A White-Light Amplitude Interferometer with 180-Degree Rotational Shear

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Abstract

The fabrication and assembly of a point symmetric, rotational shear interferometer with 180-degree rotation is given. It has been used to photograph the Michelson Stellar interferometer fringes in white light without the use of an image intensifier at a large astronomical telescope.

Introduction

We describe the fabrication, alignment, test and evaluation techniques for an equal-path wave-front folding amplitude interferometer which was used with white light for several engineering and scientific experiments.[1-3] It is a shear interferometer of 180 degrees rotation, and is useful for measurements of the phase perturbing properties of the atmosphere,[2] for fabrication of optical filters for spatial information processing[3] (optical computers), and for other applications.[3] The first photographic record of the Michelson Stellar interferometer fringes was made with this apparatus. The interferometer is useful for the testing and evaluation of optical systems. Analysis of the interferometer has been given,[1,3,4] and will not be repeated here.

Figure 1 shows a view of the coherence interferometer prisms. A plane wave front entering the interferometer is complex amplitude divided at the beamsplitter. One wave front enters the left arm of the interferometer and is rotated about a vertical axis upon reflection from the roof. The other wave front passes through the beamsplitter, enters the other arm of the interferometer, and is rotated about a horizontal axis upon reflection from the roof. Both wave fronts recombine at the beamsplitter.

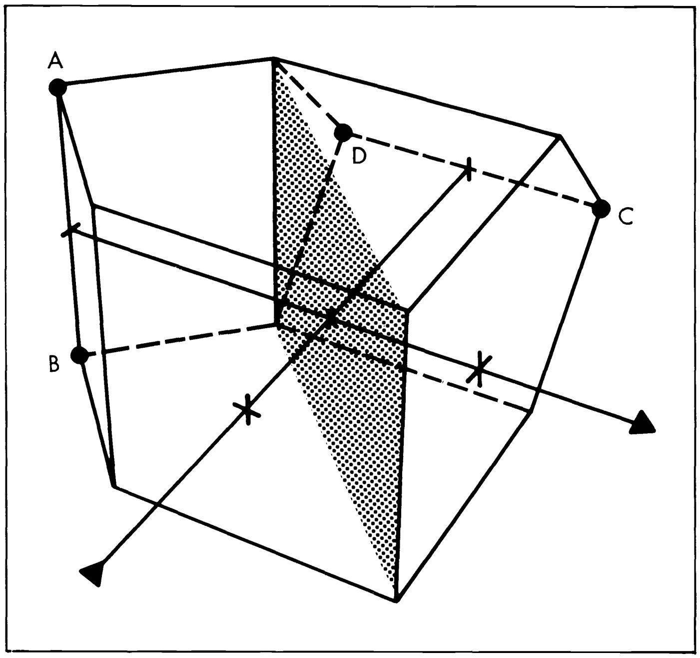

Figure 1. Perspective view of the assembled coherence interferometer prisms with roof lines AB and CD indicated.

The interferometer is a two-dimensional version of a modified Kösters prism interferometer, which was described by J. B. Saunders.[5] An optical device which looks similar was first[6] used by K. Räntsch[7] for folding intensity fields. L. Mertz[8] suggested that a 180-degree rotational shear interferometer could be used to present a display related to the two-dimensional spatial frequency Fourier transform a self-luminous or incoherently illuminated scene. An interferometer similar to the one described here was proposed (but never built) by H. R. Worthington, Jr.[9]

Prism Specification

Figure 1 shows the assembled coherence interferometer with roof lines AB and CD indicated. We use this drawing to describe a tolerance analysis of the system. Using notation of an earlier paper[3] we let ξ, η denote a point in pupil space and coordinate x, y denote a point in image space. In an earlier paper[1,3] we showed the intensity at the detector plane to be given by

$$I(\xi,\eta) = \tfrac{1}{2} < \left| V(-\xi,\eta;t) + V(\xi,-\eta;t)\right|^2 >, \qquad (1)$$

where, $V(\xi,\eta;t)$ is the analytic square representation of the electromagnetic field. We represent the electromagnetic field which returns from the interferometer arms to the beamsplitter in terms of the angular spectrum of plane waves, to give

$$V(\xi,-\eta;t) = \iint_{-\infty}^{\infty} A(x,y)\exp[-i\bar{k}(x\xi-y\eta)]\exp[-i\omega t]\,dxdy$$

$$V^*(\xi,-\eta;t) = \iint_{-\infty}^{\infty} A^*(x,y)\exp[+i\bar{k}(x\xi-y\eta)]\exp[+i\omega t]\,dxdy$$

$$V(-\xi,\eta;t) = \iint_{-\infty}^{\infty} A(x,y)\exp[-i\bar{k}(-x\xi+y\eta)\exp[-i\omega t]\,dxdy \qquad (2)$$

$$V^*(-\xi,\eta;t) = \iint_{-\infty}^{\infty} A^*(x,y)\exp[+i\bar{k}(-x\xi+y\eta)]\exp[+i\omega t]\,dxdy$$

where $\bar{k} = 2\pi/\bar{\lambda}$, $\bar{\lambda}$ is the mean wavelength, and A(x,y) is the amplitude. We assume quasimonochromatic light.

We insert Eq. (2) into Eq. (1), and let $A(x,y) \cdot A^*(x,y) = I(x,y)$, then Eq. (1) becomes

$$I(\xi,\eta) = \frac{1}{2} I + \frac{1}{4} \int_{-\infty}^{\infty} I(x,y) e^{-i\bar{k}(2\xi x - 2\eta y)} dxdy$$

$$+ \frac{1}{4} \int_{-\infty}^{\infty} I(x,y) e^{+i\bar{k}(2\xi x - 2\eta y)} dxdy. \qquad (3)$$

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We now calculate the effects of a difference in optical path length in the two arms. Assume this error to be uniform across the prism aperture and to be given by L. The phase error E is given by

$$E = e^{i\bar{k}L} \tag{4}$$

which is not a function of spatial position. We assume that the optical material in each arm is the same and that the optical dispersions are equal.

Let the path difference L be shared equally by each arm of the interferometer. Regrouping the integrals in Eq. (3), we find, under the assumption of time stationarity of the wave fields,

$$I(\xi,\eta) = \frac{1}{2}\, I + \frac{1}{2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y) \cos[\bar{k}(2\xi x - 2\eta y) + \bar{k}L]\, dxdy. \tag{5}$$

Assuming $\bar{k}L << 1$, we find

$$\cos[\bar{k}(2\xi x - 2\eta y + \bar{k}L] = \cos[\bar{k}(2\xi x - 2\eta y)] - \sin[\bar{k}(2\xi x - 2\eta y)] \cdot \bar{k}L. \tag{6}$$

If we insert Eq. (6) into Eq. (5) we see that the irradiance distribution is an integral over cosine and sine. We want the prism to give an analog cosine Fourier transform. If the maximum tolerable value of the amplitude of the sine term is 0.2, then the maximum value of $\bar{k}L = 0.2$ and $L \approx \bar{\lambda}/30$. The optical path lengths in each arm of the prism interferometer must be equal to within 1/30 wave for the value of the amplitude of the sine term in Eq. (6) to be 0.2 or less. The interferometer is designed for use in the visible and photographic part of the spectrum. We assume a quasimonochromatic wavelength of 500 nm and a bandpass of approximately ± 150 nm.

We compute next the tolerance of each roof angle such that each reflected plane wave is parallel to the incoming wave to within .1 wave (approximately 5×10^{-6} cm). For a clear aperture of 1.5 centimeters the error in the roof angle must not exceed 3.5×10^{-6} radians or approximately 0.5 arc seconds. Fabrication of a roof which deviates the incoming beam by 180 degrees ± 0.25 arc seconds over the useful area is required.

The apparent angle between the intersection of the roof apices, which ideally should be 90 degrees, is an important geometric aspect. If it were other than 90 degrees, the rotational shear of the interferometer would not be 180 degrees. We assume that the size of the Airy disk given by the image plane defining aperture is such that the spatial field of the image of the pupil is correlated over an area of 5 microns. A 2 cm diameter aperture rotated about its center by 60 arc seconds shears the rim of the field by 5 microns. The adjustment is not as critical as the others, and we specify the tolerance on the rotational shear to be on the order of one arc minute.

Another parameter is tilt of the field from one arm relative to that from the other. We see this error in Figure 1. Consider that roof AB is not perpendicular to roof DC.

We use Eq. (5) and assume a tilt error at recombination of the wave fronts as given by

$$E = e^{i\bar{k}(a\xi + bn)}. \tag{7}$$

For small a and b, the equation for the intensity across the detector plane is:

$$I(\xi,\eta) = \frac{1}{2} \int_{-\infty}^{\infty} I(x,y)[1+\cos[\bar{k}(\xi(2x - a)) - \bar{k}(\eta(2y - b))]]\, dxdy, \tag{8}$$

where $\bar{k} = 2\pi/\bar{\lambda}$. Small tilts on the recombined wave front result in a shift of the origin of the x,y coordinate for integration. A tilt in the recombined wave front yields an apparent nonuniform illumination. However, physically tilting the block eliminates this nonuniform illumination. Consequently, the tolerance that line AB in Figure 1 be parallel to the beamsplitter plane is given as a minute of arc.

The bevel on the roof establishes how close to zero spatial frequency we can record with the coherence interferometer. A bevel of .002 inch was specified. The glass is high quality Schott BK-7 (517642), which has an index of refraction uniform to within one part in 10^6 for thickness to 4 cm. This is necessary to preserve the phase uniformity of the wave front when it propagates through the 12 cm of glass. The glass is of Schlieren quality.

Prism Fabrication

The interferometer in Figure 1 has a basic cube dimension of 3.2 x 3.2 x 3.2 centimeters. Precision Optical Division of Valtec at 869 W. 17th Street, Costa Mesa, CA, fabricated the prisms from two cube corner retro-reflectors of four inch clear aperture. They modified a selected production item as follows: Each prism was cut from a solid cube corner which was tested and found to retro-reflect a plane wave front better than 0.5 arc second. They were polished to remove residual angle errors as measured with an optical collimator. Figures 2, 3, and 4 show perspective views of how the cutting was done. Figure 5 shows a photograph of the finished prisms.

An important aspect of the assembled interferometer is that it is white-light compensated. That is, the optical path is the same in both interferometer arms. The adjustment necessary for this alignment is seen in reference to Figure 1. Some thought on the part of the reader will convince him that a shear of one prism across the face of the other at the beamsplitter surface changes the OPD in one arm relative to that in the other.

The next section describes the mechanical assembly which supports the prisms and enables the alignment to be performed and held.

Prism Support Apparatus

Figure 6 shows a photograph of the mechanical assembly supporting the prism components of the interferometer. This assembly provides precision control for the adjustment of path differences. The assembled prisms rest on a 2-inch (5.08 cm) diameter reference flat. The finely polished glass surface of the prisms are the surfaces against which the manufacturer "squared up" the prisms. All glass surfaces that contact one another do so through a thin film of Dow Corning 704 silicone oil, vacuum pumped to remove air and filtered through a 0.1 micron filter.

Four Valier screws (spring-loaded set screws) provide downward forces to secure the prisms to the optical flat. Another spring-loaded set screw provides pressure to hold the prisms together at their beamsplitting surface. We take care not to apply too much pressure with the spring-loaded set screws, since pressure-induced phase inhomogenieties in the glass affect the wave front.

A differential micrometer provides for movement of one prism component relative to the other and enables alignment for the white-light fringe.

Alignment

We examined the interferometer output wave front using plane-wave input from a Spectra-Physics Model 132 laser equipped with a beam expander. A visual inspection of fringe parallelism showed that the wave fronts recombine at the beamsplitter with an accuracy of 0.1 wave over the 2 cm aperture.

Fine adjustment to equalize the OPD was accomplished viewing channel spectra. These channel spectra were formed by passing a collimated beam of white light through the interferometer on the system axis. Looking back through the system an

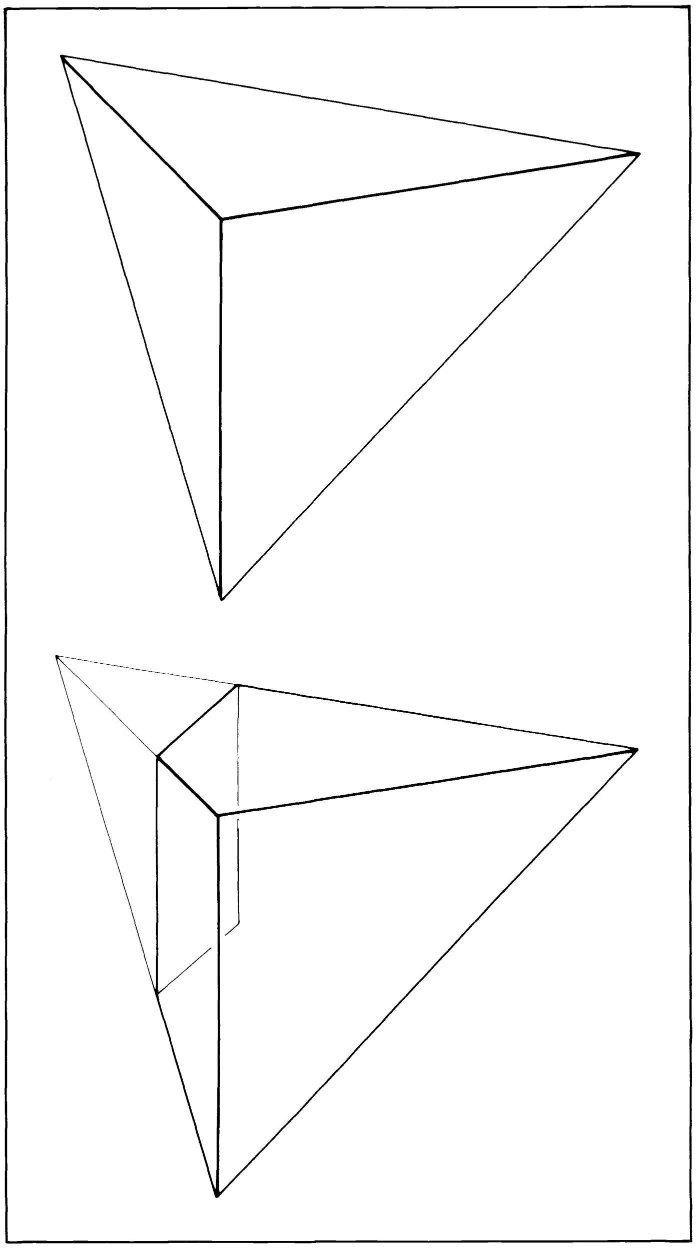

Figure 2. Fabrication of coherence interferometer from glass cube corner. Above: A complete cube corner retro-reflector. Below: Shows the first cut to fabricate each of the two prisms. Two cube corners are required, one for each prism.

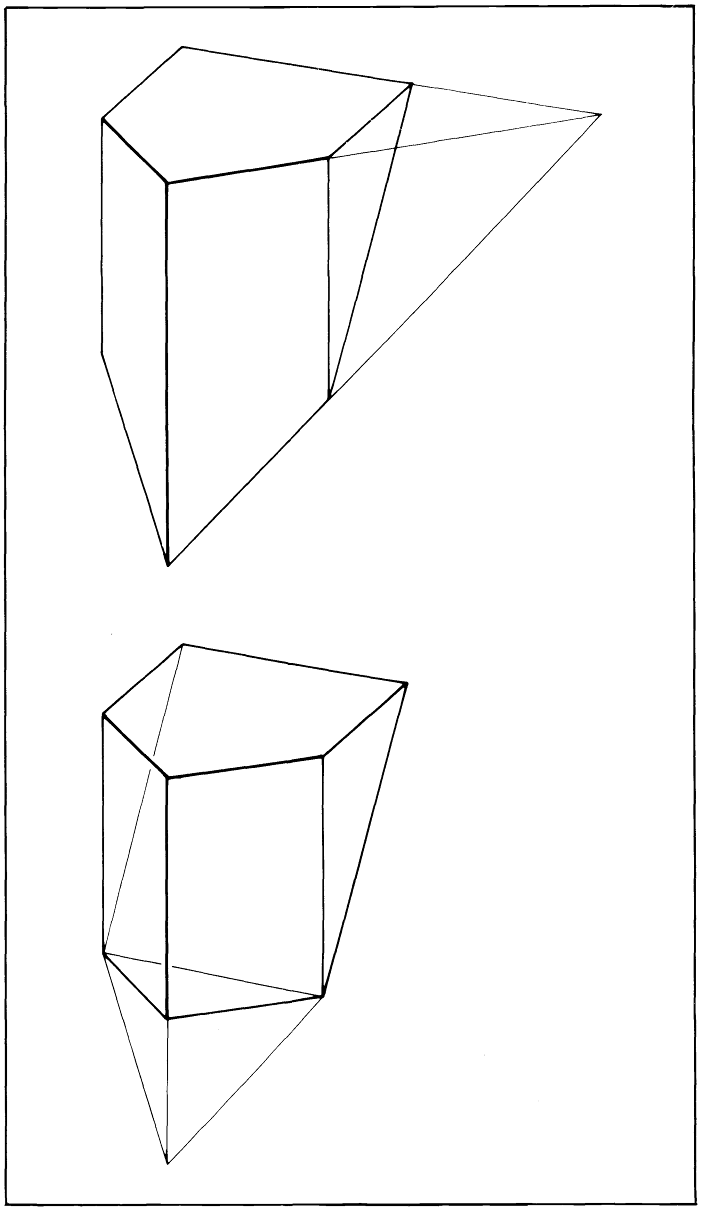

Figure 3. Cuts to form the prism shown in the upper right part of Figure 1, starting from the modified prism shown at the bottom in Figure 2.

observer sees the collimated beam split into four quadrants by the roof lines. A small direct vision spectroscope was positioned on the system axis and the spectrum of the collimated beam of white light was examined for the presence of channel spectra. We advanced the differential micrometer screw on the prism support apparatus in the appropriate direction to decrease the number of channel fringes. When the adjustment is complete the transmitted spectrum is uniform across the visible region. Experience shows that there is negligible creeping of the adjustment.

Channel spectra occur only over that portion of the slit height illuminated coherently. The Airy pattern, consisting of the central bright spot of the Fraunhofer diffraction pattern of the iris and the rings around it, define that area. That is, light from each portion of the ring is coherent with another point on the ring. We clearly see the channel pattern across the central bright area. A line appears across the top and the bottom of the spectrum. Outside of the line appears another channel spectrum on either side of the primary one and out of phase with it. That is, those channels which appear dark in the central patch appear light in the light of the two outer rings. The width and clarity of the channel spectrum increases as the iris in front of the objective at plane 2 is closed down. This is to be expected and is a consequence of the degree of coherence increasing as the aperture is closed.

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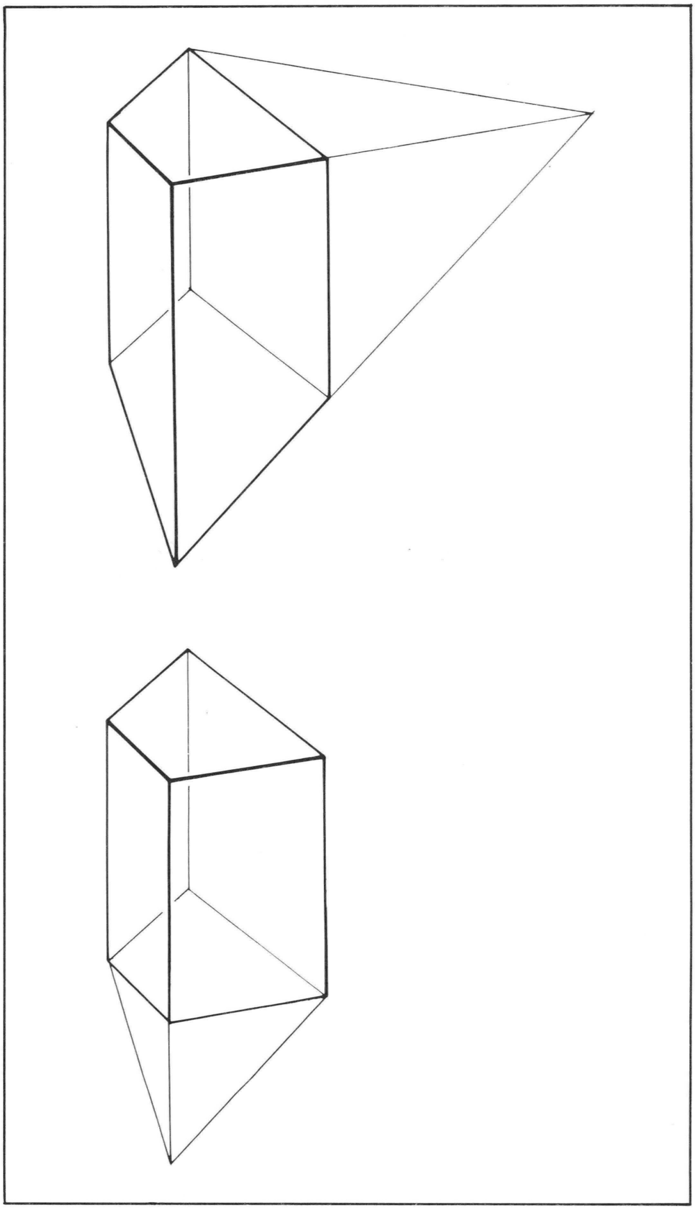

Figure 4. Cuts to form the prism shown in the lower left part of Figure 1, starting from the modified prism shown at the bottom in Figure 2.

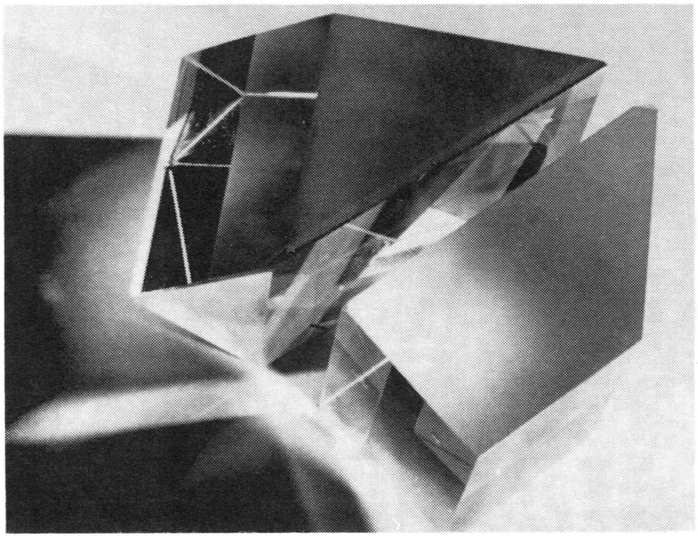

Figure 5. Photograph of the finished glass coherence interferometer prisms.

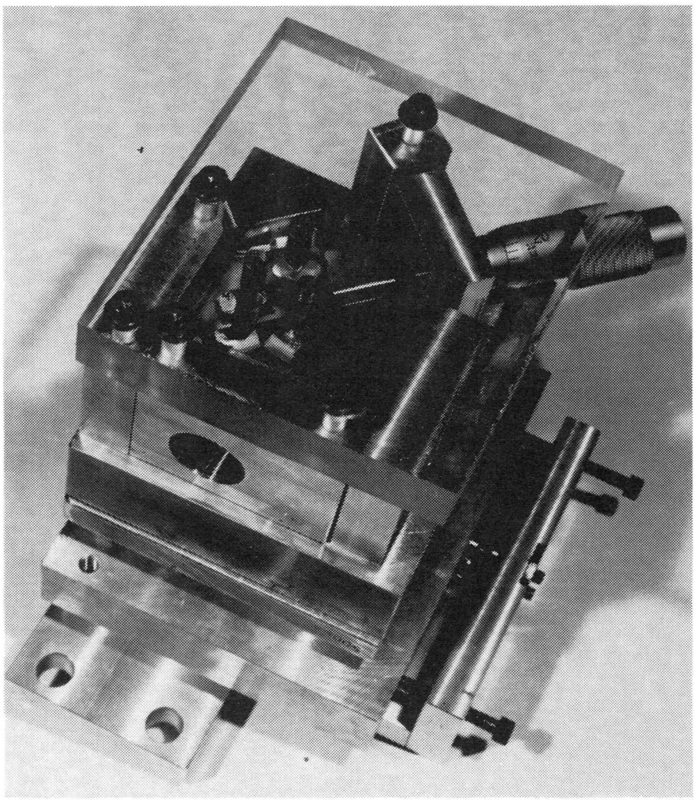

Figure 6. Mechanical assembly supporting the prism.

References

1. J. B. Breckinridge, "Coherence Interferometer and Astronomical Applications," Applied Optics *11,* 2996-2998 (1972), and "Two-Dimensional White Light Coherence Interferometer," Applied Optics *13,* 2760-2762, (1974).
2. J. B. Breckinridge, "Measurements of the Amplitude of Phase Excursions in the Earth's Atmosphere," J. Opt. Soc. Am. *66,* 143-144 (1976).
3. J. B. Breckinridge, "The Spatial Structure Analyzer and its Astronomical Applications," Ph.D. dissertation, Committee of Optical Sciences, University of Arizona, 1976.
4. J. B. Breckinridge, "Obtaining information through the atmosphere at the diffraction limit of a large aperture," J. Opt. Soc. Am. *65,* 755-759 (1975).
5. J. B. Saunders, "The Kösters Interferometer," Journal of Research of the National Bureau of Standards, *58,* 27-31, (1954).
6. L. Kreuzer, Perkin-Elmer Corp., private communication.
7. K. Räntsch, *Die Optik in der Feinmebtechnik,* Carl Hanser Verlag, Muchen, pp 178-236, 1949.
8. L. Mertz, *Transforms in Optics,* John Wiley and Sons, New York, page 111, 1965.
9. H. R. Worthington, Jr., U. S. Patent 3,558,207 Filed 6 December 1966, Patent issued 26 January 1971.