Holographic storage in bleached emulsion of N divergent object beams generated by a two-dimensional regular array: analysis of the signal-to-noise ratio

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The signal-to-noise ratio (SNR) of multiplexed holograms of N object waves recorded as volume-phase holograms in bleached silver halide emulsion are experimentally analyzed and compared with those of diffuse-object holograms. We introduce two types of SNR: one belonging to the spatial matrix itself, and the other, the overall SNR, for which the angular range of the matrix distribution was compared with the primary diffuse object. The experimental results obtained show that, even though the same range of spatial frequencies is maintained, the total number of waves that come from the matrix distribution affects the measurements, so the interrelation between the spatial-frequency distribution of noise and the number of storage waves is obtained, and the minimum SNR can be evaluated for diffuse objects.

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1. Introduction

The storage of a great number of object waves is required for the design of both holographic memories and holographic optical interconnects. The problems related to noise that come up during recording and reconstruction of these devices are quite similar and can be analyzed to improve the image quality that these optical systems provide. Noise also seriously limits the storage density, which is why the maximum storage density is a function of the hologram's signal-to-noise ratio (SNR).¹ Volume-phase holograms are attractive for holographic storage because of their high potential efficiency and high information densities. Bleached silver halide emulsions have long been used as media for recording volume-phase holograms because of several attractive advantages that they offer and because this type of material is available for holographic storage.²

Unfortunately, although the resulting phase holograms have a high diffraction efficiency, this property is usually accompanied by an increase in the noise and a consequent reduction in image quality.³

In this paper we analyze noise in experimental cases in which a large number of coherently shaped object waves are stored in a phase-recording material in a way that allows us to obtain information about the relation that exists between the recording material, the number of waves that are being stored, and the spectral distribution of the object waves. Holograms were recorded by the use of a collimated reference wave and N divergent object waves. The experimental results obtained were compared with the results obtained for diffuse-object holograms because such holograms are an extreme case of holograms with a large number of object waves.^{4,5} As we can see from the bibliography, this type of hologram has been widely studied and provides an excellent example.^{6,7}

2. Experimental Results

To analyze the influence of the number of object waves on the characteristics of diffuse-object phase holograms, we use three objects that, when illuminated by transmission, give rise to specific, or almost specific, sources. These are situated in a very orderly way, almost like a matrix, so that the emerging

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Fig. 1. Experimental setup for recording spatial-frequency-multiplexed volume-phase diffuse-object holograms of N object waves.

wave from each specific source can be considered as an object wave. In this way, by varying the size of the matrix, we can vary the number of object waves and the spatial-frequency distribution of the object waves. In Fig. 1 we show the experimental setup used in the study. The object-wave matrix that we just mentioned above was obtained by the use of different spatial filters with varying spatial-frequency distributions. The matrices of the spatial filters were pasted onto a plate of diffusing glass so that, when they were illuminated, each transmission spatial filter acted as a specific source from which an object wave emerged. Object 1 is a diffuse object (the primary diffuse object) measuring $2\text{ cm} \times 2\text{ cm}$ and has an opaque central zone measuring $1\text{ cm} \times 1\text{ cm}$ [Fig. 2(a)]. Object 2 is a diffuse object measuring $2\text{ cm} \times 2\text{ cm}$ and is formed by a matrix of 8×8 specific sources, equidistantly distributed. It generated $N = 64$ object waves [Fig. 2(b)]. The circular spatial filter of the sheet corresponding to the matrix of 8×8 sources had a diameter of $(0.97 \pm 0.02)\text{ mm}$ and an area of $(0.73 \pm 0.03)\text{ mm}^2$. When we wish to store a great number of waves we must increase the size of the plane on which the spatial filters are placed if we want to maintain the angular size distribution of the object waves, and, as a result, both the number of object waves and the range of frequencies with which we are going to work vary. Therefore we now introduce another spatial distribution of matricial spatial filters into this study: a $4.5\text{ cm} \times 4.5\text{ cm}$ square formed by a matrix of 18×18 specific sources (object 3). It generated $N = 324$ object waves [Figure 2(c)].

Intermodulation noise greatly influences diffuse-object holograms and is also a noise that depends on the object's spatial frequency. Thus, by introducing a larger size, we increase this spatial-frequency range, and it then becomes necessary to see if this modification really influences the hologram's SNR. In this sense, there is one characteristic that object 3 possesses with respect to matrix distribution that differs from the characteristics for object 1, and that is precisely the range of spatial frequencies that is covered: For object 1, this range is continuous, and

Fig. 2. Geometries of (a) object 1, (b) object 2, and (c) object 3.

for the other objects it is discrete. The information corresponding to the spatial frequencies ν that define the matrix object is listed in Table 1. The maximum spatial frequency $\nu_{\max}$, the minimum spatial frequency $\nu_{\min}$, and the total number of spatial frequen-

Table 1. Spatial Frequencies of Diffuse Objects 1–3 Used in the Analysis

Object Number	$\nu_{\max}$ (lines/mm)	$\nu_{\min}$ (lines/mm)	Number of Spatial Frequencies	ν (lines/mm)
1	105	53	continuous	53–105
2	92	13	4	13, 39, 66, 92
3	223	13	8	13, 39, 66, 92, 118, 144, 170, 223

cies that each range provides are shown for each object. In Table 1 we also include data on $\nu_{\max}$ and $\nu_{\min}$ corresponding to object 1 to compare the continuous spatial-frequency distribution with the discrete. The error in determining these spatial frequencies through geometric measurements is 5%.

In the study of holograms recorded from the matrix objects described above, the parameter that has been most closely analyzed is the SNR, because we consider this to be the most significant factor in relation to the characteristics of these holograms. The following equations were used to obtain SNR's for object 1 and object 2, the overall SNR ($\text{SNR}_{\text{overall}}$) of object 2, and the SNR and $\text{SNR}_{\text{overall}}$ of object 3:

$$\text{SNR} = \frac{\frac{1}{2} \sum_{i=1}^2 I_{\max i}}{I_{\min}},$$

$$\text{SNR} = \frac{\frac{1}{8} \sum_{i=1}^8 I_{\max i}}{\frac{1}{7} \sum_{i=1}^7 I_{\min i}},$$

$$\text{SNR}_{\text{overall}} = \frac{\frac{1}{2} [\text{maximum}(I_{\max 1,2}) + \text{maximum}(I_{\max 4,5})]}{\text{minimum}(I_{\min 2,3})},$$

$$\text{SNR} = \frac{\frac{1}{18} \sum_{i=1}^{18} I_{\max i}}{\frac{1}{17} \sum_{i=1}^{17} I_{\min i}},$$

$$\text{SNR}_{\text{overall}} = \frac{\frac{1}{2} [\text{maximum}(I_{\max 6,7}) + \text{maximum}(I_{\max 12,13})]}{\text{minimum}(I_{\min 7,8,9,10,11})},$$

respectively. The intensities that appear in the definitions of the SNR's are defined in Fig. 2. For objects 2 and 3, two SNR's were identified. The first SNR is typical of these objects,⁸ and the second, the overall SNR, was introduced to permit the comparison of its values with those obtained when object 1 was used, taking into account the spatial frequency associated with the measurements taken. In the definition of $\text{SNR}_{\text{overall}}$ we took into account the max-

imums of the matrix distribution that emerged within the shiny angular range that object 1 forms from the center of the holographic plate. We did the same for the minimums, this time keeping in mind the angle that is formed as a result of the opaque square. In this way we can make sure that the range of spatial frequencies associated with the signal is always the same and that the range of spatial frequencies associated with noise is also always the same. This way the data obtained can be compared.

Intensities were measured by use of a photodetector with a range of up to 10^{-7} W/cm² to scan the real reconstructed image. According to the experimental measurements and the repeatability of the photochemical process, the error in the SNR is 7%.

Holograms were recorded with Agfa-Gevaert No. 8E75 HD emulsion at 632.8 nm by the use of a He–Ne laser with a $K = 5$ reference-to-object-beams ratio for each exposure. The distance of the object from the recording medium was 30 cm, and the reference beam was collimated and formed a 37.5° angle with the normal of the plate, which was parallel to the object [see Figs. 1 and 3(a)]. Reflections from the glass plate were eliminated by the placement of an index-matched absorbing layer against the glass side of the photographic plate; this layer prevented the recording of unwanted gratings. After exposure, the plates were developed in a developer comprising phenidol, ascorbic acid, and sodium carbonate (PAAC) (for composition, see Table 2). The developed plates were rinsed briefly and bleached without a fixation step. The bleach bath used in these experiments was EDTA [(ethylenedinitrilo)tetraacetic acid; for composition, see Table 2], a rehalogenating bleach bath. In this rehalogenating bath, the bleach

Fig. 3. Schematic diagrams showing (a) recording, and (b) reconstruction of multiplexed holograms.

Table 2. Film Developer and Bleach Bath Formulas

Film-Processing Solution	Amount of Compound
PAAC developer	
Sodium carbonate	120 g
Ascorbic acid	18 g
Phenidon	0.5 g
Distilled water	1 L
EDTA rehalogenating bleach bath	
Ferric sulfate	30 g
Potassium bromide	30 g
Sulphuric acid	10 ml
Distilled water (to make)	1 L

contains a rehalogenating agent (potassium bromide) that converts most of the developed silver back into a silver halide. In this case a phase hologram is obtained mainly as a result of the transfer of silver halide between the unexposed and exposed areas. Rehalogenating bleaches have an advantage in that the resulting emulsion-thickness change produced by these baths is very small ($<0.05 \mu\text{m}$) in the nominally thick $6\text{-}\mu\text{m}$ film,⁹ as the overall removal of silver salts from the emulsion is minimal. Also it is assumed that the average refractive index does not change appreciably as a result of processing.⁹

As the thickness and the average refractive index of the holographic recording material show very little change when these types of chemical-processing techniques are used, the reconstruction geometry of the holograms corresponding to the maximum diffraction efficiency coincides with the construction geometry if the recording and readout wavelengths are equal. This limited change implies that Bragg's law is complied with in the reconstruction stage, even though sometimes there is displacement of the Bragg angle that is caused by sheartype effects.^{10,11} Details of the processing schedule (Table 3), as well as of the developer and bleach bath formulas, are given in Tables 2 and 3.

After processing, the holograms were replayed in air with the conjugate of the collimated reference wave, and the diffracted output beam formed the real image of the object considered [Figure 3(b)]. The SNR was measured with the same wavelength that was used during the recording stage. Figure 4 compares the SNR of object 2 (64 waves) with the SNR of

Fig. 4. SNR as a function of the exposure intensity when reconstruction is performed at the Bragg angle for object 2, with 64 waves (squares with dots) and object 3, with 324 waves (filled diamonds).

object 3 (324 waves). We can see that there is a range of exposures, specifically between 10 and $50 \mu\text{J}/\text{cm}^2$ (the linear region of the $D\text{-log } E$ curve of the developer), in which both objects have similar values, but for the rest of the exposures the SNR corresponding to 64 waves had better values than that corresponding to 324 waves. This is fundamentally due to the fact that the larger-sized object—object 3, which produces 324 waves—also produces a larger number of spatial frequencies in the noise space, which in turn increases the intermodulation noise and therefore decreases the SNR.

By representing the overall SNR of objects 2 and 3 graphically with the SNR of object 1, as we can see from Fig. 5, we find that even though the same angular range for these two parameters has been maintained—and therefore the same range of spatial frequencies—the total number of waves that comes from the object, and therefore the real range of spa-

Fig. 5. Overall SNR as a function of exposure when reconstruction is performed at the Bragg angle for object 2, with 64 waves (squares with dots), object 3, with 324 waves (filled diamonds), and object 1, a diffuse object (DO; filled squares).

Table 3. Film-Processing Schedule^a

Procedure	Time (min)
Step 1: Develop	3
Step 2: Rinse in running water	1
Step 3: Bleach	≈3
Step 4: Wash in running water	5

^aAll solutions at 20 °C.

tial frequencies that the object contributes, affects the measurements. As a matter of fact, the results confirm this, given that the overall SNR curve for object 3 (filled diamonds) is closer to that of object 1 (filled squares) than is the curve corresponding to object 2 (squares with dots). In addition to this relation, we see that the curve associated with object 3 is flatter. This means that the overall SNR of object 3 not only depends less on the value of the exposure being considered, but that it also depends less on the work zone in the D -log E curve of the developer. This experimental result is in keeping with a previous theoretical result reported by Kostuk.⁵ At high exposures we obtained an increase in the SNR, similar to the result pointed out in previous papers^{3,6} on diffuse-object holograms.

3. Conclusions

In summary, a study was done on multiplexed volume-phase holograms made in a bleached photographic emulsion; the study had applications to optical storage. The experimental measurements presented in this paper on the SNR's of diffuse-object holograms show that a correlation does exist between noise and the number of waves that are stored coherently. These results demonstrate a connection between the value that is hoped for as a minimum when N waves are stored and the noise that appears when they are reconstructed at the same time. In a previous paper¹² similar experiments performed on arrayed objects (for $N = 3$) were described. The main differences between the results reported in our paper and those from Ref. 13 are that, in Ref. 13, the objects were lines rather than points and the lines were organized in a one-dimensional rather than a two-dimensional array. Finally, and from the perspective of consideration of recording materials,⁷ it seems reasonable to think that, given a specific holographic material and knowledge of the relation between the object wave and the reference wave, if we store a diffuse-object hologram, the SNR that is obtained for the condition of the material can establish

a certain minimum limit on the value of the SNR for that material when a finite number of N waves are to be stored, without modification of the diffraction efficiency.

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