Range Commanders Council

OPTICAL SYSTEMS GROUP

SPECIAL REPORT

ASSESSMENT OF DIGITAL OPTICS FOR THE TONOPAH TEST RANGE

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ASSESSMENT OF DIGITAL OPTICS FOR THE TONOPAH TEST RANGE

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Prepared by

OPTICAL SYSTEMS GROUP
RANGE COMMANDERS COUNCIL

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PREFACE

This report summarizes the work performed in 2004 on the "Assessment of Digital Optics for the Tonopah Test Range," sponsored by Sandia National Laboratories[1] and submitted to the Optical Systems Group (OSG) of the Range Commanders Council (RCC). The work performed directly supports the required background analyses for improving the optical capabilities at the Tonopah Rest Range (TTR). The current optical capabilities rely upon older technology that is becoming less reliable, more expensive to maintain, and unable to keep pace with the more stringent optical test requirements expected at TTR. The overall goal of revitalizing the optical test equipment is to transition to state-of-the-art capabilities while simultaneously maintaining quality and exercising good cost management practices.

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CHAPTER 1

INTRODUCTION

Tonopah Test Range (TTR) possesses a unique combination of geography and environment that makes it ideal for optical flight-testing. The primary flight path is oriented nearly north-south in an isolated trough between two mountain ranges. The remote, dry, high-altitude location makes viewing conditions superb and reliable. TTR may well be considered one of the premier optical test ranges in the entire United States.

In considering enhancements for the range, it is important not to diminish the high quality of existing optical capabilities so that the range can continue to capitalize on these distinguishing attributes. However, the current optical capabilities are built around antiquated technology that is becoming less reliable and increasingly difficult to maintain. Furthermore, new capabilities can improve both operational efficiencies (costs) and data turnaround. Therefore, the goal for revitalizing the optical capabilities at TTR should be to make them efficient and robust without sacrificing quality.

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CHAPTER 2

SCOPE

One of the major enhancements being considered for TTR is the introduction of digital optics. For the purposes of this study, the optical capabilities of interest are those that produce documentary imagery and Time Space Position Information (TSPI). Documentary imagery is captured predominantly on time-stamped, high-speed (typically 100 frames per second (fps)), 35mm color movie film shot through 117.5-inch focal-length, ME-16 telescopes. TSPI information is derived from multiple time- and orientation-stamped, low-speed (typically 10 fps), 35mm color movie films shot through highly-calibrated, 60-inch focal-length, Contraves cinetheodolites. An intensive data extraction and reduction process is performed on the cinetheodolite films to produce TSPI data, with accuracies reported to be on the order of ±15 arc-seconds (i.e., ±9 inches at 10,000 feet). Cinetheodolite film data are extracted (digitized) using Telereadex film readers. The process involves, for *each* film frame, manually positioning horizontal and vertical cross-wires on a projected film image to extract bore-sight correction measurements for a target while automatically capturing the corresponding time/position matrix. This process can be repeated for orientation or multi-target solutions.

A few additional details are worth introducing at the start of this discussion. The image size for 35mm movie film is 18 mm high × 24 mm wide. This image is smaller than the 24 mm high × 36 mm wide image for 35mm still film because the movie image width is perpendicular, rather than parallel, to the sprocket holes. For surveillance bomb drops, frame width is the more important dimension. For a 117.5-inch focal-length telescope, the movie frame width translates to a horizontal field-of-view of 0.46° (2*arctan(½*(24mm/25.4)/117.5in). Now, one-third of the Contraves image width is taken up by the time/position matrix, so the net cinetheodolite image is 18 mm high × 16 mm wide. This frame width translates to a horizontal field-of-view through a 60-inch focal-length lens of 0.60° (2*arctan(½*(16mm/25.4)/60in).

Introducing digital optics is envisioned in two steps. The first step involves replacing the antiquated and virtually unsupportable Telereadex film readers with a modern system. The postulated system is called TrackEye and includes a film digitizing scanner and data extraction & motion analysis software. A TrackEye system has been procured recently for SNL/NM Area 3 photometric analysis. Twenty-four-bit color (i.e., 3 colors × 8 bits each) scanners are available with 2048 and 4096 pixels across the full width of 35mm film, generating image files that are nominally 6.8 and 27.1 megabytes per frame, respectively. The TrackEye software of initial interest to TTR is that used to extract bore-sight corrections (and the corresponding time/position information) from the digitized film images. These capabilities exist and have been demonstrated for TTR applications. The TrackEye system also includes automatic target tracking features, which, even though they were not completely robust in initial tests, should increase data extraction rates over manual cross-wire placement. The reader is referred to the test report turnaround discussion below.

There is a long-term need to assess how data reduction will continue to be done at TTR. The TTR software for generating three-dimensional TSPI solutions was developed in-house. However, the only major refinement in the last 15 years has been to port the software to newer computer platforms. The TrackEye system is reported to have 3-D solution capabilities that may be adaptable to TTR problems. Possible upgrade options for TTR include adopting the TrackEye software, porting the TTR software into the TrackEye system, or porting the data extracted using TrackEye into the existing TTR data reduction system. This issue will not be addressed as part of this assessment, except to note that a phased approach can be used such that TTR never suffers a loss of capability. The major issue to be addressed here is the viability of the TrackEye scanner options as a replacement for the Telereadex film readers. Specifically, the issue is whether either, or both, of the 2048- and 4096-pixel scanners are capable of replacing the Telereadexes without diminishing the quality of data.

The second step in introducing digital optics to TTR involves replacing the existing 35mm film movie cameras with digital cameras. The motivations were reported to be three-fold: to eliminate the expense, time delay, and threat of obsolescence associated with film technology. The annual TTR expense for film procurement and development was reported to be less than $100K, and so this expense is not a critical issue. The turnaround for film development is typically one week, which is a significant part of the typical test report turnaround of three weeks. (Typical timelines for data extraction and data reduction are one week each.) Eliminating film, and accounting for the efficiencies envisioned by the TrackEye data extraction software, test report turnaround time can likely be cut in half to 1½ weeks. Improvements to the Contraves cinetheodolites could get report turnarounds down to one week, and with some additional software development, could lead to near real-time turnarounds (albeit with some likely sacrifice in accuracy). The obsolescence of film technology will undoubtedly occur; the question of "when" is subject to immense speculation. For TTR, the enhancements to report turnaround can be viewed as the primary motivation, though other operational efficiencies will become apparent from this report. As with the Telereadex replacement, replacing film cameras should be pursued with the intent of maintaining the current quality level. As will be seen, a technical basis exists for addressing this concern for both upgrade steps, though definitive information is still lacking. Nonetheless, this formulation will be presented to foster understanding and promote the acquisition of information needed for procurement.

CHAPTER 3

FORMULATION

Performance of optical components has been qualified using a variety of techniques. A multitude of target boards has been used to gauge comparative performance, but these efforts often lack consistency and depend on the "eye of the beholder" rather than quantitative measurements. Figure 3-1 through Figure 3-6 illustrate numerous issues associated with this approach. The figures compare target board images of the existing TTR telescopic capability versus those produced with digital cameras. (The images were sized consistently such that the width of a target board was approximately 10 percent of the width of the image frame. The Vision Research Phantom 9 results were simulated using the Phantom 5 camera, taking into account differences in frame width and pixel density.) The TTR ME-16 result was taken from an enlarged print that was then scanned. As will be seen from the formulation in this report, both of these operations introduce losses in image quality. These losses preclude a more definitive comparison with the digital camera results, but they also highlight a benefit of digital technology by reducing the compounding of losses. It is useful to observe that TrackEye scans of film may indeed possess the worst attributes of both film and digital technologies. While appropriate in the short term, migrating to digital cameras is viewed as the better path for the future.

A couple of observations regarding the digital images are appropriate. Obviously, performance in monochrome mode is superior to that in color mode for both increased resolution and reduced moiré fringing. Additionally, the simulated performance of the Vision Research Phantom 9 camera represents a significant improvement over the Phantom 5 because of its 12 percent larger sensor width and 28 percent smaller pixel spacing. The goal, then, is to quantify these performance differences and provide the apples-to-apples comparisons with film that are difficult to attain.

Fortunately, there is a small cadre of individuals that is attempting to quantify digital-versus-film performance. A leader in this field is Norman Koren (http://www.normankoren.com), who has applied his expertise from a career in magnetic, high-capacity, data storage systems to his passion of photography. The basis for Koren's formulation is the Modulation Transfer Function (MTF), which quantifies the spatial frequency response of various optical components much like the audio response can be quantified for components of a stereo system. MTFs are displayed as the response percentage of input versus spatial frequency (typically in line pairs per millimeter (lp/mm), analogous to cycles per second for audio systems). For any given frequency, MTFs of individual serial components can be multiplied to provide the overall system response. Koren states the MTF relates to the bandwidth of a communication system, whereas image grain corresponds to noise.

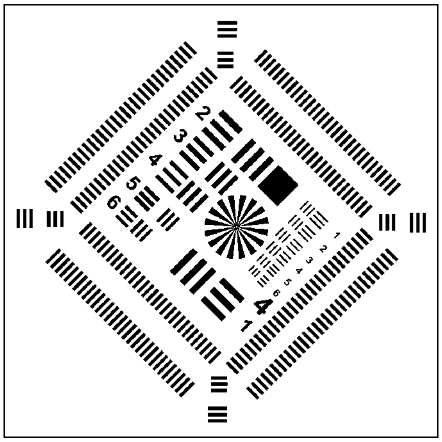


Figure 3-1. Target board.

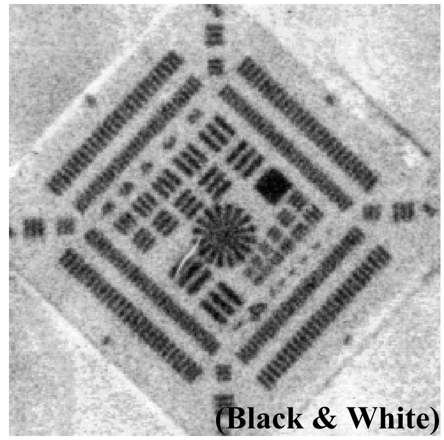
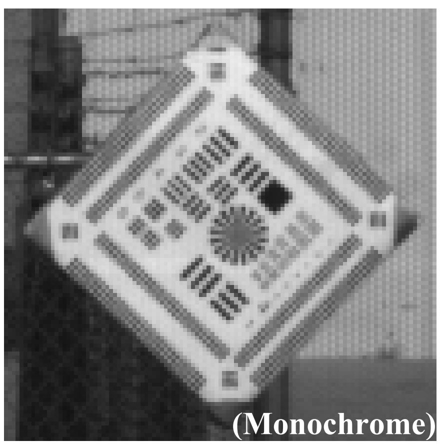
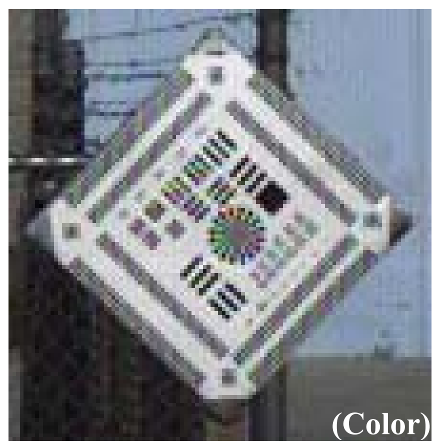
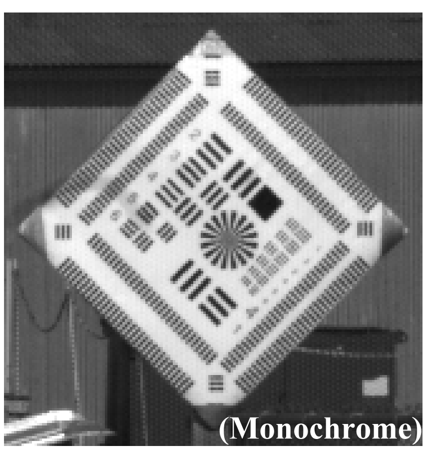


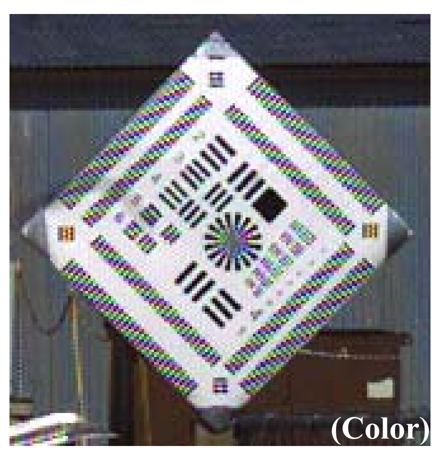
Figure 3-2. Target board through ME-16 telescope.





Figures 3-3 and 3-4. Target boards through Vision Research Phantom 5 camera.





Figures 3-5 and 3-6. Target boards through *simulated* Vision Research Phantom 9 camera.

Photographic components typically act as low-pass filters in that their responses roll off at high spatial frequencies. High spatial frequencies correspond to fine image detail and are therefore key to determining image resolution. The spatial frequency corresponding to around the 10-percent system MTF response defines the practical image resolution limit - the point where a black/white line pair appears uniformly gray. Therefore, this limit will be cited extensively in this analysis. Koren states that the 50-percent MTF response corresponds to perceived image sharpness; these results will also be reported even though the emphasis will be on resolution.

A simple example helps to illustrate concepts, introduce pertinent equations, and understand differences in film performance. Figure 3-7 provides MTFs for a variety of films. Note: A tabulated summary of all formulation results is in Table 3-1 at the end of this chapter. Koren uses the two Fujichrome films in his tutorials. The MTF for the Provia 100F film is approximated by:

$$\mathrm{MTF}_{\mathrm{film}}(f) = 1/\left(1 + (f/f_{50})^2\right), \qquad (Eq.\ 3\text{-}1)$$

where f_{50} is the 50-percent MTF response frequency (40 lp/mm for Provia 100F).

This approximation produces an f_{10} (i.e., the 10-percent MTF response frequency) of 120 lp/mm for the Provia 100F film.

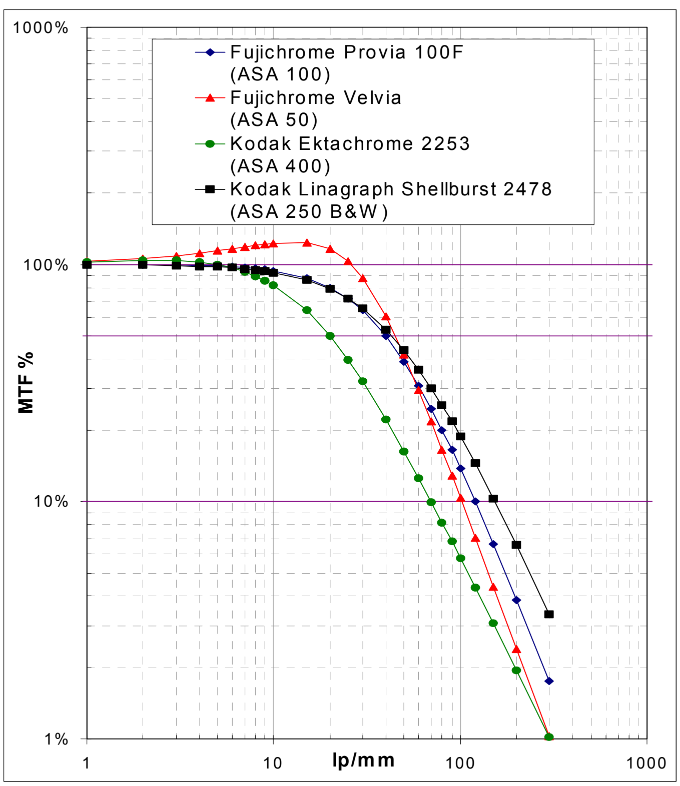


Figure 3-7. MTFs for representative films.

Fujichrome Velvia is what is known as a boosted film in that its response is greater than 100 percent for certain spatial frequencies. Boosting is caused by a phenomenon termed the adjacency effect and results in exaggerated contrast boundaries. The MTF for the Velvia film is approximated by:

$$\mathrm{MTF_{film}}(f) = \mathrm{k} \big/ \left(1 + \left((f - f_{\mathrm{boost}}) / f_{50a}\right)^2\right), \qquad (Eq.\ 3\text{-}2)$$

where f_{boost} is the frequency of maximum MTF (13 lp/mm for Velvia),

f_{50a} is the adjusted denominator frequency (derived from the 45 lp/mm f_{50} for Velvia), and

k is a constant such that $\mathrm{MTF_{film}}(0) \equiv 1$.

Note that setting $f_{\mathrm{boost}} = 0$ collapses this equation to the previous one. The boosted approximation produces an f_{10} of 102 lp/mm for the Velvia film.

The two Kodak films in Figure 3-7 are used at TTR, and their MTFs were obtained from the manufacturer's specification sheets. The MTF equations used to fit the manufacturer's data are the same as above except that the roll-off exponent (2 in the equations above) is made adjustable (*fexp* in the equations below) to allow matching of both f_{50} and f_{10} values from the manufacturer, namely:

$$\mathrm{MTF_{film}}(f) = \mathrm{k} \big/ \left(1 + \left(|f - f_{\mathrm{boost}}| / f_{50a}\right)^{fexp}\right), \qquad (Eq.\ 3\text{-}3)$$

where $f_{50a} = \left((f_{50} - f_{\mathrm{boost}})^{fexp} - 2(f_{\mathrm{boost}})^{fexp}\right)^{1/fexp}$,

$\mathrm{k} = 1 + (f_{\mathrm{boost}} / f_{50a})^{fexp}$, and

fexp is determined by trial-and-error.

Kodak Ektachrome 2253 is a 400-speed color film used in both documentary and TSPI cameras. It is slightly boosted, and has an f_{50} of 20 lp/mm and an f_{10} of 70 lp/mm. Ektachrome's performance is dramatically lower than the two portrait-quality Fuji films, primarily due to its higher film speed. Kodak Linagraph Shellburst 2478 is a 250-speed black & white film used occasionally at TTR for test shots and focus runs, primarily because it can be developed on-site. Figure 3-2 was obtained using this film. Shellburst has the highest resolution of the four films in Figure 3-7, with an f_{10} of 153 lp/mm. With an f_{50} of 43 lp/mm, Shellburst's perceived image sharpness is comparable to the two Fuji color films.

The MTFs for film are relatively simple to obtain and understand. They are uniform in all directions and over the entire image surface. In contrast, MTFs for lenses are exceptionally complex. They are functions of the distance from lens center, direction from any point on the lens, f-stop, light spectrum, focusing distance, etc. TTR's case is complicated by the fact that lens performance for the telescopes and cinetheodolites is not quantified. Koren simplified his analyses by utilizing the equation:

$$\mathrm{MTF_{lens}}(f) = 1 \big/ \left(1 + (f / f_{\mathrm{lens}})^{lord}\right), \qquad (Eq.\ 3\text{-}4)$$

where f_{lens} is the frequency where MTF_{lens} = 50 percent, and

2 is the default value for *lord*.

Throughout his analyses, Koren utilized center-of-lens properties for a Canon 28-70mm f/2.8L zoom lens at settings of 40 mm and f/8, resulting in: f_{lens} = 61 lp/mm and *lord* = 2, for an f_{10} of 183 lp/mm. Lacking any better information, this approximation will be used for the TTR systems. (Subsequent correspondence from Koren suggests *lord* = 3 might be a better fit for diffraction-limited lenses.)

The effect of lens MTF on overall system performance is illustrated in Figure 3-8 for Fuji Velvia and Kodak Ektachrome films. Velvia performance drops from f_{50} = 45 lp/mm & f_{10} = 102 lp/mm for film-only to f_{50} = 37 lp/mm and f_{10} = 69 lp/mm for film + lens. Ektachrome performance drops from f_{50} = 20 lp/mm & f_{10} = 70 lp/mm for film-only to f_{50} = 18 lp/mm & f_{10} = 49 lp/mm for film + lens. Because of the low-pass nature of the lens "filter," performance loss increases with increasing spatial frequency. Adding the lens reduces the Ektachrome f_{50} performance by 9 percent, but reduces the f_{10} performance by 29 percent. Note that the spatial frequencies are stated relative to the image size on film.

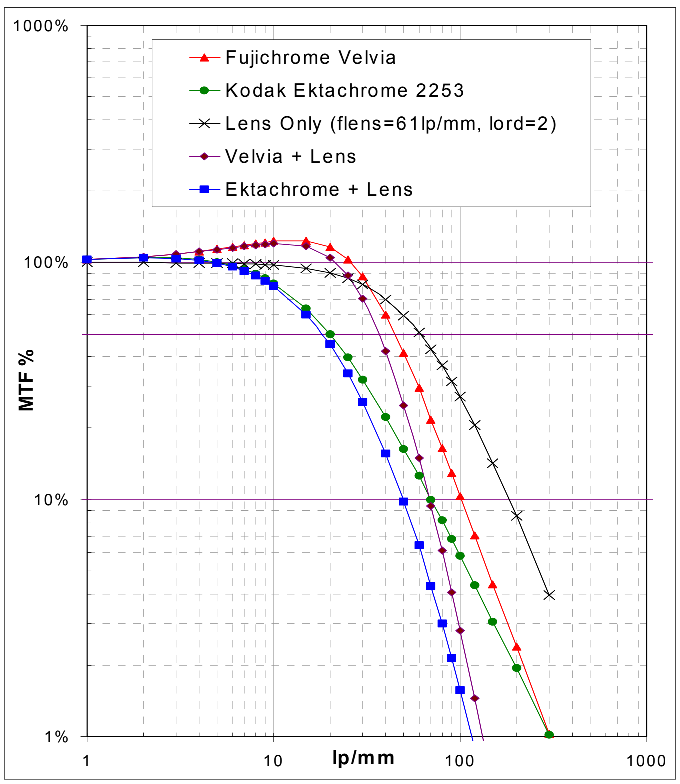


Figure 3-8. MTFs for film, lens, and film/lens combinations.

When a cinetheodolite film is projected using a Telereadex film reader, the image on film is "filtered" by another lens. The same MTF_{lens} equation can be used for the film reader, and Koren states that a quality enlarger lens has an f_{50} of 60 lp/mm (with *lord* = 2). Figure 3-9 illustrates the overall MTF for a projected film image. For consistency, the spatial frequencies continue to be stated relative to the image size on film. (The Telereadex projections are magnified ~22X, so *dividing* the spatial frequencies relative to film by 22 would give the spatial frequencies relative to the enlarged image.) The projected Ektachrome image now has an f_{50} of 17 lp/mm and an f_{10} of 41 lp/mm with respect to the image size on film. The Telereadex f_{10} is 17 percent lower than the f_{10} for lens + film and 41 percent lower than the f_{10} for film-only.

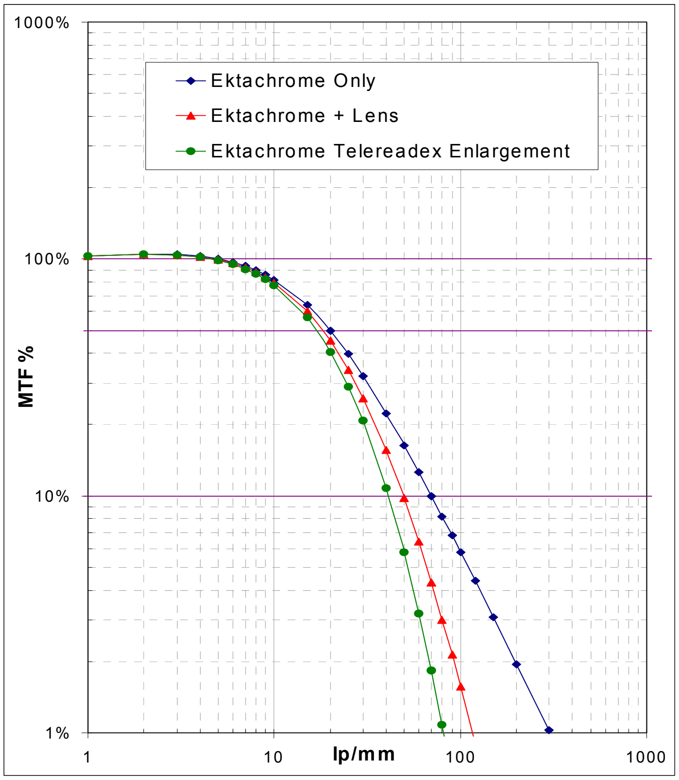


Figure 3-9. Effect of Telereadex enlargement on overall Ektachrome MTF.

The focus on resolution (i.e., f_{10}) can now be put in context to knowledge about the Telereadex film readers. The Telereadexes have a gross resolution of 142 µin (7030 counts per inch), or 3.6 microns, relative to the image size on film. However, according to John C de Baca, repeatability of bore-sight correction measurements is on the order of ±5 counts for sharp images and ±10 counts for less optimal conditions. Therefore, the actual Telereadex repeatability is on the order of ±18-36 microns. This is certainly larger than the computed $1/f_{10}$ = 24 microns per line pair (or 12-micron line width) for projected Ektachrome, but it includes other errors such as parallax, cross-wire thickness, film registry, etc. The fact that the numbers are similar in magnitude lends confidence to the formulation. Comparing resolution via f_{10} should ensure at least comparable, if not better, digital performance relative to film.

Scanners, and sensors for digital cameras, have their own MTF formulation. Koren uses the approximation:

$$\mathrm{MTF}_{\mathrm{sensor}}(f) = \left|\mathrm{sinc}(f / dscan)\right|^{sincpwr}, \qquad (Eq.\ 3\text{-}5)$$

where $\text{sinc}(x) = \sin(\pi * x)/(\pi * x)$,

$\text{sinc}(0) = 1$, and

dscan is the sensor resolution in pixels per millimeter.

Faster roll-off rates are produced by larger values of the *sincpwr* exponent. For dedicated film scanners, Koren uses *sincpwr* = 3, but he recommends *sincpwr* = 4 for inexpensive flatbed scanners and varies the exponent for various types of camera sensors.

The sensor formulation has roots in digital sampling theory. Sinc(x) has nulls at $x = 1, 2, 3, \ldots$, and the Nyquist frequency is defined as $f_N = dscan/2$. The Nyquist frequency is important because only frequencies below it can be represented accurately. Theoretically, the number of line pairs per millimeter that a scanner can resolve is half of its pixel per millimeter spacing; in practice, the number is more like a third to a fourth. Signal energy above the Nyquist frequency is aliased back into lower frequencies: the wagon wheel appearing to rotate backwards in a movie is being aliased in the time domain; in repetitive patterns, moiré fringing is a common aliasing effect in the spatial domain. Schneider Optics (in Optics for Digital Photography) states that digital cameras with a sensor Nyquist frequency greater than f_{10} of the lens + sensor will control aliasing adequately. Many digital still cameras add filters to reduce the response above the Nyquist frequency, thereby sacrificing resolution to prevent aliasing. A high-speed digital (movie) camera with an anti-alias filter has not been located.

One by-product of digital technology is the ability to enhance images via post processing. A common enhancing tool is what is known as sharpening, which increases image contrast at boundaries by darkening dark tones and lightening light tones. From an MTF perspective, sharpening algorithms boost the response for a range of frequencies – they do *not* increase actual information content. Using a Fourier transform formulation, the MTF for a simple sharpening algorithm can be represented by:

$$\text{MTF}_{\text{sharp}}(f) = \left(1 - 2ksharp * \cos(2\pi * f / dscan\right) / \left(1 - 2ksharp\right), \qquad (Eq.\ 3\text{-}6)$$

where *ksharp* is the sharpening coefficient, and

dscan is defined as before.

Maximum boost occurs at $f = dscan/2$ (i.e., the Nyquist frequency). Applying too large of a *ksharp* can accentuate any aliasing present in the unsharpened image, though the typical indication of oversharpening is excessively jagged edges.

The TrackEye system is reported to have some sharpening capabilities, but specifics are lacking. While visual improvements can be dramatic, sharpening algorithms can be computationally intensive and are far from automatic. These complexities are certainly tolerable for portrait photography, but from the TTR perspective, sharpening is viewed as having limited utility for extracting TSPI data from a massive number of movie frames. While some sharpening results will be reported, recommendations will be based on unsharpened performance.

Recall that the initial intent of the TrackEye system is to replace the Telereadex film readers with a scanner for the 35mm film. Therefore, the goal should be for the scanner to match the performance of the enlarger lens in the Telereadex, which has been assumed to have an f_{lens}

of 60 lp/mm and *lord* of 2 (which results in an f_{10} of 180 lp/mm). The 2048-pixel TrackEye scanner scanning across the entire 35mm film width translates to 1486 dots per inch (dpi, or *dscan* = 58.5), whereas the 4096-pixel scanner is equivalent to 2973 dpi (or *dscan* = 117). A comparison of the scanners with the Telereadex is provided in Figure 3-10, and at first blush, does not look too favorable. Unsharpened, the 1486-dpi scanner has an f_{50} of 21.4 lp/mm and an f_{10} of 36.8 lp/mm. The unsharpened 2973-dpi scanner is a significant improvement with an f_{50} of 42.8 lp/mm and an f_{10} of 73.7 lp/mm (i.e., double the frequencies of the 1486-dpi scanner), but still deficient relative to the Telereadex enlarger lens. Figure 3-10 also displays scanner response with the addition of sharpening, which has a greater impact on f_{50} than on f_{10}.

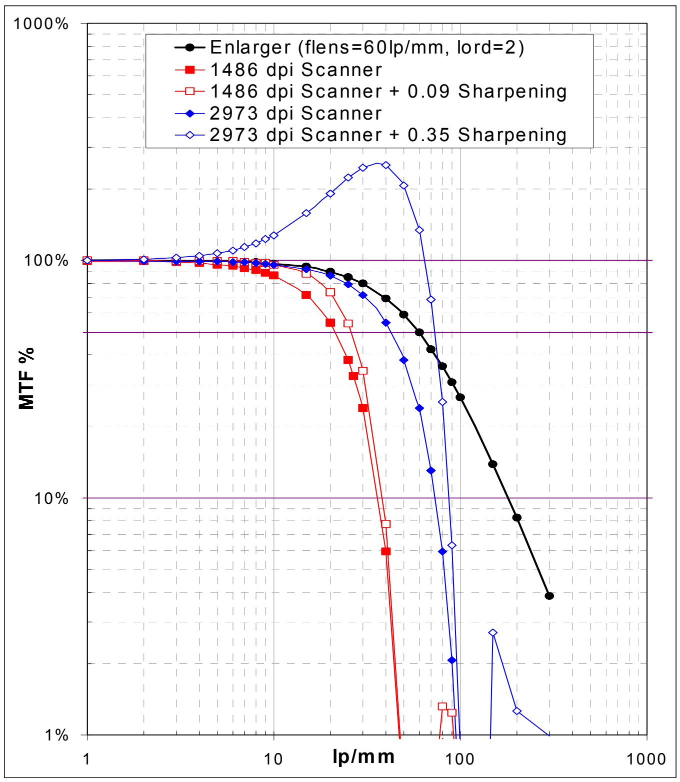


Figure 3-10. MTFs for Telereadex and scanners.

Fortunately, this comparison is misleading because it does not take into account the roll-offs already associated with the film and camera lens. A more appropriate comparison of overall system response is displayed in Figure 3-11. The Telereadex enlargement curve for Ektachrome is the same as in Figure 3-9, with an f_{50} of 16.9 lp/mm and an f_{10} of 41.2 lp/mm with respect to the image size on film. By comparison, Ektachrome film scanned at 1486 dpi has an f_{50} of 13.6 lp/mm and an f_{10} of 26.8 lp/mm, while scanning at 2973 dpi produces an f_{50} of 16.5 lp/mm and an f_{10} of 38.0 lp/mm. Obviously, the overall frequency response of an unsharpened, 2973-dpi scan of an Ektachrome image comes *close* to that of the same image projected through a Telereadex film reader. The frequencies with the greatest disparity between the Telereadex MTF and scanner MTFs are of little relevance.

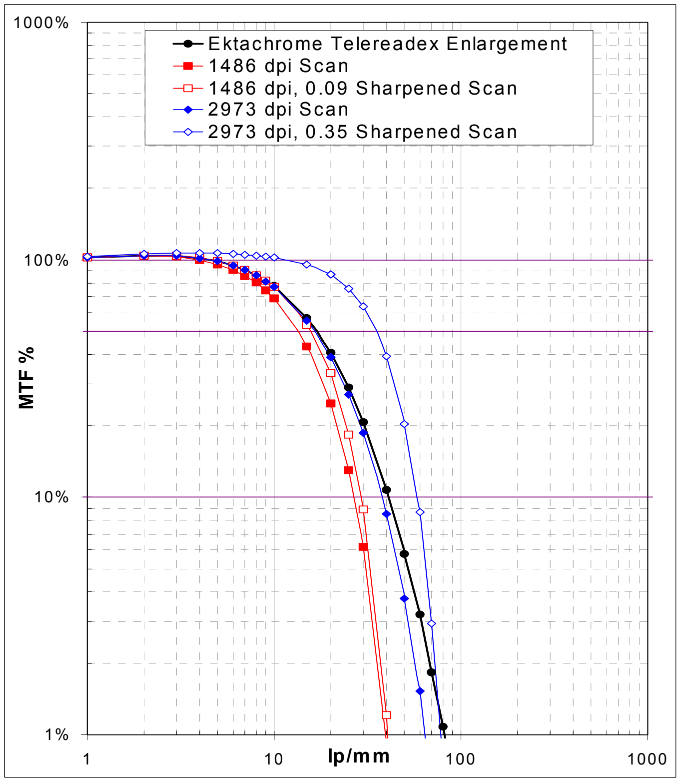


Figure 3-11. Overall MTF for Ektachrome through Telereadex and scanners.

The sharpening coefficients used in the 2048- and 4096-pixel scanners are deliberately different. The 1486-dpi scanner has a Nyquist frequency (f_N) of 29.3 lp/mm, only slightly higher than the unsharpened f_{10} frequency. With *ksharp* = 0.09, $f_{10} = f_N$; using a higher sharpening coefficient for the 1486-dpi scanner could accentuate aliasing. By comparison, f_N for the 2973-dpi scanner is 58.5 lp/mm, significantly higher than its unsharpened f_{10} frequency. Therefore, the 2973-dpi scanner can accommodate a higher level sharpening while still avoiding aliasing. Setting *ksharp* = 0.35 makes the sharpened f_{10} equal to f_N for the 2973-dpi scanner. With sharpening, the system response of the 2973-dpi scanner can actually exceed that of the Telereadex film reader.

Figure 3-12 replicates the Telereadex and 2973-dpi scanner results for the Kodak Linagraph Shellburst B&W film. Because of Shellburst's higher resolution capability compared to Ektachrome, unsharpened scanner loss relative to the Telereadex projection is increased. The f_{10} frequency is 58.3 lp/mm for the Telereadex image, compared to 49.9 lp/mm for the unsharpened scanner image. With *ksharp* = 0.17, f_{10} and f_N for the scanner are equal *and* virtually identical to the f_{10} through the Telereadex. Since Shellburst is not used extensively during flight testing, this comparison is more enlightening than significant.

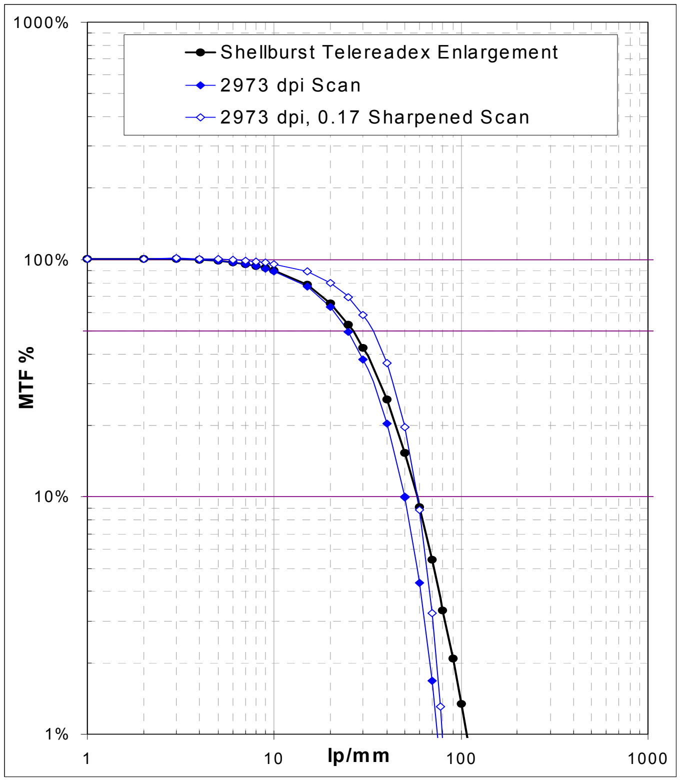


Figure 3-12. Overall MTF for Shellburst through Telereadex and scanner.

One other scanner option has been identified based on these analyses and discussions with TrackEye representatives. This option involves replacing the lensing in the 4096-pixel scanner such that it scans only across 27 mm of the film (rather than the full 35-mm film width). The 27-mm width is not arbitrary; it was chosen to capture the entire image plus enough of the sprocket holes on each side of the image to provide repeatable indexing. This special lensing will result in a 3853-dpi equivalent scan (and require 35.2 Megabytes of storage per frame). The predicted performance of this option is displayed in Figure 3-13. Unsharpened, the 3853-dpi scanner is predicted to provide slightly better resolution than the Telereadex film reader on Ektachrome ($(f_{10})_{scanner}$ = 41.4 lp/mm versus $(f_{10})_{Telereadex}$ = 41.2 lp/mm). On Shellburst, the unsharpened scan does not quite match the performance of the Telereadex, but again, this is not the typical TTR process. These results are consistent with Koren's observation that a 4000-dpi scanner can match the performance of a quality enlarger.

The Telereadex information can be used to develop another useful observation. The actual Telereadex repeatability of ±18-36 microns translates to an angular repeatability of $\pm 0.68\text{-}1.36\times10^{-3}$ degrees or ±2.4-4.9 arc-seconds. Recall that the advertised accuracy for TTR TSPI data is ±15 arc-seconds, so repeatability of Telereadex readings is 1/6 to 1/3 of the overall TSPI error (from an absolute, rather than RMS, perspective). By comparison, the 20-bit encoders in the Contraves mounts provide ±1.2 arc-second resolution (so larger-bit encoders are superfluous). Though no proof has been located, the common perception is that atmospheric distortions are the dominant source of error in TSPI measurements.

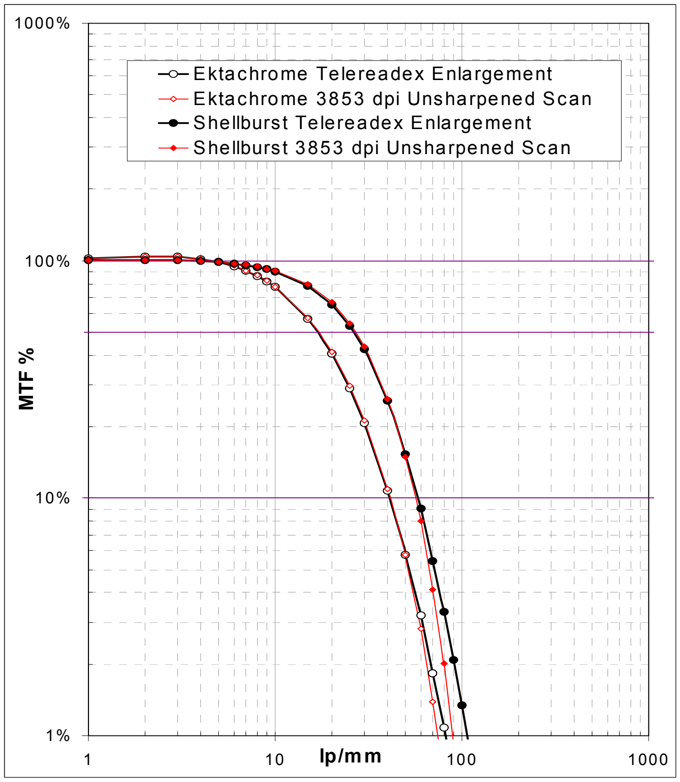


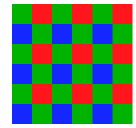
Figure 3-13. MTF comparisons of the Telereadex versus a 3853-dpi equivalent scanner.

The question then becomes whether the scanner actually *needs* to match the Telereadex resolution. The question of matching resolution will have even greater significance when considering digital cameras. Certainly, other test ranges that were early adopters of digital technology did so at the expense of resolution. However, the technology continues to improve, and because of TTR's excellent optical attributes, the feeling is that resolution should not be sacrificed. Until proven unnecessary, this will continue to be the guiding principle.

As stated previously, the long-term goal for TTR optics involves migrating to high-speed digital (movie) cameras, with the primary motivation of improving report turnaround. Film frame dimensions were discussed at the onset and are important to recall now. This is because the digital sensors used in cameras are often smaller than film image dimensions (and with different width/height ratios). Smaller sensor dimensions require either new smaller (focal-length) lenses or additional adaptor lenses to achieve the same field-of-view, both of which can adversely affect image quality. Also, *relative* resolution is inversely proportional to dimension, so a digital sensor with dimensions half that of a film frame would need double the absolute resolution for comparable image detail. The ideal solution is for digital sensors to match film frame dimensions. This has been achieved in high-end 35mm digital still cameras, but not yet for high-speed digital cameras. This will be discussed further in the context of TTR optical systems.

The photodiodes used to measure the intensity of light impinging on each pixel of a digital sensor are typically monochrome devices. To produce a color image, a Color Filter Array

(CFA) is placed over the sensor so that each pixel responds to a single color. Software interpolation later produces a full-color value for each pixel based on the filtered light intensities measured at the surrounding pixels. The GRGB Bayer pattern illustrated to the right is the most common CFA used. Half of the pixels respond to green, the dominant visual frequency, while each remaining quarter of the pixels responds to either red or blue. Recently, Fovean introduced a three-layer pixel sensor design that simultaneously measures all three colors at every pixel. To date, the Fovean X3 sensor has only been incorporated into a 35mm still camera.



The significance of this discussion is that the type of digital sensor determines the *sincpwr* exponent used to approximate MTF_{sensor} (refer back to the discussion of scanners). Koren's trial-and-error exponents for digital camera sensors are:

a. *sincpwr* = 4 for Bayer sensors with anti-aliasing filters,

b. *sincpwr* = 3 for Bayer sensors without anti-aliasing filters,

c. *sincpwr* = 2 for the Fovean X3 sensor
(also will be assumed for color cameras operating in monochrome mode).

The Vision Research Phantom series of high-speed digital cameras will be the focus of discussion, though results from other cameras are included in Table 3-1. The Phantom cameras utilize the Bayer CFA (except for the Phantom 5, but the pixel distribution between colors is the same) without anti-aliasing, so *sincpwr* = 3 was assumed for color mode and *sincpwr* = 2 was assumed for monochrome mode.

The Phantom 5, 7, and 9 cameras have width / height dimensions of 15.7 mm / 15.7 mm, 17.6 mm / 13.2 mm, and 17.6 mm / 13.2 mm, respectively. Therefore, the sensor widths are comparable to the image width for Contraves film (16 mm) but not for telescopic film (24 mm). The Phantom frame heights are all smaller that the 18 mm film height, but according to Jerry McCorkle, height is less critical for typical Tonopah operations.

The Phantom 5, 7, and 9 cameras have pixel spacings of 15.4 µm, 22.0 µm, and 11.0 µm, respectively. Assuming excellent lens properties, the performance of the Phantom cameras is illustrated in Figure 3-14 (color) and Figure 3-15 (monochrome). On average, the monochrome mode on the Phantom cameras is estimated to increase f_{50} by 17 percent and f_{10} by 16 percent over color mode. In all cases, the Nyquist frequency is *less* than f_{10}, which suggests aliasing as the cause of the moiré fringing seen in the Phantom target boards (Figure 3-3 through Figure 3-6).

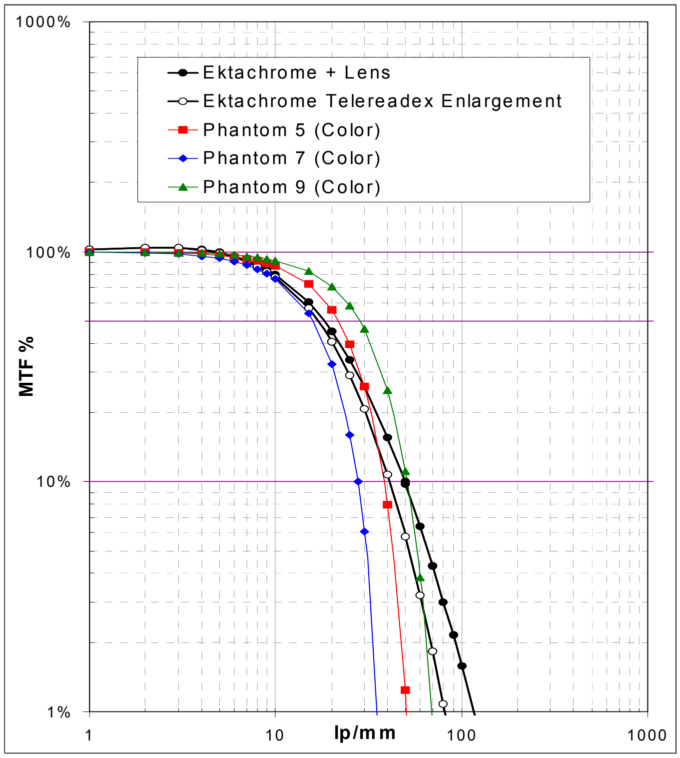


Figure 3-14. Phantom color performance comparison with Ektachrome.

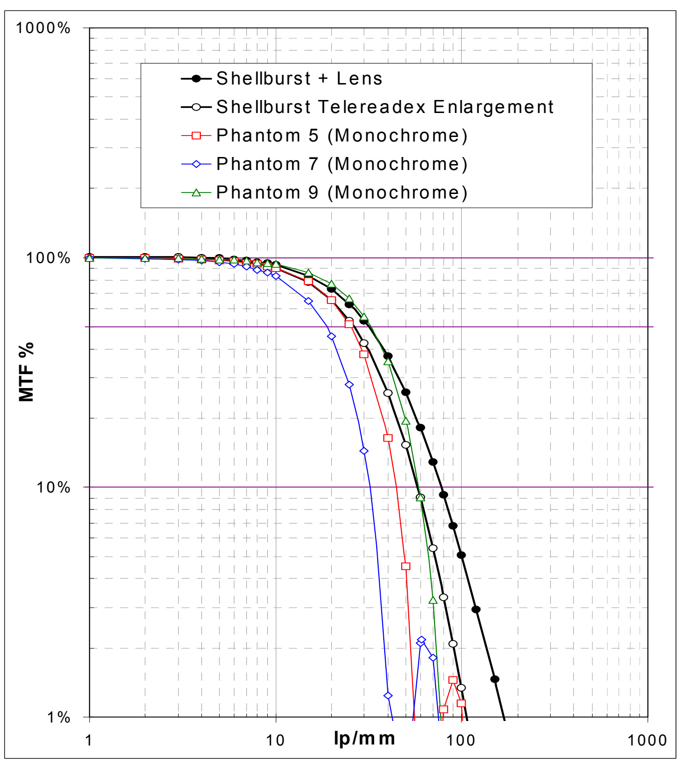


Figure 3-15. Phantom monochrome performance comparison with Shellburst.

Phantom MTFs are also compared to both film + lens and Telereadex projection MTFs, with the Phantom color comparisons to Ektachrome in Figure 3-14 being of greatest interest. At first glance of the f_{10} values, one might conclude, that the Phantom 7 is fundamentally lacking, the Phantom 5 is nearly acceptable for TSPI, and the Phantom 9 (f_{10} = 51.2 lp/mm) outperforms Ektachrome in both TSPI (f_{10} = 41.2 lp/mm) and documentary (f_{10} = 49.5 lp/mm) applications. Assuming full frame-width utilization, a Phantom 9 installed on a Contraves mount would actually *increase* the horizontal field-of-view to 0.65°, but at the expense of reduced vertical field-of-view. If this became significant, alternative digital cameras such as the Redlake MegaPlus ES 4.0/E might be considered (see Table 3-1).

More problematic for the Phantom 9 is that it does not match the 24-mm frame width of TTR documentary film. On an ME-16 telescope, a Phantom 9 would limit the horizontal field-of-view to a mere 0.33°. Alternatively, if (no-loss) lensing was added to match the current 0.46° horizontal field-of-view, the Phantom 9's *relative* color resolution would be 76 percent of the current telescopic capability, computationally defined by:

$$\begin{array}{c}\text{Relative}\\ \text{Horizontal}\\ \text{Resolution}\end{array} = \frac{(f_{10} * \text{Sensor Width})_{\text{Phantom 9}}}{(f_{10} * \text{Frame Width})_{\text{Ektachrome/ME-16}}} = \frac{51.2\,\text{lp/mm} * 17.6\,\text{mm}}{49.5\,\text{lp/mm} * 24.0\,\text{mm}} = 76\% \qquad (\textit{Eq. } 3\text{-}7)$$

The relative horizontal resolution calculation provides such a useful comparison that values have been added to Table 3-1 for both ME-16 and Contraves/Telereadex applications, benchmarked to Ektachrome film. The table shows that, in terms of relative horizontal resolution, there are a variety of cameras that are predicted to outperform the current capabilities for TSPI data, but none that can match the current capabilities for documentary imagery. Even though the absolute resolution (i.e., f_{10}) of some digital cameras exceeds that of Ektachrome shot through an ME-16 telescope, the relative resolutions suffer due to the smaller widths of the digital sensors. Note that the target boards in Figure 3-2 through Figure 3-6 actually compare relative horizontal resolutions since the ratio of target width to frame width was held constant.

Table 3-1 also provides some "proposed" digital cameras that match current TSPI and documentary capabilities. Sensor size would be required to match the image size on film. Two different sensor types were considered: one utilizing a Bayer CFA (but with anti-alias filtering to reduce moiré fringing), and another utilizing the Fovean X3 technology (though much less prevalent). Pixel spacing was then set so that the resolution of each type of digital sensor matched that of Ektachrome color film. The predictions suggest that high-speed digital camera technology is actually very close to achieving direct replacement of existing TTR film cameras, with digital sensor dimensions being the major deficiency.

A final sanity check of the formulation can now be performed. The various MTF equations can be manipulated to predict the resolution of the scanned enlargement of the target board shot onto Shellburst film through an ME-16 telescope (Figure 3-2). These results are included in Table 3-1. The relative horizontal resolution for Figure 3-2 (82 percent) is predicted to be about halfway between that of the simulated Phantom 9 camera in monochrome mode (87 percent for Figure 3-5) and color mode (76 percent for Figure 3-6), and far better than that of the Phantom 5 camera in monochrome mode (59 percent for Figure 3-5). Visual inspection of Figure 3-2 through Figure 3-6 confirms these predictions to be reasonable, or at least not egregious.[2] However, these comparisons should not be viewed as a rigorous validation of the predictions in this report. They are a poor substitute for improved digital sensor performance data from the vendors.

The focus of this formulation has been on resolution. However, resolution is just one element of image quality. Image grain, or noise, is another major attribute affecting overall image quality, and digital sensors generally have reduced noise content in comparison to film. This is certainly apparent in comparing the photographic image in Figure 3-2 to the digital images in Figure 3-3 through Figure 3-6. Koren has postulated that image quality is analogous to information transmission capacity governed by Shannon's Law. Miles Hecker has used Koren's hypothesis to generate digital-to-film comparisons using the relation:

$$\text{Image Quality} = f_{50} * \text{Sensor Size} * \log_2(SNR + 1)\,, \qquad (Eq.\ 3\text{-}8)$$

where SNR is the signal-to-noise ratio.

Note that the relationship focuses on perceived image sharpness (f_{50}) rather than practical image resolution limit (f_{10}). The results of Hecker's analysis will not be discussed. The point to be made is that there are other attributes to digital technology that will have positive effects on quality and reliability. Issues such as shutter synchronization, film registry, film bulge, shutter blur, film jamming, etc. will be eliminated or minimized.

[2] There are additional factors that compromise the direct comparison of these figures. The target board shot with the ME-16 was ~3000 feet from the telescope, and the photograph was of a negative target board (i.e., white symbols on a black background). Figure 3-2 is actually a negative image of the scanned print to facilitate better comparisons with the digital images. Also, the Phantom target boards were shot at distances more on the order of 300 feet using a telephoto lens (i.e., *not* through the ME-16 telescope – this was attempted but did not produce satisfactory results). Therefore, the digital images do not have the same amount of atmospheric distortion or the same lens properties as the ME-16 photograph, and neither of these differences was captured in the analyses.

TABLE 3-1. TABULATED SUMMARY OF RESULTS

Optical System	Frame/Sensor Size in mm			Net Frame Pixel Array			Pixel Spacing in microns	Nyq. Freq. In lp/mm	50% MTF in lp/mm WRT Frame	10% MTF in lp/mm WRT Frame	Relative Horzntl Resolution ^		Notes
	W	H	Diag	W	H	Total Mpix					ME-16	Tlrdx Enlgmt	
35mm still film													
35mm still Fuji Provia 100F (film only)	36	24	(43.3)	NA	NA	NA	NA	NA	40.0	120.0	364%	--	Unboosted
35mm still Fuji Provia 100F Excellent lens *	36	24	(43.3)	NA	NA	NA	NA	NA	30.8	71.6	217%	--	
35mm still Fuji Velvia (film only)	36	24	(43.3)	NA	NA	NA	NA	NA	45.0	101.7	308%	--	fboost=13lp/mm
35mm still Fuji Velvia Excellent lens	36	24	(43.3)	NA	NA	NA	NA	NA	36.8	68.6	208%	--	
TTR film systems													
Kodak Ektachrome 2253 (film only)	24	18	(30.0)	NA	NA	NA	NA	NA	20.0	70.0	141%	--	ASA 400 Color fboost=2.5lp/mm, fexp=1.6
Kodak Ektachrome 2253 ME-16 Telescope or Contraves (Excellent Lens assumed)	24 or 16	18	(30.0 or 24.1)	NA	NA	NA	NA	NA	18.2	***49.5***	***100%***	120%	
Kodak Ektachrome 2253 Contraves mount Telereadex enlargement ~	16	18	(24.1)	NA	NA	NA	NA	NA	16.9	***41.2***	55%	***100%***	
Kodak Ektachrome 2253 Contraves mount 1486 dpi scan	16	18	(24.1)	936	1053	(0.99)	17.1	29.3	13.6	26.8	--	65%	Unsharpened
									15.7	29.3	--	71%	ksharp=0.09
Kodak Ektachrome 2253 Contraves mount 2973 dpi scan	16	18	(24.1)	1872	2107	(3.94)	8.54	58.5	16.5	38.0	--	92%	Unsharpened
									35.5	58.4	--	142%	ksharp=0.35
Kodak Ektachrome 2253 Contraves mount 3853 dpi scan	16	18	(24.1)	2427	2731	(6.63)	6.59	75.9	17.1	41.4	--	100%	Unsharpened
									46.8	74.6	--	181%	ksharp=0.41
Kodak Shellburst 2476 (film only)	24	18	(30.0)	NA	NA	NA	NA	NA	43.0	153.0	309%	--	ASA 250 B&W Unboosted, fexp=1.73
Kodak Shellburst 2476 ME-16 Telescope or Contraves (Excellent Lens assumed)	24 or 16	18	(30.0 or 24.1)	NA	NA	NA	NA	NA	31.4	77.9	157%	--	
Kodak Shellburst 2476 Contraves mount Telereadex enlargement ~	16	18	(24.1)	NA	NA	NA	NA	NA	26.1	58.3	--	141%	
Kodak Shellburst 2476 Contraves mount 2973 dpi scan	16	18	(24.1)	1872	2107	(3.94)	8.54	58.5	24.6	49.9	--	121%	Unsharpened
									33.6	58.6	--	142%	ksharp=0.17
Kodak Shellburst 2476 Contraves mount 3853 dpi scan	16	18	(24.1)	2427	2731	(6.63)	6.59	75.9	26.7	56.6	--	137%	Unsharpened
									46.3	75.6	--	183%	ksharp=0.28
Kodak Shellburst 2476 Telescope 200dpi scan of 14X enlargement	24	18	(24.1)	2646	1984	(5.2)	NA	NA	20.5	40.4	82%	--	Predicted behavior for process that generated Figure 2
TTR digital systems (simulated)													
Vision Research Phantom V5.0 (8-bit) or V5.1 (10-bit)	15.7	15.7	(22.2)	1024	1024	(1.04)	15.38	32.5	21.7	38.3	51%	92%	Unsharpened, sincpwr=3 (Color - Figure 3)
									25.5	44.4	59%	106%	Unsharpened, sincpwr=2 (Monochrome - Figure 4)
Vision Research Phantom V7.0 (12-bit)	17.6	13.2	(22.0)	800	600	(0.48)	22.00	22.7	15.9	27.6	41%	74%	Unsharpened, sincpwr=3 (Color)
									18.9	32.2	48%	86%	Unsharpened, sincpwr=2 (Monochrome)
Vision Research Phantom V9.0 (10-bit)	17.6	13.2	(22.0)	1600	1200	(1.92)	11.00	45.5	28.4	51.2	76%	137%	Unsharpened, sincpwr=3 (Color - Figure 5)
									32.6	58.9	87%	157%	Unsharpened, sincpwr=2 (Monochrome - Figure 6)
Redlake MegaPlus ES 4.0/E (8- or 12-bit)	15.2	15.2	(21.5)	2048	2048	(4.19)	7.42	67.4	36.9	69.8	89%	161%	Unsharpened, sincpwr=3 (Color)
Weinberger SpeedCam Visario (10-bit)	16.9	11.3	(21.5)	1536	1024	(1.57)	11.00	45.5	28.4	51.2	73%	131%	Unsharpened, sincpwr=3 (Color)
Optimal Telescope Camera	24	18	(30.0)	2380	1785	(4.25)	10.08	49.6	27.3	49.5	100%	--	Unsharpened, sincpwr=4 (anti-aliased Bayer)
				1768	1326	(2.34)	13.57	36.8	28.0	49.5	100%	--	Unsharpened, sincpwr=2 (Fovean)
Optimal Contraves Camera	16	18	(24.1)	1279	1439	(1.84)	12.51	40.0	23.0	41.2	--	100%	Unsharpened, sincpwr=4 (anti-aliased Bayer)
				955	1074	(1.03)	16.76	29.8	23.8	41.2	--	100%	Unsharpened, sincpwr=2 (Fovean)

* Excellent lens defined using center-of-lens properties of Canon 28-70mm f/2.8L at settings of 40mm & f/8: flens=61lp/mm, lord=2
~ Quality film enlarger properties assumed: flens=60lp/mm, lord=2
^ Relative Horizontal Resolution = 10% MTF / 49.5 * Sensor Width / 24 (ME-16 Telescope)
= 10% MTF / 41.2 * Sensor Width / 16 (Telereadex Enlargement of Contraves film)

CHAPTER 4

RECOMMENDATIONS

The Modulation Transfer Function formulations presented herein have allowed for the prediction of digital performance and provided comparisons to film performance for Tonopah Test Range (TTR) applications. Using the practical image resolution limit as the guiding metric, and adhering to the principle of no diminished performance, certain recommendations and conclusions can be made for introducing digital technologies to TTR optical capabilities.

The need to replace the Telereadex film readers is obvious. As a critical link in extracting TSPI data, their vulnerability to loss of function must be mitigated. The 4096-pixel TrackEye film scanner and data extraction software appear to provide a reasonable replacement, especially with the proposed lensing modification to scan only across 27 mm of the film width. By all indications, the 2048-pixel version of the scanner is insufficient for TTR applications.

High-speed digital camera technology has not reached the level of capability necessary for all TTR operations. The Vision Research Phantom 9, and other cameras evaluated, appears acceptable for Contraves-based TSPI imagery. No digital camera has been located that can match the predicted relative resolution of Ektachrome film shot through an ME-16 telescope.

The most probable digital camera that could perform TTR's documentary functions would have the following predicted attributes:

a. 24 mm × 18 mm sensor size,

b. 10-micron pixel spacing (Bayer CFA with anti-alias filtering, 2400 × 1800 pixel array, 4.3 total megapixels per image),

c. 8/pixel bit depth (4.3 total Megabytes per image in no-loss, raw-image format), and

d. 400 frames per second (max.).

The sensor size matches the image size on 35mm movie film. The 10-micron pixel spacing is predicted to give an anti-aliased, Bayer sensor comparable resolution to 400-speed Ektachrome film. Anti-alias filtering is desired to achieve nearly-equal values for f_N and f_{10}. Since tonal resolution is not of extreme importance in TTR applications, a bit depth of 8 was specified to minimize storage requirements. Finally, 400 fps exceeds slightly the 360 fps maximum of the Photo-Sonics 4E film cameras currently on the ME-16 telescopes, though still well below the maximum, full-resolution frame rates of 1000 fps for the Phantom 5 and 9 and 4800 fps for the Phantom 7. (Frame rates for most high-speed digital cameras are unavoidably overkill for TTR purposes.)

The agreed-upon specifications for a TSPI-quality digital camera are somewhat less stringent, namely:

a. 18 mm × 12 mm sensor size,

b. 12.5-micron pixel spacing (Bayer CFA with anti-alias filtering, 1440 × 960 pixel array, 1.4 total megapixels per image),

c. 8/pixel bit depth (1.4 total megabytes per image in no-loss, raw-image format), and

d. 25 frames per second (max.).

The dimensions are different from those in Table 3-1. The additional width is to provide room for the time, azimuth, elevation, and mis-level data to be stamped directly onto each frame, but outside the 16-mm wide Contraves image. The sensor height is reduced because the current Contraves image height of 18 mm is viewed to be excessive.

CHAPTER 5

FINAL OBSERVATIONS

It is important to note that the formulation results presented herein are merely predictions. While they provide some value in the screening of digital technologies, the ultimate decision will require definitive MTF information from the digital vendors. Unfortunately, such information may be difficult to obtain in an industry that has not yet come to terms with quantitative performance metrics.

One attribute of migrating to digital technologies may actually become an even greater challenge. Storage requirements for digital systems will be significant. Consider a typical surveillance drop utilizing 5 Contraves mounts and 4 telescopes, and lasting approximately one minute. This roughly translates to 3000 frames of TSPI film (5 × 60 sec × 10 fps) and 24,000 frames of documentary imagery (4 × 60 sec × 100 fps). For the 4096-pixel TrackEye system scanning at 3853 dpi, the TSPI film would require 106 gigabyte of storage (3000 frames × 35.2 MB/frame). However, there is no need to save the digital scans after extracting bore-sight correction measurements because the film can serve as the historical record.

With the migration to digital cameras, however, the digital images *become* the historical record and must be preserved. For the typical drop outlined, and using the attributes of the documentary and TSPI cameras specified above, each Contraves mount would require 0.84 gigabyte of storage (60 sec × 10 fps × 1.4 MB/frame), each telescope would require 26 gigabytes of storage (60 sec × 100 fps × 4.3 MB/frame), and the total record for the drop would require 108 gigabyte of storage (5 × 0.84 GB + 4 × 26 GB). Taken one step further, the Photo-Sonics 4E film cameras currently on the ME-16 telescopes have 1200-foot film canisters. At 16 frames/foot, or 19,200 total frames, storage requirements for a single telescope to match current capacities would be 83 gigabytes. Obviously, data storage will require as much attention as data acquisition during the development of digital optics capabilities at Tonopah Test Range.

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CHAPTER 6

POSTSCRIPT

The first version of this document was released in September 2003, the primary motivation being to provide guidance for TTR's initial procurement of digital optical systems. A TrackEye film scanner (with "Sandia" lenses to scan 27 mm of film width) and data extraction software and a Phantom 9 camera have been ordered, and evaluation methodologies are being developed. In particular, standards for determining the spatial frequency response (ISO 12233), noise content (ISO 15739), and opto-electronic conversion factor (ISO 14524) of digital cameras are being investigated.

The results of this analysis were presented at a meeting of the Range Commanders Council's Optical Systems Group (OSG) held at Las Vegas in April 2004. At that time, it was noted that Koren had adjusted his empirical formulation for digital sensors, namely:

a. *sincpwr* = 3 for Bayer sensors with anti-aliasing filters,

b. *sincpwr* = 2 for Bayer sensors without anti-aliasing filters,

c. *sincpwr* = 1.5 for the Fovean X3 sensor (and color cameras in monochrome mode).

These new exponents suggest better performance (and greater possibility of aliasing) than predicted in this report. Additionally, inconsistencies for some digital camera parameters were identified (e.g., the Phantom 9 pixel spacing is actually 11.5 microns). While incorporating these changes into the report would change the results, they would not alter the conclusions, and the limitations of the empirical formulation would still exist. The main point of both the OSG presentation and this postscript is that the *vendors of digital technology need to characterize the performance of their products to established standards* so that comparisons and decisions can be made based on data rather than approximations.

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