1.45

COOP COMPUTATION BOOK

NAME	NUMBER
Juris Upatnieks	990

Course

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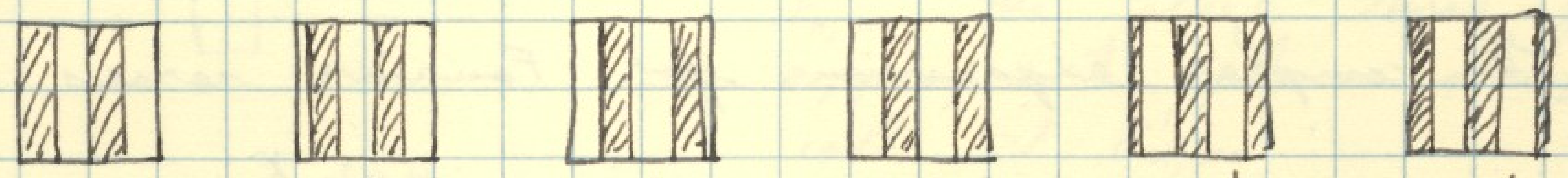
3 July 1968

Calculation of the spectra of pseudo-random phase plate.

The pseudo-random phase plate of Emmett Leith has the following phase distribution, as given by the computation data:

Basic building blocks:



Code designation:	1	ϕ_1	ϕ_2	-1	$-\phi_1$	$-\phi_2$
Relative phase:	0	$-\pi/4$	$-3\pi/4$	$-\pi$	$-5\pi/4$	$+\pi/4$

These building blocks were arranged in the following pattern, which then repeated itself in all directions:

$$\left.\begin{matrix} 1 & \phi_1 & -1 & -\phi_1 \\ \phi_2 & \phi_1 & -\phi_2 & -\phi_1 \\ -1 & -\phi_1 & 1 & \phi_1 \\ -\phi_2 & -\phi_1 & \phi_2 & \phi_1 \end{matrix}\right\}$$

This corresponds to the phase arrangement of

0	$-\pi/4$	$-\pi$	$-5\pi/4$
$-3\pi/4$	$-\pi/4$	$+\pi/4$	$-5\pi/4$
$-\pi$	$-5\pi/4$	0	$-\pi/4$
$+\pi/4$	$-5\pi/4$	$-3\pi/4$	$-\pi/4$

From this we see that the pattern is made up of pure phase patterns. Furthermore these phase patterns are basically square wave patterns without d.c., and the whole array consists of four such patterns with some phase shift introduced between each pattern. On basis of these observations we can calculate the power spectra of this pattern using known Fourier series relationships. We also observe that the carrier frequency is eight times higher than the fundamental phase pattern frequency.

In one-dimensional representation the "0" phase blocks can be represented as shown on the next page.

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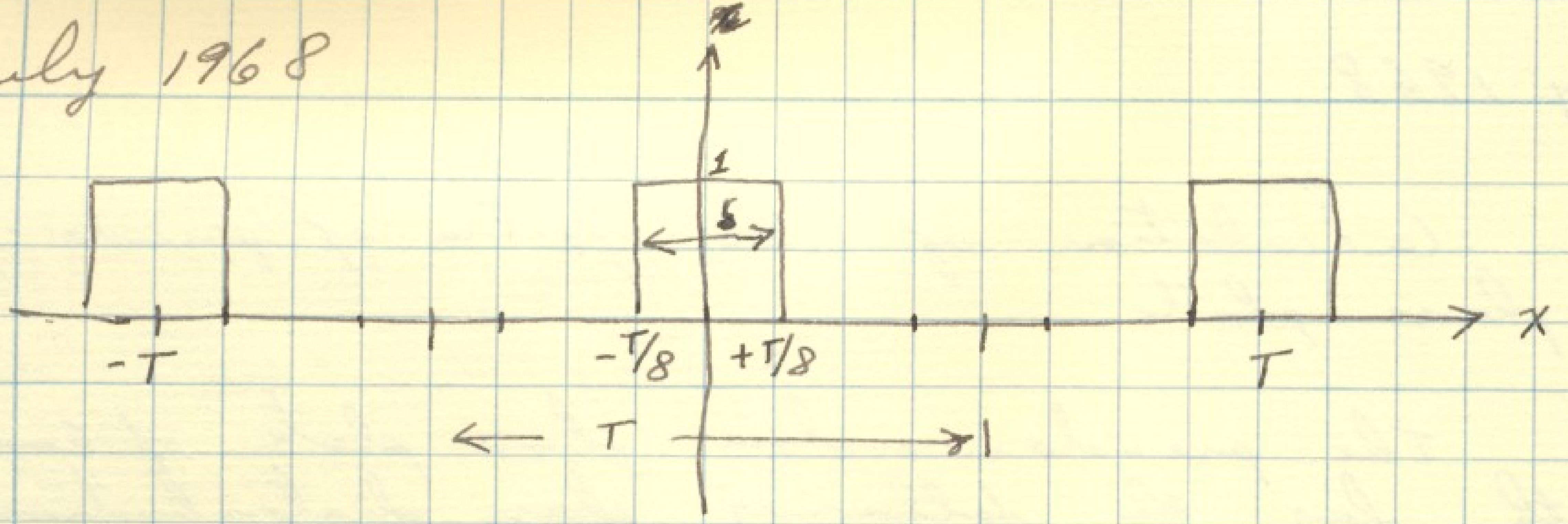

$$f(x) = 1 \qquad -T/8 < x < +T/8$$

$$= 0 \quad \text{elsewhere for one cycle}$$

The complex expression for Fourier series is

$$f(x) = \sum F_n \, e^{j n \omega_{x0} x}$$

For a square wave shown above, coefficients ~~of~~ F_n are given by

$$F_n = \frac{\delta}{T} \frac{\sin(n \omega_{x0} \delta/2)}{(n \omega_{x0} \delta/2)} \qquad \text{where} \qquad \delta/2 = T/8$$

$$\omega_{x0} = \frac{2\pi}{T}$$

$$n \omega_{x0} \delta/2 = n\left(\frac{2\pi}{T}\right)\left(T/8\right) = \frac{\pi}{4} n$$

$$\therefore \quad F_n = \frac{1}{4} \frac{\sin\left(\frac{\pi}{4} n\right)}{\left(\frac{\pi}{4} n\right)}$$

For a two-dimensional transform, the coefficients are given by

$$F_{n,m} = \left(\frac{1}{4}\right)^2 \frac{\sin\left(\frac{\pi}{4} n\right)}{\left(\frac{\pi}{4} n\right)} \cdot \frac{\sin\left(\frac{\pi}{4} m\right)}{\left(\frac{\pi}{4} m\right)}$$

The displacement relationship is

$$\mathcal{F}\left[f(x - x_0, y - y_0)\right] = F_{n,m} \cdot e^{-j(\omega_{x0} n x_0 + \omega_{y0} m y_0)}$$

To include the $-\pi$ points, we observe that

$$x_0 = y_0 = T/2, \quad \omega_{x0} = \omega_{y0} = \frac{2\pi}{T}$$

$$\text{and} \quad x_0 \omega_{x0} = y_0 \omega_{y0} = \frac{T}{2} \cdot \frac{2\pi}{T} = \pi$$

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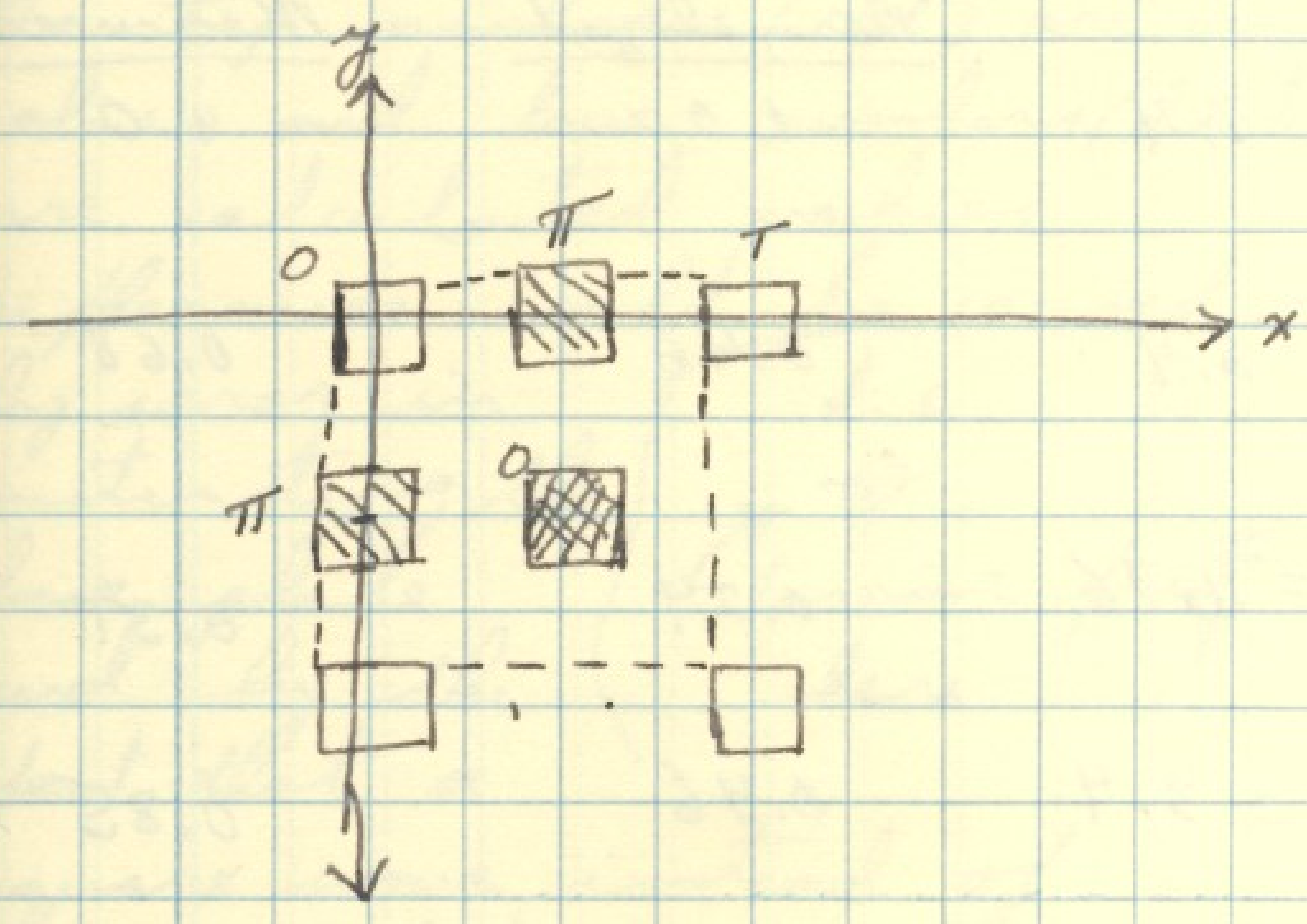
$$\therefore \quad \mathcal{F}\left[f(x - T/2, y - T/2)\right] = F_{n,m}\, e^{-j\pi(n+m)}$$



The area enclosed with dashed lines represents one fundamental cycle in two dimensions. To find the power spectra of the basic phase group having phase $e^{j\pi}$ and e^{j0}, we add to $F_{n,m}$ the other three group with appropriate phase shift and call it $F'_{n,m}$:

$$F'_{n,m} = F_{n,m}\left\{1 + e^{j(\pi n - \pi)} + e^{j(\pi m - \pi)} + e^{j\pi(n+m)}\right\}$$

$$= F_{n,m}\left\{\left(1 - e^{j\pi n}\right) + e^{j\pi m}\left(e^{j\pi n} - 1\right)\right\}$$

$$= F_{n,m}\left\{2 \ (n \text{ odd}) - 2e^{j\pi m} \ (n \text{ odd})\right\}$$

$$= 2F_{n,m}\left\{1 - e^{j\pi m}\right\} \quad n \text{ odd}$$

$$\boxed{F'_{n,m} = 4F_{n,m}, \quad n, m \text{ odd}}$$

We can now find the complete spectrum repeating the above procedure with appropriate phase shifts for each series. The phase shifts can be ~~t~~ obtained from the drawn array on p. 1 and the known translation of each pattern. For this case

$$\omega_{x_0} = \omega_{y_0} = \frac{2\pi}{T}, \quad x_0 = y_0 = T/4$$

$$x\,\omega_{x_0} = y_0\,\omega_{y_0} = \frac{2\pi}{T}\cdot\frac{T}{4} = \frac{\pi}{2}$$

$$F''_{n,m} = F'_{n,m}\left[1 + e^{-j\left(\frac{\pi}{2}n + \frac{\pi}{4}\right)} + e^{-j\left(-\frac{\pi}{2}m - \frac{3\pi}{4}\right)} + e^{-j\left(+\frac{\pi}{2}n - \frac{\pi}{2}m + \frac{\pi}{4}\right)}\right.$$

$$= F'_{n,m}\left[1 + \frac{1-j}{\sqrt{2}}e^{-j\frac{\pi}{2}n} + \frac{-1-j}{\sqrt{2}}e^{j\frac{\pi}{2}m} + \frac{1-j}{\sqrt{2}}e^{j\frac{\pi}{2}(m-n)}\right.$$

This is the equation used for power spectrum calculations.

$$\boxed{F''_{n,m} = F'_{n,m}\left[1 + \left(\frac{1-j}{\sqrt{2}}\right)\left(e^{-j\frac{\pi}{2}n} + e^{j\frac{\pi}{2}(m-n)}\right) + \frac{-1-j}{\sqrt{2}}e^{j\frac{\pi}{2}m}\right]}$$

$$= A_{n,m}\, F'_{n,m} \qquad n, m \text{ are odd}$$

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The calculated coefficients are as follows:

		Normalized	Measured val
$A_{1,1} = \frac{2.41 - j3}{\sqrt{2}}$	; $\lvert A_{1,1} \rvert^2 = 7.4$	1.0	1.0
$A_{-1,1} = \frac{2.41 + j}{\sqrt{2}}$	; $\lvert A_{-1,1} \rvert^2 = 3.4$	0.46	0.68
$A_{1,-1} = \frac{-1.59 + j}{\sqrt{2}}$	; $\lvert A_{1,-1} \rvert^2 = 1.76$	0.24	0.31
$A_{-1,-1} = \frac{2.41 + j}{\sqrt{2}}$	; $\lvert A_{-1,-1} \rvert^2 = 3.4$	0.46	0.85
$A_{1,3} = \frac{-1.59 + j}{\sqrt{2}}$	$\lvert A_{1,3} \rvert^2 = 1.76$	.02	0.025
$A_{1,-3} = \frac{2.41 - j3}{\sqrt{2}}$	$\lvert A_{1,-3} \rvert^2 = 7.4$	.09	0.10
$A_{-1,+3} = \frac{2.41 + j}{\sqrt{2}}$	$\lvert A_{-1,3} \rvert^2 = 3.4$	.04	0.06
$A_{-1,-3} = \frac{2.41 + j}{\sqrt{2}}$	$\lvert A_{-1,-3} \rvert^2 = 3.4$	.04	0.06
$A_{3,1} = \frac{2.41 + j}{\sqrt{2}}$	$\lvert A_{3,1} \rvert^2 = 3.4$	.04	0.05
$A_{3,-1} = \frac{2.41 + j}{\sqrt{2}}$	$\lvert A_{3,-1} \rvert^2 = 3.4$	.04	0.02
$A_{-3,1} = \frac{2.41 - j3}{\sqrt{2}}$	$\lvert A_{-3,1} \rvert^2 = 7.4$	.09	0.27
$A_{-3,-1} = \frac{-1.59 + j}{\sqrt{2}}$	$\lvert A_{-3,-1} \rvert^2 = 1.76$	.02	0.025

$$\left| \frac{F_{1,1}}{F_{1,3}} \right|^2 = \left| \frac{0.93}{0.28} \right|^2 = 11$$

The measured values were entered in the table from the position plot on the next page. Due to the many ways the pattern could be inserted in the optical system, the relative orientation is not known. Assumption was made that the maxima coincide and other features would also be similar.

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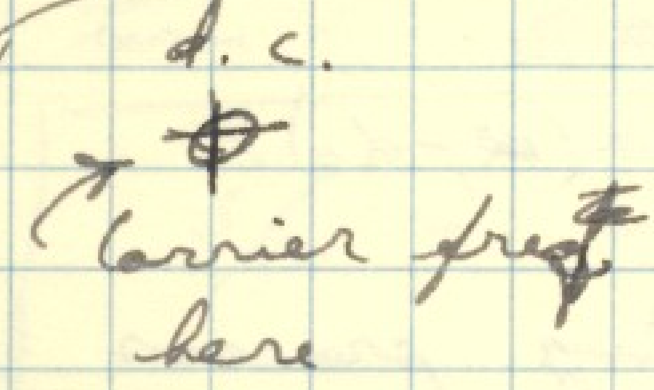
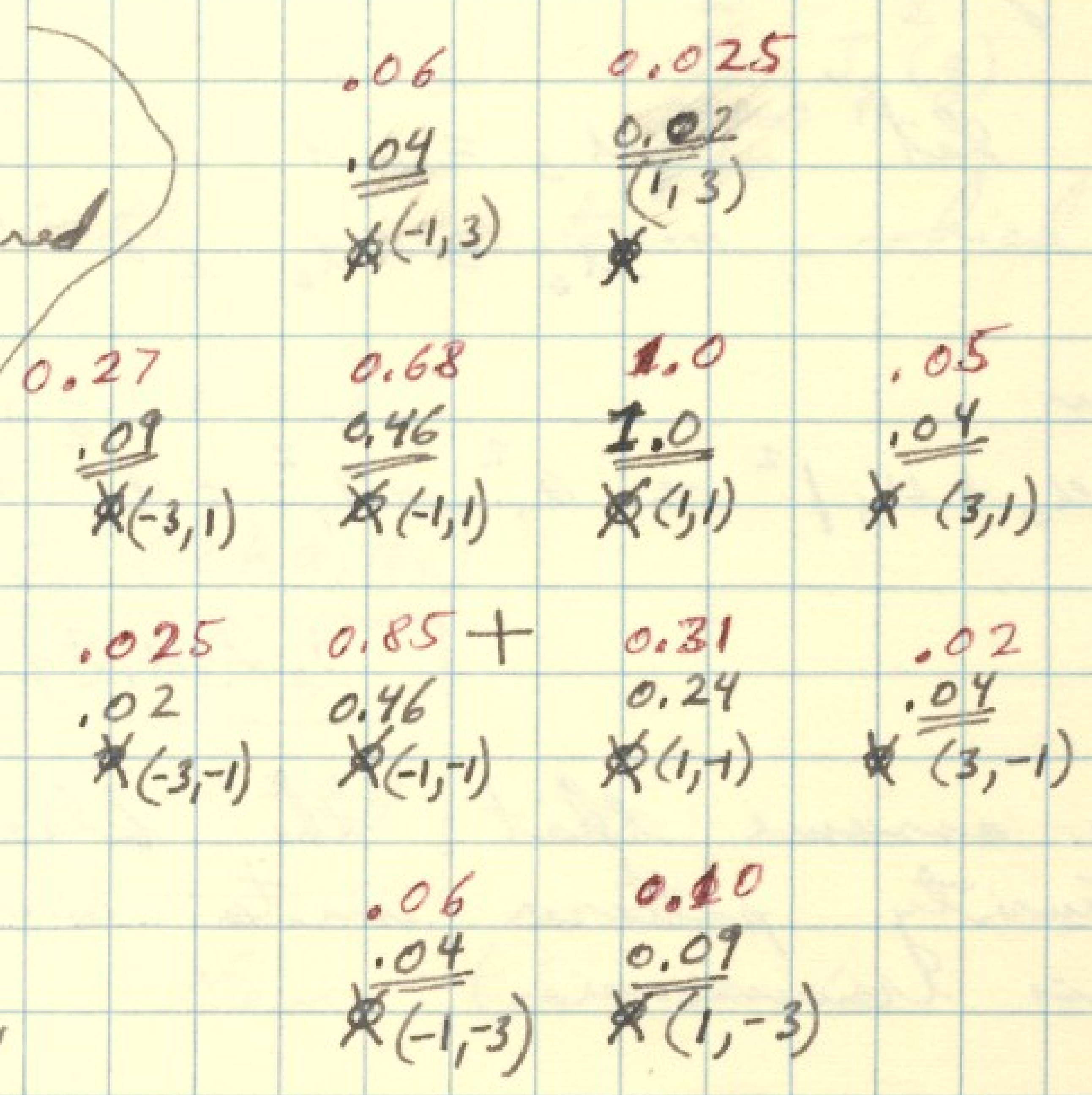
In the position plot at right, the top numbers (red) are measured values and lower numbers (black) are calculated values. Differences could be caused by error in constructing the phase plate and by the fact that a square wave instead of sinusoidal carrier was used. Agreement appears to be quite good.





The measurement of ~~power~~ spectra (graphs) can be found on pp. 150-152 ~~of~~ in notebook # 949.

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9 July 1968

Calculation of signal and noise for a bleached hologram.

Experimental observations have shown that the noise level in a hologram can be quite high. A simple hologram, in which the object beam or signal beam consists of two plane waves, will be analyzed and signal-to-noise ratio, S/N, will be calculated. It will be assumed that the angle between the reference and signal is sufficiently hight so that the 3-D properties of the film emulsion will allow only one sideorder to reconstruct. Furthermore, it will be assumed that intermodulation terms are of sufficiently low frequency that they can be assumed to be recorded in 2-D medium.

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Let $u_s = a_1 e^{j\alpha_1 x} + a_2 e^{j\alpha_2 x}$

$u_0 = a_0 e^{j\omega x}$

Then

$$|u_0 + u_s|^2 = a_0^2 + a_1^2 + a_2^2 + 2a_0a_1\cos(\omega-\alpha_1)x + 2a_0a_2\cos(\omega-\alpha_2)x$$

$$+ 2a_1a_2\cos(\alpha_1-\alpha_2)x$$

We assume that the bleaching process converts the intensity pattern into corresponding phase variations (T is transmission):

$$T = \exp jk|u_0+u_s|^2$$

$$T = \exp jk(a_0^2+a_1^2+a_2^2)\cdot\exp j[k2a_0a_1\cos(\omega-\alpha_1)x]\cdot\exp j[2ka_0a_2\cos(\omega-$$

$$\cdot\exp j[2ka_1a_2\cos(\alpha_1-\alpha_2)x]$$

The terms can be simplified as follows:

$$\exp jk(a_0^2+a_1^2+a_2^2) = e^{j\phi_0}$$

$$\exp j[2ka_0a_1\cos(\omega-\alpha_1)x] = J_0(2ka_0a_1) + J_1(2ka_0a_1)e^{j(\omega-\alpha_1}$$

$$\exp j[2ka_0a_2\cos(\omega-\alpha_1)x] = J_0(2ka_0a_2) + J_1(2ka_0a_2)e^{j(\omega-}$$

$$\exp j[2ka_1a_2\cos(\alpha_1-\alpha_2)x] = J_0(2ka_1a_2) + J_1(2ka_1a_2)\cos(\alpha_1-\alpha_2$$

$$+J_2(2ka_1a_2)\cos 2(\alpha_1-\alpha_2)x + \cdots$$

The signal term is then given by

$$J_0(2ka_1a_2)\left[J_0(2ka_0a_2)J_1(2ka_0a_1)e^{j(\omega-\alpha_1)x} + J_0(2ka_0a_1)J_1(2ka_0a_2)e^{j(}\right.$$

The noise term is

$$[J_1(2ka_1a_2)\cos(\alpha_1-\alpha_2)x + \cdots\quad][J_0(2ka_0a_2)J_1(2ka_0a_1)e^{j(\omega-\alpha_1)x} + J_0(2ka_0a_1)J_1($$

$$\cdot e^{j(\omega-\alpha_2)x}]$$

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From the relation that $1 - J_0^2(z) = \sum_{\substack{q=\pm\infty \\ q\neq 0}}^{\infty} J_q^2(z)$

we can calculate energy in the noise term, which is

$$N \propto 1 - J_0^2(2ka_1a_2)$$

and in signal term $S \propto J_0^2(2ka_1a_2)$

and
$$\boxed{S/N = \frac{J_0^2(2ka_1a_2)}{1 - J_0^2(2ka_1a_2)}}$$

Thus, if $2ka_1a_2 \to 0$, then $S/N \to \infty$

Since the signal strength depends on the values $J_1(2ka_0a_1)$, we would like to make $2ka_0a_1$ larger. We can do this by increasing a_0 which causes signal to increase without increasing noise level.

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30 August 1968

Preliminary results of experiments with bleached holograms.

A series of plates with different exposures and each plate having different signal-to-reference beam ratio were made by Carl Leonard. These plates were bleached in modified Kodak R-10 bleach with KBr, and quick checks were made of the ~~re~~ relative diffraction efficiencies and signal to noise (S/N) ratios. For some plates a polarizer was placed in front of it so that only diffuse light of same polarization as the reference beam would reach the plate. The following table gives a summary of

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These measurements:

Ref. to Signal Ratio	Polarized Signal			Unpolarized signal		
	Relative Brightness of reconstr.	S/N	Dens.	Relative Brightness of Reconstruct.	S/N	Density
1:1	22 (5)	0.5 (1.8)	1.25 (.28)			
3:1	26 (7)	3.1 (5)	1.82 (0.18)			
7.5:1	32 (2.3)	7 (14)	2.1 (0.18)	32 (1.5)	2 (10)	1.9 (0.12)
20:1	27	21	3.15	32 (5.6)	17 (26)	2.7 (.36)
50:1	15	22	1.65	19 (10)	29 (32)	2.7

The maximum relative brightness of an unbleached hologram was measured to be 3, giving an increase in brightness by a factor of 10. It seems that 3 is not the optimum brightness and this figure should be higher.

The above table indicates that diffraction efficiency of a diffuse signal beam remains relatively constant regardless of reference-to-signal beam ratio. Also, a polarized signal beam gives much ~~both~~ higher S/N ratio at ~~la~~ small reference-to-signal beam ratios.

These results proove that significant improvement in brightness can be obtained with bleaching, and that high S/N ratios ~~can~~ can be achieved by increasing the reference beam intensity.

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18 October 1968.

Illumination of transparencies for visual observation.

A diffusely illuminated transparency appears granular and effectively reduces the resolution in of the image. It should be possible to illuminate a transparency with a regular phase and amplitude pattern which would allow finer resolution and more pleasant appearance. Such a pattern could be produced by crossed and bleached phase gratings, provided that the number of sideorders and their spacing is correctly chosen.

We shall estimate the spacing by considering the sideorder spot distribution at the transform plane in one dimension. Assuming the angular resolution of the eye as 2 min. of an arc, the grating also should be such that adjacent diffracted orders for 2 min. of an arc separation. Let us assume further that a 40° angle of view is desired. We can then calculate, first of all, the spatial frequency of such grating:

$$f = \frac{\alpha}{\lambda} = 1580 \cdot \frac{2}{60 \cdot 57.3} \cong 0.92 \text{ lines/mm}$$

$$\cong 1 \text{ line/mm}$$

To cover an angle of 40°, sidebands on one side should have dispersion to 20° off axis, or the number of sideorders N should be

$$N = 20 \cdot \left(\frac{60}{2}\right) = 600 \quad \text{sideorders}$$

It would be unrealistic to expect 600 sideorders from one grating. One can, however, use several phase gratings in series. The spectrum of the first grating may have the distribution

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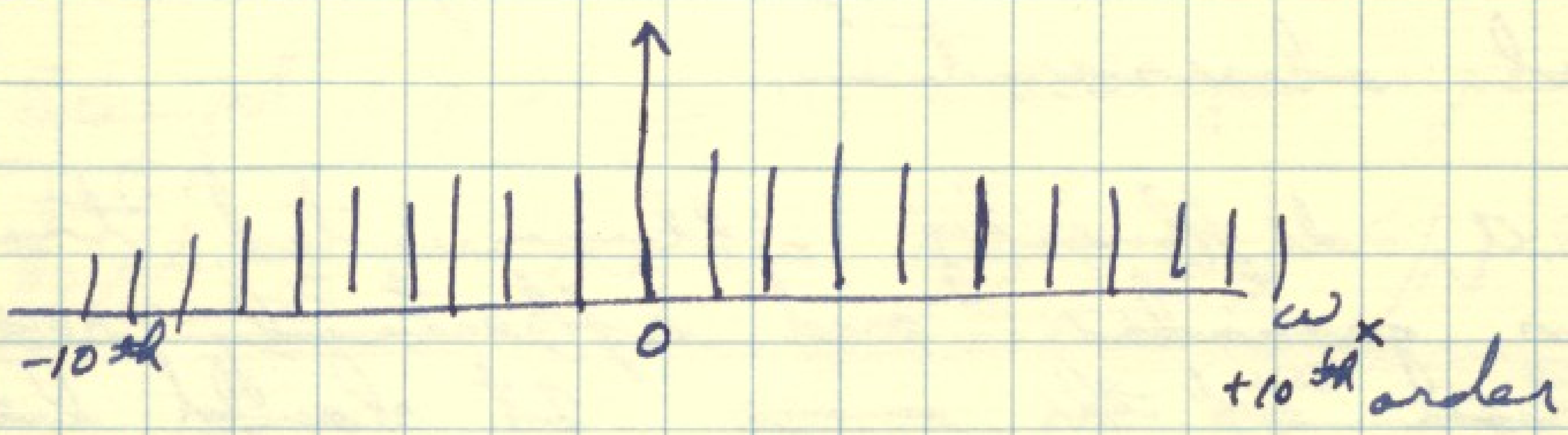
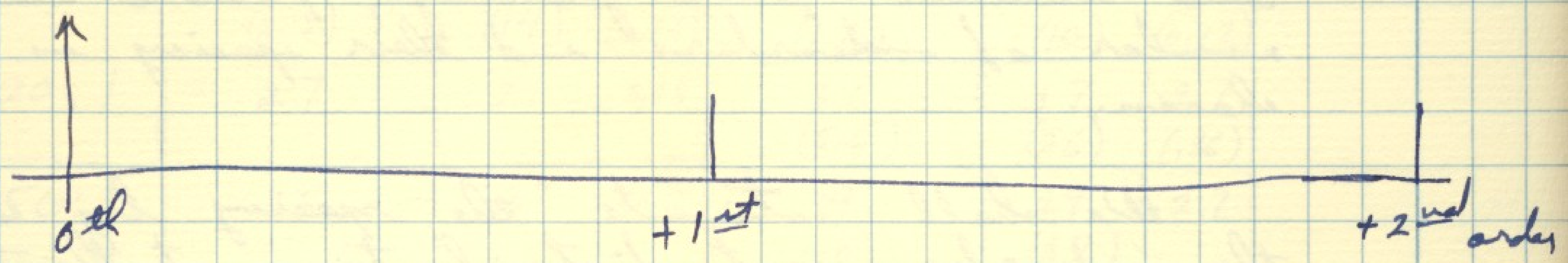
shown here:



The second grating then should have a spacing of, say, 20 lines/mm as shown below



The overall spectrum of the two gratings, a product, would then be a continuous line of points 2 min. of an angle apart and extending for $\frac{20 \times 10}{60} \approx 3.3°$, assuming the second grating also has 10 sideorders. The third grating of 200 lines/mm should have at least three sideorders to reach the 600 sideorder mark assumed for 40° angle of view. This pattern would have the advantage over ordinary diffusers that the field would consist of bright spots close together and regularly spaced, and thus should have much more pleasant appearance. If the transparency was placed at other than transform plane, the pattern would consist of regular lines at right angles to each other, and the ~~th~~ appearance still should be improved over that of diffusely illuminated transparency.

One way to make gratings would be to record interference patterns on photographic plates and bleach them to create phase gratings.

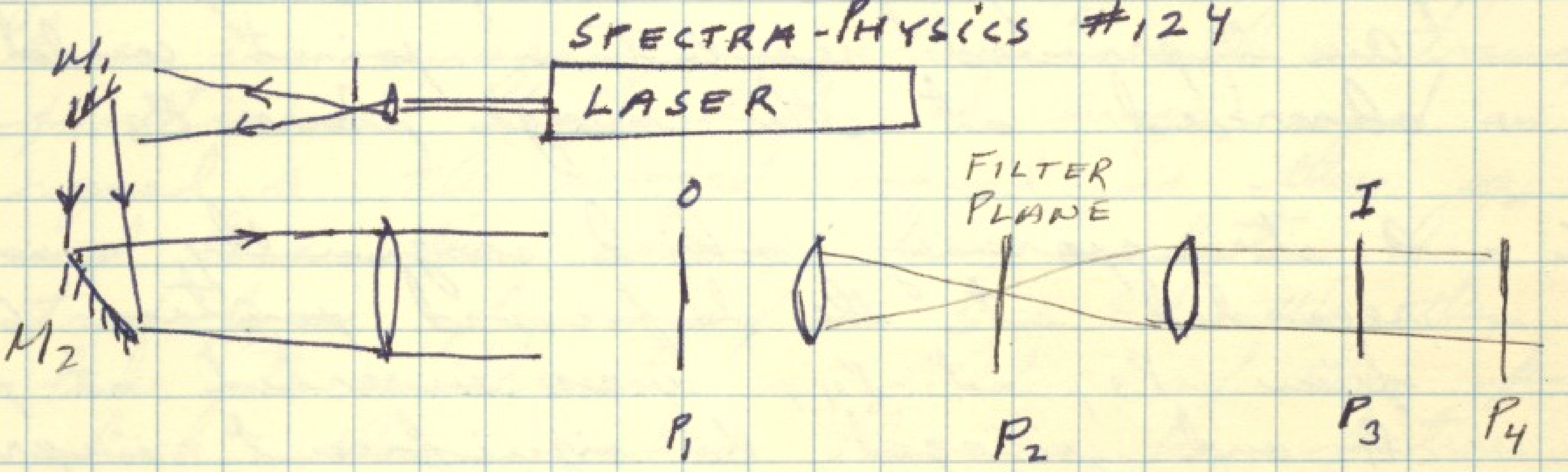
Juris Upatnieks, 18 October 1968.

22 November 1968.

Spatial Filtering Experiments.

Experiments were begun to test the feasibility of improving image resolution of defocused images by spatial filtering. The system eventually will involve the use of redundant filters mentioned previously. For the present, only a single filter will be used.

An optical system was set up as shown below:



The experiments were performed in the following manner;

1. By means of a lens, a point focus was formed in plane P_1, ~~with~~ a 3mm diameter was placed at P_2, and the out of focus image was recorded 60 mm from the focal plane P_3 (image plane) at P_4.

2. The defocused point was contact copied to obtain a positive.

3. The defocused point positive was placed at P_1 and hologram of its transform was made at plane P_2. The reference beam was introduced by placing a lens and focusing it on plane P_1 — this provided a collimated reference beam at plane P_2.

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4 December 1968

(continued from previous page).

4. The filter made in this way was reinserted at plane P_2 and the original defocused point was imaged through it and recorded at plane P_3. Only one of the sidebands gave a corrected image. The filter was made in such a way that the "signal" beam greatly exceeded the reference beam intensity at the center and exposure was adjusted to give maximum diffraction efficiency at a point further away from the peak signal. An improoved resolution point could be observed at the image plane P_3.

5. A transparency which originally was recorded at the defocused position 6 cm from P_3, at P_4, was inserted at plane P_1 and imaged. No significant improovment could be seen. The main effect of the filter was to increase contrast to an extreme level.

A number of difficulties were encountered in the experimental work. For one, the 649F emulsion did not have sufficient dynamic range to give a nearly opaque background to the positive of the defocused point image. Consequently, the d.c. buildup was much higher and the filter attenuated the d.c. term more than it should have. 2½ min development in 1:20 diluted D-19 developer was used, as suggested for linear recording in a paper by Lohmann. Also, it was impossible to obtain similar gamma from time to time, with appearantly indentical development procedure.

Juris Upatnieks, 4 Dec. 1968.

4 December 1968.

It also appears improbable that the redundant filters could be produced by a single exposure since all diffracted orders have nonuniform intensities. The filters, in theory, should affect each spectral order in an identical manner. There is also the possibility of allowing light through one filter at a time to pass and to add all the filtered images in sequency, incoherently. This procedure would improve the noise suppression although it would require more time and a more elaborate system.

The basic principles of improving images by deconvolution are as follows. Suppose we have an imaging system with a transfer function h (of a defocused image) and an input signal s. The imaged signal is then $s_i = s * h$ and have the corresponding relationship in the transform plane of $\hat{S}_i = SH$. We then would like to construct a filter of the form $H^*/|H|^2$, which then makes the transfer faction of the system with the filter h'. The result should be

$$(h * s) * h' \Rightarrow SH \frac{H^*}{|H|^2} = S$$

The arguments presented here contain one neglected fact which may affect the recovery of the signal: the defocused point image, as well as the defocused signal image, is an intensity recording only and does not contain phase information. For this reason the recovery of signal cannot be perfect. The exact effect of phase loss is not known and should be calculated.

In the experiments performed here the filter $H^*/|H|^2$ was only approximatly constructed by technique described in step 4., p. 12.

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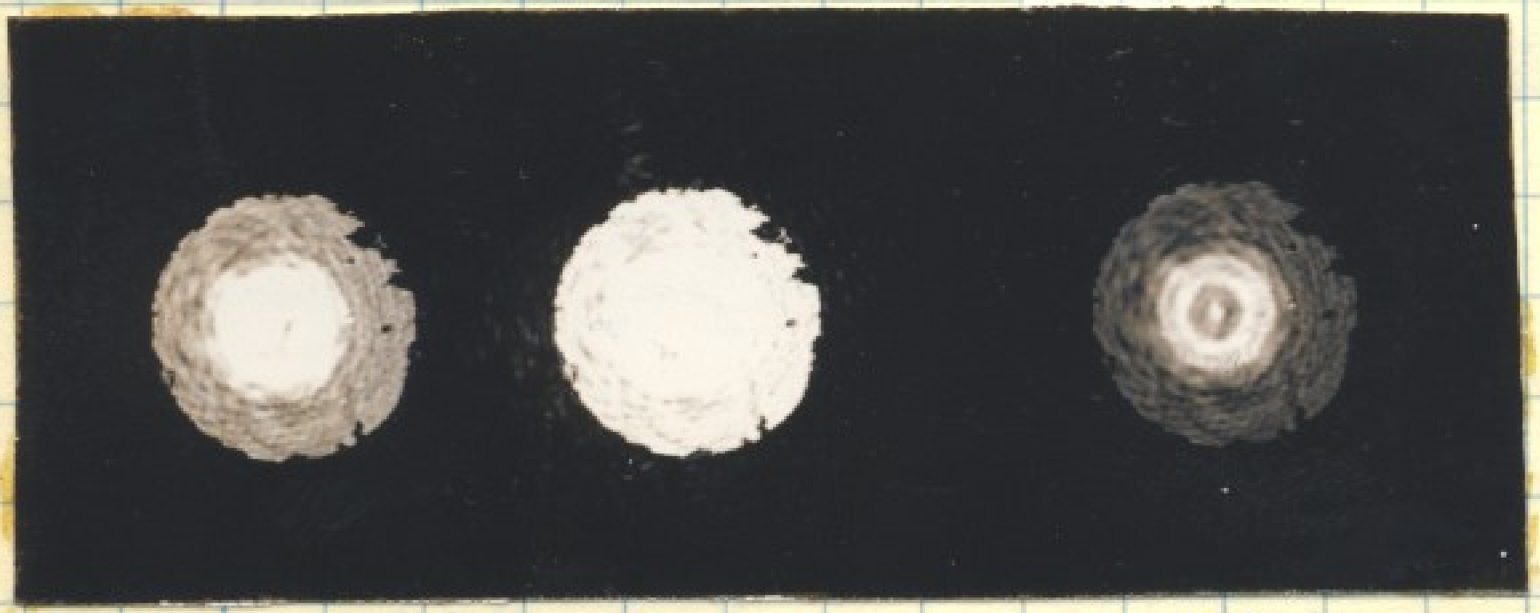
4 December 1968

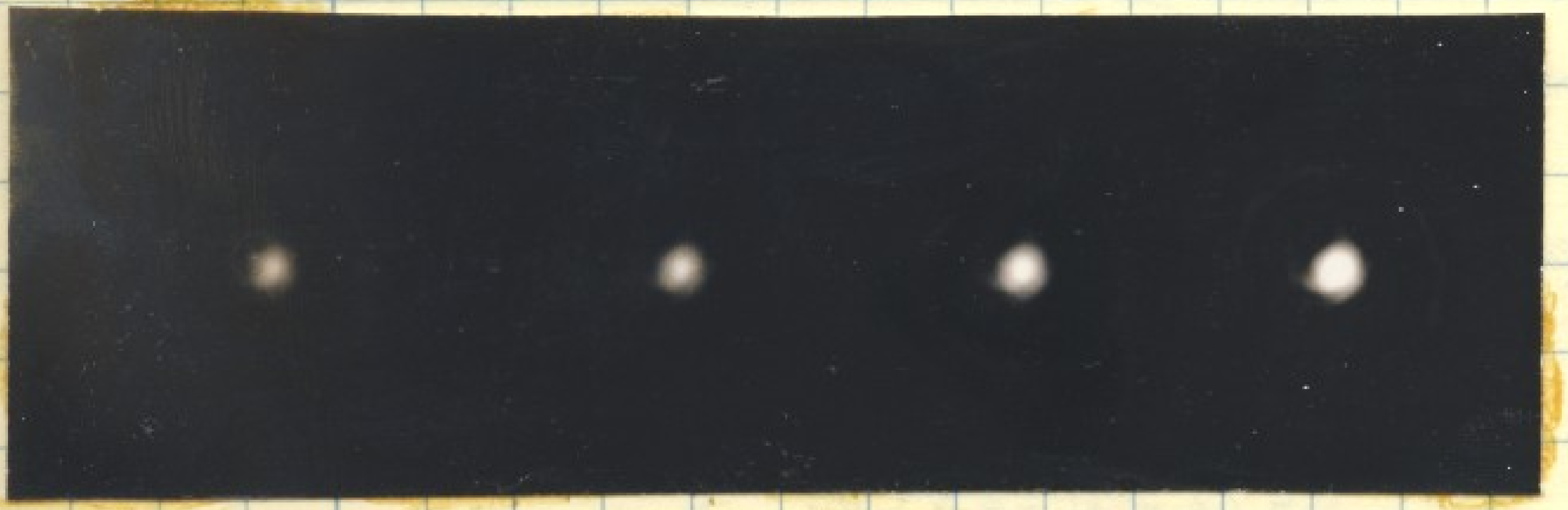
Experimental results of image improvement.

The photographs below were made with the optical system sketched on p. 11.



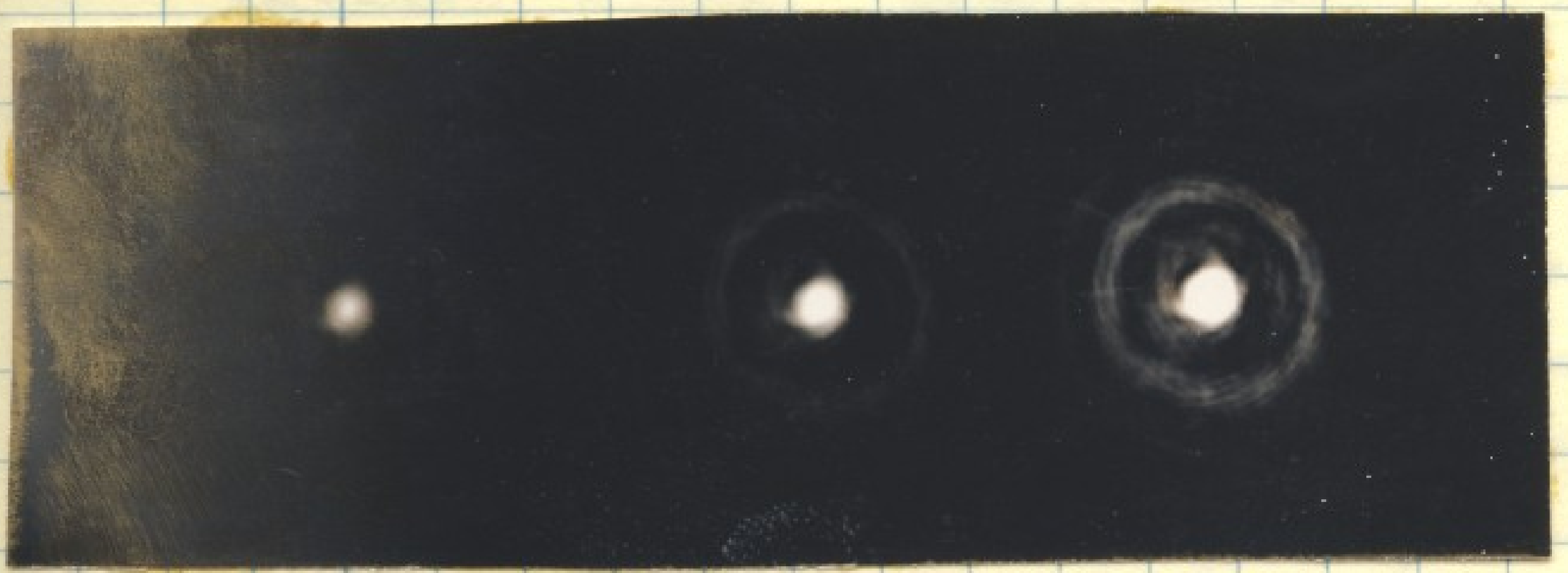
1 sec. 3 sec. 1/5 sec. exp.

Image of defocused point image. Exposed 22 Nov. 1968. Photograph #4.



1 sec. 2 sec. 10 sec. 30 sec.
exposure times.

Image of above defocused image through corrector plate. Exposures made on 22 Nov 1968. Photograph #2



3 sec. 30 sec. 150 sec.
Exposure times

Image above defocused image through corrector plate (filter), same as above. Exp. made on 22 Nov. 1968. Photograph #3.

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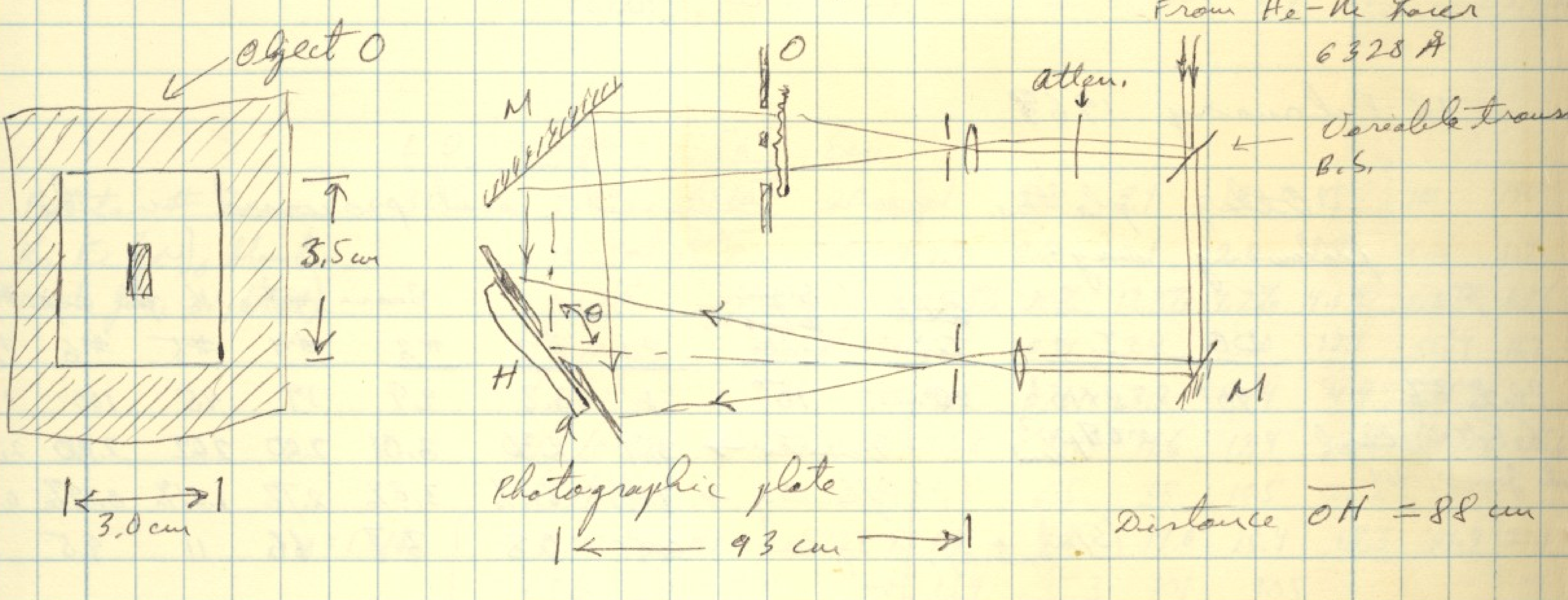
7 ~~8~~ February 1969

Efficiency and noise of bleached holograms.

An extensive study of the characteristics of bleached holograms has been conducted. Carl Leonard has carried on a series of experiments and investigations which are recorded in his notebook. Some questions concerning noise and diffraction efficiency arose when calculations in the memo "Signal and Noise in Dielectric Holograms" did not agree with experimental results. Several additional experiments were made to determine the diffraction efficiency and noise characteristics of bleached emulsions.

Since the signal beam in the memo was assumed to be narrow, creating two-dimensional intermodulation noise patterns, the experimental ~~[illegible]~~ setup was altered to produce a narrow signal beam. The figure below shows the experimental system:



The object to hologram distance was such that an angle of 2.3° at H was the signal beam width. Two plates were made ~~at~~ with this system as shown on next page. Exposure time and reference beam intensity were held constant; the signal beam was varied by inserting calibrated absorption filters, or attenuators, in the object beam. The Kodak 649F emulsion was used with backing plate and Xylene between to eliminate back reflections

Juris Upatnieks, 7 February 1969

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	I_{ref} = ~~8×10~~	Exp. time	K-factor, reference to aver. signal beam int[ensity] #1	#2	#3	#4	#5	#6	#7	#8
Plate #1 (8 Jan 1969)	8×10^{-2}	40 sec.	1	3.2	5.2	9.9	9.9	19	45	100
Plate #2 (8 Jan 1969) Bleached in R-10 (KBr)	8×10^{-2}	40 sec.	1	3.2	9.9	19	45	100	190	455

	#1	#2	#3	#4	#5	#6	#7	#8
Plate #2, max measured intensity in object	2.3 mV	4.2	9.2	6.5	4.2	1.8	850 μV	380
" , min. " " " "	2.3	3.8	3.7	1.6	0.7	.27	150 μV	39
Calculate $S/N = \frac{\text{max} - \text{min.}}{\text{min.}}$	0	0.1	1.5	3.3	5.0	5.7	7.1	8.8
Liquid gate, xylene: Plate #2 max. measured intensity in object:	4.5 mV	12.0	5.3	6.2	3.2	1.3	800 μV	270 μ
min. " " " " :	4.5	8.0	1.5	0.9	0.5	0.15	8 μV	30
Calculated S/N :	0	0.5	2.5	6.0	5.4?	7.7	9	8
Plate #2 Measured diffracte power (Inc. Pwr. = 3.4 mW):	460 μW	510	330	235	107	56.2	32	12.5
% diffractio/eff :	13.7%	17.0%	11%	7.85%	3.6%	1.9%	1.1%	0.42

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Other plates were exposed and processed in the following way:

	LO	I_0 =	Exp. Time	Sign. Beam width	Beam ratio K for exp. #: #1	#2	#3	#4	#5	#6	#7
Plate #3: $K_3Fe(CN)_6$ bleach, Made Jan. 10, 1969	90°	8×10^{-2} or 6.5 μW/cm^2 ?	20 sec.	15°	1	3.2	9.9	19	45	100	190
			Density →		3.57	3.30	3.01	2.80	2.62	2.80	2.75
			Efficiency →		4.2%	6.1%	3.8%	2.7%	1.21%	0.69%	0.32%
		$(S/N)_{\text{contrast}}$, in Xylene			0	0.8	3.7	6.6	11	9.5	8
Plate #4 Chromate bleach (R-10) Made Jan. 10, 1969	90°	8×10^{-2} or 6.7 μW/cm^2 ?	20 sec.	15°	Same beam ratios as for plate #3						
			Density →		2.8	2.4	2.3	2.27	2.27	2.28	2.25
			Efficiency →		8.4%	16.2%	9.7%	6.5%	3.1%	1.5%	0.81%

Plate #4 had some back reflections during exposure due to ~~air~~ bubles between plate & backing. Reconstructions were noisy

Juris Upatnieks, 18 February [1969]

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Plate # 5
$K_3Fe(CN)_6$ bleach
(made 16 Jan 1969)

LΘ	Signal beam angle	I_0	Exp. Time		Exposure numbers: #1	#2	#3	#4	#5	#6	#7
90°	2.3°	8×10^{-2}	22 sec.	→	1.0	1.6	3.2	6.6	9.9	19	45
			Beam Ratio K} Density	→	3.3	2.9	2.8	2.7	2.5	2.5	2.5
			Diffraction efficiency		7.0%	8.1%	9.45%	8.6%	5.7%	3.4%	1.9%
			$(S/N)_T$, Dry plate	→	.039	.068	0.31	0.62	3.1	9.0	41.5
			$(S/N)_c$, " "	→	0	0	0	0.16	1.35	3.8	6.9
			$(S/N)_T$, Xylene	→	1.42	2.0	6.1	10	30	52	136
			$(S/N)_c$, "	→	0	0.3?	0.54	1.25	5.2	7.5	12.2
			Scattered ligh level, % total	→	34%	25%	9.5%	5.8%	1.8%	0.6%	.08%
(AROCLOR 1232)			$(S/N)_c$, $n = 1.618$	→	~~0.21~~ 0	~~0.49~~ 0.21	0.48	0.96	3.9	6.10	10

Plate # 6
Chromate Bleach
(R-10 with KBr)
(Made Jan. 16, 1969)

LΘ	Signal.	I_0	Exp. Time		#1	#2	#3	#4	#5	#6	#7
90°	2.3°	8×10^{-2}	22 sec.		3.12	2.9	2.7	2.7	2.8	2.5	2.5
			Density} Efficiency:		10%	12.4%	15%	14.5%	12.4%	2.3%	4.2%
			$(S/N)_T$, dry	→	.038	.04	.24	.48	1.8	4.2	11
			$(S/N)_c$, "	→	—	—	—	—	0.82	2.2	4.2
			$(S/N)_T$, Xylene	→	0.6	0.8	3.0	5.5	20	49	184
			$(S/N)_c$, "	→	—	—	—	0.2	1.5	4.2	5.4

Plate #7
$K_3Fe(CN)_6$ bleach
(Made Jan. 31, 1969)

	LΘ	Sign.	I_0	Exp.		#1	#2	#3	#4	#5	#6	#7
	30°	2.3°	6×10^{-2}	20 sec		1	3.2	9.9	19	45	100	190
				K-ratio} Density	→	2.4	2.2	2.1	2.0	1.9	1.8	1.9
				Diffr. efficiency	→	25.6%	20%	12.3%	7.2%	4.1%	1.8%	1.1%
				$(S/N)_c$, dry	→	—	0.41	3.4	5.0	12.1	15.4	16.7
				$(S/N)_T$, "	→	0.05	0.47	3.2	9.4	44	189	—
				$(S/N)_c$, Xylene	→	0.52	2.9	11.6	12.4	17.2	17.6	15.6
				$(S/N)_T$, "	→	1.2	6.5	38	105	257	390	—
$n = 1.618$				$(S/N)_c$, AROCLOR 1232	→	1.0	4.1	17.0	15.4	18.3	21.4	21.1
				$(S/N)_c$, "	→	15.4	35.3	101	305	—	—	—

Plate soaked for 5 min. in 8 oz/gal. sol. of PAKOL print flattening sol.

		#1	#2	#3	#4	#5	#6	#7
$(S/N)_c$, dry	→	—	0.62	4.8	9.3	27.3	43.0	15.7
$(S/N)_T$, "	→	2.5	11.3	50	282	—	—	—
$(S/N)_c$, Xylene		1.6	6.6	25.6	23.5	44	58	70
$(S/N)_c$, AROCLOR 1232		3.8	14.0	40.0	41.5	81.0	94	100

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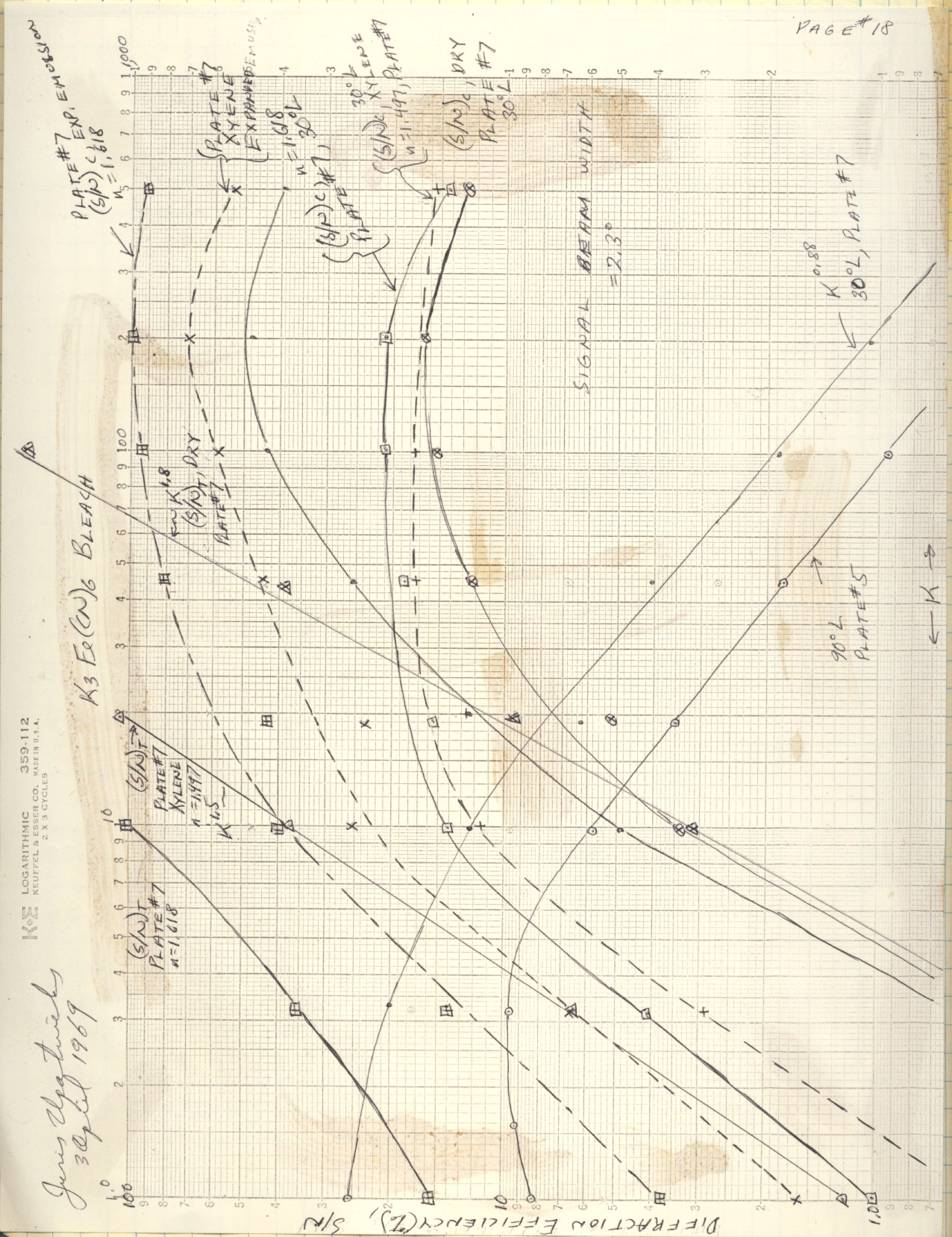


PAGE #18
K+E LOGARITHMIC 359-112
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 3 CYCLES
K3 Fe(CN)6 BLEACH
SIGNAL BEAM WIDTH
=2.3°
DIFFRACTION EFFICIENCY (%), S/N
K
PLATE #7 (S/N)c EXP. EMULSION n=1.618
PLATE #7 XYLENE EXPANDED EMULSION
(S/N)c PLATE #7 n=1.618 30°L
(S/N)c 30°L XYLENE n=1.497, PLATE #7
(S/N)c DRY PLATE #7 30°L
K^1.8 (S/N)I, DRY PLATE #7
(S/N)I PLATE #7 XYLENE n=1.497 K^1.5
(S/N)I PLATE #7 n=1.618
K^0.88 30°L, PLATE #7
90°L PLATE #5
Juris Upatnieks
3 April 1969

3 April 1969

The graph on the opposite page shows the various results obtained with unexpanded and expanded emulsions and various liquid gates. Also the total S/N is plotted for some cases. For a dry emulsion this curve has nearly the shape of that predicted by theory, that is, $(S/N) = K^2$ is the expected relationship. We note that this is ~~true~~ approximately true for $(S/N)_T$, and that the slopes of $(S/N)_T$ and $(S/N)_C$ are parallel at low K-values. At higher K-values other factors than just intermodulation noise due to refractive index variations have a significant effect. We can expect that a perfect dielectric recording media would have $(S/N)_C$ curve agree very closely to that of $(S/N)_T$ curve.

All the curves with unexpanded emulsion seem to level off at about $(S/N)_C \approx 20$. This leveling off ~~seems~~ to be caused by emulsion shrinkage, known to be about 15%. This is a uniform reduction ~~of~~ in emulsion thickness during ~~bleach~~ development and fixing process, caused in part by removal of unexposed silver grains. This shrinkage appears to cause some phase errors in the reconstructed wavefront. The curves with expanded emulsion show that $(S/N)_C$ does not level off and reaches higher values at high K-ratios. Maintaining the emulsion at constant thickness should considerably improve the $(S/N)_C$. This could be done by stabilizing the emulsion before processing and preferably before exposing. Kodak recommends using SH-5 hardening bath after exposure, but perhaps it could be done before exposure too.

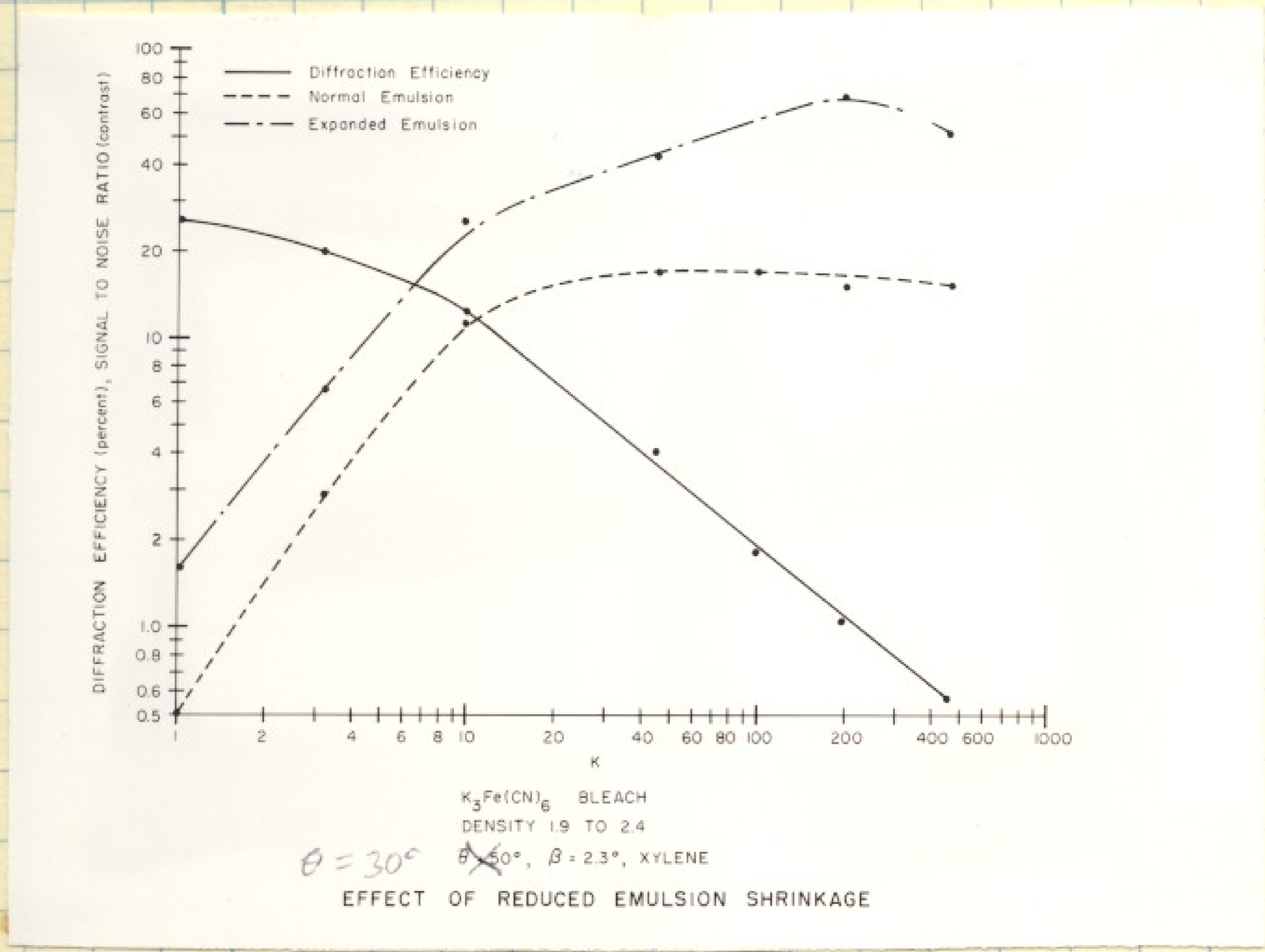
Decreasing carrier frequency improves S/N ratios. At smaller angles the emulsion distortions ~~seem~~ to have smaller effect on the phase of reconstructed wavefronts.

Juris Upatnieks, 3 April 1969

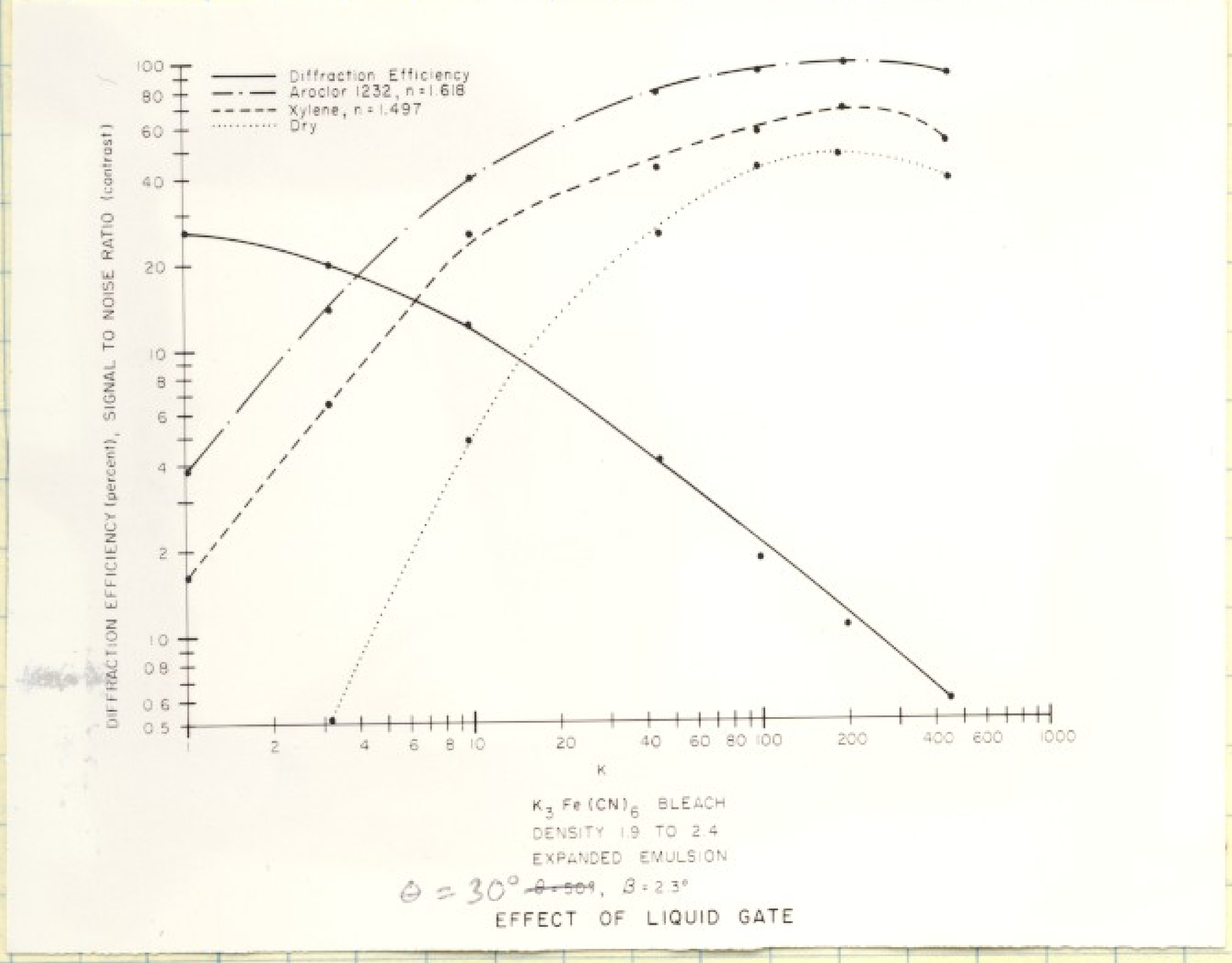
17 April 1969

Experimental results of bleaching holograms made of diffuse signal beams.

The following graphs show the experimental results obtained with potassium ferricyanide and dichromate (modified R-10 bleach with KBr) bleaches. Corrections for some of these figures are indicated on the right side of each.



The offset angle for this case is θ = 30°, not 50° as shown on the figure. Plate #7, made Jan 31, 1969, was used in these tests



θ = 30° for this figure and plate #7 was used (made Jan. 31, 1969).

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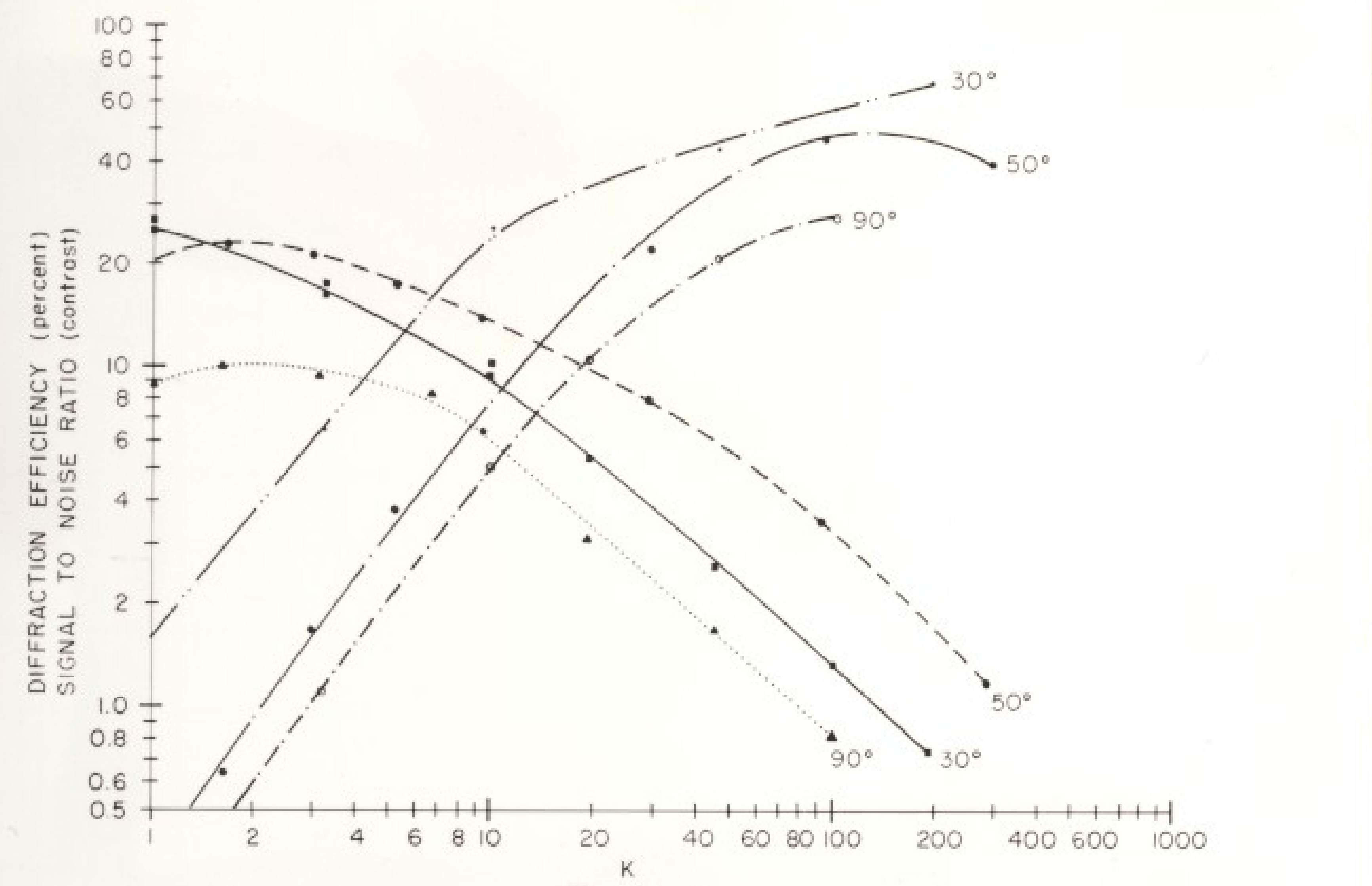
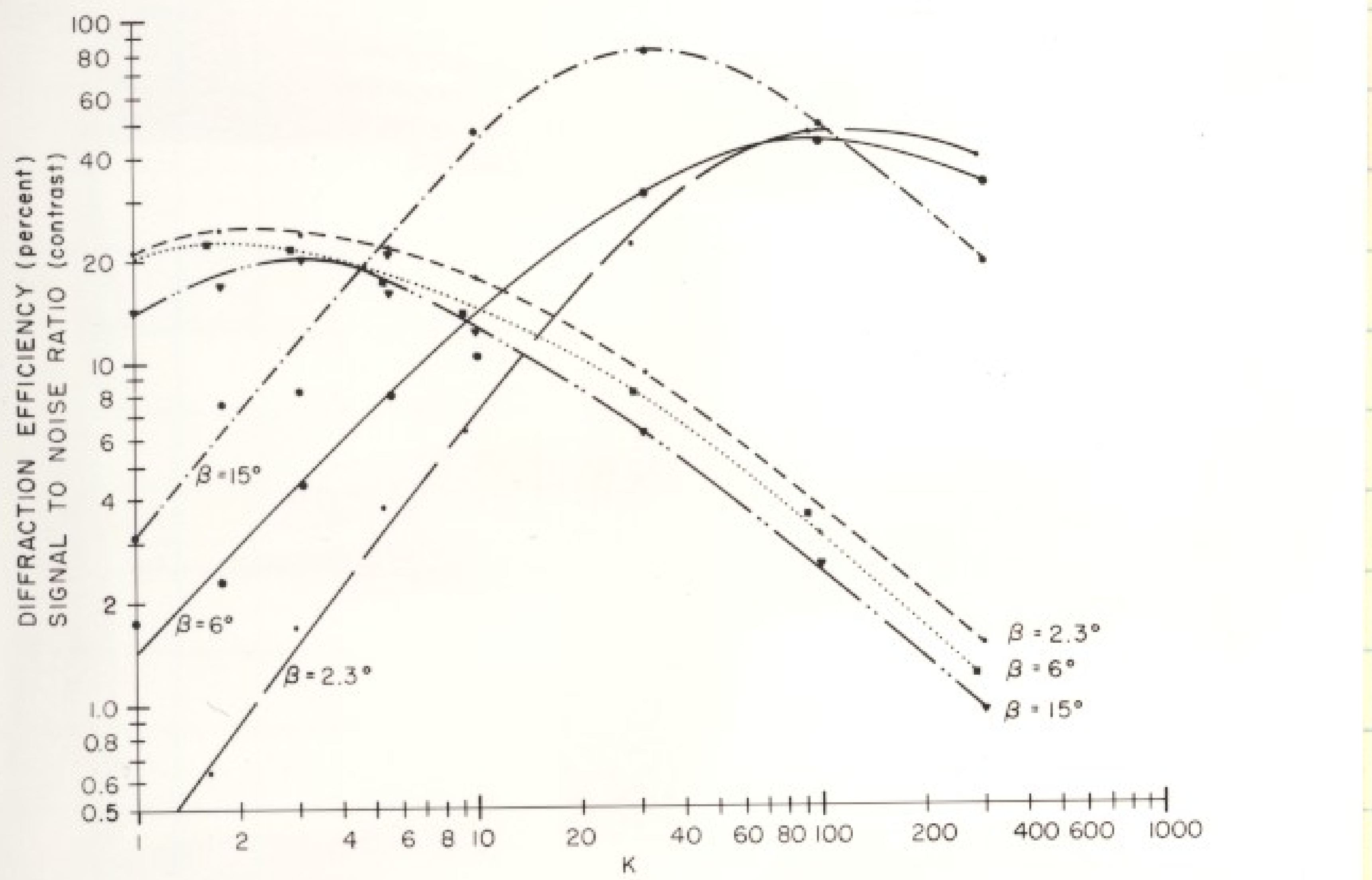


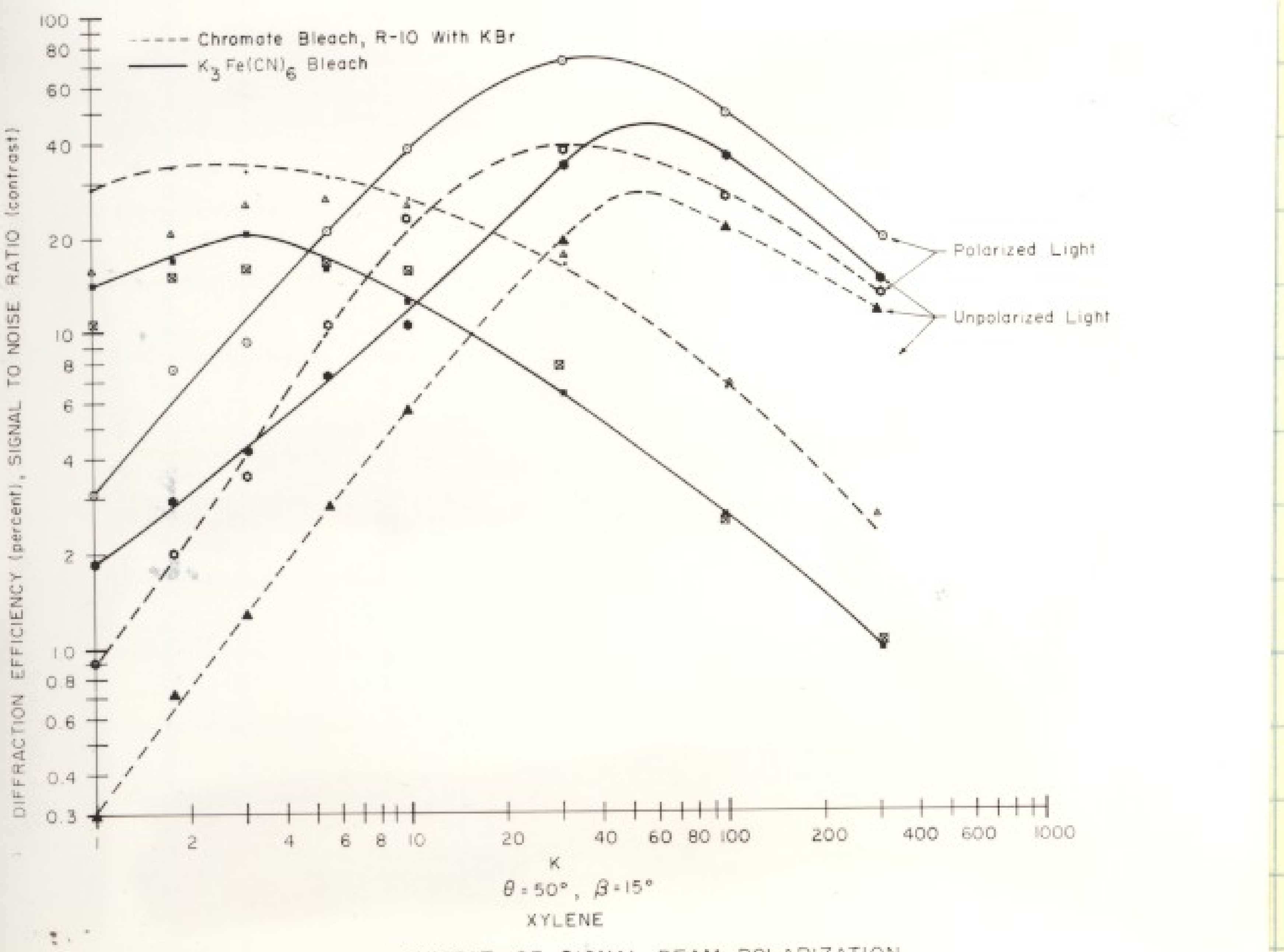
$K_3Fe(CN)_6$ BLEACH
β = 2.3°, EXYLENE
EXPANDED EMULSION
EFFECT OF REFERENCE BEAM ANGLE θ

The apparent decrease in diffraction efficiency at $\theta = 90°$ is apparently caused by increasing effect of emulsion distortions of diffraction efficiencies.



$K_3Fe(CN)_6$ BLEACH
DENSITY 2.7 TO 4.7
θ = 50°, XYLENE
EFFECT OF SIGNAL BEAMWIDTH β

Falloff at large K in S/N ratios appears to be caused by grain-scattering of the emulsion. Decreased efficiency with greater β's is probably caused by increased effect of emulsion distortions.



θ = 50°, β = 15°
XYLENE
EFFECT OF SIGNAL BEAM POLARIZATION

Comparison of both bleaches and polarized as well as unpolarized signal beams.

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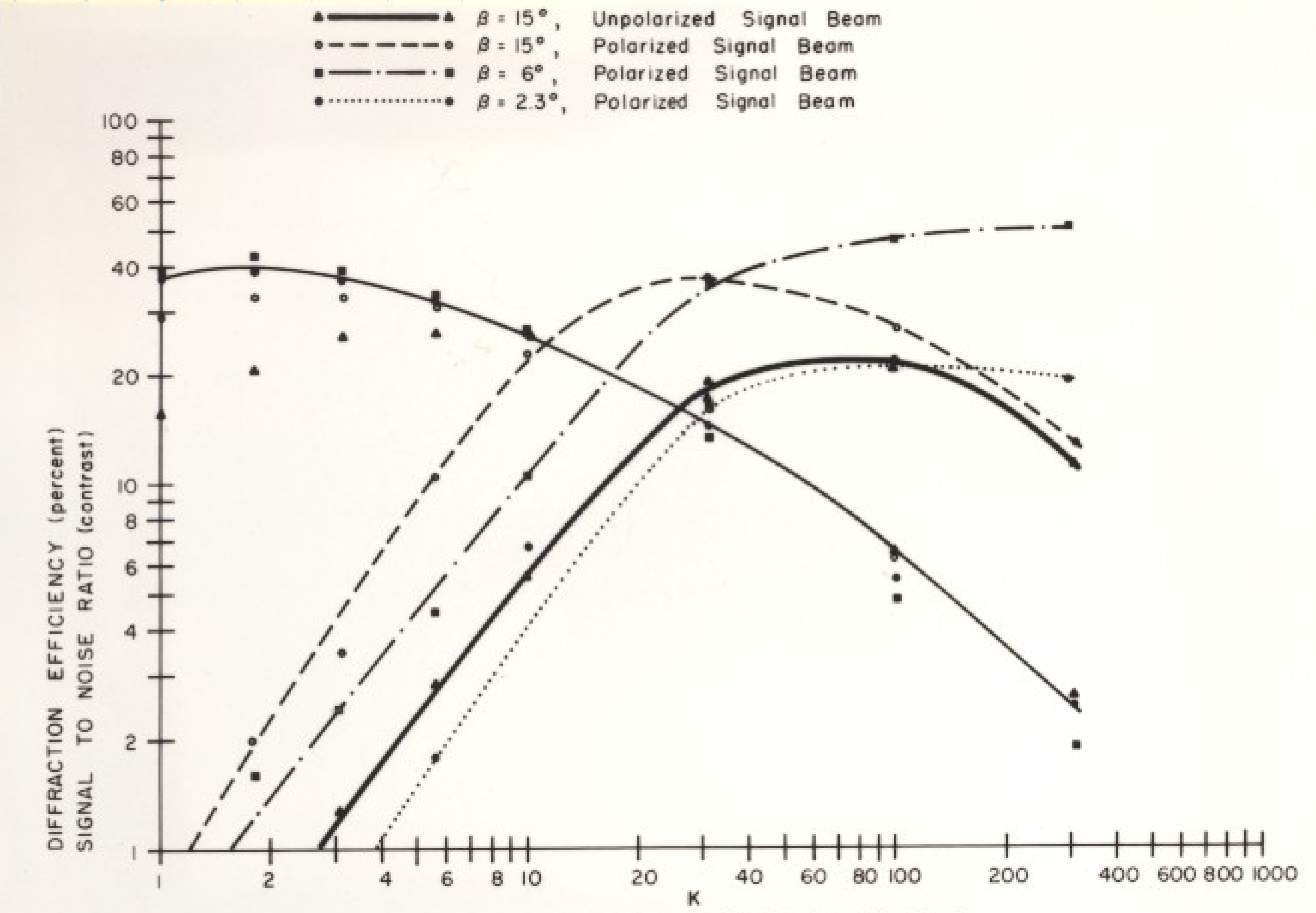


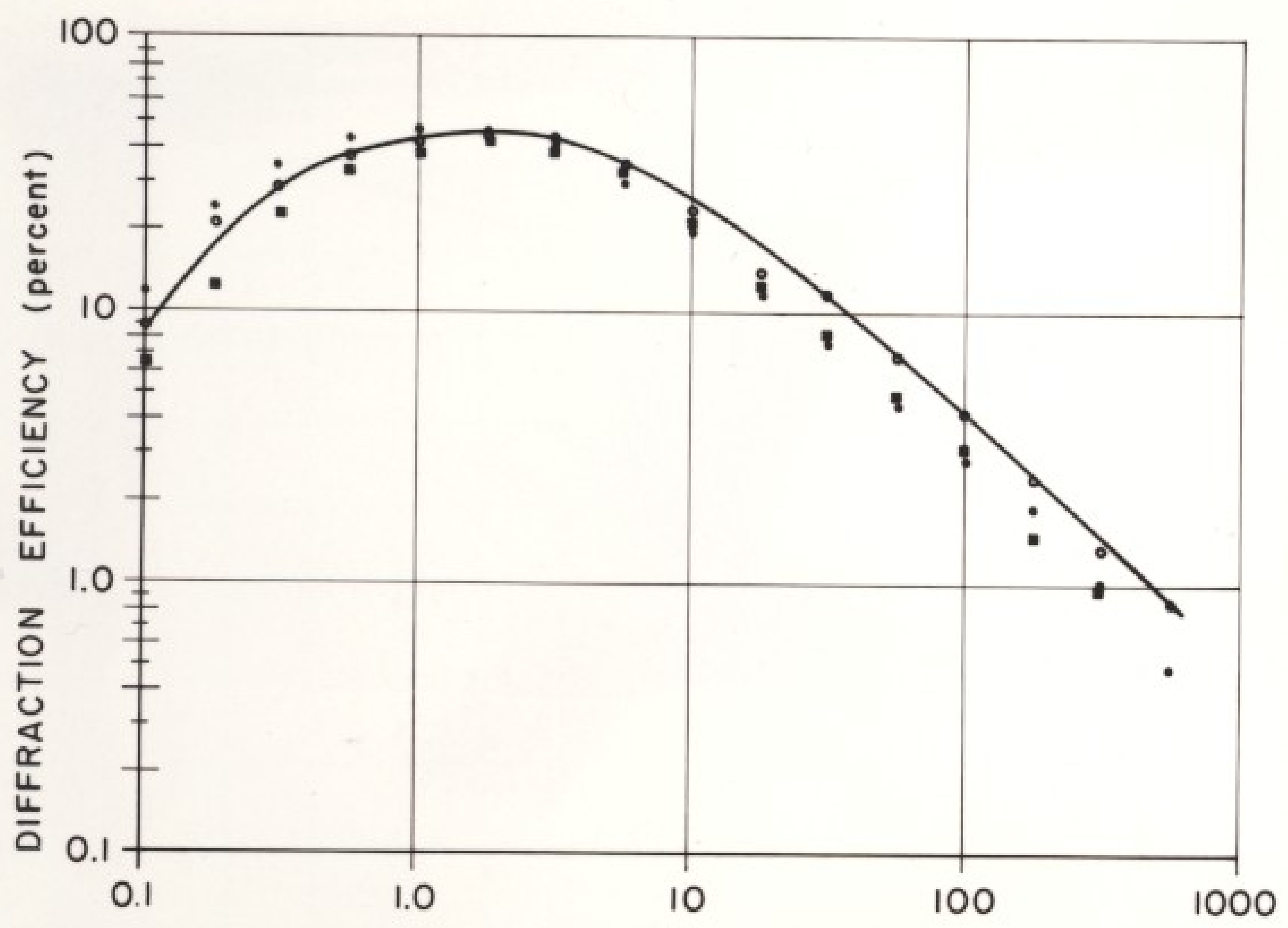
DICHROMATE BLEACH (R-10 with KBr)

XYLENE

$\theta = 50°$

EFFECT OF SIGNAL BEAMWIDTH β AND POLARIZATION

Tests with dichromat[e]
bleach, modified Kodak [R-10]
with KBr in solution.
Emulsion was not expo[sed]



$K_3Fe(CN)_6$ BLEACH

PLANE WAVE RECONSTRUCTION

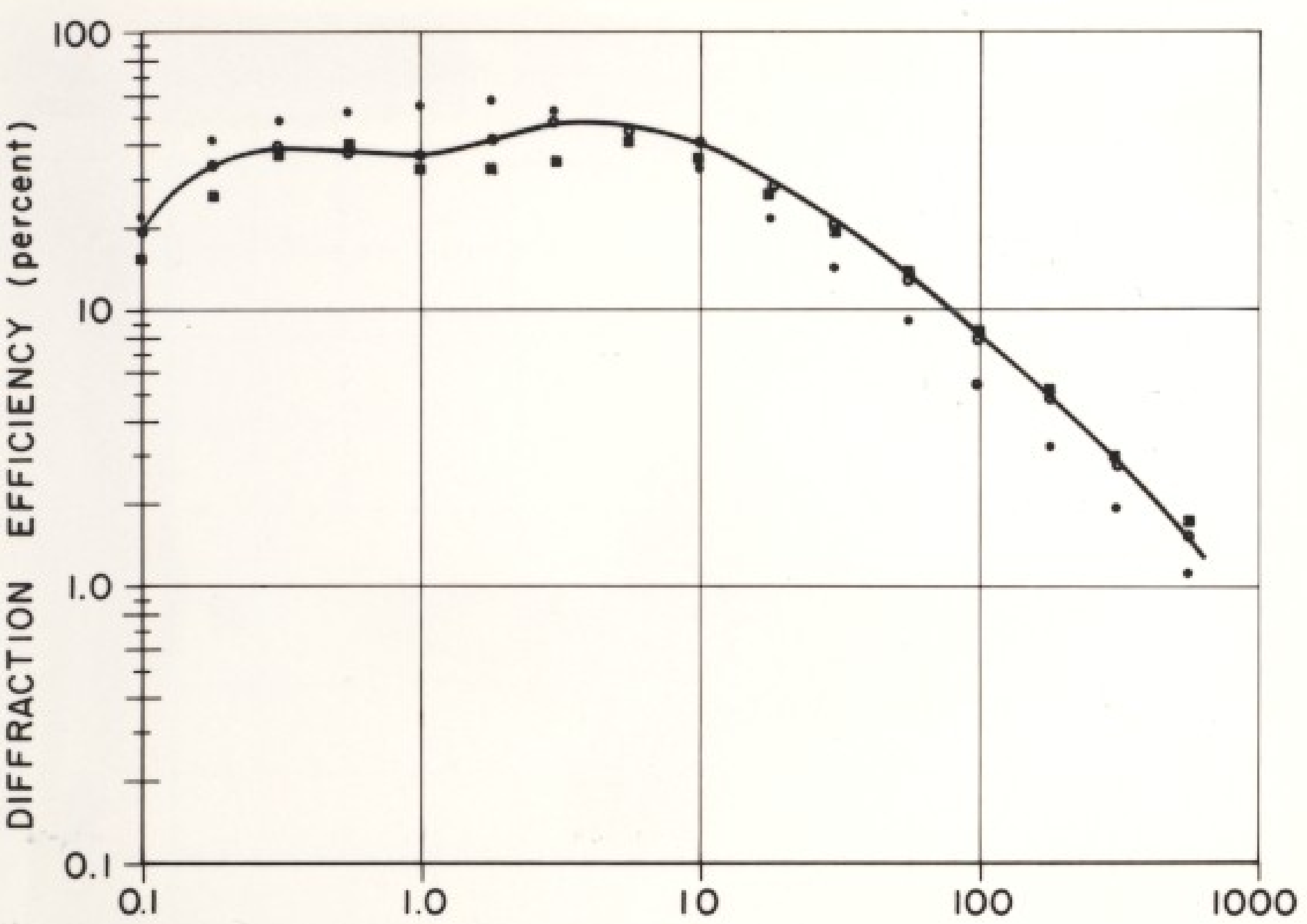
$\theta = 50°$

Diffraction efficiencies
of plane-wave interferen[ce]
patterns. Exposure time and
reference beam intensity
were held constant for eac[h]
curve. Three different
exposure times were use[d]

~~•—•~~ 1/2 sec. exposure, D

o———o 1 sec. exposure, D ≥

■ ■ 2 sec. exposure, D ≥



DICHROMATE BLEACH (Kodak R-10 with KBr)

PLANE WAVE RECONSTRUCTION

$\theta = 50°$

Diffraction efficienci[es]
of plane-wave interferen[ce]
patterns, and made same [way]
as that above. Exposures
were;

• • 1/2 sec. exposure, D ≥

o——o 1 sec. exposure, D

■ ■ 2 sec. exposure, D

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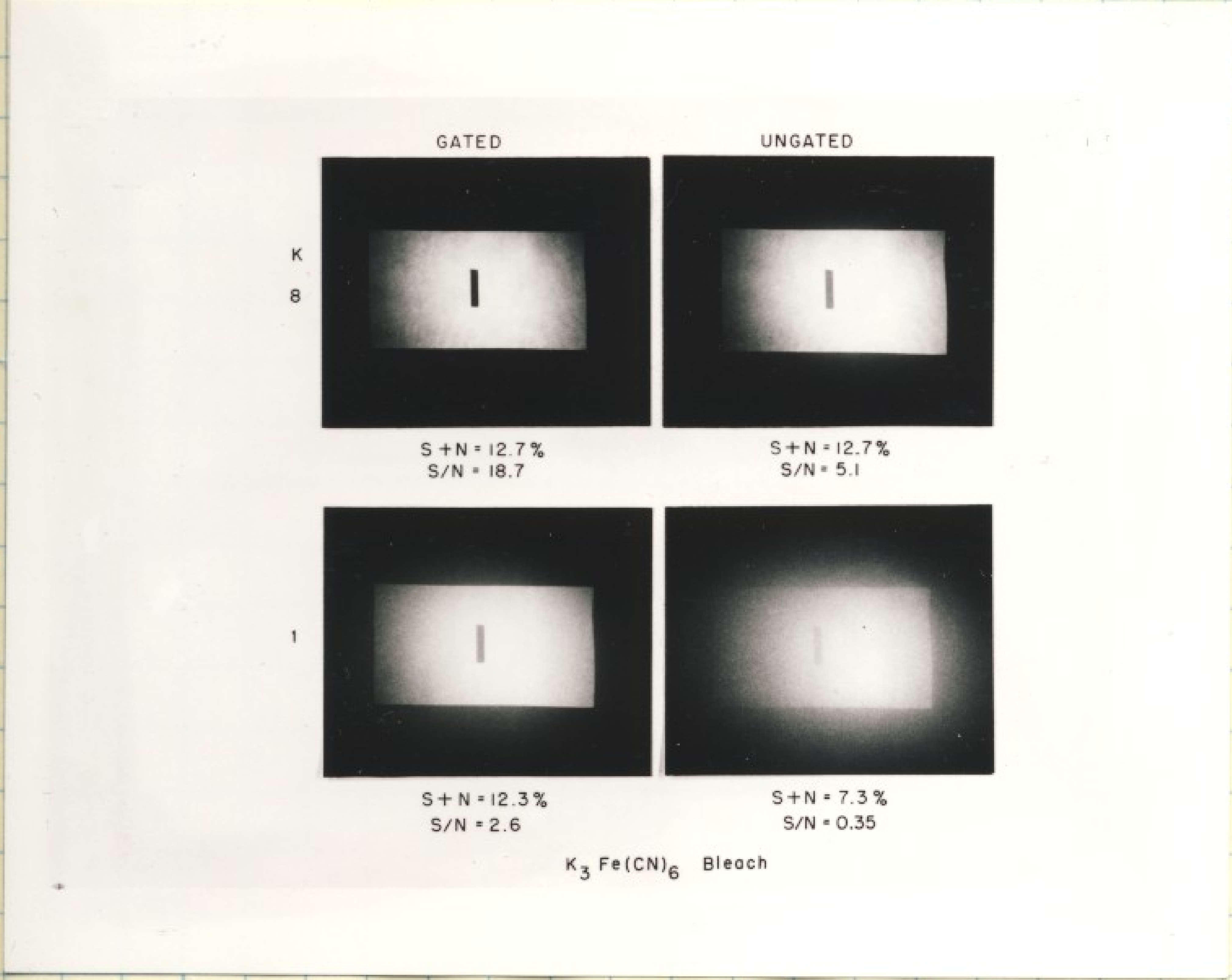
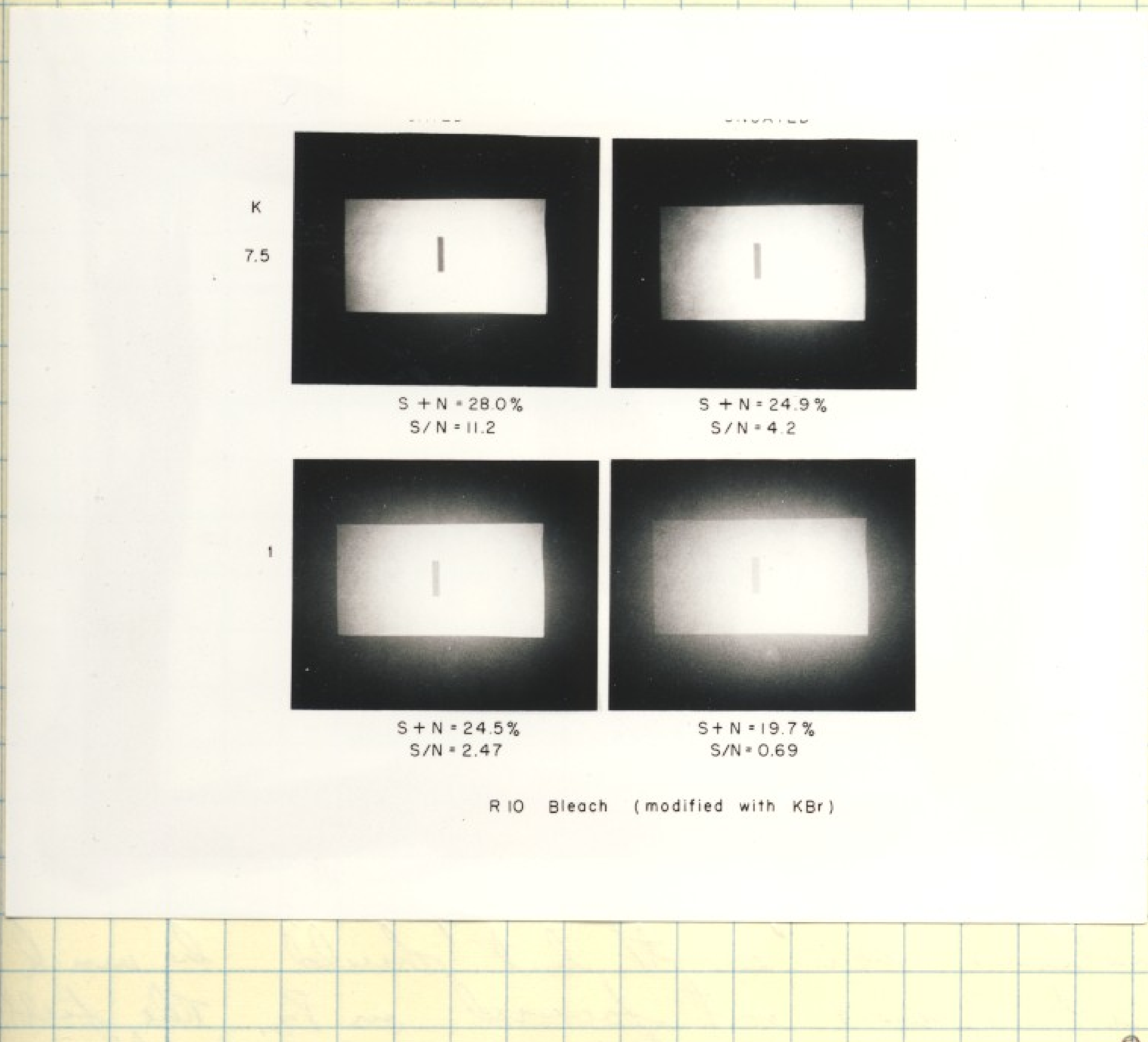


Reconstruction of images under various conditions, as indicated, Potassium ferricyanide bleach.



Reconstruction of images under various conditions, as indicated, Dichromate bleach.

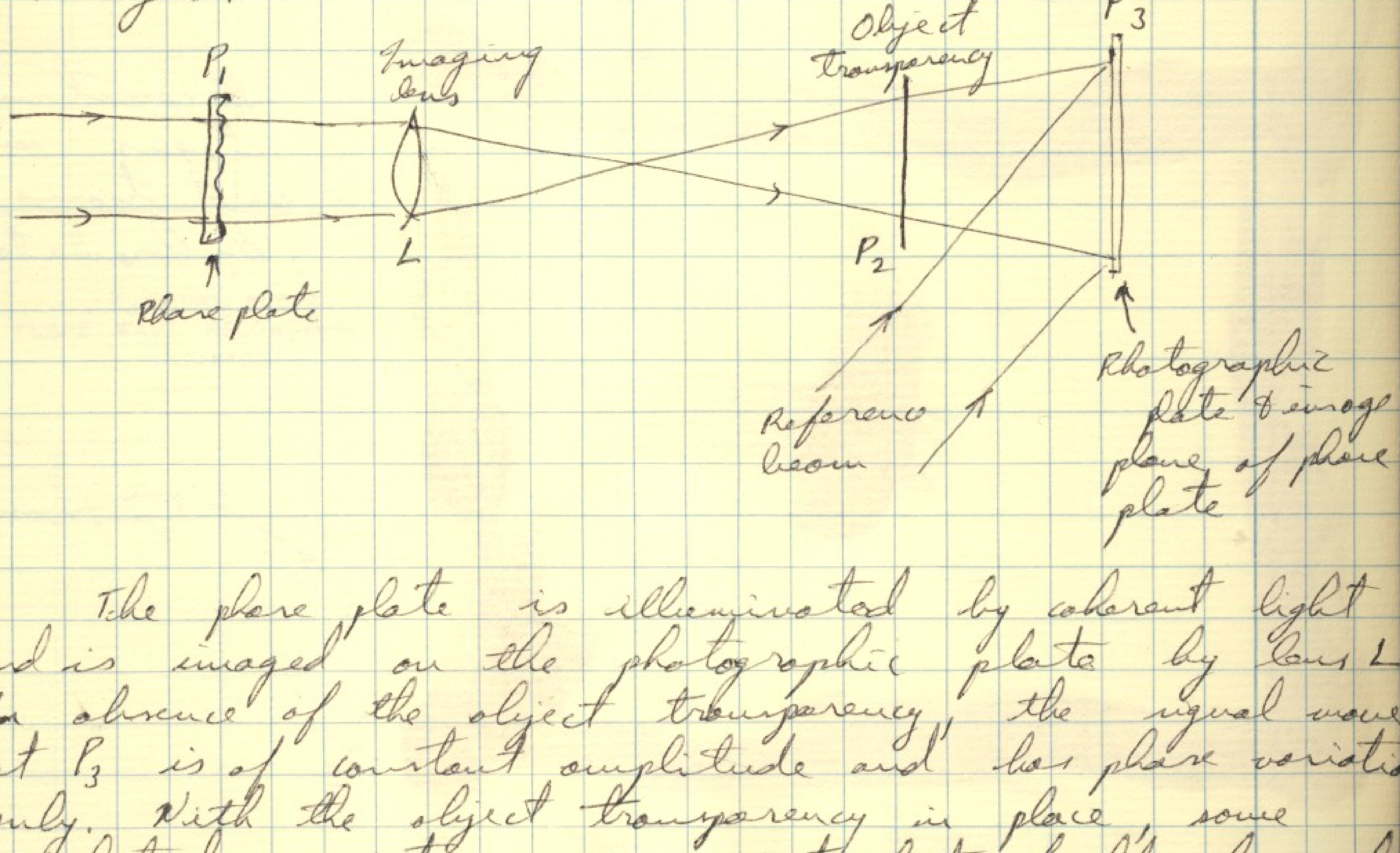
Juris Upatnieks
17 April 1969.

27 May 1969

Reduced noise level images from a bleached (dielectric) holograms.

A bleached hologram reconstructs signal that is frequently rather noisy. This noise level can be decreased with higher beam ratios, but this tends to decrease the diffraction efficiency. Also, the varying signal amplitude at the hologram plane also reduces diffraction efficiency. This can be overcome to some extend if transparencies are used as objects. Two cases will be considered, one in which a hologram is illuminated with a diffuse wavefront and the other in which the object transparency is placed at a self-focusing image plane of a phase grating.

With diffuse illumination we can use the optical system below to obtain improved images:



The phase plate is illuminated by coherent light and is imaged on the photographic plate by lens L. In absence of the object transparency, the signal wave at P_3 is of constant amplitude and has phase variation only. With the object transparency in place, some amplitude variations can exist but should be much smaller than if P_1 was not focused on P_3. The field at P_3 should be especially uniform if the object is

Read and understood by me.
May 27, 1969 Douglas B. Brumm

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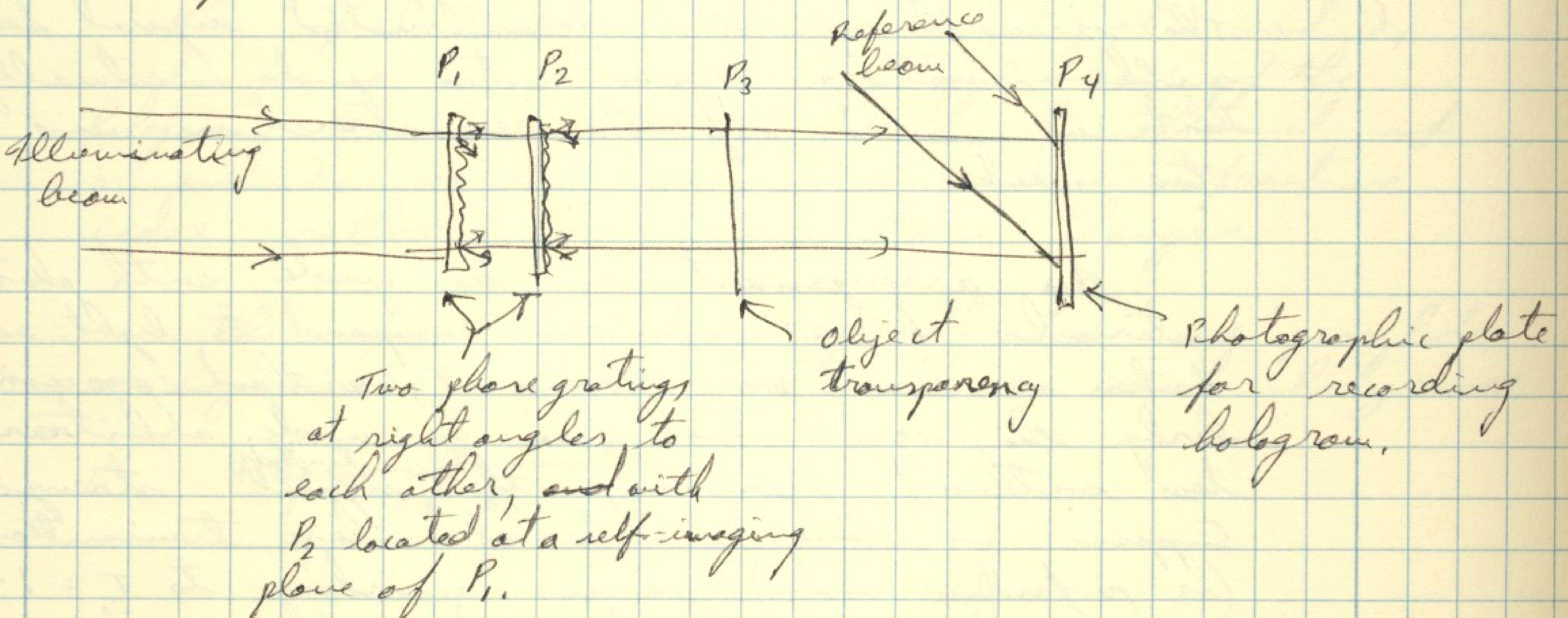
for most part clear ~~of~~ or of mostly uniformly shaded large areas. The reference wave is introduced from one side. Since the signal ~~field~~ beam has constant amplitude, noise due to bleached "grain" pattern will be absent and the image should show greatly improved signal to noise ratio and diffraction efficiency.

A similar system can be set up with self-imaging phase gratings. The system can be set up as shown below:



In this case P_2 is at ~~the~~ a self-imaging plane of P_1, and P_3 and P_4 are at the self-imaging planes of both gratings at P_1 and P_2. Thus, at P_4 the signal beam will have a uniform amplitude, except as modified by object at P_3, and again low-noise high-efficiency image could be reconstructed.

Juris Upatnieks
27 May 1969.

Read and understood by me. May 27, 1969
Douglas B. Brumm

9 June 1969

Holograms made with low irradiance of object.

Some objects, like biological specimens for example cannot tolerate a high level of irradiance as damage to it might result. One technique to lower irradiance is to increa the reference beam intensity and record a hologr with a high reference to signal beam ratio. The strength of the reconstructed signal decrease with increasing beam ratio and eventually is lost in noise if the reconstruction is too weak.

An arrangement can be made with photo-chro materials (materials that respond to light, either darken or become more transparent, without processing) whereby the signal level can be made arbitrarily low without decreasing the reconstructed signal strength. Suppose we have a material whose transmittance T_1 (or refractive index) varies according to $T_1 = 1 - k_{\lambda_1} E_{\lambda_1}$ at wavelength λ_1 and whose transmittance $T_2 = k_{\lambda 2} E_{\lambda 2}$, where E is exposure. Let a_0 be reference beam amplitude and a_s be signal beam amplitude at wavelength λ_1, and a_e be amplitu of incident wavefront at λ_2. The resulting transmittance T is then

$$T = 1 - k_{\lambda 1} E_{\lambda 1} + k_{\lambda 2} E_{\lambda 2} \qquad (1$$

$$= 1 - k_{\lambda_1}\left(a_0^2 + a_s^2 + 2a_0 a_s \cos\phi\right)t + k_{\lambda 2} a_e$$

where t is exposure time and exposure at both wavelength is accomplished simultaneously. Let us now adjust beam at λ_2 and the other beam so that $k_{\lambda 2} a_e^2 = k_{\lambda_1} a_0^2$. Eq. (1) then becomes

$$T = 1 - k_{\lambda_1} t\left(a_s^2 + 2a_0 a_s \cos\phi\right) \qquad ($$

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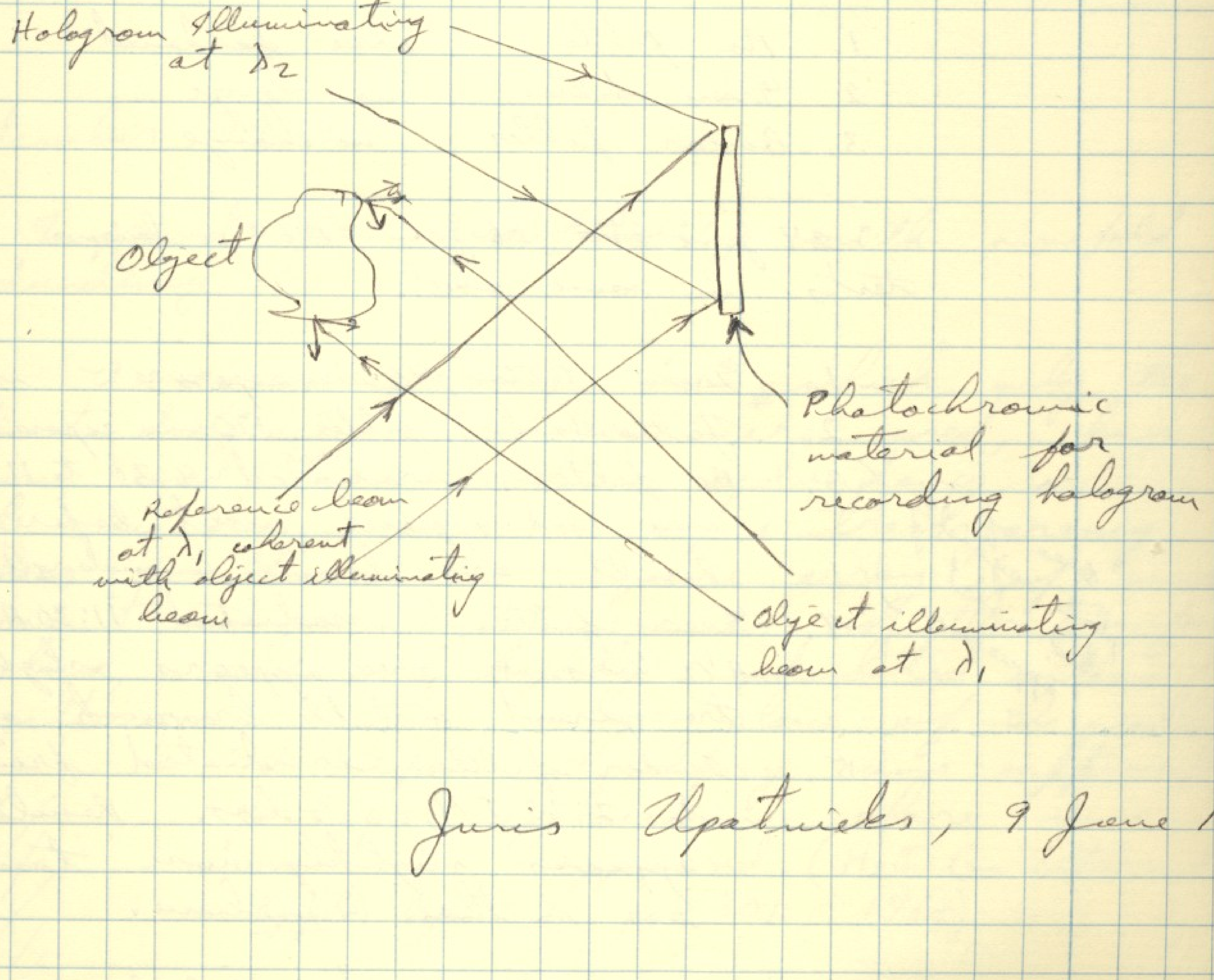
We see from eq(2) that if a_0 is increased, a_s can be kept as small as possible and no image degration should result if reference beam intensity a_0^2 is increased. It is therefore possible to have as low irradiance of the object as desired without decreasing the recorded signal contrast, and the diffraction efficiency of such a hologram.

The signal could be also recorded at λ_2 and λ_1 used for a uniform illuminating beam of the hologram. Similar results would be obtained if λ_1 and λ_2 would create corresponding refractive index rather than transmittance changes.

The figure below illustrates one possible arrangement for constructing such holograms:



Juris Upatnieks, 9 June 1969

9 July 1969

Experiments with photosensitivity of photographic plates bleached in potassium ferricyanide

Jack Walker reported the observation that holograms bleached in potassium ferricyanide bleach and illuminated with mercury arc lamp become more transparent. An investigation was began to explore this change and determine which wavelength of Hg-arc spectrum had what effect on the bleached emulsion. The following is a list of experiments and observations, with appropriate dates of each experiment:

24 June 1968, 5 min exposure tests on area of bleached hologram that had turned brownish

1. No filter – area darkened
2. Green filter – no change
3. Amber filter – no change

24 June ~~and~~ to 26 June 1968, longer exposure tests in same area;

1. Green filter, 90 min exposure – slight darkening
2. Yellow (amber) filter, 120 min exposure – no change
3. No filter, irradiated 9:30 to 11:30 A.M (2 hrs), area that appeared violet before exposure. Result: area became considerably darker.
4. Green filter, irradiated 11:30 AM to 4:00 P.M, 4½ hrs. – area appears slightly more transparent, a little brownish appearance.
5. Amber filter, irradiated from 9:00 A.M. to 2:30 P.M, 5½ hrs. Result: area appears slightly more transparent, but less so than (4.) above.

Area of plate originally had violet appearance

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Note: The areas darkened in the originally brownish part of the plate gradually become lighter, more transparent, with time. The plate was kept in darkness when not irradiated.

26 June and 27 June 1969.

Area darkened in 3. above, violet area that was darkened, was exposed from 2:30 P.M. to 4:30 P.M. on 26 June and from 11:30 A.M. to 4:00 P.M. on 27 June, total of 6½ hrs, in green light. Transmittance greatly increased of both the previously darkened area and the violet, not irradiated, area.

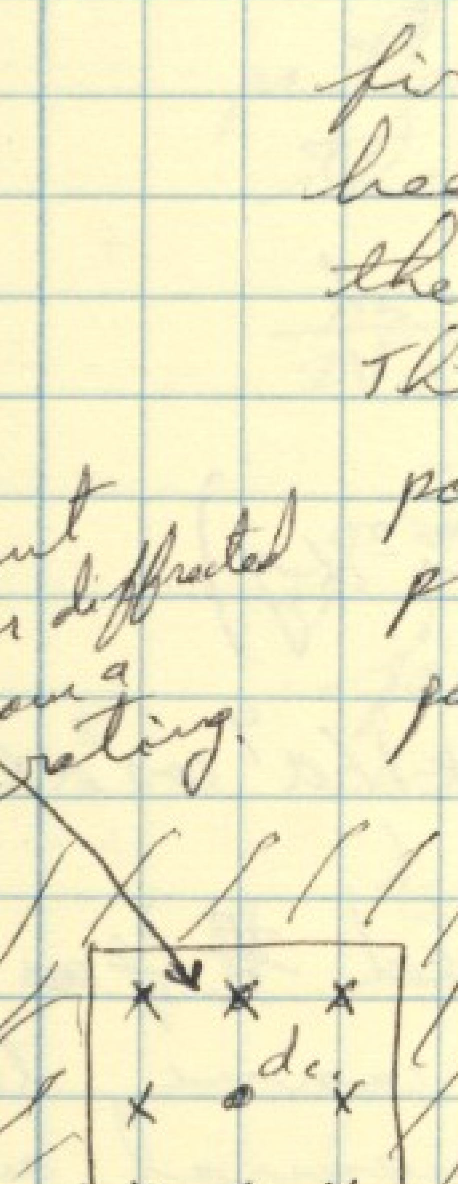
Juris Upatnieks, 9 July 1969

10 September 1969

Improved field uniformity with ninefold redundancy.

A crossed grating, from which only the first diffraction orders are used, has been used to introduce redundancy in the recorded hologram of a transparency. This results in a square array of nine point ~~images~~ light sources in the transform plane, and a highly modulated intensity pattern in the image plane of the grating. The ninefold redundancy seems sufficient for most applications where noise must be suppressed (H. J. Gerritsen et al., Appl. Opt. 7, p. 2301, 1968).

Nine point sources, or diffracted orders, from a crossed grating.



Opaque mask

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By selecting carefully another plane, the modulation can be reduced somewhat. This was suggested by E.N. Leith. Here another approach is analyzed which gives even more uniform field at the expense of resolution.

The amplitude field A resulting from a crossed grating and using only the nine orders is given by

$$A = \left(1 + a e^{j\theta} e^{j\alpha x} + a e^{j\theta} e^{-j\alpha x}\right)\left(1 + a e^{j\theta} e^{j\alpha y} + a e^{j\theta} e^{-j\alpha y}\right)$$

$$= \left(1 + 2a e^{j\theta} \cos\alpha x\right)\left(1 + 2a e^{j\theta} \cos\alpha y\right)$$

where $e^{j\theta}$ term expresses the relative phase shift between the d.c. and other terms, ~~and~~ α is the spatial frequency, and "a" is the amplitude of the 1st diffracted order of each grating. The phase shift θ is ~~th~~ determined by the distance the plane of observation is from the "image" plane and can have any value between 0 and 2π. The intensity pattern is given by AA^*:

$$AA^* = \left(1 + 4a\cos\theta\cos\alpha x + 4a^2\cos^2\alpha x\right)\left(1 + 4a\cos\theta\cos\alpha y + 4a^2\cos^2\alpha y\right)$$

Let $\theta = \frac{\pi}{2}$, then

$$AA^* = \left(1 + 4a^2\cos^2\alpha x\right)\left(1 + 4a^2\cos^2\alpha y\right)$$

$$= 1 + 4a^2\cos^2\alpha x + 4a^2\cos^2\alpha y + 16a^4\cos^2\alpha x\cos^2\alpha y$$

We now add another pattern displaced $\frac{\lambda_s}{4}$ in both the x and y directions, so that cosine terms become sines. The sum of the original and

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displaced pattern is

$$AA^* + (AA^*)_{displ.} = 2 + 4a^2(\cos^2\alpha x + \sin^2\alpha x) + 4a^2(\cos^2\alpha y + \sin^2\alpha y)$$

$$+ 16a^4(\cos^2\alpha x \cos^2\alpha y + \sin^2\alpha x \sin^2\alpha y)$$

$$= 2 + 8a^2 + 16a^4(\cos^2\alpha x \cos^2\alpha y + \sin^2\alpha x \sin^2\alpha y)$$

ection: n value is 0 18 Feb. 1970, J.U.

Since the last term ( ) has a minimum value of 0.5 and a maximum value of 1.0, we get for the minimum and maximum intensities

$$\cancel{I_{min} = 18a^2}, \quad \cancel{I_{max.} = 26a^2}$$

$$I_{min.} = 2 + 8a^2 + 8a^4 \qquad I_{max.} = 2 + 8a^2 + 16a^4$$

$$= 2(1+2a^2)^2 \qquad = 2(1+2a^2)^2 + 8a^4$$

$$= 2(1+2a^2) + 8a^4$$

For $a = 1$, or equal intensities in all orders, $I_{min} = 18$ and $I_{max} = 26$. Thus we see that modulation is reduced to about 25% of the maximum value of $I_{max.}$. For the single ~~illuminated~~ pattern has $I_{min.} = 1$ and $I_{max.} = 25$, or close to 100% modulation. Thus, considerable improvement is obtained.

The disadvantage of the two-pattern arrangement is that the ~~image~~ object illuminated by this pattern is also moved over $1/4\ \lambda_s$ along both the x ang y axis, or a total of $\frac{\lambda_s}{2\sqrt{2}}$ distance (λ_s is the spatial frequency of the grating which is assumed to be the same for both the x and y axis). Although this is undesirable, it may not be too bad if λ_s is very small or if the required resolution is not great.

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We should also note that for a one-dimensional grating we get

$$AA^* + AA^*_{displ.} = 2 + 8a^2$$

and thus we have a perfectly uniform image field. The displacement of images is $(1/4)\lambda_s$, which is also the reduction in resolution.

In some situations emulsion thickness and the distance Δz, through which we move to go from one selfimaging plane to another, can be of the same order of magnitude. In such cases we cannot assume emulsion as a 2-dimensional recording medium, and we cannot set $\cos\theta = 0$ since θ undergoes considerable change through the thickness of the emulsion. Here we may use another approach.

Assume that intensity transmission T of the emulsion is proportional to the average intensity alongth the depth dimension of the emulsion (direction z). In this case appearant field uniformity will be proportional to $\frac{1}{b}\int_0^b AA^* dz$. ~~which gives us~~ The phase delay is known to be proportional to z, so we can have an equivalent form for average intensity $= \frac{1}{c}\int_0^c AA^* d\theta$. The intensity has terms which are not multiplied by functi[on] of θ, those which are multiplied by $\cos\theta$, and those which are multiplied by $\cos^2\theta$. Since integration affects only terms containing $\cos\theta$, we find them separately:

$$\frac{1}{c}\int_0^c \cos\theta \, d\theta = \frac{1}{c}\sin\theta \Big|_0^c = \frac{1}{c}(\sin c - 0)$$

$$= \frac{1}{c}\sin c$$

and $$\frac{1}{c}\int_0^c \cos^2\theta \, d\theta = \frac{1}{c}\int_0^c \frac{1}{2}(1+\cos 2\theta)\, d\theta$$

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$$\frac{1}{c}\int_0^c \cos^2\theta \, d\theta = \frac{1}{2c}\left(\theta + \frac{1}{2}\sin 2\theta\right)\Big|_0^c$$

$$= \frac{1}{2} + \frac{1}{4c}\sin 2c$$

For $c = n\pi$, where $n = 0, 1, 2, \ldots$, we get

$$\frac{1}{c}\int_0^c \cos\theta \, d\theta = 0$$

$$\frac{1}{c}\int_0^c \cos^2\theta \, d\theta = \frac{1}{2}$$

For $c = n\pi$ we then get

$$AA^* = 1 + 4a^2\cos^2\alpha x + 4a^2\cos^2\alpha y + 16a^4\cos^2\alpha x\cos^2\alpha y$$
$$+ 8a^2\cos\alpha x\cos\alpha y$$

and

$$AA^* + AA^*_{displ.} = 2 + 8a^2 + 8a^2(\cos\alpha x\cos\alpha y + \sin\alpha x\sin\alpha y)$$
$$+ 16a^4(\cos^2\alpha x\cos^2\alpha y + \sin^2\alpha x\sin^2\alpha y)$$
$$= 2 + 8a^2 + 8a^2\cos(\alpha x - \alpha y)$$
$$+ 16a^4(\cos^2\alpha x\cos^2\alpha y + \sin^2\alpha x\sin^2\alpha y)$$

We see that in this case an extra term exist which can vary between $\pm 8a^2$. For $a = 1$, intensity varies between $(2 + 16a^2 + 16a^4) = I_{max}$ and $I_{min} = (2 + 16a^4)$ or $I_{min} = (2 + 8a^2 + 8a^4)$, which is $I_{max} = 38$ and $I_{min} = 18$. Thus we have up to $\sim 50\%$ modulation. We should again note that for a one-dimensional grating $\cos^2\theta$ term does not exist and therefore the field is perfectly uniform.

Juris Upatnieks, 22 Sept. 1969

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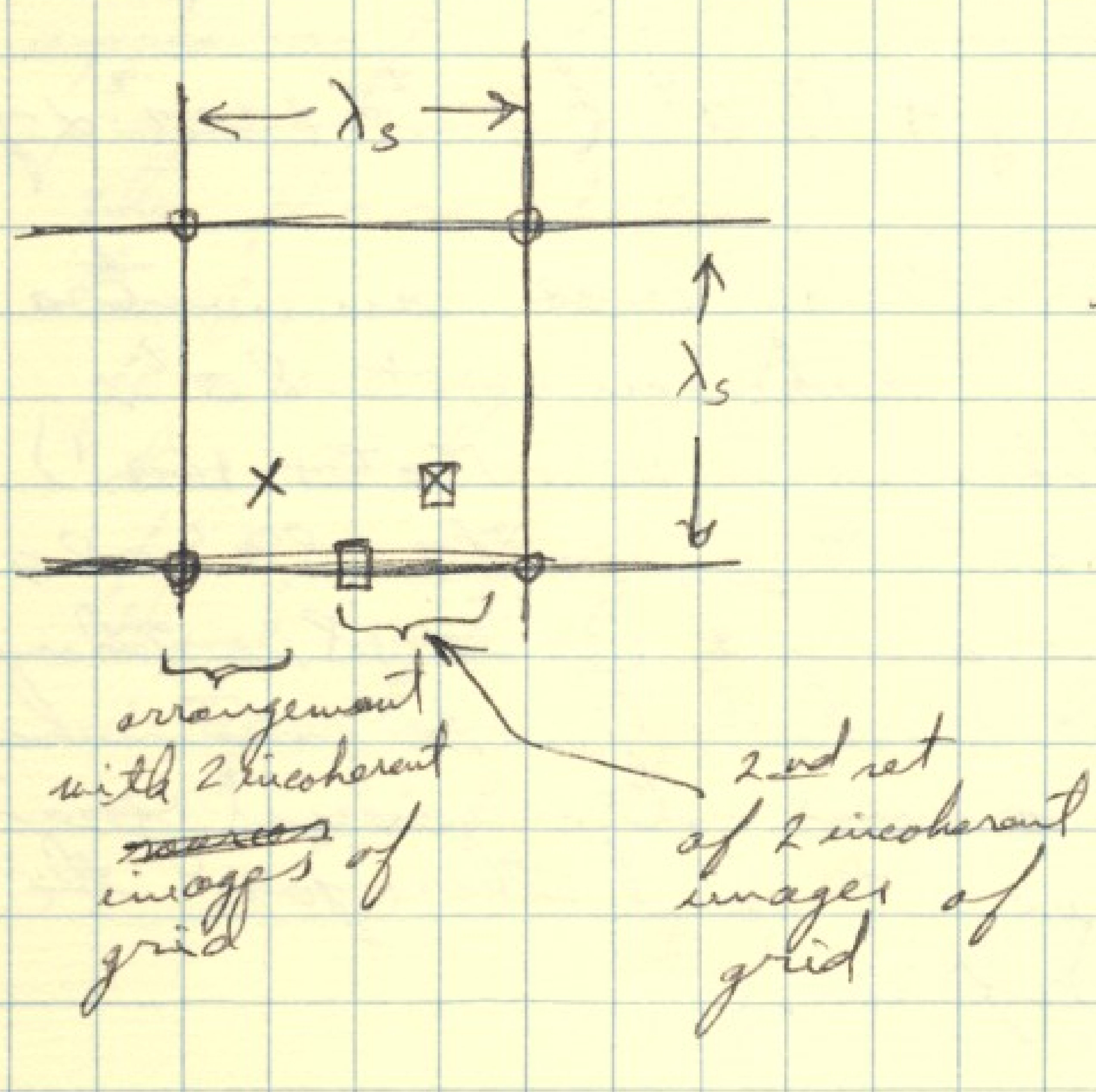
In the equation on the previous page the undesirable term $8a^2(\cos\alpha x \cos\alpha y + \sin\alpha x \sin\alpha y)$ could be eliminated if another pattern, similar to that described previously, would be superimposed and displaced by, for example, $(\lambda_s/2)$ in the x-direction. We would then have
$\cos(\alpha x + \pi\cancel{/2}) = -\cos\alpha x$ and $\sin(\alpha x + \pi) = -\sin\alpha x$.
The net result would be that $\cos\alpha x \cos\alpha y$ and $\sin\alpha x \sin\alpha y$ terms would cancel each other, leaving only the $(\cos)^2$ and $(\sin)^2$ terms:

$$AA^* + AA^*_{(\text{displ. } \lambda_s/4)} + \left[AA^* + AA^*_{\text{displ. } \lambda_s/4}\right]_{\substack{\text{displ. } \lambda_s/2 \\ \text{in } x\text{-dir.}}}$$

$$= 4 + 16a^2 + 32a^4(\cos^2\alpha x \cos^2\alpha y + \sin^2\alpha x \sin^2\alpha y)$$

Thus, the modulation would be again reduced to 25%, as before.

The required displacements for the latest described scheme, requiring 4 incoherent superpositions of the image, are shown here where the points indicate intersections of grid lines:



The resolution loss for the 4-source arrangement is $\sqrt{\left(\frac{3}{4}\lambda_s\right)^2 + \left(\frac{1}{4}\lambda_s\right)^2} = \frac{\lambda_s}{4}\sqrt{10}$

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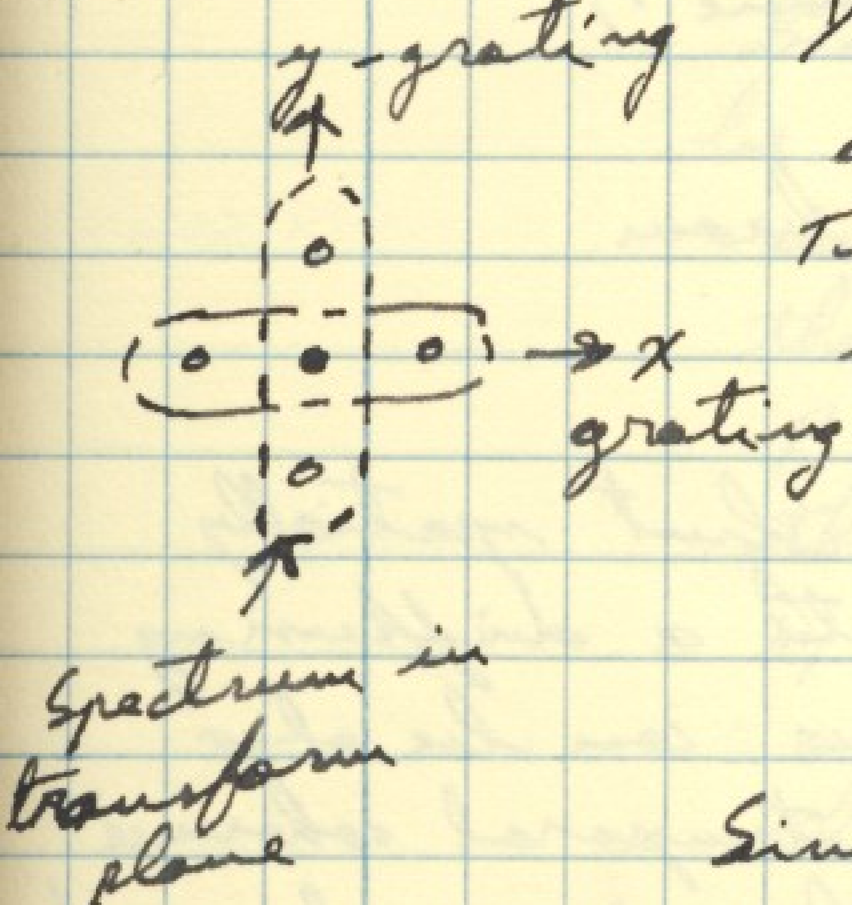
Corrections to calculations on p. 31 of this notebook.

At the top of p. 31 we have the expression

$$AA^* + (AA^*)_{disp.} = 2 + 8a^2 + 16a^4(\cos^2\alpha x \cos^2\alpha y + \sin^2\alpha x \sin$$

The last term has values between 0 and $16a^4$ since x and y are independent variables. Thus for $a = 1$, $I_{min.} = 10$ and $I_{max} = 26$. Thus, the percent modulation of the maximum value is $\frac{16}{26} \simeq 64\%$ and not 25% as mentioned before. This still is considerable improvement over 96% modulation obtained with a single crossed grating, without incoherent superposition.

A way to eliminate modulation completely would be to use two incoherently superimposed holograms that can be reconstructed one at a time. For each hologram, a onedimensional grating is used at right angles to the grating in the other exposure. Each hologram would then be reconstructed incoherently twice with $1/4\,\lambda_s$ phase shift between, to give a total of four incoherently superimposed images. The result for each grating or hologram would be



$$A_x A_x^* = 1 + 4a^2\cos^2\alpha x + (1 + 4a^2\sin^2\alpha x)$$

$$= 2 + \cancel{4a^2}\ 4a^2$$

Similarly $A_y A_y^* = 2 + 4a^2$

In this case the redundancy would be five if $a = 1$.

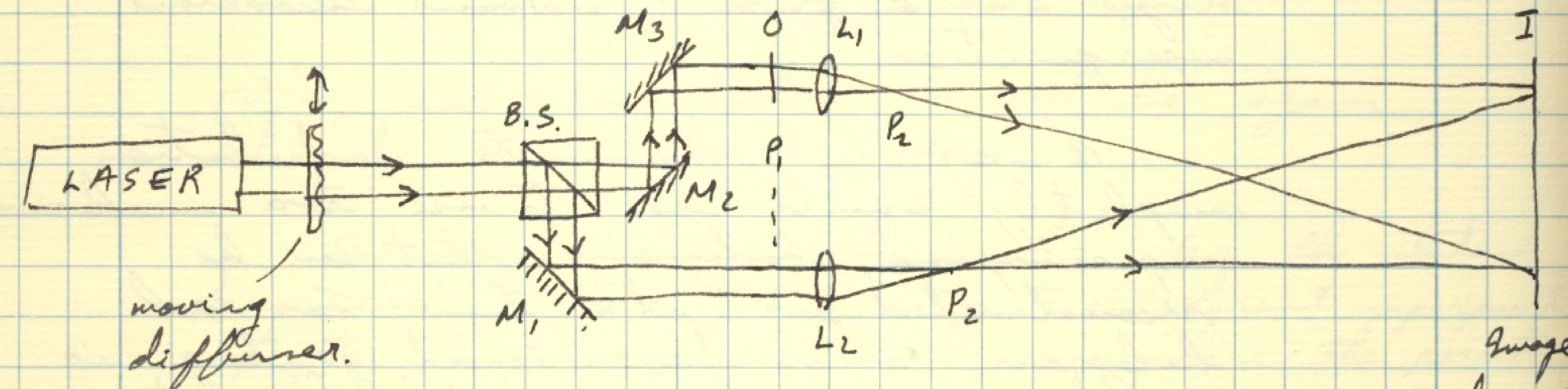
Juris Upatnieks, 22 December 1969.

22 December 1969

System noise reduction in holographic microscopy.

Elimination of diffraction patterns from dust and defects of optical components is still a major problem in holographic microscopy. Here as solution is proposed by using partially coherent light to ~~make~~ construct the hologram. Only objects near the image plane will be recorded while those further away will become incoherent with both the signal and reference waves and will be suppressed.

The optical system is shown below:



B.S. - beam splitter
M_1, M_2, M_3 - mirrors
O - object, such as a ~~mircoscope~~ slide, at plane P_1
L_1, L_2 - lenses, same focal length
P_2 - plane of focus for illuminating beam

The light source can be monocromatic but spatially not coherent, such as a laser beam with a diffusing screen moving in it. The light source can be also a filtered arc lamp of sufficient temporal coherence to form fringes (interferance) at the image plane of the object. The system must be carefully adjusted so that corresponding parts of both beams overl

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at the image plane and the path lengths for both beams are the same. Since corresponding parts of both beams are coherent, interference fringes will form at the image plane. A hologram of object O ~~t~~ will be formed and also of planes close to O but slightly out of focus. Plates distant from O will be incoherent and will not form fringes, thus their effect will be eliminated. The degree of coherence can be adjusted by choosing proper moving diffuser and beam diameter combination, or by adjusting the source aperture of a non-laser light ~~source~~.

The overlap of both beam at image plane can be obtained in several ways. Mirrors M_1 and M_3 can be tilted so that beam overlap at P_3 with lenses L_1 & L_2 removed; alternatly, ~~plane~~ diffraction grating can be inserted at P_1 with both beam parallel to each other before plane P_1. This latter arrangement would make the system partially achromatic.

To align the system, an ~~unct~~ collimated laser beam without diffuser and lenses L_1 & L_2 could be used. With a flat mirror at P_3, reflection of both beams should return to the laser when beams are paralld. A lens and test object can then be inserted before B.S. and arranged ~~st~~ so that image forms at P_1 in place of object O. M_1 can then be ~~mod~~ translated until image forms at P_1 in the second beam as well. A grating can then be inserted across both beams at P_1 and lenses L_1 and L_2 adjusted so that the diffracted images of the test object overlap at the image plane. These adjustments will make the system partially achromatic.

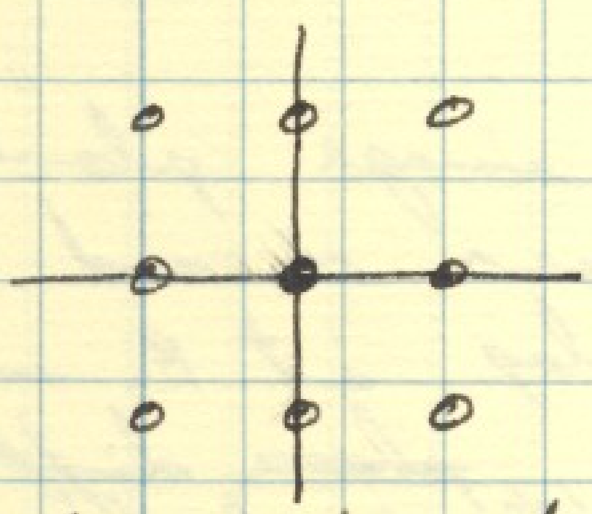
With monochromatic light sources, gratings need not be used.

Juris Upatnieks, 22 December 1969

23 December 1969

Technique for eliminating amplitude modulation from hologram images.

Previously, on p. 29 to p. 34, the case of the field uniformity obtainable with nine-fold redundancy was examined. With two incoherent superpositions of the fields, modulation could be reduced. Here we show that with four incoherent superpositions the modulation can be decreased to zero with nine and five plane waves (coherent) illuminating the object.



Fourier transform of nine plane waves

We consider nine plane waves obtained from, for example, a crossed phase grating. In the transform field it would form the pattern as shown at left. Higher order diffractions are eliminated by, for example, ~~as~~ a spatial filter.

As before, we obtain for the intensity for the case $\theta = \pi/2$

(1) $$AA^* = 1 + 4a^2(\cos^2 \alpha x + \cos^2 \alpha y) + 16a^4 \cos^2 \alpha x \cos^2 \alpha y$$

and by adding another pattern with $\frac{\lambda_s}{4}$ shift in both x and y directions we get

(2) $$AA^* + (AA^*)_{\substack{displ. \\ \lambda/4 \text{ in } x,y}} = 2 + 8a^2 + 16a^4(\cos^2 \alpha x \cos^2 \alpha y + \sin^2 \alpha x \sin^2$$

(3) $$= 2 + 8a^2 + 8a^4 + 4a^4[\cos 2\alpha(x+y) + \cos 2\alpha(x-y)]$$

The last relation is obtained by trigonometric identities.

We also note that in the above relations $\alpha = \frac{2\pi}{\lambda_s}$, where λ_s is the spatial frequency of the grating.

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If we now take the pattern described by ~~eq.~~ (3) and displace it by letting ~~y~~ $= y - \frac{\lambda_s}{4}$, or by $\frac{1}{4}\lambda_s$ along the x-axis, then we get, after adding the original pattern of eq. (3) and the displaced pattern,

$$AA^* + (AA^*)_{\substack{\text{displ.}\\ \lambda_s/4 \text{ in } x,y}} + \left[AA^* + (AA^*)_{\substack{\text{displ.}\\ \lambda_s/4 \text{ in } x,y}}\right]_{\substack{\text{displ.}\\ \lambda_s/4 \text{ in } y}} \tag{4}$$

$$= 4 + 16a^2 + 16a^4 + 4a^4\left[\cos 2\alpha\left(x+y-\tfrac{\lambda_s}{4}\right) + \cos 2\alpha(x+y) + \cos 2\alpha\left(x-y+\tfrac{\lambda_s}{4}\right) + \cos 2\alpha(x-y)\right]$$

$$= 4 + 16a^2 + 16a^4 + 4a^4\left[-\cos 2\alpha(x+y) + \cos 2\alpha(x+y) + (-)\cos 2\alpha(x-y) + \cos 2\alpha(x-y)\right]$$

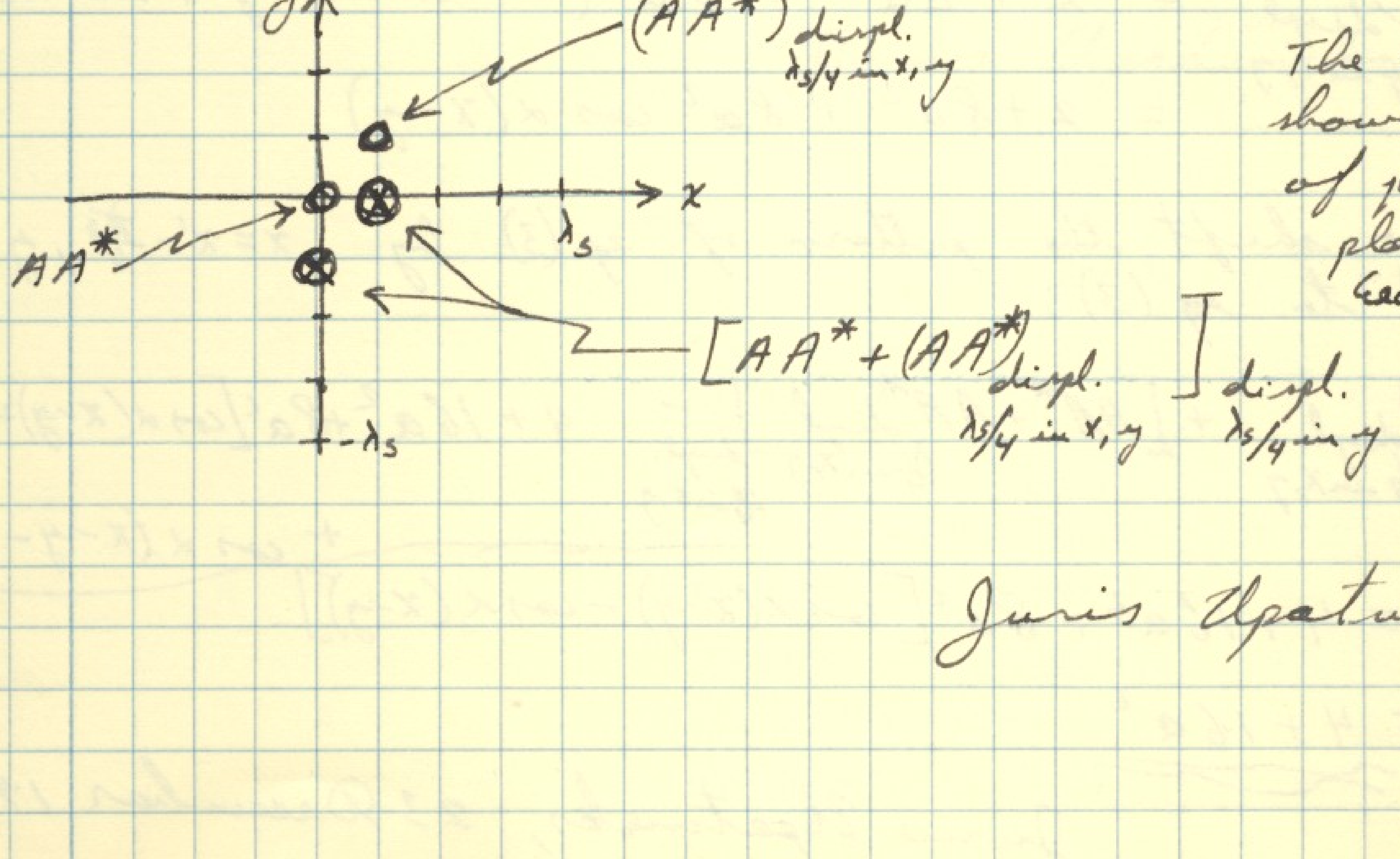
$$= 4 + 16a^2 + 16a^4$$

since $2\alpha\left(x-y+\frac{\lambda_s}{4}\right) = \frac{4\pi}{\lambda_s}\left(x-y+\frac{\lambda_s}{4}\right)$

$= 2\alpha(x-y) + \pi$

and $\cos(x+\pi) = -\cos x$

Thus we see that we obtain a completly uniform field with 0% modulation.



The diagram at left shows displacements of patterns in the ~~image~~ object plane (image plane of object). Each O indicates center of each pattern.

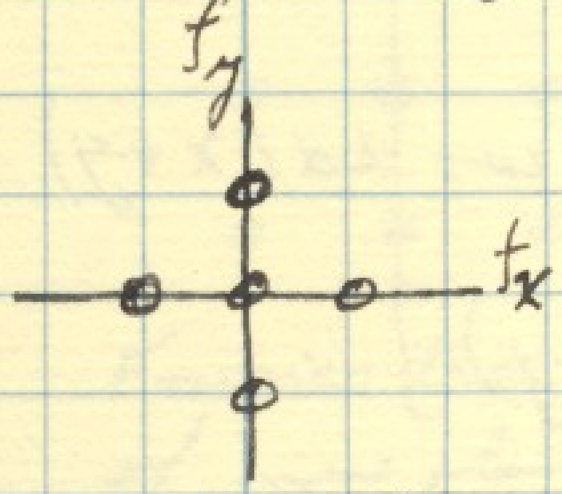
Juris Upatnieks, 23 December 1969

23 December 1969

From the diagram on previous page we see that loss of resolution due to displacement of images is $(\lambda_s/2)\sqrt{5/4}$. In summary, the technique described previously has the following properties:

1) % modulation $= 0$
2) Maximum loss of resolution $= \frac{\lambda_s}{2}\sqrt{\frac{5}{4}}$
3) Number of incoherent superpositions $= 4$
4) Redundancy, assuming $a = 1$, is 9-fold.

For the case of fivefold redundancy, we can perform similar analysis. Assume the Fourier transform relation as shown at left with corresponding amplitude field



Fourier transform of 5 plane waves

$$A = 1 + a(e^{j\alpha x} + e^{-j\alpha x} + e^{j\alpha y} + e^{-j\alpha y})e^{j\theta}$$

$$= 1 + a2e^{j\theta}\cos\alpha x + a2e^{j\theta}\cos\alpha y \qquad (1)$$

$$AA^* = 1 + 4a^2\cos^2\alpha x + 4a^2\cos^2\alpha y + 8a^2\cos\alpha x\cos\alpha y$$

$$4a\cos\theta\,(\cos\alpha x + \cos\alpha y) \qquad (2)$$

Shifting the pattern by $\frac{\lambda_s}{4}$ in both x and y directions, and $\theta = \frac{\pi}{2}$, we obtain

$$AA^* + (AA^*)_{\substack{\text{displ.}\\ \frac{\lambda_s}{4}\text{ in } x,y}} = 2 + 8a^2 + 8a^2(\cos\alpha x\cos\alpha y + \sin\alpha x\sin$$

$$= 2 + 8a^2 + 8a^2\cos\alpha(x-y) \qquad (3$$

We now shift the pattern of eq. (3) by $x = x' - \frac{\lambda_s}{4}$, $y = y' +$ and add to eq (3):

$$AA^* + (AA^*)_{\substack{\text{displ.}\\ \lambda_s/4\text{ in } x,y}} + \left[AA^* + AA^*_{\substack{\text{displ.}\\ \frac{\lambda_s}{4}\text{ in } x,y}}\right]_{\substack{\text{displ.}\\ \frac{\lambda_s}{4}\text{ in } x,y}} = 4 + 16a^2 + 8a^2\Big[\cos\alpha(x-y) + \cos\alpha\left(x - y - \tfrac{\lambda_s}{2}\right)\Big]$$

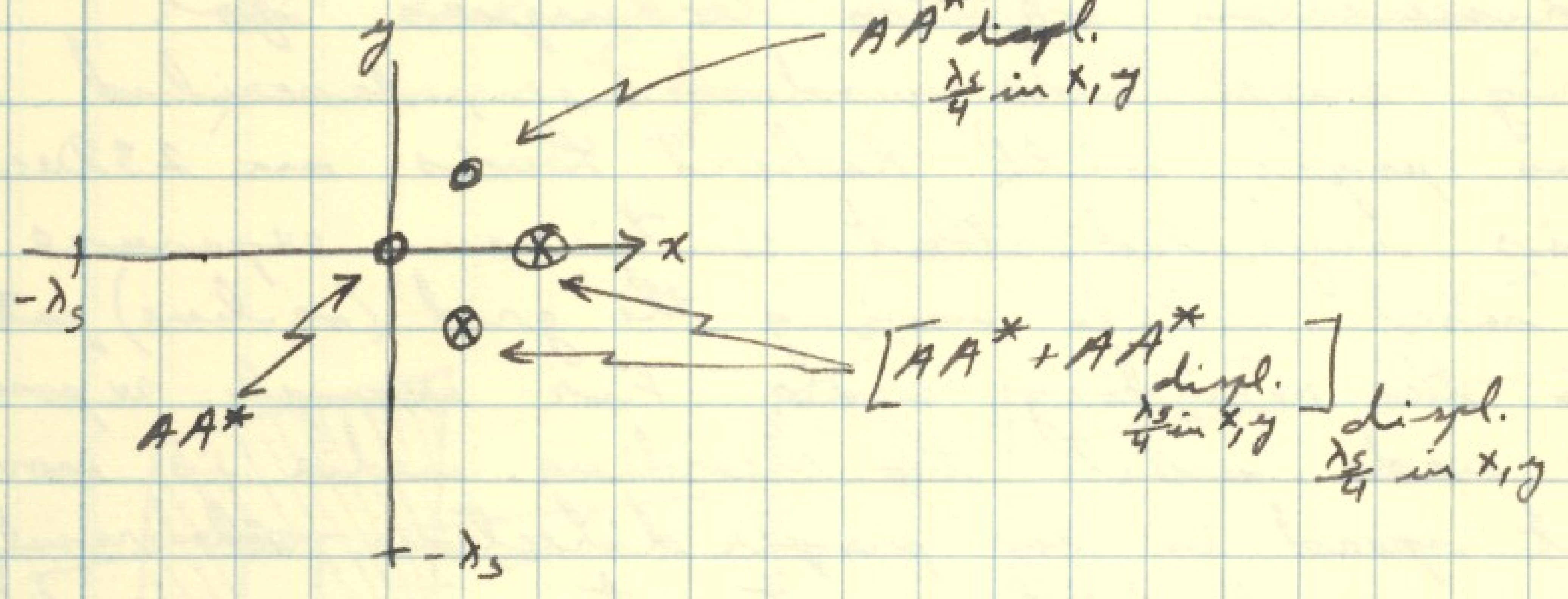
$$= 4 + 16a^2 + 8a^2\left[\cos\alpha(x-y) - \cos\alpha(x-y)\right]$$

$$= \underline{4 + 16a^2}$$

Juris Upatnieks, 23 December 1969

23 December 1969

Thus, we see that again uniform field is obtained. The displacement pattern of the fields is shown below.



The characteristics of this arrangement are:

1) % modulation $= 0$

2) Maximum loss of resolution $= \frac{\lambda_s}{2}$

3) Number of incoherent superpositions $= 4$

4) Redundancy, assuming $a = 1$, is 5-fold

In ~~this~~ description $e^{i\theta}$ is a relative phase factor between the d.c. term and diffracted orders. It can be changed at will by going appropriate distance along the optical axis, z direction, and it can have any value in the range 0 to 2π radians.

Juris Upatnieks, 23 December 1969.

30 December 1969

An alternate technique for eliminating amplitude modulation from hologram images.

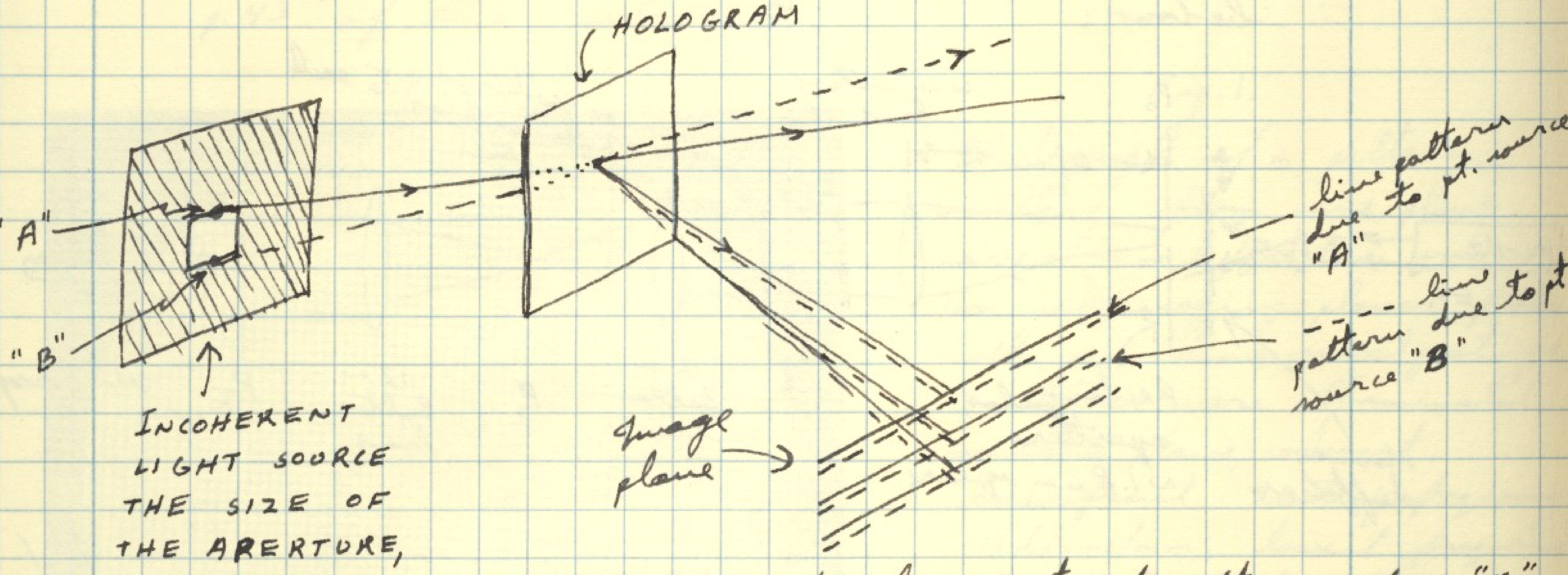
In a discussion of the techniques for eliminating amplitude modulation, described on previous pages, with Robert Lewis on 23 December 1969, Lewis sugested that continuous exposure could be used while moving the grid (or line) pattern relative to the recording media. For example, exposure would be made while the recording media is moved at constant speed in the proper direction. The result would be equivalent to integration over some distance. If the distance is chosen to be one full cycle of the lowest spatial frequency present, then a uniform exposure would result without amplitude (intensity) modulation by the grid pattern. For a two-dimensional field this would require repatative scanning.

A two-dimensional integration can be easily carried out by illuminating the hologram with a spatkially incoherent light source of proper dimensions. The light source should be a rectangular aperture for a rectangular array of point sources in the Fourier transform plane that are used to illuminate the object transparency. The sides of the rectangle should be parallel with the directions of the grid lines in the image plane, and the size of the aperture should be such that a point light source traversing the aperture from one edge to the other would move the grid pattern over one full period of the lowest spatial frequency component. If this condition is satisfied for both x, y directions ~~of~~ in the image plane, then a uniform ~~i~~ ~~expo~~ intensity field would result in the image plane. This technique should work well with holograms and with lens systems provided the gratings generating the multiple wavefronts are not in the image plane.

Juris Upatnieks, 30 December 1969.

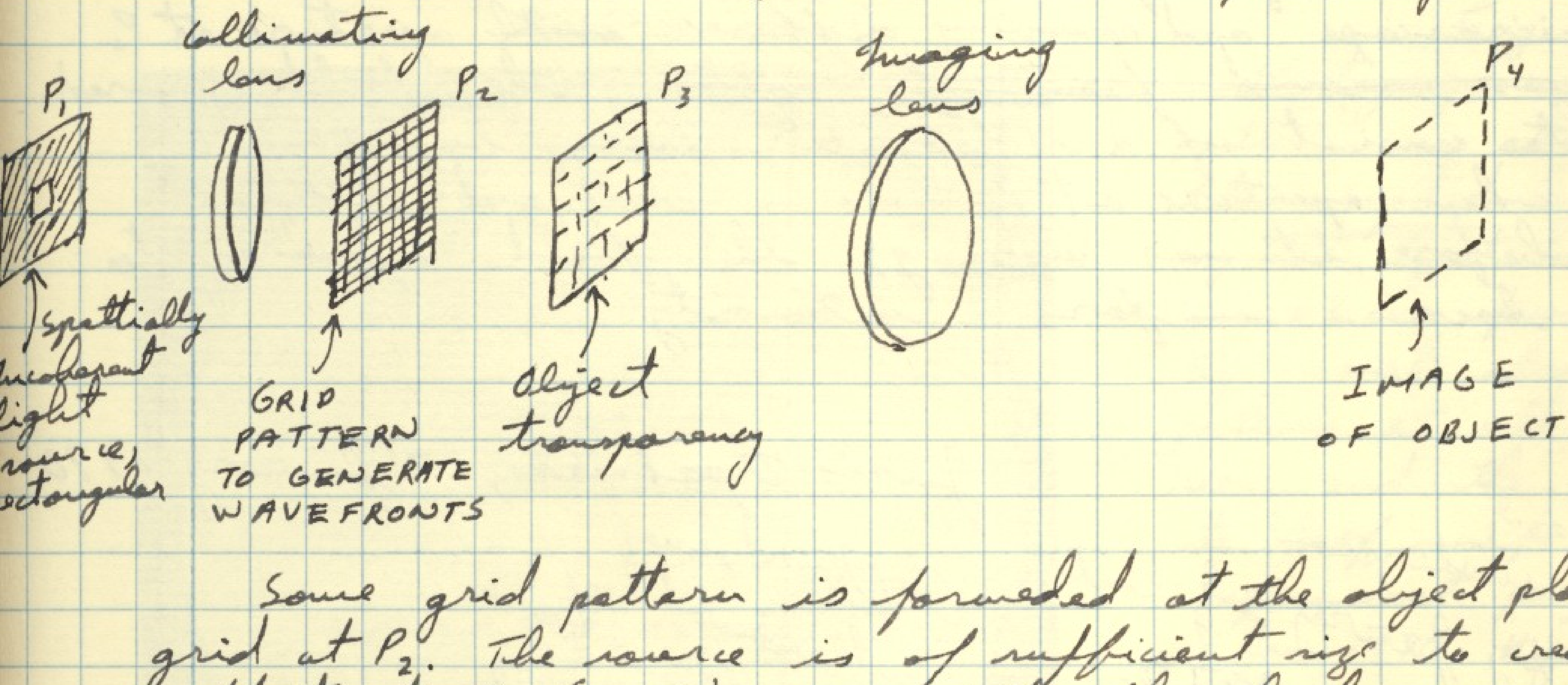
30 December 1969

If the grating in a lens system is in the image plane, then the recording medium would have to be moved relative to the image. In this case the technique of discrete motions, described on previous pages, would be preferable.



The displacement of patterns from "A" and "B" is that of the longest period present in the pattern.

With a lens system, the following arrangement could be used (this is an example only):



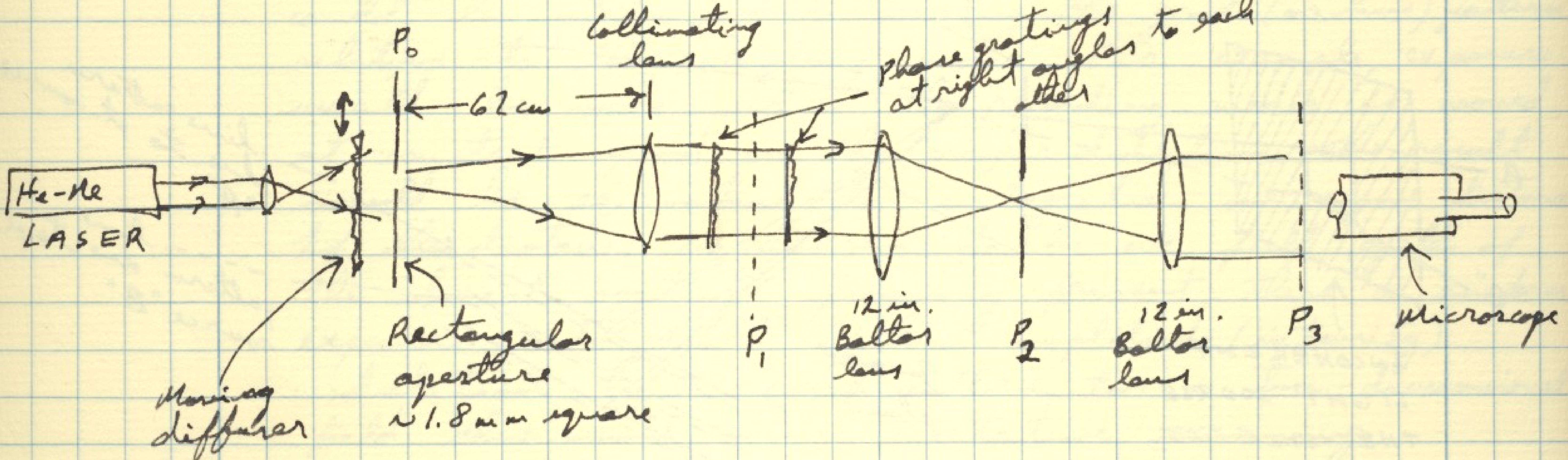
Some grid pattern is formed at the object plane from the grid at P_2. The source is of sufficient size to create the same effect at P_3 (or P_4) as with the hologram above.

Juris Upatnieks, 30 December 1969.

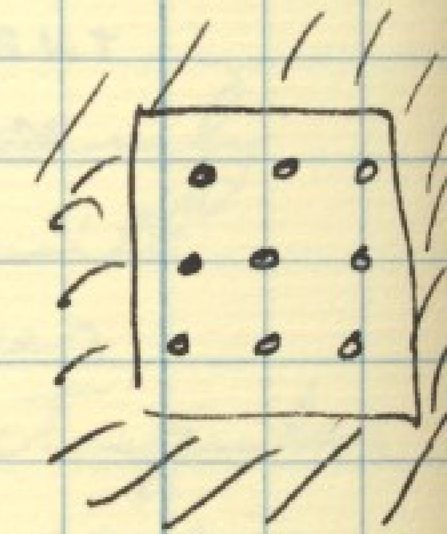
7 January 1970

Obtaining uniform intensity fields with nine spectral orders from a crossed phase grating and incoherent light source.

An optical system was set up as shown below:



P_3 is image plane of P_1
Filter at P_2 allows nine sideorders to pass:



Grating frequency 16 l/mm
Distance between gratings is 27 mm, P_1 13.5 mm from each grating.

When image of P_1 was observed at P_3 with a microscope and no moving diffuser, or ~~with~~ aperture at P_0 ~~was removed from the system~~, the field appeared to consist of a rectangular array bright spots; when aperture at P_0 was in place and diffuser before it was moving, the field appeared to have a uniform intensity.

Juris Upatnieks, 7 January 1970

Witnessed and understood by Jerry S Zelenka Jan. 7, 1970.

Witnessed, observed and understood by [signature]
23 Jan 1970

23 January 1970

Experimental results of obtaining uniform intensity fields from nine coherent plane waves.

The experimental results shown here were made with the optical system shown on p. 44 and involves the principles described on p. 42 and p. 43 of this notebook.

\# 70 - 27

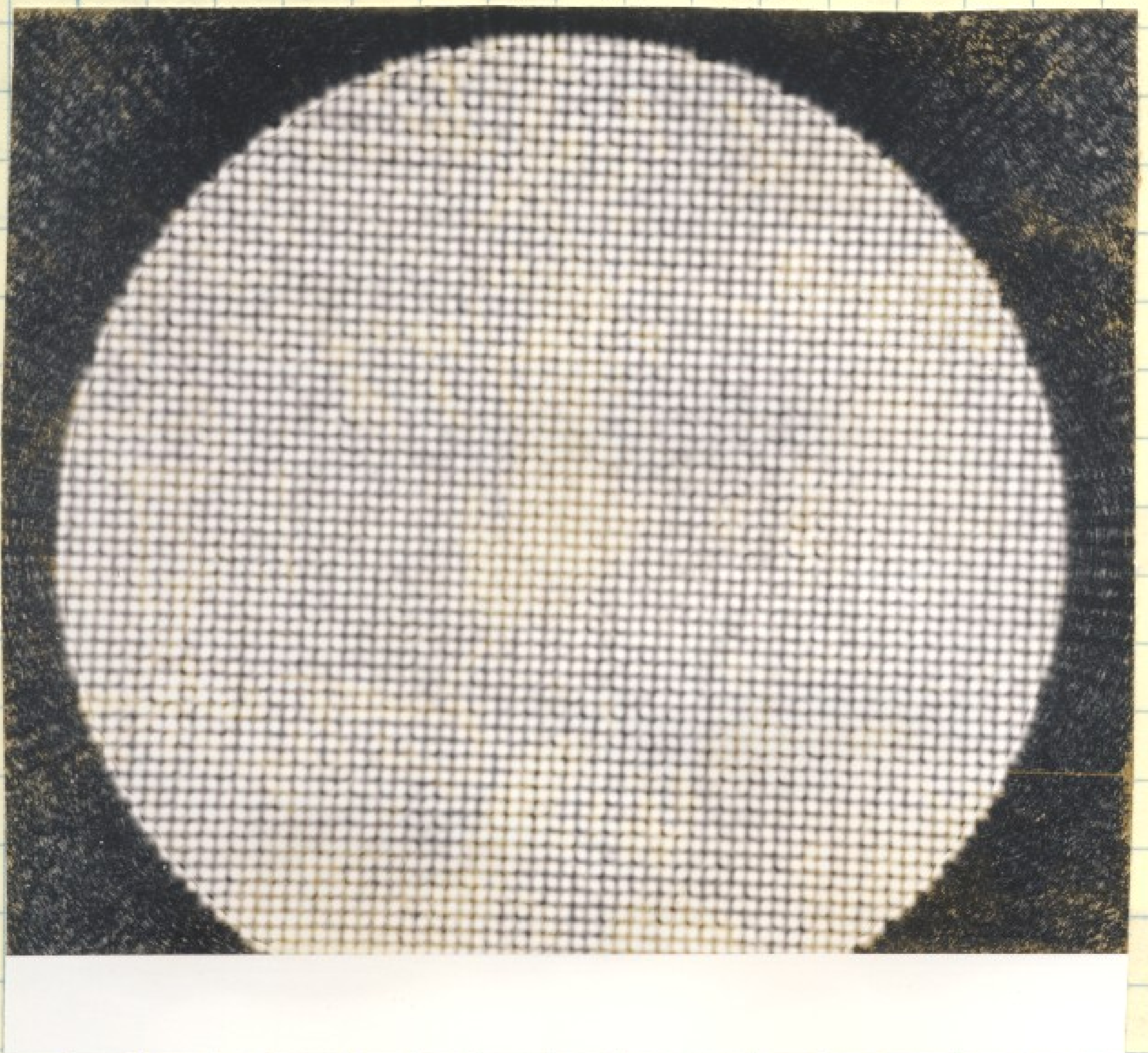


Fig. 1.

Photograph of a pattern resulting from nine plane waves (nine diffraction orders) two selfimaging planes from both one-dimensional gratings. Gratings were illuminated with a plane, coherent, wavefront. Grating frequency: 16 lines/mm, lowest frequency here corresponds to 32 lines/mm. Experiment performed on 6 Jan. 1970. Negative marked: 6, Jan. 6, 1970.

\# 70 - 28

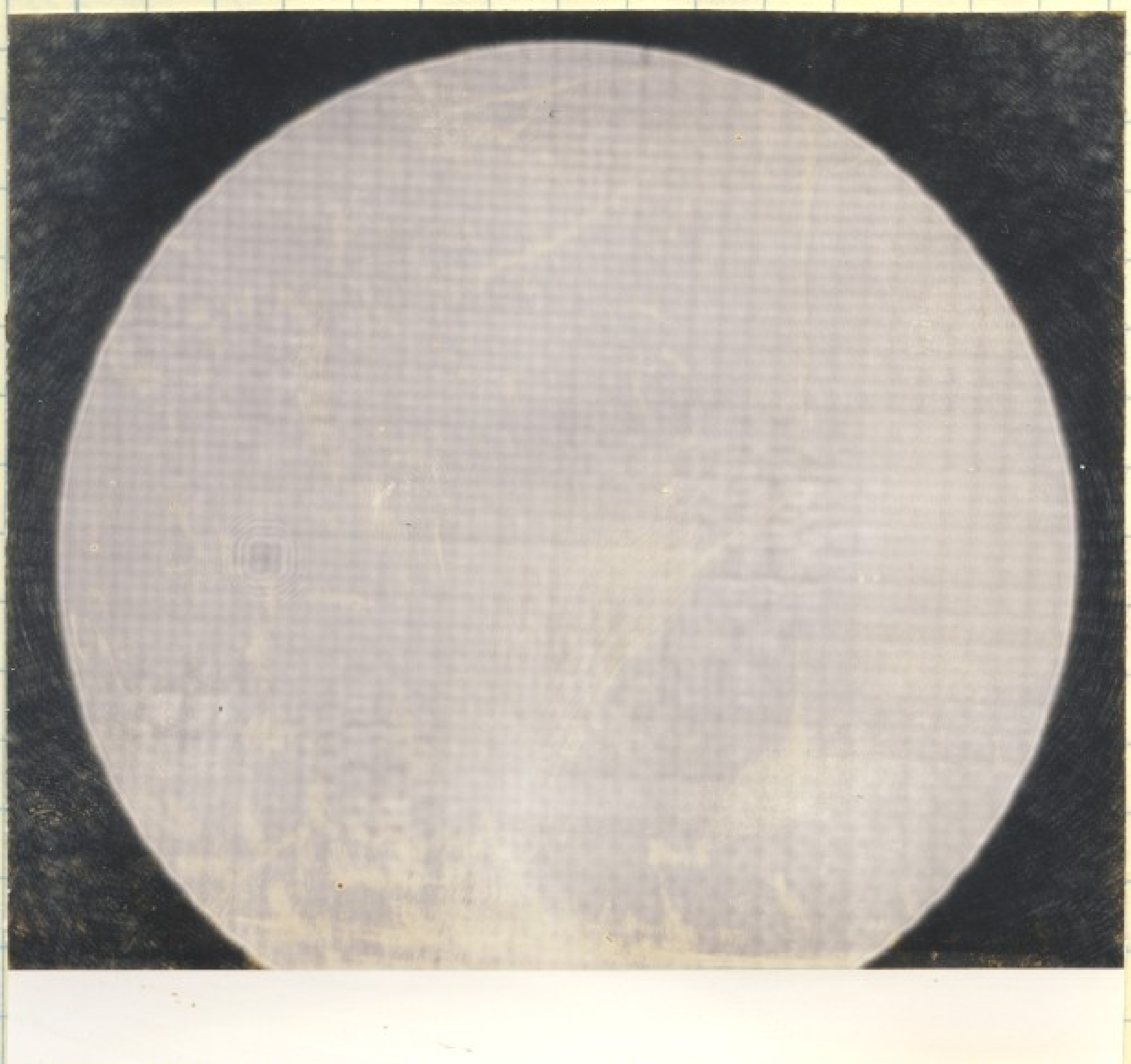


Fig. 2.

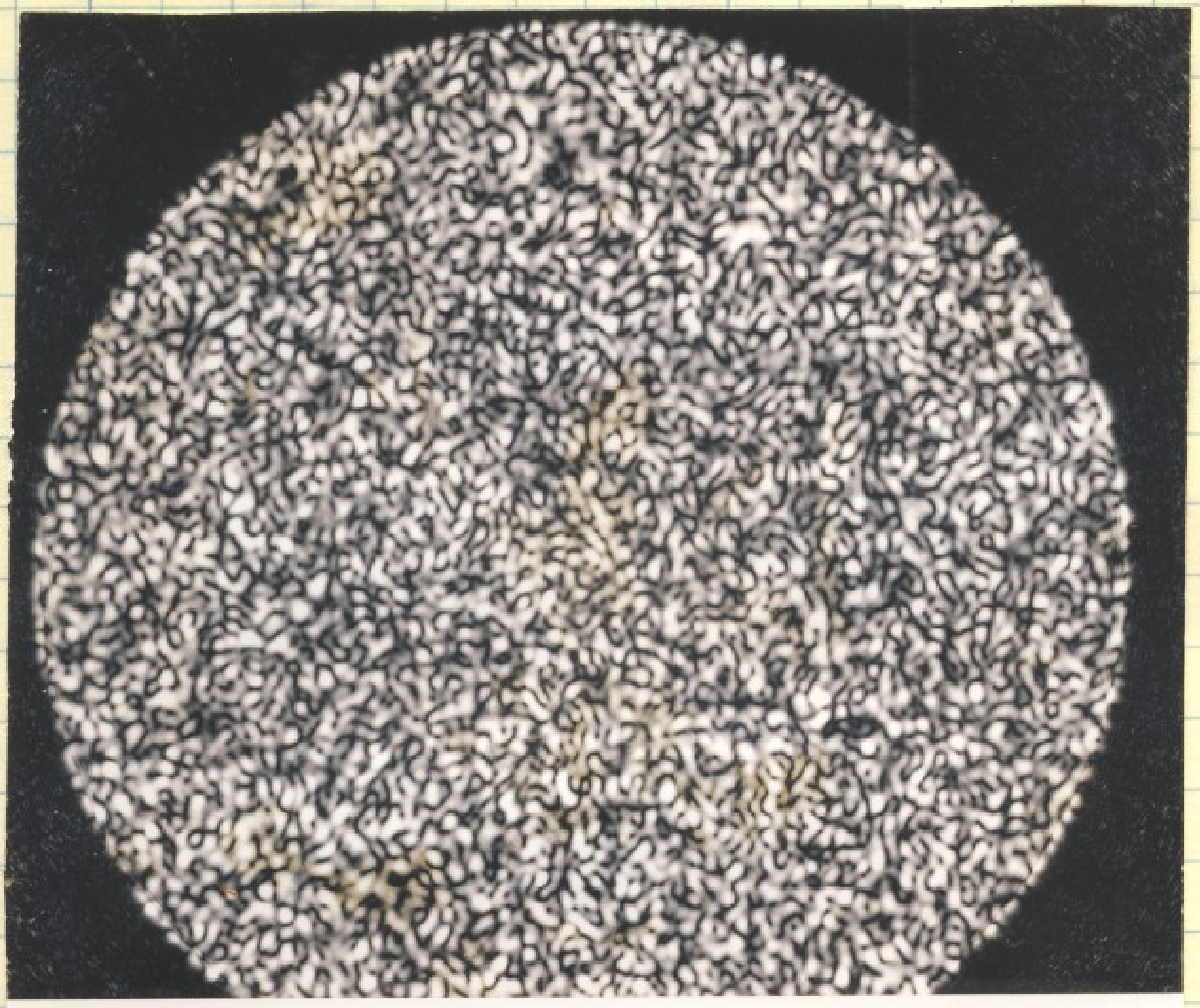
Photograph of the same pattern as above but illuminated by a ~1.8 mm square incoherent light source collimated by 62 cm focal length lens. By visual observation, no pattern at all could be seen, and the field appeared to be of uniform intensity. Experiment performed on 6 Jan. 1970. Negative marked 6, Jan 6, 1970.

Juris Upatnieks
23 January 1970.

Read and understood. D.B. Brumm 2/25/70

Read + understood Carl Leonard 3/16/70

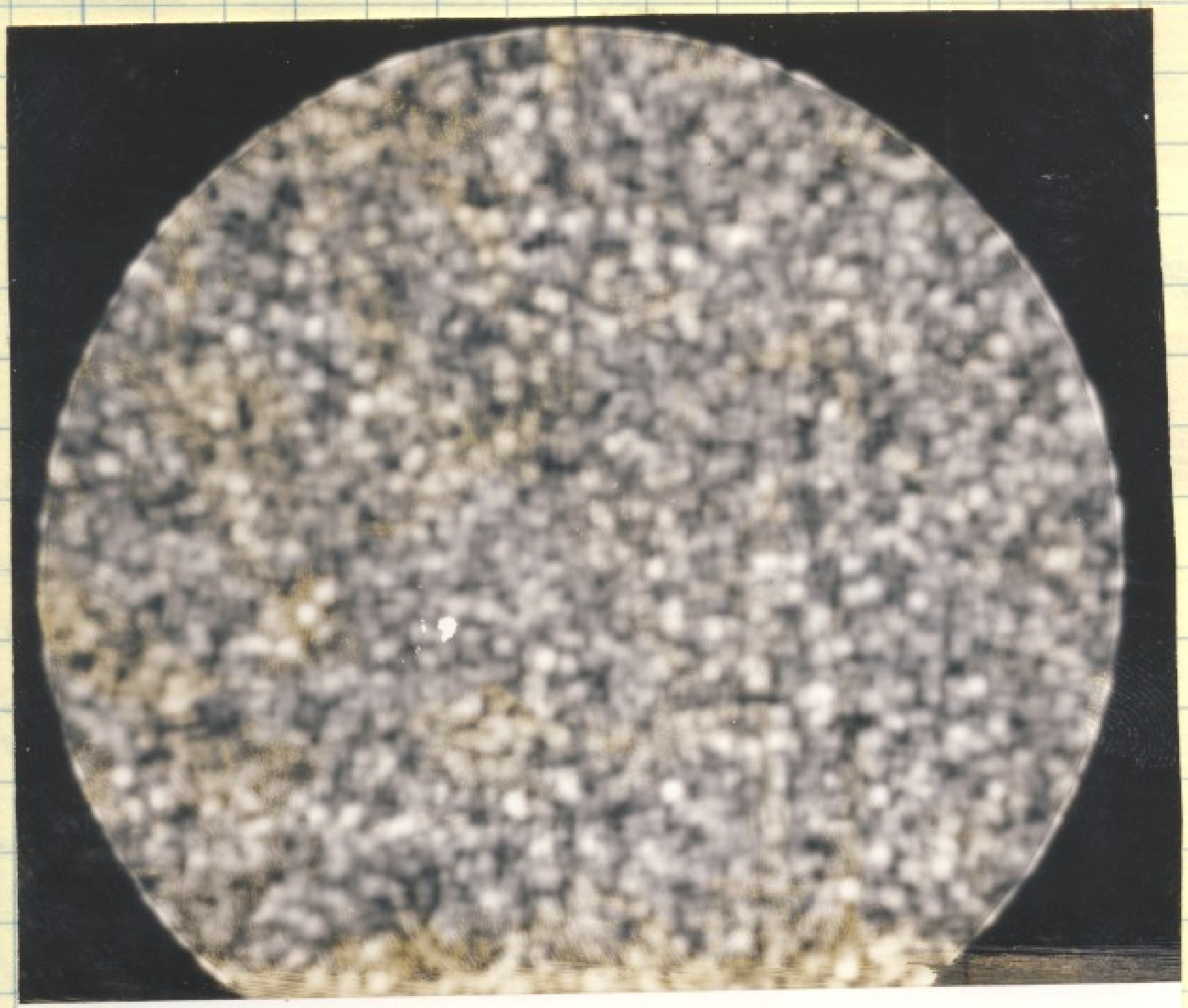
23 January 1970.



\# 70-29

Fig. 3

Photograph produced by replacing one of the phase gratings with a diffuser, removing the other grating and maintai[ning] the same aperture as before at P_2, p. 44. Diff[user] was illuminated with a plane, coherent wavefro[nt]. Experiment performed on 7 Jan. 1970. Negative marked 2, Jan. 7, 1970.



\# 70 - 30

Fig. 4

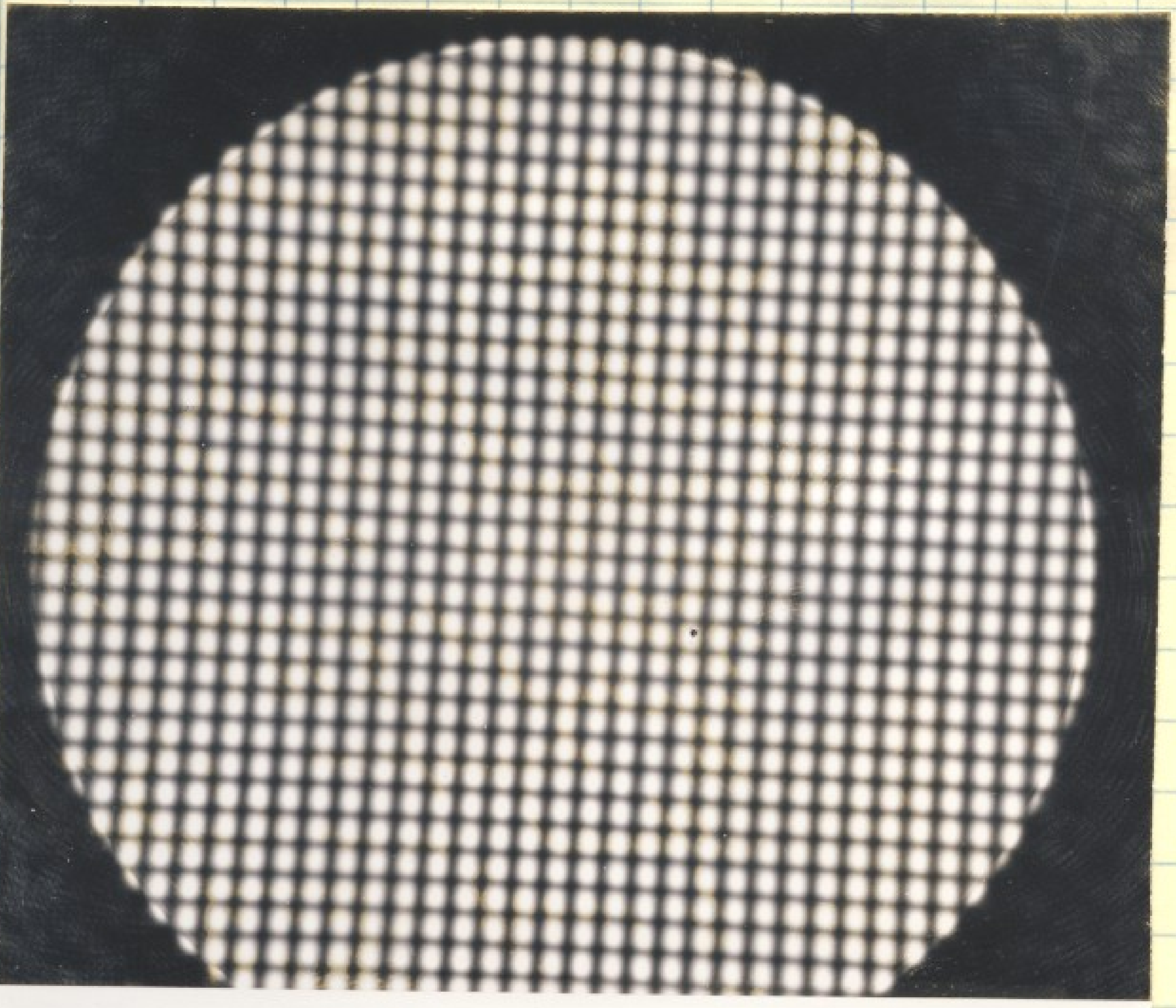
Same system and diffuser as in fig. 3, but illuminated by an incoherent light source ~1.8 mm square, collimated by a 62 cm focal length lens. Illumin[ation] same as for Fig. 2, p. 45. Experiment performed on 7 Jan. 1970. Negative marked: 3, Jan. 7, 1970.

Read and understood
D. B. Brumm 2/25/70

Read and understood
Carl Leonard 3/16/70

Juris Upatnieks, 23 January 1970.

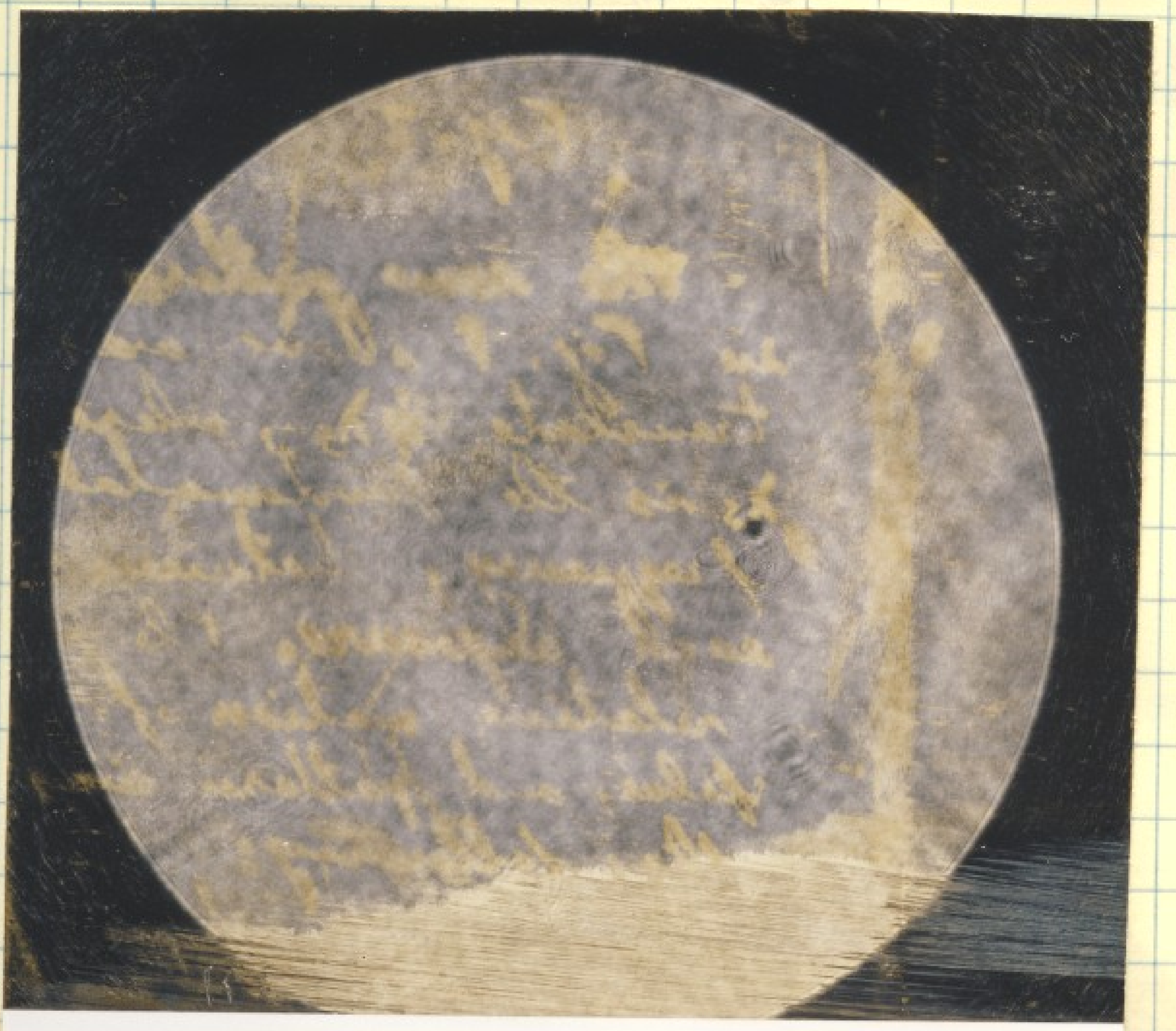
23 January 1970.



#70-31

Fig. 5.

Photograph of intensity pattern resulting from the illumination of two crossed gratings with an rectangular incoherent light source, same as for Fig. 2 p. 45. The microscope (image at left) was focused ½ the selfimaging distance of grating from plane P_1, p. 44, or approximatly ~3.4 mm from P_1. The spatial frequency here is one-half that shown in Fig. 1, p. 45. Experiment performed on 7 Jan. 1970. Negative marked: 8, Jan. 7, 1970.



#70-32

Fig. 6.

Photograph of the clear field through the optical system shown on p. 44. Both gratings were removed. Experiment performed on 6 Jan. 1970. Negative marked: 4, Jan 6, 1970.

Juris Upatnieks
23 January 1970.

Read and understood
D. B. Brumm 2/25/70

Read + understood
Carl Leonard 3/16/70

18 February 1970

Experiments with addition of incoherent images

The experiments on pages 48 through 50 were performed by Robert W. Lewis.

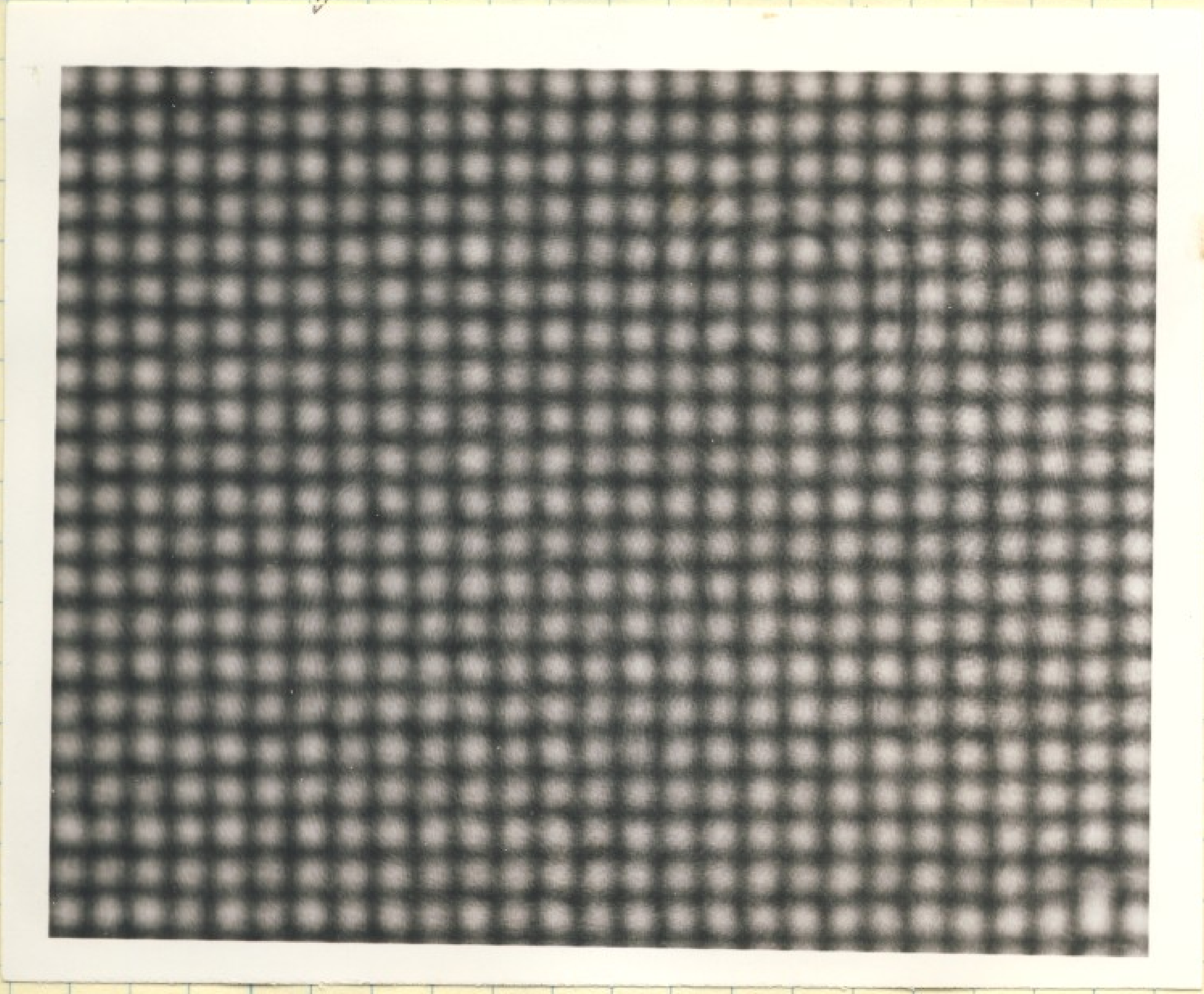
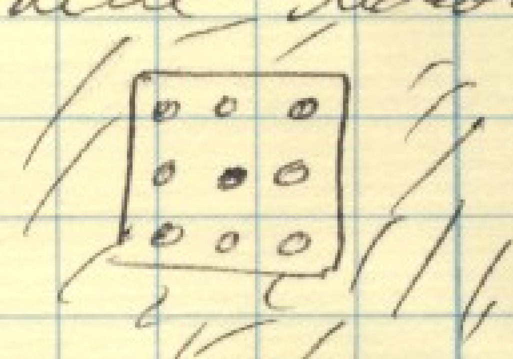


Fig. 1

Intensity pattern resulting from a crossed phase grating illuminated with a plane coherent wave front. The pattern has twice the fundamental spatial frequency. A spatial filter in the transform plane allowed nine sideorders to pass:



The spacing between points (length of cycle) is about $(\frac{1}{32})$ mm.

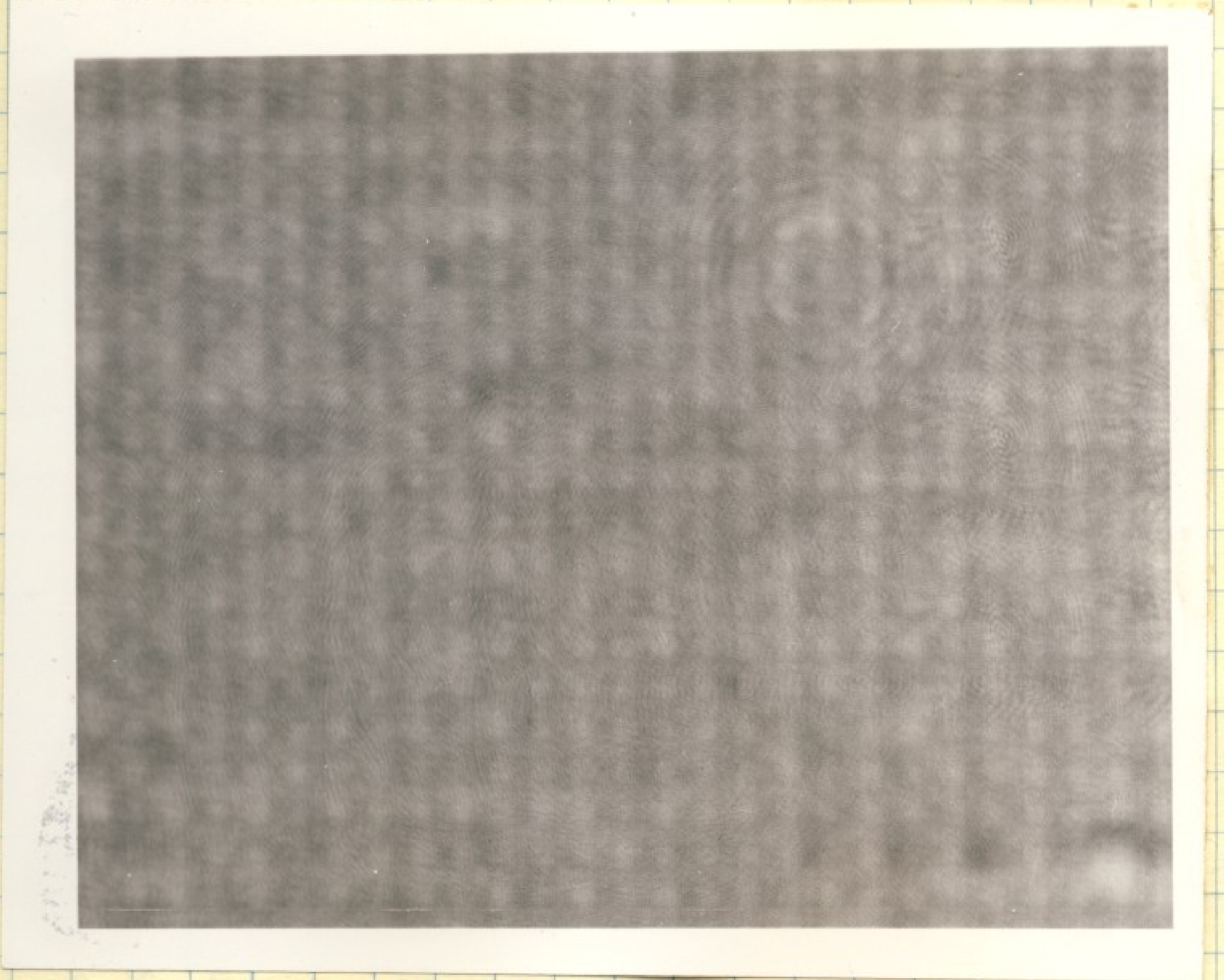
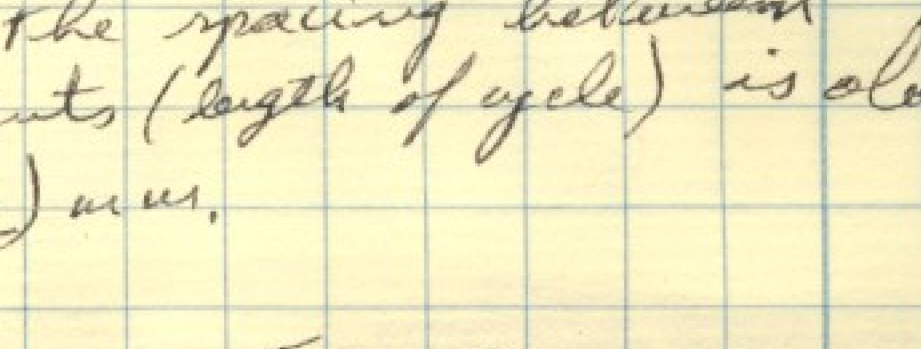


Fig. 2

The same pattern as in Fig. 1 above was translate $\frac{1}{4}\lambda_s$, where λ_s is the fundamental frequency, between each exposure. The relative motion of film and pattern was the following:



All exposures were of equal length. Theoretically, the intensity field should be perfectly uniform.

Juris Upatnieks, 18 Feb. 1970.

Read and understood. D. B. Brumm 2/25/70

Read + Understood 5/16/70

18 February 1970.

Fig. 3

Same as Fig. 1 except a ~~#~~ transparency is placed in the pattern. Note the defect between letters R and A.

Fig. 4

Same as Fig. 2 except that letters were present. Due to motion between the image and recording film, resolution loss has taken place as can be seen by degraded edges. In theory, the background should be perfectly uniform.

Juris Upatnieks
18 February 1970.

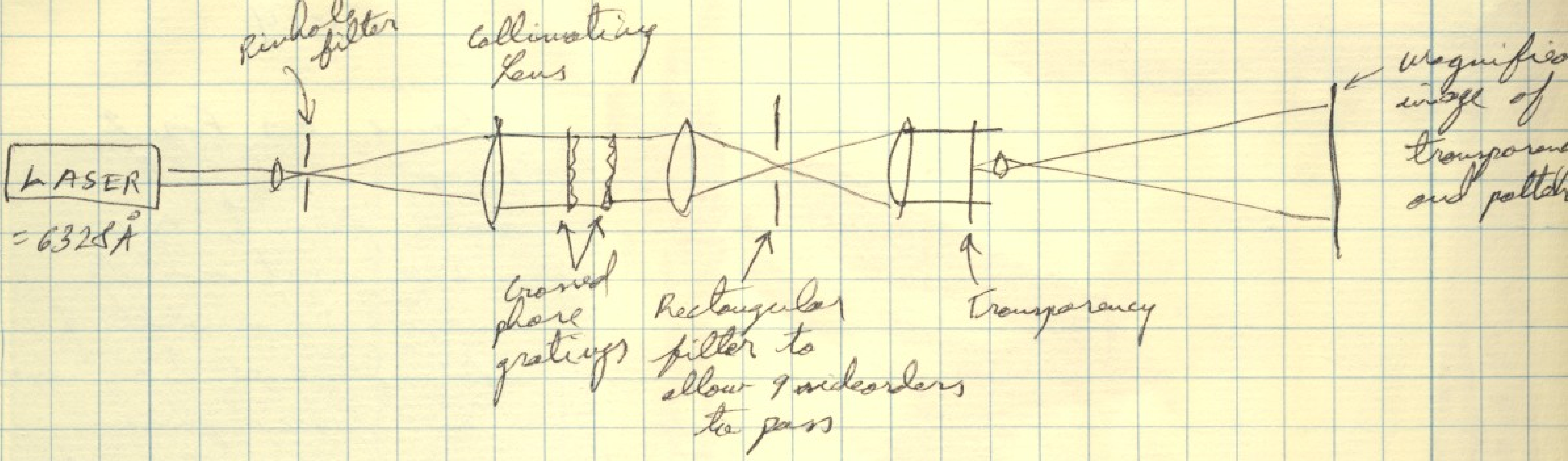
Read and understood.
D.B. Brumm 2/25/70

Read + understood.
Carl Leonard 3/16/70

18 February 1970.

Fig. 5

Same as Fig. 3 except a plane wavefront was used to illuminate the transparency. Various defects are more visible here than in either Fig. 3 or Fig. 4. All experiments were performed with the optical system shown below.



Juris Upatnieks,
18 February 1970.

Read and understood.
D. B. Brumm 2/25/70

Read and understood
Carl Leonard 3/16/70

24 February 1970

Summary of previous analysis and application to spatial filtering.

Let us consider the previous case in which two crossed grating produce a total of nine diffracted orders with amplitude of 1 for the zero order term and "a" for each diffracted order. The intensity pattern is then

$$AA^* = \left|1 + 2a e^{j\theta} \cos\alpha x\right|^2 \left|1 + 2a e^{j\theta} \cos\alpha y\right|^2$$

$$= \left(1 + \overset{4}{2}a \cos\theta \cos\alpha x + 4a^2 \cos^2 \alpha x\right)\left(1 + \overset{4}{2}a \cos\theta \cos\alpha x + 4a^2 \cos^2 \alpha x\right)$$

We now let $\theta = \frac{\pi}{2}$

$$AA^*\Big|_{\theta=\frac{\pi}{2}} = \left(1 + 4a^2 \cos^2 \alpha x\right)\left(1 + 4a^2 \cos^2 \alpha y\right)$$

$$= 1 + 4a^2\left(\cos^2 \alpha x + \cos^2 \alpha y\right) + 16a^4 \cos^2 \alpha x \cos^2 \alpha y$$

If we now superimpose four of the above patterns, each displaced with respect to the other, so that the following relations exist.

1) $x = x'$, $y = y'$
2) $x = x' + \frac{\pi}{2\alpha}$ $\quad y = y'$
3) $x = x'$ $\quad y = y' + \frac{\pi}{2\alpha}$
4) $x = x' + \frac{\pi}{2\alpha}$, $y = y' + \frac{\pi}{2\alpha}$

where x', y' is the displaced coordinate system. We see that the sum of AA^* with the four displacements add to a constant intensity pattern.

Read and understood.
D.B. Brumm 2/25/70

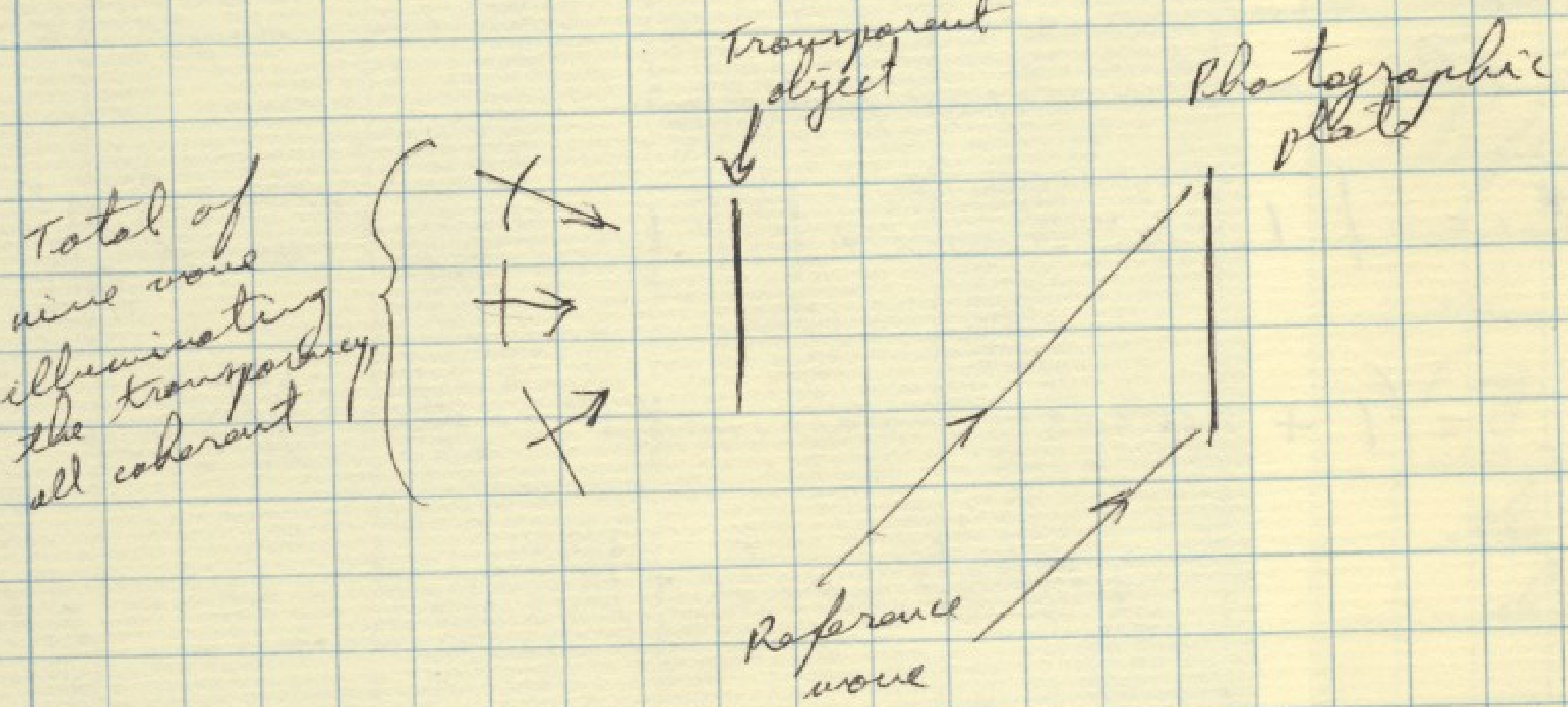
Read and understood.
Carl Leonard 3/6/70

Juris Upatnieks
24 February 1970.

24 February 1970.

When used in holography, the pattern may be used and its elimination may ~~be done~~ be accomplished in one of ~~the~~ two ways:

1. A hologram is made with a transparency illuminated by nine coherent waves:



In reconstruction, the illuminating wave is translated between exposures to produce shift in the intensity pattern (and image) as described on the previous page. Maximum displacement between image points would be $\frac{\sqrt{2}\lambda_0}{4}$.

2. A hologram is produced with transparency illuminated as above, but four holograms are superimposed on the same photographic plate in such a manner that each can be reconstructed at a time. For each hologram, the pattern illuminating the object transparency is shifted according to the description on previous page, p.51. In reconstruction the four images from four holograms are incoherently superimposed resulting uniform background and no loss in resolution.

Other combinations of wavefronts can be used. The number nine is just an example.

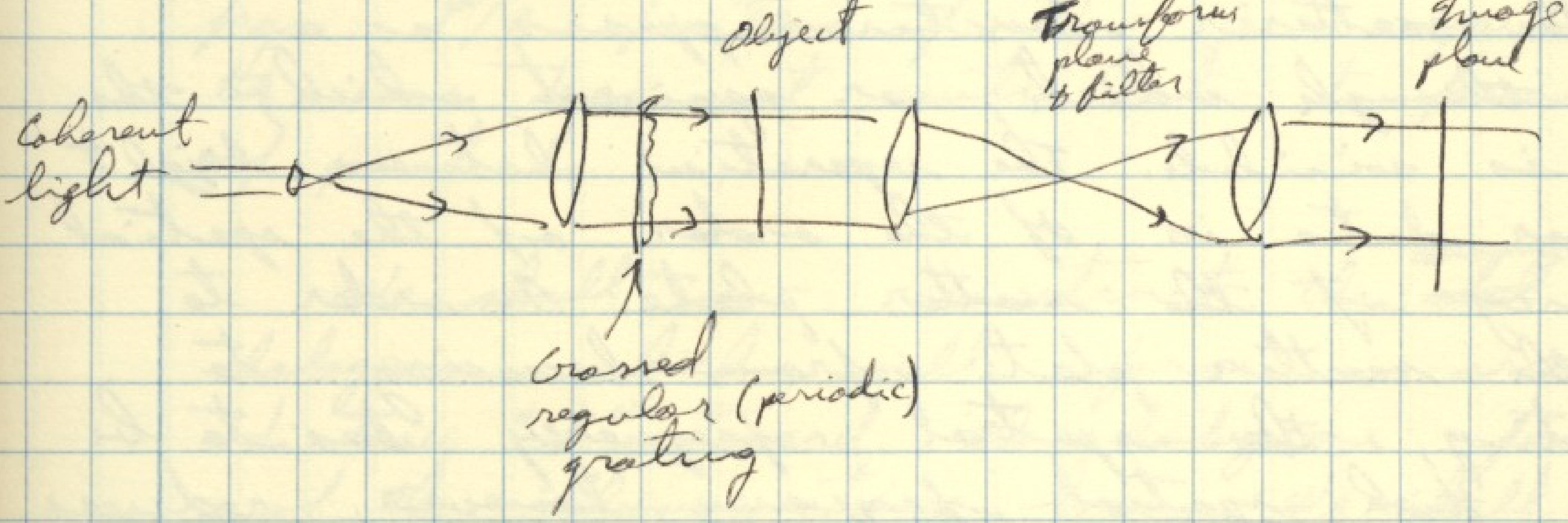
Read and understood.
D. B. Brumm
2/25/70

Read + understood.
Carl Leonard
3/16/70

Juris Upatnieks
24 February 1970

24 February 1970

Another use of a crossed grating to increase redundancy is in optical data processing. Suppose some filtering is desired as in the figure below:



The crossed grating creates several points in the transform plane with spatial frequencies due to the object around each point. A filter can be constructed for each point which operates on the object spectra. The crossed grating can be moved since this motion will not affect the position of spectrum in the Fourier transform plane or the image position in the image plane. The intensity pattern, due to a finite aperture of the system or limited number of plane waves illuminating the object, at the object and image planes can be averaged to give a uniform background. Numerous plane waves gives this system redundancy and therefore decreases noise from defects. Motion of the gratings would also eliminate defects originating in the grating.

Read and understood.

D. B. Brumm 2/25/70

Juris Upatnieks

24 February 1970.

Read and understood
Carl Leonard 3/16/70

16 March 1970

A technique for eliminating scatterer structure in information reduction systems.

A problem usually encountered with holographic information reduction systems is that the scatterer structure appears as a screen through which, or against which, the image is visible. The separation between bright lines or dots is of the order of the spatial frequency of the scatter plate. In order to keep the scatter plate from becoming to distracting, the spatial frequency has to be high. High spatial frequency, however, reduces the resolution. Thus, a balance between resolution and scatter plate pattern must be reached.

An arrangement is proposed here which, in principle, can eliminate the scatter plate pattern entirely. A lower frequency scatter plate then could be used which would improve the resolution of the system. The proposed system is the following:

Consider a negative fly's eye lens array, as in the figure below, acting as the scatter plate:

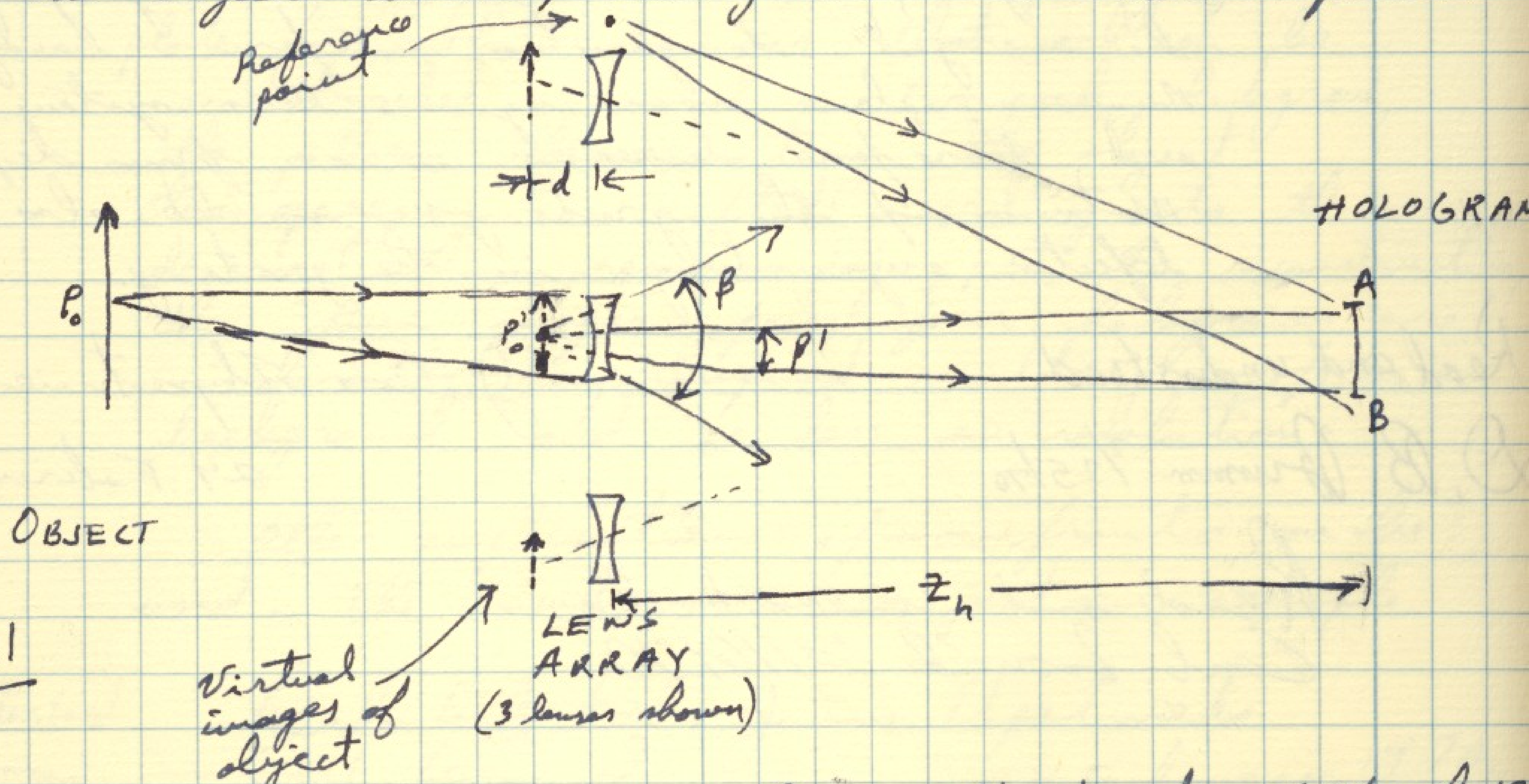


FIG. 1

Juris Upatnieks, 16 March 19

Read & understood
Carl Leonard 3/16/70

Read and understood, Jack Walker, 16 March 1970

16 March 1970.

The lens array forms an array of virtual images as shown in the figure. Each lens spreads light from each point P_o' over an angle β, but the hologram accepts only light spread over angle β'. In reconstruction process with the same lens array, light to each point P_o comes only from β'/β fraction of the lens aperture. The rest of the lens does not contribute to formation of the image of point P_o.

We shall now reconstruct the ~~real~~ conjugate image from the hologram which will form an array of real images distance "d" toward the hologram from the point focus of the illuminating beam. We shall also use an array of positive lenses with the same focal length as in the construction of the hologram.

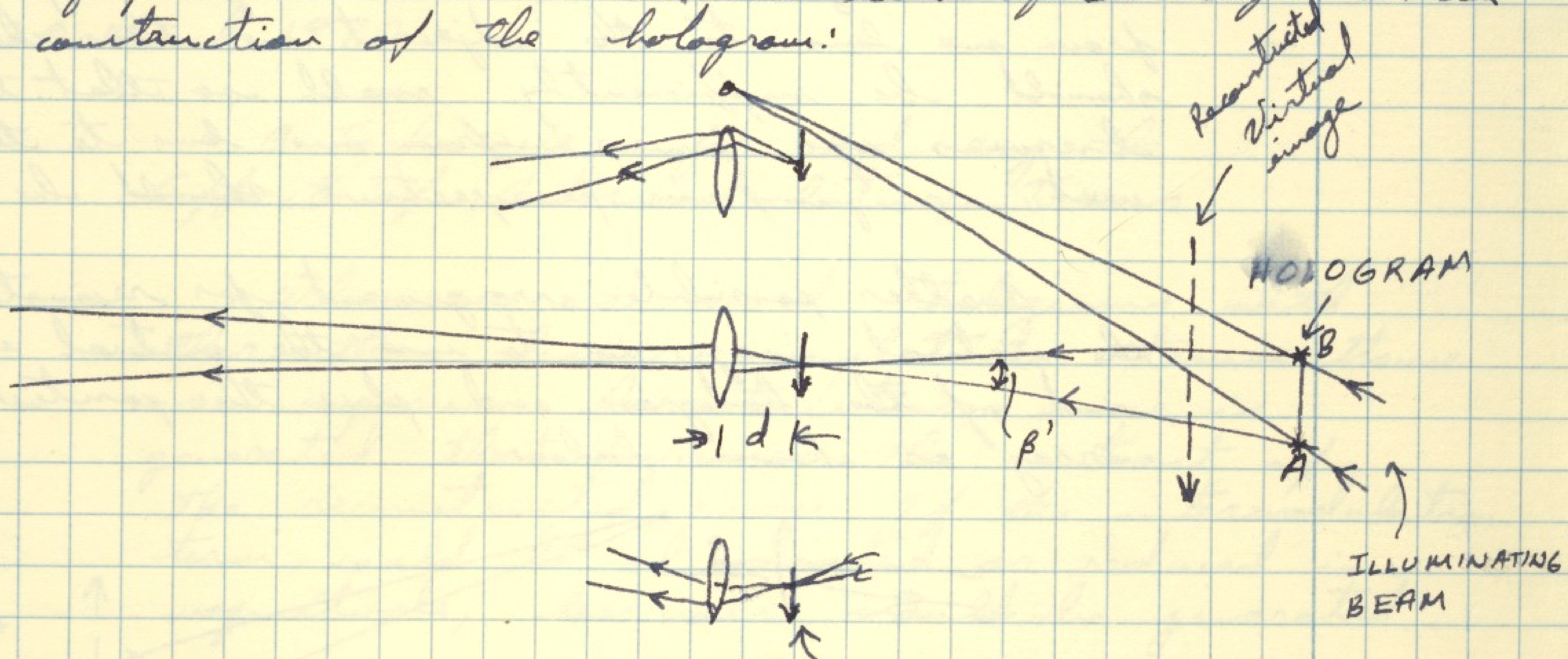


FIG. 2

POSITIVE LENS ARRAY (3 lenses shown)

Plane at which (conjugate) real images are formed. Thin diffuser should be placed in this plane.

Since the equivalent f-number of the hologram is much smaller than that of the lens, the resolution will be determined by the hologram and its aperture. The lens merely reimages the image formed by the hologram. If the focal length of the lenses are short compared to the object-lens distance, the the images will be formed at one focal length from the lens, and all images will be in the same plane. We can place a moving thin diffuser in this plane (for example, and optical flat with one side sandblasted)

Read and Understood, Carl Leonard 3/16/70

Juris Upatnieks, 16 March 1970.

Read and understood, Jack Walker, 16 March 1970

16 March 1970

which would disperse light over a wider angle and could fill the lens aperture. If the lens aperture is filled, then the whole lens array would appear to reconstruct the image and there would be no dark areas in the array as viewed looking ~~from~~ at any point in the image. We have thus eliminated the intensity pattern usually caused by the scatter plate (a lens array in this case).

Since the scatter plate pattern would be eliminated, we could use larger lenses, lower the spatial frequency of the scatter plate structure, and increase the image resolution. The limitation on lens size would be the change in paralax from one lens to the adjacent one. This change should be sufficiently small so that the observers eye moves from one lens to the next, no jump in perspective should be visible.

Another possible arrangement for reconstructing the virtual image is to use the virtual image ~~out~~ of the hologram and place the positive lens array as shown below:

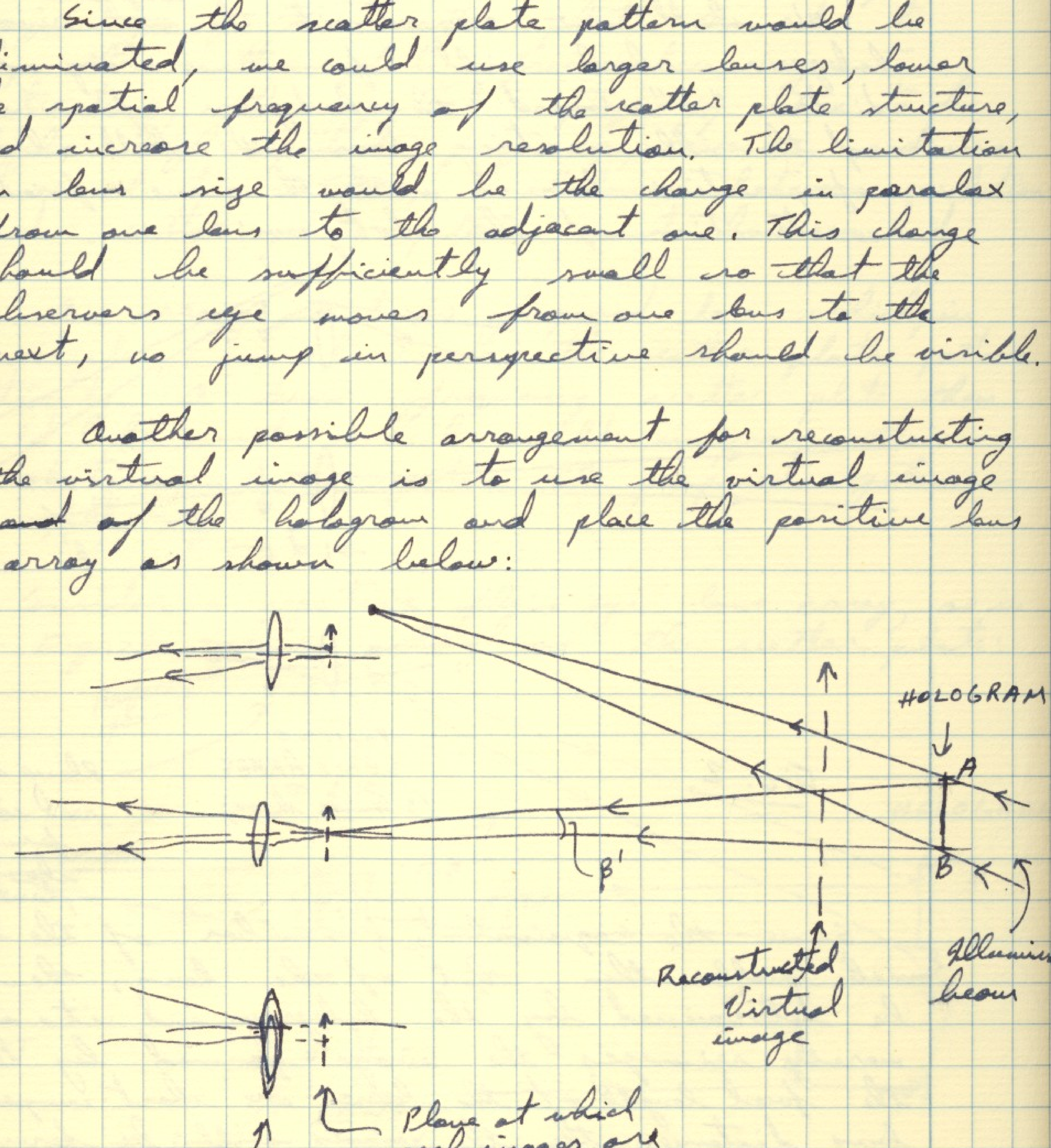


FIG. 3

Read and Understood, Carl Howard, 3/16/70

Juris Upatnieks, 16 March 1970

Read and understood, Jack Walker, 16 March 1970

16 March 1970.

In Fig. 3 the positive lens array is moved to the left of the position of virtual images. Slight adjustment in the convergence of the reconstructing beam may be required. This arrangement would recover the ~~sim~~ reconstructed non-pseudoscopic image right side up. A thin moving diffuser again could be placed in the plane of the array of images.

Juris Upatnieks, 16 March 1970

Read and understood, Jack Walker, 16 March 1970

Read + understood, Carl Leonard, 3/16/70

20 March 1970

A Technique for Reducing the Effect of Intermodulation Terms

Whenever we record holograms with other than linear amplitude transmittance vs. exposure characteristics, noise is generated that decreases the contrast of the reconstructed image. If the intermodulation term could be eliminated or reduced in magnitude, less noise would be generated.

Consider the exposure E falling on an emulsion

$$E = t a_0^2 \left[1 + \left(\frac{a_s}{a_0}\right)^2 + 2 \frac{a_s}{a_0} \cos \phi_{os} \right]$$

where t is exposure time, a_0 is the reference wave amplitude and a_s is the signal wave amplitude. A way to reduce the effect of the intermodulation term, a_s^2 is to increase a_s/a_0 ratio. This, however, reduces the modulation amplitude $a_s/a_0 \cos \phi_{os}$ and therefore such approach has the disadvantage of decreasing the diffraction efficiency.

Read and understood, Jack Walker, 20 March 1970

Juris Upatnieks, 20 March 1970

20 March 1970

The decrease in diffraction efficiency, caused by lower fringe modulation, can be avoided by the following technique.

Let D be amount of exposed and developed silver in the emulsion. Assuming $D = c_1 E$, where c_1 is a constant, we get

$$D = c_1(t a_0^2)\left[1+\left(\frac{a_s}{a_0}\right)^2 + 2\left(\frac{a_s}{a_0}\right)\cos\phi_{os}\right]$$

Let us now increase to many times the normal exposure so that the developed emulsion is very dense. We then place the processed (developed & fixed) emulsion in a sub-proportional reducer so that equal amounts of silver are removed from all parts of the emulsion. Assume that silver density D decreases in proportion to time T in reducer, or

$$D = c_1(t a_0^2)\left[1+\left(\frac{a_s}{a_0}\right)^2 + 2\left(\frac{a_s}{a_0}\right)\cos\phi_{os}\right] - c_2 T$$

where c_2 is a constant. Thus the reducer will decrease the bias level but will not affect the modulation. The factors $t, (a_s/a_0), T$ can then be chosen to give a recording with a low bias term and negligible intermodulation term $(a_s/a_0)^2$, and a relatively large modulation term $2 a_s/a_0$. After a hologram is obtained by the above technique, it may be further processed in the desired way, perhaps bleached. Or, it could be used as a " transmittance (absorption) hologram.

For bleaching the above procedure might be especially desirable: the grain scattering increases with prebleached plate density. By reducing ~~both a_s/a_0~~ the prebleach density and also a_s/a_0 ratio, grain scattering and effect of intermodulation terms could be reduced without reducing efficiency.

Read and understood, Jack Walker, 20 March 1970 Juris Upatnieks, 20 March 1970

20 April 1970.

Experiment with reducing an overexposed hologram.

The idea of increasing the modulation of a film, described on p. 57 and 58 of this notebook, was tested. Two plane wavefronts were interfered and the pattern recorded on Kodak 649F emulsion on 35 mm film. A spatial frequency of approximatly 150 l/mm was recorded, with a reference beam exposure of 110 μW/cm², beam ratio K = 50, and 10 min. development in D-19. The data on each frame is listed below:

Frame #	Exp. time sec.	Exposure ergs/cm²	Density	Transm.	Transm. after ~~that~~ reducing	Effic. after reduc.	
1	1	1,100	1.2	6.4%	22%	0.4%	(eff. 0.3 before red
2	1.5(?)	1,700(?)	2.6	.26	12 %	0.38%	
3	2.0	2,200	2.1	.85	14%	0.4 %	
4	3.0	3,300	3.8	.017	20%	0.12%	
5	4.0	4,400	4.0	.010	13 %	.07%	
6	6.0	6,600	4.2	.008%	19%	.06 %	
7	9.0	9,900	4.4	.006	16%	.045%	

These results indicate that the expected improvement in modulation was not achieved by reducing in the Farmer's reducer, but that modulation was approximatly constant over a range of exposures. Other reducers could probably achieve the desired result.

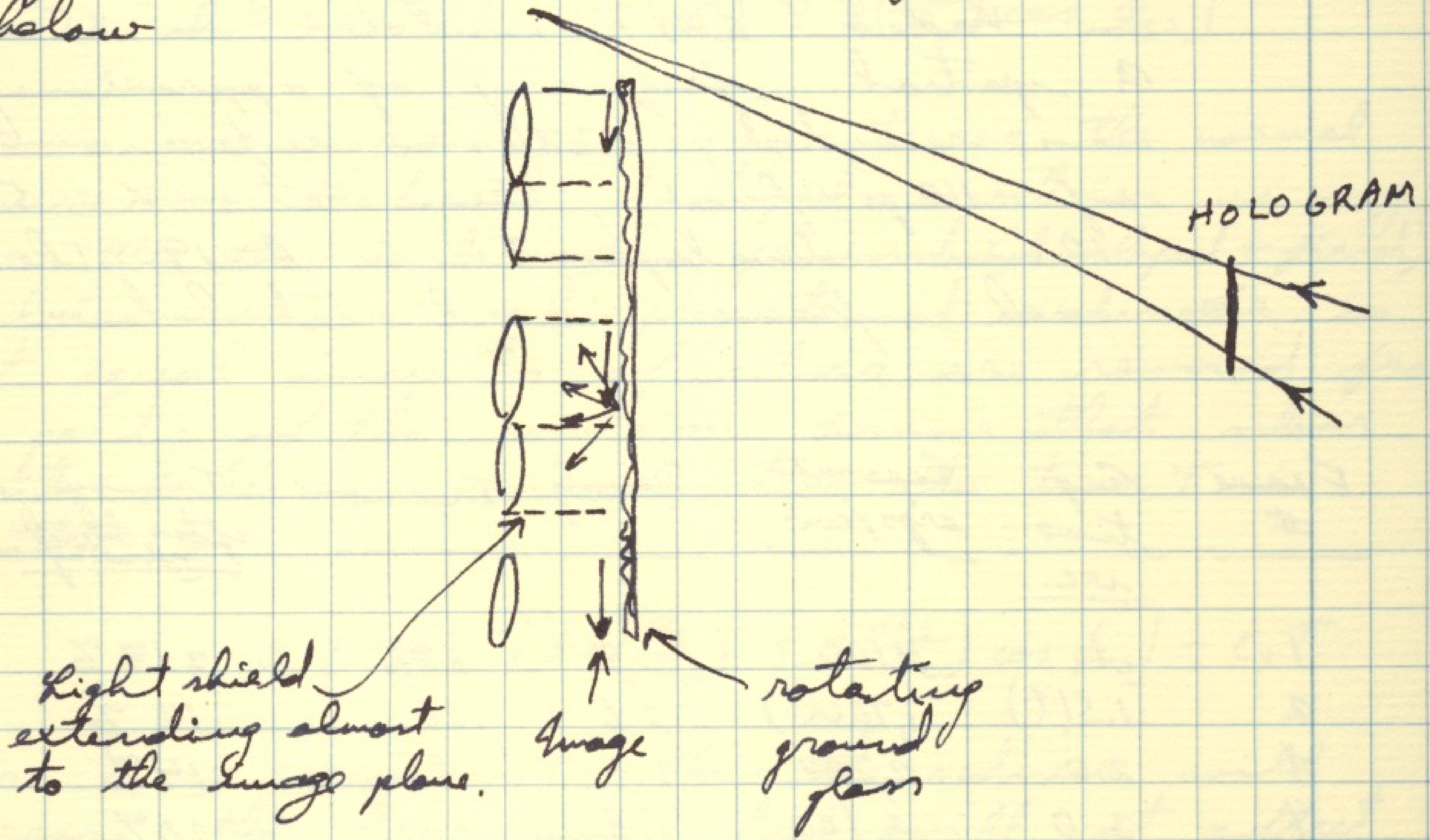
Juris Upatnieks

20 April 1970.

20 April 1970.

Some comments on information reduction systems.

A scene was described where real images are formed and a rotating scatter plate is positioned in this plane. A question was raised whether such a system would work if light is scattered into the adjacent lenses, as below



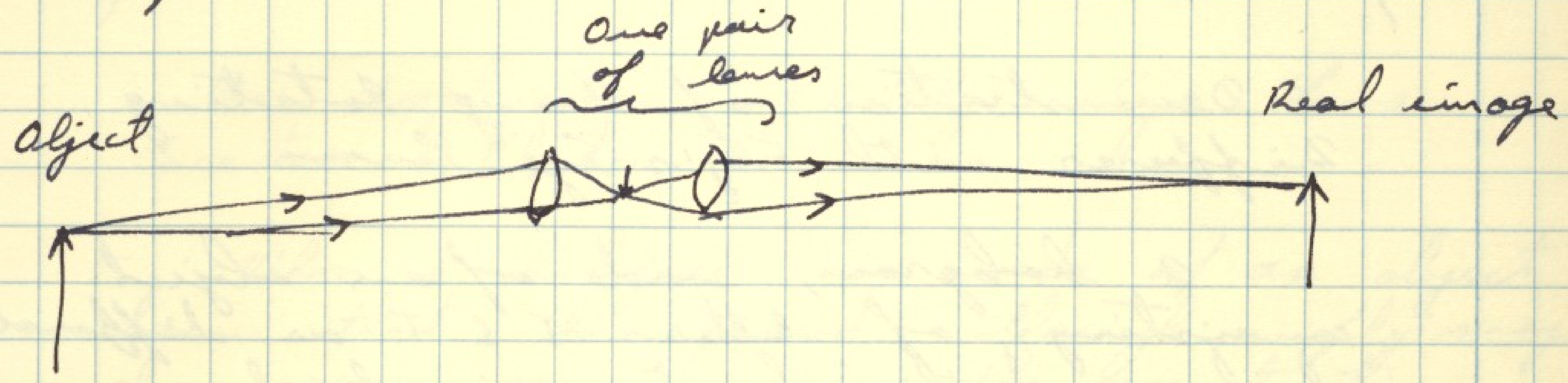
This does not appear to be bothersome for if adjacent lens receives light ~~for~~ intended for another lens since this image should appear outside the field of view. Also, it is possible to place a light shield around each lens, as shown above, and to prevent light from reaching the wrong lens.

Another scene discussed in a progress report by Brumm was the use of two fly's-eye lens arrays in series to achieve pseudoscopic image inversion. If we consider the object at infinity, the image is formed one focal length from the first lens. The second lens forms a real image then, as shown in the following figure

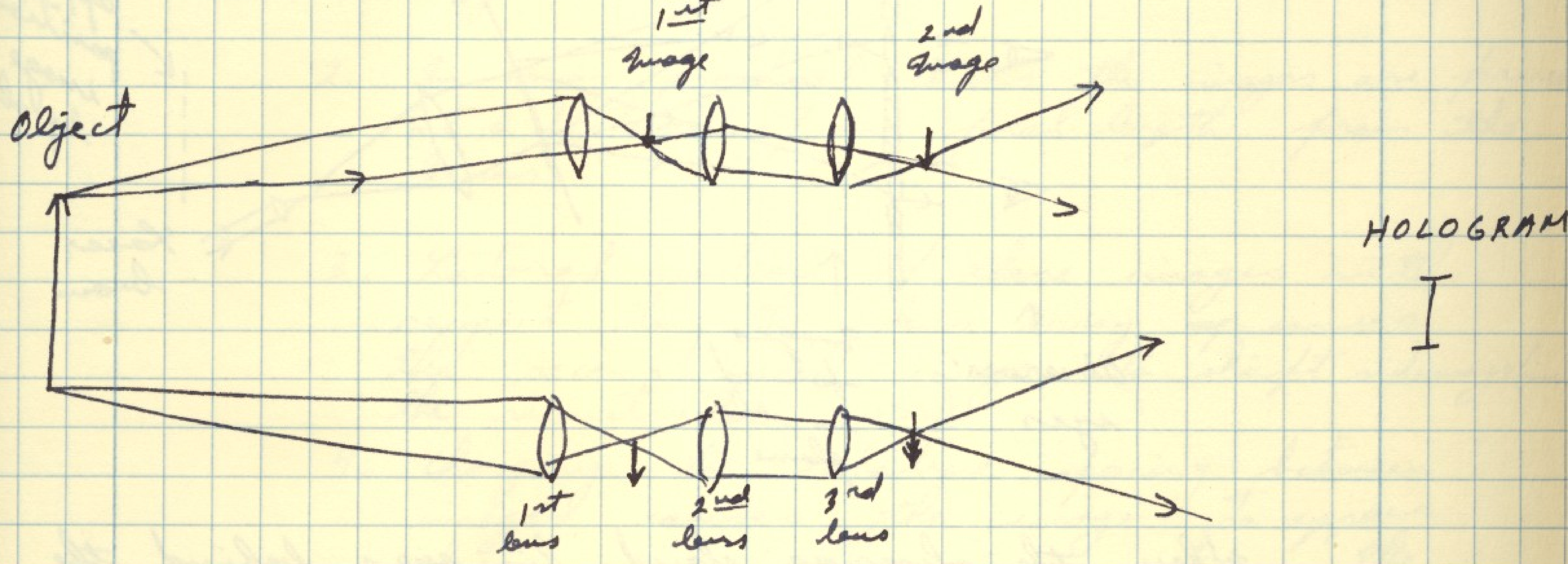
Read & Understood 24 April 1970

Juris Upatnieks, 20 April 1970

20 April 1970.



This arrangement does not provide dispersion of all rays, so another lens is required, as shown below:



If a hologram is reconstructed through the third lens only, then a virtual nonpseudoscopic image is recovered. In the 2nd image plane a rotating diffuser can be placed as described before. The image probably gets somewhat degraded in passing through two ~~lens~~ fly's-eye lens arrays, however (1st + 2nd lenses).

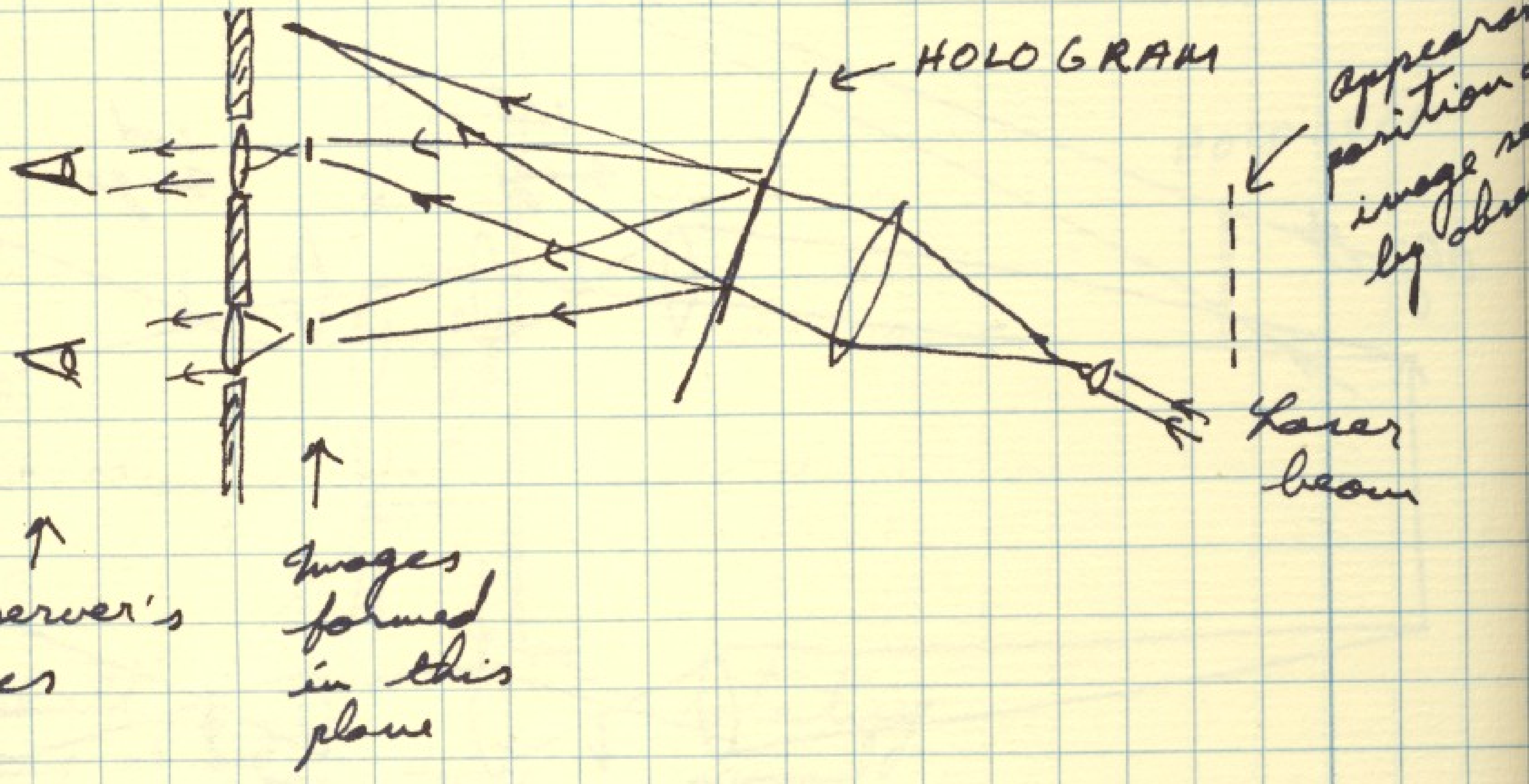
Juris Upatnieks
20 April 1970.

Read and understood. Jerry Zelenka
29 April 1970

24 April 1970.

Demonstration of Using Rotating Diffuser with Fly's Eye Lenses.

A hologram, made of an object consisting of letters I.S.T. on diffuse background through two simple lenses, was reconstructed and the image observed through the same two lenses. The optical system used for reconstruction was:



When the observer placed his eyes behind the lenses, an image could be seen that seemed to be 3 to 4 feet ~~behind~~ on the hologram side of the lenses. The image could be seen over a small part of the lens aperture.

When a rotating ground glass was placed in the image plane, the image could be seen roughly in the same location and from any part of the lens aperture.

The lens aperture was about 12 mm, and without the diffuser light came through about 3 or 4 mm diameter area of the lenses.

Juris Upatnieks, 24 April 1970
Carl Leonard, 24 April 1970
Observed demonstration Jack Walker 24, April 1970
Observed demonstration, Jerry Zelenka 28 April 1970

28 May 1970

An Application of Fly's-Eye Lens Scatter Plate.

When a hologram is made of an object beam that has passed through a fly's-eye lens array scatter plate, the reconstruction process has several interesting and usefull properties. These are:

1. Behind each lens a small image of the object is seen.

2. In many practical cases the images are formed at a distance of one focal length from the lenses.

3. Lateral motion of these images with respect to the lens array ~~of~~ causes the reconstructed image to shift sideways (in the reconstruction process).

4. Changing the relative spacing between images causes the image to appear closer or further away from the scatter plate.

5. Since the hologram can occupy a number of positions relative to the scatter plate and reconstructs the image as though it came from the whole scatter plate, it is obvious that a number of images can be reconstructed through the same scatter plate by a number of independent holograms.

From properties (3) to (5) we can conclude that several images can be projected through the scatter plate and their relative positions adjusted. It is possible for two images to be superimposed on each other. These properties lend themselves

Jack Walker 9 June 1970 Juris Upatnieks, 28 May 1970
Robert W. Lewis June 9, 1970

28 May 1970

applications such as displays with stationary reference scene and moving objects, the whole display being three-dimensional.

One application is to use such a three-dimensional display for air trafic control. One hologram could provide a high-resolution relief map of an area surrounding an airport. Each aircraft in vicinity could be represented by a dot of light with possibly some identifying number next to it. The dot would be recorded on a hologram and information about the position of ~~the~~ aircraft would be used to adjust the apparent position of the dot to the airport. This could be done for each aircraft in the area. In addition, color coding could be used since holograms made at different wavelengths could be reconstructed through the same scatter plate. As a whole, such a system could represent a dynamic three-dimensional display of an air control area and would simplify the work for air trafic controllers.

Juris Upatnieks, 28 May 1970
Robert W. Lewis June 9, 1970
Jack Walker 9 June 1970

The above was disclosed to:

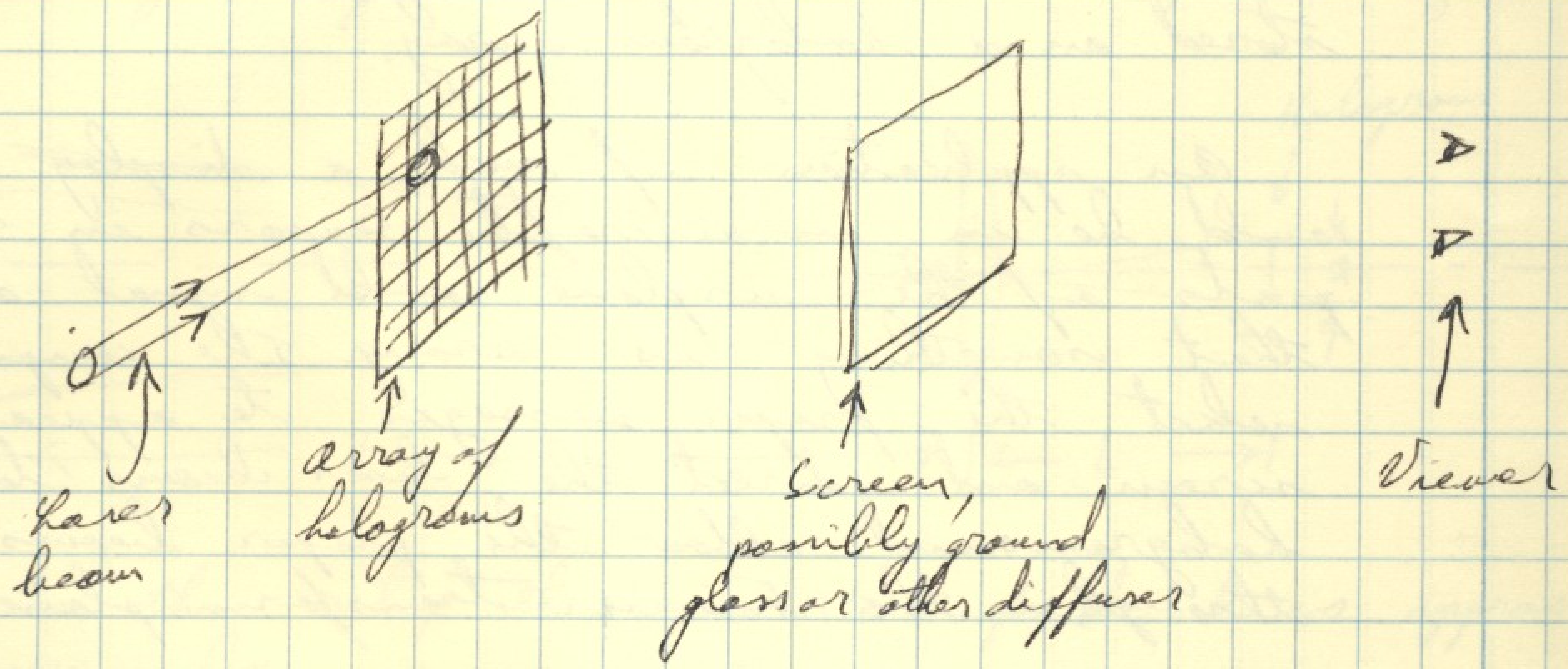
E.N. Leith, about May 27, 1970
John N. Latta, June 2, 1970
Tom Williamson, June 3, 1970 } Air Force Avionics
Harold W. Rose, June 3, 1970 } Laboratory, Dayton
C.E. Harema, June 1, 1970

Juris Upatnieks, 4 June 1970

4 June 1970

Application of Holographic Data Storage to Visual Displays.

An application of holographic data storage for displays is proposed here. Consider the figure shown below:



An array of small holograms are recorded on a film of plate and one or more laser beams are directed to a particular hologram or several selected holograms. The reconstructed image is projected on a screen displaying some short message or instruction to the viewer. For the case where several laser beams are directed, the messages could appear one under the other.

The directing of each laser beam could be done by some electromechanical device. For example, galvanometers or ~~ma~~ step-switches could be used. In the first case beam position is determined by current through the galvanometer, in the second the number of electrical impulses determine the shaft position (to which a mirror is attached). A set of two could direct one beam to any position ~~of the ho~~ for illumination of a particular hologram.

Jack Walker 9 June 1970 Juris Upatnieks, 4 June 1970
Robert W. Lewis June 9, 1970

4 June 1970

If the information content of each hologram is relatively small, then a small spatial frequency range is occupied by each message. A spatial filter in the Fourier transform plane could be used to select any one of several messages that are placed on different spatial frequency carriers. This would multiply, or increase, the total number of messages that could be stored on a hologram array.

An application of such a display system could be in an aircraft. Sensors in various parts of the airplane could signal a computer that something is wrong. The computer could select the proper messages to appear on the screen and direct the laser beams to the appropriate holograms and allow the proper beams to pass through the Fourier transform plane.

If an array of 30 x 30 holograms is recorded, and each has 10 ~~holog~~ superimposed holograms with different carrier frequencies, then 9,000 messages could be recorded on each array. If, for example, 100 hologram arrays are available, then 9×10^5 messages could be stored.

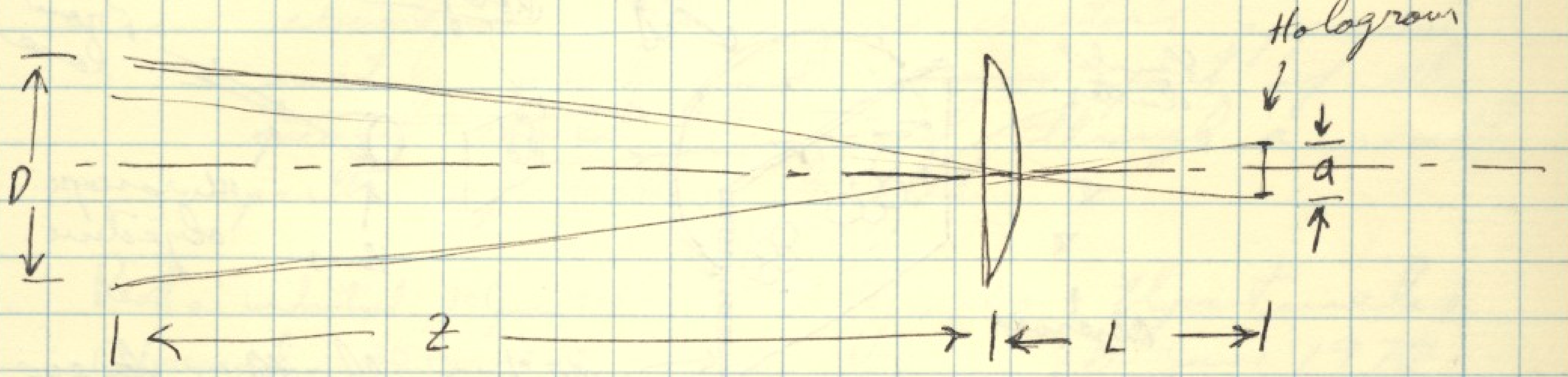
Juris Upatnieks, 4 June 19
Robert W. Lewis June 9, 19
Jack Walker 9 June 1970

Disclosed to: E. N. Leith, on or before June 2, 1970
John N. Latta, June 2, 1970
Tom Williamson, June 3, 1970 } Air Force Avionics Lab, Dayton, Ohio
Harold W. Rose, June 3, 1970

24 June 1970

A Method for Increasing the Viewer's Field (the field from which a viewer ~~can~~ see the image) in a Hologram Display System.

The ~~field of~~ viewer's field in the optical system below is limited by the focal length of the lens and the film size.

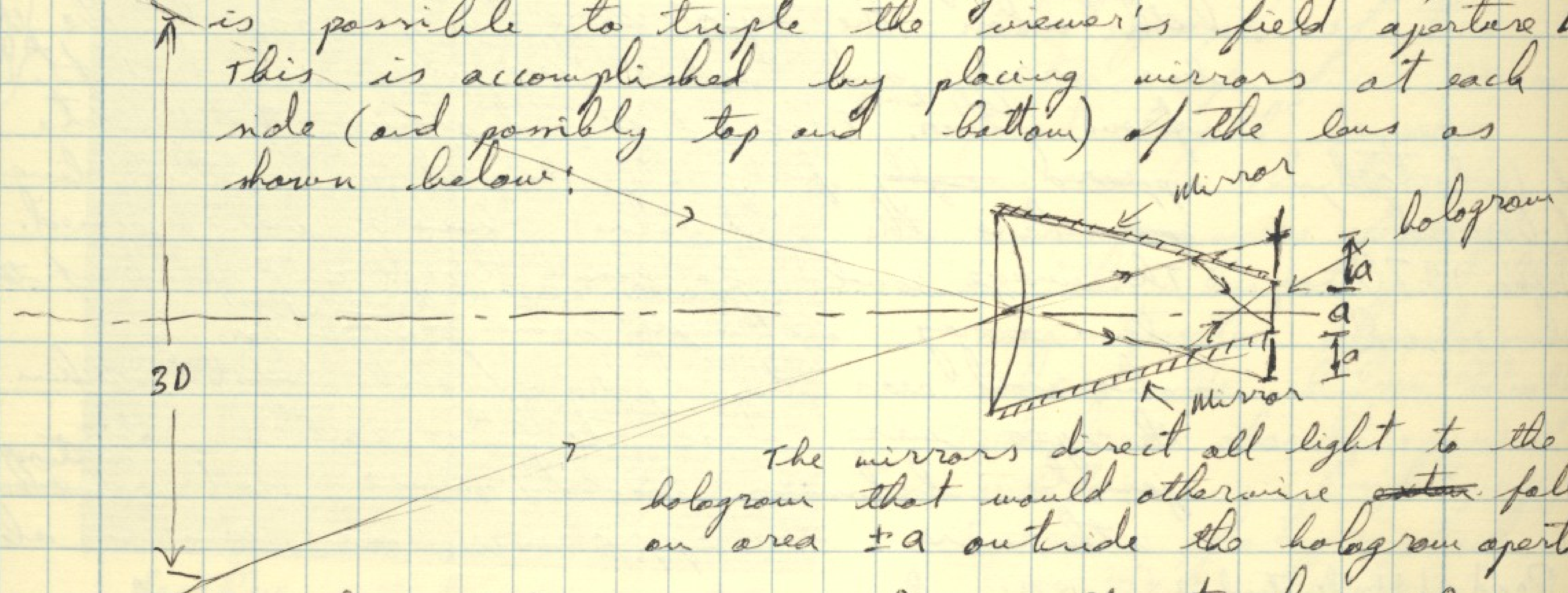


In this setup the viewer's field D is approximately given by

$$D = a\,\frac{Z}{L}$$

where L is distance from lens at which aperture D is imaged. Since large aperture lenses have long focal lengths and consequently large L, the viewer's field D is severly limited for reasonable lengths of Z.

With the same geometry as shown above, it is possible to triple the viewer's field aperture D. This is accomplished by placing mirrors at each side (and possibly top and bottom) of the lens as shown below:



The mirrors direct all light to the hologram that would otherwise ~~enter~~ fall on area ±a outside the hologram aperture.

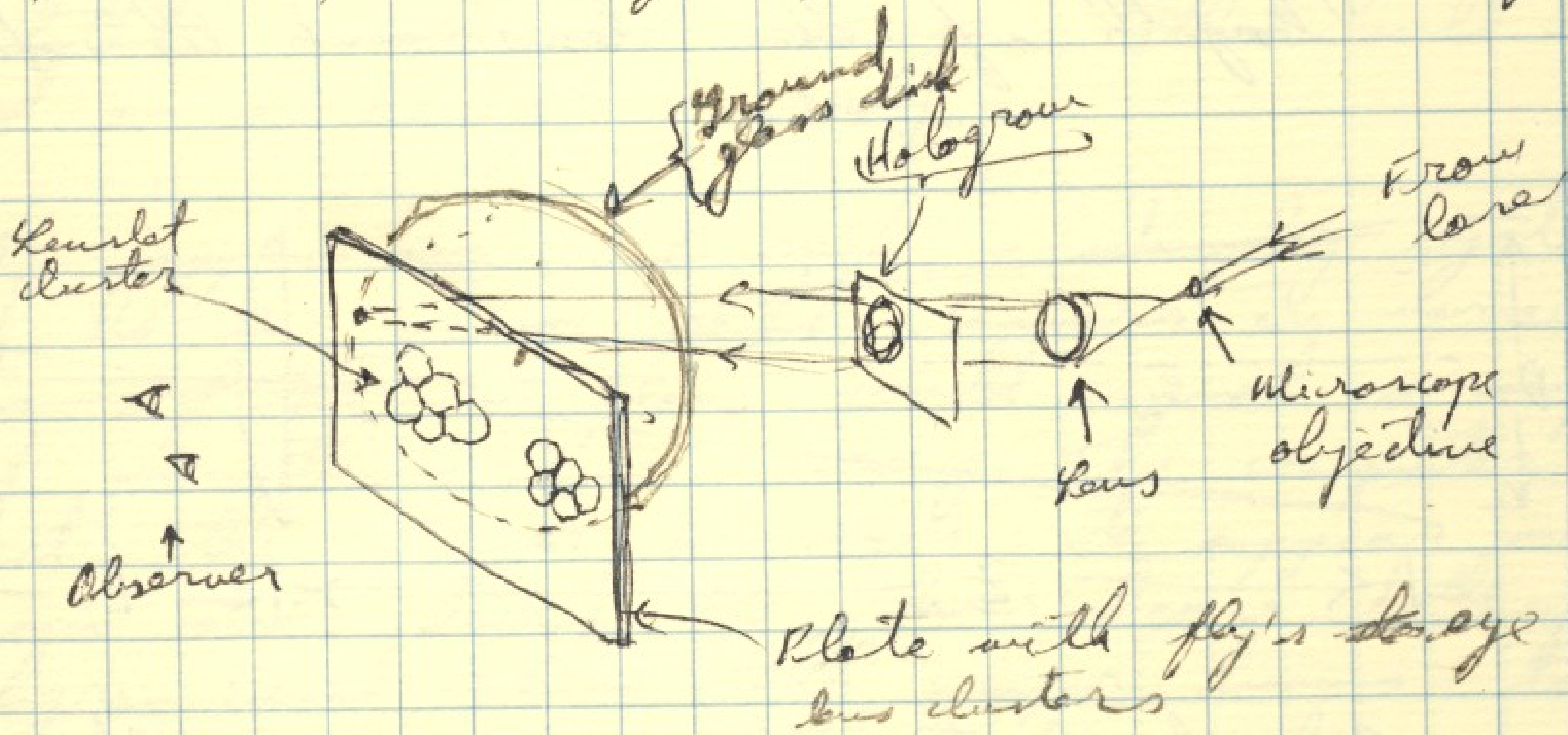
Read and understood Jack Walker 24 June 1970

Juris Upatnieks, 24 June 1970

30 June 1970

Demonstration of the reduction of scatter-plate pattern visibility.

An optical system, as shown below, was set up consisting of two clusters of fly's eye lenses, 5 each, a hologram, and illuminating beam.



The ground glass disk, when used, was placed with the ground side coinciding with the image plane of the images reconstructed by the hologram.

The following was observed:

1. With the ground glass in place and rotating, an image, ~~of the lett~~ consisting of letters "I.S.T." and the word "OPTICS" could be seen about 3 ft. behind the fly's-eye lenses. The image could be seen both when the eyes were very close to the lens arrays and when eyes were about 2 ft. from lenses. From 2 ft. distance, the lenslets appeared ~~roughly~~ fully illuminated with thin lines ~~on~~ where the individual lenses were joined. The image could be seen through any part of the lens array, although some distortion was observed near the edges of each lenslet. When the eyes were close to lens clusters, the joints between lenslet were not objectionable ~~visible~~, otherwise the appearance was same as above

seen continued from 2...

Read, Understood, and Observed 30 June 1970 Carl Leonard

Read and Understood 30 June 1970
Observed 30 June 1970
Jack Walker

Juris Upatnieks
30 June 1970

30 June 1970.

2. With the ground glass removed, the image could be seen at about the same distance from the fly's-eye lens clusters. Careful positioning of the eyes was necessary in order that light would enter the pupil. The image could not be seen from ~~any~~ every position looking through the lens clusters. At about 2 ft. distance from the clusters, the lens clusters appeared mostly dark and ~~images~~ part of the image could be seen through a small part of each lenslet.

Read and understood, 30 June 1970
Observed 30 June 1970
Jack Walker

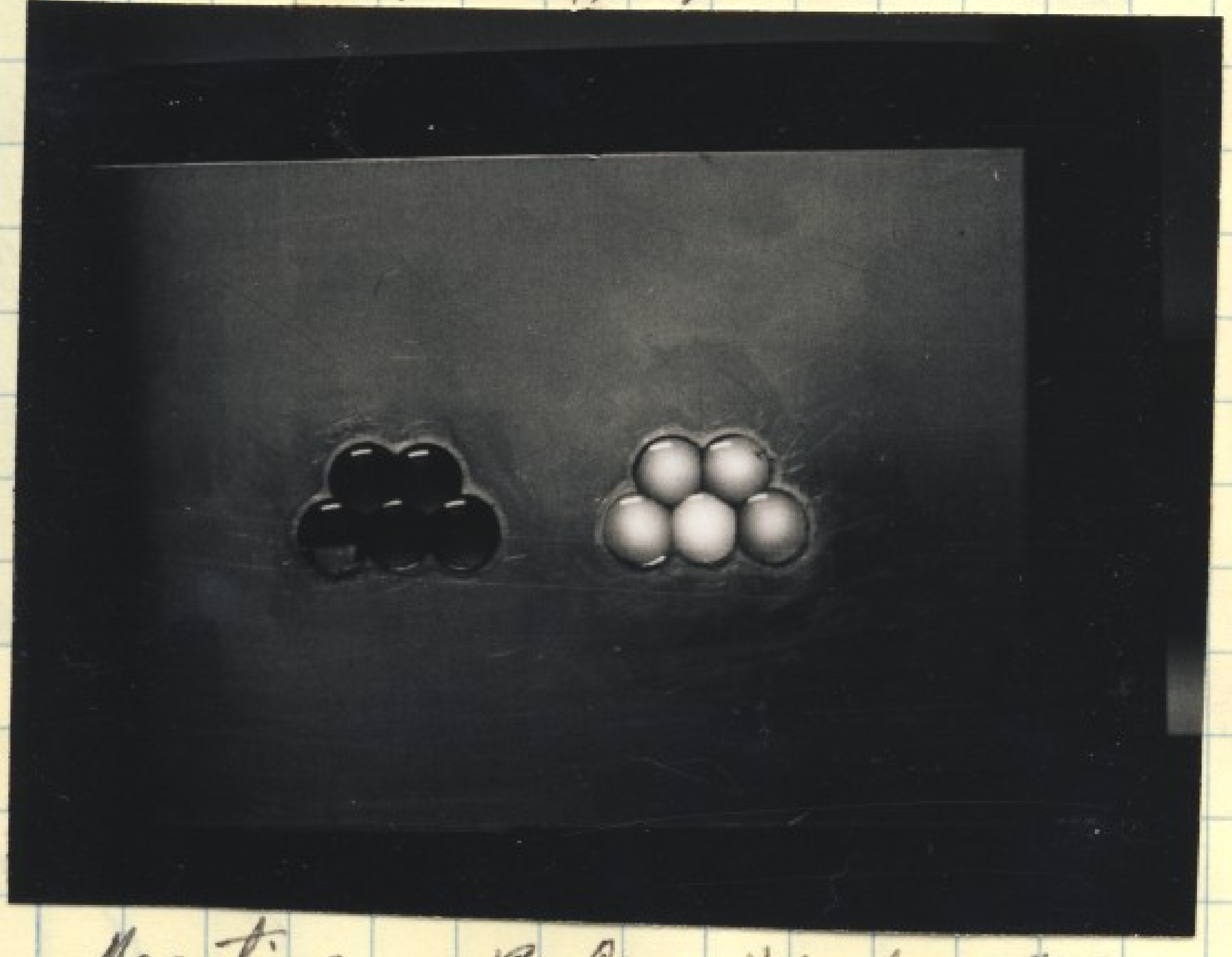
Juris Upatnieks
30 June 1970.

Read, understood, and Observed
Carl Leonard 30 June 1970

15 July 1970

Experiments with fly's-eye lens lenslet pattern visibility reduction.

Photograph #1



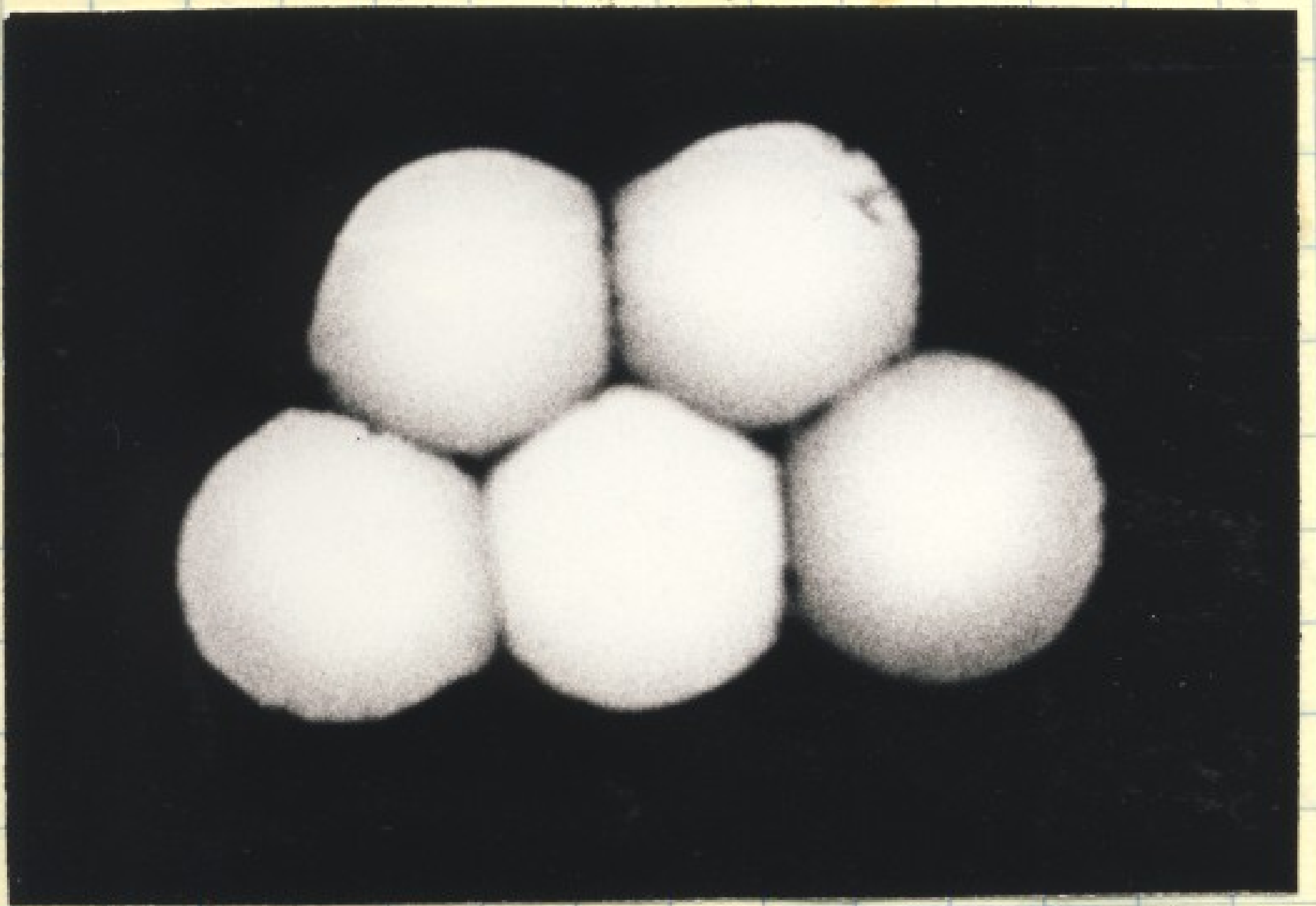
Negative p. 19, line #1, frame #3

Photograph of two clusters of five 29 mm focal length lenses in each cluster. The camera was focused on the lenses and the reconstructed object appears behind the lenses. Ideally, each lens should appear uniform in brightness. Experiment photographed on 30 June 1970.

Juris Upatnieks
15 July 1970.

15 July 1970

Photograph #2 p. 19, line #2, frame #14

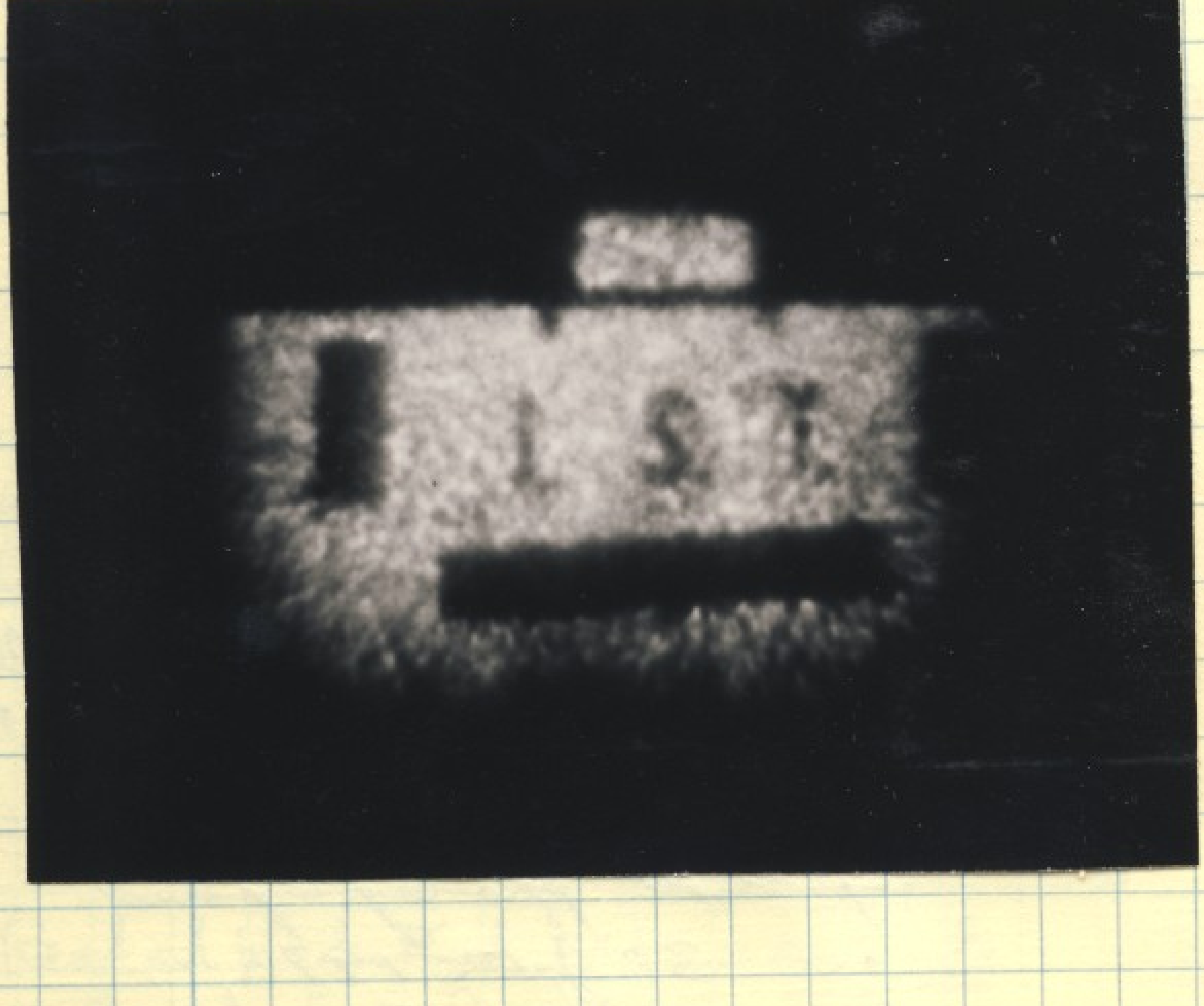


Same as on previous page, but an enlarged view of the illuminated lens cluster. The room light were turned off for this photograph. A rotating diffuser was used in the image plane.

Photograph #3 p. 19, line #4, frame #15

Same as #1 but camera focus adjusted for image plane. Photograph taken with a 50 mm lens at f-2 opening. Photograph taken on 30 June 1970. A rotating diffuser was used in the image plane.

Photograph #4 p. 19, line # 5, frame 32.

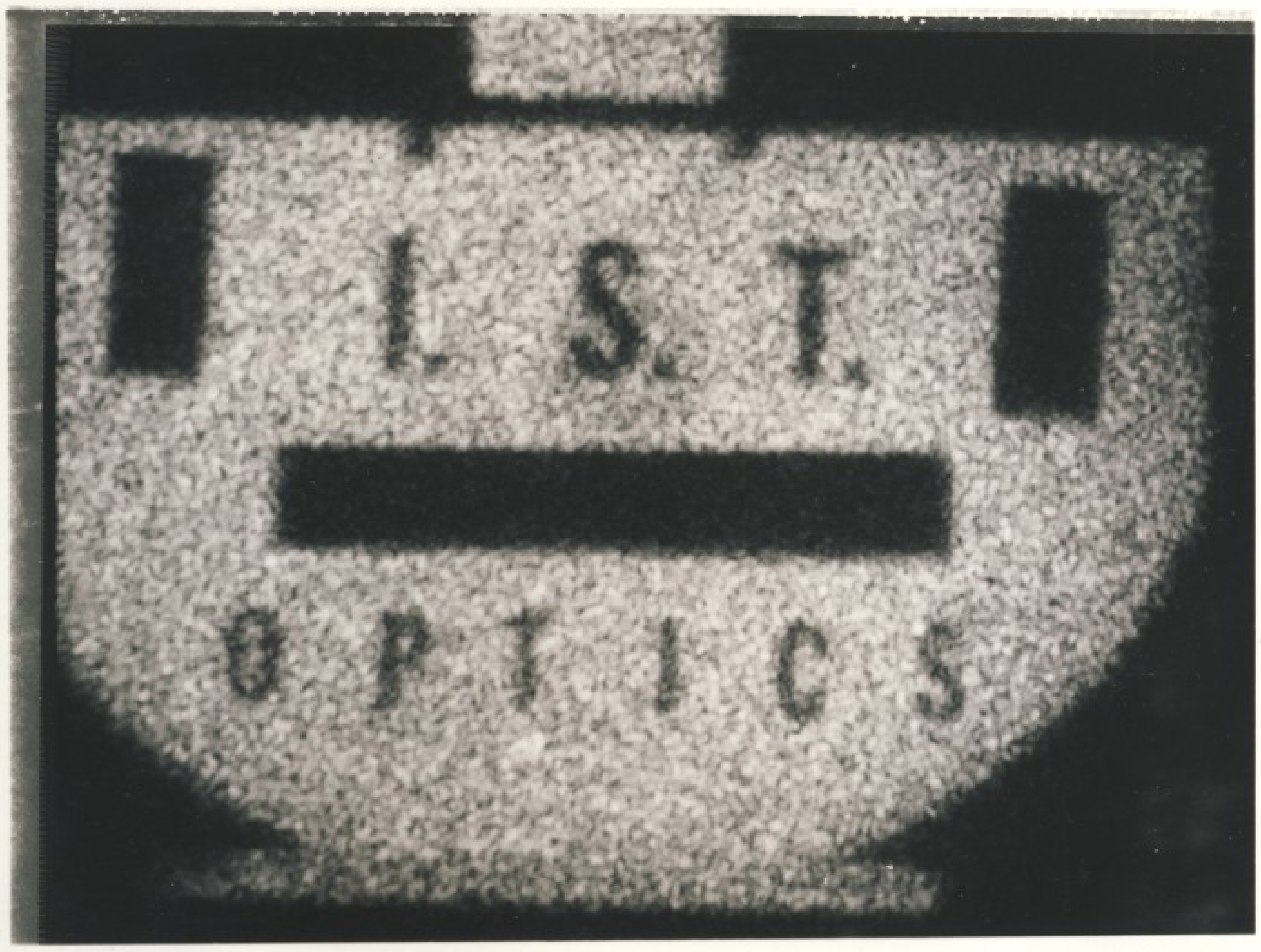


Photograph taken with 35 mm camera, as before, but camera moved up closer to the lens array. Camera focused on the image. Photograph taken on 30 June 1970. A rotating diffuser was used in the image plane.

Juris Upatnieks
15 July 1970

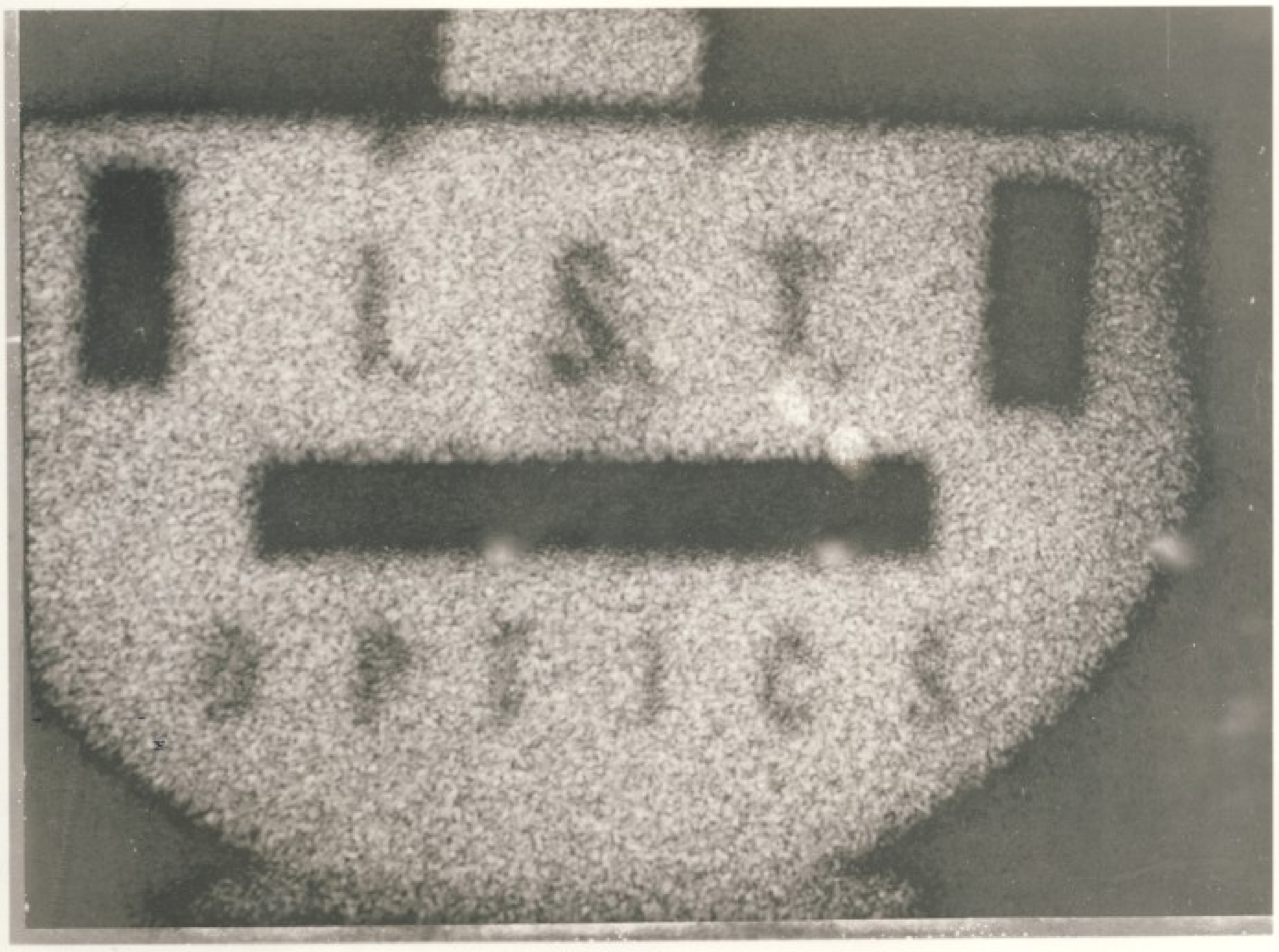
15 July 1970.

Photograph #5



Reconstruction of the real image through ~~the~~ both lens arrays with 5/8 in aperture of hologram used. The photograph shows the original size of the object. Photograph taken on June 30, 1970.

Photograph #6

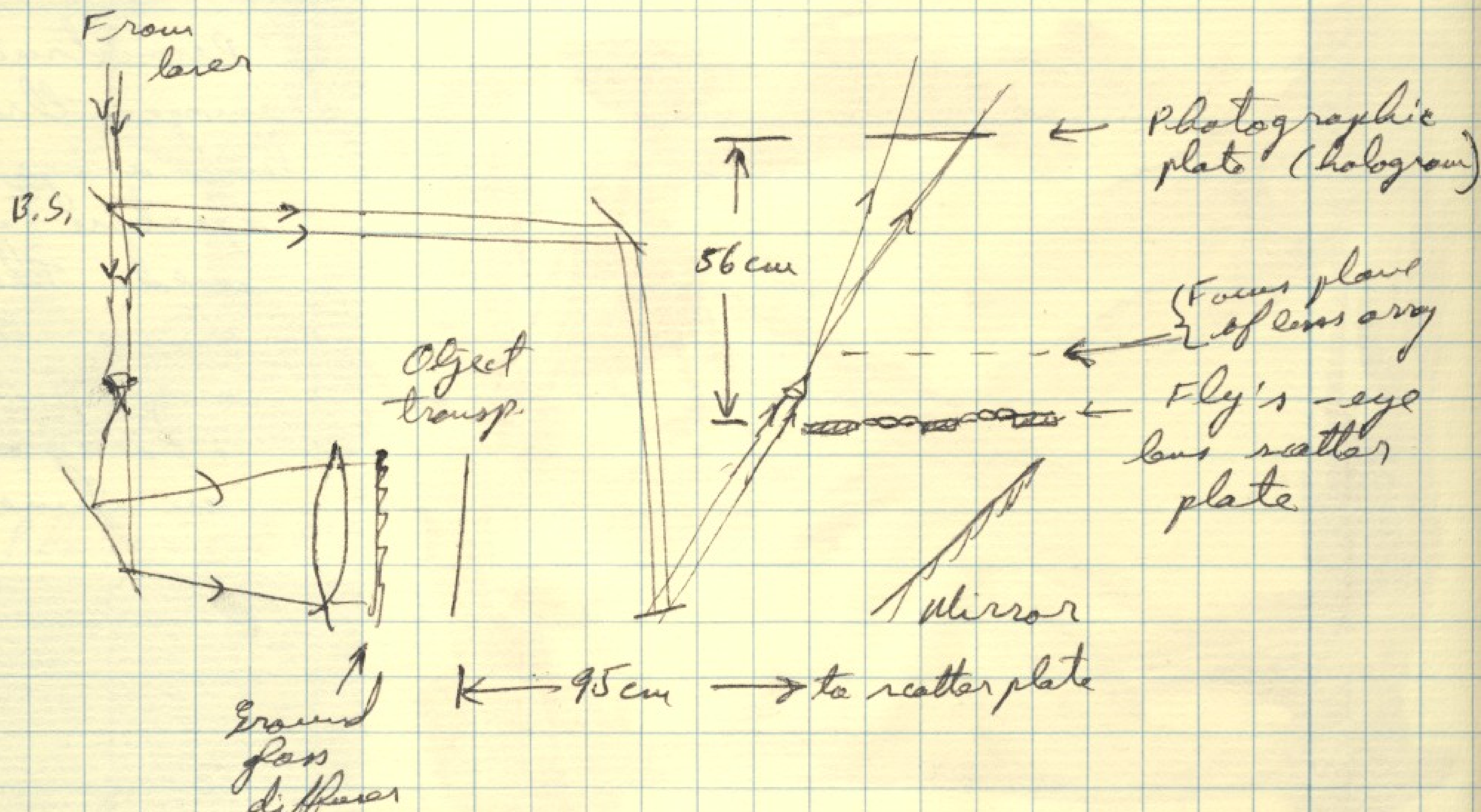


Same as #5 above, but hologram aperture increased to 1¼ in. Nonflatness of plate apparantly degrades the image. Photograph taken on June 30, 1970

Juris Upatnieks
15 July 1970.

15 July 1970

The optical system for making the previous photographs was the following



The lenslets for the scatter plate had 29 mm focal length and 15 mm diameter. A rotating diffuser was placed in the focus plane when reconstructing the image. For the photographs #1 through #4 on the previous page, the hologram was moved closer to the scatter plate and the illuminating beam was readjusted. Photographs #5 & #6 were taken with system as for making the holograms and with the direction of the reference beam reversed.

Juris Upatnieks.
15 July 1970.

17 November 1970

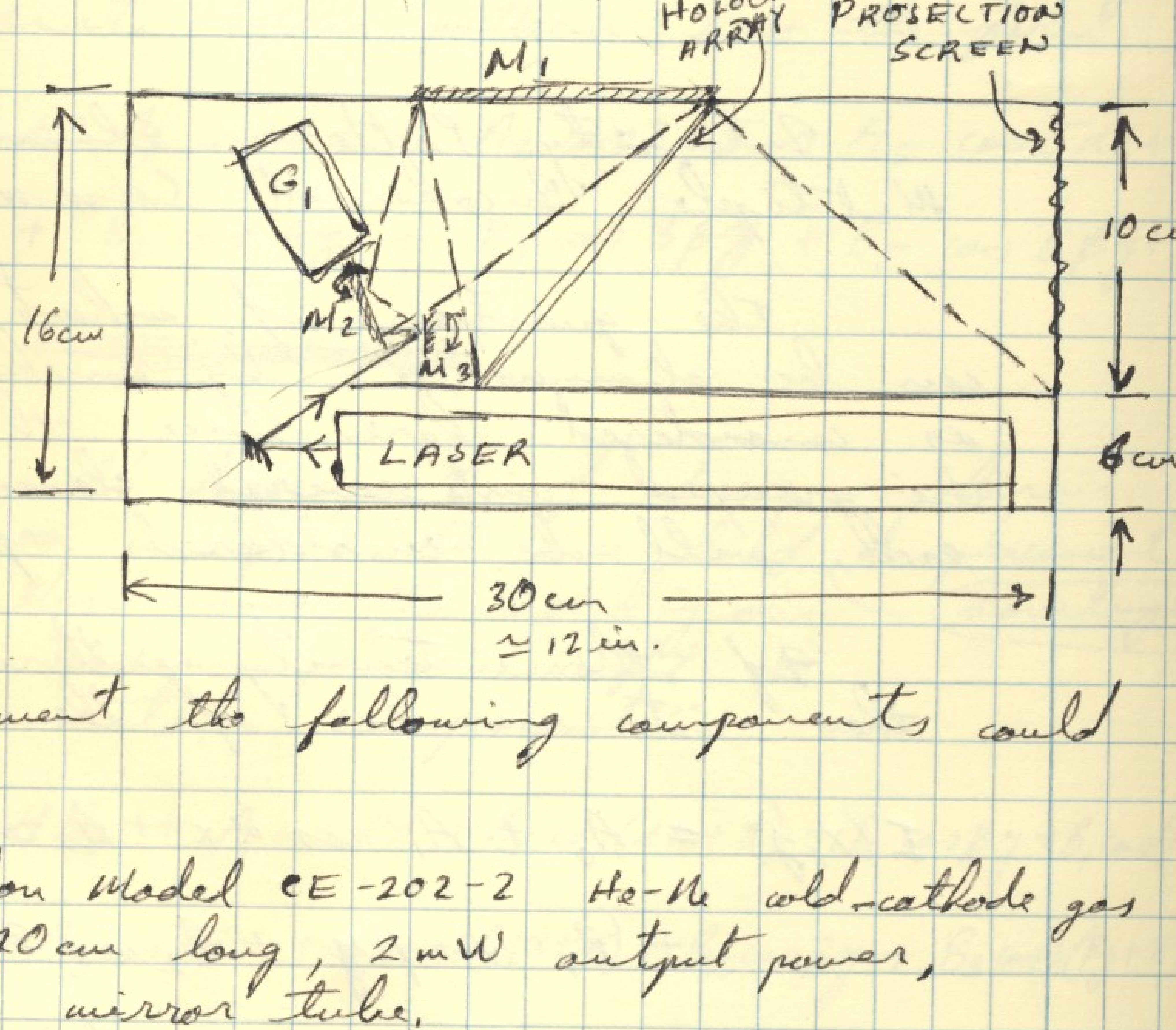
Holographic Information Display Device for Aircraft.

On pages 64 and 65 of this notebook the basic concepts of this display system were described. Here some estimates on the sizes of such a display unit are made and ~~the~~ a possible arrangement is indicated.

One layout for the system is indicated below:

M_1, M_2, and M_3 are mirrors

G_1 is galvanometer



In this arrangement the following components could be used:

1. Laser, Jodon Model CE-202-2 He-Ne cold-cathode gas laser, 20 cm long, 2 mW output power, internal mirror tube.
2. Deflectors: two General Scanning Inc. G-150 galvanometers, 15° rotation pt p., 3 watts power, 3 oz. max. weight, resonance 1,000 Hz.

The screen size would be 10 × 10 cm, hologram array size approximatly 10 × 12 cm with ~~a~~ individual hologram size ≃ 3 × 3.5 mm. and an array of 32 × 32 holograms. With a 2 mW laser and 25% hologram efficiency, message brightness would be about 180 μW/cm² or 115 ft.-L. By using a screen with restricted scattering angle (holographically produced), the effective

Juris Upatnieks, 17 Nov. 1970

17 November 1970

brightness could be greatly increased. Since some aircraft specifications require 250 ft-L. ...ge brightness, possibly also a larger single laser or two small lasers could be used.

Juris Upatnieks
17 November 1970.

29 March 1971

Intensity Pattern Elimination by Multiple Incoherent Summation.

The question of what types of patterns can be eliminated by incoherent summation is considered here. Since the patterns can be grouped into several classes of patterns, each will be considered seperatly.

If the intensity pattern is orthogonal, then it can be of the type

$$I(x,y) = A_0 + A_1 \cos \alpha x + A_2 \cos 2\alpha x + A_3 \cos 3\alpha x + \cdots$$

$$+ B_1 \cos \beta y + B_2 \cos 2\beta y + B_3 \cos 3\beta y + \cdots$$

Considering the pattern along the x-axis first, it can be eliminated if four incoherent ~~ay~~ additions are made with the pattern translated one-half the fundamental spatial frequency and each exposure of the recording material is t seconds:

$$I'(x) = t \{ 4A_0 + A_1 [\cos \alpha x + \cos(\alpha x + \tfrac{\pi}{2}) + \cos(\alpha x + \pi) + \cos(\alpha x + \tfrac{3\pi}{2})]$$

$$+ A_2 [\cos 2\alpha x + \cos 2(\alpha x + \tfrac{\pi}{2}) + \cos 2(\alpha x + \pi) + \cos 2(\alpha x + \tfrac{3\pi}{2})] \} + \cdots$$

$$= 4t A_0$$

Read and understood,
Jack Walker
30 March 1971

Juris Upatnieks, 29 March 1971

29 March 1971

To eliminate the intensity variations along the y-axis, the four displacements and additions along the x-axis are repeated with each one-half the fundamental frequency displacement along the y-axis. The total number of incoherent additions is then 4×4 or 16. If there are any cross product terms, such as $\cos n\alpha x \cos m\beta y$, where n and m are integers, then these terms ~~also~~ will be eliminated by the above incoherent summation.

A special case of the above is when only odd terms exist. This pattern has the form

$$I(x,y) = A_0 + A_1 \cos\alpha x + A_3 \cos 3\alpha x + A_5 \cos 5\alpha x + \cdots$$

$$+ B_1 \cos\beta y + B_3 \cos 3\beta y + B_5 \cos 5\beta y + \cdots$$

$$\cancel{+ C_1 \cos\alpha x \cos\beta y}$$

The pattern will disappear if four incoherent additions are made, with one-half displacements ~~to~~ of the pattern along the x and y axis (wavelength) causing π radian phase shift in the fundamental component:

$$I'(x,y) = t\{4A_0 + A_1 \cos\alpha x + A_1 \cos(\alpha x + \pi) + B_1 \cos\beta y + B_1 \cos(\beta y + \pi)$$

$$+ A_3 \cos 3\alpha x + A_3 \cos 3(\alpha x + \pi) + B_3 \cos\beta y + B_3 \cos 3(\beta y + \pi) + \cdots$$

$$= 4tA_0$$

Again, the cross product terms $\cos(2n-1)\alpha x \cos(2m-1)\beta y$ will be also eliminated. The case discussed earlier in this notebook is ~~a spec~~ the same as this one but with all but the first terms retained, the $A_0 + A_1 \cos\alpha x + B_1 \cos\beta y + C \cos(\alpha x)\cos(\beta y)$, with $\alpha = \beta$.

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The next case we consider is one in which the two intensity patterns are not orthogonal to each other. This pattern can be described as

$$I(x,y) = A_0 + A_1 \cos \alpha x + A_2 \cos 2\alpha x + A_3 \cos 3\alpha x + \cdots$$

$$+ B_1 \cos(\gamma x + \beta y) + B_2 \cos 2(\gamma x + \beta y) + B_3 \cos 3(\gamma x + \beta y)$$

$$+ \cdots$$

To obtain a uniform field, the above pattern must be translated and incoherently added in such a manner that the total exposure becomes independent of x and y (same condition as for the previous cases). One way to accomplish this is to translate the above patterns along the y-axis in $\frac{\lambda_y}{2}$ steps, to four ~~times~~ different positions (to two positions if only odd terms are present). This will eliminate any patterns due to B_n coefficients. Next, the patterns are translated along the x-axis (in $\lambda_x/2$ steps) as described before. This results in a total of 16 exposures if odd and even terms are present, or 4 exposures if only odd terms are present.

A special case of the above is if $\alpha = \gamma$. In that case it is sufficient to translate the intensity patterns along the x-axis by $\lambda_x/2$ four times (or twice if only odd terms are present) to completely eliminate the patterns along both x and y axis.

So far the translations have been those that would require minimum amount of translation between the image and the recording material. For example, in the case of sixteen superpositions the relative

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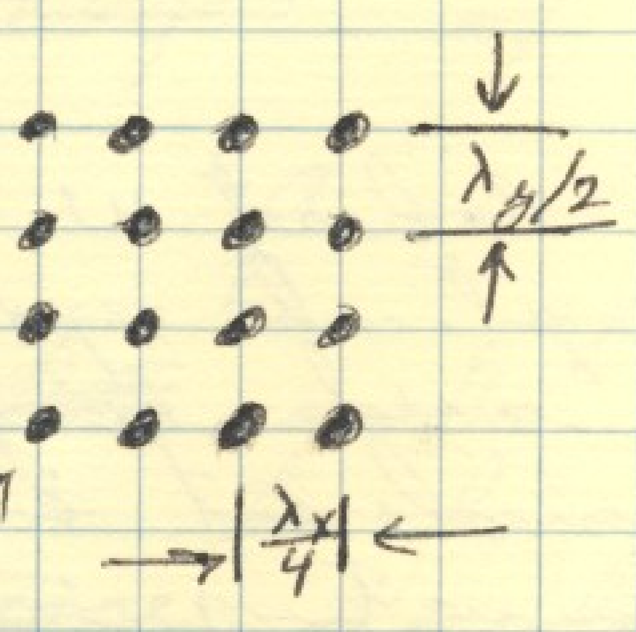
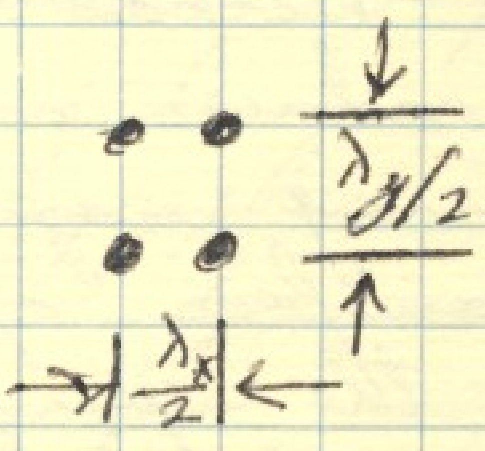
translations could have the format as indicated below:



Positions of a point on the image relative to the recording material

For the case of odd terms only, the translations could be:



Other translation schemes also could be used. For example, the translation along the x-axis could be of the form, with each relative position:

		1st exp.	2nd exp.	3rd exposure	4th exp.
x-axis	Displacement equal to:	$2n\lambda_x$	$(2n-1\frac{1}{2})\lambda_x$	$(2n-1)\lambda_x$	$(2n-\frac{1}{2})\lambda_x$
y-axis	" " ":	$2m\lambda_y$	$(2m-1\frac{1}{2})\lambda_y$	$(2m-1)\lambda_y$	$(2m-\frac{1}{2})\lambda_y$

where n is zero or a positive integer. Similar displacements could be made along the y-axis, and m and n can be independent. The total number of displacements would be 16 for a two dimensional or 4 for a one-dimensional pattern containing both odd and even terms, or 4 for a two-dimensional and 2 for a one-dimensional pattern for a pattern containing only odd terms. There are, in fact, an infinite number of combinations that would eliminate the pattern. To preserve maximum resolution, the displacements should be minimized and it seems that a rectangular array of positions is the most desirable one.

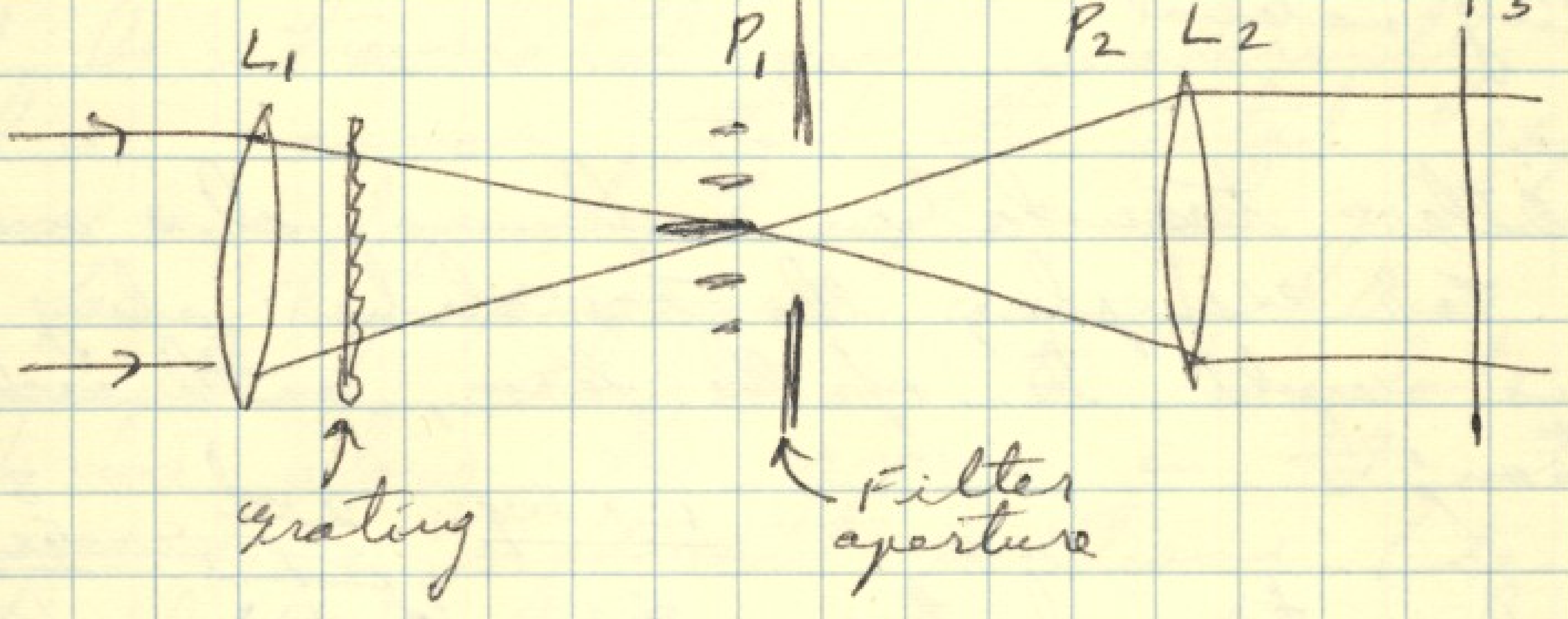
Juris Upatnieks, 30 March 1971.

Read and understood,
Jack Walker
30 March 1971

30 March 1971

A Method for Generating Multiple Incoherent Wavefronts.

A method proposed by Robert W. Lewis to reduce noise in an optical spatial filtering system can be used to generate a number of mutually incoherent wavefronts for the purpose of eliminating intensity patterns, as described on the previous pages. The system for generating these is indicated below:



A grating is placed somewhere between L_1 and P_1, generating a number of point light ~~sour~~ spots at P_1. If the grating is in motion, the the phase relationship between the points at P_1 changes and therefore they are mutually incoherent. The spacing between the points in P_1 can be changed by positioning the grating at different locations between L_1 and P_1, and also to the left of L_1. Plane, incoherent waves of various angles exist to the right of L_2; spherical waves exist to the right of P_1 and before L_2.

Although most of the discussion has dealt with plane waves and intensity patterns, spherical waves also could be used. Also, the patterns previously described exist, in some cases, ~~ob~~ over considerable distance along the optical axis, or the z-axis. Thus, intensity ~~~~ variations ~~cat~~ can be reduced by the above techniques at various planes along the z-axis.

Read and understood,
Jack Walker
30 March 1971

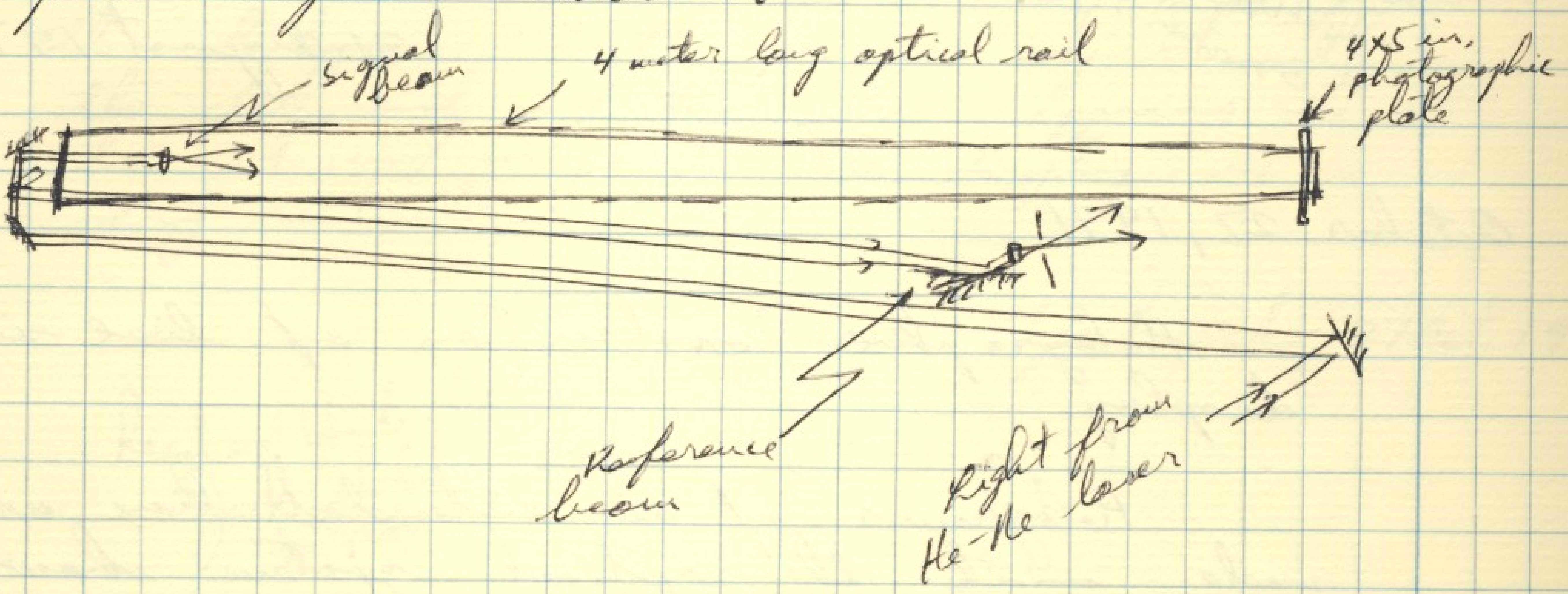
Juris Upatnieks, 30 March 1971

August 31, 1971

Experiments with Producing Holographic Images of Infinite Line Length

A number of applications require the generation of an infinite line in space whose direction can be adjusted. Holographic techniques appear to be ideally suited for this purpose. We have made a simple experiment to examine the appearance of such lines as well as to test some possible arrangements for constructing such holograms.

The hologram was made using the optical system shown:



With this system, instead of a continuous line, a number of equally spaced point light sources were recorded on a hologram. A number of incoherently superimposed holograms were made with the point light source at a different distance from the hologram each time and with the reference point remaining stationary. On reconstruction, all point light sources were reconstructed simultaneously. Holograms were made with two to six point sources. They appeared to extend to the depth of the rail and the most realistic view was obtained when the observer was above the line of points.

Juris Upatnieks
August 31, 1971

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Jack Walker
3 November 1971

August 31, 1971

The furthest point from the hologram could appear to be at an infinite distance when the illuminating point was moved further away from the hologram.

An infinite line could be generated by illuminating a flat surface with a narrow laser beam and recording the reflection holographically. In reconstruction the image could be magnified in such a manner that the furthest point is at infinity.

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3 November 1971

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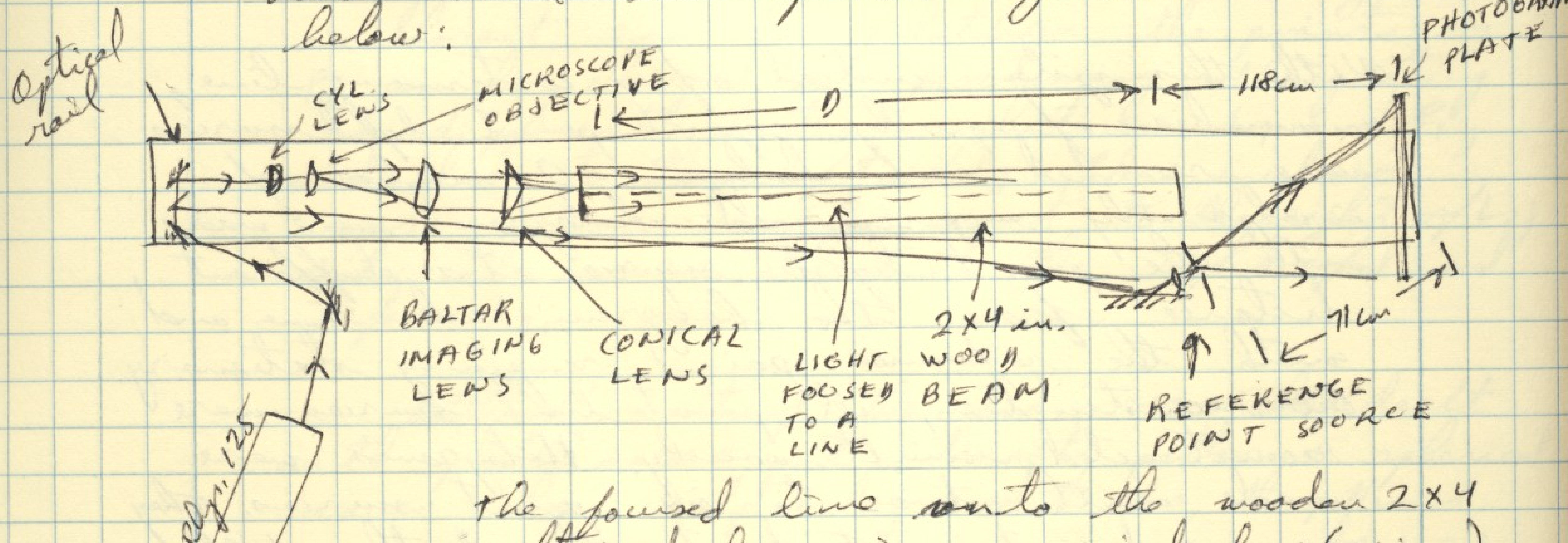
31 August 1971

October 27, 1971

Holographic construction of line-in-space display.

Holograms of an extended line were made with the optical system shown below:



The focused line onto the wooden 2X4 was obtained by using a conical lens (axicon) in conjuction with a spherical lens (Baltar). A cylindrical lens before the microscope objective

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3 November 1971

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27 October 1971

was used to obtain a narrow vertical line at the plane of the conical lens. This was necessary to reduce the abberations present in the conical lens. A well focus beam could be obtained over a length of $D = 176$ cm of the 2×4 in. beam. The length was primarily limited by the nonflatness of the 2×4. One end of the line was 294 cm from the hologram, the other 118 cm. The optical rail was suspended on inflated inner tubes to reduce effects of vibration.

The line ~~source~~ hologram is reconstructed with a point source wave that 71 cm from the hologram. With proper adjustment the far end of the line appears to be at infinity and the display is very realistic.

Juris Upatnieks, 27 Oct. 1971.

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3 November 1971

28 June 1972

Moire Suppression in Coherent Imaging

To compare various types of wavefronts illuminating an object, a qualitative expression of redundancy and noise suppression is needed. Bob Lewis has prepared an expression for redundancy R as

$$R = \frac{\Sigma |a_n|^2}{|a_{max}|^2}$$

where a_n is the amplitude of the nth wave illuminating the object transparency and

Juris Upatnieks, 28 June 1972

28 June 1972

$a_{max.}$ is the amplitude of the ~~two~~ strongest wavefront. This expression appears to be very reasonable for a number of plane wavefronts, such as illumination provided by a phase grating.

Another quantity of interest is the ability of an illuminating wavefront to be less susceptible to noise, or defects, of an imaging system. This might be called noise suppression factor, N.S. Since N.S. should be proportional to the dispersion as well as the intensity of the various wavefronts, N.S. should be given by

$$N.S. \propto \frac{\sum \alpha_n |a_n|^2}{|a_{max}|^2}$$

where α_n is the angle between the on-axis wavefront and the n^{th} illuminating wavefront. For a single plane wavefront illumination $\alpha_{n=0} = 0$ and N.S. $= 0$.

Assuming that system noise is primarily that of microscopic dust particles and scatterers, the scattered energy density is inversely proportional to the distance of the scatterer from the image plane, or N.S. $\propto \frac{1}{z^2}$. Thus, the total noise suppression should be given by

$$N.S. = \frac{z^2 \sum \alpha_n |a_n|^2}{|a_{max}|^2}$$

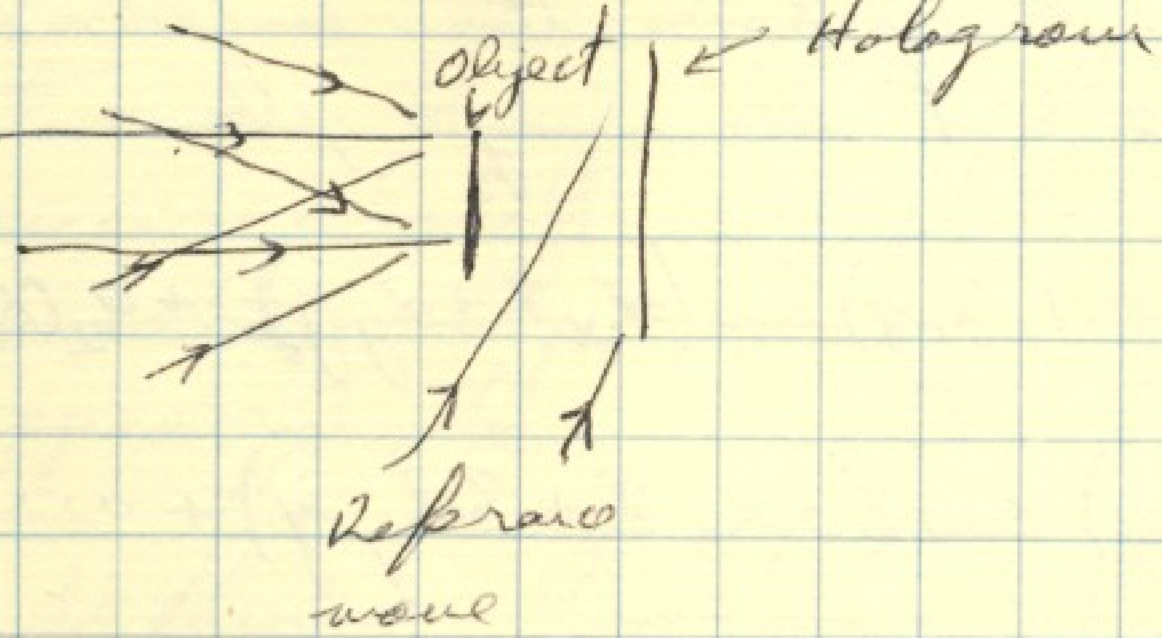
Juris Upatnieks, 28 June 197

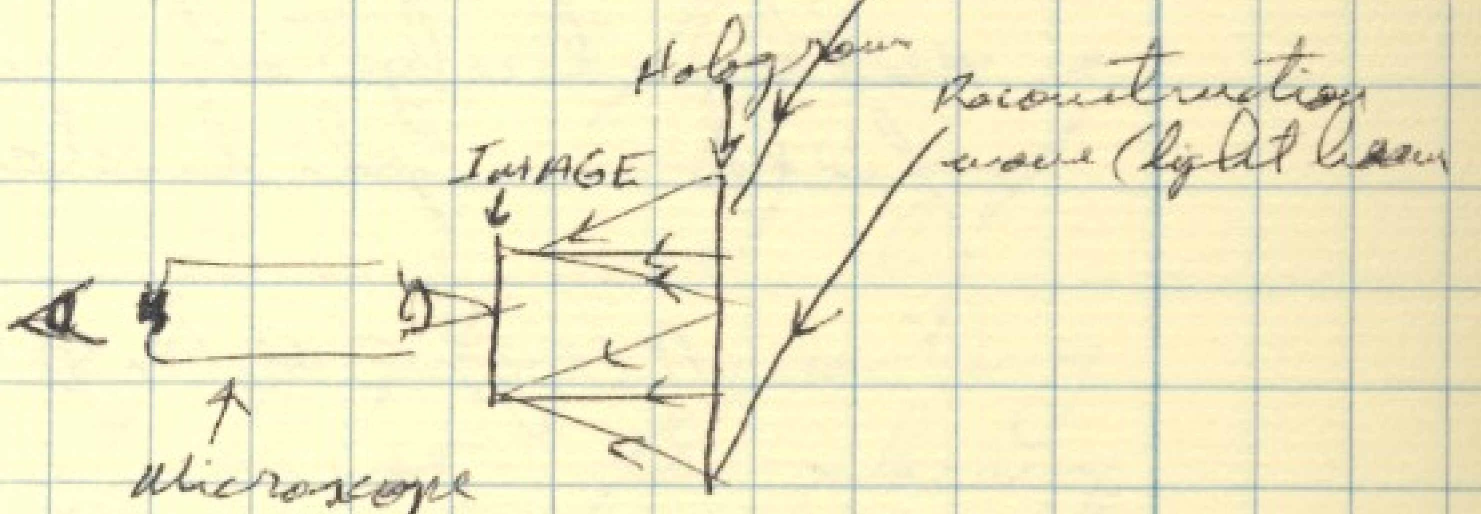
6 November 1972

Noise suppression in holographic microscopy.

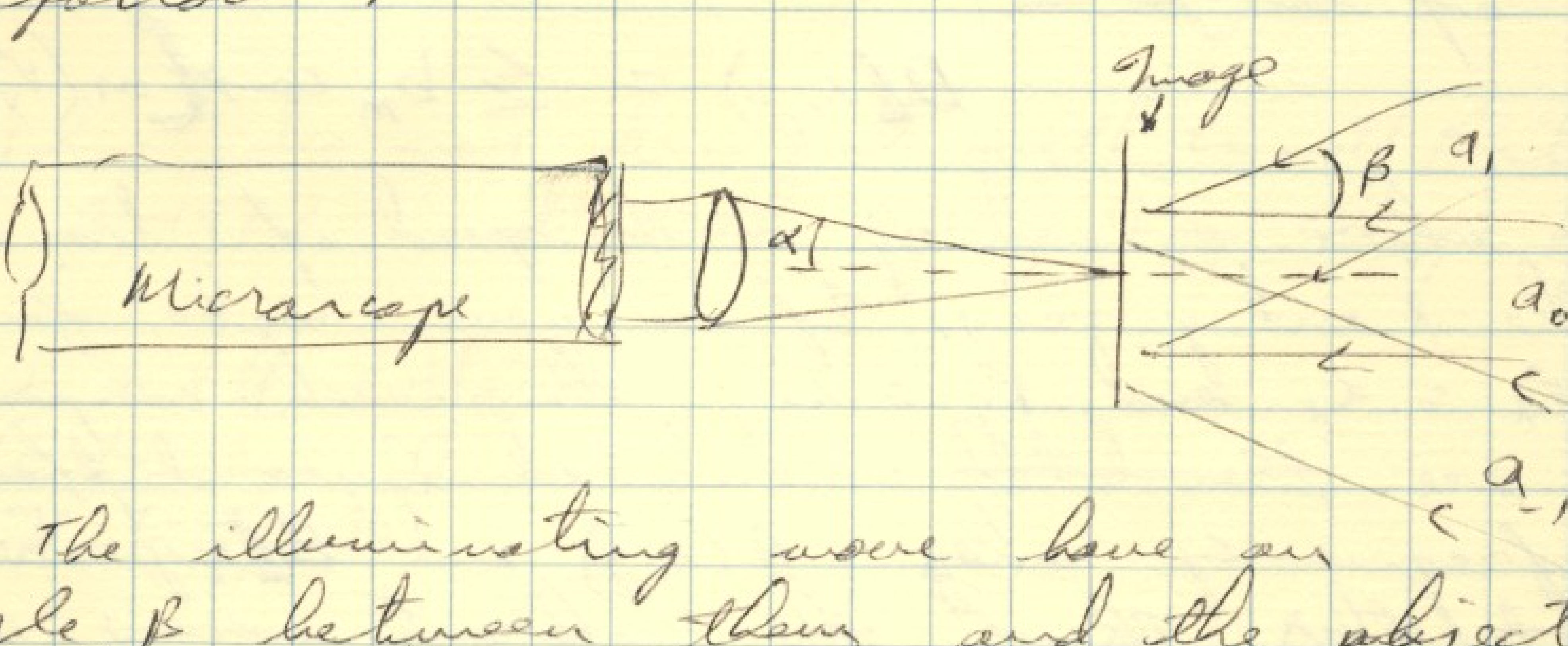
While noise from scatterers and defects in an imaging system can be suppressed by using redundancy in the form of multiple coherent waves, greater noise suppression can be achieved if if these waves are rendered mutually incoherent. While hologram construction requires coherence, coherence is not essential in the reconstruction process. Here we propose to incoherently sum a number of coherently reconstructed images to achieve improved image quality and lower noise level.

First a system with a number of plane wave illumination will be described. The usual construction arrangement and observation arrangement are shown below:





In enlargement, the viewing system is as follows:



The illuminating wave have an angle β between them and the objective used to observe the microscope subtends an angular field of 2α. Let $\alpha < \beta$. Thus, in figure above, only the direct beam a_0 enters the microscope and contributes to the image that is seen

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6 November 1972

through the microscope.

We now introduce a grating in the image plane in such a way that part of the a_1 and a_{-1}, as well as higher order waves, are diffracted into the microscope objective. Thus, the images formed by the other waves are also visible, and all are coherently added. The grating is carefully adjusted and maintained in the ~~imag~~ focus as viewed through the microscope.

To render the images formed by the various waves (or beams) a_n (incoherent) we move the grating. Since each ~~order~~ incident wave is diffracted in a different direction, the temporal frequency of each a_n waves is different from all others, thus rendering them mutually incoherent. Mathematically we can write the incident light field amplitudes at the image plane as

$$A(x,y) = a_0(x,y) + a_1(x,y)\cos(\alpha_x x + \alpha_y y) + a_2(x,y)\cos(2\alpha_x x + 2\alpha_y y)$$
$$+ a_3(x,y)\cos(3\alpha_x x + 3\alpha_y y) + \cdots$$

In the image plane all the a's are the same and differ only by a constant. We now place a grating of the form

$$B(x,y) = \sum b_m \cos\left[m(v_x x + v_y y - \frac{2\pi}{\ldots}(v_x x + \ldots\right.$$

where v_x and v_y is the speed of translation along the x and y axis. If we now make, for example, $v_x = \alpha_x$ and $v_y = \alpha_y$, then each component of $A(x,y)$ are ~~translated~~ modulated by a different temporal frequency when $A(x,y)$ and $B(x,y)$ are multiplied together. Thus, the coherent waves reconstructed from a hologram are incoherently ~~att~~ added and observed through a microscope.

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15 Nov. 1972

6 November 1972

A number of advantages are evident for this arrangement as for either coherent addition of these waves or simple viewing of the image without a grating or scatterer in the image plane. One, redundancy is introduced without decreasing the resolution of the imaging system. The band-width (B.W.) ordinarily not utilized is here used to suppress noise. Two, addition is incoherent and thus interference between various beams is not visible. Third, a three-dimensional as well as two-dimensional objects or surfaces can be examined and seen equally well. The microscope and grating (or other diffuser) can be moved as a unit to observe different planes in the image field. The image is equally good everywhere, unlike the schemes employing image periodic plane structures. Fourth considerable improvement should be possible even with diffuse objects, reflecting or transmitting. In this case a number of uncorrelated speckle patterns will be incoherently added. While a phase grating appears to be the best choise for placing in the image plane, other gratings or random diffuse screens also could be used.

Juris Upatnieks, 6 Nov. 1972

Note: This idea was discussed with Emmett Leith on Nov. 3, 1972, and with Byung Jin Chang on Nov. 6, 1972.

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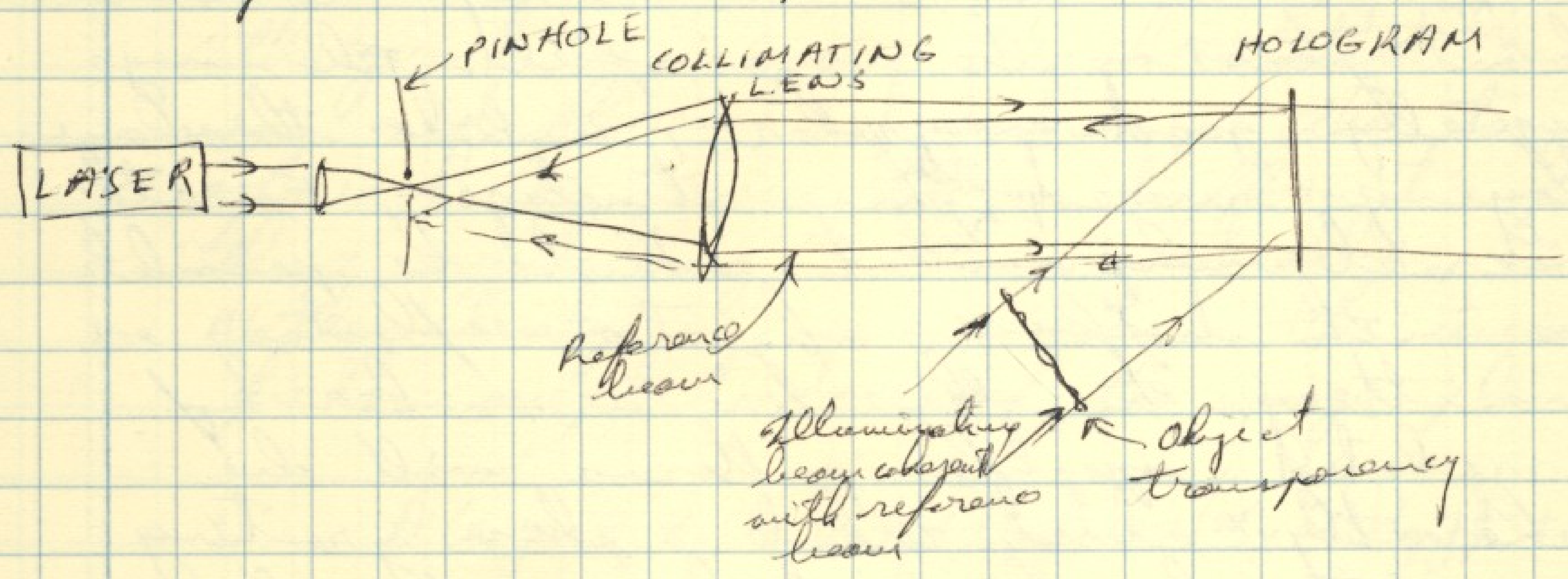
15 Nov 1972

7 December 1972

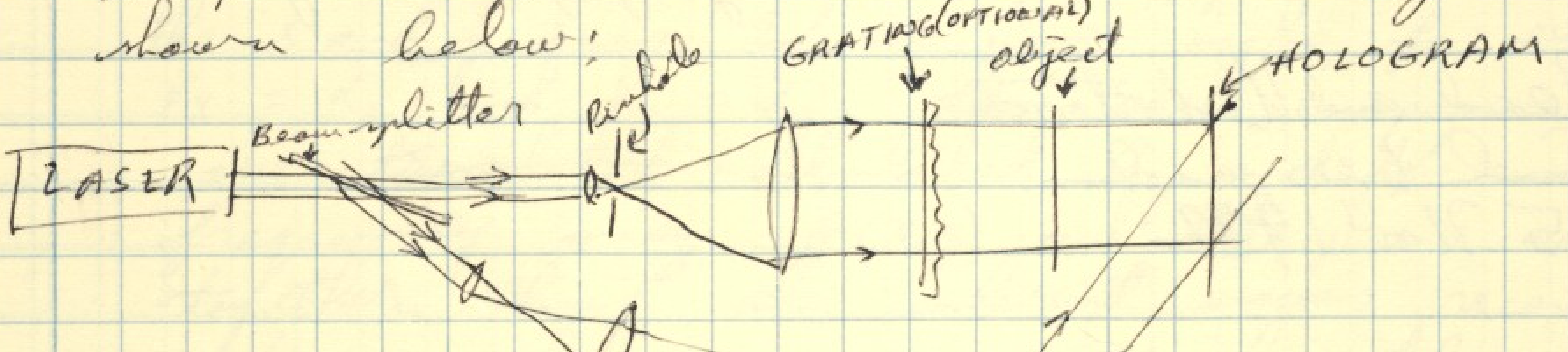
Precision alignment technique of holograms

Frequently it is necessary to align holograms to a high degree of precision. A common technique is to position the hologram perpendicular to a collimated reference beam. In reconstruction one can observe the reflected light from the hologram forming a point image near the pinhole of the point light source in the collimator. By adjustment the reflected point image can be made to coincide with the pinhole, ~~at~~ which then indicates an exact alignment. The schematic for this arrangement is shown below:

Hologram construction setup



A disadvantage of this scheme is that the object and hologram are not parallel to each other. For high-resolution systems, as one described in the previous pages on holographic microscopy, it is highly desirable to have the object transparency (or surface) parallel to the hologram and for the reference beam to form a large angle with the perpendicular to the surface. A possible and desirable arrangement is shown below;



Juris Upatnieks
7 December 1972

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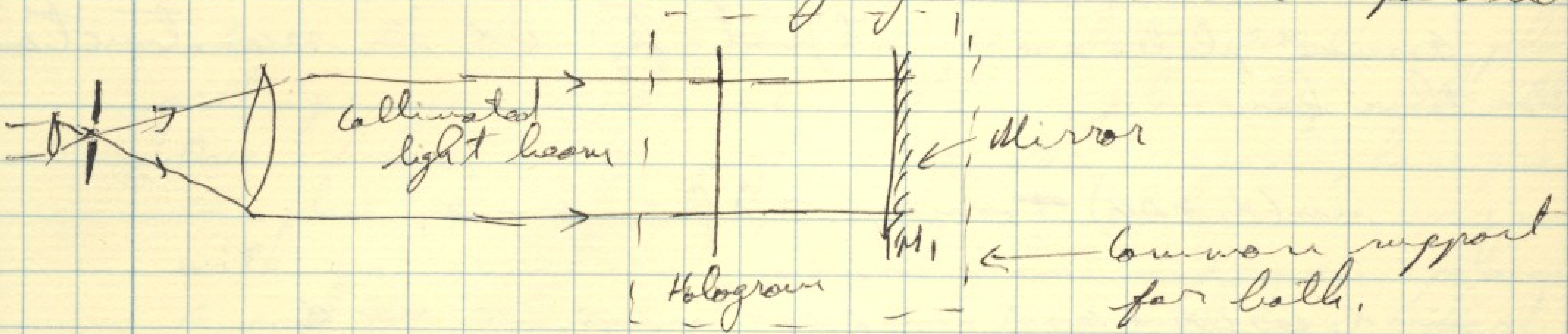
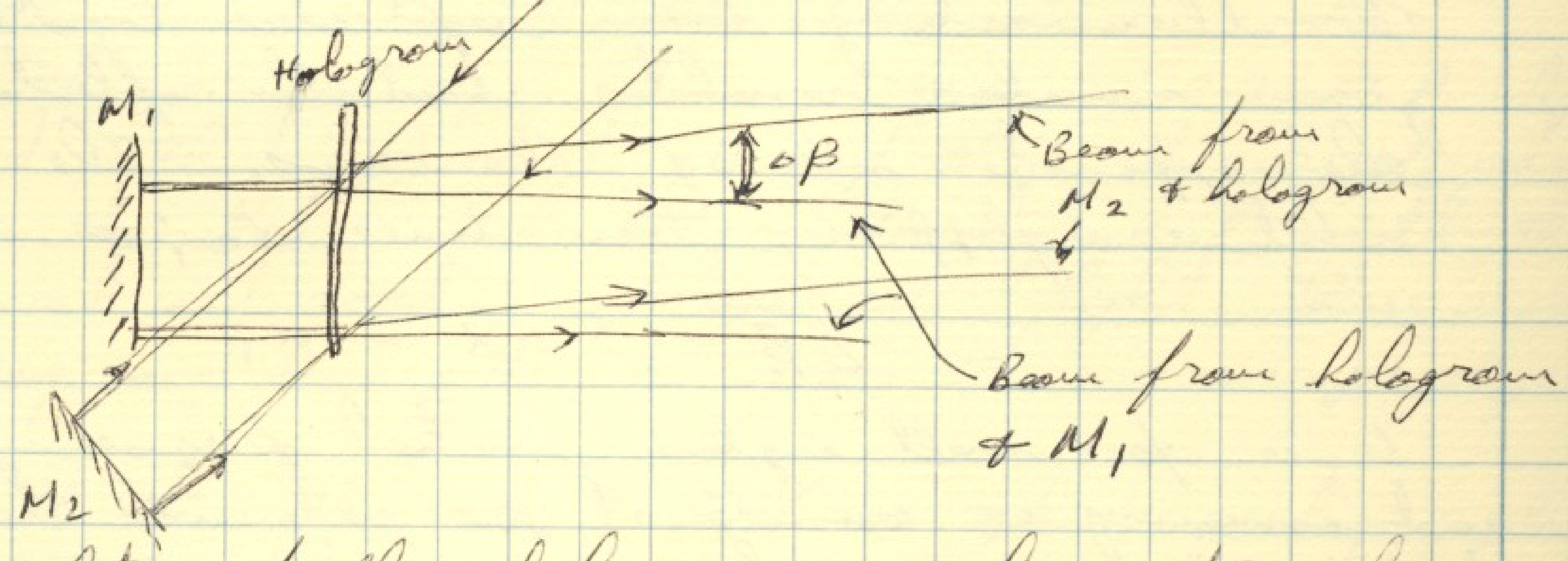
In the hologram construction step the hologram is aligned perpendicular to the illuminating beam, or if the grating is used, perpendicular to the zero order diffracted beam. This is accomplished by observing the point image formed by surface reflection from the hologram (or a plain glass substituted for the photographic plate). In the reconstruction process it is essential that the identical angle between the reference beam and the photographic plate is obtained. This can be done in the following manner. First, set both the hologram and a mirror ~~both~~ perpendicular to a collimated beam of light. Mount these rigidly on a platform so that both can be moved without changing their relative position.



This insures that the hologram and the mirror are parallel to each other. Then set the hologram in a collimated beam to reconstruct the conjugate image from a hologram, and set a second mirror perpendicular to this collimated beam of light:

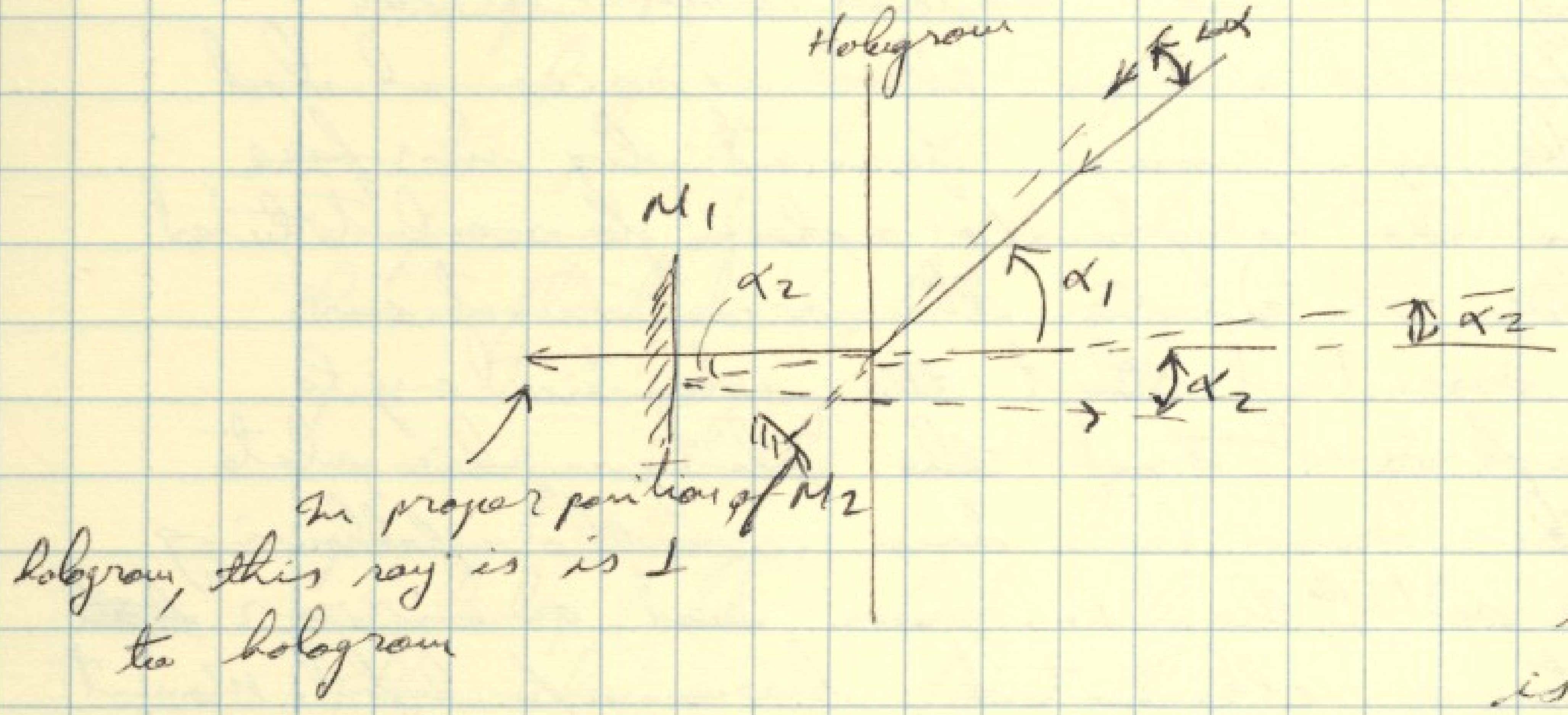


To the right of the hologram we have two beams reconstructed by the hologram: one from the conjugate image and the other from the virtual image. There is also a reference beam reconstructed by the beam reflecting off M_1. By suitable arrangement, interference fringes between this beam and the one reflected from M_2 can be observed.

7 December 1972, Juris Upatnieks

7 December 1972

The angle between the two wavefronts $\Delta\beta$ can be calculated from the following diagram:



The grating equation is $\lambda f = \sin\alpha_1 - \sin\alpha_2$ where f is spatial frequency and α_1 and α_2 are angles relative to the $\perp$ of the plate. In construction of hologram $\alpha_2 = 0$ and therefore is also zero in reconstruction if properly aligned.

Assume plates are misaligned by $\Delta\alpha$ in reconstruction. We then have

$$\sin(\alpha_1 + \Delta\alpha) - \sin\alpha_2 = \lambda f = \sin\alpha_1$$

$$\sin\alpha_1 \cos\Delta\alpha + \cos\alpha_1 \sin\Delta\alpha - \sin\alpha_2 = \sin\alpha$$

since $\cos\Delta\alpha \simeq 1$ and $\sin\Delta\alpha \simeq \Delta\alpha$,

$$\sin\alpha_1 + \Delta\alpha\cos\alpha_1 - \sin\alpha_2 = \sin\alpha$$

$$\sin\alpha_2 = \Delta\alpha\cos\alpha_1 \simeq \alpha_2$$

The illuminating beam reflected by M_2 also gives similar results but the reflection is on the opposite side of the axis. The total relative angle $\Delta\beta$ is then twice α_2;

$$\Delta\beta = 2\Delta\alpha\cos\alpha_1$$

Since for small angles spatial frequency is given by $\frac{\Delta\beta}{\lambda}$, and assuming we can adjust the plate with one fringe across aperture d, then

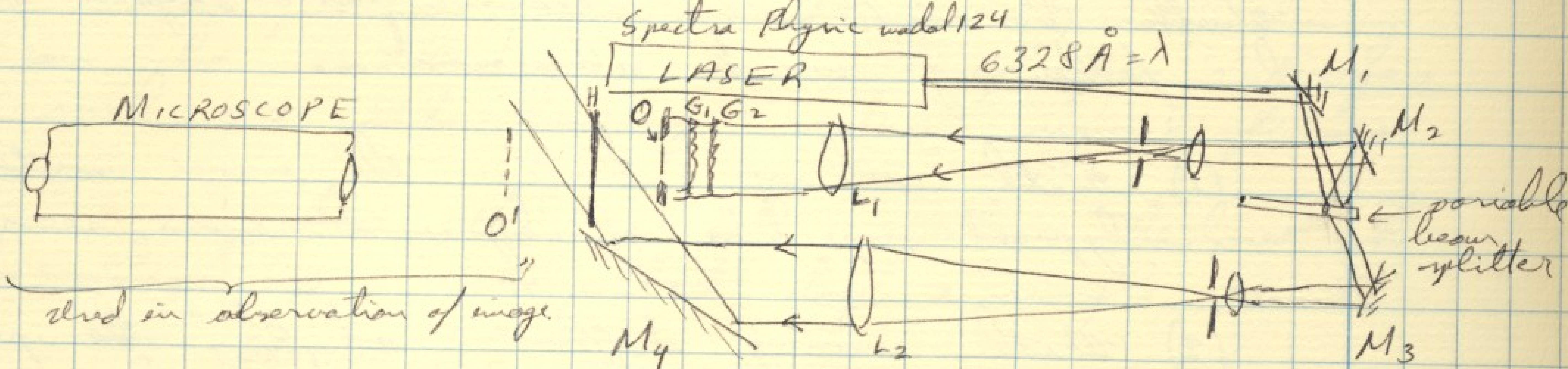
$$\Delta\alpha = \frac{\lambda}{2d\cos\alpha_1}$$

Where $\Delta\alpha$ is the angular misalignment

7 December 1972, Juris Upatnieks

29 December, 1972

Holograms were constructed with the optical system shown below:



O is the object, G_1 and G_2 are two 200 l/mm phase gratings positioned at right angles to each other. One hologram was made with the crossed phase gratings in place as indicated, and one hologram was made with an additional ground glass diffuser placed near G_1 and G_2. The object was an air force resolution chart.

In reconstruction the beam from mirror M_2 was blocked, hologram H was rotated 180° and reinserted at it's original position. The conjugate image appeared at plane O', and it was observed with a microscope. The following was observed when the hologram constructed with G_1 and G_2 was used:

1. With a microscope having 48 mm 0.08 N.A. objective, and nothing placed at plane of O', the object was reconstructed without granularity but with the usual artifacts of coherent light. These included ring and line patterns from the microscope objective.

2. With two crossed 200 l/mm phase gratings placed at O', a low frequency interference pattern was superimposed on the image.

3. With two crossed 200 l/mm phase gratings at O' and moving during observation, the low frequency interference pattern was not visible and coherent noise was reduced.

Witnessed and understood
Byung Jin Chang
Dec. 29, 1972

Juris Upatnieks, 29 Dec. 1972

This reduction to practice
witnessed by me, Dec 29, 1972 Emmett N. Leith

29 Dec. 1972

4. With a moving diffuser at O′, all coherent noise due to the microscope was absent

With the diffusely illuminated object backgroun, the following was observed:

(1) With nothing at O′, the image with typical speckle background was seen.

(2) With moving diffuser at O′, the speckle pattern was not seen and image seemed to have a clean, noise-free background.

(3) With a stationary crossed phase grating at O′, the image appeared to be the same as at (1).

(4) With a moving crossed phase grating at O′, the speckle pattern was reduced in contrast but was still visible.

This reduction to practice was witnessed by me, Dec 29, 1972
Emmett N. Leith

Juris Upatnieks, 29 Dec. 1972

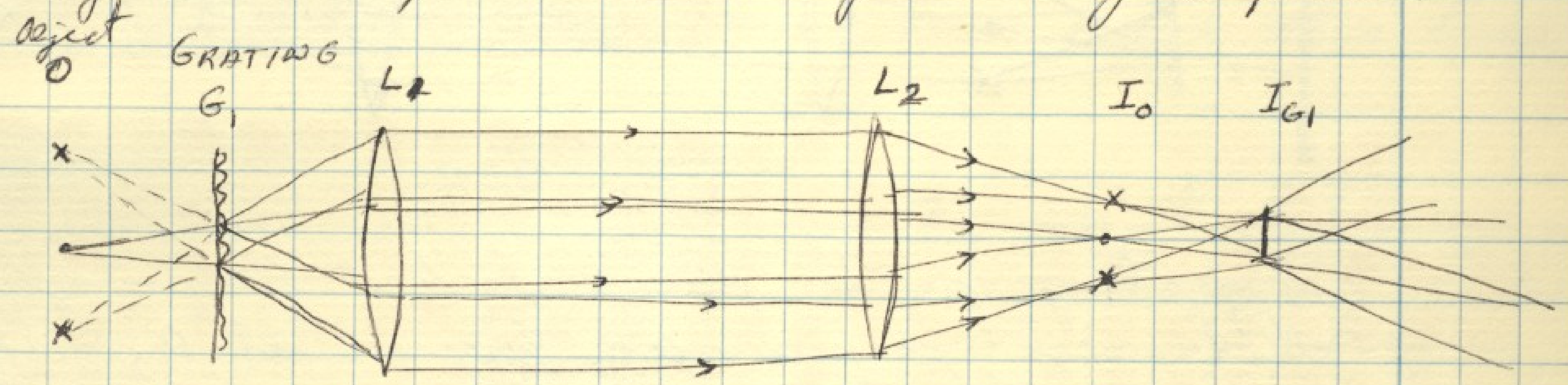
Witnessed and Understood
Byung Jin Chang Dec. 29, 1972

5 January 1973

Redundancy in Optical Data Processing Systems.

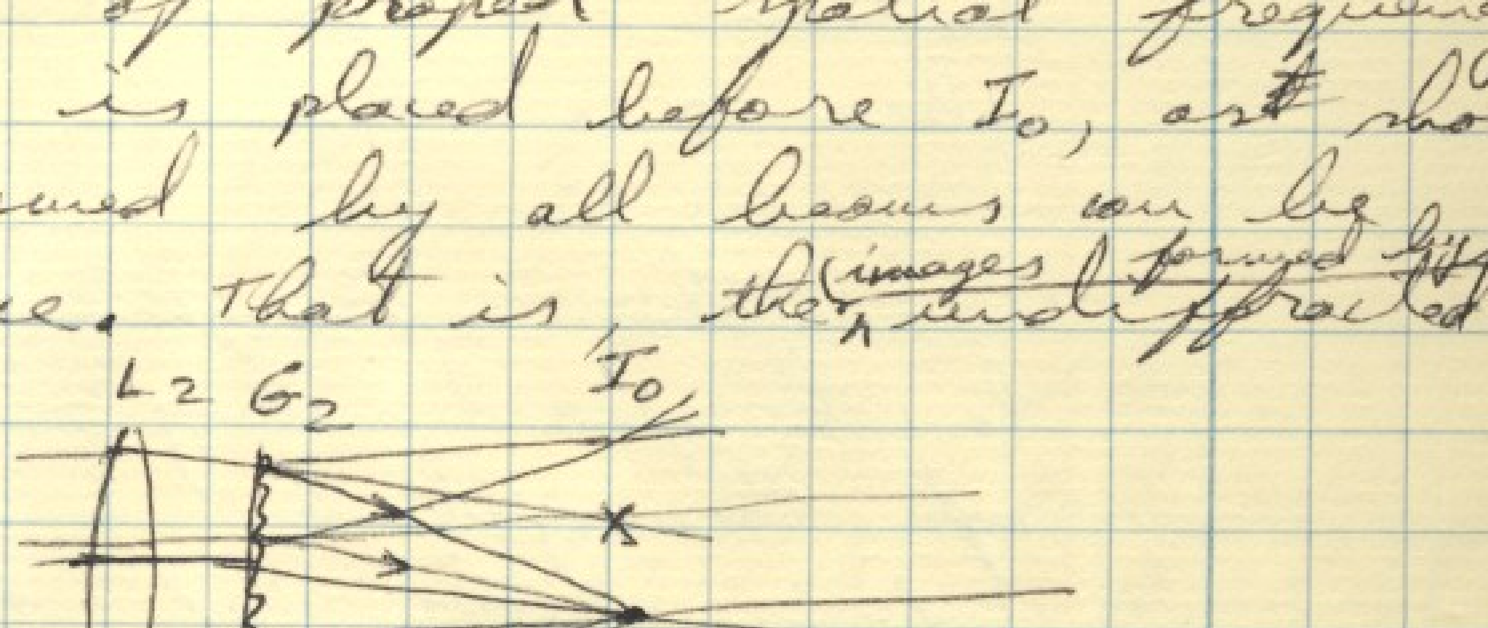
Various schemes of introducing redundancy in optical data processing systems are known. All of these illuminate an in-focus object transparency by various forms of wavefronts. ~~This~~ Here a technique is described where redundancy can be introduced in out-of-focus images, such as side-looking radar signal films.

Consider the optical system below where the ~~object~~ object is represented by a single point.



If a grating is placed after the image plane, several displaced points will be seen, shown by x's above. These are imaged in a displaced form and are not useful.

If another grating of proper spatial frequency and at proper position is placed before I_0, as shown below, then images formed by all beams can be brought into coincidence. That is, the images formed by the undiffracted



central beam is brought into coincidence by those of 1st order diffracted upper and lower beams. Other images exist which probably are of no interest.

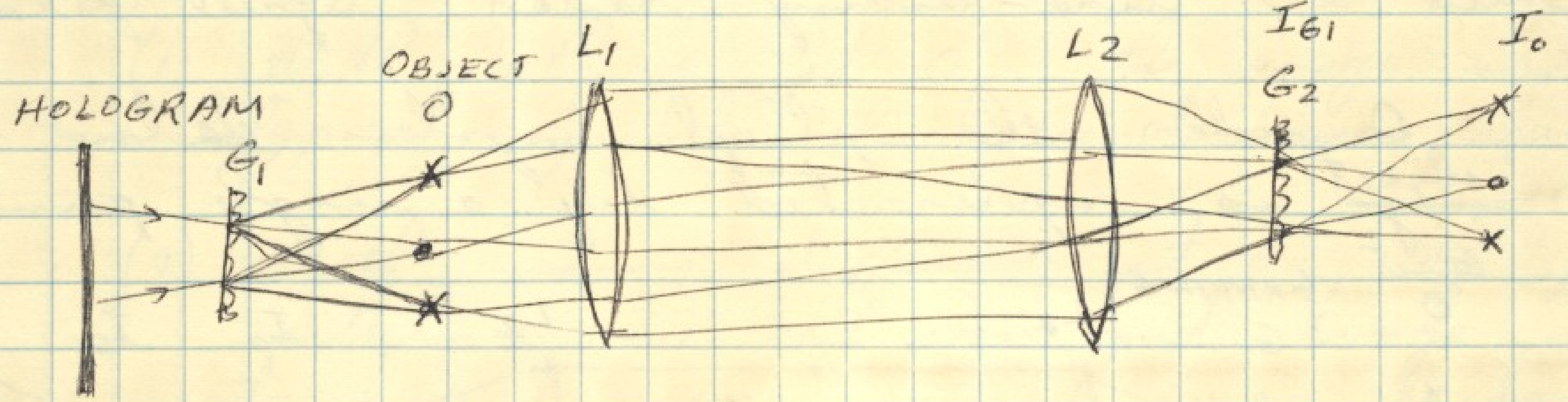
Juris Upatnieks, 5 Jan. 1973

Read & Understood
Carl Leonard
10 Jan 1973

5 January 1973

This technique restricts the image size to be equal to or less than the spacing between the images seen when looking through G_1. Otherwise, various unwanted images will overlap the image of interest.

Another case, where a real image is formed by a hologram, is shown below. Here



a grating can be placed before the image plane so that multiple images appear at O. Grating G_1 is imaged to I_{G_1} where a second grating G_2 is positioned. On axis of this system a point image is formed from all beams of light passing through L_1 and L_2. For a unity magnification telescope arrangement (L_1 and L_2 of equal f.l. separated by distance equal to twice the focal length), spatial frequency should be the same for G_1 and G_2. One or both gratings could be in motion to destroy coherence between adjacent beams or channels.

Other arrangements are possible both as to the positioning of gratings, magnification of the system, and ~~their~~ the spatial frequencies of the gratings.

Juris Upatnieks, 5 January 1973

Read + Understood
Carl Leonard
10 Jan 1973

10 January 1973

Experimental Results – Noise Suppression in Holographic Microimages

The experimental system is described on pages 89 & 90 of this notebook.

Film #6, Exp. 3, dated 29 Dec. 1972
From negative 1-3-6

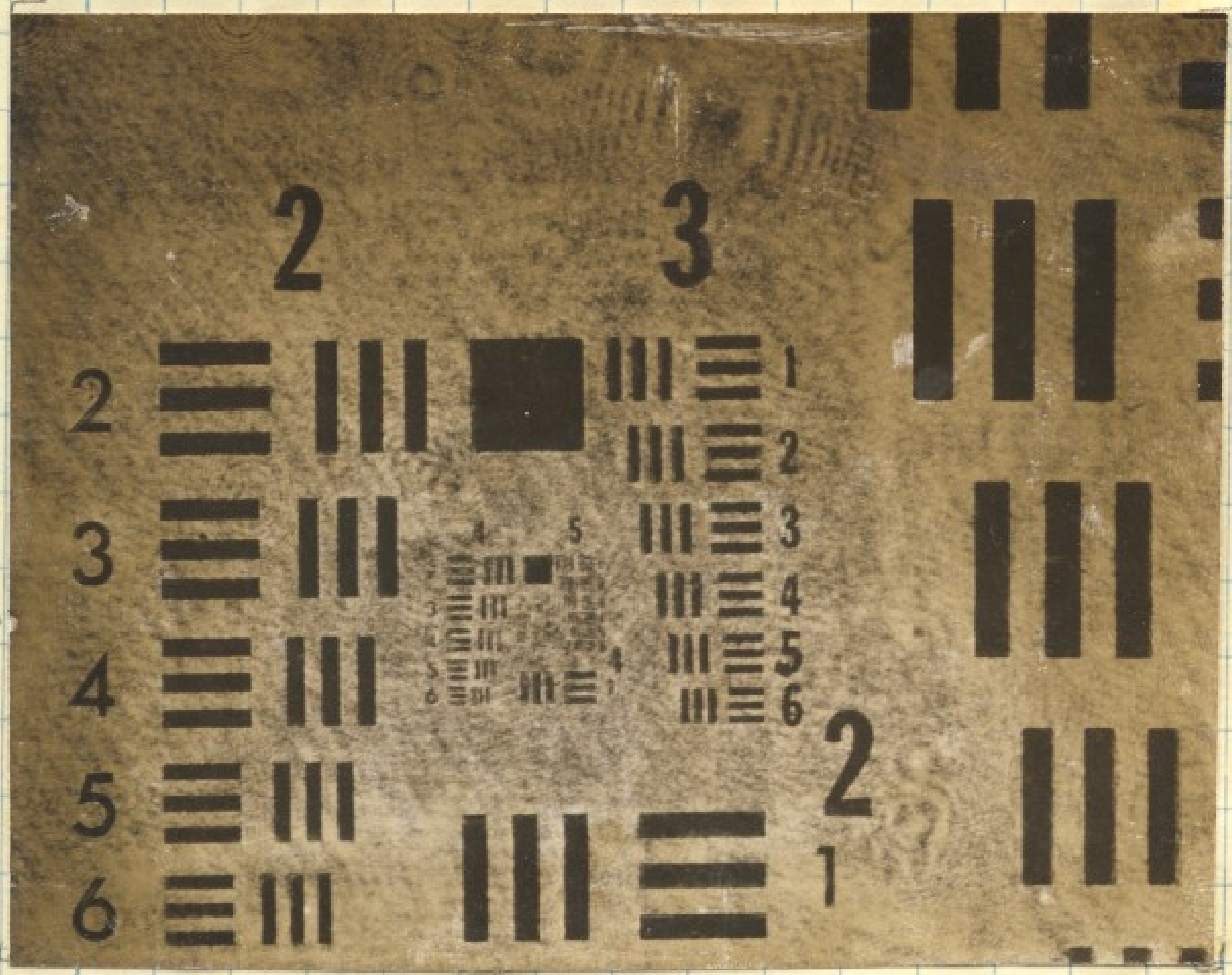


Fig. 1. Hologram reconstruction of the object, a resolution chart, illuminated with ~~a single~~ multiple plane waves and enlarged using a microscope. Coherent noise is visible. Since no grating is used in viewing this, only one beam forms this image.

Film #1, Exp. 5, dated 29 Dec. 1972
From negative 1-5-37

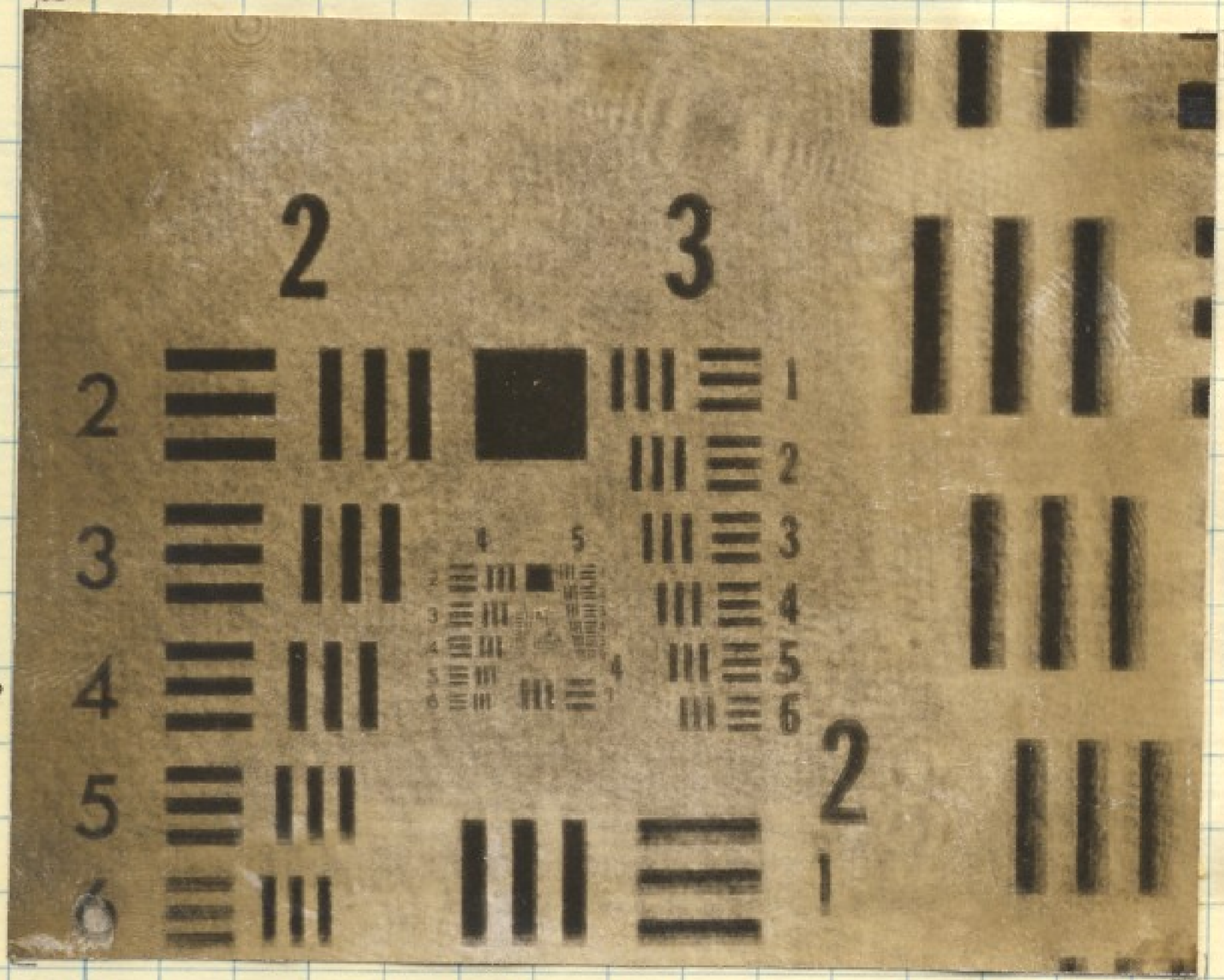


Fig. 2. Reconstructed image, with moving crossed grating in focal plane of microscope. Hologram made with same crossed grating that generated about 9 plane waves. Redundancy ≃ 4. Note decreased contrast of diffraction patterns and improved appearance of image.

Film #2, Exp. 2, dated 29 Dec. 1972
From negative 1-7-9

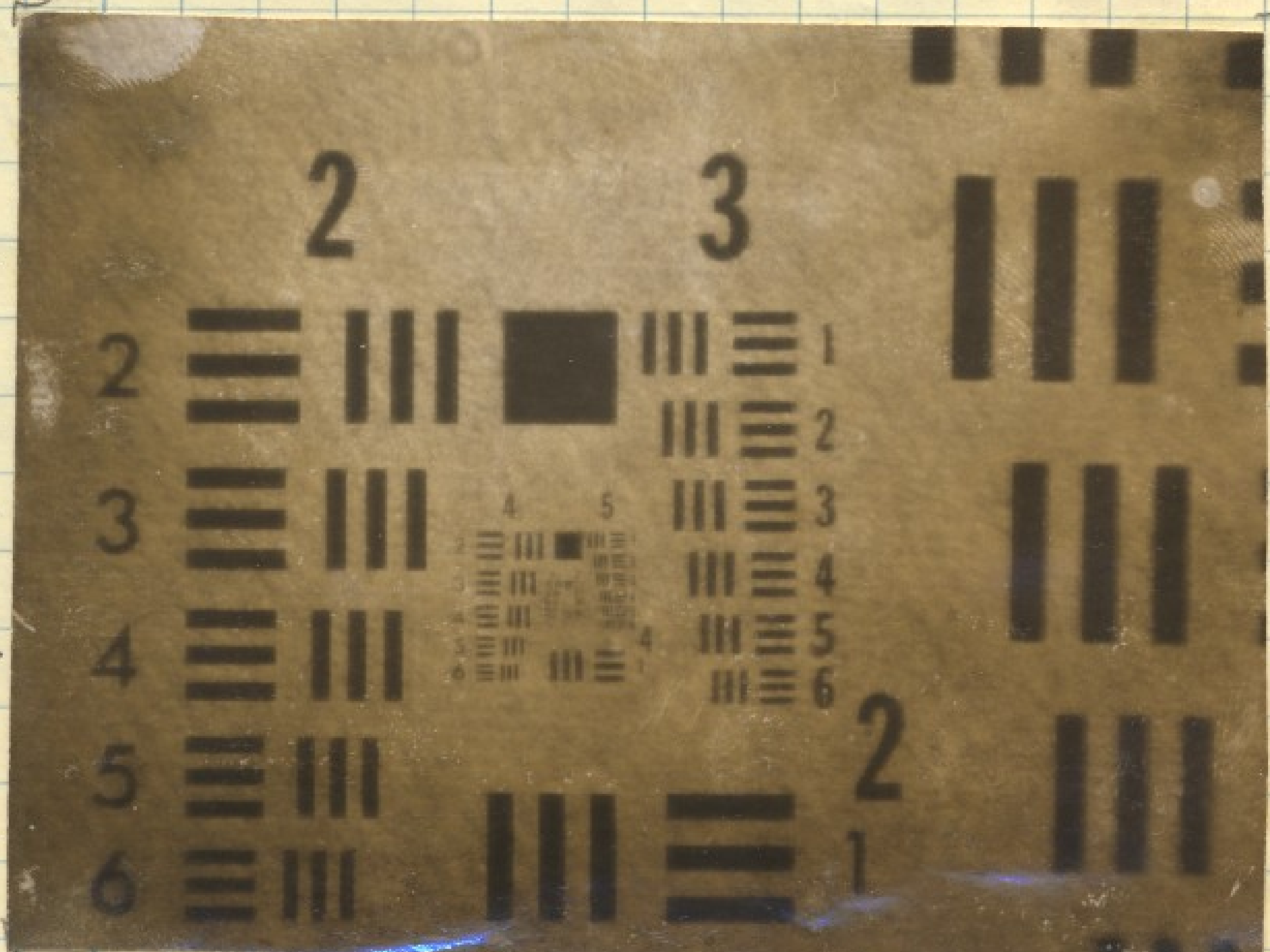


Fig. 3. Reconstructed image, with moving diffuser in the focal plane of the microscope. Same hologram as in Fig. 2 above. Residual fringe patterns were probably caused by multiple reflections within the slide of the resolution target. These fringes exist in the reconstructed image and are not removed by a moving diffuser.

Juris Upatnieks, 10 January 1973

Read & Understood, Carl Leonard, 10 Jan 1973

10 January 1973.

Film #1, Exp. 4, dated 29 Dec. 1972
From negative 1-4-44

Fig. 4. Same as Fig. 2. except that grating is stationary in the reconstruction process. The visible pattern is caused by various wave fronts that enter the microscope. The fringe spacing depends on the angular alignment of crossed grating and their frequency.

Film #2, Exp. 3, dated 29 Dec. 1972
From negative 2-1-1

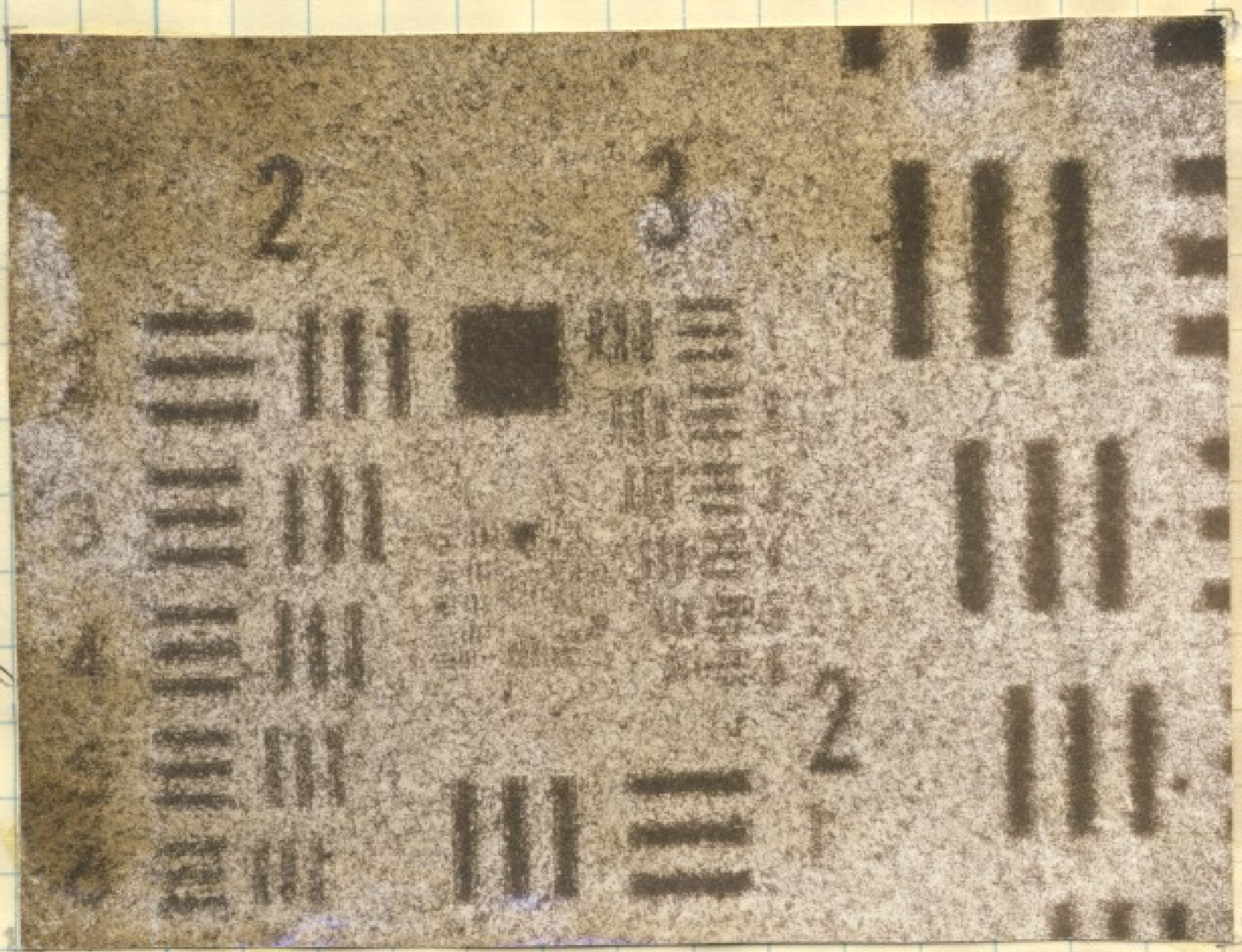


Fig. 5. Same as Fig. 3 except the diffuser is stationary. The diffuser used here is a piece of sand-blasted glass which has relatively coarse structure.

Film #4, Exp. 1, dated 29 Dec. 1972
From negative 3-1-26

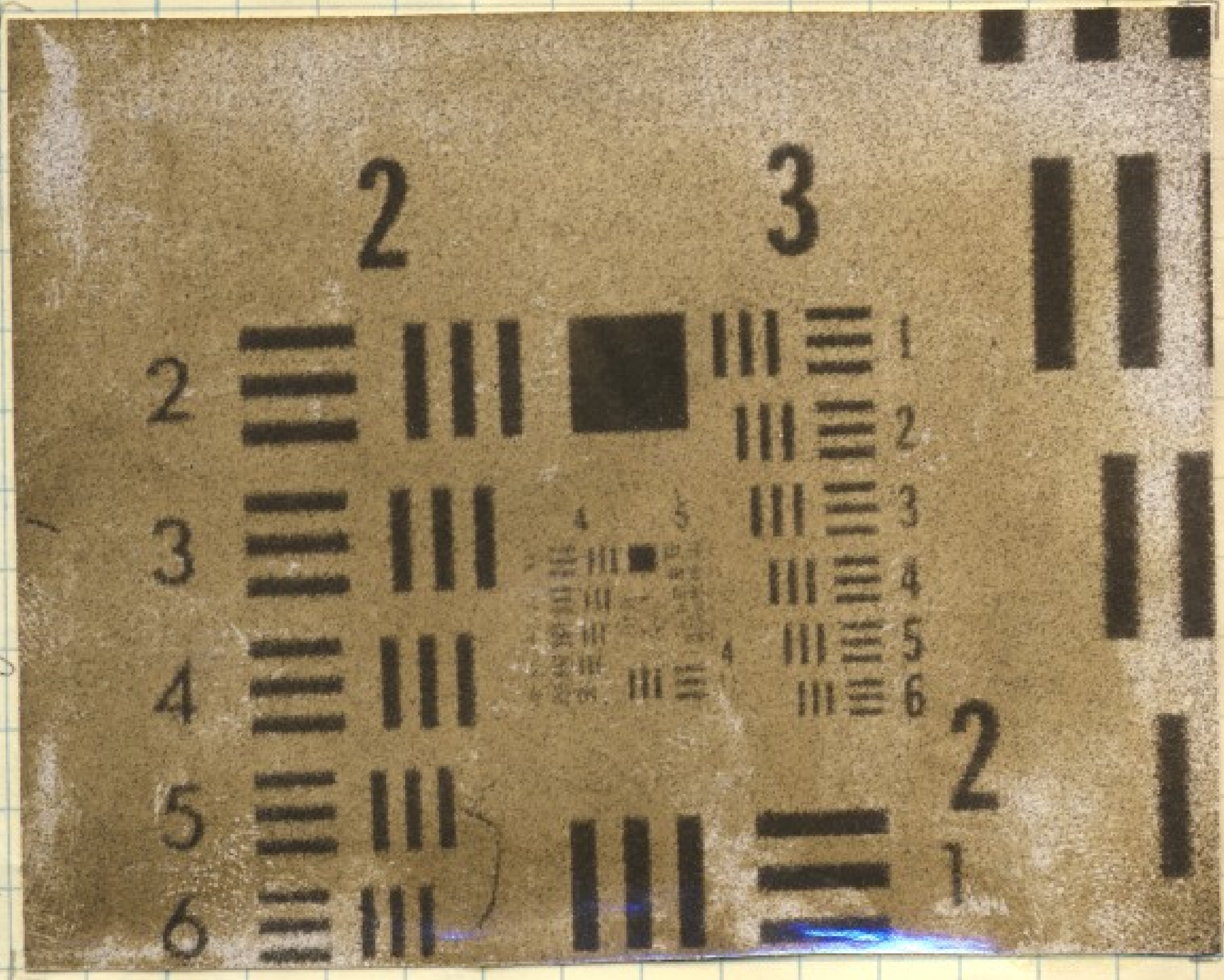


Fig. 6. Reconstructed image from a hologram. The object was illuminated with diffuse light. A stationary, crossed phase grating is in the focal plane of the microscope. Note the dust particle on grating surface visible to the right of bar groups 2-5 and 2-6.

Juris Upatnieks
10 January 1973

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Carl Leonard 10 Jan 1973

10 January 1973

Film #3, Exp. 3, dated 29 Dec. 1972
From film negative 2-7-15

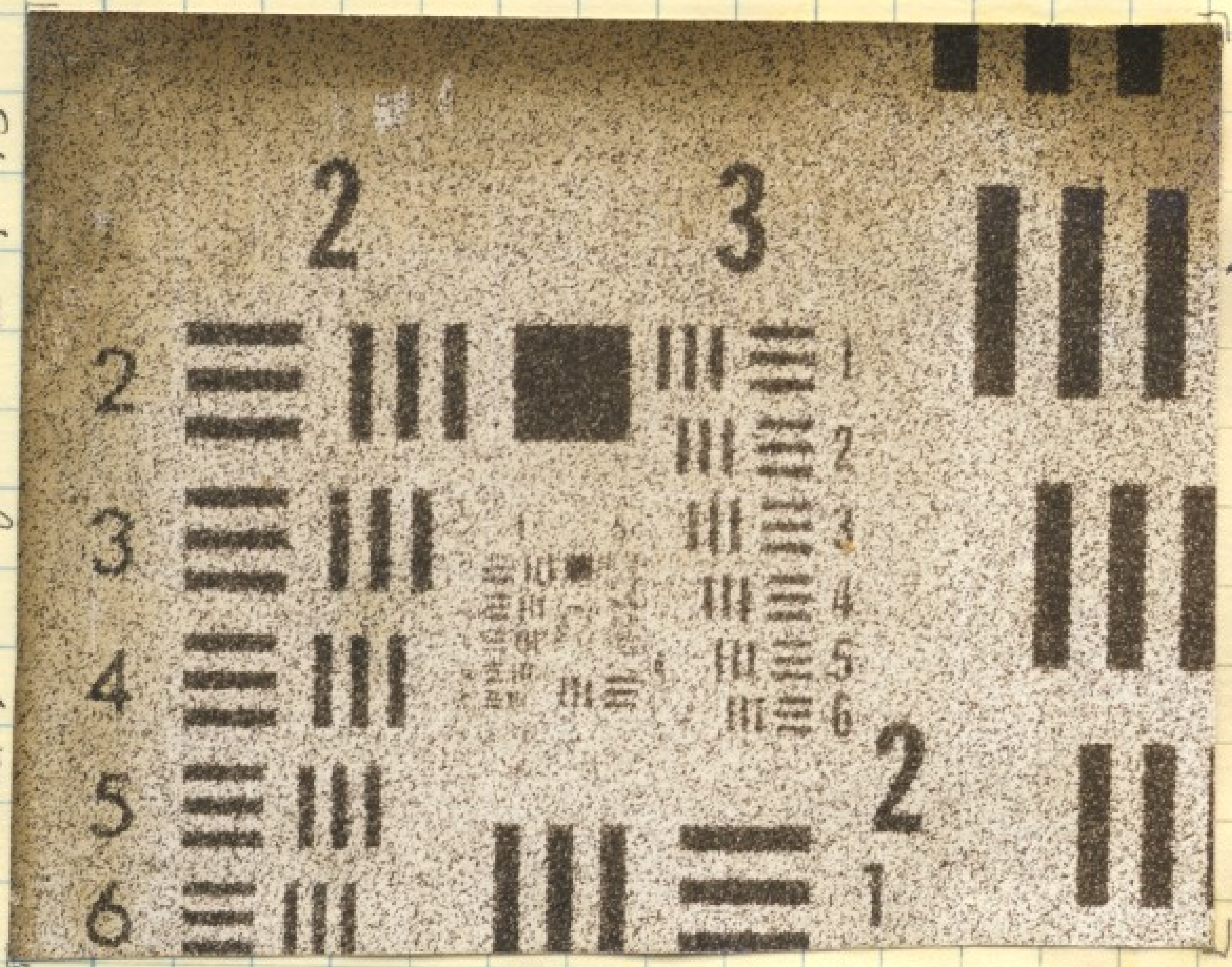

Fig. 8. To photograph this figure, a circular aperture 3mm diam. was placed in front of the 48mm f.l. microscope objective. The hologram is same as used in Fig. 6. No diffuser or grating is in the focal plane of the microscope.

Film #3, Exp. 2, dated 29 Dec. 1972
From negative 2-6-20

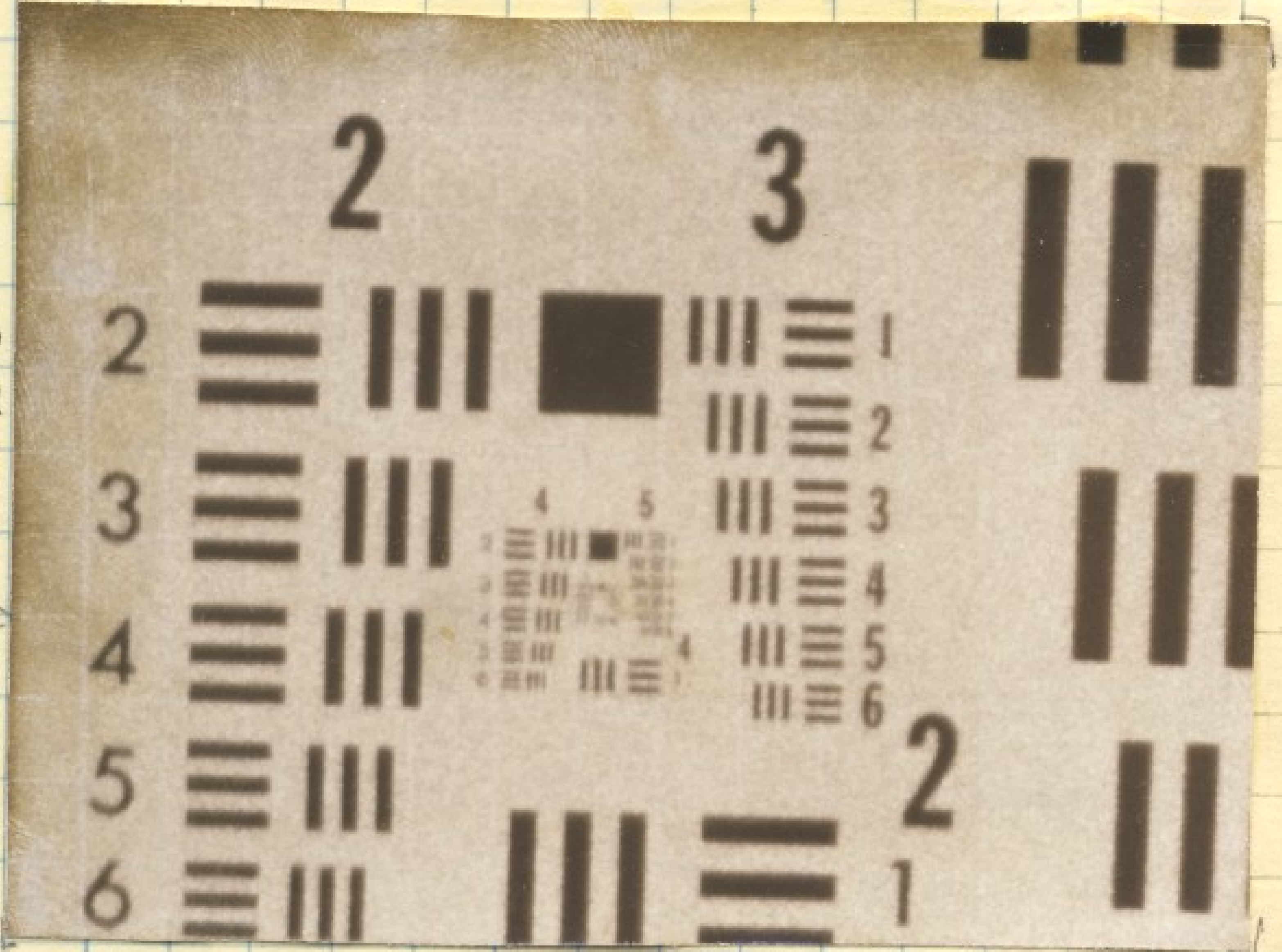

Fig. 9. Same as Fig. 8 above except that a rotating diffuser is placed in the focal plane of the microscope. Note improved resolution and almost complete absence of granularity.

Film #4, Exp. 2, dated 29 Dec. 1972
From negative 3-2-22

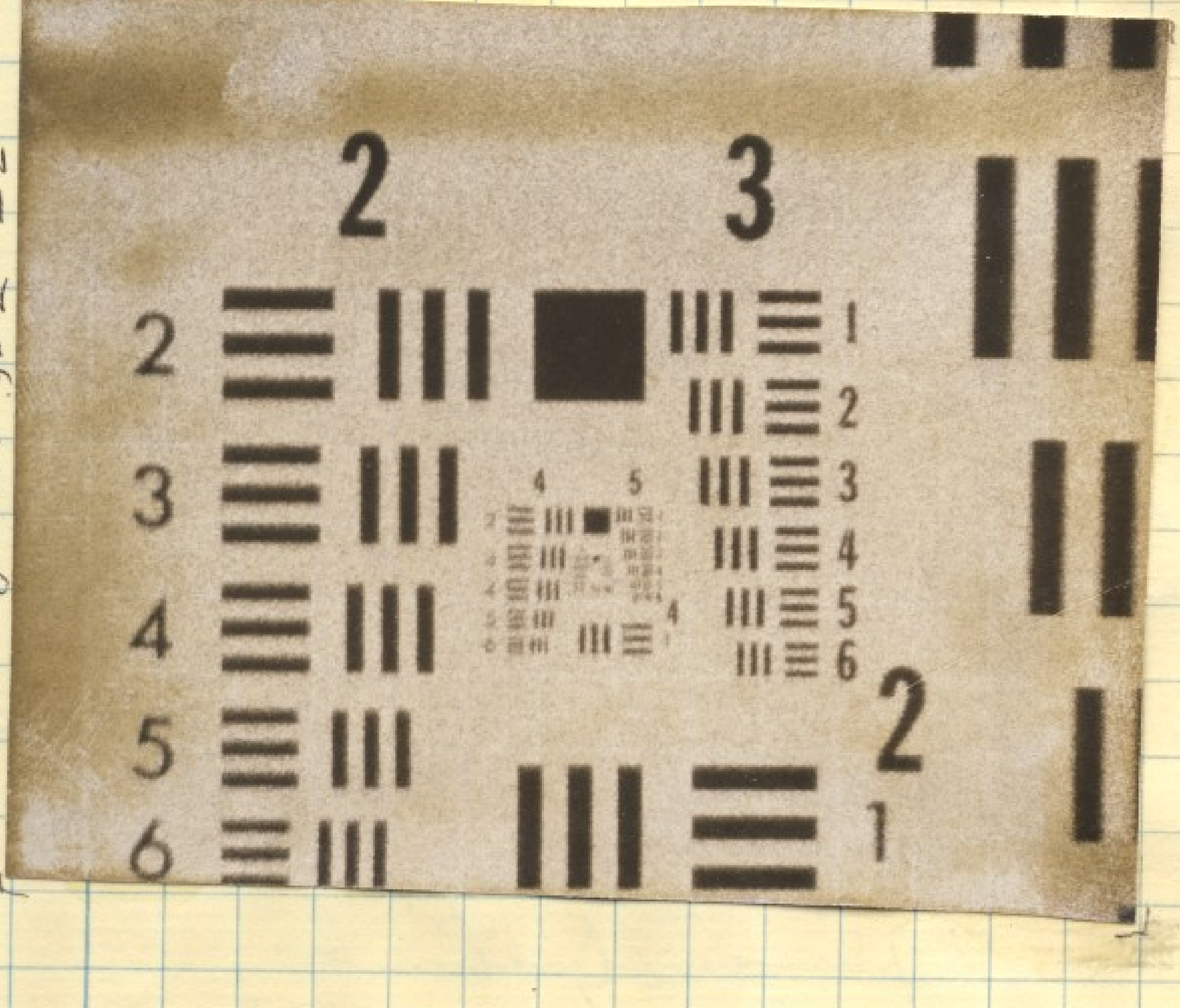

Fig. 7. Same as Fig. 6 except that the crossed grating is moving. Note the absence of dust particle. Redundancy introduced by the crossed grating is 4 or more. Reduction in granularity can be seen.

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10 January 1973

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Film #2, Exp. 6, dated 29 Dec. 1972
From negative 2-4-30

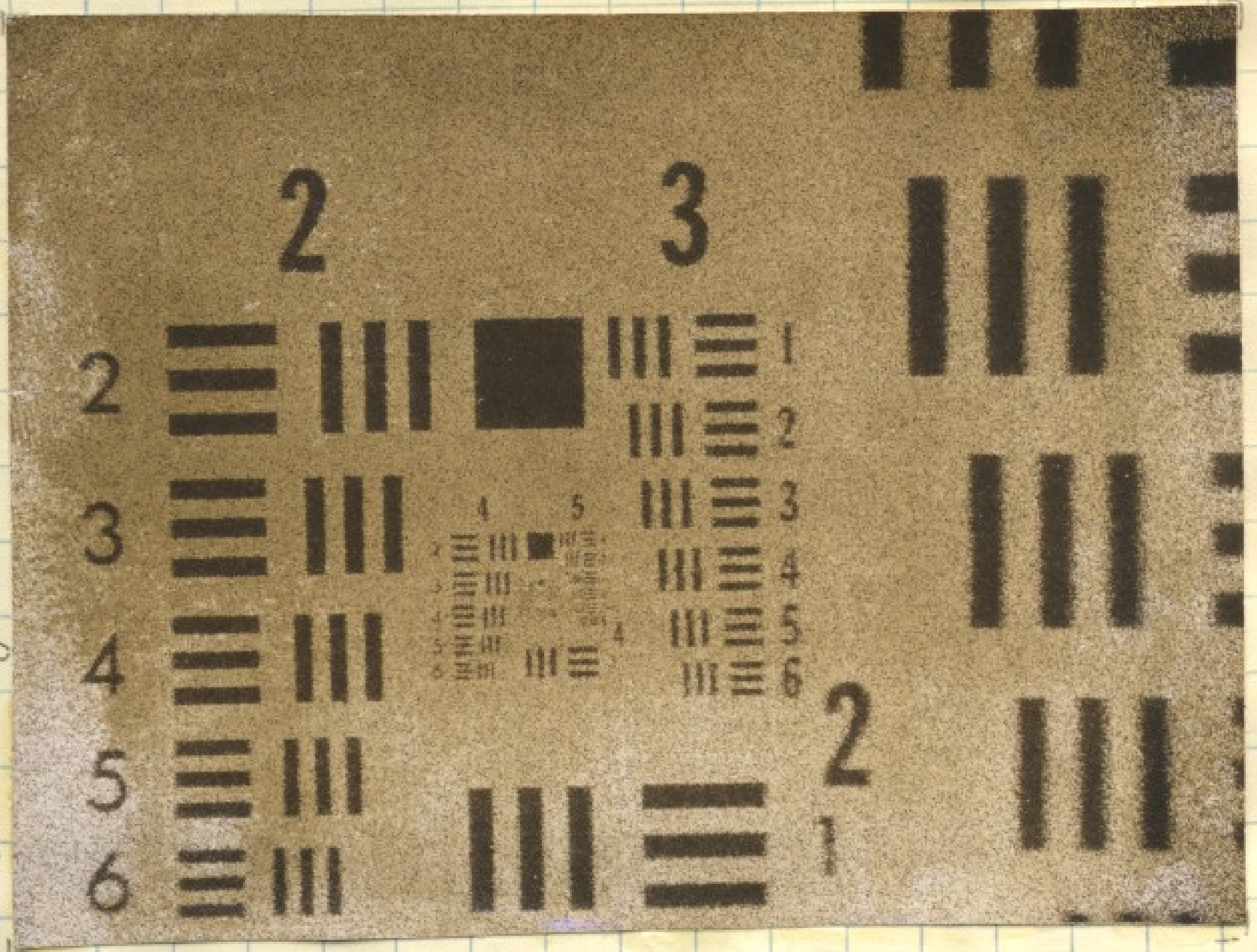

Fig. 10. Same as Fig. 6 except nothing is in the focal plane of the microscope.

Film #2, Exp. 3, dated 29 Dec. 1972
From negative 2-3-35

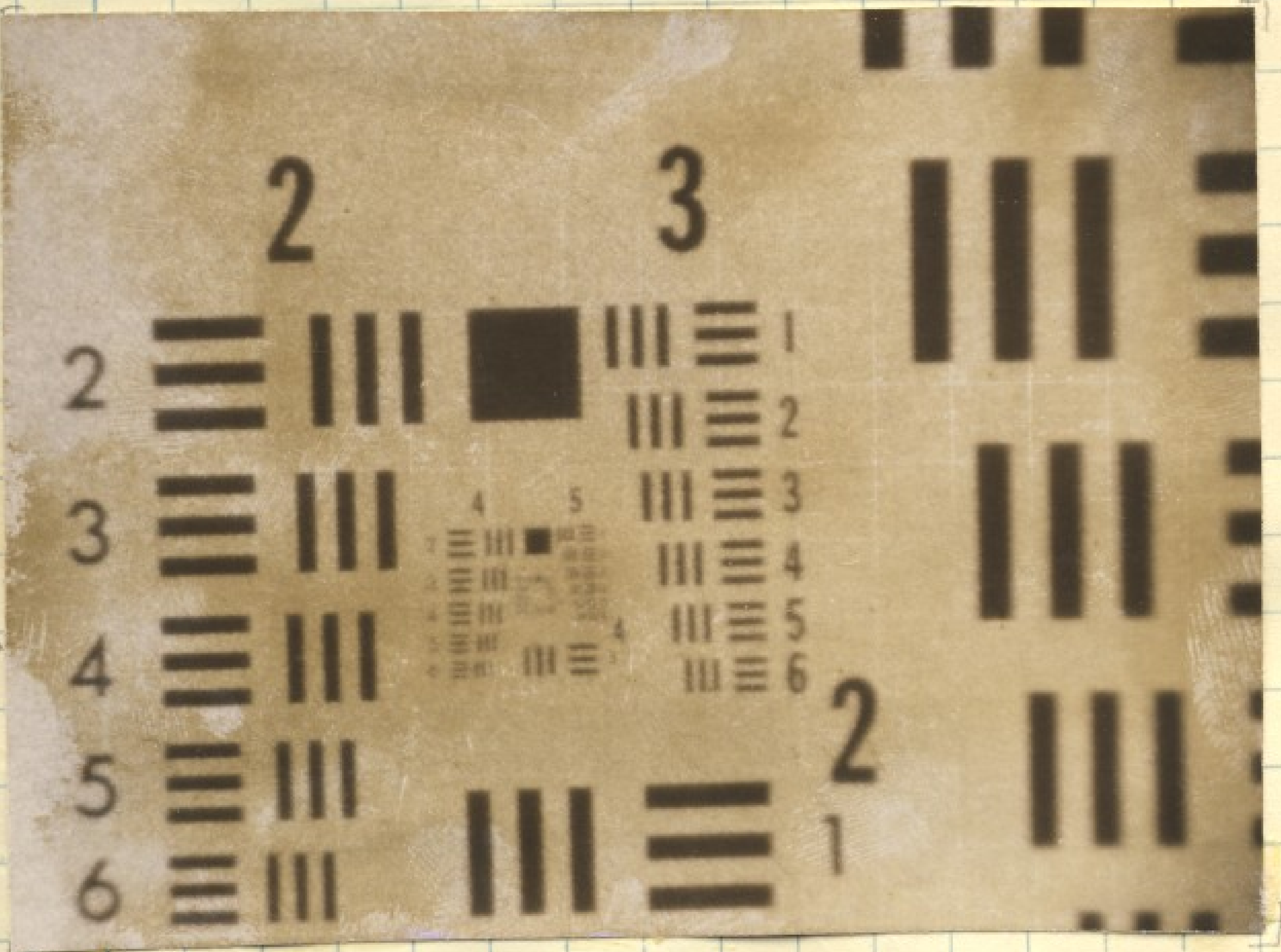

Fig. 11. Same as Fig. 6 except a rotating diffuser is in the focal plane of the microscope.

The experimental work shown here was done primarily by Byung Jin Chang. The work was done during December 1972 and the results were photographed with a 35 mm camera on 29 Dec. 1972.

The various films are listed on the next page:

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Film storage Page #	Row #	Film #	Exp. series #	Description
1	1	1	1	Multiple beam hologr., stationary one-dim. grating
"	2	1	2	" " ", moving one-dim. grating
1	3	1	3	" " ", no grating
1	4	1	4	" " ", stationary crossed grating
1	5	1	5	" " " moving crossed grating
1	6	2	1	" " ", moving crossed grating not in focus
1	7	2	2	" " ", moving crossed grating in focus
2	1	2	3	" " ", stationary diffuser
2	2	2	4	" " ", moving crossed grating out of position (focus)
2	3	2	5	Diffuse hologram, moving diffuser
2	4	2	6	" ", no diffuser
2	5	2	7	" ", moving diffuser
2	6	3	1	" ", 3mm aperture objective, rotating diffuser
2	7	3	3	" ", 3mm aperture objective, no diffuser
3	1	4	1	" ", stationary crossed grating
3	2	4	2	" ", moving crossed grating.

Juris Upatnieks, 10 January 1973

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Carl Leonard 10 Jan 1973

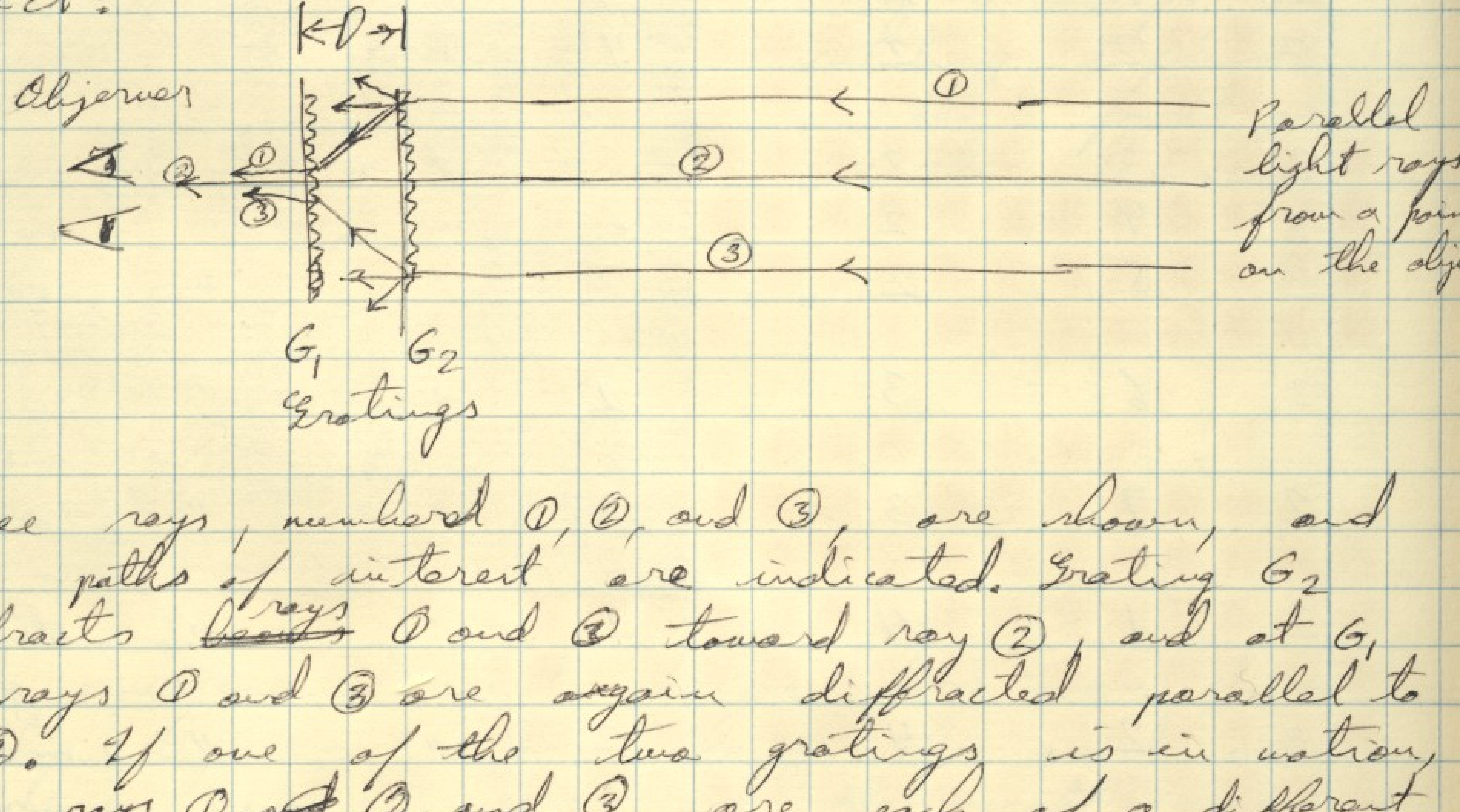
~~Jan~~

21 March 1973

A Technique for Reducing Speckle Pattern Contrast when Observing Coherently Illuminated Objects.

Whenever a diffusely reflecting object is illuminated with coherent light, the object appears to have speckle-like surface. A technique is proposed here for reducing or eliminating this speckle-like appearance.

Consider an object located at infinity. The light rays arriving at the observer are parallel to each other, originating from a point on the object. Two diffraction gratings having equal spatial frequency are placed at distance D from each other and are located somewhere between the observer and the object:



Three rays, numbered 1, 2, and 3, are shown, and their paths of interest are indicated. Grating G_2 diffracts ~~beams~~ rays 1 and 3 toward ray 2, and at G_1 ~~the~~ rays 1 and 3 are again diffracted parallel to ray 2. If one of the two gratings is in motion, then rays 1, ~~and~~ 2, and 3 are each of a different temporal frequency and therefore are temporally incoherent with each other. Thus, three mutually incoherent rays are produced along the direction of, say, ray 2. If the spacing between the three rays is greater than the aperture of the pupil, then three uncorrelated speckle patterns are incoherent

Juris Upatnieks, 21 March 1973

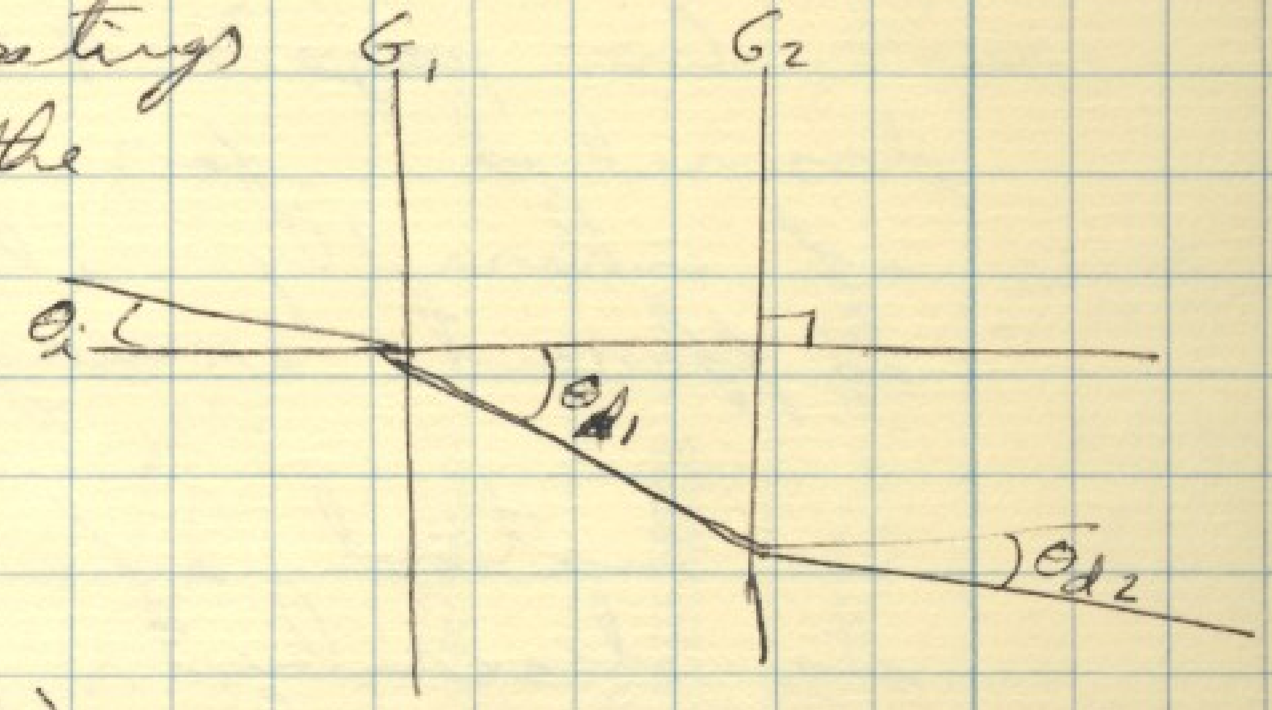
This has been read and understood by
Ralph H. Mitchel, March 21, 1973
1204 Arella Blvd
Ann Arbor, Mich

Read + Understood by Carl P. Leonard
3 May 1973

21 March 1973

added by this technique and a reduction in speckle contrast is achieved. No loss of resolution is introduced by this technique.

The geometry of the two gratings is shown at right. If the period of the gratings is d, then



$$d\,(-\sin\theta_i + \sin\theta_{d1}) = \lambda$$

and

$$d\,(\sin\theta_{d1} - \sin\theta_{d2}) = \lambda$$

Rewriting, we get

$$\sin\theta_i = \sin\theta_{d1} - \frac{\lambda}{d}$$

$$\sin\theta_{d2} = \sin\theta_{d1} - \frac{\lambda}{d}$$

and therfore $\theta_i = \theta_{d2}$. Thus, the rays remain parallel after ~~the~~ passing through G_1 and G_2 regardless of the wavelength of light, the spatial frequency of the gratings, and the angle between the gratings and the incident ray, angle θ_i.

The distance D determines the displacement between adjacent rays, ① and ② and ③, that are colinear after G_1. The displacement is also a function of the grating frequency. While three rays are shown in the figures, ~~other~~ diffracted orders can be utilized. A crossed set of gratings could be used to obtain two-dimensional incoherent addition.

While G_1 and G_2 were assumed to have equal spatial frequencies, other combinations are possible. If the object to be observed is near the observer, sligthly different spatial frequencies for G_1 and G_2 can give an improved appearance of the image. Also, the gratings could be generated by ultrasonic waves in an appropriate medium.

Juris Upatnieks
21 March 1973.

Note: This concept was disclosed to E.N. Leith on 20 March 1973.

this has been read + understood by
Ralph N. Mitchell, March 21, 1973
1204 Arella Blvd
Ann Arbor, Mich

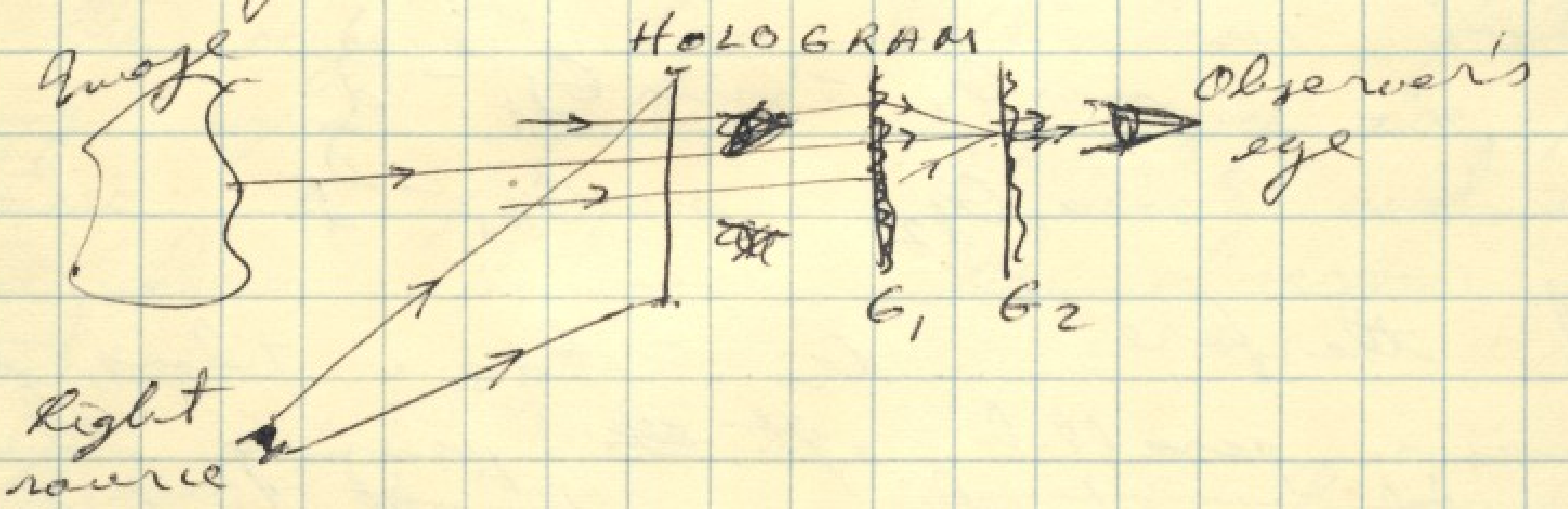
Read & Understood by
Carl D. Leonard
3 May 1973

27 April 1973

Speckle reduction of coherently illuminated objects.

On pages 98 and 99 a technique was described for reducing the speckle contrast of coherently illuminated objects. A slightly different arrangement is described here.

Instead of moving one of the gratings as described previously, a similar effect can be achieved by using a light source with limited spatial coherence. Consider the case of a hologram as shown below:



If the source size is such that the coherence area at G_1 is less than the separation between any two adjacent rays, then gratings G_1 and G_2 will cause several spatially incoherent images to merge. Thus, the same effect will be achieved as with a coherent source and a grating moving. By proper design, the light from any one beam can ~~be~~ remain coherent. Thus, no loss of resolution will result from using a slightly incoherent source.

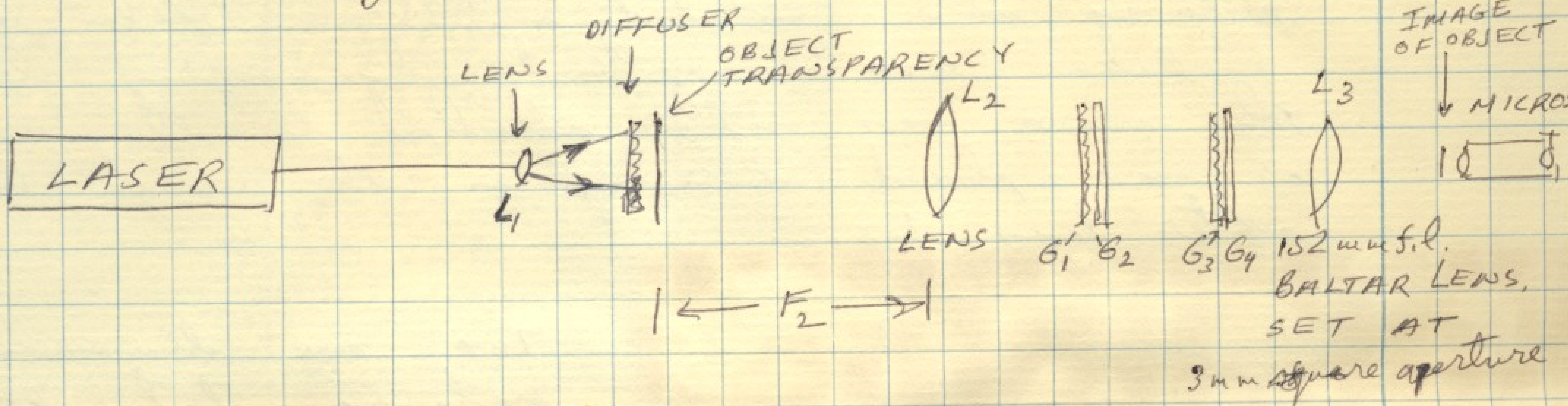
Juris Upatnieks
27 April 1973.

Read & Understood
Carl D. Leonard
3 May 1973

31 July 1973

Experiment to demonstrate speckle reduction of coherently illuminated objects.

An experiment was set up as shown in the diagram below:



A stationary diffuser is placed in the expanded laser beam. An object, in the form of a transparent cross, is placed after it. Lens L_2 is one focal length from the object to place the object at infinity as viewed from the right of L_2. G_1 and G_2 are two gratings at right angle to each other, and so are G_3 and G_4. L_3 is an imaging lens that forms the image of the object, and a microscope is used to observe the image.

When one looks in the microscope, the image of the cross is seen, having a coarse speckle pattern. When gratings G_3 and G_4 are moved, the speckle pattern is greatly reduced. The experiment was performed by Byung J. Chang.

Juris Upatnieks
31 July 1973.

Read & Understood
Byung J. Chang
31 July 1973

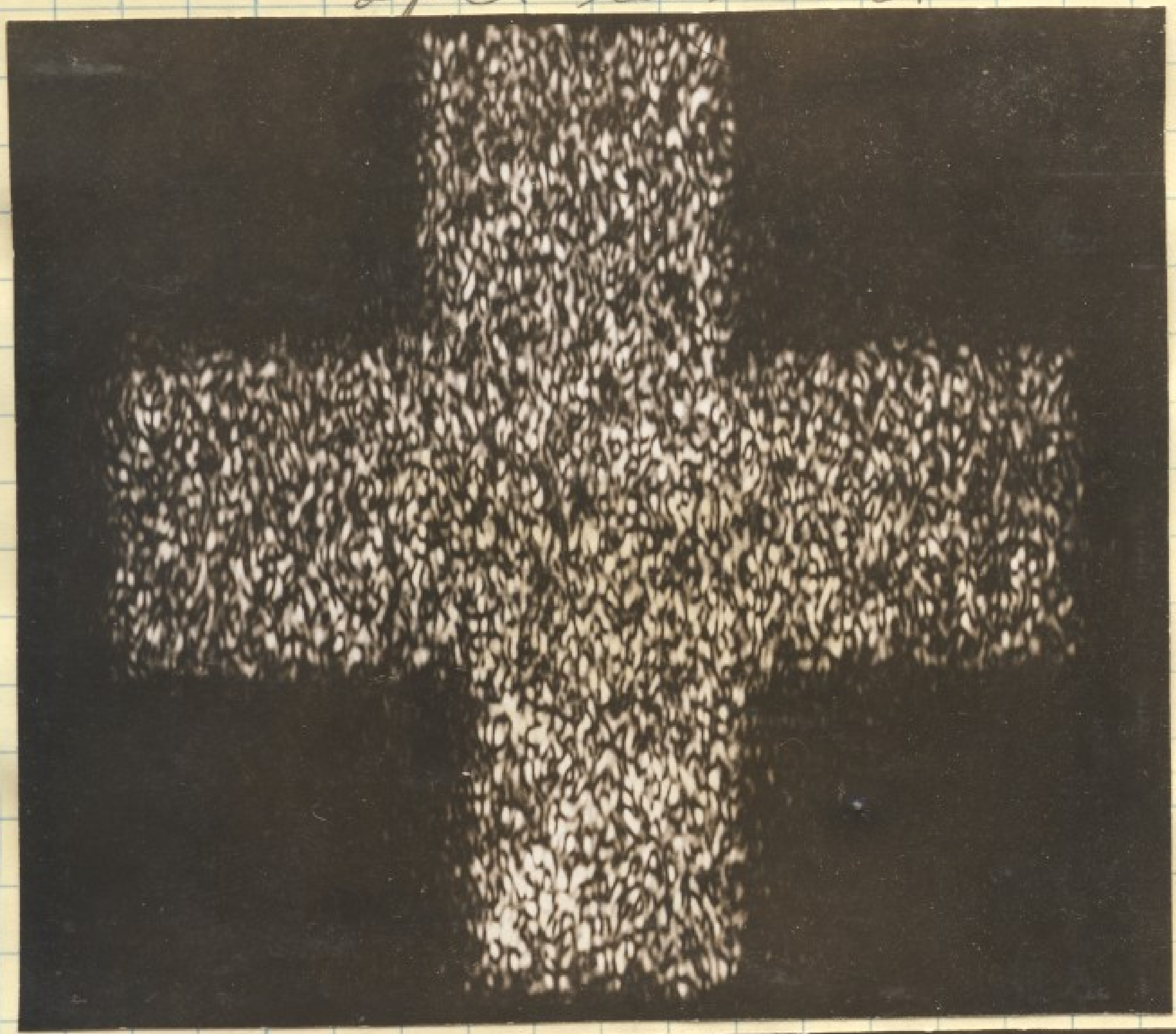
Observed, Read, and Understood
Ralph H. Mitchel
7/31/73

Observed Read and understood
Robert W. Lewis
7/31/73

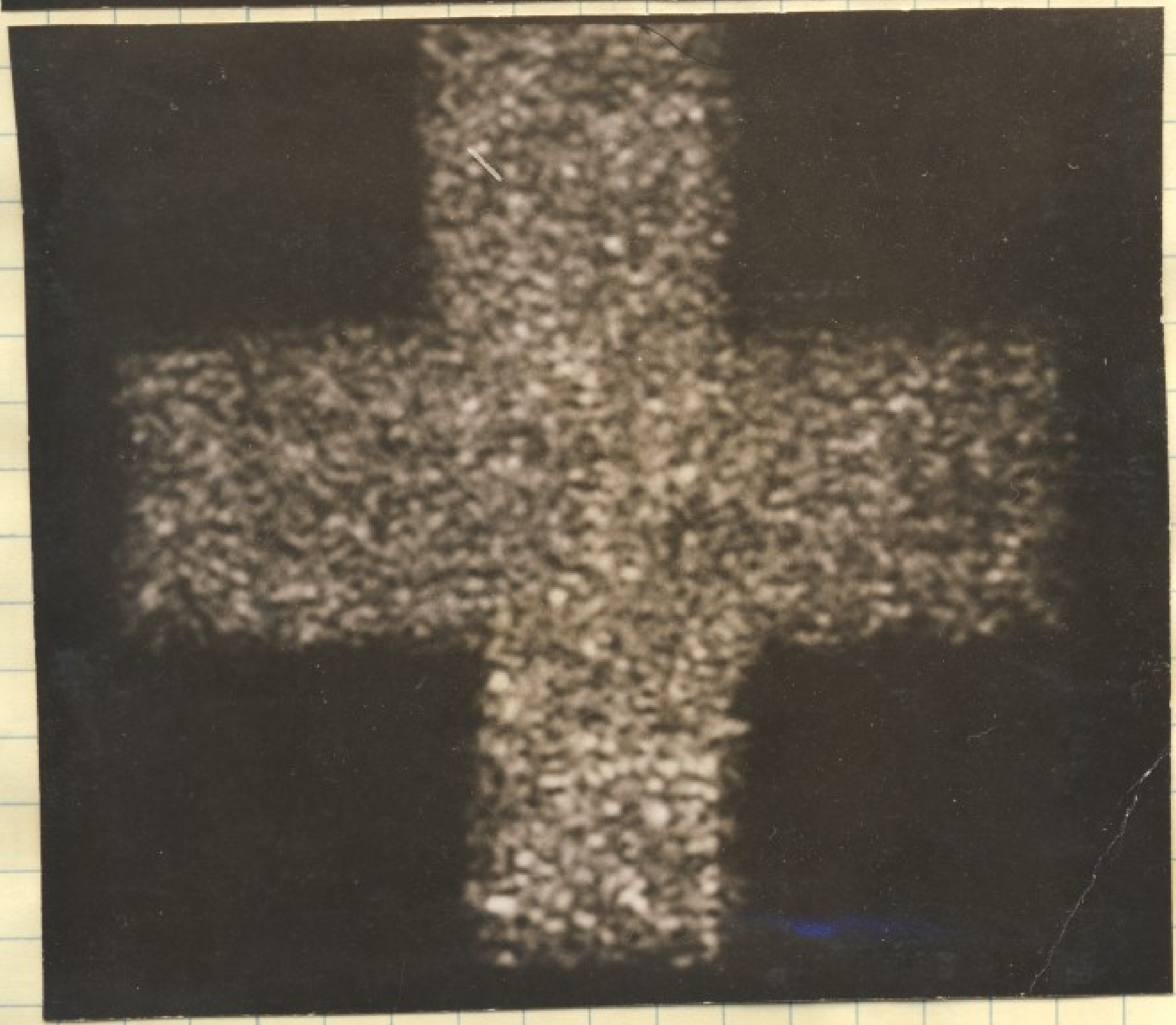
15 August 1973.

Experimental Results of Speckle reduction of Coherent Images or objects.

The photographs shown on the following pages were made with the optical system shown on page 101 of this notebook. The pictures were recorded on 35 mm film using a Nikon camera without its imaging lens. The camera was either attached to the microscope or was placed directly in the image plane after lens L3.



Two one-dimensional gratings stationary, all beams coherent. Gratings G_1 and G_3 (see p. 101) in place.



Two one-dimensional gratings, one is moving rendering the various beams mutually incoherent. Gratings G_1 and G_3 in pla[ce]. Speckle contrast is redu[ced] from that above.

Juris Upatnieks, 15 Aug. 19[73]

Read & Understood
Carl Leonard
20 Aug 1973

15 August 1973

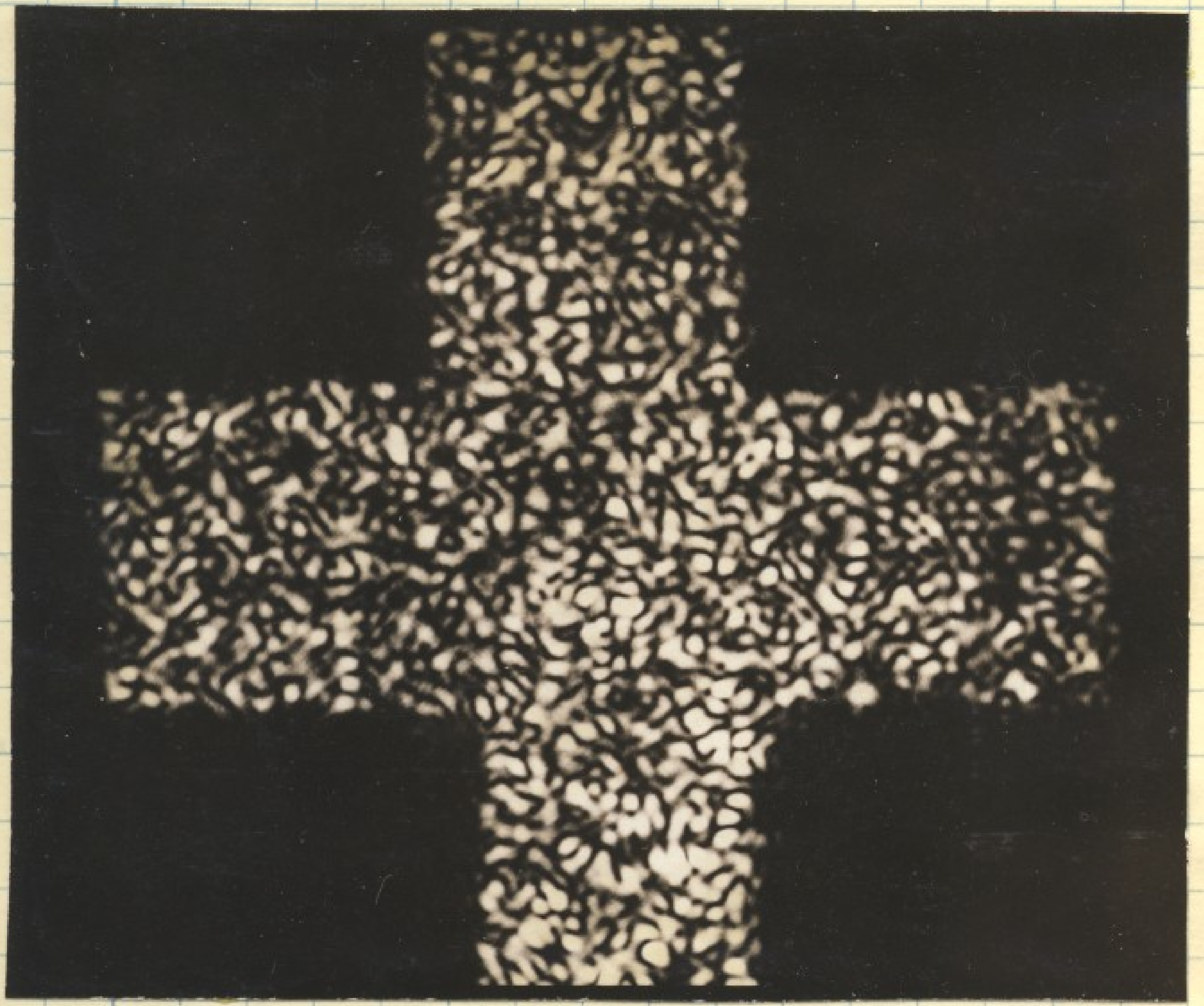
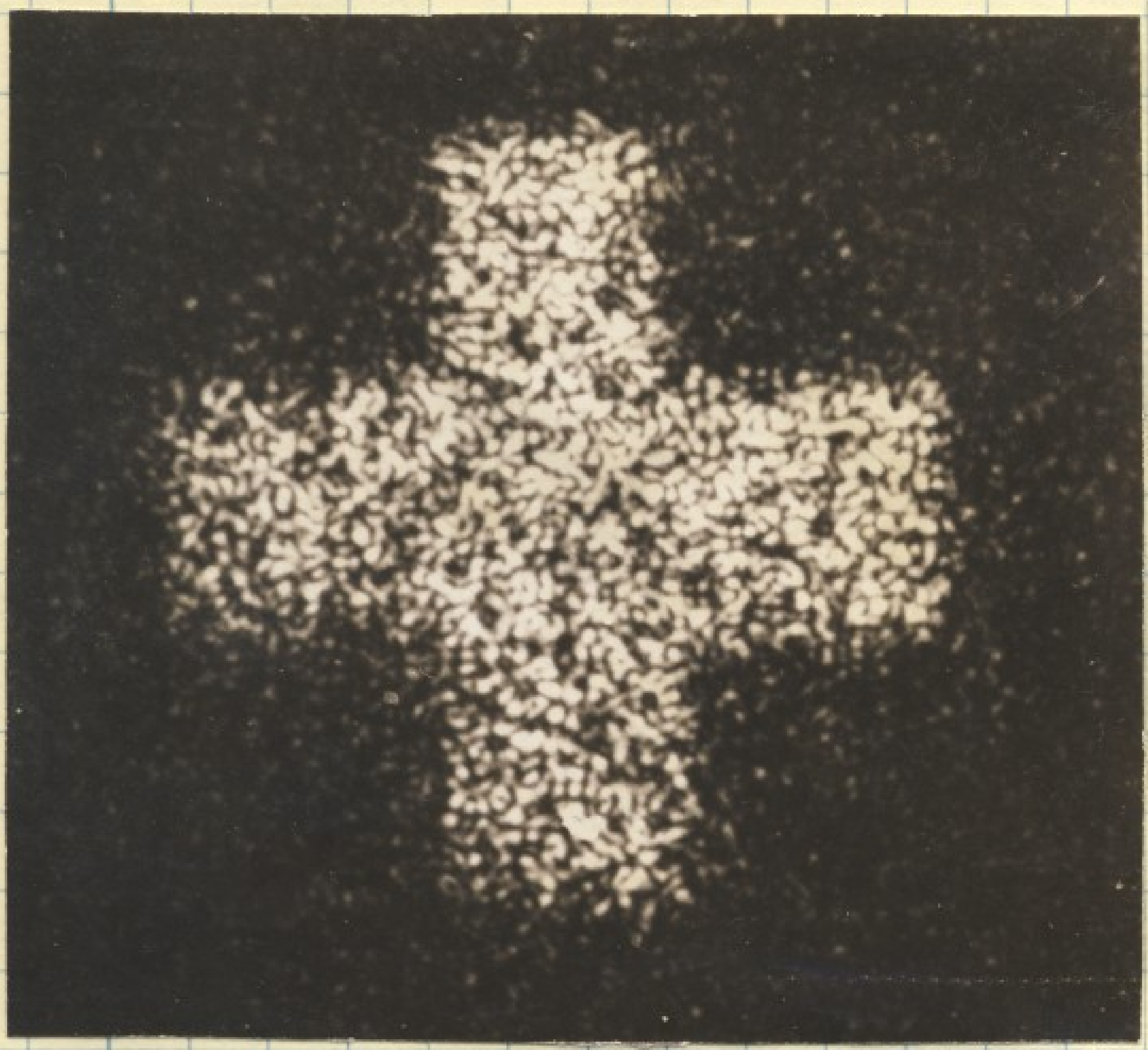


Image without any gratings in the system.



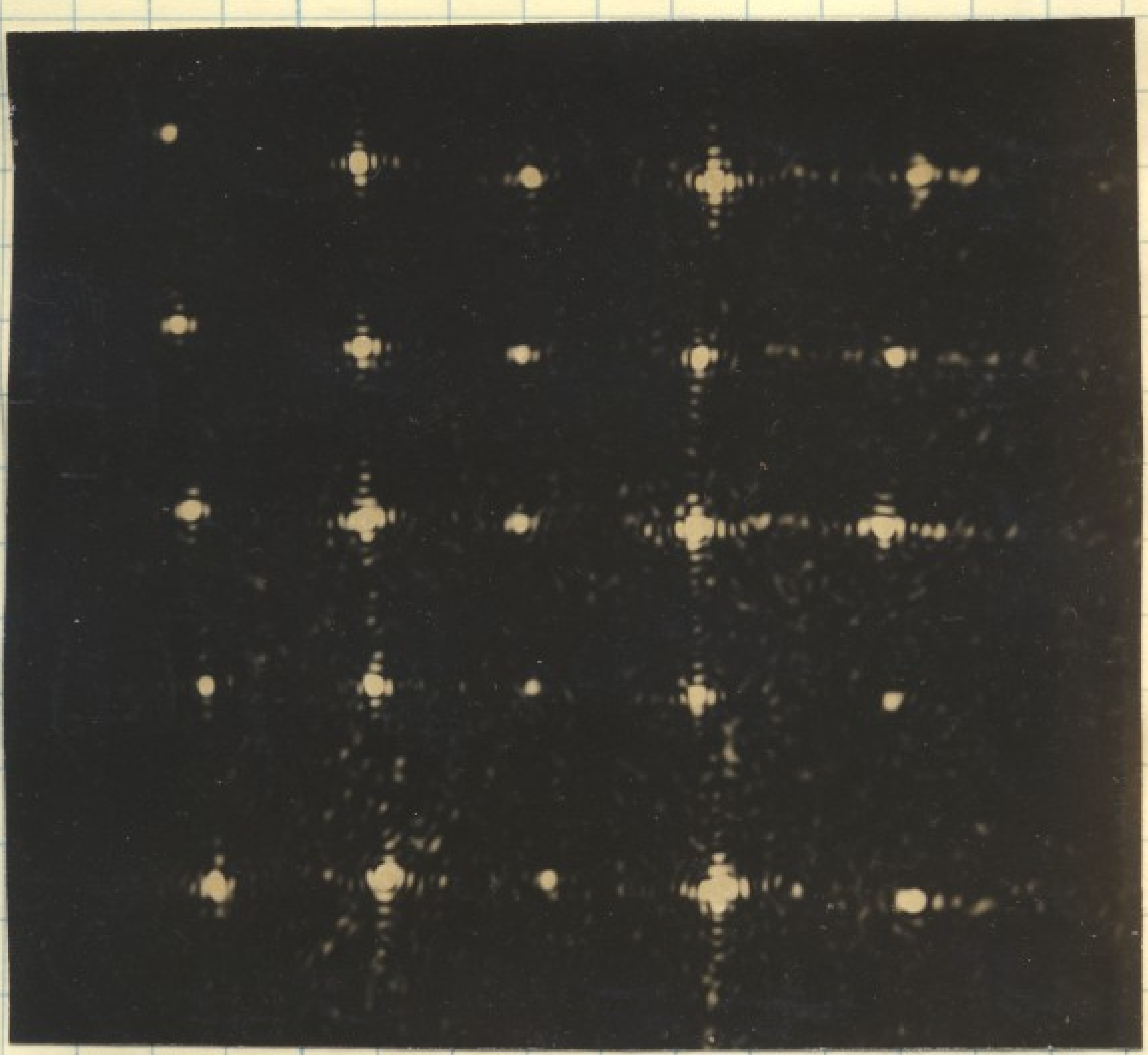
Two two-dimensional gratings in place, both are stationary rendering all beams mutually coherent. The two-dimensional grating is made up of two one-dimensional gratings placed at right angles to each other.

Same as above but one grating in motion rendering all beams mutually incoherent.

Juris Upatnieks, 15 August 1973

Read + Understood
Carl Leonard
20 Aug 1973

15 August 1973.



Spectrum of the two two-dimensional gratings in place. To make this picture, the diffuser and object were removed from the system shown on p. 101. The point image is not at infinity (not collimated by lens L2) causing the various diffracted beams to be displaced from each other in angular position.

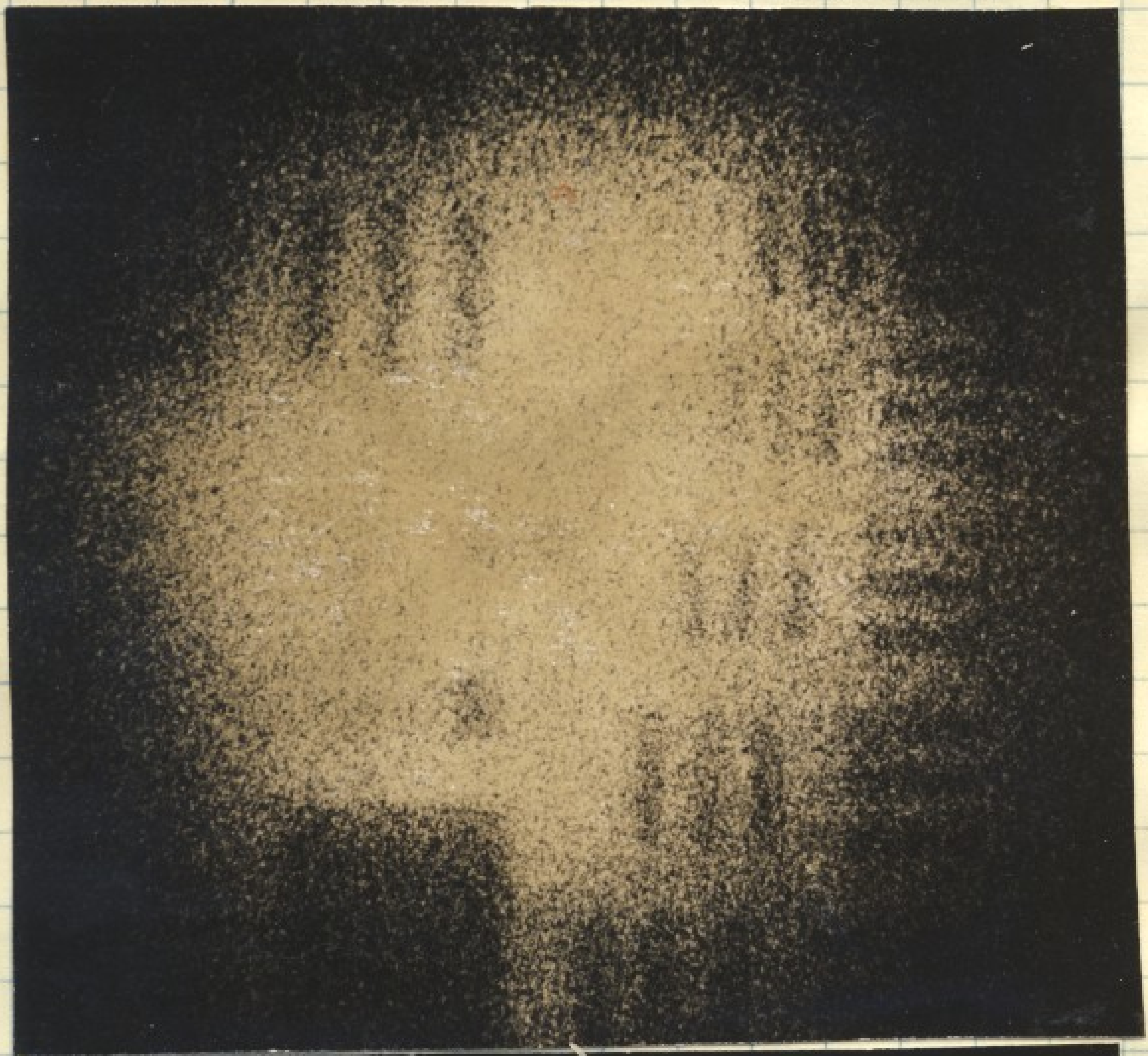


Image through two two-dimensional gratings, all stationary and all beams mutually coherent.

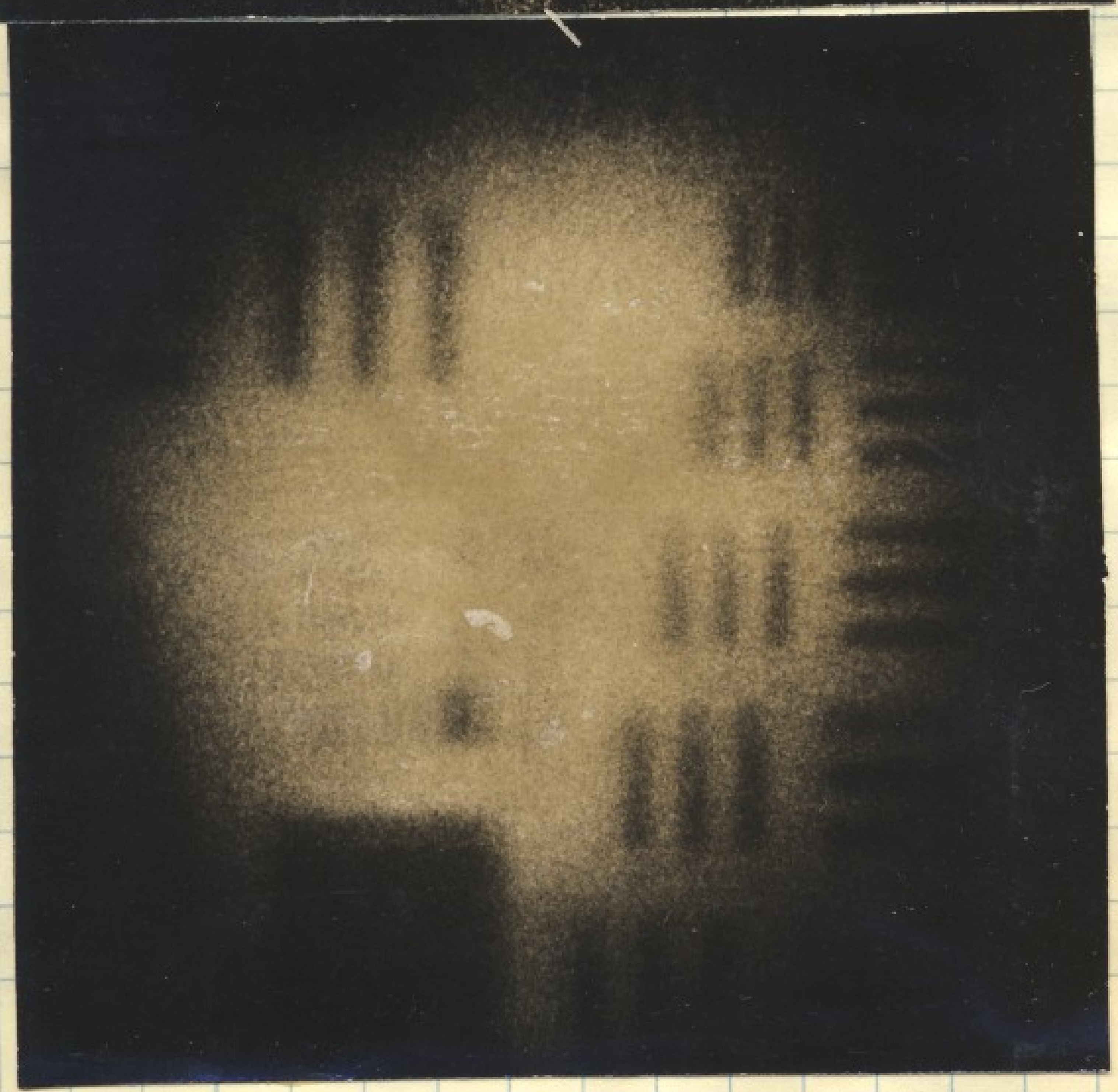
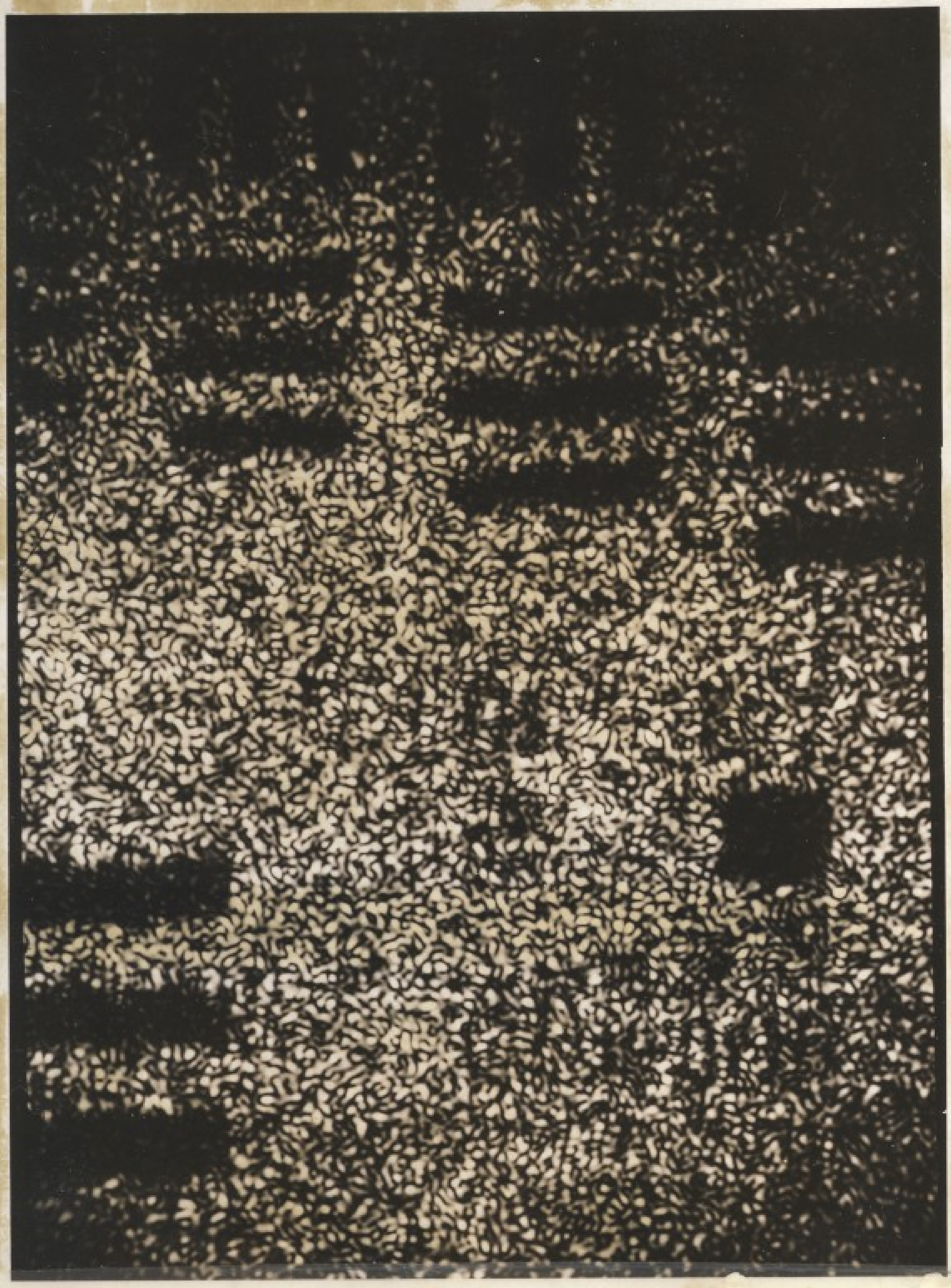


Image through two two-dimensional gratings, one moving, all beams mutually incoherent. Speckle contrast is reduced as compared to the photograph above.

Juris Upatnieks, August 15, 1973

Read + Understood
Carl Leonard 20 Aug 1973

15 August 1973



Imaged through two one-dimensional gratings, G_1 and G_3 on p. 101, all beams mutually coherent.

Imaged through two one-dimensional gratings, one grating moving, all beams mutually incoherent. Speckle contrast is reduced from that above.

Juris Upatnieks, August 15, 1973.

Read + Understood
Carl Leonard
20 Aug 1973

4 December 1973

Three-Dimensional Light Line Display.

A display device can be constructed in which ~~the~~ a narrow beam of light appears to originate near a glass plate (hologram) and to extend to infinity or any arbitrary distance. Such lines appear very realistic and can be useful for a variety of applications. Some uses of a three-dimensional light line are:

1) Aircraft heads-up displays
   (a) To indicate true heading of aircraft
   (b) To indicate aim of a weapon
   (c) To indicate direction of a target that is either visible or invisible due to the distance to it.

2) Sight for various weapons
   (a) For automatic wheapons (machineguns, anti-aircraft guns, etc).
   (b) Vehicle-mounted weapons (tanks, armored personnel carriers, trucks, etc.)
   (c) Helicopter-mounted weapons
   (d) For small patrol boats

3) True heading indicator for ships

4) Industrial applications
   (a) Alignment aid for assembly of parts or components
   (b) Non-contact measurement

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23 Jan 1974

Juris Upatnieks
4 December 1973

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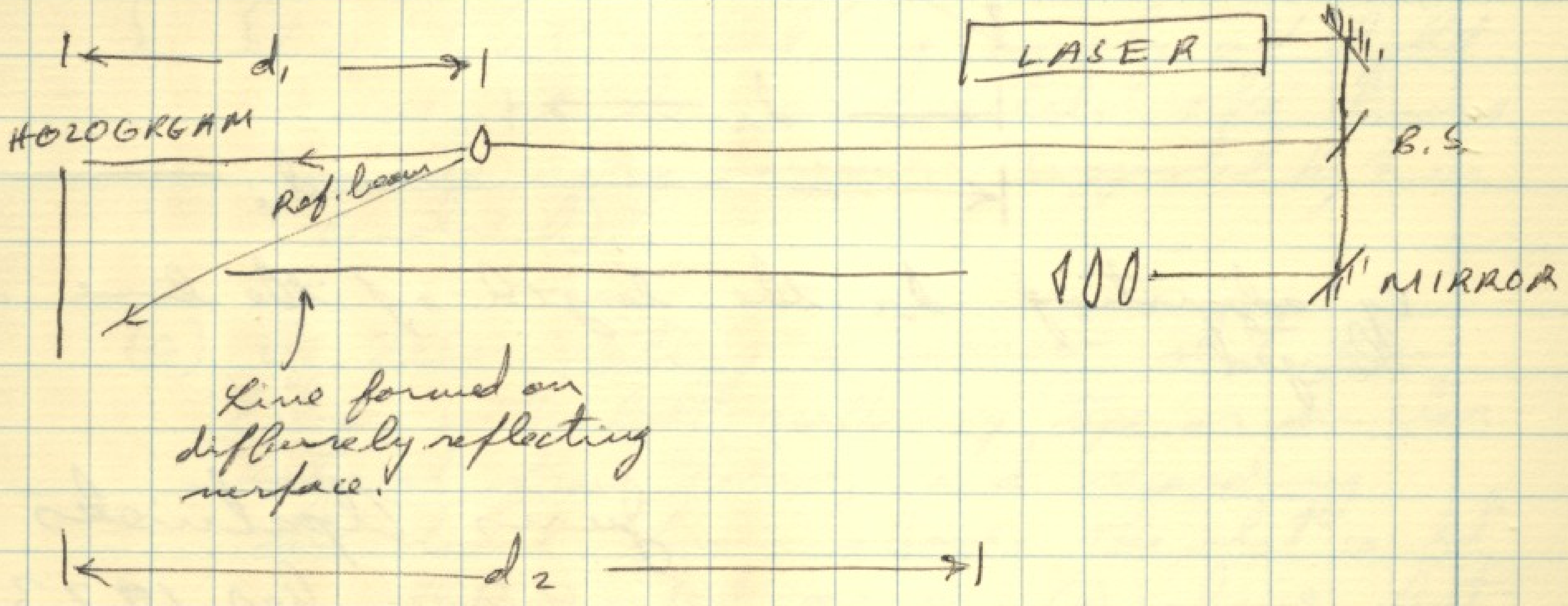
5) Motor vehicle displays
   (a) a safe distance to follow indicator
   (b) Parking aid (shows extremities of vehicle)

6) Miscellaneous military applications
   (a) Sight for observation posts
   (b) For triangulation of gun flashes
   (c) Sight for lasers (range finders, communication links, target designators).

<u>Light-line display construction</u>

The light line display is constructed by recording holographically a straight line and magnifying it in the reconstruction process. Basically, the hologram is made by shining a laser beam on a flat or curved diffusely reflecting surface in a narrow line. The scattered light, in part, is recorded on a hologram as shown below:



The line can be formed by using a combination of lenses, such as spherical, cylindrical and conical lenses. To emphasize the far end of the line, a point source of light can be added and recorded after

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23 Jan 1974

Juris Upatnieks
4 December 1973.

4 December 1973

the line itself has been recorded. That is, a double exposure is made, first recording the line, then removing the line and placing a point source at the end, and recording the point source on the same plate.

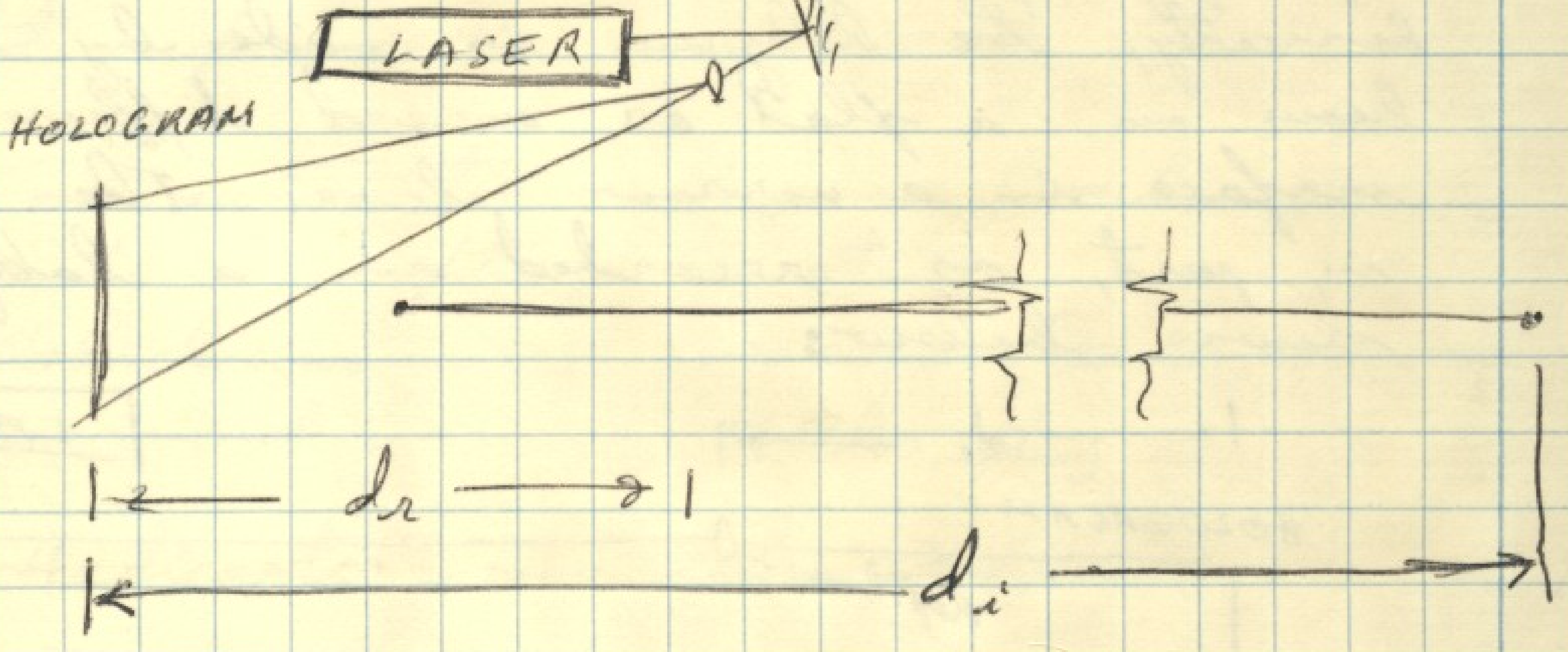
The focal length of the far end of the line is given by

$$\frac{1}{f} = \frac{1}{d_1} - \frac{1}{d_2}$$

In reconstruction, the illuminating point source can be moved from d_1 to d_r, and the location of the far end is then d_i and is given by

$$\frac{1}{f} = \frac{1}{d_r} - \frac{1}{d_i}$$

When $d_r = f$, $d_i \to \infty$ and the line can be made infinitely long. The viewing geometry is shown below:



By adjusting d_r the length of the line can be changed.

Juris Upatnieks
4 December 1973

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Carl Leonard
23 Jan 1974

10 December 1973

Techniques of light-line construction

A narrow, diffusely reflecting light line has to be formed that can be recorded on a hologram. Several techniques are listed below:

(a) Projection of a narrow laser beam on a flat, diffusely reflecting surface. This can be done by
   (1) Using a cylindrical lens to expand the laser beam in one direction (suggested by J. Upatnieks)
   (2) By using a conical lens in combination with spherical and cylindrical lenses to obtained a focused light line on a surface (suggested by E.N. Leith)

(b) Using a fiber optics light guide with slightly roughed surface to guide a light beam. Scattering ~~from~~ through the surface ~~roughness~~ provides light. Since fibers can be of very small diameter and they can be placed on flat or curved surfaces, straight or curved, a variety of light lines can be constructed. The lines can be very narrow. (Suggested by Ivan Cindrich).

(c) ~~By~~ Illuminating a narrow slit from below, with light-scattering tape or similar material from below, and recording the line from above. The slit could be illuminated as in (a) above, but width could be made very narrow. (Suggested by J. Upatnieks.)

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23 Jan 1974

Juris Upatnieks
10 December 1973

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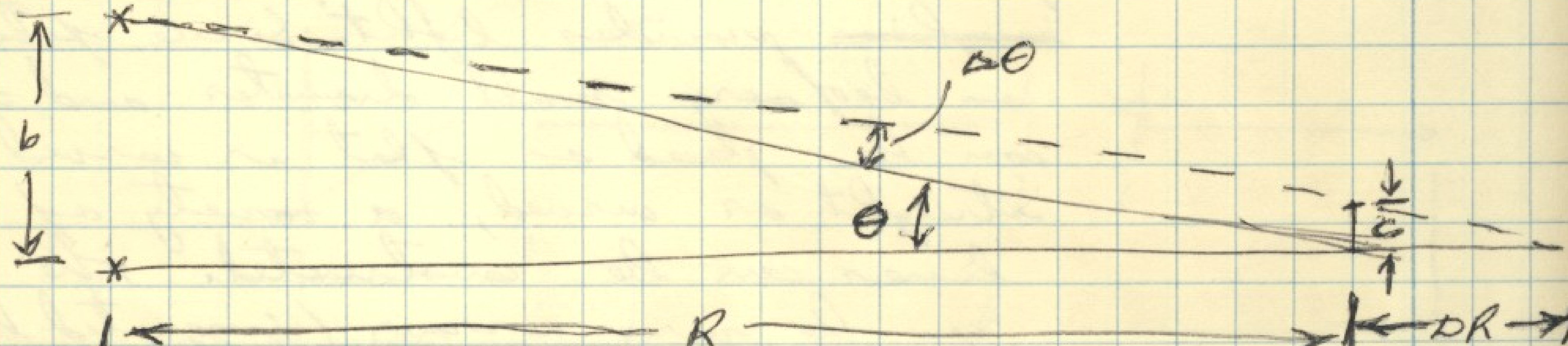
(d) Illuminating a row of ball bearings with a laser beam in such a manner that the reflected light reaches the hologram. This arrangement provides a series of coherent light points closely spaced and is preferable to diffuser surface, since a regular instead of random phase shift exists. Thus, speckle is reduced to a regular intensity pattern. Also, the effect point size can be much less than the width of the illuminating beam of light. (Suggested by Juris Upatnieks).

Range accuracy with holographic paralax range finder

Consider a hologram having width b with observations being made from both ends. If



J.U. 23 Jan '74 the target is at range R and a point generated by the hologram at R+ΔR, then a paralax displacement c is generated at R. Δθ is the angular error. Let Δθ be the observation error. Then we can calculate ΔR ~~with~~ which is the range error. From the figure,

$$\theta = \frac{b}{R}$$

$$c = R\,\Delta\theta = (\theta - \Delta\theta)\,\Delta R$$

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23 Jan 1974

Juris Upatnieks
10 December 1973

10 December 1973.

$$\Delta R = \frac{R\Delta\theta}{\theta - \Delta\theta} = \frac{R\Delta\theta}{\frac{b}{R} - \Delta\theta}$$

$$\boxed{\Delta R = \frac{R^2\Delta\theta}{b - R\Delta\theta}}$$ for $R\Delta\theta < b$ J. U. 23 Jan. '74

If target is observed with a telescope or binoculars having magnification M, and they are diffraction limited, then the effective angular resolution $\Delta\theta_{eff}$

$$\Delta\theta_{eff.} = \frac{\Delta\theta_{eye}}{M}$$

where $\Delta\theta_{eye}$ is the resolution of the eye.

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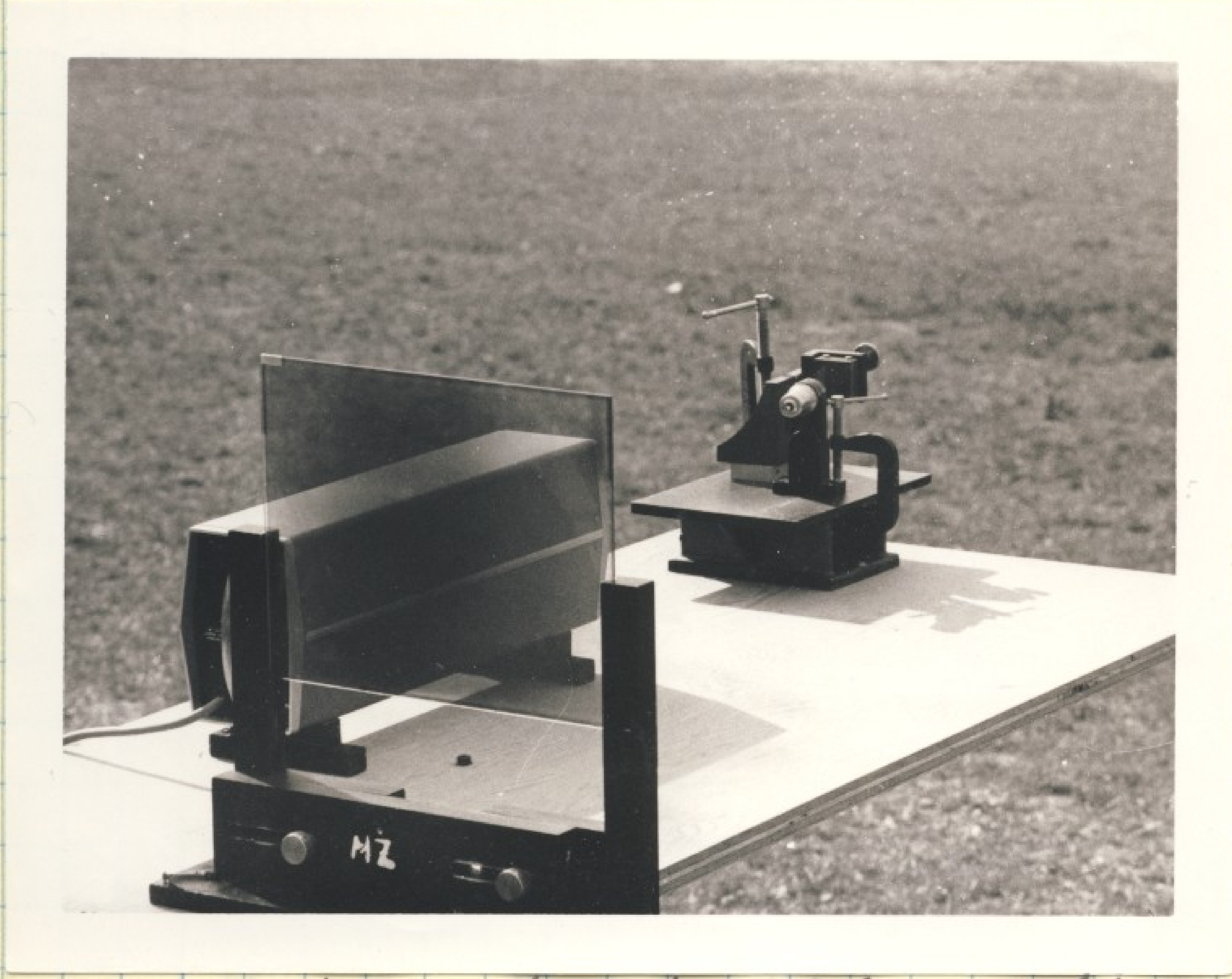
Carl Leonard
23 Jan 1974

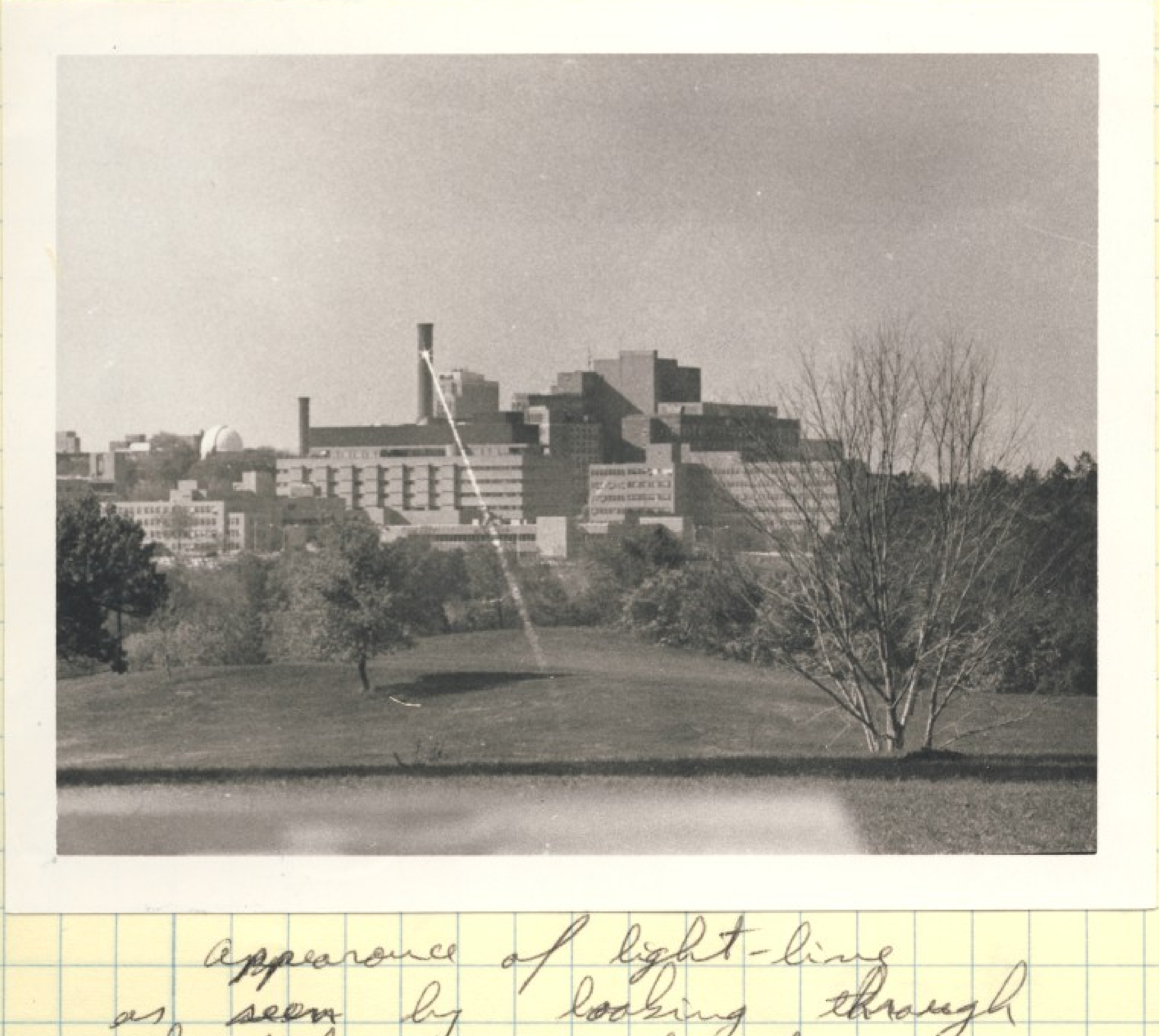
Juris Upatnieks
10 December 1973.

19 February 1975

First operational model of light-line sight.



First operational model of light-line sight.



appearance of light-line as seen by looking through the hologram in the top picture.

The two photographs on this page were taken in the Fall of 1971. The top photograph shows a laser, mirror, lens and a large hologram of a light line mounted on a plywood base on top of a tripod. This was the first operational model of a light-line sight. The photograph below shows the ~~view~~ view through the hologram in the direction of University Hospital from I.S.T. Bldg. in Ann Arbor. The light line is clearly visible aimed at the chimney behind the hospital.

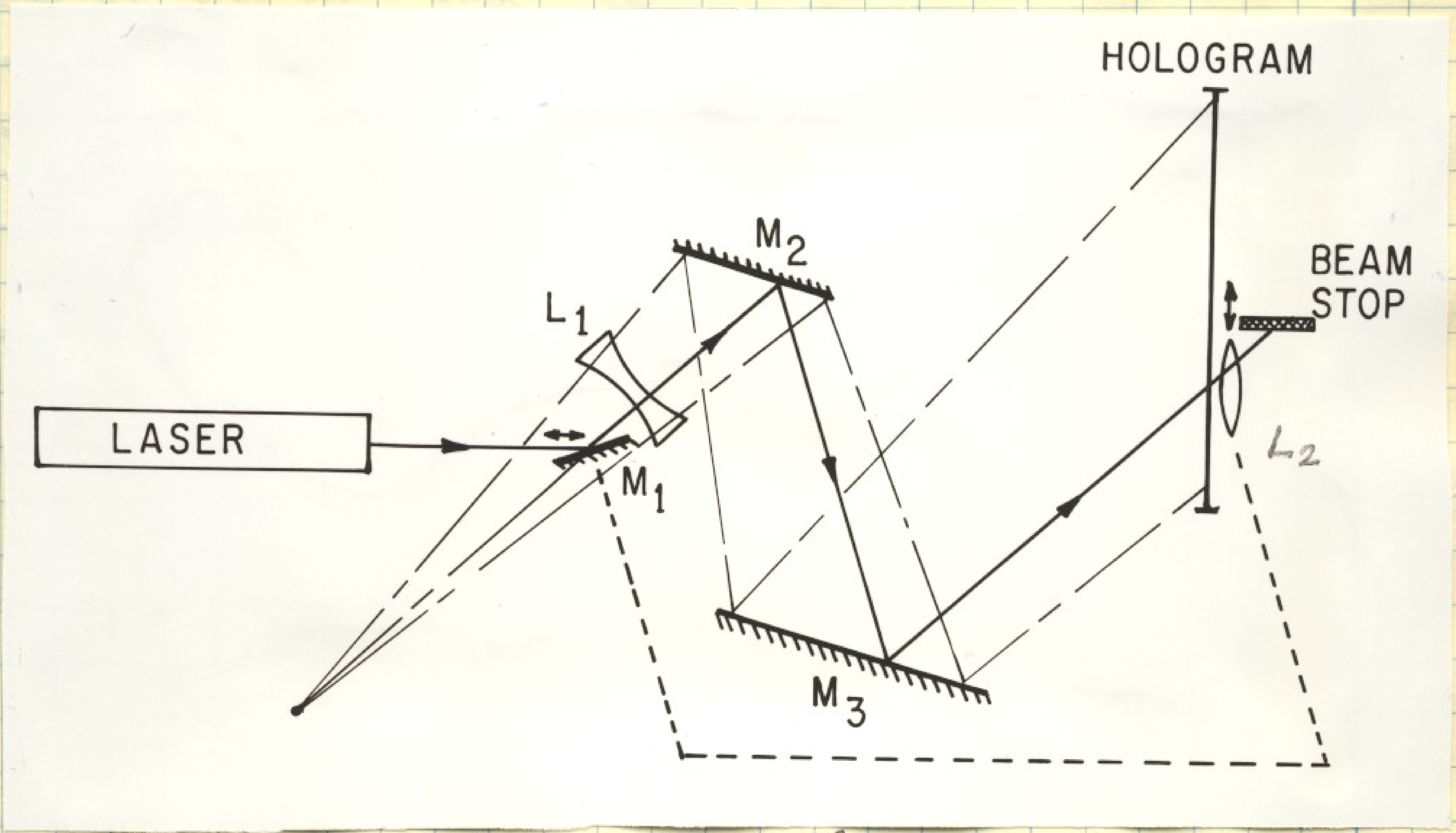
Juris Upatnieks
19 February 1975

Read and understood
W. E. Colburn
March 14, 1975

12 March 1975

Variable focal length lens for 360°
Hologram Projector.

The cross-sectional view ~~shown~~ below shows the arrangement of components in the present hologram projector. In order to focus various parts of the three-dimensional image on a screen, L_2 consists of four lenses of different focal lengths mounted on a rotating turret. Each



HOLOGRAM PROJECTOR

lens images one plane exactly with other planes being more or less out of focus. A lens with variable focal length L_2 is desirable to bring any plane into sharp focus.

The effect of variable focal length lens can be achieved by placing two lenses close together and varying their spacing. Consider two lenses L_3 and L_4 in the following drawing:

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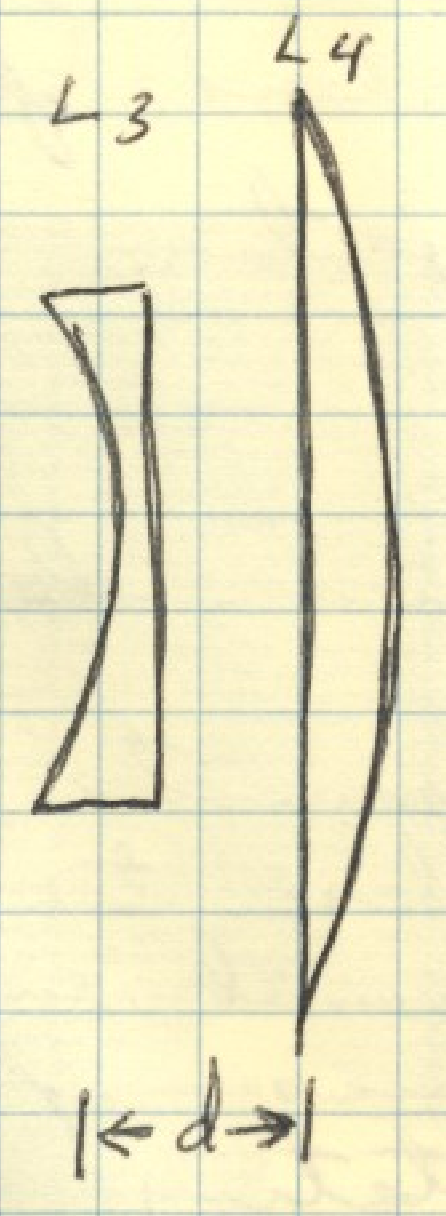
W. S. Colburn, Mar. 14, 1975

Juris Upatnieks
12 March 1975

12 March 1975



When moving $d = 0$, the ~~effect~~ efective focal length f of the two lenses is

$$\frac{1}{f} = \frac{1}{f_3} + \frac{1}{f_4}$$

If $f_3 = -f_4$, then $f = \infty$ and the lenses in combination do not have any focusing power. But as d increases from zero, the two lenses in combination do have focusing power. If both f_3 and f_4 are choose to be very small (short focal length lenses), then rapid decrease in f is possibl, from ∞ to a small number.

Or, f_3 and f_4 need not be of same focal length and thus would have some focusing power even when $d = 0$.

To find the plane imaged, the common thin lens formula can be used twice

$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$

where p is ~~image~~ object to lens distance, q is image to lens distance, and f is the focal length of the lens. Image location is first found for the first lens, then this is the object location for the second lens.

Example:

Let screen to L_3 distance be 200 cm, $f_3 = -20$ cm and $f_4 = +15$ cm. From these numbers we can calculate that L_3 to object distance varies from 100 cm for $d = 0$ to 25 cm for $d = 5$ cm. To cover other ranges, focal length of L_3 or L_4 or both can be changed, or range of d changed.

Read and Understood
Willis S. Collum, Mar. 14, 1975

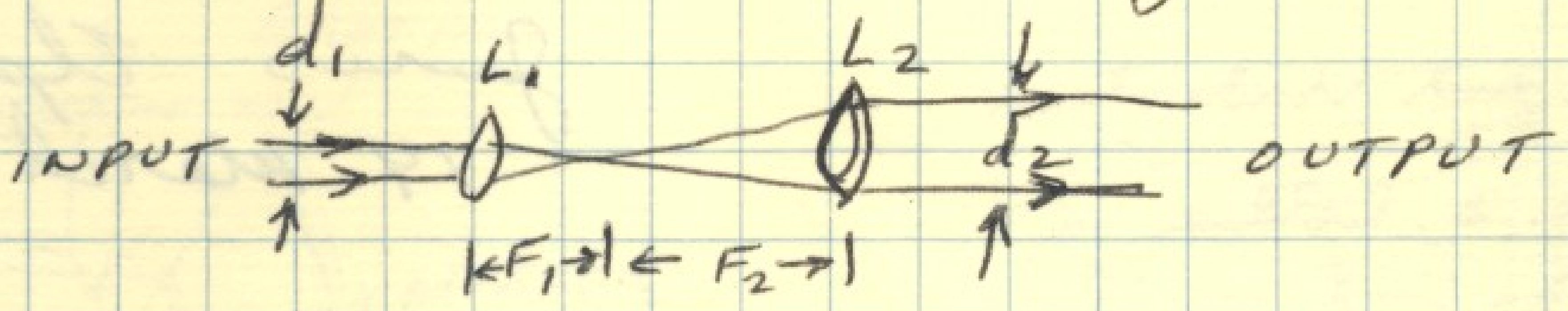
Juris Upatnieks, 12 March 1975

14 March 1975

Changing Beam Diameter at Hologram Plane of 360° Holograms

The 360° Hologram Projector shown on p. 113 of this notebook was originally constructed with a fixed illuminating beam diameter. There are several ways of changing this beam diameter:

1. Use a two lens system:



where F_1 is focal length of L_1 and F_2 is focal length of L_2. If d_1 is diameter of input beam and d_2 is diameter of output beam, then the ratio of the two is

$$\frac{d_2}{d_1} = \frac{F_2}{F_1}$$

if both lenses are spaced the sum of focal lengths apart. The input and output beams are both of same divergence.

To change diameter, lenses L_1 and/or L_2 are changed to different focal lengths to obtain different d_2/d_1 ratio. Since these lenses can be microscope objectives, they can be mounted on a microscope objective turret for quick and convenient interchange.

If the lens separation L_1 to L_2 is changed, beam divergence changes which might be used to change plane of best focus.

Read and Understood
W. J. Collins
March 14, 1975

Juris Upatnieks
14 March 1975

14 March 1975

Another arrangement was suggested by Carl D. Leonard. He suggested that beam diameter at hologram plane can be conveniently changed by changing the spacing of lenses L_1 and L_2 on the previous page. Since the change in curvature can be expected to be ~~[illegible]~~ small relative to change in beam diameter, this system should work out quite well and is very simple.

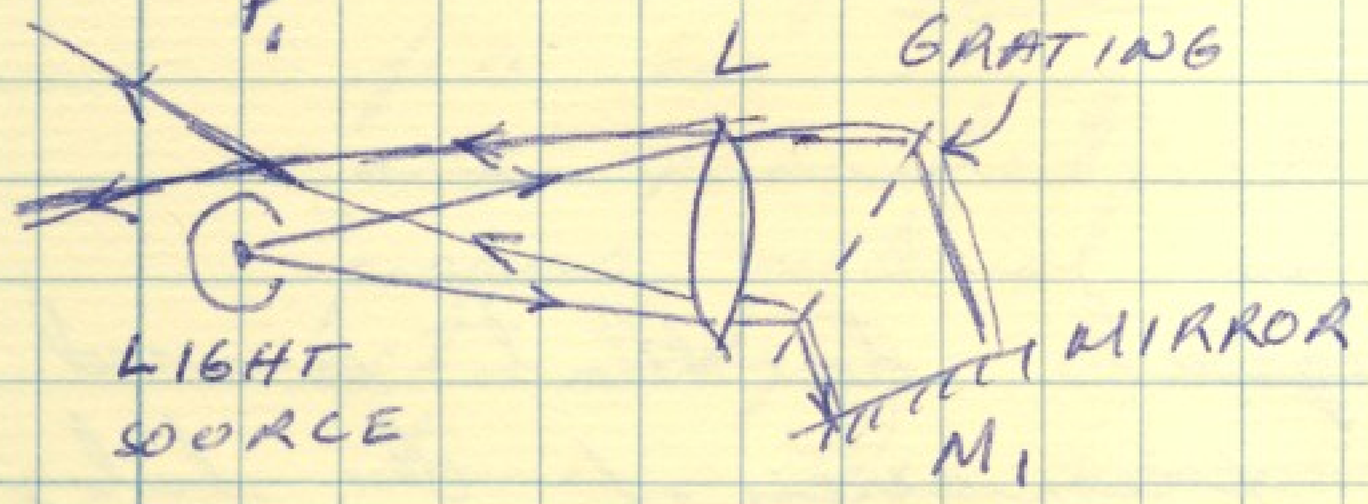
Read and Understood
W. S. Colburn
March 14, 1975

Juris Upatnieks
14 March 1975

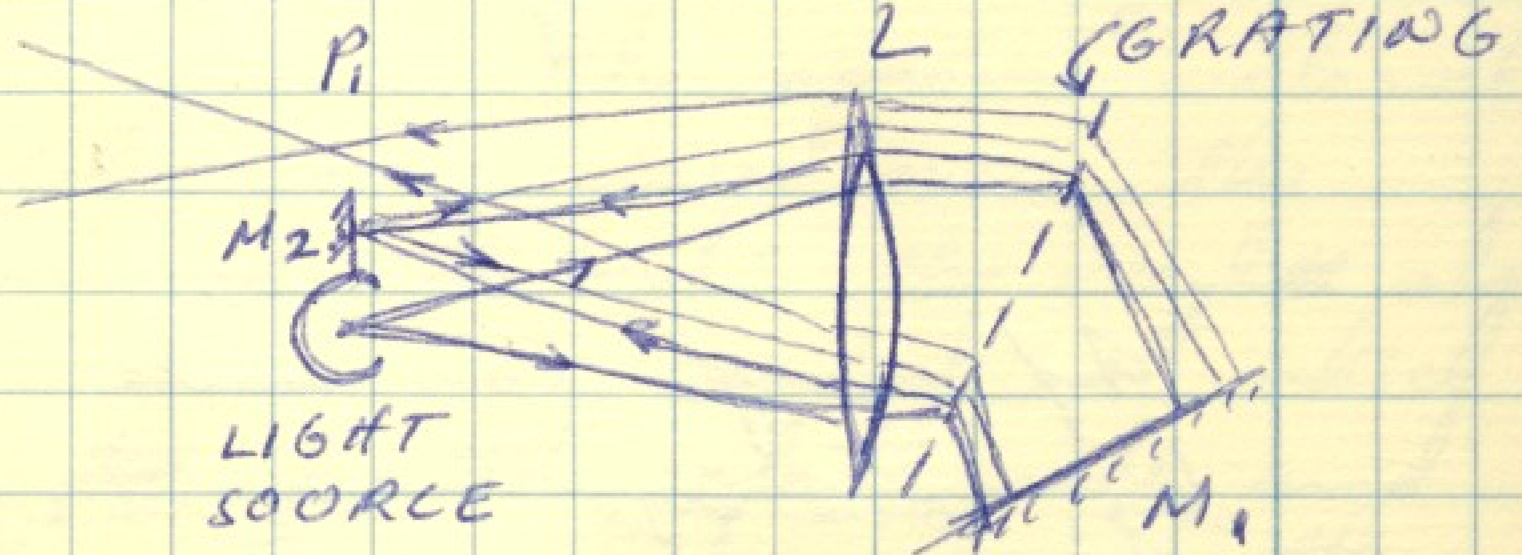
11 April 1975

Low-cost monochromator for Hologram Viewing.

Hologram viewing requires a light source reasonably monochromatic and/or with dispersed spectra for ~~compensating of~~ the carrier frequency dispersion. If the light source is small, the following arrangement can be used:



TWO - PATH MONOCROMATOR



FOUR - PATH MONOCHROMATOR

Light from the light source is collimated by lens L, is diffracted by the grating and is the reflected back through the grating and comes to focus near the light source ~~at~~ plane P_1. Since the spectrum is dispersed at P_1 a spatial filter can be placed there, if desired, to select the bandwidth of the source. Alternatly, a mirror M_2 can be placed there and the light reflected to pass twice more through the grating, as shown at right. Any convenient number of passages can be selected.

If θ_1 and θ_2 are the angles that the light beam ~~forms~~ with the grating (angle of incidence, diffraction) then the grating equation gives the diffration angle

$$\sin\theta_1 + \sin\theta_2 = \lambda f$$

Read and Understood
Carl D. Leonard
May 19, 1975

Juris Upatnieks
11 April 1975

11 April 1975

Taking derivative and solving for $d\theta_2$,

$$d\theta_2 = \frac{f}{\cos\theta_2}\, d\lambda$$

where $d\lambda$ is the band-width of the source.
To find dispersion Δy at plane P_1, we multiply $d\theta_2$ by F, the focal length of the lens, and N, the number of passes through the grating;

$$\Delta y = FN\, d\theta_2 = \frac{fFN}{\cos\theta_2}\, d\lambda$$

If Δy is made equal to that caused by average carrier frequency of the hologram, then considerable reduction in light dispersion is possible in the image formed by the hologram.

Juris Upatnieks
11 April 1975

Read and Understood
Carl P. Leonard
19 May 1975

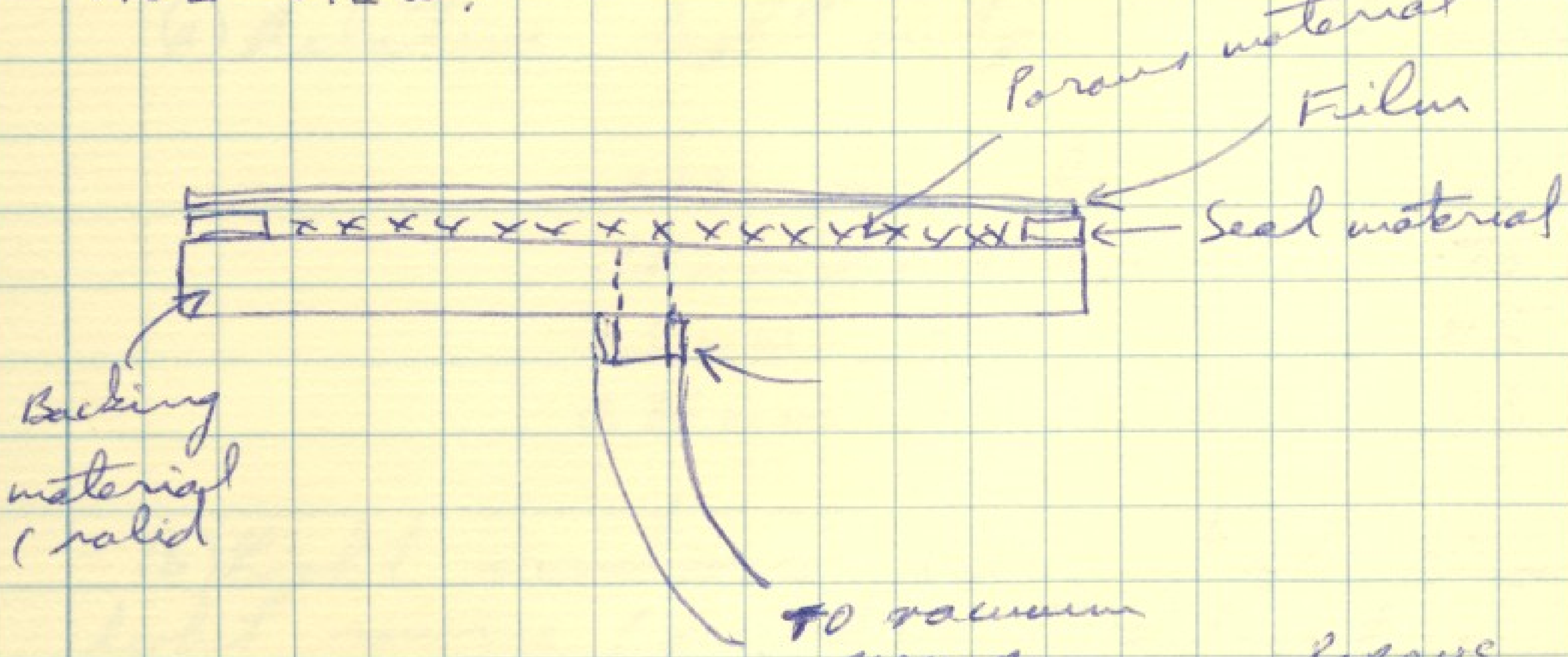
19 May 1975

Vacuum Holder for Holographic Film

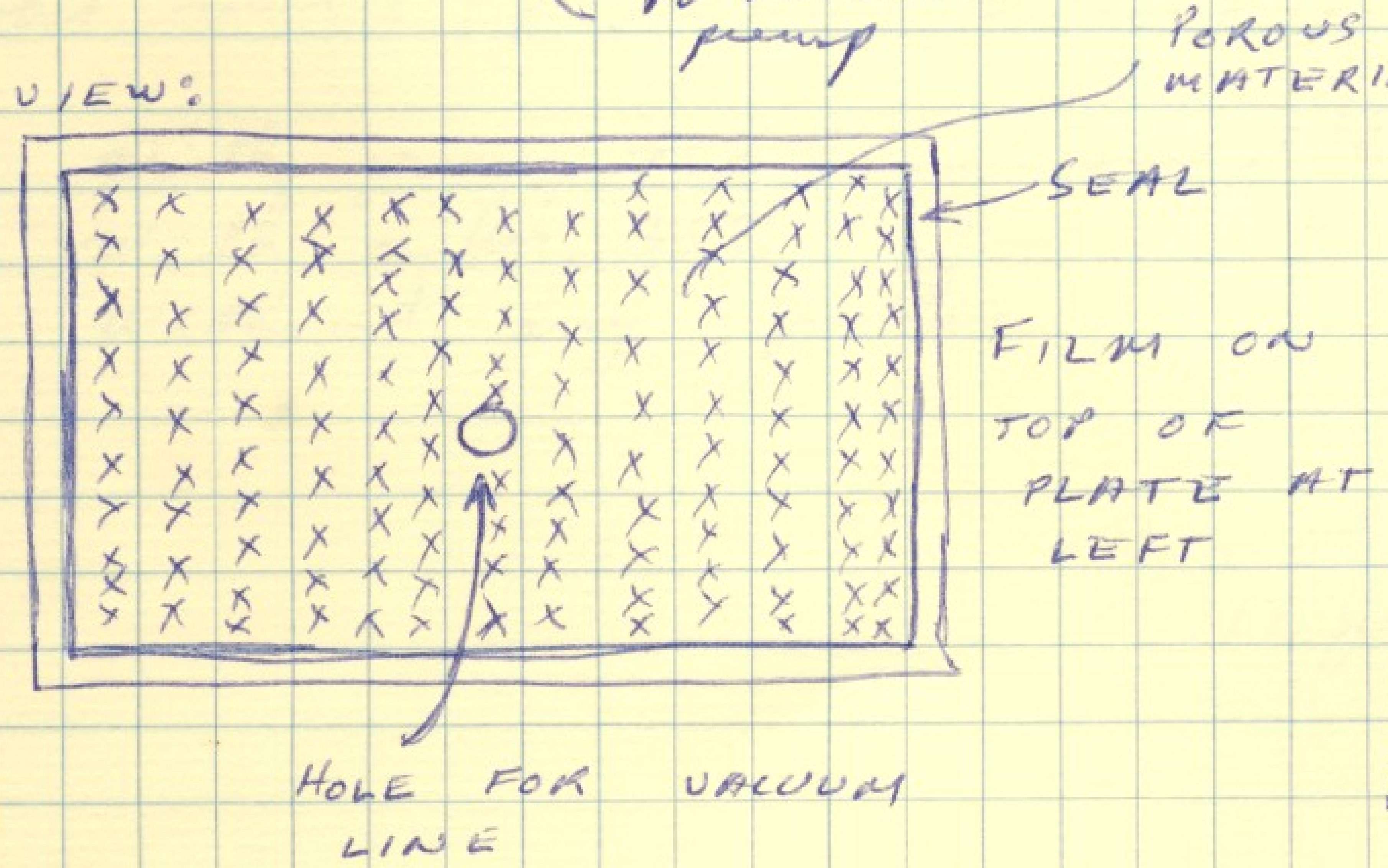
Film motion due to thermal and mechanical instability is a serious problem during hologram recording. A way of mounting film in more ~~rig~~ rigid manner is described here.

The film mount consists of a rigid material backing plate overlayed with porous material and having a seal~~er~~ around the outer edge. Means for evacuating air from the porous material are provided. The film is placed over the porous material and pressed toward the seal~~er~~ along its edges until vacuum is created, at which time the vacuum ~~for~~ on the plate side and air pressure on the other side forces the film against the seal~~er~~ and the porous material. The sketch below shows the main components of the film mount.

SIDE VIEW:



TOP VIEW:



Juris Upatnieks
19 May 1975
Read and understood
Carl D. Leonard
19 May 1975

19 May 1975

As an example, the film holder could be made of the following materials. The plate can be made from aluminum, the seal from rubber, and the porous material could be a piece of window screen or mosquito nett attached to the plate. The hole can be drilled in the plate and threaded for attaching vacuum line.

If the film holder is to be used for holding film in a cylindrical arrangement, the plate could be thin, perhaps 1/8 in., aluminum sheet or plexiglass bend into proper shape. For holding large film sizes several vacuum lines could be attached at various locations of the backing plate.

Juris Upatnieks
19 May 1975

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Carl D. Leonard
19 May 1975

16 July 1975

Some Measurements Relating to 360° Hologram Displays

Measurements were made on the 360° Hologram viewer on 15 July 1975:

Argon laser output: $5.5 \times 1.85 = 10\,mW$ in green ($\lambda = 5145\,Å$)

Measured irradiance at hologram plane (behind film and glass cover plate): $5\,\mu W/cm^2$

Calculated film irradiance based on laser output and film area (9"x11") $\frac{10}{9 \times 11 \times (2.54)^2} = 15\,\mu W/cm^2$

apparent losses amount to ~70%.

Measurements made with a mercury arc lamp, HBO-107, after a collimating and focusing lens:

(a) Relative light output with various pinhole sizes:

No pinhole			100%
1.0 mm diameter pinhole			75%
0.5 mm	"	"	45%
0.36 mm	"	"	25%

(b) Light irradiance measured at 30 in. distance from light source (focused point), without pinhole:

With green, 70% transmittance filter	:	$27\,\mu W/cm^2$
With amber, 35% " "	:	$14\,\mu W/cm^2$
Without any filter		$180\,\mu W/cm^2$

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16 July 1975

16 July 1975

(c) Light irradiance measured immediatly behind 360° hologram, bleached, illuminated by light from arc lamp diffracted by a plane grating:

With green, 70% transmittance filter: 10 $\mu W/cm^2$
With amber, 35% transmittance filter: 5.5 $\mu W/cm^2$

Several interference filters for the green mercury arc lamp were tested and were found to have 70%, 45% and 20% transmittances in the green line.

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16 July 1975

20 August 1975

Light Systems for Reconstructing Holograms with Arc Lamps.

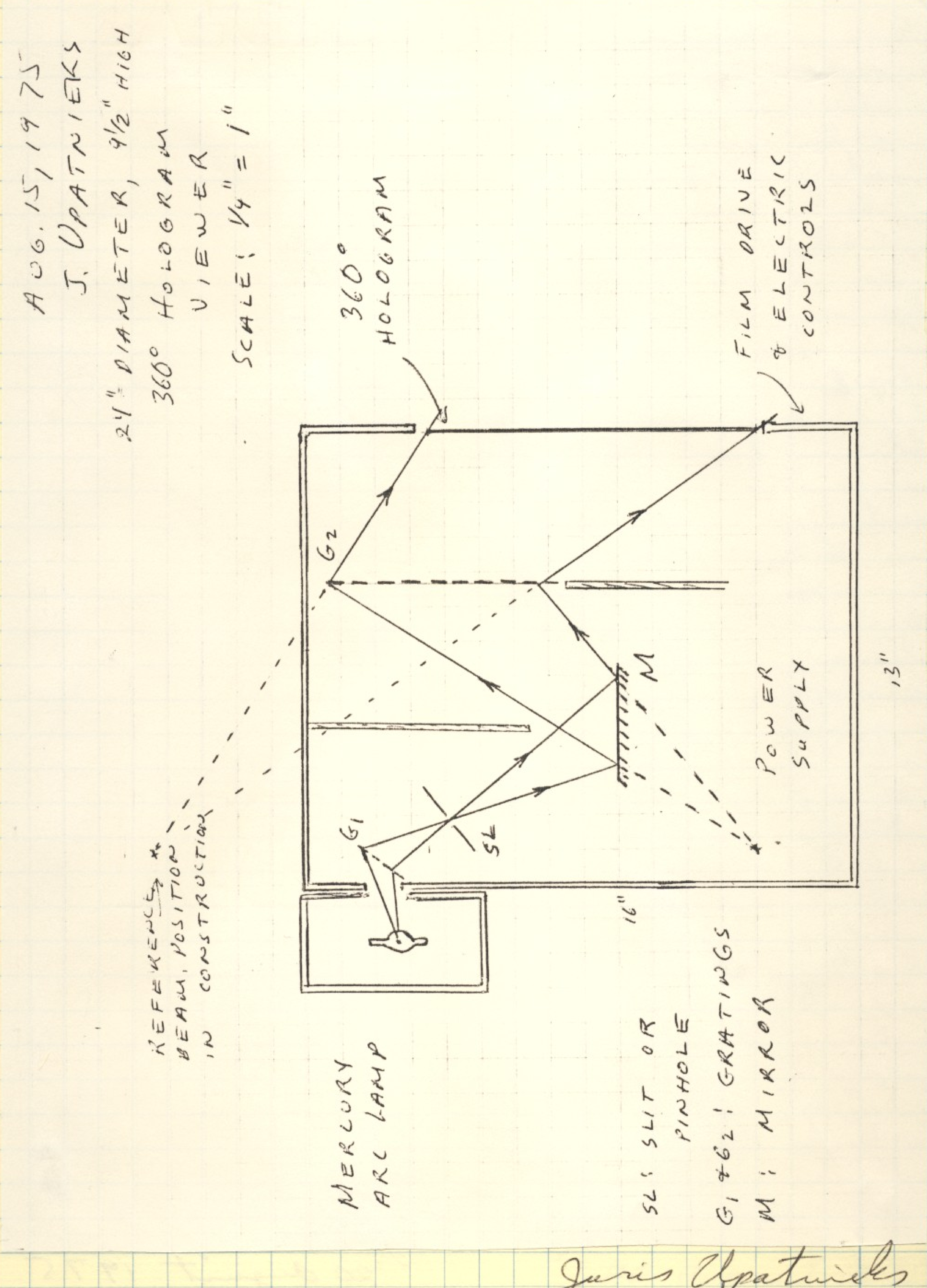

FIG. I.

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20 August 1975

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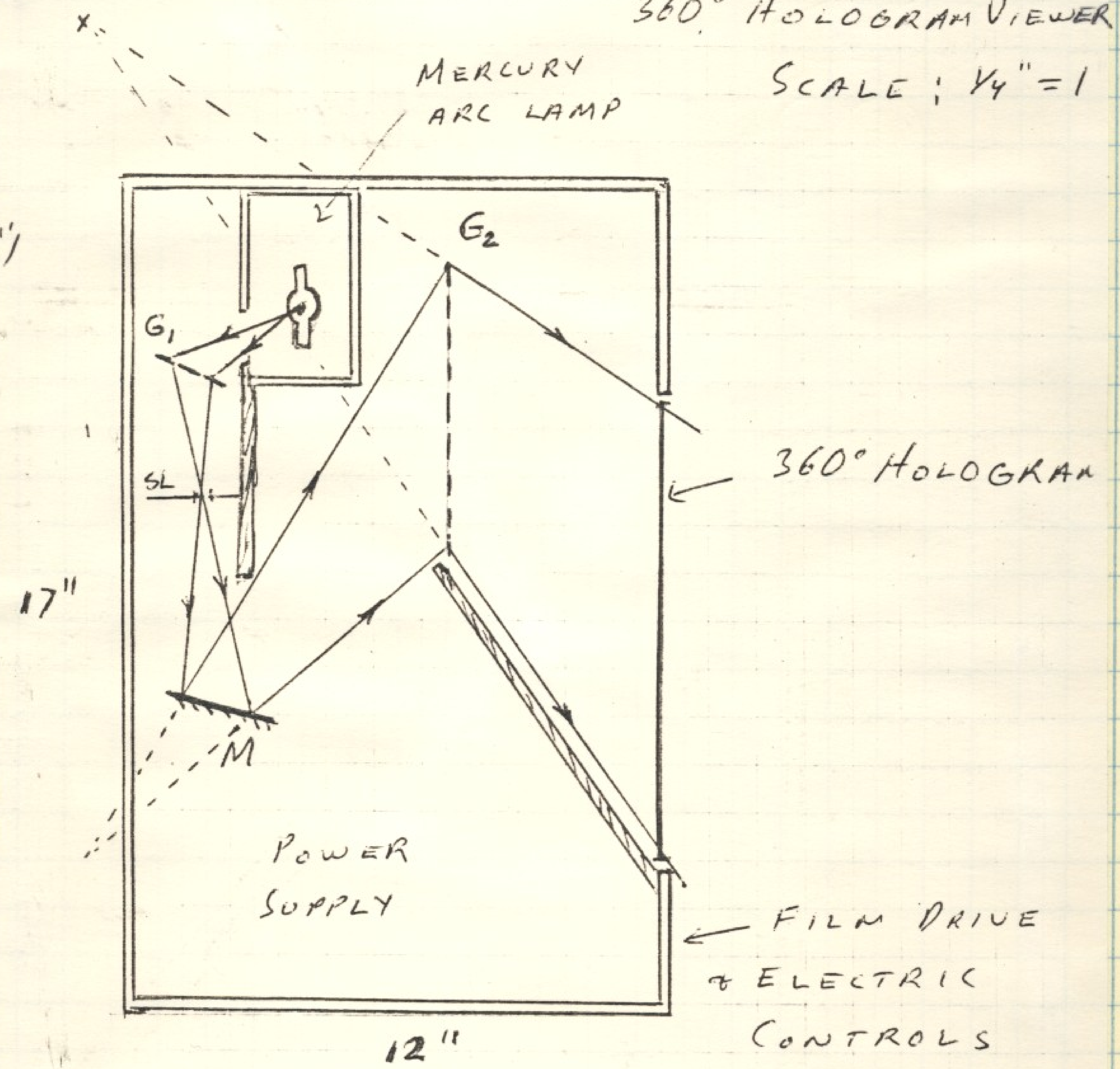
In these drawings, G_1 is used to disperse light so that aperture at SL can act to limit bandwidth of light reaching the hologram. Correction for color dispersion is achieved primarily by grating G_2. In Fig. 2 & 3 G_1 also helps in this correction; in Fig. 1, G_1 disperses light in opposite direction from that of G_2 and therefore reduces the overall dispersion.

The lamp should be, for best results a short-arc high-intensity lamp, such as, for example, are mercury arc lamps.

AUG. 15, 1975
J. UPATNIEKS
24" DIAM., 9 1/2" HIGH
360° HOLOGRAM VIEWER
SCALE: 1/4" = 1



G_1 & G_2: GRATINGS, HIGH EFFICIENCY
M: MIRROR
SL: SLIT OR PINHOLE

FIG. 2

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20 August 1975

20 August 1975

· AUG. 18, 1975

48" DIAMETER, $9\frac{1}{2}$" HIGH

360° HOLOGRAM VIEWER

SCALE: 1/4" = 1"

G_1 & G_2: DIFFACTION GRATINGS, HIGH EFFICIENCY

SL: SLIT OR PINHOLE

M: MIRROR

NOTE: ANGLES ARE FOR CORRECTION 3" ABOVE BASE OF FILM.

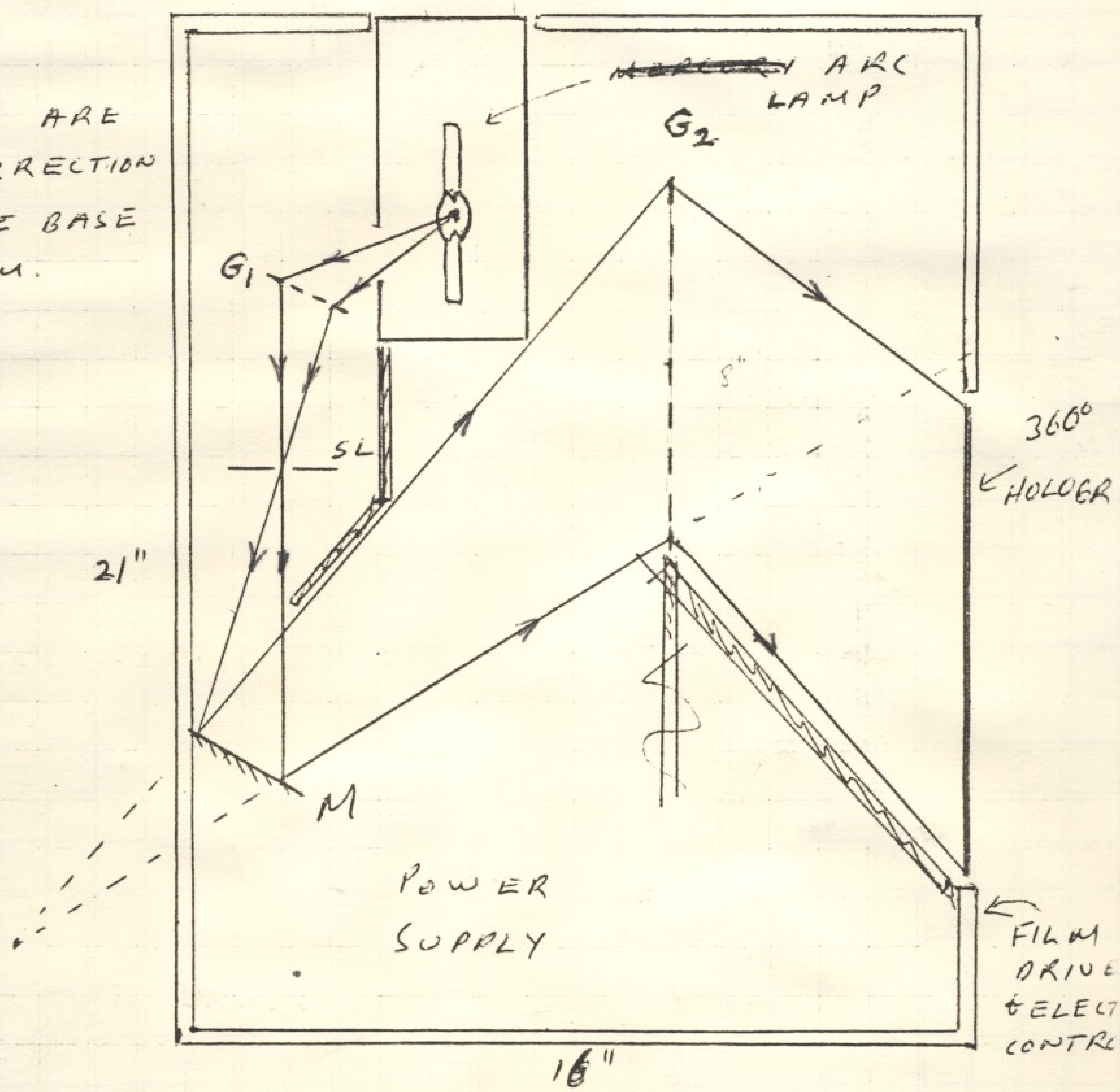

FIG. 3

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20 August 1975

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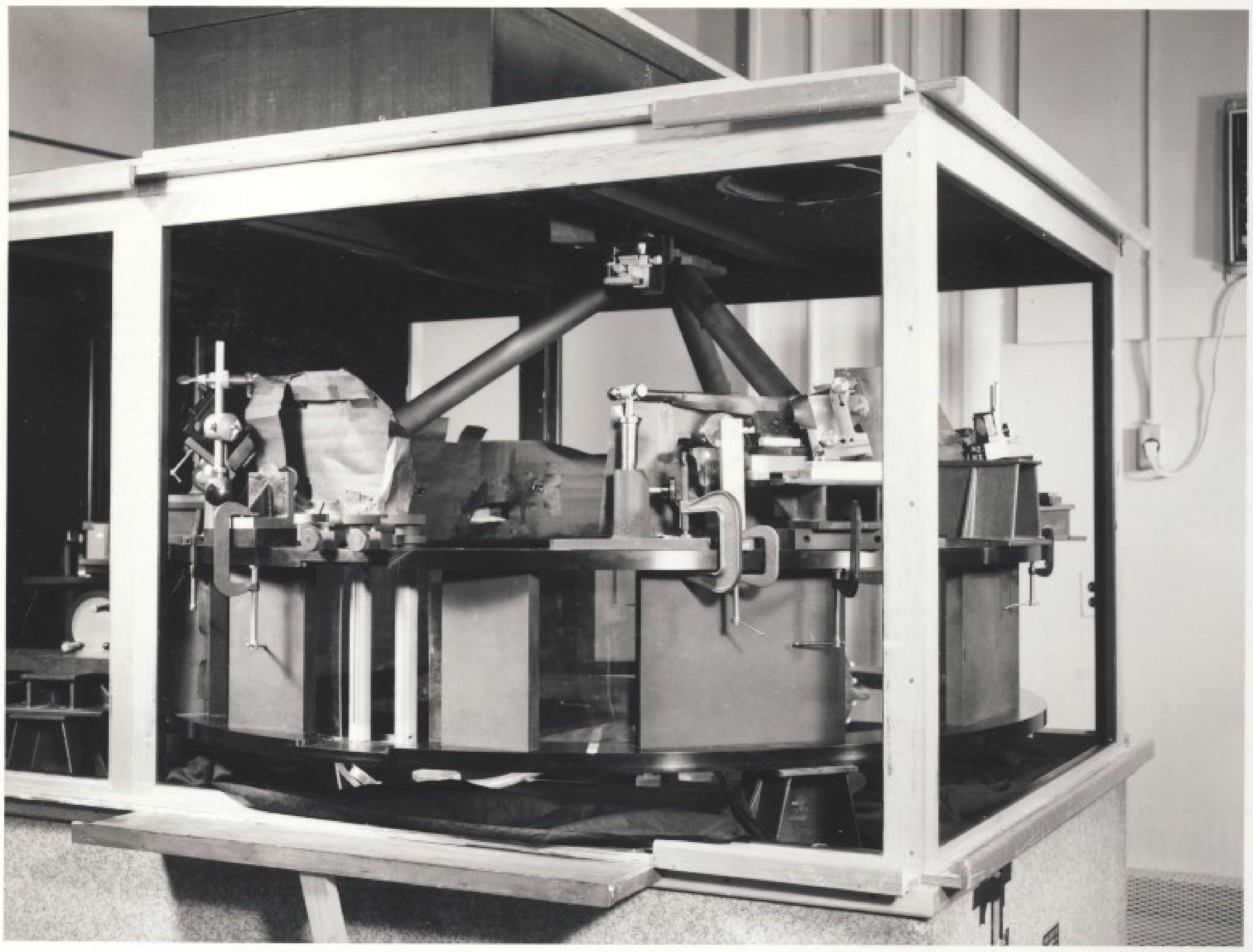
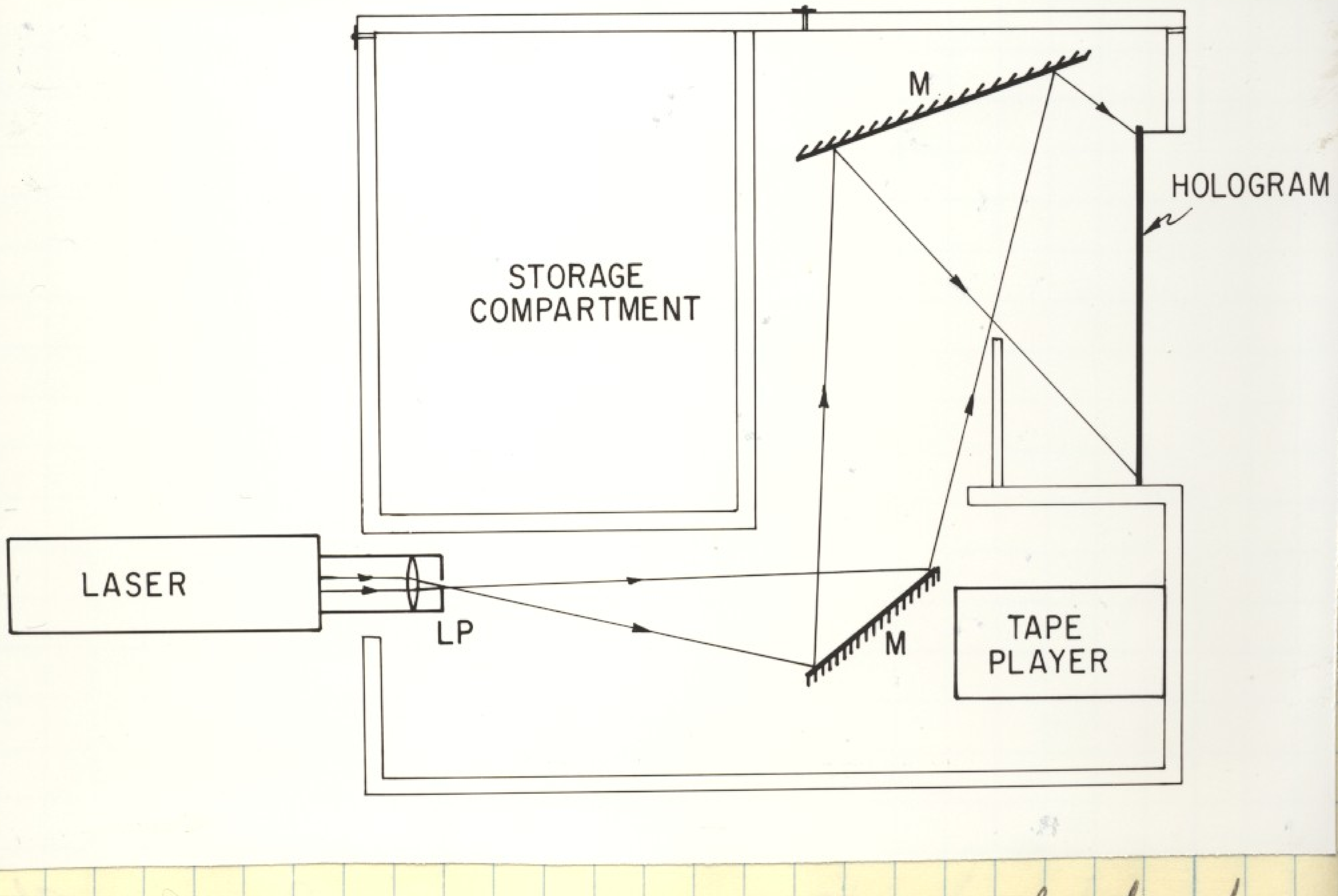
Photographs of 360° Hologram Recording and Display Equipment.

360° Hologram camera, for 9½ in. wide film, 4 ft. in diameter. Reference beam assembly is visible at top, including lens-pinhole assembly. Film goes between top and bottom ring. Top ring is used as base for holding components for directing illuminating beams. Camera constructed during Dec. of 1973 and January of 1974.



Schematic diagram of hologram viewer. Hologram film slides over curved supports.



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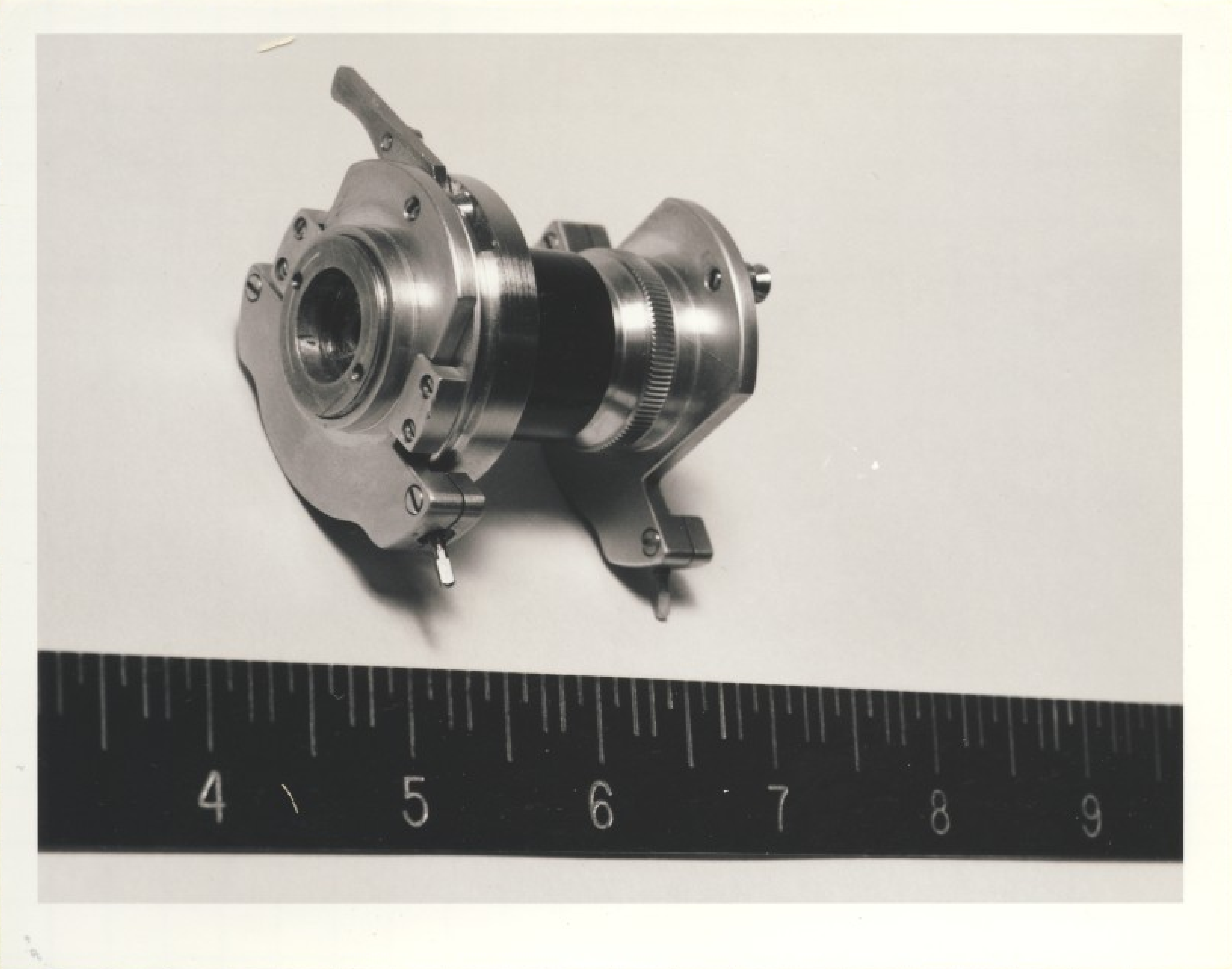
Photograph of hologram viewer. Hologram film is visible in rectangular aperture. Tape player is in center, knobs for moving film are on both sides of the cabinet. Constructed during spring of 1974.



Custom-made lens-pinhole assembly made to be used with hologram viewer. Pinhole is on the left front.

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20 August 1975

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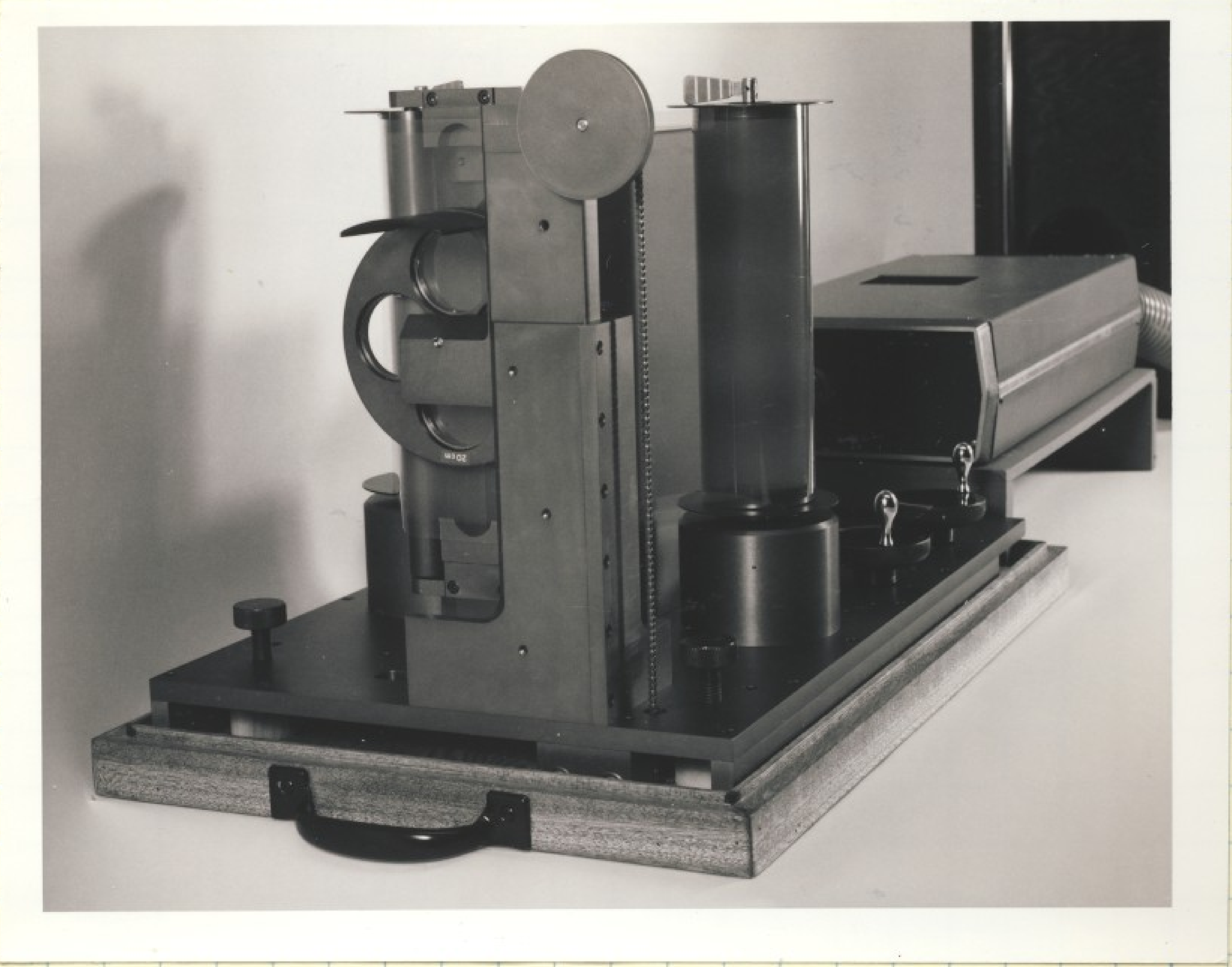
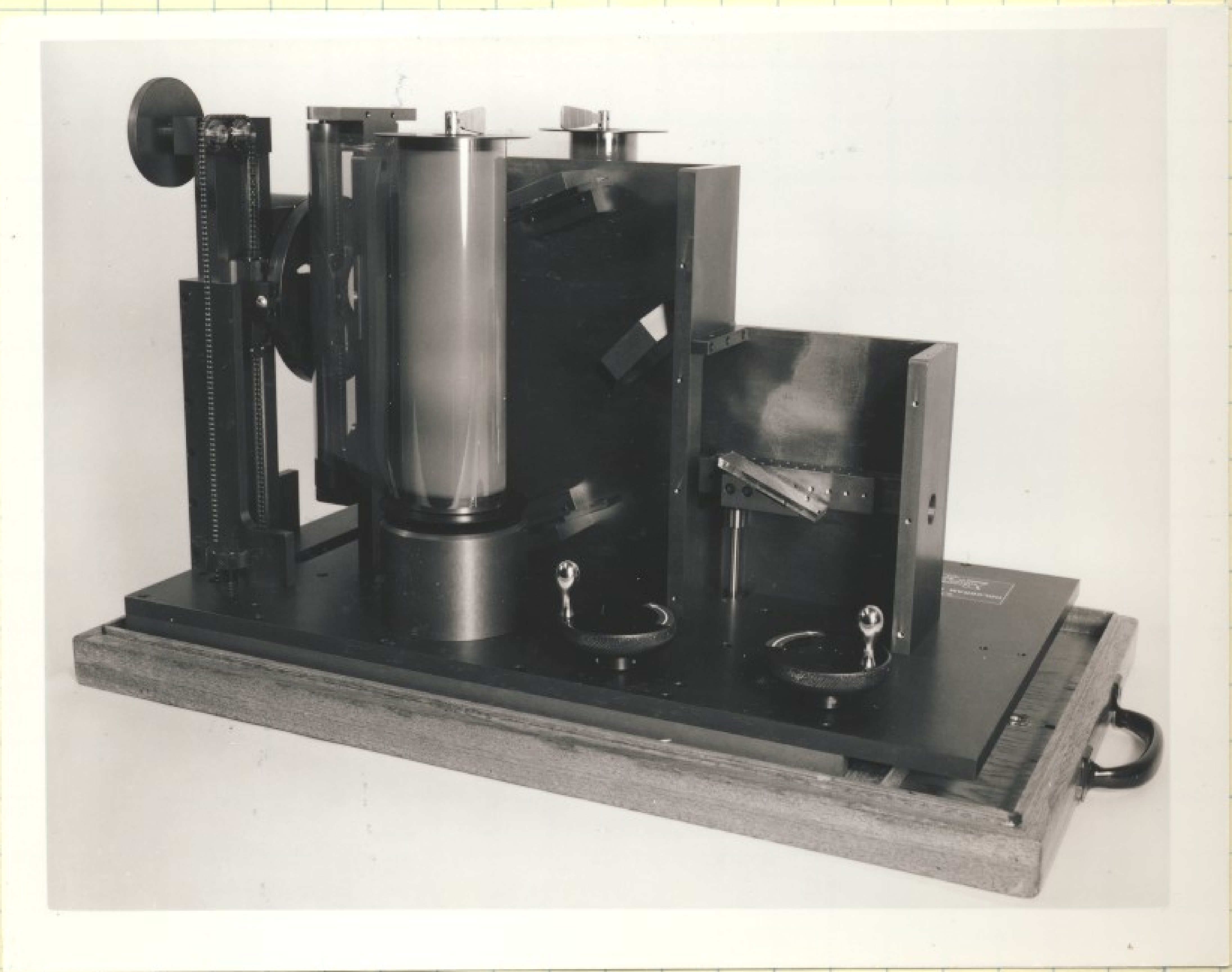
Note: diagram of the 360° hologram projector is on page 113 of this notebook.

Photograph of hologram projector. Front of the projector is visible, including lens turret, vertical beam adjustment knob at the top, film spools on either side, and film ~~knobs~~ knobs on the right side. Laser is visible in the background.



Photograph of hologram projector. With the cover removed, the movable mirror for beam steering is on the right, negative lens holder is to the left of the movable mirror, and path folding mirrors are at the top and bottom. The projector was constructed during the spring and summer of 1974.



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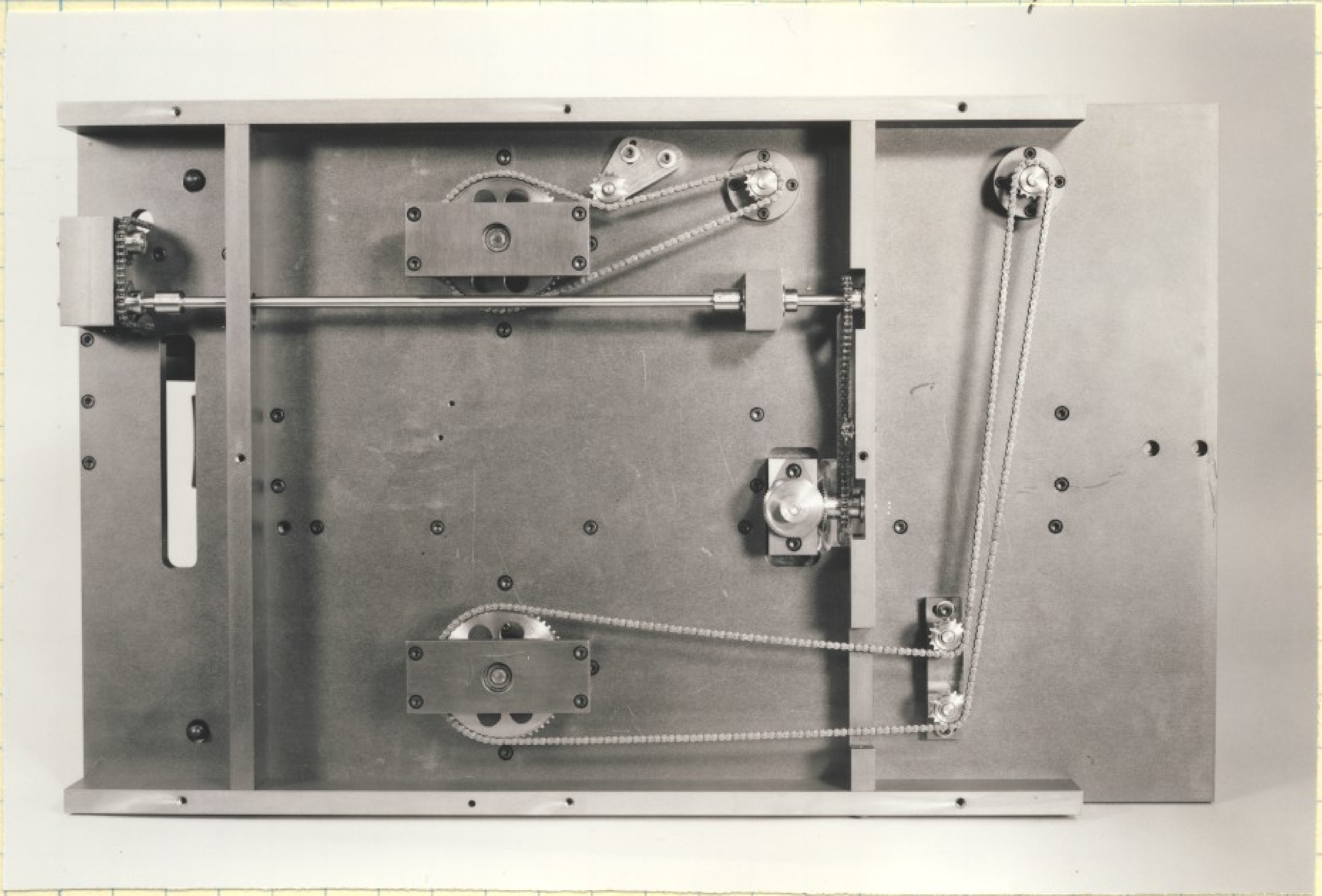
Bottom view of hologram projector. The rod connects lens turret drive with the movable mirror; the chain and sprocket drives are for moving film spools.



Photograph of equipment used in hologram construction besides the camera. On left is oscilloscope for film stability monitoring, argon laser power supply with timer on top, argon laser, and helium neon laser.

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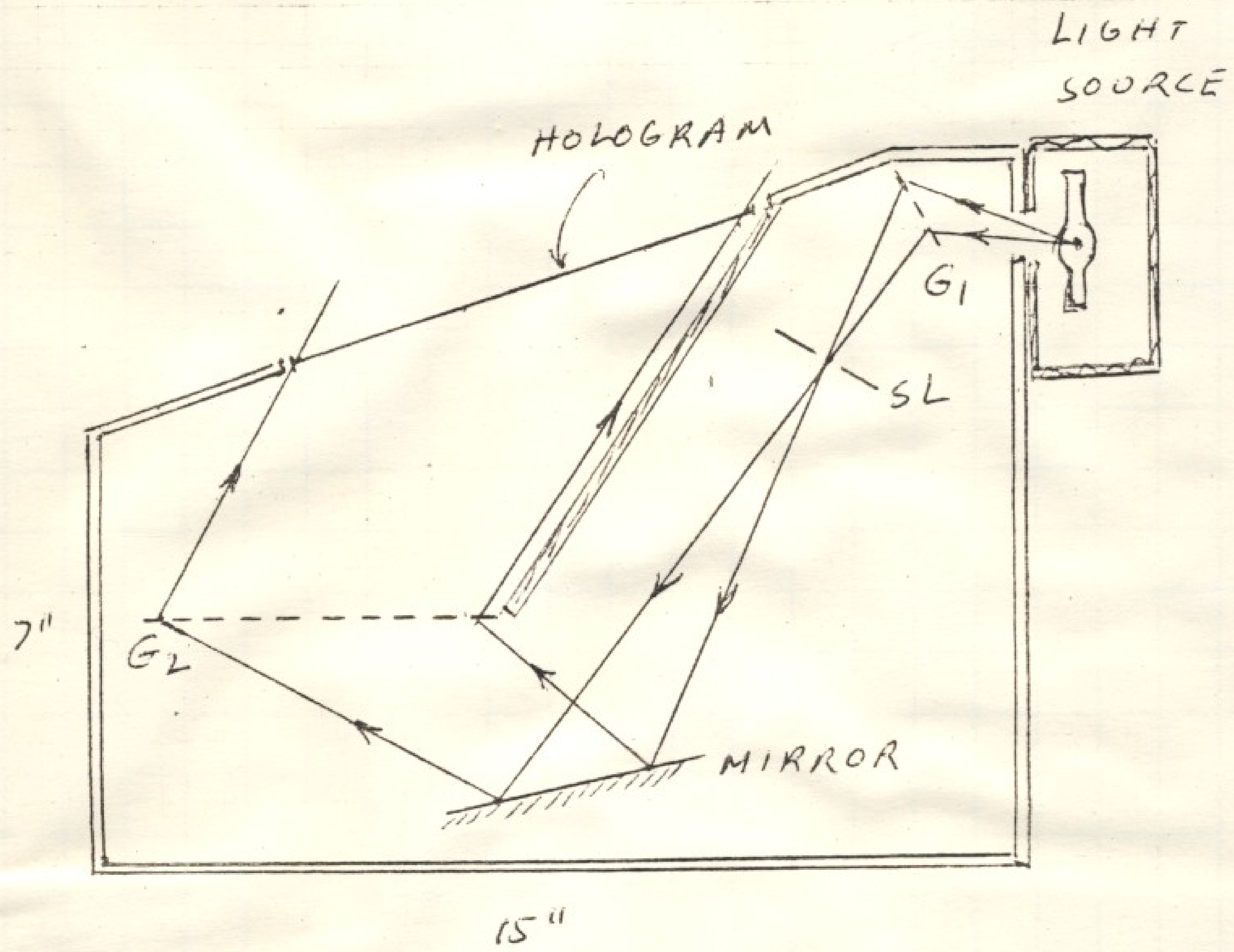
Diagram of 8" x 10" size plate hologram viewer using an non-laser light source.



SL: SLIT OR PINHOLE

G_1 & G_2: GRATINGS, HIGH EFFICIENCY.

8" X 10" HOLOGRAM VIEWER

SCALE: 1/4" = 1"

J. UPATNIEKS

20 AUGUST 1975

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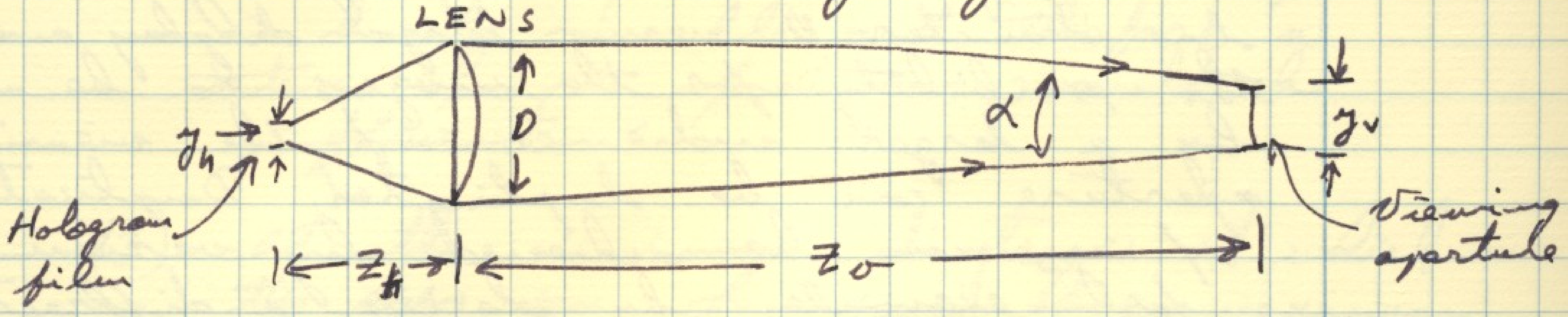
20 August 1975.

28 August 1975

Large Hologram Displays, Movie or Slide Projector.

A major problem with large-size holographic displays has been been the problems associated with construction of large holograms. A lens system may be used to reduce the viewing aperture and film size to a reasonable size, as proposed by Emmett Leith. This system can be scaled up, that is, the lens can be made larger without significantly increasing the needed film size. The tradeoffs are considered here.

Consider the viewing system shown below:



The lens diameter is D, viewing aperture is y_v, and hologram film aperture is y_h. The following relationship between the parameters is evident if the lens images y_h on the viewing aperture y_v:

$$\frac{y_v}{y_h} = \frac{z_o}{z_h} \qquad (1)$$

The image formed by hologram of size y_h is visible everywhere from aperture of size y_v and can appear to be located anywhere near the lens location to the right of it or anyplace to the left of the lens.

For a viewer to see the image, a certain width y_v is needed so that both eyes can be

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28 August 1975

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positioned within the aperture. This aperture remains constant regardless of the lens size D against which the image can be seen and the distance of this lens from the viewing aperture. Let us now assume that we scale up the system by increasing the lens diameter D and increasing z_o and z_h so that $\frac{z_o}{z_h}$ = constant. Then, from Eq. 1, we see that y_h, the hologram size, also remains constant and is independent of the lens diameter D. This means that we can scale up the lens size D to an arbitrary size. The lens in this case is analogous to a projection screen in ordinary movie display systems. Large lens diameter D means larger display and the possibility for the images to be observed by a larger audience if the viewing aperture can be duplicated. Duplication of y_o can be achieved by various means, for example, by placing a diffracting screen near the lens so that the diffraction orders would form duplicate viewing apertures near original viewing aperture shown in the Figure.

The hologram could be replaced by some system of distinct perspective projection either by means of several holograms side by side, with y_h/N being the individual hologram width and N being an integer, or by a lens and ordinary photograph arrangement, with the lens being positioned in place of the holographic film in the fig. The viewing aperture would be likewise divided into equal width segments, each segment having width y_o/N, and each width presenting one distinct perspective view.

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28 August 1975

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The question is then what is the smallest N for a realistic three-dimensional appearance of the display? The value of N depends on the distance of the scene from the viewing aperture and also on the depth of the scene. Assume that the scene is approximatly at the same distance as the lens. Then the following conclusions can be made:

(1) If $z_v \simeq \infty$, one view is sufficient as no paralax information is present. Thus, ordinary single-perspective projector is sufficient.

(2) As z_v decrease from infinity, there is a position where some paralax is barely visible and therfore a stereo pair of images would be sufficient.

(3) At the minimum distance at which the eyes can focus and have maximum resolution, $\Delta y_v = y_v/N$ should equal the aperture of the observers eyes (approximatly) or about 1 to 4 mm. Thus, $N \simeq \frac{y_v}{\Delta y_v} \simeq \frac{y_v}{2\,mm}$.

(4) Between cases (2) and (3), an intermediate N should be sufficient.

Example:

Assume $z_v = 50$ ft., $z_h = 15$ ft., $D = 10$ ft., $y_v = 12$ in.

Then $y_h = \frac{15}{50} \times 12 = 3.6$ in.

Thus, a 5 in. wide film strip would be sufficient. The film arrangement might

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28 August 1975

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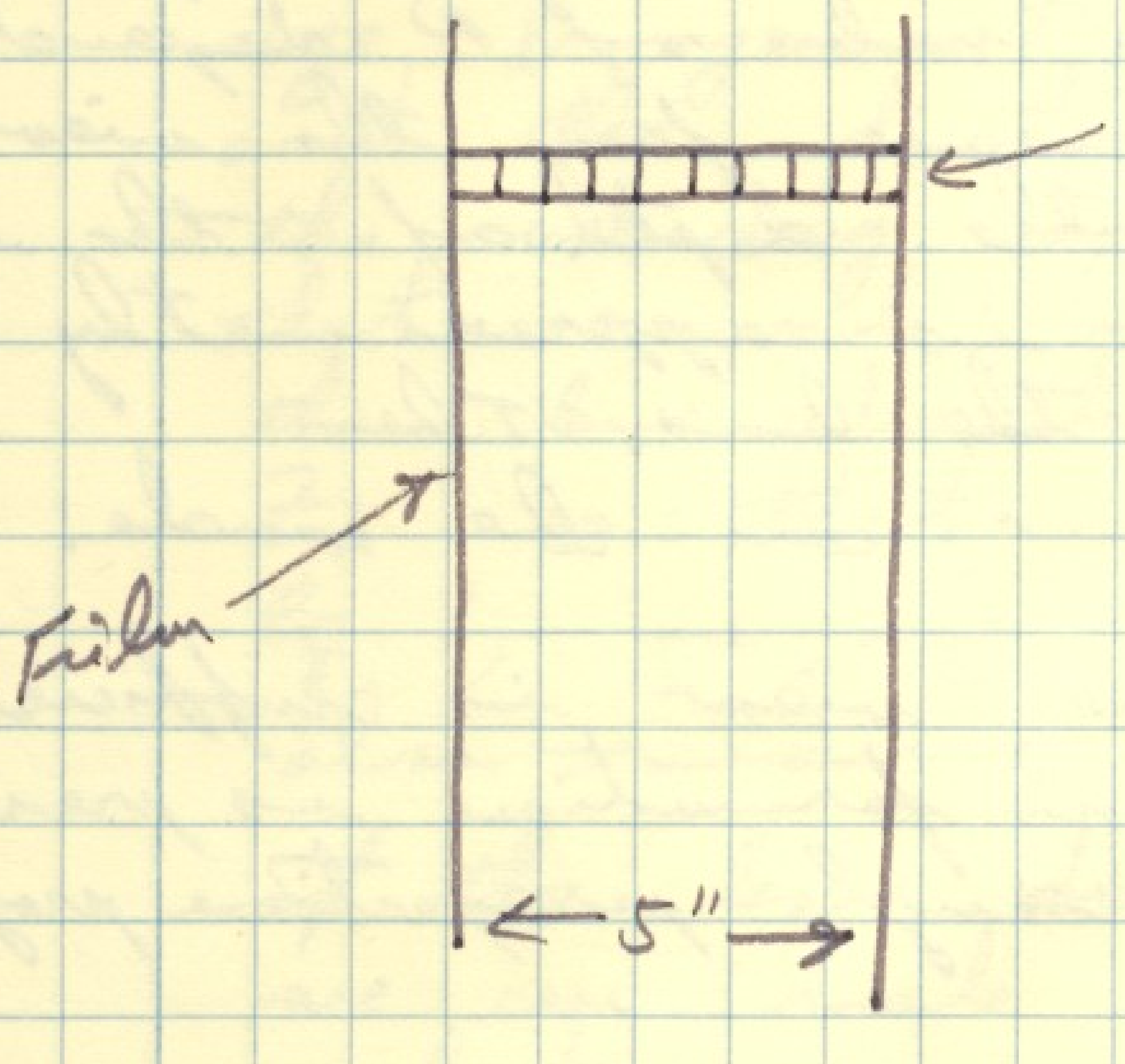
be as follows:



One row of holograms or images represent one frame at one instant of time, with subsequent images in time recorded along the length of the film. Each square represents one perspective.

If strip width is 1/2", the film speed could be very reasonable even at 24 frames/s

If film consists of holograms then continuous motion without shutter would be possible; with images, a system similar to ordinary movie projectors would be needed.

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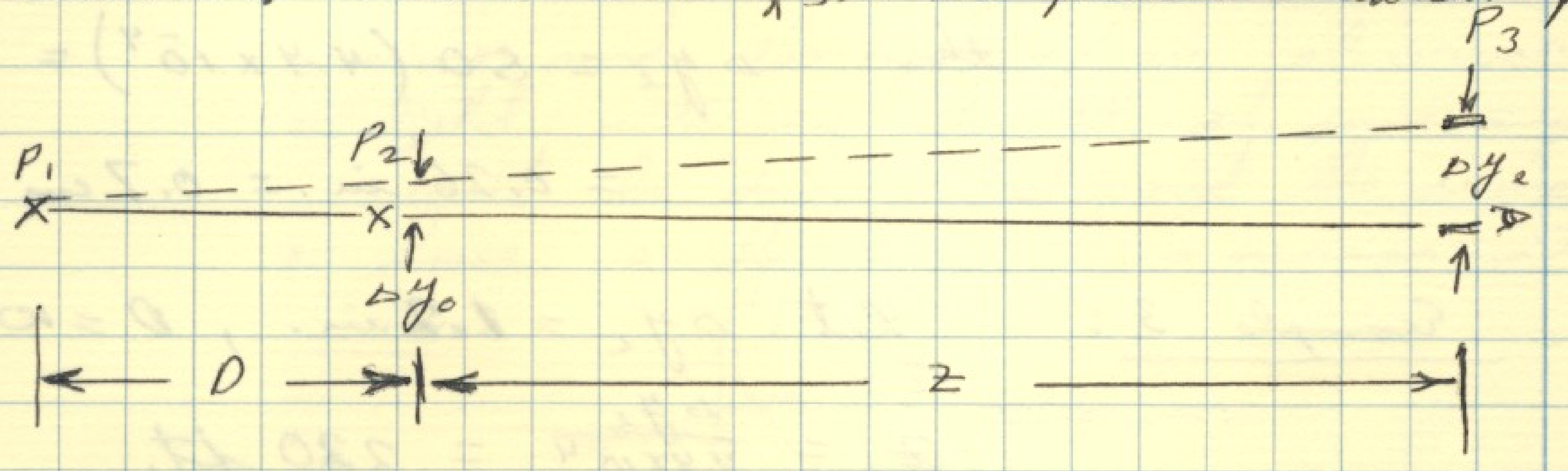
28 August 1975

3 September 1975

Estimate on the Number of Views Needed to Create a Realistic 3-Dimensional Image.

We can think of a holographic image as one in which many perspectives, or views, of a scene are presented. As a viewer moves, different perspectives are seen. The same illusion can be created by displaying distinct views (photographs), each taken from a different viewing angle, and arranged so that different views are visible as the eyes move. By proper choice of parameters a very realistic three-dimensional image should result.

The number of distinct views needed per given ~~to~~ width of a viewing aperture will be calculated. Consider points P_1 and P_2 distance D apart and distance Z from the viewer. For a viewer at P_3 to see paralax between points



P_1 and P_2, P_1 must move relative to P_2 one resolvable increment Δy_0 over for paralax to be visible. Since resolution of the eye is 4.4×10^{-4} radians,

$$\Delta y_0 = 4.4 \times 10^{-4} Z \qquad (1)$$

The corresponding distance at P_3 is

$$\Delta y_e = \frac{Z+D}{D} \Delta y_0$$

$$\Delta y_e = \frac{Z(Z+D)}{D} (4.4 \times 10^{-4}) \qquad (2)$$

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3 September 1975

3 September 1975

For a total width w of the viewing aperture, the number N of distinct perspectives needed is

$$N = \frac{w}{\Delta y_e} \qquad (3)$$

In order to see paralax from any position of viewer, the spacing Δy_e should not exceed the distance between the viewer's eyes, or about 2.5 inches. Thus,

$$\Delta y_e \leq 2.5 \text{ in.} \qquad (4)$$

Example 1: Let $z = 50$ ft., $D = 10$ ft.,

then $\Delta y_e = \frac{50(60)}{10}(4.4 \times 10^{-4}) = 0.132$ ft.

$= 1.6$ in. $= 4.0$ cm.

Example 2: Let $z = 50$ ft., $D = \infty$,

then $\Delta y_e = 50\,(4.4 \times 10^{-4}) = .022$ ft.

$= 0.26$ in. $= 0.7$ cm

Example 3: Let $\Delta y_e = 1.2$ in., $D = \infty$

$$z = \frac{\Delta y_e}{4.4 \times 10^{-4}} = 230 \text{ ft.}$$

In practice, Δy_e possibly could be larger than that given by Eq. 1.

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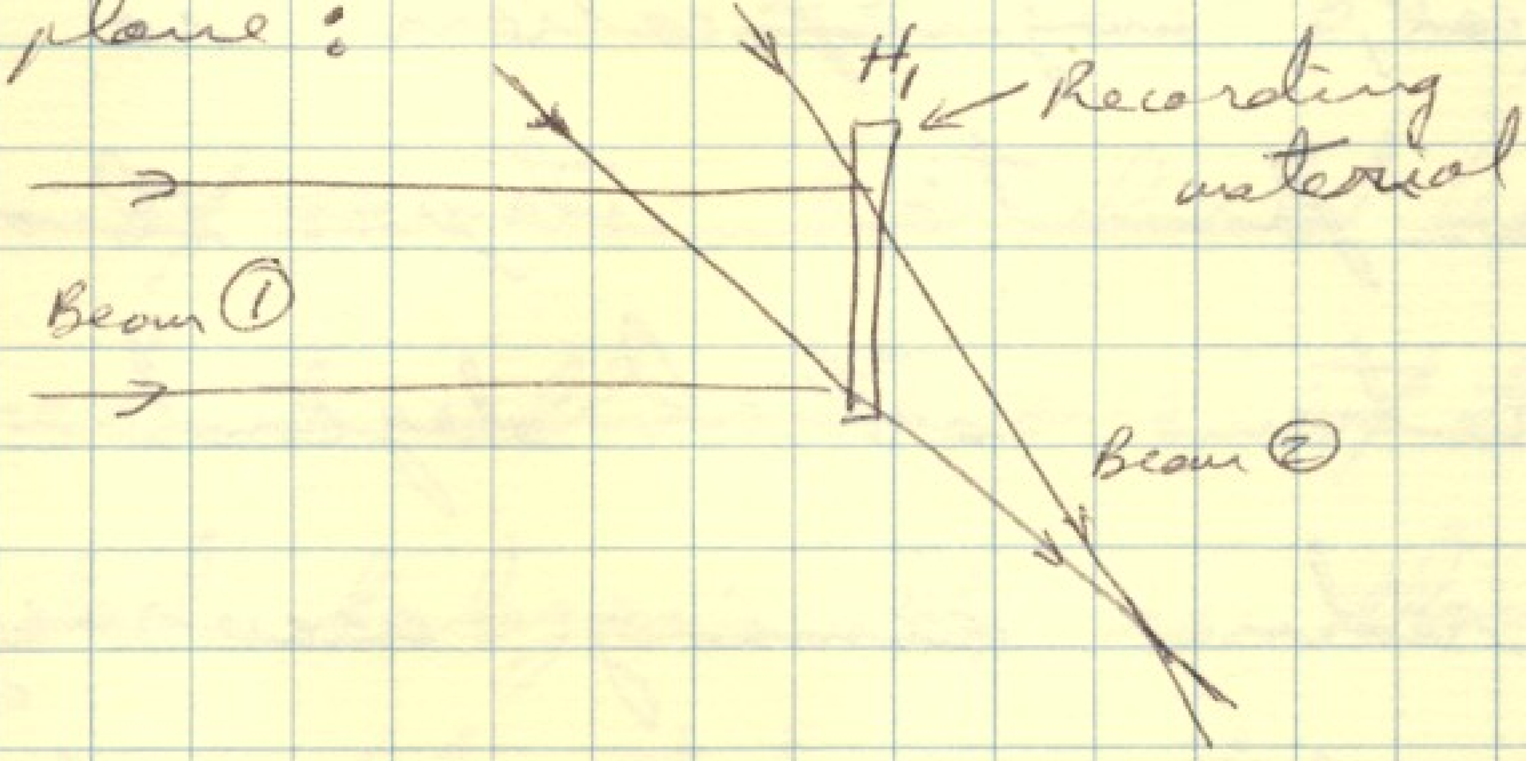
3 September 1975

18 December 1975

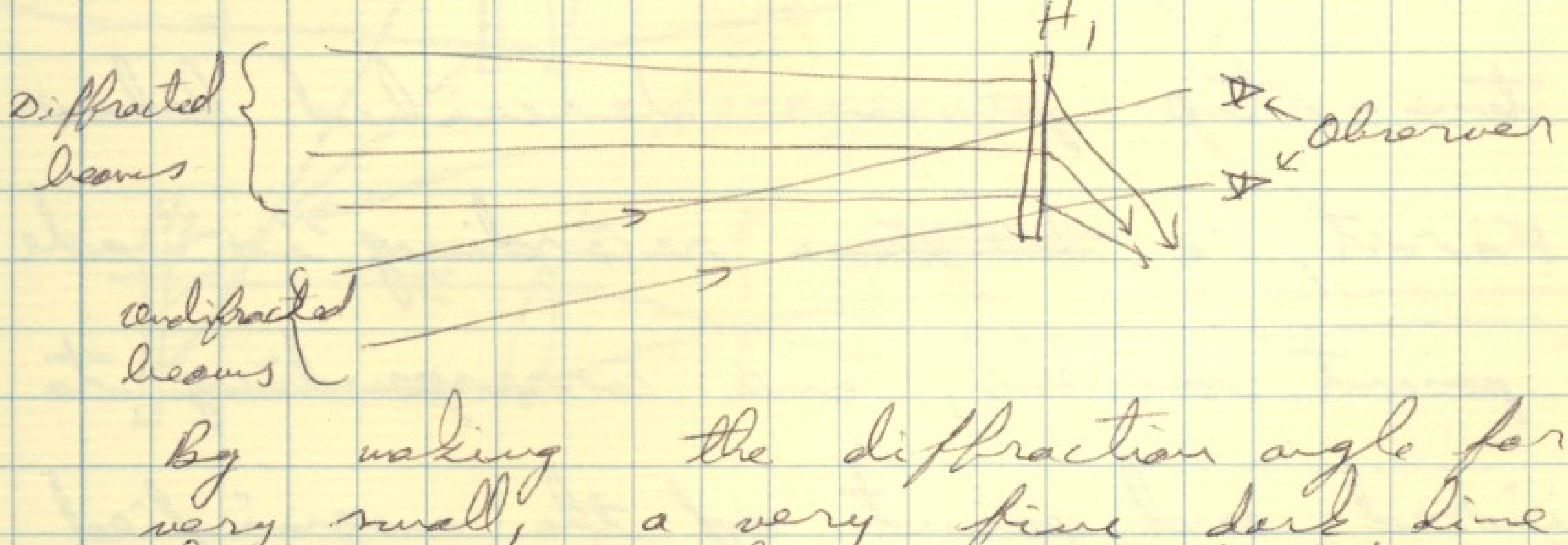
Holographic Sight Using Natural Light

A holographic sight can be constructed from volume ~~holograms th~~ gratings that will form a visible aiming mark using only natural light.

Consider a volume grating constructed by recording a plane wave and second wave, at necessary plane:



If beam two is also collimated, a regularly spaced grating will be recorded. If H_1 is now placed between a scene and the eyes of an observer, some of the light entering the ~~H~~ H_1 at same angle as beam ① will be diffracted and the scene will seem to a have a darker line across it.



By making the diffraction angle for incident light very small, a very fine dark line can be formed. This line will be in same direction as as the grating lings. Two gratings can be assembled with lines not parallel, forming two intersecting dark lines. This intersection can be used as an aiming mark for sights, and such a sight does not require an active, ~~~~ light source to illuminate the gratings.

Juris Upatnieks
18 December 1975

Read and Understood
B. Jin Chang
March 17, 1976

21 January 1976

Construction Technique of
Aberration-Free Light-Line Sight Hologram.

Since light-lines have to relatively short to make hologram construction practical, magnification is needed in the image formation step. this step introduces abberations which degrade image quality an reduce aiming accuracy.

The abberations of the light-line's end point can be eliminated by recording the hologram with an appropriate reference beam. The reference beam is obtained by a two-step process described below.

First, a ~~hologram~~ recording is made of two point sources, one corresponding to the desired end point of the magnified light line and the other to the illuminating point:

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21 January 1976

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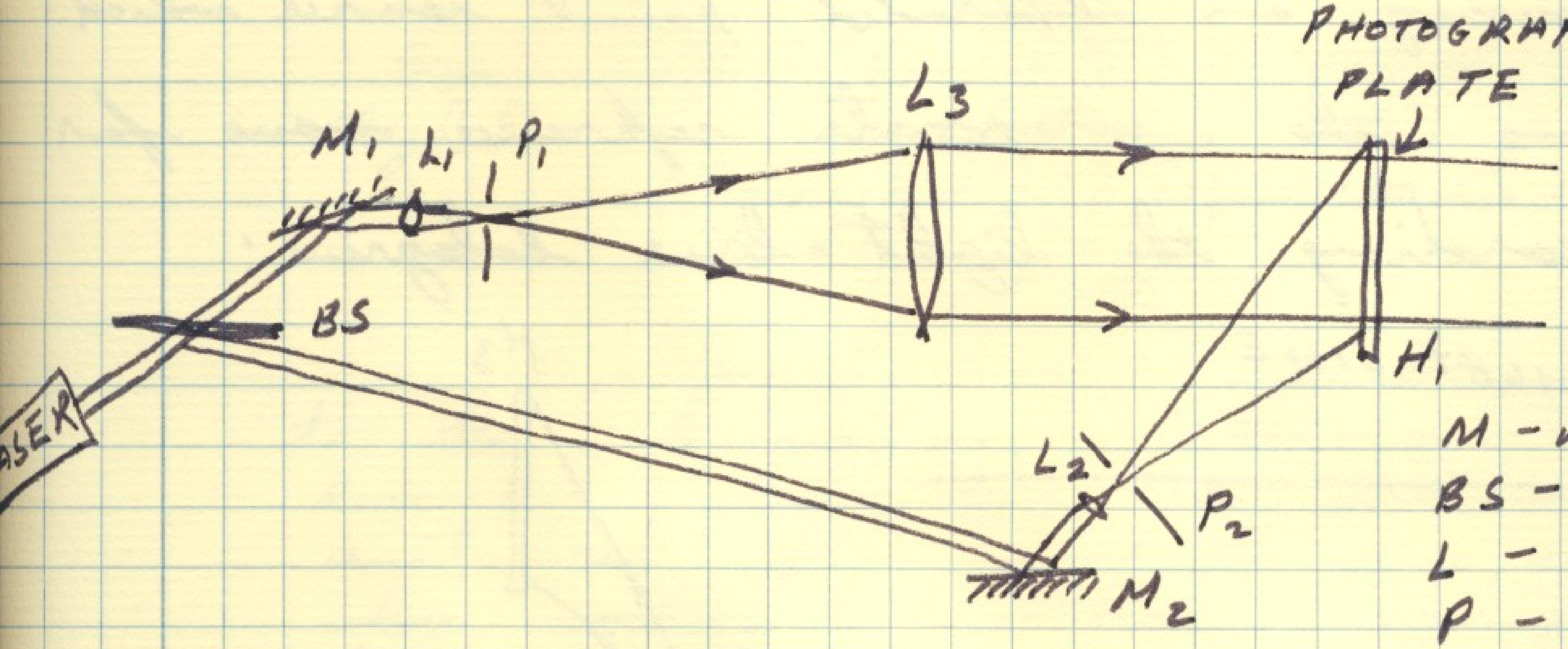
March 17, 1976

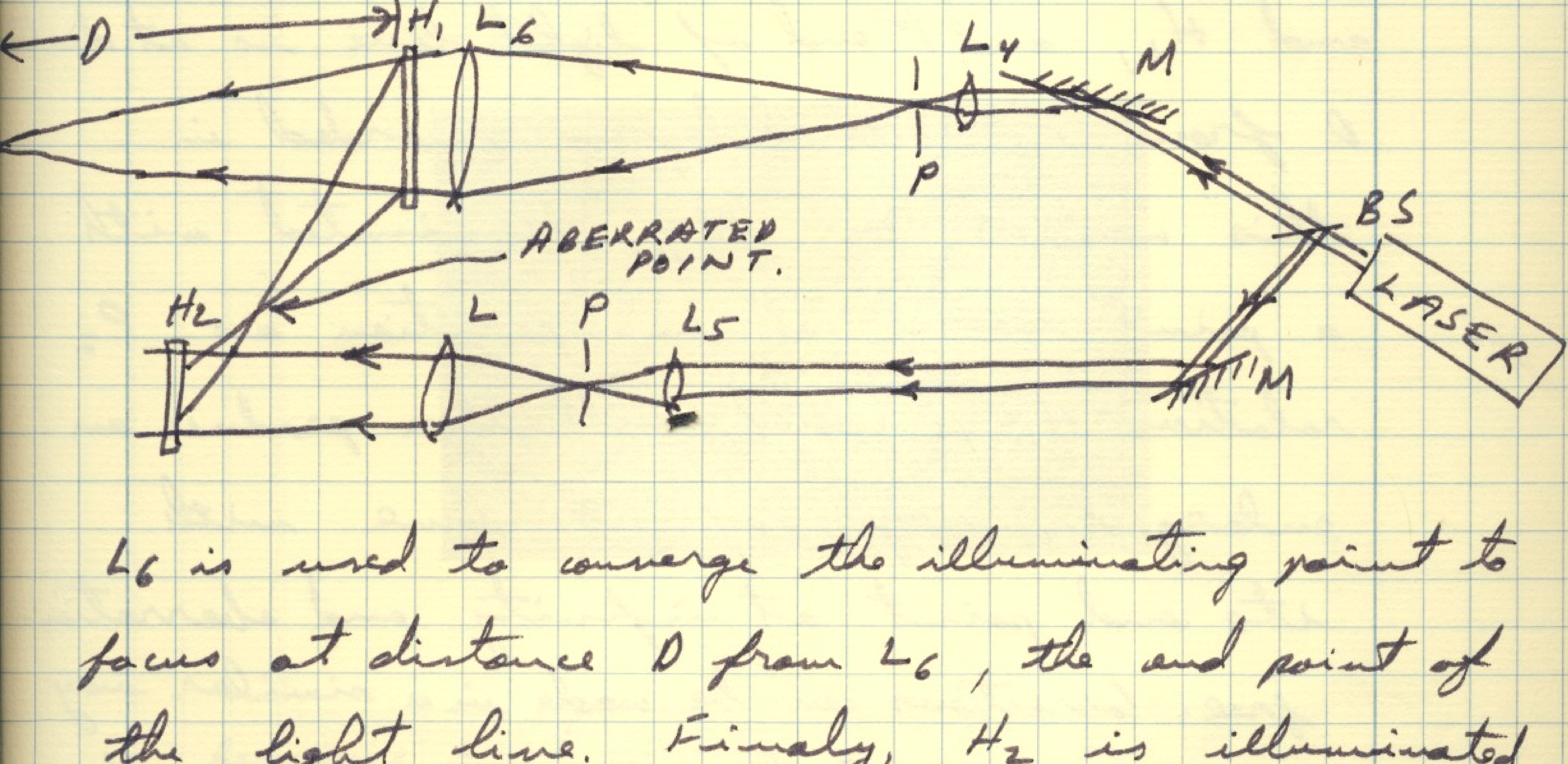
21 January 1976



M - mirror
BS - beam splitter
L - lens
P - pin-hole

Since one of the points should be at infinity, lens L_3 is used to collimate one of the two beams.

The recorded hologram H_1 is then used to generate an abberated point and this abberated beam is recorded on H_2:



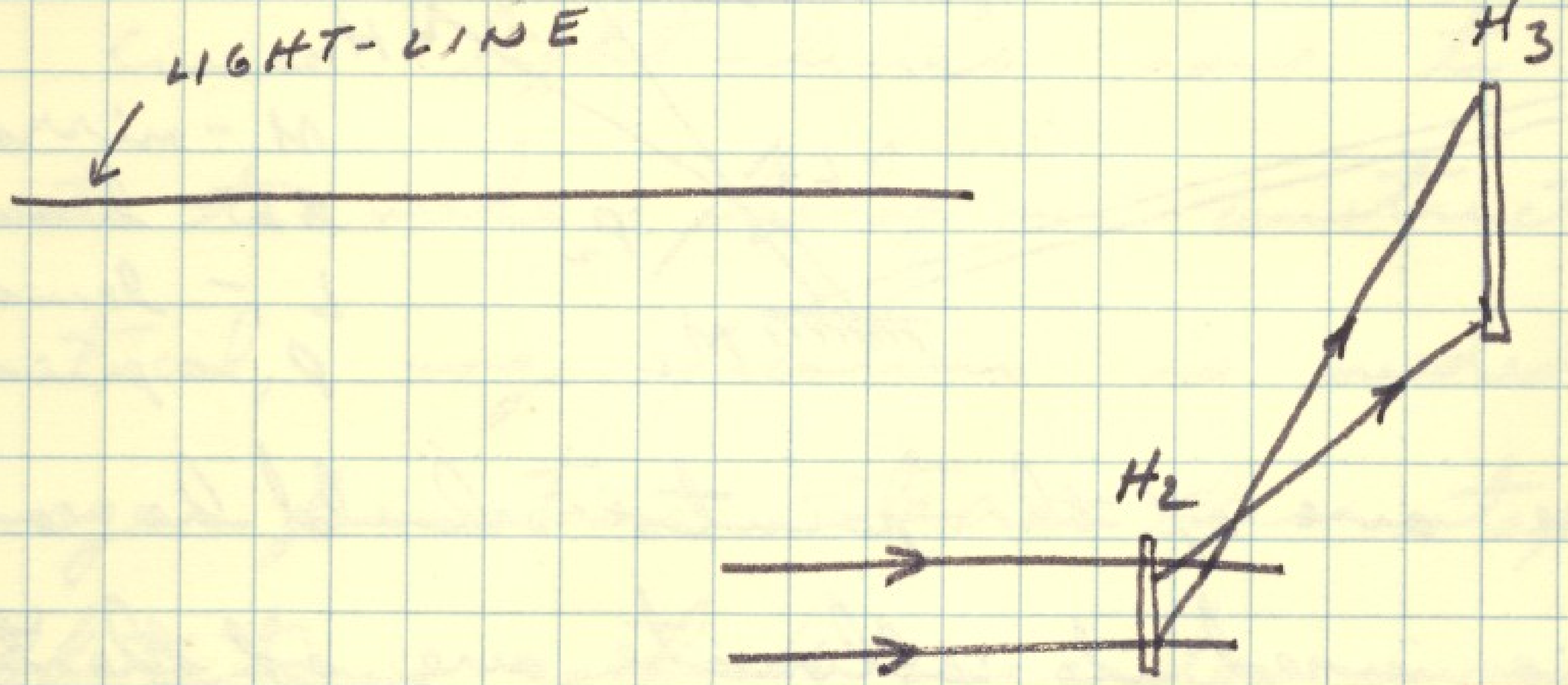
L_6 is used to converge the illuminating point to focus at distance D from L_6, the end point of the light line. Finaly, H_2 is illuminated by a conjugate wave to that shown above

Juris Upatnieks
21 January 1976

Read and Understood
B. Jin Chang
March 19, 1976

21 January 1976.

forming an abberated point source which forms the appropriate reference wave for recording the light-line hologram:



Both the line and H_2 are illuminated with light from the same laser. Also, H_2 and H_3 have the same relative position as H_2 and H_1, and far end of light line is at distan D from H_3. A hologram recorded in this manner can be illuminated with a point source at same position as P_2 relative H_1, which will then produce an enlarged image of the line with its end point at infinity and aberration-free. Corrections can be made in a similar way for end-points of the line closer to the hologram H_3.

Juris Upatnieks
21 January 1976

Read and Understood
B. Jin Chang
March 17, 1976

25 March 1976

Experimental Verification of the Aberration-Free Light-Line Construction Techniques
(Described on pages 138 ~~to~~ 140 of this book)

Experiments were carried out according to the description of the correction technique described previously. The correction element was constructed for end of the line at infinity when magnified and at 280 cm from the hologram at recording. The illuminating point source-to-hologram distance was 273 mm at an angle of 37.2° to the normal of the plate, from the center of recording plate. A hologram was constructed using the aberrated reference wave front generated by H_2 and the object was a point at the end of the light-line. The photographs below show the results.

Reference point generated by H_2, one to one scale.

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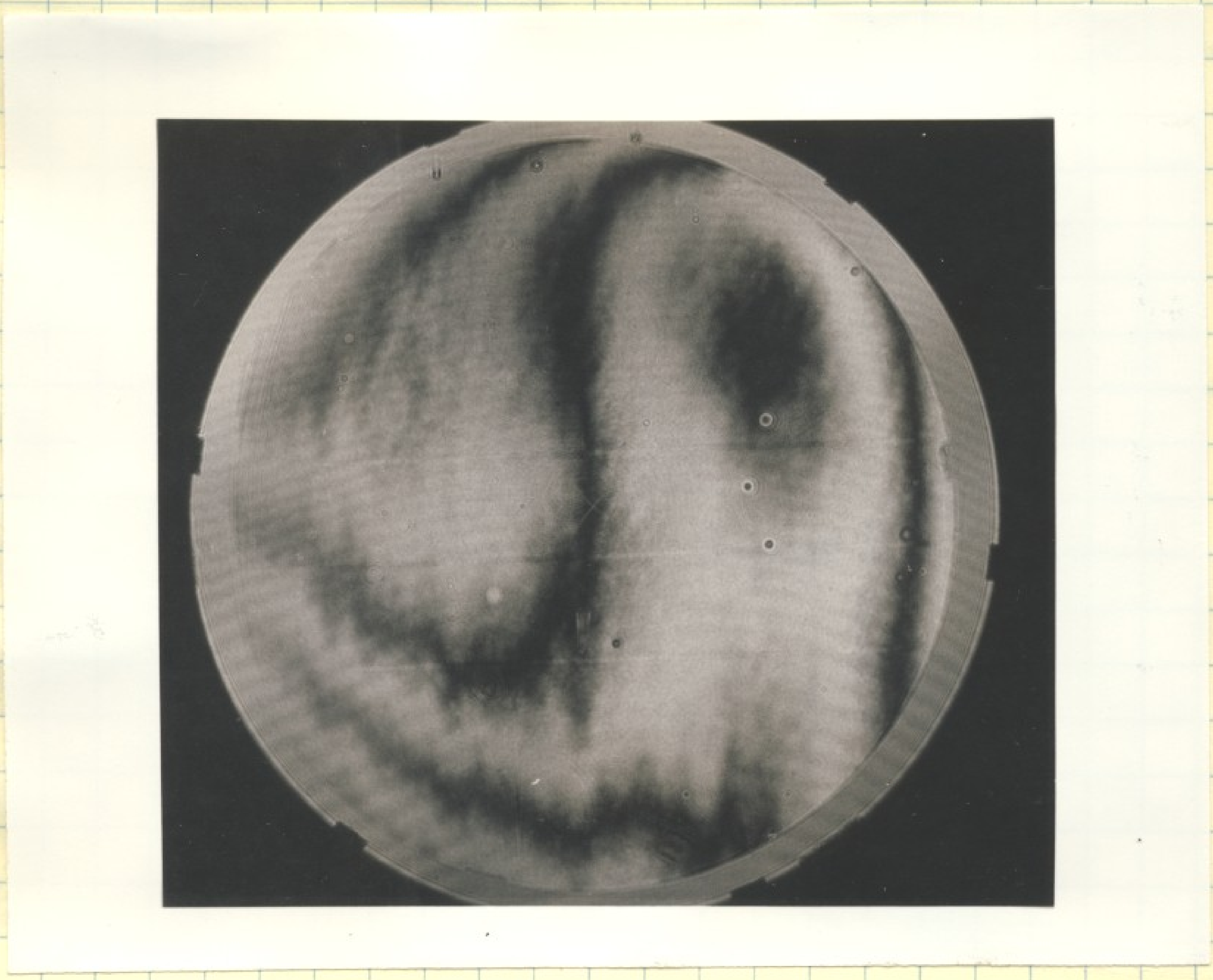
December 21, 1976

Juris Upatnieks
25 March 1976

25 March 1976



Above: ~~ao~~ interferogram of reconstructed wavefront from H_3 illuminated with a point source. H_3 was recorded with the wavefront photographed on the previous page.

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25 March 1976

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December 21, 1976

LIGHT - LINE

LIGHT - WEIGHT SIGHT

J. UPATNIEKS

APRIL 1976

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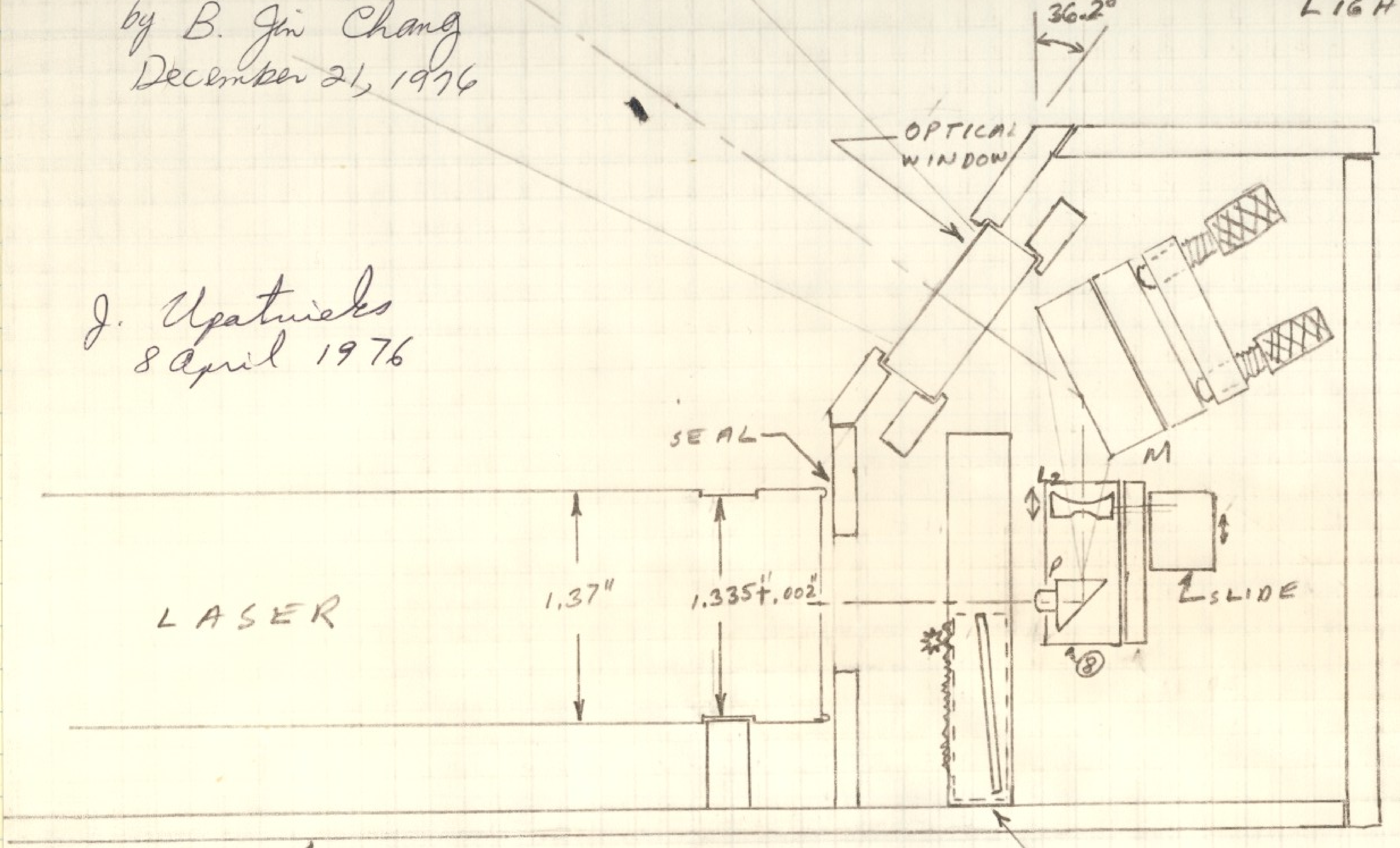
December 21, 1976

J. Upatnieks
8 April 1976



SCALE: ≈ 1:1

E-CHANNEL
1 1/2" WIDE, 3/8" HIGH

ATTENUATOR
SLIDE ASSEMBLY
3/8" WIDE × 2 1/4" LONG × 1/8" THICK

CARRIAGE: 1 1/8" LONG

NOTES:

(1) L_1 : 2.5 mm DIAM., 3.0 mm f.l.

(2) L_2 : 10 mm DIAM., -5 mm f.l.

(3) P : 7×7×8 mm PRISM

(4) WINDOW: 25.4 mm DIAM. × 9 mm THICK

(5) LASER: SPECTRA PHYSICS MODEL 136

(6) M: MIRROR, 25.4 mm DIAM. × 9 mm THICK

(7) L_2 MOUNTED ON SLIDE

(8) PRISM MOUNTING BLOCK

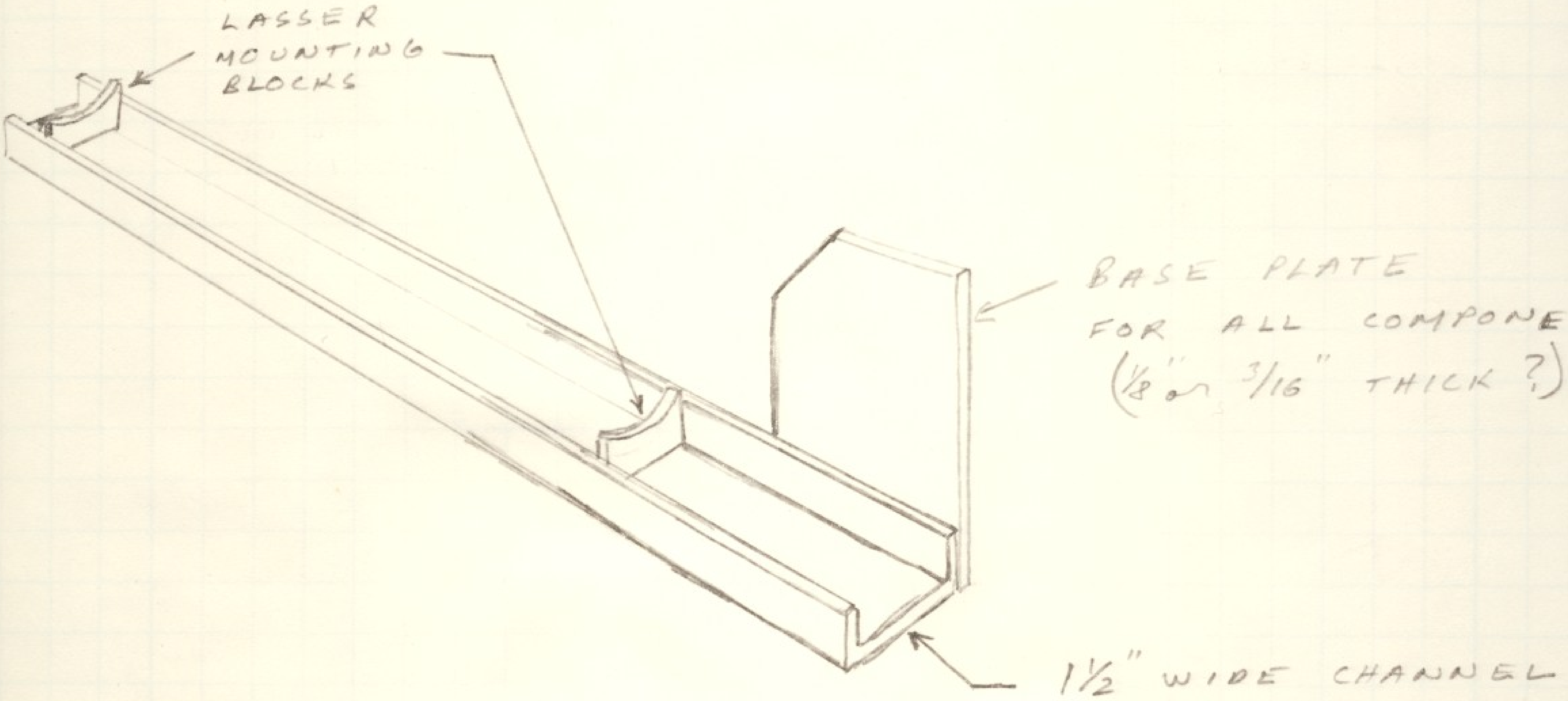
(9) ALL COVER BOLTS + SCREWS RECESSED

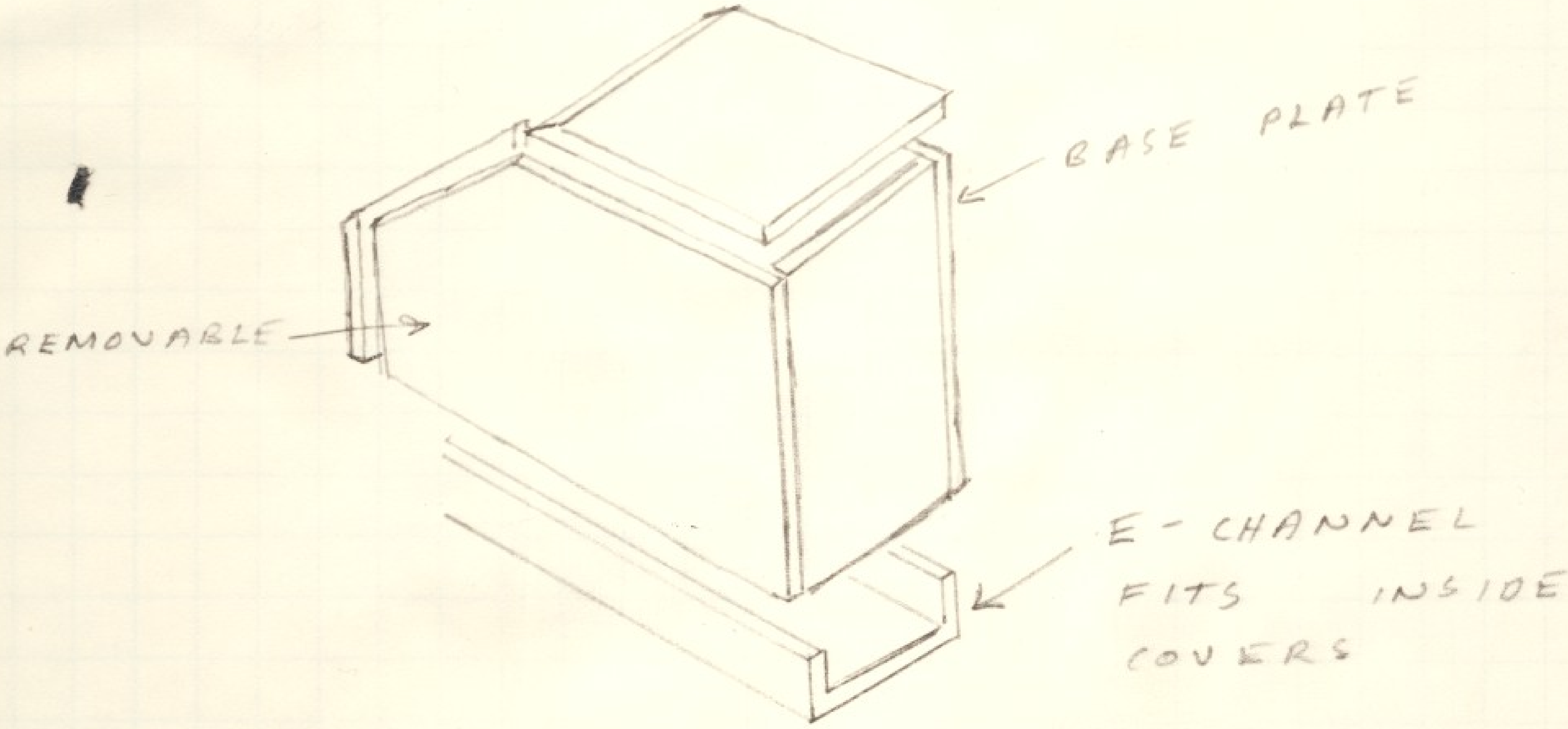
8 April 1976

LIGHT-LINE

LIGHT-WEIGT SIGHT

J. UPATNIEKS
APRLIL 1976





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December 21, 1976

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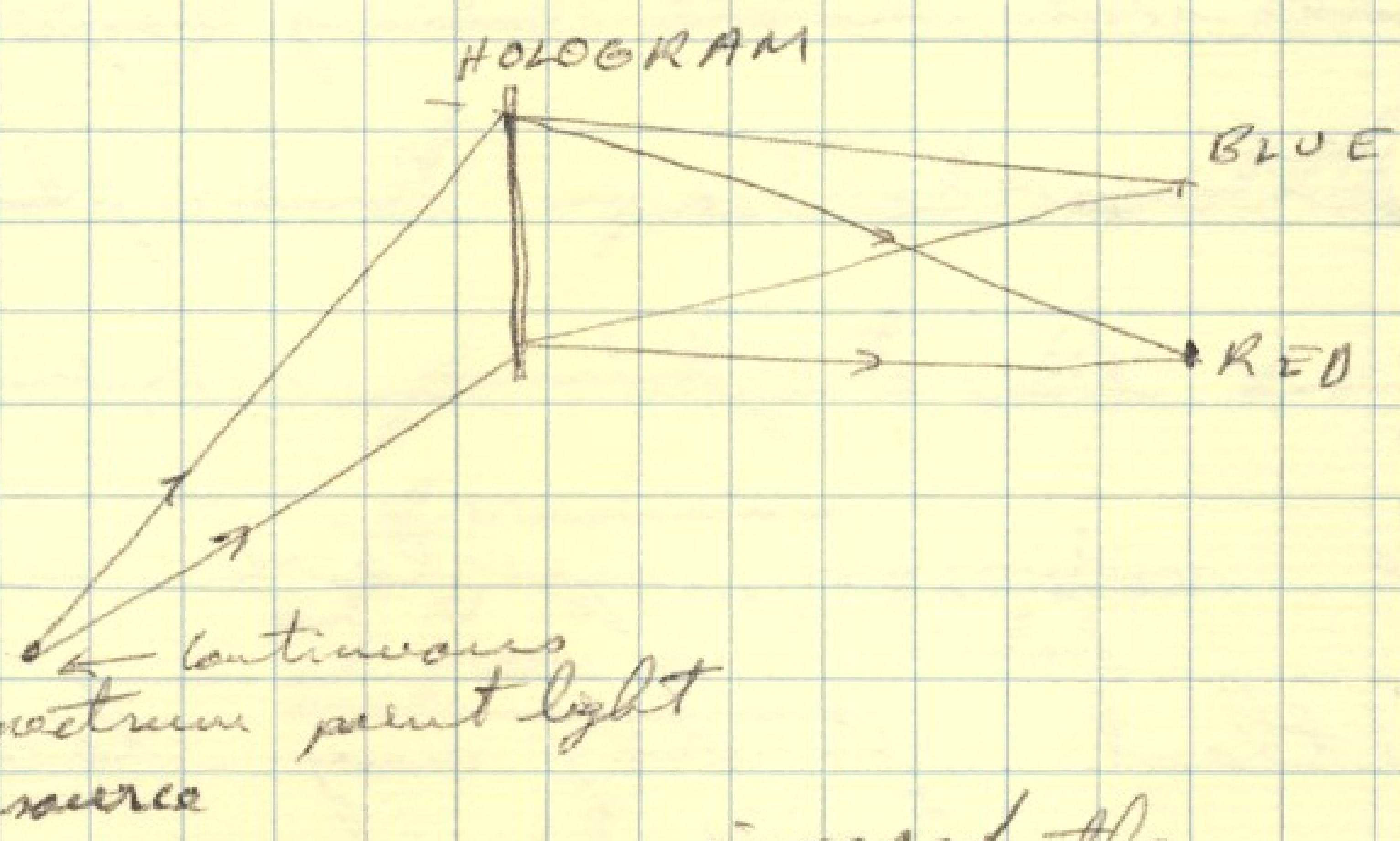
8 April 1976

9 December 1976

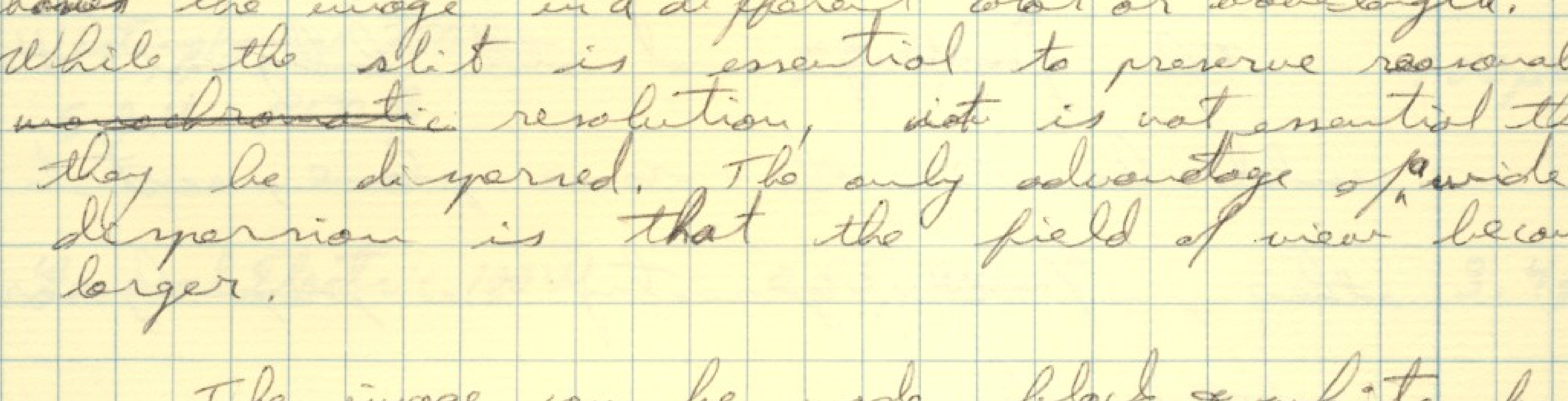
A Method of Producing Black & White 3-D Hologram Images.

Consider the rainbow hologram illustrated below:



The hologram forms real images of the slits. Each "slit" ~~shows~~ the image in a different color or wavelength. While the slit is essential to preserve reasonable ~~monochromatic~~ resolution, it is not essential that they be dispersed. The only advantage of wide dispersion is that the field of view becomes larger.

The image can be made black & white by predispersing the illuminating beam in such a manner that the slits formed by all wavelengths overlap. This can be accomplished by placing an appropriate grating in the illuminating beam, just as it is done with ordinary holograms:



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By B. Jin Chang
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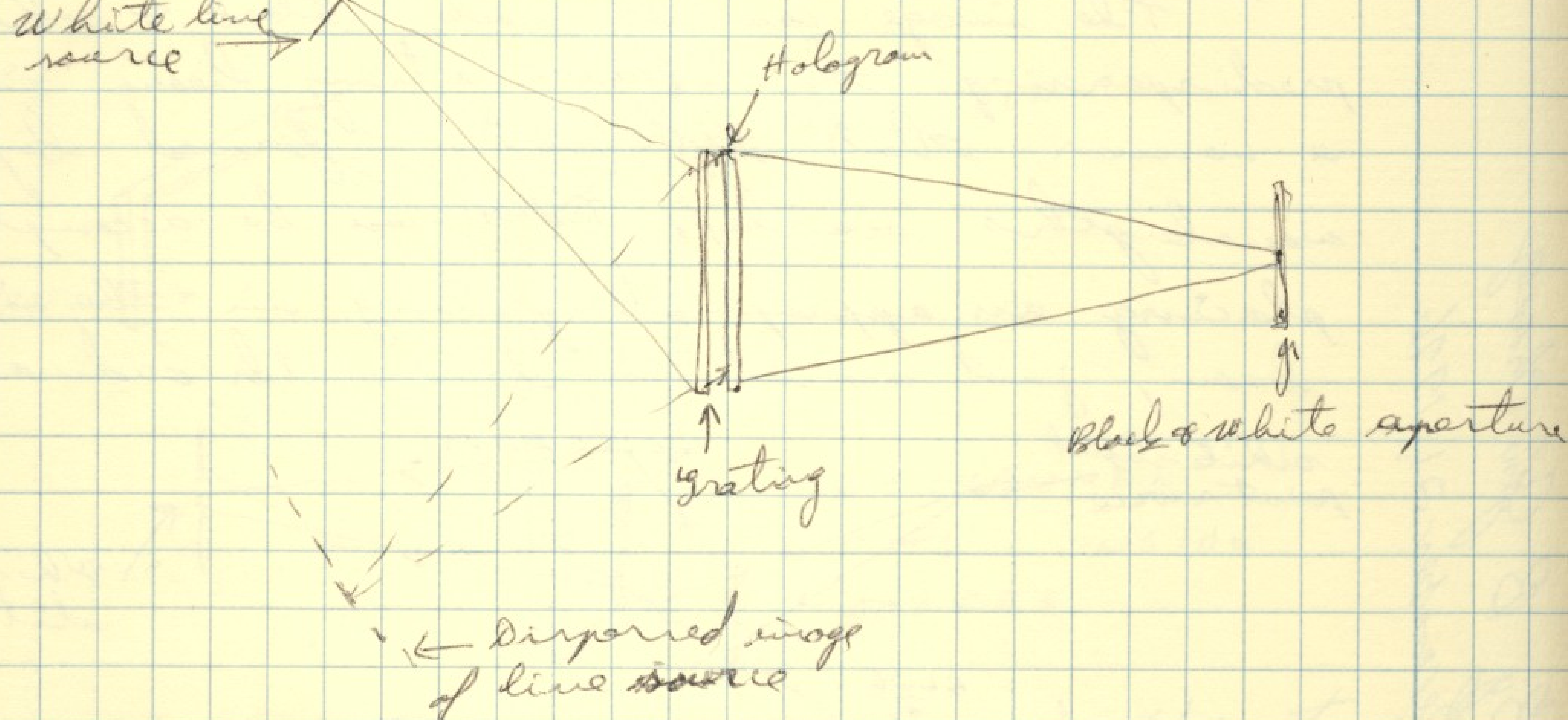
The image viewed through this slit will be black & white since light from images of all colors pass through this slit. To increase the viewing aperture, the point light source can be replaced by long, thin line light source. By this means the viewing aperture will be increased without hardly any loss of image resolution.

The grating and the hologram could be in the same plane, next to each other, if the geometry is properly arranged:



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May 20, 1977

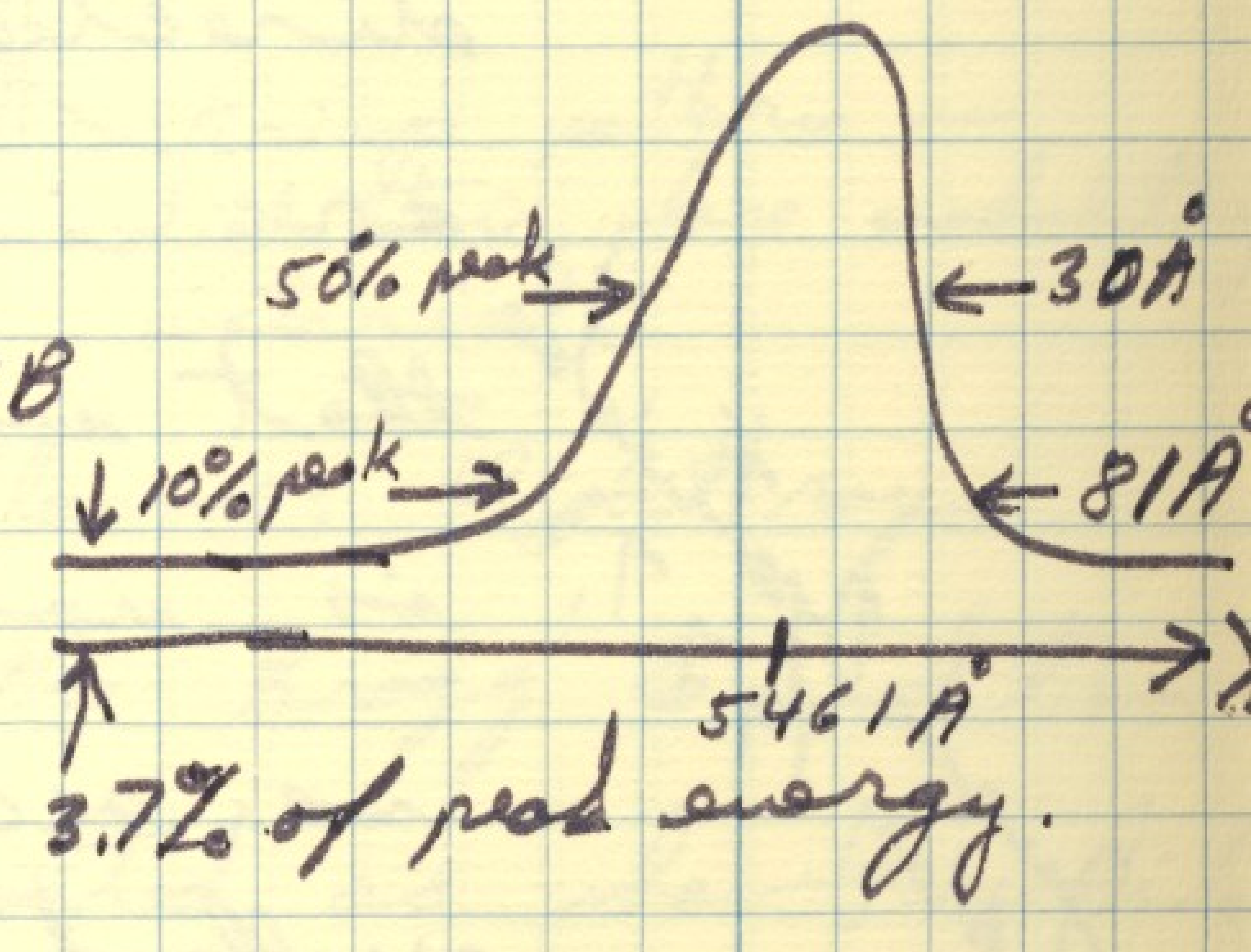
Westinghouse ~~SAH~~ SAH - 250 B Mercury Arc Lamp as a Light Source for Hologram Illumination.

This lamp was examined both for its brightness and spectral width. The brightness was found to be as follows;

Lamp type	Irradiance at ~ 76 cm, 1.2 mm diam. at green line pinhole	Irradiance with ~ 3 mm diam pinhole same as at left atten
1. OSRAM 100 W HBO 107	13 μW/cm²	13 μW/cm² *
2. Westinghouse 250 W SAH - 250 B	22 μW/cm² *	100 μW/cm²
3. General Electric 100 W	0.55 μW/cm²	3.4 μW/cm² *
4. General Electric 85 W	1.5 μW/cm²	8 μW/cm² *

* Estimated

The spectral width of the green line for the SAH-250B lamp was measured as at right.



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20 May 1977.

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The lamp was tested with the 360° holograms. The illumination was sufficiently bright to view unbleached holograms in a normally lit room if no pinhole filter is used (arc length ~3 mm). It is estimated that to obtain equivalent brightness with an argon laser, 90 mW output would be needed. The image appears very sharp and virtually speckle free if viewed from a distance of 6 ft. or more. At close range loss of resolution is visible especially in the vertical direction due to dispersion. The arc is sufficiently small so that imaging it on a pinhole is not essential and direct illumination is acceptable. It seems to be an excellent source for hologram reconstruction. A grating dispersion corrector should greatly improve the image at short observation distances.

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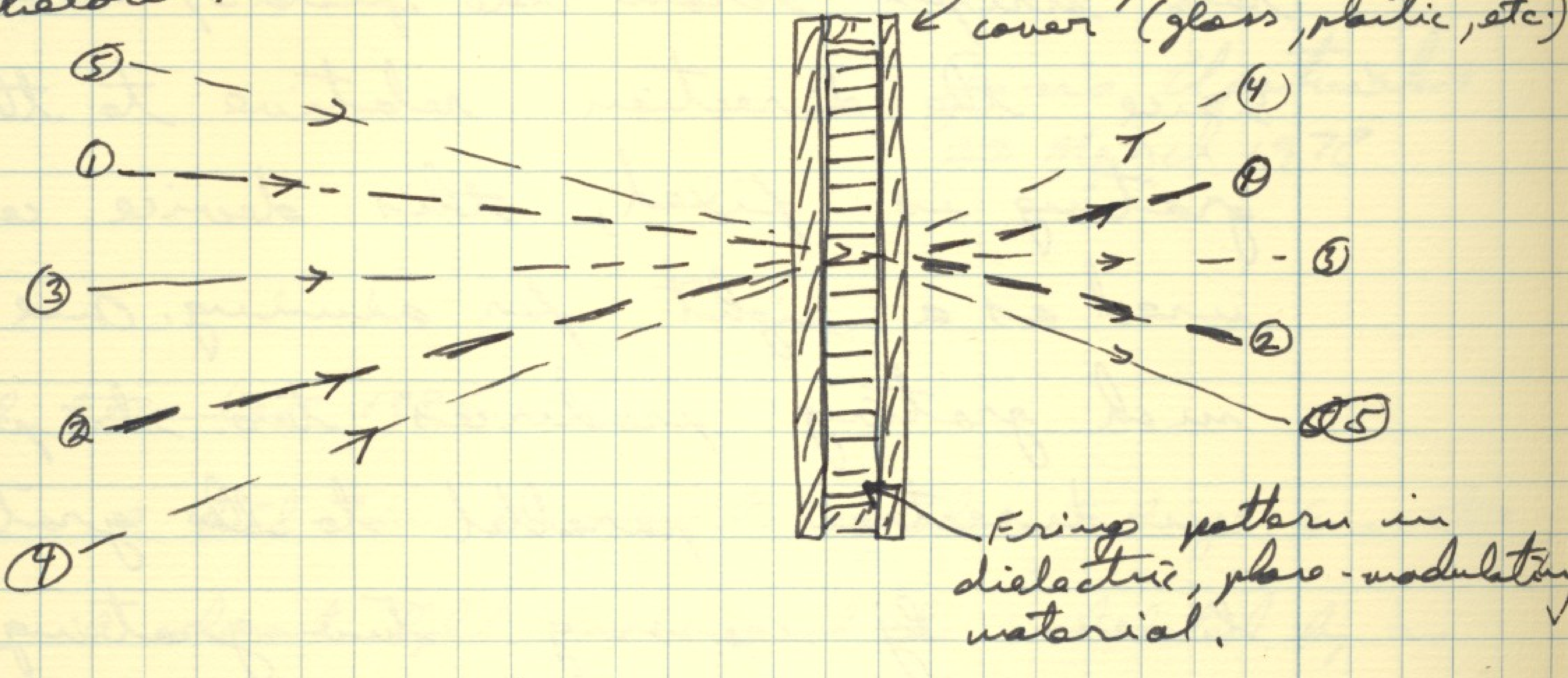
20 May 1977.

22 March 1978

A passive sight

A sight is proposed that does not require an active light source or lenses and that forms an aiming mark at infinity or at a predetermined distance. The basic component of the sight is a very thick grating recorded in a phase material such as, for example, dichromated gelatin. The operation of the sight is shown below:



The sight operates as follows: Light rays 1 and 2, which satisfy the Bragg ~~to~~ condition of the grating, are diffracted as shown while all other rays pass through the plate undisturbed.

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One has therefore the appearance as though looking through a clear glass ~~pl~~ except that in two angular directions, marked by ① & ② in the Figure, the scene is ~~reflected~~ diffracted by the grating. The appearance is though as a strip of image were cut out and inverted, with ~~the~~ image from direction ① appearing in direction ② and vice versa. Thus, an anomality is produced in the image appearing as two strips across the field of view. Since the direction relative to the grating is fixed, this device can be used as a sight for aiming. One such grating produces two stripes in direction parallel to the grating lines. By crossing two gratings, two ~~such~~ sets of such strips are produced in directions not parallel to each other. The orientation is arbitrary

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and could be perpendicular. The direction in which the strips appear to intersect is fixed relative to the grating and therefore designates a fixed direction which, when used as a sight with a weapon, can be used for aiming.

By proper choice of material thickness, refractive index modulation and grating spacing, the apparent width and spacing of the strips can be adjusted.

Juris Upatnieks
22 March 1978

2 December 1982.

A Real-Time Noncoherent-To-Coherent Image Converter.

A coherent light beam could be modulated by an incoherent beam of light, or image formed by one, in the following manner. A reflection hologram is constructed in a high-efficiency recording material in such a way that either due to wavelength shift, ~~or~~

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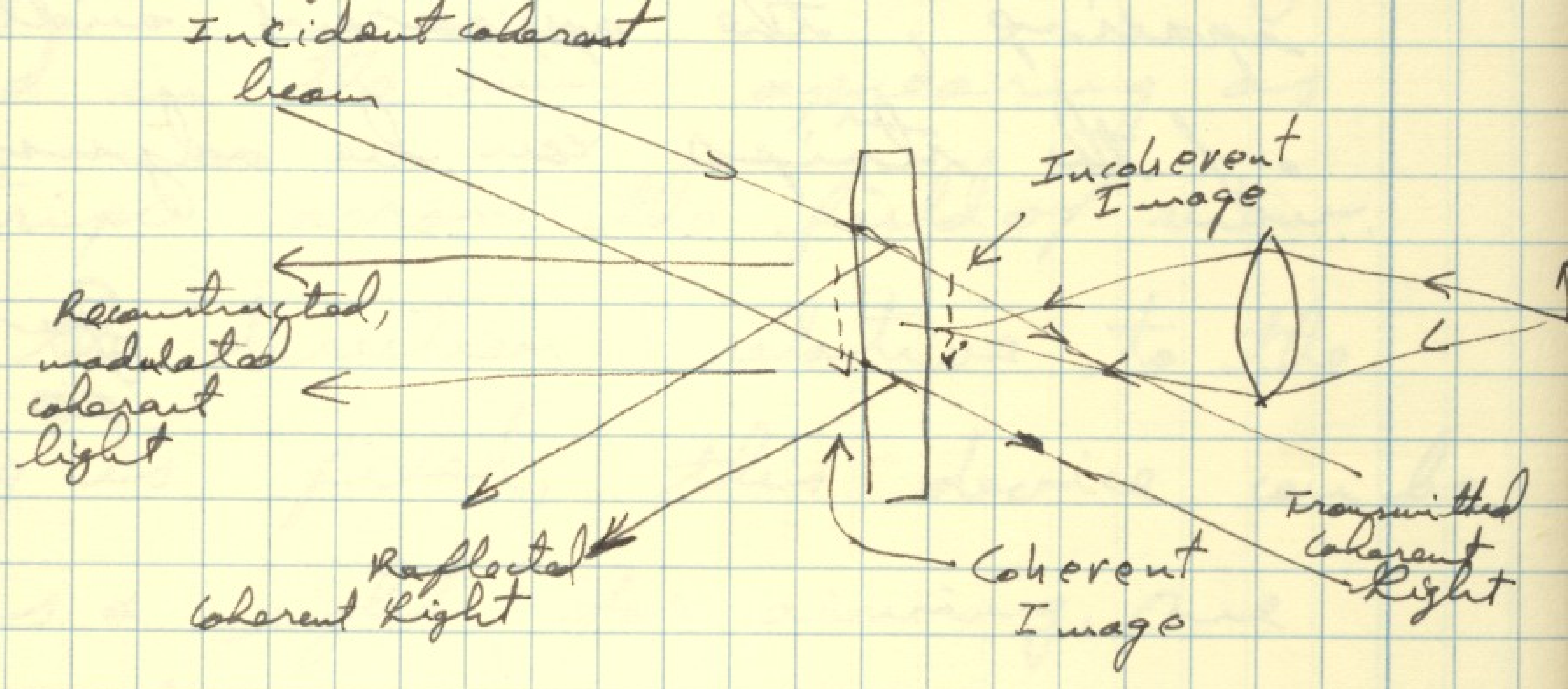
material thickness change or change of illuminating geometry. the reflected reconstructed beam is not forwa[rd]
The hologram is then illuminated with incoherent light causing fringe spacing changes. These changes may be caused due to localized heating or photochemical changes. The illuminating beam is arranged in such a way that ~~after~~ changes in fringe spacing cause light to be diffracted, thus modulating the incident coherent beam.



An absorbing material might be added to convert incident coherent light into heat and to block incoherent light from passing through the element. alternatly, The reconstructed beam may be arranged in a different direction from that of the incoherent light beam.

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December 2, 1982