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Publication Date
1966-01-03

UCRL-16260 Rev.

University of California

Ernest O. Lawrence Radiation Laboratory

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Berkeley, California

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Submitted to the
Review of Scientific Instruments

UCRL-16260 Rev.

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
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AEC Contract No. W-7405-eng-48

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ABSTRACT

Apparatus and techniques were developed for accurately measuring azimuthal distortion in camera lenses. Great care was taken in fabricating the camera, which was made cylindrical so that the lens could be rotated. The experimental setup included a collimating telescope, the cylindrical camera containing the lens to be tested, and the test pattern. By rotation of the cylindrical camera, the same portion of the test pattern could be used for checking azimuthal distortion in different sectors of the lens. The distortion was recorded on film plates, which were then measured with a linear micrometer. Results were obtained to an accuracy of 1 part in 100,000. Causes for distortion were investigated but not quantized.

INTRODUCTION

Previous tests for azimuthal distortion were accurate to about 1 part in 10,000.[1-3] With the purchase of new lenses for the stereo cameras of the 72-inch LRL and 80-inch Brookhaven National Laboratory's hydrogen bubble chambers, we wanted to obtain better accuracy and precisely "map" the distortions in the lenses. Some methods of distortion analysis involve indirect measurements. As we wanted to avoid such measurements, we developed a technique for measuring the distortions directly.

The testing of the new lenses required a precision test pattern, a precision camera, and a precision set-up. The idea for the camera and set up was initiated and designed by Duane Norgren. The lenses were tested for symmetry (azimuthal distortion) only. Other lens parameters such as resolution and astigmatism were given a gross examination but were not investigated.

INSTRUMENTATION

The test pattern was a grid of 105 illuminated cross hairs (5 rows of 21 columns) set in a flat aluminum plate. The measurements between cross hairs are recorded by Eckman.[4] The aluminum plate, shown in Fig. 1, is 84 by 30 by 1-1/2 inches. The 72-inch bubble chamber has a viewing area roughly 72 by 16 inches, and the 80-inch bubble chamber has a viewing area roughly 80 by 25 inches. Each cross hair was made by depositing an aluminum film on a sandblasted Lucite disk on which an 0.008-inch wire cross hair had been placed. With the wire removed, an aluminum-free cross remained to transmit light from behind. The Lucite disks were imbedded in the aluminum plate and precisely measured. Each disk was lit from behind by a General Electric No. 327 lamp which shone through holes in the back of the plate. A thermometer, mounted on the front surface of the plate, made it possible to determine expansion of the plate due to heat from the lamps.

The camera was made with the least number of adjustments possible in order to avoid setting errors. Lens-to-image distance was determined from the required lens-to-object distance. The camera was made cylindrical so that the lens could be rotated and the same portion of the test pattern used for checking distortions in different sectors of the lens. The camera rotated on two rails set into a brass plate, as shown in Fig. 2. The brass plate rotated both horizontally and vertically with respect to the base by means of differential threads (Fig. 3); turning the adjustment screw 90° rotated the camera only 30 sec.

The base of the camera stand (Fig. 1) was an aluminum tube 8 inches in diameter and 27 inches high, set upon a triangular aluminum plate 1 inch thick and 16 inches on a side. Three leveling bolts were used in the foot. The entire assembly weighed about 200 lbs, to which 75 pounds of lead bricks were added for toe-stubbing stability.

The set-up was done in the following manner: The test pattern, because of its bulk, was left stationary, and a collimating telescope was placed 120 inches away and adjusted so that its axis was normal to the surface of the test pattern; then the camera and test stand were placed in position and adjusted so that the film plane was normal to the axis of the telescope and therefore parallel to the test pattern.

The collimating telescope (Brunson model 83, accurate to ±1 sec) had an internal light source and a reference cross hair that was projected onto a mirror. By reflection, the displacement of the reflected cross hair represented twice the angular displacement. A precision mirror with ground feet was placed against the test pattern and moved in a small circle to average surface deviations. The telescope was moved until the reflected cross hair coincided with the reference cross hair.

The film used, Kodak GH649 high-resolution emulsion on special 1/4-inch micro-flat glass, was developed in Kodak D-19 developer for 6 minutes at 68°F.

Variation in the lamps and in the translucence of the Lucite disks caused a great variation in the quality of the cross hair on film. Light intensity was measured with a spot photometer; by means of neutral density filters placed over the Lucite disks, the intensities of the middle three rows were brought to within 25% of each other. Due to the high-resolution quality of the film, the film "speed" was extremely low and exposures were made on the toe of the exposure curve. Thus the variation in light intensity became an important correction factor.

PROCEDURE

A lens was mounted in the camera and the camera was moved until the real image of the target cross hair was centered in the telescope. The camera was then collimated with a micro-flat mirror placed in the film plane (Fig. 3). These two procedures were repeated until the camera was centered and collimated at the same time.

After the camera was positioned and collimated, a film plate was mounted in it. The surface of the plate was used as a mirror to check plate collimation. Despite careful alignment, there was almost always some displacement, usually 2 to 4 seconds. If the displacement was greater than four seconds, the film plate was turned 90° in its mounting until the displacement was less than 4 sec when the camera was rotated; if this 90° rotation did not result in a displacement less than 4 seconds, the camera was recollimated.

The exposure was made with the lens in one position, then rotated 90° for another exposure, until four exposures were on the plate. For each exposure, the lens number, displacement, light voltage, time, and temperature were recorded. The film plates were then developed and measured.

Tests were done in two series on 11 Schneider-Krauznach f8 121mm Super Angulon lenses. Eight, recently purchased from the factory, were made to our specificifications, but three were purchased "off the shelf" and used for 6 years in the 72-inch bubble chamber.

The first series of tests was done on five new lenses and the three old ones. The measurements shown in Table I were made with a Bowers linear micrometer accurate to 1 micron in 5 inches over the range used. Measurements, made between the axial cross hair and the cross hair roughly corresponding to 30° of coverage, were done in each of the four directions. In the second series, the three lenses were not measured on the micrometer.

The measurements in Table I were made in order to help select the best lenses for use in the bubble chamber. When the lenses were selected, they were oriented with respect to the test pattern so that they would duplicate exactly their predetermined positions in the bubble chamber. With the lenses selected from the first and second series of tests, exposures were then made for distance from beam level to the first principal point of the lens. This provided accurate "maps" of the distortion the lens delivers to the film used in the bubble chamber. A comprehensive measuring program will be done on these maps by Frank T. Solmitz to coordinate the distortion with measurements of the bubble chamber data on film.

Two of the new lenses gave double images of equal density and resolution. The separation of the image centers was aperture dependent, i.e., the image centers moved closer as the size of the aperture decreased. At about f22, the two images were indistinguishable and the lenses were useable at this or smaller apertures. A further study will be done to determine the cause of this particular aberration.

By placing the lens in the camera and reflecting light off the surface of the lens elements with the collimating telescope, we could see if the elements were mechanically centered. Most of the elements were not centered and some varied by as much as several minutes, despite the factory's especially fitting the element seats to each individual element in the eight new lenses tested. The new lenses apparently varied less than the three "off the shelf" lenses. Not enough time was available to develop a system of quantizing this eccentricity, but future study should make this parameter meaningful in terms of distortion, contrast, and resolution.

ERRORS

Expansion of Test Pattern

The coefficient of expansion of the aluminum plate is 23.86×10^{-6} cm/cm/C°. If the change were coordinated—i.e., if the cross hairs moved in only one direction—a cross hair at the edge of field would move 24 μ/C° in space, or 1.4 μ on the film plate (demagnification factor of 18 from object to film).

Keystoning

A keystoning effect came about from the slight eccentricity of the camera perimeter. The fact that the film plane was out of parallel by 4 seconds caused an image displacement of 1.02 μ, at the extreme edge of field, or about 1 part in 75 000.

The lens mounting surface was off-axis by 15 seconds. The approximate error for small angles is $1/K^2$, where K is the error from keystoning, as above, or 1 part in 56×10^{-8} at edge of field (negligible).

Nonflatness of Plate

The aluminum plate containing the crosshairs was surveyed for flatness and found to have not only an "S" shape, but a vertical twist as well. This would not affect the tests for symmetry, but would affect the "maps," the worst case being an error of 1.61 μ.

Accountable Errors

Displacement due to	Square
Temperature (max) 3.5 μ	12.25
Keystoning 1.02 μ	1.04
	13.29

The error in the displacement figure is thus the square root of 13.29 or 3.65 μ.

For the "map" exposures, two errors were reduced. The plates were adjusted so that there was no keystoning, and the temperature change was reduced to 0.5°C. Thus the maximum error for these exposures would be

Displacement due to	Square
Temperature 0.7 μ	0.49
Nonflatness 1.61 μ	2.59
	3.08

Errors for the map are thus 1.75 μ.

ACKNOWLEDGMENTS

The author thanks Frank Solmitz and Duane Norgren for their suggestions. Special appreciation is given to Roland Michaelis and William Wainright, and to the rest of the staff of Technical Photography, for their help in processing the film plates.

FOOTNOTE AND REFERENCES

*This work was performed under the auspices of the U. S. Atomic Energy Commission.

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2. Francis E. Washer and Walter R. Darling, Evaluation of Lens Distortion by the Modified Goniometric Method, J. Res. Natl. Bur. Std. 63-c, No. 2, 112 (1959).

3. Francis E. Washer, W. P. Tayman, and Walter R. Darling, Evaluation of Lens Distortion by Visual and Photographic Methods, J. Res. Natl. Bur. Std. 61, No. 6, 509 (1958).

4. Glenn Eckman (Lawrence Radiation Laboratory), 72-inch Bubble Chamber Camera Distortion Measurement Grid, unpublished internal report, July 7, 1962.

Table I. Measurements of distance from axial cross hair to cross hair S3 in each of the four directions.

Lens No.	0° (μ)	90° (μ)	180° (μ)	270° (μ)	Temp change in plate (°C)	Maximum difference (μ)
262 (new)	73 787	73 757	73 761	73 767	2.5	30
268 "	73 799	73 812	73 804	73 799	2.5	13
276 "	73 622	73 659	73 666	73 613	1.0	53
318 "	73 644	73 631	73 650	73 658	1.4	27
326 "	73 664	73 644	73 621	73 624	1.8	43
6901[a] (old)	85 440	85 428	85 464	85 501	0.5	73
6890[a] "	85 469	85 463	85 508	85 388	0.5	120
6902[a] "	85 512	85 531	85 562	85 547	0.5	50

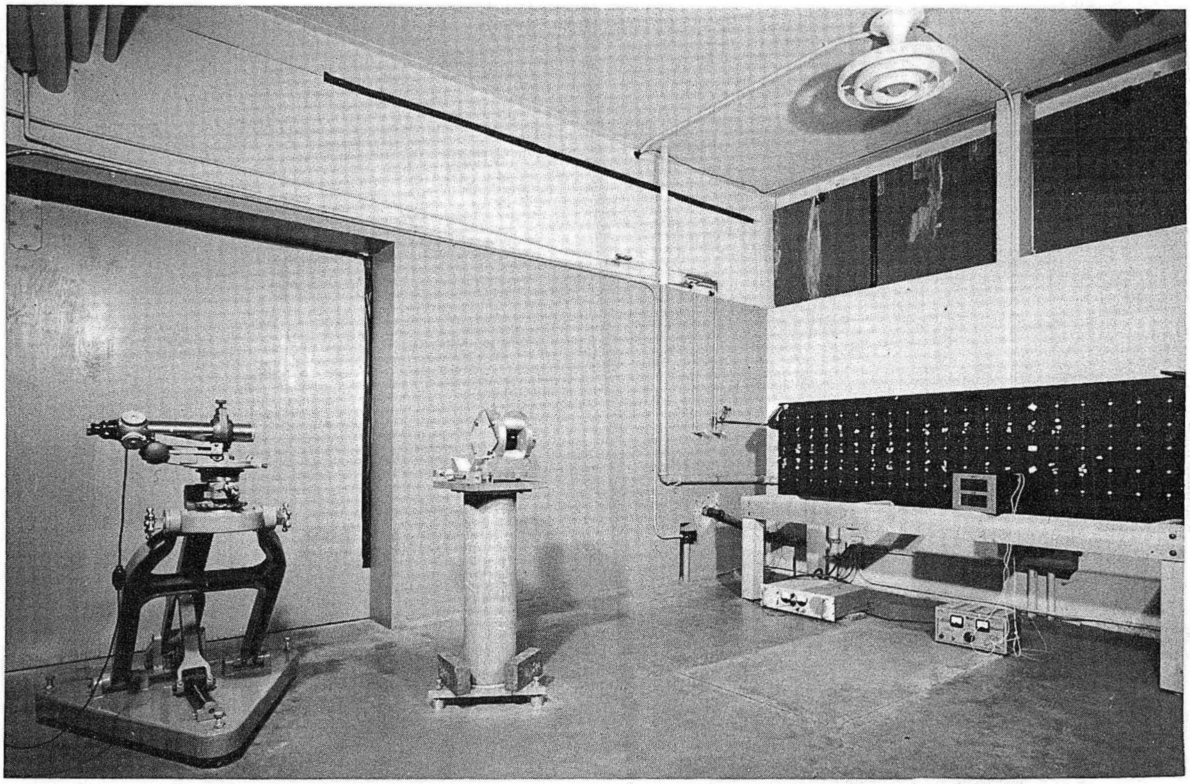
[a]Axial cross hair to U3.

FIGURE CAPTIONS

Fig. 1. Experimental set-up: (from left) the collimating telescope, the camera and stand, and the test pattern.

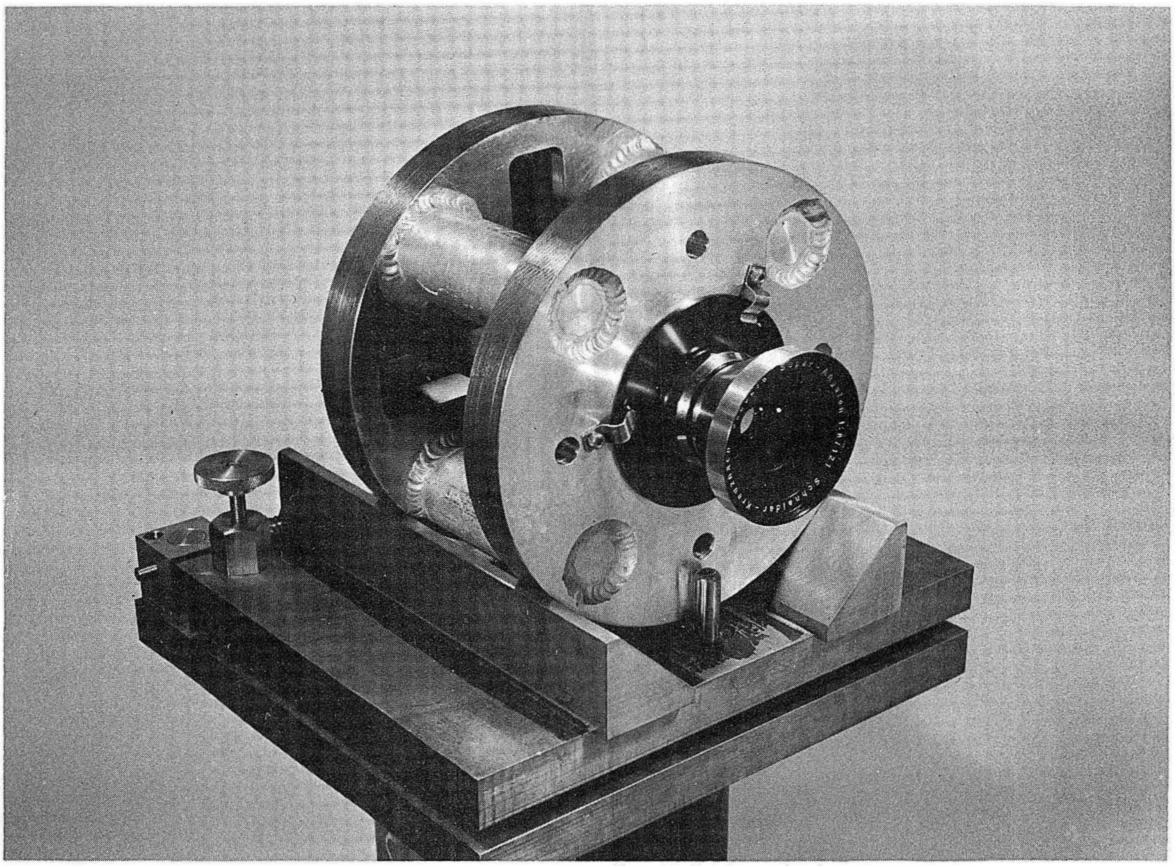
Fig. 2. The lens in position in the camera. Note the two rails on which the cylindrical camera rotates.

Fig. 3. The camera from rear, showing adjustment screws and collimating mirror.



ZN-5059

Fig. 1



ZN-5058

Fig. 2

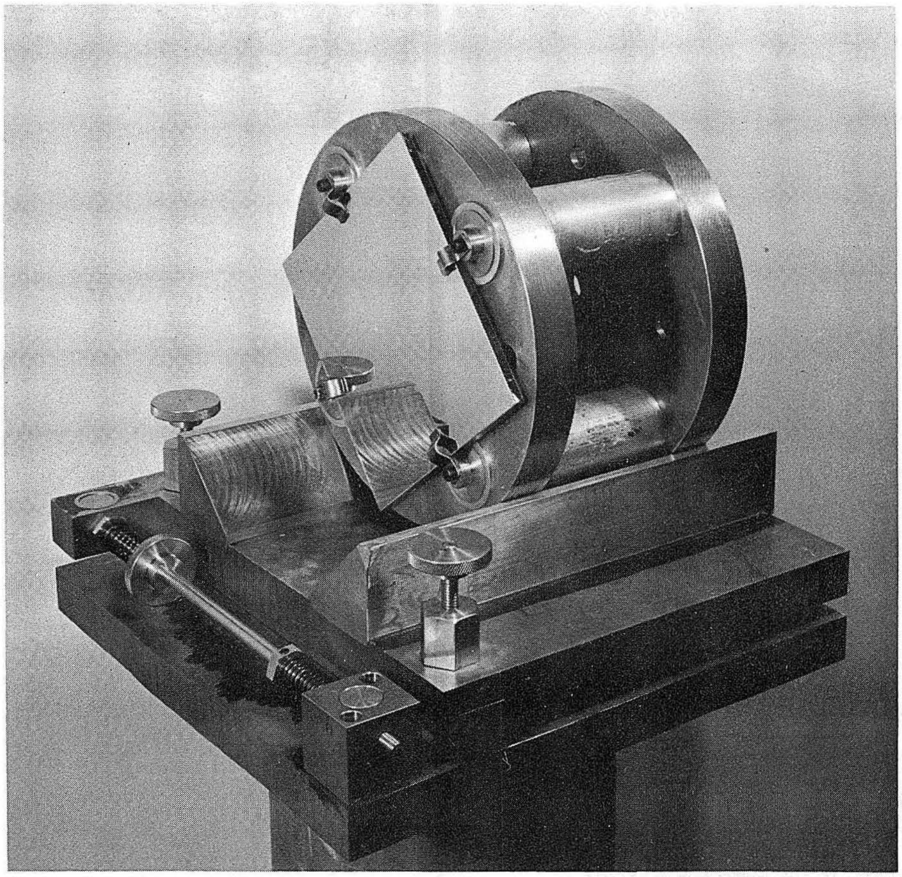


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Fig. 3