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TECHNICAL MEMORANDUM NO. 87

SUBJECT : A Comparison of Silver Halide Film and Linear Arrays of Solid State Photodiodes as the Image Transducer for a Near Real Time Readout System

REFERENCE : Technical Memorandum No. 44

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1. There are four first order considerations to be examined in assessing the utility of any transducer candidate for an image readout function:

(1) Quantum efficiency/integration time.

(2) Dynamic range.

(3) Spectral response.

(4) Format size.

This memorandum is primarily concerned with treating the comparison of silver halide film versus solid state photodiode detectors with respect to quantum efficiency and dynamic range as related to image quality performance. Both the Westinghouse and TRW detectors have a sufficient spectral response to form useful images, and both can be configured with adequate format sizes for the near real time application. However, it is worth noting that the Westinghouse photodiode array has a considerably broader spectral response than does silver halide film. The potential value of this broad response characteristic has not yet been fully assessed.

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2. The Reference develops the basic equations governing the image quality performance of any system involving a sampling process. Figure 1 shows the two fundamental equations derived in the Reference for the two limiting conditions of transducers dominated by internal noise and transducers dominated by shot noise due to the statistical distribution of the photon flux from the scene. Although these equations were specifically developed for the case of arrays of discrete detectors, they can be directly applied to any imaging system which is characterized by a two-dimensional sampling process. In the more general case, (X) refers to the characteristic sampling dimension referred to the focal plane of the optical system, (T_A) refers to the transfer factor associated with the sampling process, and (A) refers to the effective area of the sampling aperture. The optical system parameters are generally applicable as are the scene parameters. The detector quantum efficiency (η) and the integration time characteristic of the imaging process are also concepts independent of any particular transducer and, similarly, for internal transducer electrical noise and photon noise generated as a function of (B), the average scene radiance.

3. The analysis that follows compares two imaging systems, one designed around linear arrays of solid state detectors and the second designed around silver halide film with on-orbit processing and laser scanner readout. Both systems are presumed to have the same optical system diameter [redacted] but with the focal length adjusted to match the characteristics of the two transducers. Tables I and II summarize the key imaging systems characteristics for the two cases.

4. For the silver halide system, an F/4 optical system and type 1414 film was selected. This is approximately the F/number of the current GAMBIT-3 system which also uses type 1414 film. The exposure times required to satisfy the film exposure criteria over the relevant range of average scene radiance values for this choice of F/number is shown in Figure 2. This analysis is based on the assumption that uncompensated image motions are sufficiently small so that the resulting

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image quality degradation is negligible. This condition would be difficult to satisfy for the larger exposure times (5-10 ms) and, therefore, the film system performance estimates are optimistic for the low scene brightness condition. It is also possible to choose a larger F/number leading to improved performance for bright scenes and accepting the resulting image quality penalties for scenes of lower average brightness. However, all of these considerations are refinements which would not significantly impact the conclusions of this memorandum.

5. A number of other simplifying assumptions have been made with regard to the silver halide system. However, all of these assumptions tend to err on the side of making the film system performance appear better than could be expected in practice. First, silver halide film is assumed to be photon noise limited as opposed to film grain noise limited. Most of the calculations for the silver halide system have been carried out for both quantum efficiencies of .005 and .01. Experimental measurements on typical film materials indicate that for optimum processing and ideal exposure the effective value of film quantum efficiency falls between these two numbers. The film processing assumed in this analysis is similar to that currently used for ground processing of type 1414 film (see Figure 3). No additional degradations were included for any potential degradation resulting from on-orbit film processing. The laser readout process is assumed to be noiseless. Also, the effect of the film optical properties on the laser readout transfer function have been assumed negligible. Finally, the scene brightness statistics used are characteristic of minimum haze conditions. This assumption also favors silver halide film since haze will tend to bias the brightness statistics towards increased average scene radiance and lower contrast.

6. In order to formulate a comparative analysis, it is necessary to assume a scene model. Figure 4 shows the relationship between average scene radiance and sun angle for a 12% reflectance

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target and minimum haze conditions. Although there are variations in average scene reflectance model depending upon target type, this model is supported by experimental data as a reasonable representation of the "average" world. In any case, the analysis that follows is not sensitive to this selection. Unlike conventional film systems where the exposed film is recovered for direct viewing, the basic quantity of interest is radiance changes in the ground scene to be imaged. The signal-to-noise performance of sampled systems can be measured either against a given radiance difference (Δ B) assumed to be constant over all sun angles or against a given reflectance difference in the ground scene resulting in a radiance difference input to the system varying as a function of sun angle. The following analysis is developed for both models and the conclusions on the comparative imaging performance of the solid state detectors and silver halide film are not significantly different for either model.

7. Figure 5 compares a family of silver halide film system designs to a family of solid state array system designs. In this case, the imaging performance is maintained for a constant radiance difference of 6.8 watts per square meter per steradian (400 foot lamberts) at a signal-to-noise ratio of 5. The ground sampled distance (GSD) parameter is designed into a system and is a characteristic determined by focal length, altitude, and sampling pitch. The curves of Figure 5 for silver halide systems and solid state array systems are the locus of points for which a system could be designed to achieve a signal-to-noise ratio of 5 for the given radiance difference. For example, a silver halide system can be designed with a GSD of 20 inches at an average scene radiance of approximately 15 watts per square meter per steradian. This average scene radiance corresponds to a sun elevation angle of approximately 44 degrees for the assumed scene model. For a film system designed for a 30 inch GSD, this same signal-to-noise ratio condition is met at a higher average scene brightness of approximately 25 watts per square meter per steradian appropriate to a sun angle approaching 90°. This variation in silver

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halide system performance is accounted for by the increasing contribution of photon noise with increasing average scene brightness and decreasing integration time required to maintain a proper film exposure. The solid state detectors on the other hand have a sufficiently wide dynamic range so the integration time need not be decreased with increasing average scene brightness. Furthermore, for detectors characterized by a noise equivalent signal of 1.2 microjoules per square meter, the total noise of the imaging process is dominated by this internal electrical noise and even for bright scenes, photon noise is only a negligible contributor as shown by the N=1.2 microjoules per square meter curve in Figure 5. The N=0 curve in Figure 5 shows the performance of solid state detectors assuming that the internal noise is reduced to negligible proportions leaving only photon noise. The quantum efficiency of the detectors is 0.43, averaged over the 0.4 to 0.8 micron portion of the optical spectrum.

8. The silver halide film system performance approaches that of the internal electrical noise-dominated solid state array detectors at an average scene brightness of approximately 5 watts per square meter per steradian. In this region the silver halide exposure times have increased to over five milliseconds and, in an actual system design, significant image motion degradation would begin to occur. As mentioned above, this effect is not included in the analysis. Nonetheless, the performance of the solid state array detectors is everywhere better than silver halide film even for the non-ideal internal noise limited devices. Some detectors are now being made with internal noise sufficiently low to approximate the N=0 curve. In this case, the solid state array performance is two to four times better than that for silver halide film. The silver halide film curve in Figure 5 is for an effective quantum efficiency of 0.01.

9. Figure 5 is a parametric comparison of different potential systems designs. Figures 6 & 7 on the other hand select specific designs for a silver halide film system and for a solid state array

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system and compare the performance of those designs over a range of scene conditions. In both designs the ground sample dimension has been fixed at 12 inches. Again, the optical diameter and the operating altitude of the systems are identical. Figure 6 shows the signal-to-noise ratio that would be achieved as a function of average scene brightness for a constant radiance difference of 6.8 watts per square meter per steradian. Figure 7 is the same relationship assuming a constant reflectance difference in the ground scene of 0.06. The apparent radiance difference in this case is a function of average scene radiance through the solar elevation and equals 6.8 watts per square meter per steradian at a 40° sun angle. In both cases, the solid state array system is internal noise limited with a noise equivalent signal of 1.2 microjoules per square meter. Two cases are shown for film, one with a quantum efficiency of 0.005 and the other with a quantum efficiency of 0.01. Again, except for low scene radiances, the solid state array system is everywhere better than the silver halide film system. For the 40° sun angle and an average scene radiance of 13.9 watts per square meter per steradian, the solid state array system provides approximately two and one-half times the signal-to-noise ratio performance of the silver halide film system.

10. Still another way of comparing the system performance is to show the minimum reflectance difference which could be reproduced through either of the systems at a given signal-to-noise ratio (Figure 8). This method of comparison, however, leads to exactly the same conclusions as those based on Figures 5, 6, and 7. For completeness, Figure 9 is included to show the comparison between an ideal photon noise limited solid state detector and silver halide film.

11. Figure 10 compares a film readout system based on the GAMBIT-3 44" diameter optical system operated at 170 n.mi. with the [redacted] solid state array system operated at 283 n.mi. Again both systems are evaluated for the 12" nadir GSD design point.

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Because the reduced altitude for the film system does not completely compensate for the smaller optical diameter, the performance in this case compares even less favorably with the solid state array system.

12. The general trend of the results discussed in the preceding paragraphs are what should be expected from an inspection of the equations in Figure 1. The two key parameters dominating the image quality performance of the two transducer systems are the quantum efficiency and the integration time. The quantum efficiency of the solid state detectors is approximately two orders of magnitude greater than that of silver halide film (0.5 versus 0.005). On the other hand, because of the linear construction of the solid state arrays, practical system designs are limited to integration times no greater than three to four milliseconds while silver halide film systems can be designed to integration times of five to ten milliseconds. Comparing a one millisecond solid state array system with a quantum efficiency of 0.5 to a ten millisecond silver halide film system with a quantum efficiency of 0.005, the product of these two quantities is an order of magnitude greater for the solid state arrays than for film. This leads to a ground sample dimension distance advantage for solid state arrays of something like the square root of ten. This advantage is somewhat reduced because of the relatively large sources of internal noise characteristic of solid state detectors currently being fabricated, but this internal noise is already sufficiently low to give the solid state devices a substantial performance edge over silver halide film based readout systems for most operating conditions.

13. A more meaningful operational comparison between the two types of systems can be made by examining the actual statistics of average scene radiance against the target distribution of interest. Figure 11 is a probability density function derived from examining the actual distribution of GAMBIT-3 targetting for the year 1968. This includes some 45,000 targets. Assuming the constant delta

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reflectance scene model, Figure 12 shows the probability density as a function of signal-to-noise ratio that would have been achieved by the silver halide readout system and the solid state array system with the internal noise limited detectors. As can be seen from Figure 11, an appreciable fraction of the 1968 GAMBIT-3 targets were taken at low sun angles. Here again, any potential image motion degradation at long exposure times required by the film system have been neglected. Even though these effects have not been modeled in this comparison, something in excess of 60% of 1968 GAMBIT-3 targets would have been imaged with better quality by the solid state array system.

14. Dynamic range enters this transducer comparison in two ways. As has been discussed above, the dynamic range of film is great enough to produce useful images of most scenes photographed under reasonable illumination conditions. However, the range of radiance values in many scenes is sufficiently great so that the exposure time must be carefully adjusted as a function of average scene radiance to keep the average scene exposure on the linear, high resolution portion of the film response curve (see Figure 3). This reduction in exposure time with increasing scene brightness is one of the important contributors to the relatively lower performance of the film system. However, even with optimum exposure control, the film dynamic range is not sufficient to accommodate many scenes without appreciable loss of information. This degradation in quality is a result of the strong dependence of film performance on exposure as indicated by the variation in tri-bar target resolution with exposure shown in Figure 3. In most scenes shadow areas will fall well down on the toe of the response curve, while fully illuminated, high reflectance objects will fall well up toward the shoulder of the curve (see Figure 12). A careful statistical study of brightness distributions in scenes of practical interest is necessary to determine the relative impact of these considerations, but clearly silver halide film is at a disadvantage compared to solid state detectors characterized by a dynamic range several orders of magnitude greater than film.

TABLE I

SILVER HALIDE FILM READOUT SYSTEM

Operating Altitude	283 n. mi.
Optical Diameter	[redacted]
Focal Length	[redacted]
Optical Transmission Factor	[redacted]
Film	Type 1414
Average Quantum Efficiency	.005 - .01
Laser Scanner Noise	0

TABLE II

SOLID STATE ARRAY SYSTEM

Operating Altitude	283 n. mi.
Optical Diameter	[redacted]
Focal Length	[redacted]
Optical Transmission Factor	[redacted]
Array Pitch (X)	[redacted]
Noise Equivalent Signal (N)	1.2 microjoules/m^2
Average Quantum Efficiency	0.43