AD-770 423

A DEVICE AND TECHNIQUE FOR OPTICALLY ALIGNING A LIGHT BEAM RELATIVE TO A REFERENCE AXIS

Wallace H. Clay, et al

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

October 1973

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MEMORANDUM REPORT NO. 2331

OCTOBER 1973

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W. H. Clay
J. R. Patchell

Exterior Ballistics Laboratory

RDT&E Project No. 1T061102A33D

A B E R D E E N   P R O V I N G   G R O U N D ,   M A R Y L A N D

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Unclassified
Security Classification

AD 770423

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Ballistic Research Laboratories Aberdeen Proving Ground, Maryland 21005	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
A DEVICE AND TECHNIQUE FOR OPTICALLY ALIGNING A LIGHT BEAM RELATIVE TO A REFERENCE AXIS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
Wallace H. Clay
James R. Patchell

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
OCTOBER 1973	37	3

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. RDT&E 1T061102A33D	BRL MEMORANDUM REPORT NO. 2331
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Materiel Command 5001 Eisenhower Avenue Alexandria, Virginia 22304

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DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Optical Alignment Yawsonde Yawsonde Calibration Parallel Light Mirror						

1b

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LIST OF SYMBOLS

d	the width of the entrance and exit channels of the optical alignment tool
r	length of the optical arm of the alignment system
S_E	the distance, measured on a viewing screen, between the position of the primary image and the true position for exact alignment
x, y	orthogonal coordinates used for the analysis of the geometry of the optical alignment tool
L	the length of the entrance and exit channels of the optical alignment tool
R	the distance from the center of rotation of the alignment tool to the center of the reflecting mirror (See Figure 12)
α	angle of misalignment
α_c	cut off angle, the angle at which the width of the primary beam is zero
δ_E	error angle, represents an error in the alignment of the light beam
Δ_A, Δ_B, Δ_D	widths of the primary beam and the two secondary beams, measured at the exit of the alignment tool
Δ_1	the distance from the left edge of beam D to the left wall of the exit channel (See Figure 8)
Δ_2	the distance from the right edge of beam D to the right wall of the exit channel (See Figure 8)

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I. INTRODUCTION

Yawsondes, together with on-board electronics and a telemeter system provide a means for studying the dynamic behavior of artillery shell over long flight paths. Yawsondes have been used routinely for the past several years to study the free-flight behavior of a variety of projectiles.[1,2] The yawsonde is an instrument that measures solar aspect angle during the flight of a projectile. The solar aspect angle is the angle between the longitudinal axis of the projectile and a vector directed from the projectile to the sun. The measurement is made using light-sensitive silicon cells (solar cells) that are mounted in fixtures that provide narrow fields of view in two planes. Several types of yawsondes are described in references 1*, 2, and 3.

Reduction of yawsonde data requires that the sensors be physically calibrated in the laboratory prior to use. The calibration consists of simulating the yawing and pitching motion of the shell while illuminating its yawsonde with a collimated beam of light. As the angle between the shell's axis and the light beam is varied (that is, as the shell is yawed with respect to the beam), the voltage signals from the solar cells are monitored and recorded. The calibration procedure is described in detail in reference 3.

The angle between the axis of the shell and the light beam is measured with respect to the reference condition wherein the beam is perpendicular to the longitudinal axis of the shell. In order to assure accuracy in the calibration procedure, it is necessary that this reference condition be determined accurately and precisely. This report describes a device designed to optically align the light beam perpendicular to the longitudinal axis of the shell. Although the tool was developed specifically for the yawsonde calibration system, the instrument and the technique could be adapted to other applications.

II. YAWSONDE CALIBRATION SYSTEM

A schematic of the yawsonde calibration system used at the Ballistic Research Laboratories (BRL) is shown in Figure 1. The system includes a zirconium-arc, point light source and a collimating lens to produce a beam of parallel light. A mechanism is provided to yaw the projectile with respect to the light beam, and to roll the projectile about its longitudinal axis.

The yaw angle is measured with respect to the reference condition that the light beam is perpendicular to the axis of the shell. This reference condition occurs when the angle σ_n in Figure 1 is zero. The optical alignment tool is used to obtain a precise setting of the reference σ_n.

*References are listed on page 31.

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III. THE OPTICAL ALIGNMENT TOOL

A. Description

The optical alignment tool is sketched in Figure 2 and consists of a pair of mutually perpendicular channels milled into a block of aluminum. Each channel is 4.375 inches long and .125 inch wide and 0.3 inch deep. A plane, front-surfaced mirror is mounted at the intersection of the two channels so that each channel makes an angle of 45° with respect to the front surface of the mirror. The threaded section of the tool is designed so that the fixture can be installed in the place of the conventional nose fuse of an artillery shell. Thus the axis xx' in Figure 2, is colinear with the roll axis of the shell. Photographs of the alignment tool, as used in a typical application, are shown in Figure 3. The top cover has been removed in the lower view exposing the two channels.

The tool works on the principle of optical reflection. If the collimated beam of light is parallel to the walls of the entrance channel, then the beam is reflected only by the mirror. This single reflection leaves the tool through the exit channel. A single image of the slit formed by the walls of the exit channel can be observed on a screen placed opposite the exit. If, however, the light beam is misaligned by some small angle, α, with respect, to the walls of the entrance channel, then multiple images are observed on the screen. In this case, the light beam is reflected by the channel walls as well as by the mirror before it exits the fixture. Thus more than one image is produced. For values of misalignment angle within the interval $0 < \alpha < \alpha_c$ (where α_c is the cutoff angle of the device) only three images of the exit slit are observed. The brightest image is due to the reflection by the mirror. The other two images are of equal intensity, but less bright than the first. They result from reflections of the light beam from both the walls of the channels as well as by the mirror. The conditions of alignment ($\alpha = 0$) and misalignment ($0 < \alpha < \alpha_c$) are shown schematically in Figure 4.

B. Analysis

The analysis of the optics of the alignment tool is based on the assumption that the beam of light is perfectly collimated and that the diameter of the beam is large enough to fully illuminate the entrance slit. The second criterion is important for the yawsonde calibration technique.

A sketch of the geometry of the perpendicular channels in the alignment tool is shown in Figure 5. The tool is oriented so that the light beam makes a small angle, α, with respect to the walls of the entrance channel. The numbered rays divide the incident beam into various regions determined by the various possible internal reflections. The angle α is kept smaller than a cutoff angle α_c so that no more than two reflections can occur.

Four regions in the beam need to be considered:

Region A. The region included between rays (1) and (2+). Light entering the tool is reflected only from the mirror before leaving the tool. This reflected beam is referred to as the primary beam and is easily distinguished from secondary beams by its greater intensity.

Region B. That part of the light beam included between rays (2-) and (3+). Light is reflected first from the mirror and then from the wall of the exit channel. This reflected beam is called a secondary beam.

Region C. The region between rays (3-) and (4+). Light is reflected back from the mirror to the walls of the entrance channel. Since the light does not leave the tool, this region is not considered.

Region D. The region between rays (4-) and (5). Light entering the tool is reflected first from the walls of the entrance channel and then from the mirror before leaving the tool. This reflected beam is also called a secondary beam.

Three images of the exit slit are observed on a screen placed opposite the exit channel. The primary image is the brightest; the two secondary images are of lower intensity and are displaced from the primary image. The analysis is simplified if each region is considered separately. For a given misalignment, α, the parameters to be determined are the angle that the exiting beam makes with respect to the channel wall and the width of the beam.

Figure 6 shows the geometry associated with region A. From the geometry in the figure,

$$x_1 = y_1 = \frac{d - L \tan \alpha}{1 + \tan \alpha}$$

$$x_{2+} = y_{2+} = \frac{(L + d) \tan \alpha}{1 + \tan \alpha} \qquad (1)$$

where the subscripts refer to the labels on the light rays bounding region A. As α approaches 0 (that is, as alignment is approached) y_{2+} approaches 0 and y_1 approaches d. The width of beam A at the exit is

$$\Delta_A = [d - (2L + d) \tan \alpha] \cos \alpha \qquad (2)$$

As α approaches zero, Δ_A approaches d. That is, for the aligned condition, beam A, the primary beam, fills the entire channel. The primary beam vanishes when the misalignment angle is at cutoff:

$$\tan \alpha = \tan \alpha_c = \frac{d}{2L + d} \qquad (3)$$

The appropriate equations for region B are obtained from the geometry shown in Figure 7:

$$x_{2-} = y_{2-} = \frac{L \tan \alpha}{1 + \tan \alpha} \qquad (4)$$

$$x_{3+} = y_{3+} = \frac{d \tan \alpha}{1 + \tan \alpha} \qquad (5)$$

$$\Delta_B = L \tan \alpha \cos \alpha \qquad (6)$$

At $\alpha = 0$, y_{2-}, y_{3+}, and Δ_B are zero so that, as alignment is approached, the secondary beam disappears. At $\alpha = \alpha_c$, the width of beam B at the exit is

$$(\Delta_B/\cos \alpha_c) = L \tan \alpha_c$$

$$= \frac{Ld}{2L + d} \doteq \frac{d}{2} \qquad (7)$$

The final region of interest, region D, is shown in Figure 8. The important relationships for this region are

$$x_5 = y_5 = \frac{L \tan \alpha}{1 - \tan \alpha} \qquad (8)$$

$$\Delta_1 \doteq (L + d) \tan \alpha \qquad (9)$$

$$\Delta_2 = d - (2L + d) \tan \alpha \qquad (10)$$

$$\Delta_D \doteq L \tan \alpha \qquad (11)$$

If Equation (11) is compared with Equation (6), it is seen that $\Delta_D = \Delta_B$. Both secondary beams B and D exit at angle $|\alpha|$ but in an opposite sense relative to the primary beam. When $\alpha = 0$, $\Delta_1 = \Delta_2 = \Delta_D = 0$ and when $\alpha = \alpha_c$,

$$(\Delta_D/\cos \alpha_c) = \frac{Ld}{2L + d} \doteq \frac{d}{2} \qquad (12)$$

The position of the left edge of beam (D) at the exit is given by Equation (9). The position of the right edge of beam B is given by Equation (6). The separation between the two secondary beams at the exit is given by

$$\Delta_1 - \Delta_B = (L + d) \tan \alpha - L \tan \alpha$$

$$= d \tan \alpha \tag{13}$$

This shows that the two secondary beams do not overlap.

In summary, then, the following statements can be made concerning the optical alignment tool.

1. The aligned condition is $\alpha = 0$. That is, the light beam is perpendicular to the axis xx' of the alignment tool. A single bright image is visible on a screen placed at the exit.

2. For α within the range, $0 < \alpha < \alpha_c$, the axis of the tool is not perpendicular to the light beam. There exist three images of the slit on a screen placed at the exit, the brightest due to the primary beam and the other two due to secondary beams less intense than the primary. The primary beam is at an angle α corresponding to the misalignment with respect to the channel wall. The direction of this angle for the primary beam is in the same sense as the misalignment of the tool with respect to the light beam. The two secondary beams are parallel and also at the same angle α with respect to the channel wall, but in an opposite sense to that of the primary beam.

3. At the cutoff angle, $\alpha = \alpha_c$, the primary beam disappears and only the two secondary beams can exit the tool. The width of each of the two beams at exit are the same and slightly less than one-half the width of the exit channel. For α larger than α_c, additional secondary beams are generated due to multiple reflections; the analysis becomes more difficult. It is, however, sufficient to consider only the range $0 \leq \alpha \leq \alpha_c$ since, in practice, α can easily be kept within this range. Figure 9 shows a plot of the widths of the three beams as a function of the misalignment angle α.

If the tool is misaligned by an angle α within the range $0 < \alpha < \alpha_c$, three images of the exit slit are observed on a screen at the exit. These images are located at the points A, B, and D shown in Figure 10. Point P in Figure 10 is the location of the single image observed for the case when $\alpha = 0$. It can be shown that if the tool is misaligned by an α whose sense is the opposite of that considered above, then a similar analysis can be made with similar results. The images are now at points A', B', and D' in Figure 10.

C. Alignment Procedure

The above properties of the alignment tool can be used to provide a fast, simple, and accurate method of aligning the light beam perpendicular to the axis, xx', of the tool (and, hence, perpendicular to the axis of the projectile to be calibrated).

At the start of the alignment procedure, the tool will be at some angle α with respect to the light beam. The position of point P on the screen (Figure 10) is unknown but the images at A, B, and D (or A', B', and D') are visible. As α changes within the limits $0 \leq \alpha \leq \alpha_c$, the positions of the secondary images at B and D change very little. In practice, it is difficult to detect any motion in the secondary images. The primary image, A, however, moves a considerable distance across the screen. This, together with the fact that the primary image is brighter than the secondary images, allows the images to be easily identified.

A possible technique to determine point P (that is, $\alpha = 0$) would be to rotate the tool until a single image is observed. As α approaches zero, however, the secondary beams vanish and it is difficult to judge precisely when the secondary images disappear and a single image remains. Several alternative techniques can be used. The easiest can be demonstrated by considering the situation shown in Figure 10 and the images observed on the screen as shown in Figure 11. The position of image D is marked on the screen and the tool is rotated until the primary image is centered on the mark. This is considered the aligned position with the light beam nearly perpendicular to the axis of the tool. It differs from exact alignment by a small error angle δ_E.

The magnitude of the error angle δ_E can be estimated by considering Figure 12. The distance between position D and the unknown point P on the screen is shown as the distance s_E. The error angle is approximately

$$\delta_E = \tan^{-1}\left(\frac{s_E}{r}\right) \qquad (14)$$

where r is the optical arm of the exit channel, and is approximately equal to the distance between the viewing screen and the mirror of the tool. It can be shown, using Figure 12, that

$$s_E = (L + d/2) \sin \alpha + R (1 - \cos \alpha_c) - \Delta \cos \alpha \qquad (15)$$

where R is the distance between the center of rotation of the tool and the center of the mirror (see Figure 12), and Δ is the distance from the centerline of exit channel to the center of beam D. When the secondary image D is marked on the screen, the only thing known about the angle α is that it lies within $0 < \alpha < \alpha_c$. An upper bound to the error angle δ_E can be obtained by letting $\alpha = \alpha_c$. Then

$$\delta_{E\,max} \doteq \tan^{-1} \frac{\left(L + \frac{d}{2}\right) \sin \alpha_c + R (1 - \cos \alpha_c) - \frac{d}{4} \cos \alpha_c}{r}$$

$$\doteq \tan^{-1} \frac{R}{r} (1 - \cos \alpha_c) + \frac{d}{4r} \cos \alpha_c \qquad (16)$$

Equation (16) shows that if the optical arm of the exiting beam is large (that is, if R/r << 1) and if the tool is designed so that α_c is small (that is, if d/L << 1), then the maximum error inherent in using the optical alignment tool as described can be made small. For the arrangement used in calibrating at BRL, d/L = 1/35. External mirrors, shown in Figure 13, were used to increase the optical arm to 40 feet. Therefore, R/r was approximately $\frac{2}{40 \times 12} = \frac{1}{240}$, making $\delta_{E_{max}}$ about 0.004 degree or less than 15 seconds of arc.

This analysis of the error in alignment assumed a perfectly collimated light beam and parallel channel walls with the two channels perpendicular. The light beam, of course, is not perfectly collimated and the dimensions of the alignment tool are accurate only to within certain machining tolerances. An analysis of these sources of error adds an error of about 1 minute of arc, which at present is insignificant for the purpose of yawsonde calibration.

IV. SUMMARY

A method of aligning a beam of parallel light perpendicular to the longitudinal axis of an artillery shell has been developed. The method provides an accurate beam alignment for the calibration of yawsondes and can be adapted to other applications.

An optical alignment tool has been designed and consists of a mirror placed at the intersection of two mutually perpendicular channels. If the beam is in alignment, light is reflected only off the mirror and a single image of the slit formed by the exit channel is observed. If the beam is not in alignment, then light is reflected off both the mirror and the channel walls and multiple images are observed. Additional mirrors are used in order to extend the optical arm of the system. The alignment tool and technique have been used to align a beam of light at an angle of $90^\circ \pm .017^\circ$ with respect to the longitudinal axis of a projectile.

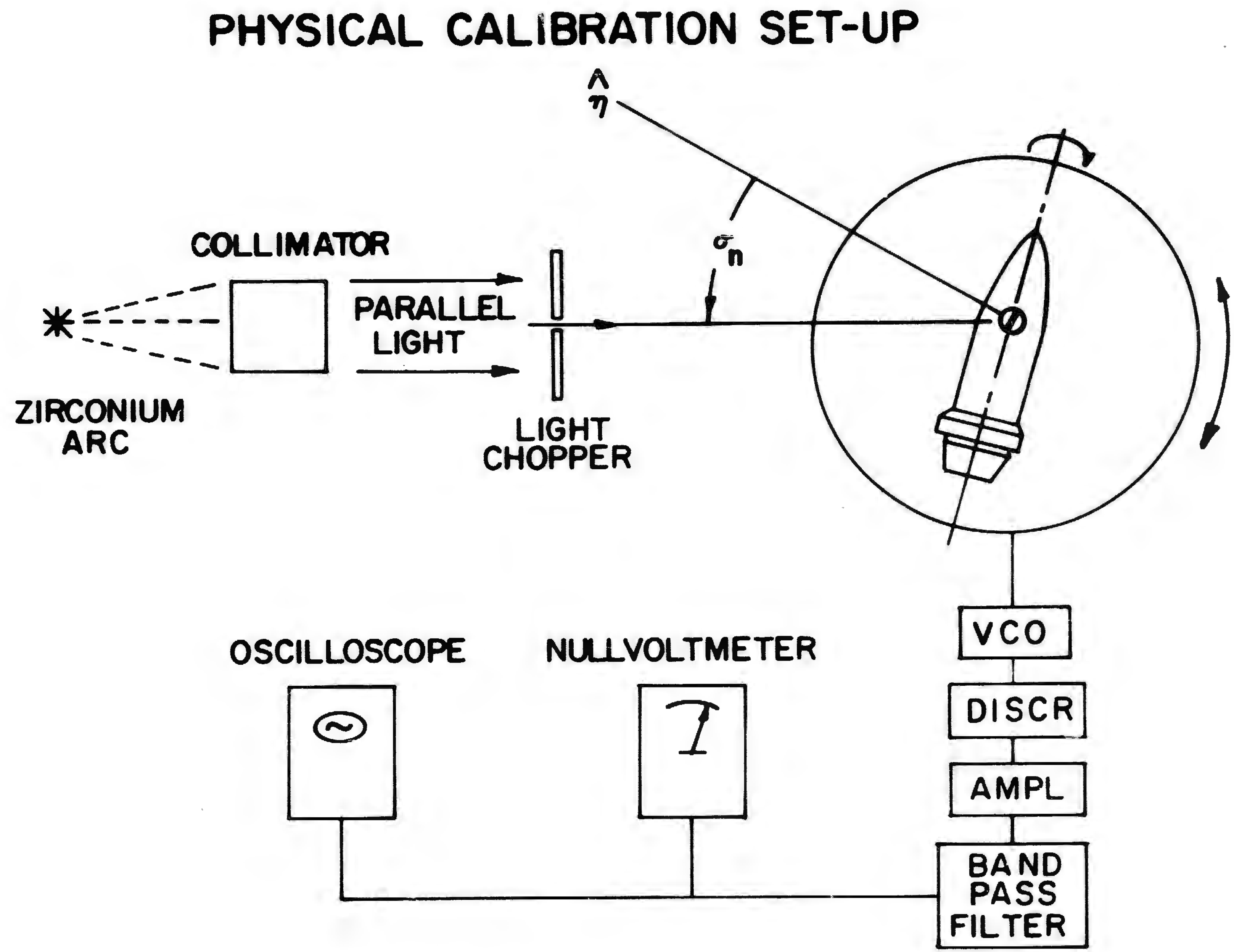


Figure 1. Schematic of the Yawsonde Calibration System at BRL

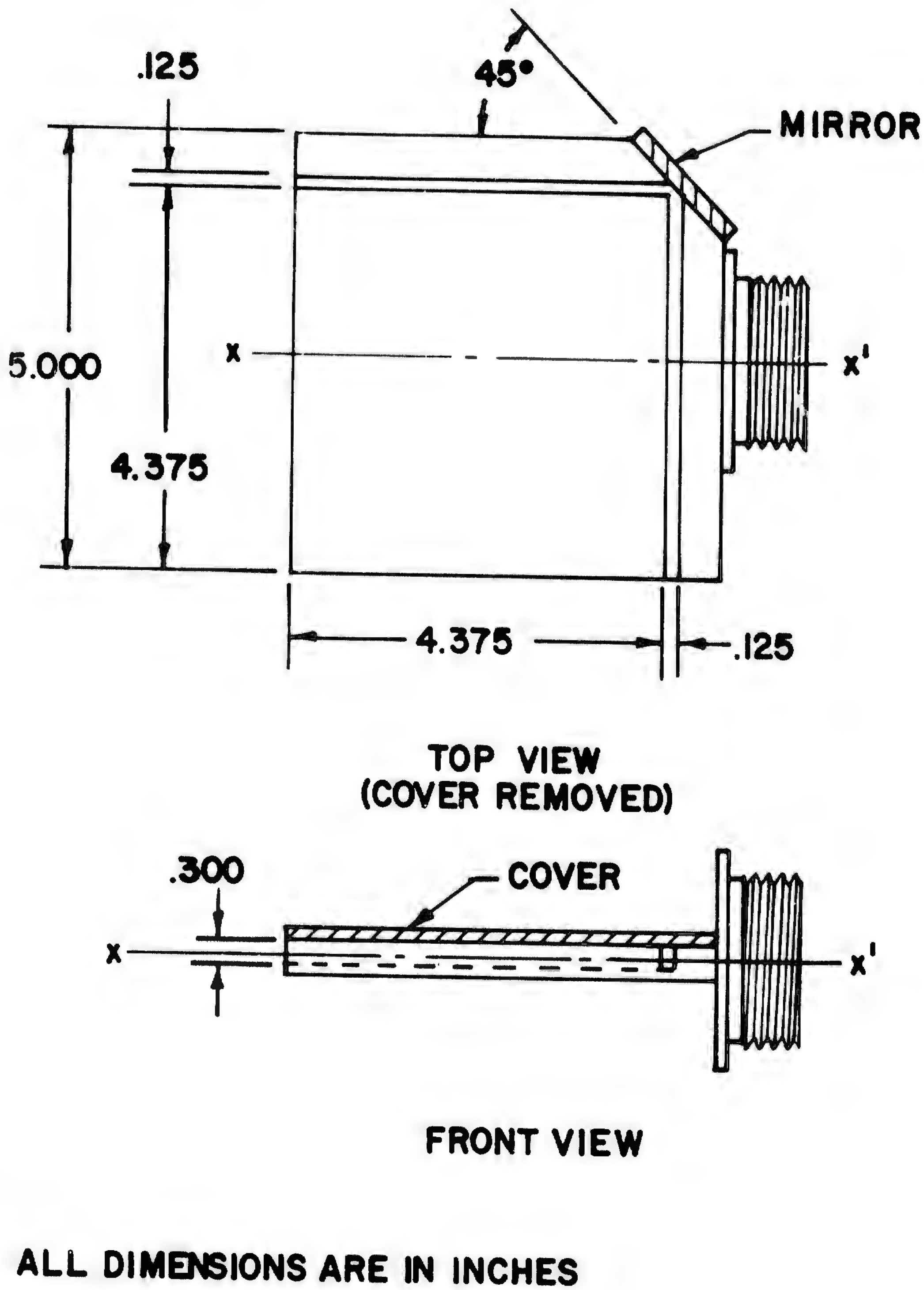
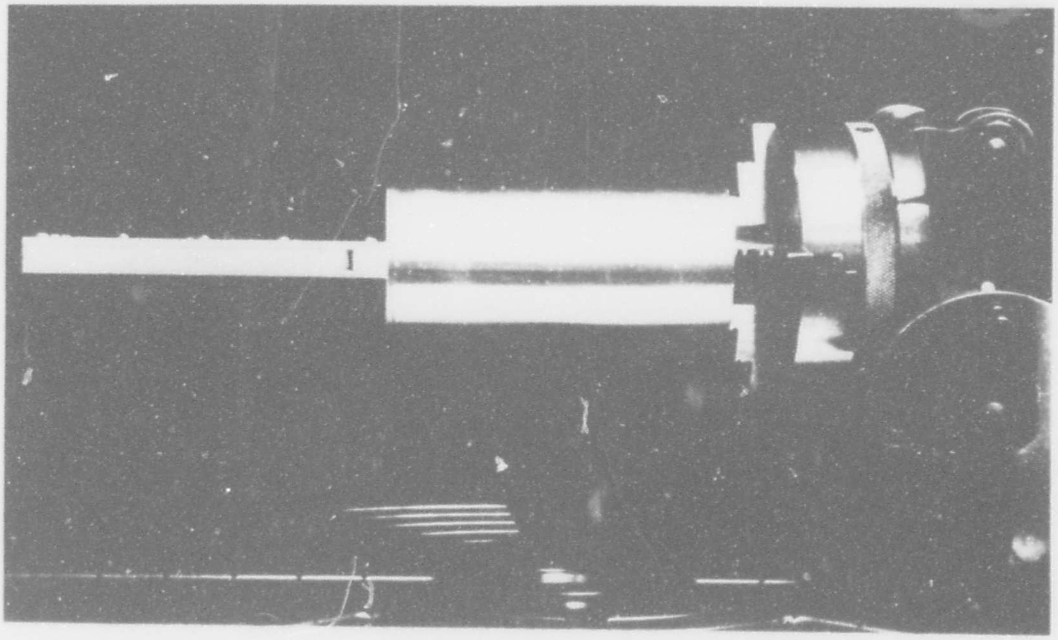


Figure 2. Sketch of the Optical Alignment Tool



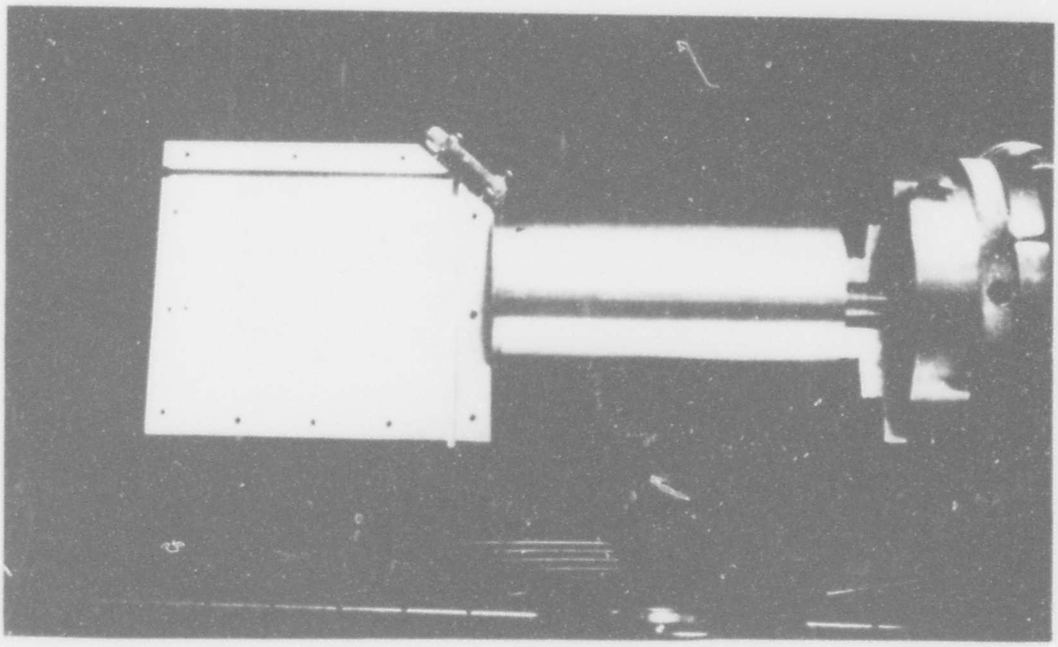


Figure 3. Photograph of the Optical Alignment Tool
Top: Front View Showing the Entrance Slit
Bottom: Top Plate Removed Showing the Two Perpendicular Channels

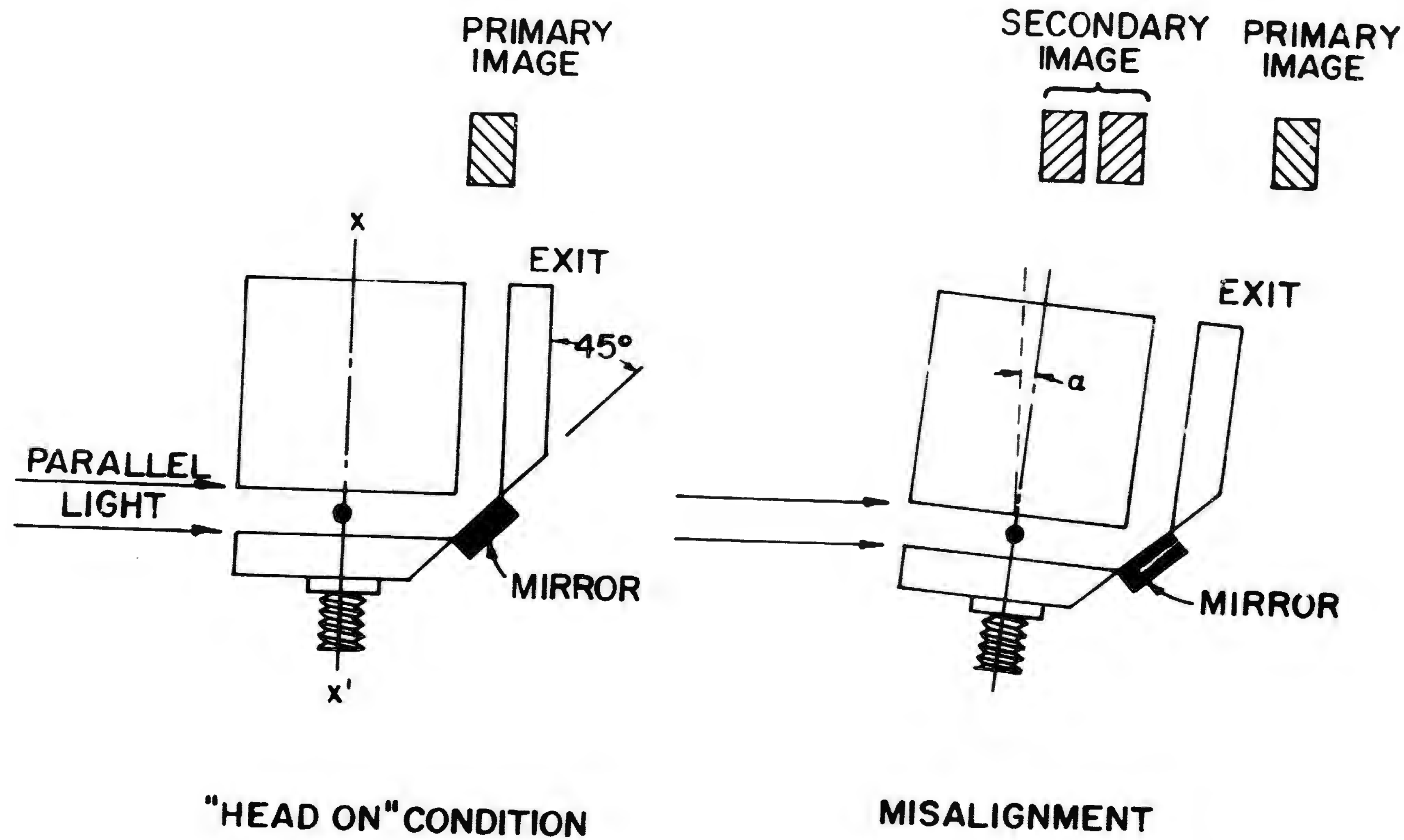


Figure 4. A Sketch Showing the Beam-Aligned and Beam-Misaligned Conditions

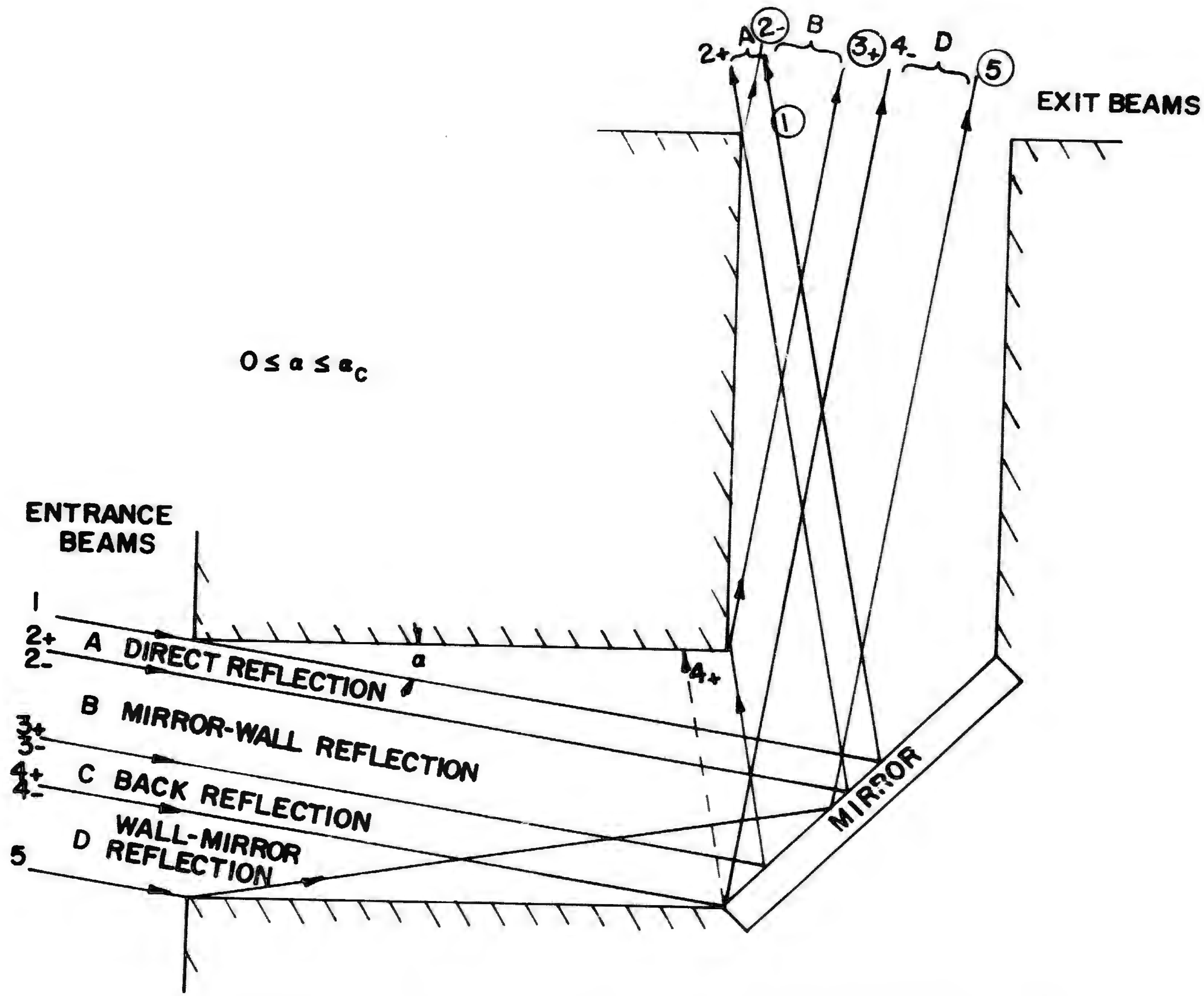


Figure 5. A Sketch Showing Entrance Light Beam Divided into Various Regions According to the Type of Reflections Occurring Within the Optical Alignment Tool

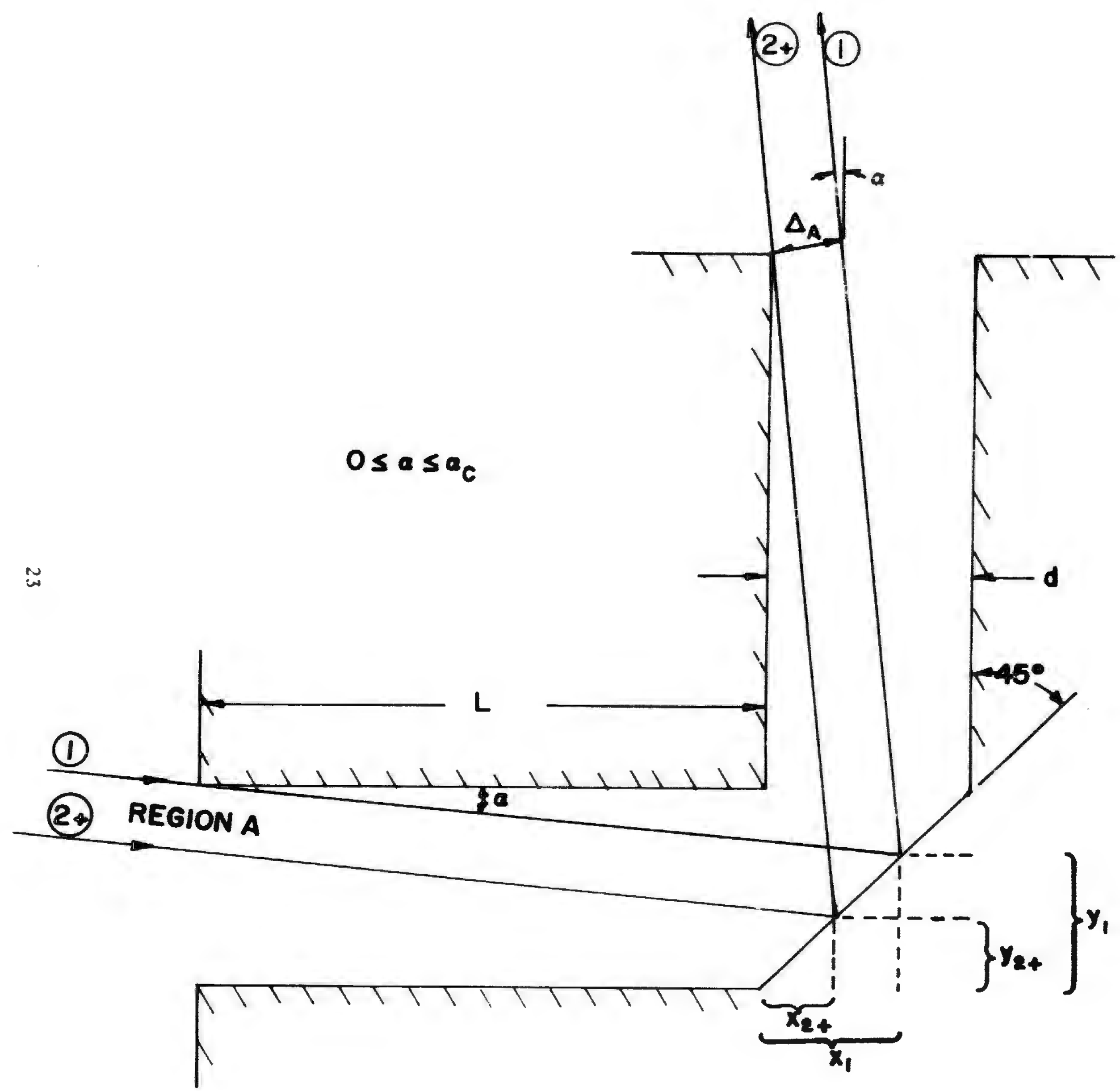


Figure 6. Region A; A Single Reflection Off the Mirror Produces a Primary Beam at the Exit

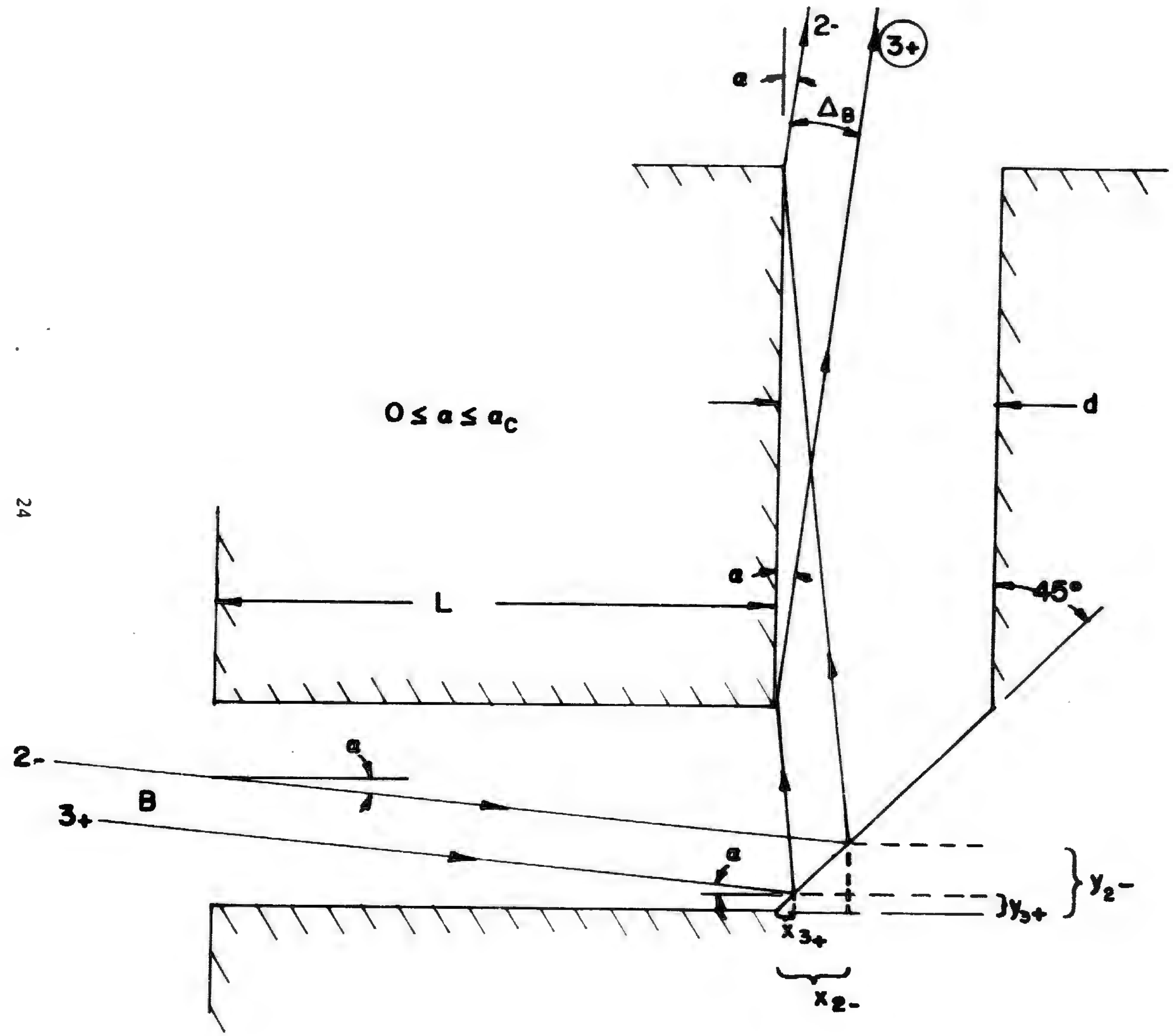


Figure 7. Region B; Subsequent Reflection by the Mirror and then the Wall of the Exit Channel Produce a Secondary Beam at the Exit

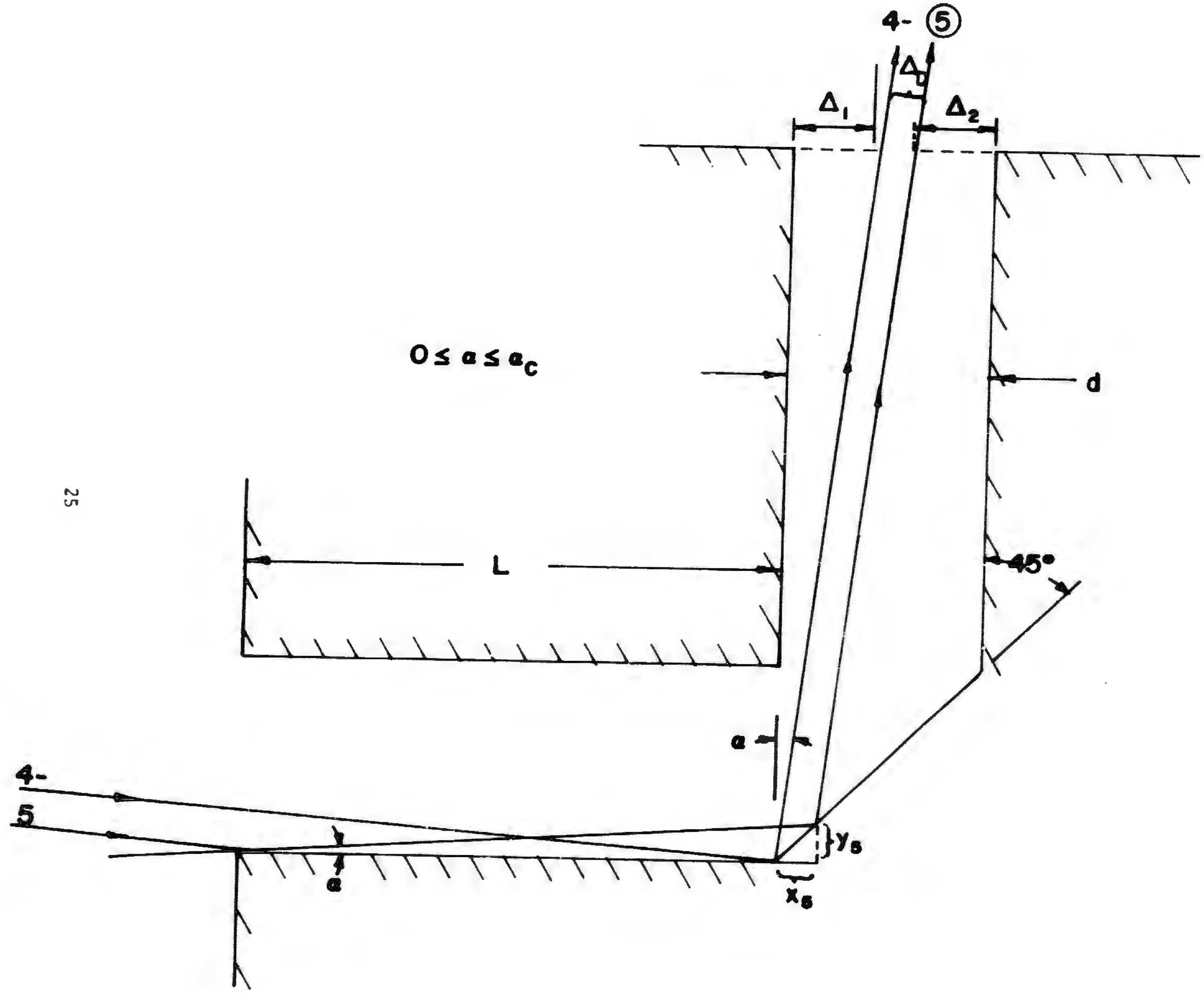


Figure 8. Region D; Subsequent Reflection by the Wall of the Entrance Channel and then the Mirror Produce a Secondary Beam at the Exit

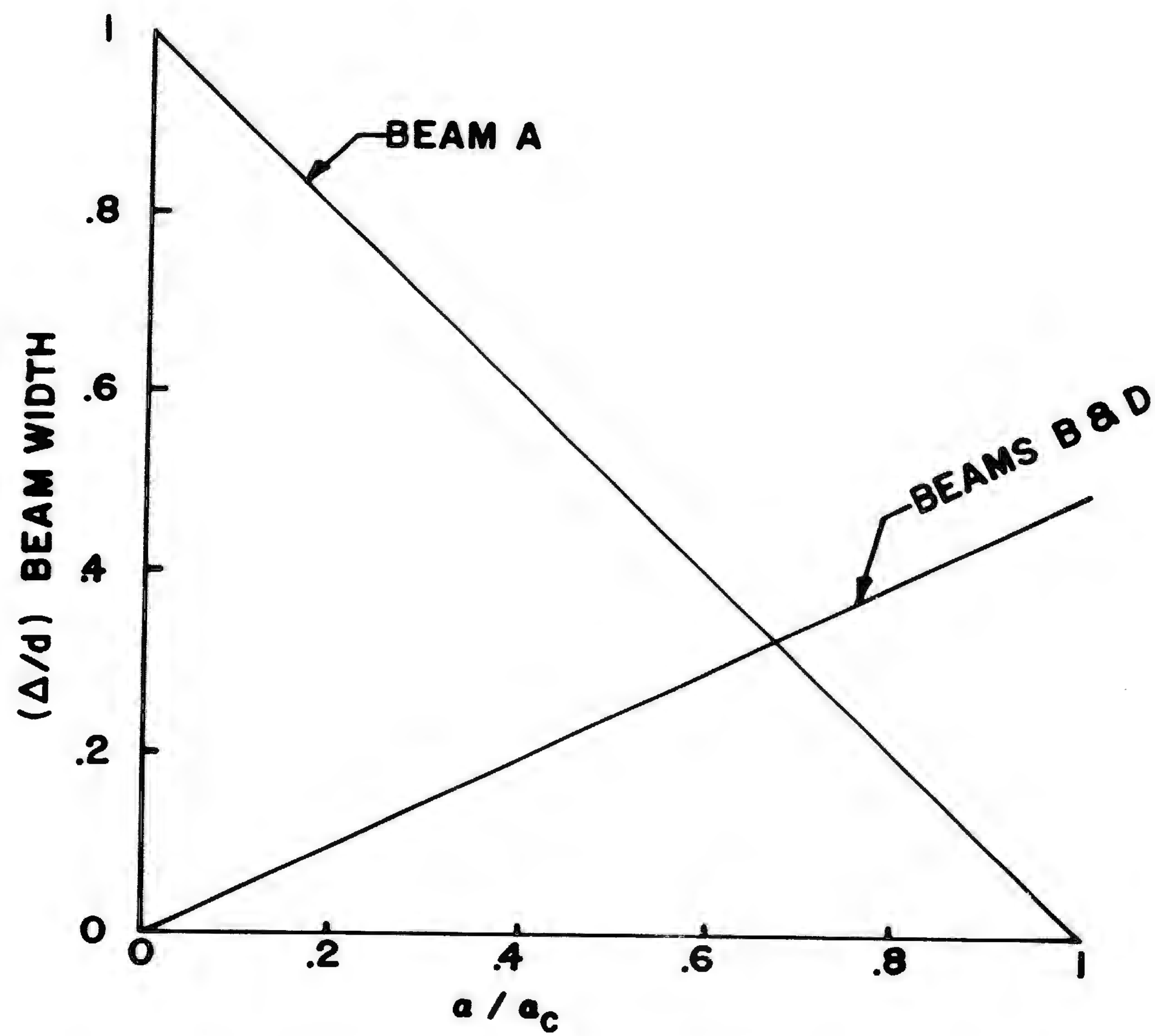


Figure 9. A Plot of the Beam Width at the Exit of the Alignment Tool vs the Angle of Misalignment.

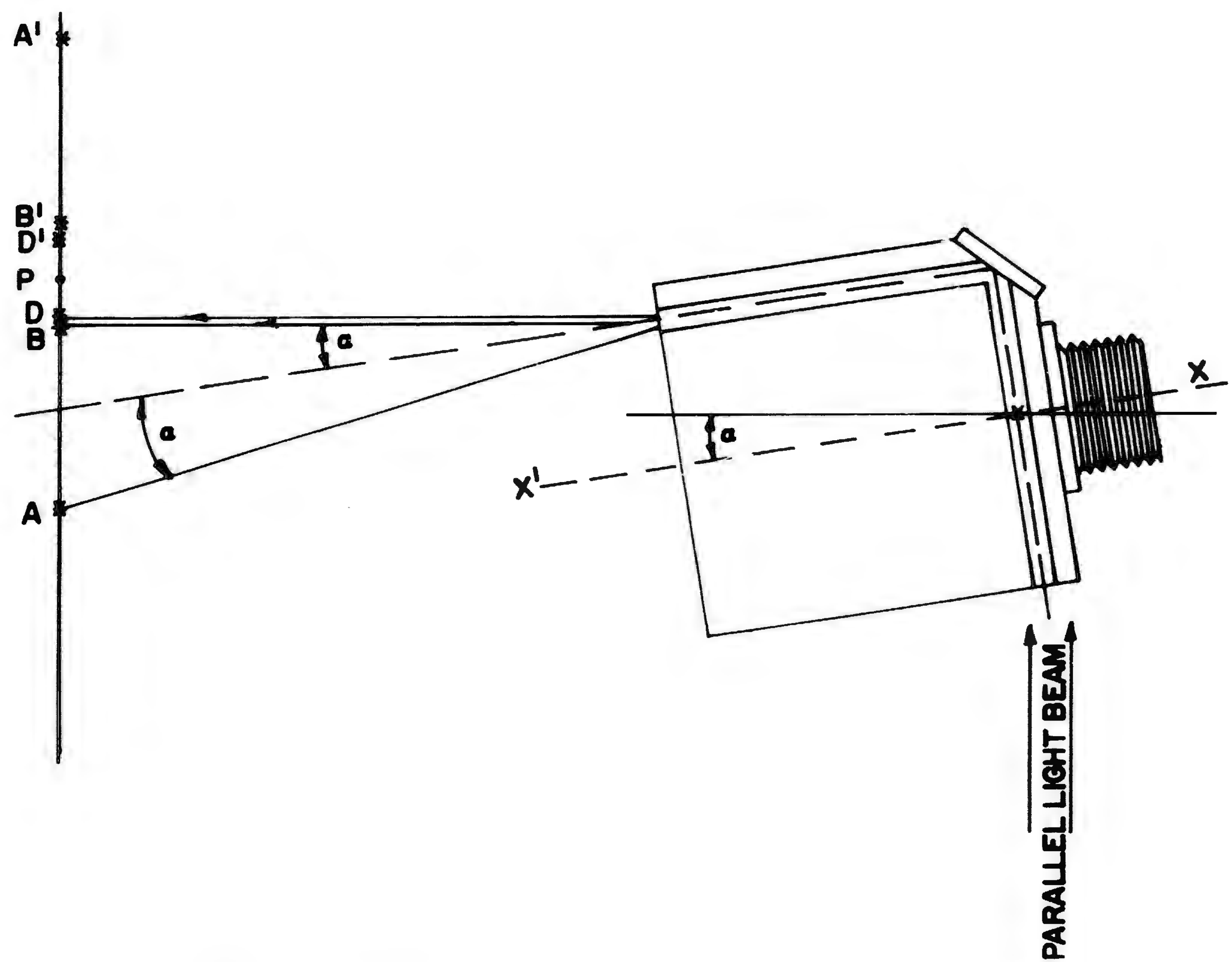


Figure 10. The Relative Positions of the Slit Images on a Screen Placed Opposite to the Exit Channel of the Alignment Tool

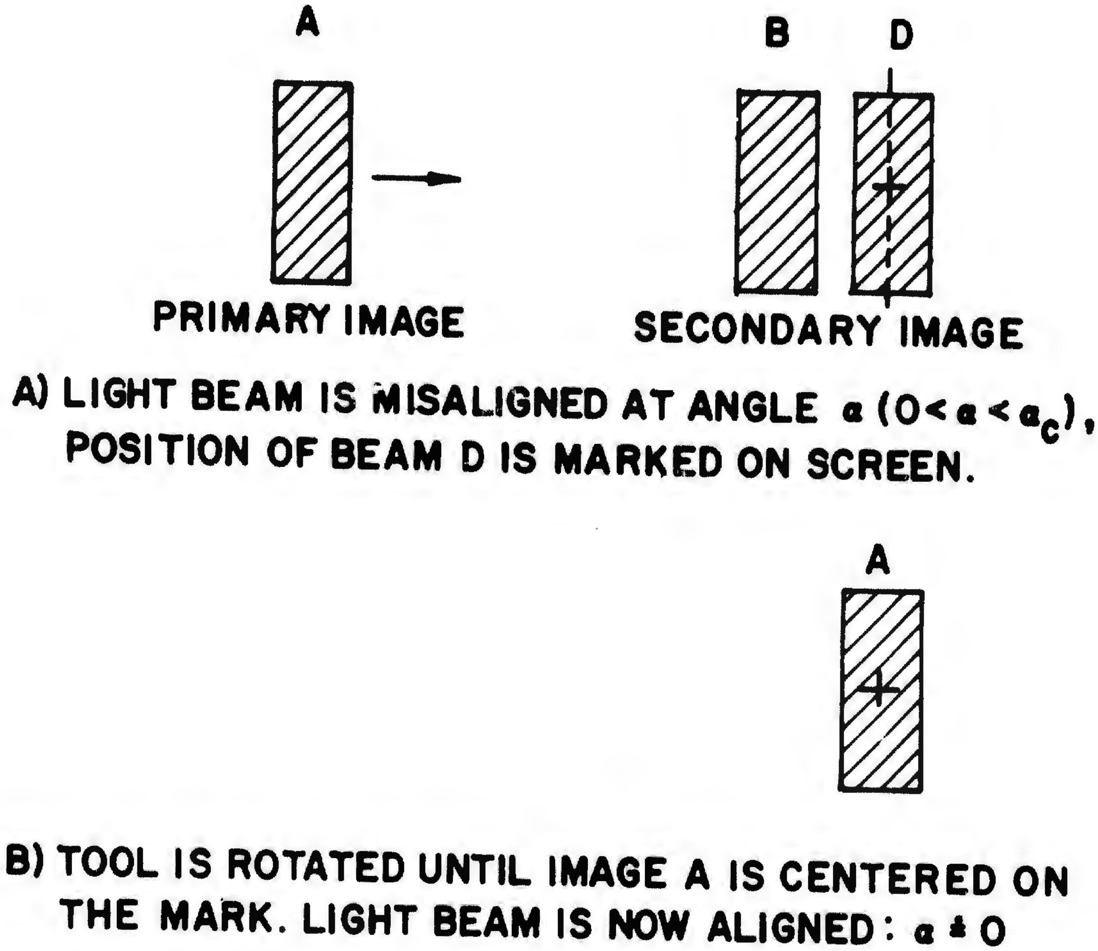


Figure 11. A Sketch Illustrating the Technique Used to Align the Light Beam

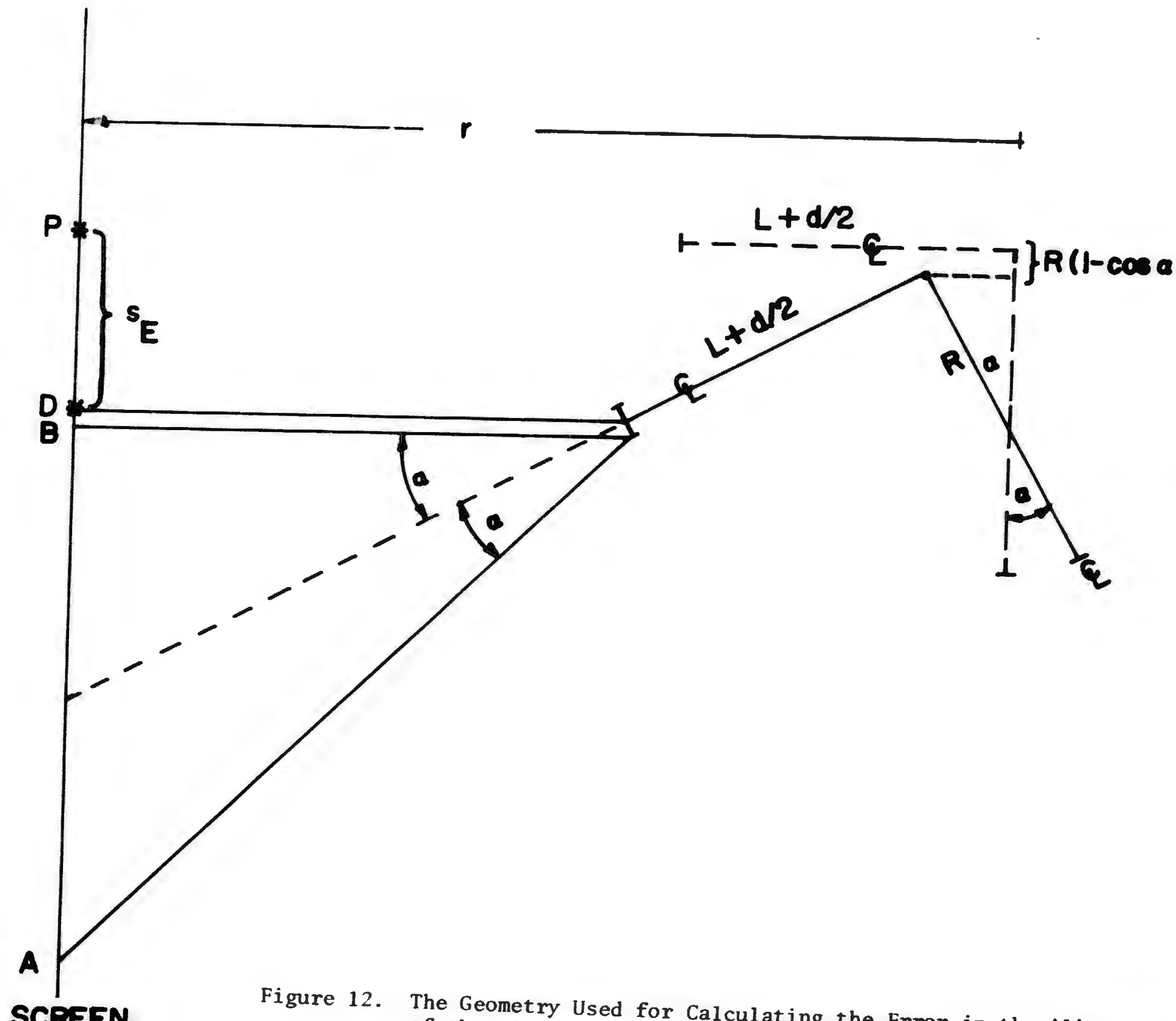


Figure 12. The Geometry Used for Calculating the Error in the Alignment of the Light Beam

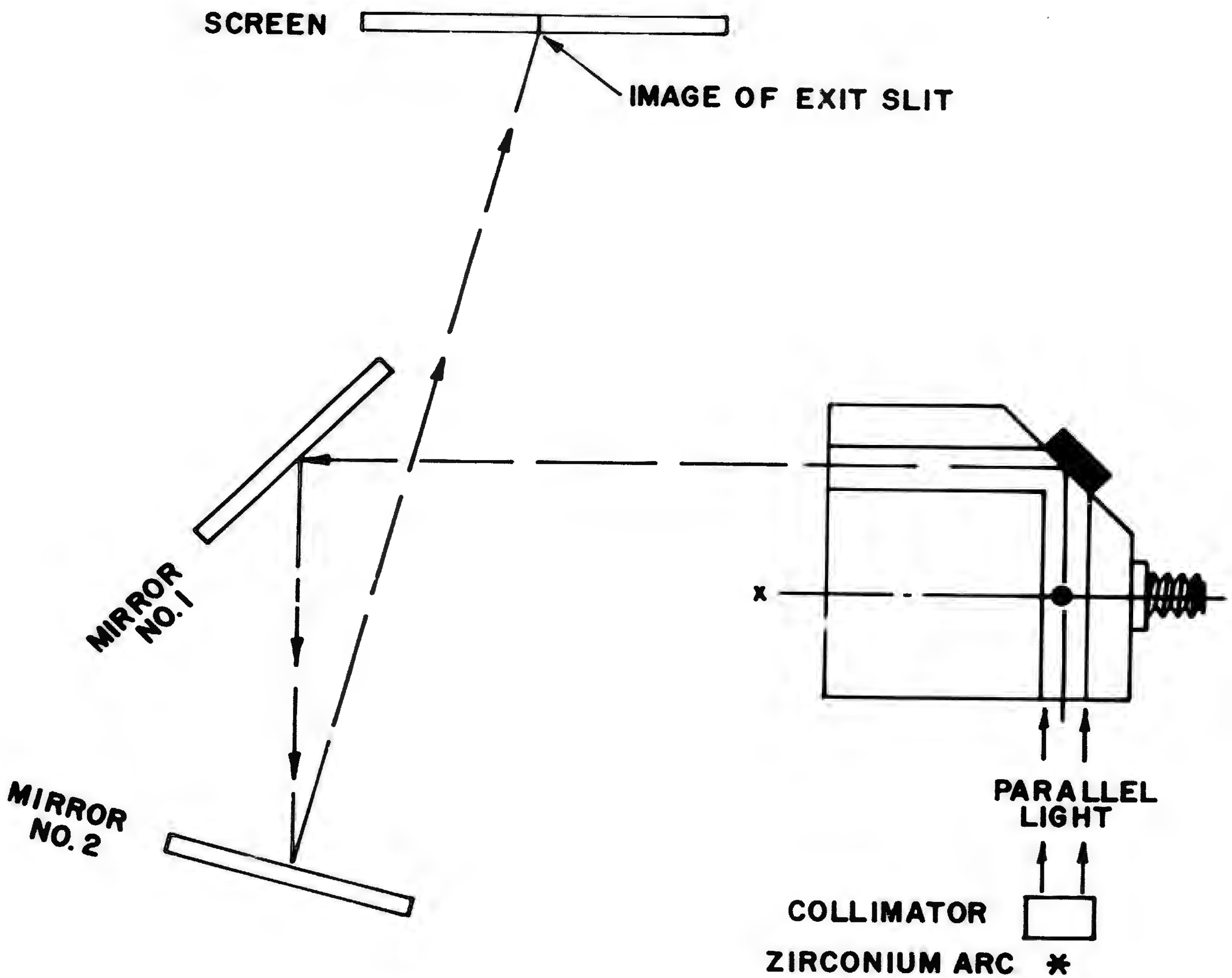


Figure 13. A Sketch Showing the Alignment Tool and the Two Additional Mirrors Used to Extend the Optical Arm of the System

REFERENCES

1. W.H. Mermagen, "Measurements of the Dynamical Behavior of Projectiles Over Long Flight Paths," Journal of Spacecraft and Rockets, Vol. 8, No. 4, April 1971, pp. 380-385; also published as Ballistic Research Laboratories Memorandum Report No. 2079, November 1970, AD 717002.

2. R.E. Elmore, "HDL Yawsonde Instrumentation," Harry Diamond Laboratory Report No. HDL-TM-71-19, September 1971, AD 732342.

3. W.H. Clay, "A Precision Yawsonde Calibration Technique," Ballistic Research Laboratories Memorandum Report No. 2263, January 1973, AD 758158.