High-Fidelity Video Recording Using Ultrasonic Light Modulation

By LEO LEVI

The method described makes it possible to record electronic signals at video frequencies on photographic materials. Employing the modulation of light intensity by ultrasonic waves, the system is capable of resolution and dynamic range performance well in excess of that obtained with conventional methods. Both black-and-white and color modulation of light are possible. Ultrasonic light modulation has been successfully employed to obtain high-quality radar information, and it is inherently capable of providing a similar function in video recording — either field-by-field or continuous.

An interesting concomitant of high bandwidth video work is the problem of translating high-frequency information into a sensible form. A related problem is that of storing such information for viewing or extraction at a later date. The present paper describes a method of solving these problems, making possible high quality video recordings on photographic film. At the present state, this method makes possible the recording of video information with bandwidths up to 20 mc and, therefore, could be used for television recording.

A brief analysis of the problems involved will be followed by a description of the ultrasonic light modulation method and its application to video recording.

Problems in High-Fidelity Video Recording

Basically, video recording involves the conversion of high-frequency electronic signals into a form which is amenable to storage on the recording material. Basically, two approaches are used to perform this conversion—magnetic tape recording and light modulation in conjunction with photographic recording. The major disadvantages of the magnetic tape recording method are inherent in the high tape speeds required for recording information at 4- or 5-mc rates.

The alternative, light modulation, presents other difficulties. When electronic signals must be converted into a visible form at video frequencies, the only conventional method available employs a cathode-ray tube.

With this device, the intensity of the spot on the screen is controlled by varying the current in an electron beam in accordance with the electronic signal. This method is very convenient but, unfortunately, suffers from serious shortcomings. These shortcomings are in the nature of limited resolution and low dynamic range. The limitation in resolution is due to difficulties in focusing the electron beam. In practice, it is not possible to obtain much more than 1000 elements across a tube diameter with any appreciable contrast.

The limitation in dynamic range is inherent in the halation effects which accompany a cathode-ray tube display. Dynamic range is defined as the ratio of the maximum signal recorded (linearity specified) to the minimum signal observable. Now, if we measure a certain low light intensity on a spot of the cathode-ray tube display, we will not be certain whether there actually is a cathode-ray impinging on this spot or whether, perhaps, there is a very bright spot in the immediate neighborhood of the spot we are observing and it is merely halation effects which illuminate it. It thus becomes obvious that a relatively high signal intensity is required if the presence of signal is to be determined with certainty. In practice, the dynamic range of the cathode-ray tube is limited to approximately 15 to 1.

A further shortcoming of the cathode-ray tube display device lies in the lack of linearity. The response of a cathode-ray tube display is nonlinear to an extent somewhere between quadratic and cubic. In many applications this deficiency can impose rather serious difficulties.

The deficiencies of the cathode-ray tube type light modulator made it imperative that a new method of light modulation be developed which would make it possible to overcome the limitation in resolution, dynamic range and nonlinearity. The Ultrasonic Light Modulator was developed by the Fairchild Camera and Instrument Corp. to overcome the shortcomings of the cathode-ray tube.

The Ultrasonic Light Modulator

Ultrasonic light modulation is based on the diffraction of light at ultrasonic wavefronts (Fig. 1).

A slit in diaphragm D_1 is illuminated from the source S by means of condensing lens L_1. An image of this slit is formed on an opaque bar at D_2 by means of lenses L_2 and L_3. The bar at D_2 is slightly larger than the image of D_1 so that it

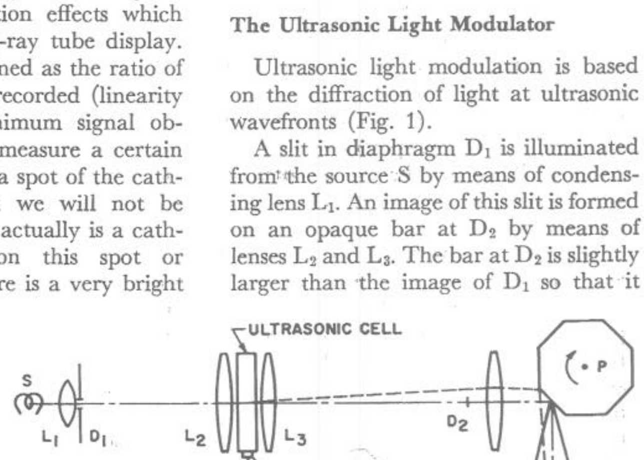

Fig. 1. Ultrasonic Light Modulator schematic.

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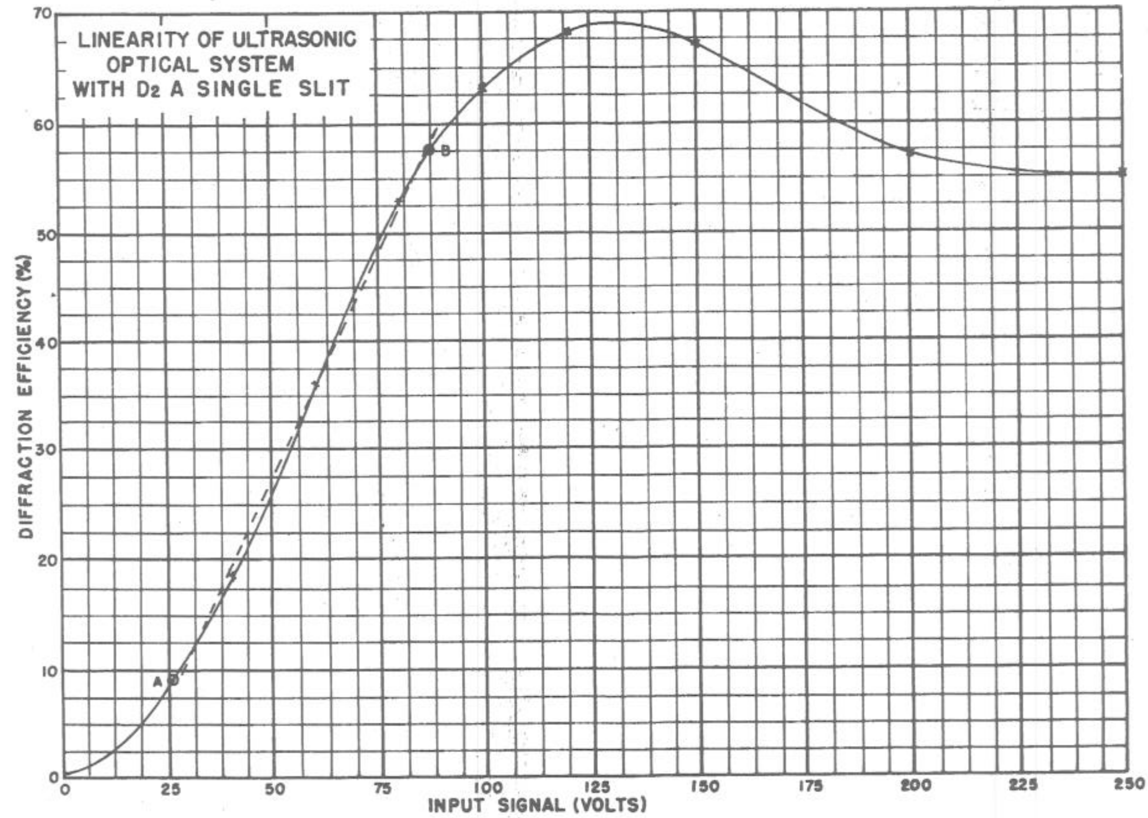


Fig. 2. Linearity of ultrasonic optical system with D_2 a single slit.

stops all the light that enters the system at D_1. The ultrasonic cell is placed in the collimated region between L_2 and L_3. A lens L_4 forms an image of this ultrasonic cell in the plane F after reflection from a mirror shown at P. Under the circumstances just described, the image shown at F will appear completely dark since none of the light illuminating the cell can pass D_2. When a signal is applied to the ultrasonic cell, light is diffracted around the stop D_2, as indicated by the dotted line. This light now passes D_2 and, as a result, the image at F becomes bright.

The operation of the ultrasonic cell may be understood from the following description. The cell consists essentially of a medium, such as water, in contact with a piezoelectric transducer. This transducer has the property of expanding or contracting when a potential is applied across it. When an alternating potential is applied, it will vibrate and thus send pressure waves down the column of liquid in contact with it. These pressure waves produce periodic variations in the refractive index of the liquid. Thus the portions of the incident light wave which pass through pressure troughs will be advanced in phase and those passing through the pressure peaks will be retarded in phase. As a result, a plane wavefront entering the ultrasonic cell at the left (Fig. 1) will leave it as a corrugated wavefront on the right, producing the diffraction grating effect.[1–4]

If now a short burst of carrier waves is applied to the transducer, a short train of pressure waves will travel down the ultrasonic cell. At F this will appear as a bright spot traveling the length of the cell image with a velocity corresponding to that of sound in the cell medium, as indicated by the arrow in the cell image shown at F. In order to make a recording of this spot of light, we may use either a very short exposure or make the spot stand still by rotating the reflector P. A rotation of the reflector in the sense indicated in the diagram will make the cell image move in the direction indicated by the lower arrow at F. If the velocity of this image motion is now made equal (and opposite) to the velocity of the pulse inside the cell, this pulse will have no net velocity with respect to the surface F, much as a man running down a railroad car will appear stationary with respect to ground when we move the car with the same speed in the opposite direction.

Incidentally, this scanning makes the total time interval recorded during one sweep independent of the cell length. The cell window length determines only the length of time the pulse remains visible at F, that is, the exposure time.

It can now be seen why the Ultrasonic Light Modulator does not suffer from the same resolution limitations as the cathode-ray tube display device. An almost arbitrarily small spot size, combined with an almost arbitrarily long scan line, makes it possible to obtain many thousands of resolution elements in a single scan line. The only limitations are those inherent in the photographic procedure—specifically, the resolution performance of the photographic material and the optical components.

So far, resolution has been discussed in terms of number of elements in a scan line. Resolution in terms of time will, of course, be limited by the bandwidth performance of the light modulator; but, since information bandwidths close to 20 mc have been obtained with the Ultrasonic Light Modulator, this limitation is not likely to be of serious nature.

Furthermore, in the Ultrasonic Light Modulator there are no halation effects analogous to those in the faceplate of the cathode-ray tube. As a result, the dynamic range performance of the Ultrasonic Light Modulator is extremely high. The limitations in dynamic range are again identical to those obtained in photographic recording, namely, scattering of light in the optical path and halation effects in the photographic material. As a result, dynamic ranges of several hundred to one have been obtained in field models of the Ultrasonic Light Modulator. In these models the spot intensity varied over a range from 200 to 1 as the signal intensity went from maximum to zero. In laboratory models considerably higher ratios are obtainable. It should be noted that the dynamic range of the light modulator is not limited by these values. Dynamic range is defined as the ratio of maximum signal recordable to minimum signal detectable in the recording. This minimum signal is limited not by the output level at no signal but rather by the fluctuations in this level, i.e., by the noise.

On this basis, the dynamic range of the light modulator itself should certainly exceed 1000 to 1. Primarily, limitations enter only in the signal-to-noise values maintained in the transducer drive system and in deficiencies of the recording material — the photographic film.

The linearity performance of the Ultrasonic Light Modulator is good. Figure 2 shows the response curve of the light modulator. It shows the diffraction efficiency as a function of input voltage for one ultrasonic light modulator arrangement. Diffraction efficiency here is defined as that percentage of the light entering the system at D_1 which goes into the formation of the final image and when approximately 125 v rms is applied to the transducer, the diffraction efficiency is close to 70%. The portion of the response curve between points A and B, corresponding to 9% and 58% diffraction efficiency, respectively, is linear within 2%.

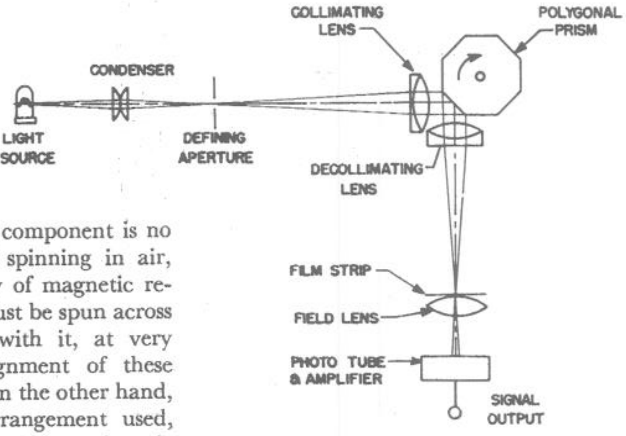
Application to Video Recording

The Ultrasonic Light Modulator (Fig. 1) may readily be adapted to video recording. If photographic strip film is placed in the plane of F and driven in a direction into the plane of the diagram with a speed sufficient to move the film the width of a single scan line during the period of a single scan, the film will be filled with transverse scan lines density-modulated in accordance with the signal intensities applied to the light modulator. In order to start the second scan immediately after completion of the first scan, a mirrored polygonal prism is used for the reflector, P. In order to maintain uniform light intensity across the full scan, it is, as a practical matter, preferable to use two polygonal prisms mounted coaxially, these sharing time equally. This enables the reflecting face of one polygon to completely enter and cover the scanning beam while the face of the other prism does the actual scanning.

This procedure will effect considerable economy of recording materials. For example, assuming that 4-mc information is to be recorded on 70mm film capable of resolving 30 lines per millimeter, a 1000-ft roll would accommodate considerably more than one hour of recording. This can be compared with one conventional method of magnetic tape recording in which 1000 ft of tape would accommodate less than 2 min of recording. There are other methods of magnetic tape recording which are somewhat more economical but which do not approach the economy of photographic recording.

These methods also use a scan transverse to the tape. In magnetic tape recording, the rotating component is no longer a simple prism spinning in air, but rather an assembly of magnetic recording heads which must be spun across the tape, in contact with it, at very high speeds. The alignment of these heads is very critical. On the other hand, due to the optical arrangement used, the tolerances on the position and angle of the prism faces are quite generous.

Fig. 3. Flying-spot scanner schematic.



These examples apply only to straight video recording. In recording television, it might be of interest to have the record in pictorial form. In order to obtain this, it is necessary only to synchronize the transverse scan with the line sync signal and to choose a film speed to yield the same scale for transverse and longitudinal scan. The recording should be similar to kinescope recordings but of higher quality.

Playback

The video recorder described in the first part of this paper will result in a photographic strip film containing density modulations which correspond to the electronic signals received. It then becomes necessary to convert these density modulations back into the electronic signals originally received. This conversion can best be accomplished by means of a flying-spot scanner. In this flying-spot scanner (Fig. 3) the image of a brightly illuminated pinhole is scanned across each recorded line on the film. The light transmitted by the film is made to fall on the cathode of a multiplier phototube. The output of the phototube will then be proportional to the transmissivity of the point on the film which was scanned. This transmissivity, in turn, will be proportional to the signal originally recorded if a linear positive film is used. In the event that a negative material is used, the output signal will be inversely proportional to the signal intensity originally recorded.

Light from a lamp is condensed on a pinhole and then collimated by a lens. It is then reflected from a rotating polygonal prism and refocused by another lens whose optical axis is perpendicular to that of the collimating lens. The film strip is placed in the focal plane of this decollimating lens and is followed by a "field lens" which images the reflecting prism face on the photosensitive cathode of a multiplier phototube.

In practice it may be possible to use either the identical recording instrument or a duplicate of it in the playback mode. It is only necessary to replace the ultrasonic cell in Fig. 1 by a point source of light and to place the field lens and phototube behind the film at F.

It should be noted that the playback speed need not be identical to the recording speed. The record may be played back either at a higher speed or, for close analysis, at a lower speed than the original recording.

Scanning Accuracy

Another great advantage of the proposed video recorder over both magnetic tape and cathode-ray recording lies in the great accuracies in scanning speed that can be obtained in recording and in playback. This accuracy potential is inherent in the type of scan and nature of the scanner as shown below.

One major difficulty in video recording is due to two conflicting requirements of the recording medium — the material must be flexible for storage purposes, but, if a uniform drive is to result, the material must be stiff. As a result, uniformity of scan speed is one of the major problems in accurate video (and audio) recording.

This difficulty is further aggravated by the substantial load that the drive mechanism must carry and by the correspondingly large torque fluctuations that are encountered as a result.

We shall now attempt to show how the proposed type of scan remains totally unaffected by minor speed fluctuations of the recording material and how an extremely uniform scanning speed may be attained with the proposed scanner.

The proposed scan is transverse to the direction of travel of the recording medium, say photographic film. The information is thus laid down in the form of lines (i.e., narrow strips) running transverse to the film strip, much as scan lines on a television screen. It is played back by means of a similar scan. Under these circumstances, the rate of scanning is obviously independent of the film velocity. Only if the error is sufficient to make the scanning spot skip from one information "line" to the next, will information be lost. Needless to say, mechanical tolerances close enough to prevent an error of such magnitude can

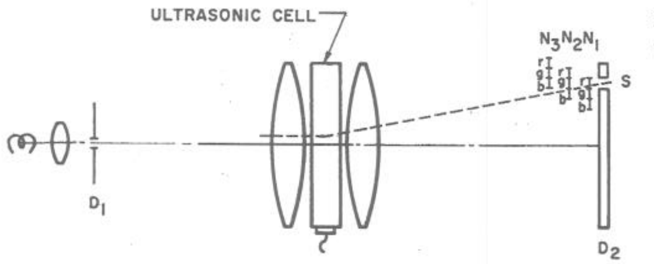


Fig. 4. Color modulation system.

readily be maintained. Cumulative, long-term errors can be eliminated by tying the scan to the film velocity by a closed loop (mechanical or electronic).

It remains to show that the scanning speed may be maintained to a very high accuracy.

By mounting the scanner on the shaft of a synchronous motor, driven from a crystal-controlled oscillator, the power supply frequency — and therefore the long-term motor speed — can be maintained constant to within one part in several million.

The motor speed is also subjected to short-term (within one revolution) fluctuations due to changes in load and supply torques. A quantitative analysis, given below, shows that these fluctuations may be reduced to the same order of magnitude.

The fractional change in scanner velocity is given by

$$\frac{\Delta\omega}{\omega} = \frac{\alpha t}{\omega} = \frac{\Delta T}{M} \times \frac{\Delta\theta}{\omega^2}$$

where the angular acceleration

$$\alpha = \frac{\Delta T}{M} = \frac{\text{torque fluctuation (net torque)}}{\text{moment of inertia}}$$

and the time of application of the torque

$$t = \frac{\Delta\theta}{\omega} = \frac{\text{arc over which torque is active}}{\text{angular velocity}}$$

For instance, in the successful breadboard of a video recorder the scanner rotated at 24,000 rpm. If a 2-in.-diameter disk, $1\frac{1}{2}$ in. high, of Mallory 1000 metal (S. G. 17), is used as a flywheel, the moment of inertia will be about 4235 g/sq cm. If we now assume a torque fluctuation of 0.45 oz-in.* applied over 10° of the rotation, the resulting fractional speed change is one part in five million.

This should also be compared with the scanning accuracy obtainable with a cathode-ray tube, where one part in a thousand is considered excellent.

One additional source of fluctuation of scanning speed is due to distortion in the objective lens focusing the collimated scanning beam on the film.† But, if identical objectives are used in the recording and playback modes, this error is automatically eliminated — the errors in the two modes can be seen to cancel.

It should be noted that — to maintain these accuracies — the plane of the recording medium must be held constant to the same tolerance.

Color Modulation

It may be of interest to note that inherent in the ultrasonic light modulation method is also the possibility of color modulation of light. As pointed out earlier, the ultrasonic cell is essentially a diffraction grating and, like a diffraction grating, it separates the incident light into its spectral component. The image of a narrow slit at D_1 (Fig. 1) will appear drawn out to a full spectrum in each diffraction image at D_2. If we now select one color from one spectrum (Fig. 4), the cell image will appear in that color.

If the frequency of the signal applied to the transducer is changed, the ultrasonic wavelength in the cell will change and the diffraction angle will be changed proportionally to the frequency change. As a result, the color light selected by the same slit at D_2, too, will change. In other words, the color of the cell image may be changed by frequency modulating the carrier signal applied to the cell, just as the brightness of the cell image is changed by amplitude modulating this carrier. It should be noted that a continuous change of hue is thus possible.[5]

Conclusions

The proposed method of photographic video recording employing ultrasonic light modulation is not only practical but also capable of high performance and great economy not achieved by more conventional methods. The system is relatively simple, requires no unusual mechanical or optical tolerances, and contains no particularly sensitive components. Several devices using ultrasonic light modulation have been successfully developed. Most of these are radar recorders and the results obtained are classified, but it can be said that they show striking improvements over standard radar recording techniques and have established the reliability of ultrasonic light modulation equipment in field use. The Ultrasonic Light Modulator should be a useful tool in video recording.

Acknowledgment

The author would like to take this opportunity to acknowledge the work of Dr. A. H. Rosenthal due to whose vision this program was initiated and who also contributed many of the basic concepts and that of Mrs. Sophie Tinto, whose original work in the development of ultrasonic transducers made possible the performance reported on in the present paper.

References

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Discussion

Rolf A. Seitle (*WTTW, Chicago*): In the application to television image recording, the original image, of course, has to have synchronization signals added to it and in the playback you will have to record the synchronization. Would this be accomplished by recording the synchronization signals in the same manner as the picture information, or how otherwise would you try to accomplish this?

Mr. Levi: Synchronization would definitely be a problem. One solution would be to use a very stable generator for the line frequencies. Used with a stable mechanical method of playback, this would maintain the short-term stability. For long-term stability you can use just the regular sync signal to make sure that the frequency roughly corresponds to the frequency of the recording. Again, in this case, the speed of the prism in the recording equipment at the time of recording must conform exactly to the speed of the playback.

To suggest an example, you might use the sync pulses to operate a multivibrator and to filter out from this multivibrator a sinusoidal wave which can be used to drive a synchronous motor, and, if these fluctuations are kept very low, this method should provide satisfactory synchronization.

Mr. Seitle: If they are recorded on the same film medium, would they be visible in playback?

Mr. Levi: Yes, they could be recorded as a track on the side.

Mr. Seitle: Has Fairchild made any attempt to use this unit as a commercial video recording system?

Mr. Levi: No. As I said, the only commercial application has been in radar recording.

Mr. Seitle: Are you planning to use it for video recording?

Mr. Levi: If there should be a demand for this type of recording, we'd certainly consider going into developing it.

Franklin D. Hood (*Tektronix*): There is another possible light modulation system — the Kerr type of cell. I understand that it has recently been developed by Baird Associates to quite a high degree of usefulness. Have you considered using this type of modulation instead of the ultrasonic?

Mr. Levi: Yes, we have certainly considered it. The reason for choosing the ultrasonic method instead of the Kerr cell was chiefly that using the Kerr cell requires extremely high voltages which create difficulties in military application.

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* This value is about one-third of the total torque applied to the scanner, i.e., its friction and windage losses.

† The fact that the scanned distance is proportional to the tangent rather than the arc of the scanned angle can be considered part of this distortion.

Also, by choosing the ultrasonic light modulation method there is an economy in light. If you use a Kerr cell you can expose only one element for the period of that one element. For instance, if you're recording 4-mc information, you can record for possibly an eighth of a microsecond. With the ultrasonic method, you expose any element for the full period that it is present in the ultrasonic cell, which may be about 40 microseconds. So, in this example, there would be 320 times more light for a given light source than would be the case with a Kerr cell.

Mr. Hood: Could the same apparatus be used for a playback that is used for recording with a photocell located behind the film by removing the light modulator in the playback?

Mr. Levi: Yes. The only change would be to replace the ultrasonic cells by a point source of light and to have a phototube mounted behind the film. As a matter of fact, in one instrument that we developed for testing radar units, such a device was designed as a pushbutton conversion. A mirror was used which flopped into the light path, blocking out the ultrasonic cell and imaging a pinhole in its place. The multiplier phototube was permanently mounted behind the film. It served no function during recording and during playback it picked up the modulated light.

Hans Wohlrab (Bell & Howell Co.): I can confirm how excellent this ultrasonic system is. During World War II the German Air Force developed it for wireless transmission of air photographs and used it very successfully. In reference to the Kerr cell as a light relay, I worked on its development at the Leipzig University from 1923 on, as an assistant to Professor Karolus, who made its use possible for phototelegraphy and sound recording. But after many years of practical use, we preferred the ultrasonic light relay because of its higher efficiency and much simpler operation. After World War II, Professor Karolus used it for an FM sound-recording system with a 40-kc basic frequency and recording across the film similar to the Ampex Videotape System.

R. M. Morris (American Broadcasting Co.): With this ultrasonic transmission line in which you have several elements moving and stored at any one time, what do you do about terminating it to avoid reflection?

Mr. Levi: Termination has two requirements. It must match, acoustically, the medium itself, otherwise you're going to get reflection. It must also be highly absorptive of energy. With the ultrasonic medium that we use, it turns out that a certain neoprene serves both these requirements; we are using that as a termination in the lines and, to within a factor of 1000, there is no reflection from this absorber.

Robert G. Neuhauser (Radio Corp. of America): With a second drum to produce a second direction to scanning, is there good possibility of getting enough light through the system to use this as a television projection system?

Mr. Levi: The system has been used for television projection in England. It was known as the Scophony system and was successful, but not economically practical. I'm not certain of the exact reasons for discontinuing it, but it's not being used at present. The advances that we introduced were improvements in the resolution beyond the capabilities of ordinary television.

Mr. Seitle: Having the information recorded on the film as a negative does not make any difference as such since it can be inverted upon playback in an amplifier. However, if there is a possibility of making multiple prints, problems of distortion and loss of high frequencies due to image spread would have to be solved somewhat analogous to optical sound recording and printing, by cancelling this image spread in the print development. Is this correct?

Mr. Levi: Would you clarify your use of the terms "image spread and cancellation?"

Mr. Seitle: Image spread occurs in the development of a variable-area negative and causes fill-in of the high-frequency image. In the development of an optical print made from this negative, fill-in also occurs which helps to cancel such negative degradations. Since your process has many similarities to optical sound recording of the variable-area and variable-intensity type, but contains much higher frequencies, do you feel that it may be feasible to make prints from an original?

Mr. Levi: Certainly. As a matter of fact, this would remedy the inversion that you mentioned. You get your original film with the negative, but by printing and paying careful attention to the processing, maintaining your gamma of one, you've maintained your linearity and all your copy prints would be positive again; and you could use these positives in the playback.

Mr. Seitle: It would certainly call for new laboratory techniques in printing.

Mr. Levi: Why?

Mr. Seitle: The vertical resolution of a television imaging process is mainly limited by the number of scanning lines employed. In a normal photographic television recording using cathode-ray-tube photography, I have noticed that printer slippage in a continuous printer results in a noticeable degradation of vertical resolution in the print. In order to preserve the high original quality of your negative, even tighter control of the printing process would be necessary.

Mr. Levi: It would be the same. I don't know why it would be more serious. In either case you have to control slippage in order to maintain resolution. Any deterioration you get in your printing, of course, would show up in your final playback.

Ellis D'Arcy (D'Arcy Associates): How many bits of information per square inch can you obtain with your method; do you happen to have that information?

[Reply in detail supplied in writing:

[*Mr. Levi:* The information density, in bits, is given by $C = \frac{1}{a} \log_2 N$, where a is the area of one information element and N is the number of discernible gray steps. It can be shown* that N, as limited by granularity, is given by

$$N = \frac{\sqrt{a}}{2\sqrt{2}} \frac{\Delta D}{G}$$

where ΔD is the overall linear density range available from the emulsion and G is the Selwyn granularity.

[On the basis of $G = 1.5$ (corresponding to Eastman Super XX film), $a = 0.00028$ (corresponding to 30 line pairs per mm) and $\Delta D = 2.5$, N is found to be 9.44. This would make the information density $C = 11{,}700$ bits per sq mm.]

[In practice, halation effects in the emulsion will lower this figure, which is based on granularity alone, so that one can say safely only that the information density is somewhere between 3,600 and 11,700 bits per sq mm (between 2.3×10^6 and 7.5×10^6 bits per sq in.).]

Walter Bach (Berndt-Bach, Inc.): I would like to make a brief statement on printing and slippage. About 25 years ago, E. W. Kellogg of RCA presented a paper on "Non-Slip Printers for Sound Track," and in New York we spent a number of years developing nonslip printers for optical soundtracks on 16mm. These completely eliminate slippage, even though the negative is shrunk and the positive isn't. We were able to print up to 10,000 cycles 16mm soundtracks with no degradation on the prints whatsoever. Precision Film Labs. in New York used these printers for a number of years.

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*Leo Levi, "On the effect of granularity on dynamic range and information content of photographic recordings," *J. Opt. Soc. Am., 48:* 9, Jan. 1958.