

# Hologram Heterodyne Scanners

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*Several techniques are proposed in this paper which use a scanning coherent light beam to produce an electrical signal which corresponds to a scanned hologram. The hologram itself is not formed at the transmitting end of the system as a physical entity, rather the modulated electrical carrier frequency corresponding to the spatial carrier frequency of the hologram is generated by heterodyning. An advantage of the hologram heterodyne scanner is that it reduces the spatial resolution required of the camera tube in a holographic television system by at least a factor of four.*

## I. INTRODUCTION

In principle, it is possible to conceive of a holographic television system, but a practical system hinges on removing a number of formidable roadblocks. Among these is transducing the holographic information into a relatively narrowband electrical signal by means of a camera that has limited spatial resolution. This problem is shared by both a three-dimensional and a two-dimensional holographic system, but with present technology the 3-D system certainly presents many more problems. The two-dimensional system becomes much more tractable if the camera resolution problem is overcome. It is to this problem and our proposed solution that this paper addresses itself.

Consideration of this problem is not new, as evidenced by the early outline of the bandwidth requirements of a holographic television system by E. N. Leith and others in 1965.<sup>1</sup> There have also been reports of experiments involving the transmission via television of a Fresnel type of hologram in which the original object was a transparency.<sup>2, 3</sup> The difficulties encountered in these transmissions illustrate the crux of the problem.

A hologram consists of low spatial frequency information (dictated by the spatial information content of the object) which has been modulated onto a high spatial carrier frequency derived from the

interference of the reference and object beams. Conventionally, a television camera converts a spatial display, which in this case is a hologram, into an electrical signal by scanning it with an electron beam. However, the camera has a spatial frequency response that is low-pass in nature and limited in extent. Hence, the spatial carrier frequency rests out on the skirt of the passband, and the positive and negative sidebands are thus treated differently, producing distortion. We have so far lacked a feasible technique which would allow the effective use of the available bandwidth. That is to say, we need a technique which would allow the hologram information to be low-pass in nature until after being processed by the photosensitive surface of whatever transducer is used. The method we propose, which we call the heterodyne scanner, does exactly this. As a consequence, the required spatial resolution is reduced by at least a factor of four compared with the transmission of a conventional off-axis reference beam hologram.

The technique we propose envisions a scanning coherent light beam to produce an electrical signal which corresponds to a scanned hologram. In contrast with conventional methods, the hologram itself is not formed at the transmitting end of the system as a physical entity; instead the modulated electrical carrier frequency corresponding to the spatial carrier frequency of the hologram is generated by heterodyning.

These heterodyne scanners have important potential advantages over conventional methods of scanning. First, the nuisance terms corresponding to the direct beam in the reconstruction of a conventional hologram are not transduced. This halves the scanning beam aperture's resolution requirements. Second, the necessity for resolving the spatial carrier frequency of the equivalent hologram with the scanning beam is circumvented. This halves again the scanning beam resolution requirements, thus reducing resolution requirements to a quarter of the original requirements.

Let us briefly review the formation of a conventional hologram in order to point out the terms involved in the formation and reconstruction. We will then be in a better position to discuss the desired reduction and the means for accomplishing it.

## II. CONVENTIONAL HOLOGRAM

Figure 1 depicts a typical holographic situation, showing an object beam

$$E_o(x, y) = A_o(x, y)e^{j[\omega_o t + \phi_o(x, y)]}$$

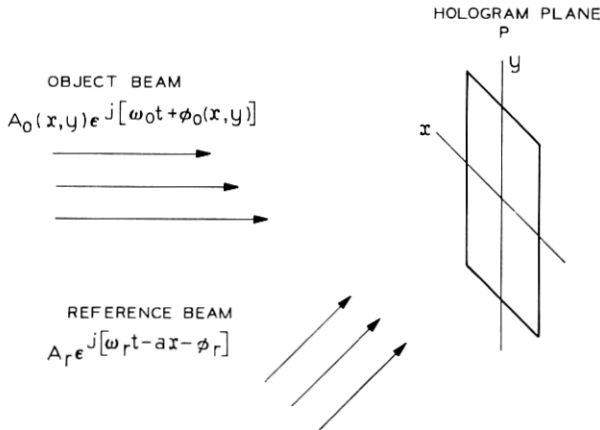


Fig. 1—Formation of a conventional hologram. Object and reference beams impinge on hologram plane  $P$ .

and a reference beam

$$E_r(x, y) = A_r e^{j[\omega_r t - ax - \phi_r]}$$

impinging upon a hologram plane  $P$ . The intensity is given by

$$I = A_r^2 + A_o(x, y)^2 + 2A_r A_o(x, y) \cos [(\omega_o - \omega_r)t + \phi_o(x, y) + ax + \phi_r]. \quad (1)$$

For the formation of a conventional hologram the two beams must be at the same frequency, that is\*,  $\omega_r = \omega_o$ , so that equation 1 becomes

$$I = A_r^2 + A_o(x, y)^2 + 2A_r A_o(x, y) \cos [\phi_o(x, y) + ax + \phi_r]. \quad (2)$$

During reconstruction, the first two terms of equation 2 form the direct beam and are unimportant except that they tend to obscure the reconstructed image which comes from the third term. Notice that the third term is a spatial carrier wave which is amplitude and phase modulated. If the spatial bandwidth of the wave to be reconstructed,  $A_o(x, y)e^{j\phi_o(x, y)}$ , is  $2W$ , then the bandwidth of the direct beam,  $A_r^2 + A_o(x, y)^2$ , and the bandwidth of the desired term,  $A_r A_o(x, y) \cos [\phi_o(x, y) + ax + \phi_r]$ , will each be  $4W$ , as shown in Figure 2. Thus if angular overlap between the direct beam and the desired reconstructed wavefront is to be avoided, we require that the spatial carrier frequency  $a$  of the desired third term in equation 2 be at least  $3W$ . This results in a total spatial bandwidth of  $8W$ .

\* There are exceptions. See Ref. 4.

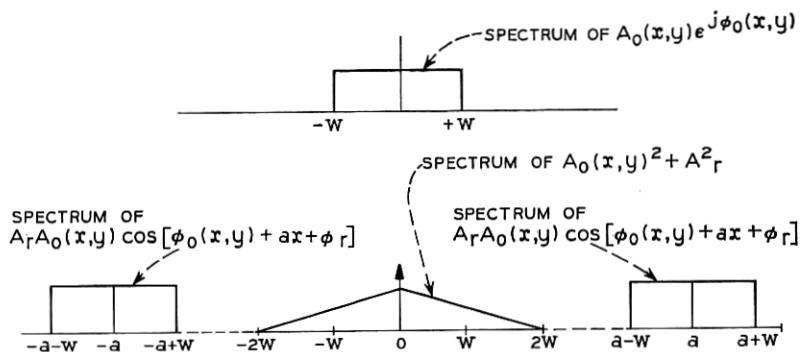


Fig. 2—Spatial spectra of a conventional hologram signal. This representation is only intended to convey the limits of the spatial spectra and not the explicit form of the function.

### III. ELIMINATING TERMS CORRESPONDING TO THE DIRECT BEAM

Since the third term in equation 2 is all that is necessary to reconstruct a hologram, it is desirable to eliminate the generation of the direct beam. The spatial carrier frequency  $a$  could then be reduced from its present minimum value of  $3W$  to  $W$ , reducing the minimum total spatial bandwidth which must be transduced from  $8W$  to  $4W$ . We are able to accomplish this rather easily with the heterodyne techniques discussed in this paper.

If equation 2 represents the intensity formed on a television camera tube, the camera output current will be proportional to the intensity being scanned by the electron beam. For an  $x$ -direction scan, the amplitude and phase modulated spatial carrier frequency is converted to a correspondingly modulated electrical signal. Notice that precisely the same electrical signal can be obtained by using a photomultiplier or other large area photodetector with a pinhole aperture placed just in front of the photosurface, the pinhole being scanned over the photosurface in a raster-like fashion in the same manner that the electron beam scans the photosurface in a camera tube. The output current from the photodetector would be proportional to the intensity of the light sampled by the pinhole.

A more desirable transducer is obtained if one shrinks the reference beam into a small pencil beam of pinhole dimensions which is then scanned over the photosurface. The pinhole aperture is now superfluous and can be removed, thereby gaining a distinct advantage. The intensity of the light on the photosurface contributed by the

object beam acting alone and the reference beam acting alone is now constant as a function of time. Thus, the nuisance terms corresponding to the direct beam in the reconstructed hologram, that is, the first two terms of equation 2, are not transduced as time varying currents. The only time varying term is produced by the interaction of the pencil reference beam with the object beam as it scans out the raster. This time varying signal is proportional to the desired third term in equation 2 which represents the useful information. Thus, the carrier frequency (dictated by the angle between the reference and object beams) can be reduced from  $3W$  to  $W$ , which cuts in half the resolution requirements of the aperture of the scanning beam. (See Fig. 2).

#### IV. ELIMINATING THE SPATIAL CARRIER FREQUENCY

In the situation discussed in the previous section, spectrum overlap in the electrical signal is prevented by adjusting the angle between the object and reference beams to provide a sufficiently large spatial carrier frequency. As a consequence, the aperture of the scanning beam must resolve the highest spatial sideband frequency associated with this spatial carrier frequency.

As an alternative to generating the electrical carrier frequency by scanning a corresponding spatial carrier frequency, it is possible and indeed advantageous to generate the electrical carrier by heterodyning the object beam with the reference beam. This can be done in such a manner that it is unnecessary for the scanning aperture to resolve an equivalent modulated spatial carrier frequency. It must resolve only those spatial frequencies present in the complex field of the object beam itself, that is, it must resolve only a spatial bandwidth of  $2W$ . This realizes a subsequent reduction in the resolution requirements of the scanning beam by a factor of two over and above the reduction discussed in Section III.

For convenience, let us rewrite equation 1,

$$I = A_r^2 + A_o(x, y)^2 + 2A_r A_o(x, y) \cos [(\omega_o - \omega_r)t + \phi_o(x, y) + ax + \phi_r], \quad (1)$$

which represents the intensity of the light incident on the photodetector when the object beam and reference beams are at different frequencies  $\omega_o$  and  $\omega_r$ , respectively. Conceptually, these two frequencies can be sidebands produced by modulation, or can be two phase-locked modes of

the same laser, or produced by two phase-locked lasers, to name just a few methods.

In the present situation, the scanning pencil-like reference beam has an amplitude which may be written as a delta function,  $A_r = \delta(x - ut)\delta(y - vt)$ , where  $u$  and  $v$  are the horizontal and vertical scanning velocities, respectively. When this is substituted into equation 1 and integrated over the surface of the photodetector to find the output current, we obtain for the time varying component:

$$i(t) = 2A_0(ut, vt) \cos [(\omega_0 - \omega_r + au)t + \phi_0(ut, vt) + \phi_r].$$

We see that the frequency difference  $\omega_0 - \omega_r$  has been added to the electrical carrier frequency  $au$  produced by scanning the spatial carrier frequency  $a$ . Thus, we may use a spatial carrier frequency of zero and avoid spectrum overlap (which produces beam overlap problems at reconstruction) by controlling the frequency difference between the reference and object beams. This means that the aperture of the scanning beam need resolve only those spatial frequencies present in the complex field of the object beam. For example, in Fig. 2 it need resolve only the spatial spectrum of  $A_0(x, y)e^{i\phi_0(x, y)}$ . Thus, the total spatial bandwidth required has been reduced by a factor of four.

#### V. ADDITIONAL CONSIDERATIONS

It might be appropriate to speculate on other aspects of the hologram heterodyne scanner. One might consider other means of implementing this technique. For example, one could replace the large area photodetector with a small area or point detector such as a photodiode. Rather than deflecting the pencil-like reference beam relative to a fixed object beam, the object beam is deflected relative to a fixed pencil reference beam. This allows one to reduce the size of the photodetector from that equal to the size of the equivalent hologram to that equal to a point. The price paid for this simplification is the difficulty associated with deflecting the information-bearing object beam without introducing excessive distortion. This will, of course, be more difficult than deflecting a pencil-like reference beam.

Another aspect of the use of the hologram heterodyne scanner is its potential sensitivity. Heterodyning is a well known technique for converting a weak light signal into an electrical current whose signal-to-noise ratio is determined by the fundamental quantum nature of light.<sup>5</sup> The heterodyne scanner should have potentially the best sensi-

tivity obtainable by any technique which does not use charge storage.

Without reported experimental verification of the hologram heterodyne scanner, it would not be especially fruitful to spend much time at this point speculating on possible display devices. There are a number of possible approaches to this problem but they are admittedly speculative. These include the Swiss Eidophor System<sup>6</sup> as a direct recording medium for the holographic electrical signal, or the use of photochromic materials for recording the output of a laser beam modulated by the holographic electrical signal and raster scanned over the photochromic surface. Both these methods have been referred to by E. N. Leith and his colleagues.

#### VI. COMMENTS AND COMPARISONS

Let us compare the hologram heterodyne scanner to the method proposed by C. B. Burekhardt and E. T. Doherty.<sup>7</sup> An extension of their technique\* reduces the spatial resolution required of the camera tube by the same factor of four as the hologram heterodyne scanner, but even in its improved version it still requires a 50 percent greater electrical information rate than the scanner. However, the technique can be implemented with present technology.

A technique has been reported by L. H. Lin which involves spatial frequency sampling to reduce the information content of the hologram.<sup>8</sup> This is accomplished by an iterative Fourier transform technique. It is possible to augment Lin's technique with the hologram heterodyne scanner to increase the bandwidth saving. The translation of the hologram peculiar to Lin's technique can be carried out at the receiver. K. Haines and D. B. Brumm have also reported on a technique which can be used to reduce the information to be transduced and is compatible with the hologram heterodyne scanner.<sup>9</sup>

The hologram heterodyne scanner is a general technique that would apply to three-dimensional objects or two-dimensional transparencies. However, this does not mean that the implementation of this technique presents the same difficulties in each case. The spot size of the scanning reference beam and the speed of scan are directly influenced by the type of object to be transduced. The requirements are more stringent for the three-dimensional object if reasonable parallax is to be observed. Advances are currently being made in laser scanner technology which will help alleviate one aspect of the problem. A. B.

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\*The technique presented in Ref. 7 has been extended by C. B. Burekhardt to apply to TV transmission but this specific aspect is unpublished.

Larsen of Bell Telephone Laboratories is conducting experiments implementing the hologram heterodyne scanner technique. Many of the concepts of this paper have been improved and extended by him and will be reported in the near future.

#### VII. ACKNOWLEDGMENTS

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