used and approximantly unity magnification was obtained. The image looks good when enlarged to 8×11" size.

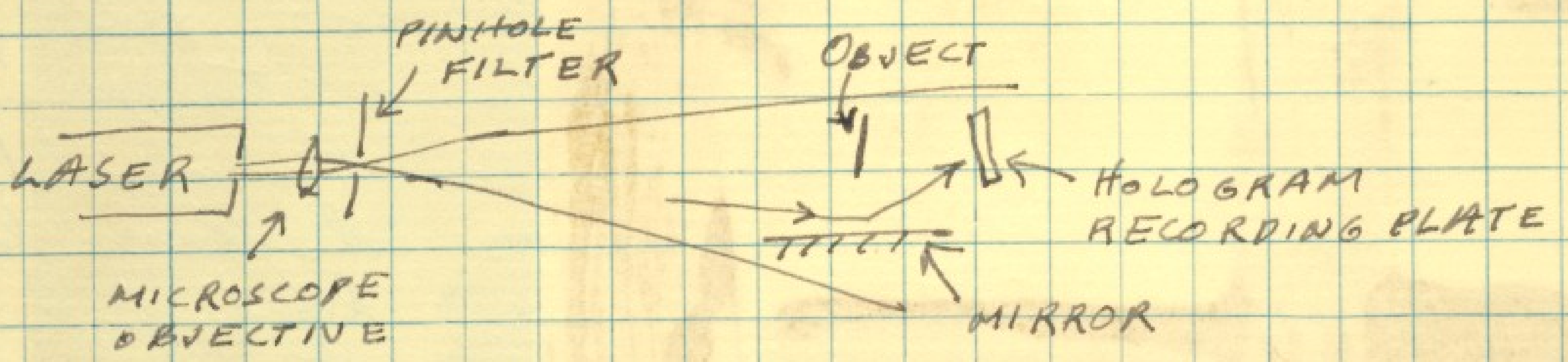
Juris Upatnieks, 18 June 1964.

29 September 1964

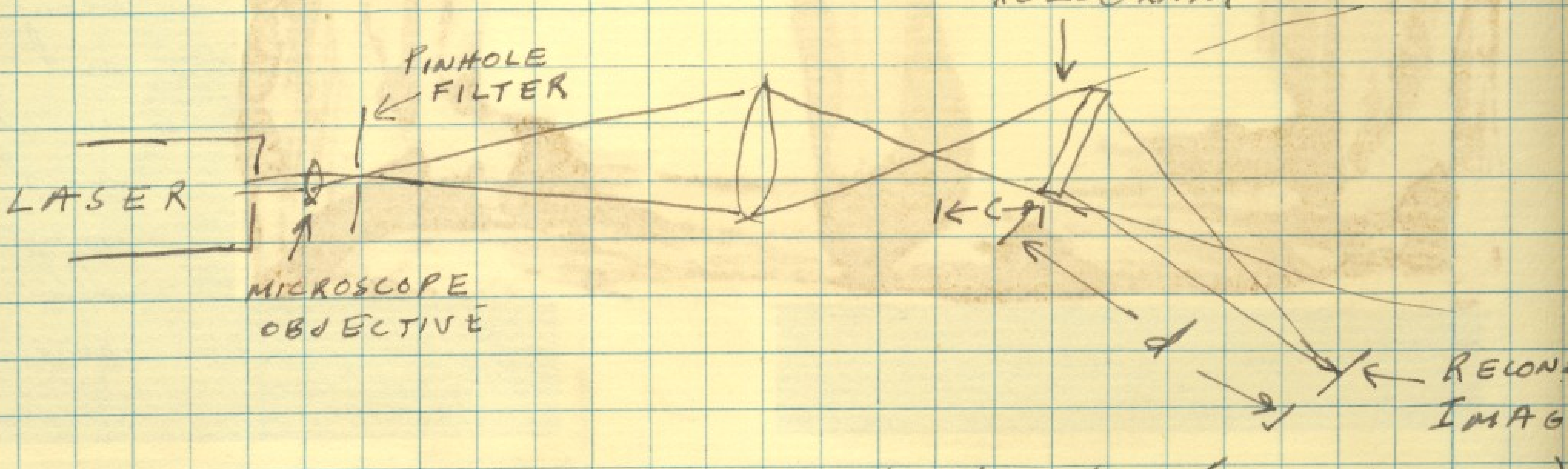
Image magnification without the use of lenses, as applied to microscopy.

A number of experiments were made durin the months of July and August on application of the two-beam hologram technique to microscopy. Magnifications up to X130 times were obtained. It was found that small magnifications, under X10, have considerable distortion which increases with the angle between the reference and signal beams. The best orientation for the hologram were found to be the case when the angles of incidence of both reference and signal bea were equal. The reference beam in all cases was greater than the signal beam, with ratios abo 3:1 or 4:1. The hologram recording plate was positioned about 1¼" to 1½" from the object. Kodak 649F emulsion on ¼" thick microflat glass plate was used.

The optical system for making hologram is shown below:



To reconstruct, the following system was used:

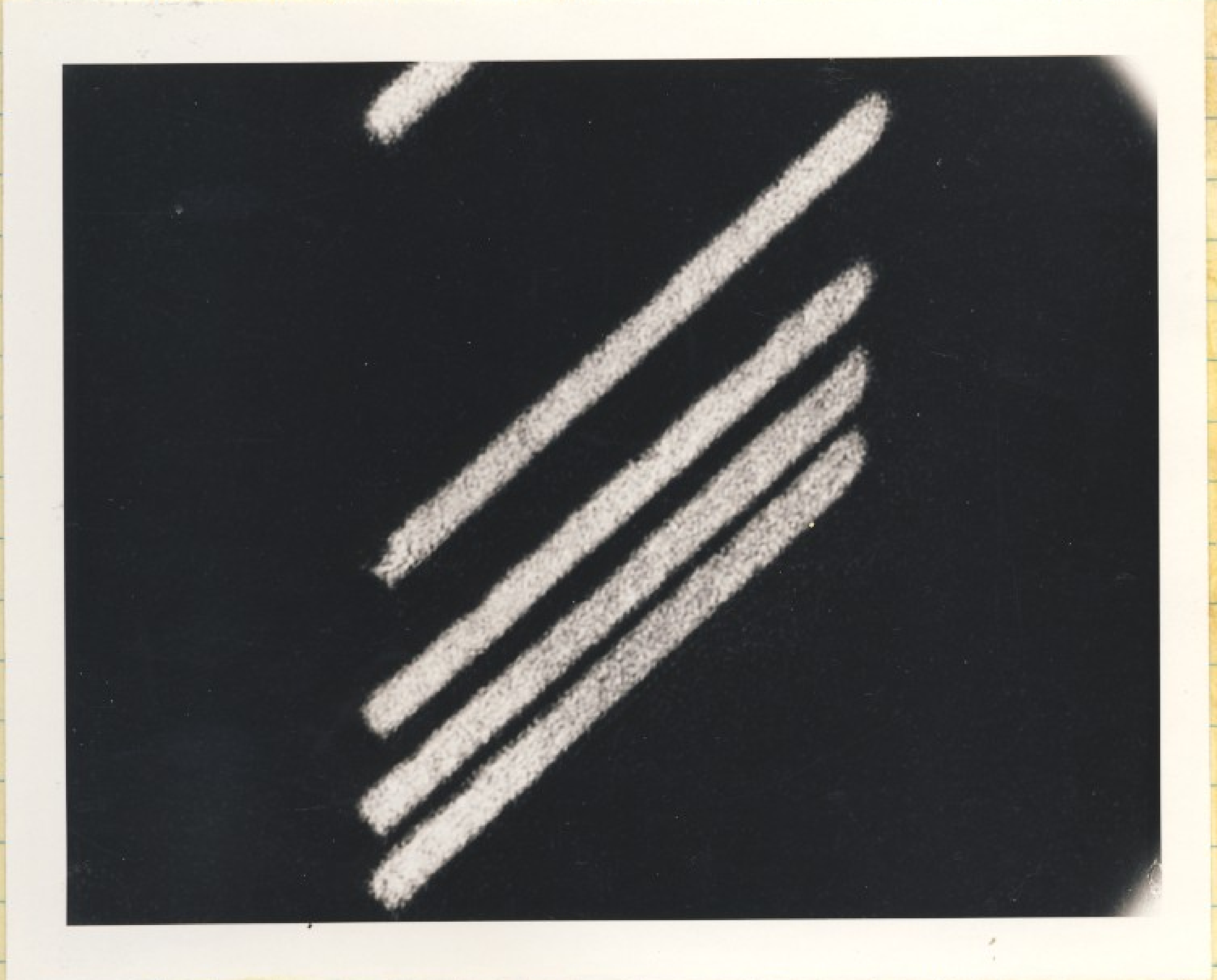


Juris Upatnieks (29 Sept. 1964)

29 September 1964

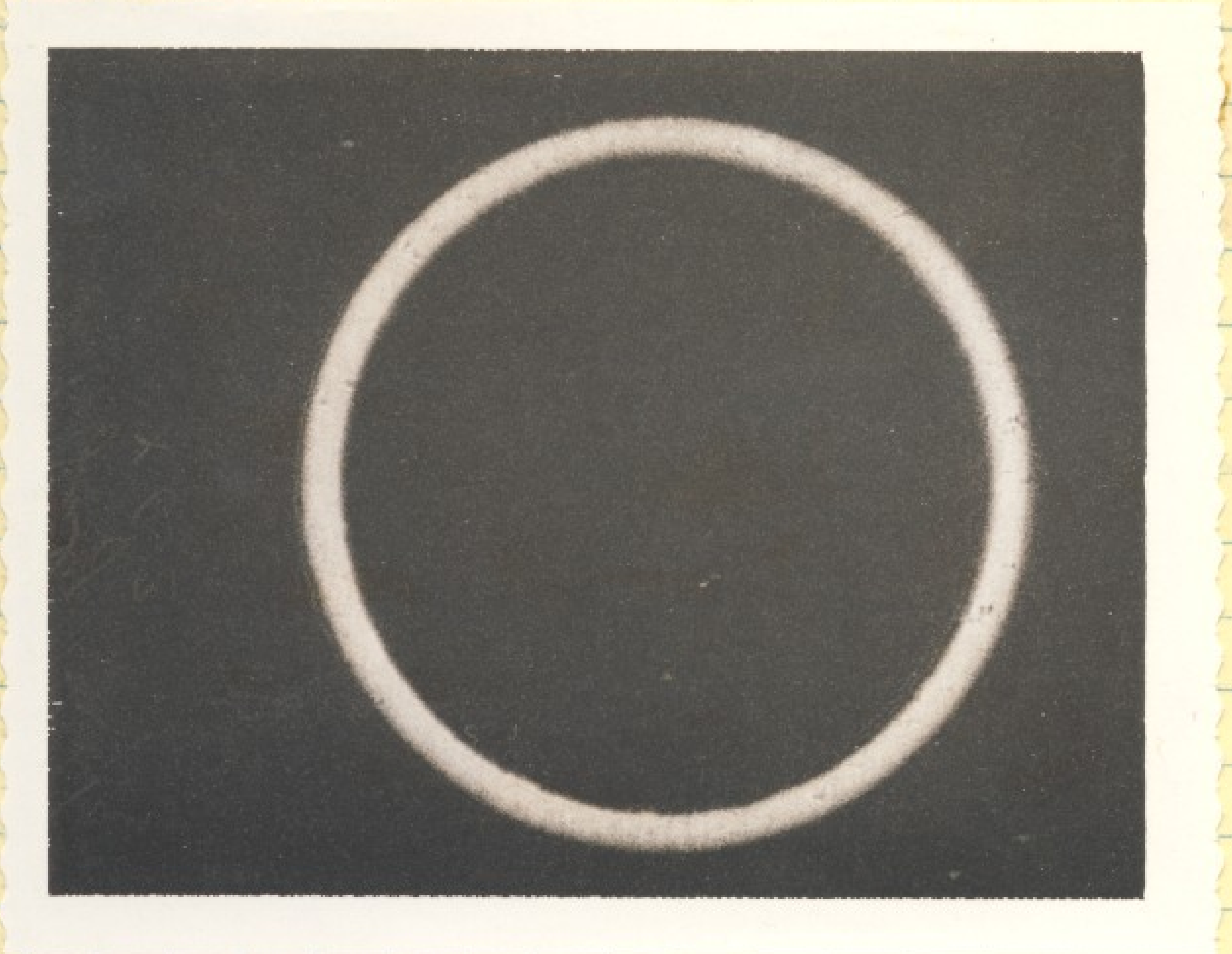
The focal length of the hologram is given by # $\frac{1}{f} = \pm\left(\frac{1}{b} - \frac{1}{a}\right)$, where "a" is the distance from pt. source to hologram, and "b" is the distance from object to hologram. The in-focus reconstructed image appears at "d" distance away from the hologram, where "d" can be found from the equation $\frac{1}{f} = \frac{1}{c} + \frac{1}{d}$: Distances "c" and "d" are shown in the drawing. The magnification is $M = \frac{d}{d}$.

M = 130



Reconstructed image made on 24 July 1964. M = 130. Picture shows part of a reconstructed test pattern. The seperati between lower two lines is 10μ, with about 5μ at the narrowest part.

M = 62



Reconstruction made on 24 July 1964. M = 62. A reconstructed circle from the test pattern. Note the shap edges and circular appearance, indicating absence of distortion.

Juris Upatnieks
29 September 1964

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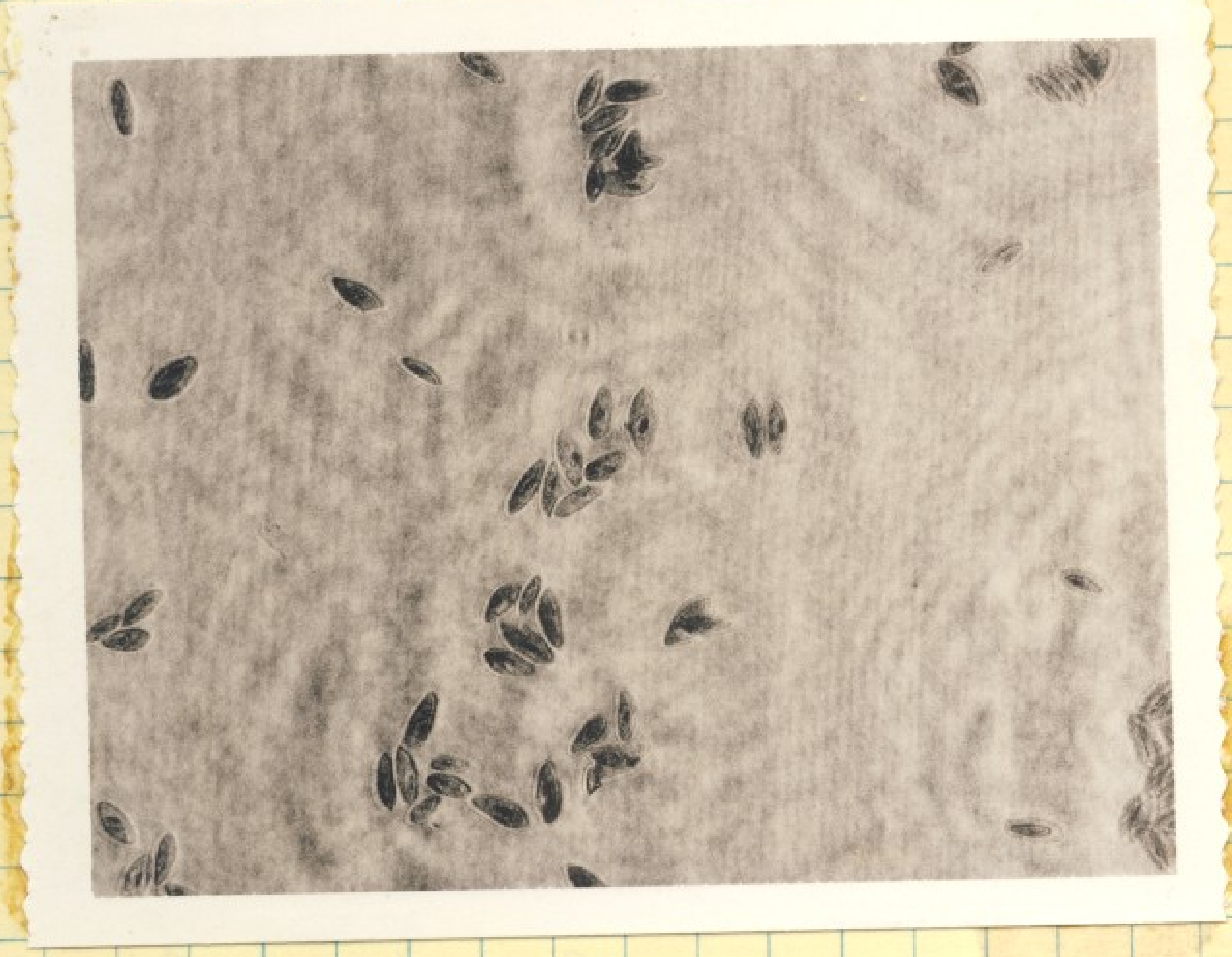
the wing of a fly

Hologram & reconstructio
made in July 1964. M≈
This picture shows the
reconstructed image of
a fly's wing. Th holog
was made from the actu
wing of a fly mount
between two glass sl
Note the hair around
the edge which are ba
resolved.

Paramecium



Reconstruction made on
5 August 1964. M ~ 40
This is a reconstructio
from a hologram. The
hologram was made fr
a standart microscope
slide.

Note: the experimental work was done by myself
and D. Brumm, under my direction.

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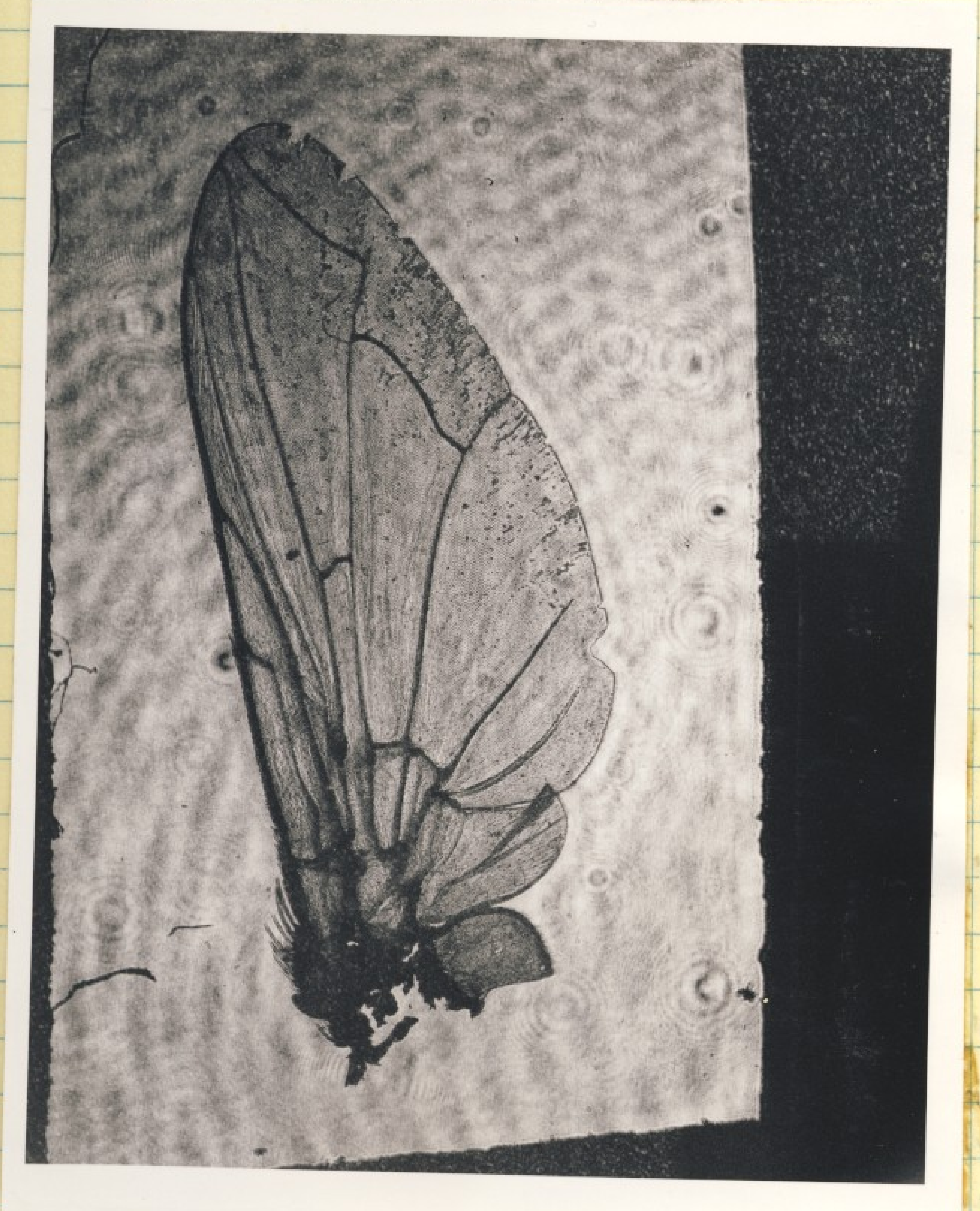
16 November 1964

Fly's wing



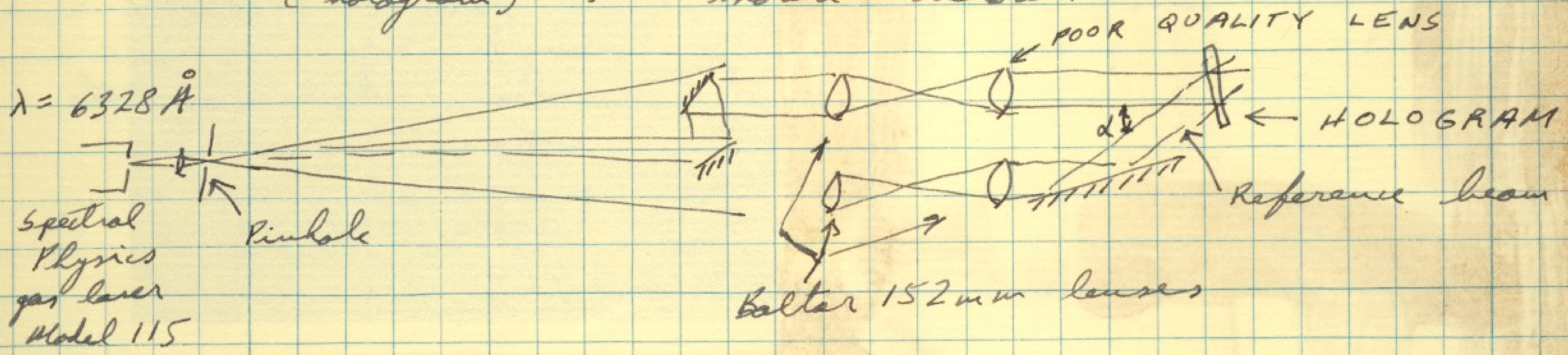
Hologram made in July 1964, reconstruction in October 1964. M = 12. This reconstruction was made from the same hologram as the wing on pg. 50. Concentric rings are from dust particles on the hologram.

Juris Upatnieks, 16 Nov. 1964

16 November 1964

Lens correction holograms

A hologram was of the abberations present in a poor lens. This hologram will be used as a phase correction device to obtain high quality imaging using a poor lens. The optical arrangement for making the phase correction plate (hologram) is shown below:



The light beam is divided into two parts, one used as a reference, the other to obtain phase error from the poor lens. The lens to hologram distance is 9½ in. The holograms were made on 3 Nov. 1964, with slightly different exposure times. Intensity of the referance beam was slightly higher that of signal beam. To check the quality of phase correction using this technique, the hologram was placed back in identical position and interferance fringes between diffracted and transmitted waves was observed, and recorded on 35 mm Pan-X film (Sheet #001, 6 Nov. 1964).

Film recordings show: (Sheet #001, 6 Nov. 1964)

#1 Interferance between reference beam and phase corrected beam collimated by a poor lens. ~~and~~ Result shows $\sim 1\lambda$ phase error.

#2 Same as above, but with offset frequency.

Juris Upatnieks, 1964, 16 Nov

16 November 1964

#3 Interferance between referance beam and uncorrected beam collimated by a poor lens (same lens as in #1 & #2). A high-quality diffraction grating was used at the place of hologram in Fig. on p. 52. Phase error $\sim 19\lambda$

#4 Same as #3 but curvature of referance beam changed. Phase error $\sim 14\lambda$.

Note: #3 & #4 do not show complete circle because part of the reference beam was obstructed by lens mount.

Related data:

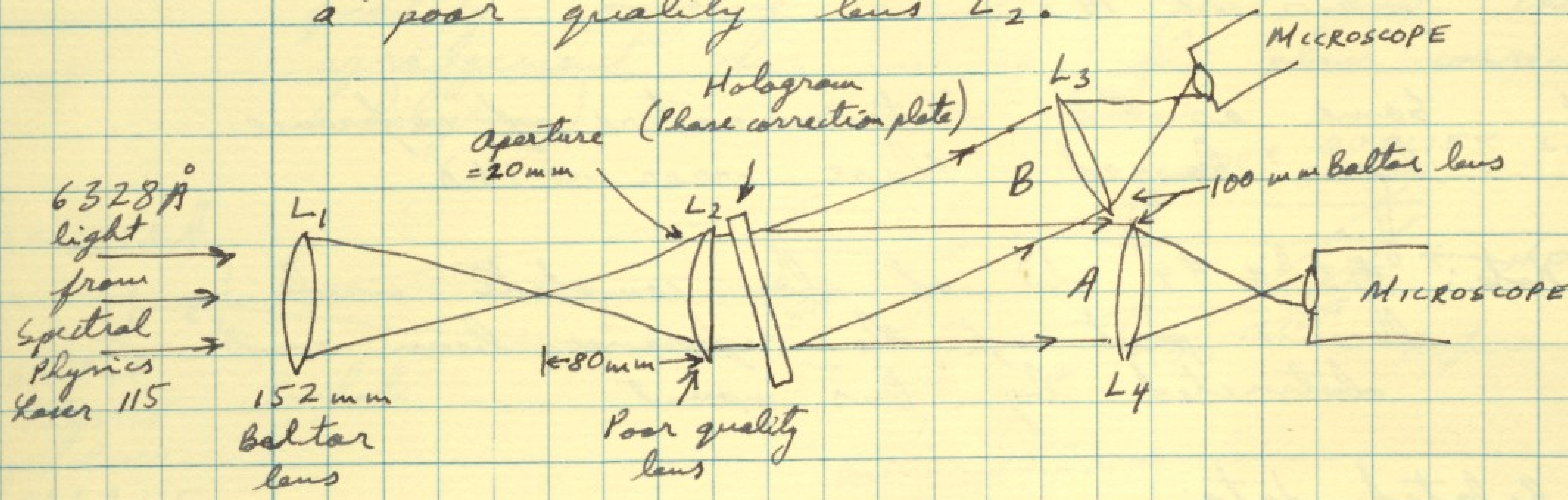
Hologram recorded on: 649 F emulsion on $\frac{1}{4}$" × $1\frac{1}{2}$" microfla
glass plates
λ of light: 6328 Å, laser light
Plate development: 5 min in D-19, room temp.
Mirror flatness: $\frac{1}{4}\lambda$ over aperture
Exposure time of hologram: $\simeq$ 15 sec.
Reference beam angle: $\sim 20°$
Carrier frequency = 550 l/mm

Juris Upatnieks, 16 Nov. 1964

17 November 1964

Lens Correction Holograms, or plates

A lens correction plate (hologram), made on Nov. 3, 1964 was inserted in the optical setup, shown in the diagram, to correct the phase errors introduced by a poor quality lens L_2.



The optical system consists of lens L_1, which focus the light to a point; lens L_2 collimates the light. The hologram after L_2 diffracts light into beam B and corrects the phase front from lens L_2, giving a corrected wavefront. This beam is focused to a small point by lens L_3 and observed ~~by~~ using a microscope.

Some of the light passes through the hologram without having its wavefront altered. This is beam A. Beam A is also focused by L_4, identical to lens L_3, and the focus can be observed with a microscope.

The focused points of both beams A and B were observed using the same microscope and same focusing lens. A scale, having divisions of 0.1 and 0.01 mm was placed also at the foca points in both cases and the diameter of

Juris Upatnieks, 17 November 19

Witnessed by
Adam Kozma 17 Nov 1964
Alex K. Forster Jr. 17 Nov 1964

17 November 1964

of point focuses was observed. Beam A gave a point focus of 1.4 mm or 1400 μ, and beam B had a point focus of 0.05 mm diameter, or 50 μ. The point diameter was therefore reduced by a factor of 28 using the phase correction plate.

These results were observed by Juris Upatnieks, Adam Kozma, and Alex Klooster, Jr., of the Optics Group, Radar Laboratory, University of Michigan, on 17 November 1964.

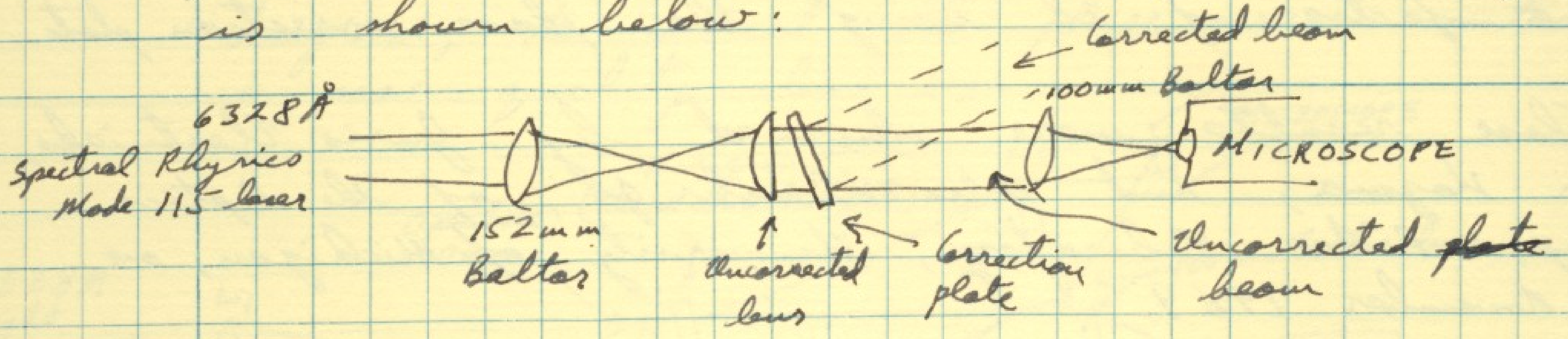
Juris Upatnieks, 17 November 1964

Witnessed by
Adam Kozma 17 Nov 1964
Alex Klooster Jr. 17 Nov 1964

19 November 1964

Lens correction plate

On 17 Nov., several pictures were made of the focused, uncorrected lens. The optical arrangement is shown below:



For the microscope, 22.7 mm objective was used, and film was 20 cm from objective. Exposure times were: 1/1000, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$ sec. Best exposure: $\frac{1}{1000}$ sec. for center image, $\frac{1}{100}$ sec. for scattered light. Similar photographs were made of corrected beam, but those were out of focus due to incorrect camera adjustment.

Recordings show (Sheet #001, 17 Nov. 1964):

#5 Uncorrected beam of light, full aperture. Exposures as above.

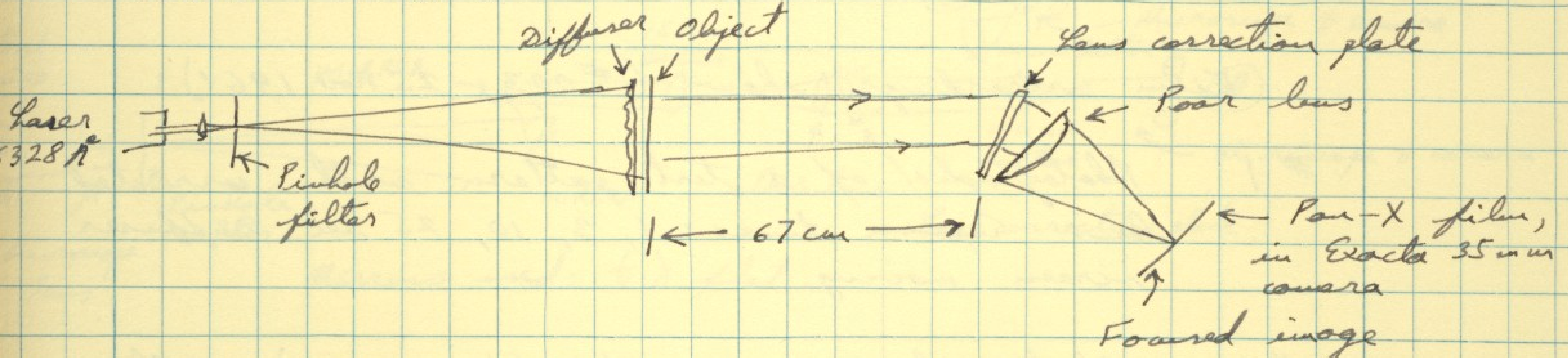
#6 Uncorrected beam, 10 mm aperture. Best exposure ~ $\frac{1}{1000}$ sec.

Juris Upatnieks, 24 Nov. 1964

24 November 1964

Tests with lens correction plate

A number of photographs were made using a poor lens and the lens correction plate, made on 3 Nov. 1964. The test was done on 20 Nov. 1964. The test setup is shown below:



The sketch shows the arrangement for testing lens with correction plate in proper position. To obtain uncorrected image, the lens-plate assembly was rotated until the lens was on optical axis and exposures were made.
Lens aperture = 20 mm, focal length = 80 mm

Film recordings show (Shot #002, 20 Nov. 1964):

#1 Image of corrected picture, diffuser stationary.
Exp. times: $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$, 1, 4, 12 sec.

#2 Same as #1, but diffuser moving during exposure.
Exposures $\frac{1}{5}$ to 30 sec.

#3 Uncorrected lens, diffuser moving. Exposures same as #2.

#4 Uncorrected lens, diffuser moving, photograph of test pattern. Exposure 1 to 30 sec.

#5 Corrected lens, diffuser moving. Exp. 1 to 30 sec.

Juris Upatnieks, 24 Nov. 1964

1 December 1964

Tests with lens correction plate

The test recorded on p. 57 was repeated after adjusting the position of the lens correction plate. The distance of object (transparency) to lens was 79 cm, otherwise the test was identical. Tests were made on 25 Nov. 1964.

Film recordings show (#003, 25 Nov. 1964):

#1 Photographs of a test pattern with corrected lens. Exposure times: 1, 3, 10, 25 sec. Diffuser screen moving.

#2 Photograph of an office (transparency) with corrected lens. Exposure times: 1, 3, 10, 35 sec. Diffuser screen moving.

#3 Photograph of an office (transparency) with uncorrected lens. Exposure times: $\frac{1}{5}$, 1, 3, 10 sec. Diffuser moving.

#4 Photograph of test pattern with uncorrected lens. Exposure times: $\frac{1}{5}$, 1, 3, 10, 5 sec. Diffuser moving.

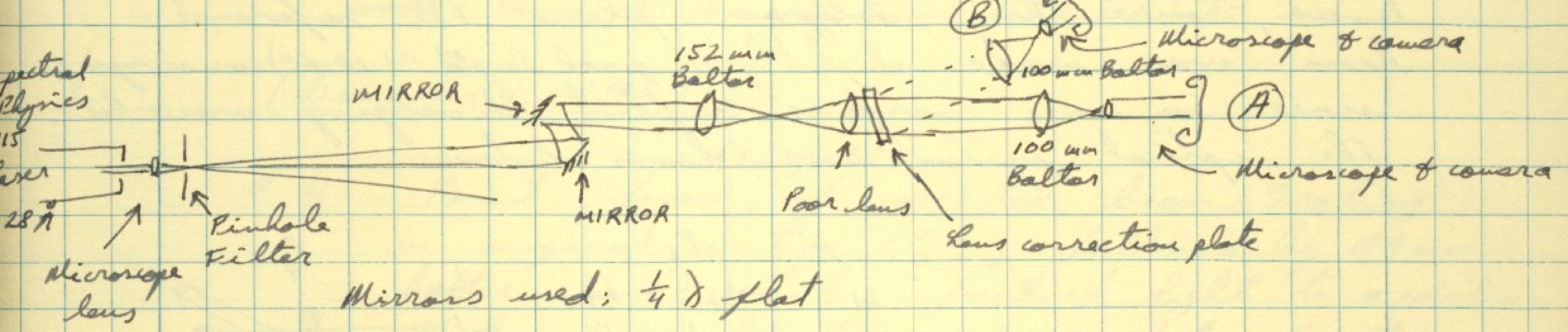
Note: The uncorrected lens focuses part of incident light into a point, the rest appears as a large flare around it. Thus when photographing the test pattern, lines remain sharp but have fuzzy halos around them. The corrected lens focuses all of the light in smaller area, but with more equal intensity over the whole area. This area is somewhat larger than the central point of the uncorrected lens. It appears that the plane at which correction plate will be placed should be projected on the hologram to obtain better results.

Juris Upatnieks, 1 December

1 December 1964

Tests with lens correction plate

On 25 November 1964 several tests were made with the lens correction plate made on 3 November 1964. For the first part, the optical system used was as shown below:



Mirrors used: $\frac{1}{4}\lambda$ flat

In position Ⓐ, the microscope enlarges the image of the focused point from the uncorrected lens; in position Ⓑ, the beam is corrected by the lens correction plate and then focused to a point. In both cases Pan-X film was used in Exacta camera mounted on the microscope. The objective focal length of microscope was 16 mm.

Film recordings (Sheet #003, 25 November 1964):

#5 Point image of uncorrected lens. Exposure times: $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$ sec.

#6 Point image of corrected lens. Exposure times: $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$ sec.

For the second part, the poor lens was placed about 150 cm from the pinhole filter without any lenses inbetween.

Film recordings (Sheet #004, 25 November 1964):

#1 Point image of corrected lens (no 100 mm Baltar used). Exposure times: $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$ sec., then repeated with reduced laser intensity

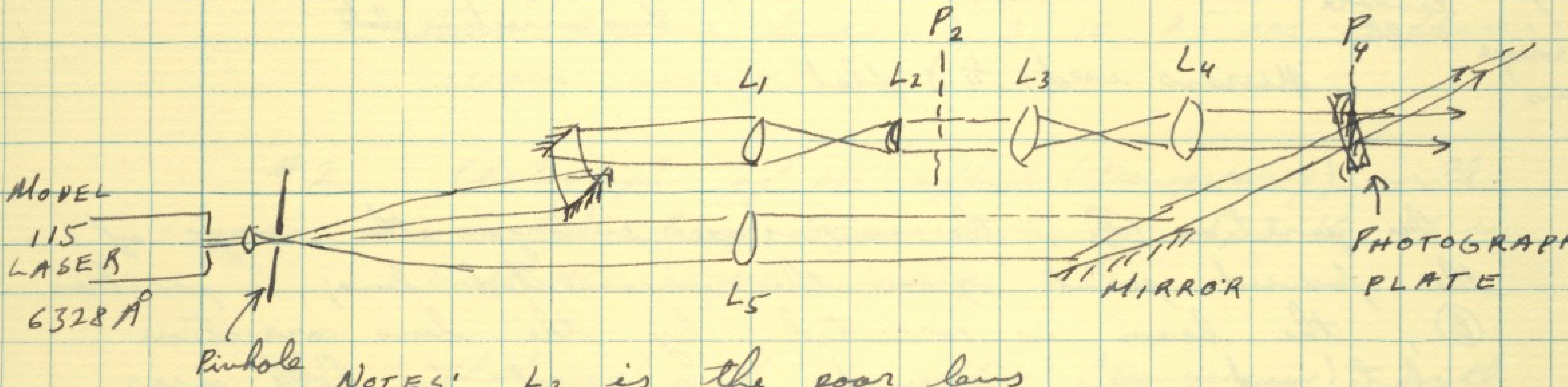
#2 Photograph of scale through microscope in white light. Separation between wide marks = 0.1 mm, between close ones = 0.01 mm

Juris Upatnieks, 1 December 1964.

23 December 1964

Tests with lens correction plate.

To improve the quality of the lens correction grating, the plane at which the grating would be used ~~made~~ was projected, using a pair of relay lenses, on the hologram plane. The referance beam was made slightly (focal length ~ 10 ft) converging, since in use surfaces reflect diverging wavelets. The optical system is shown below:



NOTES: L_2 is the poor lens
L_1, L_3, L_4 are 152 mm Baltar lenses
All mirrors ar $1/4\ \lambda$ flat over entire surface
L_5 is a 60 in. lens
P_2 is imaged on P_4
L_3 and L_4 are two focal lengths apart.

Tests with this plate did not give the expected improvement in resolution over the previous correction gratings. The interferance pattern with the plate at the original position showed that wavefront from the poor lens is corrected to within one λ of light. Further tests revealed that poor focusing is caused by variations in thickness of the emulsion (glass without emulsion showed no effect). Bothe the corrected beam, and undiffracted beam with plane wavefront, gave a sharp focus. The following films were madde to record test results. Film was made on Dec. 3, 1964, and on Dec. 4, 1964.

Juris Upatnieks, 1964., Dec. 23

23 December 1964

Film recordings (Sheet #004, 3 December 1964):

#3 Interference between reference & corrected beam; grating in position at which it was made. Exposure times: $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$ sec.

(December 4, 1964):

#4 Point focus (horizontal) of corrected beam. Grating in original position (P_4), followed by 100 mm Baltar lens which focused light to a point. Microscope objective: 4 mm f.l., Exacta camera mounted on microscope. This setup was used for all the following photographs. Exp.: $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$ sec.

#5 Same as #4, but vertical focus. Same exposure times

#6 Plain wavefront through correction plate, not diffracted. Exp.: $\frac{1}{25}$, $\frac{1}{1000}$, $\frac{1}{250}$, $\frac{1}{100}$ sec. Horizontal focus.

(Sheet #005, 4 Dec. 1964):

#1 Same as #6 above, but vertical focus. Same exposure, in increasing order

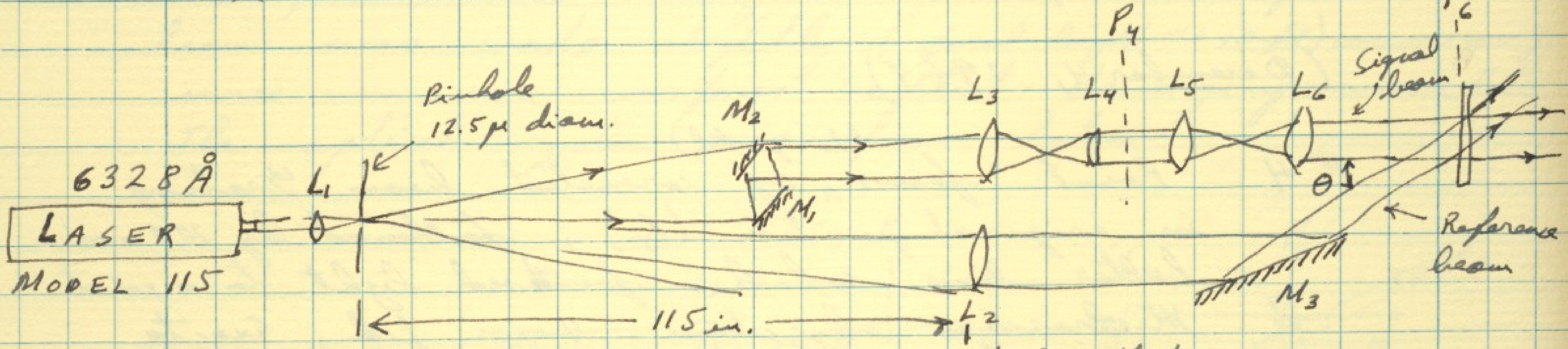
#2 Focus of good quality wavefront without grating. Same exposures as #1

Juris Upatnieks, 23 December 196

24 December 1964

Making of Phase Correction Gratings

Several new grating were made on 23 December 196 to study the causes of imperfect phase correction. The optical system shown below was used to make them:



Mirrors: M_1, M_2 + M_3 - all 1/4 λ flat

Lenses: L_1 : 22.7 mm focal length microscope objective
L_3, L_5, L_6 : 152 mm Baltar lenses
L_4 : Poor quality lens, 80 mm f.l., 20 mm di
L_2 : 60 in. focal length
Plane P_6 is projection of plane P_4

Angle between ⊥ of photographic plate and signal beam was set zero to simplify ~~th~~ alignment problem when correction grating is placed in plane P_4.

Photographic plate: microflat (λ or less per in. flat) with 649 F emulsion

Relative intensity of the two beams was approximatly the same. θ = 18.5°. Light meter: Science + Mechanics Model 250

Plates:
a) 23 Dec. 64, #1, 40 sec. exp., $I = 23 \times 10^{-3}$ ← Light meter
b) 23 Dec. 64, #2, 20 sec. exp., $I = 23 \times 10^{-3}$
c) 23 Dec. 64, #3, 50 sec. exp., $I = 30 \times 10^{-3}$
d) 23 Dec. 64, #4, 50 sec. exp., $I = 30 \times 10^{-3}$

Note: Interference pattern between reference + signal beams indicate presentee relative phase shift, slowly varying. Presum these are caused by thermal variations of air (temp. + pre variations).

Juris Upatnieks, 24 December 1964

24 December 1964

Performance and errors of phase correction gratings.

To test the quality of phase correction gratings made on 23 Dec. 1964, they were placed in position of plane P_6, (see p. 62), and a 100 mm Baltar lens ~~fc~~ was used to focus light. A microscope was used to examine the detail of the focused point. A white card in front of the 100 mm lens was used to observe the interferance fringes between the referance beam and corrected signal beam. The following results were observed:

a) All four phase grating showed that the signal beam was well corrected with respect to the referance beam. All showed a maximum of one λ of light maximum phase shift, and #3 dry and #4 in liquid gate showed nearly perfect ~~reconstruction~~ correction.

b) The focused point of corrected signal beam showed astigmatism for gratings #1, #2, and #4, and perhaps some other type of abberation. #3 could be adjusted to what appeared to be a sharp focus (round point). #4 in liquid gate still had abberations, ~~spher~~ that is, astigmatism.

c) The referance beam, which passed through the phase correction grating ("central image"), for all four plates showed astigmatism. #4 plate, after being placed in liquid gate, did not show any astigmatism for the referance beam.

d) Amplitude of diffracted, corrected, wavefront did not have uniform intensity across the aperture.

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28 December 1964

Causes and Correction of Phase Correction Grating Errors.

From the observed results of tests, recorded on 24 December 1964, it is obvious that the gratings do not perform as well as could be expected from the interferance tests of the corrected wave front with the referance wave front. Three deficiencies could be contributing to these inferior results:

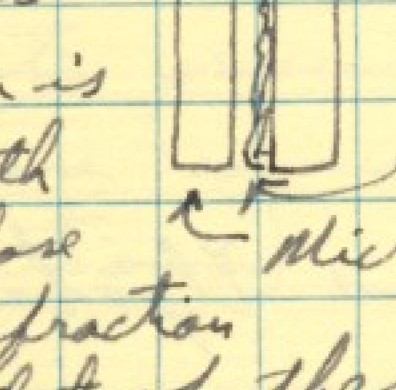
1) The emulsion is not flat over the aperture used. If the referance beam is of the form $A_0 e^{j\omega x}$, the signal beam $A_1 e^{j\phi(x,y)}$, then the recorded signal is $A_0^2 + A_1^2 + A_0 A_1 e^{+j(\phi+\omega x)} + A_0 A_1 e^{-j(\phi-\omega x)}$. When the grating is illuminated with the signal beam, or the distorted wave fron, the last term becomes:

$$A_1 e^{j\phi}\left[A_0 A_1 e^{-j(\phi-\omega x)}\right] = A_0 A_1^2 e^{+j\omega x}$$

which is the same as the referance beam. If the emulsion is not flat and its phase variations are expressed by $e^{j\alpha(x,y)}$, then the last term becomes

$$A_0 A_1^2 e^{j(\omega x+\alpha)}$$

and thus a phase error is introduced in the corrected beam. Identical error is introduced in the referance beam when it passes through the grating, as was done in the tests on previous page. This defect could be corrected by using a liquid gate to reduce or eliminate phase error $e^{j\alpha(x,y)}$ due to the emulsion:



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2) Grating #4 of Dec. 23, '64, showed oberations before and after being placed in liquid gate. The undiffracted referance showed abberation when it passed through the dry grating, but did not show any after the grating was placed in liquid gate. This indicates that the liquid gate corrected phase errors introuced by nonuniform emulsion thickness, but this did not corrected the diffracted signal beam entirely. A probable cause of this is that <u>intensity</u> variations in diffracted beam are sufficient to destroy good focus. The last term in previous eq. becomes:

$$A_1 \left[A_0 A_1 (x,y) \right] e^{+j \omega x}$$

indicating that $|A_0 A_1|$ changes with position on the grating. Amplitude variations could destroy focusing qualities, and these are not readily appearant on interferance patterns with the referance beam. Variations in intensity could result from:

a) Nonuniform signal and referance beams. Measurments have not been made to determine their uniformity, but there was no appearant variation in intensity for the gratings made on 23 Dec. 1964

b) Phase variations between the signal and referance beams as a function of time. This is a very likely cause, and variations would not be uniform across the grating. Averaged over the exposure, this could reduce fringe intensity considerably. Assuming phase variation increases with beam seperation, the region where "outside" parts of the beam interfere would have lower intensity ~~than~~ the "inside". See Fig. on p. 62. This could be corrected by enclosing optical system in a box, and by using beam splitters to obtain the two beams.

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c) Nonuniform grating could be caused by laser operating in a number of off-axis modes. Variations in intensity of interference because of this have been observed on other occations. Careful adjustment of laser cavity and monitoring it with a spectrum analyzer could correct this deficiency.

3) The spacing of the fringes in the emulsion could change after development due to various causes. Also, placing the emulsion in liquid gate could affect their uniformity of spacing. No data is available to estimate the significance of this possible cause.

Grating #3 showed good focus when dry, but the focused reference beam through showed abberations. Apparently intensity variations in this case compensate for phase variations, or the phase variations are such that slight misalignment of the grating compensa for the phase error due to emulsion.

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Errors in Phase correction Gratings.

An additional error in the phase correction grating is caused by the lenses used in the system. Although these are high-quality lenses and were assumed to be perfect, in practice they do have some spherical abberations at low f-numbers

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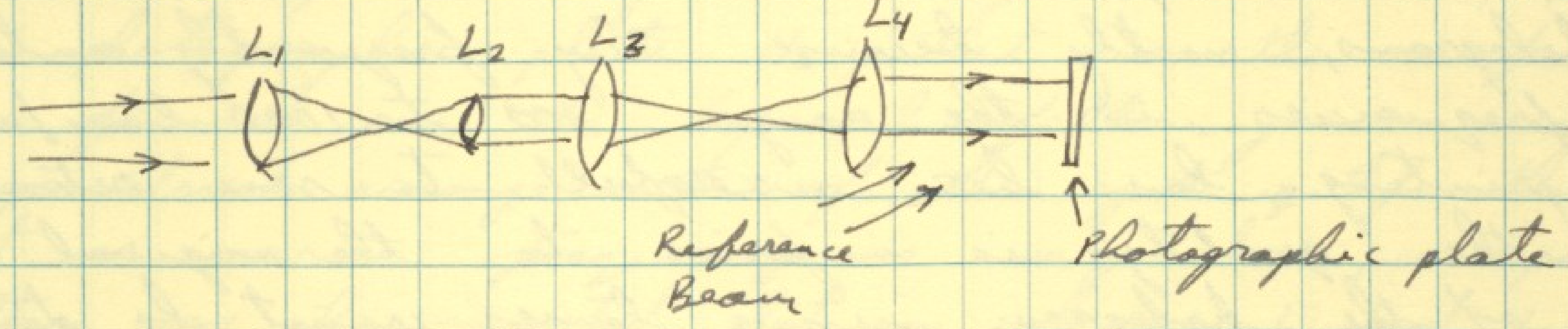
The part of the optical system using lenses is shown below:



L_1, L_3, L_4 are 152 mm Baltar lenses
L_2 is poor quality lens, ≈ 80 mm focal length

L_1 is used at full aperture, f-2.3, and all of the light is approximatly collimated by L_2. At f-2.3, the lens has a central point surrounded by a flare ≈ 70μ in diameter. Since the focal length of L_2 is approximatly 80 mm, L_3 and L_4 are used at effective f-number of about 5.0. The phase correction grating, when operating perfectly, will therefore, in conjuction with L_2, focus a collimated beam of light to an identical "point" focus to that of L_1. For the optical system shown on p. 62, the poor lens cannot be corrected to be better than the lenses used in the system, namely L_3, L_5, and L_6 (see p. 62).

To see the effect of lenses L_1, L_3, and L_4 above on quality of reconstruction, L_2 was replaced by a 100 mm Baltar lens and another was placed after L_4. The focused point image had a flare of about 70μ diam. around it. The focused point by the grating and poor lens L_2 alone also had a point with a flare of the same order of magnitude.

A good point image between L_1 & L_2 could be obtained by using sufficiently small pinhole filter, possibly about 2 to 4 μ in diameter.

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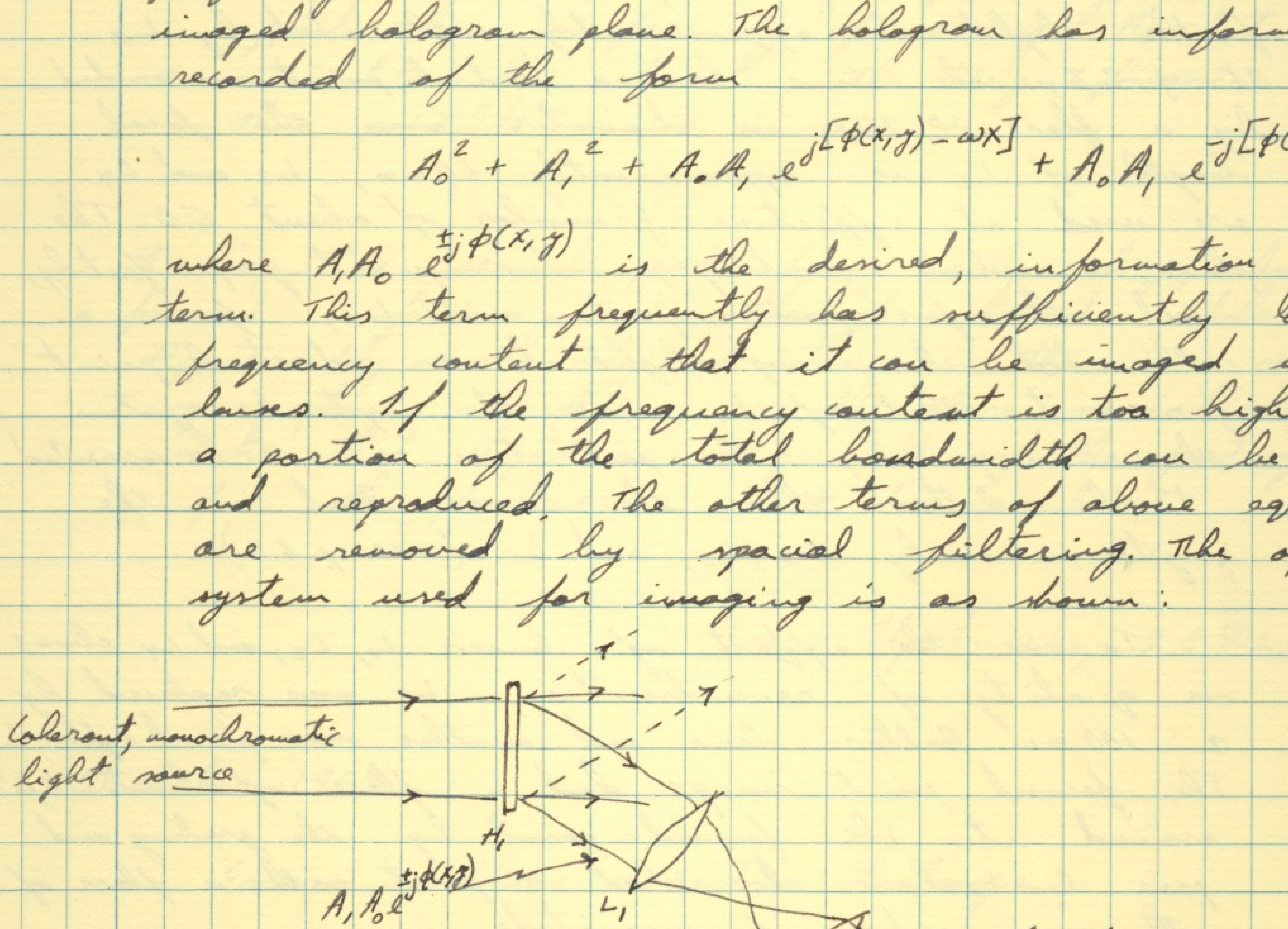
Reproduction of Holograms.

Some difficulties have been encountered in reprodu holograms, mostly because they frequently contain spacial frequencies in the range 300 to 1000 lines/mm. Contact printing has been successfull to some extent, although the quality is inferior to the original. Imaging of the hologram using lenses cannot be done since an ordinary lens has a frequency response 100 to 300 l/

Holograms can be imaged, however, if the carrier frequency is removed and is reintroduced at the imaged hologram plane. The hologram has information recorded of the form

$$A_0^2 + A_1^2 + A_0A_1 e^{j[\phi(x,y)-\omega x]} + A_0A_1 e^{-j[\phi(x,y)-\omega x]}$$

where $A_1A_0 e^{\pm j\phi(x,y)}$ is the desired, information carrying term. This term frequently has sufficiently low spacial frequency content that it can be imaged using lenses. If the frequency content is too high, then a portion of the total bandwidth can be selected and reproduced. The other terms of above equation are removed by spacial filtering. The optical system used for imaging is as shown:



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A coherent, monochromatic, light source illuminates the hologram H_1 to reconstruct one of the sidebands. This sideband is focused by means of two lenses, L_1 & L_2, on a photographic plate H_2; that is, the surface of H_1 is focused on H_2. Spacial filtering is accomplished by geometrical arrangement of the system. If the offset or carrier frequency is very low, a spacial filter may be inserted between lenses L_1 and L_2. A reference beam, coherent with the illuminating beam of H_1, also falls on H_2. Note that the reproduced hologram may have different carrier frequency, and it also can have magnification introduced in this step. L_1 and L_2 are lenses with equal focal length, and the separation between lenses is equal to twice the focal length of one lens.

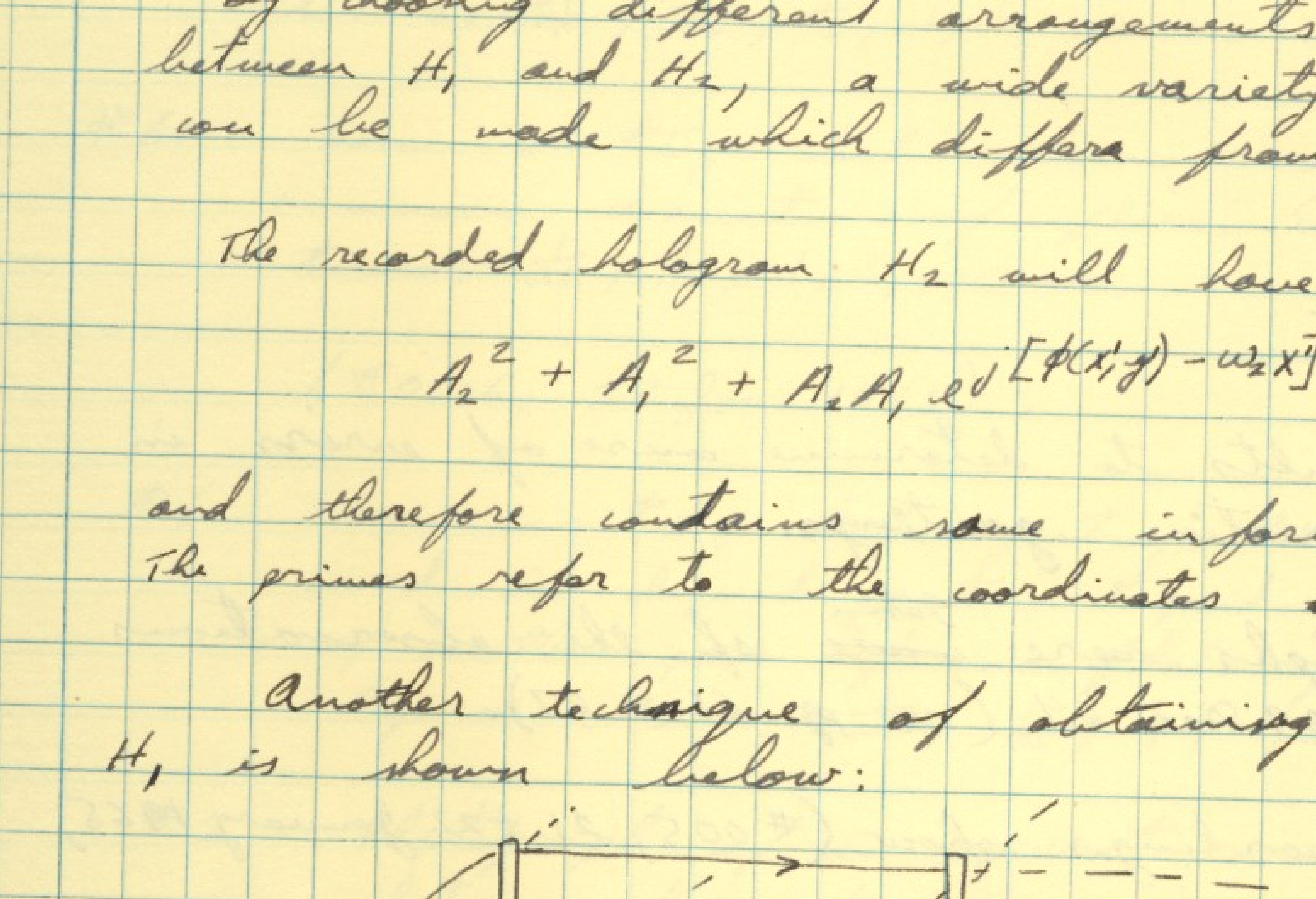
By choosing different arrangements of lenses between H_1 and H_2, a wide variety of holograms can be made which differs from that of H_1.

The recorded hologram H_2 will have the form

$$A_2^2 + A_1^2 + A_2A_1 e^{j[\phi(x',y') - \omega_2 x']} + A_2A_1 e^{-j[\phi(x',y') - \omega_2 x']}$$

and therefore contains same information as H_1. The primes refer to the coordinates ~~of~~ at H_2.

Another technique of obtaining hologram H_2 from H_1 is shown below:



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In this case lenses are not used. One of the reconstructed sidebands from H_1 falls on H_2. The reference beam is introduced at H_2 and may be different from that of H_1. If the virtual image is reconstructed from H_1, then the reconstructed image from H_2 will have the appearance of view as though it was observed through two windows, one the size of H_1 and the other the size of H_2. This arrangement has the advantage that it is quite simple and the spacial frequency content of the signal is not restricted by lens aperture.

Juris Upatnieks, December 29, 1964

25 January 1965

Test results to determine cause of errors in phase correction gratings.

Photographs were ~~made~~ taken of the observations made on 29 Dec. 64 (see pg. 66 & 67).

Fill recordings show (#005, 21 & 22 January 1965)

#3 Photographs of point image as shown in figure, with the poor quality lens L_2 replaced by 100 mm Baltar lens. Effective apertures used of L_3, L_4, L_5 is f-5. Microscope adjusted so that flare is centered around point focus (f-no. of objective apparently too low to accept all of the beam. Exp. times: $\frac{1}{1000}$, $\frac{1}{500}$, $\frac{1}{250}$, $\frac{1}{100}$ sec.

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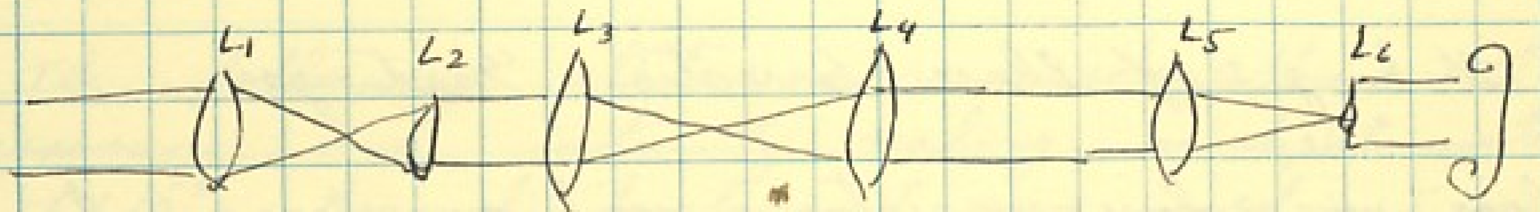


L_1, L_3, L_4 – 152 mm Baltar lenses

L_2, L_5 – 100 mm Baltar lenses

L_6 – 4 mm, 0.65, 43X B.&L. microscope objective

#4 Same as #3, but microscope adjusted for min. diameter of flare. Same exp. times.

(#005, 22 January 1965)

#5 Focused point of light by corrected lens, using grating #3 of 23 Dec. 1964. Exposure times: $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, 1, 5, 10 sec.

#6 Same as #5, but microscope adjusted for minimum diameter of flare. Exposure times: $\frac{1}{25}$, $\frac{1}{5}$, 1, 5, 10 sec.

(#006, 22 Jan. 1965)

#1 Same as #5, but grating #4 of 23 Dec 1964 used in liquid gate. Liquid gate consisted of another piece of microflat glass plate. Exposure times: $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, 1, 5, 10 sec.

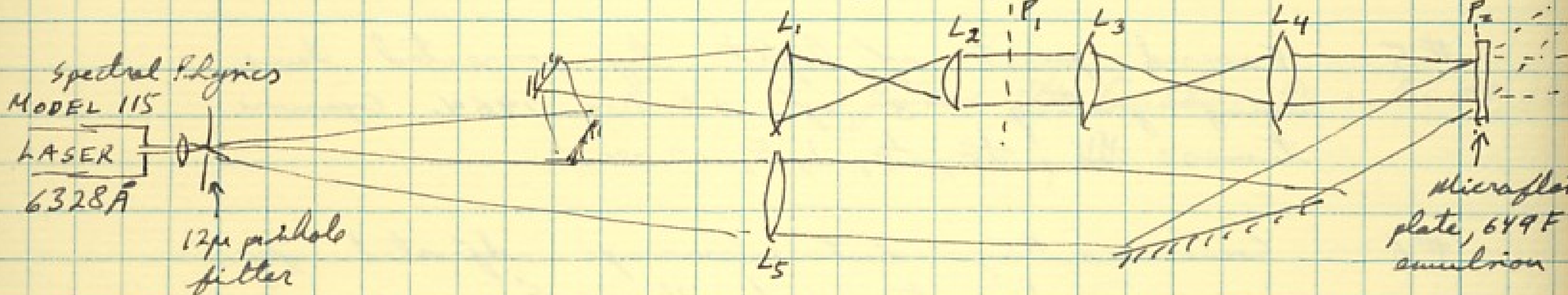
#2 Photograph of an accurate scale. Distance between large division 0.1 mm, distance between small divisions is 0.01 mm.

Juris Upatnieks (25 January 1965).

28 January 1965

Making of Phase Correction Gratings

Three new phase correction gratings were made in a manner similar to the previous ones. All lenses in the system were tested for aberations, and the best ones were selected for the most critical locations. The lenses were tested by focusing a slightly diverging beam, and observing the focus with a microscope (magnification ~ 200X). The aperture was then reduced until what appeared to be a good point focus appeared. The aperture setting was noted. The optical system below was used to make phase correction gratings:



P_1 is projected on P_2

L_1 - 100 mm Baltar lens at f-2.8. Focal point appeared to be a point. A 12.5μ pinhole made the field appear slightly nonuniform, indicating the diameter of point focus is slightly larger than 12.5μ.

L_2 - lens to be corrected

L_3 & L_4 - 152 mm Baltar lenses, which appeared to give point focus at f-6 setting. Lenses were used with f-5.6 aperture.

L_5 - 60 in. focal length, 4 in. diam. lens.

All mirrors wer flat to 1/4 λ.

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The following plates were made, all with 180 sec. exposure and intensity reading on light meter of 6×10^{-3}. Normal development was used: 5 min. in Kodak D-19, fixed for 5 to 10 min. in rapid fix., at room temperature

a) Plate made on 26 Jan. 1965

b) Plate #1, 27 Jan 1965

c) Plate #2, 27 Jan 1965

Juris Upatnieks (28 Jan. 1965)

4 February 1965

Tests of phase correction plates made on 26 & 27 Jan. '65

The plates were tested by placing them with the lens to be corrected in nearly collimated beam of light. All three showed absence of spherical abberations, but astigmatism was present. The plate made on 26 Jan. 65 was moundet as a liquid gate, with a clear piece of microflat glass plate against the emulsion and with liquid Xylene between them. This removed the astigmatism and an excellent focus was obtained. The diameter of the focus (central point and nearby bright points) ~~are~~ is somewhat less than 20 μ across.

The mounting of the correction plate on the lens was not very secure, as black tape was used. This accounts for some degradation of results, since the plate slipped slightly during the time of the tests. Also, since no pinhole

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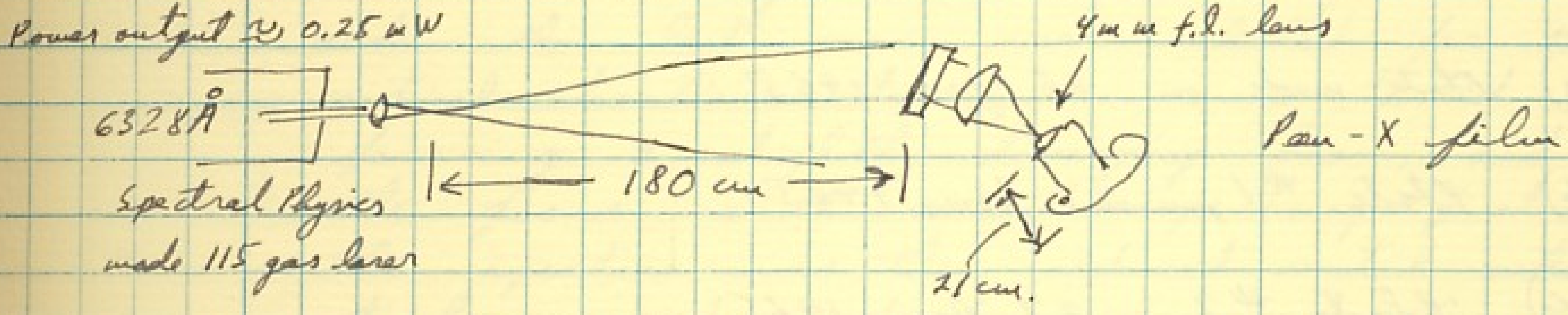
was placed in front of the microscope lens, illumination of the office scene was nonuniform.

The optical system used is shown here:



Film recordings show (#006, 1 Feb. 1965)

\#3 Point focus of corrected lens, with grating of 26 Jan. 1965 and Xylene in liquid gate.
Exp. times: 1/25, 1/5, ?, 1, 5 sec.

(#006, 2 Feb. 1965)

\#4 Point focus of corrected lens, same grating as #3, Xylene liquid, point to lens distance = 240 cm
Exposure: 1/25, 1/5, 1, 5 sec.

\#5 Test pattern through microscope, with moving diffused glass in beam. Pattern to lens distance equal to 120 cm. Exposure: 5, 15, 45, 120 sec.

\#6 Office scene through microscope, otherwise same as #5 above. Exposure: 5, 15, 45, 120 sec.

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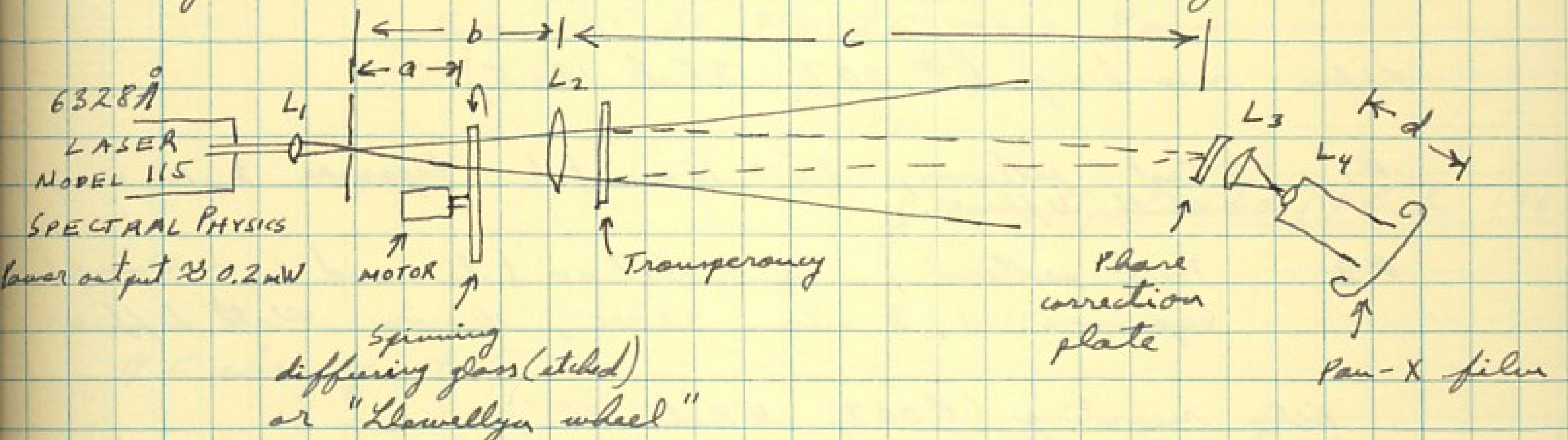
9 February 1965

Tests of the phase correction plate made on 26 Jan. 1965

For these tests the phase correction plate was used in the liquid gate arrangement. The optical system used is shown in the drawing:



Note: dashed line indicates ray path with L_2 in and diffuser out. Pinhole was not used.

$a = 67$ cm $c = 200$ cm

$b = 67$ cm $d = 20$ cm

$L_1 = 22.7$ mm microscope objective for first part.

$L_2 = 20$ in. focal length, 6" diameter lens

L_3 = Uncorrected, poor quality lens

L_4 = microscope objective, various f.l.

To increase available light intensity at the recording film, lens L_2 was inserted and focused to a point at the center of the phase correction gratings. Etched glass, having small dispersion angle, was used for rotating disc. Pinhole was removed when L_1 was replaced by 8 mm microscope objective, as proper adjustment could not be made. Observations indicated that longer focal length microscope objectives did not have sufficient numerical aperture to resolve all detail, sometimes giving inferior appearance of the image. Difficulties were in focus Exacta camera, as the ground glass screen made it difficult to judge when best focus was reached.

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Microscope objective focal lengths and their corresponding numerical apertures are listed here:

32 mm	– 0.10	16 mm	– 0.30
22.7 mm	– 0.17	8 mm	– 0.50

Film recording (# 007, 3 Feb. 1965):

#1 Test pattern, L_4 = 16 mm f.l. Exposure 2, 10 min. With diffuser.

#2 Test pattern, L_4 = 22.7 mm f.l. and L_1 ~ 16 mm f.l. Exposure: 1, 3 min., 30 sec., 10 min. With diffuser

Film recordings (#007, 4 Feb. 1965):

#3 Diffuser removed, L_4 = 8 mm f.l., test pattern. Exposure: $\frac{1}{25}$, $\frac{1}{5}$, 1, 5 sec. L_1 = 16 mm f.l.

#4 Diffuser removed, L_4 = 8 mm f.l., test patter, different part of it. Exposure: $\frac{1}{25}$, $\frac{1}{5}$, 1, 5 sec. L_1 = 16.

#5 With diffuser, test pattern, L_4 = 22.7 mm f.l. Exposure 2, 8, min., 45 sec. L_1 = 16 mm f.l.

#6 With diffuser, L_4 = 22.7 mm f.l., office. Exposure: 30 sec., 1½, 5 min. L_1 = 16 mm f.l.

Film recording (#008, 5 Feb. 1965): (L_1 = 8 mm f.l.)

#1 Office, with diffuser, L_4 = 22.7. Exposure: 10, 20, 40, 120 sec.

#2 Office, with diffuser, L_4 = 16 mm. Exposure: 60, 120, 300 sec. Some reflections off the sides of microscope tube were visible.

#3 Same as #2 above but with reflections reduced. Office, with diffuser, L_4 = 16 mm f.l. Exposure: 60, 120, 300 sec.

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Film recording (#008, 8 February 1965)

#4 Office, with diffuser, 32 mm objective (L_4).
Exposure: 1, 5, 10, 20, 40, 120 sec., 5 min.

#5 Test pattern, diffuser in, L_4 = 8 mm f.l.
Exposure: 10, 30, 90 sec., 4 min.

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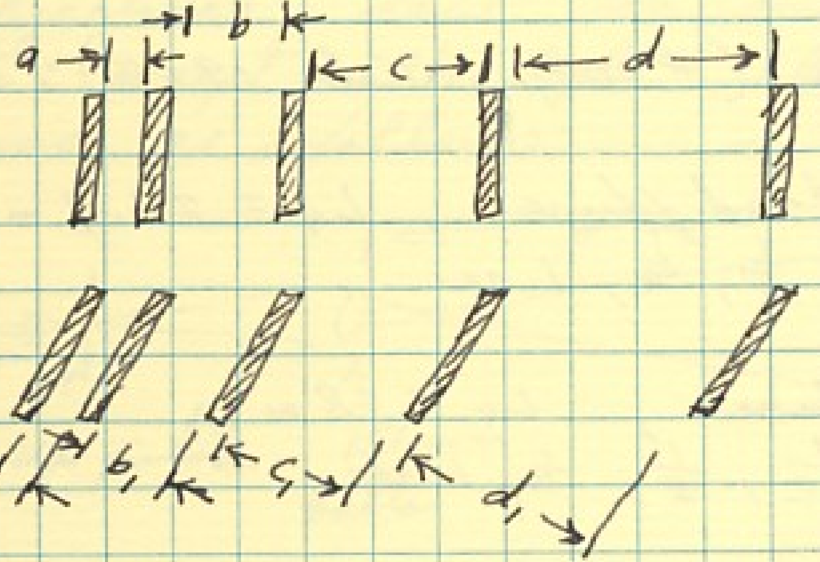
Measurements on Test Pattern used to test corrected lens performance.

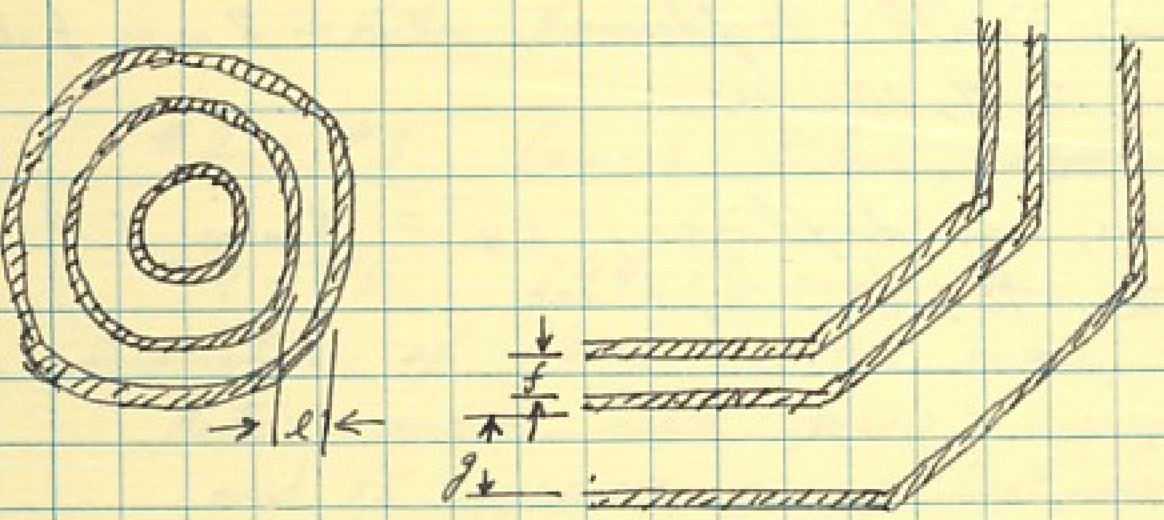
All measurement's were made with Gartner toolmaker's microscope. Measurements are made with calibrated mechanical stage, with divisions of 1μ obtainable.



a = 0.105 mm
b = 0.199 mm
c = 0.391 mm
d = 1.259 mm

a_1 = 0.061 mm
b_1 = 0.093 mm
c_1 = 0.224 mm
d_1 = 0.980 mm

e = 0.141 mm
f = 0.175 mm
g = 1.461 mm



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15 February 1965

Tests with uncorrected poor quality lens.

The tests recorded on pages 75 to 77 were repeated, but with the uncorrected lens. All other test parameters were held as closely as possible to those before. The diagram of optical setup on pg. 75 apply, with only difference that phase correction plate was removed and the poor lens, L_3, and camera are on optical axis.

Film recordings (#008, 9Feb. '65,):

#6 Test patter, with diffuser, $L_4 = 32$ mm f.l.
Exposure: $\frac{1}{5}$, 1, 3, 10, 30 sec.

Film recordings (#009, 9Feb. '65):

#1 Test pattern, with diffuser, $L_4 = 22.7$ mm f.l.
Exposures: $\frac{1}{5}$, 1, 3, 10 sec.

#2 Office, with diffuser, $L_4 = 32$ mm lens f.l.
Exposure: $\frac{1}{25}$, $\frac{1}{5}$, ?, $\frac{1}{2}$, 1 sec.

Film recordings (#009, 10Feb. 1965):

#3 Office, with diffuser, $L_4 = 22.7$ mm f.l.
Exposure: $\frac{1}{10}$, $\frac{1}{5}$, $\frac{1}{2}$, 1 sec.

#4 Office, diffuser, $L_4 = 8$ mm
Exposure: $\frac{1}{10}$, $\frac{1}{5}$, $\frac{1}{2}$, 1 sec.

#5 Test pattern, with diffuser, $L_4 = 8$ mm f.l.
Exposure: 1, 2, 4, 10 sec.

#6 Test pattern, no diffuser, $L_4 = 8$ mm f.l.
Exposure: $\frac{1}{25}$, $\frac{1}{10}$, $\frac{1}{5}$, $\frac{1}{2}$, 1 sec.

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~~A~~ Film recordings (#010, 10 February 1965):

#1 Test pattern, no diffuser, L_4 = 22.7 mm f.l.
Exposure: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, 1 sec.

Film used for above recordings: Pan-X

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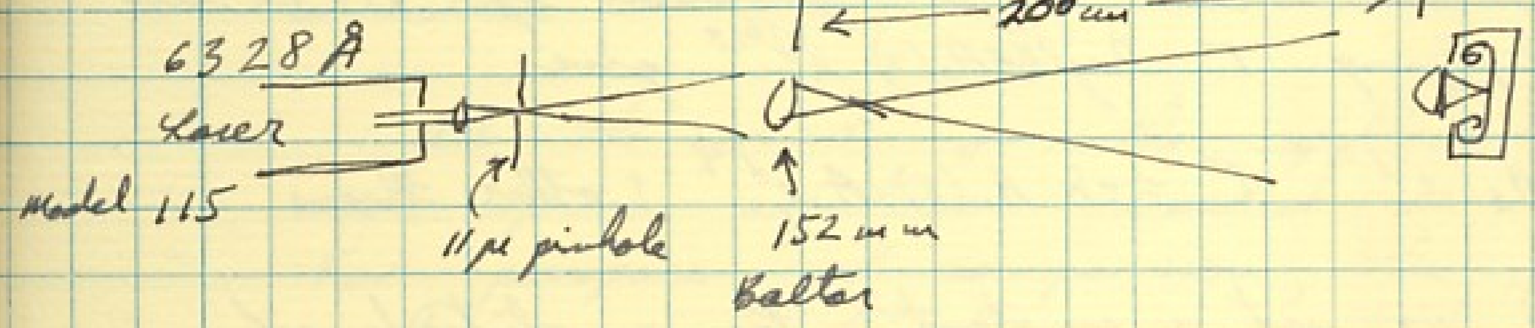
15 February 1965

Photographing of point focus of uncorrected lens.

The point focus of the uncorrected poor lens was recorded directly on film, without enlarging it first using a microscope. This was necessary to record the whole point focus with the surrounding flare, because microscope objectives have too small numerical aperture to accept all light. The optical arrangement was as follows:



Film Recordings (#010, 12 February 1965)

#2 + #3 Pan-X film, exposures $\frac{1}{1000}$ to $\frac{1}{5}$ sec.

#4 + #5 649-F emulsion, exposures 60 sec. to 4 sec.
Diameter of flare = 2.08 mm.; of center point, = 0.018 ~~μ~~ mm.
Note: camera was focus using a microscope with 8 mm objecti
and ×5 eyepiece, giving best possible focus with Exacta camera

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16 February 1965

Requirements of the reference beam in recording holograms with offset frequency.

The resulting transmission of the transparency on which a hologram has been recorded was given (in J.O.S.A. Vol. 53, p. 1378, Dec. 1963) as

$$T = T_0 - kA_0^2 - kA^2 - 2kA_0A\cos(\varepsilon_c x - \phi)$$

where A_0 is amplitude of the reference beam, A is amplitude of the signal, and k is related to the gamma of the film. Usually A_0 is considered a constant and the reconstruction is then obtained if the hologram is illuminated with $A_i e^{j\varepsilon_c x}$ which then gives a component that is same as the original signal:

$$A_i e^{-j\varepsilon_c x} T = -kA_0AA_i e^{j\phi} + \text{other terms}$$

Here kA_0A_i is simply a constant and therefore relates to the brightness of the reconstructed image, but not to its quality.

Suppose now that $A_0 = A_0(x)$, that is, the amplitude of the reference beam is a function of x. In this case multiplying T by $A_i^{-j\varepsilon_c x} = A_0(x)\, e^{-j\varepsilon_c x}$ gives

$$A_i e^{-j\varepsilon_c x} T = -kA_0^2(x) A e^{j\phi} + \text{other terms}$$

Since $A_0(x)$ is not a constant, the amplitude of the reconstructed signal departs from the desired value, say A_0 aver. by $\dfrac{A_0^2(x)}{\text{aver}[A_0^2(x)]}$

Therefore, a hologram made with reference beam whose amplitude varies, and reconstructed with

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identical illuminating beam (identical to reference beam) will have the correct phase but not amplitude. Poor quality reconstruction therefore can be expected.

To obtain good quality reconstruction, A_i must be $A_i e^{-j\varepsilon_c x} = \frac{1}{A_0(x)} e^{-j\varepsilon_c x}$, which gives

$$A_i e^{-j\varepsilon_c x} T = \frac{e^{-j\varepsilon_c x}}{A_0(x)} T = -k A e^{j\phi} + \text{other terms}$$

which is the desired signal. Thus, correct output can be obtained is the hologram is illuminated with a beam of the form $\frac{1}{A_0(x)} e^{-j\varepsilon_c x}$. Since the amplitude of $A_0(x)$ may be zero, $\frac{1}{A_0(x)}$ may not be realizable in practice. Also, it appears to be rather difficult to produce in practice a signal of this form, namely $\frac{1}{A_0(x)} e^{-j\varepsilon_c x}$, and the resulting signal to noise ratio will be higher than usual, with constant A_0.

Juris Upatnieks (16 February 1965)

23 February 1965

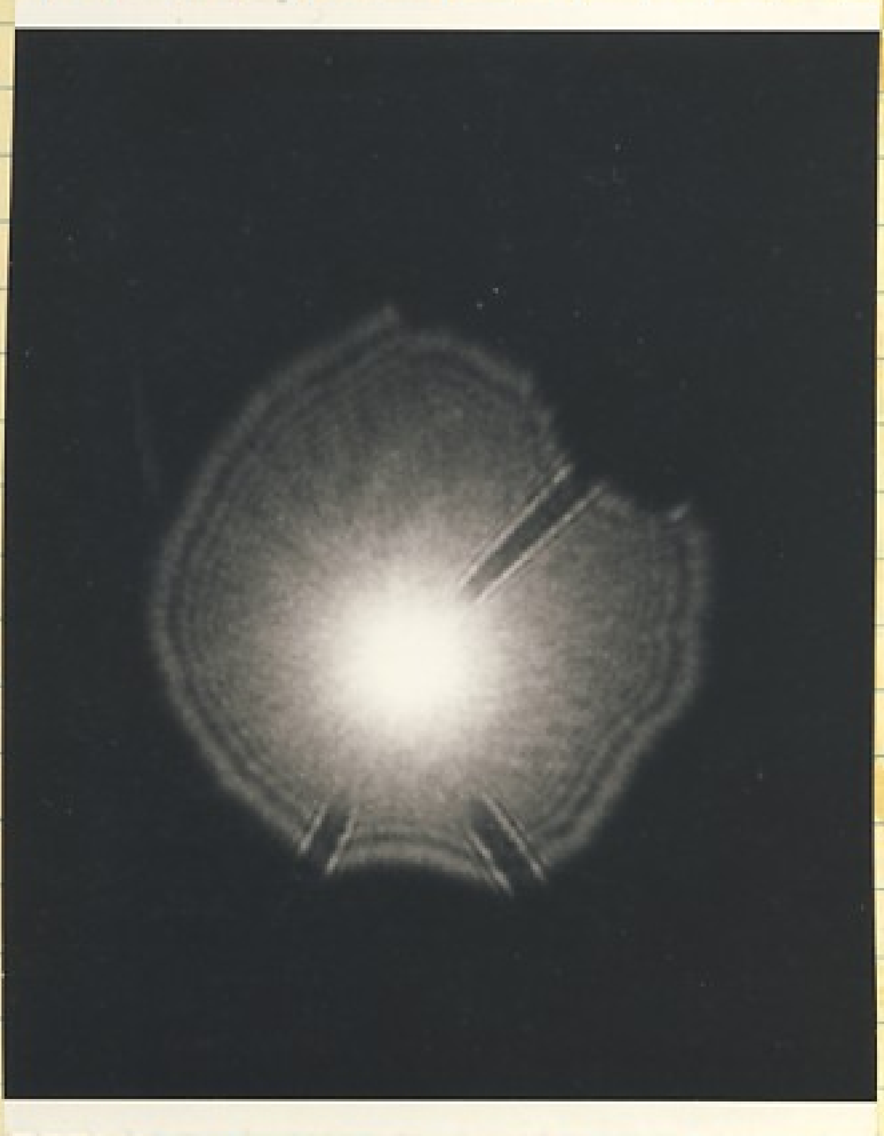
Photographs of test results with lens correction

All the prints on the following pages were made from negatives recorded in this record. For purpose of comparison, the top picture on each page is from the uncorrected lens, the bottom from the corrected lens. Each pair of pictures were made under identical conditions, that is, same distance of object from lens, same magnification and same microscope lens. Photographs of transparencies were demagnified 25 times; object to lens distance ~ 185 cm; focal length of lens, ~ 7 cm.

Juris Upatnieks (23 February 1965)

23 February 1965

Point image, uncorrected, 1X



Point focus of uncorrected len
(Print of #010 ; row #3)

The diameter of the point focus at left is 2.10 mm. The dark lines pointing toward center are shaddows from three wire markers obstructing edges of the lens. These were used for alignment purposes. The central bright ~~point~~ area contains a point of about 18 μ diameter (This was measured from direct recording of point on 649-F emulsion, which may be larger than at optimum focus).

Point image, corrected, 33X

Point image of corrected lens, magnified 33 times as compared to the upper image.
(Sheet # 006 - 4)

The distance between first minimum was 4.3 μ measured vertically and ≈ 6.1 μ measured horizontally. This would mean that expected resolution could be expected of about 2.15μ to 3.05μ. This does not represent perfect point focus, since the original point also was not diffraction limited.

Juris Upatnieks (23 February 1965)

23 February 1965

Uncorrected lens.

Imaged transparency with uncorrected lens (Print of #009 - 3)

Size of imaged transparency was 2.12 x 4.0 mm, then photographed through 22.7 mm microscope objective. Streaks in this, as well as in other prints, is from rotating diffuser disc.

Corrected lens

Imaged transparency with corrected lens. (Print #008 - 1)

This photograph was made under identical conditions to those for the above picture.

Juris Upatnieks (23 February 1965)

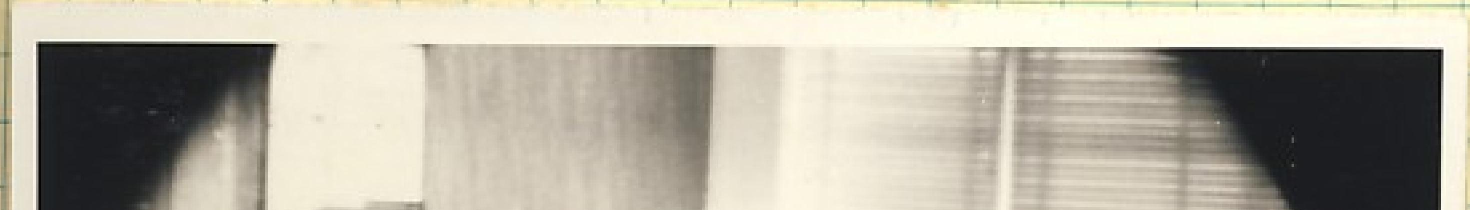
23 February 1965

Uncorrected lens

Imaged transparency through uncorrected lens (Print of #009-4)

This photograph is much worse than the one on previous page because 8mm microscope objective was used. The 8mm objective has num. aper. of 0.50, as compared to 0.17 for the 22.7mm objective. This lens accepts more light from the poor imaging part of the lens.

Corrected lens



Imaged transparency through corrected lens. (Print of #008-3)

Similar to one above, but photographed with a 16mm objective, num. aperture = 0.30. The numerical aperture does not matter here because the lens is corrected. This image seems ~~to~~ not to be in best focus, or perhaps horizontally displaced.

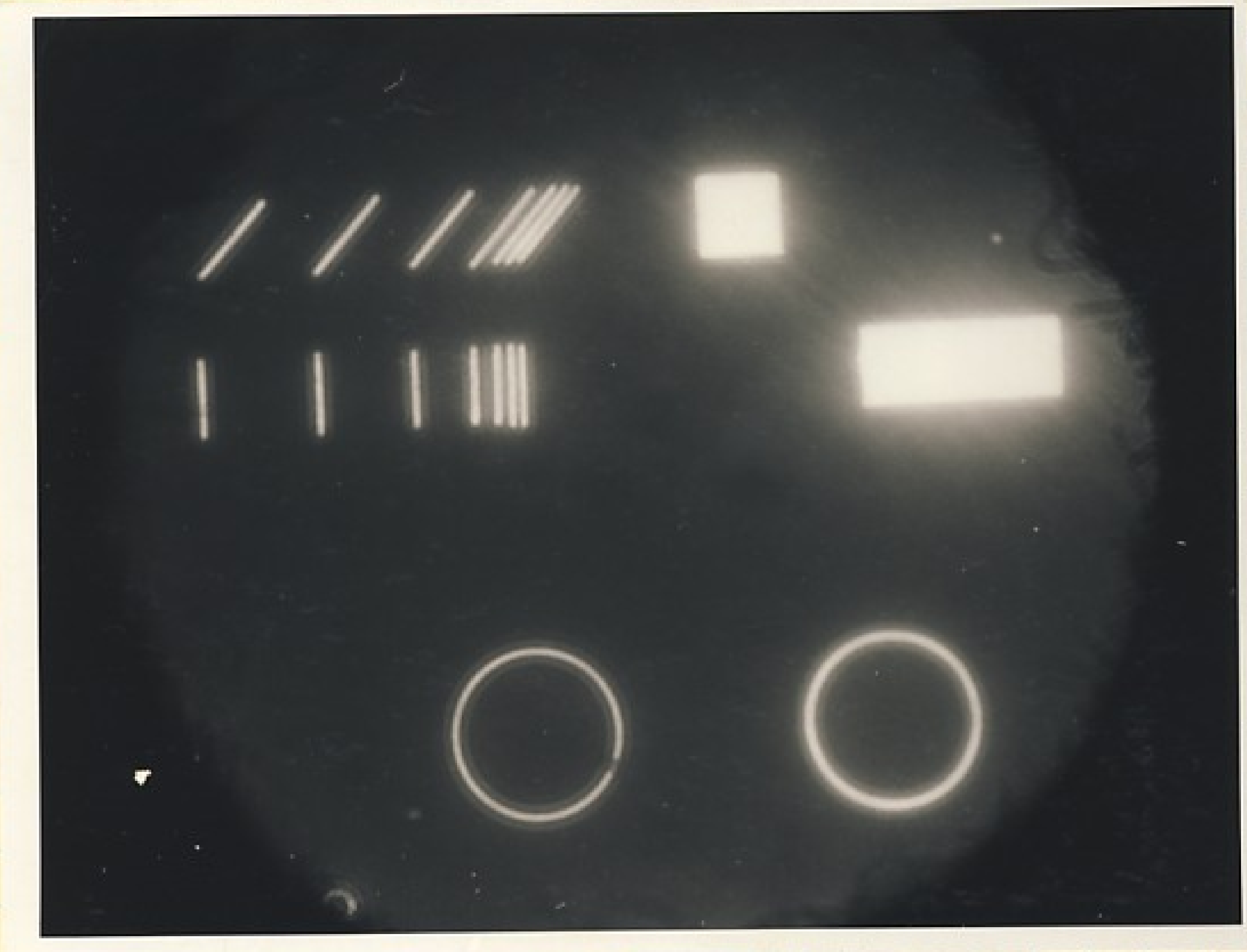
Juris Upatnieks (23 February 1965)

23 February 1965

Imaged test pattern through uncorrected lens (#009 - 3)

The seperation between the last two slanted lines was 61 μ on the original, or about 2.5 μ on the projected image. This appears to be beyond the resolving power of the uncorrected lens.

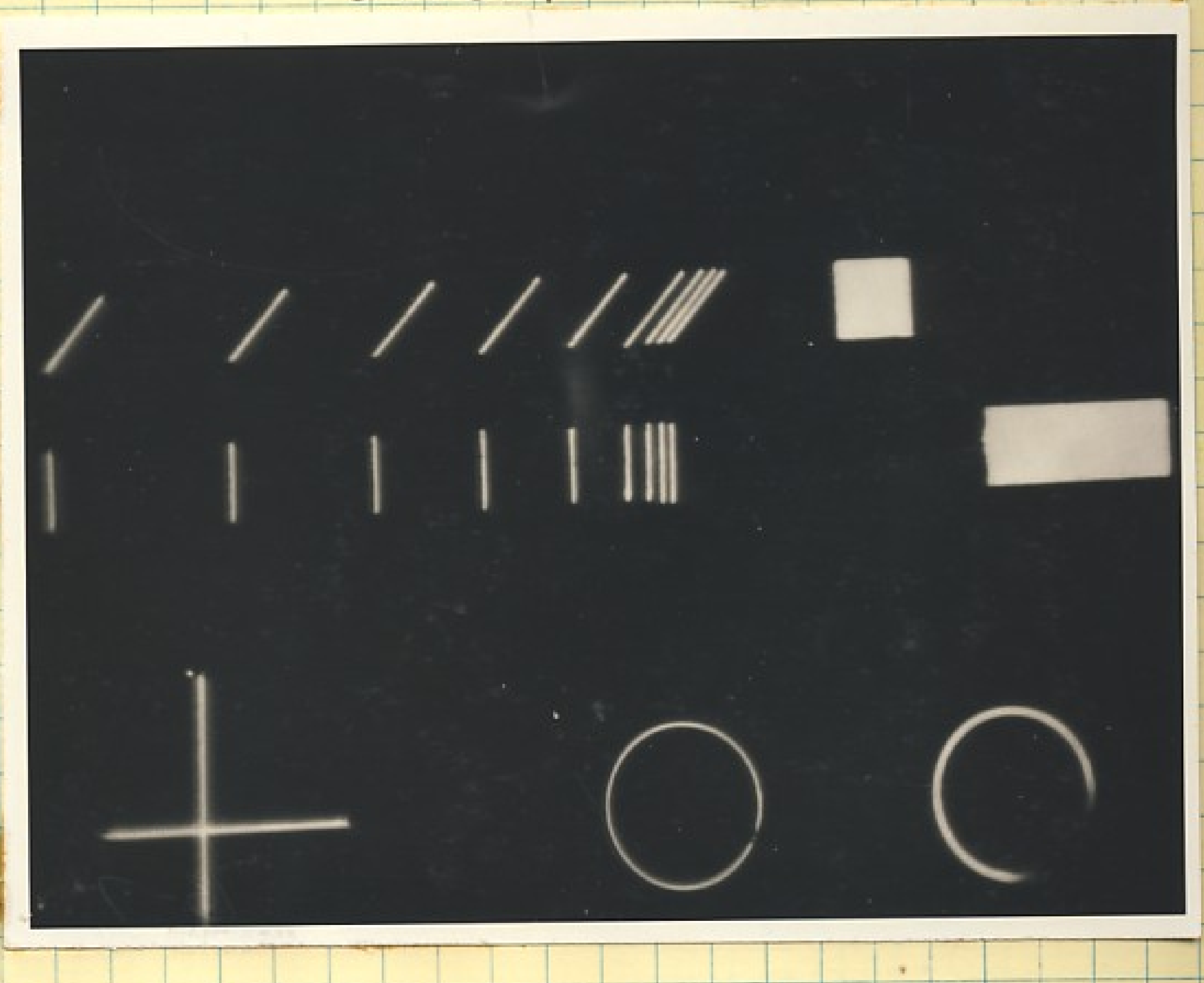
Uncorrected lens



Imaged test pattern through corrected lens (#008 - 5)

Photographed under identical conditions: using 8 mm microscope objective, diffuse, incoherent light. Laser light was made incoherent by rotating etched glass disc.

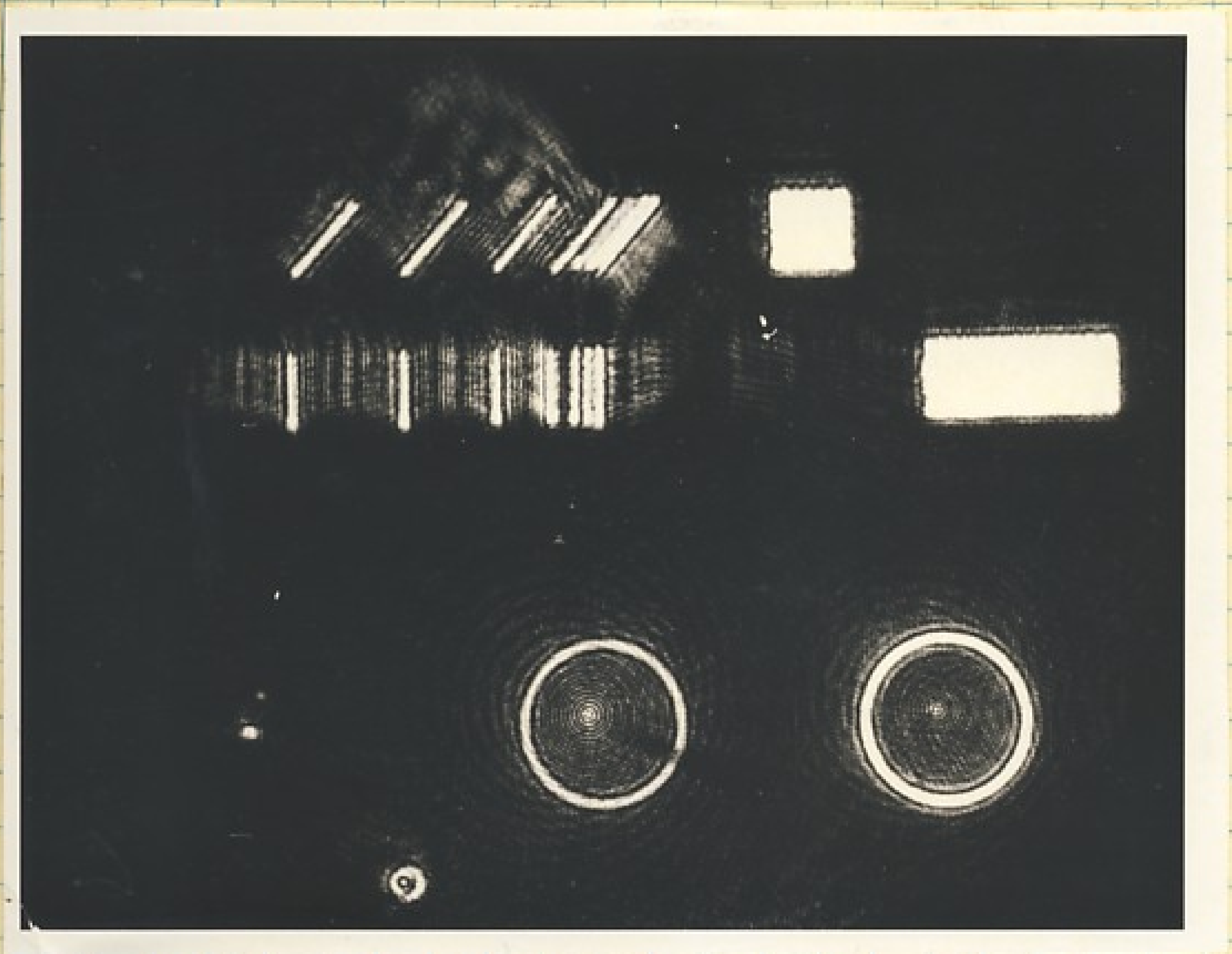
Corrected lens



Juris Upatnieks (23 February 1965)

23 February 1965

Uncorrected lens



Imaged test pattern
through uncorrected
lens
(Print of #009-6)

This print is same
as on the page befo
except coherent light
is used. Coherence
produces interferenc
fringes which
were "smeared" out
in the incoherent
case.

Corrected lens

Imaged test pattern
through corrected lens
(Print of #007-4)

In this print
interference fringes
are not visible
since there is
very little scattered
light. Abberations
become most annoying
in coherent light.

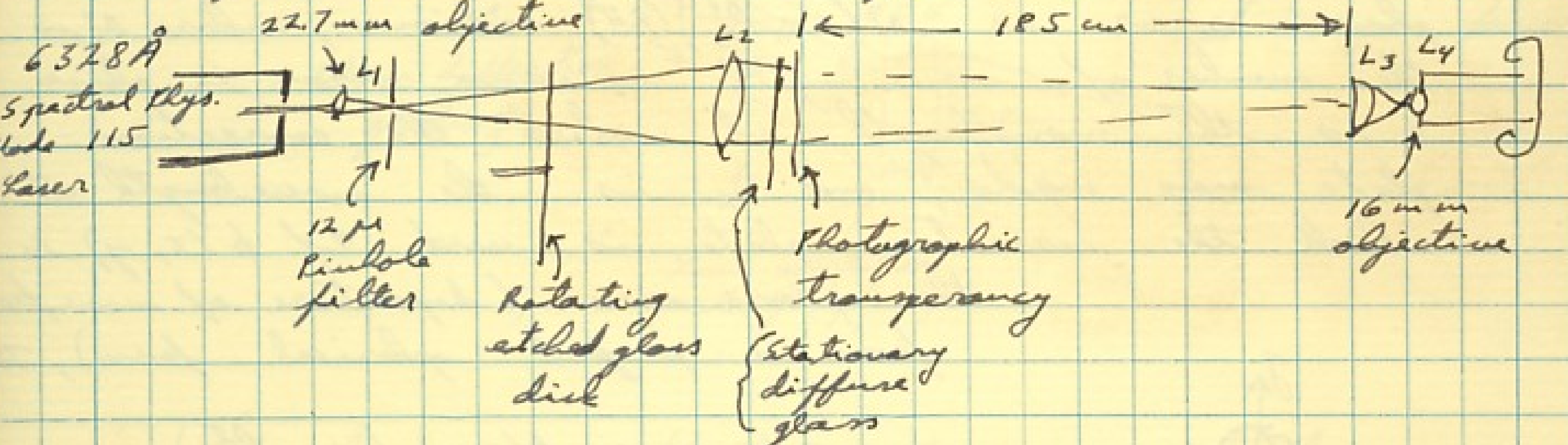
Juris Upatnieks (23 February 1965)

1 March 1965

Photographs with corrected and uncorrected lens.

Three sets of photographs were made under identical conditions except for the lenses used. One was made with uncorrected lens, one with corrected lens, and one with high-quality, selected, Baltar 100-mm lens. The purpose of this test is to show comparison, as the uncorrected lens gives very poor imaging.

Pan-X film was used, developed for normal gamma. The optical system is shown below:



Film recordings show (#010, 26 Feb. 1965):

#6 Uncorrected lens, stationary diffuse glass in.
Exposures: 3, 10, 30, 90 sec.

(#011, 26 February 1965):

#1 Corrected lens, grating in Xylene liquid, stationary diffuse glass removed to give more light. Exposures: 3, 10, 30, 90, 180 sec.

#2 High-quality, selected 100 mm Baltar lens, same as used for making correction plate.
Exposures: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.
Stationary diffuser in.

Juris Upatnieks (1 March 1965).

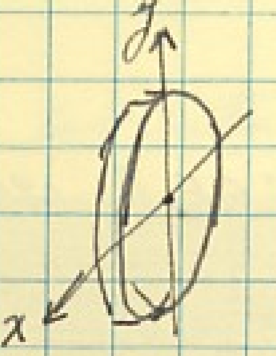
8 March 1965

Correction for color in ~~plas~~ lens corrections gratings (lens correction plates).

The phase correction plates made in the tests described on previous pages give good results for the wavelength of light for which they were made. At another wavelength, the correction will be somewhat worse, but better than without the correction plate. If one assumes that the error in phase for the lens remains constant for all wavelengths considered, then the residual phase error is $N(1-\frac{\lambda_2}{\lambda_1})(2\pi)$ radians, where N is the number of wavelength maximum error in phase, λ_1 is the wavelength at which the correction plate was made, and λ_2 is the wavelength at which the correction plate is used. If $\phi(x,y)$ is the phase error (departure of wavefront from a perfect spherical form), then

$$\epsilon(x,y) = \phi(x,y)\left(1-\frac{\lambda_2}{\lambda_1}\right)$$

for each poin (x,y) on the lens.



Coordinates of a lens.

The phase of the correction grating usually consists a carrier term, say (ωx), and the phase term, $\phi(x,y)$

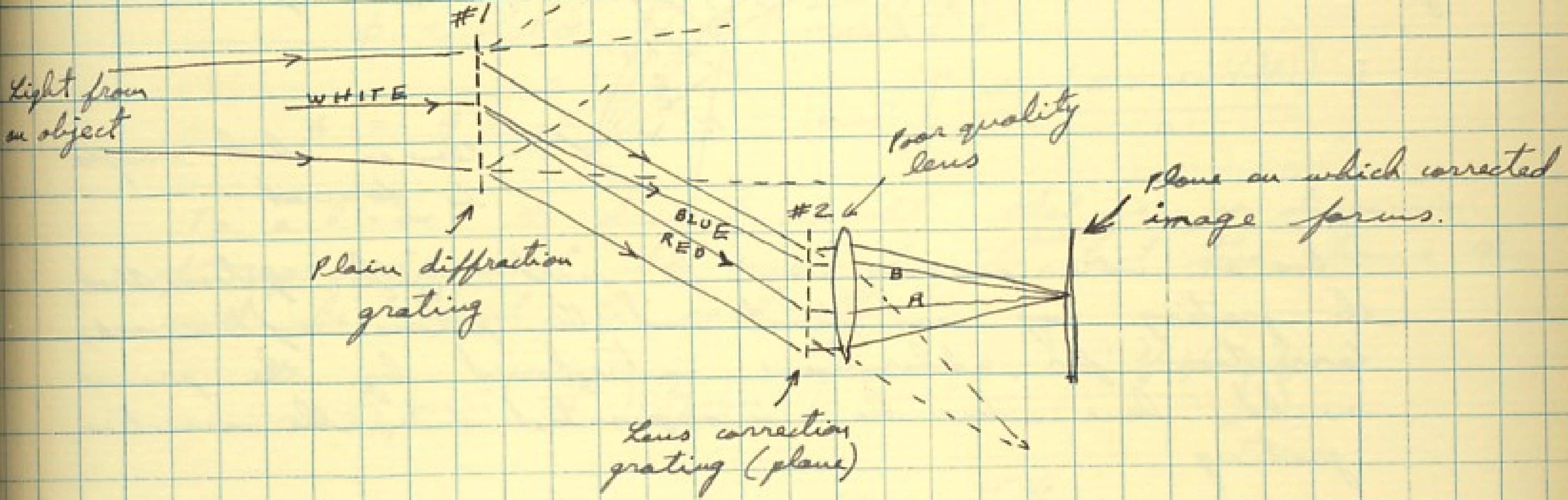
If monochromatic light is not used, then the carrier term, ωx, will spread out the focus point; that is, each λ_2 will come to a focus at a different position. Thus a line, instead of a point, will result for each point on the image. If a system can be designed which would remove the ωx term, or compensate for it, then only the relatively small abberation $\epsilon(x,y)$ would remain. In that case, a broader bandwith of time-varying frequencies could be used

Juris Upatnieks (March 8, 1965)

8 March 1965

Two methods can be used for compensating for the wx term, as proposed by Emmett N. Leith. One uses a second grating, the other a prism.

If two gratings are used, the optical system shown below would be used:



In the figure, both gratings are of the same spacial frequency, that is, same carrier frequency. The first one is not modulated, the second one is modulate by the phase error function. A white ray of light is seperated into its colors at the first grating, the blue being diffracted less than the red one, other wavelengths in between. At the correction grating, all colors are diffracted in the apposite direction and emerge parallel to each other. Thus there rays will be focused to a single point. In other words, the wx terms are canceld by the gratings. This system would give the best correction, but the two gratings would attenuate light considerably.

The other method employs a grating and one or prisms in series. Since the prism refracts more the short wavength than the longer one, and the grating diffracts the long wave-lengths more than short ones, they can be used to partially compensate for each other.

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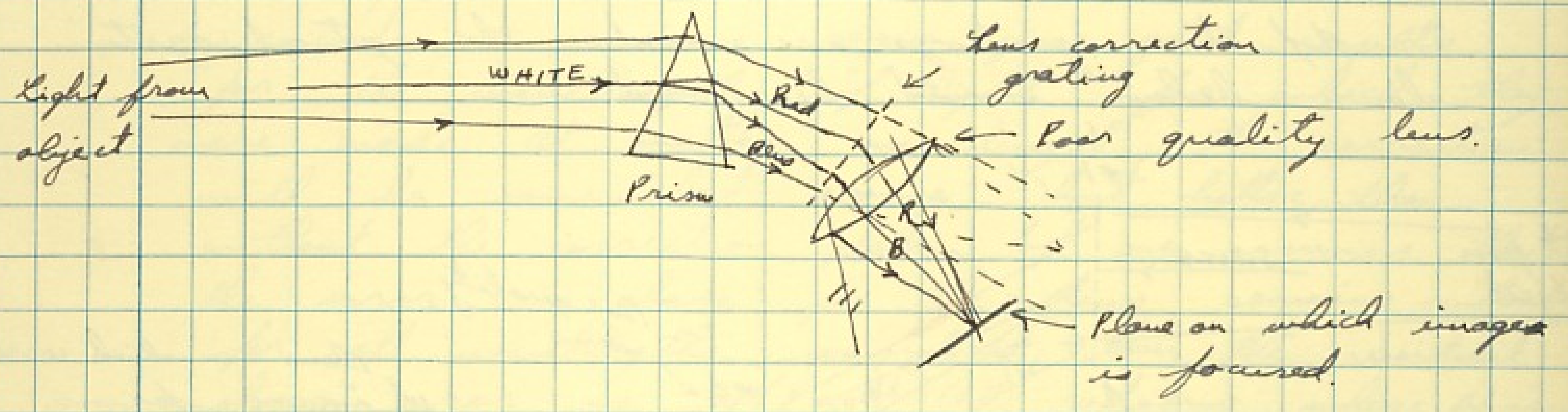
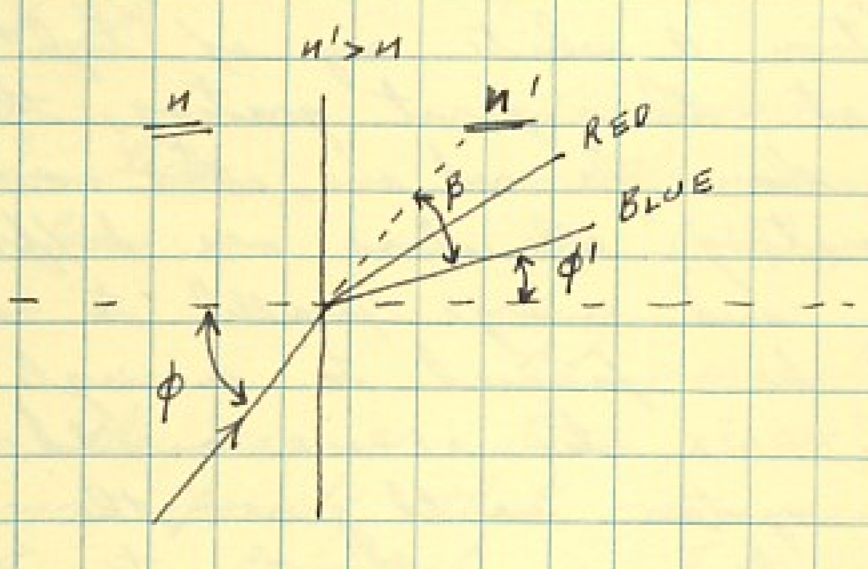
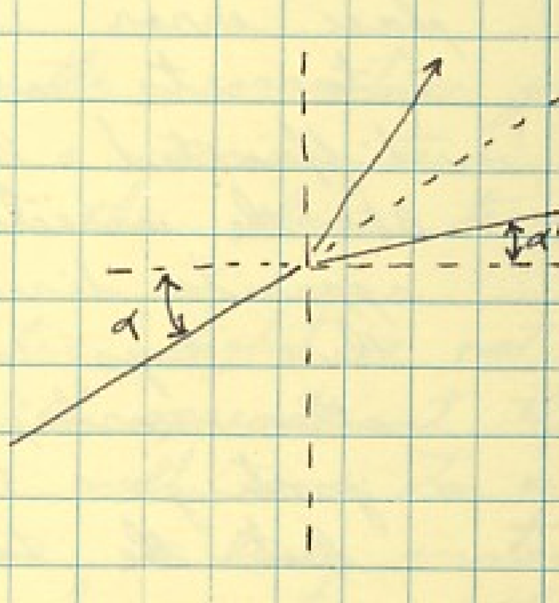
The arrangement of optical elements would be as follows:



One or more prisms may be used in the system. Also, the grating may come first and the prism afterwards. Correction for abberations introduced by the prism would have to be incorporated into the correction grating.

For the purpose of calculating the degree of correction, consider refraction at one boundry only. The calculations can be repeated for each air-glass boundry in th system.





$\sin\phi' = \frac{n}{n'}\sin\phi$

If $n = 1$,

$\phi' = \sin^{-1}\left(\frac{\sin\phi}{n'}\right)$

where n' is a function of wavelength: $n' = n'(\lambda_e)$

$\sin\alpha + \sin\alpha' = \frac{\lambda}{d}$

where d is the period of spacial frequency

If $\alpha = 0$, then $\sin\alpha' = \frac{\lambda}{d}$

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From geometry of the problem,

$$\beta = \phi - \phi' , \quad \phi' = \sin^{-1}\left(\frac{\sin\phi}{n'}\right) , \text{ and } \phi = \alpha' + \theta$$

where θ is an arbitrary angle and depends on the orientation of the elements of the optical system.

$$\phi = \alpha' + \theta = \theta + \sin^{-1}\left(\frac{\lambda_e}{d}\right)$$

$$\beta = \theta + \sin^{-1}\left(\frac{\lambda_e}{d}\right) - \sin^{-1}\left[\frac{\sin\left(\theta + \sin^{-1}\left(\frac{\lambda_e}{d}\right)\right)}{n'}\right]$$

To achieve the desired result, that is, no dispersion of rays, $\frac{\partial\beta}{\partial\lambda_e}$ must be constant. The deriv. of last two terms then must be equal to each other:

$$\frac{\partial}{\partial\lambda_e}\left[\sin^{-1}\frac{\lambda_e}{d}\right] = \frac{\partial}{\partial\lambda_e}\left\{\sin^{-1}\left[\frac{\sin\left(\theta + \sin^{-1}\frac{\lambda_e}{d}\right)}{n'}\right]\right\}$$

~~or $\frac{\lambda_e}{d} = \frac{\sin\left(\theta + \sin^{-1}\frac{\lambda_e}{d}\right)}{n'}$~~

~~$\frac{\lambda_e}{d} n' = \frac{1}{d}\sqrt{d^2 - \lambda_e^2}\sin\theta + \frac{\lambda_e}{d}\cos\theta$~~ ~~since $\sin^{-1}\frac{\lambda_e}{d} = \cos^{-1}\left(\frac{\sqrt{d - \lambda_e^2}}{d}\right)$~~

~~n' can be approximated by $n' = A + \frac{B}{\lambda_e^2} + \frac{C}{\lambda^4} + \dots$~~

~~where the constants can be determined from the known characteristics of the glass used.~~

~~$\frac{1}{d}\sqrt{d^2 - \lambda_e^2} = 1 - \frac{1}{2}\left(\frac{\lambda}{d}\right)^2 - \frac{1}{8}\left(\frac{\lambda}{d}\right)^4 - \dots\dots$~~

~~$\therefore \boxed{\lambda_e(A - \cos\theta) + \frac{B}{\lambda_e} + \frac{C}{\lambda_e^3} = (d\sin\theta)\left[1 - \frac{1}{2d^2}\lambda_e^2 - \frac{1}{8d^4}\lambda_e^4 - \dots\right]}$~~

~~This eq. must be satisfied for dispersion to be zero. This can be accomplished for two points only, that is, two wavelengths of light. If we neglect the higher order terms, the above eq. is:~~

~~$\lambda_e(A - \cos\theta) + \frac{B}{\lambda_e} = (d\sin\theta)\left[1 - \frac{1}{2d^2}\lambda_e^2\right]$~~

Juris Upatnieks (9 March 1965)

16 March 1965

Reconstruction of Images from Holograms using Incoherant Light.

One way to describe a hologram is to say that it contains a summation of Fresnel zone plates, one generated for each point on the object with amplitude corresponding to the brightness of the point. When this hologram is then illuminated with a monochromatic point light source, the Fresnel zone plates focus the source of light at some point in space. If the object was a transparency, the reconstruction will be in a single plane; if the object was 3-dimensional, the reconstruction will also be 3-dimensional. The important factor is though, that the source is imaged on the output plane (for a 2-dim. object). If we place a light-sensitive detector at the focal plane, the image will be recorded or detected by it. For a perfect hologram, the imaging can be described by

$$g(x, y) = \iint_{\text{Aperture}} f(x-\tau, y-\sigma)\, h(x, y)\, dx\, dy$$

where f is the "perfect image", h is the source and is $\delta(x, y)$ if the ligh source can be approximated by an ideal point. In the later case

$$g(x, y) = f(x, y)$$

or, the output is exactly the input. One can also consider f as the focusing element which images the source on the output plane

$$g(x, y) = \iint f(x_1-\tau, y_1-\sigma)\, h(x, y)\, dx\, dy$$

$$= A\, h(x, y)\ \cancel{dt}$$

for a particular point x_1, y_1 of the hologram (for one zone plate).

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If the source is coded with a function of the type

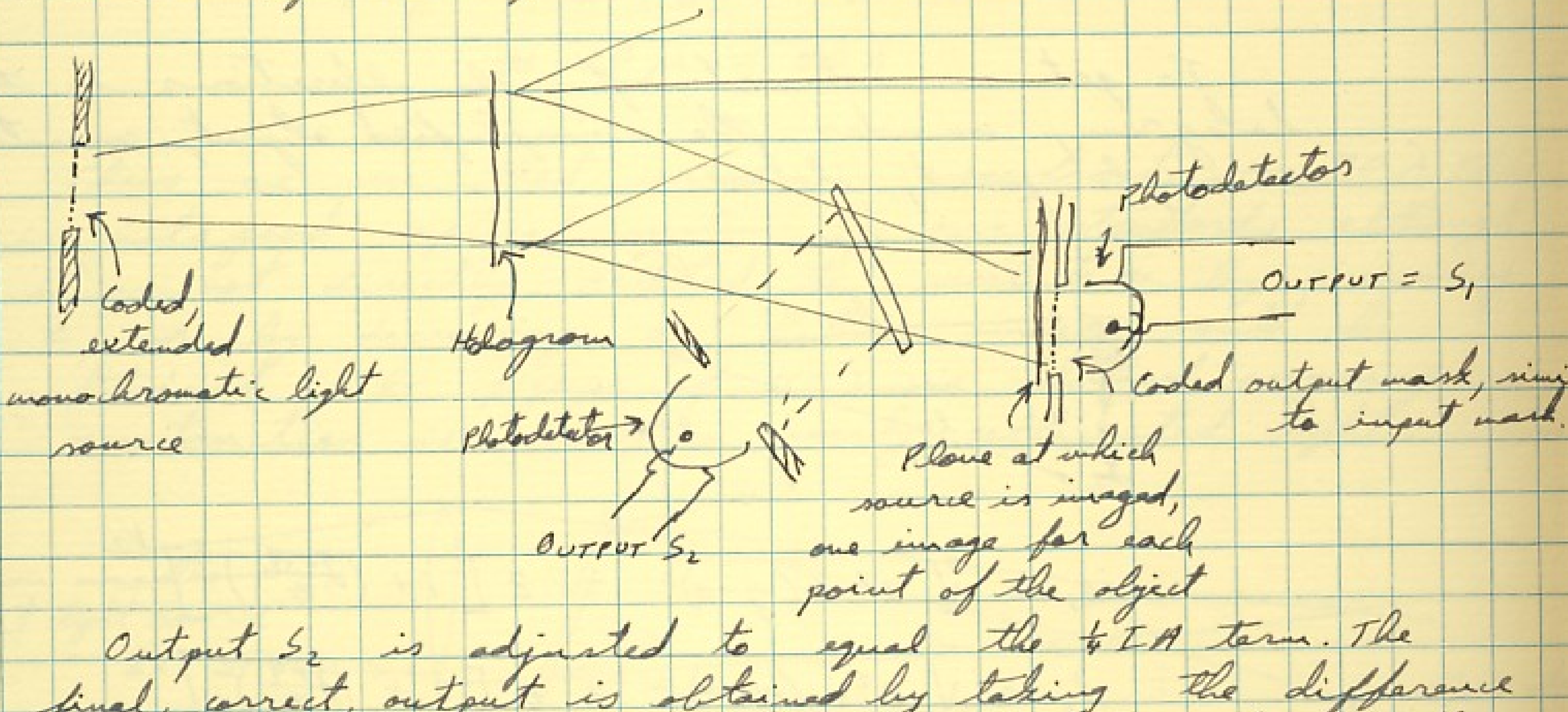
$$h(x,y) = 1 + \frac{\cos k(x^2+y^2)}{|\cos k(x^2+y^2)|}$$

and it is correlated with an identical function at the output, then the output is of the form

$$\int_{\substack{\text{area of}\\ \text{aperture}}} g(x,y) = \tfrac{1}{2} I A \quad \text{for exact coincidence of two patterns}$$

$$\approx \tfrac{1}{4} I A \quad \text{for misalignment}$$

where I is the total energy of the source, and A is the relative brightness of the imaged source. The residual intensity term can be removed by using another photodetector which picks up this average or D.C. term, and subtracting them electronically. The optical system can be of the form shown below.



Output S_2 is adjusted to equal the $\frac{1}{4} I A$ term. The final, correct, output is obtained by taking the difference of the two signals $S_1 - S_2$. Thus each position of the detectors gives the intensity of the corresponding point of the reconstructed image. To obtain complete reconstruction, the whole output plane must be scanned, as is done in TV for example.

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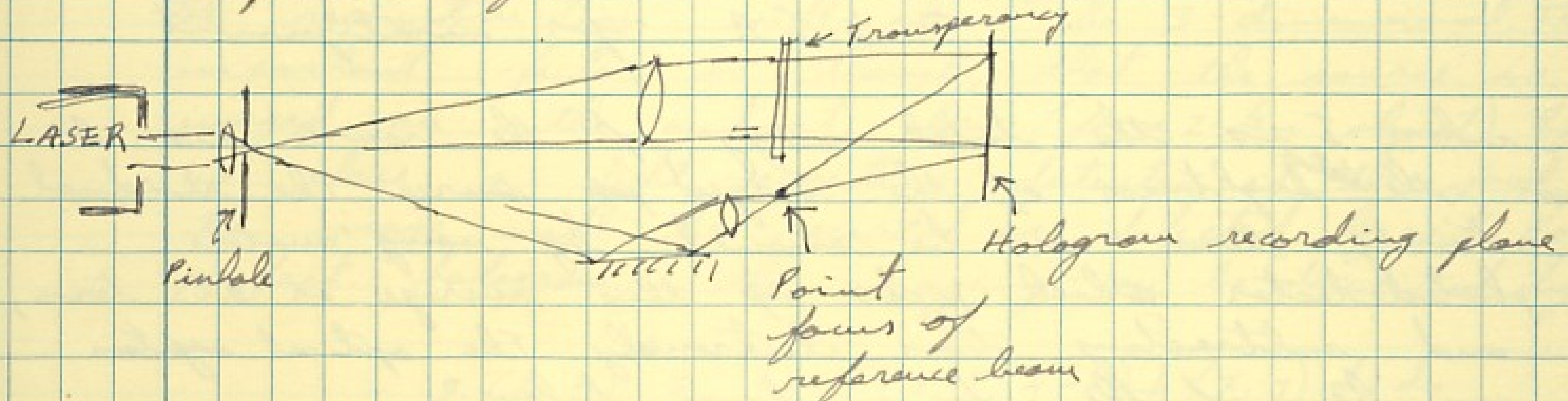
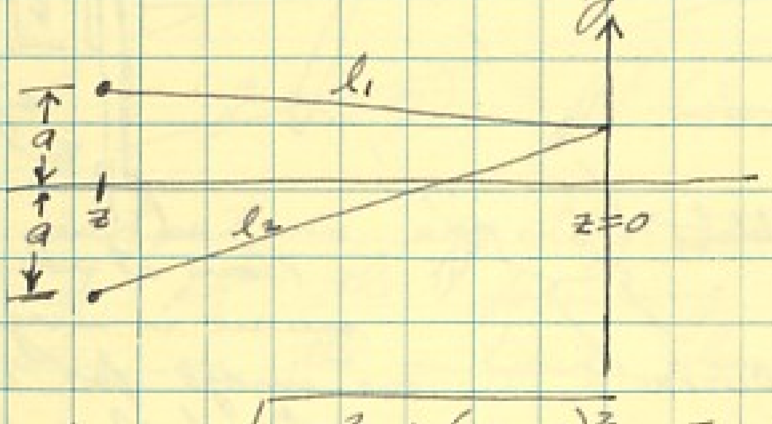
Expected quality of image using "constant frequency" holograms.

A "constant frequency hologram can be made by placing the reference beam point source in the same plane as the transparency. For each point on the transparency, the interference pattern is a constant frequency grating of the form $(\omega_x x + \omega_y y)$, where ω_x and ω_y are the frequency components in each direction. The quantity in ( ) is the phase term. The hologram can be made using the optical system shown below:



To get an estimate of the abberations in this hologram, consider the simplified object, consisting of a single point, below:



$$l_1 = \sqrt{z^2 + (y-a)^2} = z\left[1 + \left(\frac{y-a}{z}\right)^2\right]^{1/2}$$

$$l_2 = \sqrt{z^2 + (y+a)^2} = z\left[1 + \left(\frac{y+a}{z}\right)^2\right]^{1/2}$$

$$\text{Phase} = \phi(y) = \frac{2\pi}{\lambda}\left|l_1 - l_2\right|$$

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$$l_1 = z\left[1 + \frac{1}{2}\left(\frac{y-a}{z}\right)^2 - \frac{1}{8}\left(\frac{y-a}{z}\right)^4 + \cdots\right]$$

$$= z\left[1 + \frac{y^2-2ay+a^2}{2z^2} - \frac{y^4-4y^3a+6y^2a^2-4ya^3+a^4}{8z^4} + \cdots\right]$$

$$l_2 = z\left[1 + \frac{y^2+2ay+a^2}{2z^2} - \frac{y^4+4y^3a+6y^2a^2+4a^3y+a^4}{8z^4} + \cdots\right]$$

$$l_2 - l_1 = \left(\frac{2a}{z} - \frac{a^3}{z^3}\right)y - \left(\frac{a}{z^3}\right)y^3$$

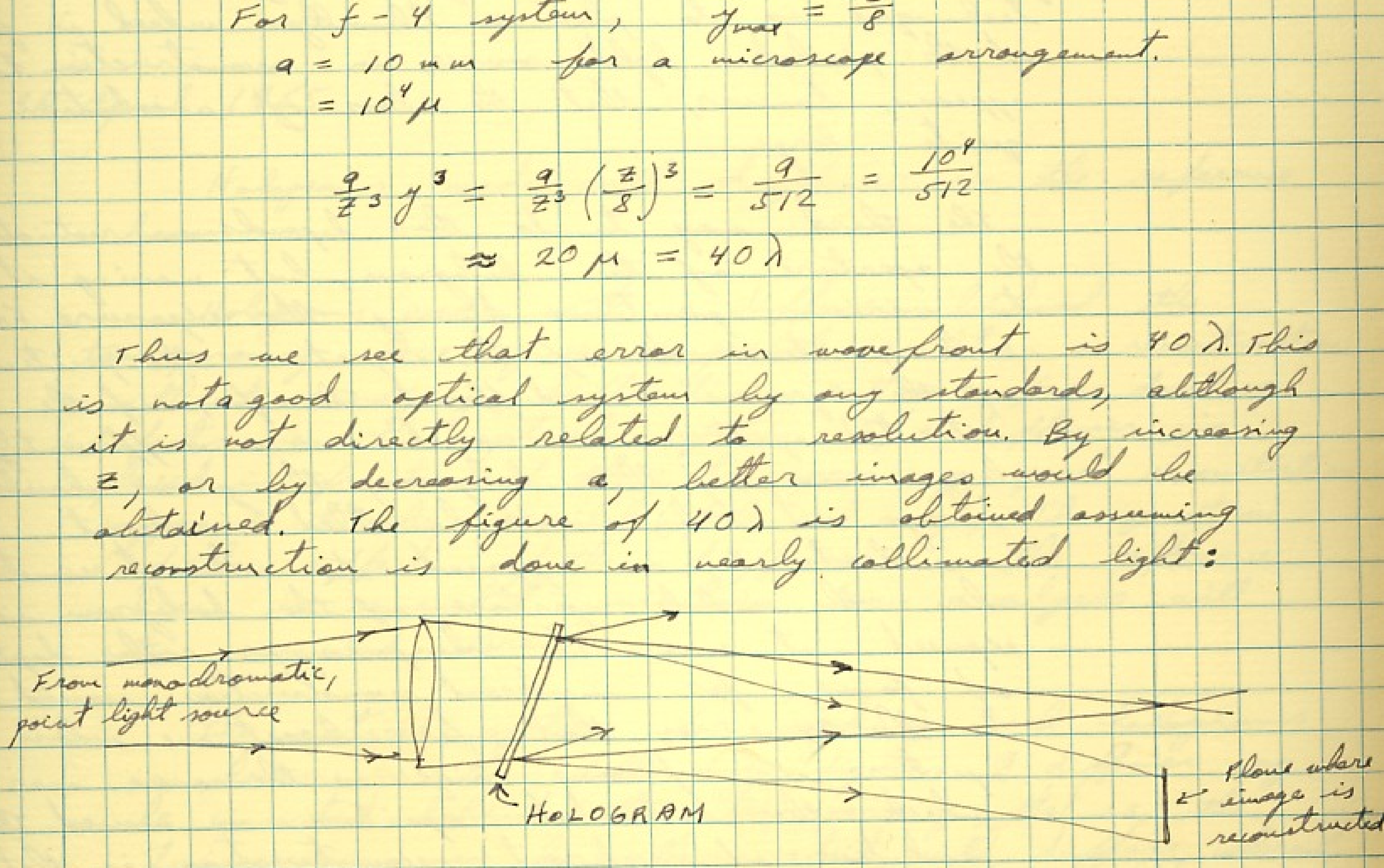
From this we see that the coefficient of y is the f_y term, and that coefficient of y^3 is a distortion term. If $\frac{a}{z^3} = 0$, then no distortion would be present and the grating would have evenly spaced lines. To determine the amount of error, let us choose some typical values:

For f-4 system, $y_{max} = \frac{z}{8}$
$a = 10$ mm for a microscope arrangement.
$= 10^4 \mu$

$$\frac{a}{z^3}y^3 = \frac{a}{z^3}\left(\frac{z}{8}\right)^3 = \frac{a}{512} = \frac{10^4}{512}$$

$$\approx 20\mu = 40\lambda$$

Thus we see that error in wavefront is 40λ. This is not a good optical system by any standards, although it is not directly related to resolution. By increasing z, or by decreasing a, better images would be obtained. The figure of 40λ is obtained assuming reconstruction is done in nearly collimated light:



Juris Upatnieks (29 March 1965)

15 April 1965

Techniques of reducing grainy appearance in hologram reconstructions.

In the usual case of reconstructing holograms with limited aperture, the reconstructions always give grainy appearance. The size of these grains can be decreased appreciably if very large apertures are used. It appears, however, that the grain size can be completly eliminated at the expense of losing resolution.

The most direct method is to move the recording film around for a distance somewhat greater than the average grain size. Another technique is to place a Llewellyn wheel in front of the pinhole light source in reconstruction. It appears, however, that the loss of resolution is quite large.

The third way to do this depends on restricting the aperture of the hologram, but moving it to various positions during the exposure. From each position ~~th~~ of the aperture the position of the "grains" is different. Therefor, if the restricted aperture is moved over a sufficiently large area of the hologram, the grain should average out. This could be called "incoherent reconstruction", as opposed to coherent reconstruction when the whole aperture of the hologram is exposed at once. The sharpness, or rather depth of focus, for incoherent reconstruction would be the same as that for coherent one whose aperture is of same size as the area over which the restricted aperture is moved. The resolution of incoherent reconstruction is that limited by the size of the restricted aperture.

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Thus, resolution again is traded for decreasing graininess of the image.

Another point of view is that the incoherent reconstruction can be compared to incoherent, or sequential, hologram making. It is known that successive holograms superimposed on the same photographic plate decrease the amount of diffracted light into the images due to d.c. bias buildup. Some kind of d.c. bias buildup takes place in incoherent image reconstruction, except in this case the property is a desirable one.

Juris Upatnieks (30 April 1965)

30 April 1965

Holograms made with diffuser in the reference beam.

Holograms made with a diffuser behind the transparency have given improved results, a reconstruction without annoying diffraction patterns from dust or defects in the optical system. If a diffuser is placed <u>in front</u> of the transparency, good reconstruction appears to be possible (of the real image). The question of the effect of the diffuser in the reference beam is somewhat uncertain. Some analysis will be presented here.

The optical system for making such holograms is shown in the following figure. A diffuser may be inserted behind the transparency, that is, the transparency may be illuminated with diffuse, coherent, monochromatic light. For the sake of simplicity, it will be assumed that the object transparency is

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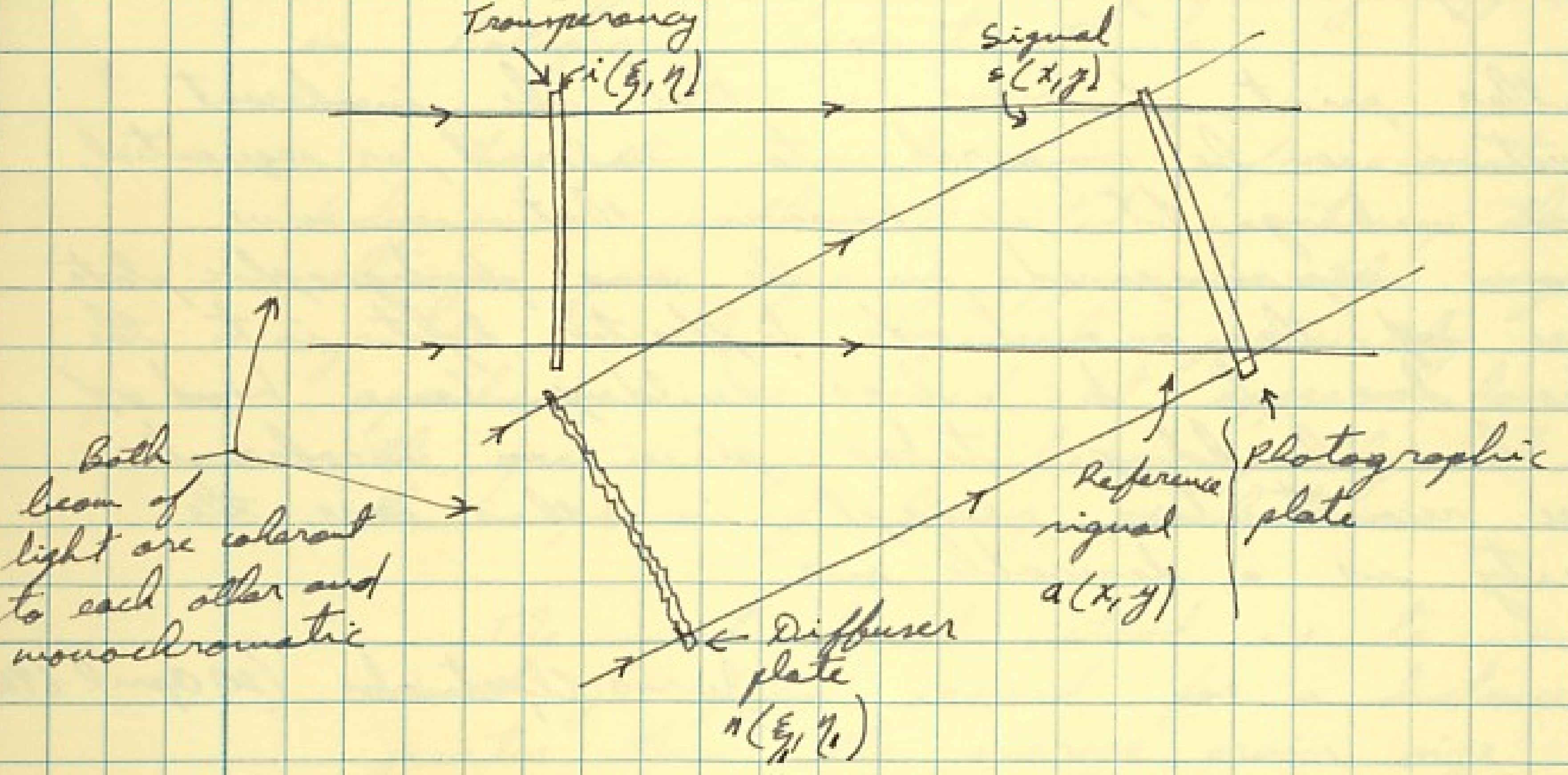
illuminated with a plane wave front. The transparency



is described by the function $i(\xi,\eta)$, the diffuser gives a noise-like signal $n(\xi_1,\eta_1)$ which has constant amplitude but varying phase, $s(x,y)$ is the signal at the surface of the photographic plate, and $a(x,y)$ is the reference ~~sign~~ beam at the photographic plate. Also, note that

$$s(x,y) = s(x,y)\, e^{j[\phi(x,y) - \alpha x]} = s$$

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

The photographic film responds to intensity only, and therefore to

$$|s+a|^2 = s^2 + a^2 + 2as\cos[\phi(x,y) - \theta(x,y) - \alpha x]$$

If, after development, the photographic plate is replaced in the above figure in identical place, and the signal beam is removed, then the amplitude immediatly to the right of the hologram is approximatly

$$a[1 - k|s+a|^2] = a - k[s^2 a + a^3 - 2a^2 s e^{j\theta} \cos(\phi - \theta - \alpha x$$

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Here k is the slope of the amplitude of transmission vs. ~~signal~~ $|s+a|^2$ curve. Since k is a constant, it will be neglected future discussion. The last term can be ~~expanded~~ rewritten ~~to~~ as

$$2a^2 e^{j\theta} s \cos(\phi-\theta-\alpha x) = a^2 s\, e^{j\theta}\left[e^{j(\phi-\theta-\alpha x)} + e^{-j[\phi-\theta-\alpha x]}\right]$$

$$= a^2 s\, e^{j[\phi(x,y)-\alpha x]} + a^2 s\, e^{-j[\phi(x,y)-2\theta(x,y)-\alpha x]}$$

The second term above contains $e^{j2\theta}$ term, which means it has incorrect phase and therefore can be expected to give unrecognizable reconstruction. The second term is the real, or conjugate, image.

The first term is

$$a^2(x,y)\, s(x,y)\, e^{j[\phi(x,y)-\alpha x]}$$

In this equation $s(x,y)\, e^{j[\phi(x,y)-\alpha x]}$ is the original signal, the virtual image term, which we want to recover. The $a^2(x,y)$ is a real, nonnegative function which can be expressed as

$$a^2(x,y) = a_0 + a_1(x,y)$$

where a_0 is the average ~~or~~ bias term, $a_1(x,y)$ is the modulating term and $|a_1(x,y)| \le a_0$. Thus,

$$a^2(x,y)\, s(x,y)\, e^{j[\phi(x,y)-\alpha x]} = s(x,y)\, a_0\, e^{j[\phi(x,y)-\alpha x]} + a_1(x,y)\, s(x,y)\, e^{j[\phi(x,y)-\alpha x}$$

Thus we see that $a_0 s$ is a term which will give exact reconstruction of the original image. The other term, $a_1 s$, will scatter light and appear as noise at the output.

To find the angle over which $a_1 s$ will scatter light, consider the geometry in the next figure. Light from two points, P_1 and P_2, interfere at the surface of the photographic plate at point P_3. The spacial frequency f due to this interference is

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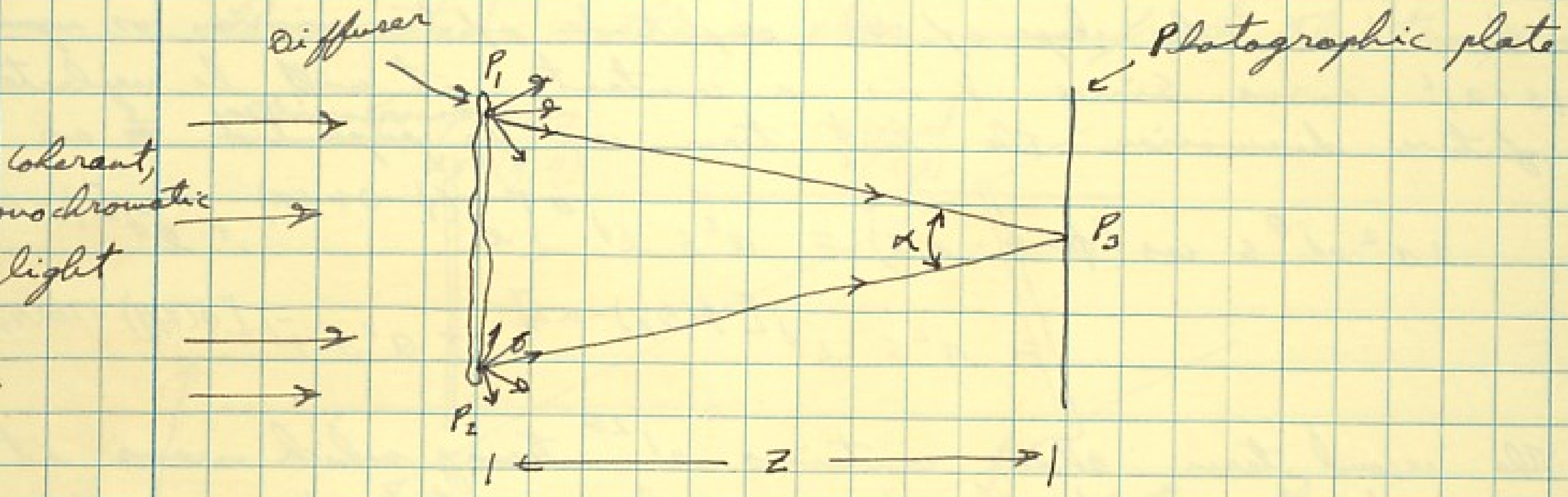


given by the equation $f = \frac{\sin\alpha}{\lambda}$. Thus we see that $a_1(x,y)$ will contain spacial frequencies ~~terms~~ between $f = 0$ and $f_{max} = \frac{\sin\alpha_{max}}{\lambda}$. In reconstruct therefore, each point on the hologram will scatter light over ~~an~~ angle 2α, including both 1st orders. Note that the optical system shown above can be used to obtain a simulated $a^2(x,y)$ function.

If we make the appropriate transformations on the a^2s term to find the virtual image, then

$$a_0 s \longrightarrow a_0 i(\xi,\eta)$$

$$a_1 s \longrightarrow n_1(\xi,\eta)$$

where $n_1(\xi,\eta)$ is a noise-like function due to the light scattered by the $a_1 s$ term. Thus the reconstructed image is $o(\xi,\eta)$:

$$o(\xi,\eta) = a_0 i(\xi,\eta) + n_1(\xi,\eta)$$

Therefore, a hologram made with a diffuse screen in the reference beam will reconstruct the object, but a noise term is superimposed on it. Whether the reconstruction is good or bad depends entirely on the magnitude of $n_1(\xi,\eta)$ relative to $a_0 i(\xi,\eta)$,

Juris Upatnieks (30 April, 1965)

30 April 1965

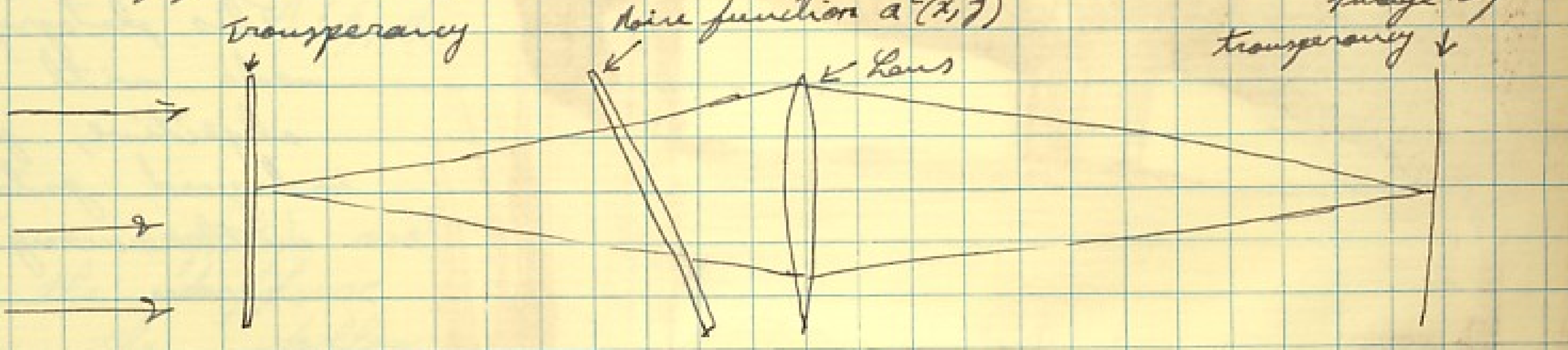
and also on the spacial frequency content of $n_1(\xi,\eta)$. As ~~$n_1(\xi,\eta)$~~ the frequency content of $n_1(\xi,\eta)$ approaches zero, $o(\xi,\eta) \rightarrow i(\xi,\eta)$ and perfect image is attained. This means, however, that the diffuser approaches the qualities of an optical flat. It appears a diffuser could be chosen with properties which could give high-quality reconstruction. In this case it may happen that the hologram could be reconstructed without the diffuser, simply by shining a narrow laser beam through the hologram.

It is interesting to note that the reconstruction of a hologram which was made with diffuser behind the transperancy and a plain, uniform reference beam, would have the form

$$o(\xi,\eta) = i(\xi,\eta)\, n(\xi,\eta)$$

Here, the reconstruction is a product of noise and signal terms, which is not objectionable provided ~~$n(\xi$~~ $n(\xi,\eta)$ has sufficiently high spacial frequency content.

It is easy to simulate reconstruction of a hologram with diffuse reference beam by the optical system shown below. The function $a^2(x,y)$ could be simulated using the figure on p. 100.



Juris Upatnieks (30 April 1965

5 May 1965

Experimental Results of Lens Correction

Uncorrected lens

Imaged transparency through uncorrected le

(Print # 010-6)

This photograph was made with the uncorrected lens, with 16 mm microscope objective. Projected image size, through the poor lens, ~ 4×2 cm.

Corrected lens

Imaged transparency through corrected l

(Print # 011-1)

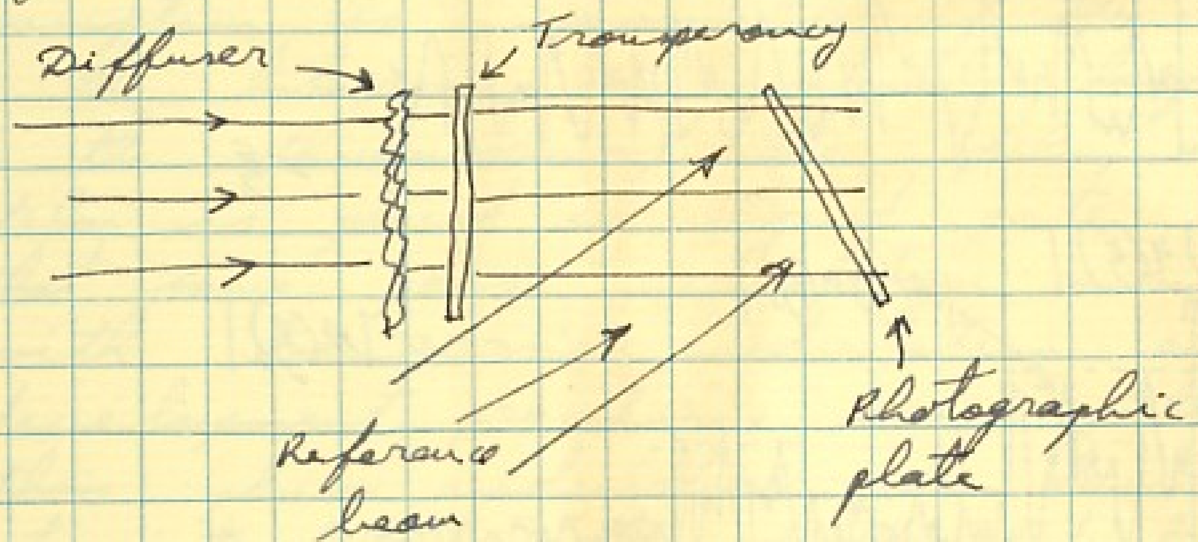
This photograph was made with a 16 mm objective, grating in liquid gate arrang with moving diffus screen.

Juris Upatnieks
(5 May 1965)

10 May 1965

Mathematical description of a hologram made from a transparency with diffuse glass behind it.

This arrangement is the usual one when hologram of a transparency is made and moderate resolution is desired. The following optical system may be used to make such a hologram:



The light amplitude immediatly to the right of the transparency can be described by $o(\xi, \eta)$:

(1) $$o(\xi, \eta) = u(\xi, \eta)\, A(\xi, \eta)$$

where $o(\xi, \eta)$ = amplitude over object plane (phase is included)

$u(\xi, \eta)$ = amplitude and phase function due to the diffuse glass, noise-like function

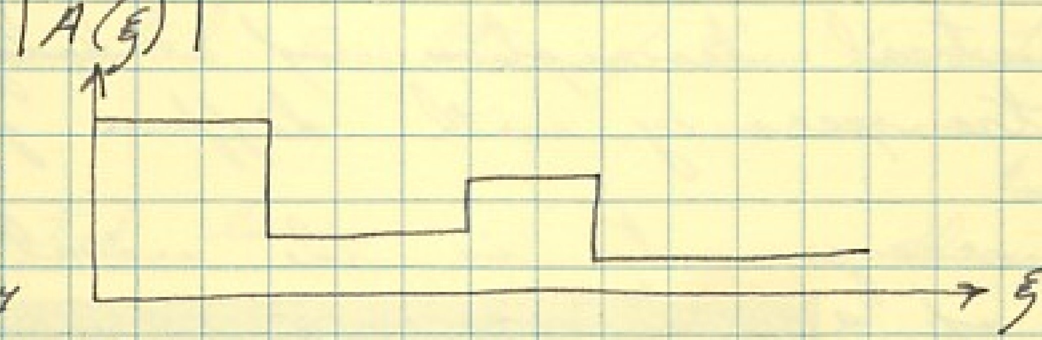
$A(\xi, \eta)$ = amplitude of the object (for a transparency, phase is assumed to be zero; otherwise, $A(\xi, \eta)$ includes phase and amplitude).

From eq (1) we see that the object is noise-modulated by the diffuse screen. Graphically, this can be represented by the following three graphs:

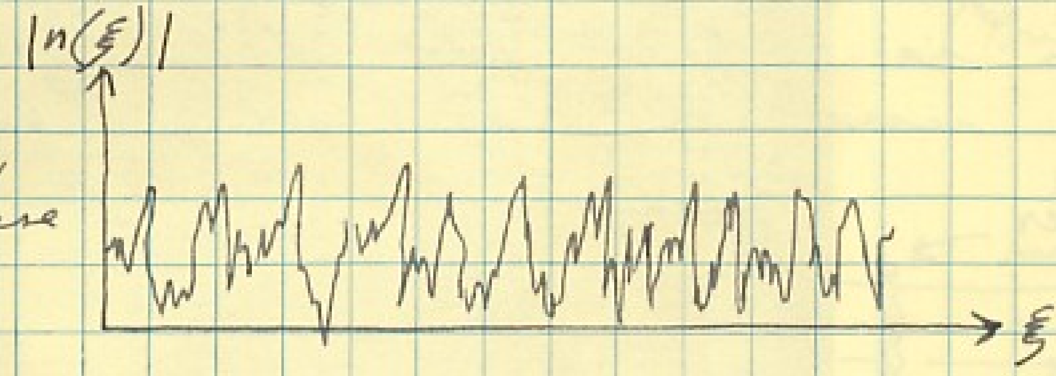
Juris Upatnieks (10 May 1965)

10 May 1965

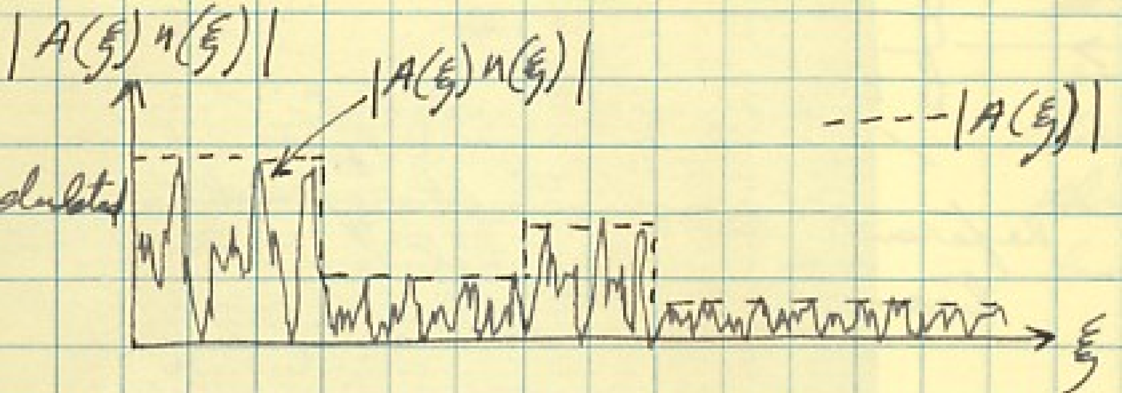
Signal only, or transmission of transparency



Noise only, due to diffuse glass



Signal modulated by noise



If the frequency content of $A(\xi)$ is low compared to $n(\xi)$, the eye will perceive the integrated, or averag level. If the frequency content of $A(\xi)$ is much higher than that of $n(\xi)$, then recognizable reconstruction can be expected although average brightness will change from one area to another area. If both $A(\xi)$ and $n(\xi)$ are of about the same frequency, then the reconstructed image will not be recognizable.

When light from the transparency arrives at the hologram plane, it has undergone a transforma which may be represented by $s(x,y)\,e^{j[\phi(x,y)-\alpha x]}$ $= F[A(\xi,\eta)\,n(\xi,\eta)]$. Since the hologram reconstructs the identical $s(x,y)$, the original scene is recovere For the case of the real, or conjugate image, we should note that $F^{-1}\{F[A(\xi,\eta)\,n(\xi,\eta)]\} = A(\xi,\eta)$ n(ξ that is, the inverse transformation gives bac the original image.

Juris Upatnieks (11 May 196

12 May 1965

Comparison of 2-dimensional and 3-dimensional recording medium for holograms.

Most of the theory relating to holograms has been derived on the assumtion that an infinetly thin film is the recording medium, and that the density varies with exposure. This assumption is reasonable if the fringe spacing on the hologram is relatively large with respect to the thickness of the film, and if the film is placed in liquid gate. There is evidance that some phase modulation occurs together with transmission modulation even if normal development procedures are followed. Usually this phase modulation is desirable since it intensifies the diffracted light without causing great distortion.

When high spacial carrier frequencies are used and the hologram is recorded on 649F emulsion, the above assumtions are not satisfactory to explain all of the observable effects. The emulsion thickness on glass plates is about 10 μ, and fringe spacing of less than 1 μ are sometimes encountered. In this case the hologram is recorded in 3-dimensional space. It has been suggested, for example by P.J. van Heerden in Applied Optics, Vol. 2, p. 239, April 1963, that since greater volume is ~~stored, mo~~ available, more information can be stored in it. This point of view has some falacies, since it is equivalent in some respects to placing several emulsions in series, that is, one behind the other. It would be difficult to recover the information from, say, the 5th layer in a stack of 10. The other layers would at least attenuate the light coming

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from it even if other difficulties could be overcome. Thus it appears that even though in principle more information can be stored in a volume than in a plane, ~~it~~ more could not be recovered. This is true if we not only consider the recovered information, but also the noise, or scattered light, from the unwant images in the volume.

One great advantage of recording holograms in large 3-dimensional ~~holograms~~ volumes is that they could be superimposed one on top of another, and yet recovered one at a time. The light from the unwanted images would appear as scattered light, or noise. Each record image in the volume could be considered as generating its own "crystal pattern", in analog to light diffraction from crystals in, say X-ra which depends on Bragg's reflections. In reconst only one particular orientation of the recording volume, and only the identical λ of light, will give reinforcing diffraction and thus reconstruc the original image (λ identical to that at whic the hologram was made). All other λ's, and orientation of the recording volume with respect to the illuminating beam, will not reconstruc a recognizable image and will simply scatter light. It is important to note that the wavefront must be identical to the one used as a reference, or it must be its exact conjugate. In the first case, the virtual image will be reconstructed, in the second, the real or conjugate image will reconstruct.

The sensitivity of the recorded hologram in a volume recording medium to orientation

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of the volume, λ, or shape of wavefront can be calculated from the geometry of the interference pattern. If, considering direction of illuminating beam, refracted beam, and depth of fringe pattern, phase between the nearest and furthest scatterers is changed by about $\frac{\pi}{2}$, then destructive interference can be expected and reconstruction would be lost by the rotation of recording volume creating this change. The more depth, the more sensitivity. This property would be useful in color holograms, where it is undesirable that green light reconstructs an image from red hologram.

In other instances such great sensitivity is undesirable. Such instances would be where 3-dimensional scenes are recorded and then observed without aid of lenses; another case is microscopy, since to change magnification the shape of the wavefront must be changed. In general, any system where magnification is desired sensitivity to orientation or wavefront is undesirable. For microscopy, very thin recording mediums appear desirable.

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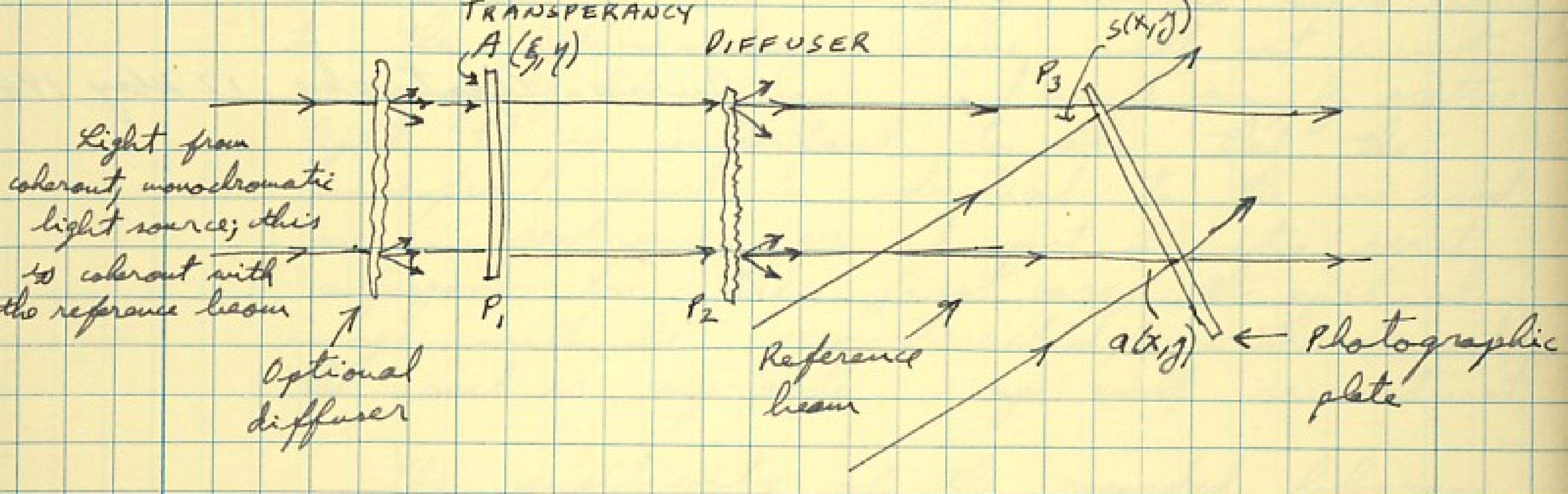
14 May 1965

Making of Holograms with diffuser in front of the ~~holo~~ transperancy.

The hologram in this case is made in the usual way, but with one difference: a diffuser is placed between the transperancy, or a 3-dimensional ~~image~~ object, and the photographic plate on which the hologram is recorded. If the diffuser scatters light over sufficiently wide angle, then the object is unrecognizable when viewed through the diffuser; consequantly, the reconstructed image from the hologram is also unrecognizable unless the identical diffuser is inserted in the system, as will be described later. Thus, this technique is a way to encode an ~~holo~~ image in such a way that the image can be recovered only using the proper "key". It would be very difficult, if not impossible, to recover the image without the exact "key".

The optical system to make the hologram is shown below:



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Let us call the signal $A(\xi, \eta) e^{j\theta_s}$ the amplitude and phase distribution immediatly next to the transparancy, at plane P_1. At P_2 the signal has undergone a transformation F_1 and is called $A_2(\xi', \eta') e^{j\theta_s'}$

$$A_2(\xi', \eta') e^{j\theta_s'} = F_1 \left[A(\xi, \eta) e^{j\theta_s} \right]$$

If the diffuser is such that phase changes are introduced but no attenuation takes place, then this can be expressed as $e^{j\theta_2(\xi', \eta')}$; if attenuation also takes place, then it can be represented by $n(\xi', \eta') e^{j\theta_2(\xi', \eta')}$. The signal immediatly to the right of plane P_2 is then

$$n(\xi', \eta') A_2(\xi', \eta') e^{j[\theta_s' + \theta_2(\xi', \eta')]}$$

At the surface of the photographic plate the signal undergoes another transformation, F_2;

$$s(x, y) e^{j[\phi(x,y) + \alpha x]} = F_2 \left\{ n(\xi', \eta') A_2(\xi', \eta') e^{j[\theta_s' + \theta_2]} \right\}$$

Reference beam is added, and the recorded signal is

$$|s + a|^2 = s^2 + a^2 + 2as \cos[\phi + \alpha x]$$

Here $|s+a|^2$ is the intensity of radiation falling on the surface, and the sign (−) and film characteristic constant has been neglected to simplify description.

In reconstruction, the hologram is illuminated with wavefront similar to the reference beam, that is, having same wavelength λ, same curvature, and same angle with respect to the emulsion. The only difference is that the direction of propagation has been reversed from that in making the hologram. See the next figure. As for the phase of the reference beam, this implies that the complex conjugate of the reference beam is used.

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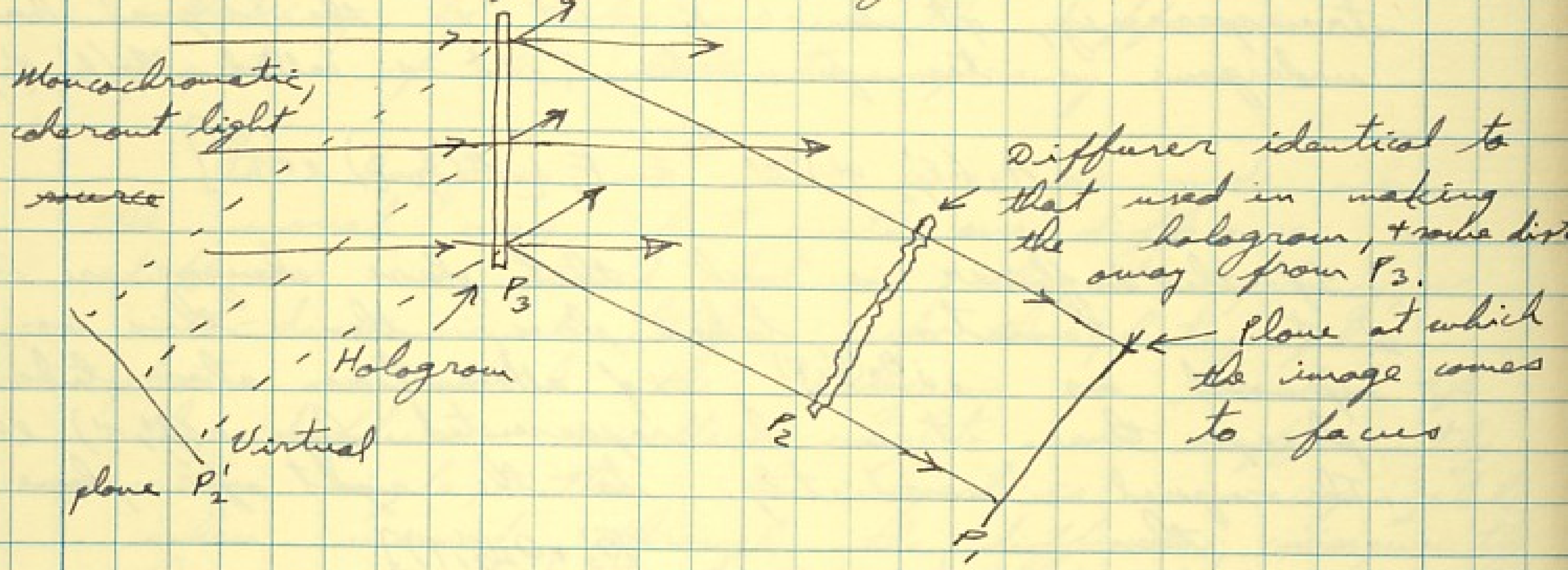
Reconstruction of encoded hologram:



When the hologram is illuminated in the manner shown above, the light emerging from the hologram has the form

$$a|s+a|^2 = a s^2 + a^3 + 2a^2 s \cos[\phi + \alpha x]$$

Note that if the reference beam had a variable phase factor, of the form $a(x,y)e^{j\psi(x,y)}$, then

$$|s+a|^2 = \cancel{a} s^2 + a^2 + 2as \cos[\phi + \alpha x - \psi]$$

and $a|s+a|^2 = a e^{-j\psi} s^2 + a^3 e^{-j\psi} + 2a^2 e^{-j\psi} \cos[\phi + \alpha x - \psi]$

and the desired signal would stil be

$$2a^2 s e^{-j[\phi + \alpha x]}$$

, or the conjugate image.

The desired signal thus is the conjugate, or real, image sideband. At plane P_2 the conjugate signal has undergone the inverse transformation F_2^{-1}:

$$F_2^{-1}\left\{a^2 s e^{-j[\phi + \alpha x]}\right\} = \eta(\xi', \eta') A_2(\xi', \eta') e^{-j[\theta_s' + \theta_2]}$$

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14 May 1965

In passing through the diffuser in reconstruction, it gets multiplied by $\eta(\xi',\eta')\, e^{+j\theta_s}$ and the resulting signal is

$$\eta(\xi',\eta')\, e^{+j\theta_s}\, \eta(\xi',\eta')\, A_2(\xi',\eta')\, e^{-j[\theta_s'+\theta_2]}$$

$$= [\eta(\xi',\eta')]^2 A_2(\xi',\eta')\, e^{-j\theta_s'}$$

In going from plane P_2 to P_1 the signal undergoes the inverse transformation F_1^{-1}. Above, if the diffuser only phase-modulates the signal, then $\eta^2(\xi',\eta')$ is a constant and it can be neglected in the following equations. From geometrical considerations, $\eta^2(\xi',\eta')$ can be a constant only if all of the scattered light in making the hologram is recorded, and is reconstructed with proper amplitude and phase.

$$F_1^{-1}\left\{A_2(\xi',\eta')\, e^{-j\theta_s'}\right\} = A(\xi,\eta)\, e^{-j\theta(\xi,\eta)}$$

Thus we see that the original signal has been recovered with proper amplitude distribution, but with conjugate phase. In this case a transparency was used, but a three-dimensional object should be equally good. The geometrical arrangement of the hologram and diffuser must be very accurate.

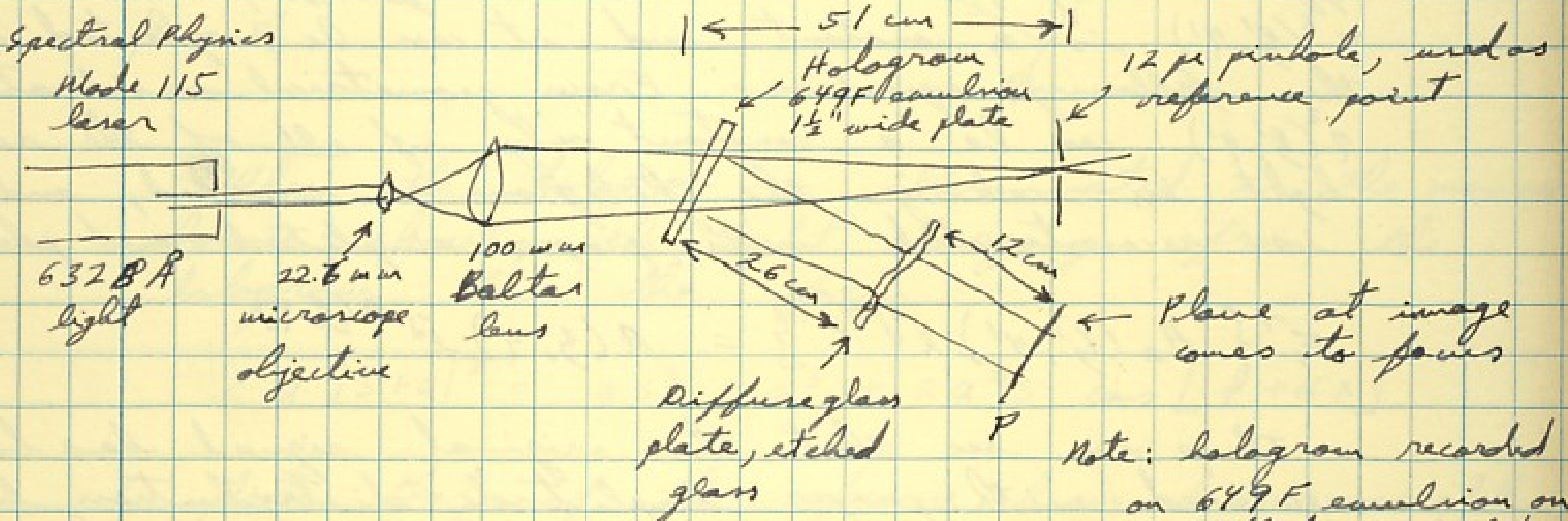
The virtual image will not reconstructed to a recognizable image in this case.

Juris Upatnieks, 14 May 1965

19 May 1965

Reconstruction of a hologram made with a diffuser in front of the transparency.

A hologram, which was made by placing a diffuser between the transparency and the hologram recording plane, was reconstructed. The optical system used in reconstruction is shown in the figure below:



Note: hologram recorded on 649F emulsion on microflat glass plate.

When the hologram was inserted as shown in the figure, and light beam accurately focused on a pinhole which was in a fixed position, a legible reconstructed image appeared on the plane P. The image consisted of 2 lines with letters. When the diffuse glass was moved slightly, or removed from the system, the image was not legible and the words were unrecognizable.

Juris Upatnieks, 19 May 1965

Witnessed May 19 1965 Charles

Witnessed May 19, 1965 Ralph H. Mit

20 May 1965

A Technique for reducing the effects of damaged hologram emulsion in the reconstruction process.

In the early experiments with holograms the transparency was illuminated with a uniform spherical wavefront without any diffuse glass plate in the system. This type of a hologram gave a sharper image, since it did not contain a fine noise-like structure, but had some undesirable properties: any minute defect of the hologram emulsion produced annoying diffraction patterns on the reconstructed image. These defects are shown in Fig. 5, in the paper "Wavefront Reconstruction With Continuous-Tone Objects", J.O.S.A. Vol. 53, pp. 1377-1381, December 1963, and also are discussed in the paper. One technique to reduce this is to place a diffuse glass screen between light source and the transparency. This does not work well, however, if fine structure is to be recovered, since in that case the noise from the diffuser is of the same resolution size as the desired information.

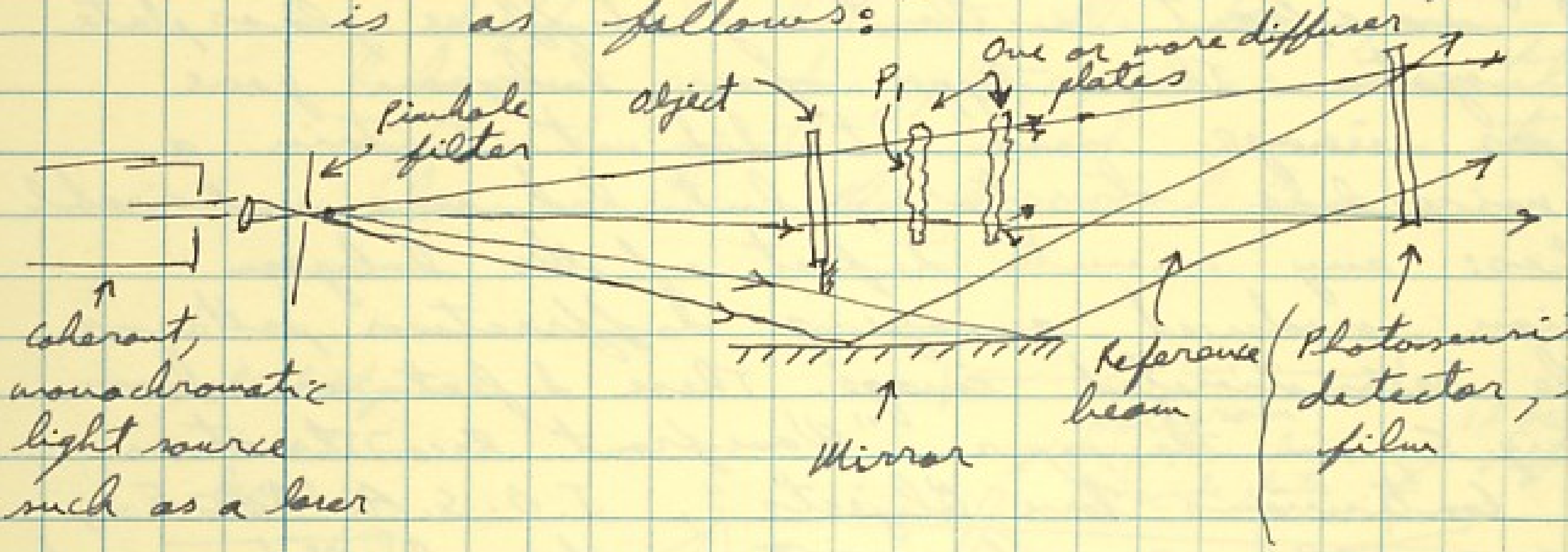
A way to recover information about the original transparency, or other object, is to make a hologram with one or more diffuse plates between the transparency and the hologram, and then to reconstruct through the same diffuse plates. In such a system the defects in emulsion will not appear as some regular diffraction pattern, but only as a small amount of randomly scattered light. The only surface which may produce the same kind of regular diffraction patterns is the last diffuse surface closest to the transparency. If this surface is such as etched, ground, or opal glass, or some similar device, then it could be kept clean quite easily. This is not the case with

Juris Upatnieks, 20 May 1965

20 May 1965

emulsions, since emulsions are soft and usually contain some defects which scatter light.

The optical system for making such holograms is as follows:



To reconstruct the above hologram, it is replaced in the same optical system in its exact place, but the reference beam is directed in the oposite directi and focused on the pinhole; light source + object at the left is removed, and same wavelength light is u in reconstruction. The reconstructed object will appear at same place as it was originally and will have the same size, phase, and amplitude. Light scattered by the hologram defects will be further scattere by the diffuser, and therefore appear as some fine-structu and low-amplitude noise; the rest of the diffracted light will reconstruct the object. Since the phase is preserved, interferometric techniques can be used to exami the object, such as in phase contrast microscopy.

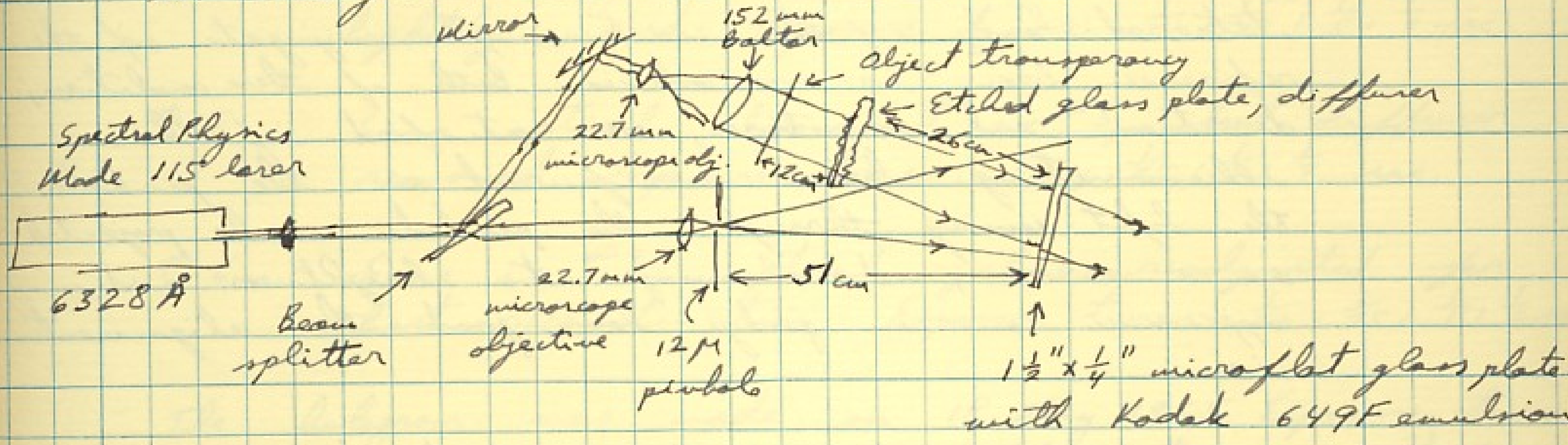
If the object has large uniform density areas, the shadows of these will fall on the first diffuser, plane P_1 and could be recognized if viewed from the right. If on or more diffusers are placed between P_1 and the hologram, they will completly encode the object in such a way as to make it unrecognizable. Thus, several diffusers in front of the transparency can be used to encode an object ~~to~~ a completly unrecognizable form.

Juris Upatnieks, 20 May 1

20 May 1965

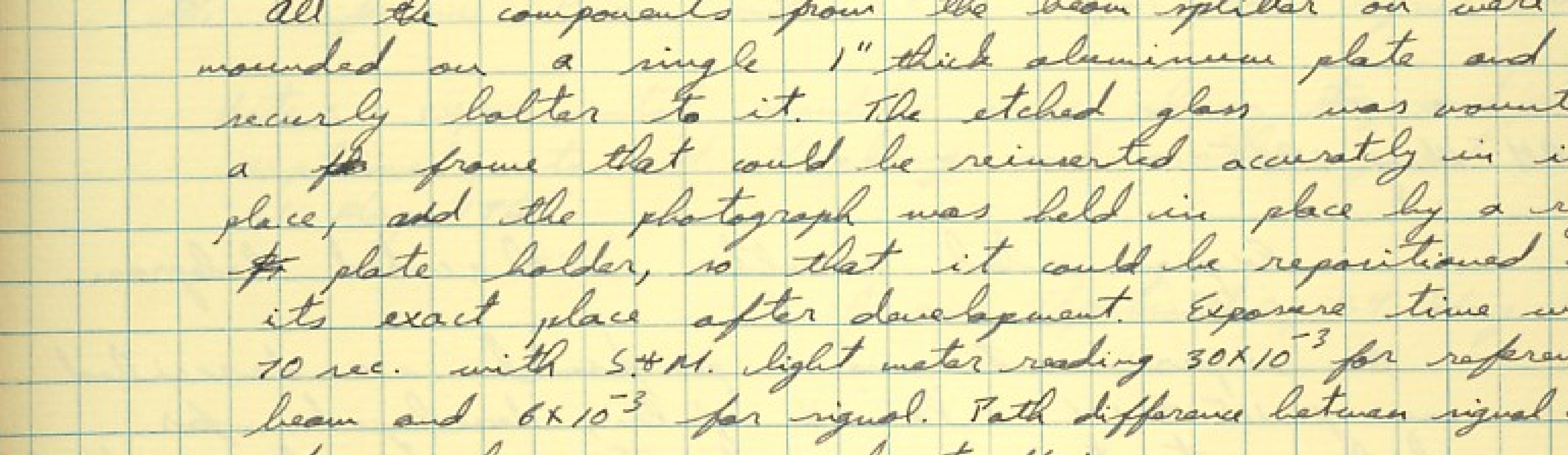
Experimental setup for making and reconstructing hologram with diffuser between the object and photographic plate.

The experimental optical system used to make the holograms is shown below:



All the components from the beam splitter on were mounted on a single 1" thick aluminum plate and securly bolted to it. The etched glass was mounted on a frame that could be reinserted accuratly in its place, and the photograph was held in place by a rigid plate holder, so that it could be repositioned in its exact place after development. Exposure time was 10 sec. with S.&M. light meter reading 30×10^{-3} for reference beam and 6×10^{-3} for signal. Path difference between signal and reference beams was about 4 in.

The reconstruction is accomplished by shining the reference beam from the opposite direction and focusing it on the pinhole:



Juris Upatnieks, 20 May 1965

20 May 1965

The hologram, diffuser, and the pinhole are the critical elements in the reconstruction process, and should not be moved after the hologram is exposed. The direction on curvature of the illuminating beam is extremely critical as reconstruction will be obtained only if the exact complex conjugate of the reference beam is reproduced. Both of these condition, direction and curvature, are satisfied if the illuminating beam is focused on the pinhole. The light coming through the pinhole can be projected on a screen, and observing its brightness and appearance one can judge how good the alignment is.

Juris Upatnieks, 20 May 1965

24 May 1965

Experimental results with a coded hologram.

An experiment was performed as described on p. 115 & 116. Pan-X film, developed for high contrast, was used to record the reconstructe images. Exacta camera was placed so that the image came to focus directly on the film, without the use of lenses between the film and the hologram. The small amount of scattered light is apparently caused by imperfections in the recording process. It was also observed that a ¼" microflat glass plate inserted between the hologram and the diffuse glass plate made reconstruction impossible probably because the path length was effectivly reduced.

Juris Upatnieks, 24 May 19

24 May 1965

Experimental results show (~~#~~ sheet #011, 21 May 1965):

#3 Optical system aligned for best reconstruction. Exposure times: $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

#4 Same arrangement as above, but diffuser slightly moved. Exposure times: $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

#5 Same optical alignment as #3, but diffuser removed. Exposure times: $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

#6 Same as #3, optical system readjusted for best reconstruction. Exposure times: $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

The hologram was made on 18 May 1965. Exposure time was 70 sec., reading on S.+M. light meter $\sim 30 \times 10^{-3}$ for the reference beam and 6×10^{-3} for the signal beam.

Note: experimental results were shown ~~to~~, and principles explained, to H. Hopkins and another guest on 21 May 1965.

Juris Upatnieks, 24 May 1965

7 June 1965

Further experiments with phase-coded signal beam holograms.

Five more holograms were made in the same way as described on p. 115 + 116. Two were made with transparent letters on opaque background as the object, the letters covering a 2.3 x 1.3 cm area; two with letters covering 1.9 x 0.2 cm area, same as above otherwise; and one was made of a continuous tone transparency. The lettering reconstructe well from all holograms, except that not all of the area could be reconstructed at once, and a noisy background was present. The continuous-tone hologram reconstructed to some recognizable detail, but due to high noise level the image was poor. The noise level apparently is high due to incorrect phase reconstruction from the hologram. This could be caused by the following:

1) Poor lenses in the system. Baltar lenses were used to obtain converging illuminating beam in the reconstruction. They are known to be diffraction-limited over an f-8 aperture, which is not sufficient for this case.

2) Thickness variations of the emulsion. Examination in the Mach-Zehnder interferometer of develope plates showed that some variation exists over the central part, and is quite high along the edges.

3) Hologram too small. Analysis of this type of hologram showed that if all the light scattered by the diffuser is not recorded, then noisy reconstruction can be expected.

4) Mechanical misalignment. Care is taken to avoid this. Warping of the base could cause misalignment.

Juris Upatnieks, 7 June

7 June 1965

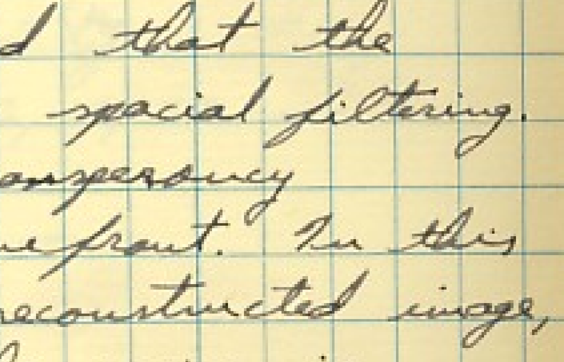
Variation in thickness could be the most severe defect in the previous experiments. A liquid gate should reduce these errors. Since introduction of the liquid gate will change path length, the gate will have to be inserted when making the exposure, or else the emulsion must be away from the source during exposure time.

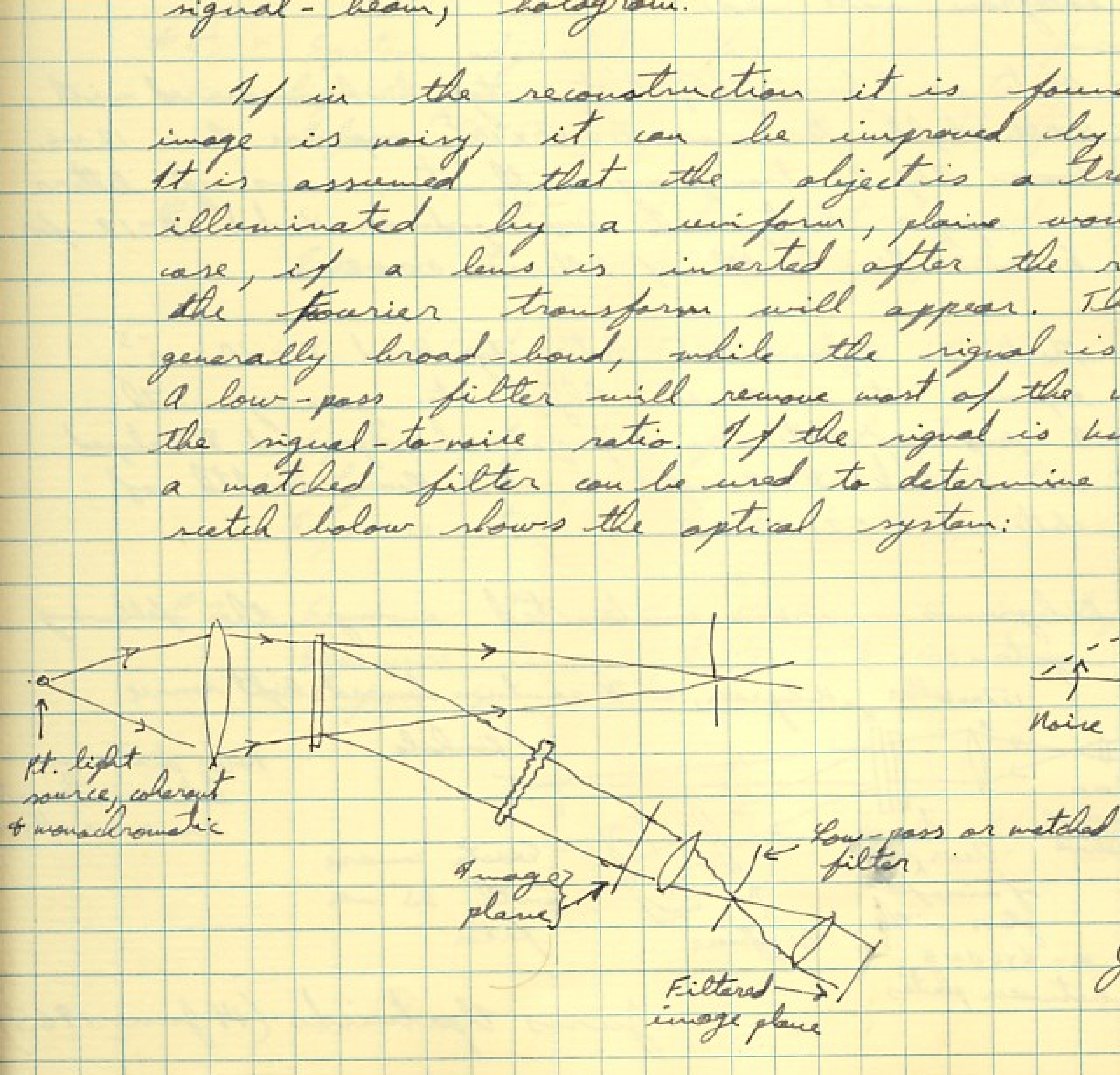
Juris Upatnieks, 7 ~~th~~ June 196

7 June 1965

Technique for improving quality of phase-encoded, signal-beam, hologram.

If in the reconstruction it is found that the image is noisy, it can be improved by spacial filtering. It is assumed that the object is a transparency illuminated by a uniform, plane wavefront. In this case, if a lens is inserted after the reconstructed image, the Fourier transform will appear. The noise is generally broad-band, while the signal is narrow band. A low-pass filter will remove most of the noise and improve the signal-to-noise ratio. If the signal is known beforehand, a matched filter can be used to determine its presence. The sketch below shows the optical system:



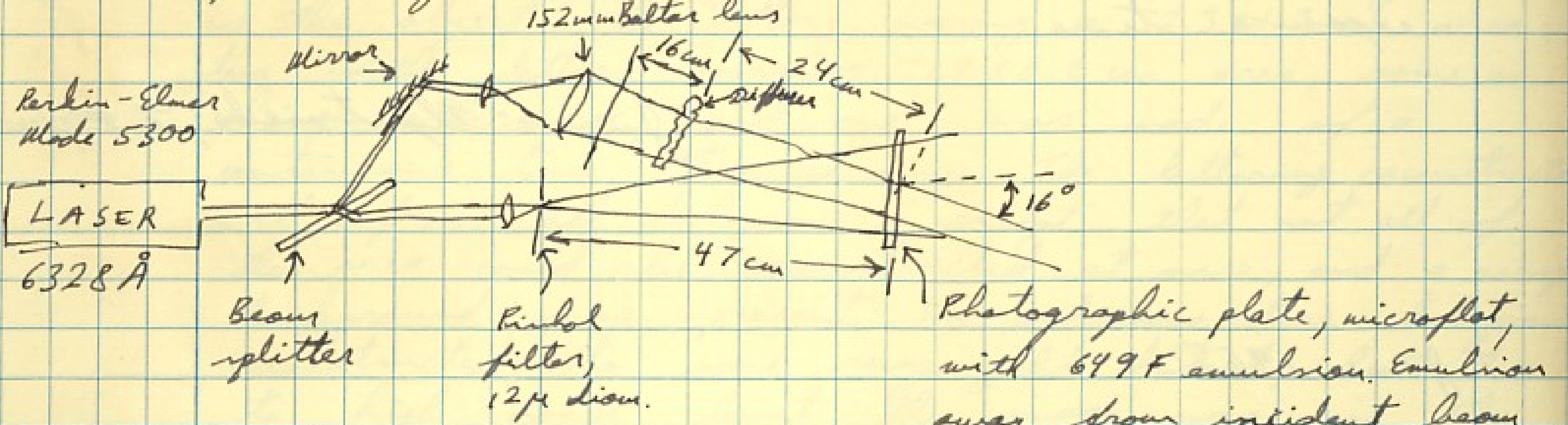


Juris Upatnieks
7 June 1965

14 June 1965

Experiments with phase-encoded signal beam holograms.

Two holograms were made of an object consisting of transperant letters on opaque background, illuminated from behind with plain, uniform, wavefront. The optical system was as shown:

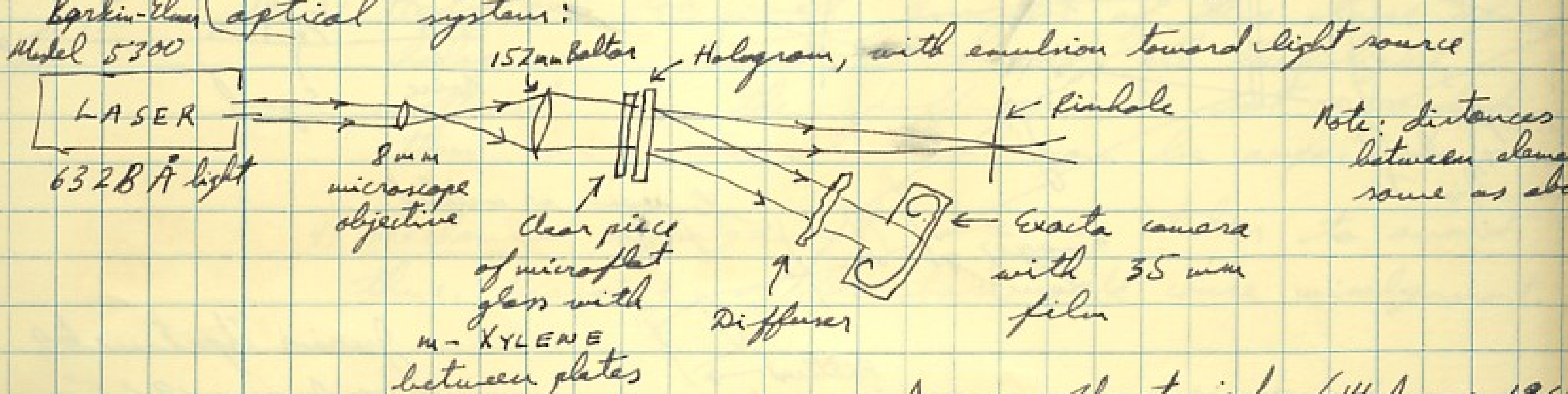


Two holograms were made:

#1 Made on 9 June 1965, Intensity level measured with S.&M. light meter was $I = 40 \times 10^{-3}$, exposure time 12 sec. [illegible] Object: transperancy with two rows of letters on opaque background. Developed in Kodak D-19 fo 6 min. Line width of letters 0.022 mm.

#2 Made on 9 June 1965. Intensity level $I = 60 \times 10^{-3}$, exposure time 9 sec. Object: transparancy with 9 rows of letters on opaque background. Developed in Kodak D-19 for 6 min. Line width of letters 0.021 mm.

The holograms were reconstructed using the following optical system:



Juris Upatnieks (14 June 196

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The reconstructed images were recorded on Pan-Sep. film and were developed for normal contrast.

Experimental results show (sheet # 012, 11 June 1965):

#1 System adjusted for optimum focus, liquid gate used, hologram #1 of 9 June 1965. Lens aperture wide open; exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.

#2 Same as #1 but aperture restricted to 19 mm diameter. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.

#3 Same as #1 but diffuser not in proper position, aperture wide open. Exp. times: 1, 3, 10, 30 sec.

#4 Same as #1 but diffuser removed, aperture wide open. Exp. times: 1, 3, 10, 30 sec.

#5 System adjusted for optimum focus, without liquid gate, aperture: 15 mm diameter, hologram #1 of 9 June 1965. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.

#6 Same as #5, but aperture wide open. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.

(Sheet # 013, 11 June 1965):

#1 System adjusted for best focus, without liquid gate, hologram #2 of 9 June 1965. Aperture: 17 mm diameter. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec.

#2 Same as #1 of this sheet, with liquid gate, aperture: 18 mm. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3, 10, 30 sec., + $\frac{1}{2}$ sec. on separate piece of film.

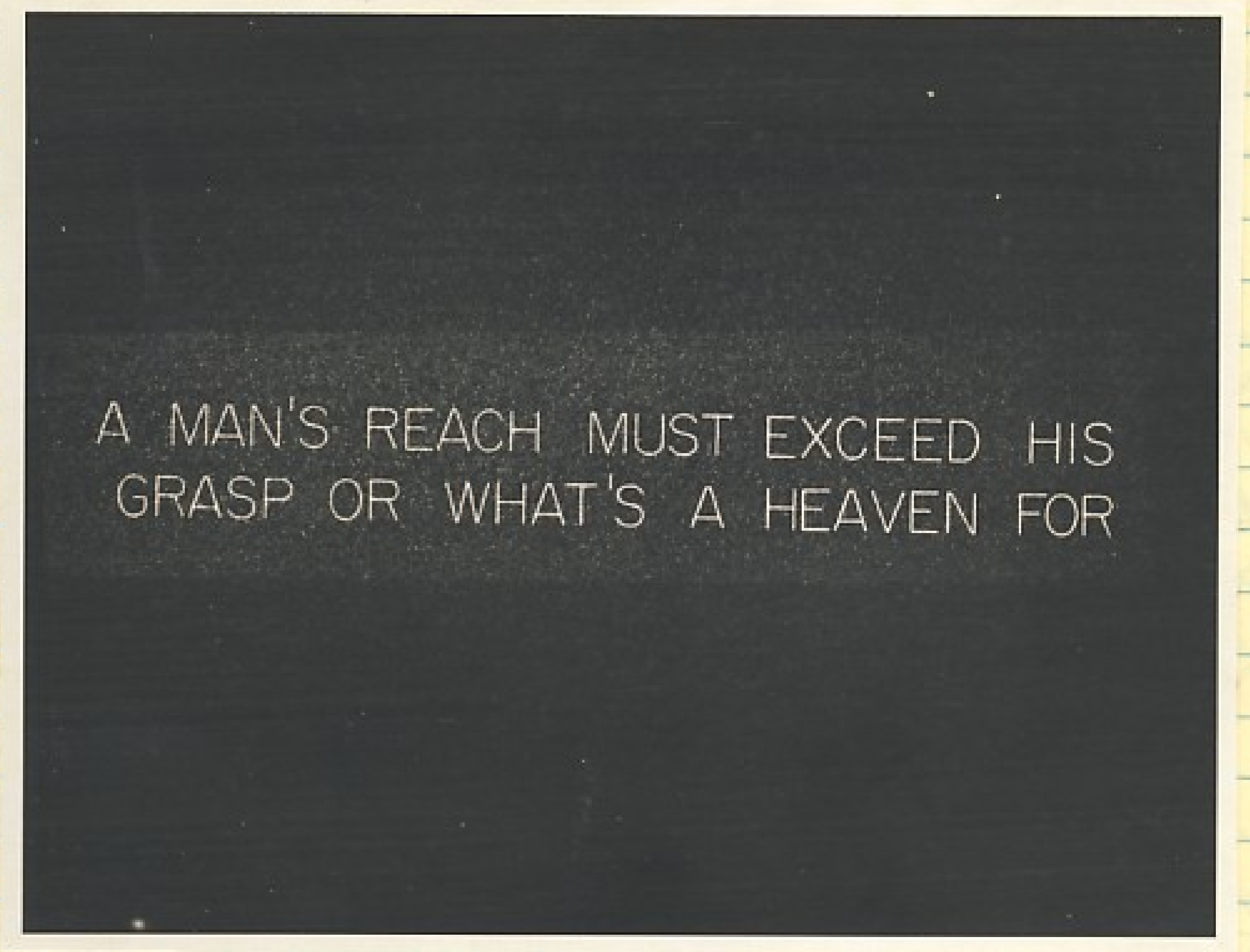
Juris Upatnieks, 14 June 1965

16 June 1965

Experimental results of phase-encoded signal holograms.

These two images are reconstructions of holograms made as shown on p. 120, and reconstructed as shown on p. 120 + 121.

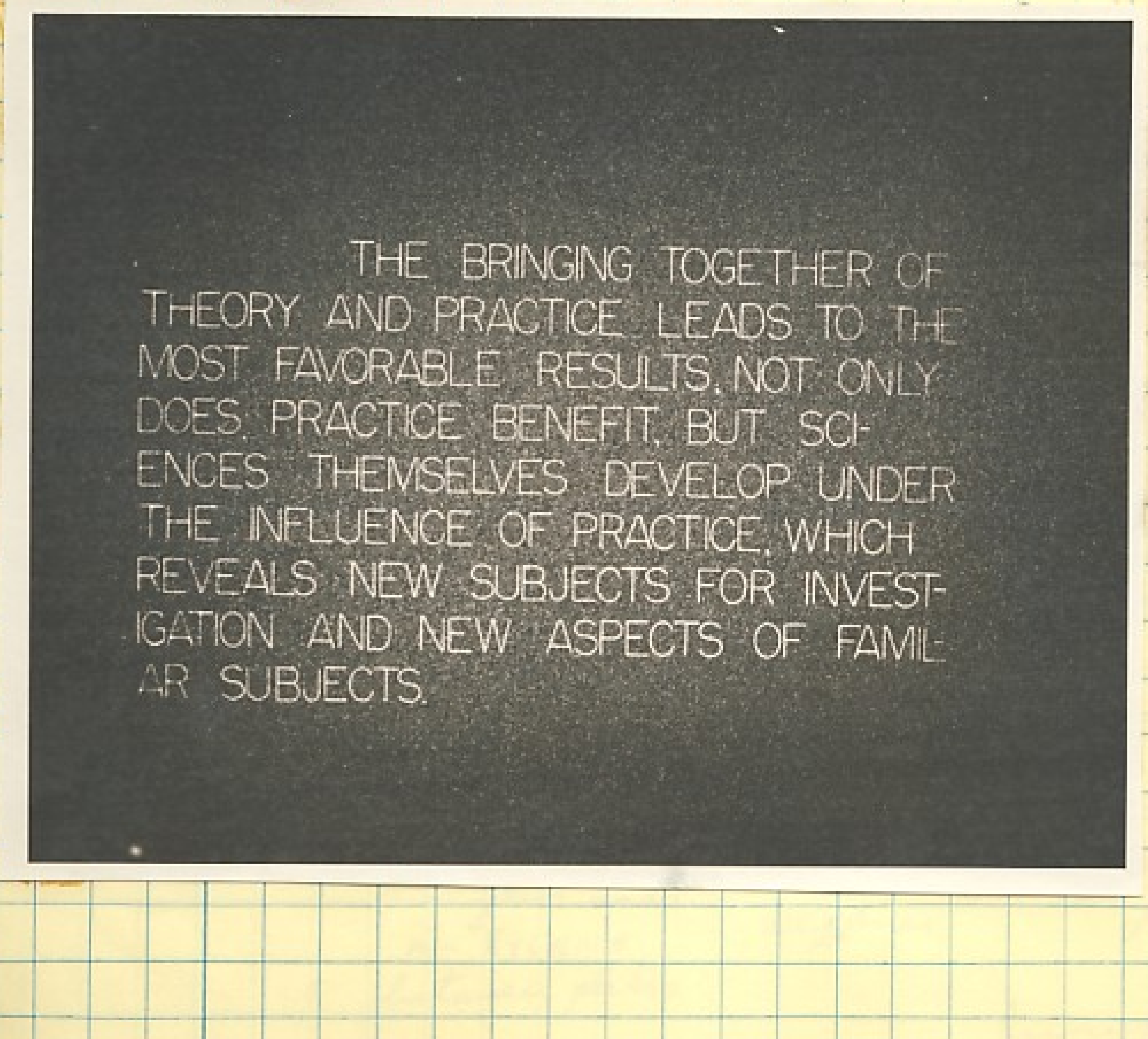
Reconstruction (#012-2, 2nd exp.)



A MAN'S REACH MUST EXCEED HIS
GRASP OR WHAT'S A HEAVEN FOR

Original size of imag
was 19 mm long,
2 mm high, and lin
width 0.022 mm.
The object consisted
of transperant letter
on opaque backgroun
enclosed in rectangle
of black tape The
slightly lighter area
is due to light comi
through the dark part
of the slide. Liquidga
was used, with Xylene
as the liquid.

Reconstruction (#013-2, 2nd exp).



THE BRINGING TOGETHER OF
THEORY AND PRACTICE LEADS TO THE
MOST FAVORABLE RESULTS. NOT ONLY
DOES PRACTICE BENEFIT, BUT SCI-
ENCES THEMSELVES DEVELOP UNDER
THE INFLUENCE OF PRACTICE, WHICH
REVEALS NEW SUBJECTS FOR INVEST-
IGATION AND NEW ASPECTS OF FAMIL-
AR SUBJECTS.

Here the original im
was similar to the
one above. Original si
was 10 mm by 16 m
long, with line wid
of 0.021 mm. Liquid
gate was used. The
higher noise level
is from imperfecti
in the reconstructio
process. The holograms fo
both were made on 9 Ju
and reconstructions o
11 June 1965.

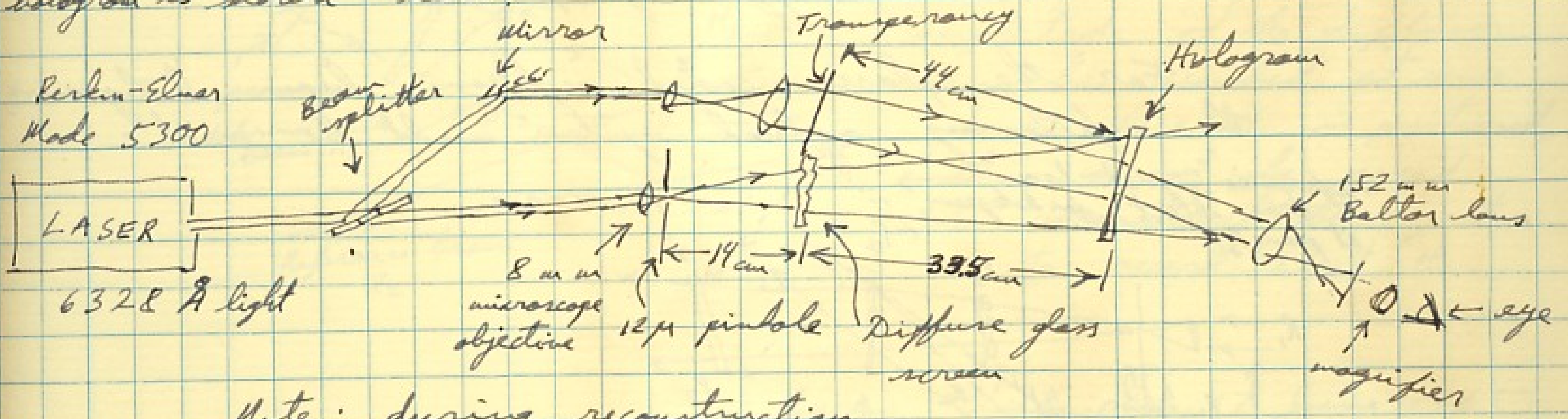
Juris Upatnieks
16 June 1965

16 June 1965

Reconstruction of a hologram with a diffuser in the referance beam.

A hologram was made with a diffuse glass plate in the reference beam, before the hologram. This is equivalent to having an extended, coherent, monochromatic, light source for the referance. Reconstruction was made by placing the hologram in same position and illuminating by the same referance beam.

The optical system used in reconstruction and in making hologram is shown here:



Note: during reconstruction,
an opaque screen was placed in
front of the transperancy

With an opaque card in front of transperancy and hogram in place, a clear and recognizable image was observed; with the hologram slightly misaligned, the image disappeared and only scattered light was visible.

Juris Upatnieks, 16 June 1965

Witnessed by: A. Friesem – 16 June 6

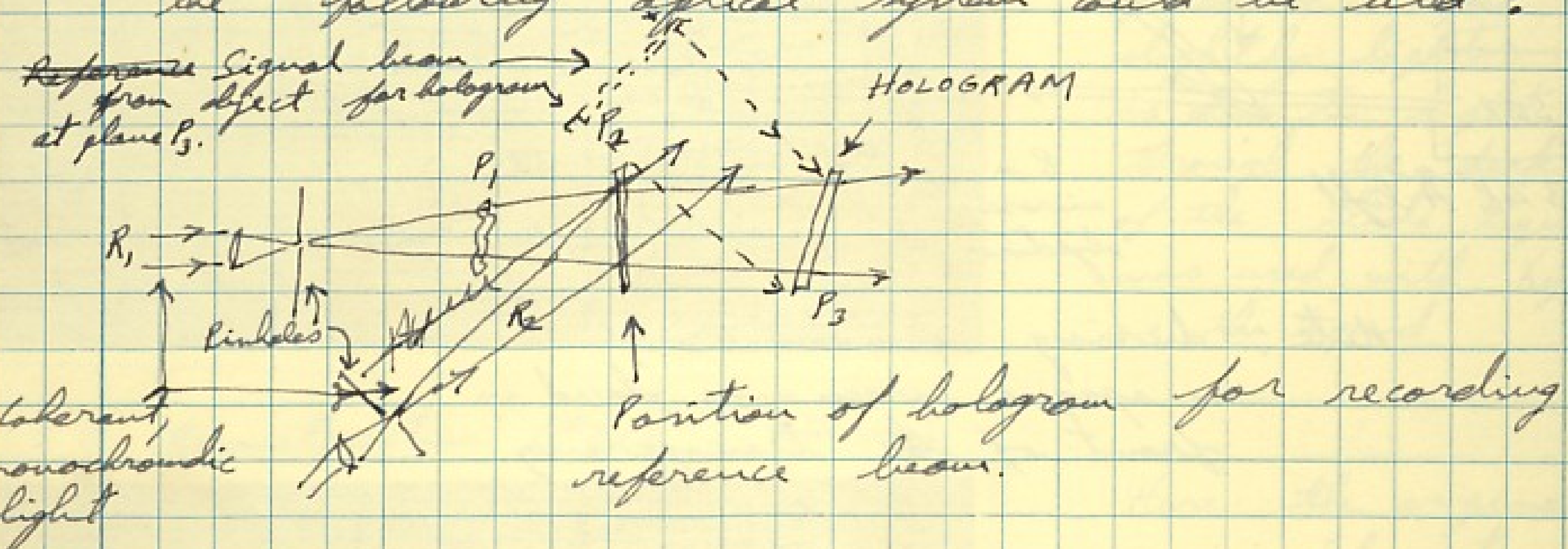
Witnessed by: Fred R. Rotz 17-June 65

17 June 1965

Method for making duplicates of diffusing screens photographically.

If one intends to use the phase-encoded signal beam, or phase & amplitude encoded reference beam, for secure communications, it is necessary for both the sender and receiver to have identical diffusing plates. Since holograms are capable of recording both phase and amplitude, they can be used to record and reconstruct a diffusing plate.

For the phase encoded reference beam holograms, the following optical system could be used:



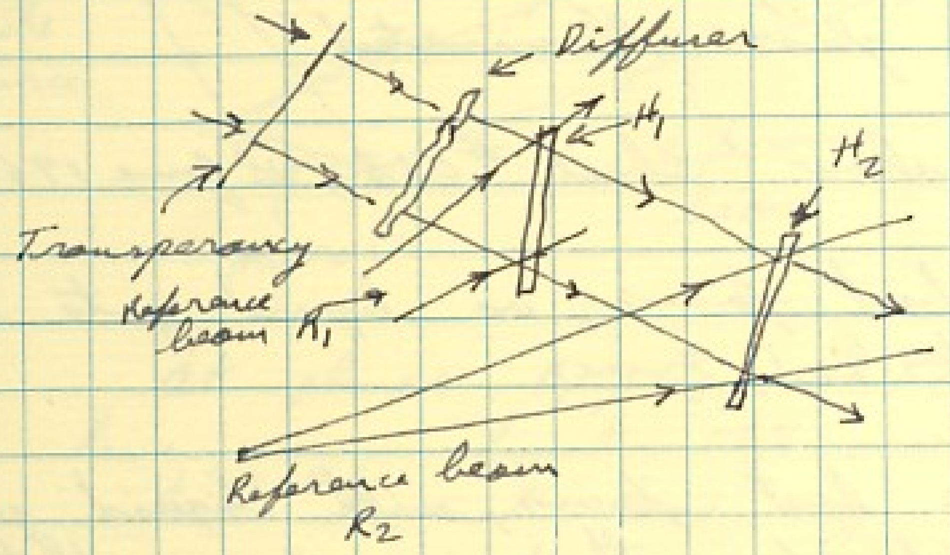
P_1 is the diffuse or etched glass (also could be refections from a diffusely reflecting surface), P_2 is position of photographic plate (or other photosensitiv material) anywhere between planes P_1 and P_3. A refere beam is brought in from the side in the usual manner. After development, the hologram can be replaced in identical position and the diffuse glass ~~screen~~ reconstructed by illuminating with ~~the~~ reference beam R_2. The reconstructed virtual image of diffuser P_1 can then be used as a reference beam for the hologram at P_3, or for reconstruction of the hologram at P_3. The hologram at P_3 can thus be either made or reconstructe

Juris Upatnieks, 17 June 1965

17 June 1965

with either the original diffuser or its reconstruction. If diffuser is used for making hologram at P_3, something equivalent to the optical thickness of the glass + emulsion at P_2 should be placed there.

For the case where diffuse glass is placed in front of the object, that is, between the object and the hologram, the following optical system could be used:



Although the phase ~~of~~ and amplitude of the diffuser can be recorded at some plane where H_1 is positioned, this cannot be used to reconstruct the object, or to record it at H_2.

Juris Upatnieks, 17 June 1965

18 June 1965

Experiment~~s~~ with phase-encoded reference beam

A hologram was made with the optical system as shown on p. 123. The hologram was recorded on a~~n~~ 1½ x 4 x ¼" microflat glass plate with 649F emulsion, with emulsion on the opposite side from the source of light. Intensity measured with M+S light meter was 30×10^{-2}, exposure time 2 sec., and development was 6 min. in Kodak D-19 developer. The hologram was made on 16 June 1965.

The hologram was then reconstructed with the same optical system as shown on p. 123, except that

Juris Upatnieks, 18 June 1965

18 June 1965

imaging of the virtual image was done with a 210 mm lens. An exacta camera was used to record the image on Pan-X 35 mm film. The film was developed for 14 min. in D-76 developer. It was observed that the quality of reconstruction varies with the area of the etched glass illuminated by the light source: when same area is illuminated as when making the hologram, the image is best. This is to be expected since the phase and amplitude distribution at the hologram plane varies with the area of diffuse glass illuminated.

Film recordings show (Sheet #013, 18 June 1965):

#3 Image adjusted for best focus, no liquid gate used. Exposure times: $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$, 1, 3 sec.

#4 Image adjusted for best focus, with liquid gate. Liquid gate consisted of another piece of microflat glass with Xylene liquid between them. Exposure times: $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$, 1, 3 sec.

#5 Film positioned at the Fourier transform plane of the image. Exposure times: $\frac{1}{25}$, $\frac{1}{5}$, 1 sec.

#6 Same as #4 but system readjusted. Exposure times: $\frac{1}{5}$, $\frac{1}{2}$, 1, 3 sec.

(Sheet #014, 18 June 1965):

#1 Diffuser removed from the optical system and hologram illuminated with plane wavefront. Exposure times: $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$, 1, 3 sec.

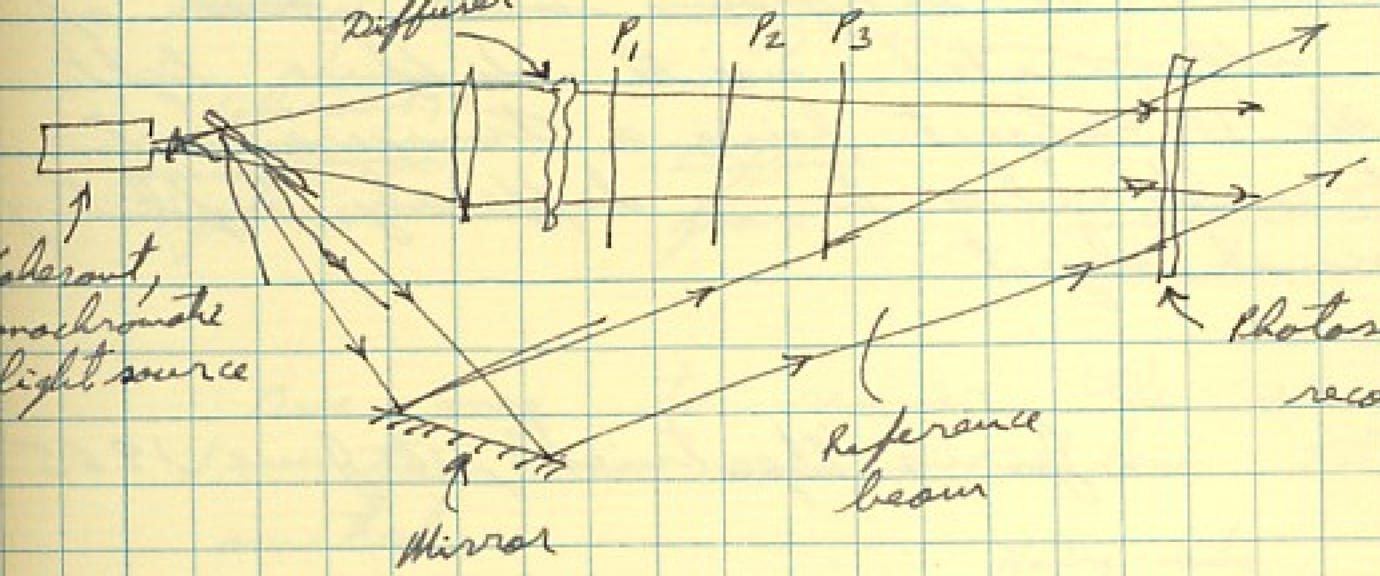
#2 Diffuser in proper position, but hologram misalignm
Exposure time: $\frac{1}{5}$, $\frac{1}{2}$, 1 sec.

Juris Upatnieks, 18 June 1965

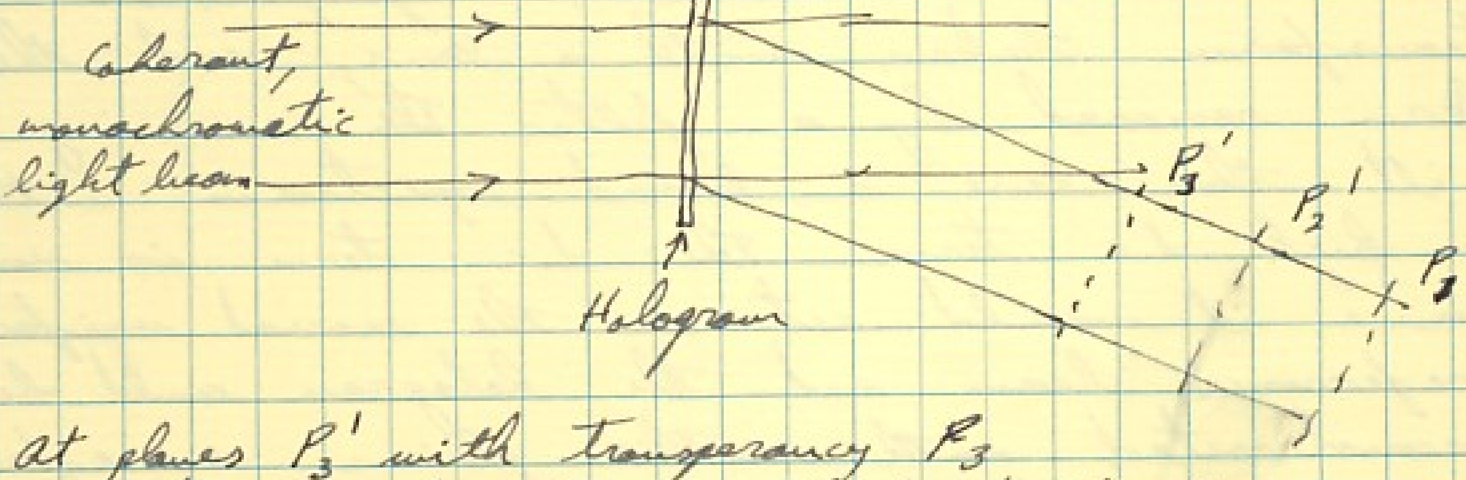
18 June 1965

Technique of recording several images from same direction in space.

Consider the optical system shown below:



At planes P_1, P_2, and P_3 are transparencies which have, say, about 50% average transmission each and which do not have any large opaque areas. More, or fewer, transparencies may be inserted between the hologram plane and the diffuse glass screen. If transparencies $P_1 + P_2$ in this case are such that light falling on P_3 is uniform noise-like, then this is equivalent to having only P_3 after the diffuser and this transparency should reconstruct well. At plane P_2 in reconstruction process, however, P_3 will be out of focus and P_2 should reconstruct. Same goes for P_1, and any other additional transparencies. The optical system used to reconstruct the images is as follows:



At plane P_3' with transparency P_3 reconstruct, at P_2' - P_2, and at P_1' - P_1.
The desired image can be viewed by focusing on the right plane, or can be recorded by placing film at the ~~right~~ desired plane. This scene can be

Juris Upatnieks, 18 June 1965

18 June 1965

combined with one of previous ones, that is, with phase-encoded signal beam or phase-encoded referance beam. The placing of several transperancies one behind the other is a way of utilized the redundancy inherent in holograms made ~~from~~ of transperancies illuminated with diffuse light. Instead of the 1st object being a transperancy at plane P_1, it could also be a diffusely reflecting three-dimensional object.

Juris Upatnieks, 18 June 1965

28 June 1965

Technique for making phase-encoded reference beam from a transperancy.

Another technique for making a phase-encoded referance beam is to expose a film and record the amplitudes only of a pattern resulting from shining coherent monochromatic light through a diffuse glass. This record will not contain phase information in a way that can be recovered. However, a different phase distribution can be obtained in this transperancy is illuminated with coherent monochromatic light, its Fourier transform taken with a lens, and the d.c. term removed by a filter. The remaining signal will then have a broad spectrum without a high d.c. term. The d.c. term is undesirable since it would act as the usual uniform-aplitud plane referance beam and the hologram could be easily reconstructed with another plaine wavefront. The a.c. components would add noise as a background.

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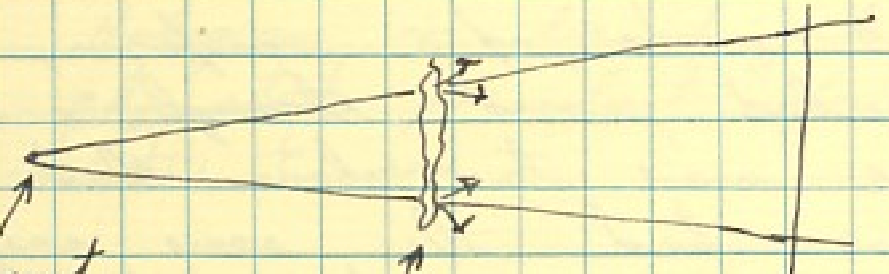
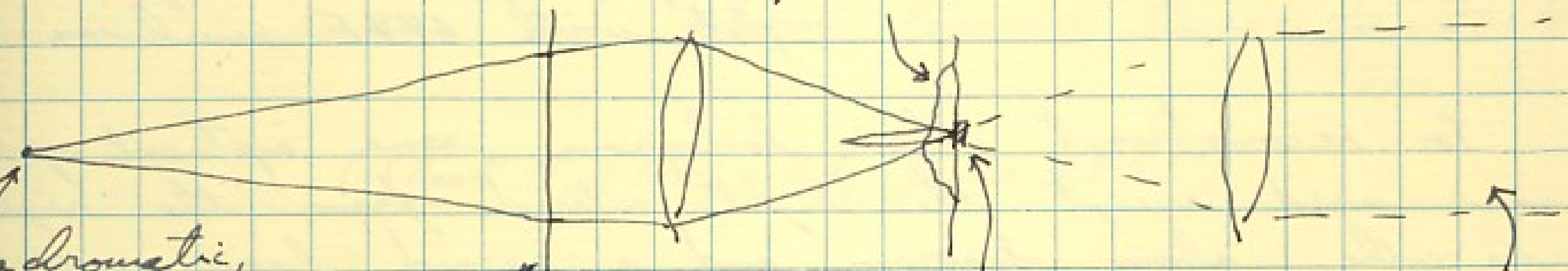
28 June 1965

A way of making such a transparency is shown here:



One way to recover the a.c. components without the d.c. term is shown below. The second lens may be omitted.



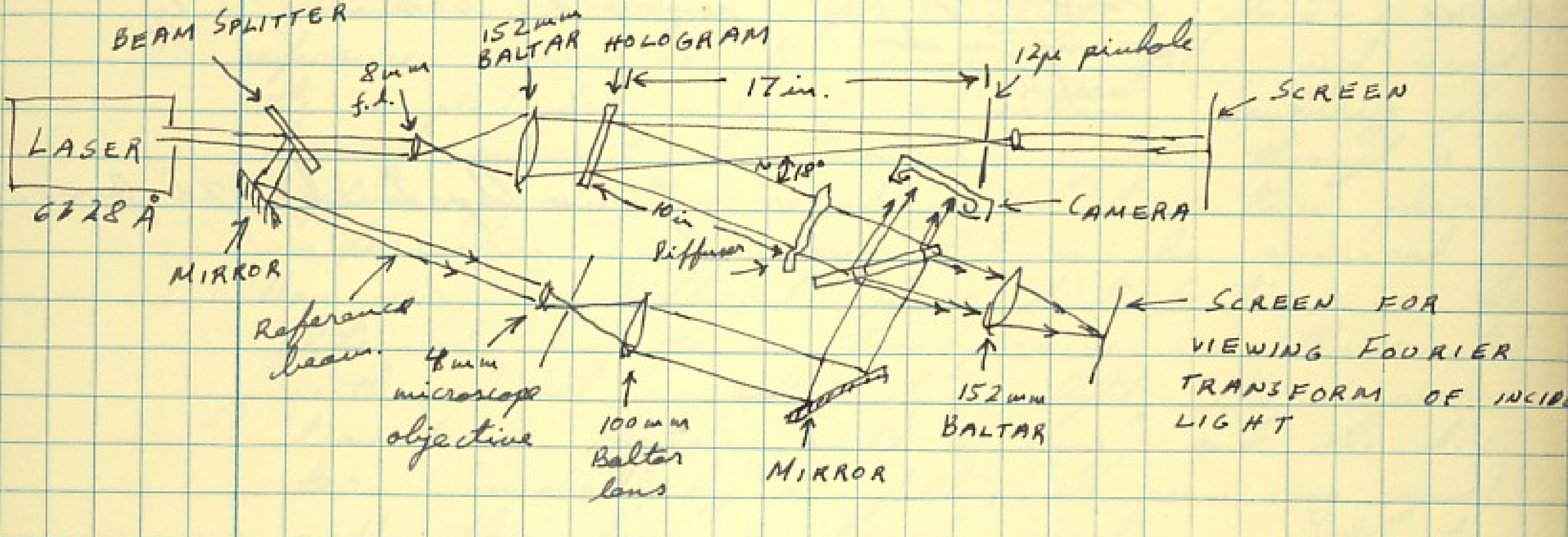
Juris Upatnieks, 28 June 1965

29 June 1965

Experiments with phase-encoded signal beam.

A hologram was made of a uniform, plain signal beam that had passed through a diffuse glass. The purpose was to show that the reconstructed wave had the same original uniform phase. The experimental optical system for making the hologram is shown below:

To reconstruct the hologram, same optical system was used except the light entered from the right in the above diagram, and a second beam was introduced as a reference:



Pan-X film in Exacta camera was used to record the interference pattern between the reconstructed beam and the reference beam.

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29 June 1965

Film recordings show (Sheet # 014, 29 June 1965):

\#3 Hologram in liquid gate, with Xylene as the liquid, adjusted for best fringes. Exposure times: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{50}$, $\frac{1}{25}$, $\frac{1}{5}$ sec.

\#4 Same as #3 but with a thin wire (#20) in front of the emulsion to simulate defects in emulsion. Exposure times: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{50}$, $\frac{1}{25}$ sec.

\#5 Same as #3, film developed for higher contrast. Exposure times: $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

\#6 Diffuse glass screen removed, otherwise setup same as above. Exposure times: $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

(Sheet # 015, 29 June 1965)

\#1 Photographs of the optical system for reconstructing a plane wave, as shown at bottom of p. 130.

\#2 Same setup as #1, film developed for higher contrast.

The hologram was made on 24 June 1965 on $\frac{1}{4} \times 1\frac{1}{2} \times 4$ in. microflat glass plate with Kodak 649 F emulsion, developed in D-19 for 6 min. Reading on S.+M. light meter was 35×10^{-2}, exposure time $1\frac{1}{2}$ sec.

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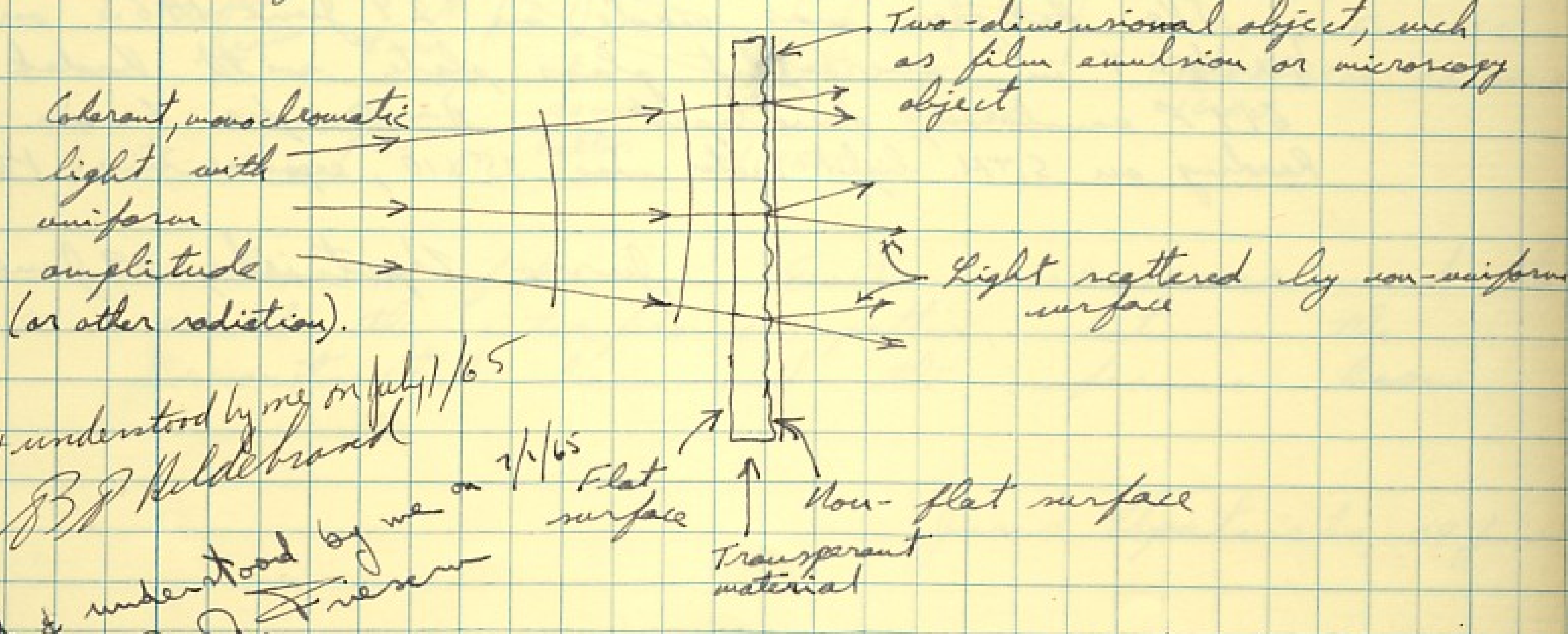
1 July 1965

Technique for improving the quality of two-dimensional holograms.

It has been customary to use two types of illumination for transparencies: diffuse light from a ground glass for large transparencies without ~~a~~ fine detail, and plain uniform wavefr for transparencies with fine detail and for microscope slides. Illumination with light from diffuse glass has the advantage that defects in the hologram do not create annoying diffraction pattern in the reconstruction process.* These diffraction patterns are not visible because it interferes with the reconstructed image where phase is changing from point to point. Diffuse illuminat can~~t~~ not be used with objects containing fine detail because the grain, or amplitude variation of illuminating light is then of the same order of ~~sam~~ size as the desired detail. With the diffuser, the grain size in reconstruction becom objectionable when aperture at the hologram is decreased.

The good qualities of both the diffuse and plaine light illumination can be combined by illuminating the two-dimensional, transparent object as shown below:



Read + understood by me on July 1/65
B J Hildebrand

Read & understood by me on 7/1/65
A. A. Friesem

Juris Upatnieks, 1 July 196

1 July 1965

The light must be of uniform amplitude and suitable for hologram work, that is, it must be coherent and monochromatic. Otherwise it can be collimated, converging or diverging. The light passes through a transparent medium, such as glass for example, and is scattered by the non-flat surface. This surface ~~but~~ refracts light in different directions and is attenuated by the two-dimensional object (or a very thin 3-dimensional object). The object is placed in contact, or very near, the non-flat surface. At the two-dimensional surface the light has uniform amplitude but quickly changing phase from point to point. Therefore graininess is absent but phase changes are present, which both are desirable and should result in reconstructions of higher quality.

At the hologram plane, information from every part of the object will be dispersed over some area of the hologram, possibly the whole hologram with proper choice of the scattering surface. Size of the aperture at the hologram will not create grainy appearance, but will vary the rate of phase change across the reconstructed ~~sto~~ surface of the object.

An application of this technique is in determining accuratly the plane of focus of an object without fine, recognizable detail. Immediatly on eithe side of the infocus plane image becomes grainy in appearance, and is smooth only at the exact in-focus plane.

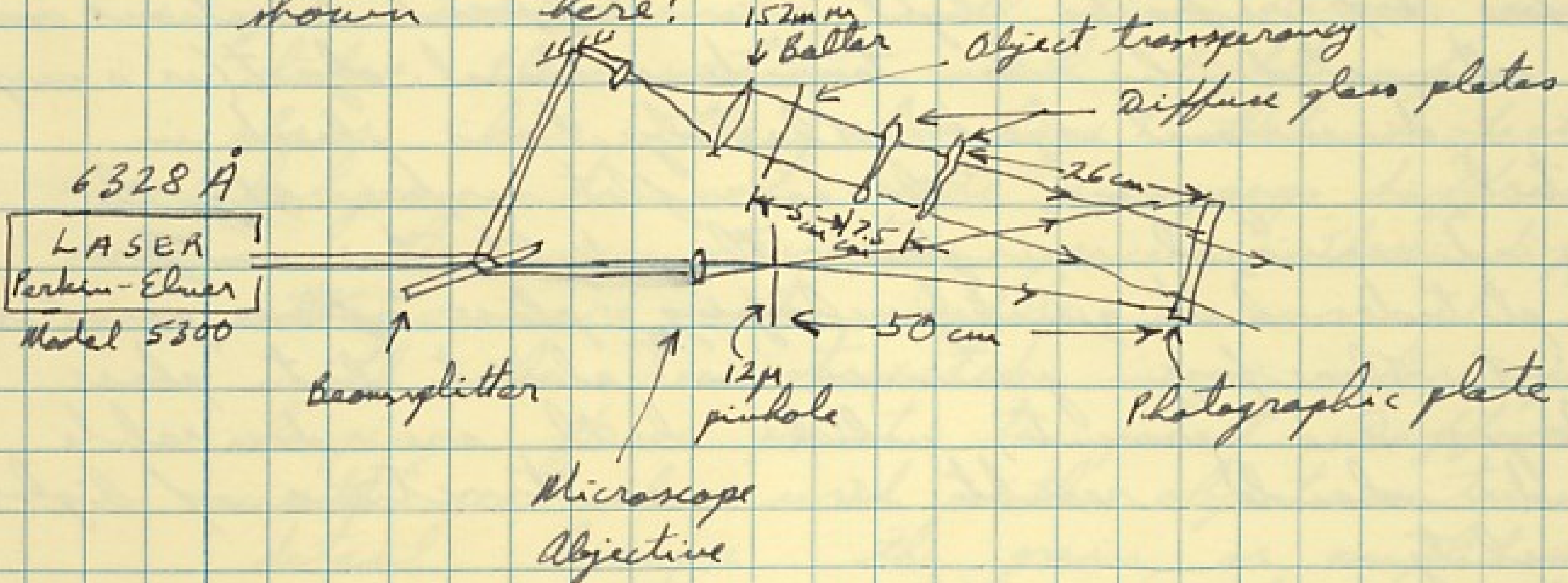
With transparencies as objects, emulsions themselves could be made of nonuniform thickness.

ead & Understood by me on July 1/1965 Juris Upatnieks, 1 July 1965
B P Hildebrand
ead & understood by me on 7/1/65

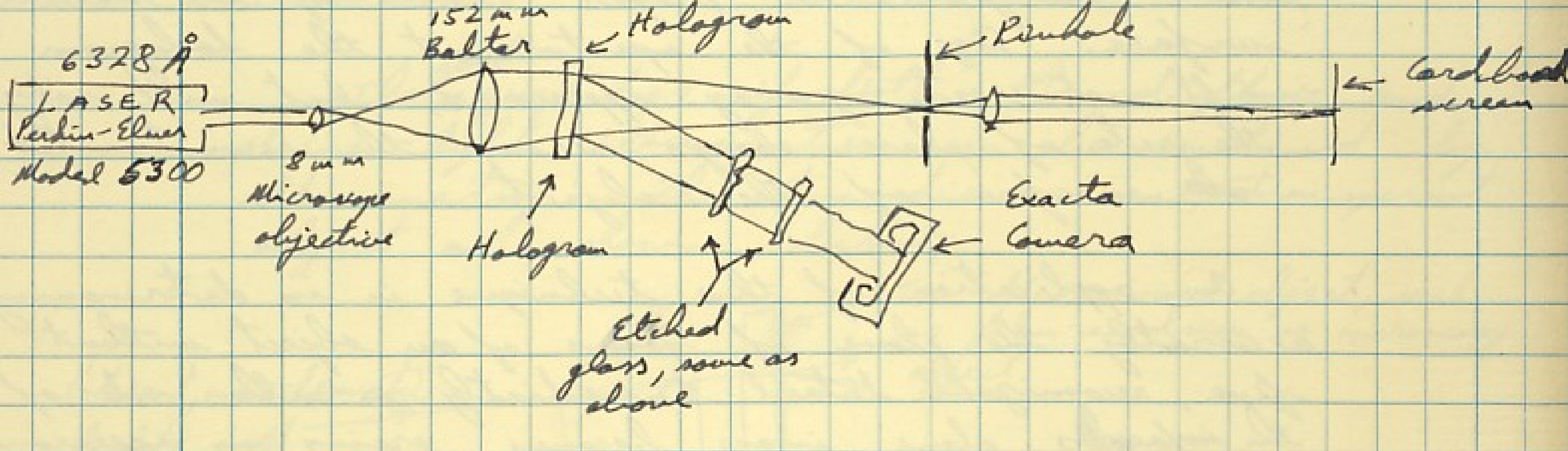
8 July 1965

Experiments with phase-encoded signal beam.

A hologram was made of an object consisting of transparent letters on opaque bacground through two diffuse glass plates. The diffuse glass plates were plates with both sides etched. The optical system for making the hologram is shown here:



The hologram was reconstructed using the same system except that light was focused on the pinhole through the photographic plate:



The reconstruction was not more diffucult than with a single etched glass plate and in one way better: that part of light which did not contribute to the reconstructed image was scattered more by the second diffuser and thus had lower intensity.

Juris Upatnieks, 8 July 19

8 July 1965

Pan-X film was used to record the reconstructed image, and it was developed for normal contrast.

Film recordings show (sheet #015, 8 July 1965):

#3 System adjusted for best focus, no liquid gate. Exposure times: $\frac{1}{500}$, $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$ sec.

#4 Same as above, system readjusted for best focus. Exposure times: $\frac{1}{250}$, $\frac{1}{100}$, $\frac{1}{25}$, $\frac{1}{5}$, $\frac{1}{2}$ sec.

Juris Upatnieks, 8 July 1965

11 October 1965

Experiments with animated motion.

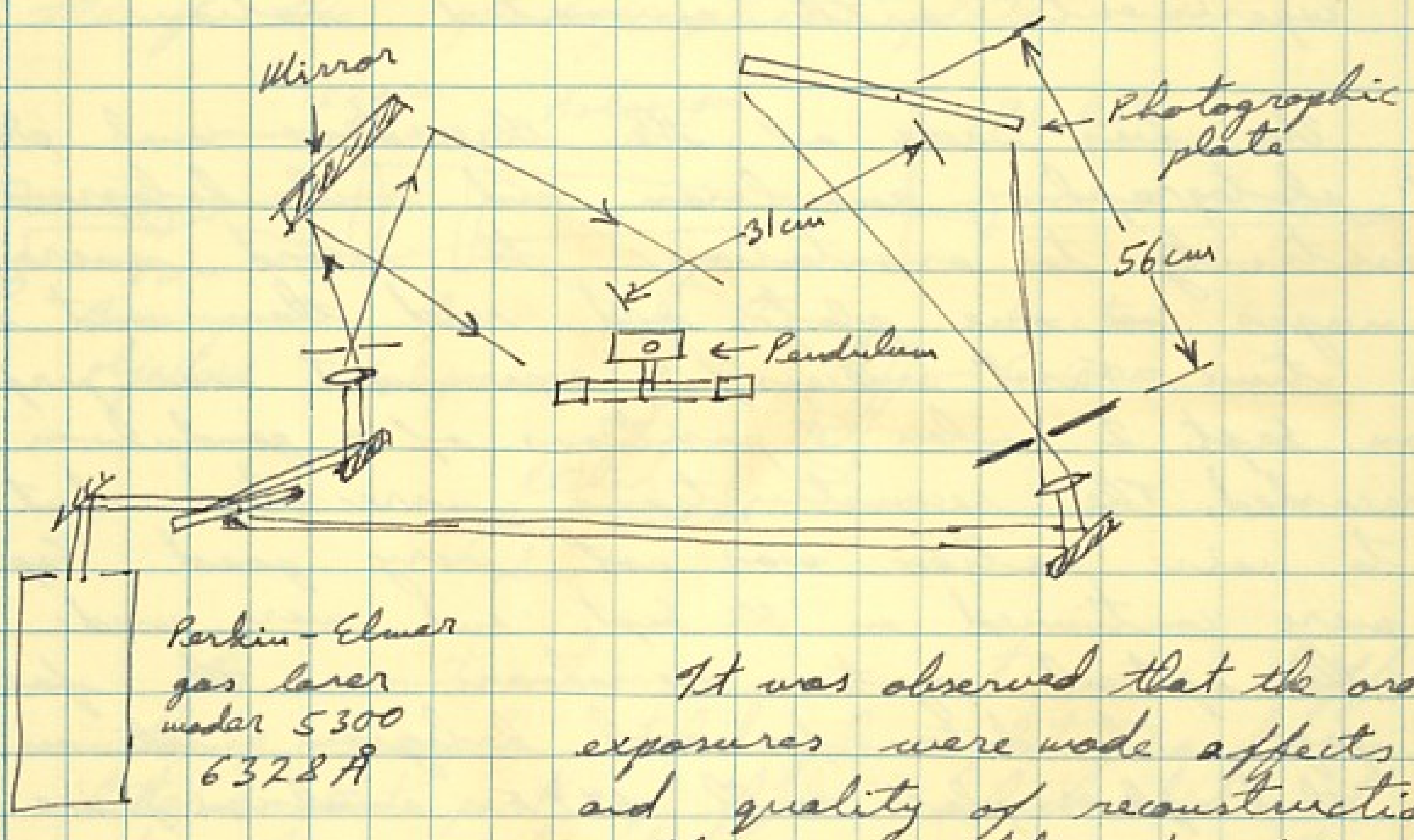
Use was made of the three-dimensional properties of photographic emulsion, and such hologram's sensitivity to orientation, to record several images on one plate and read them out one at a time. First successful experiment was performed on Sept. 2 when 5 positions of a pendulum were recorded. The reconstructions were clear, but signal to noise ratio was not very good. Experiments were continued on 30. Sept. and were made with the optical system as shown on the following page. The data for each hologram, made on 0.060 in. thick glass plate with 649F emulsion, are as follows:

Juris Upatnieks, 11 October 1965

11 October 1965

Date of exp.	Intensity of light	Exposure times	Comments
30 Sept. '65 ~~4 Oct. 19~~	8×10^{-3} ref., 4×10^{-3} signal	One exp., 3 min.	overexpose on $1\frac{1}{3} \times 4 \times \frac{1}{4}$
4 Oct. '65	33×10^{-4} ref. 11×10^{-4} signal	One exp. $3\frac{1}{2}$ min.	Somewhat overexposed
5 Oct. '65 (#1)	35×10^{-4} ref. 10×10^{-4} signal	Total exp. 175 sec. (7 exp. each 25 sec.)	Overexposed, f images reconst
5 Oct. '65 (#2)	18×10^{-4} ref. 8×10^{-4} signal.	Total exposure 280 sec. (7 exp. 40 sec. each)	Slight overexp. vibration, ord reversed
5 Oct. '65 (#3)	36×10^{-4} ref. 8×10^{-4} signal	Total exp. 120 sec. (6 exp. 20 sec. each)	Exp. good, vib present, or reversed
6 Oct. '65	27×10^{-4} ref. 12×10^{-4} signal	Total exp. 170 sec. (7 exp. 24 sec. each)	Very good holo all 7 images a

The optical system used is shown below:



It was observed that the order in whic exposures were made affects the numbe and quality of reconstructions. Best results were obtained if first the photog plate was oriented toward the subject, then rotated toward the reference If in reverse order exposures were made, some images did not reconst

Juris Upatnieks, 11 October 1

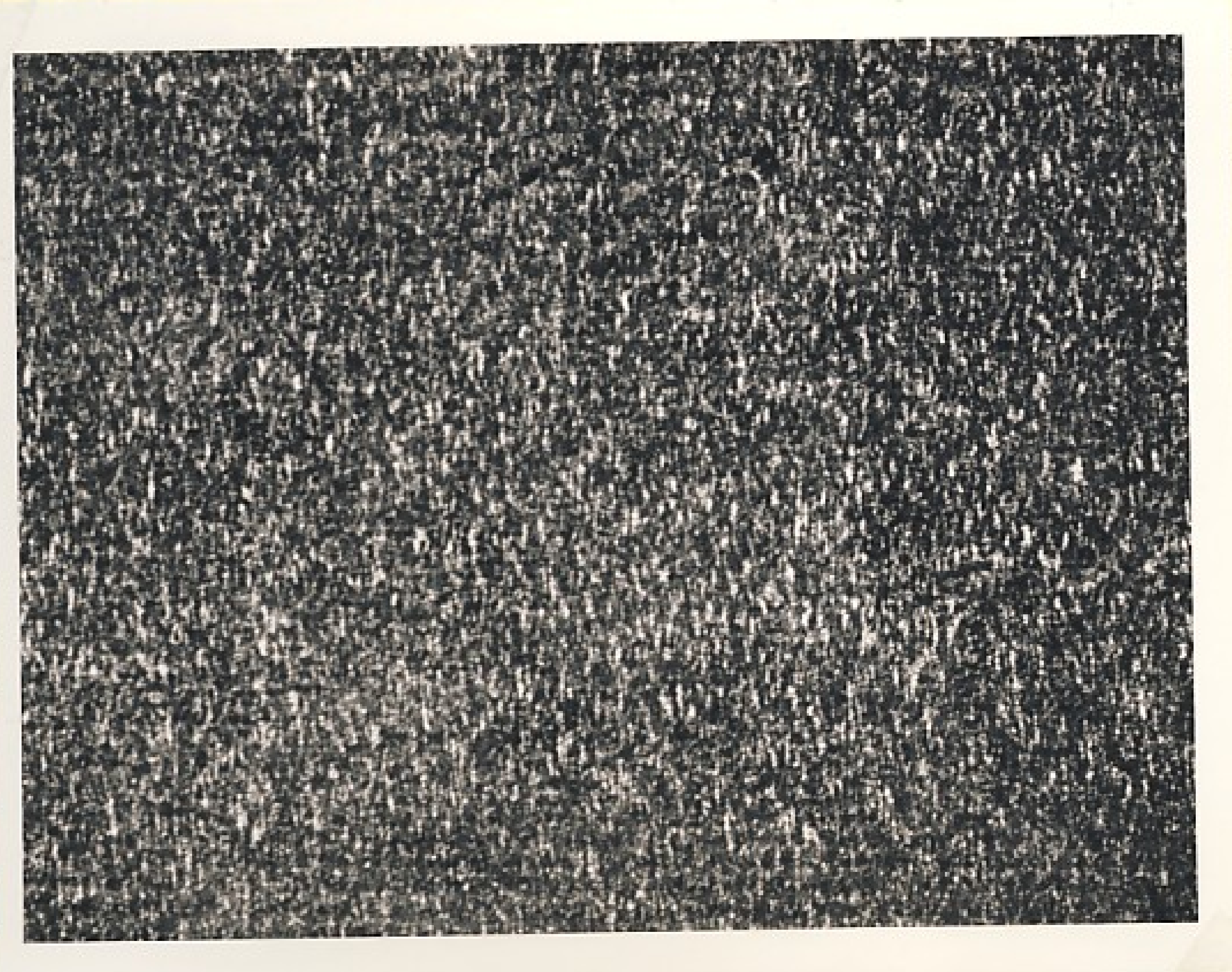
12 October 1965

Experimental results with phase-encoded signal and reference beams

Reconstruction (#014-5)

In this photograph the interference between a plain reference wavefront and a reconstructed wavefront through diffuse glass is shown. The granular appearance indicates that some light is scattered, that is, reconstruction is imperfect.

Reconstruction (#014-6)

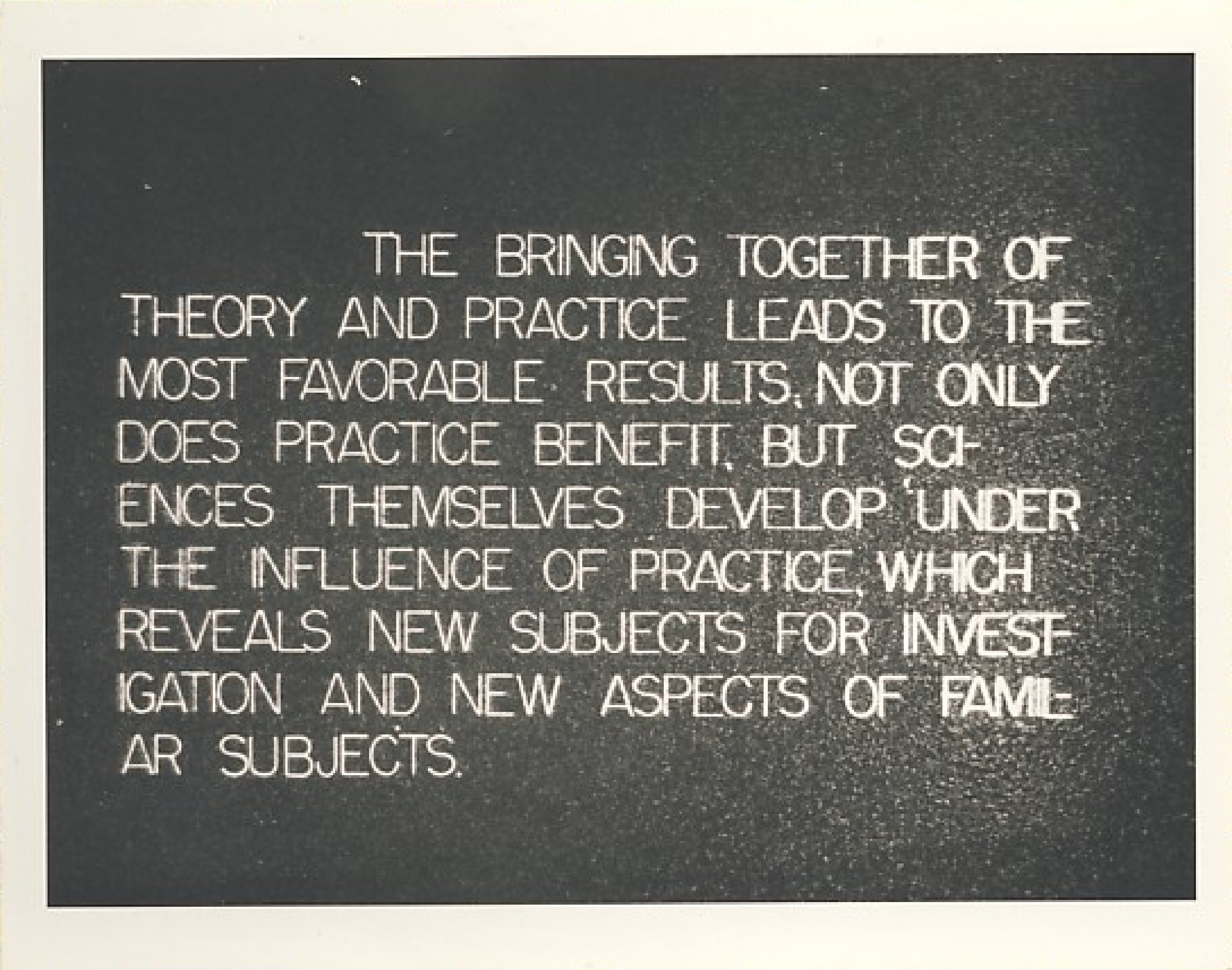


This photograph was made in an identical manner to that above, except the ground glass screen was removed. Thus phase was not corrected and the resulting beam was grainy in appearance. This, mixed with reference beam, still gives grainy appearance.

Juris Upatnieks
12 October 1965

12 October 1965

Reconstruction (#013-4)



THE BRINGING TOGETHER OF THEORY AND PRACTICE LEADS TO THE MOST FAVORABLE RESULTS. NOT ONLY DOES PRACTICE BENEFIT, BUT SCIENCES THEMSELVES DEVELOP UNDER THE INFLUENCE OF PRACTICE, WHICH REVEALS NEW SUBJECTS FOR INVESTIGATION AND NEW ASPECTS OF FAMILAR SUBJECTS.

This photograph sho
the reconstructed virt
image from a hologr
made with plane-w
reference beam. To
reconstruct, an idea
beam was used.

See p. 125 and
126 for details
of the experiment.

Juris Upatnieks, 12 Oct. 1965.

15 October 1965

Hologram displays.

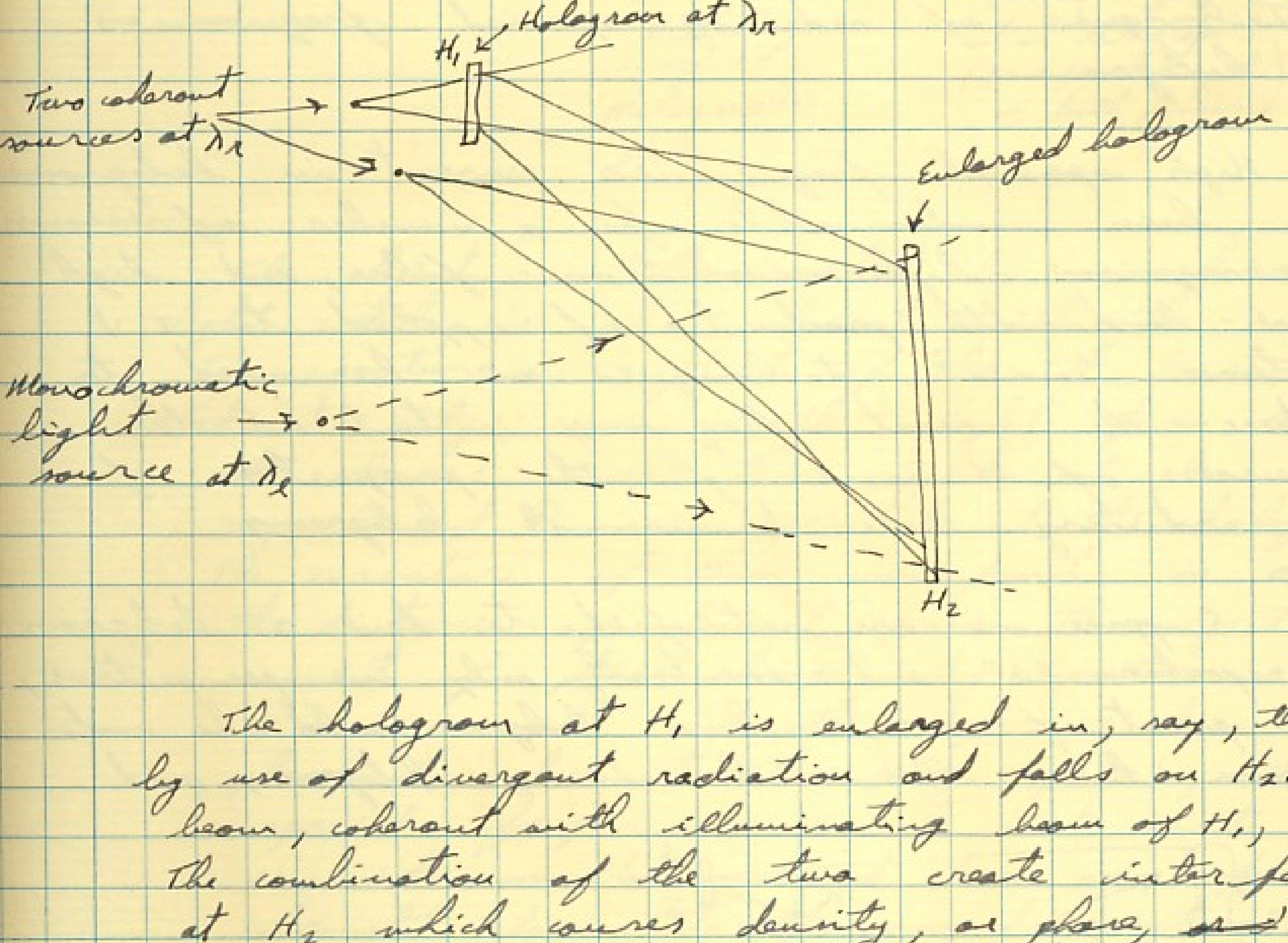
One of the major problems of using three-dimensio
holograms for display purposes is that its size
has to be large in order that many observers can
see it at once. This problem is especially great
in the case of motion pictures, where 16 to 24
frames per second would have to be displayed.
It would be convenient to use a small hologram
and project it on the screen, but this causes

Juris Upatnieks, 15 October 1965

15 October 1965

the loss of the three-dimensional effect. One could, however, in principle record enough information on a small hologram for a large hologram if shorter wavelength were used. For example, if $\lambda_r = \frac{\lambda_e}{100}$, where λ_r is wavelength of the hologram which contains the record, and λ_e is the visible light wavelength, then enough information for a 100 X 100 cm hologram at visible wavelength could be stored on a 1X1 cm hologram at the shorter wavelength.

Assuming that the desired information is on the 1X1 cm hologram, it has to transferred to the larger hologram, that is, the larger one has to be made from the smaller one. This could be accomplished by the optical system as shown below:



The hologram at H_1 is enlarged in, say, the ratio $\frac{\lambda_e}{\lambda_r}$ by use of divergent radiation and falls on H_2. Also a reference beam, coherent with illuminating beam of H_1, falls on H_2. The combination of the two create interference pattern at H_2 which causes density, or phase, ~~and~~ variations, or variations of both for the wavelength at λ_e. The hologram at H_2 is large and its reconstruction could be viewed by many observers at once.

Juris Upatnieks, 15 October 1965

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The material of H_2 must be such that its density and/or phase variation occurs instantaneously. Then, if H_1 is rapidly changed as in ordinary motion pictures, H_2 will also change. The phase and/or density changes must affect radiation at λ_e; at λ_r, it does not have to change.

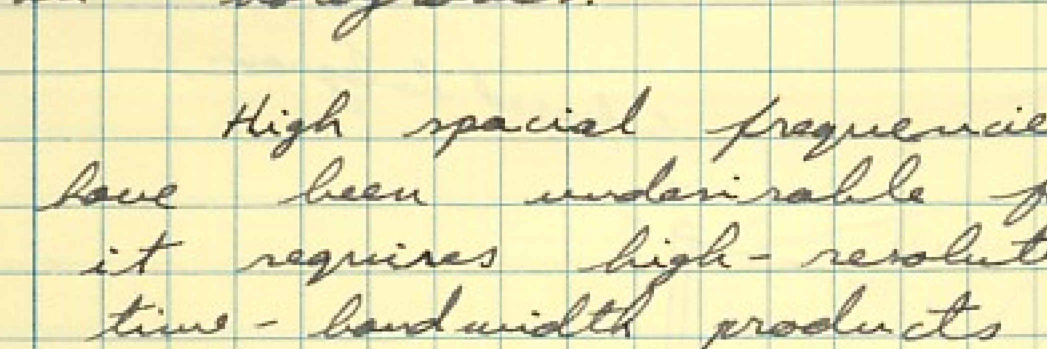
Juris Upatnieks, 15 October 196

21 October 1965

Techniques of reducing spacial frequencies in holograms.

High spacial frequencies present in holograms have been undesirable for a number of reasons: it requires high-resolution film, and high time-bandwidth products if applied to T.V. systems. Several techniques can be used to reduce the spacial frequency content at the expense of ~~t~~ some of the properties of the ordinary three-dimensional holograms.

Suppose we are satisfied to have a hologram of aperture "a" and essentially only one perspective, or point of view. Such a hologram could be made as shown below. This is the ordinary hologram, and



Juris Upatnieks, 21 Octobe

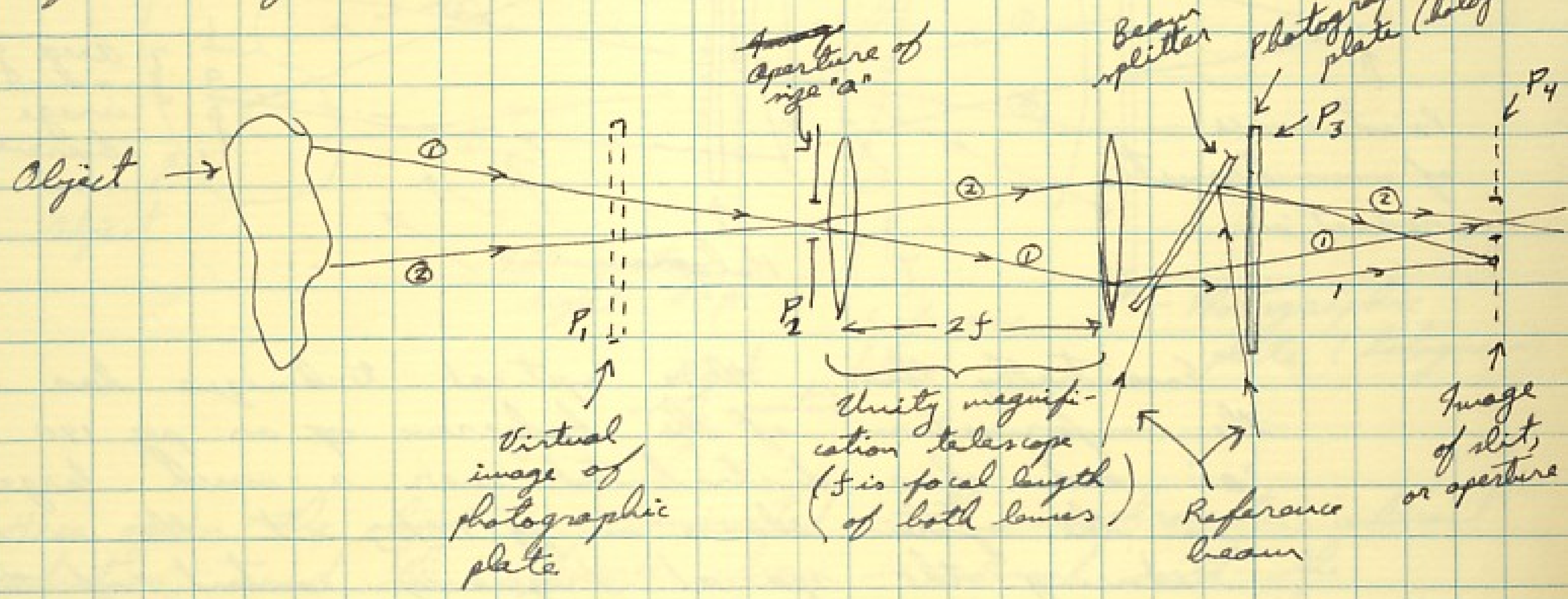
Read & understood A. Friesem, 22 Oct

Read & Understood. R.L. Powell Oct 22,

21 October 1965

the frequency content is determined by maximum angle between light reflected from the object and the reference beam. This angle has to be somewhat greater than α.

The same information recorded on a hologram of size "a" can be recorded in a different way at much lower spacial frequencies. The optical system for doing this is shown below:



The object is illuminated by monochromatic, coherent light which is also coherent with the reference beam. The aperture in front of the 1st lens, of size "a", admits only some of the light from the object, and the lenses image this light at plane P_4. Note that rays ① and ② are separated at the hologram plane P_3. The curvature of these wavefronts is determined by the distance of plane P_1 from the object, and the amount of phase change by aperture "a". If aperture "a" is small and the reference beam focused on plane P_4 close to the image of "a", then the spacial frequencies can be made quite small. As "a" is made smaller and pt. focus of reference beam is brought closer to the imaged aperture "a", the spacial frequency content of hologram at P_3 will approach zero. Yet the hologram, when

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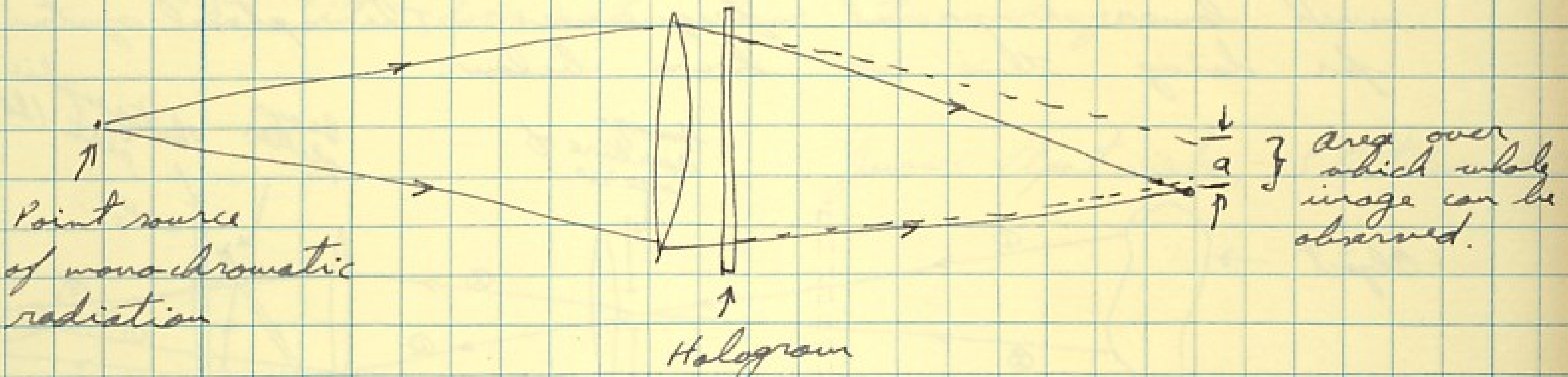
21 October 1965

viewed over the aperture "a", will appear exactly as the regular three-dimensional hologram of size "a" on pg. 140. The hologram made in this manner can be displayed as follows:



Essentially then, this optical technique has taken the information of the hologram ~~of~~ on pg. 140 of size "a" and has distributed over a much larger are in the system shown on pg. 141, at the same time reducing the spacial frequency content of the holog In this case, the spacial frequency has been reduced at the expense of eliminating all but one perspective, or point of view.

As compared to the ordinary large-size hologram, the brightness is greatly increased by this scheme. The large-size hologram diffracts light in many direction and the observers eye collects only a small part it at a time. With the hologram described here, all of the diffracted light falls in the small area "a". Thus, the brightness will be increased by several orders of magnitude.

Since light from each part of the object falls on a different part of the hologram, the hologram could be made by illumi each part of the object by a pulse of light, simultaneou providing the reference beam for the corresponding pa

Juris Upatnieks, 21 October

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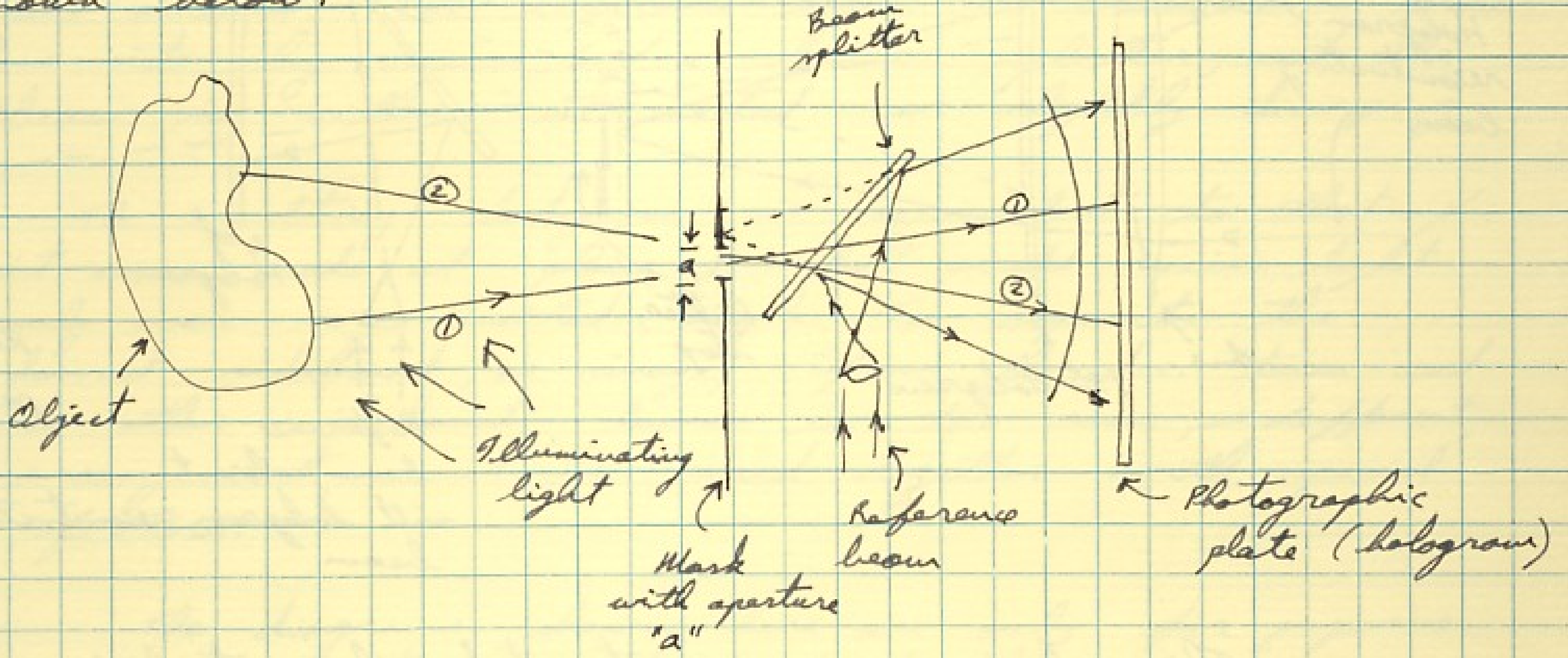
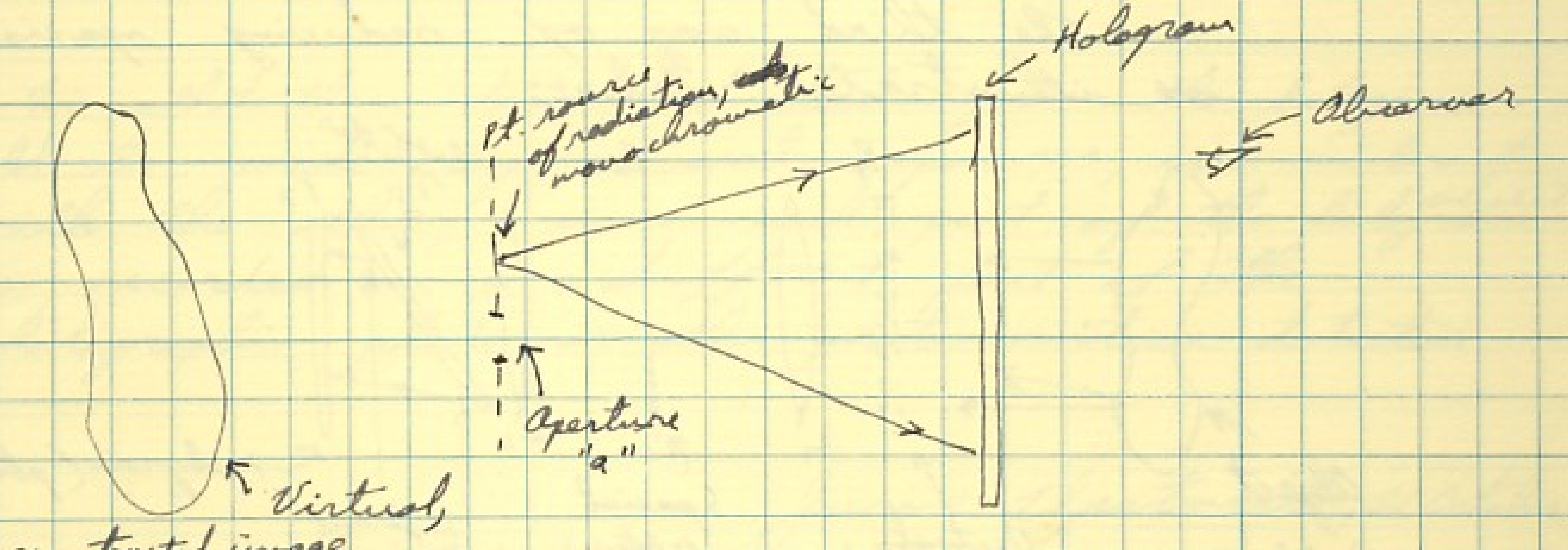
21 October 1965

of the hologram. The d.c. buildup would be absent, or small, since successive exposures would fall on different parts of the hologram, or overlap only slightly.

Another way of reducing spacial frequencies is shown below:



Here again the object is illuminated with monochromatic, coherent radiation, and the reference beam is coherent with the illuminating beam. The virtual point source for the reference beam is in the plane of the aperture "a", and slightly to one side of it. Since the wave front of the reference beam is nearly parallel to that signal, low spacial frequencies result. Reconstruction is done as below:



The reconstructed virtual image appears to be behind an aperture of size "a". Thus, an observer can see only a small part of the reconstructed image at one time. This can be corrected

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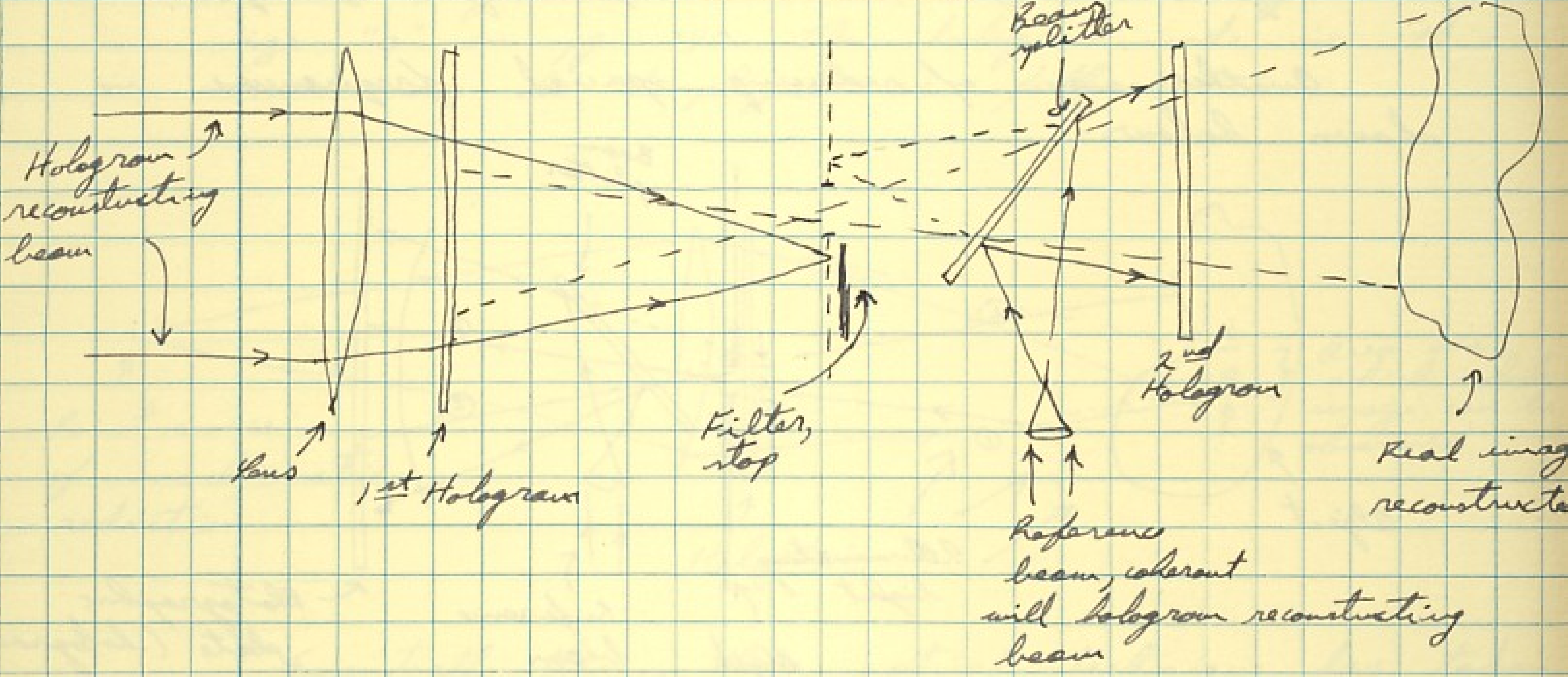
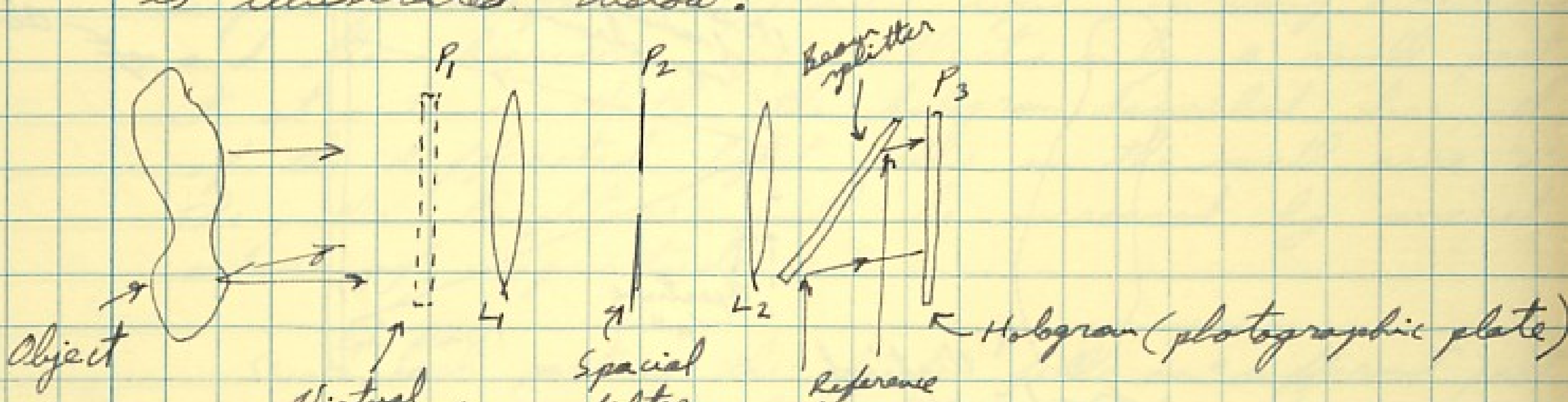
if a second hologram is made from the first one in the following manner:



The real image is reconstructed, the virtual image and d.c term is removed by a spacial filter, and a 2nd holog made from the 1st one. The virtual point source of the reference beam is made to fall in the plane of the reconstructed aperture. Thus, the 2nd hologram, will be the same to all appearances to that made with the lenses and described before.

The third way of reducing spacial frequencies is illustrated below:



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The lenses L_1 and L_2 make up a unit magnification telescope, and a spacial filter is placed between the lenses. Since this filter allows only a limited range of spacial frequencies to pass through, the spacial frequencies arriving at plane P_3 is limited to the same amount. The reference beam is brought in from one side by means of a beam splitter, and the beam is either collimated or slightly diverging.

The resulting hologram is equivalent to that if it were made at plane P_1 but would receive light only over very limited angle. To seperate the desired sideband, or image, from the d.c. term and the other sideband, lenses in the same, or different, arrangement must be used together with spacial filters.

The diagrams shown here are only for purposes of illustration, and are not the only ways of accomplishing spacial frequency reduction. The holograms could be detected and/or recorded on any suitable photo-sensitive detector. Other radiation than light could be used; and possibly other ways than using a beam splitter could be employed to introduce the reference beam.

In all the three described techniques the hologram could be made by several exposures, each incoherent with the other, since each part of the ~~hologram~~ object is recorded on a different part of the photographic plate, or other photosensitive detector.

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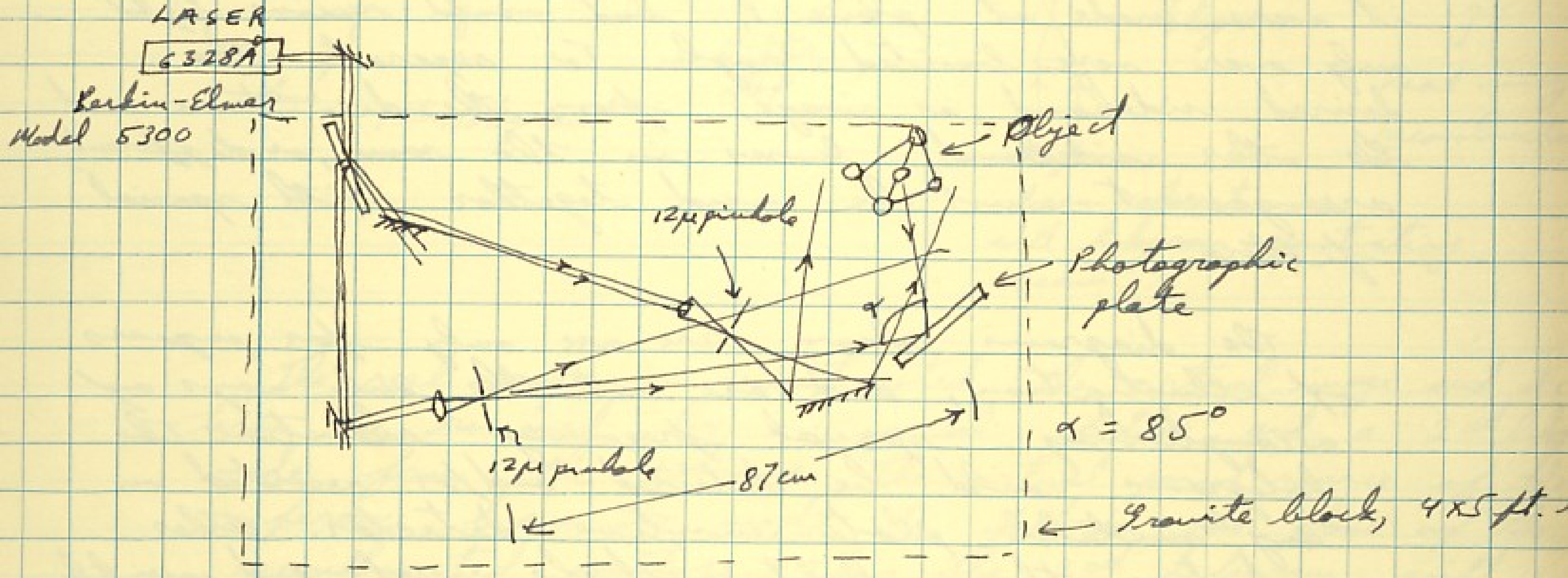
Experiments with animated motion.

Several additional experiments were made in an attempt to improve the quality of animated holograms. The pendulum seemed to vibrate slightly, so a different object was chosen. This was a small toy consisting of nine spheres separated by rods. A different optical system was also used:



Both the object and photographic plate were set on rotating stage so that they could be rotated through a set number of degrees. The first exposures on the photograp plate made with face of the plate toward the object, and then roted toward the reference beam in successive exposures. All the components on the granite block were enclosed in a cover, so that air disturbances were kept down to a minimum. All plates were developed in Kodak D-19 for 6 minute

Exposure data are summirized in the following table. Intensity readings were made with a Science + Mechanics light meter.

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Date	Light Intensity	Exposure time	Comments
12 Oct. '65	25×10^{-4} ref. 14×10^{-4} sig.	Total exp. 170 sec. (8 exp. 24 sec. each.)	Exposure good, pendulum appears to be vibrating
13 Oct. '65	20×10^{-4} ref. 15×10^{-4} sig.	Total exp. 190 sec. (27 sec. each, 7 exp.)	Exposure good, pendulum not very bright
18 Oct. '65 #1	22×10^{-4} ref. 9×10^{-4} sig.	Total exp. 200 sec. One exposure	Subject: 9 steel balls, excellent reconstruction
" " " #2	22×10^{-4} ref. 10×10^{-4} sig.	Total exp. 175 sec. (7 exp. 35 sec. each)	Exposure good
19 Oct. '65 #1	20×10^{-4} ref. 9×10^{-4} sig.	Total exp. 190 sec. (7 exp. 27 sec. each)	$\frac{1}{4}$" plate Somewhat underexposed
" " " #2	24×10^{-4} ref. 10×10^{-4} sig.	Total exp. 245 sec. (7 exp. 35 sec. each)	1/4" plate, exposure good (light)
" " " #3	22×10^{-4} ref. 10×10^{-4} sig.	Total exp. 250 sec. (5 exp. 50 sec. each)	$\frac{1}{4}$" plate, exp. good (light)
20 Oct. '65 #1	25×10^{-4} ref. 12×10^{-4} sig.	Total exp. 245 sec. (7 exp. 35 sec. each)	$\frac{1}{4}$" plate, exp. good Obj. vibrated in one frame?
#2	25×10^{-4} ref. 12×10^{-4} sig.	Total exp. 245 sec. (7 exp. 35 each.)	1/4 plate, exp. good Object vibrating in one frame
#3	24×10^{-4} 11×10^{-4}	Total exp. 240 sec. (7 exp. 34 sec. each)	$\frac{1}{4}$" plate, exp. good Looks good.

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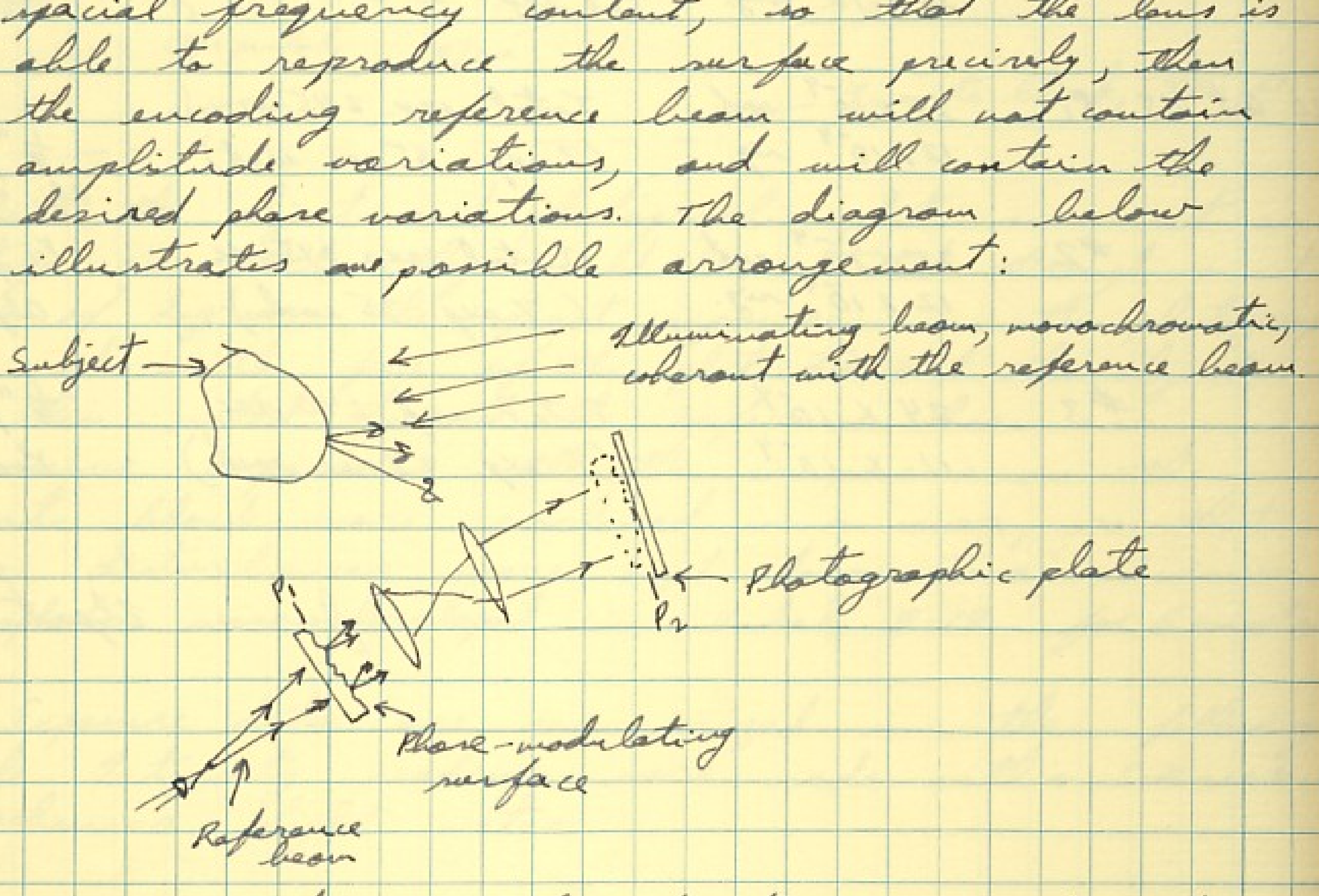
Improved technique for encoding referance beam, and for reproducing two-dimensional objects.

On pages 97 to 101 of this notebook the characteristics of phase-encoded reference beam holograms was described. One of the defects of this type of encoding was that the referance beam at the hologram recording plane had both phase variations, which are desirable, and amplitud variations, which are undesirable. The amplitude variations introduce noise which cannot be removed in the reconstruction process from the desired signal.

A way to eliminate the amplitude variation at the surface of the hologram plate is to image the surface of the diffuser on the hologr plate. If this diffuser has sufficiently low spacial frequency content, so that the lens is able to reproduce the surface precisely, then the encoding reference beam will not contain amplitude variations, and will contain the desired phase variations. The diagram below illustrates one possible arrangement:



P_1 is imaged on P_2 by the two lenses. The rest of

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the system is standard for making holograms.

The imaging of pure phase-variations can also be applied to another case, described on p. 132 + 133. If the phase-modulated plane is projected on an essentially two-dimensional object, such as a photographic transparency or a microscope slide, then the hologram made of such an object will contain the desirable properties of phase-modulated images and will not contain the undesirable properties of amplitude modulated illuminating beam, or noise.

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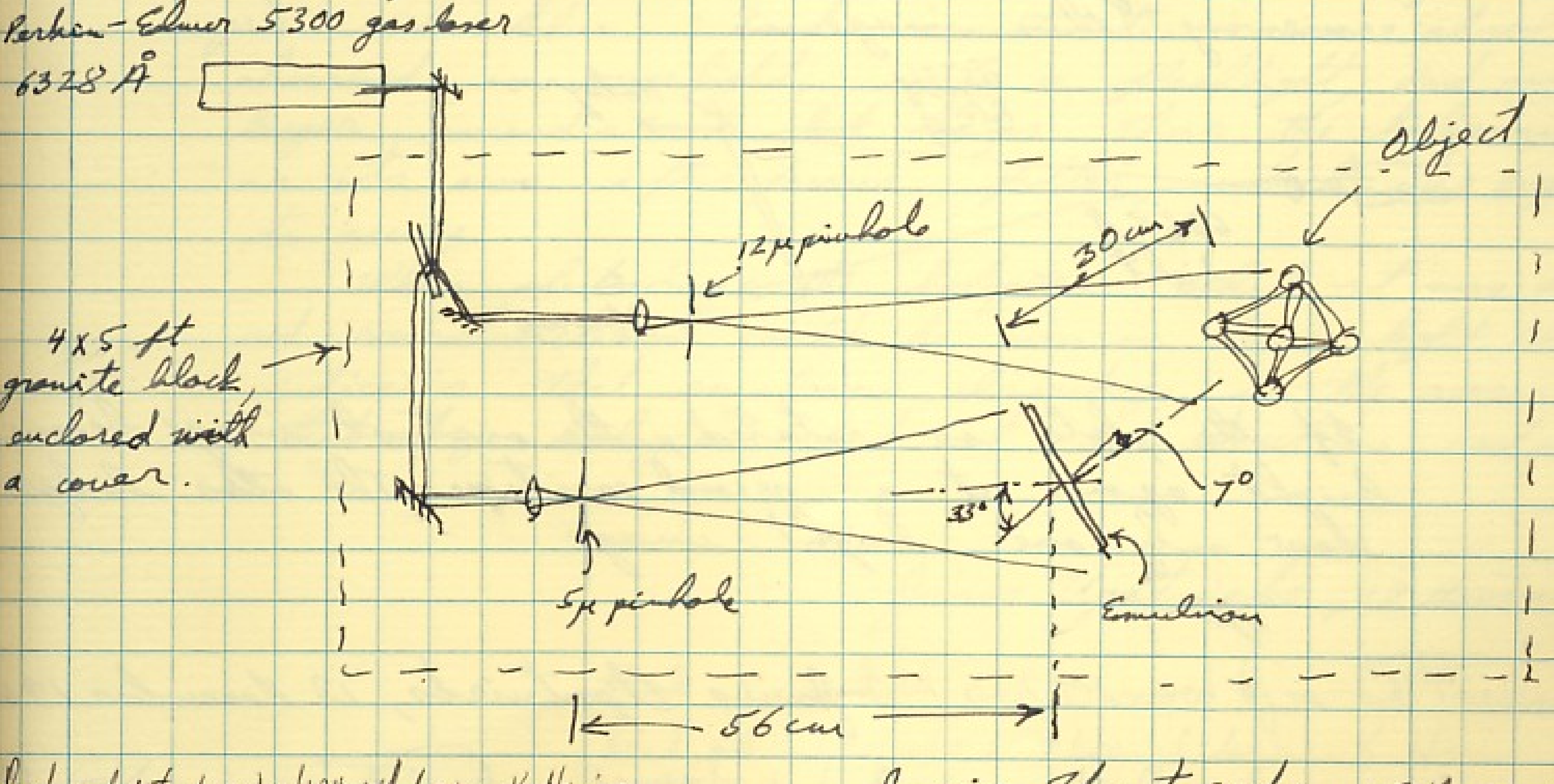
Holograms made with reference beam from the back side of the photographic plate.

Several holograms were made on 4×5×1/8 in. glass plates with 649 F emulsion and the reference beam coming from behind. The optical system is as follows:



Read, understood and observed by me, K. Haines
Nov. 17, 1965

Juris Upatnieks, 12 November 1965

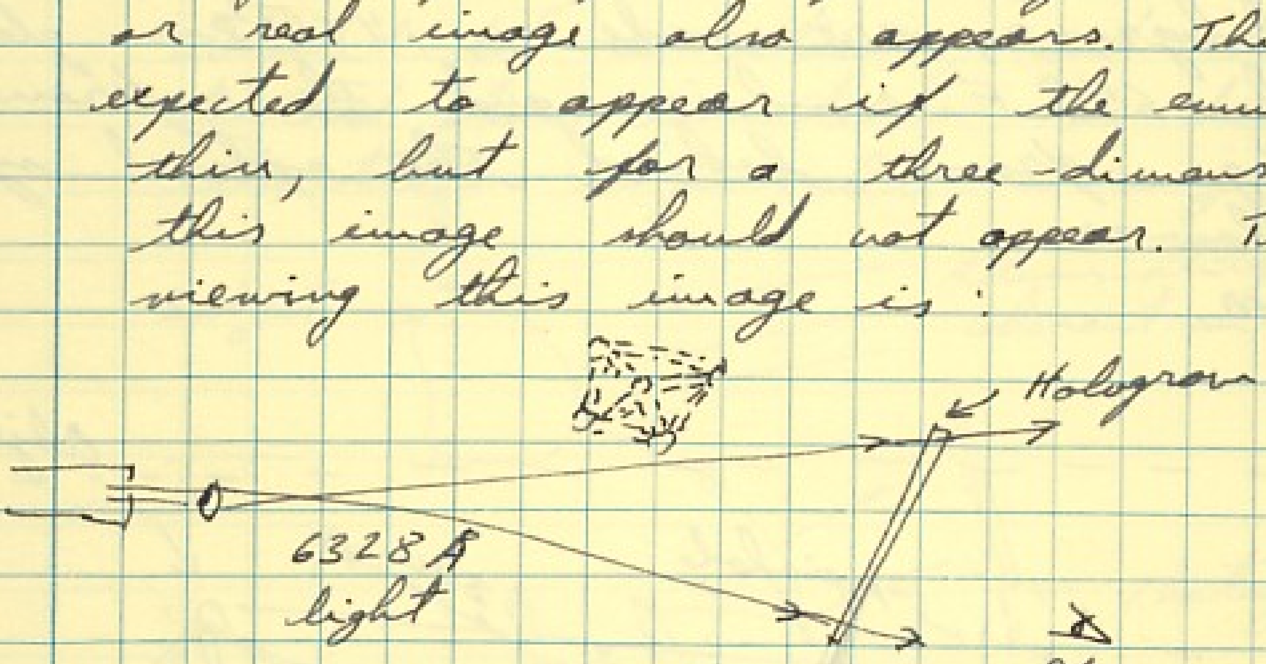
Read, understood & Observed A. Friesem, Nov. 15, 65

12 November 1965

One exposure was made ~~each day of~~ on 8 Nov. 65 and two 9 No
but only partial reconstruction was obtained becau
most of the plate was vibrating. By using a
better plate holder, good holograms were obtaine
Data pertaining to these are as follows:

Date	Exposure reading with S.&M. light meter	Exposure time	Comments
9 Nov. '65 (2nd plate)	22×10^{-4} reference ~~signal~~ 11×10^{-4} signal	150 sec.	Good exposure an good reconstructi
10 Nov. '65	20×10^{-4} reference 11×10^{-4} signal	160 sec.	Good exposure an good reconstructio After bleaching w mercuric cloride, im brighter but noisie

These holograms exibited several interesting
characteristics. When illuminated like the hologra
made with reference beam from the front, an
image of equal quality is visible. The conjug
or real image also appears. This image would b
expected to appear if the emulsion was infinite
thin, but for a three-dimensional recording medi
this image should not appear. The arrangement fo
viewing this image is:



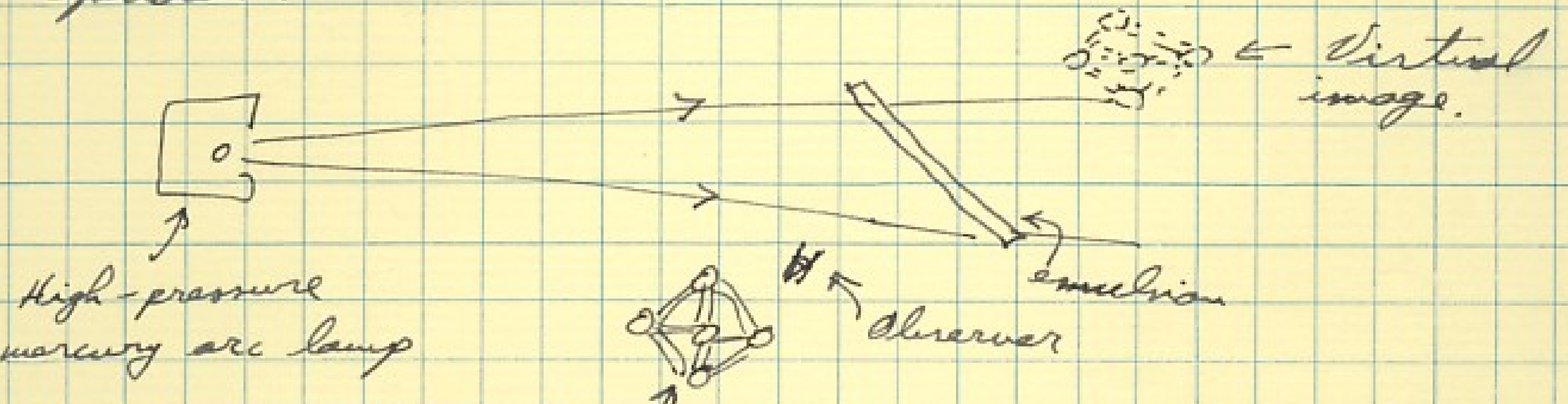
If the plate is rotated, the virtual image become
bright again at a second position. The other hologra
show only one bright image.

Juris Upatnieks, 12 November 196

Read, understood & observed A. Friesem Nov. 15
Read, understood and observed by me K. Haines Nov. 17,

12 November 1965

If the hologram is illuminated in the same way as the referance beam in making it, reconstruction is visible in green through violet light. The hologram does not reconstruct in red light since the emulsion shrinks and thus reduces the spacing between fringes. This image is the one expected from this type of a hologram. If the hologram is turned around, then only the real image reconstructs. The optical system used was as follows:



Although the hologram was viewed in non-monochromatic light, the image appeared to be monochromatic and reasonably well defined. By rotating the hologram, one could obtain reconstructions at all wavelength between green and blue. Good reconstructions were also observed in sunlight, using a flashlight and using larger incandescent ~~[illegible]~~ lamps. Thus the hologram acts as its own ifterferance filter, which was expected to occure.

When observing the hologram while it was drying, red reconstructions could be seen in laser light. This indicates that emulsion shrinkage is the reason that a dry hologram did not reconstruct in red light.

Juris Upatnieks, 12 November 1965

Read, understood and Observed by me A. Friesem 15/11/65
Read, and Understood and Observed by me K. Haines 17/11/65