Use of spatial light modulators in frequency modulation reticle trackers

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Abstract. Advances in spatial light modulator (SLM) technology have resulted in an active search for signal processing algorithms for use with SLMs in incoherent electro-optical systems. This paper presents an effective means of generating tracking algorithms for locating small targets with a single detector using FM reticle theory. A simple "barrel transformation" of a spinning FM reticle pattern to an SLM is shown to allow tracking systems to be constructed with solid state devices and avoids the need for moving parts. Also, SLMs allow the FM patterns to change over time, allowing adaptive interrogation of targets in a particular region of a system's field of view.

Subject terms: active optical components; reticles; spatial light modulators; tracking devices.

Optical Engineering 29(11), 1398-1403 (November 1990).

CONTENTS

1. INTRODUCTION

Many types of models are used to generate light modulating algorithms for optical systems that use spatial light modulators (SLM). It is shown in this paper that reticle theories[1–4] are an effective means of generating these algorithms for tracking systems. Consider the spinning FM reticle tracking system shown in Fig. 1. The reticle is placed in an intermediate focal plane and the target image is modulated with a signal unique to the target location in the field of view (FOV). The reticle is designed based on three types of FM parameters[5]: frequency versus angle $f(\theta)$, frequency versus radius $m(r)$, and phase $\rho(r)$. For a point source that is imaged onto the reticle, the parameters give a unique temporally modulated optical signal for each point source location, which the detector converts into a temporal signal. This temporal signal is then decoded by the system electronics to provide the target location. Recent developments[6] in modulation rates of SLMs allow reticles to be replaced with these solid state devices.

Some of the advantages of using an SLM over a spinning reticle are that, (1) there are no moving parts in an SLM, which can provide better reliability in a tracking system, and (2) SLMs allow adaptive processing since the FM patterns can be changed over time. The latter advantage allows adaptive interrogation of targets in a particular region of a system's FOV. This is a particularly useful tool in an arena where multiple targets exist in a system FOV but only a single target or a few targets are of interest. Using an adaptation technique, unwanted target or decoy signals can easily be removed.

The replacement of a reticle with an SLM is a simple one, with the main issues being the bandwidth and transmission limitations of the SLMs. Since most SLMs are constructed in rectangular form and most spinning FM reticles are in polar form, a direct polar to rectangular conversion seems to be the most direct approach to implementing reticle algorithms on SLMs. However, this type of conversion means that a large number of calculations must be completed at a high rate for each SLM pixel. A total SLM digital data rate can be considered to be each pixel bandwidth times the number of pixels in the SLM. A more simple "barrel transform" can be applied to the reticle algorithms to provide a modulation scheme in rectangular coordinates that uses current spinning FM reticle techniques and may allow the total SLM digital data rate to be reduced by one of the SLM linear dimensions.

2. BARREL TRANSFORMATION

Consider the mapping function shown in Fig. 2. Given the y dimension of the SLM, the reticle is digitized into discrete ring functions whose number corresponds to the y dimension of the SLM. The innermost ring function is mapped to one end of the barrel, and the outermost ring function is mapped to the other end of the barrel. The rings between the center of the reticle and the outer edges of the reticle are mapped between the reticle ends accordingly. Now, when the reticle rotates, the barrel can be thought of as spinning. The transmission function can be thought of as unwrapping from around the barrel and scanning across the SLM. The barrel provides the same scanned function each time the barrel completes one rotation. Hence, the scanned function is periodic in the x direction. The phase $\rho(r)$ can be thought of as the edge of the function rolling off the barrel.

The barrel type mapping is a more direct approach to rectangular array utilization than a polar to rectangular conversion. For a polar to rectangular conversion, each temporal pixel value must be calculated from the spinning reticle polar transmission values. The total system data rate required for this calculation is equivalent to each required pixel data rate times the total number of pixels in the SLM. The barrel mapping requires the pixels on the y axis to each have a modulation data rate, but the

Invited paper AD-113 received Jan. 22, 1990; revised manuscript received June 6, 1990; accepted for publication July 20, 1990.
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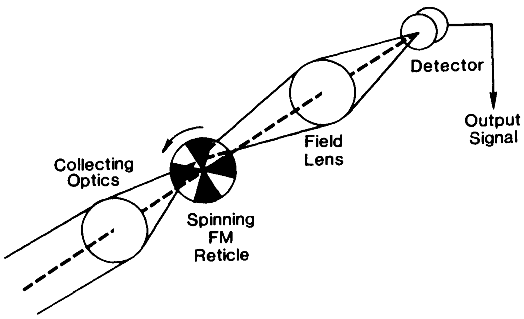


Fig. 1. Typical FM reticle tracker.

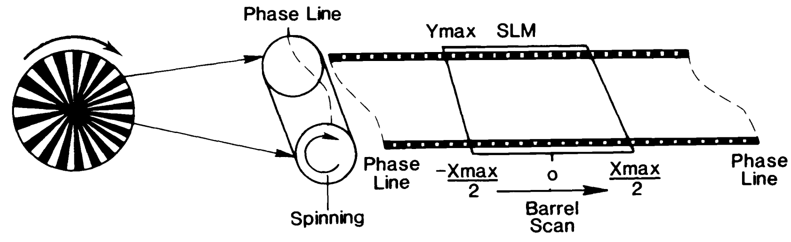


Fig. 2. Mapping from reticle to barrel to SLM.

pixels just to the right of the y axis take on the same values as the pixels on the y axis as the functions are shifted in the x direction. Therefore, if the SLM is connected in a shift register manner, the system bandwidth is just the required pixel data rate times the y dimension of the SLM. This is a reduction in system data rate by a factor equal to the x dimension of the SLM.

Optically addressed SLMs are usually modulated with a raster-scanned laser and patterns must be written a frame at a time in a serial manner. This constraint does not let optically addressed SLMs take advantage of the data rate reduction described above. SLMs with kilohertz frame rates and arrays of 1000×1000 pixels are being developed in research laboratories.[6] With these SLM capabilities, the data rate reductions may not be required. On the other hand, electronically addressed SLMs use serial addressing with electron beams or addressing with microcircuitry. The microcircuitry can be configured for serial, parallel, or a combination of addressing schemes. The parallel configuration allows an electronic shift register array to be coupled to the SLM in a manner that allows a pattern shift to take advantage of the bandwidth reduction described above.

It is interesting to consider how the barrel functions and the SLM provide target location information. In reticle theory, $f(\theta)$ is the frequency versus angle parameter that is periodic for one rotation of the reticle. This periodicity, compared to some reference, provides angular target location. $m(r)$ is the radial frequency parameter that provides a single-valued mapping of radial location to $m(r)$ for radial target location determination. Finally, $\rho(r)$ is the reticle spoke function that shapes the reticle spokes to correlate well with certain targets and poorly with unwanted background signals. Once the three parameters are determined, a reticle transmission function can be found using[5]

$$T(r,\theta) = \frac{1}{2} + \frac{1}{2}\cos\left[m(r) \int_0^{\theta+\rho(r)} f(\alpha)d\alpha\right] , \tag{1}$$

where α is a dummy variable, θ is defined from $-\pi$ to π, and r ranges from 0 to the radius R of the reticle. The SLM transmission equation is equivalent to Eq. (1) with a few modifications. That is,

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left[m(r) \int_0^{\theta+\rho(r)} f(\alpha)d\alpha\right] , \tag{2}$$

where

$$\theta = \pi\left(\frac{x - x_{\max}/2}{x_{\max}}\right) , \quad r = R\frac{y}{y_{\max}} .$$

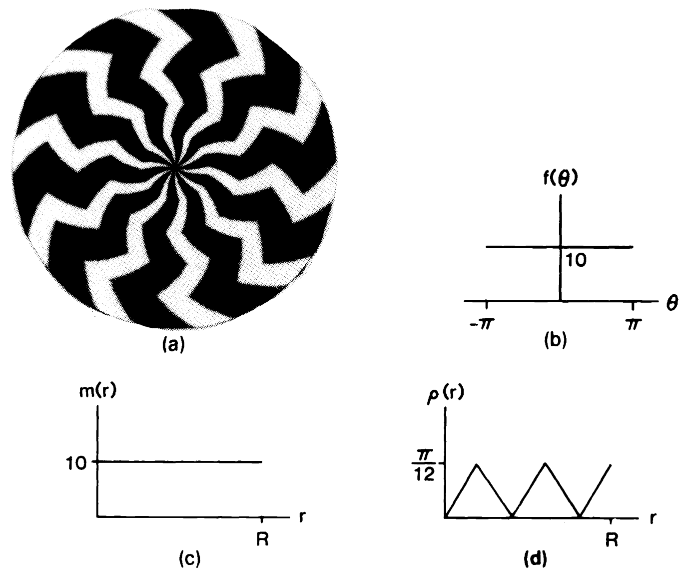


Fig. 3. (a) Reticle one. (b) Frequency versus angle. (c) Frequency versus radius. (d) Phase.

$f(\theta)$, $m(r)$, and $\rho(r)$ now become $f(x)$, $m(y)$, and $\rho(y)$ with the substitutions shown in Eq. (2). The value used for $y_{\max}$ is the spatial dimension of the SLM in the y direction. The value used for $x_{\max}$ can be larger than the x dimension of the SLM but cannot be smaller than the x dimension since the periodic scanning function would have a period smaller than the SLM. This would result in more than one target location delivering the same frequency content to the detector, creating an ambiguity that cannot be resolved by the system electronics.

To illustrate a simple example of the SLM barrel mapping, consider the reticle shown in Fig. 3; the frequency parameters $f(\theta)$, $m(r)$, and $\rho(r)$ are also shown in the figure. Note that $f(\theta)$ and $m(r)$ are constant, so no target location can be determined in r and θ or x and y. There is, however, a nonconstant phase function, $\rho(r)$. The transmission function is evaluated using Eq. (2) to be

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{10\left[\pi\left(\frac{x - 256}{512}\right) + \rho\left(\frac{250y}{512}\right)\right]\right\} . \tag{3}$$

Figure 4(a) shows how the pattern from Eq. (3) would look on an SLM of dimensions 512×512 at $t = 0$. The scanning of the pattern across the SLM is accomplished by letting $x = x - vt$, where v is the velocity of the pattern in pixels per second. The maximum frequency content of a pixel modulation in the SLM is found by taking the derivative of the cosine argument with respect to time and finding its maximum value. Figure 4(b) shows how the pattern evolves over time as the pattern rolls off the barrel. Note that for this pattern, any transmitted impulse, or

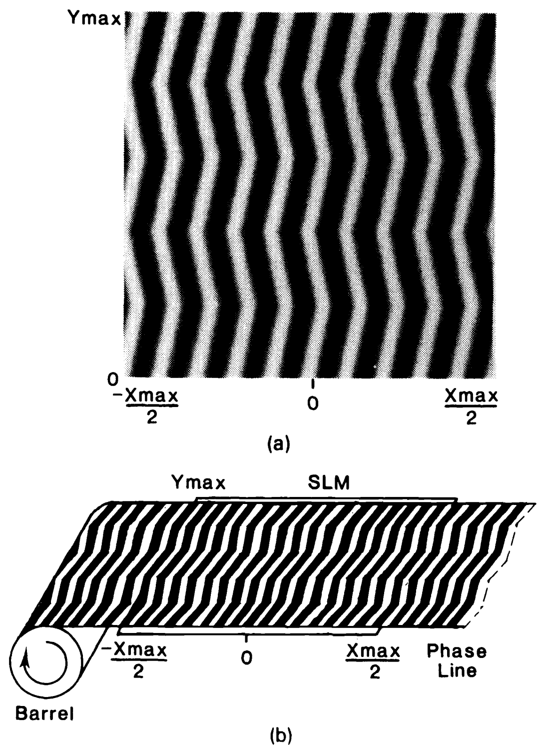


Fig. 4. (a) Reticle one pattern on SLM array. (b) Reticle one scanning across the SLM.

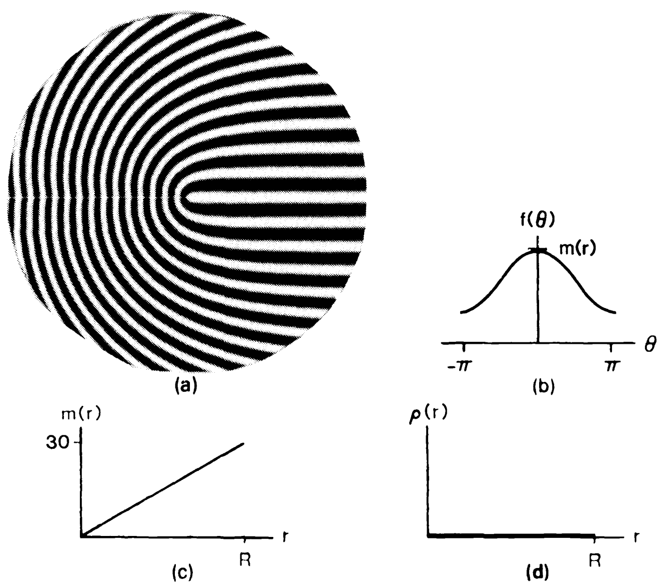


Fig. 5. (a) Reticle two. (b) Frequency versus angle. (c) Frequency versus radius. (d) Phase.

point source, signal through the SLM would contain identical frequencies. Hence, in this example of the barrel transformation, location of the point source is not possible.

3. TRACKING EXAMPLES

With this conceptual understanding of the barrel mapping, one can transform reticle functions that are useful in locating a target in (r,θ). Consider reticle two and its frequency parameters, shown in Fig. 5. The frequency versus angle parameter is of cosine form, and the frequency versus radius parameter is a linear

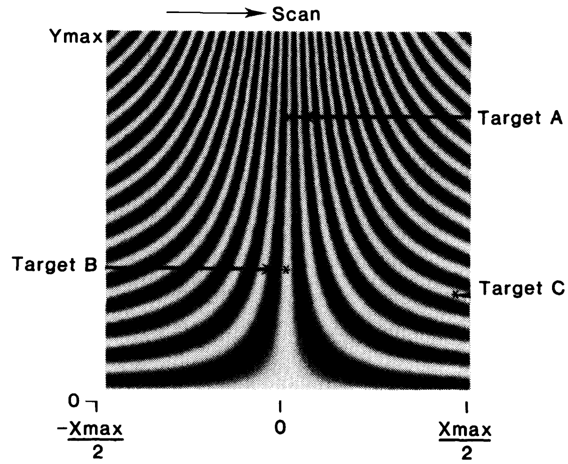


Fig. 6. Equivalent SLM pattern.

function with respect to radius. For simplicity, the phase function is set to a constant (zero). However, for a particular target, the phase would be set to a function that provides good correlation with the target. For the reticle shown, the transmission function is

$$T(r,\theta) = \frac{1}{2} + \frac{1}{2}\cos\left[\frac{30r}{250}\left(\theta + \frac{1}{2}\sin\theta\right)\right] \; . \tag{4}$$

The SLM equivalent reticle pattern is found by replacing r and θ with the x and y parameters of Eq. (2) and is shown in Fig. 6. The SLM equation for the pattern is

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{\frac{30y}{512}\left[\pi\left(\frac{x-256}{512}\right) + \frac{1}{2}\sin\left(\pi\frac{x-256}{512}\right)\right]\right\} \; . \tag{5}$$

Remember that the pattern is scanned across the SLM FOV in the x direction and is periodic. The temporal signal of a transmitted point source imaged on the SLM is found by replacing x and y in Eq. (5) by $x_o - vt$ and y_o:

$$T(t) = \frac{1}{2} + \frac{1}{2}\cos\left\{\frac{30y_o}{512}\left[\pi\left(\frac{x_o - vt - 256}{512}\right) + \frac{1}{2}\sin\left(\pi\frac{x_o - vt - 256}{512}\right)\right]\right\} \; , \tag{6}$$

where x_o and y_o are point source location coordinates on the SLM.

Consider the three point source locations A, B, and C shown on the SLM pattern of Fig. 6. Figure 7 shows the temporal frequency variations of the detector signal due to the SLM pattern scanning across the SLM FOV with the point sources imaged onto the SLM at points A, B, and C. Note that the average frequency content of the signal due to point source A is higher than the average frequency content of point sources B or C. The signal due to C has the same average frequency as B; however, the variation in frequency due to C is leading the variation in frequency due to B. The difference in variation, or phase lead, of C to B can be converted into a distance in the x direction if the scan rate of the pattern is known. For the absolute target location to be determined, a reference signal must be supplied each time the pattern is scanned across the SLM FOV. Since the SLM driving electronics must supply the scan pattern, a

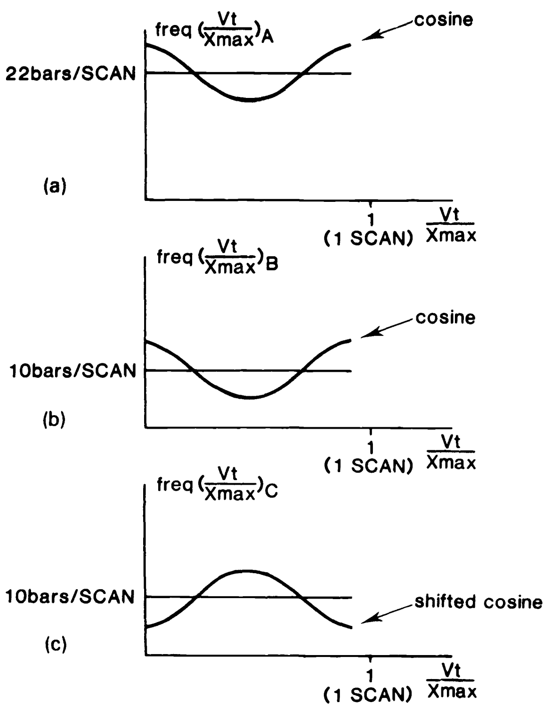


Fig. 7. Temporal frequency responses due to point sources A, B, and C of Fig. 6.

reference signal could be provided from the electronics. Also, another way to provide a reference signal would be to focus an LED somewhere on the SLM and to calculate target offsets in reference to the LED location. The y direction target location can be determined simply by the average frequency content of the signal.

As in the case with spinning FM reticles, the transmission function can provide any FM signal imaginable. A one-to-one mapping of y to $m(y)$ is required, and $f(x)$ must be periodic with a period greater than or equal to the x dimension of the SLM. There are no restrictions on $\rho(y)$ since it is an edge function and the edge is designed for target correlation and background filtering. Before an optimum $\rho(y)$ can be determined, spatial information on the target and background must be known. For example, the phase function used in Fig. 4(a) is useful in tracking point source targets and filtering large objects like clouds and horizons. At any rate, there are an infinite number of SLM patterns using reticle theory since there are an infinite number of $f(x)$, $m(y)$, and $\rho(y)$ combinations. To show one last SLM pattern where none of these parameters are constant, consider the pattern and its three frequency parameters shown in Fig. 8. The SLM transmission function was evaluated to be

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{\left(\frac{y}{512}\right)^2 \exp\left[-3.25\left(\frac{x+\rho(y)-250}{512}\right)^2\right]\right\} , \tag{7}$$

where

$$\rho(y) = \exp\left[-4\left(\frac{y-125}{512}\right)^2\right] .$$

The temporal intensity signal on the detector due to a point source located at (x_o, y_o) with the pattern scanning at a velocity v, in pixels per second, is

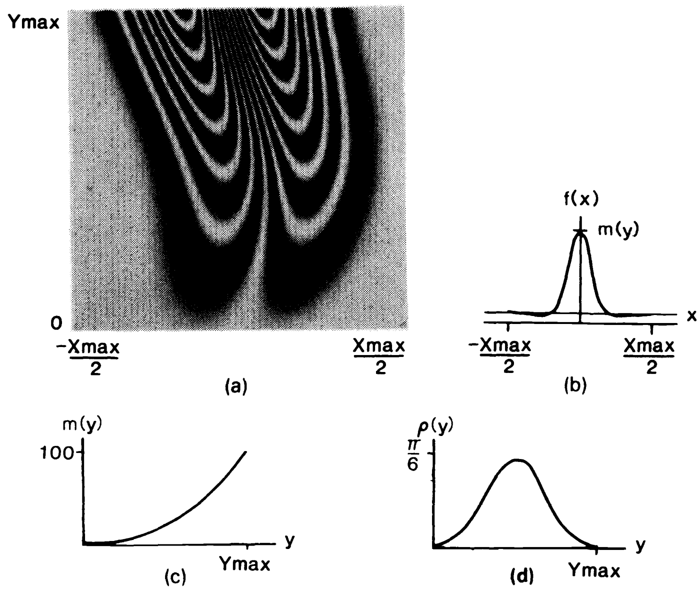


Fig. 8. (a) SLM pattern three, with nonconstant parameters. (b) Frequency versus x. (c) Frequency versus y. (d) Phase.

$$I(t) = \cos\left(\left(\frac{y_o}{512}\right)^2 \exp\left\{-3.25\left[\frac{x_o - vt + \rho(y_o) - 250}{512}\right]^2\right\}\right) . \tag{8}$$

The temporal frequency content of the intensity signal may also be found by taking the derivative of the cosine argument with respect to time, as was done for the last example.

4. ADAPTIVE PATTERNS

The use of SLMs instead of reticles as image modulators allows the changing of modulation patterns to enhance the signal of a target in a particular region of the optical system FOV. Figure 9 shows a scene with a large number of targets. Let the pattern shown in Fig. 6 scan across an SLM where the SLM replaces the spinning reticle shown in Fig. 1. Now, let the optical system image the scene shown in Fig. 9. A unique signal is provided to the detector for every target in the scene. These signals allow the optical system to determine the location, velocity, acceleration, etc., for each target. If a particular target were identified as a target of high interest, the SLM pattern can be changed to accommodate an increased location resolution in the neighborhood around the target of interest while decreasing location resolution for other targets of less interest.

For example, consider the situation where a tracking system decides that target A in Fig. 9 is a target of high interest and decides to interrogate the target. The system can increase resolution around the target by changing the pattern that scans the SLM. The pattern in Fig. 10(a) has an average frequency as a function of y position on the SLM shown by the plot in Fig. 10(b). The frequency variation in the x direction scan is shown in Fig. 10(c). Note that all of the targets above y_1 have the same average frequency, whereas all of the targets below y_2 contain the same average frequency. The only targets that give a change in frequency as a function of their y location are those located between y_1 and y_2. Also, the change in frequency that a target

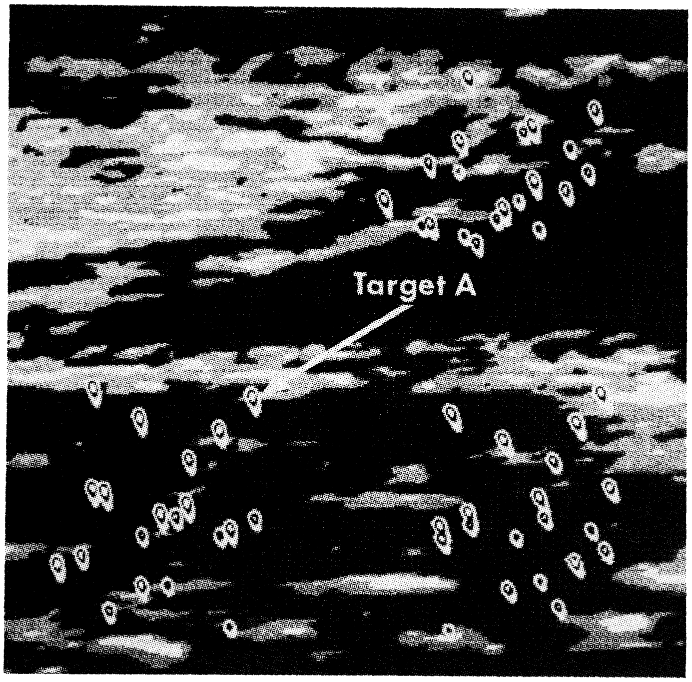


Fig. 9. Target scene.

gives for a change of y location is twice what it would be for the pattern shown in Fig. 6. This larger change is due to the increased frequency gradient or slope of the frequency versus y curve in this region. Simply put, the resolution in y location for targets outside the y_1 to y_2 band is zero and for targets within the band is double the previous resolution. Note that the periodic increasing and decreasing of the pattern frequency in the x direction has not changed. This variation in frequency has been retained for target location determination in the x direction as before.

The transmission equation of the pattern for the region from y_1 to y_2 is

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{\frac{60y}{512}\left[\pi\left(\frac{x-256}{512}\right) + \frac{1}{2}\sin\left(\pi\frac{x-256}{512}\right)\right]\right\} , \tag{9}$$

whereas the transmission equations for the regions above y_1 and below y_2 are

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{\frac{60y_1}{512}\left[\pi\left(\frac{x-256}{512}\right) + \frac{1}{2}\sin\left(\pi\frac{x-256}{512}\right)\right]\right\} , \tag{10}$$

$$T(x,y) = \frac{1}{2} + \frac{1}{2}\cos\left\{\frac{60y_2}{512}\left[\pi\left(\frac{x-256}{512}\right) + \frac{1}{2}\sin\left(\pi\frac{x-256}{512}\right)\right]\right\} , \tag{11}$$

respectively. Note that the only transmission region that is a function of y target location is the neighborhood of target A.

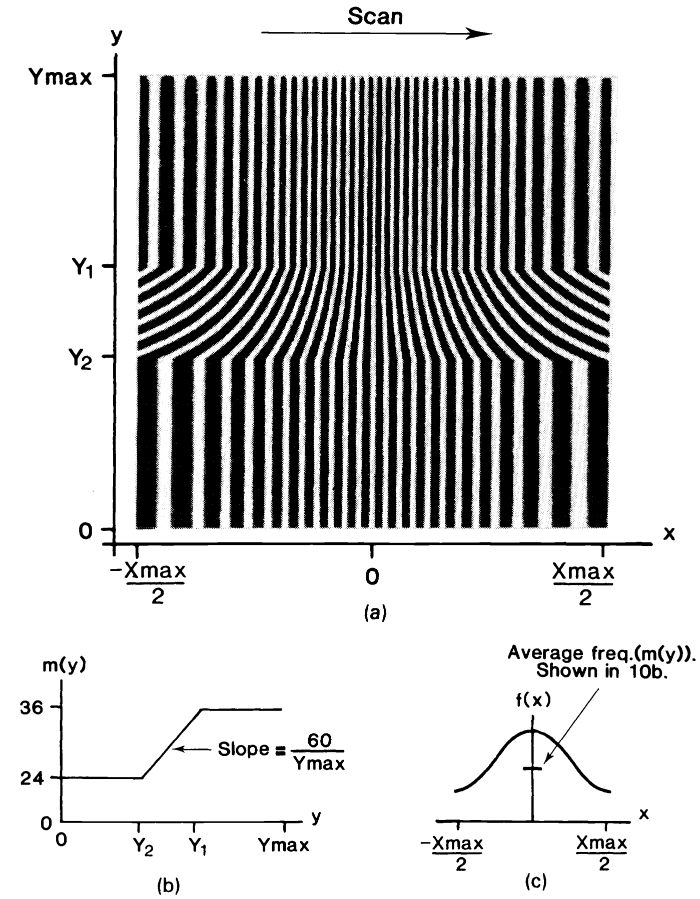


Fig. 10. (a) Adaptive pattern. (b) Frequency versus *y*. (c) Frequency versus *x*.

The region of interest can easily be changed by changing the values of y_1 and y_2. The location resolution can also be changed quite easily by changing the slope of the frequency gradient. However, one must be careful not to change the resolution of the reticle pattern beyond the spatial resolution of the SLM. If a larger temporal frequency is desired, the scan rate of the pattern can be increased to the limit of the SLM's frame rate capabilities.

5. CONCLUSION

A useful SLM pattern is determined by designing each of the three FM parameters associated with an FM reticle. The resulting scanned SLM pattern can be optimized to be compatible with SLM and detector bandwidths, spatial characteristics of targets and backgrounds, and the resolution required for determining the location. The optimum and/or adaptive SLM transmission function is found by applying Eq. (2) once the three FM reticle frequency parameters are determined.

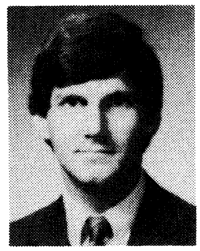
It appears that FM reticle theory may be useful in other areas such as determining focal plane geometries for use with SLMs. It is possible that one or two of the FM parameters may be implemented with the SLM while the detector array provides the remaining FM parameter(s). This topic will be the subject of a future study.

6. ACKNOWLEDGMENT

This work was partially supported by the Florida High Technology and Industry Council.

7. BIBLIOGRAPHY

1. L. M. Biberman, *Reticles in Electro-Optical Devices*, Pergamon Press, New York (1966).
2. R. D. Hudson, "Optical modulation," in *Infrared System Engineering*, p. 235, Wiley, New York (1968).
3. Z. W. Chao and J. L. Chu, "General analysis of frequency-modulated reticles," Opt. Eng. 27(6), 440–442 (1988).
4. D. J. Lovell, "Electro-optical position indicator system," U.S. Patent No. 2, 997, 699 (Aug. 22, 1961).
5. J. N. Lee, "Devices for optical signal processing," Opt. News (Oct. 1985).
6. R. G. Driggers, C. E. Halford, G. D. Boreman, D. J. Lattman, and K. F. Williams, "Parameters of spinning FM reticles," Appl. Opt. 29, (Dec. 10, 1990).
7. R. O. Carpenter, "Comparison of AM and FM reticle systems," Appl. Opt. 2(3), 229 (1963).
8. R. C. Anderson and P. R. Callary, "Computer modeling of optical trackers," Opt. Eng. 20(6), 861–865 (1981).
9. K. Suzuki, "Analysis of rising sun reticle," Opt. Eng. 18(3), 350–351 (1979).
10. S. Craubner, "Digital simulation of reticle systems," in *Image Processing for Missile Guidance*, Proc. SPIE 238, 414–424 (1980).
11. A. Gedance, "Comparison of infrared tracking systems," Appl. Opt. 51, 1127 (1961).
12. T. Buttweiler, "Optimum modulation characteristics for amplitude-modulated and frequency-modulated infrared systems," JOSA 51(9), 1011 (1961).
13. P. Menger and K. O'Brien, "Analysis of error response of amplitude modulated reticles," JOSA 54(5), 668 (1964).
14. Z. W. Chao and J. L. Chu, "Parameter analysis for frequency-modulated reticle design," Opt. Eng. 27(6), 443–451 (1988).



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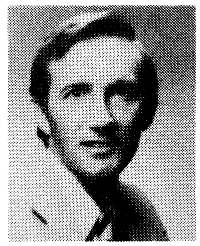

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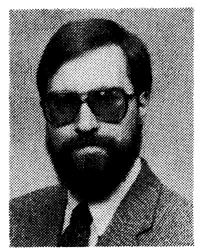

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