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MEASUREMENT OF MODULATION TRANSFER FUNCTIONS OF SIMULATOR DISPLAYS

George R. Kelly

University of Dayton Research Institute
300 College Park Avenue
Dayton, OH 45469

HUMAN RESOURCES DIRECTORATE
AIRCREW TRAINING RESEARCH DIVISION
Williams Air Force Base, AZ 85240-6457

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BYRON J. PIERCE
Project Scientist

DEE H. ANDREWS, Technical Director
Aircrew Training Research Division

LYNN A. CARROLL, Colonel, USAF
Chief, Aircrew Training Research Division

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George R. Kelly

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300 College Park Avenue
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The theory and methodology necessary for measuring the Modulation Transfer Function (MTF) of flight simulator displays is presented. The mathematical development of the MTF from linear system theory is outlined. The two primary methods for measuring MTF, namely the direct and indirect methods, are described and compared. The implementation of the indirect method is described in detail including measurement of the line spread function of a display, calculation of MTF from the line spread function and calibration of the resulting MTF. The MTFs of various simulator display components and displays were measured with the indirect method and presented in graphical form. Some of the more interesting characteristics of each MTF are discussed.

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PREFACE

The research presented in this paper was conducted by the University of Dayton Research Institute (UDRI) for the Aircrew Research Training Division of the Armstrong Laboratory (AL/HRA) under Contract No. F33615-90-C-0005, Work Unit No. 2743-25-17, Flying Training Research Support.

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MEASUREMENT OF MODULATION TRANSFER FUNCTIONS OF SIMULATOR DISPLAYS

SUMMARY

This paper describes the theory and methodology necessary for measuring the Modulation Transfer Function (MTF) of flight simulator displays. Linear System Theory, which is the mathematical basis of MTF theory, is reviewed. The mathematical development of the MTF from linear system theory is outlined.

The two primary methods for measuring MTF, namely the direct and indirect methods, are described with a brief discussion of the merits of each. Although the indirect method is more complicated to develop, it involves fewer measurements than the direct method and, thus, was used for this research.

The implementation of the indirect method is described in detail including measurement of the line spread function of a display, calculation of MTF from the line spread function and calibration of the resulting MTF. The MTFs of various simulator display components and displays were measured with the indirect method and presented in graphical form. Some of the more interesting characteristics of each MTF are discussed.

INTRODUCTION

Pilots flying high performance tactical aircraft rely heavily on their visual skills. Although fighter aircraft can be flown by instruments alone, many of the critical tasks such as low-level flight, weapon delivery, threat avoidance and air-to-air combat require the pilot to perform complex and demanding visual tasks. If these skills are to be trained in flight simulators, flight simulators must be equipped with out-the-window visual displays that can provide high-detail, high-resolution imagery.

In the past, visual displays have not been adequate for the training of these tasks. The only exceptions are dome display systems with target projectors which are very effective for training air-to-air combat but are of little use for other types of training. The lack of good visual displays has limited the use of flight simulators by the Air Force. Recently, progress has been made in the development of visual display systems. The Aircrew

Research Training Division of the Armstrong Laboratory (AL/HRA) has been a leader in this technology through the development of both rear- and front-screen-projected dome displays and helmet-mounted display technology. In parallel with display technology development, there has been a comparable advancement in computer image generation. Modern image generators, if used correctly, can provide enough scene detail or content for the training of a variety of visually intensive flying tasks.

Despite these technological advances, it is still difficult to assemble a visual system from these components that will guarantee effective training of the crucial flight skills in a simulator. The high cost of simulators means that the engineers developing the simulator usually have only one iteration to make it work. A trial-and-error process is simply not feasible. In fact, the procurement process requires the contractors to state the technical details of their design in their proposals, thus locking them into one particular design before any engineering is done. The situation is exacerbated by the fact that the contractors are sometimes more concerned with providing a simulator that will meet the procuring agency's specifications than with providing a simulator that will effectively train pilots. The procurement process could be improved if the procurement agency can provide specifications that, if met, will ensure that the simulator will be an effective training device.

In the area of visual display systems, such training effectiveness specifications do not exist. Traditionally, brightness, contrast, resolution and field of view have been used to characterize displays. These objective quantities are easy to measure, but their relation to pilot performance is not well understood. The relationship between pilot performance and the above quantities in a given visual task is a complex function. For instance, perception performance (i.e., target detection, discrimination or recognition) as a function of brightness is a highly nonlinear function. There is very little perceptible difference between a display which is 20 foot-lamberts versus a display that is 40 foot-lamberts, but there is a significant difference between 1 foot-lambert and 5 foot-lamberts. This is because the visual system transitions from mesopic (rod and cone vision) to photopic vision (cone vision only) at approximately 3 foot-lamberts. In addition, perception of brightness is itself nonlinear, due to the visual system's ability to adaptively alter its gain. These factors make the prediction of perception performance as a function of scene brightness extremely difficult. Similar nonlinear relationships occur for contrast, while the nature of the relationships between the performance of specific visual tasks and either field of view or resolution are even less understood.

Although brightness, contrast, resolution and field of view are of limited use for prediction, they can be of great use in comparing display systems. Often, one display system will be either equal or superior to another display in all of the above areas and, thus, is obviously the superior display. Difficulties arise when, for instance, one display has a greater contrast but a lower resolution than another display. At this time, a methodology does not exist to judge which display in this situation is the superior display. Despite our ignorance of the effects of brightness, contrast, resolution and field of view on performance, useful generalization can be made from these quantities.

The MTF is a formalism which shows promise as a solution to the above-stated dilemma. The MTF of a display combines both contrast and resolution of a display into one function. Some image quality metrics which are based on display MTF also take into account display brightness. Only field of view cannot be accounted for by MTF. The combining of brightness, contrast and resolution into one construct allows for the empirical measurement of pilot performance as a function of only one parameter, namely, the MTF. Once empirical relationships between particular tasks (i.e., target detection) and the MTF of a display are established, it will be possible to predict performance of that task in any display given the MTF of that display. To date, little work has been done in this area. The majority of the work focuses on the prediction of subjective image quality from the MTF.

Initially, this report provides the theoretical background for the measurement of MTF. The relative merits of two MTF measurement techniques known as the direct and indirect methods are discussed. A methodology for using the indirect method is then described. Finally, the MTFs of various display systems at AL/HRA are reported.

LINEAR SYSTEM THEORY

The mathematical basis of the Modulation Transfer Function is linear system theory (Gaskill, 1978). In linear system theory, a device or system is abstractly considered a "black box" which outputs a specific, although not necessarily unique, signal for every unique input. The contents of the black box are unimportant. All that is considered important is the input/output relationship, which is called the transfer function of the black box or system. This approach simplifies system analysis by eliminating irrelevant details from consideration.

A system is said to be linear if the output of the system for an input consisting of the addition of two or more signals is simply the addition of the outputs obtained when each of the given signals are applied to the system independently. If a system is linear, then it possesses two important characteristics: (1) there is a unique output for every unique input, and (2) complex input and output signals and their respective relationships can be broken down into elementary input and output signals. These two characteristics simplify the analysis of linear systems. The output signal for every possible input signal does not have to be known in advance. To completely specify a system, only a knowledge of the outputs corresponding to a finite number of elementary input functions is necessary. In this way, any complex system can be represented as a sum of the input/output relationship of elementary signals. The output for an arbitrary complex input signal is merely the sum of the elementary output signals associated with each elementary input signal.

An infinite number of elementary functions called basis vectors exists, which can be used to represent complex signals. The most common types are delta functions and sine/cosine functions. The delta function is a function that is zero except for one position at which it is equal to one.

$$\delta(x) = \begin{cases} if\ x=0 & then\ 1 \\ if\ x\neq 0 & then\ 0 \end{cases} \tag{1}$$

Although such functions do not physically exist, they can be used as mathematical abstraction. Delta functions, displaced in time or space, form sets of elementary functions that, when linearly combined, can approximate any piecewise continuous function. Despite their apparent complexity, their usage is familiar. Any sampled signal such as a digital recording is simply the weighted sum of delta functions equally separated in time or space. Each weight is equal to the amplitude of the signal at the particular time or location of the weight's delta function. Images can also be represented by summations of delta functions, one for each pixel (picture element) or position in the image. The digital representation of an image in a computer is such a representation. Each pixel is a delta function, and its associated gray-scale value stored in the computer's memory is the coefficient or weight for that delta function at that particular pixel location. Television images or any video image transmitted and then reconstructed with a raster scan are images represented by delta functions only in the vertical direction. The signal in the horizontal direction (along a single scan line) is not sampled and thus is left in its original continuous form. Any continuous signal that is sampled, that is represented by delta functions, is called a discrete signal. Some confusion arises when such signals are called digital signals. Digital refers to the quantization of discrete signal into a finite number of values or levels rather than representing it as a continuous range of values, as the signal may originally exist. Digital signals are always discrete signals, but the converse is not necessarily true.

Delta functions provide a compact and efficient means for representing signals and images but are of little use in representing the transfer functions of systems. Most physical systems have a one-to-one mapping or transfer function between input and output delta functions. If this were not the case, the system would degrade the signal or image substantially. Imaging systems that do not alter the value of pixels other than a fixed constant for all pixels are said to be shift-invariant. This means that if the input is shifted, then the output will not change except for a corresponding shift. A slide or transparency is an example of a nonshift-invariant system. A slide modulates the light falling on it at various locations by differing amounts. Optical systems that are free from aberrations are shift-invariant. Aberration-free optical systems are rare, but they do exist and are called diffraction-limited. Diffraction-limited optical systems will degrade the image, but the degradation is the same at every point in the image.

For systems which are shift-invariant, a different set of elementary functions is needed to represent the transfer relationship or transfer function. The most common set is that of sine and cosine functions with different wavelengths (or frequencies). The Fourier transform is the mathematical formalism used to decompose arbitrary functions into linear combinations of elementary sine and cosine functions. The Fourier transform is defined as,

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t} d\omega \qquad (2)$$

To obtain the original function from its transform, the inverse Fourier transform is used.

$$f(t) = \int_{-\infty}^{\infty} F(\omega)\, e^{i\omega t} dt \qquad (3)$$

The Fourier transform and its inverse are integrals of continuous functions. Images, as stated earlier, are usually created or stored as a discrete set of regularly spaced impulse functions. For discrete functions, the Fourier transform becomes the Fourier series, also called the Discrete Fourier Transform (DFT).

$$X(mF) = \sum_{n=0} x(nT)\, e^{-i2\pi mnFT} \qquad (4)$$

This equation gives the amplitude of the weights or coefficients for a finite set of sine and cosine functions, which when summed together will approximate the original discrete function. The coefficients are complex numbers since the exponential term in the sum can be expanded by Euler's formula given by,

$$e^{i\theta} = \cos(\theta) + i\sin(\theta) \tag{5}$$

The Inverse Discrete Fourier Transform (IDFT) is therefore,

$$x(nT) = \frac{1}{N}\sum_{m=0} X(mF)\, e^{i2\pi mnFT} \tag{6}$$

The data set being transformed must be a periodic function from negative infinity to positive infinity. This complicates matters somewhat because it requires that all series of finite length that are to be transformed must be considered as an infinitely repeating series. The function calculated by the DFT is also an infinitely repeating series. This is generally not a problem because the redundant portions of the series can simply be ignored. When equations (4) and (6) are actually computed, the sums in each need only be calculated up to the end of the last unique frequency (i.e., before the series repeats itself). If there are N points in the original series, there will be N/2 unique frequency points in the transform.

MODULATION TRANSFER FUNCTION

The MTF is the physical basis of the majority of the image quality metrics used in the display industry. To make use of these metrics, one must have a solid understanding of what an MTF is and how to measure the MTF of display systems.

If linear system theory is applied to image formation and display, then the output of a display system at any given moment can be determined from a knowledge of the input to the system and the system's transfer function. A transfer function, in general, specifies the attenuation (and sometimes the amplification) of each input frequency as it passes through a particular system. In the case of the MTF, the input and output frequencies are spatial frequencies. The use of linear system theory allows the complete characterization of the display system's spatial qualities in one mathematical function.

The traditional image quality measures of contrast and resolution employed by the simulation industry are contained within the concept of the MTF. For instance, modulation depth or simply modulation as defined by,

$$Modulation = \frac{Max\ Luminance - Min\ Luminance}{Max\ Luminance + Min\ Luminance} \tag{7}$$

is essentially a contrast measure. The contrast ratio, which is the ratio of the maximum and minimum luminance, is normally measured over large sections of the display, thus corresponding to the contrast at a spatial frequency approaching zero. This contrast ratio can be transformed to a modulation called the dc modulation which is equivalent to the modulation at the zero spatial frequency.

$$DC\ Modulation = \frac{Contrast\ Ratio - 1}{Contrast\ Ratio + 1} \qquad (8)$$

This means that the y-intercept of the MTF curve is directly related to the contrast ratio.

Resolution, another common image quality measure, is roughly the spatial frequency at which the modulation falls to zero. Some confusion may result due to different usages of the term resolution. Typically, the nominal resolution of a given display is assumed to be the maximum displayable pixels or lines. In reality, the maximum displayable pixels or lines is not the display's resolution but is, in fact, the addressability of the display which may not necessarily have any correlation with the display's resolution.

Resolution, properly defined, is the highest spatial frequency that can be displayed with a modulation that is detectable by an observer. This definition requires a knowledge of the display MTF and the minimum modulation necessary for human visual detection as a function of spatial frequency/viewing angle known as the Contrast Sensitivity Function or CSF. The spatial frequency at which these functions intersect is then the resolution of the display. Since resolution is at a premium in simulator displays (primarily due to large fields of view), the displays are designed so that the display addressability and resolutions are approximately equal. In fact, engineers rarely quote actual resolution specifications for simulator displays.

The display measures of contrast and resolution describe only the performance of the system at two spatial frequencies: zero and the limiting resolution of the display. The modulation at all other frequencies is ignored. This, in general, is not a bad approximation since most MTF curves tend to fall off smoothly from the modulation at zero spatial frequency to nearly zero modulation at the limiting resolution. The assumption behind the use of MTF in image quality metrics is that there are differences in the response of display systems at intermediate frequencies, and these differences are significant to image quality.

DISPLAY MTF MEASUREMENT TECHNIQUES

Since the MTF forms the objective basis on which image quality metrics can be developed, tested, and used, the MTF measurement techniques employed must be accurate and practical. There are two methods for measuring MTF: the direct and indirect methods (Beaton, 1988).

Direct Method

The direct method is the most straightforward but is also the most labor-intensive. It consists of "directly" measuring the modulation at each spatial frequency by applying a sine wave with that frequency to the input of the display and then measuring the maximum and minimum brightness of the displayed sine wave with a photometer. The modulation is calculated by equation (7). This is repeated for different spatial frequency sine waves so that the complete spectrum can be measured.

Despite the obvious nature of the direct method, there are a few pitfalls that need to be avoided. The photometer used must sample a sufficiently small field of view so that it does not average an area of the display where the brightness of the display is changing significantly. For high spatial frequencies such as one cycle per line pair, the area sampled must be smaller than a single line. Otherwise, the averaging would act like a low pass filter resulting in a measured modulation much lower than the actual. This requires a spotmeter with an extremely small spot size. The other difficulty is in providing a sine wave video input at varying spatial frequencies. Video signal generators provide test patterns of square waves at programmable frequencies but not sine waves. Image generators, on the other hand, can be programmed to output sine waves, but their video output is essentially a discrete valued "staircase" which approximates a sine wave but becomes a square wave at high spatial frequencies.

If square waves are used as the input in the direct method, then the measured transfer function is technically not an MTF. It is possible to mathematically transform the square wave transfer function into a conventional MTF.

Indirect Method

The indirect method makes use of linear system theory by calculating the MTF from a point spread function or a line spread function. The point spread function is the two-dimensional cross section (luminance) of a pixel. Likewise, the line spread function is the one-dimensional cross section of a raster line or a vertical line of pixels. In terms of linear system theory, the line and point spread functions are impulse responses of the system. For instance, if a single pixel is on, the point spread function will be a light distribution approximately the shape of a Gaussian distribution centered on the pixel. Similarly, the line spread function is the response of the display to a line input function.

From the convolution theorem, the MTF can be calculated by

$$MTF = \left[\frac{O(f)}{I(f)} \times \frac{O(f)^*}{I(f)^*}\right]^{1/2} \tag{9}$$

Where I(f) is the Fourier transform of the input, O(f) is the Fourier transform of the output and f is spatial frequency. If the input is an impulse function (delta function), then I(f) = 1 and equation (9) becomes,

$$MTF = [O(f) \times O(f)^*]^{1/2} \tag{10}$$

The MTF of a display system is the magnitude of the Fourier transform of the point spread function. This greatly simplifies the measurement of the MTF since only one measurement is needed (the point spread function), unlike the direct method which requires one measurement for each frequency. Once the point spread function is obtained, the magnitude of its Fourier transform is calculated using a Discrete Fourier Transform (DFT).

If the measured point spread function consists of an array of N horizontal by N vertical samples, its DFT will consist of an N by N array of the modulation depth at equally spaced spatial frequencies. Only one fourth of the points in the array contain unique information about the MTF. The remaining points are redundant and can be ignored. The MTF curve should be scaled or normalized such that the dc modulation (0 cycle/deg.) of the MTF is equal to the dc modulation calculated by measuring the contrast ratio and using equation (8) (Barten, 1988).

The measurement and analysis are much simpler in the one-dimensional case where the DFT of the line spread function is calculated. In this case, the DFT of a line spread function with N samples will itself have N values, N/2 of which are unique. The actual measurement of the line spread function can be accomplished with two different but analogous methods. The first method uses a narrow slit which moves in the image plane of a lens focused on the line (or column of pixels) on the display. A photodetector behind the slit records the intensity of the light imaged on the slit. If the slit is sufficiently narrow, it can be considered an impulse function in the direction perpendicular to the slit. In the direction parallel to the slit, the signal is averaged or integrated. The resultant signal from the photodetector is the convolution of the slit (impulse function) and the image of the line and is, by definition, the line spread function of the line.

An alternative to the moving slit is to use a linear array of slit-shaped photodetectors. The use of the array can essentially be thought of as a discrete implementation of the continuous process of moving the slit. Each detector on the array is equivalent to a discrete position of the slit. As with the direct method, the field of view imaged onto individual detector cells must be small enough so that the high-frequency components in the measured point spread function are not filtered out.

The main advantage of the indirect method over the direct method is that the indirect method requires only one measurement, while the direct method requires one measurement for each spatial frequency. The indirect method also allows for the measurement of the MTF at specific locations within the field of view in the event that the MTF is not constant throughout the field.

Comparison of Direct and Indirect Methods

The two methods, when used to measure the MTF of a display, should give the same results. This assumption was tested by measuring the MTF of a General Electric Talaria projector using both methods. The results are shown in Figure 1.

A Silicon Graphics IRIS graphics workstation was used to supply the video to the projector. For the direct method sine wave, luminance patterns with spatial frequencies of 13, 26, 64, 107, 142, 183, 213, 256, 320 and 427 cycle/picture height were generated by the IRIS and displayed by the projector. The modulation contrast (equation 7) of each displayed sine wave was measured with a Photo Research PR-719 Spatial Photometer. The same PR-719 photometer was used for the indirect method. The procedure for the indirect method is described in detail below. Measurements for both methods were taken on the front surface of a projection screen.

As can be seen in Figure 1, the two methods agree well at high frequencies (i.e., > 250 cycles/picture height). At low frequencies the MTF measured with the direct method is considerably lower than the MTF measured with the indirect method. Such a discrepancy is not surprising if the nature of the two methods is examined closely. The indirect method measures the MTF only in a small region of the display while the direct method measures the low frequencies over a relatively large area and the high frequencies over a relatively small area. This large range of scale required for the direct method means that the photometer must be repositioned several times during an MTF measurement. This undoubtedly will result in measurement errors. Additionally, the

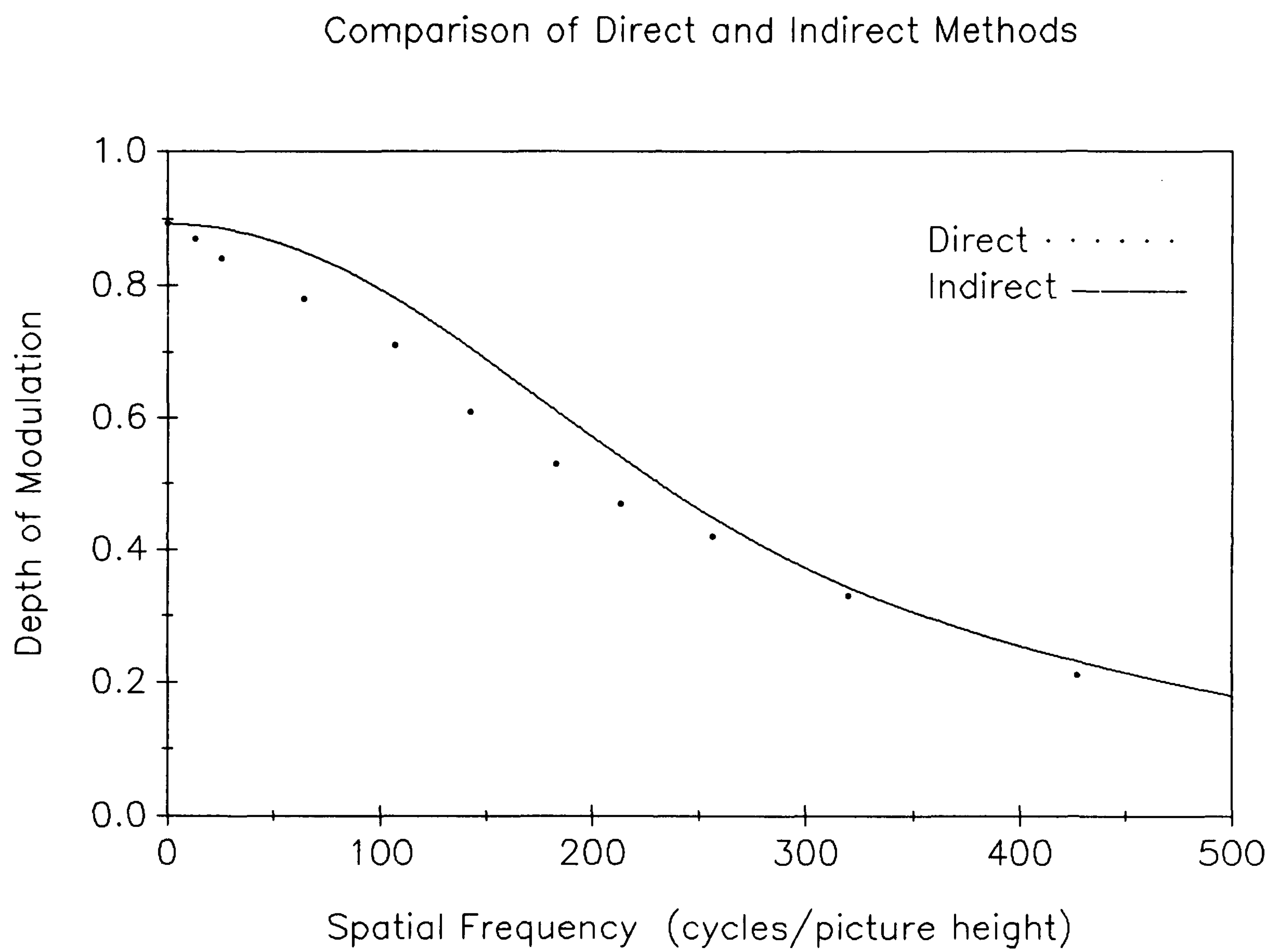

Figure 1
Comparison of Direct and Indirect Methods

direct method assumes that the MTF of the display is the same at every location on the display. Consequently, the direct method suffers from errors due to variations in the MTF across the display. The indirect method does not have this problem because it is a local measure of MTF. Several measurements with the indirect method at various positions on the display can actually characterize the variance of the display's MTF.

IMPLEMENTATION OF THE INDIRECT METHOD

Measurement of the Line Spread Function

The line spread functions of various displays at AL/HRA were measured with a Photo Research® PR-719 Spatial Photometer. The PR-719 images light from a display screen onto a photodetector array with 111 elements which are 0.025 mm wide by 2.49 mm long. The long narrow shape of the elements allows the array to sample in one direction (perpendicular to the length) and integrate or average in the other direction. Thus, the array is effectively measuring in one dimension only.

The output of each element is proportional to the amount of visible light falling on it during an integration period. Output from the array is passed to a personal computer (PC) through an interface card located in an expansion slot of the PC. Photo Research® software running on the PC then displays the output from the array and stores it in a file on a hard disk drive on the PC.

A video signal generator was used instead of the simulator's image generator so that the measured MTF would not include any image generator effects, such as antialiasing. The signal generator produced test patterns consisting of either vertical or horizontal parallel lines. The PR-719 was then positioned at the eyepoint of the display when possible; when not possible, it was placed on a line between the eyepoint and the display.

After the PR-719 was correctly positioned, it was optically aligned with one of the lines in the test pattern using the view finder on the PR-719. The view finder is similar to a camera view finder, except when looking through the view finder, the active area of the photodetector array is covered with a black mask. The PR-719 was aligned using its view finder so that the displayed line passed through the center of the photodetector array (black mask) and was parallel to elements in the array. When the horizontal line spread function was measured, the test pattern with vertical lines was used, while the test pattern with horizontal lines was used to measure the vertical line spread function. This meant that the PR-719 was positioned upright when measuring the horizontal line spread function and was rotated 90° about its optical axis when the vertical line spread function was measured.

Spatial Calibration

The PR-719 was intended primarily for measuring the MTF of cathode ray tubes (CRTs). It comes from the factory with a 1X lens (MS-55) specifically designed for this purpose. The MS-55 must be focused at 44 mm from the CRT for the spatial calibration of the PR-719 to be correct. When the MTFs of simulator displays were measured, this restriction could not be met because the PR-719 required positioning at the eyepoint of the display which was always greater than 44 mm from the display. The MS-55 then had to be refocused, thus altering its magnification and subsequently changing the spatial calibration in the PR-719 software. The system can be recalibrated by the manufacturer only. Since returning the PR-719 to the manufacturer before measuring the MTF of each display was clearly impractical, an alternative means of calibration was developed.

The purpose of the spatial calibration was to determine a constant that represented the scale or magnification of the lens in appropriate spatial dimension units (i.e., pixels, lines, picture height or degrees per PR-719 photodetector element). This was accomplished by using the PR-719 to measure the distance in units of photodetector elements between two lines in the display which were separated by a known distance. A video signal generator was used as the video source for the displays. The signal generator was programmed to display two lines separated by integer multiples of raster lines (vertical scaling) or pixels (horizontal scaling). The PR-719, when focused on this pattern, measured the luminance cross-section of the two lines. A plot of the output consisted of two peaks or humps. The output was saved in a file on a hard disk for post processing.

The post-processing algorithm calculated the distance between the lines by finding the difference in the position of the centroids of the two peaks. The centroids were calculated by multiplying the luminance measured by each element by its position in the photodetector array and then dividing by the sum of the luminances of all the elements. For the centroid calculations the array was divided into two halves (elements 0-55 and 56-111) so that the two peaks could be easily separated. Since the luminance between the peaks was always non-zero, all elements with a luminance below a threshold of one half the maximum luminance were eliminated from the calculation. For this reason, the peaks had to be at least twice as bright as the background luminance for the centroid algorithm to function properly. Even though the photodetector array has only 111 elements, substantially higher resolutions were obtained due to the nature of the centroid calculations.

Calculation of the MTF from the Line Spread Function

After the line spread function and the spatial calibration data were collected, a DFT was performed on the line spread function to determine the corresponding MTF. A DFT can be performed only on an even number of data points. As stated earlier, the DFT transforms N data points into N/2 unique frequency points. If 110 of the 111 elements were transformed with the DFT, the frequency data would contain 55 data points. During the development of the data analysis, it was discovered that the spectrum of a typical line spread function fell to zero after approximately 5 frequency points. This was due to the fact that the spatial sampling rate of the PR-719 was much higher than the highest spatial frequencies in the line spread function. To obtain a higher resolution in the frequency domain, a standard technique known as "padding" was used.

Padding increases the spatial frequency resolution of the DFT by adding data points (often zeros) to the line spread function. Since padding involves altering the measured data, great care must be taken to ensure that the added data do not alter the resulting spectrum significantly. Line spread functions are always limited to a finite spatial region. In other words, the line spread function falls quickly from a maximum value to zero or a constant baseline value. If the maximum of the line spread function is centered within the data set, the function should have a small slope at the beginning and end of the data set. The extension of both ends of the line spread function with zeros or a constant baseline value will not significantly change the spatial frequency content of the line spread function. Padding, therefore, provides a means of increasing the spatial frequency resolution of the MTF without corrupting the results.

The measured line spread functions were padded to 500 data points, resulting in 250 discrete spatial frequencies in the MTF. For all of the MTFs measured at AL/HRA, the amplitude of the spectrum was, for practical purposes, zero after the first 100 frequency points. The rest of the frequency points were ignored. The final step in the analysis was the calibration of the amplitude of the MTF.

DC Modulation Calibration

Mathematical transforms must be normalized to ensure the amplitude of the transform is correctly scaled. Many researchers using MTF to characterize displays follow the optical engineering convention by normalizing the dc-modulation of the MTF to numerically equal one. This assumes the system which the MTF describes does not alter the contrast ratio of the system from input to output. This approximation is valid for lens systems but is not necessarily appropriate for display systems. The amount of contrast degradation due to scattering in lens systems is generally small enough to be ignored. Display systems, on the other hand, exhibit a significant amount of contrast degradation due to ambient light and non-zero dark fields.

The dc-modulation of each simulator display was determined by measuring the maximum and minimum luminances of the display with a Pritchard spot meter and then using Equation 8. A video signal generator was used to drive the display with a test pattern which consisted of a dark field (zero drive voltage) with a square area of maximum luminance (maximum drive voltage). The square covered an area of approximately 5% to 10% of the total display area. The spot meter was then used to measure the luminance at the center of the square (maximum luminance) and of the dark field (minimum luminance).

Once the dc modulation was determined, the MTF was normalized by multiplying the amplitude at each frequency by the dc modulation divided by the amplitude of the MTF at f=0 (i.e., y-intercept of the MTF). The resulting MTF intercepted the y-axis or modulation axis at the dc modulation and retained its overall shape.

RESULTS AND DISCUSSION

The MTFs of several displays at AL/HRA were measured. The research examined the MTF of a General Electric (GE) Talaria Single Light Valve (SLV) projector, GE Multi-Light Valve (MLV) projector, GE Limited Field- of-View Dome (LFOV) and the GE-constructed Display for Advanced Research and Training (DART). The MTFs are plotted on graphs with modulation ranging from 0 to 1.0 on the vertical axis and spatial frequency on the horizontal axis. For the SLV and the MLV, the spatial frequency axis has units of cycles per picture height while for the LFOV Dome and DART, the units of the spatial frequency axis are cycles per degree. The units of cycles/picture height can be converted to cycles/degree provided the angular size (in degrees) of the vertical and horizontal dimensions of the display are specified.

Figure 2 shows the measured horizontal and vertical MTF of an SLV. The vertical MTF is significantly better than the horizontal MTF. This is not surprising due to the manner in which the SLV functions. The SLV uses a phase diffraction grating written with an electron beam onto a thin oil film to modulate the intensity of the light passing through the oil. Green light is modulated vertically by the grating while magenta light is modulated horizontally by the grating. The MTF is limited in each direction by the diffraction of grating. More specifically, the MTF of green light is limited vertically while the MTF of magenta light is limited horizontally. The grating, therefore, limits the green vertical MTF to a relatively low level when compared to the green

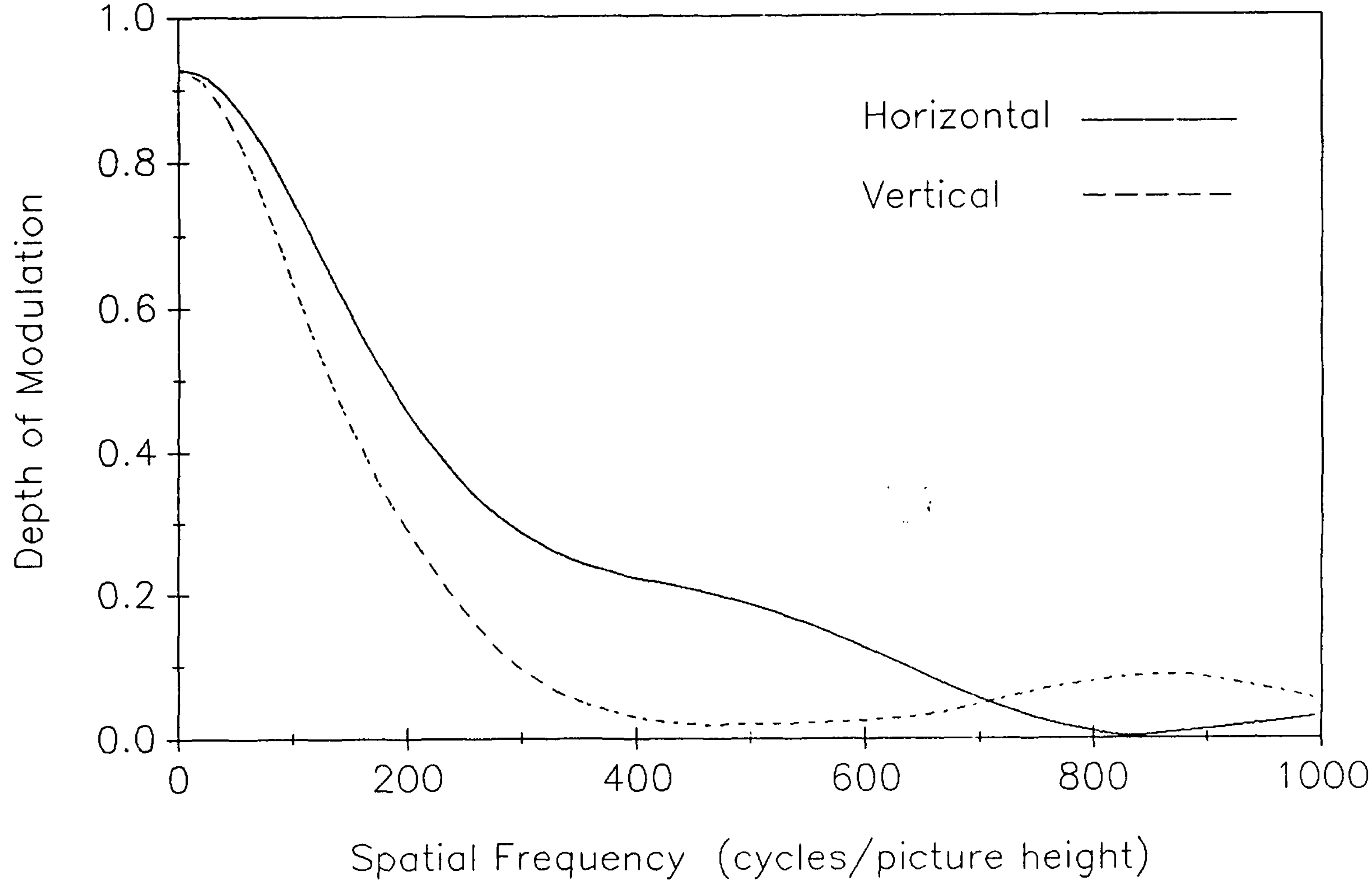

Figure 2
Horizontal and Vertical MTF of an SLV Projector

horizontal MTF which is limited only by the spot size of the electron beam. Since MTF of any display is dominated by the MTF of the green primary, due to the relative photopic energy of each primary, the MTF of the SLV is significantly better in tne horizontal direction than in the vertical direction. Further measurements of the MTF of each of the SLV primary colors are consistent with this explanation.

Figures 3a and 3b show the measured MTF of each of the three primary colors of the SLV in the horizontal and vertical directions, respectively. The MTF of the green primary is substantially poorer in the vertical direction than it is in the horizontal direction.

The horizontal MTFs of the red and blue primaries and the vertical MTF of the green primary all have a similar and somewhat peculiar shape. All three MTFs decrease to a minimum and then increase to a secondary maximum. This shape is very similar to a sinc squared function which is the diffraction pattern associated with a rectangular aperture or slit. In this case the rectangular aperture in the diffraction grating is caused by the electron beam which writes the grating being abruptly turned on and off at the beginning and end of each pixel. This effect manifests itself in the shape of the pixel. Red and blue pixels have two ghost pixels appearing on both sides of the pixels. Green pixels have ghost pixels above and below them. Likewise, blue and red vertical lines and green horizontal lines appear as three lines.

Figure 4 shows a series of five SLV horizontal MTF curves. The top curve is the measured SLV MTF at maximum brightness (10 foot-lamberts). Subsequent curves show the measured MTF with decreasing brightness steps of 80%, 60%, 40% and 20% of maximum brightness. The curves all share the same basic shape. The difference between the curve is due only to the change in y-intercept or dc modulation with a decrease in brightness. This change in dc modulation is caused by the fact that the dark field of a light valve is constant and thus independent of the average scene brightness. If these curves were all normalized to 1, they would be identical. This means that the MTF of an SLV changes with brightness levels only because the contrast ratio is changing and not because the shape of the pixel line spread function is changing.

Figure 5 shows the measured MTF of the MLV. Although the MLV is supposed to have performance superior to that of the SLV, a comparison of Figures 2 and 5 clearly shows that the MTF of the SLV is always greater than the MTF of the MLV except at low frequencies. In other words, the MLV has a better contrast ratio while the SLV has better resolution. A possible explanation for this is that the combining optics of the MLV degrade the MTF of the MLV.

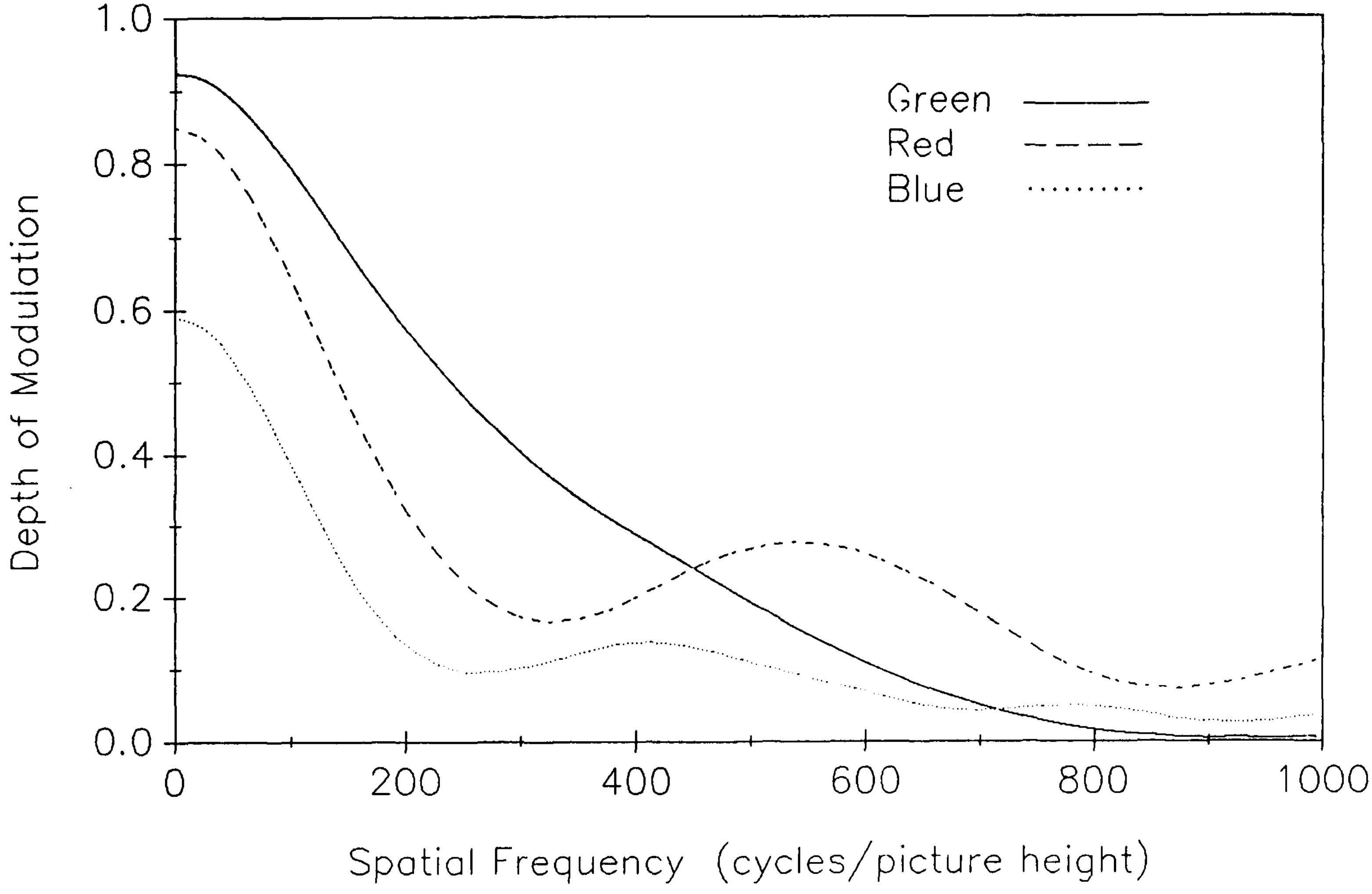

Figure 3a
Horizontal MTF of the Three Primary
Colors of an SLV Projector

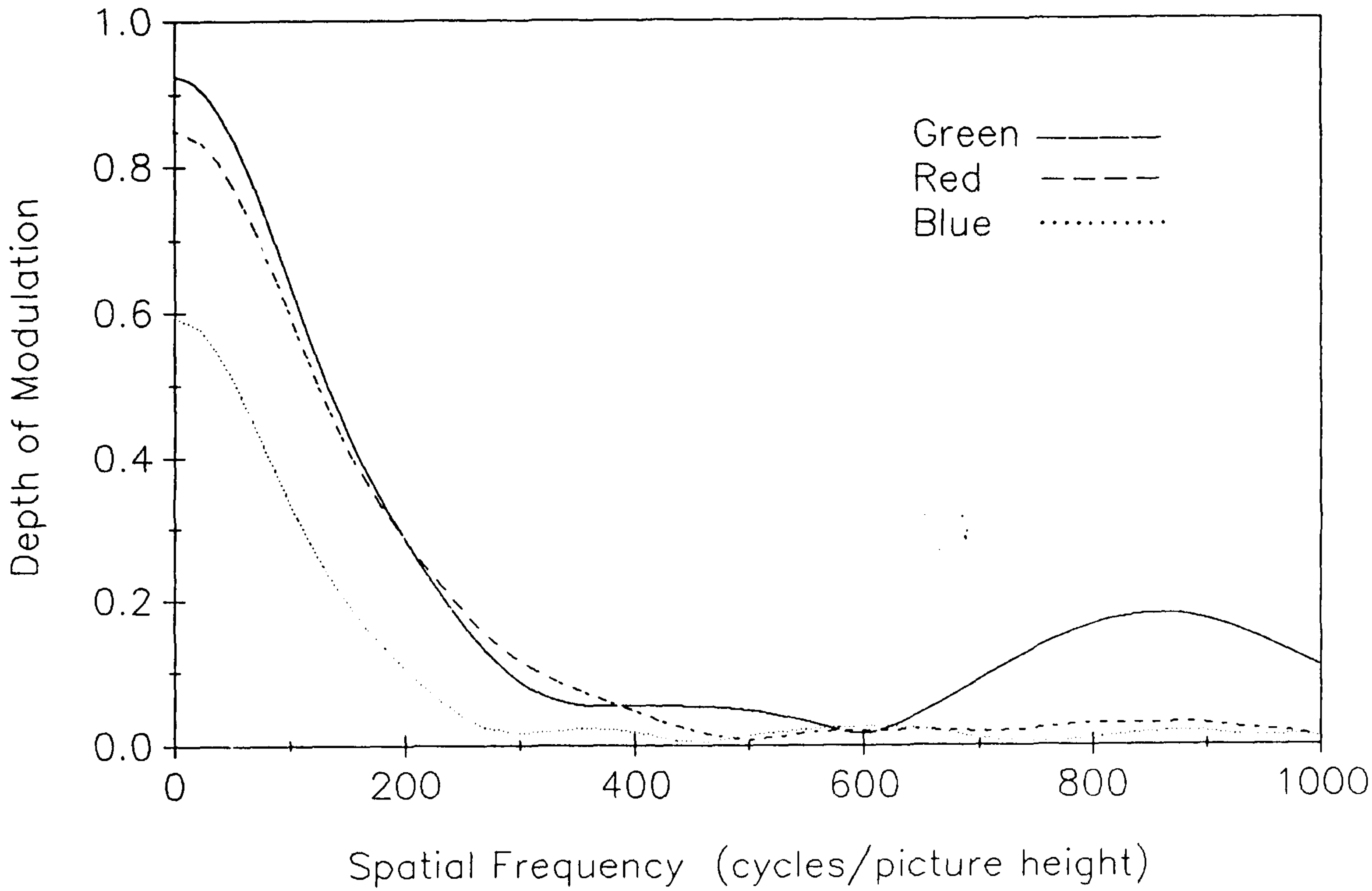

Figure 3b
Vertical MTF of the Three Primary Colors of an SLV Projector

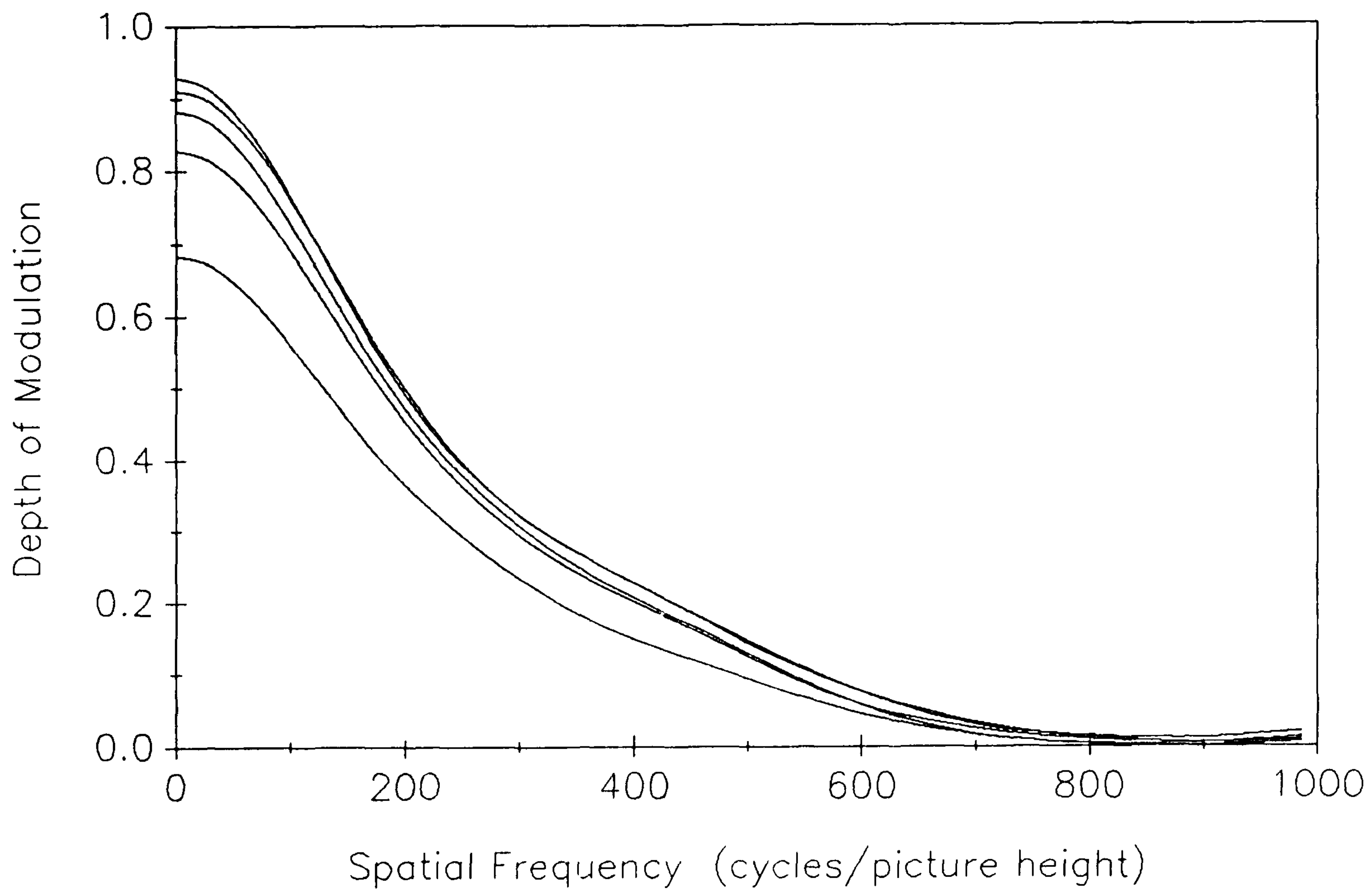

Figure 4
Variance of the MTF of an SLV Projector with Brightness

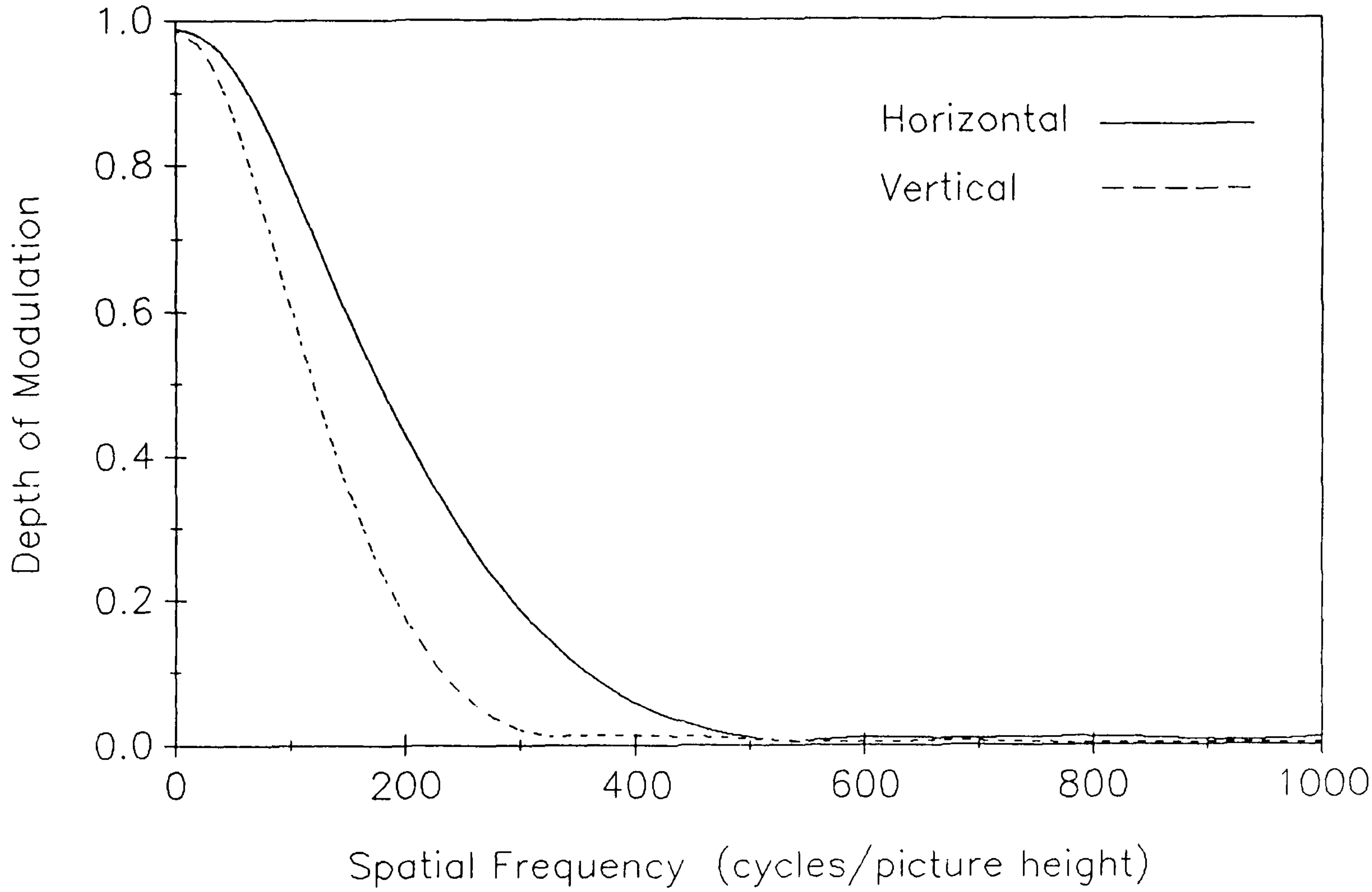

Figure 5
Horizontal and Vertical MTF of an MLV Projector

The LFOV Dome can be used with one of two high-resolution areas of interest (AOI), one with a 40° x 30° field of view and the other with a 25° x 19° field of view. The measured horizontal and vertical MTFs of the two AOIs are shown in Figures 6a and 6b. Both use the same light valve projector as an input, so both have the same number of pixels and raster lines. The difference in MTF between the two is due to their difference in magnification. This is evidenced by the measured MTF curves which are nearly identical for each AOI, except for a scale change in the spatial frequency axis which is the result of the magnification difference.

Figure 7 shows the measured MTF of DART. Figure 8 compares the horizontal MTF of DART and the large AOI of the LFOV Dome. Figure 8 is particularly interesting because the two MTF curve intersect. DART has superior low frequency response due to its relatively high contrast ratio while the large AOI of the LFOV Dome has superior high frequency response. In this case, deciding which display is better from the MTF curves is difficult because we are ignorant of the relative importance of the high versus low frequencies to image quality or to visual task performance.

CONCLUSIONS

Although the interpretation and understanding of MTFs is at this time limited, MTFs do provide valuable information about the output of the displays they characterize. MTFs are obtained through physical measurements and are repeatable and therefore provide an objective basis for the comparison of the image quality of various display devices.

In most cases the advantages of the indirect method over the direct method will justify the additional investment in time and hardware necessary for the indirect method. The primary advantage of the indirect method is that it requires only a few measurements for each MTF, while the direct method requires at least ten measurements for reasonable spatial frequency resolution. Consequently, data acquisition time is greatly reduced by the indirect method. Additionally, the indirect method is essentially a local measure. This feature allows the measurement of the variance of the MTF at many different points on the display. The direct method, on the other hand, involves measurements at several spatially separated points on the display. If there is a significant variation in the actual MTF at these disparate points, errors will be introduced to the measured MTF. Despite these weaknesses the direct method is by far the simpler of the two methods to implement. It remains the method of choice in situations where a relatively small number of MTF measurements are needed.

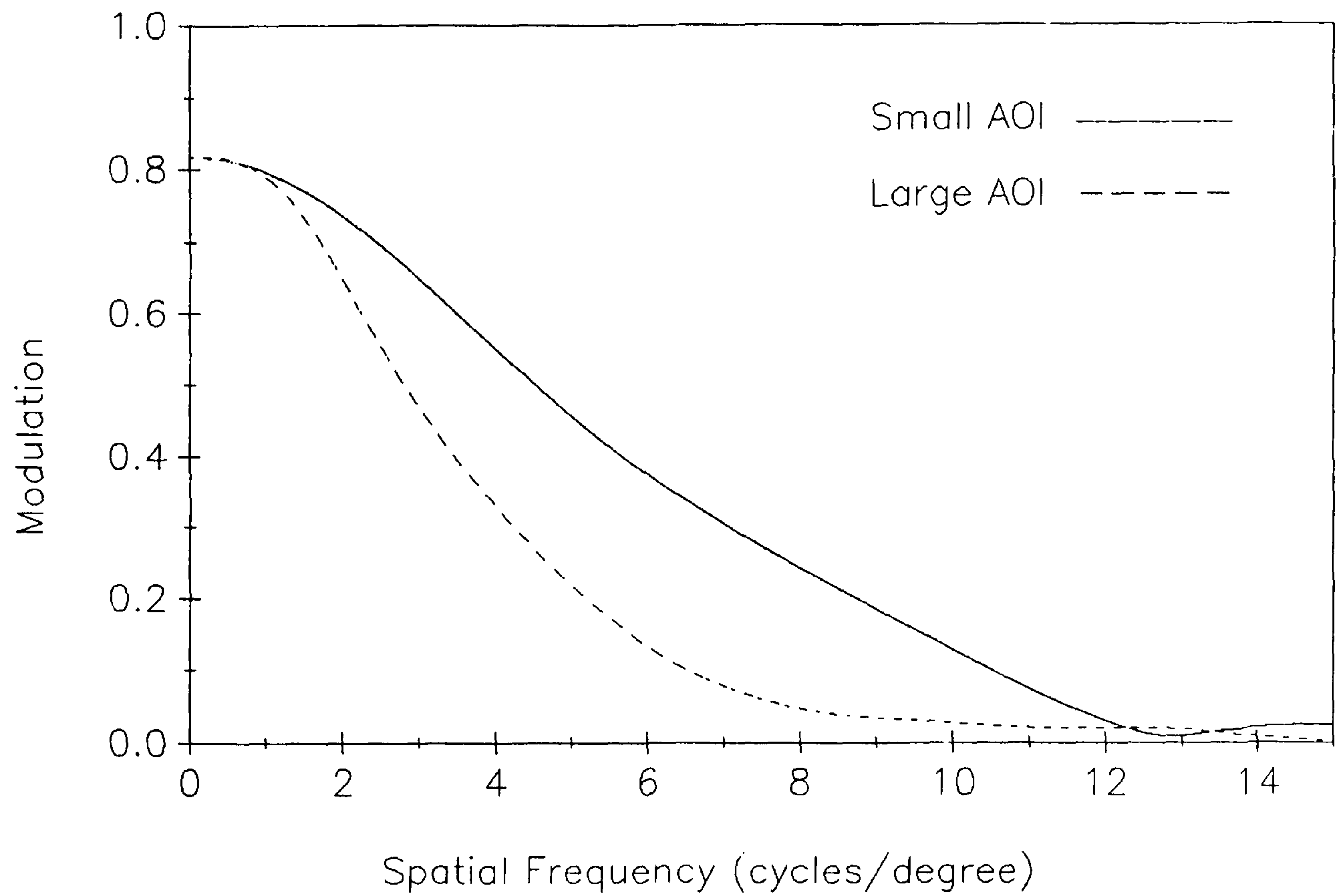

Figure 6a
Horizontal MTFs of the LFOV Dome AOIs

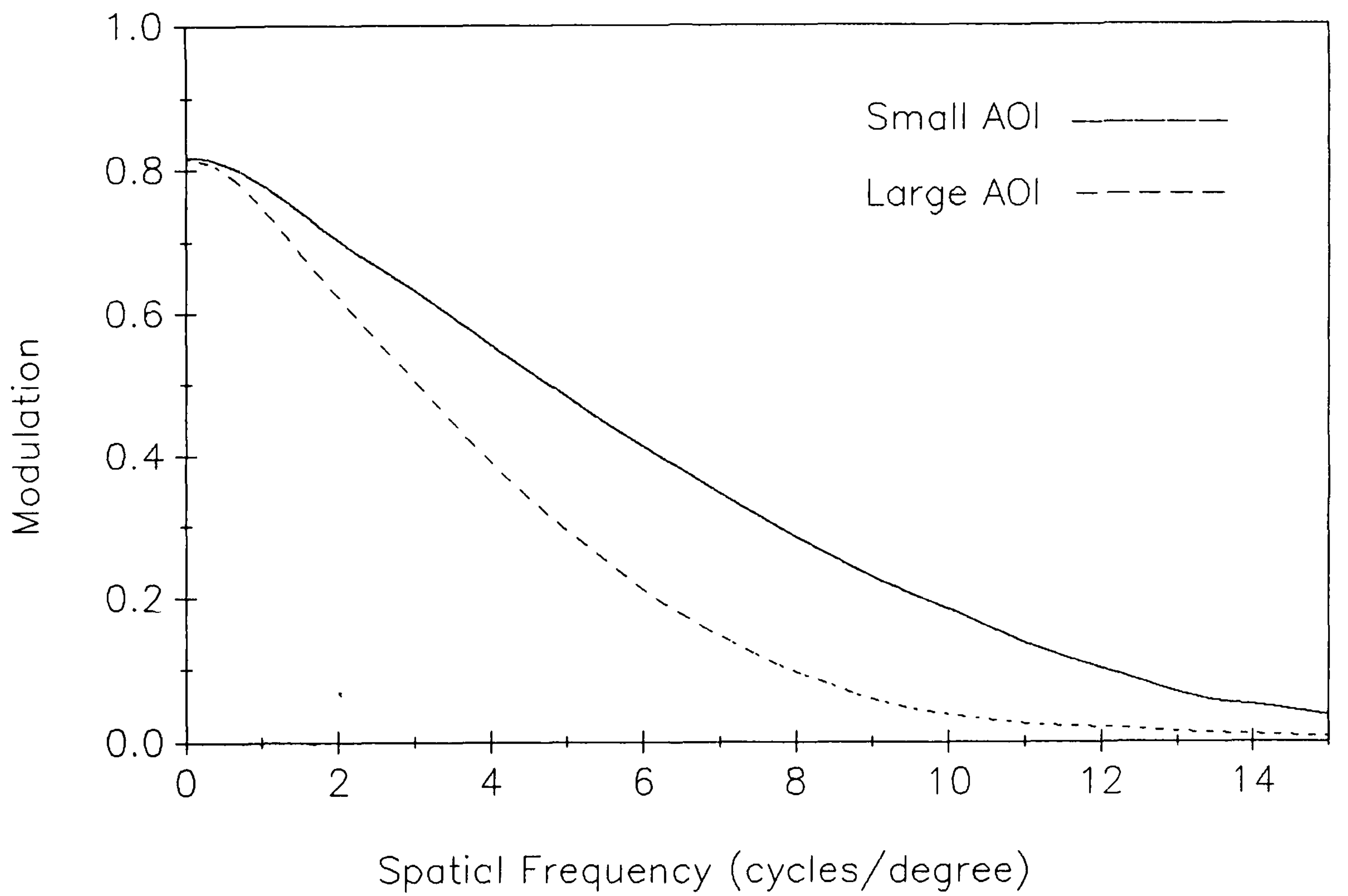

Figure 6b
Vertical MTFs of the LFOV Dome AOIs

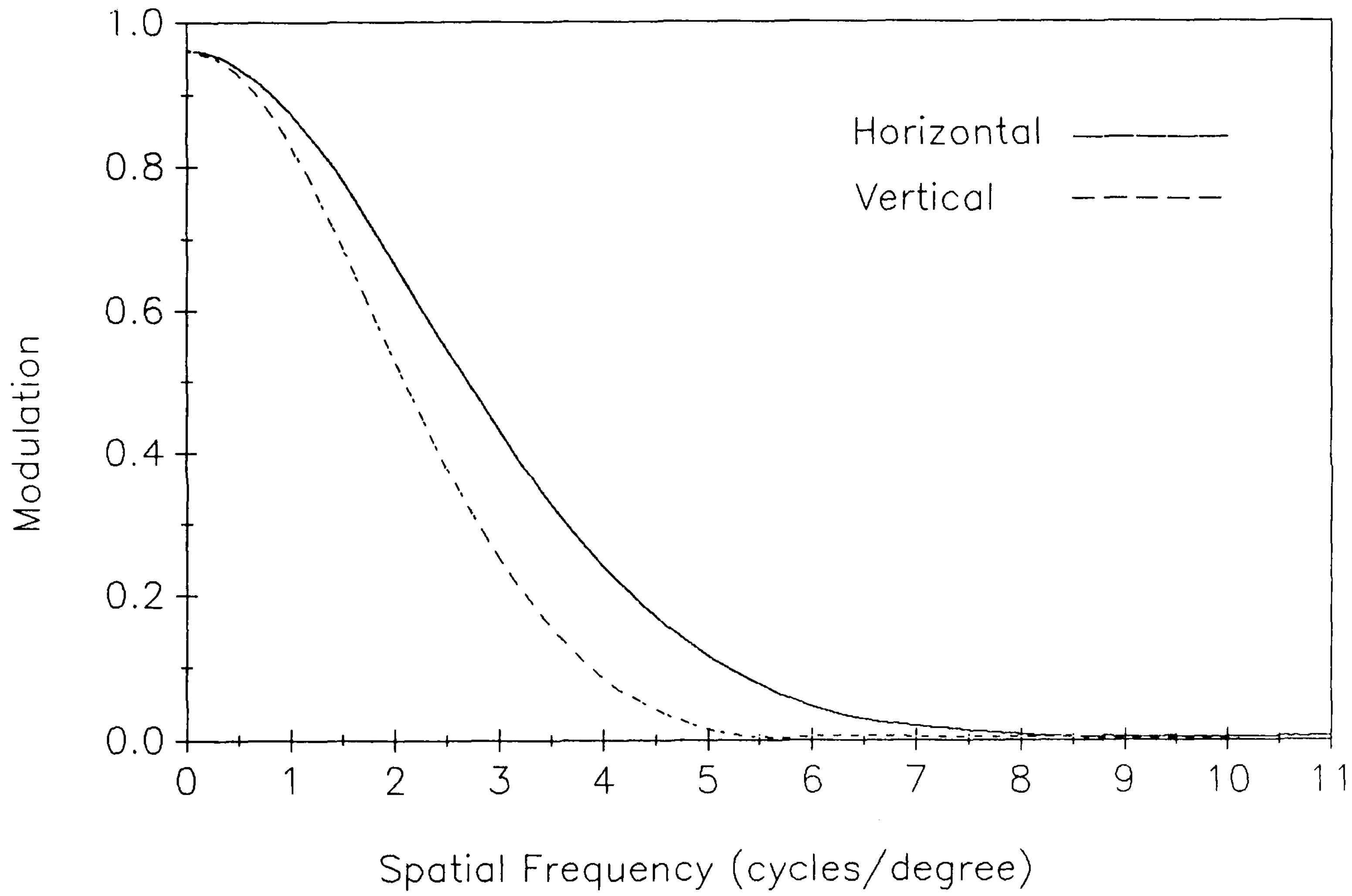

Figure 7
Horizontal and Vertical MTF of DART

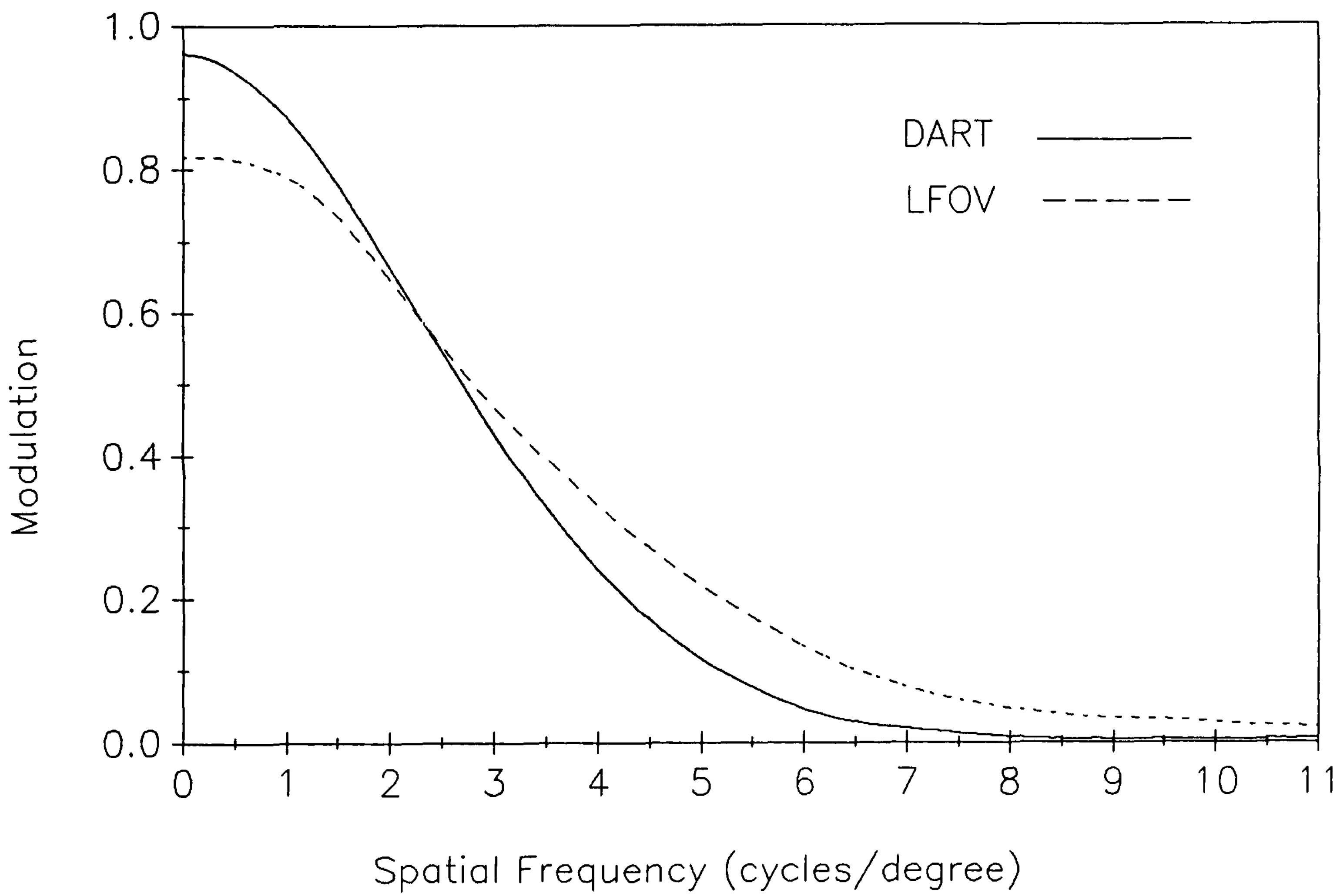

Figure 8
Horizontal MTF of DART and the LFOV Dome Large AOI

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