A Compact Derotator Design*

D. S. L. DURIE

Bell Aerospace Company, Division of Textron, P.O. Box 1, Buffalo, New York 14240

(Received August 21, 1973)

ABSTRACT

The optical and mechanical design of a derotator unit employing a Delta prism are described. Comparisons with other derotation prisms demonstrate the space and weight advantages of the Delta in collimated light. Curves showing the dependence of input FOV and apex angle on refractive index are presented. The small size and single-piece construction of the Delta facilitate a mounting design which is environment resistant and enables precise adjustment.

INTRODUCTION

In a periscope in which a rotating prism or mirror provides scanning capability, a derotation prism is needed to prevent image rotation at the eyepiece. It is connected by direct mechanical drive or by a servo loop to the motion of the scanning element.

A compact derotator unit is desirable to minimize discontinuity in the structure of the periscope body. This is significant in an aircraft periscope where minimum space and weight are important design goals.

The following discussion describes the optical and mechanical design of a derotator unit which employs a Delta prism, a type used less frequently than the Dove or Pechan. It was designed for a stabilized sight in an aircraft where it was required to perform in rigorous thermal and vibration environments.

* *Supported in part by Frankford Arsenal, Philadelphia, Pennsylvania.*

PRISM DESIGN

Figure 1 shows the passage of the axial ray of a collimated beam through the Delta prism. Total internal reflections occur at both input and output surfaces. The base surface is silvered to provide the third internal reflection. With the proper choice of apex angle, index, and prism height, the internal path is made symmetrical about the vertical axis of the prism and the output ray emerges co-linear with the input ray. A prism rotation of R about the instrument axis will cause an image rotation of 2R; hence, in the derotation application the servo loop must drive the prism through one half the initial image rotation caused by the periscope scanning motion. Like the Dove prism, the Delta can only be used in collimated light.

In Figure 1 the axial input ray is parallel to the prism base. If the apex angle has the value 2θ, it follows that the angle of incidence at face AB is θ. From the geometry of the figure the angles of incidence and reflection at face AC are equal to $(2\theta-\theta')$, where θ' is the angle of refraction at face AB.

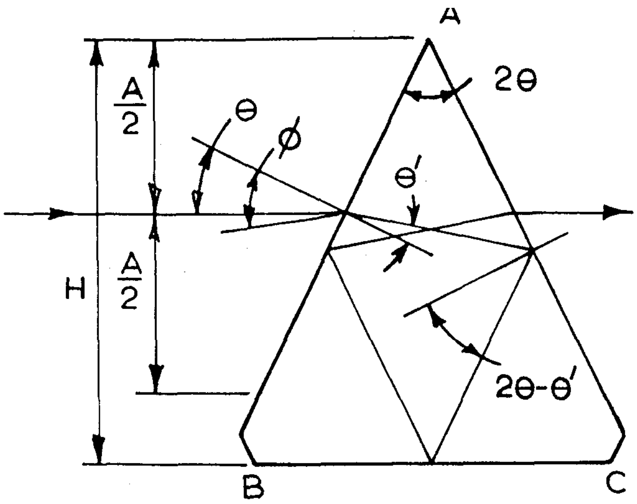

Figure 1. Passage of axial ray through Delta prism.

Assuming for the moment that total internal reflection does occur successfully at face AC, the first step is to choose the apex angle such that the axial ray travels parallel to AB and AC inside the prism. This minimizes the volume of glass required. This is obtained when, for a given index, $4\theta = 90 + \theta'$ as illustrated in the tunnel diagram (Figure 2).

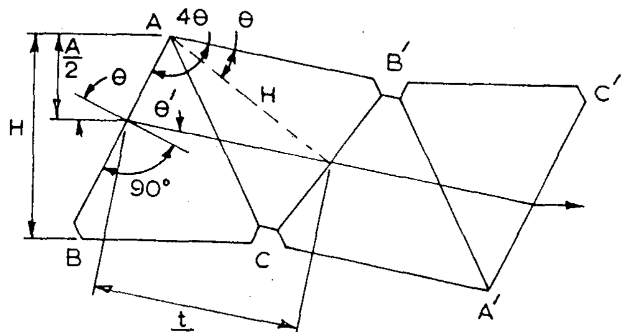

Figure 2. Tunnel Diagram.

The second step is to test if internal reflection occurs at face AC, i.e., does incident angle $(2\theta-\theta')$ exceed the critical angle. If not, a higher index must be selected and step one repeated.

The third step is to determine if a ray at the edge of the field will also be reflected at face AC. In Figure 1 this ray is incident at angle ϕ on AB which results in a semi-field angle of $(\phi-\theta)$. If total internal reflection does not occur for the edge ray, the glass index must again be increased and steps 1 through 3 repeated.

The curves in Figure 3, plotted from a series of step one and step three calculations, are suitable for preliminary design purposes. Starting with a desired FOV, curve A gives the minimum necessary glass index. If a glass of that index is not available, a higher index must be selected. Having selected the index, curve B then gives the corresponding apex angle.

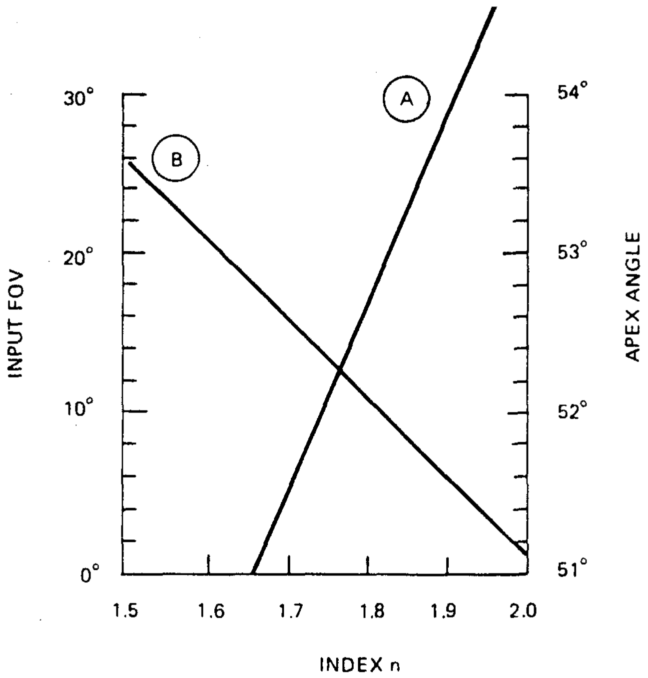

Figure 3. Graphs of Input FOV(A) and Apex Angle(B).

After selection of glass index and apex angle, prism height H and glass path t can be determined from the tunnel diagram where, using the sine law,

$H = A \cos\theta'/2 \cos\theta \cos(3\theta - \theta')$, and

$t = A \sin 3\theta/\cos\theta \cos(3\theta - \theta')$

In the tunnel diagram it can also be seen that rays not parallel to the axial ray can be reflected internally thus producing ghost images. This can be prevented by either increasing prism aperture or reducing beam diameter. A convenient approach is to place bevels of adequate width on the two base corners of the prism. These create the two notches at C and B′ in the tunnel diagram which constrict the beam diameter inside the prism and block the paths of unwanted reflections.

Using the above formulas and those in MIL-HDBK-141 (pages 13-34 through 13-37) a comparison of various derotation prisms can be made in terms of aperture diameter A (Table I).

Swept diameter and axial length are the dimensions of the cylindrical space required to contain the prism rotation. In the weight column, "d" represents glass density.

The larger index was selected for the Dove to minimize length. A smaller index can be used in the Pechan and K prisms because the internal incident angles of the axial ray (45° and 60°) are adequately in excess of the critical angle (41°). This is not the case in the Delta, hence a larger index must be used.

Table 1 shows that, for a given A, the unmounted Delta has a somewhat smaller swept diameter than the Pechan. The Delta also has the advantage of being a one piece prism which simplifies its mounting thereby minimizing the additional swept diameter required. Additional metal structure must be provided in a Pechan mount to maintain a constant air space between the two prisms and provide means for adjusting them as a unit.

Further advantages of the Delta, again due to it being a one piece prism, are fewer reflections (3 instead of 5), fewer locations for manufacturing tolerances, and a shorter glass path.

Table I: Sizes and Weights of Derotator Prisms

	Index	Axial Length	Swept Diameter	Glass Weight
Delta	1.720	1.20 A	1.72 A	.73 dA^3
Pechan	1.517	1.21 A	2.08 A	1.8 dA^3
Dove	1.720	4.01 A	1.49 A	3.9 dA^3
K Prism	1.517	3.46 A	3.16 A	4.2 dA^3

ADJUSTMENTS AND TOLERANCES

Figure 1 assumes a perfect prism that is perfectly aligned with an input ray proceeding along the optical axis of the instrument, henceforth called the optical axis. Since a derotator should produce only pure rotation of the image, derotation error is defined as any radial or eccentric image motion due to deviation of the input ray by the prism.

Two alignment procedures are required to minimize derotation errors. The first is made inside the derotator unit and consists of making the prism "square" to the mechanical rotation axis, which will be called the mechanical axis. This is done on a fixture prior to installation in the sight. The second procedure is the alignment of the mechanical axis with the optical axis during the installation of the derotator unit in the sight. Since the Delta prism can be used only in collimated light, only angular adjustments are required.

The prism is made square to the mechanical axis by orienting it so that both base surface BC and a principal section are parallel to that axis.

The base surface adjustment is the more sensitive one. In Figure 1, if the prism is rotated through a small angle e_1 in a clockwise direction the output ray is deviated 2 e_1 relative to the input ray, also clockwise. This is made more evident if two of the three reflecting surfaces are considered to be acting as a constant deviation prism. The deviation of the output ray is then entirely due to the rotation of the third surface through angle e_1. There is no deviation of a refractive nature since the prism is equivalent to a window with parallel faces.

Parallelism of the principal section to the mechanical axis is not critical. This can be demonstrated by rotating the prism through a small angle about an axis perpendicular to the base surface and observing the effect of rotating the three reflecting surfaces. Rotation of the base surface has no effect since it is rotated in its own plane. Due to their symmetry with respect to the axis of rotation, the other two surfaces cause equal and opposite deviations thereby cancelling each other. As before, there is no refractive deviation. It follows that no adjustment about this axis is needed.

Two errors of prism geometry must be considered, namely, pyramidal error and inequality of the base angles. In Figure 1 we can calculate the effect of pyramidal error by holding the prism fixed and tilting the base surface BC toward the apex through a small angle e_2. The reflected ray is thereby tilted below the plane of the diagram by an angle 2 e_2 cos i, where i is the angle of incidence at the base surface. After refraction at AC the deviation below the plane of the diagram becomes $2ne_2$ cos i, where n is the refractive index of the glass.

The effect of base angle inequality can be similarly determined by rotating BC through e_3 about an axis parallel to the apex edge. Inside the glass the ray is rotated $2e_3$, but after leaving AC it is deviated $2ne_3$.

The last error of consequence is misalignment of the mechanical axis relative to the optical axis during the installation of the derotator unit in the instrument. If an alignment error of e_4 occurs in Figure 1, the resulting deviation is 2 e_4.

In the above discussion the deviations have been evaluated for only one prism position. When the prism rotates about the mechanical axis the deviations due to e_1, e_2, e_3, trace circular paths with angular radii of 2 e_1, 2n e_2 cos i, and 2n e_3, respectively. All are centered on the mechanical axis and are single speed, i.e., rotate 1:1 with respect to prism rotation. When making the e_1 adjustment the criterion is minimum deviation of the output ray. The e_1 adjustment can therefore be used to compensate for any e_3 that is present, thus eliminating inequality of base angles as a source of derotation error. The tolerances on base angles are instead related to the chromatic effect of wedge. Pyramidal error e_2, however, cannot be compensated by prism adjustment and must be controlled by a manufacturing tolerance.

The deviation due to e_4, unlike the others, reaches a maximum twice in each revolution of the prism and is not a single speed error. The manner in which the deviations due to e_1 through e_4 combine as a function of prism rotation has been analyzed by Sullivan.[1]

MECHANICAL DESIGN

The requirements of the mechanical design can be summarized as follows:

1. Minimum size and weight.
2. Optical function to be unaffected by the temperature and vibration environments of an aircraft.
3. Prism mount to be strain-free and to provide necessary angular adjustments to minimize eccentric image motion when prism rotates.
4. Prism bearings to have low friction and servo drive to be free of backlash to avoid jerky motions of image.
5. Provision for driving resolver pickoff which controls prism servo drive.

In approaching the mechanical design three basic decisions were made. The first was that cantilever structures would not be used in order to ensure the stiffest possible prism suspension. This was a consequence of the prism being located in high power space where an angular vibration of a few seconds could be detected at the eyepiece. It was also decided to use glass-to-metal bonding in the prism mount to obtain the space saving that occurs as compared to a more conventional mount involving a metal cage. It was felt that a sufficiently strain-free mount could be achieved using adhesive bonding due to the small bonding area involved.

The third decision was to employ a direct drive torquer to rotate the prism. This avoids the reduction in servo performance due to shaft flexure and backlash that can occur when a conventional servo motor and gearhead are used.

Figure 4 shows the method of mounting the prism. Two steel stub shafts are bonded to the non-working faces of the prism in line with each other. The shafts rest in journal surfaces in a gimbal thereby providing pivotal motion for small angular adjustments. The gimbal, in turn, is supported on two ball bearings which fit into a cylindrical housing. The common axis must be made parallel to the instrument optical axis when the derotator unit is installed in the instrument.

In Figure 4 a lever bar is attached to one of the stub shafts where it protrudes through the gimbal. Precise angular adjustment of the prism is obtained by turning the set screws which are threaded into the ends of the bar: this minimizes e_1. After the set screw adjustment is completed, the stub shaft carrying the lever bar is clamped such that it constrains all six degrees of prism freedom. The other stub shaft acts

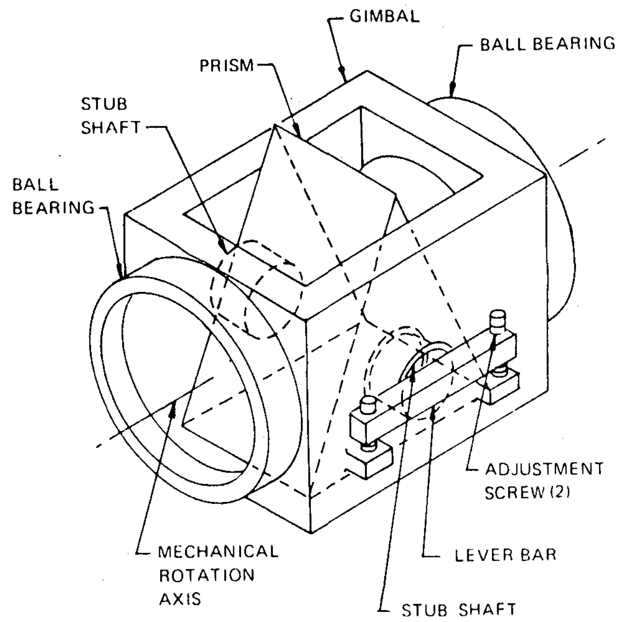

Figure 4. Delta prism mounted in gimbal.

only in a radial steadying role. It mates with a floating journal which assumes the radial position imposed by the shaft. The floating journal is clamped to the gimbal only after the lever bar stub shaft has been clamped to the gimbal. This procedure prevents strain in the glass due to small misalignments of the shafts during bonding. Additional strain due to differential thermal expansion between the glass and the magnesium gimbal is avoided by allowing axial sliding between the floating journal (now clamped radially) and its shaft.

From the standpoint of bonding technique, it is fortunate that the axis about which angular adjustment is required is perpendicular to two prism faces that have no optical function and, in addition, are parallel to each other. These circumstances minimize the problems of holding the prism in the bonding fixture and of positioning the stub shafts so that their axes are both co-axial and perpendicular to the prism faces. The stub shafts are made from steel to match the thermal coefficient of the glass.

The bearings supporting the gimbal are of the preloaded, angular contact type which provides the stiff constraint needed on the prism to prevent angular vibration that would result in loss of image resolution.

Metals were chosen for minimum weight and for thermal characteristics that would not adversely affect performance during a temperature change from -40°C to +71°C. In the axial direction it was necessary to prevent loss of bearing preload due to differential thermal expansion. Both gimbal and housing were therefore made from the same metal, in this case magnesium.

In the radial direction there was the additional complication of requiring non-magnetic materials adjacent to torquer components to prevent leakage of magnetic flux. Here titanium was the choice because it is non-magnetic, and has a thermal coefficient very close to the torquer components and the 440C steel in the bearings.

The cylindrical body of the assembled unit has a length and outside diameter of 11.3 and 10.7 cm. Aperture A has a diameter of 4.3 cm. The total weight of the unit is 2 Kg of which the prism contributes 0.36 Kg and the torquer 0.14 Kg.

After all adjustments were completed a derotator error of 3 minutes of arc, peak to peak, remained during 180° of prism rotation. During typical operation only 1.5 minutes of error occur because the prism rotates less than 90°. Since this rotation occurs in a time period of several seconds, the 1.5 minute error grows at a rate that is too slow to be perceived. If the derotator follows the reticle in the optical train, any derotator error present affects image and reticle equally and no pointing error is introduced.

ACKNOWLEDGMENTS

The writer wishes to acknowledge valuable discussions with Dr. Seymour Rosin of Photronics Corporation concerning ghost prevention, and for furnishing the t and H equations. He also acknowledges the contribution of L. Janowsky in the layout of the unit.

REFERENCE

1. D. L. Sullivan, Alignment of Rotational Prisms, "Applied Optics," Vol. 11, pp. 2028-2032 (1972).