3.8 DEVELOPMENT OF WIDE-ANGLE LENSES FOR THE ARGONNE 12 FT. BUBBLE CHAMBER

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This project began in October 1964, at which point the shape and size of the 12ft. chamber were roughly settled: a vertical cylinder, 3.5m diameter 2.5m high. The following were chiefly involved in drawing up specifications, E. Gale Pewitt, A. Tamosaitis, H. Courant, J. Fetkovich, L. Turner, M. Derrick and the present writer; the detailed optical design is due to M.J. Buzawa of Tropel, Inc., Fairport, N.Y.

The following requirements soon became clear:

a) Wide field angle, since as much as possible of the chamber must be seen by each lens.

b) Telecentricity, since rapid cycling would be expected.

c) Small diameter front elements, to permit a ring source for Scotchlite illumination.

d) Diffraction-limited correction of aberrations (except distortion, to permit use of high-resolving power film (e.g. Kodak Microfile) at great demagnification.

e) Rather small overall length; this requirement occurs because it soon appeared that the camera axes might be considerably inclined to the vertical but it was desirable to have the cameras set in vertical wells through the magnet iron.

Requirements a) and c) together imply that the entrance pupil must be near the front of the lens. The whole design would then be very asymmetric about the aperture stop and this with telecentricity causes difficulty in correcting transverse chromatic aberration over a large wavelength range; we therefore specified colour correction over a restricted wavelength range, a few hundred angstroms.

Requirement a) leads to the now familiar configuration of concentric ("fish-eye") windows, since flat windows into hydrogen reduce the field angle (a field of ±70° in vacuum is equivalent to only ±59° in hydrogen through a flat window). Flat windows have other optical disadvantages for large field angles, the chief being transverse chromatic aberration, large entrance pupil movement and large distortion. Fish-eye windows are free from all these troubles and have the wellknown advantage of eliminating reflections from the ring light-source.

The initially chosen arrangement was four lenses equally spaced around the top rim of the chamber, with the axes suitably angled to optimize the field coverage. It was not clear at first how large a field angle could be assumed and we started with full field of 110° (i.e. ±55°), to be photographed on 70 mm perforated film; it is perhaps fortunate that film width is quantized in large steps by the manufacturers, since it is difficult to see how to choose an optimum film width very accurately.

It was decided early in the project to allow a considerable amount of barrel distortion, which is the kind which appears naturally in a lens with most of the positive power behind the aperture stop. There are several reasons for this decision: first, the distortion, if left to itself, will be roughly such that angles in object space are mapped linearly as distance on the film, and since the chamber shape is such that equal volumes of hydrogen are contained in equal solid angles, approximately, it seems sensible to make use of this to ensure that equal volumes are mapped on equal areas; distortion-free mapping would devote much more film area to volumes remote from the lens axis. Secondly most events of interest will occur near the centre of the chamber and only a few tracks, which will usually have low momentum, will reach the edge of the field of any camera. Thirdly, we hope to arrange that each lens has the other three just in its field of view, in order to help to constrain the chamber fiduciary system, and this will be right at the edge of the field; for this purpose it would be very wasteful of film to have a distortion-free lens.

The argument against permitting distortion is chiefly that the scanning is difficult, and this is also an argument against inclining the lens axes. R. Ammar wrote a programme to construct bubble chamber negatives to show the effect of inclined axes and any chosen distortion function. The consensus based on the output from this programme has been that inclined axes (20°-40° to the vertical) and heavy barrel distortion contribute equally to scanning difficulties, but nevertheless it is perfectly possible to recognize corresponding tracks in different views; furthermore it should be possible to train new scanners to scan such film as quickly as ordinary film, allowing for the possibly greater complexity of the average frame on a large chamber.

Initial design study contracts placed with three firms produced very different results. We rejected one which involved a heavily aspherized surface and another which had exceptionally deep curvatures and looked as if it would be very difficult to make. The third firm, Tropel, Inc., produced an initial result which complied with the specifications and looked reasonably straightforward to make, so we proceeded with this. It became clear to M.J. Buzawa, the designer, that the field originally specified (110°) was not necessarily the limit of the design type, if we allowed a slight increase in the diameter of the front elements. At the same time our experiments with Scotchlite illumination indicated that it is not vital to have the light source inside the half width of the Scotchlite maximum. Also a programme due to C. Turner and J. Fetkovich indicated that we could maintain good coverage of the chamber, good x-y precision and good stereo if the lenses were brought in somewhat from the top rim of the chamber and the inclination of the axes was decreased, provided the field was increased.

We therefore asked for some trials to increase the field, and the resulting lens design is shown in Fig. 1. This covers 140° full field and will be used with an inclination to the vertical of about 20°; the four lenses will be on a circle about 2m diameter at the top of the chamber. The fiduciary volume extends 1.8m from the piston upwards, and with this configuration of lenses almost all of this will be seen by all lenses, in good focus at f/16.

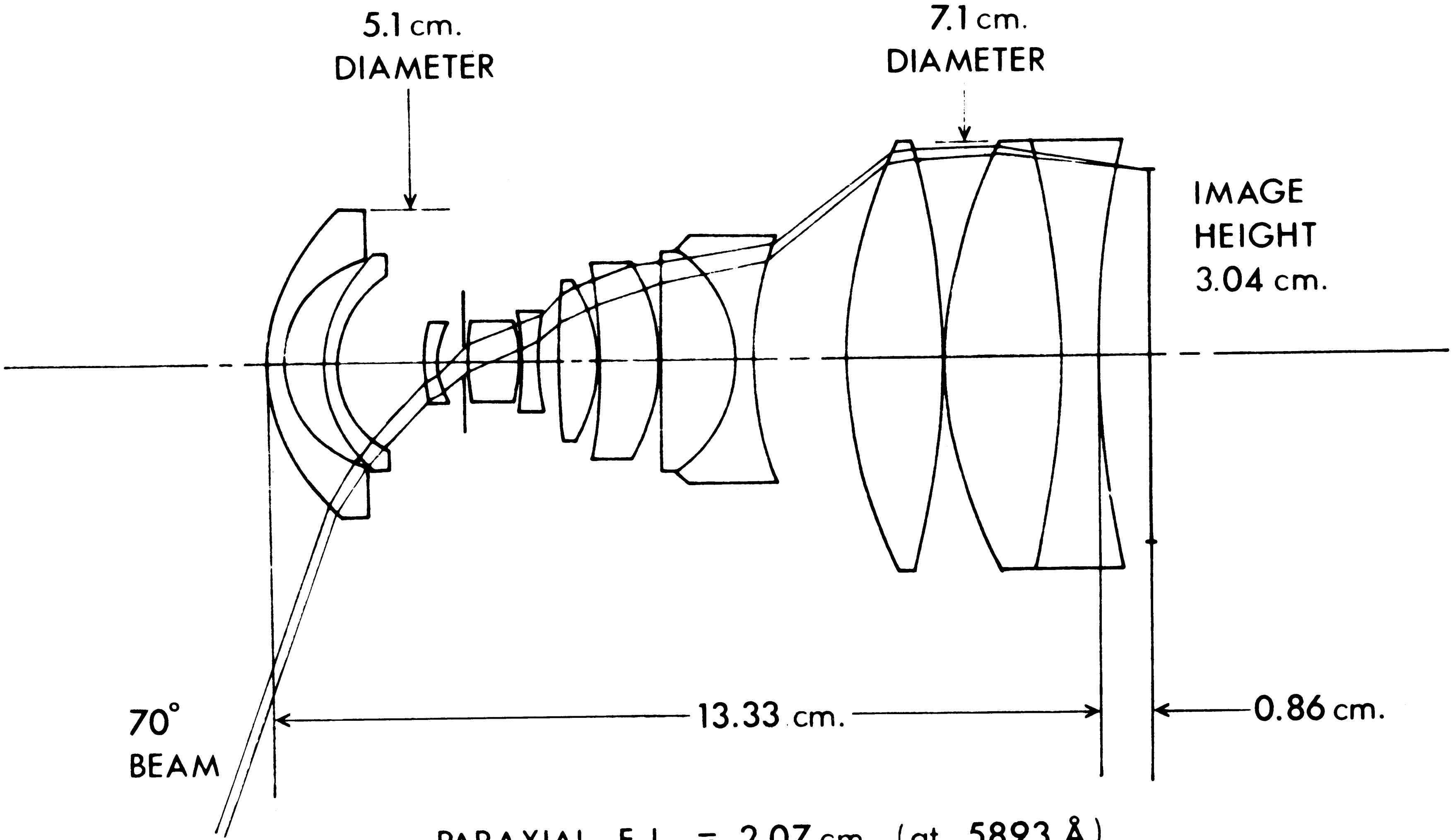
The front of the lens including mount will be about 55mm diameter, which will be adequate for ring illumination with an angle of about 0.5°. Fig. 2 shows the wavefront aberration in the tangential section for a range of field angles; it can be seen that even at full aperture (f/8) the aberration correction is well within the diffraction limit; these calculations apply, of course, to a finite object distance and the fish-eye windows and hydrogen are included in the calculation, since they make a significant contribution to the field curvature. It can be seen that the pupil is considerably elongated at large field angles, thus preserving luminosity at the edge of the field; this is due to pupil coma from the elements in front of the stop and it is a useful bonus from this type of design.

Fig. 3 shows the departure from strict telecentricity as a function of field angle: the maximum is 5°, at the edge of the field. Fig. 4 shows the distortion as a fraction of the ideal image size and fig. 5 shows a direct plot of image size against field angle, showing how nearly linear this is. The effect of the residual distortion is shown also by Fig. 6 which shows the effect on a square grid covering the full field.

J. Bjorkland has built a Twyman and Green interferometer to test the lens; this incorporates a nodal slide which will enable us to check that the aberrations are diffraction limited everywhere in the field; there is also included a negative lens which simulates the effect of the fish-eye windows, so that the lens itself can be tested at the correct conjugates. We shall also test the lens by direct inspection of point images (the so-called "star-test") since this is a sensitive test for systems which are expected to be diffraction limited.

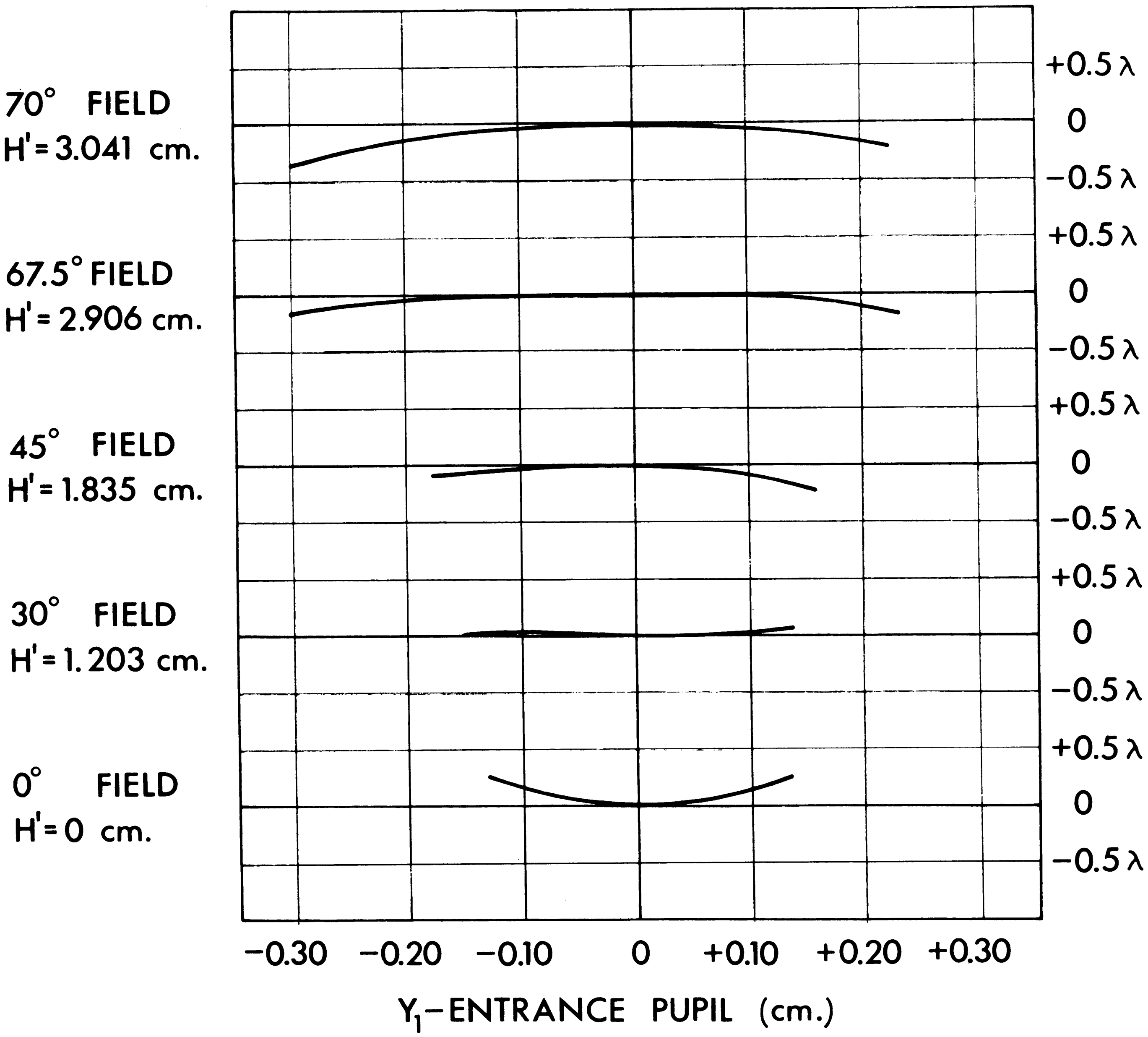
The distortion calibration of the lens presents major problems.

The cameras, which are being designed by M. Bougon, will incorporate camera-based fiduciaries to which the distortion calibration can be referred. We then have to obtain a correlation between points on the film, with positions given by reference to the camera fiducials, and lies in object space, i.e. the various principal rays. This has to be done in air, so that the effective image surface with respect to which the raytracing was done is now strongly concave to the lens with a radius of about 600mm, instead of being a plane, We plan to achieve this calibration by constructing an array of illuminated crosses and photographing it in a known position relative to the lens. In the reduction of the data it is necessary to take account of movement of the entrance pupil along the axis with field angle; this occurs in all wide-angle lenses and it is of order of magnitude 1-2mm.



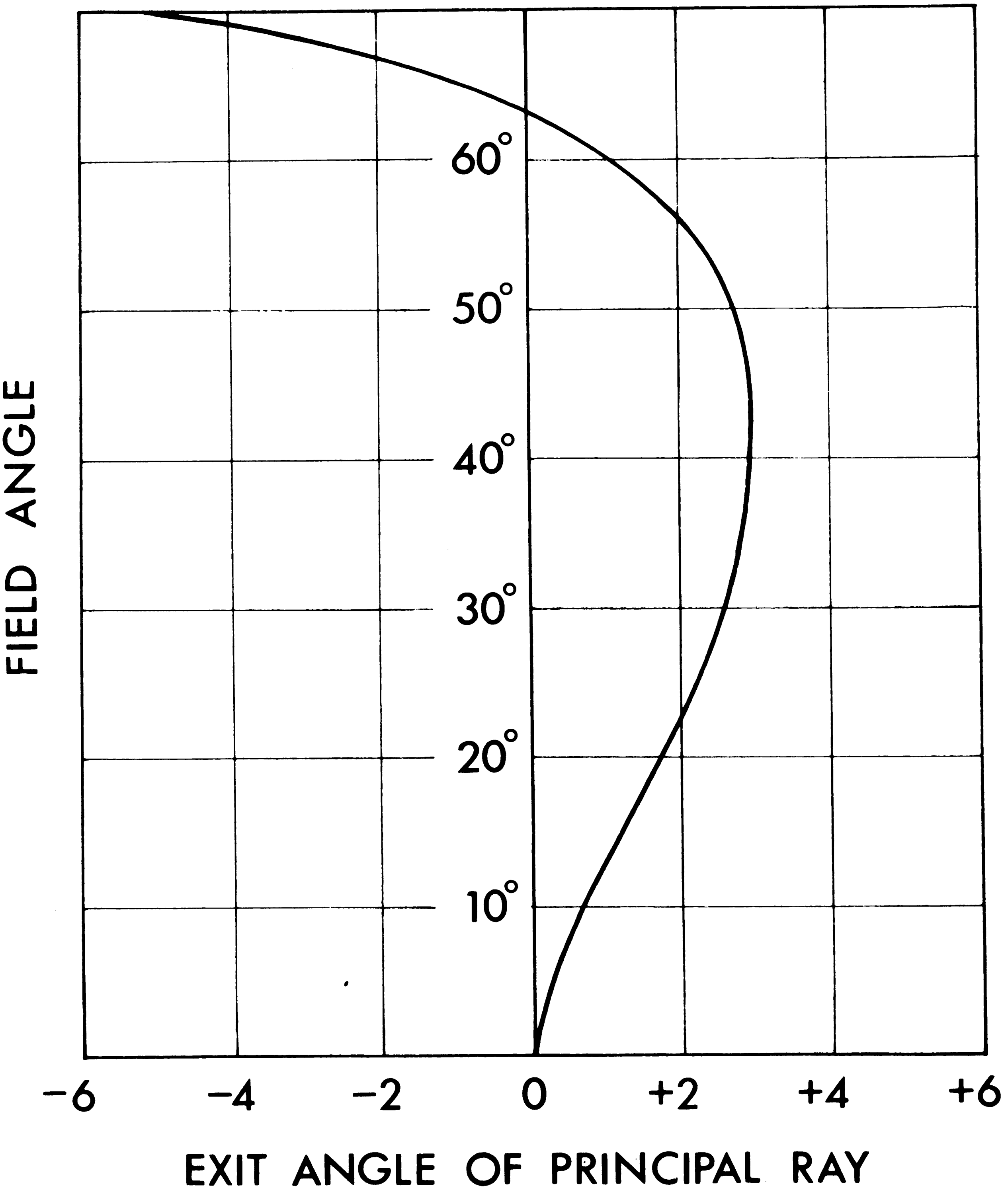
PARAXIAL F.L. = 2.07 cm. (at 5893 Å)
EFFECTIVE F.L. = 1.11 cm.
F/NO. = F/8.0

Fig. 1 140° TELECENTRIC CAMERA LENS FOR 12 ft. BUBBLE CHAMBER



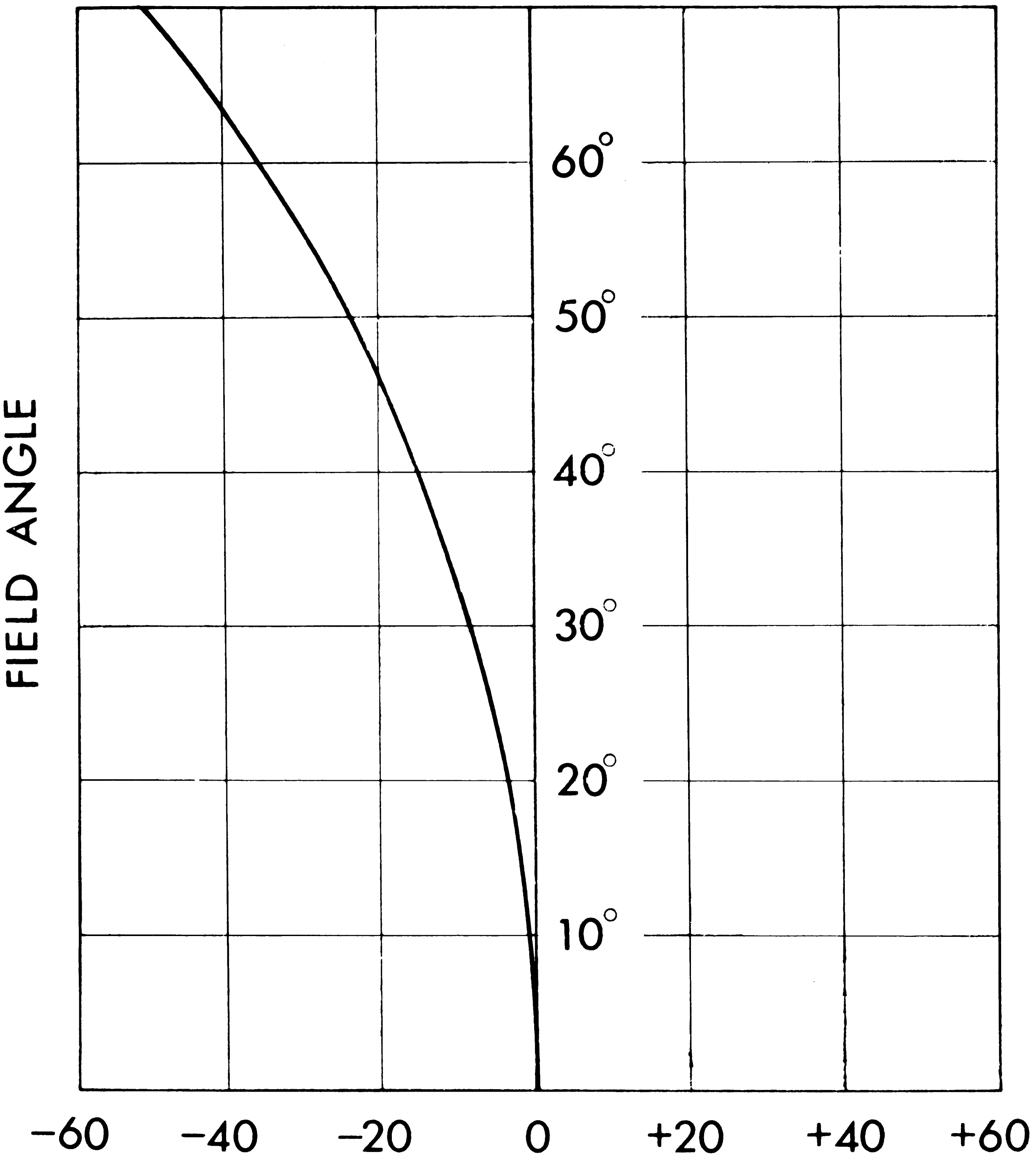
WAVEFRONT ABERRATION IN TANGENTIAL SECTION OF 140° LENS
$\lambda = 5890$ Å

Fig. 2



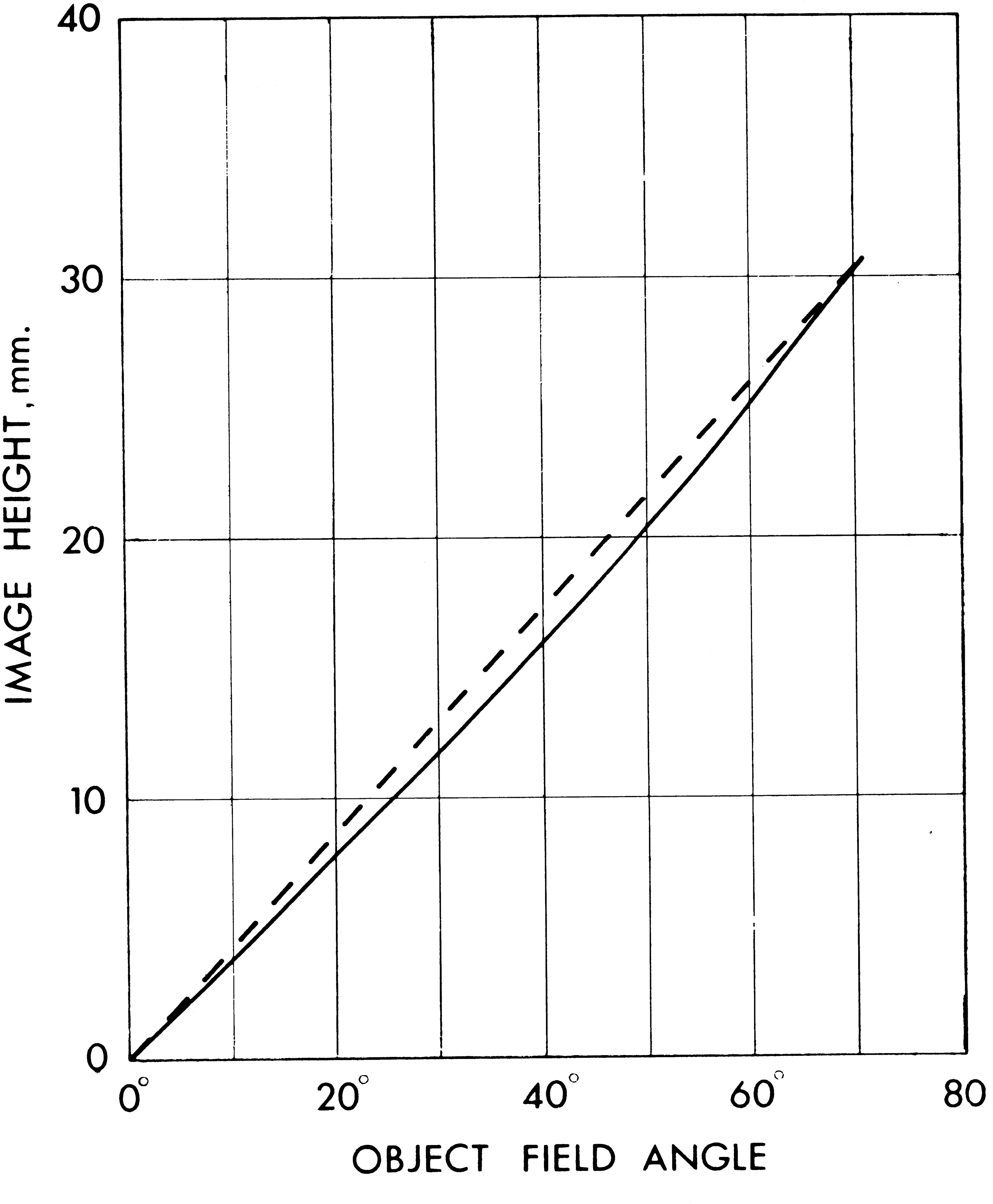
DEPARTURE FROM TELECENTRICITY OF 140° LENS

Fig. 3



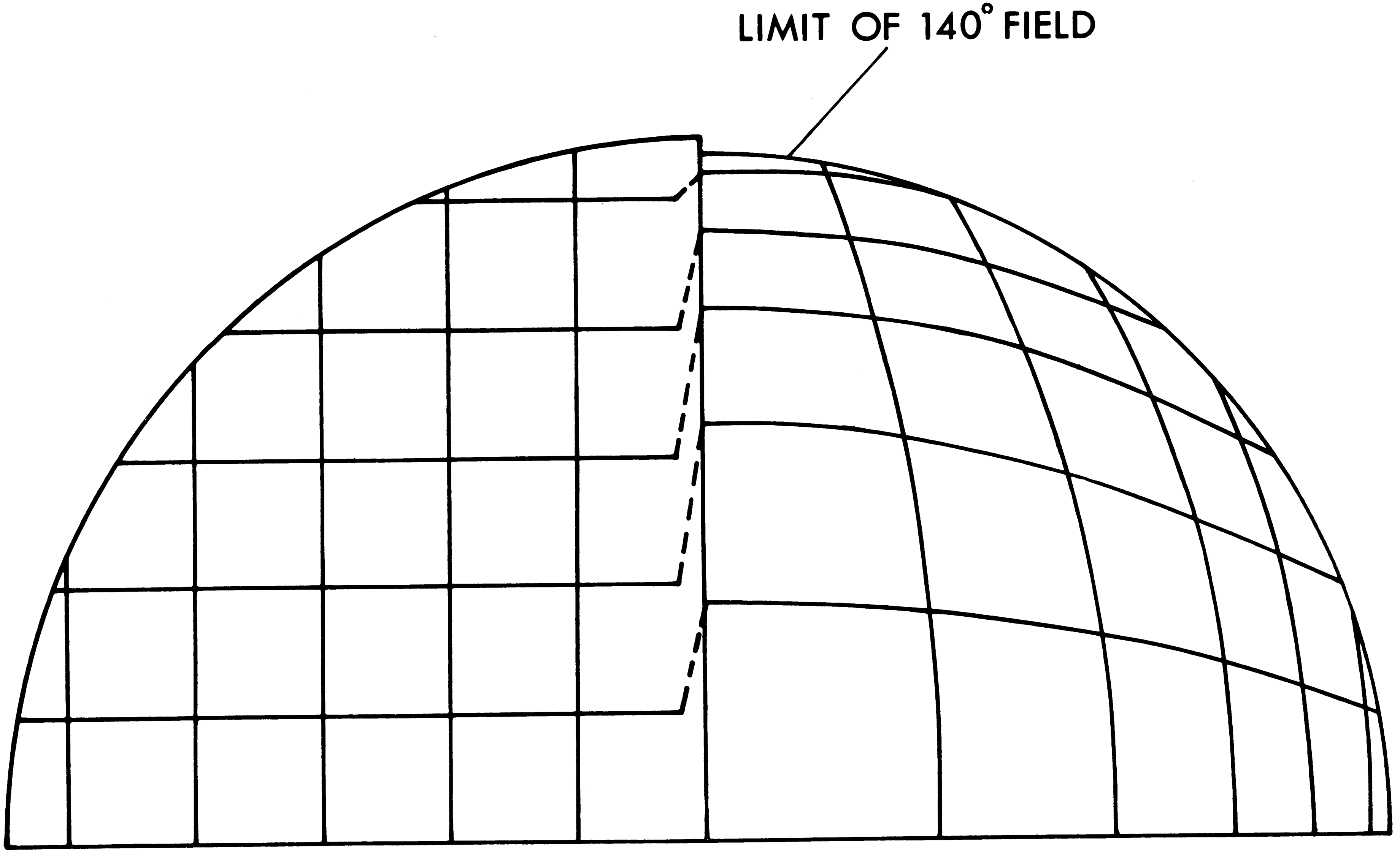
PERCENTAGE DISTORTION OF TELECENTRIC LENS $\left(= \frac{\Delta\eta}{\eta_0} \times 100 \right)$

Fig. 4



DISTORTION OF 140° LENS

Fig. 5



DISTORTION OF SQUARE GRID BY 140° LENS

Fig. 6