Wide-angle achromatic prism beam steering for infrared countermeasures and imaging applications: solving the singularity problem in the two-prism design

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Abstract. A two-rotating-prism system is an inexpensive lightweight two-dimensional beam steering device. It can be designed to be achromatic over a wide spectral range. However, the current two-prism achromatic design has a singularity problem at the center of the "field of view": if a beam is to be steered through the center, one of the prisms must make an instantaneous 90° flip. In our work we proposed a solution to this problem by adding a third prism to the system. The main thrust of this study was optimization of the apparatus by minimizing dispersion effects as well as predicting the theoretical speed and manner in which the beam may be steered. [DOI: 10.1117/1.2802147]

Subject terms: infrared countermeasures; achromatic prism; beam steering; Risley prism; dispersion correction.

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1 Introduction

Protecting aircrafts from infrared (IR) guided missiles is a high priority for the U.S. Air Force and, recently, the civil aviation industry. An aircraft under missile threat will need to have the capability of defending itself against the ever more popular IR guided missile. Highly mobile, low cost IR missile threats are diverse and can be countered with efficient, affordable, closed-loop IR countermeasure (IRCM) systems. Modern IRCM systems are designed to slew a stabilized pointer along the threat's line of sight in order to passively detect and track the threat in the $2-5$ μm midwave IR (MWIR) spectrum. Once a course track is achieved, a precise fine track mode centers the threat in the IRCM system's field of view. The IRCM system then jams or destroys the threat by projecting a powerful, often modulated, narrow divergence (about 1 mrad) MWIR laser beam onto the missile's seeker head. Using traditional optical components, it is difficult to design an IR imaging system that does not protrude from an aircraft (spacecraft or satellite) body and is capable of "scanning" a wide field of view with great precision at the same time. A nonprotruding apparatus reduces wind resistance and improves stealth capabilities while a wide field of view allows for maximum protection.

To address these issues, the thrust of this research is centered on the design and optimization of a wide angle broadband MWIR laser beam steering apparatus comprised of three rotating achromatic prisms. The challenge will be to design a prismatic beam steerer that is capable of steering to at least 45°, while remaining achromatic over the entire $2-5$ μm MWIR spectrum.

The concepts of prismatic beam steering and achromatic prism design are well documented, however their application to MWIR countermeasures presents several unique challenges.[1,2] For example, the thin prisms usually chosen as achromatic prisms are designed to operate only in a narrow portion of the visible wavelength spectrum ($\sim$400–700 nm).[1] As mentioned previously, the prismatic beam steerer must be achromatic over the entire $2-5$ μm (MWIR) spectrum. The small apex angle prisms are used in combination with beam expanders, phase retarders, and planar waveguide couplers resulting in an achromatic range of only 110 nm.[3,4]

Chromatic dispersion, the phenomenon whereby the velocity of light propagation in a material varies with wavelength, must be minimized. In Ref. 2 it has been shown that the first-order chromatic dispersion can be reduced by the use of doublet prisms (in this paper, "first-order dispersion" will be referred to as "dispersion"). For a desired average maximum steering angle the optimum apex angle for a doublet prism, which ensures that secondary dispersion is minimized, was also calculated.[2] However, the two-prism system can be used only for continuous target tracking outside of a 2° cone at the center of the prism system's field of view, where a speed of 360°/s is needed to achieve a 1 rad/s slew rate (see Fig. 1). Around the zero axis, i.e. inside the 2° cone, the two-prism system has a singularity point where crossing the zero position will require a sudden 90° prism position change. Figure 1 illustrates this. As an example, we will try to move the beam along the OA, OB, OC, and OD lines with initial relative orientation of two prisms as shown. This will require the following prisms

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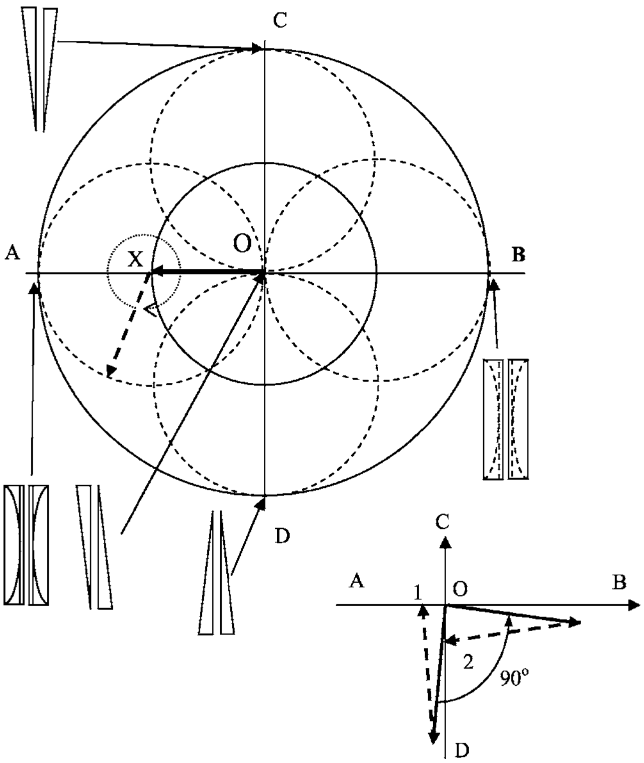

Fig. 1 Idealized two-prisms system steering pattern and relative positions of prisms (side view) in extreme points. Since each prism will deflect a light beam towards its base, it is customary to represent a steering pattern of apparatus on a distant screen, as in this figure. For example, if the first prism is motionless and deflects a light beam towards point *X* (the base of the prism is directed to the left), rotation of the second prism will move the beam around a dashed circle centered on point *X*. As one can see, deflection of the light beam can be conveniently represented as a sum of two vectors with the arrow pointing towards the base of the prism (see inset). This convention is also used in Fig. 3.

rotation patterns: In the *OA* line, first the prism should be rotated from the up position to left position (counterclockwise); then the second prism from down to left (counterclockwise). To reach the extreme left point each prism has to make a 90° rotation. In order to achieve a 1 rad/s slew rate for a maximum steering angle of 45°, one has to use a rotator with maximum speed of 72°/s. The same is true for the *OB* line. The only difference is both prisms should be rotated clockwise.

The situation is different if one needs to go along the line *OD* (or line *OC*). To be able to just start moving the light beam, prism No. 1 has to be rotated 90° to the left or right instantaneously. This movement is shown in the inset of Fig. 1. Crossing point *O* back will again require 90° rotation. The necessity to instantaneously rotate one of the prisms by 90° when crossing a singularity point limits the system's capability of real time target tracking. A new design is needed to fit the desired specifications of a prismatic beam steerer that is capable of steering to at least 45°.

A solution to the singularity problem is to allow an additional degree of freedom to the system by adding the third prism (Fig. 2). Recently, the same solution along with a control algorithm was proposed in Refs. 5 and 6 for monochromatic beam steering devices. Designing an achromatic system is the primary goal of this study. Employing this new design, the beam can be continuously steered in any direction without a 90° swing (Fig. 3). There are a few downsides to this configuration: (1) it will use an additional rotator; (2) it will require a complicated algorithm to find the shortest path between two points;[6] and (3) the minimization of dispersive characteristics is more difficult.

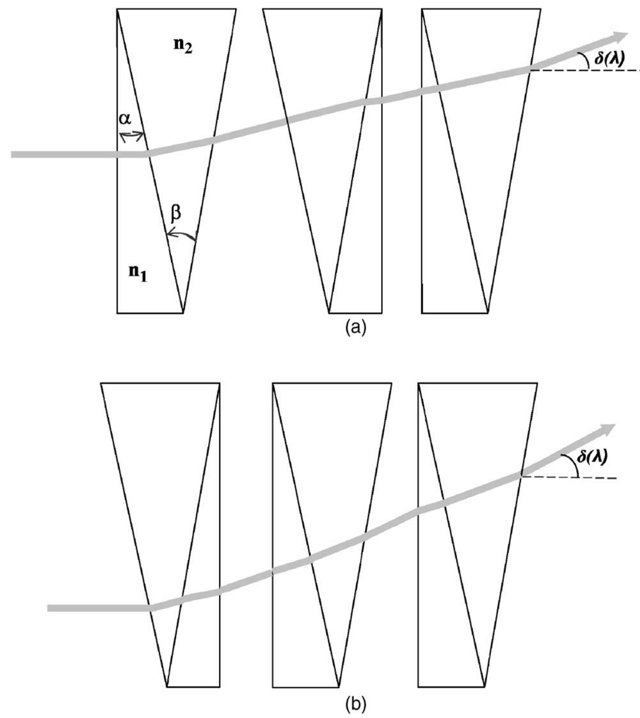

Fig. 2 (a) Illustration of the maximum steering angle option *A*; and (b) illustration of the maximum steering angle option *B*.

This study takes the methods outlined in Ref. 2 and recalculates the desired apex angles for the minimization of dispersion. The values and equations are calculated using a three-prism design rather than a two-prism design (discussed later in this section). Through nonexperimental means, the calculations of chromatic dispersion minimization along with various characteristics of the apparatus such as maximum steering angle, etc. were derived.

This research also revises a description of the basic concepts of rotating prism beam steering. Several issues relating to the azimuth and elevation angles into which light is steered as a function of prism rotation angles are also studied. Next, the geometric relationships describing the maximum steering angle is derived, which in turn leads to a discussion of first- and second-order dispersion reduction.

2 Determination of the Maximum Steering Angle

The maximum steering angle as a function of wavelength λ, $\delta(\lambda)$, is the maximum angle at which an incident beam may be steered as illustrated in Fig. 2. This angle is derived using multiple applications of Snell's law of refraction. Since each prism will deflect a laser beam towards its base, the position of the maximum steering angle will also be a position of maximum chromatic dispersion.

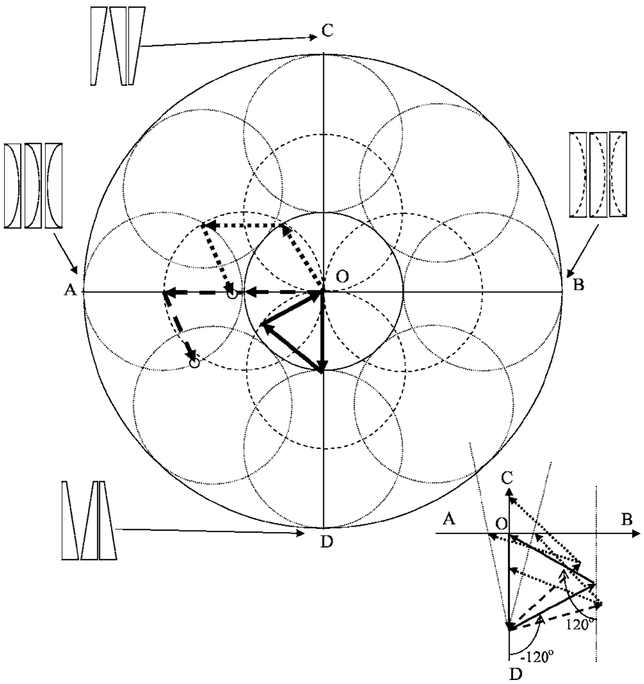

Fig. 3 Idealized three-prisms system steering pattern and relative positions of prisms (side view) in extreme points. If "thick edge down position" for any particular prism corresponds to 0°, than the up position will be 180° etc. Thus, the (0,0) position in terms of prism orientation angles will be (α, $-120+\alpha$, $120+\alpha$), as an example—solid arrows, or (α, $120+\alpha$, $-120+\alpha$), where α is any arbitrary number. Two examples of arbitrary steering points are also shown (dashed arrows).

At the beginning of the design process, a configuration for the three prisms was chosen. The two options for a three prism design are shown in Figs. 2(a) and 2(b). Dispersion must be minimized and it is clear that if the configurations in Fig. 2(b) is used, there will be an extra interface at which dispersion will occur, namely the first interface. Nevertheless, in this research both configurations in Fig. 2 will be used for calculations.

We will use the following conventions: $\delta_{xk}(\lambda)$ refers to the deviation angle where k refers to the prism number, $k=1$, 2, or 3, and x determines whether it is the incident (i) or the exit (o) angle; n_1 and n_2 refer to the index of refraction of the two materials used in the two sections of the prism (here we will assume that $n_1<n_2$ for all calculations); lastly, α and β refer to the apex angles of the two sections of the prism, [see Fig. 2(a)].

We start from the configuration shown in Fig. 2(a). The maximum steering angle is[2]

$$\delta_{o,3}=(\alpha-\beta)+\sin^{-1}\left\{n_2\sin\left[\beta-\sin^{-1}\left(\frac{n_1}{n_2}\sin\left\{\alpha-\sin^{-1}\left[\frac{\sin\delta_{i,3}}{n_1}\right]\right\}\right)\right]\right\}. \quad (1)$$

Under a small angle approximation, i.e., α and β less than 20° (an assumption that will shown to be valid), Eq. (1) becomes

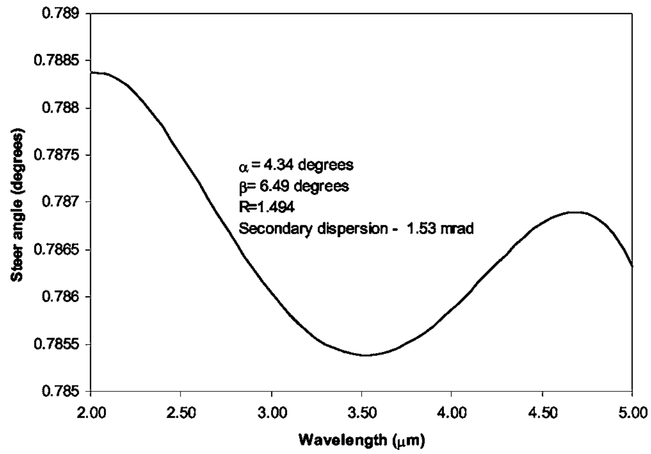

Fig. 4 Steering angle dispersion for AMTIR-1/Ge doublet prisms in the geometry as shown in Fig. 2(b). The prism apex angles were adjusted to yield an average maximum steering angle of 45°, while for this figure only first-order dispersion reduction at a wavelength of 3.5 μm was addressed.

$$\delta_{o,3}=\beta(n_2-1)-\alpha(n_1-1)+\delta_{i,3}. \quad (2)$$

Similarly, the exit angle of the second prism is

$$\delta_{o,2}=-\sin^{-1}\left\{n_1\sin\left[\alpha-\sin^{-1}\left(\frac{n_2}{n_1}\sin\left\{\beta-\sin^{-1}\left[\frac{\sin\delta_{i,2}}{n_2}\right]\right\}\right)\right]\right\}. \quad (3)$$

Again, using a small angle approximation

$$\delta_{o,2}=\beta n_2-\alpha n_1+\delta_{i,2}. \quad (4)$$

Combining Eqs. (4) and (2) and the geometry that $\delta_{o,2}=\delta_{i,3}$ yields the maximum steering angle of

$$\delta_{o,3}=2\beta n_2-\beta-2\alpha n_1+\alpha+\delta_{i,2}. \quad (5)$$

Finally, as can be seen in Fig. 2(a), the first prism has the same orientation as the third prism. As a result, the equations are the same with the incident angle equaling zero

$$\delta_{o,1}=(\alpha-\beta)+\sin^{-1}\left\{n_2\sin\left[\beta-\sin^{-1}\left(\frac{n_1}{n_2}\sin\alpha\right)\right]\right\}, \quad (6)$$

or, using a small angle approximation, Eq. (6) becomes

$$\delta_{o,1}=\beta(n_2-1)-\alpha(n_1-1). \quad (7)$$

Combining this with Eq. (5) and using the fact that $\delta_{o,1}-(\beta-\alpha)=\delta_{i,2}$ yields the final maximum steering angle for a three-prism beam steerer

$$\delta_{o,3}=3\beta(n_2-1)-3\alpha(n_1-1). \quad (8)$$

With the maximum steering angle now derived, it is now possible to minimize the effects of dispersion.

3 Minimization of Dispersion

In order to find the apex angles at which dispersion is minimized, it is necessary to determine how varying the wave-

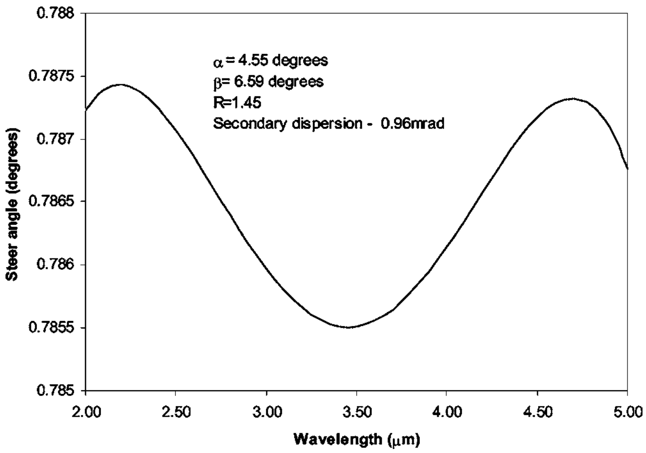

Fig. 5 Steering angle dispersion for AMTIR-1/Ge doublet prisms in the geometry as shown in Fig. 2(a). For this figure the prism apex angles were iteratively adjusted to yield an average maximum steering angle of 45°, while also reducing second-order dispersion to a minimum.

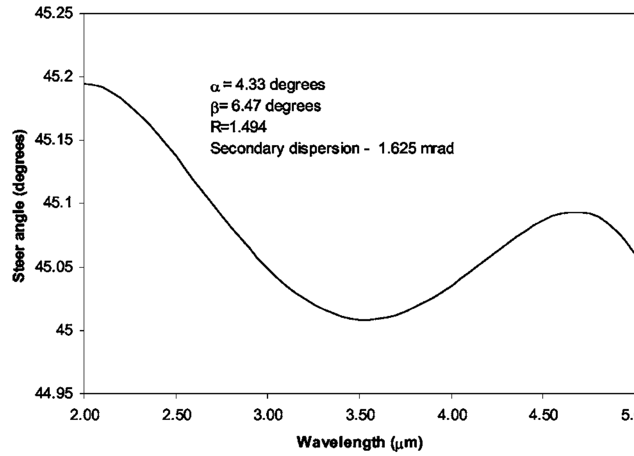

Fig. 6 Steering angle dispersion for AMTIR-1/Ge doublet prisms in the geometry as shown in Fig. 2(b). The prism apex angles were adjusted to yield an average maximum steering angle of 45°, while for this figure only first-order dispersion reduction at a wavelength of 3.5 μm was addressed.

length changes the deviation angle. In the maximum steering angle equation, the only dependence on wavelength, λ, is n_1 and n_2. Therefore, to find the local extremum the derivative of Eq. (8) is set equal to zero, yielding

$$\beta = \alpha \frac{n_1'(\lambda_c)}{n_2'(\lambda_c)}. \tag{9}$$

In Eq. (9), $n_1'(\lambda_c)$ is the derivative of the index of refraction with respect to wavelength evaluated at some wavelength, λ_c. As a result, by choosing apex angles that are related by Eq. (8), dispersion will be minimized.

Equation (9) shows that the relationship for the apex angles of the prisms to minimize dispersion is the same as for the two-prism design outlined in Ref. 2. It was shown that for an optimized system with λ_c chosen to be in the middle of the MWIR spectrum, λ_c=3.5 μm, the desired materials are amorphous material transmitting infrared radiation (AMTIR-1) for the low index material n_1 and germanium for the high index of refraction material, n_2. The relevant data for these materials are as follows:

$$n_1 = 2.5449 \quad \text{(Ref. 2)},$$

$$n_1' = -0.00286/\mu\text{m} \quad (\text{AMTIR}-1)$$

$$n_2 = 4.04433$$

(Ref. 7)

$$n_2' = -0{,}01914/\mu\text{m} \quad \text{(germanium)}.$$

Plugging these values into Eq. (9) yields

$$R = \frac{\beta}{\alpha} = 1.4942. \tag{10}$$

Using Eqs. (1), (3), and (6) the dispersive properties of AMTIR-1/Ge doublet prisms configured as shown in Fig. 2(a) are shown in Fig. 4, where the maximum steering angle as a function of wavelength is presented. To generate this figure, the apex angle α was iteratively adjusted to create an average maximum steering angle of 45° over the full MWIR spectrum, while β was fixed at 1.4942α. Notice that for AMTIR-1/Ge doublet prisms the apex angles that are needed for wide angle steering are quite small. On the other hand, $\delta_{i,3}$ in Eq. (1) is about 30°, which questions the validity of the small angle approximation that was made in the derivation of Eq. (8). Nevertheless, as it is seen from Fig. 4, Eq. (10) is a good starting point for further system optimization. Notice also that the first-order steering angle dispersion (i.e., the slope of the curve in Fig. 4) at λ =3.5 μm is precisely zero, as expected, but that the steering angle is clearly still a function of wavelength. This residual dependence of steering angle on wavelength is known as secondary dispersion, which we define here to be

$$\Delta\delta_0 = \frac{|\delta_0|_{\max} + |\delta_0|_{\min}}{2}. \tag{11}$$

For AMTIR-1/Ge prisms, as seen in Fig. 4, the secondary dispersion is $\Delta\delta_o$=1.53 mrad. Further minimization of secondary dispersion, according to the algorithm described in Ref. 2, yields $\Delta\delta_o$=0.96 mrad (Fig. 5), which is within the specs of the laser beam steering device.

Similar analysis was also performed to predict the dispersive properties of the AMTIR-1/Ge doublet prisms configured as shown in Fig. 2(b). The process is straightforward

$$\delta_{o,3} = (\alpha - \beta) + \sin^{-1}\left\{ n_2 \sin\left[\beta - \sin^{-1}\left(\frac{n_1}{n_2} \sin\left\{ \alpha - \sin^{-1}\left[\frac{\sin \delta_{i,3}(\lambda)}{n_1} \right] \right\} \right) \right] \right\}, \tag{12}$$

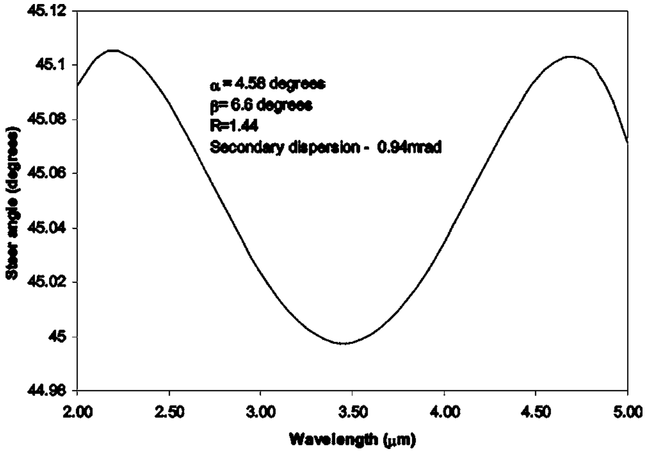

Fig. 7 Steering angle dispersion for AMTIR-1/Ge doublet prisms in the geometry as shown in Fig. 2(b). For this figure the prism apex angles were iteratively adjusted to yield an average maximum steering angle of 45°, while also reducing second-order dispersion to a minimum.

$$\delta_{o,2} = \delta_{i,3} = (\alpha - \beta) + \sin^{-1}\left\{ n_2 \sin\left[\beta - \sin^{-1}\left(\frac{n_1}{n_2} \sin\left\{ \alpha - \sin^{-1}\left[\frac{\sin \delta_{i,2}(\lambda)}{n_1} \right] \right\} \right) \right] \right\}, \tag{13}$$

$$\delta_{o,1} = \delta_{i,2} = -\sin^{-1}\left\{ n_1 \sin\left[\alpha - \sin^{-1}\left(\frac{n_2}{n_1} \sin\left\{ \beta - \sin^{-1}\left[\frac{\sin(\beta - \alpha)}{n_2} \right] \right\} \right) \right] \right\}. \tag{14}$$

Combining Eqs. (12)–(14) and rewriting the result under a small angle assumption we will again obtain Eq. (8), thus, the same value of $R=\beta/\alpha=1.4942$. Using Eqs. (12)–(14) the dispersive properties of AMTIR-1/Ge doublet prisms configured as shown in Fig. 2(b) are shown in Fig. 6, $\Delta\delta_o=1.625$ mrad. Further minimization of secondary dispersion gives $\Delta\delta_o=0.94$ mrad (Fig. 7). We also compared the exact solutions to the approximate one, obtained using Eq. (8). The minimization of secondary dispersion of AMTIR-1/Ge doublet prisms using Eq. (8) yields $\Delta\delta_o=0.79$ mrad.

4 Conclusion

The effects of dispersion can be minimized for a three rotating prism beam steering system using the relationship in Eq. (10). As a result, a third prism may be added to the former two-prism design to allow full visibility throughout the desired 90° cone without losing any of the important dispersion-minimization characteristics.

In order to accurately defend against missile threats, there cannot be any blind spots in the necessary visible range. It is clear that this new design will be an important addition to wide-angled prism beam steering. As a result, this proposed three-prism design will be an important addition to the Air Forces' defense capabilities.

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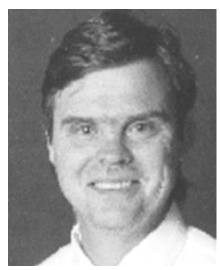

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