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Absolute Specular Reflectometer with an Autocollimator Telescope and Auxiliary Mirrors

Tie Ming Wang, Kenneth L. Eckerle, and Jack J. Hsia

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ABSOLUTE SPECULAR REFLECTOMETER WITH AN AUTOCOLLIMATOR TELESCOPE AND AUXILIARY MIRRORS

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ABSTRACT

The Strong method for measuring reflectance is used in many laboratories. However, an uncertainty in the angular position of the sample can lead to large errors. A novel use of an autocollimator telescope with two auxiliary mirrors (ACTAM) can reduce this angular uncertainty and lead to more accurate measurement of reflectance. The instrumentation, its adjustment, measurement procedure, results, and uncertainties are discussed. The total uncertainty for the reflectance measurement of a gold mirror was found to be less than 0.0025 over the wavelength region 2 to 22 μm.

Key words: alignment; autocollimator telescope; auxiliary mirrors; specular (regular) reflection; strong (vw) method; uncertainty

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1. INTRODUCTION

The Strong [1] or "V-W" method of measuring absolute specular reflectance is well known. In this method, the light is reflected twice from the sample; and thus, the absolute reflectance is a square root of the ratio of signals of sample in and sample out. However, it has the disadvantage that the light beam must make three reflections in the "W" geometry. Thus, the device is very sensitive to angular settings. The "V-W" accessory is usually an accessory which is inserted into the sample compartment of a spectrophotometer. Therefore, the light path relative to the optic axis of the host spectrophotometer can be different for the V geometry and W geometry. The method used in the present apparatus uses an autocollimator telescope and two auxiliary mirrors (ACTAM) to align the mirrors of the V-W accessory when changing from the V geometry to the W geometry. This method is more accurate than the conventional one, especially when using apparatus which does not have a radiation averaging detection system.

2. INSTRUMENTATION

A commercial IR spectrophotometer is used, and a diagram of the optical system with ACTAM is shown in figure 1. The spectrophotometer is a double beam instrument. The optical system consists of three sections: the source, the sample area, and interior optical system.

(a) The source:

Beam source - S_o

Chopper - C_1

Concave mirrors - M_1, M_1'

(b) The sample area

(c) The interior optical system:

Concave Mirrors - M_4, M_7, and M_9

Flat Folding Mirrors - M_2, M_2', M_5, M_6, and M_8

Semi-circular Rotating Flat Mirror - C_2

Optical Filter to Remove High Orders of the Gratings and Reduce Stray Radiant Energy - OF

Entrance Slit - S_1

Four Gratings for Different Spectral Regions - Grating Table

Exit Slit - S_2

Detector - D

First, consider the alignment of the spectrophotometer when the sample area does not contain the V-W accessory and ACTAM. The source S_o is imaged at E_o by the ellipsoid mirror M_1, and E_o is imaged at the entrance slit S_1 by the toroidal mirror M_4. The plane mirrors M_2 and M_5 are used to fold the beam paths. Figure 2 shows an equivalent diagram of the optical path for mirrors M_1 and M_4 in the horizontal plane. For alignment purposes, a visible source B is placed between the slit S_1 and the parabolic mirror M_7 with B placed as close as possible to the entrance slit S_1 (shown in fig. 1). A bright image of the slit S_1 is formed at E_o. The distance between E_o and the cover of the interior optical system is found to be about 14 mm. The images of both S_o and S_1 are at E_o, but the image sizes are quite different, since S_o and S_1 are magnified by different amounts. Since the magnification of S_1 is 1, the image size S_1' is the same as the size of S_1. The height of S_1 is 12 mm. The width of S_1 is about 0.5 mm at 1050 cm^{-1} wavenumber (the largest width of S_1 is 2.184 mm at 400 cm^{-1} wavenumber). (See fig. 3.) The height of source S_o is 8 mm and the width of S_o is 4 mm. The magnification of S_o is 236/95 or 2.5. The height of S_o' is 20 mm, and the width of S_o' is 10 mm. (See fig. 3.)

Thus, the image S_o' of the source S_o at E_o is larger than the image S_1' of the slit S_1 at E_o. Therefore, the position of S_o' is not critical with these optical parameters, and the effect on the signal to noise will be small with a minimal measurement error for reflectance. The reason for this will become evident later when it is shown that the beam path is the same for the cases of sample in the beam (W geometry) and sample out of the beam (V geometry). The beam flux through E_o is the same even if the center of S_o' is moved away from the optical axis (or E_o) by approximately 3.9 mm. This conclusion assumes the beam flux at S_o' is nearly uniform. The spatial relationship between the entrance slit S_1 to the gratings and IR receiving system was not changed after the IR spectrophotometer was calibrated. Therefore, we adjust the V-W accessory with S_1 rather than with S_o', the former case being more accurate. (See sec. 4.)

3. REFLECTOMETER WITH V-W ACCESSORY AND ACTAM

The V-W accessory is placed in the sample compartment of this IR spectrophotometer. The V-W accessory consists of flat mirrors M_{10}, M_a, and M_{11} as well as a concave mirror M_{12}. M_T and M_T', are auxiliary mirrors used with the autocollimator telescope (ACT) and together comprise ACTAM. In figure 4, the beams drawn with dashed lines illustrate the W geometry and the solid lines illustrate the V geometry. In figure 4, only the mirror M_a is used for the V geometry, but two mirrors, M_a' and M_s, are used for the W geometry. By using a rotatable mount, M_a and M_a' can be the same mirror used at two positions. It will be shown in section 4 that the optic axis and beam paths of the IR spectrophotometer can be the same with and without the V-W accessory in the sample area. Also, when the V geometry and W geometry are interchanged, ACTAM reduces angular error in alignment.

The signal S_v with the V geometry and the signal S_w with the W geometry are given by

$$S_v = K \phi R_a \tag{1}$$

$$S_w = K \phi R_a R_s^2 \tag{2}$$

where K is the instrumental response function, ϕ is the incident flux, R_a is the reflectance of the same mirror used as M_a and M_a', and R_s, is the reflectance of the sample mirror M_s,. From eqs (1) and (2), we obtain

$$R_s = (S_w/S_v)^{1/2}. \tag{3}$$

It is necessary that M_s and M_a' be parallel to M_a to keep the error of the incident angle, α, as small as possible. The mirrors M_a' and M_s have been made parallel external to the ACTAM. For a discussion of this procedure, see appendix A. The mechanical mount that is used can degrade the measurement accuracy of R_s. The ACTAM is an optical feedback system to monitor and to correct the angular positions of the mirrors. This decreases the measurement error in R_s since the positioning accuracy with the ACTAM is better than the mechanical positioning accuracy of the rotatable mirror mount.

In section 4, adjustment of the V-W accessory after insertion into the spectrophotometer is outlined. This includes positioning and alignment of the mirrors in the V-W accessory. In section 5, alignment of the auxiliary mirrors and the autocollimator telescope are presented as well as how to use ACTAM to align test samples in the V-W measurement.

4. ADJUSTMENT OF V-W ACCESSORY IN THE IR SPECTROPHOTOMETER

The V-W accessory is placed in the sample compartment. The resulting beam paths in the interior optical system, after insertion, must be the same with and without the V-W accessory in the sample compartment. If the adjustment of the V-W accessory meets this requirement, light throughput, the S/N (signal to noise ratio), and measurement accuracy will be optimum. The adjustment procedure is now described. There are two rectangular holes, H_1 and H_1', on the cover of the interior optical system. H_1' allows the reference beam to pass through the cover, and H_1 allows the sample beam to pass through the cover. According to the conjugate principle of optical image theory, the object and the image can be interchanged. Let us assume that the entrance slit S_1 and source S_o are geometrical points. The point E_o is not only an image of the entrance slit S_1 formed by the mirror M_4 but also an image of the source S_o formed by mirror M_1. When the V-W accessory is placed in the sample compartment, it must reimage the beam at point E_o.

4.1 The position of the V-W accessory.

An optical diagram of the V-W accessory is shown in figure 5. It consists of two folding mirrors, M_{10} and M_{11}, an off-axis parabolic mirror M_{12}, a sample mirror M_s and a narrow mirror M_a. Since this accessory uses first surface mirrors, its focusing effects are the same at all wavelengths e.g., visible and infrared. The optical axis passes through S_o, D_o and E_o without the V-W accessory. When the V-W accessory is in the IR spectrophotometer, the optical axis passes through S_o, D_o, D_1, D_2, D_3, D_4 and E_o in the V geometry. The optic axis in the W geometry passes through points S_o, D_o, D_1, C_1, D_2', C_2, D_3, D_4 and

E_o. The V geometry is discussed first. Mirrors M_{10}, M_{11} and M_{12} are adjusted until the length D_1D_2 equals the length D_1E_o and the length D_2D_3 equals the length $D_3D_4E_o$. Mirrors M_{10} and M_a are adjusted until the image of S_o is at the surface of M_a. In a similar way, M_{12} and M_{11} are adjusted until the image of S_o is at E_o. Let the mirror M_a turn 180° around the axis which is vertical to the horizontal plane through C_o. The mirror M_a is moved to position M_a'. Then, the sample mirror M_s is inserted. M_a' and M_s are separated by the length $D_2'C_o$. The V geometry is thus changed to the W geometry. The reflecting surface of the sample mirror M_s coincides with the plane "P" which is perpendicular to the horizontal plane. The size of S_o' and the position E_o are not changed when the V geometry is changed into the W geometry. The reflecting surfaces of M_a and M_a' are equidistant to the plane P and also the reflecting surface of M_s coincides with the plane "P."

4.2 Adjustment procedure for the V-W accessory.

The adjustment procedures stated in sections 4.1 are summarized here.

4.2a A visible source B is placed between the slit S_1 and the mirror M_7, as close as possible to slit S_1. (See fig. 1.) The position E_o which is the image position of the slit S_1 is found.

4.2b M_s and M_a' are mounted on opposite sides of this holder, whose faces are nearly parallel. M_a' is aligned using the ACT and three mirrors external to the instrument until it is parallel to M_s. (See appendix A.)

4.2c The image position of the source S_o can be found at D_2 on the surface of the mirror M_a. (See fig. 5.) The image length (D_3D_4 + D_4E_o) of M_{12} is equal the object length D_2D_3 of M_{12}. The object size at D_2 and the image size at E_o on the reflecting surface of M_a will then be equal. (Of course the focal length of mirror M_{12} equals $D_2D_3/2$.)

4.2d The light flux from source S_o which passes through the V-W accessory and E_o is imaged on the entrance slit S_1. M_a is moved along the 00′ axis and the mirror M_{11} rotated about the point D_4 slightly until the image of the source S_o on the entrance slit S_1 is of maximum brightness, and the center of the image of S_o lies on E_o as well.

4.2e The mirror M_a is rotated to position M_a' and the sample mirror at position M_s is inserted (see fig. 5) i.e., the V geometry is changed to the W gerometry.

5. USE OF THE ACTAM TO ALIGN THE SAMPLE IN THE V-W ACCESSORY

5.1 Principle of Operation of ACT.

There are two bright image spots which can be seen in the field of view of the autocollimator telescope. (See figs. 6A and 6B.) One bright spot "a," formed by a plane mirror in the autocollimator, in the middle of the field of view is fixed. Spot "b" is formed by the reflected beam from an outside mirror M. The collimated beam which comes from the autocollimator telescope is projected onto the surface of the mirror M. If the reflecting surface of M is perpendicular to the incident beam, the spot "b" will coincide with spot "a." The autocollimator telescope can be used to determine the angular position of a mirror and to keep its orientation fixed when this mirror is moved.

5.2 Adjustment of the Sample Mirror with the ACTAM.

There is only one mirror M_a in the V geometry. But in the W geometry, there are mirrors M_a' and M_s (shown in fig. 7). The length C_oD_2 is equal to the length C_oD_2' when the V geometry and the W geometry are interchanged since M_a, M_a', and M_s are mounted on the same holder.

5.2a The mirror M_T' in the V geometry is shown in figure 7. The center rays from the ACTAM are reflected to D_2 on the mirror M_a. The angle I in figure 7 must be larger than the angle α in figure 5 so that the mirrors, M_T' and M_T, do not block the source beam from S_o.

5.2b The mirror M_T is positioned such that it is perpendicular to the collimated beam which comes from the autocollimator telescope and is either folded by the mirror M_a, or by the combination of mirror M_a' and the sample M_s. This will occur when the two bright spots coincide.

5.2c When the two bright spots coincide, the beam direction and the beam path for the folding mirrors M_T' and M_T are unchanged when the V geometry and W geometry are interchanged. If the two bright spots do not coincide, the movement error of the mechanical mount of the V-W accessory is the cause. Therefore, the adjustment of the mechanical mount of the V-W accessory must be meticulous in order to achieve high accuracy specular reflectance measurements.

5.3 Angular accuracy of the V-W accessory with ACTAM.

If the V geometry and the W geometry are interchanged without using the ACTAM to monitor and to adjust their positions, one cannot assess how much error in the reflectance R_s is due to position errors. After alignment of the V-W accessory in the sample compartment of the IR spectrophotometer with the ACTAM is completed, measurement of the reflectance R_s of the specular sample according to eq (3) can be performed and the error in R_s due to misalignment is known. If M_a in the V geometry is tilted by an angle ß, the reflected light is rotated by an angle 2ß. The autocollimator telescope has a resolution of 10 s of arc so that the beam direction passing through the accessory and into the interior optical system is accurate to 10/2 or 5 s of arc.

6. UNCERTAINTY AND RESULTS

After the V-W accessory was operational, tests were performed using an electroplated gold mirror Standard Reference Material (SRM) No. 16 which has been certified from 0.6 to 2.5 μm[3,4], and a test aluminum mirror. The absolute reflectance of the gold mirror SRM was measured between the wavelength 2 μm to 22.22 μm. The test aluminum mirror (M_s) is not to be confused with the aluminum mirror (M_a) which is used as a part of the V-W accessory. Besides being used to compare at two wavelengths, the gold mirror SRM was also used to evaluate setup and alignment errors. The test aluminum mirror was used to determine the error caused by misalignment between the V and W geometries, and the error caused by nonuniformity of the other aluminum mirror (M_a) used in the V and W geometries to measure the gold mirror SRM. The measurements are made in a convergent beam with the central ray incident at an angle of 12.8 degrees. The "equivalent f/no" (image distance divided by mirror diameter) is 4.5.

6.1 Alignment error of the V-W accessory

Four pairs of spectral reflectance measurements of the gold mirror SRM were made. Each pair consists of one value with the polarizer (P in fig. 1) in the 0° position, R_o and the other value with the polarizer in the 90° position, R_{90}. The V-W accessory was then removed from the sample compartment after the four pairs were measured (Setup 1). The V-W accessory was inserted again and four more pairs of measurements (Setup 2) were made after the V-W accessory was realigned. The results are shown in table 1. There was a systematic difference between the measurements resulting from the two alignments. This systematic difference was attributed to the fact that the light beam is not perfectly uniform and the slits which open and close depending on the sensitivity function of the spectrophotometer, may not reproduce the exact settings.

For each Setup, the four values of spectral measurements for each polarization were averaged to give the $\bar{R}$ values in table 1. The individual pairs of values for the 0° and 90° polarizations for Setups 1 and 2 were averaged to yield $\bar{R}_1$ and $\bar{R}_2$ with standards deviations ΔR_1 and ΔR_2. $\bar{R}_1$ and $\bar{R}_2$ with respective standard deviations, ΔR_1 and ΔR_2 are shown in table 2. The value $|\bar{R}_1 - \bar{R}_2|/2$ represents the maximum difference from the average, and is an upper bound for the systematic error (3σ) for the average of Setup 1 and Setup 2, $(\bar{R}_1+\bar{R}_2)/2$. The total uncertainty, ΔR_T, is discussed below.

6.2 Uncertainty

Factors which were considered in the error analysis were the alignment error after insertion of the V-W accessory, angle sensitivity as determined by the ACTAM, linearity, stray light, wavelength errors, scattering, random uncertainty, and nonuniformity of the small aluminum mirror used in the measurements.

From section 6.1, the whole V-W accessory alignment uncertainty is estimated by $|\bar{R}_1-\bar{R}_2|/2$ in table 2(3σ).

The angle sensitivity uncertainty was estimated by measuring the test aluminum mirror with a deliberate misalignment of the ACTAM. A misalignment of one spot diameter in the ACTAM in the up, down, left and right directions caused variations of 0.00077, 0.00028, 0.00001, and 0.00029 in $\bar{R}$ when compared to the alignment spot centered. For this test $\bar{R}$ was again measured by four pairs of R_o and R_{90} for each condition i.e., centered down, left, and right. Therefore upper bounds for the vertical uncertainty were estimated to be 0.0008(3σ) and the lateral uncertainty was estimated as 0.0003(3σ). This test was done at 1000 cm^{-1} or 10 μm wavelength.

The linearity was measured by the double aperture method [2]. The reflectances of the gold and test aluminum mirrors are higher than 0.98. There is little error caused by nonlinearity, since the signal in the V geometry is very near to the signal in the W geometry. This uncertainty was estimated to be 0.00013(3σ).

Instrumental stray light and wavelength errors were negligible since these mirrors are spectrally neutral in the mid infrared range.

Quality mirrors are known to scatter light several orders of magnitude less than the main specular component and the error due to scattering is assumed to be negligible.

The standard error (standard deviation of the mean) for R_1 and R_2 was calculated from the four pairs of polarized measurements.

$$SE = \left[\sum_{i=1}^{4} (R_{ji} - \bar{R})^2]/[n(n-1)] \right]^{1/2}$$

with n = 4 and j = 1 or 2,

and standard error for the average $\bar{R}$ is propagated as:

$$\overline{SE} = (1/2) [(SE)_1^2 + (SE)_2^2]^{1/2}$$

where $(SE)_1$ and $(SE)_2$ are the standard errors calculated above. Three times $\overline{SE}$ is the random uncertainty with a confidence level of 99.7%.

The image of the illuminating beam is reversed for the V and W geometries. Therefore, if the small aluminum mirror is nonuniform, an error is introduced. This error was estimated by rotating the small aluminum mirror 180° about its own axis and comparing signals at 0° and 180°. The range was 0.00020, and this was taken to be an estimate of the uncertainty (3σ).

These uncertainties were added in quadrature (square root of the sum of squares) with the result ΔR_T in table 2. ΔR_T varies between 0.0014 to 0.0024 in the wavelength range of 2 to 22.22 μm. The uncertainty of instruments which do not use ACTAM are typically 0.01 to 0.02.

6.3 Comparison with previously published values.

Two values for 12.8 degree incidence in parenthesis in table 2 result from interpolation from values at 6° and 30° angle of incidence for the SRM No. 16 gold mirror. The agreement is within the combined uncertainty. The values for a freshly evaporated quality gold coating, which are always greater than those for an electroplated mirror, serve as an upper bound and are shown in table 3 for this wavelength region. [5]

7. SUMMARY

It has been shown that the ACTAM can be used to position the V geometry and W geometry in a very reproducible way. Therefore, one of the most uncertain features of this type of measurement is reduced and quantified. An example of measuring a gold mirror standard gives results within the combined uncertainties. Finally, the uncertainty of the measurements of the gold mirror SRM using this reflectance accessory is calculated and shown to be less than 0.0025 at all wavelengths tested from 2 to 22 μm.

8. REFERENCES

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9. ACKNOWLEDGMENT

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Table 1. Measured specular reflectance at 12.8° of gold mirror SRM No. 16 for two orientations of the polarizer for two Setups of the reflectance attachment. Each value is the average of four independent runs.

			Setup 1	Setup 2	Setup 1	Setup 2
No.	$\nu(cm^{-1})$	$\lambda(\mu m)$	$\bar{R}_o$	$\bar{R}_o$	$\bar{R}^{90}$	$\bar{R}_{90}$
1.	5000	2.000	0.9831	0.9855	0.9819	0.9865
2.	4800	2.083	0.9822	0.9862	0.9832	0.9873
3.	4600	2.174	0.9824	0.9864	0.9833	0.9868
4.	4400	2.273	0.9828	0.9860	0.9832	0.9871
5.	4200	2.381	0.9828	0.9857	0.9836	0.9873
6.	4000	2.500	0.9828	0.9868	0.9839	0.9880
7.	3200	3.125	0.9847	0.9884	0.9850	0.9883
8.	2800	3.570	0.9847	0.9883	0.9852	0.9889
9.	2000	5.000	0.9870	0.9879	0.9870	0.9895
10.	1500	6.666	0.9868	0.9885	0.9878	0.9895
11.	1000	10.00	0.9879	0.9890	0.9879	0.9897
12.	800	12.50	0.9889	0.9915	0.9888	0.9934
13.	700	14.30	0.9890	0.9923	0.9896	0.9939
14.	500	20.00	0.9890	0.9908	0.9893	0.9917
15.	400	22.22	0.9900	0.9931	0.9898	0.9938

Table 2. $\bar{R}_1$ and $\bar{R}_2$ are the specular reflectances at 12.8° of the gold mirror SRM No. 16 for the average of the paired combinations of 0° and 90° polarizations for Setups 1 and 2. ΔR_1 and ΔR_2 are their standard deviations. $(\bar{R}_1-\bar{R}_2)/2$ is the magnitude of the systematic difference from the average $(\bar{R}_1+\bar{R}_2)/2$. ΔR_T is the total uncertainty as defined in section 5. The two values in parenthesis are taken from the certificate for NIST SRM 2011.

No.	$\nu(cm^{-1})$	$\lambda(\mu m)$	$\bar{R}_1$	ΔR_1	$\bar{R}_2$	ΔR_2	$\lvert\bar{R}_1-\bar{R}_2\rvert/2$	$(\bar{R}_1+\bar{R}_2)/2$	ΔR_T
1.	5000	2.000	0.9825	0.00030	0.9860	0.00010	0.0017	0.9843	0.0023
								(0.9812)	
2.	4800	2.083	0.9827	0.00050	0.9867	0.00053	0.0020	0.9847	0.0024
3.	4600	2.174	0.9828	0.00063	0.9866	0.00022	0.0022	0.9847	0.0020
4.	4400	2.273	0.9830	0.00063	0.9866	0.00059	0.0018	0.9848	0.0023
5.	4200	2.381	0.9832	0.00078	0.9865	0.00062	0.0017	0.9849	0.0022
6.	4000	2.500	0.9834	0.00020	0.9874	0.00038	0.0020	0.9854	0.0023
								(0.9803)	
7.	3200	3.125	0.9848	0.00034	0.9883	0.00076	0.0018	0.9866	0.0022
8..	2800	3.570	0.9850	0.00074	0.9886	0.00079	0.0018	0.9868	0.0024
9.	2000	5.000	0.9870	0.00022	0.9887	0.00026	0.0008	0.9878	0.0014
10.	1500	6.667	0.9873	0.00018	0.9891	0.00034	0.0009	0.9882	0.0014
11.	1000	10.00	0.9879	0.00088	0.9894	0.00042	0.0008	0.9887	0.0016
12.	800	12.50	0.9888	0.00044	0.9923	0.00067	0.0017	0.9906	0.0022
13.	700	14.30	0.9893	0.00036	0.9931	0.00037	0.0019	0.9912	0.0023
14.	500	20.00	0.9891	0.00031	0.9913	0.00076	0.0011	0.9902	0.0017
15.	450	22.22	0.9899	0.00065	0.9935	0.00036	0.0018	0.9917	0.0022

Table 3. Reflectance values for a freshly evaporated gold coating [Ref. 4]

$\lambda(\mu m)$	R(%)
2	99.1
3	99.3
4	99.4
5	99.4
6	99.4
7	99.4
8	99.4
9	99.4
10	99.4
15	99.4
20	99.4

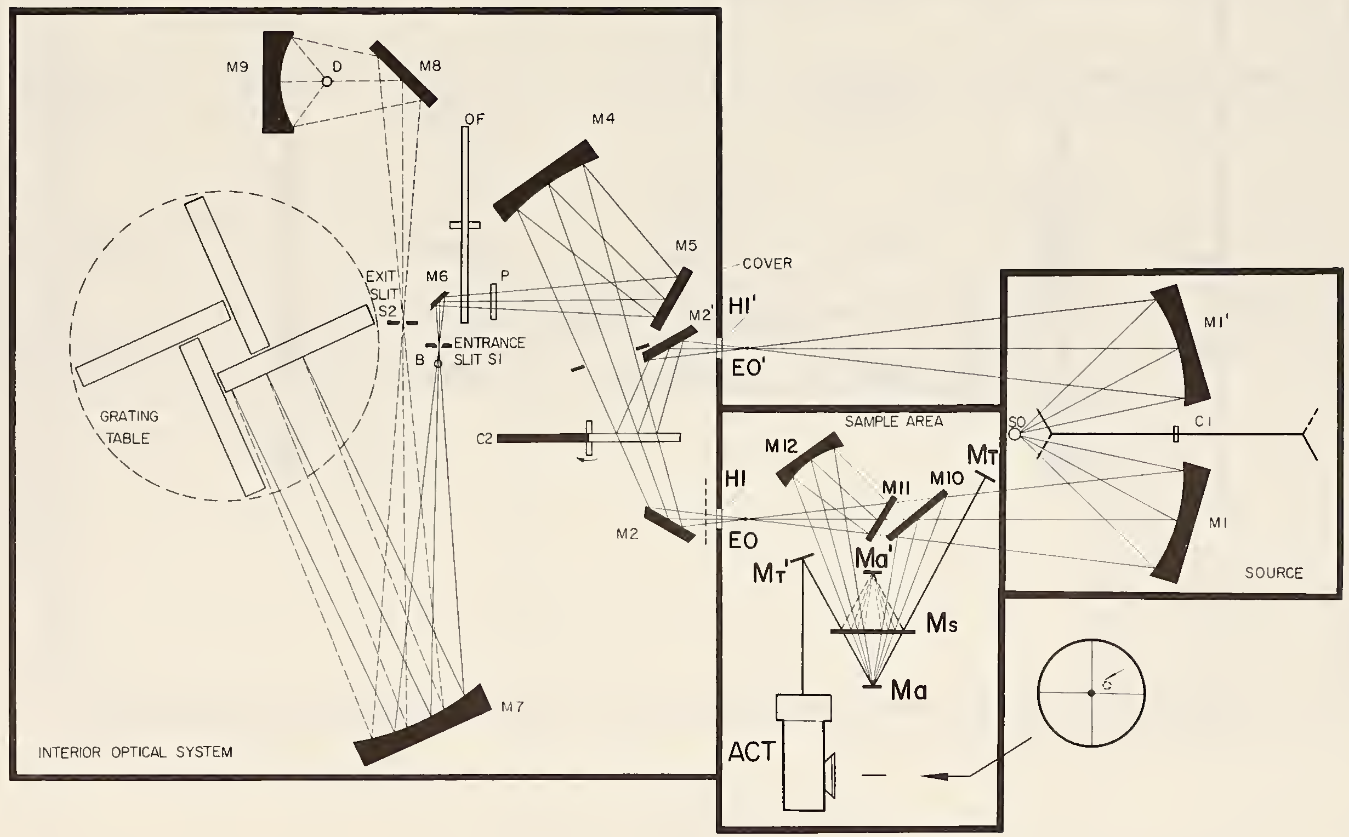

FIGURE 1. Optical Diagram of the Spectrophotometer showing the ACTAM with the V Geometry and W-geometry. The key elements are defined in the text.

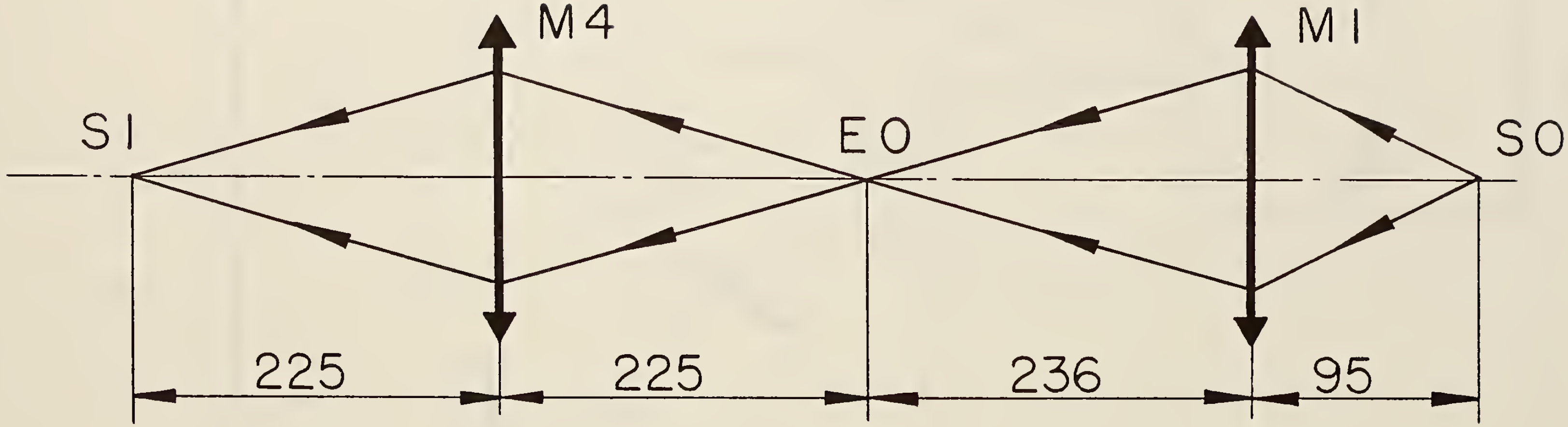

FIGURE 2. Equivalent optical diagram showing critical points in the spectrophotometer. The dimensions are expressed in mm.

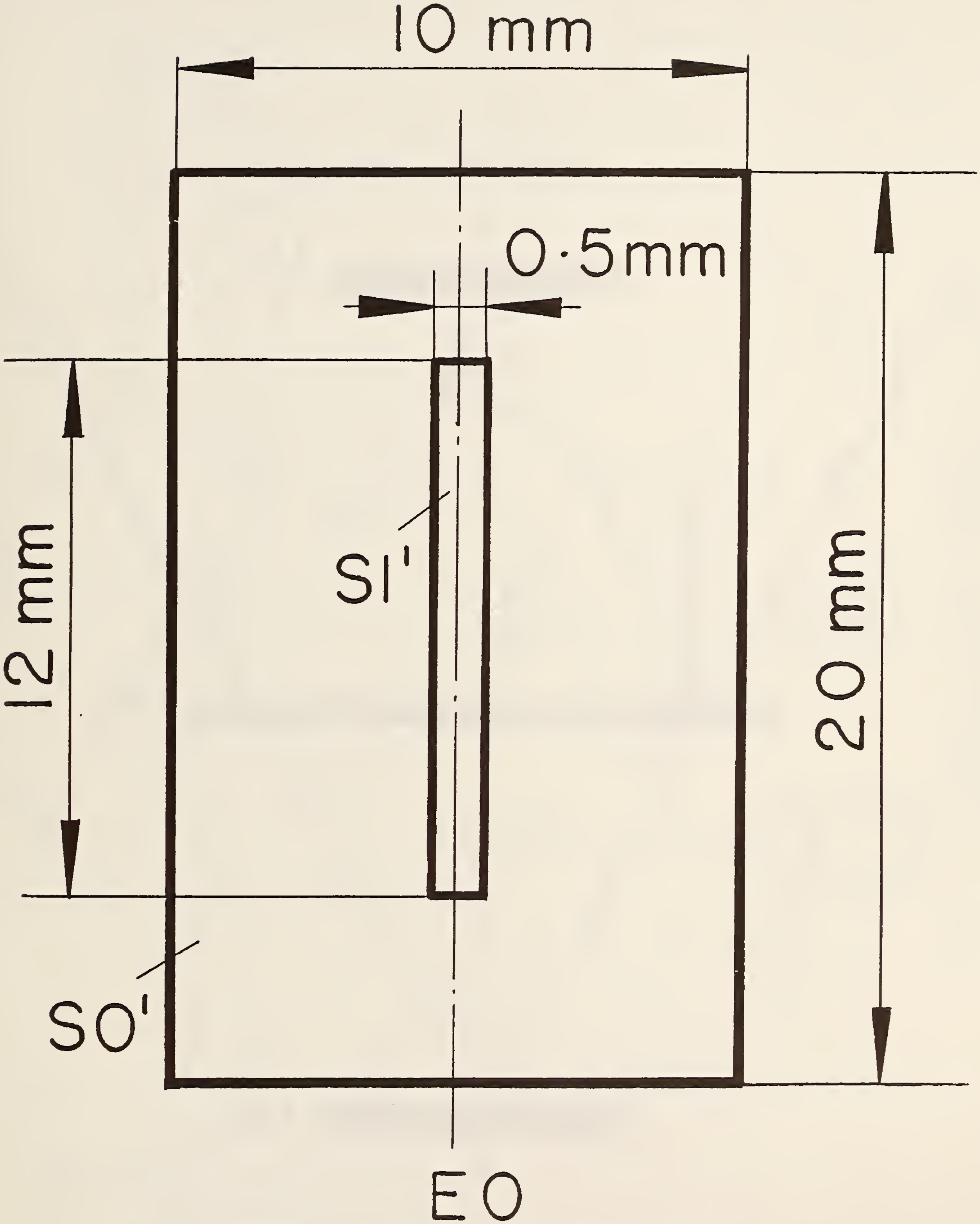

FIGURE 3. Slit and light beam at point E_o.

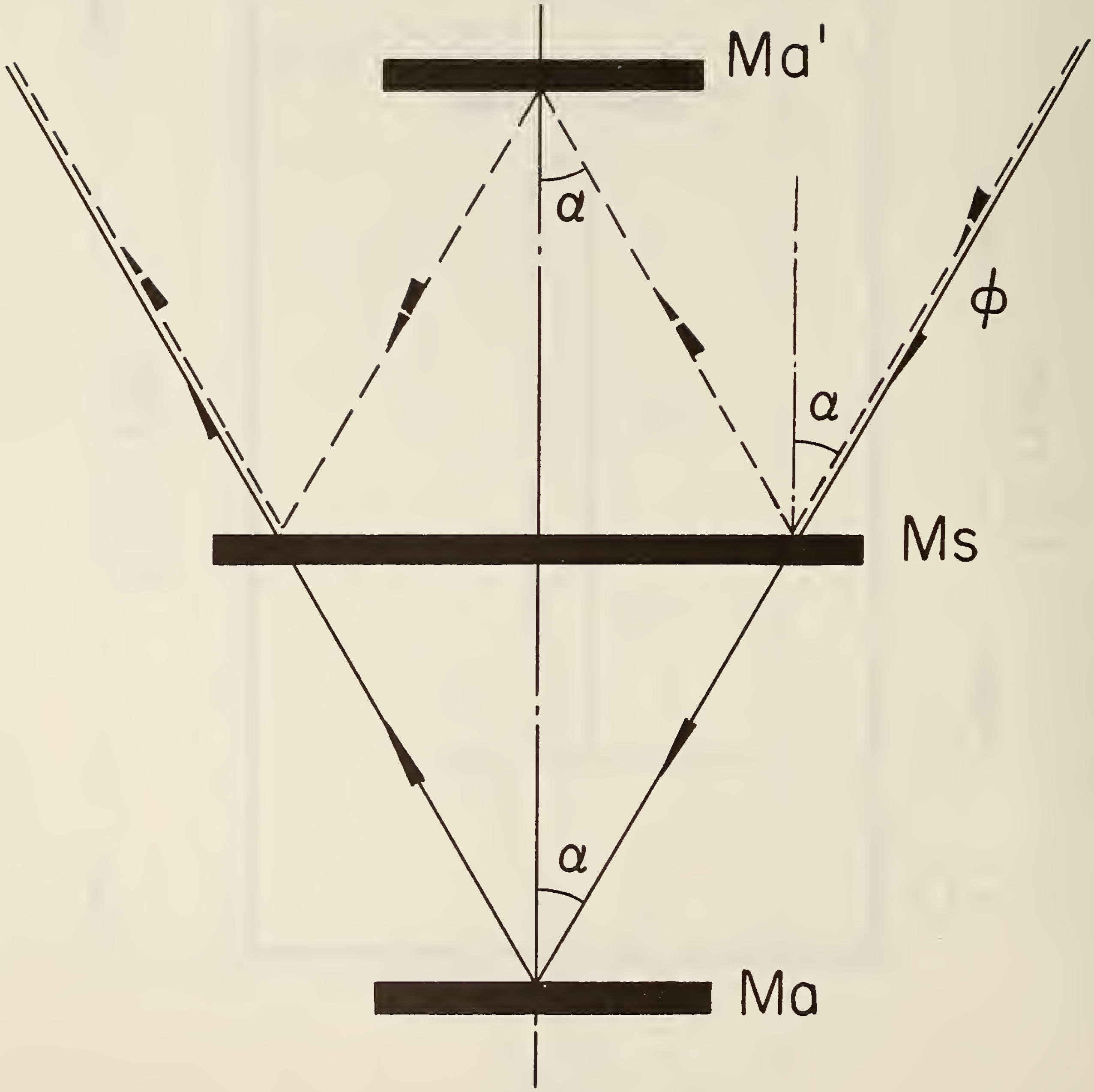

FIGURE 4. The V and W geometries with angle of incidence α.

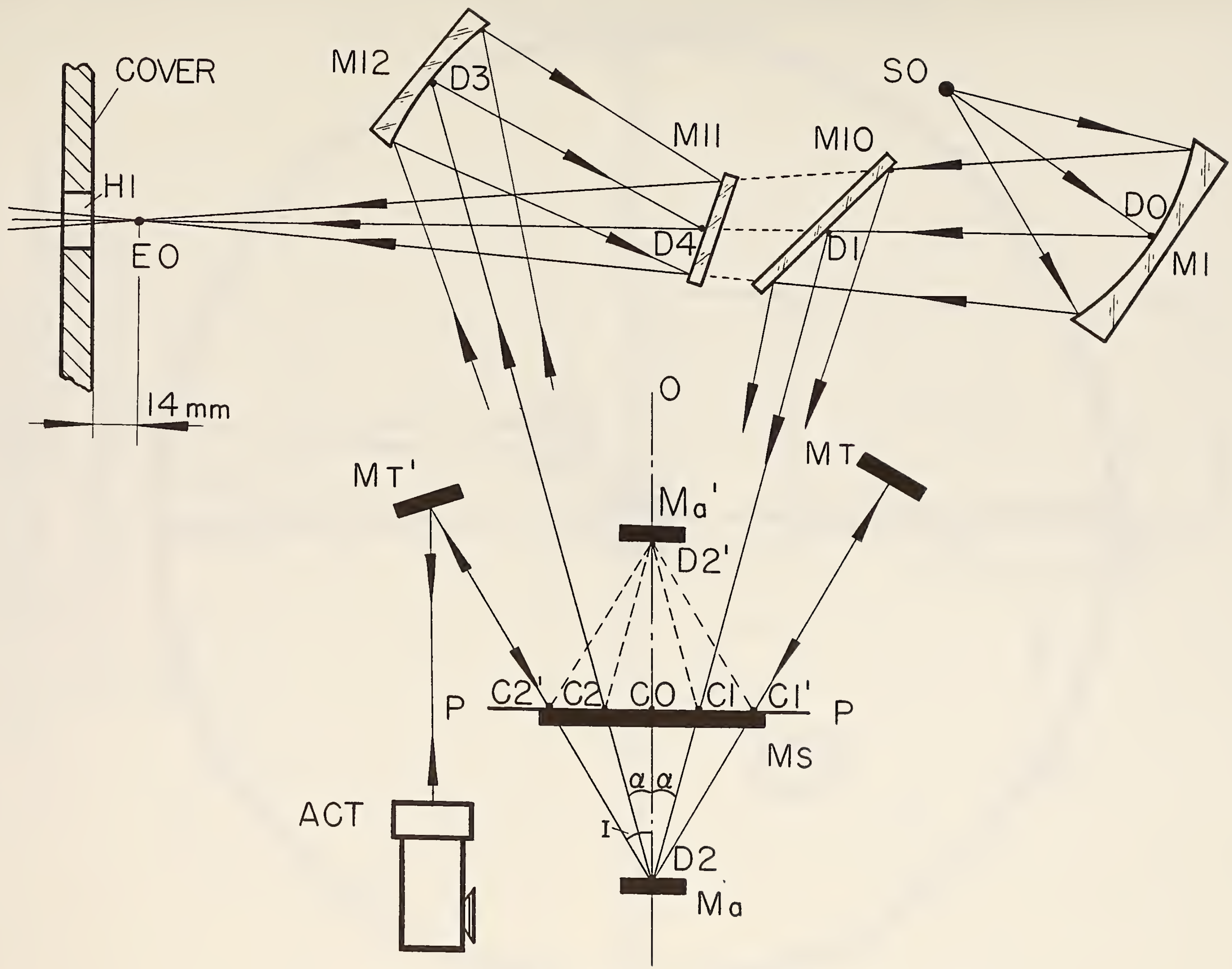

FIGURE 5. Diagram showing how the ACTAM interacts with the V-W accessory in the spectrophotometer.

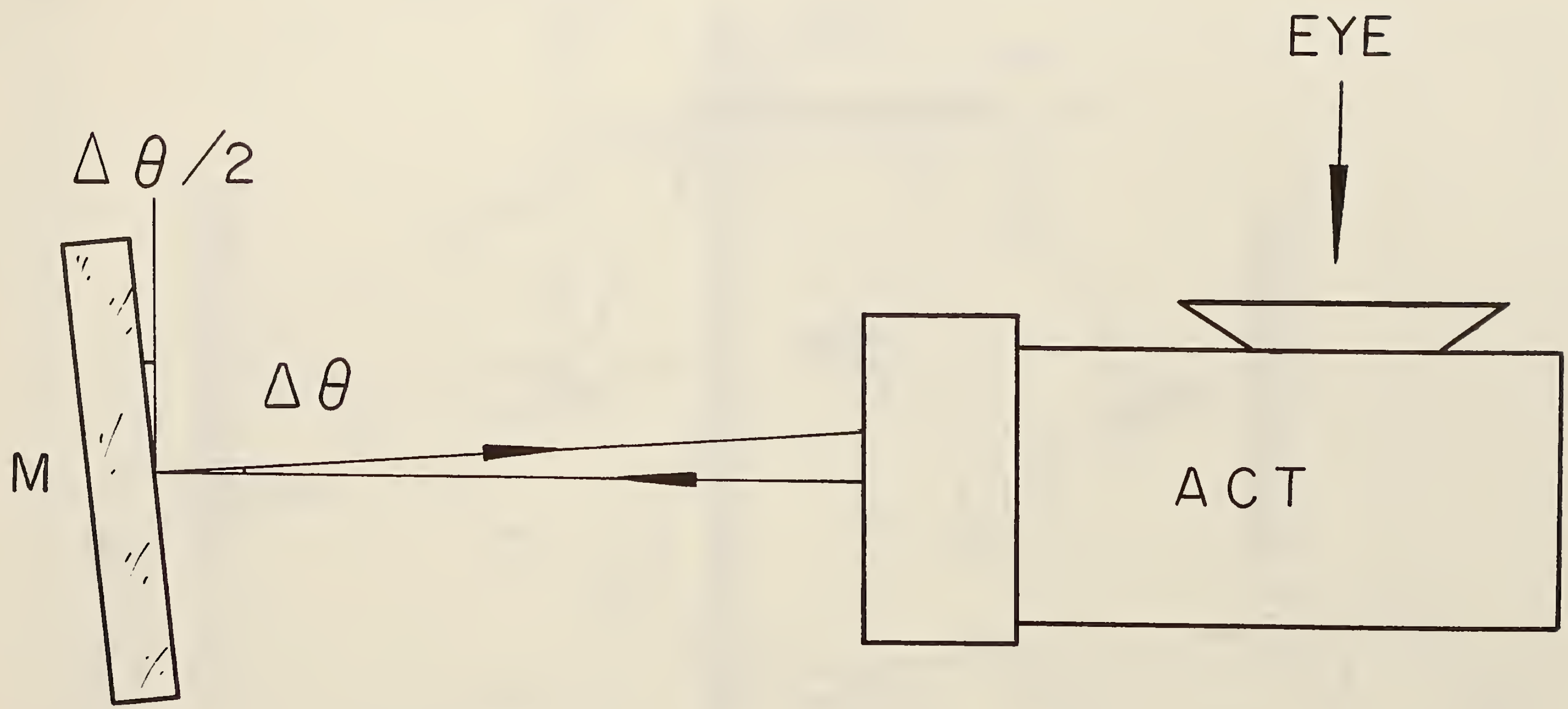

FIGURE 6A. Autocollimator telescope interacting with a mirror tilted by an angle $\Delta\Theta/2$.

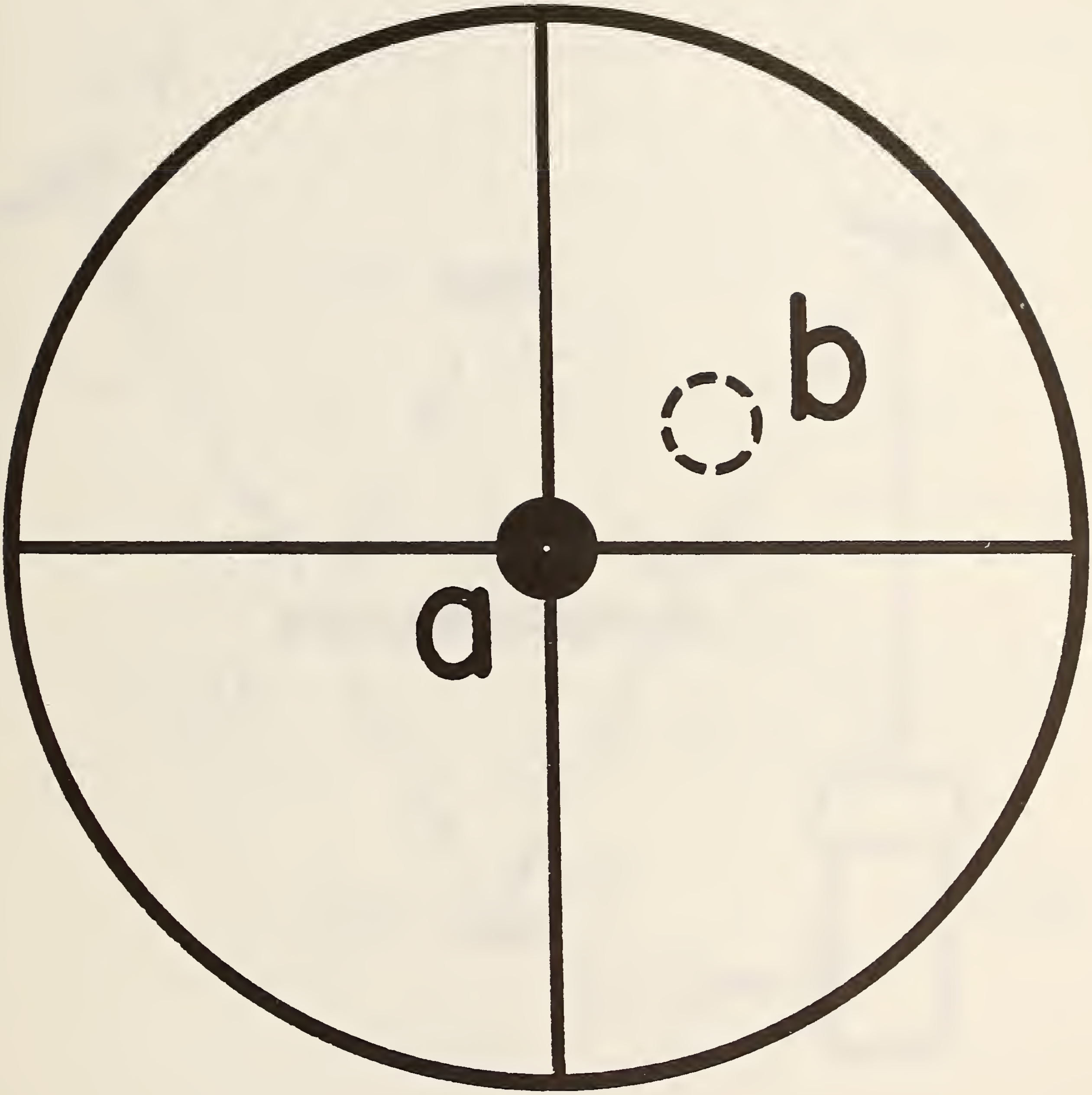

FIGURE 6B. Field of view of autocollimator telescope; "a" is the reference bright spot and "b" is the reflected bright spot.

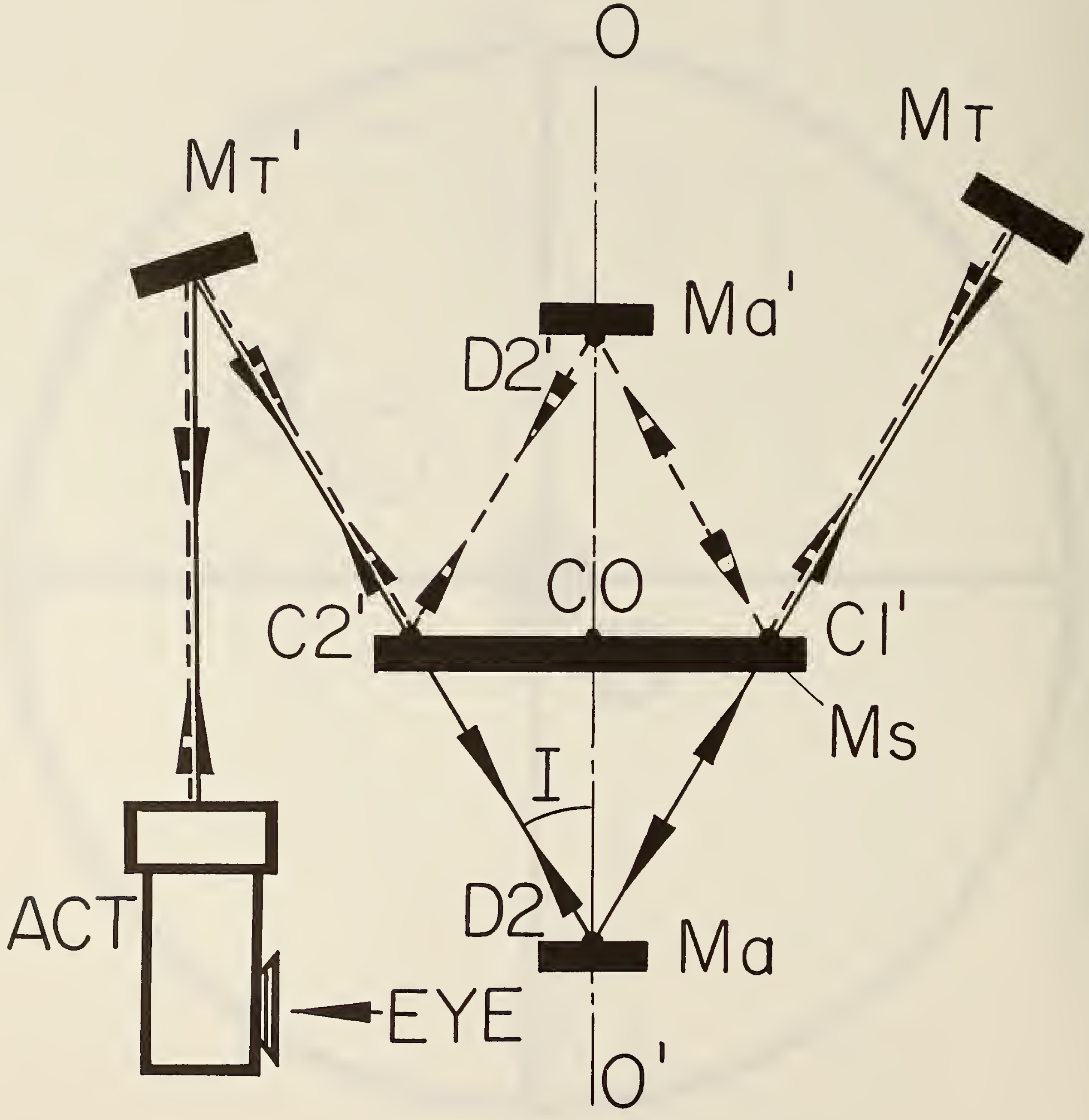

FIGURE 7. Diagram showing ACTAM with mirrors in the V and W geometries.

APPENDIX A: ADJUSTMENT OF MIRROR HOLDER

Mirror M_a' and sample M_s are held on two sides of the same holder (see fig. A1).

The procedures for checking and adjusting parallelism of M_a' and M_s are as follows:

(a) A test arrangement (See fig. A2) is set up with mirrors K_1, K_2, K_3 and autocollimator telescope (ACT) without M_a' and M_s. The beam from the ACT is reflected from mirrors K_1, K_2 and K_3 and then back to the ACT forming one bright spot at the center of the field of view of the ACT in addition to the reference spot. This test arrangement is shown in figure A2.

(b) Next, the holder with mirrors $M_a'$and M_s is placed in the beam path of the test arrangement (See fig. A2) with the coated surface of M_s against the holder. The holder is then adjusted until M_s is perpendicular to the beam from K_3. The image spot reflected by M_s and by mirrors K_3, K_2 and K_1 is superimposed on the reference spot at the center of the field of view of the ACT.

(c) After M_s is removed, the beam from the ACT is directed to M_a'. This beam is reflected by M_a' back to the ACT. M_a' is adjusted (See fig. A1) so that the image spot is superimposed on the reference spot also.

Thus M_a' is parallel to M_s since both images are superimposed on the reference spot.

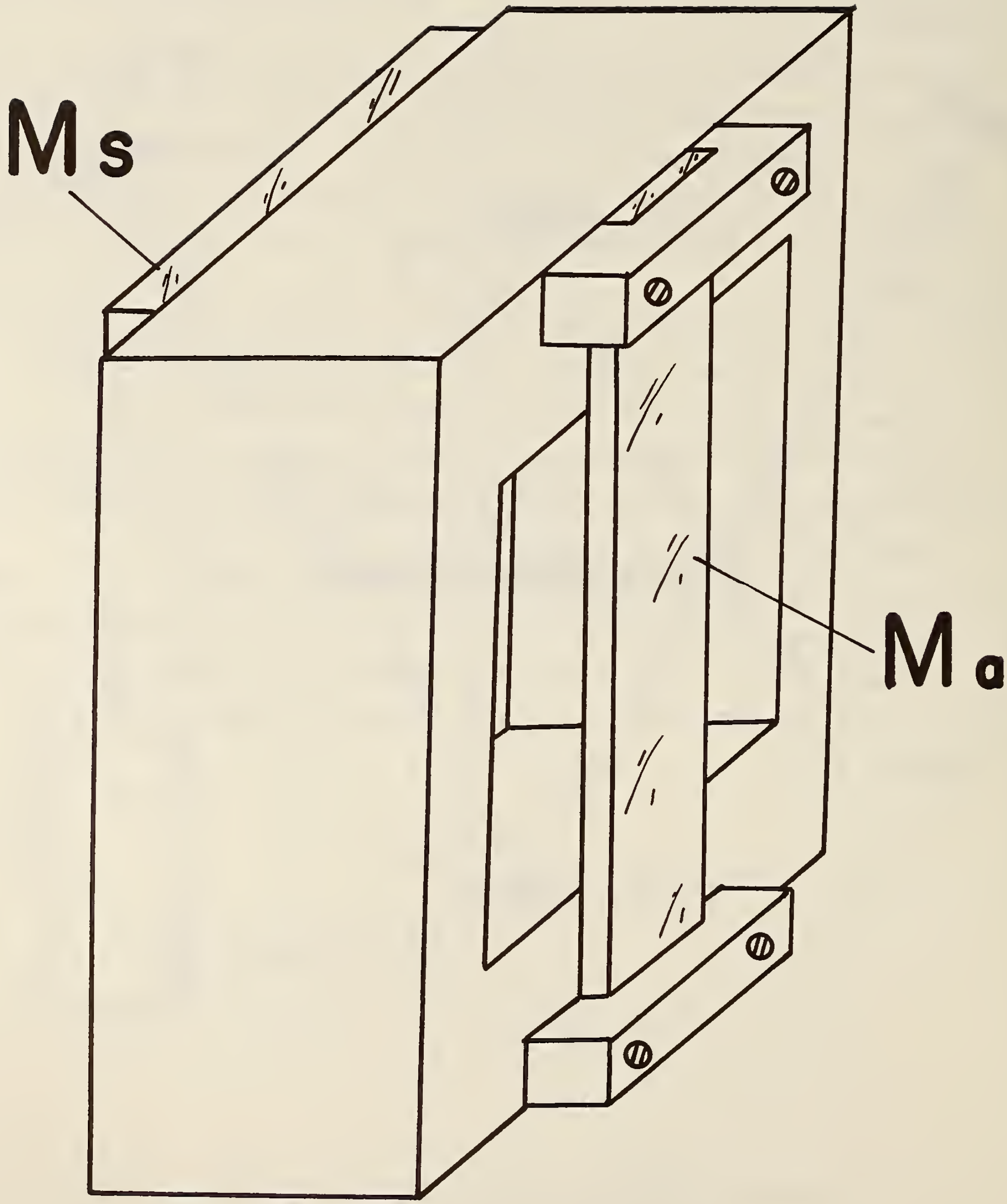

FIGURE A1. Mirrors M_a' and M_s mounted on holder.

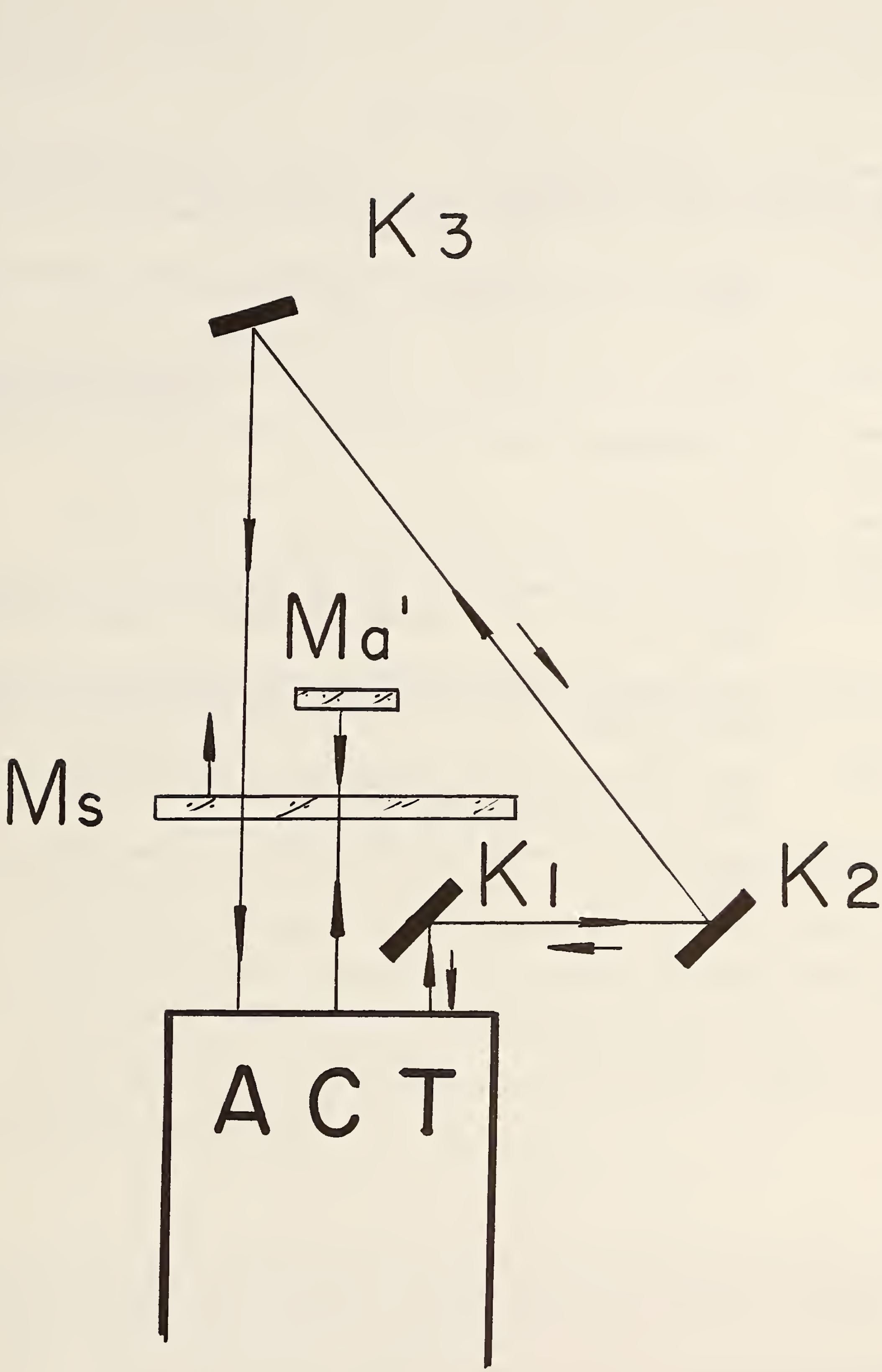

FIGURE A2. Arrangement for making M_a' parallel to M_s.

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5. AUTHOR(S)

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12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

alignment; autocollimator telescope; auxiliary mirrors; specular (regular) reflection; strong (vw) method; uncertainty

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