TITLE HIGH-SPEED CAMERAS FOR STREAK TUBE READOUT

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High-speed TV cameras for streak tube readout

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ABSTRACT

Two fast framing TV cameras have been characterized and compared as readout media for imaging of 40 mm diameter streak tube (P-11) phosphor screens. One camera is based upon a Focus-Projection-Scan (FPS) high-speed electrostatic deflected vidicon with 30-mm-diameter PbO target. The other uses an interline transfer charge-coupled device (CCD) with 8.8×11.4 mm rectangular Si target. The field-of-view (FOV), resolution, responsivity, and dynamic range provided by both cameras when exposed to short duration ($\approx 10 \mu\text{s}$ full width at half maximum [FWHM]) transient illumination followed by a single field readout period of < 3 ms are presented.

1. INTRODUCTION

For applications that require readout and telemetry of streak tube images, TV cameras are frequently utilized. In some cases, readout times of less than 16.66 ms per field are required, precluding the use of conventional TV cameras that operate at RS170 rates. We have developed two fast readout TV cameras^{1,2} for similar applications, one based upon FPS vidicons¹ and the other based upon interline transfer CCD imagers.² Both cameras have been evaluated as streak readout candidates in terms of FOV, resolution, signal-to-noise, dynamic range, and responsivity provided by each at readout rates as high as 500 fields per second. To provide nearly equivalent FOV for the 8.8×11.4 mm CCD to that of the large area 30 mm diameter vidicons, two methods of demagnification for use in front of the CCD were investigated. One used a coherent fiber optics reducer and the other used a diode image intensifier with electron optics minification. The salient results for both cameras in this application are presented.

2. CAMERA DETAILS

Two fundamental constraints were placed on the TV cameras. The first was to perform complete single-field readout in 2.8 ms, including portions of the read cycle waveform that do not contribute to the active readout phase. Both camera types have time consuming requirements or "overhead" prior to readout of their image, which adds to the total readout period. The second was to provide FOV sufficiently large to image most of the full streak tube phosphor screen ≈ 40 mm diameter with fiber optics coupling to a 40 mm image intensifier. The TV cameras are then coupled to this intensifier through additional reducers (see Fig. 1). Typically, a single 40-28 mm reducer is used for the FPS camera. For the CCD, a 40-18 mm reducer is followed by another 18 or 20-10 mm reducer. The additional demagnification required for the CCD is because its imaging area is approximately 7X smaller than that of the FPS (100 mm^2 for the CCD versus 707 mm^2 for the FPS).

The FPS camera used for these tests was a Xedar Corp Model #504 developed initially by Los Alamos National Laboratory with technology transfer to Xedar Corp of Boulder, Colorado, for commercialization. It used an Amperex Model 88XQ PbO target. The CCD camera jointly developed by

Fig. 1. The streak tube coupling arrangements for the FPS and CCD cameras. The FPS setup (A) and the CCD setup (B) illustrate the extreme differences of demagnification required by the two sensors.

Los Alamos National Laboratory and Lawrence Berkeley Laboratory (LBL) and fabricated by LBL was a LANL/LBL Model GY-2, which used an Interline Transfer CCD, Fairchild Model 222. The streak tube to be imaged was an ITT F4157/U.

The FPS camera raster format was set up to give active readout phase of ≈ 2.4 ms, providing 300 scan lines of $7.4 \mu\text{s}$ active and $0.6 \mu\text{s}$ blanked for $8.0 \mu\text{s}$ total. The vertical blanking interval was $100 \mu\text{s}$ and a hold-off period of $200 \mu\text{s}$ precedes the active readout phase for a total of 2.8 ms per readout cycle. The hold-off period is to allow EMP-induced noise associated with some optical events in the camera to subside prior to readout and also to provide a "soak" period for light-induced charge in the vidicon target to migrate to the read side of the target prior to scanning. This represents the "overhead" for the FPS camera prior to start of its active readout phase. The raster dimensions were 21 mm vertical by 21 mm horizontal, noninterlaced mode. From our previous work,^{3,4} the scan beam diameter for this type of vidicon was measured to be $\approx 36 \mu\text{m}$ and this scan line raster density indicates clear separation of individual scan lines.

The CCD camera was also operated noninterlaced with 244 rows (equivalent of scan lines for the FPS camera) and 380 pixels per row. A pixel rate of ≈ 50 MHz was selected to give active readout phase of ≈ 2.1 ms. The horizontal scan line period was $8.6 \mu\text{s}$ total, $7.6 \mu\text{s}$ active, and $1.0 \mu\text{s}$ blanked. The vertical blanking interval was $100 \mu\text{s}$. Prior to active readout phase, the CCD is programmed to provide two consecutive "dump" cycles, which are designed to clear the imager of radiation-induced noise⁵ and "ghost" images^{6,7} resulting from light falling on the vertical shift registers during transfer of images from these registers to the output horizontal register. Each dump cycle is accomplished in $244 \mu\text{s}$ with arbitrary dead time between the two cycles of $12 \mu\text{s}$ to $500 \mu\text{s}$ resulting in $\geq 500 \mu\text{s}$ "overhead" prior to start of the active readout phase of this camera. The total readout cycle is 2.8 ms. The CCD provides imaging area of 11.4 mm horizontal by 8.8 mm vertical. The interline architecture of this CCD gives a pixel geometry composed of three components: one even photosite, one odd photosite, and a semitransparent vertical shift register adjacent to the photosites. The pixel site is $1080 \mu\text{m}^2$ overall, with photosites of $18 \mu\text{m}$ (V) by $12 \mu\text{m}$ (H) on $30 \mu\text{m}$ centers.

The timing diagrams for both cameras are shown in Fig. 2, depicting "overhead" and active periods associated with the two camera's respective single-field readout sequences.

Fig. 2. Timing diagrams for the FPS and CCD cameras. The FPS waveform (B) shows the hold-off period immediately following the reset pulse (A). The hold-off period is followed by one field of video. The CCD waveform (C) shows the two consecutive dump cycles followed by one field of video.

3. ANALYSIS OF ACTIVE AND PASSIVE IMAGE REDUCERS

As indicated earlier, to increase effective FOV for the CCD, the array required additional demagnification between the 40-18 mm reducer of Fig. 1. Both active and passive minifiers were evaluated. A Cohu Model 4815 CCD camera operated at RS-170 rates with fiber optic input was butt-coupled to the minifiers for gain and resolution measurements. An Optronics 730A radiometer was placed in the array focal plane for radiometric measurements.

Several passive coherent fiber optic reducers were characterized for gain increases due to higher flux density (photons/unit area) from demagnification. To a first approximation, the flux density at the input versus output surfaces should scale by the ratio of their respective areas. However, due to losses from numerical aperture mismatches between emitting and receiving surfaces and losses due to absorption in the individual fibers, the predicted increases from area reduction are much higher than measured values. The gain data for several fiber optic reducers are in Table I. It is noteworthy that although the output of a fiber-coupled image intensifier is transmitting an image of the phosphor screen, which is a Lambertian source, the fiber coupler is not because of exit cone angles associated with its numerical aperture. The spatial resolution degradation of the fiber optic reducers was characterized by measuring output contrast transfer function (CTF) at several input spatial frequencies. These data are in Table II.

Table I. Gain data for coherent fiber optic reducers and for the image intensifier minifier. The video amplitudes are for front surface illumination of the reducer/minifier with circular spot of ≈ 3.3 mm diameter from continuous wave (CW) illumination from an Optical Instruments Corp. Model K2000 TV Optoliner spectrally attenuated to provide a 550 ± 5 nm average flux of $\approx 1.9 \times 10^{-7}$ W/cm² directly or attenuated as noted using neutral density (ND) filters. The video scan time across the back surface for the spot illumination image was compared with front surface scans to determine demagnification.

	Video		Gain			Total
	Ampl (mV)	Atten (ND)	Reduced Area	NA & Length	Kinetic Energy	
Optoliner signal	250	0.0	---	---	---	---
20:10 mm $\times$ 17.6 mm FO	450	0.0	4.0	0.45	---	1.8
15:15 mm $\times$ 18.75 mm FO	200	0.0	1.0	0.8	---	0.8
18:10 mm minifier	140	2.1	3.19	---	27.6	88.1
40:16 mm $\times$ 122 mm FO	350	0.3	6.25	0.45	---	2.8

Table II. Measured CTF and observed increases in spatial frequencies between input and output surfaces for the coherent fiber optic reducer and image intensifier/minifier. Input frequencies are images projected from a standard PERT-10 resolution slide in Optoliner optics. Only the first four sets of bars are shown because the fifth set of 11.5 lp/mm results in frequency higher than the Nyquist limit of 16.7 lp/mm for the Fairchild CCD-222.

Input	Spatial Frequency (lp/mm)		CTF (% of dc response)	
	20:10 mm Reducer	18:10 mm Minifier	20:10 mm Reducer	18:10 mm Minifier
2.3	4.6	4.1	94	90
4.6	9.2	8.2	84	72
6.9	13.8	12.4	76	48
9.2	18.2	16.6	63	32

To provide additional gain beyond that obtained from demagnification, an image intensifier was evaluated. The intensifier was a DEP Model XX1840 inverting diode with demagnifying electron-optics and with P-20 phosphor screen on fiber optic output faceplate. Although this intensifier exhibited pin-cushion distortion (not a problem with the passive coherent fiber optic reducers), it provided much higher gain. The total measured gain of approximately 88X is attributed both to demagnification for increased photoelectrons/unit area at the phosphor and to kinetic energy from 15 kV acceleration of photoelectrons from the photocathode. The gain data for the minifier are in Table I and the resolution data are in Table II.

4. EXPERIMENTAL SETUP

The experimental setup shown in Fig. 3 used an Optical Instruments Corp. Model K2000 TV Optoliner and Standard PERT-10 resolution chart for CTF measurements. Additional resolution data were obtained by using a specially designed slide that projected an array of pinholes (Fig. 4) onto the focal plane of the TV cameras. The pinhole arrays were designed to provide impulse response data directly without requiring conversion of the CTF data to modulation-transfer-function (MTF) data followed by Fourier Transform techniques for impulse determination. The pinhole arrays are designed to transmit light through four pinholes of given diameter separated by an opaque area corresponding to the pinhole diameter. The circular pinholes are tangent to the opaque area. The design provides measurement of both horizontal and vertical resolving power from a single image. Several slides with different diameters of pinholes in the range from ≈ 5 microns to ≈ 75 microns were used.

Fig. 3. The Optoliner light source used for resolution and dynamic range measurements for the impulse and CCD cameras.

Fig. 4. The pinhole array geometry used for direct impulse measurements.

The Optoliner was used to provide both pulsed and CW modes of illumination (from incandescent lamps). The pulsed light was either from a Xenon flash of $\approx 10 \mu\text{s}$ FWHM or from a laser pulse of $\approx 10 \text{ nS}$ FWHM as shown in Fig. 3. To simulate the 40 mm intensifier's P-20 phosphor emission, the Xenon white light spectrum was spectrally attenuated using a narrow band transmission filter centered at 550 nm. Alternatively, the laser, a Nd:Yag doubled, provided 535 nm spectra.

The responsivity and dynamic range data were obtained by using a variable diameter aperture iris projecting a spot of $\approx 3 \text{ mm}$ diameter onto the TV camera sensor targets and measuring video amplitudes as ND filters were added.

The resolution data were recorded by a Tektronic 7104 oscilloscope and by photographing a Hewlett Packard Model 1311 real-time x-y display. The oscilloscope records give individual scan line or row resolution characteristics for the two TV sensors. The x-y displays depict total area response across the sensor to identify spatially distributed nonuniformities.

5. COUPLED SYSTEM RESPONSES

The coupled system CCD camera responses for the intensifier/minifier when coupled to the CCD imager is compared with the FPS camera unintensified responses in this section. The intensifier/minifier was selected over the fiber optic reducer because the increased gain was required. The fiber optic reducer would have provided higher resolution but reduced gain as shown in measurements tabulated in Tables I and II.

The FOV for the two cameras is shown in Fig. 5. The cameras were DC-illuminated by the Optoliner with a PERT-10 resolution slide imaged at normal and perpendicular orientations with respect to the camera axes. The larger FOV provided by the FPS camera is obvious. In addition, the CCD/minifier camera shows some pin-cushion distortion. For the total streak system, the FOV for both cameras will be nearly equal. However, independent characterization of each camera prior to coupling was the only method of identifying individual performance of the two camera types. Therefore, these FOV data as well as the resolution data that follows give the CCD/minifier a slight advantage, which will not be realized in the final coupled system.

The vertical and horizontal resolution for both cameras is depicted qualitatively in Fig. 6. These x-y display photographs show the third set of bar patterns clearly resolved, corresponding to 6.9 lp/mm. The fourth set (9.2 lp/mm) is not clearly resolved by either camera as seen in Fig. 6 and noted in Table III. The horizontal CTF measurements for both cameras are indicated in Table III. Although both cameras show similar limitations in resolution, the reasons are different. For the FPS camera, the amplifier bandwidth with -3 dB corner frequency set to 25 MHz is the limiting factor whereas for the CCD/minifier camera, the Nyquist threshold is reached before the amplifier bandwidth approaches its limit. The FPS camera bandwidth could be extended to $>50 \text{ MHz}$ by moving the -3 dB corner frequency to 45 MHz, but with increased noise that would limit its dynamic range.

Because of the discrete nature of the CCD pixels, the imager's resolution is calculated by assuming two pixels are required per line pair. In the horizontal direction pixels are on $30 \mu\text{m}$ centers, giving $60 \mu\text{m}/\text{lp}$ or $0.0167 \text{ lp}/\mu\text{m}$, hence, the 16.7 lp/mm Nyquist frequency. In the vertical direction, for noninterlaced mode, the pixel dimension is $36 \mu\text{m}$. This gives $72 \mu\text{m}/\text{lp}$ or $0.0139 \text{ lp}/\mu\text{m}$ or 13.9 lp/mm resolution. From Table II, the 6.9 lp/mm input translates to 12.4 lp/mm through the minifier, while the 9.2 lp/mm increases to 16.6 lp/mm. Therefore, the observed resolution for both axes is expected.

The FPS vidicon resolution is calculated differently because it is a rastered system. In the vertical direction the quantity of scan lines, their diameter, and the size of the raster establish the resolution. If the scan lines are clearly separated or just merged, the resolution is calculated by

Fig. 5. Measured FOV for the FPS and CCD/minifier cameras. The measurements were taken for both axes, horizontal (top) and vertical (bottom).

dividing the quantity of scan lines by the raster height to get scan lines per height. Because two lines are required for one line pair, the FPS raster of 300 scan lines/21 mm gives 7.14 lp/mm. The observed vertical resolution limit between 6.9 lp/mm and 9.2 lp/mm is expected. In the horizontal direction, the

Fig. 6. Vertical resolution for FPS and CCD/minifier cameras as imaged in Fig. 5. Horizontal resolutions are shown on left and vertical resolutions are shown on right.

FPS scan beam has no discrete nature, therefore, the resolution is primarily a function of the beam's MTF and the amplifier's frequency response taken in quadrature. However, in this application as indicated earlier, the amplifier bandwidth (as set by its filter) is the main limit on horizontal resolution. This feature is noted in Table III.

Table III. Coupled system CTF and associated electronic frequencies at several input spatial frequencies. The FPS camera has a multipole sharp cut-off filter that is -3 dB at 25 MHz and -50 dB at 30 MHz. Therefore, the 9.2 lp/mm frequency that transforms to 33 MHz is unresolved. Similarly, because the 9.2 lp/mm that transforms to 16.6 lp/mm approaches the CCD camera's Nyquist limit, it is not resolved.

Freq (lp/mm)	FPS		CCD/Minifier	
	CTF (%)	F (MHz)	CTF (%)	F (MHz)
2.3	95	8.33	83	5.88
4.6	55	16.67	34	11.76
6.9	15	25.0	20	17.64
9.2	Band width limit		Alias threshold

Fig. 7. Horizontal pin hole responses for CCD/minifier and FPS.

Our pinhole arrays are designed to produce two adjacent spots or circles (per axis) of light of uniform intensity. The spots vary in diameter from $5\text{ }\mu\text{m}$ to $75\text{ }\mu\text{m}$. By observation of the FPS video as the scan beam traverses the spots horizontally, the corresponding scan line profiles provide beam diameter data directly. The point spread function (PSF) of the FPS electron scan beam lens/aperture is assumed to have a Gaussian current density distribution.⁸ For profiles indicating 50% overlap of basewidths, the PSF roughly corresponds to the spot diameter. For the CCD/minifier, however, the number of pixels horizontally with photocharge from a given spot diameter does not provide PSF data directly because of the noncontiguous geometry of the CCD.

The horizontal pinhole responses for both the FPS and CCD/minifier are shown in Fig. 7. The FPS clearly resolves the $50\text{ }\mu\text{m}$ pinholes. It also resolves the $25\text{ }\mu\text{m}$ pinhole pairs with sufficient overlapping to estimate PSF. This is consistent with measurements and calculations for 1-mil FPS vidicons (see Appendix) where we estimated $\approx 23\text{ }\mu\text{m}$ beam width at one standard deviation or $\approx 28\text{ }\mu\text{m}$ at FWHM.

The CCD/minifier response to the $50\text{ }\mu\text{m}$ pinholes shows the effects from demagnification. These pinholes are transformed to $\approx 28\text{ }\mu\text{m}$ ($84\text{ }\mu\text{m}$ width total), with the result that each spot can illuminate two-pixels ($12\text{ }\mu\text{m}$ width on $30\text{ }\mu\text{m}$ centers) as observed in Fig. 7. The 20 and $25\text{ }\mu\text{m}$ pinholes are transformed to ≈ 11 and $14\text{ }\mu\text{m}$, respectively. Depending upon alignment between the spots and pixels, the CCD/minifier showed two-pixel illumination on the average.

The vertical $50\text{ }\mu\text{m}$ pinhole response data indicated three scan line participation (one peak and two lobes) from the FPS (again consistent with $\approx 28\text{ }\mu\text{m}$ FWHM beam) and three row participation from the CCD/minifier (also consistent with expectations from the contiguous $36\text{ }\mu\text{m}$ pixel dimension and the $84\text{ }\mu\text{m}$ total height for the two spots).

Although our impulse measurements can estimate PSF responses for both sensors, only base widths of PSF can be inferred. The actual distribution or shape from base to peak cannot be identified without more rigorous experiments, including better knowledge of the light pulse distribution through the pinholes.

Additional measurements for the FPS and CCD sensors to quantify their horizontal and vertical resolution are in the Appendix.

The relative sensitivity and dynamic range of both cameras were measured. The responses of the CCD alone and the CCD/minifier are shown in Fig. 8. Because the two cameras have amplifiers with

Fig. 8. Relative sensitivities of the FPS and CCD/minifier cameras. The raw data and normalized data are shown for both the CCD/minifier and the CCD alone.

different gains, the raw data from the CCD and the CCD/minifier are normalized upward 5X for comparison with the FPS data. The normalized results indicate nearly identical sensitivity and dynamic range for the CCD and FPS cameras. The increased sensitivity for the CCD/minifier combination of $\approx 20X$ shown in Fig. 8 is as expected from the $\approx 88X$ gain shown in Table I and a quantum efficiency of $\approx 25\%$ for the CCD at 650 nm emission of the minifier's P-20 phosphor. The absolute responsivity for the CCD/minifier is $\approx 30 \text{ mV}/0.001 \mu\text{J}$ as noted in Fig. 8. For the FPS, the responsivity is estimated at $30 \text{ mV}/0.02 \mu\text{J}$. The absolute values for the light source were measured using the Optronic 730A radiometer.

6. CONCLUSIONS

Both cameras can provide adequate FOV to image the streak tube phosphor screen of $\approx 40 \text{ mm}$ diameter. Under those conditions, the FPS camera provides $\approx 25\%$ higher resolution in both the vertical and horizontal axes. The CCD/minifier provides $\approx 20X$ higher sensitivity. Both cameras have approximately the same dynamic ranges. The FPS camera, if coupled to an image intensifier with similar gain to that provided by the CCD's intensifier, could produce equivalent sensitivity while conserving its higher resolution. In essence, both the CCD and FPS sensors can deliver similar gain and resolution if one has control over pertinent external parameters.

7. ACKNOWLEDGMENTS

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APPENDIX

1. FPS RESOLUTION ANALYSIS

1.1 Horizontal PSF estimates from CTF data

The impulse response or PSF is usually determined by taking Fourier Transforms of the MTF response. Calculated values are obtained by converting measured horizontal square wave CTF response to MTF by the following equation:⁹

$$MTF = M(N) = \frac{\pi}{4} \left[C(N) + \frac{C(3N)}{3} - \frac{C(5N)}{5} + \frac{C(7N)}{7} \right], \quad (A-1)$$

where N = the number of cycles/unit length for M and the number of lp/unit length for C , and C = measured amplitude response (percentage of the dc response) at the fundamental and indicated harmonic frequencies of the square wave. After the conversion from CTF to MTF is completed, the spatial frequency is converted to electronic frequency as follows:

$$f_{\text{electronic}} (\text{MHz}) = (N) \frac{\text{cy}}{\text{mm}} \times \frac{\text{scan line length (mm)}}{\text{scan line duration } (\mu\text{s})}, \quad (A-2)$$

where N is the spatial frequency of interest, and the scan line length and duration are the active dimensions of the horizontal scan line.

This effectively transforms square-wave spatial frequencies to electronic sinusoidal frequencies or MTF for cascading with the amplifier's MTF to obtain composite MTF for the camera.

However, the CTF to MTF conversion can be made easily¹⁰ by using specially designed paper for MTF's of the form $\exp -(f/f_c)^n$ where f_c and n are the frequency constant and the MTF index, respectively. Their technique uses the fact that the MTF given by this equation is equal to $1/e$ (37%), when $f = f_c$, independent of the value of n . When the horizontal CTF data are plotted on their graph paper (see Fig. A-1a), the negative slope of the resulting MTF curve gives the value for n . The value of f_c is the spatial frequency at which the MTF is at its $1/e$ value. A line is then drawn parallel to the MTF plot that intersects the spatial frequency scale at the bottom of the graph (through the *) and the MTF index scale at the top of the graph.

Plots for typical 1- and 2-mil aperture vidicons as shown in Figs. A-1a and A-1b indicate average MTF indices of 2.2 and 1.8, respectively. Within the error limits of the data, an MTF index range of $2.5 \geq n \geq 1.5$ was calculated. Therefore, the beam shape for these vidicons is estimated to be somewhere between sub-Gaussian ($n < 2$) and super-Gaussian ($n > 2$), with the average value of $n = 2 \pm 10\%$ approximating a basically Gaussian response.

For Gaussian waveforms, the width for PSF is normally given at the FWHM point. It can also be given at the one- or two-standard deviation points. The standard deviation, σ , is defined as the $e^{-1/2}$ (0.607 of peak value) point. The full base width is assumed to be sufficiently defined by $\pm 3\sigma$. For f_c in lp/mm, σ acquires units of length:

$$\sigma_x = \frac{1}{2\pi f_c}. \quad (A-3)$$

To obtain FWHM from σ_x , first correct for the differences between 50% and 1σ widths (50% width ≈ 1.22 1σ width) for half of the waveform width and multiply by 2 to give the full waveform width at 50% of peak amplitude. This results in the following equation:

Fig. A-1. The CTF plots for 1-mil and 2-mil aperture are shown in (a) and (b), respectively. Two vidicons of each aperture size, labeled a and b, were selected to show typical spread in resolution for a given aperture. The a' and b' plots give the range for n and f_c is read from the spatial frequency scale where a' and b' cross the $1/e$ value (dotted line).

$$\text{FWHM} = 2.44\sigma_x \quad (\text{A-4})$$

Using equations (A-3) and (A-4) and the measured values for f_c obtained from Figs A-1a and A-1b, calculated PSF of approximately $28 \mu\text{m}$ and $49 \mu\text{m}$ FWHM were obtained for 1- and 2-mil vidicons, respectively. Using the $\pm 1\sigma$ points, the widths are approximately 23 and 40 mm, respectively, for the two vidicons.

1.2 Vertical PSF estimates from raster line density

We investigated the possibility of experimentally determining scan beam diameters from controlled overlapping of individual scan lines. This should produce predictable amplitude response based upon the degree of beam overlap as indicated in Fig. A-2 for separated, merged, and overlapped scan lines. Assuming uniform charge distribution on the target and in the beam, the separated and merged conditions should give identical signal amplitudes. However, the 50% overlapped condition should collect charge from only 50% of the target area scanned by the nonoverlapped conditions. This would result in reduced amplitudes of approximately 50% for the same input light. The absolute response depends upon the physical shape and energy distribution of the beam. Figures A-3a and A-3b show that different overlapping is required for sinusoidal and Gaussian shaped beams to merge the waves to their FWHM points. Our data have insufficient resolution to determine beam profile characteristics this accurately. Therefore, to a first approximation the signal amplitudes observed are roughly proportional to the degree of beam overlap expected from either shape.

The scan line density was varied from <2.5 to >25 lines/mm for these tests. After adjusting the number of scan lines, the FPS video amplitude was measured at each line density by illuminating the vidicon target with a square pattern $\approx 4 \times 4$ mm of uniformly diffused light. Separation occurs between 14 and 28 lines/mm for typical 1-mil beam apertures as indicated in Fig. A-4. This is obvious from the fact that in Fig. A-4 the amplitudes for 4 and 7.5 lines/mm are identical and the amplitude for 14

Fig. A-2. Simplified model of beam width control by overlapping of raster lines. The path swept out by the beam for the 50% overlapped case addresses the target with width $\approx d/2$, where d is the beam width or diameter.

(a)

(b)

Fig. A-3. Pulse peak separation for 50% base overlapping of sinusoidal (a) and Gaussian (b) waveforms. Pulse widths for FWHM and RMS are noted.

lines/mm is only slightly reduced. At 28 lines/mm the amplitude is $\approx 50\%$, implying $\approx 50\%$ overlapping of scan lines. The raster line separation at 14 lines/mm corresponds to a beam diameter of approximately $71.5 \mu\text{m}$. Assuming a Gaussian profile, the beam width of $\pm 3\sigma$ corresponding to $71.5 \mu\text{m}$ gives $11.92 \mu\text{m}/\sigma$ resulting in $29.1 \mu\text{m}$ FWHM or $23.8 \mu\text{m}$ for $\pm 1\sigma$ for PSF.

2. CCD RESOLUTION ANALYSIS

To test spatial resolution of the CCD 222, a $4 \mu\text{m}$ diameter pinhole was used. The pinhole was housed in a TV Optoliner slide and illuminated with continuous light. The CCD camera was mounted on a positioner that was movable along x, y, and z axes in front of the Optoliner. Two manually operated precision micrometers with $2.5 \mu\text{m}$ resolution were used to move the CCD horizontally along its rows and vertically along its columns to measure pixel resolution and opacity characteristics.

Each pixel is composed of one even and one odd photosite and the adjacent segment of vertical shift register as shown in Fig. A-5.

The video signal from several consecutive pixels along a row (Fig. A-5, top) showed the maximum amplitude at the photosite center. Only a small amount of light ($\approx 1\%$) was detected in adjacent photosites when the pinhole was focused on a photosite center. When the pinhole is moved to the center of the vertical shift register, about 11% of the peak signal was detected by two adjacent photosites. As the pinhole was moved (left) to the next photosite, the signal of the preceding one exhibited a plateau, probably from photons straying into the semi-opaque vertical registers.

Fig. A-4. Transfer curves versus raster line density for typical 1-mil beam aperture vidicon. The same amplitude observed at different line densities indicates separation of individual lines.

Fig. A-5. Horizontal scan (top) in $2.5 \mu m$ steps along a CCE row by a $4 \mu m$ diameter pinhole light source. Separation of individual photosite signals is due to the semi-opaque vertical register between photosites along this axis. Similar vertical scan (bottom) along a column with even and odd photosites combined showed crossing at 50% amplitude point because there is no boundary gap between pixels along this axis.

The results from scanning the pinhole vertically along a column are shown in Fig. A-5 (bottom). The even and odd photosites were combined into a single noninterlaced pixel 36 μm in height. Transition from one pixel to another showed no gap because in that direction pixels are contiguous. The individual pixel amplitudes showed a dip in the middle due to some loss in quantum efficiency caused by various polysilicon layers across pixels on the sensor surface.

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