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# Optics designs and system MTF for laser scanning displays

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## ABSTRACT

The Virtual Retinal Display™ (VRD™) technology is a new display technology being developed at Microvision Inc. The displayed image is scanned onto the viewer’s retina using low-power red, green, and blue light sources. Microvision’s proprietary miniaturized scanner designs make VRD system very well suited for head-mounted displays. In this paper we discuss some of the advantages of the VRD technology, various ocular designs for HMD and other applications, and details of constructing a system MTF budget for laser scanning systems that includes electronics, modulators, scanners, and optics.

**Keywords:** laser scanning, display resolution, Virtual Retinal Display, VRD, head mounted displays, modulation transfer function

## 1. INTRODUCTION

Virtual Retinal Display™ (VRD™) technology is a novel scanning-based display technology where the displayed image is scanned in a raster format onto the viewer’s retina in a raster pattern using low-power red, green, and blue light sources, such as lasers, laser diodes, or LEDs. [1-4] The VRD systems use two uniaxial scanners or one biaxial scanner to create a raster pattern. The horizontal scanner is a flexure-based mechanical resonant scanner[5] that operates at several KHz and the vertical scanner is also a mechanical scanner operated at a non-resonant mode at the frame rate of the display, which is typically 60Hz.

The resolution and the modulation transfer function (MTF) are key performance indicators in display systems. Resolution of mechanical scanners is proportional to scan mirror size and scan angle, and inversely proportional to wavelength. High-resolution systems demand horizontal scanners that provide a large mirror-size scan-angle product and high frequency. System resolution issues and scanner design issues are discussed in more detail elsewhere.[5,6]

This paper is divided into three parts. In the first part, we briefly discuss the VRD system operation and its advantages compared to other display technologies. The second part is dedicated to VRD ocular designs for HMD applications and the MTF performance of different ocular designs. In the last part, we give formulas that are used compute the MTF contributions of electronics, modulators, pixel duty-cycle, and scanner optics, then we illustrate how to construct a system MTF budget for the horizontal and the vertical axes in laser scanning display systems.

## 2. VRD OPERATION AND TECHNOLOGY COMPARISON

Figure 1 illustrates the four subsystems (drive electronics, photonics module, scanner module, and viewing optics) in a color VRD system.

*Drive Electronics* receive and process signals from an image or a graphics source. The processed signals contain information that controls the intensity, mix of color, and the coordinates to position the pixels that comprise the image. Electronics synchronize data source with scanner position information obtained from sensors.

*Photonics Module* consists of light sources, modulators, and color combining optics. VRD displays use very low power light sources to create an image a single pixel at a time. Gray-levels are created by varying the luminance on a pixel-by-pixel basis. Modulators take the pixel voltage from the video processor and feed it to an optical modulator. Laser diodes (LD) and LEDs can be modulated directly by changing the drive current. Thus, external modulators are not needed for LD and LED based systems. For laser-based VRD systems, acousto-optic modulators (AOM) are used to modulate the beam. AOMs provide good performance in terms of static contrast ratio, insertion efficiency, and diffraction efficiency. Simple circuitry with low RF power (~1W) is enough to drive AO systems. Electro-optics modulators (EOMs) can also be used in VRD ssytems. However, EOMs require high voltage from 100s to 1000s volts. Complex driver design is also required to maximize the modulation bandwidth. Bulkier EOMs should only be used when a designer can afford to trade-off optical efficiencies, static contrast ratio, and size for bandwidth or rise-time. The potential of waveguide modulators in the visible band will drive future modulator research due to their compactness and reduced cost when manufactured in volume. With color images, three light sources—red, green, and blue—are modulated and then merged to produce a pixel of the appropriate color and intensity.

An inherent advantage of VRD displays is that we can separate the function of luminance control (or dimming) from the modulator. The high video contrast provided by the modulator, whether it is from an AOM or an EOM, would be reduced if luminance control is done by adjusting the video input voltage. When luminance control is done using an optical attenuator, the video contrast can be kept intact. Choice of dimming technologies is dependent upon the optical system configuration. Polarizers, motorized or manual fiber optic attenuators, or electro-optic attenuators can be used.

In laser-based VRD systems, different color modulated beams are combined together and then coupled to a single mode fiber that carries the light to the HMD. The entire photonics module can be located remotely. VRD poses no danger to the eye since it operates at low intensity levels. Studies have been conducted which indicates VRD power levels are safe in normal operating mode and in failure modes[7,8]. In addition, the system is equipped with a number of hardware and software safety features that attenuate or block the light automatically in the event of system malfunction.

*Scanner Module*. Mechanical horizontal and vertical scanners project one pixel at a time to a diffuser screen, then the image is relayed through the viewing optics to the retina. This process, in effect, "paints" an image by rapidly moving the light source across and down the retina, in a raster pattern, with exacting precision. The current VRD design uses a mechanical resonant scanner (MRS) to sweep the horizontal axis (fast scan) and a non-resonant scanner to sweep the vertical axis (slow scan). The sinusoidal motion of the fast scan combined with the linear motion of the slow scan creates a 2-dimensional sinusoidal raster pattern. Nonlinearities in scanner speed along the horizontal scan line result in uneven spacing between pixels and sinusoidal brightness variation across the scan line. However, sinusoidal brightness variation, pixel time variations, and optical distortion in the horizontal axis can be easily corrected electronically using lookup tables to adjust pixel timing and intensity. The next-generation VRD design uses micro-electro-mechanical (MEMS) scanners that are smaller and lighter than the MRS.

*Viewing Optics*. In scanning retinal display systems, display exit pupil is located at the eye-pupil of the observer and located at a conjugate plane with the scanner. At a conjugate location with the point light source (e.g., single mode fiber), there is an intermediate image plane in between the scanner and the exit pupil planes. Simple optic designs create a diffraction limited intermediate image. Refractive, reflective, and diffractive optical elements can be used to expand and transmit the scanning beam of light through the pupil and onto the retina to create an image within the viewer's eye. Viewing optics magnification, total optical scan angle and scanning mirror size determine the field of view and exit pupil size. Scanning systems typically create an exit pupil in the order of few millimeters. If a large exit pupil is desired, a diffractive optical element or a forward-scattering diffuser can be used at the intermediate image plane. For HMDs, there are many different optics design for relaying the image from that intermediate image plane to the retina. Those are referred to as oculars and discussed in detail in Section 3.

Similar to CRTs, the VRD systems sweeps a point (containing 1 or a few pixels) across the screen and can create megapixels using one or two scanners. The CRT, based on scanning an electron beam, has been the dominant display technology for years. However, their size and lack of color mask at small sizes make it unsuitable for microdisplays. By switching from an electron beam to a photon beam, the bulk of the vacuum bottle, color mask, and phosphor screen are eliminated, wavelength multiplexing is enabled, and the advantages of the scanning retained. There are many competing matrix display technologies that have in the order of $10^6$ pixels that must be defect free and output matched. Defect problems and the highly constrained problem of providing controlled amount of light at each pixel for high-resolution HMDs, especially for military applications, limit the matrix display approach.

VRD systems use spectrally pure light sources, thus providing a larger color gamut compared to CRTs and matrix displays. Unlike other display technologies, the brightness of laser-based VRD systems is not limited by the source power. Any brightness level can be achieved, both for day and night operations for HMD and other applications. Laser-based display systems generally suffer from coherent artifacts. In VRD systems pixels are created serially one at a time, therefore, VRD pixels are mutually incoherent and any coherence artifacts (e.g., speckle) are typically at subpixel level and below the resolution limit of the eye. As illustrated in Figure 1, light sources and modulators can be located remotely, allowing for light weight HMDs. Another important advantage of the VRD systems is the ease of brightness control using optical attenuators without reducing the contrast. In CRTs, increasing the luminance requires compromise in displayed image contrast. Similarly, increasing the backlight illumination to increase luminance in matrix displays reduces the video contrast significantly. In VRD systems, red, green, and blue beams are combined at the photonics module and couple to a single-mode fiber. Therefore, unlike CRTs and matrix displays, wavelength multiplexing does not have an impact on the system MTF.

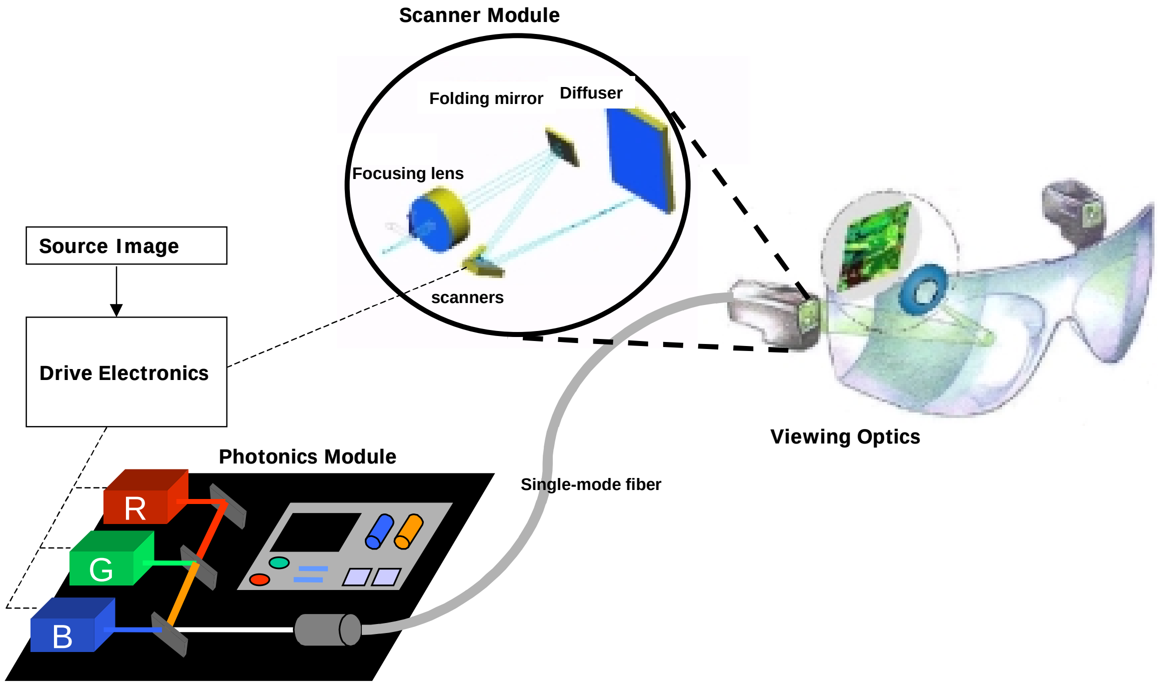


**Figure 1: VRD system detail.**

The VRD technology is well suited for numerous applications across several market areas (e.g., military, medical, simulation, portable communications, entertainment) and in a wide array of products ranging from helmet/head-mounted displays for military command-and-control, medical, and information display environments.

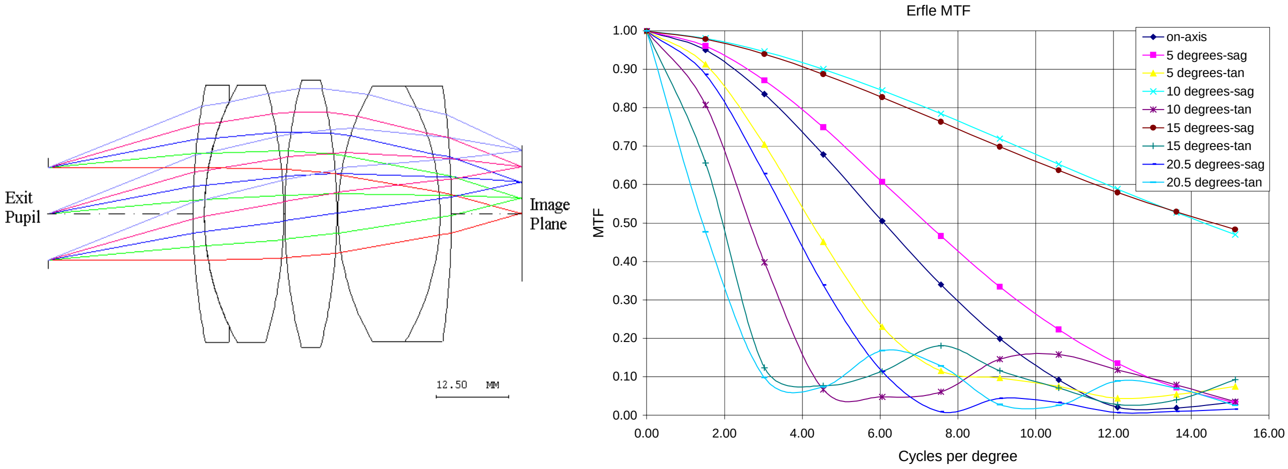
## 3. OCULAR DESIGNS AND OCULAR MTF

In this section we discuss the performance of oculars in current VRD systems. Many of these design forms have been used in commercial or simulator based applications. A brief summary of the optical performance, and manufacturing considerations is given in Table 1for the four oculars detailed in this paper.

**Table 1: Performance summary of four types of oculars for HMDs**

| | Ocular #1 | Ocular #2 | Ocular #3 | Ocular #4 |
|---|---|---|---|---|
| Form | Refractive | Birdbath | Catadioptric | Visor Relay |
| Field of View | 40 degree diagonal | 40 degree diagonal | 40 degree diagonal | 40 degree diagonal |
| Image Transmission | >90% | >20% | >20% | >70% |
| See-Through Transmission | None Possible | >40% | >40% | >50% |
| Image Quality | Good | Good | Very Good | Very Good |
| Distortion | <7% symmetric | <4% symmetric | <2% symmetric | <15% asymmetric |
| Field Curvature | <0.5 Diopters | <1.5 Diopters | <0.25 Diopters | <0.25 Diopters |
| Exit Pupil Diameter | 15mm | 15mm | 15mm | 12mm |
| Eye Relief | >25mm | 25mm on axis | 25mm on axis | 75mm on axis |
| Weight | Low | Low | High | Medium-High |
| Volume | Low | Low | High | Medium-High |
| Complexity | Low | Low | Medium | Very High |
| Aspheric Elements | No | No | Yes, conic | Yes |
| Relative Manufacturing Cost | Low- Medium | Low | High | Very High |

The fully refractive optical relay is the most basic form of ocular. It is merely one or more lenses designed to magnify an image. There are a large number of designs that use this form, and many of the basic forms can be found in Ref. 9. One design example is the Erfle eyepiece, which is shown in Figure 2(a) below. The advantages of this type of optical relay are compact size, low weight, and manufacturing simplicity. However, these types of designs do not allow for see-through application because the refractive optics distort the see-through scene, and the eye relief of these oculars is usually short. This distance from the eye to the first refractive element is usually on the order of 35 millimeters or less, depending on the field of view required.

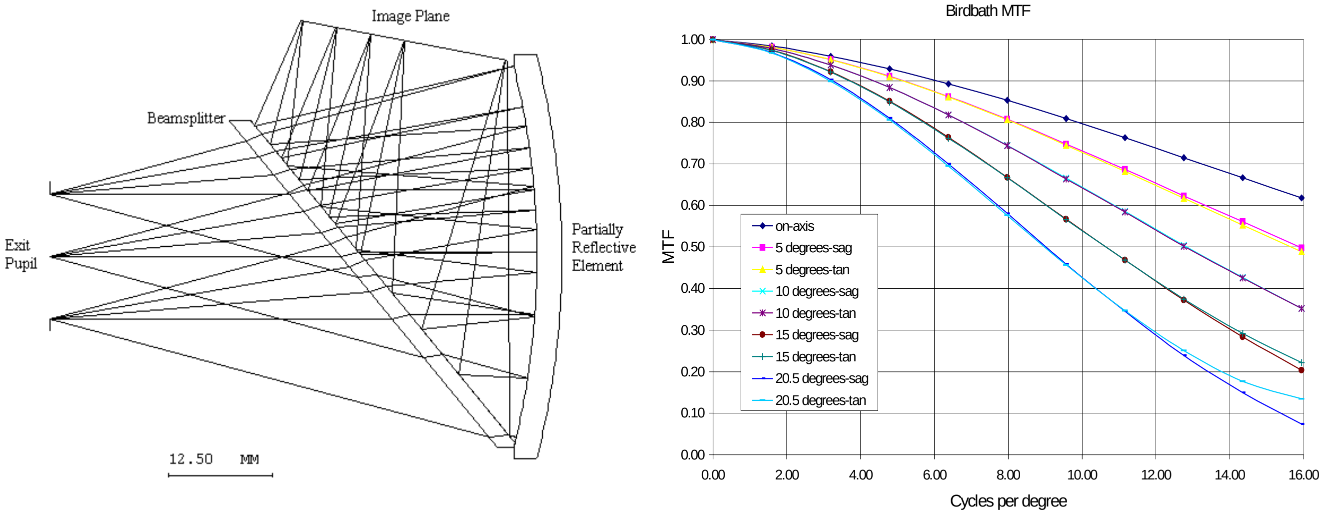


(a) (b)

**Figure 2: (a) Erfle ocular and (b) corresponding MTF.**

The sample Erfle design described here is a standard design, not specifically optimized for any one use. As such, the performance of this particular eyepiece is not as good as it could be if a custom design was employed. The MTF of this design is evaluated over a 5 mm exit pupil, as are all of the other designs considered, and is shown in Figure 2(b). The maximum spatial frequency relates to a 1280 x 1024 scene over a 41 degree horizontal field of view. Most of the degradation in MTF is a result of astigmatism and lateral color in the ocular. The eye, under normal viewing conditions, compensates some of the astigmatism of the ocular, so these MTF values are worst-case values.

The Birdbath optical relay, illustrated in Figure 3(a), utilizes a beam-splitter to allow a single reflective powered element to perform all of the imaging requirements. This form has a relatively small package size and very good performance for its simplicity. Likewise, this optical relay is extremely light when compared to other optical relay forms, and it is very easy to fabricate.



(b)

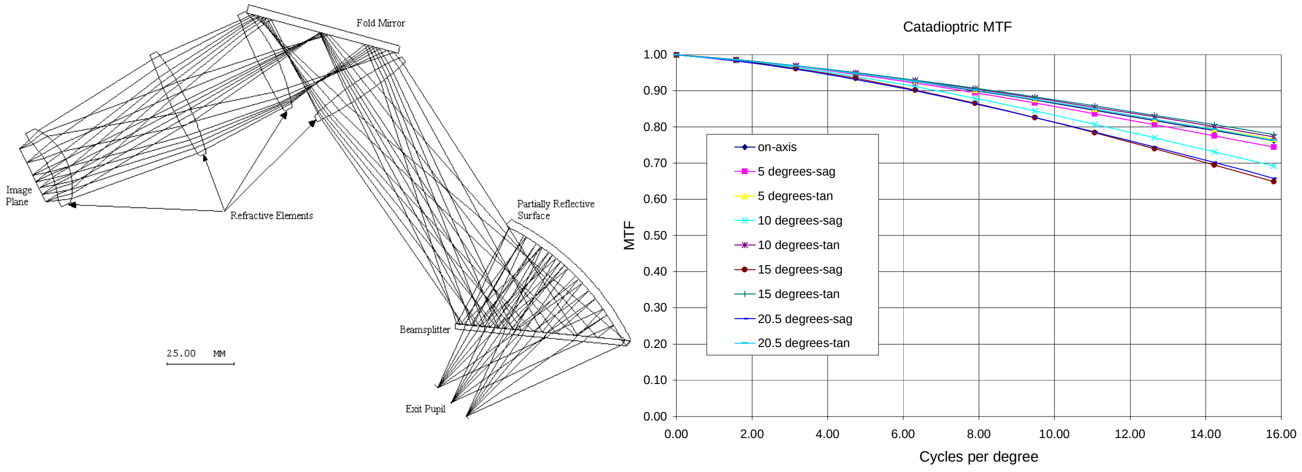
(a)

**Figure 3: (a) Birdbath ocular and (b) corresponding MTF.**

There are several advantages to the birdbath optical relay. Most importantly it has very good optical performance with respect to optical aberrations. Astigmatism due to the beam-splitter is non-symmetric with the field, and can cause a loss in MTF as shown in Figure 3(b). Distortion is relatively small, less than 4% for fields of view less than 40 degrees. Since there are no refractive elements in this optical-relay, chromatic problems are also non-existent. The only other aberration that could cause some problems is field curvature. For optical relays with short focal lengths and high fields of view, one can expect inward curving focal shifts of greater than 1.5 diopters. This is a large amount of field curvature for any ocular, and if this optical relay is to be used to overlay information on a flat screen or in an aircraft, there could be a great deal of focal disparity between the image and the background scene. A field flattening lens could be added to this design near the image plane to cure this problem, however the addition of this lens could cause unwanted chromatic effects, increase distortion and might introduce some vignetting of the exit pupil.

The major drawback to this form is the inherent inefficiency of the system. After light is emitted from the image plane, 50% of this light is reflected towards the reflective combining element, and 50% is transmitted and lost. The same effect occurs the second time the light passes through the beam-splitter on the way to the eye, and as such the theoretical best one can hope for in this system is 25% optical transmission without polarization preserving elements.

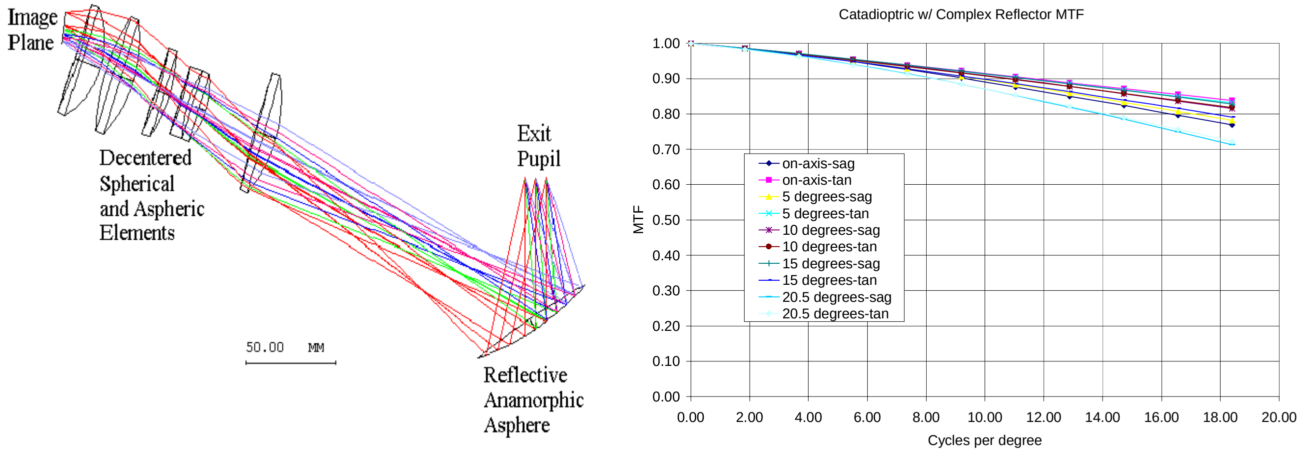
Catadioptric optical relays have become the standard optical configuration for aircraft retained helmet mounted displays, with systems fielded by a number of companies. These systems have a reflective eyepiece of some sort and a refractive relay. A combination of reflective and refractive elements is known as a catadioptric relay. Some of these relays use an eyepiece similar to that found in the birdbath, while more complex systems may use just one single reflector placed in front of the eye. A typical arrangement of a simpler catadioptric relay is found in Figure 4(a).



**(a)** **(b)**

**Figure 4: (a) Catadioptric ocular and (b) corresponding MTF.**

The main benefit of this type of optical relay is excellent optical performance, as there are many variables in this type of system to correct aberrations. The field of view of these systems can also be higher for an equivalent focal length than a comparable fully refractive system, or a birdbath ocular. However, these systems tend to be bulky and heavy, and they suffer from poor optical transmission as well as introducing obscurations to the external scene. The MTF for a typical catadioptric ocular is shown in Figure 4(b).



**(a)** **(b)**

**Figure 5: (a) Top View of Catadioptric Ocular with an Anamorphic Aspheric Reflector, (b) corresponding MTF**

A final design that was examined utilizes an anamorphic aspheric reflector as the final optical element. The ocular form is shown in Figure 5(a). This design is very complex and difficult to manufacture. Not only is the final optical surface an anamorphic asphere, but the backside of this element must be matched to the front surface to minimize see-through distortions. Included in the optical relay portion of the ocular are many decentered elements, some of which are aspheric as well. Not only are the optical elements difficult to fabricate, but aligning these decentered elements to one another can prove to be a very challenging task.

At the expense of difficult manufacturing issues, the performance of this ocular can be very good. The MTF of this design is shown in Figure 5(b). Astigmatism that is due to the anamorphic shape of the final reflector, is the dominant aberration in this design. However this aberration is correctable through the use of decentered elements. Unfortunately this design has a considerable amount of residual distortion, upwards of 15% at the corners of the field. This distortion is also radially non-symmetric, so more complex algorithms must be used to define the image plane deformation to create a rectilinear format.

## 4. SCANNING MULTIPLE LINES

As illustrated in Table 2, raster-scanning dynamic displays demand high-resolution and high-frequency from horizontal scanners. Bidirectional scanning and scanning multiple lines reduce the frequency requirements of horizontal scanners. Bidirectional scanning refers to writing or displaying a new line of data in both scan directions as opposed to writing a line only during forward sweep of horizontal scanner. Bidirectional scanning doubles the display line rate in vertical axis but it requires buffering one line of data and displaying it in reverse order during backward sweep of horizontal scanner. Likewise, adding many beams to scan multiple lines simultaneously increases the vertical resolution by the number of beams. Required horizontal scanner frequency is proportional to the refresh rate or frame rate ($F_r$) of the display system (typically 60 Hz) and the vertical resolution ($N_v$). Required scanner frequency can be calculated using the following formula

$$f_s = \frac{F_r N_v}{K_{ub} K_{vos} n_v} \tag{2.c}$$

where $K_{vos}$ is the vertical overscan factor (or retrace time), $K_{ub}$ is 1 for unidirectional and 2 for bidirectional scanning, and $n_v$ is the number of lines.

**Table 2: Resolution and approximate line rates for some of the standard display formats.**

| Display Format | VGA | SVGA | XGA | SXGA | UXGA | HDTV |
|---|---|---|---|---|---|---|
| Horizontal resolution | 640 | 800 | 1024 | 1280 | 1600 | 1920 |
| Vertical resolution | 480 | 600 | 760 | 1024 | 1200 | 1080 |
| Refresh rate (Hz) | 60 | 60 | 60 | 60 | 60 | 60 |
| Approximate horizontal line rate assuming 9-10% blanking lines for vertical retrace time (lines/sec) | 31500 | 37900 | 48400 | 64000 | 75000 | 69000 |

## 5. MTF BUDGET

The modulation transfer function (MTF) concept has been used to evaluate the quality of CRT displays[10] and matrix displays[11,12]. The MTF of a display system is the optical response of the system to a sine wave excitation. Equivalently, MTF is the absolute value of the Fourier transform of the line-spread function (LSF) normalized to one at zero spatial frequency. Under certain conditions (e.g., system has to be linear), the display system MTF is simply the product of the MTF of each component. This property of MTF makes it a powerful tool for analyzing complex systems.

In laser scanning display systems, various system design and performance parameters associated with electronics, modulators, scanners, and optics contribute to the system MTF. Unlike CRTs and matrix displays, wavelength multiplexing does not have an impact on the system MTF. The horizontal system MTF and vertical system MTF are different. Pixel-duty-cycle (ratio of pixel-on-time to pixel-time), electronics bandwidth, and modulator bandwidth affects only the horizontal MTF. Table 3 below defines crucial system parameters that determine system MTF. In the remainder of this section, we will discuss how to calculate component MTFs, and then the system MTF for the horizontal and vertical axis. MTF is also a function of pixel coordinate. We will discuss MTF at the center and edges of the display, MTF of all other pixel coordinates can be calculated in a similar way.

**Table 3: Definitions of parameters that determine scanner frequencies and MTF**

| Symbol | Unit | Definition |
|---|---|---|
| $N_h$ , $N_v$ | Pixel | Horizontal and vertical resolution of the system |
| *HFOV, VFOV* | Degree | Horizontal and vertical field of view |
| $n_h$ | - | Number of parallel write beams used in multiline scanning systems |
| $f_h$ , $f_v$ | Hz | Horizontal and vertical scanner frequency |
| $K_d$ | - | Pixel duty cycle. $0<K_d<1.0$ |
| $R_\theta = HFOV / N_h$ | Degree/Pixel | Angular resolution (=VFOV / $N_v$) |
| $t_c$ | Second | Pixel time at the center of the display |
| $t_e$ | Second | Pixel time at the edge of the display |
| $u$ | Cycles/Degree | Angular spatial frequency |
| $K_{hos}$ | - | Horizontal-overscan factor. Ratio of scan line used for writing to total scan line length. $0<K_{hos}<1.0$ |
| $K_{sp}$ | - | Ratio of FWHM Gaussian spot size to pixel size. Typical range $0.7<K_{sp}<1.3$ |

### 5.1. Pixel Duty-Cycle ($K_d$)

For each pixel from video source, display electronics produces a rectangular pulse of certain width and amplitude. The amplitude determines the pixel intensity (i.e., gray level) and the width of the pulse determines pixel duty-cycle ($K_d$), which takes on values between 0 and 1. $K_d$=1 corresponds to the case where the light source is on during the entire pixel time, and $K_d$=0 corresponds to the case where electronics sends an impulse for each pixel. The tradeoff is between light source efficiency and resolution. Increasing the duty-cycle better utilizes the light source power, however, scanner motion during the pixel on-time results in blurring of the spot along the scan direction and reduces the resolution. Spatial cut-off frequency ($u_c$) and horizontal MTF component due to pixel-duty-cycle are given by

$$u_c = \frac{1}{2K_d R_\theta}, \tag{1}$$

$$MTF_d(u) = \left| \frac{\sin(\pi u K_d R_\theta)}{\pi u K_d R_\theta} \right|, \tag{2}$$

### 5.2. Pixel Time

In VRD systems, a high Q (quality factor) resonant scanner is used in the horizontal axis to achieve high resolution and high-frequency operation at low power levels. The scanner moves fastest at the center of the scan and comes to a stop at the extremities of the scan. This sinusoidal motion of resonant scanners results in speed and, thereby, brightness variations across the scan line. This variation can be easily corrected electronically. Typically, some fraction of the scan line at the extremities is not used for writing. Horizontal-overscan-factor ($K_{hos}$) takes this into account and typically takes on values between 0.5 and 0.95. The edge of the used portion of the horizontal scan line will be referred to as the edge of the display in the remainder of the paper. The pixel time at the center *($t_c$)* and the edges *($t_e$)* of the display can be expressed as a function of $K_{hos}$:

$$t_c = \frac{K_{hos}}{\pi f_h N_h}, \tag{3}$$

$$t_e = \frac{K_{hos}\sqrt{1-K_{hos}^2}}{\pi f_h N_h}, \tag{4}$$

### 5.3. MTF of Electronics and Modulators

Response time of electronics and modulators contribute to the horizontal MTF of the display system. What is typically specified is the 10% to 90% rise-time ($t_r$), which is the unit step function response of the component. The impulse response is the derivative of the unit step response, and the MTF is the Fourier transform of the impulse response.

The step response of acousto-optic modulators and electronics can be approximated with an error function (*erf*), which is the integral of Gaussian function. The impulse response, therefore, is a Gaussian. Based on this approximation, one can show that there is a simple relationship between the measured 10%-90% rise-time of the step response and the full-width at half-maximum (FWHM) width ($h_{FWHM}$) of the corresponding Gaussian impulse response:

$$h_{FWHM} = 0.92 t_r \,, \tag{5}$$

The horizontal scanner converts the modulated signal from temporal space into angular space. The angular FWHM of the Gaussian impulse response ($s_{FWHM}$) is a function of scanner speed and, therefore, its value changes sinusoidally across the scan line. $s_{FWHM}$ at the center and at the edge of the display can be calculated as

$$s_{FWHM,c} = h_{FWHM} \frac{R_\theta}{t_c} \,, \tag{6}$$

$$s_{FWHM,e} = h_{FWHM} \frac{R_\theta}{t_e} \,, \tag{7}$$

where $t_c$ and $t_e$ are as given in Equations 3 and 4.

For a Gaussian spot, MTF can be expressed as[10]

$$MTF(u) = \exp(-3.56 u^2 s_{FWHM}^2) \,, \tag{8}$$

where u is the spatial frequency in cycles/degrees and s is the full-width of the spot measured at 50% irradiance.

### 5.4. MTF of Scanner Optics

In laser-based VRD systems, single mode laser beam produces a diffraction-limited Gaussian spot at the intermediate image plane using simple optics. Beam profile changes slightly if the beam the Gaussian beam is clipped by hard system apertures, we will assume beam clipping is negligible in this paper.[5] Size of the Gaussian beam spot determines the resolution of the system. System MTF is primarily determined by the amount of spot overlap between adjacent pixels. The parameter $K_{sp}$, defined in Table 1, determines the amount of overlap. MTF due to scan optics can be expressed in terms of $K_{sp}$,

$$MTF_s(u) = \exp(-3.56 u^2 R_\theta^2 K_{sp}^2) \,, \tag{9}$$

### 5.5. System MTF

Up to now we discussed how to compute the MTF of each component in a scanning display system. Now we can make a system MTF budget for the exemplary system in Table 4 using all the formulas in previous sections. As noted earlier, electronics, modulators, and duty-cycle results in spot growth only in the horizontal scan axis, and therefore, do not contribute to the vertical axis MTF budget. Horizontal and vertical system MTF budgets are shown in Figures 6 and 7. Spatial cut-off frequency for this display system is 16 cycles/degree (1280 pixels or 640 cycles within 40 degrees FOV). This system provides above 15% and 40% MTF at the spatial cut-off frequency (i.e., line-on line-off frequency) along the vertical and the horizontal axis, respectively. Since there are fewer contributors, vertical MTF is better than the horizontal MTF. The two can be made equal by adjusting the horizontal and vertical dimensions of the scanners in the system.

**Table 4: Component and system specifications for an exemplary system**

| | |
|---|---|
| Resolution | SXGA (1280 x 1024) |
| Frame rate | 60 progressive |
| Number of lines | 4 |
| Ocular type | Catadioptric |
| Field of view | 40 x 32 |
| Pixel duty-cycle | 1.0 |
| Electronics rise-time | 3 nsec |
| AOM rise-time | 10 nsec |
| $K_{hos}$ - Horizontal over-scan factor | 0.8 |
| $K_{sp}$ – Spot size to pixel size ratio | 0.8 |
| ** Horizontal scan frequency (Hz) | 16,000 |
| ** Pixel time at center (nsec) | 12.43 |
| ** Pixel time at edge (nsec) | 20.72 |

** calculated using the formulas in this paper

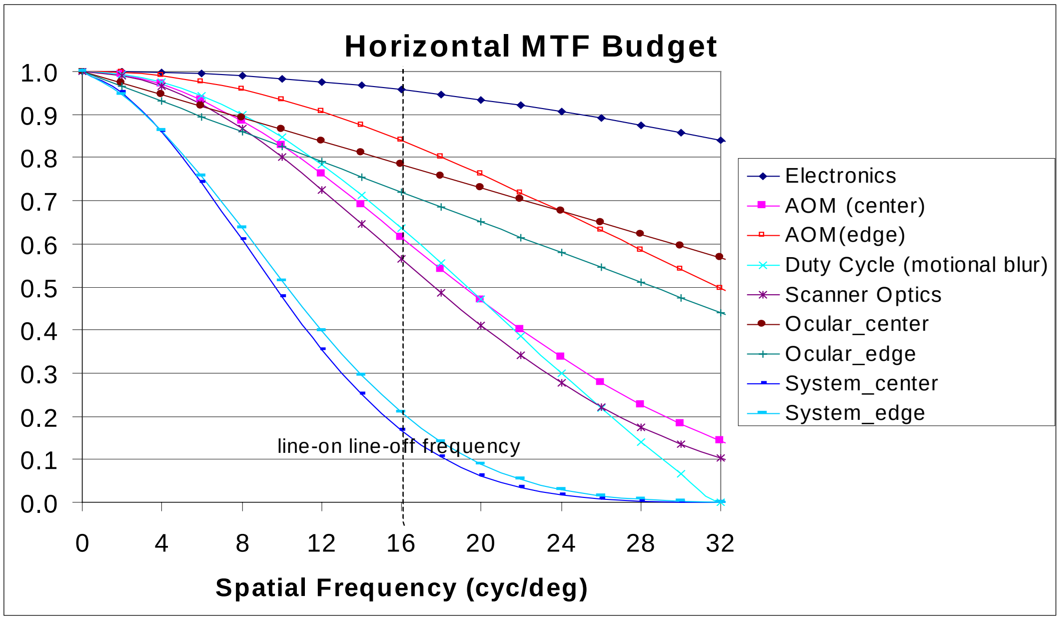


**Figure 6 Horizontal system MTF for the system in Table 4.**

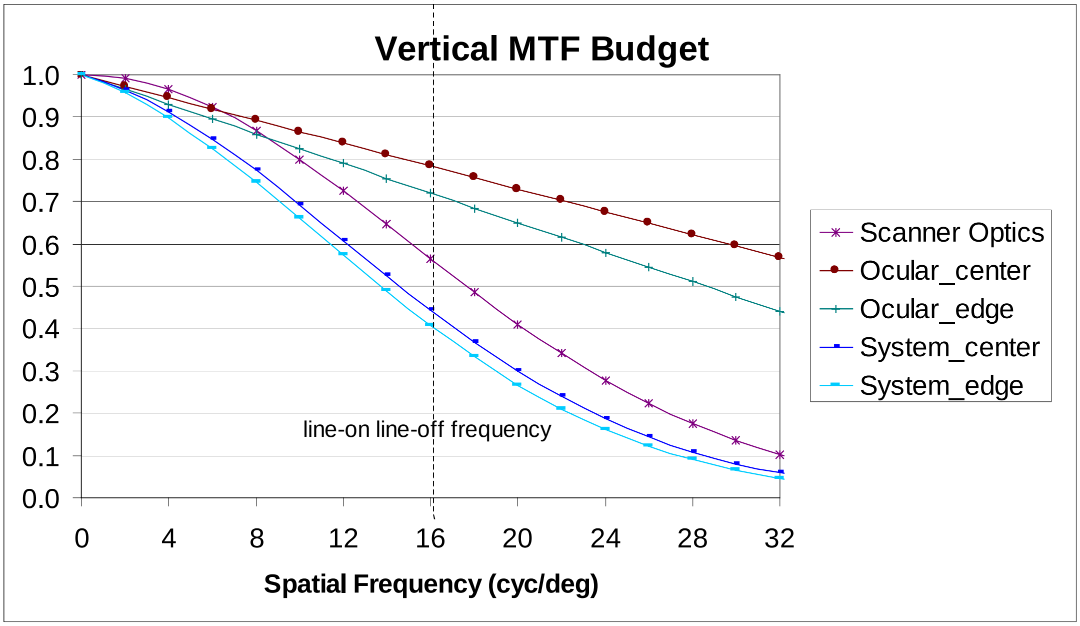


**Figure 7 Vertical system MTF for the system in Table 4.**

## 6. SUMMARY REMARKS

We discussed the operation and performance advantages of the VRD technology compared to competing display technologies. High luminance, high-resolution, large color gamut, and wavelength multiplexing and luminance control without affecting the system MTF are the most important advantages of VRD systems for microdisplay applications.

The system MTF budget method discussed in this paper provides an easy way to predict the image quality for scanning display systems.

## ACKNOWLEDGMENT

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