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LOW SCATTER LENS DESIGN/DEVELOPMENT

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PRICES SUBJECT TO CHANGE

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A. OPTICAL DESIGN

I INTRODUCTION

   During the preliminary design stage of this investigation,
approximately twenty different types of lens configurations were
selected for the initial study effort. These lens systems were
typical representations of three basic categories of physical
arrangements:

   1. Catadioptric - Consisting of both refracting and reflect-
      ing elements

   2. Reflecting - Consisting mainly of first surface reflect-
      ing elements

   3. Refracting - Consisting totally of refractive lens elements

   The method used for selecting the optimum solution contained five
essential criteria:

   1. Image Quality - The blur circle diameters must not exceed
      0.150 mm across the field of view considering 80% of the
      available energy.

   2. Obscuration - The lens system should exhibit a minimum
      amount of energy losses due to physical obstructions within
      the system.

   3. Distortion - The target objective for the system should be
      3 arc minutes, or less, anywhere in the image format.

   4. Collecting Area - The lens system should provide at least
      18.3 cm^2 of collecting area for on-axis targets.

5. Physical Restrictions:

    a) System Envelope - The maximum dimensions of the
package should not exceed a cylindrical volume
of six inches diameter by six inches in length.

    b) Weight - The design goal was given as five pounds
or less.

The following criteria were used as additional weighting para-
meters in selecting a lens configuration which would possess desir-
able attributes in terms of producing a suitable prototype model of
the theoretical solution:

1. Material Considerations - High ultra-violet transmitting
glasses, of low cost, ready availability, and good working
characteristics would be needed.

2. System Sensitivity Factors - The final solution should poss-
ess relatively low insensitivity with respect to nominal op-
tical fabrication tolerances and individual mechanical seat-
ing errors in the lens mount.

3. Ghost Image Locations - A suitable design would possess a min-
imum number of ghost images close to the final focal plane.

As was reported on in the first preliminary report there were four-
teen individual lens designs that were brought to a point of semi-final
completion. From these, only one solution exhibited outstanding perform-
ance characteristics in terms of the first five rating criteria. This
particular system was a six element refracting design, operating at a

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relative aperture of f/1.0 and possessing good image quality across the entire image format. The limiting factor in this design select-ion was the necessity of using rather high index materials. Since high refractive indexes usually indicates dense flint glasses of comparatively low ultra-violet transmission, or heavy lanthanum type crown materials which are expensive, it was realized that this partic-ular solution would require careful study to insure the best material choices.

II.   FINAL DESIGN PROCEDURES

There were many factors governing the final selection of appropr-iate materials for this solution. Since the specifications require high transmission in the low ultra-violet spectral region, only those glass types in the Schott catalog which gave values of 90% or greater, at 400 NM were considered useable. Therefore, the initial effort consisted of adjusting the nominal theoretical solution to accommodate the exact catalog values. Schott lists eighteen separate lanthanum type glasses. Of these only six possess refractive indexes of 1.7, or greater: LaK-8 (713556), LaK-10 (720504), LaKN-16 (734517), LaK-17 (788505), LaKN-18 (729542) and LaKN-19 (755531). The last two types are special order items only and should be avoided for volume fabrication systems. LaK-17 contains thorium and is four times more expensive than more conventional lanthanum glasses. Therefore, it was eliminated. LaKN-16 is twice as expensive and not manufactured as frequently as other glasses in this classification. Therefore, the final selection of LaK-8 was based on its lower cost, desirable Abbe dispersion value of 53.83 and its slight-ly better transmission value, over LaK-10, in the U-V region. Identical

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procedures were followed in the selection of SF-1 and SF-19 for suitable materials. There is a wider choice of heavy flint materials, however, so these two glass types could be chosen quite selectively in terms of how closely they matched the theoretical glasses of the preliminary design solution. These flint materials, of course, were less expensive than the lanthanum glasses by a factor of about four times. However, there was no suitable low cost substitute for the lanthanum type crowns and they had to be used.

Upon completion of suitable optical material selection, the preliminary theoretical design values were then bounded so as to squeeze the solution towards the actual catalog values of the selected glass types. The optimization program uses all the lens variables, such as: lens radii of curvature, element center thicknesses and air spaces. Both damped least squares and ortho normal matrix inversion techniques are utilized in this optimization program to achieve rapid convergence of the final design solution.

III. DETAILED TECHNICAL DISCUSSION

As the optimization cycles progressed it became quite obvious that the image quality below 440 NM degraded very rapidly. This is quite typical when correction over a rather broad spectral range is attempted, particularly at fast relative apertures. Therefore, as mentioned in the earlier report, this obstacle was anticipated. There are very few optical materials which permit a lens system to be corrected down near 400 NM, especially when good quality is required in the red portion of the spectrum. The exact transition point could not be predicted prec-

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isely since the tolerable blur circle diameter of 150 microns
is quite modest and it was hoped that even at 420 to 430 NM, a
satisfactory performance level could be attained. The dominant influ-
ence affecting the cut-off point for the low end of the spectrum was
the fast operational speed of f/1.0. At this relative aperture, the
lens radii are quite short which, in turn, produces higher order aber-
ration contributions. These surface contributions must then be bal-
anced by equally strong contributions of opposite sign, which produces
strong zonal characteristics.

The system was also severely restrained by the requirement on the
long back focus value of 1.00 inch. Ordinarily, in such a fast system,
this working distance would be of the order of 10 to 20% maximum of
the equivalent focal length, rather than the required 50%. As the de-
sign progressed then, there was a continual struggle to improve the
image quality across the field and yet maintain the desired 1.00 inch
distance.

A careful check was also maintained on the individual positive ele-
ment edge thicknesses and negative element center thicknesses. Both
these values had to be maximized to insure adequate ease in fabrication
and sufficient strength in mechanical mounting to assure long life under
operational conditions. The final lens prescription that evolved from
this analysis is detailed in the Table I below:

TABLE 1

LOW SCATTER LENS SYSTEM: CONSTRUCTION DETAILS

SURFACE NUMBER	RADII OF CURVATURE	VERTEX SEPARATIONS	GLASS MATERIALS	CLEAR APERTURE RADII
1	Entrance Pupil	-2.7000		0.971
2	3.599	0.540	LaK-8	1.147
3	-6.109	0.004		1.092
4	1.844	0.633	LaK-8	0.895
5	4.251	0.156		0.640
6	-2.061	0.250	SF-19	0.636
7	0.999	0.179		0.553
8	Glare Stop	0.070		0.555
9	-2.680	0.200	SF-1	0.557
10	1.995	0.002		0.627
11	1.811	0.640	LaK-8	0.643
12	-1.236	0.004		0.695
13	1.509	0.380	LaK-8	0.624
14	21.849	1.004		0.557
15	Image Surface: Flat	-		-

NOTE: In order to achieve high volume productive capacity, the lens radii were constrained to equal 1.000 inch, or greater. This factor did not exert an unduly severe restraint upon the optical design.

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The performance characteristics for this final optimized
solution are shown in Fig. 1, 2 and 3. These are conventional
ray intercept versus ray height in the entrance pupil plots, for
each of three field angles. Fig. 1. is the information for the
on-axis analysis, Fig. 2. for half-way out in the field, and Fig.
3. shows the image quality at the extreme edge of the field. In
each set of these plots, there are three separate representations.
The first, located at the top of the page and labeled SAG FAN Y,
shows the Δy, or comatic type errors, for the sagittal fan of energy.
The second plot, in the center of the page and labeled SAG FAN Z,
gives the ΔZ, or skew errors, for the sagittal fan. These two plots
are given only for the center to the edge of the pupil since the
negative side of the data will be a mirror image of the positive side
of the pupil aperture. The bottom plot provides the image errors for
the meridional or tangential, energy fan. The total aperture, from a
relative height of +1.0 to a relative height of -1.0, must be shown here
since there is no inherent symmetry between the two halves of the pupil
aperture. The main vertical divisions are the image errors directly,
for any particular ray height in the entrance pupil, and are given in
.010 mm steps. Three separate wavelengths are distinguished on each
plot, indicated by L (for low index), M (for mean index) and H (for
high index). In this instance, as mentioned previously, L = 0.55 mic-
rons, M - 0.4935 microns, and H = 0.45 microns.

An examination of Fig. 1. shows that essentially all the available
energy is within a blur circle of about 0.080 mm diameter. Similarly,
Fig. 2. which is for a position half-way out in the field, shows all

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the energy is concentrated within a 0.085 mm diameter blur circle. Finally, Fig. 3., for the edge of the field, shows about the same degree of correction.

All these curves show the effect of very strong zonal errors which is quite typical of very fast optical systems. This necessity for balancing very strong opposing aberrations is usually the limiting factor in the level of image quality attained. For this case, the burden upon the optical design was intensified due to the enhanced working distance requirement and the extended spectral range coverage into the blue region.

IV.   FINAL PERFORMANCE ANALYSES

The performance characteristics of this lens system in a more pictorial form in Plates #1 through # LVII. These plots give the exact physical shape of the blur circle pattern for each wavelength and each designated field angle. Seven discrete steps in the spectral range extending from 0.400 microns to 0.600 microns are given at six different field angles from 0.0 degrees out to 7.50 degrees, half-angle. The representations for the low blue region of 0.40 microns are included even though the lens system could not be corrected this far down into the blue region.

All the plots are initially scaled for one inch equals 0.005 mm. However, if the energy plots exceed this value then the program automatically scales the data to keep the total plot on the page. The

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new scale is printed out at the top left hand position on the
sheet. Plate I, for example, shows a scale factor of one inch
equals 0.034630 mm. This is for a wavelength of 0.400 microns,
at a field angle of 0.0 degrees, as shown. In this plot 100% of the
available energy will be within 0.303 mm. Of course, the blur
circle diameter becomes substantially smaller, as a lower energy
concentration is considered. For example, if 75% of the available
energy is considered, then the blur circle diameter becomes about
0.140 mm.

A total summary of all this data is given in Table II below.

TABLE II.
SPOT DIAGRAM ANALYSIS

| | | BLUR CIRCLE DIAMETER, mm. 100% ENERGY | | | | | | |
FIELD ANGLE;SINE	λ	0.4	0.45	0.475	0.500	0.525	0.550	0.600
0.000° 0.000		0.303	0.126	0.088	0.066	0.058	0.062	0.063
0.026105		0.313	0.133	0.095	0.089	0.074	0.074	0.066
0.052210		0.332	0.150	0.111	0.086	0.072	0.071	0.091
0.078316		0.361	0.146	0.105	0.109	0.109	0.107	0.086
0.104421		0.351	0.153	0.132	0.112	0.099	0.093	0.101
0.130526		0.0348	0.217	0.175	0.149	0.138	0.105	0.106

The above results show that the system is well corrected over
the entire spectral range extending from 0.45 to 0.60 microns, even
when considering the full 100% of the available energy. The perform-
ance at 0.40 microns is also within the allowed 0.150 mm. if about
80 to 90% of the available energy is considered. Therefore, in terms
of the minimum weight package, the best available solution of suitable
glass types, and considering reasonable restraints for manufacturing

ease, the final solution represents an optimum compromise of all the factors involved.

During the actual fabrication procedure for this lens system there would be a so-called melt adaptation required. This process is necessary because the actual refractive index of the manufactured glass could differ slightly from the catalog values used for the theoretical solution. In this melt adapting re-vision an attempt would also be made to extend the back focal length slightly to provide more working distance between the last surface of the lens barrel and the image plane. Even though this represents a difficult parameter to move, the performance of the lens is still comfortably within the 150 micron blur circle diameter allowance. Therefore, a slight increase might be possible.

V. GENERAL CONCLUSIONS

To a great extent the success or failure of this lens system will be largely dependent upon the reduction of the scattering effects, latent in the lens system. These effects will be produced by a variety of contributing factors as shown below:

1. Proximity of "ghost" image planes to the true focal plane.

2. Size and quantity of foreign inclusions within the glass volume, including bubbles, striae, and inhomogeneities.

3. Presence of surface defects such as:

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a. Sub-surface micro-fractures due to surface grind-

      ing techniques

   b. Surface scratches and digs

   c. Polishing sleeks on the surface

4. Non-uniform optical coatings including sputters, stains,

   and pin-holes.

5. Surface dust particles and stains.

Under the first item above a detailed analysis was performed
to determine the location of all ghost images due to internally
reflected energy. Since the first set of energy reflecting pairs is
most critical it is important that the reflected image formed by the
first lens element is not located near the true image surface. As
shown in the attached computer output the ghost image formed by the
combination 3, 2 is located at 10.021 inches from the last vertex.
This is well removed from the image plane and will not contribute
any spurious image signal to the detector. The next ghost image of
importance is formed by the pair 4, 3 and is located at 2.112 inches
from the last vertex. This distance also is well removed from the
true image surface. All other ghost images are considerably attenu-
ated due to multiple reflections and would not need to be considered.*

The remaining factors on the above list pertain directly to the
optical shop finishing techniques and to the perfection of the optical
coating processes. Since the methods of optical fabrication technology

*Ref, Discussion on theoretical energy scattering - Dr. A. Quesada

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represent especially advanced areas of skilled expertise by SORL optical shop technicians, the actual optical fabrication should present no unusual problem. SORL has achieved considerable success and background knowledge with the production of low scatter surfaces for the laser fusion industry using high energy lasers. However, the quality control of the coatings will demand painstaking attention. Inspection equipment must be designed to monitor the surfaces after coating and those which do not meet specifications imposed must be rejected and re-done.

The lens system, finally, must be assembled in a true, clean room environment where the atmosphere is micro-filtered to remove all contaminating dust particles. SORL does maintain an electronically filtered clean room for such assembly purposes.

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B. SCATTERING ANALYSIS

I Introduction

Techniques to estimate the fraction of light scattering from very rough surfaces have been known for several decades (1). They are based on mathematical models that assume the phenomenon to be capable of description within the scope of geometrical optics, by combining statistical methods with estimates of the path differences of luminous rays that have been operated on by the irregularities of the rough surface. The experimental evidence that was available showed that, although consideration of the magnitude and number of irregularities led to a qualitatively acceptable interpretation of the scattering phenomenon, quantitative predictions were incorrect, particularly when the spatial distribution of scattered energy was desired. The need for closer agreement between theory and experiment led the early investigators to the conclusion that a theory from which acceptable quantitative estimates could be derived required that diffraction effects be taken into account. This requirement becomes mandatory when surface or refractive defects become very small and/or are few in number. Attempts to develop diffraction oriented theories have not been very numerous. To our knowledge, the earliest one is due to A. Marechal (2) who treated the problem in the light of the theoretical framework of Fourier methods described in detail by Duffieux (3). In the present work we shall extend some of the techniques introduced by Marechal to include explicitly the effects of off-axis geometry and to take into account the effects of microscopic inhomogeneities in refractive

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.elements. In agreement with references (2, 4, and 5),

we shall be concerned primarily with optical surfaces of good

quality, whose irregularities are small enough to make all

deformations imposed upon a wave front small in comparison

to the wave length. The results to be presented are of

two types. We shall obtain expressions for total integrated

energies and, later, we shall develop the expressions for the

corresponding energy distributions. Detailed derivations

of equations that are not directly concerned with the

evaluation of those energy expressions will be relegated to

appendices. Whenever it seems appropriate, we have applied

the equations to the numerical evaluation of scattered

energy ratios for conditions that may arise in practice,

or for the establishment of order of magnitude estimates

that can serve as guidlines to determine whether detailed

computer evaluation of multiple integrals are necessary

to improve precision to a satisfactory degree. The appli-

cability of Fourier methods is a consequence of simpli-

fying assumptions regarding the geometry of a system. When

the conditions that allow the simplification are not met, it

becomes necessary to use a more general formulation in which

the diffraction integrals have to be evaluated either

numerically, on high speed computers, or asymptotically,

by means of methods such as Laplace's, Kelvin's, or Debye's.

The particular choice is primarily dependent on the limits

that appear on the integrals to be evaluated.

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The next two sections are devoted to the development of the theory on the basis of Fourier methods. The extensions to the more general formulation is, in most cases, immediate.

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II. The total energy diffracted

Suppose we have a refractive surface S, approximately flat, that creates small irregular deformations on the wave front. To compute the total energy diffracted, we shall imagine that a lens L is placed as in the following figure to transform the quasi-plane wave front into a nearly spherical front Σ_1' having the same irregularities. To calculate the distribution of amplitudes at a point P (x, y) of the focal plane of the lens, we shall use on the wave front the angular coordinates (α, β), the angles that the direction of the line joining the origin with the point on the wave front makes with the planes xOz and yOx. The use of the angular coordinates simplifies the exponent of the phase function that appears in the diffraction integrals. Further simplification to transform the integrals into Fourier integrals requires that certain conditions be satisfied by the coordinates of the observation point on the focal plane or near the focal plane of L. These are discussed in appendix 2. We know that under the conditions that allow writing the integrals as Fourier integrals (6) it is possible to express the amplitude of the electric field E (x, y) at the point P (x, y) by Huygens' principle, according to which if F (α, β) is the amplitude distribution on a sphere centered at 0, then

$$E(x,y) = \frac{iR}{\lambda} \iint_S F(\alpha,\beta) e^{ik(\alpha x + \beta y)} \, d\alpha \, d\beta$$

(1)

where R is the radius of the reference sphere and $k = 2\pi/\lambda$.

If the wave front is deformed by an amount Δ with respect

to the reference sphere the amplitude on the sphere is of the

form $E_o e^{ik\Delta}$, where E_o is a constant over the wave front. If

we now postulate that Δ is small in comparison to λ ,

we can write

$$e^{ik\Delta} \simeq 1 + ik\Delta$$

(2)

We can choose the radius of the reference sphere in such a

way that the mean value of Δ vanishes $(\bar{\Delta} = 0)$. In these

circumstances, the amplitude distribution over the aperture

is the sum of two terms: a) a uniform amplitude $F_1 = E_o$

and b) a fluctuating amplitude of mean value zero $F_2 (\alpha, \beta) =$

$ik E_o \Delta (\alpha, \beta)$.

Consequently, the resultant field E (x, y) is the sum of

two terms. The field E_1 is the field diffracted by the

aperture utilized. It is very small, except near the

geometrical image of the source, within a domain whose area

varies inversely as the area of the aperture. We shall be more

interested in the field E_2, whose amplitude generally

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decreases far more slowly. The defects represented by the function F_2 are, in general, small in extent by comparison with the extent of the aperture. Consequently, they diffract light into an area far more extensive than the area over which E_1 has appreciable magnitude. To compute the energy diffracted, we must introduce a more precise definition. We shall adopt, with Marechal, a definition based on the integral of the flux due to the amplitude E_2. Using Parseval's theorem, which expresses energy conservation, we can write this energy as proportional to

$$\iint |E_2(x,y)|^2 \, dx \, dy = R^2 \iint |F_2(\alpha,\beta)|^2 \, d\alpha \, d\beta \tag{3}$$

which, in view of the definition of F_2 is equivalent to

$$R^2 k^2 E_0^2 \iint_{S} \Delta^2 \, d\alpha \, d\beta \tag{4}$$

This integral is recognized as the mean square value of Δ. It is convenient to introduce the relative energy scattered, by division of the above expression by the total energy, which equals $E_0^2 R^2 \iint_{E} d\alpha \, d\beta$. Then,

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$$P = \frac{k^2 \iint_{\Sigma} \Delta^2 \, d\alpha \, d\beta}{\iint_{\Sigma} d\alpha \, d\beta} = \left(\frac{4\pi^2}{\lambda^2}\right) \overline{\Delta^2}$$

(5)

Thus, the energy scattered over the image plane, expressed as a fraction of the total energy, is proportional to the mean square value of the optical path-length error Δ. We may recall that a similar result is obtained in connection with the loss of illumination at the center of a diffraction pattern when small aberrations are introduced. It is known that in this case, the relative loss of illumination is precisely equal to $k^2 \overline{\Delta^2}$ and that the energy taken away from the central spot is distributed over the focal plane.

III. Computation of Δ for a scratch, a bubble, and micro-scopic irregularities.

Let us apply Eq. (5) to an irregularity in the shape of an ellipse. Limiting cases are clearly a narrow straight groove that can simulate a scratch and a crater-like depression that may be representative of a flaw in an anti-reflection coating. In line with the discussion of section 2.1, the dimensions of the ellipse are small in comparison to the effective area of the domain of integration. From appendix 1, we have the Δ values

$$\Delta = 2n\varepsilon \, ws \, i \qquad \text{for a reflector, and}$$

$$\Delta = (\cos r - n\cos i) \, \varepsilon \quad \text{for a refractive}$$

surface. Since the dimensions are small, the angles i and r are essentially constant. Also, strictly speaking, to satisfy the condition $\bar{\Delta} = 0$, we should modify the definitions of Δ above. However, since the area, A, of the irregularity is such that $\Delta \ll \Sigma$, where Σ is the area of the aperture, the correction to ε is of order A/Σ and, therefore, entirely negligible. We then have

$$\overline{\Delta^2} = \iint_{\Sigma_1} \Delta^2 \, d\alpha \, d\beta = 4\Delta^2 \int_0^{\Delta\beta} d\beta \int_0^{\left(\sqrt{1-\frac{\beta^2}{\Delta\beta^2}}\right)\Delta\alpha} d\alpha$$

$$= 4\Delta^2 (\Delta\alpha) \int_0^{\Delta\beta} \sqrt{1 - \frac{\beta^2}{\Delta\beta^2}} \, d\beta$$

$$= 4\Delta^2 \cdot \frac{\pi}{2} (\Delta\alpha)(\Delta\beta)$$

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Hence, $$P = \frac{2\pi \, (1-n) \, (a/b) \, \Delta^2}{\Omega} \left(\frac{2\pi}{\lambda}\right)^2$$

where Ω is the solid angle subtended by the aperture at the focal point. This equation can be modified to read

$$P = \frac{2\pi a b \, \Delta^2}{A} \left(\frac{2\pi}{\lambda}\right)^2$$

where a.and b are the semi-axes of the elliptical irregularity and A is the effective area of the aperture. For a refractive surface, for example, we have in the worst possible case

$$\Delta = (1-n) \, \varepsilon$$

Therefore,

$$P = \frac{2\varepsilon \, (n-1)^2 \, \left[\text{volume of irregularity}\right]}{A} \left(\frac{2\pi}{\lambda}\right)^2$$

For an axi-symmetric system whose effective aperture is defined by an f-number we can write

$$P = \frac{8\pi (n-1)^2 \, (\text{area of irregularity})}{(f-number)^2} \left(\frac{\varepsilon}{\lambda}\right)^2$$

In other words, the fraction of the energy scattered is proportional to the area of the irregularity, to the square

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of the depth of the irregularity measured in wave lengths
and inversely proportional to the effective area of the
aperture. For a bubble of radius a inbedded in a refrac-
tive surface, we have approximately,

$$\Delta = 2(n-1)\, a \cos\Theta$$
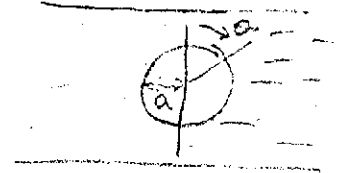
and

$$P = \frac{3\pi (n-1)^2 a \left[\text{volume of bubble}\right]}{A} \left(\frac{2\pi}{\lambda}\right)^2$$

Finally, for microscopic irregularities, let us consider
a very simple model in which they are distributed in such
a way as to cause a random error in the mean position of
the wave front, for which the probability of finding a
value of ε between ε and ε & $d\varepsilon$ is given by the expression

$$\frac{d\varepsilon}{\sqrt{\pi} \, (t\,\Delta n)^2} \; e^{-\left(\frac{\varepsilon}{t\,\Delta n}\right)^2}$$

where t represents the thickness of the refractive element
and Δn is a representative value of the index fluctuation
in the medium. Taking the ensemble average, we find that
with N the average number of volume elements with distinct
values of the index encountered by a luminous ray.

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$$\langle \bar{\Delta}^2 \rangle = \Omega \left(t \, \Delta n\right)^2 \frac{1}{N}$$

Hence,

$$P = \frac{4\pi^2}{N} \left(\frac{t \, \Delta n}{\lambda}\right)^2$$

Since Δn can be as small as 10^{-6}, the energy loss from this source of irregularities is generally very small, as N is of the order of 1000/cm.

IV Distribution of Intensities.

To characterize the intensity distribution, we must construct the function

$$D(x,y) = |E_2(x,y)|^2$$

(6)

The function E_2 (x, y), by virtue of Huygens' principle can be expressed as a Fourier transform of the function F_2 (α, β). Since, in general, the function F_2 (α, β) is random, it may appear that we can only calculate the mean value of its square. This, however, is not the case. It is possible to calculate the energy distribution because this energy distribution is the Fourier transform of the correlation function of F_2. Recall that

$$E_2(x, y) = \frac{iR}{\lambda} \iint_{S_1} F_2(\alpha,\beta)\, e^{ik(\alpha x + \beta y)}\, d\alpha\, d\beta$$

(7)

The energy distribution is $|E_2(x, y)|^2$, a function whose Fourier transform may be found by means of the correlation function, that is, its own Fourier transform. The derivation is straight-forward and may be found, for example, in reference (7). The result can be stated as follows:

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If $G(\xi, \eta)$ is the two-dimensional Fourier transform of $g(x, y)$, then

$$\mathcal{F}\left\{ \iint g(x,y)\, g^*(x-\xi, y-\eta)\, dx\, dy \right\}$$

$$= |G(\xi, \eta)|^2$$

(8a)

and similarly,

$$\mathcal{F}\left\{ |g(x,y)|^2 \right\} = \iint G(\xi,\eta)\, G^*(\xi+\xi', \eta+\eta')\, d\xi\, d\eta$$

(8b)

where the script F stand for "the Fourier transform of."
Let us apply Eq. (8b) to $E_2(x, y)$, identifying $g \leftrightarrow E_2$, and denoting the resultant transform $d(\xi, \eta)$. We have

$$d(\xi, \eta) = R^2 \iint_{S_1} F_2(\alpha, \beta)\, F_2^*\left(\alpha + \frac{\xi}{\lambda}, \beta + \frac{\eta}{\lambda}\right) d\alpha\, d\beta$$

(9)

Or,

$$d(\alpha', \beta') = k^2 R^2 E_0^2 \iint_{\Sigma_1} \Delta(\alpha, \beta)\, \Delta(\alpha + \alpha', \beta + \beta')\, d\alpha\, d\beta$$

Note that in Eq. (9), we have introduced the non-dimensional displacements ξ/λ and η/λ. This is necessary to preserve the dimensional homogeneity of the arguments of

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the functions Δ (d, β) and Δ (d $+$ d', $\beta+\beta'$). It is
sometimes convenient to write the correlation integral in
the form

$$\iint \Delta(\alpha,\beta)\, \Delta(\alpha+\alpha', \beta+\beta')\, d\alpha\, d\beta = \Omega\, \overline{\Delta^2}\, \psi(\alpha',\beta')$$

(10)

where Ω is the solid angle subtended by the aperture and
ψ (d', β') is a normalized correlation function

$$\psi(\alpha',\beta') = \frac{d(\alpha',\beta')}{d(0,0)}$$

Using Eq. (10) establishes a direct link between the energy
distribution, its Fourier transform, and the mean square
value of the path length errors that we calculated in
section 2.1. Eq. (10) indicates that if a defect covers
an appreciable portion of the aperture (for example, an
error of figure) the correlation function decreases slowly.
In the case the functions Δ (d, β) and Δ (d $+$ d', $\beta + \beta'$)
are nearly identical and the integral of the product is
approximately equal to $\Omega\, \overline{\Delta}^2$. If, on the other hand, Δ (α, β)
varies rapidly, the two functions contribute to the integral
only over a limited range of displacements. In either case,
the energy distribution, $|E_2(x, y)|^2$ is obtained by inversion
of the transform, Eq. (10). That is,

$$D(x,y) = \int_{-\infty}^{\infty}\int d(\alpha',\beta')\, e^{-\frac{2\pi i}{\lambda}(\alpha' x + \beta' y)}\, d\alpha'\, d\beta'$$

(11)

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or equivalently,

$$D(\lambda, \gamma) = \frac{k^2 R^2 E_0^2 \Omega \bar{\Delta}^2}{\lambda^2} \iint_{\infty} \psi(\zeta, \eta) e^{-2\pi i \left(x\frac{\zeta}{\lambda} + y\frac{\eta}{\lambda}\right)} d\zeta d\eta$$

$$= 4\pi^2 R^2 E_0^2 \Omega \frac{\bar{\Delta}^2}{\lambda^4} \Phi\left(\frac{x}{\lambda}, \frac{y}{\lambda}\right)$$

(12)

where $\Phi\left(\frac{x}{\lambda}, \frac{y}{\lambda}\right)$ denotes the double integral inverse
transform.

This expression suggests a simple way of measuring the
energy distribution. Suppose we can determine the mean
square value of Δ and can measure the ratio of the flux
D (x, y) to the total flux $(=R^2 \Omega E_0^2)$ at given locations,
but as functions of the wave length. Suppose that
subsequently we construct the curve representing $\left\{\frac{\lambda^4}{R^2 \Omega E_0^2}\right\} \times$
D(x, y) as a function of x/λ and y/λ. According to Eq. (12),
this curve represents the product $\bar{\Delta}^2 \Phi$. Since $\bar{\Delta}^2$ is a very
weak function of the wave length, upon division by $\overline{\Delta}^2$
and subjecting the function Φ to the condition that its
Fourier transform is equal to unity when $\alpha=\beta=0$, there
results the function $\Phi\left(\frac{x}{\lambda}, \frac{y}{\lambda}\right)$. The spatial energy
distribution for a given wave length follows immediately
by a simple change of variable. To avoid interference from
the intense direct images, the experiment should be conducted
with a black hole to eliminate the contribution from the
direct images. The construction of such a device is des-
cribed in reference (8).

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The decrease in illumination is again a Gaussian function. Again, these examples show that large scale defects, such as figure errors, lead to large values of ω and, consequently, energy distributions that fall off rapidly. On the contrary, when the defects are small, the correlation has short range and the diffracted light is spread out widely over the focal plane.

V Examples of Energy Distribution.

Let us consider the case of an irregularity of rectangular shape, of dimensions w and ℓ, simulating a small scratch. In this simple case, the normalized correlation function is

$$\psi(\alpha, \beta) = \text{...} \left(\frac{\omega}{2} - |\alpha| , \frac{\ell}{2} - |\beta| \right) \quad |\alpha| \leq \frac{\omega}{2} , |\beta| \leq \frac{\ell}{2}$$
$$= 0 \quad \text{elsewhere}$$

and, therefore,

$$\Phi(\xi, \eta) \sim \frac{\sin^2\left(\frac{\pi \omega}{\lambda}\right)\left(\frac{\omega}{\lambda}\right)}{\left(\frac{\pi \lambda}{\lambda}\right)^2} \cdot \frac{\sin^2\left(\frac{\pi \ell}{\lambda}\right)\left(\frac{\ell}{\lambda}\right)}{\left(\frac{\pi \ell}{\lambda}\right)^2}$$

As a second example, let us consider an autocorrelation function of Gaussian character. We might expect such a correlation function to describe the wave front distortions introduced by microscopic inhomogeneities. Let, then,

$$\psi(\alpha, \beta) = e^{-\frac{\alpha^2 + \beta^2}{\omega^2}}$$

where ω is a parameter that fixes the scale of correlation and, in general, can be interpreted as indicating that the irregularities of the wave front are seen from the origin 0 as subtending an angle of order ω. The function $\Phi\left(\frac{x}{\lambda}, \frac{y}{\lambda}\right)$ is in this case

$$\Phi\left(\frac{x}{\lambda}, \frac{y}{\lambda}\right) = \pi \omega^2 e^{-\frac{\pi^2 \omega^2}{\lambda^2}(x^2 + y^2)}$$

VI SUMMARY OF SCATTERING ANALYSIS

The theory that was developed to deal with levels and
spatial distribution of scattered light can be applied with
little modification to define limits on the number and extent
of scattering centers that may be tolerated in the tracker optics.
It is important to bear in mind that a theoretical study can very
effectively provide tolerance criteria to be met by the optical
designer, rather than predict in detail how a system will perform.
The latter requires that a system already in existence be examined
to determine the type, magnitude and distribution of bulk and sur-
face defects in each component. If this is known then the theory
can predict how much light will be scattered and how will the energy
be distributed. Theoretical considerations are also useful in in-
terpreting the results of scatter measurements on a system being
tested. This is particularly true of the stretch correlation, that
provides outputs that are invariant under changes of scale.

When the theory is applied to determine tolerances it becomes
apparent that the most critical parts of the system are the front
elements. This is because the intensity of the scattered light reach-
ing the image plane is proportional to the flux incident on the irreg-
ularities responsible for diffracting the light and introducing dis-
tortion of the wavefront. The effect of the irregularity itself, as
far as diffraction effects are concerned, is the same regardless of
where that irregularity is located. It leads to distortions of the
wavefront characteristic of the type and dimensions of the irregularity.
A small bubble, for example, that diffracts 1/10 of 1% of the light
may be tolerated in an inner element shielded by geometry from direct
sun light at all angles of interest. The same bubble would totally

destroy the system performance if present in the front element under conditions that allow exposure to direct sun light. In this case, even the fact that the distribution of scattered light will in general be oriented at some angle with respect to the axis of the system would not be sufficient to compensate for the direct effect of incident flux. The incident flux is generally strong enough to cause an intolerable loss of contrast in spite of the small fraction of side scattered light that reaches the image plane.

When the equations were specialized to account for effects of small bubbles it was found that the front elements have to be essentially bubble free. Although the equations were used to define some limiting upper size for a bubble, they may be interpreted also as indicators of how many smaller bubbles can be allowed. The trade-off is not immediate because it must be recalled that even though a small bubble is responsible for a small distortion of the wavefront, the light that it scatters in the forward direction is spread over a much wider solid angle that would be the case if the size of the bubble is allowed to increase. Reference to the table on page 14 is necessary to estimate how the angular factors are to be changed when the bubble size is decreased.

A similar argument can be used to estimate the effects of surface defects. If the equations applicable to a scratch are used, we find that in the worst case no scratch of depth of order of the wavelength and longer than a few millimeters can be tolerated for the front surface or any surface that may be illuminated directly by the sun.

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The worst case corresponds to a scratch oriented in a direction that will cause maximum spread of the diffracted light. It is important to remember that the quality of the surface finish or the quality of a coating can be evaluated in a variety of ways. For the small defects that we have considered electron microscopy, phase microscopy, dark field light microscopy and ellipsometry are suitable. For larger surface areas phase contrast and knife edge tests can be used. The measurements by any of these techniques can be used as inputs to the formulation that has been developed, to confirm that irregularities have been kept below the limits needed to meet performance specifications.

From the literature references, these are 4 main points which require special attention in terms of securing low scattering in lens systems. They are:

1. For a multiple lens element system the effect of flare is less at higher relative apertures than lower apertures.

2. For extended self-luminous objects, such as the horizon, the magnitude of the flare is proportional to the number of air-glass interfaces and not determined by the relative aperture.

3. In designing lens systems for low scatter applications, ghost reflected images adjacent to the image plane must be scrupulously avoided.

4. Good optical coatings do reduce the absolute magnitude of scattered energy, but porous films will slightly increase the amount of scattered energy.

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Eg's. (3) and (6) of Part I can be used to determine the effect of a small bubble in the front element of the proposed systems, when illuminated by direct sunlight falling on that element at an angle beyond the field of view. Several simplifying assumptions will be introduced, but in every case the simplification will be chosen in such a way as to produce 'worst' effects. This way we obtain criteria that, if met, will insure proper performance of the system.

Since the correlation function will in every case be analogous to the first example in section 3.2, the worst case can be approximated by distributing the total energy evaluated from eg. (3) over solid angles bounded by annular areas of radii equal to the distances corresponding to consecutive zeros of the function

$\sin \dfrac{\pi \chi}{\lambda} \dfrac{\omega}{R}$. We shall identify ω with the radius of the bubble. It is convenient to express the argument of this function in terms of angular quantities measured from the direction of the incident light. The zeros, then, occur at angles θ_η such that,

$$\pi \frac{\omega}{\lambda} \tan \theta_\eta = \eta \pi \quad \eta = 1, 2, 3, \ldots$$

or $\quad\quad \tan \theta_\eta = \dfrac{\eta \lambda}{\omega} \quad\quad$ (1)

Values of θ_η for $\eta = 1, 2, 3, 4$ are given in the following table for a large range of values of $\dfrac{\omega}{\lambda}$.

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TABLE III.

ω/λ	θ_1	θ_2	θ_3	θ_4
0.1	84.3°	87.1°	88.1°	88.6°
0.5	63.4	76	80.5	82.9
1.0	45	63.4	71.6	76
1.5	33.7	53.1	63.4	69
2.0	26.6	45	56.3	63.4
3.0	18.4	33.7	45	53.1
5.0	11.3	21.8	31	38.7
10.0	5.71	11.3	16.7	21.8
20.0	2.9	5.71	8.5	11.3
50.0	1.15	2.29	3.43	5.71
100.0	0.57	1.15	1.71	2.29
200.0	0.29	0.57	.86	1.15

The normalized peaks of energy density within each one of the areas bounded by zeros are 1, 0.047, 0.0034 and 0.0024, respectively.

From eg. (3), we find that the total energy scattered by the bubble is,

$$E_B = C \; R^2 k^2 E_o^2 \; (\overline{\Delta^2})$$

where E_o is the amplitude of the E-field and CE_o^2 can be taken as the energy density of the incident light.

Now, according to eg. (3) and the table shown before, the smaller bubbles scatter little light, but the scattering is over a very wide angle. On the other hand, the large bubbles scatter far more energy, (large $\overline{\Delta^2}$) but that energy is concentrated in the forward direction and relatively little is deflected to the sides. For example, when the bubble size is of the order of 10λ, the first zone extends to

less than 6° from the direction of incidence. Letting f be the attenuation factor due to angular effects we can then write:

$$p = \frac{\text{Energy density of scattered light in direction of } \eta\text{-th maximum}}{\text{Energy density of incident light}}$$

$$= \frac{1}{\pi} \left(\frac{2\pi}{\lambda}\right)^2 \left(\frac{\omega}{\lambda}\right)^2 \frac{1}{\Delta^2} f \qquad (2)$$

If p is to be less than some small fraction E we must have

$$16\pi \left(\frac{\omega}{\lambda}\right)^6 \left(\frac{\lambda^2 \eta_2}{R_o^2}\right)^2 f < E$$

$$\text{or} \quad \frac{\omega}{\lambda} < \left(\frac{E}{16\pi f}\right)^{1/6} \left(\frac{R_o}{\lambda(\eta-1)}\right)^{1/3} \qquad (3)$$

The light that is scattered is allowed to pass through other elements of the system. When the angle of scattering is such that the fraction f reaches the focal plane, a further weakening of intensity takes place because the front element in general will not be in focus.

The decrease in intensity can be estimated when the position of the image plane for the bubble is known. The problem is similar to that encountered when one computes the flare of a system due to secondary reflections of air-glass interfaces. In this case, it is known* that the amount of flare light is proportional to the square of the f/ number of the system and is inversely proportional to the (distance)^2

*See, for example, Kuwabara, G., J. O. S. A., 43, 53 (1953).

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of the secondary image from the focal plane. The latter effect is more serious and in designing an optical system it is desirable to avoid any pair of reflecting surfaces which produce a reflection image in the vicinity of the image plane. For the 6-element system, based on the figures obtained for the position of secondary image planes at normal incidence, we estimate that the reduction is of the order of 10. In general, we can call this factor f_1 and write instead of eg. (3)

$$\frac{\omega}{\lambda} < \left[\frac{E}{16\pi \, ff_1}\right]^{1/6} \left[\frac{R_o}{\lambda \, (\eta-1)}\right]^{1/3}$$

If $\lambda = .5 \times 10^{-4}$ cm, $= 1.5$, $R_o = 3$ cm, $E = 10^{-5}$,

$f = 0.001$, $f_1 = 0.1$

$$\frac{\omega}{\lambda} < \sim 20$$

This means that bubbles in the first 2 elements must be essentially absent. The last condition may be relaxed somewhat, by recalling that the derivation of eg's. (3) and (6) required the wavefront distortion to be small. For bubbles $\sim 10 \, \lambda$ this is not strictly true and a more geometrical approach indicates that most of the scattering is forward, with edge effects superimposed on it, and amounting to a fraction proportional to some effective volume of the edge as compared with the entire bubble.

Equally important is the problem associated with anti-reflection coatings for the first 2 elements. Coatings are effective in reducing the flare caused by reflected light, but one must be very careful to

have coatings very homogeneous. Porous films enhance slightly
the scattered light and tend to reduce contrast in the vicinity
of a bright image.

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Since a fractional rejection level of 10^{-5} will attennate sunlight to the equivalent of a uniform background brightness of 0.1 foot-lambert, we shall examine the expected performance of the systems in terms of fractional rejection levels. The same criterion will be used for other sources such as the full moon or the earth's sunlit horizon. For conversion, it is convenient to use the fact that a star of visual magnitude 0, corresponds to illumination outside the earth's atmosphere of 2.65×10^{-10} lumens/cm^2. Thus, the full moon, with an equivalent visual magnitude of -12.70, leads to an illumination of 3.2×10^{-5} lumens/cm^2. The effect of the full moon, as far as incident flux on irregularities is concerned, is then nearly 300,000 weaker.**

The computations that follow were carried out under the assumption that glasses will be specified, at least for the first two elements of each system, which will have:

a) Homogeneity: H2, that is, $\Delta n = \pm 5 \times 10^{-6}$

b) Bubble Group 0, that is, total bubble cross-section in mm^2/100cc volume of glass between 0 and 0.029. For the calculation, we require selection of the glass to have no bubble $> ^. 60\mu$ and it will be assumed that smaller bubbles that may be present will have

**Allen, C. W., Astrophysical Quantities, U. of London, Athlone Press (1963) (pg. 145).

a maximum cross section of 0.015 mm^2/100cc with a mean
size approximately 20λ.

The volumes of the first two elements for the two
systems were estimated to be 30cc and 27cc for the 6-
element system and 9.1 and 7.2cc for the 4-element system.

For these circumstances, we can apply the equations
developed in Part I of the theoretical analysis and
construct Table I for the cases where the sources are
outside the field of view.

These levels are comparable to the total values measured
for good coronograph lenses where (for those lenses not limited
by florescence) the fraction of solar light scattering was
between 1.2 x 10^{-6} and 5.7 x 10^{-6} (See Newkirk and Bohlin,
App. Optics, 2, 131, 1963).

For the case of the full moon within the field of
view, we have similar results. The most serious effect
is due to the small angular deviations that we must now
consider and the possibility of involving all elements of
the system.

Since, however, the incident flux due to the full
moon is some 300,000 weaker, in spite of the requirement
for the equivalent background brightness to be 0.05
foot-lambert, the changes in the factors shown in Table II
as compared with Table I are well within the 10^5 factor

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that the weaker source and equivalent background allow.
Thus, either system will satisfy this specification.
Again, we emphasize that the figures represent worst cases.

A similar analysis for the case of the earth's sunlit
horizon within the field of view shows that the specifica-
tion can be met at angles of about $3\frac{o}{-}$ away from the edge of
the horizon image. At closer angles, the presence of
bubbles in the size range 20λ to 50λ may lead to areas
where the specification is violated.

Ray tracing was used to determine the location of
secondary image planes and to estimate the effects of the
secondary images as sources of unwanted stray light.
Assuming the reflectivity of air-glass interfaces to be of
the order of 1%, we can summarize the results in Table III.

When the full moon is within the field of view spurious,
images may be formed with illuminations in the image plane
as bright as $6.4 c 10^{-8}$ lumens/cm^2 and $1.6 c 10^{-7}$ lumens/cm^2
(for 6-element and 4-element systems, respectively).

A fourth magnitude star having its energy distrib-
uted within 12arc minutes square field of view corresponds
to an illumination of 2×10^{-6} lumens/cm^2 for the 6-element
system and $.8 \times 10^{-7}$ lumens/cm^2 for the 4-element system.

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We, therefore, have signal to noise ration of

For the 6-element system:

$$S/N = \frac{2 \times 10^{-6}}{6.4 \times 10^{-8}} \simeq 30$$

For the 4-element system:

$$S/N = \frac{.8 \times 10^{-7}}{1.6 \times 10^{-7}} = 1/2$$

which shows the 6-element system as a more promising

system in this respect also.

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TABLE I

MAXIMUM FRACTION OF INCIDENT INTENSITY SCATTERED

SYSTEM	ANGLE	DUE TO BUBBLES	DUE TO BULK INHOMOGENEITIES	DUE TO SURFACE DEFECTS* (PER DEFECT)
6-Element	$30^{\underline{0}}$	1.6×10^{-6}	3×10^{-7}	10^{-6}
	$16^{\underline{0}}$	4×10^{-6}	7.5×10^{-7}	10^{-6}
4-Element	$30^{\underline{0}}$	5×10^{-6}	1.5×10^{-7}	10^{-6}
	$16^{\underline{0}}$	1.2×10^{-5}	4×10^{-7}	10^{-6}

* EACH DEFECT EQUIVALENT TO A MICROSCRATCH OF DEPTH λ,

   WIDTH = 1 MICRON AND LENGTH = 1000 MICRONS IN WORST

   POSSIBLE ORIENTATION (i.e. ANGULAR FACTOR = 1).

TABLE II

MAXIMUM FRACTION OF INCIDENT INTENSITY SCATTERED

SYSTEM	DUE TO BUBBLES	DUE TO BULK INHOMOGENEITIES	DUE TO SURFACE DEFECTS (PER DEFECT)
6-Element	6×10^{-3}	3×10^{-4}	10^{-6}
4-Element	10^{-2}	10^{-4}	10^{-6}

TABLE III

SPURIOUS IMAGE REJECTION

SYSTEM	AT $16^{\underline{0}}$	AT $30^{\underline{0}}$	AXIALLY
6-Element	Rays do not reach image plane	Rays do not reach image plane	$< 2 \times 10^{-3}$ for reflections due to 1st two elements
4-Element	$< 10^{-3}$	$< 10^{-3}$	$< 5 \times 10^{-3}$ for reflections due to 1st two elements

C. Fabrication Details

   I. General Fabrication Summary

      The complete specifications covering the optical

      fabrication tolerances are itemized in Table I. Most

      of these values are rather modest and easily held.

      However, some of the tolerances pertaining to

      individual element wedge, and lens centering error,

      are severe and must be carefully controlled. There is

      also one air space tolerance value which may require

      special assembly adjustment in order to obtain peak

      theoretical performance.

   II Glass Material Selection

      The particular glass materials chosen for this design were

      dictated by the design requirements discussed in the

      previous sections. However, the quality is determined

      by specifying "Schlieren Grade", PH4 with Special

      Bubble Selection. This insures that the variation in

      inhemogeneity will be of the order of $\pm 1 \times 10^{-6}$ with-

      in each blank, stress birefringence $\lesssim$ 3-4 nm/cm and

      maximum inclusions (i.e. bubbles) of 0 - .029 cross

      section per 100 cc.

   III Distortion Characteristics

      The general distortion characteristics of the lens

      system are summarized in Table II. These values were

obtained directly from the computer print-out of spot
diagrams giving the image centroid heights. The tolerance
value of 3arc minutes for distortion was then converted
directly into the allowed linear displacement value
of 0.044mm. Then, the calculation of the residual
distortion in the lens system was derived directly from
the value in the table.

IV Transmission Characteristics

Table III shows the given catalog values of nominal
internal transmittance values for the selected glass
types. These glasses all show high values of trans-
mittance at 400 nm, which is primarily why they were
chosen. A sampling of various firms specializing in
optical coatings also indicate that the nominal value
of 0.5% represents the lowest reflectivity value to be
expected over the range from 0.40 to 0.62 microns.
These coatings will satisfy MIL-C-675 specifications for
abrasive resistance and weathering characteristics.

V Mechanical Considerations

The cell will be made of a stainless steel which most
nearly matches the glasses with regards to the thermal
co-efficient of expansion. The elements will be edge
shimmed at assembly for zero clearance. A window, for
protection of the optical elements, is provided at the
front of the cell and is removable by means of one

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retaining ring.

The lens will incorporate a lockable focussing arrange-
ment providing 2mm of motion on each side of best focus.
The focus housing will engage the 2.118-48 thread and
a shoulder will bottom on the system face. The lens
cell is piloted in the focus housing on two lands and
moves axially by means of a 12 pitch thread. Locking is
accomplished by a set screw.

Light baffling will be accomplished by providing all
retainers and spacers with deep grooves such that light
entering the grooves cannot continue downstream except
after two or more reflections. All retainers and spacers
will be surface treated for minimum reflectivity with
minimum specular component.

TABLE I

TABLE OF TOLERANCES

SURFACE	ΔR	SURFACE FIGURE	(ELEMENT CT) Δd	AIR SPACE Δs	ΔN$\bar\lambda$	WEDGE	ELEMENT TILT LENS SEAT	ELEMENT DECENTER
1 & 2	±0.014	.50λ	±.0040	-	±0.0016	0.0012"	0.0011"	0.0010"
3	±0.012	.50λ		±0.0014				
2 {4	±0.003	.33λ	±.0011		±0.0008	0.0004"	0.0004"	0.0008"
5	±0.015	.33λ		±0.0018				
3 {6	±0.004	.25λ	±.0015		±0.0011	0.0002"	0.0003"	0.0004"
7	±0.001	.25λ		±0.0012				
-8	-			±0.0012				
4 {9	±.012	.25λ	±.0014		±.0020	0.0004"	0.0002"	0.0006"
10	±.002	.25λ		±0.0006*				
5 {11	±.002	.25λ	±.0017		±.0006	0.0002"	0.0003"	0.0004"
12	±.001	.33λ		±0.0031				
6 {13	±.005	.50λ	±.004		±.0016	0.0005"	0.0007"	0.0019"
14	±.246	.50λ						

Note: All glasses must be Schlieren Grade, PH4 quality with
-Special Bubble Selector.

*MAY REQUIRE ASSEMBLY ADJUSTMENT

General Surface Finish:

	Target	Required
Element I and II	0/0	5/0
Elements III, IV, V		
VI	5/5	10/5

TABLE II

DISTORTION VALUES

FIELD ANGLE (Radius)	GAUSSIAN HEIGHT (mm)	IMAGE CENTROID (mm)	DISTORTION* (min)
0.000	0.0000	0.000	0.00
0.026105	1.3057	1.2992	0.44
0.05221	2.6141	2.6043	0.67
0.078315	3.9278	3.9128	1.02
0.104420	5.2497	5.2268	1.56
0.130525	6.5826	6.5558	1.83

Tolerance Value = 3.0 min.

TABLE III

TRANSMISSION & REFLECTION LOSSES: 400 NM

MATERIAL	INTERNAL TRANSMITTANCE	
	5mm	25mm
LAK-8	0.988	0.940
SF-19	0.985	0.920
SF-1	0.980	0.890

Reflection losses for 12 air-glass interfaces, assuming a very
realistic coating value loss of 0.5%, will amount to 5.8%.
The total absorbtion losses will be, nominally, less than
15.1%. Therefore, the average transmittance of the system
will be about 79.1%. This value is somewhat pessimistic
since the absorbtion values are given for plane parallel plates
of glass and the lens elements are much thinner at the edges.
The coatings will be broad band coatings, peaked for 4,000Å.
The target value of 70% than appears to be definitely a practical
working value.

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APPENDICES

Appendix 1. Calculation of Optical Path Errors Due to Surface Defects.

Consider first a refracting surface separating two media of indices n_1 and n_2. If a defect of depth ε is present, the difference in optical path for the ray that is refracted at I and the ray that would have been refracted at I' if the defect were absent is, from the figure,

$$AI - AI' = \frac{IM}{\cos\alpha}$$
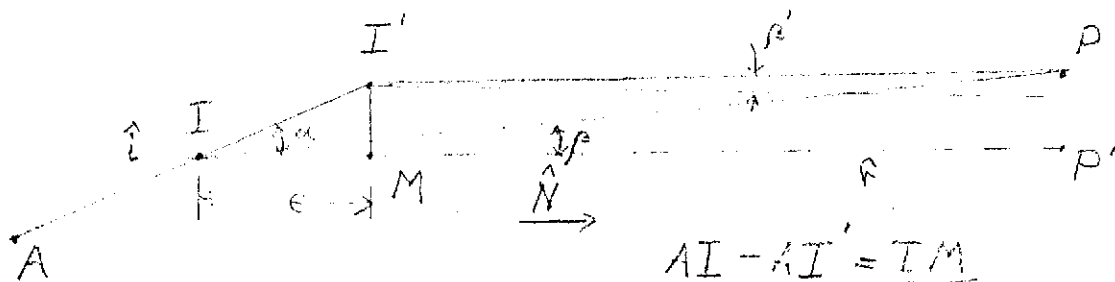
$$IP - I'P = \frac{IP'}{\cos\beta} - \frac{MP'}{\cos\beta'},$$

$$\delta W = n_1\left(AI - AI'\right) + n_2\left(IP - I'P\right) \qquad (a.1)$$

Let $\quad \delta W = n_1\left(\dfrac{IM}{\cos\alpha}\right) + n_2\left(\dfrac{IP'}{\cos\beta} - \dfrac{MP'}{\cos\beta'}\right)$

then,

$$\overrightarrow{II'} = -\overrightarrow{\delta I}$$

$$IM = \overrightarrow{\delta I} \cdot \hat{N}$$

$$IP' = \overrightarrow{IP} \cdot \hat{N}$$

$$MP = \overrightarrow{I'P} \cdot \hat{N} \qquad\qquad (a.2)$$

where $\hat{N}$ is the unit normal to the surface in the absence of defects. Substituting Eqs. (a.2) into Eq. (a.1) leads to

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$$\partial_L = n_1 \left(\frac{\partial \vec{I} \cdot \hat{N}}{\cos \alpha} \right) + n_2 \left(\frac{\overrightarrow{IP} \cdot \hat{N}}{\cos \beta} - \frac{\overrightarrow{I'P} \cdot \hat{N}}{\cos \beta'} \right)$$

(a.3)

Since ε is assumed to be very small, $\beta \simeq \beta'$ and

$$\overrightarrow{IP} - \overrightarrow{I'P} \simeq - \left[\overrightarrow{PI} - \overrightarrow{PI'} \right] \partial \vec{I}$$

Hence,

$$\partial_L = - \left(n_1 \hat{i} - n_2 \hat{r} \right) \cdot \partial \vec{I}$$

The law of refraction in vector form reads,

$$n_2 \hat{r} - n_1 \hat{i} = (n_2 \cos \underline{r} - n_1 \cos i) \hat{N}$$

(a.4)

Therefore, we can write

$$\partial_L = \left(n_2 \cos \underline{r} - n_1 \cos \hat{i} \right) \hat{N} \cdot \partial \vec{I}$$

But $\hat{N} \cdot \partial \vec{I} = \varepsilon$. The deformation of the wave front is $\Delta = - \partial_L$.

Consequently,

$$\Delta = (n_1 \cos i - n_2 \cos \underline{r}) \, \varepsilon$$

(a.5)

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' For a reflecting system, we have
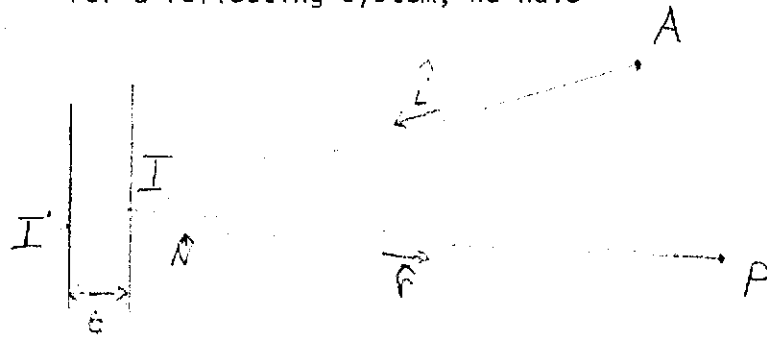
$$\delta L = n\left[\, \partial \vec{I}\cdot \hat{\imath} \; + \; \partial \vec{I}\cdot \hat{r}\,\right]$$

But the law of reflection in vector form reads

$$\hat{r} = -\hat{\imath} + 2 \cos i \; \hat{N}$$

Hence,

$$\partial L = n\left[\, 2 \cos i \; \delta \vec{I}\cdot \hat{N}\,\right]$$

Again, $\hat{N}\cdot \partial \vec{I} = \epsilon$ Hence, the deformation of the wave front is

$$\Delta = 2\,n\,\epsilon\,\cos i$$

$$(a.6)$$

If a converging wave front has phases represented by
a phase function F (x', y', z'), the amplitude of the disturb-
ance that reaches a point P (x,y,z) is given by the classical
Huygens-Fresnel formula (see, for example, ref. 6).

$$U(P) = -\frac{i}{\lambda} \iint F(x',y',z') \frac{e^{ikd_2}}{d_2} dS'$$

(b.1)

To evaluate d_2, we consider an axially symmetric (or nearly
so) wave front whose vertex is situated at a distance f from
the origin of a coordinate system whose z-axis is in the
direction of the symmetry axis. Let R represent the
radius of curvature of the wave front at the vertex. From the
figure it is clear that the distance from a point M on the
wavefront to an
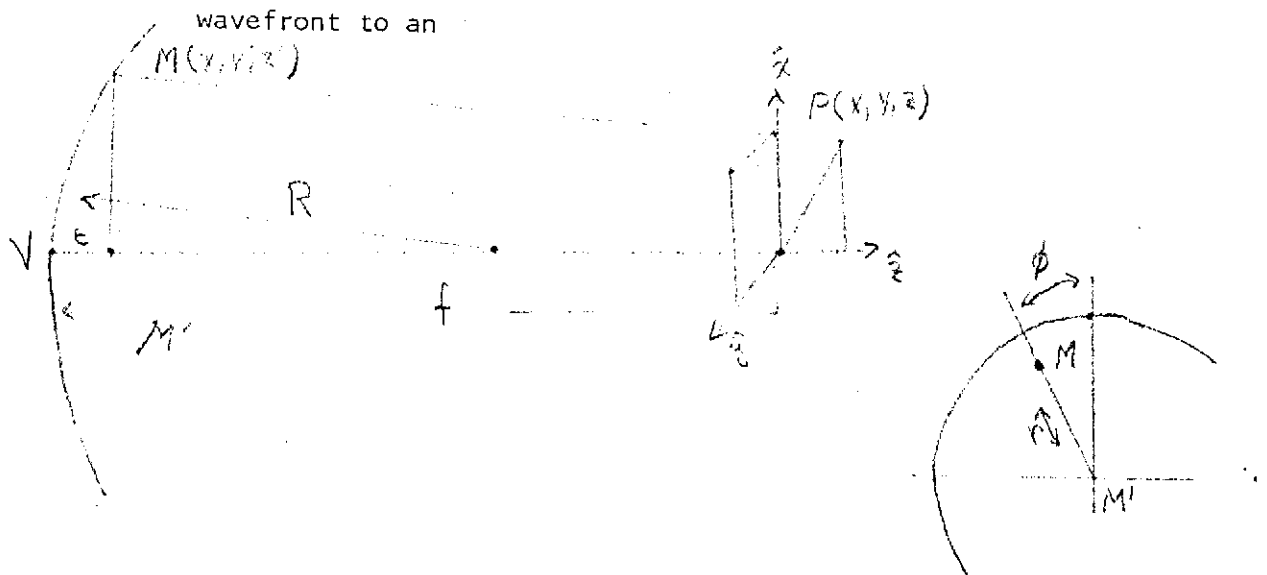
observation point near the plane x-y is

$$d_2^2 = (x - x')^2 + (y - y')^2 + (z - z')^2$$

(b.2)

The position of the point M can be more conveniently
specified by the coordinates r and ϕ plus the distance
along the axis ϵ.

We can then write for d_2

$$d_2^2 = f^2 \left\{ 1 + \left(\frac{r}{f} \right)^2 + \frac{x^2 + y^2 + z^2}{f^2} - 2 \left(\frac{\epsilon}{f} \right) + \left(\frac{\epsilon}{f} \right)^2 \right.$$
$$\left. + 2 \left(\frac{z}{f} \right) \left(1 - \frac{\epsilon}{f} \right) - 2 \frac{r}{f} \left(\frac{x}{f} \cos \phi + \frac{y}{f} \sin \phi \right) \right.$$

(b.3)

For the special but important cases where the wave front
is spherical or paraboloidal, we have that

$$\epsilon^2 = R^2 \left[1 - \sqrt{1 - (r/R)^2} \right]^2$$
$$\epsilon = \frac{r^2}{2R}$$

and

respectively.

A simplification is obtained when all five of the conditions

hold $\frac{r}{f} \ll 1$, $\frac{\epsilon}{f} \ll 1$; $\frac{x}{f}$, $\frac{y}{f}$ and $\frac{z}{f} \ll 1$

(b.4)

-55-

In this case

$$d_2 = f\left[1 - \frac{\xi}{f} + \frac{z}{f}\left(1 - \frac{\xi}{f}\right) - \frac{r}{f}\left(\frac{x}{f}\cos\phi + \frac{y}{f}\sin\phi\right)\right]$$

This is the usual form of d_2 for diffraction work. We shall be interested in a different form and also in the case where $z = 0$, that is, we want to have the observation point in a plane, that in general will be the focal plane of a lens or a mirror. Let us introduce the new variables.

$$\frac{r\sin\phi}{f} = \sin\beta \quad , \quad \frac{r\cos\phi}{f} = \sin\alpha$$

As seen from the following figure, the angles α and β are in orthogonal planes and allow us to write d_2 in the form

$$d_2 = f\left\{1 - \frac{1}{f}\left(x\sin\alpha + y\sin\beta\right)\right\}$$

$$(b.5)$$

Since the condition $r/f \ll 1$ implies that the angles α and β are small, we can replace the sines by the angles and have only the linear combination as the variable part of the exponent, in which case the integral becomes a Fourier integral, with exponential term

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$$e^{ikt} \quad e^{-ik(x\omega + y\beta)}$$
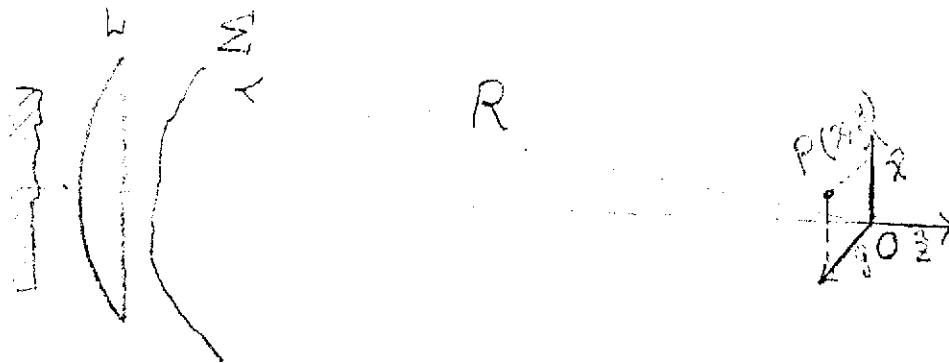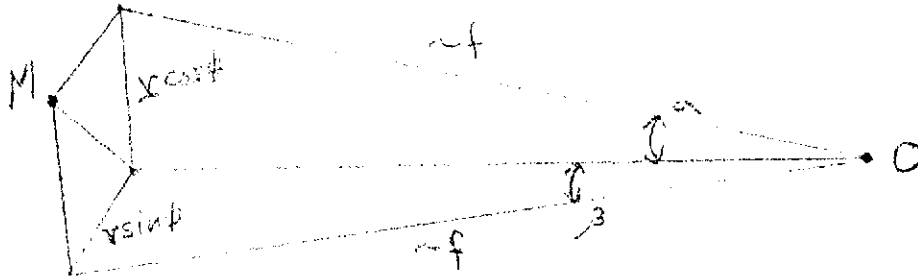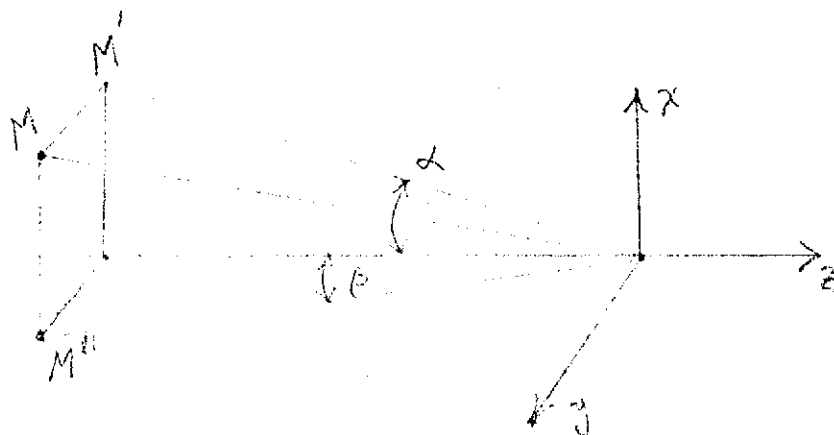
figure 1

Figure 2

REFERENCES

1. J. Urbanek, Rev. d'Opt., p. 247 (1930)

2. A. Marechal, Opt. Acta, vol. 5, 70 - 74 (1958)

3. Diffieux, P. M., L'integrale de Fourier et ses applications a l;optique, Oberthur, Rennes (1946)

4. E. Diederichs, and A. Lohmann, Optik, vol. 12, 751 (1958)

5. Linfoot, E. H., Fourier methods in Optical image evaluation,,The Focal Press, New York (1964)

6. Born, M. and Wolf, E., Principles of Optics, New York, (1964)

7. Goodman, J. W., Introduction to Fourier Optics, New York, (1968)

8. G. Kuwabara, J. Opt. Soc. Am., vol. 43, No. 1 (1953)

<u>Appendix 3.</u>   <u>Sample Scattering Computation.</u>

Computations are based on the following three equations that represent the amount of light scattered by an irregularity as a fraction of the flux incident on it.

<u>For Bubbles</u>:

$$\varepsilon = 16\pi \left\{ \frac{\lambda (n-1)}{Ro} \right\}^2 \left(\frac{\omega}{\lambda} \right)^6 f_1(\theta) \ f_2(d)$$

<u>For scratches</u>:

$$\varepsilon = (2\pi)^3 (n-1)^2 \left(\frac{h}{\lambda} \right)^2 \frac{\Delta x \ \Delta y}{Ro^2} \ f_1(\theta) \ f_1(d)$$

<u>For bulk inhomogeneities</u>:

$$\varepsilon = \left(\frac{2\pi t}{\lambda} \right)^2 \left(\frac{\Delta n}{N} \right)^2 f_1(\theta) \ f_1(d)$$

where

λ = wave length of light
n = index of refraction of glass
Ro - radius of curvature of wave front forming image
ω = radius of bubble
$\Delta x, \Delta y$ = dimension of scratch determining projected area
h = depth of scratch
t = thickness of lens or optical element
Δn = fluctuation of index in optical element
N = av. number of domains/unit thickness showing the
    fluctuation Δn.
$f_1(\theta)$ = factor to account for angular distribu-
    tion of scattered light
$f_2(d)$ = factor to account for defocussing effects
    that tend to spread out the light over the
    image pane.

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For bubbles, for example, we have selected a glass belonging to bubble group 0, specified as having a total bubble cross section between 0 and 0.029 mm^2/100cc volume of glass. We shall assume a value of 0.010, for 1st element. For the 6-element system, we further require that there be no bubble or inclusion of diameter 50u or greater. This is consistent with the lower limit of bubble group 0. Since the 1st element of the system has an approximate volume of 30cc, we have a total area, according to specifications, between 0 and 0.01 $(mm)^2$. Assuming a log-normal distribution for the bubble present, the mean bubble radius is in the vicinity of 20λ. The radius of curvature of the front surface will be taken as 10cm and for a 20λ bubble with direct illumination from a direction making an angle of 30° with the optic axis we have an angular factor $< 10^{-3}$. With these values, and recalling that the true image plane is about 2.5 cm behind the last element we have

$$\varepsilon = 16\pi \; \{ \frac{.16 \times 10^{-8}}{4 \times 100} \} \; (\frac{10}{.4\sqrt{\pi}})^6 \times 10^{-3}$$

$$= 16\pi \; (\frac{16 \times 10^{-10}}{4 \times 10^2}) \; (\frac{10^{12}}{4^6 \times \pi^3}) \times 10^{-3}$$

$$= \frac{10^{-4}}{64} \approx 1.6 \times 10^{-6}$$

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For this case, we have taken $f_2(d)=1$, to consider what might be regarded as a worse case. For scratches, we have taken the angular factor to be 1, since there may be cases where the orientation of a very narrow scratch spreads the light over a considerable angle from the direction of the incident light.

For bulk inhomogeneities, we consider an element 14mm thick made of galss in homogeneity group H^2 $(\Delta n = \pm 5 \times 10^{-6})$. Since N is of order $(10^A)^{-1} cm^{-1}$, we have

$$\epsilon = (5 \times 10^{-6})^2 \frac{(2\pi \times 1.4)^2}{4 \times 10^{-5}} \frac{10^{-3}}{1.4 \times 10^3 \times 2.5}$$

$$= 1/3 \times 10^{-6}$$

We also have assumed that when illumination is such that more than one element receives light from the source, the net effect is additive.

Appendix 4.   Computer Design Data.

1	-10		0.00000000	.40000000		
1	-0		-2.69992512	1.00000000	0.00000000	.02706479
2	-3	R.	3.59887889	-0.00000000		
2	1	L.	.54035222	N2 1.72135300	∼ 54.69410000	-.00332940
3	-3	R	-6.10936901	-0.00000000		
3	1	L.	.06409174	1.00000000	0.00000000	.02706479
4	-3		1.84401385	-0.00000000		
4	1		.63253628	1.72135300	54.69410000	-.00332940
5	3		4.25087752	-0.00000000		
5	1		.15607882	1.00000000	0.00000000	.02706479
6	-3		-9.86141478	-0.00000000		
6	1		.25063480	1.67971500	32.23500000	.09636757
7	3		.99928437	-0.00000000		
7	1		.17926524	1.00000000	0.00000000	.02706479
8	3		0.00000000	-0.00000000		
8	1		.06979460	1.00000000	0.00000000	.02706479
9	-3		-2.68013362	-0.00000000		
9	1		.20010344	1.73293700	28.65500000	.09939056
10	3		1.99530907	-0.00000000		
10	1		.00241218	1.00000000	0.00000000	.02706479
11	-3		1.81068819	-0.00000000		
11	1		.64039832	1.72135300	54.69410000	-.00332940
12	3		-1.23557531	-0.00000000		
12	1		.08399380	1.00000000	0.00000000	.02706479
13	-3		1.50874608	-0.00000000		
13	1		.38039748	1.72135300	54.69410000	-.00332940
14	3		21.84930678	-0.00000000		
14	1		1.00716463	1.00000000	0.00000000	.02706479
15	3		0.00000000	-0.00000000		
15	2		-.00346960	1.00000000	0.00000000	.02706479
16	3		0.00000000	0.00000000		
16	1		0.00000000	1.00000000	0.00000000	0.00000000

50 MM F/1.03 LOW SCATTER LENS SYSTEM

CONSTRUCTION DATA

RAY HEIGHT VS INTERCEPT ERRORS

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```
 2    .4802490   -.1142391   -.0000000    .0000000   -.4802400    .1142391
 3    .4607044   -.3126261   -.0000000    .0000000   -.4607044    .3126261
 4    .4159040   -.3718891   -.0000000    .0000000   -.4159040    .3718891
 5    .3192543   -.5265472   -.0000000    .0000000   -.3192543    .5265472
 6    .3167466   -.1580422   -.0000000    .0000000   -.3167466    .1580422
 7    .2754990   -.1807201   -.0000000   -.0000000   -.2754990    .1807201
 8    .2767512    .1807201   -.0000000   -.0000000   -.2767512   -.1807201
 9    .2778139    .1919862   -.0000000   -.0000000   -.2778139   -.1919862
10    .3129313    .6409423   -.0000000   -.0000000   -.3129313   -.6409423
11    .3210183    .1675822   -.0000000   -.0000000   -.3210183   -.1675822
12    .3472845   -.1988678   -.0000000    .0000000   -.3472845    .1988678
13    .3115337   -.2911654   -.0000000    .0000000   -.3115337    .2911654
14    .2730998   -.4819296   -.0000000    .0000000   -.2730998    .4819296
 0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0   0   0   0   0   0   0
  1    480    0      2    432    0      3    384    0      4    336    0      5    288    0      6    240    0
  7    192    0      8    144    0      9     96    0     10     48    0     11      0    0     12    -48    0
 13    -96    0     14   -144    0     15   -192    0     16   -240    0     17   -288    0     18   -336    0
 19   -384    0     20   -432    0     21   -480    0     22      0   48     23      0   96     24      0  144
 25      0  192     26      0  240     27      0  288     28      0  336     29      0  384     30      0  432
 31      0  480     32    336  336     33    288  336     34    240  336     35    192  336     36    144  336
 37   -144  336     38   -192  336     39   -240  336     40   -288  336     41   -336  336
SINE(ANGLE)= 0.00000
```


SAG FANY

SAG FANZ

MP FAN Y

SINE(ANGLE)= 0,00000
-50----+----40----+----30----+----20---- Y,Z MICRONS, PL MICRONSX100- +20----+----+30----+----+40----+----+50

SKEW FAN ; DY ERRORS

SKEW FAN ; DZ ERRORS

MERIDIONAL FAN

FIG. 1.

ML — — H — — — — — M — — — ↓

-50 — — 40 — — 30 — — 20 — — Y,Z MICRONS, PL MICRONSX100, +20 — — 30 — — 40 — — 50

IL

(YZP)SKEW   H   M   IL   L M   M L   H M L
                         H H   IL   M   M
            M   IL M L   M
                         M I   L   M   L   H   L
                                        L   M

IM
PL,SAG   M I   L   M I   M
              M   I   M   M   M
            M   I   M
                                        M I

IM   M I   M
              I M   M   M
            M I   L   M I   M   M
IM   I
PL,MP

IM   M I
              M I   L   M I   M   M
              I M   M   M
            M   M I

WAVE FRONT ERRORS
NON-APPLICABLE

```
2   .3461485   -.0442909   -.0881320    .0584324   -.5155643    .1597565
3   .3364845   -.1573804   -.0724947    .1178024   -.4904629    .4025034
4   .3238346   -.2403492   -.0718176    .1016930   -.4282268    .4277989
5   .2562387   -.3256336   -.0399270    .1603860   -.3148594    .6207701
6   .2448544   -.0879095   -.0273664    .0846267   -.3092350    .2087862
7   .2264297    .2054315   -.0186940    .1193878   -.2571840   -.0355496
8   .2338563    .2054315   -.0059494    .1193878   -.2578410   -.0355496
9   .2367566    .1932877   -.0017532    .0683376   -.2581802   -.1025939
10  .2878356    .5822220    .0051010    .1221900   -.2750868   -.4107233
11  .2735488    .1766066    .0052498    .0685431   -.2778971   -.0881640
12  .3077341   -.0975890    .0272068    .0862027   -.2956987    .2559896
13  .2936533   -.2242025    .0274747    .0347491   -.2627027    .2950489
14  .2628576   -.3679365    .0340724    .0620680   -.2178869    .4924357
```

```
0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
0   0   0   0   0   0   0   0   0   0   0
```

```
 1   432    0        2   389    0        3   345    0        4   302    0        5   259    0        6   216    0
 7   172    0        8   129    0        9    86    0       10    43    0       11     0    0       12   -43    0
13   -86    0       14  -129    0       15  -172    0       16  -216    0       17  -259    0       18  -302    0
19  -345    0       20  -389    0       21  -432    0       22     0   48       23     0   96       24     0  144
25     0  192       26     0  240       27     0  288       28     0  336       29     0  384       30     0  432
31     0  480       32   302  336       33   259  336       34   216  336       35   172  336       36   129  336
37  -129  336       38  -172  336       39  -216  336       40  -259  336       41  -302  336
```

SINE(ANGLE) = .06525


```
     -50--------40--------30--------20---- Y,Z MICRONS,  PL MICRONSX100·  +20--------+30--------+40-------+50
```

SAG FANY

SAG FANZ

MP FAN Y

FIG. 2.

-50 ---- -40 ---- -30 ---- -20 ---- Y,Z MICRONS, PL MICRONS X100 ---- +20 ---- +30 ---- +40 ---- +50

(YZP)SKEW

PL.SAG

PL,MP

2	.2325075	.0205876	-.1765469	.1169402	-.5735479	.2108439
3	.2375698	-.0208217	-.1461685	.2366471	-.5461319	.5126823
4	.2366910	-.1214714	-.1421335	.2022115	-.4466181	.5008921
5	.2066070	-.1409675	-.0788053	.3206732	-.3166303	.7392184
6	.1934943	-.0054650	-.0533475	.1690532	-.3090793	.2628306
7	.1924603	.2928229	-.0314969	.2406973	-.2446671	.0905904
8	.2081026	.2928229	-.0095155	.2406973	-.2423358	.0905904
9	.2135456	.2367398	-.0008615	.1386190	-.2411514	-.0254731
10	.2498438	.6489767	.0131550	.2500817	-.2450370	-.2369223
11	.2550295	.2204036	.0134700	.1389158	-.2461903	-.0145648
12	.3013617	-.0000478	.0579895	.1712921	-.2495903	.3160970
13	.3013548	-.1758466	.0592156	.0660091	-.2204182	.3060998
14	.2779670	-.2839690	.0716595	.1183783	-.1694253	.5147858

| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 |

| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 |

1	408	0	2	367	0	3	326	0	4	285	0	5	244	0	6	204	0
7	163	0	8	122	0	9	81	0	10	40	0	11	0	0	12	-40	0
13	-81	0	14	-122	0	15	-163	0	16	-204	0	17	-244	0	18	-285	0
19	-326	0	20	-367	0	21	-408	0	22	0	48	23	0	96	24	0	144
25	0	192	26	0	240	27	0	288	28	0	336	29	0	384	30	0	432
31	0	480	32	285	336	33	244	336	34	204	336	35	163	336	36	122	336
37	-122	336	38	-163	336	39	-204	336	40	-244	336	41	-285	336			

SINE(ANGLE) = .13050

FIG. 3.

```
I         I         I         I     _  M   H  M       I         L  I         I         I         I         I
I-M-------------------L----------------------------------------------I-----------------------------------------I
-50-------40--------30--------20----- Y,Z MICRONS,   PL MICRONSX100-   +20--------+30--------+40--------+50
I         I         I     L  I     L M       M       I         I         I         I         I
(YZP)SKEW I         I         I     L         M M       I         I         I         I         I
I         I         I         I     L       M L       I         I         I         I         I
I         I     H   I         I     I M   M L         I         H         I       L I         I
I         I     IM  I         I     M       I         L         I       L I         I
I---------------------------IM----------I-----------------I-----------------I-------------------------------------
I         I         I         I         I         I         I       IM         I         H   I
PL,SAG    I         I         I     M   I     H   I     M   I     M I   M   I         H   I
I         I         I     M   I         I         I         I         I         I
I         I         I         I         I         I         I         I         I
I---------------------------------------------H-----------------------------------------------------
I         I         I     H I         I         M I         I         I
I         I         I         I         I         I         I     HL         I
I         I         I         I         I         I     M   I     H   I     M   I
I         I         I         I         M IM       I         I     H I
PL,MP     I         I         I         I         I     M   I-----M-------------------------
I         I         I         I         I         I         I         I
I         I         I         I         I         I         I     L   I
I         I         I         I         I         I         I         I
I         I         I     H I         I         I         I         I
I-----------------------M---------------------------------------------------------------------
```

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LOW SCATTER   50 MM F/I.   SYSTEM DATA (MM)

R/CT↓

2	89.071972	-0.	-0.	-0.	-0.	-0.	
2	13.548805	1.736479	1.727143	1.723612	1.720619	1.718053	1.715831	1.712177
3	-152.734225	-0.	-0.	-0.	-0.	-0.	
3	.702294	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
4	46.700346	-0.	-0.	-0.	-0.	-0.	
4	15.213407	1.736479	1.727143	1.723612	1.720619	1.718053	1.715831	1.712177
5	106.571938	-0.	-0.	-0.	-0.	-0.	
5	3.001958	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
6	-51.535370	-0.	-0.	-0.	-0.	-0.	
6	6.350957	1.705295	1.689163	1.683353	1.678546	1.674509	1.671078	1.665571
7	24.982100	-0.	-0.	-0.	-0.	-0.	
7	4.481631	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8	0.000000	-0.	-0.	-0.	-0.	-0.	
8	1.744065	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9	-67.503341	-0.	-0.	-0.	-0.	-0.	
9	1.322022	1.764271	1.744437	1.737355	1.731519	1.726637	1.722500	1.715888
10	0.000000	0.	0.	0.	0.	0.	
10	3.680556	1.764271	1.744437	1.737355	1.731519	1.726637	1.722500	1.715888
11	49.982727	-0.	-0.	-0.	-0.	-0.	
11	.660304	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
12	45.265205	-0.	-0.	-0.	-0.	-0.	
12	16.609958	1.736479	1.727143	1.723612	1.720619	1.718053	1.715831	1.712177
13	-30.989383	-0.	-0.	-0.	-0.	-0.	
13	.599845	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
14	37.718652	-0.	-0.	-0.	-0.	-0.	
14	9.509937	1.736479	1.727143	1.723612	1.720619	1.718053	1.715831	1.712177
15	546.232520	-0.	-0.	-0.	-0.	-0.	
15	25.179116	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
16	0.000000	-0.	-7.970000E-05	-2.690900E-04	-0.	9.981253E-01	
16	-.686740	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000

SPOT DIAGRAM ANALYSES

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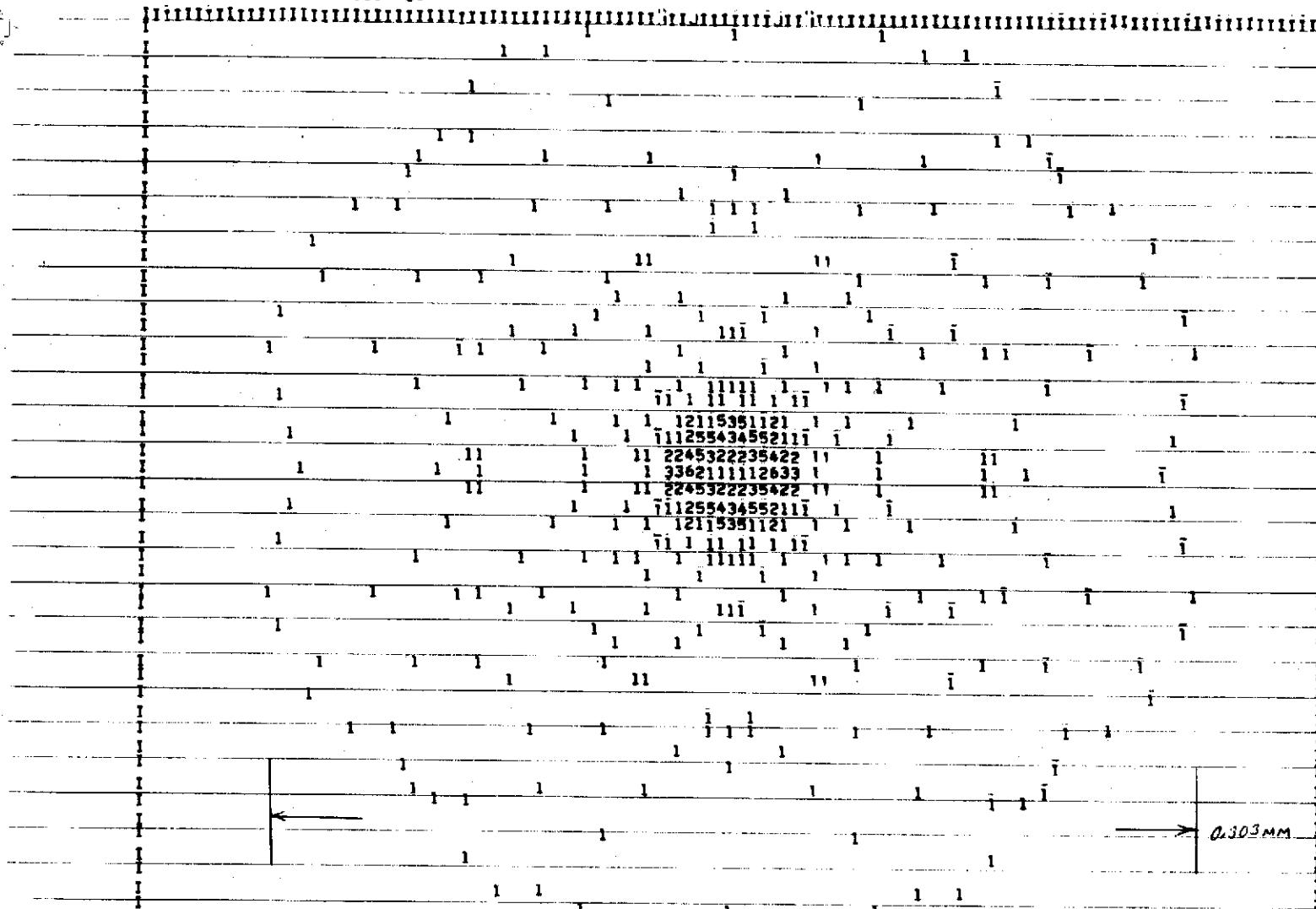
X   X=   .034630

0.303 MM

PLATE I

WAVELENGTH= .40000 IMAGE HEIGHT= .0000
FIELD 1   4 RAYS OUTSIDE 184 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

X   X=   .014444

38ACA83   11
6A86A68A6
774JZJ477
6A86A68A6
38ACA83   11

0.126MM

Plate II

WAVELENGTH= .45000 IMAGE HEIGHT= .0000
FIELD 1   4 RAYS OUTSIDE 184 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X=   .010000

1 121 212 121 1
1 22 32423 22 1
12 111342121243111 21
2 31222232222213 2 1
12 132322575223231 21
1 5423 4789874 3245 1
12 132322575223231 21
2 31222232222213 2 1
12 111342121243111 21
1 22 32423 22 1
1 121 212 121 1
1 1111111 1

0.0875mm
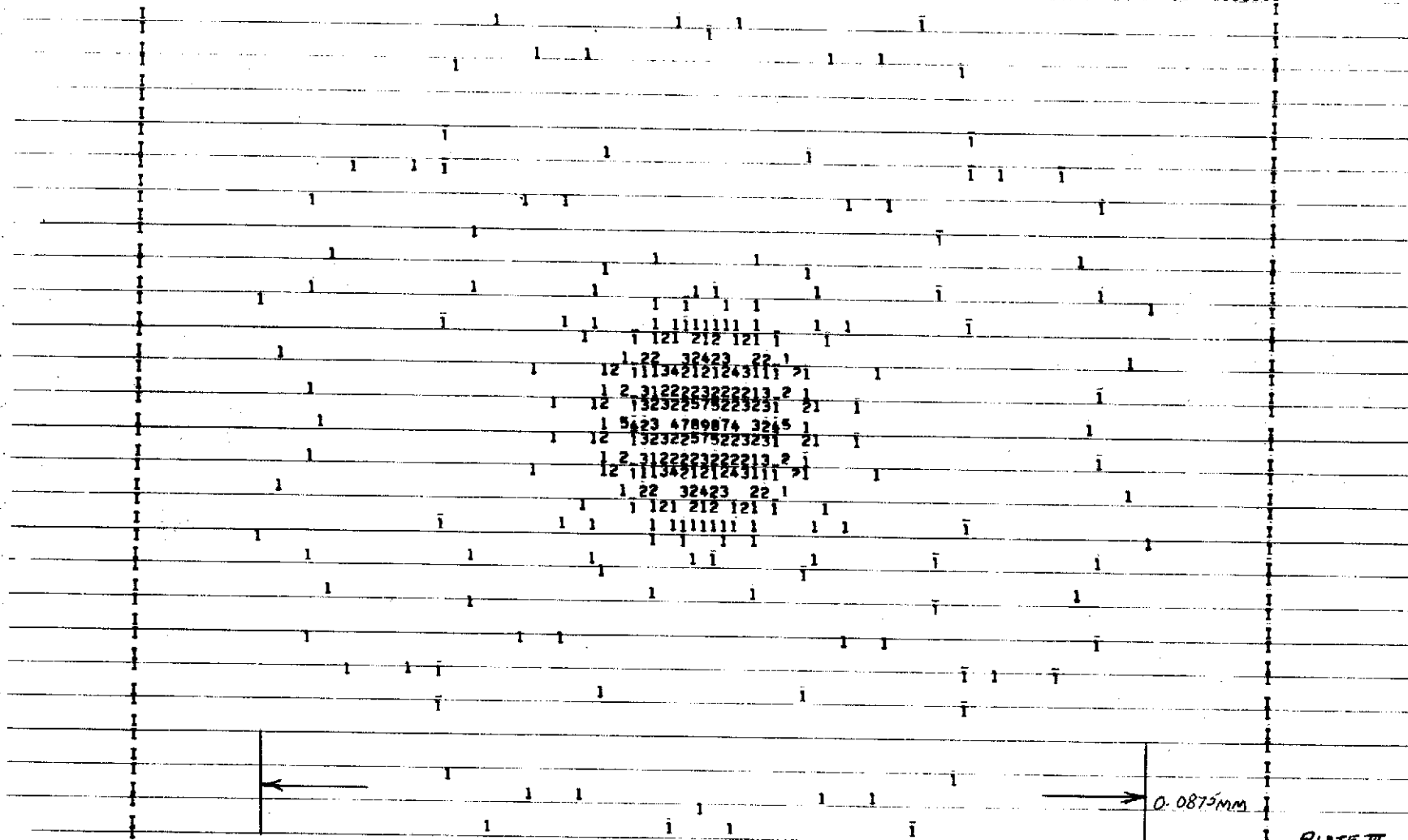
PLATE III

WAVELENGTH= .547500   IMAGE HEIGHT=   .0000
FIELD 1   4 RAYS OUTSIDE 184 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

Plate 14

X   X=   .007593

```
                              ī111 222 1111
                           11  11 1 11  1 1
                         112 12111 2 11121 211
                      13   1 2 121 1 121 2 1   31
                        1111 11 323 11 13111
                      11 12  1211 1 1121    21 11
                    11 122112 221323122 211221 41
                    21 1 1121121 4 1211211 1 12
                    2111 111 12 4L4 21 111 1112
                    21 1 1121121 4 1211211 1 12
                    11 122112 221323122 211221 11
                    11 12  1211 1 1121    21 11
                      1111 11 323 11 13111
                      13  1 2 121 1 121 2 1  31
                         112 12111 2 11121 211
                           11 11 1 11  1 1
                              ī111 222 1111
```

|←   →| 0.066MM
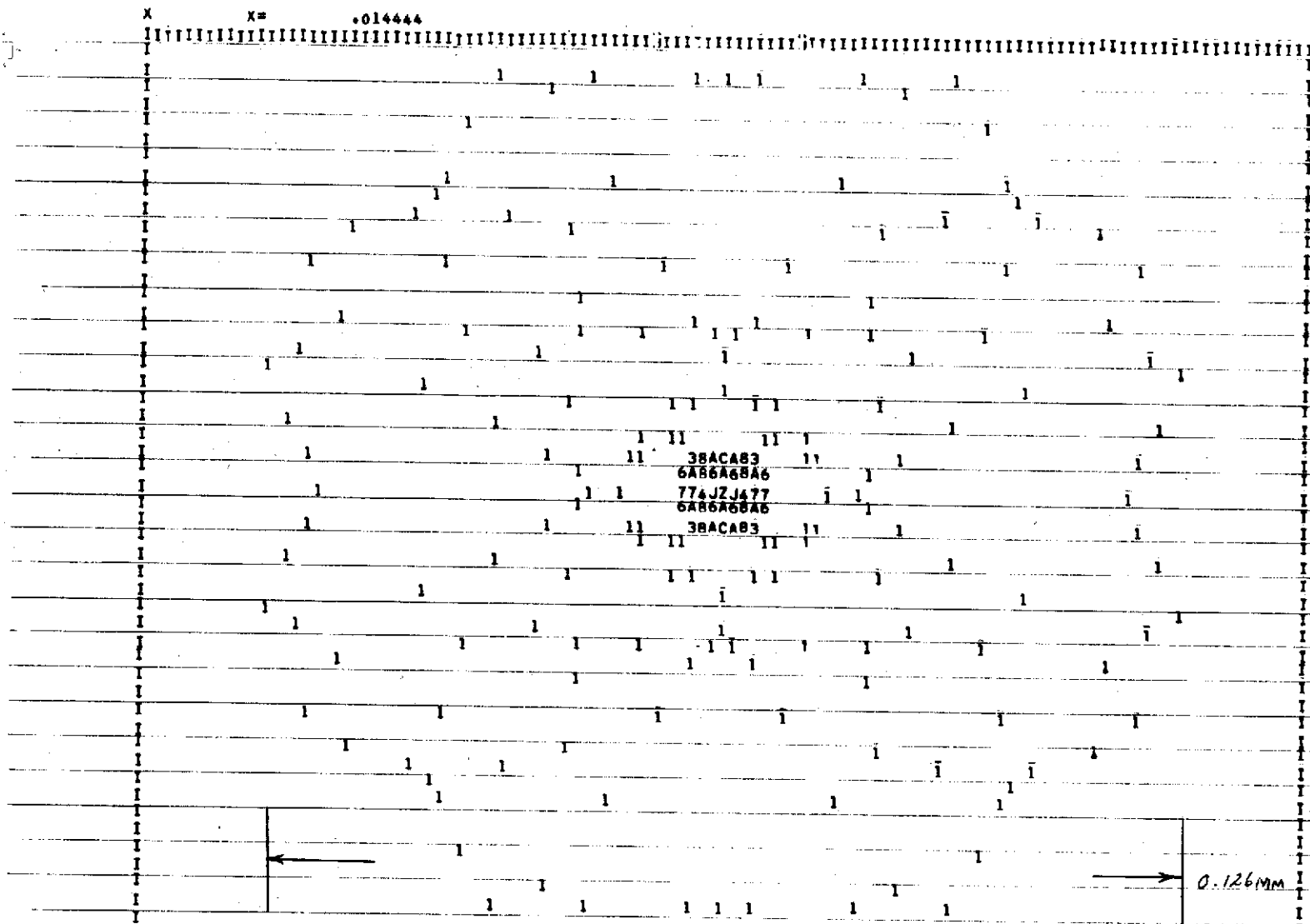
PLATE IX

0.058 MM

PLATE V

WAVELENGTH= .52500   IMAGE HEIGHT=   .0000
FIELD 1   0 RAYS OUTSIDE 184 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X=   .006111

WAVELENGTH .55000   IMAGE HEIGHT   .0000
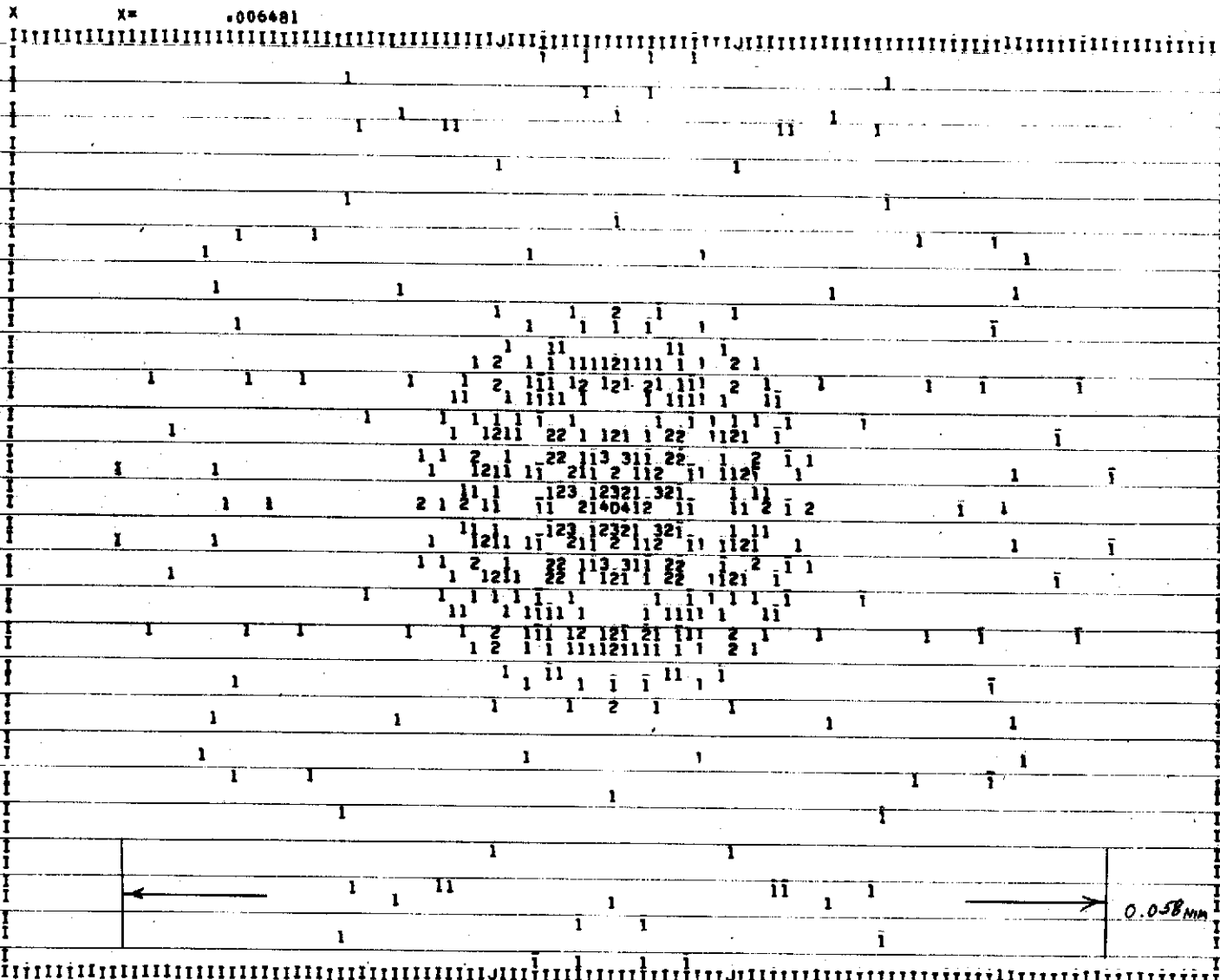FIELD 1   0 RAYS OUTSIDE 184 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

.062 MM

PLATE VI

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Plate VII

0.063 MM.
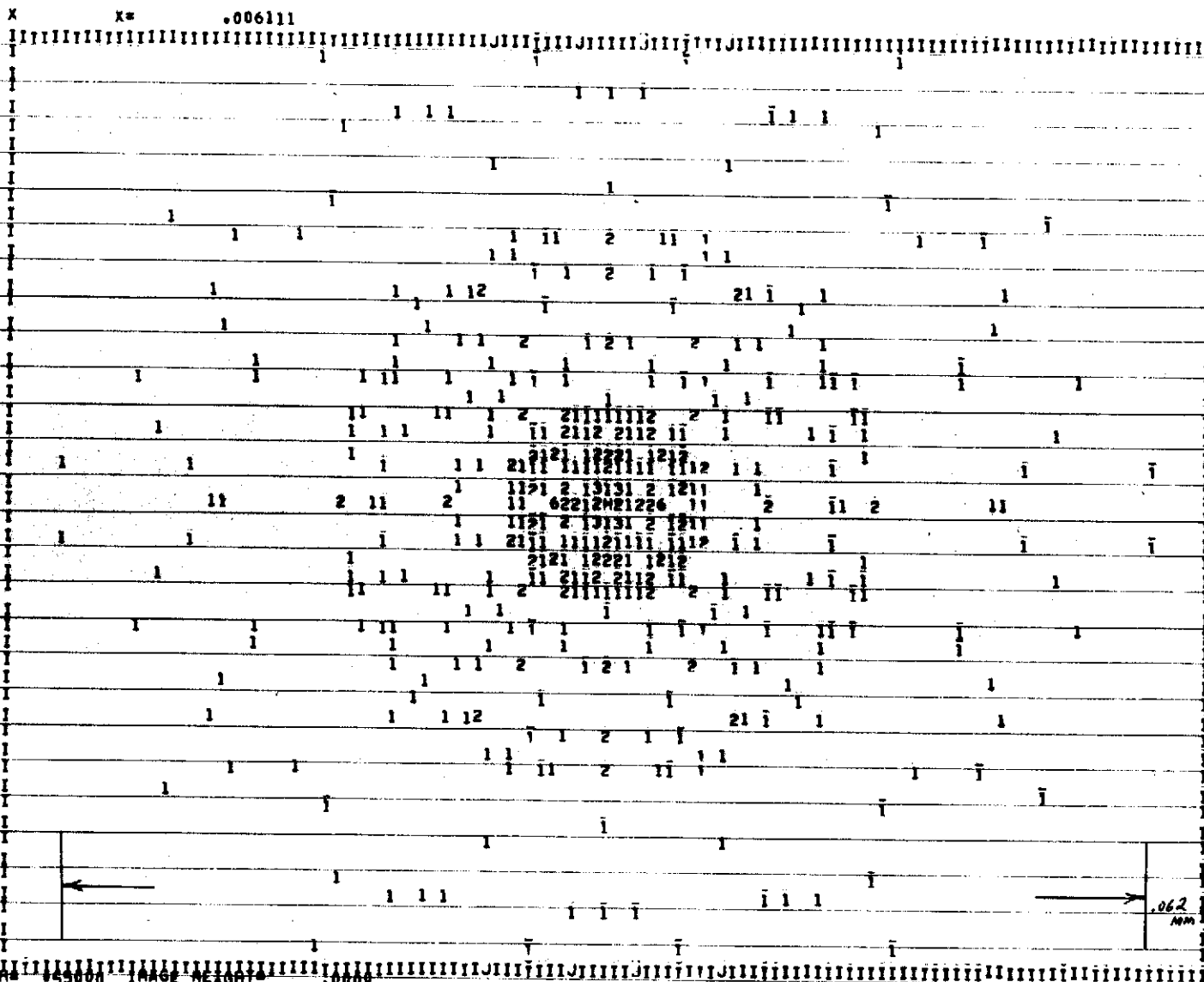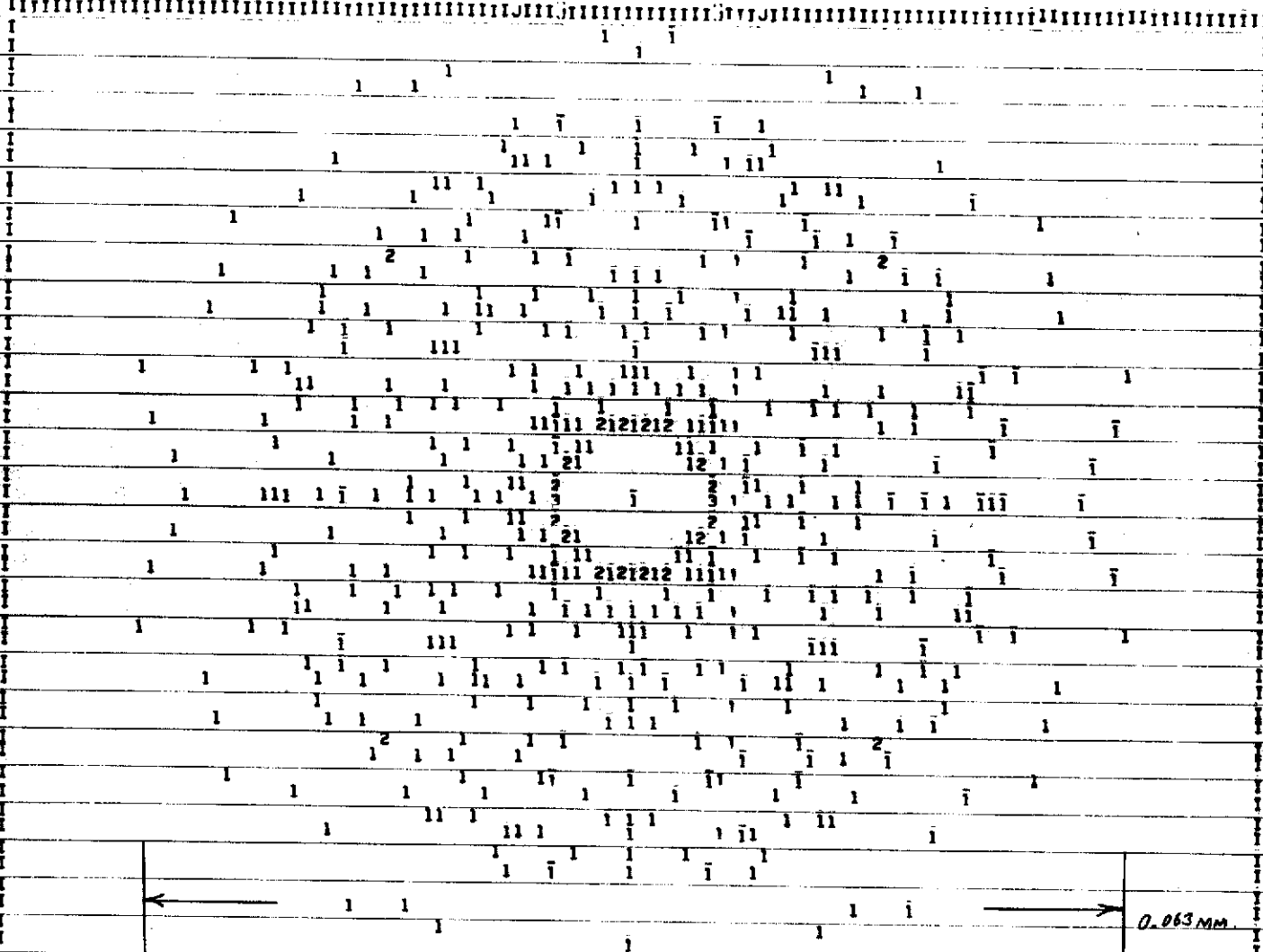
WAVELENGTH= .60000 IMAGE HEIGHT= .0000
FIELD 1   0 RAYS OUTSIDE 188 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

WAVELENGTH= 540000   IMAGE HEIGHT=   1.2902
FIELD 2   4 RAYS OUTSIDE 200 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

0.313 MM.

PLATE VIII

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PLATE VIII

0.133 MM.

1223221
15457475451
11453462786435411
314242A7J7A242413
2 432425505524234 2
111 2124534354217 111
21 315232513 17
12111 11 111 11 11171
2111113 3111112
1 1
11112321111
1 11 1

Plate IX

0.095 mm.

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18

X X= .0088°9

PLATE X

.089 MM

X   X=   .008246

Plane XI

0.074 MM.

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Plate XII

0.014 MM.
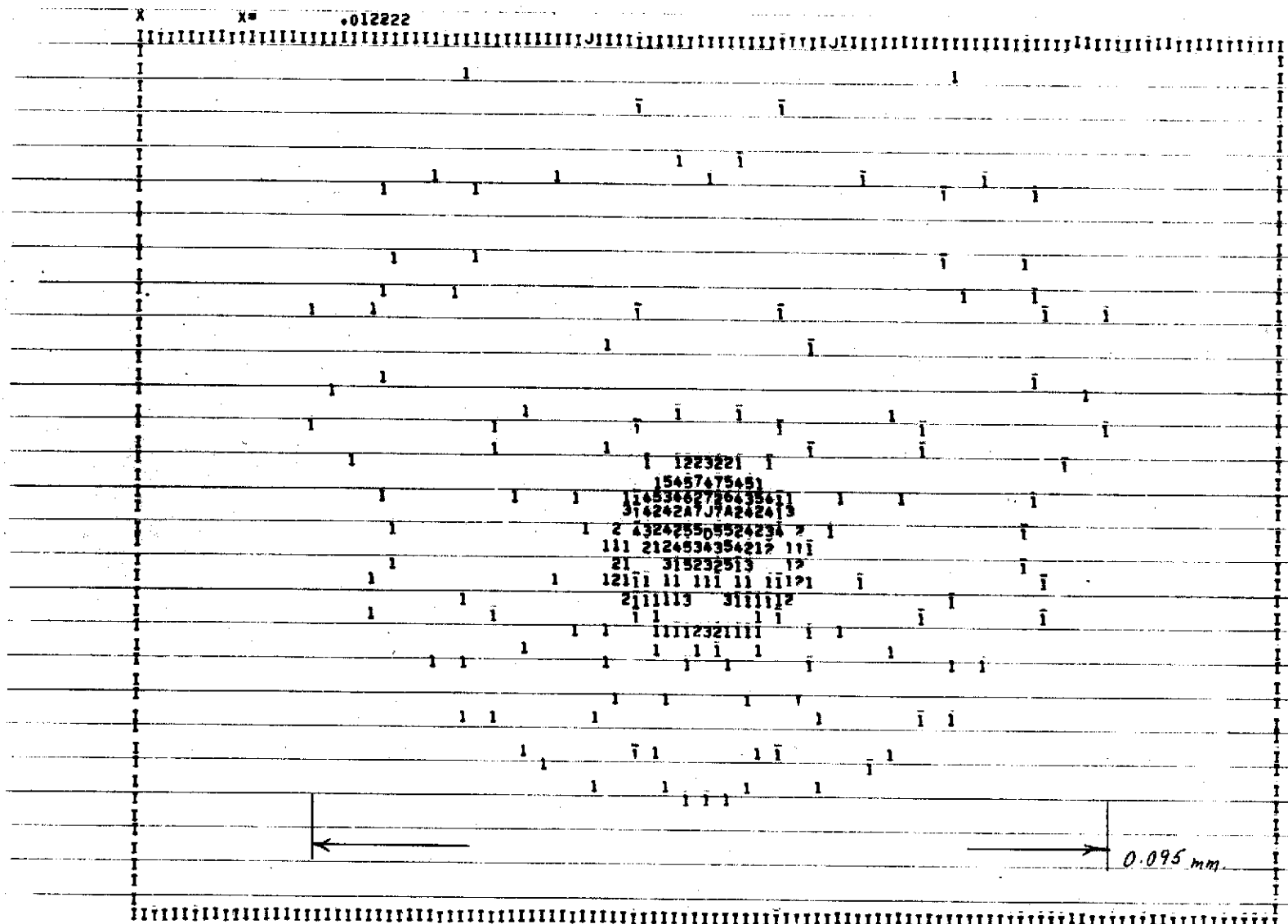
WAVELENGTH= .55000   IMAGE HEIGHT= 1.2992
FIELD 2   2 RAYS OUTSIDE 206 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X=   .008519
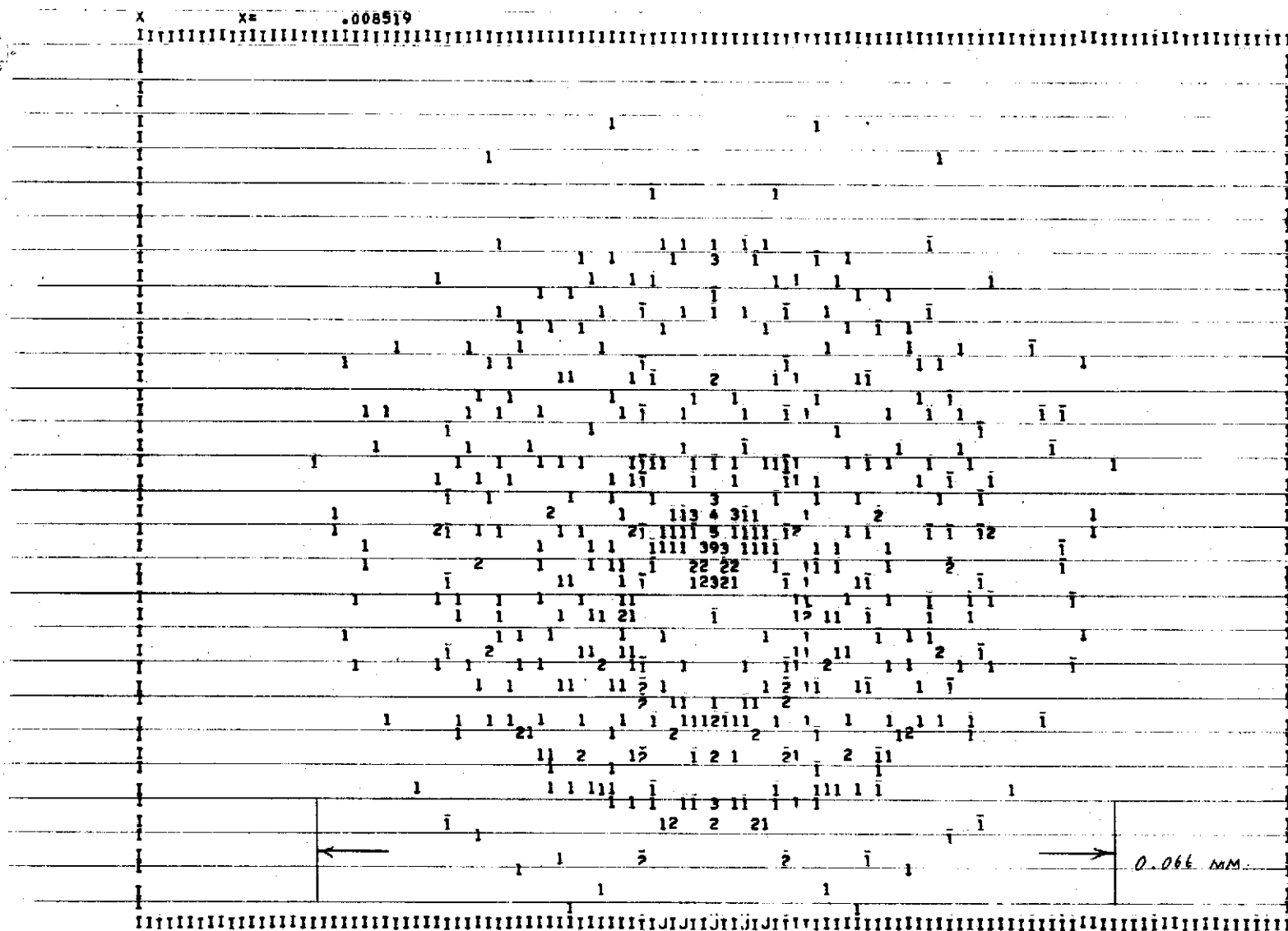
Plate XIII

0.066 MM

WAVELENGTH= .60000 IMAGE HEIGHT= 1.2992
FIELD 2   0 RAYS OUTSIDE 212 RAYS BLOCKED OUT OF A TOTAL OF 729 RAYS

X   X=   .043519

0.332 MM

PLATE XIV

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Plate XV
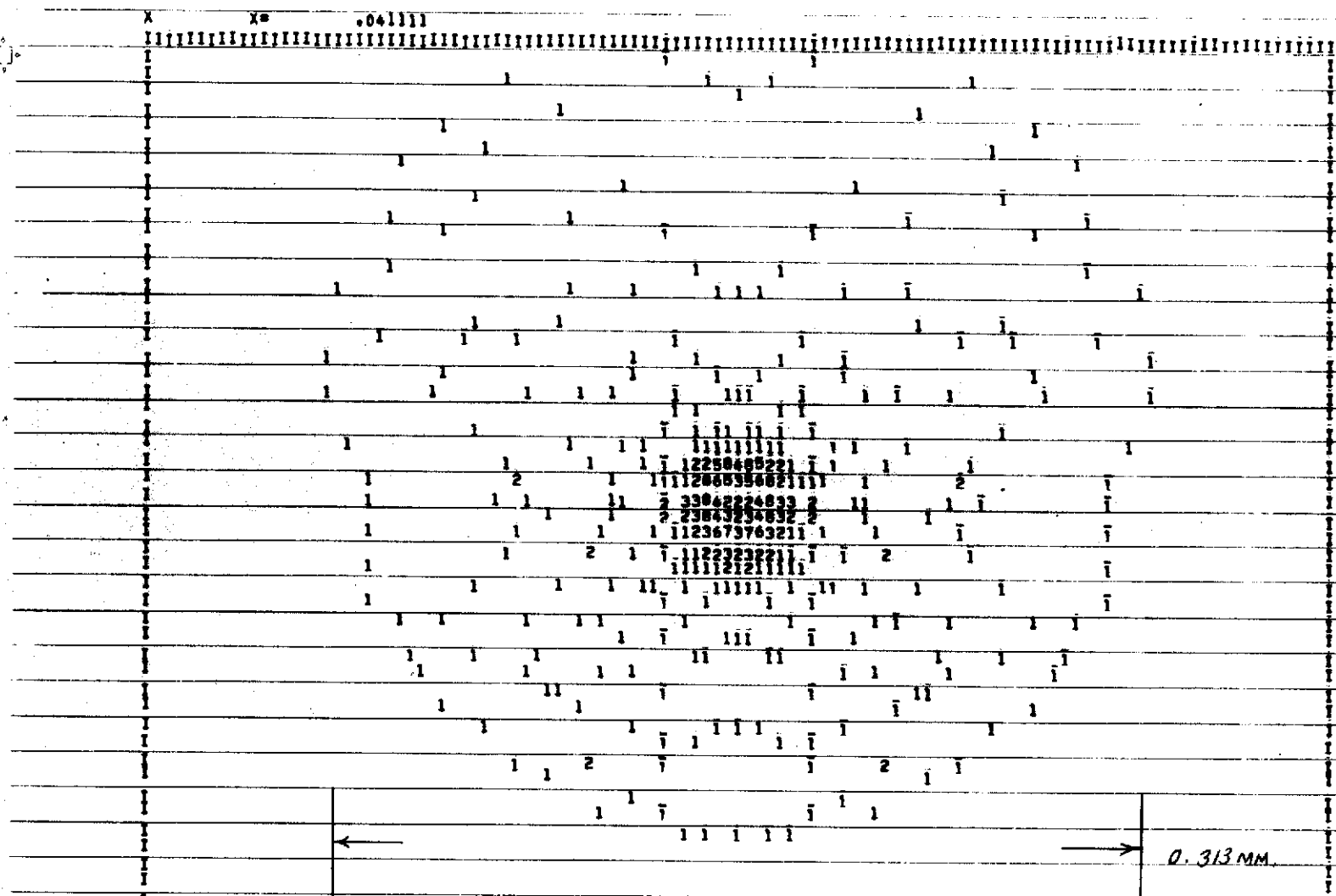
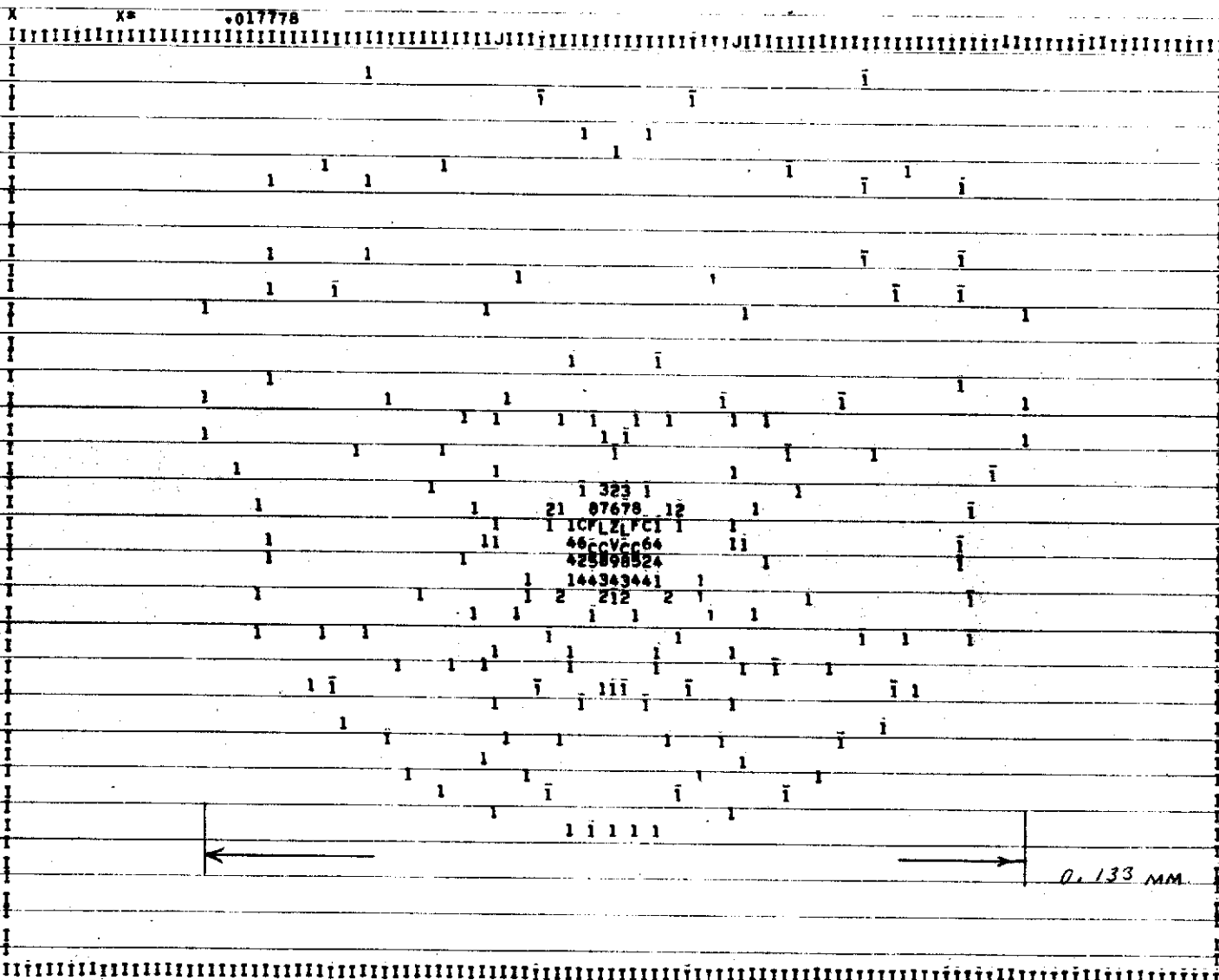X   X= .017963

0.150 MM

Plate XVI

0.111 mm.
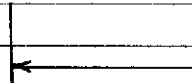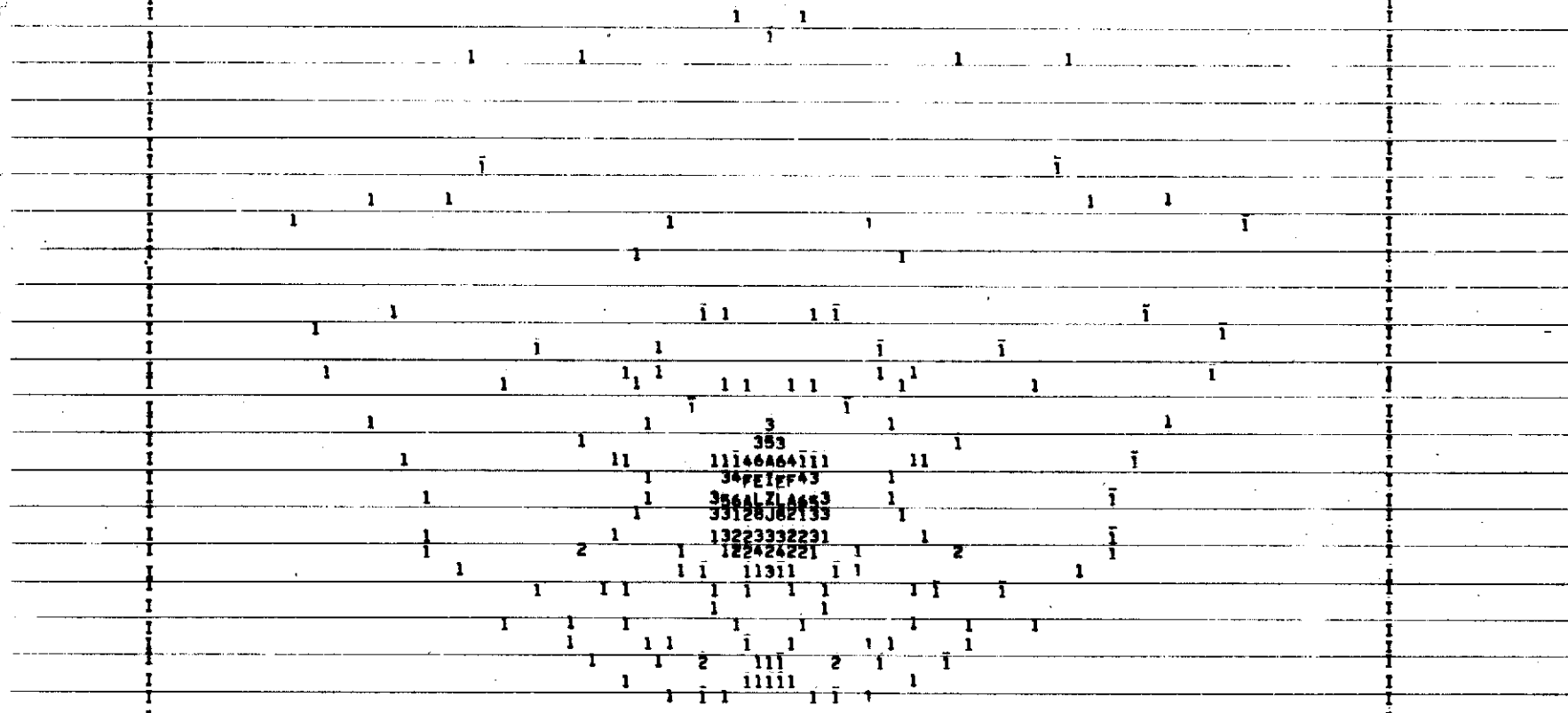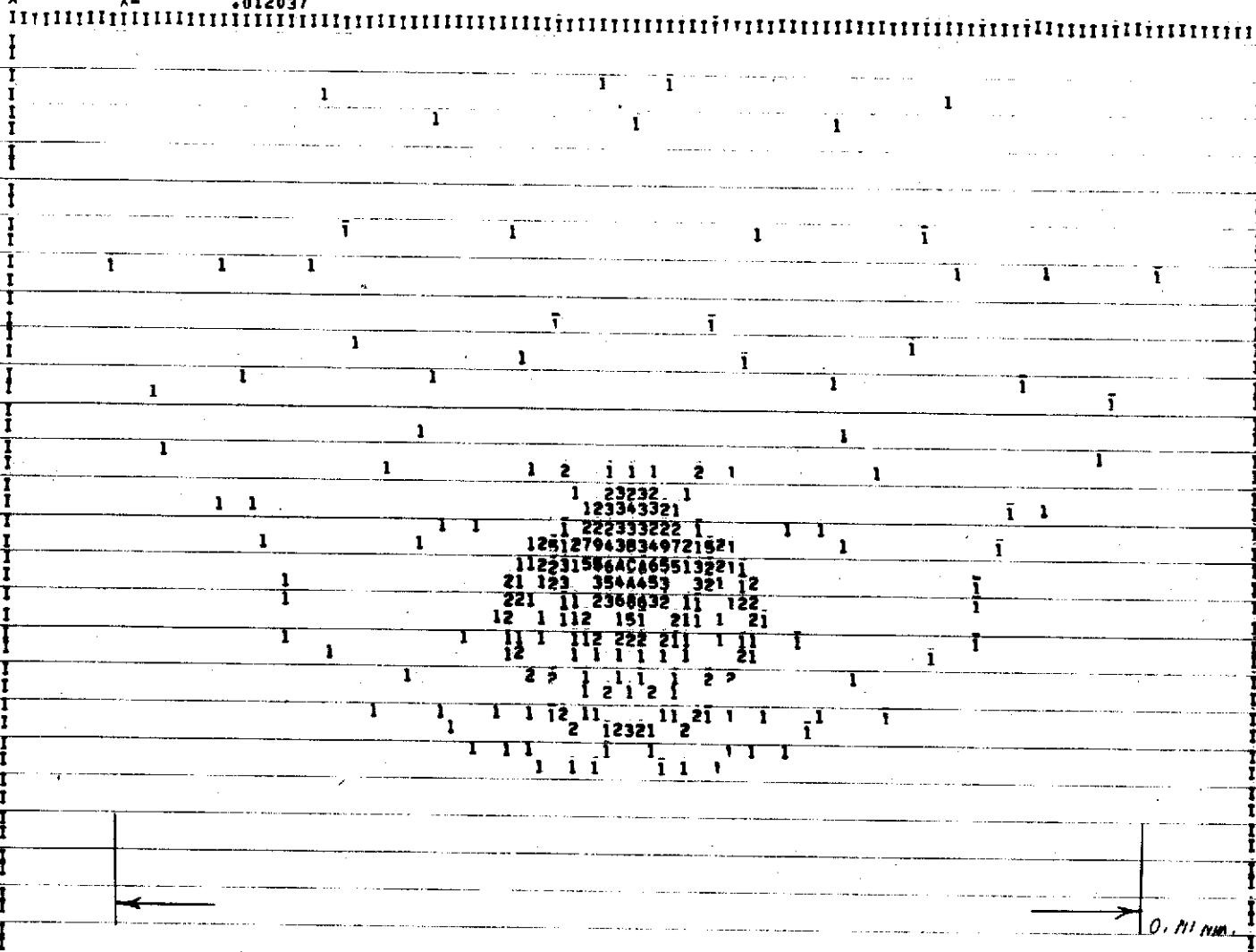
WAVELENGTH= .47500 IMAGE HEIGHT= 2.6043
FIELD 3   2 RAYS OUTSIDE 220 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS
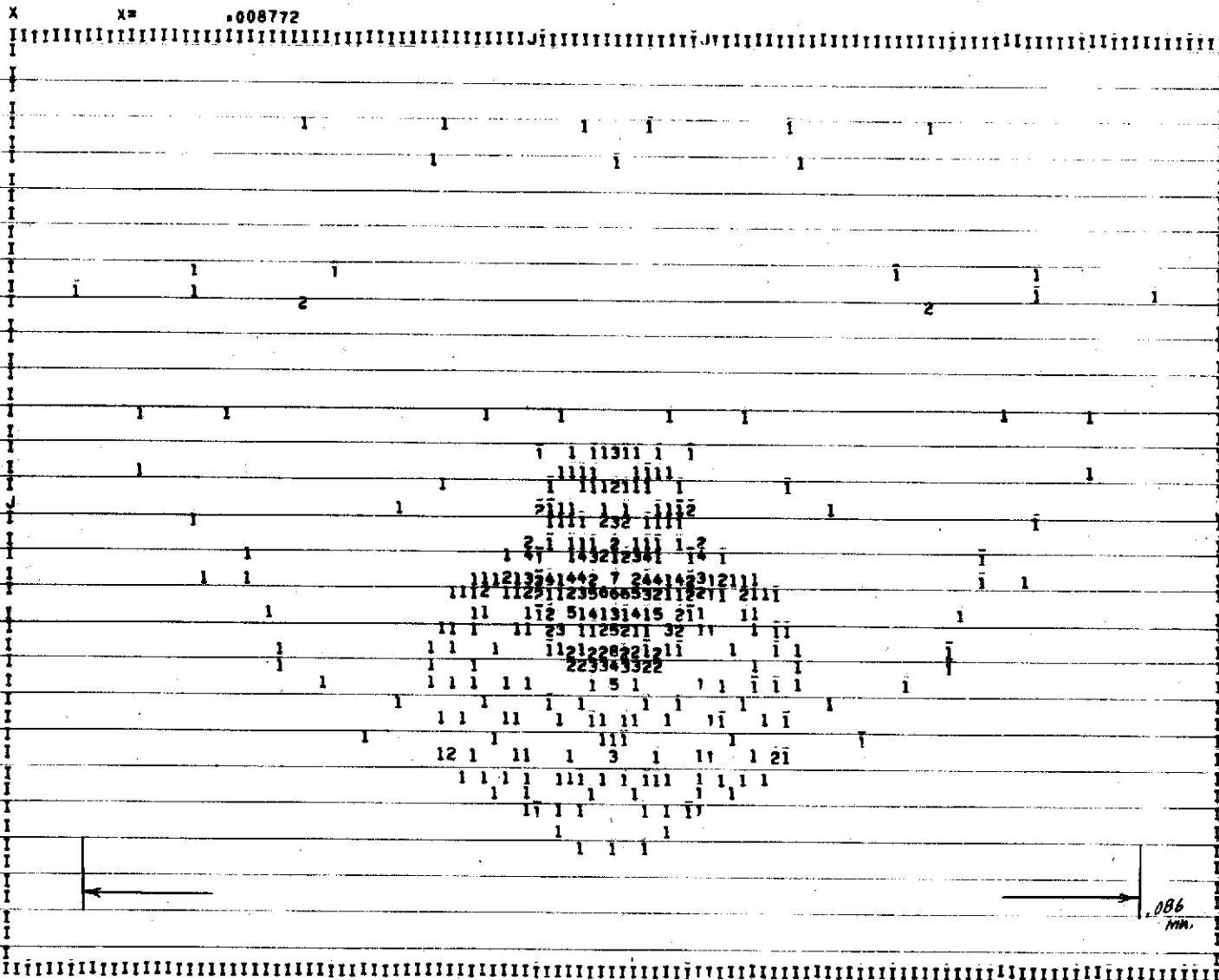
Plate XVII

WAVELENGTH= .50000   IMAGE HEIGHT= 2.6043
FIELD 3   0 RAYS OUTSIDE 220 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X=   000298
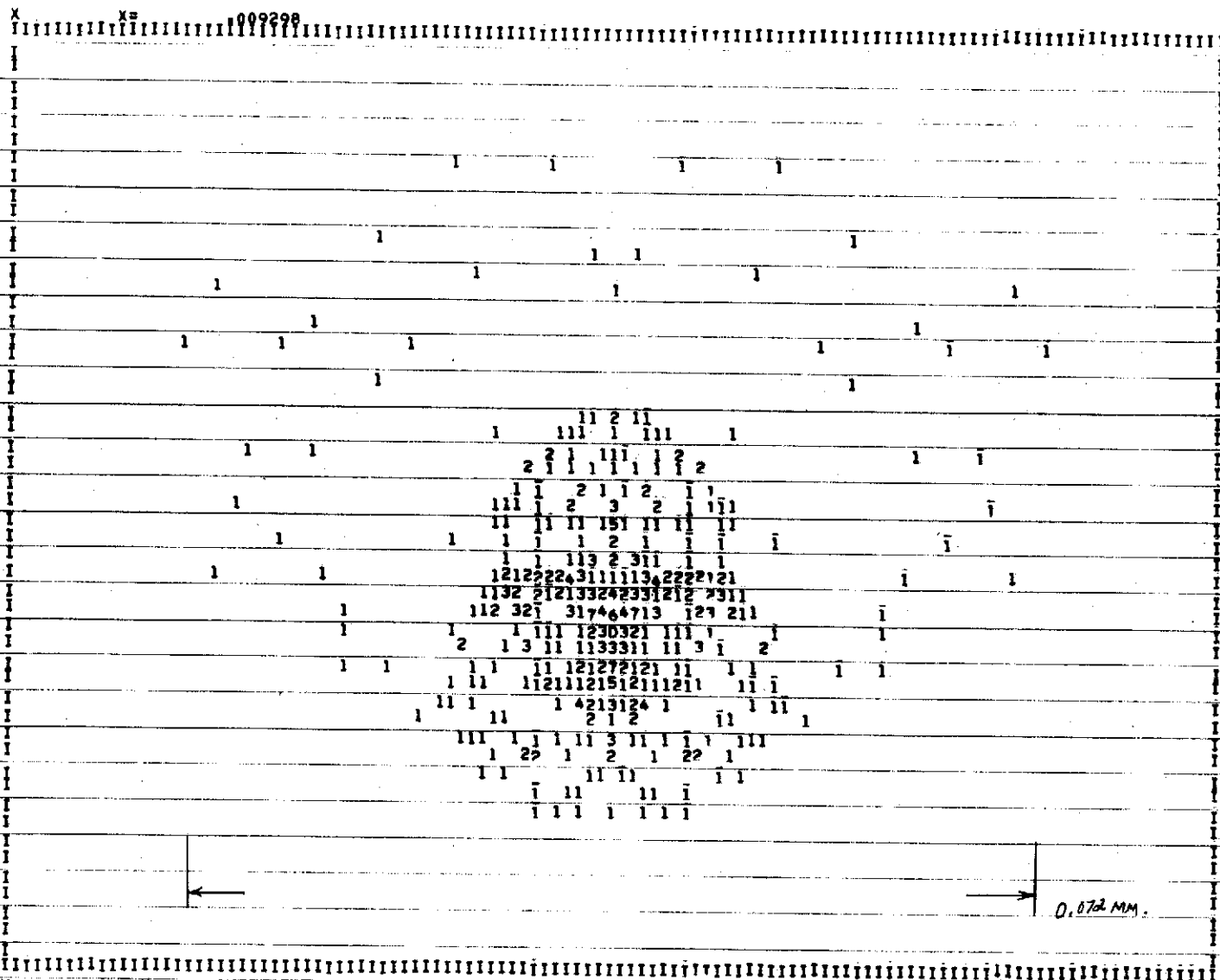
0.072 MM.

PLATE XVIII

X X= .009298

WAVELENGTH= .55000   IMAGE HEIGHT=   2.6043
FIELD 3   2 RAYS OUTSIDE 222 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

0.071 MM

PLATE XIX

PLATE XX

0.091 MM.

WAVELENGTH= .60000   IMAGE HEIGHT= 2.8083
FIELD 3   0 RAYS OUTSIDE   224 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X= .033158

WAVELENGTH= .40000   IMAGE HEIGHT= 3.0128
FIELD 4   2 RAYS OUTSIDE 245 RAYS BLOCKED OUT OF A TOTAL OF 729 RAYS

Plate XXI

0.361 MM.

96

(Page 93)

X   X=   .014815

```
                              4E4
                            1 29A92 1
                          174739797937471
                          232876C8C676232
                          121 5697965 121
                          211116 611112
                         1 1113223111 1
                          1 111711 1
                           1 4 1
                          1 11211 1
                    11  1 1 1114111 1  1  1  1
```

Plate XXII

0.146 MM.

WAVELENGTH= .45000   IMAGE HEIGHT=   3.9128
FIELD 4   2 RAYS OUTSIDE 243 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   X=   .010789

J   J

Plate XXIII

0.105 MM

Page 96

X   X=   .010789

PLATE XXV

222
1321231
3115113
2 222 2
21123132112
3311 2 1132
112141 28142424182 141211
1111325121222222222221215231111
2 1 144361314364441 1 2
23484748432
1 1 1 1 11 4357534 11 1 1 1 1
2557552
1111 11 11 11 11 1111
11 12 12 555 21 21 11
121

0.109 MM.
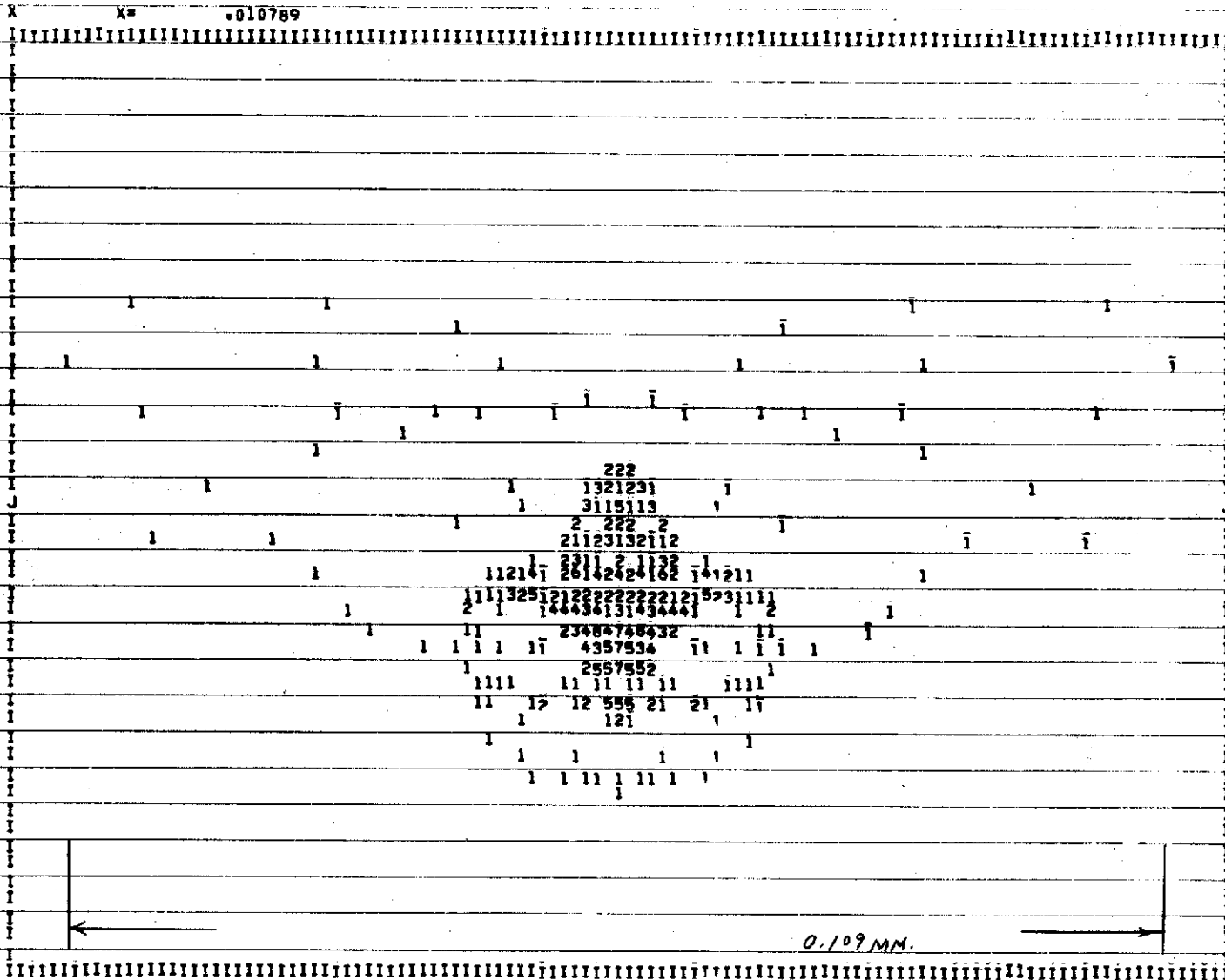
WAVELENGTH= .50000 IMAGE HEIGHT= 3.9128
FIELD 4   0 RAYS OUTSIDE 243 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

Page 96

X   X=   .011228

```
                        1212121
                      12 21112 21
                       2 3  5  3 2
                      2  1 2 2 1  2
                       21  3  1 2
                     121 1415141 121
                      11 2 12121 2 11
                   12132442  5  24423121
                    1 323212 21212 212321 1
                  12 1 134233111332431  1 21
                   11 1 12 913232315 21 1 1
                 12   11 113541453111 1 1   21
                    1 131659565131
                  11 1  11 115404511 1  1 11
                    1 1  2 737 2  1 1 1
                   1 1  1  101  1   1 1
                  1 1 1       1 1 1
                    1 1 1   1 1 1
                     111
```

PLATE XXV

0.109

X   X= .011228

```
                              1              1
            1                        2                    1        1                    1
                      1    21    12 1        1        1
                      2  11  121  11  2
                            1 11      1    11 1
        1          1      1  2 1   2 111 2   1 2   1          1        1
                      1 1  111   1  131  1  111     1 1
                      1   1  11411 1   1    1
              1          11 11  1 111 1   11  11
                      11  1 1 2112112 1 1  11
                  1    212   211 2 112   212
                      123123 121 32132 1
                            2212132 151 2312322
                      122 31 341212143 13 221
                  1      1    111 12 1113 3111 21 111   1
                      111   2 12421 2  1111   1   1
                      1  212  1131311  212  1
                      21  7121 23232 1211  12
                      1  1 12 2138312 21 1  1
                         1  32134143123  1
                      1 1  2133A3312 1 1
                         1113 3111
                            11611
```

Plate XXVI

0.107 mm

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X   X=   .009074

PLATE XXVII

0.096 mm

WAVELENGTH= .60000   IMAGE HEIGHT=   3.9128
FIELD 4   5 RAYS OUTSIDE   247 RAYS BLOCKED OUT OF A TOTAL OF 729 RAYS

X   X=   .033070

Plate Exit

0.351 mm

WAVELENGTH= .40000 IMAGE HEIGHT=   5.2268
FIELD 5   2 RAYS OUTSIDE 274 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

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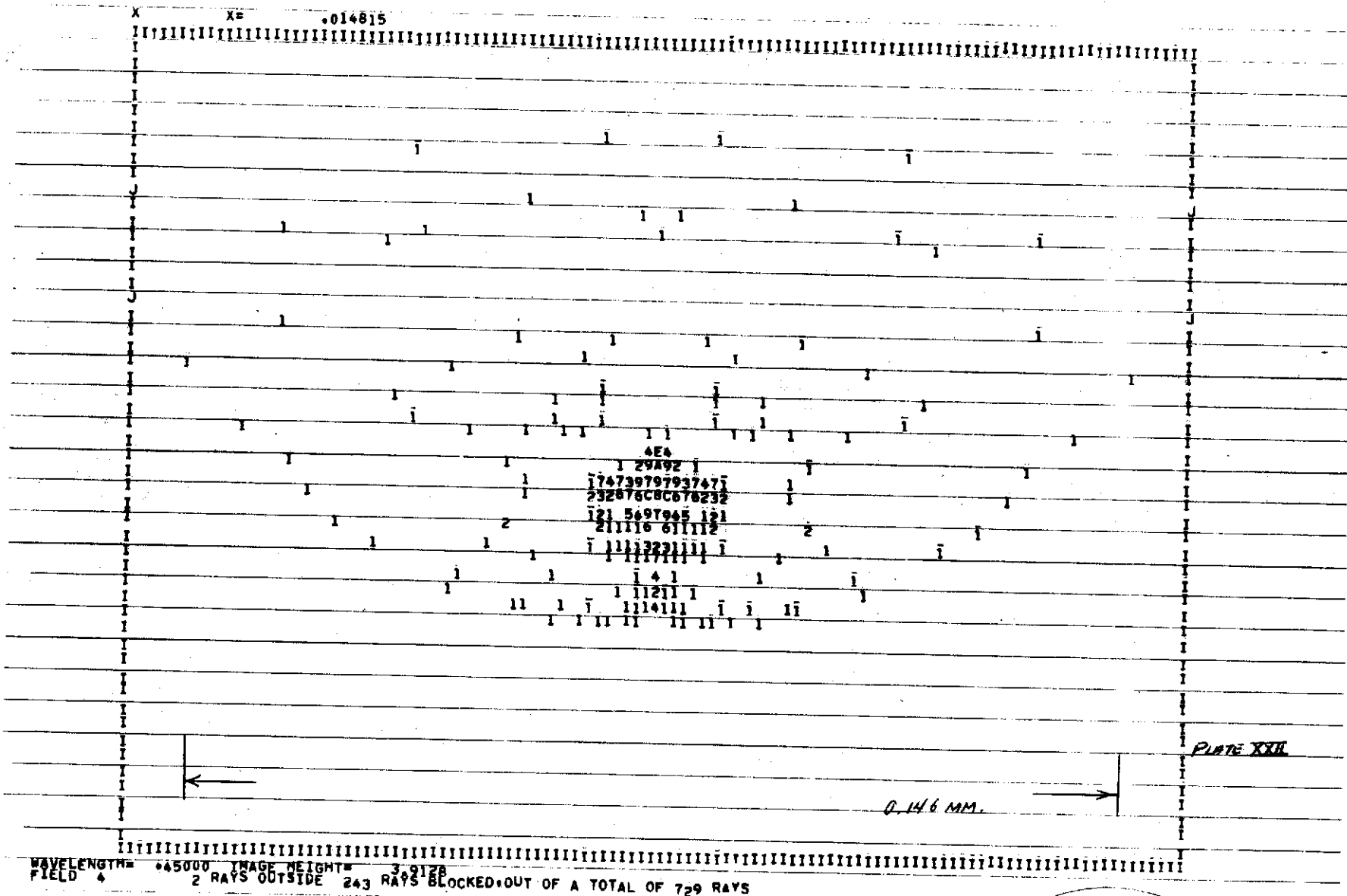X   X=   .015789

PLATE XXIII

0.153 mm

WAVELENGTH= .45000   IMAGE HEIGHT=   5.2268
FIELD 5   2 RAYS OUTSIDE 274 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS
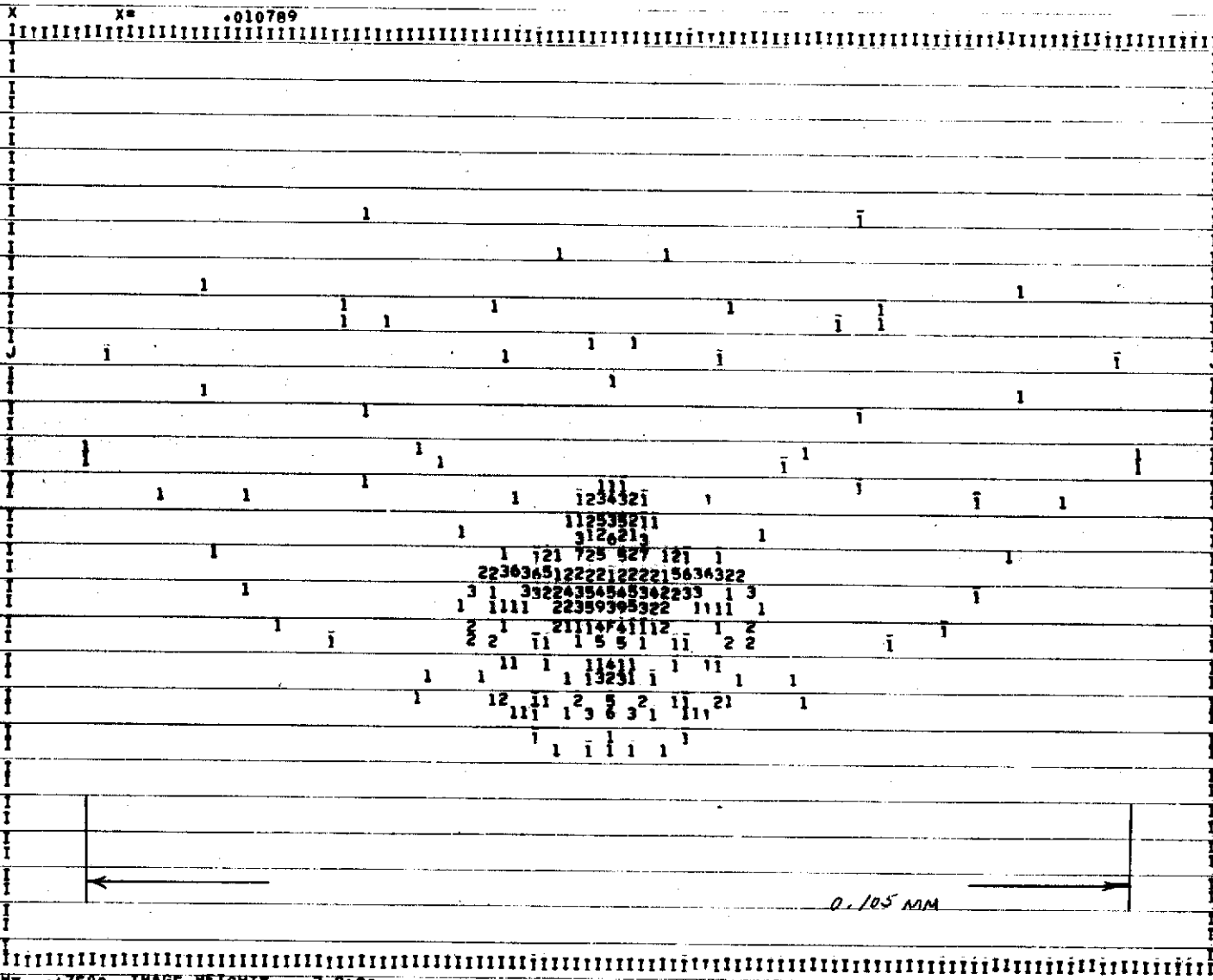
page 101

X   x=   .012193

11 262 11
15E51
11 1 23 47874 32 1 11
49434313113231131343494
1344443232444232344443
222133663787366331272
1 121231137873113232 1
1 31 2 4 2 13 1
1 1 1   1 1 1
1 1 1 1 1 1
1 2   2 1
1 1 1

WAVELENGTH= .47500 IMAGE HEIGHT=   9.2208
FIELD 5   0 RAYS OUTSIDE 272 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS
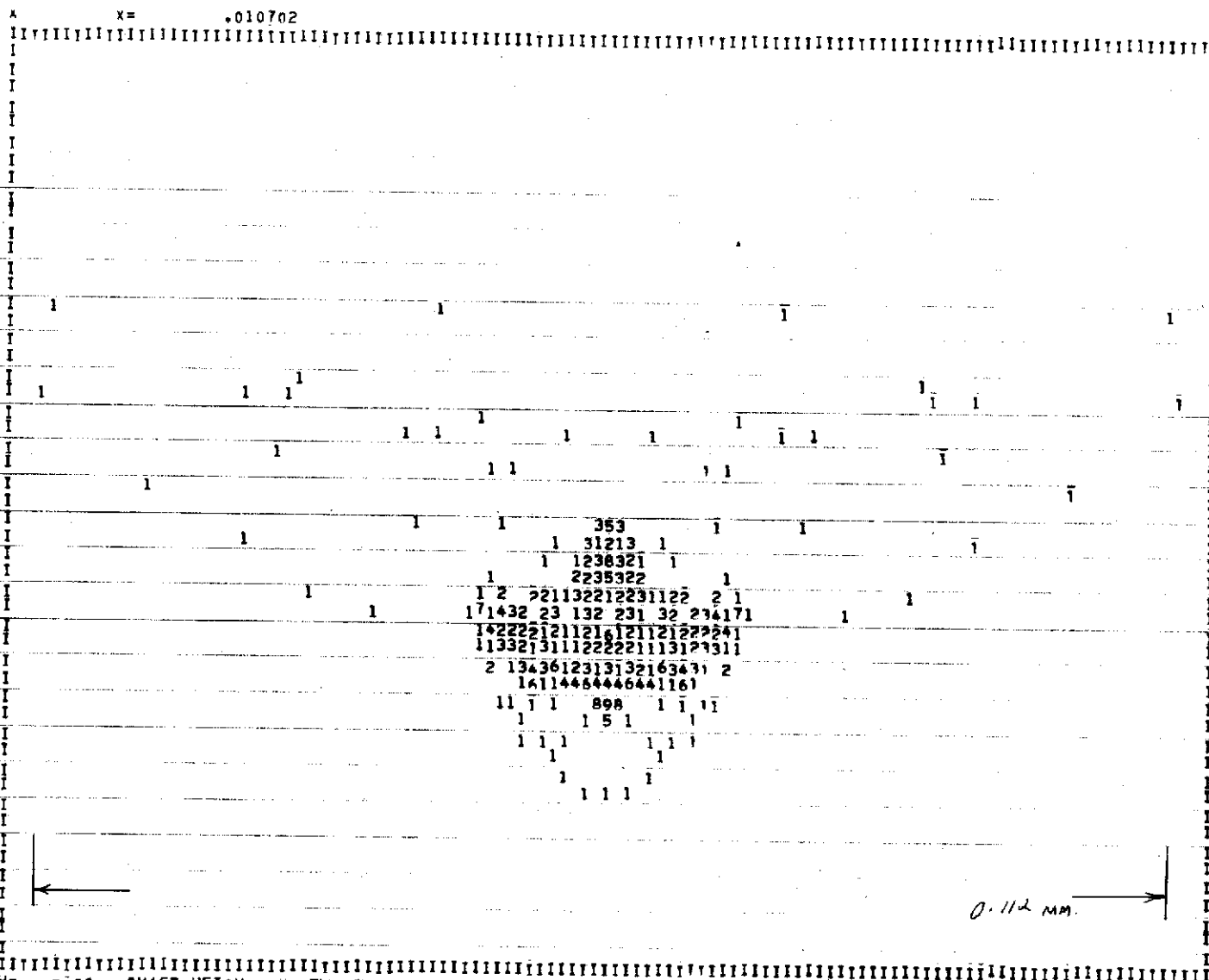
X= .010702

353
31213
1238321
2235322
221132212231122 2 1
1432 23 132 231 32 234171
142222121121612112122241
1133213111222221113123311
2 13436123131321634312
161144644464411611
898
151

WAVELENGTH= .50000 IMAGE HEIGHT= 5.2268
FIELD 5   2 RAYS OUTSIDE 272 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

PLATE XXXI

0.112 MM.

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X   X=   .010614

          2112112
          22 1 22
          2 11311 2
       21 2 7 2 12
         1 2 2 1
      11 24214141242 11
        11111² 111 211111
     24221322 5 3 5 2233²²42
   131312112111111121121³131
       125142 2 241221
      1 12212112121121221 1
     12143132 121 23133171
      323134131431323
      1162455565554261
        1 26062
         1 151 1
          1 1 1 1 1

0.099 MM.

PLATE XXXII

WAVELENGTH= .52500 IMAGE HEIGHT=   5.2268
FIELD 5   2 RAYS OUTSIDE 272 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

page 104
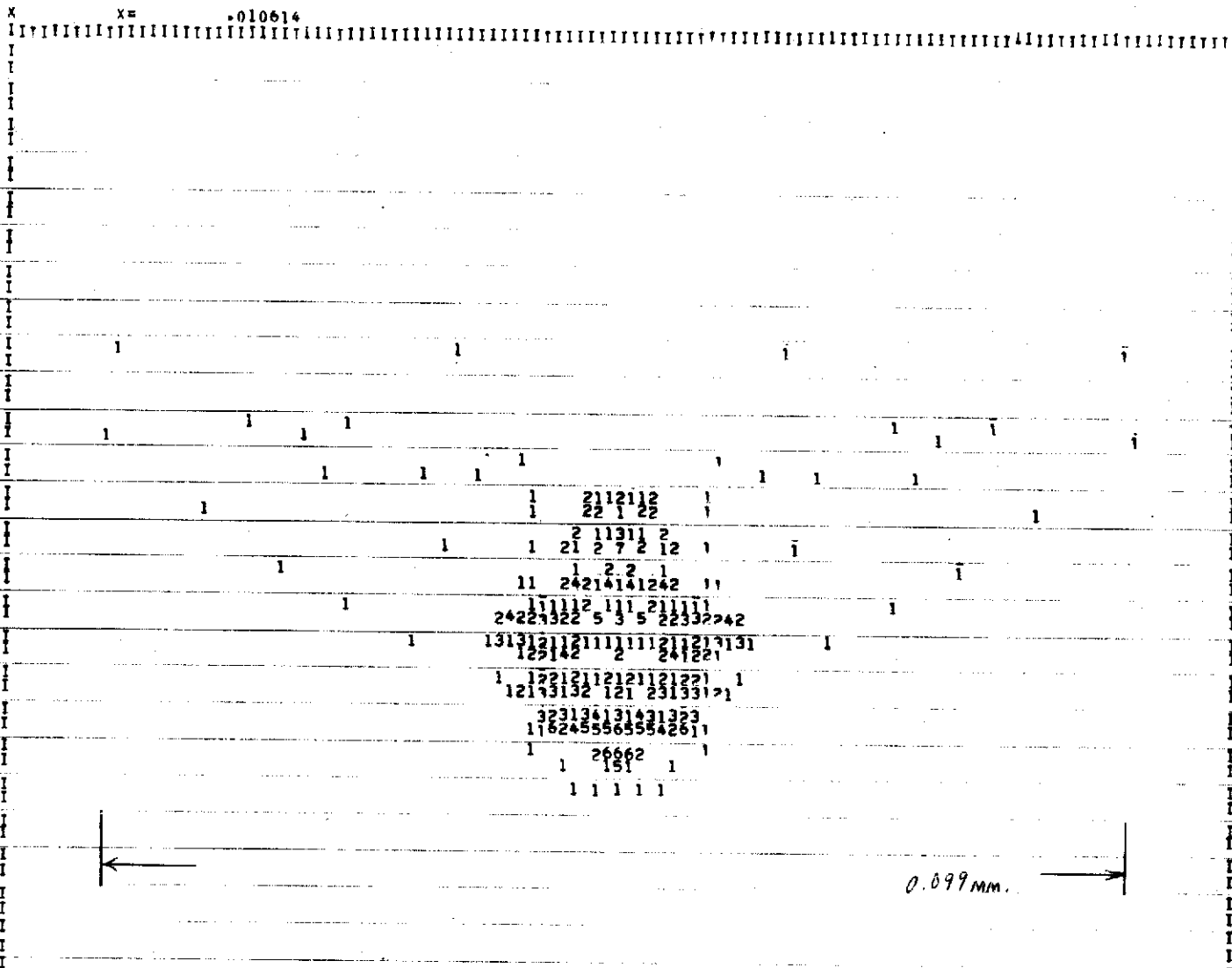
X   X=   .010088

PLATE XXXIII

0.043 mm.

WAVELENGTH= .55000   IMAGE HEIGHT=   9.2208
FIELD 5   2 RAYS OUTSIDE   272 RAYS BLOCKED, OUT OF A TOTAL OF 729 RAYS
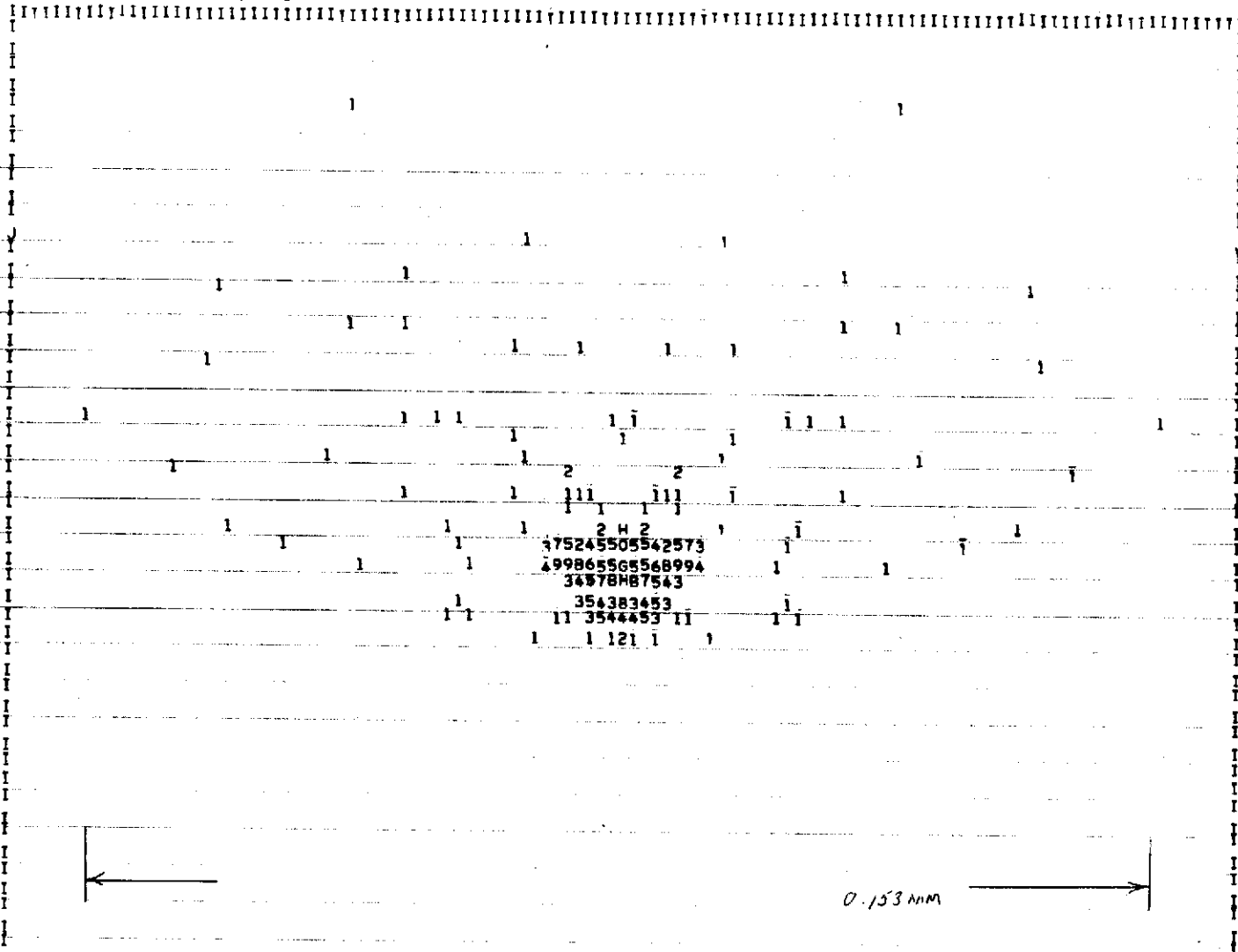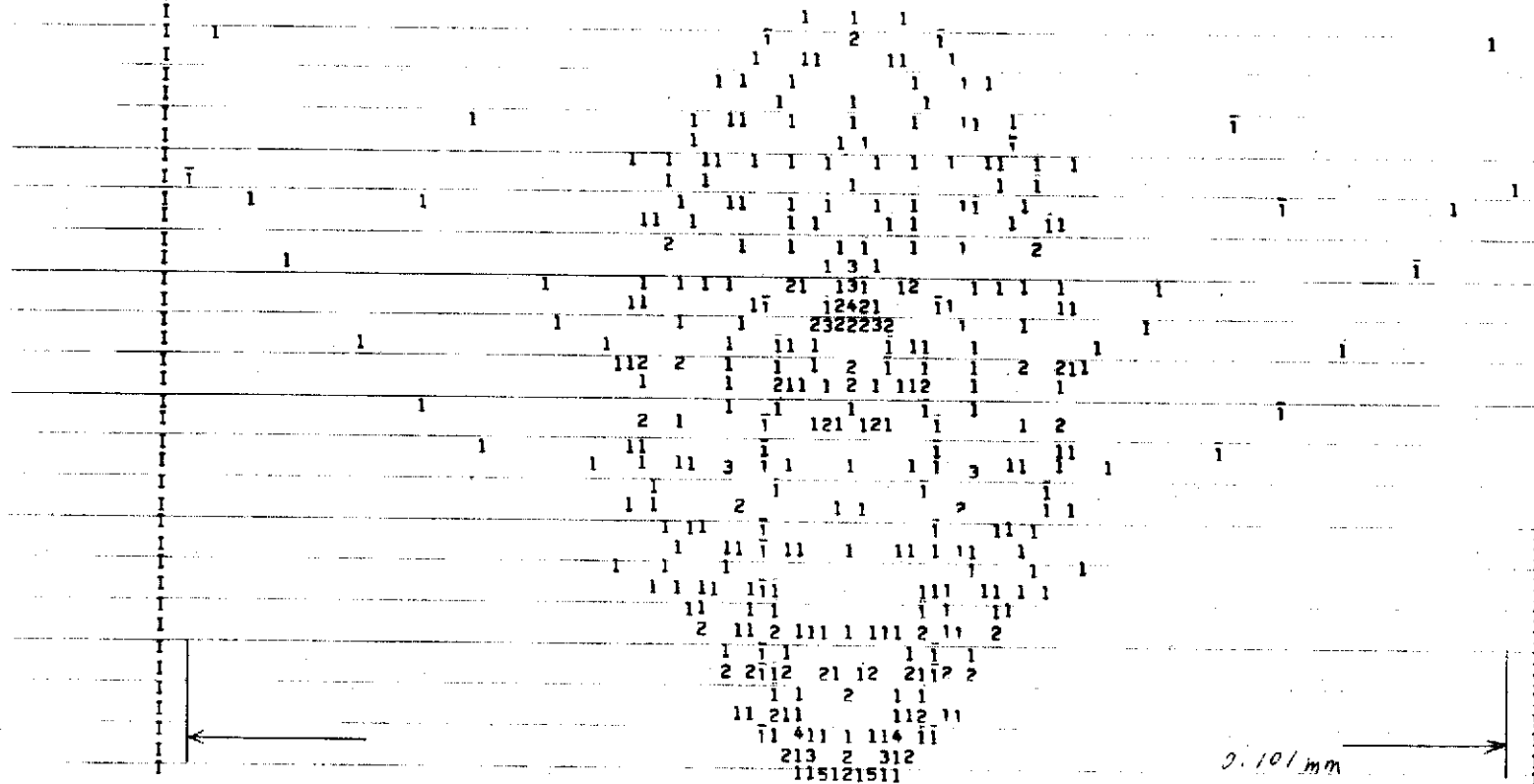
X   X=   .009444

PLATE XXXIV

0.101 mm

WAVELENGTH= .60000 IMAGE HEIGHT= 5.2200
FIELD 5   0 RAYS OUTSIDE 274 RAYS BLOCKED OUT OF A TOTAL OF 729 RAYS

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0.348 mm

PLATE XXXX

Plate XXXVI

0.217 mm

WAVELENGTH= .45J00 IMAGE HEIGHT= 6.555R
FIELD 2   2 RAYS OUTSIDE 390 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X   Z=   .015007

```
                          1                                    1
              1                                                            1
                    1                                              1
                    1                                            1
              1        1                                  1            1
                    1    1        1                  1      1
                 1    )      )    1                1    1
          1          1    1                            1          1
                       1                                2
                    2            1    1  1  1                  1      1
        1        1              1  1  1                1    1
               1    1  1  1    1              1 2 1  1 1      1
                    1    2  1            1  2    1
                  21  121111 1 111121  12
                  23211 121313121 11232
                  847542341 3 14324574B
                  1234444410144444321
                   123644M446321
                      358AA53
                       696
                       121
                       141
```

0.175 mm

PLATE XXXVII

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WAVELENGTH= .47500 IMAGE HEIGHT=   6.5558
FIELD 2   2 RAYS OUTSIDE   300 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

X=   .014561

0.149 mm
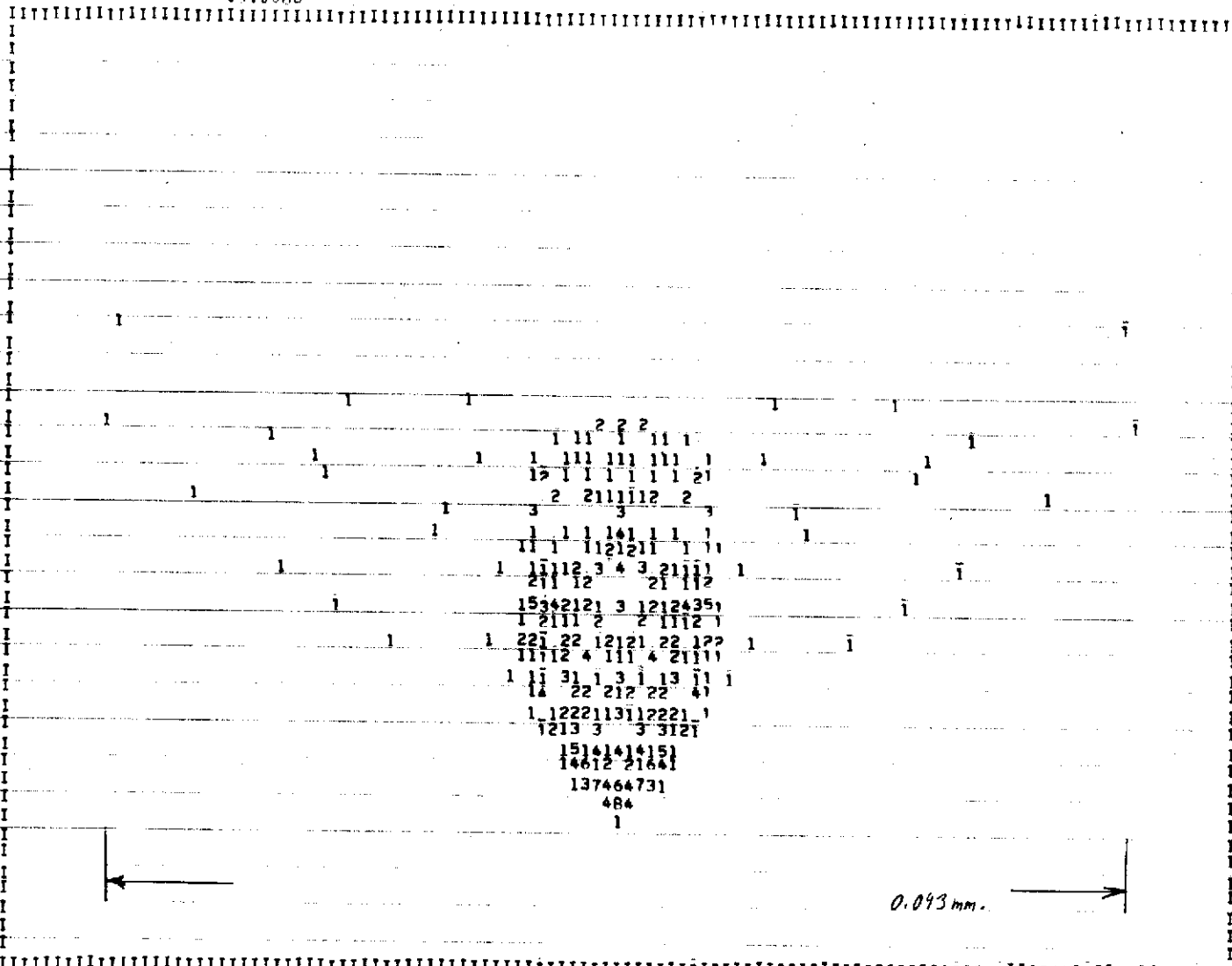
PLATE XXXVIII

WAVELENGTH= .55000 IMAGE HEIGHT=   6.5559
FIELD 2   2 RAYS OUTSIDE 300 RAYS BLOCKED,OUT OF A TOTAL OF 729 RAYS

page 110

```
            1                   1                              1
      1                                                 1              1

                     1                               1
                1  1                          1            1  1
           1         1                  1          1
                              1                1            1
                  2 1              1             1      1
          1              1     11           11       1     1 2     1
                          1   1   1   1      1
             1       1   1    111        111    1    1      1
                            1 3424243 1          1
                      1   1  1   143434341     1   1  1
                          1 1124554554211 1
                      11  211113323C323311112  11
                       1  1213133218123313121  1
                       35*2 11  25252  11 2453
                       3122 213303312 2213
                       113214 8 412311
                         121545121
                           26762
                             4
```
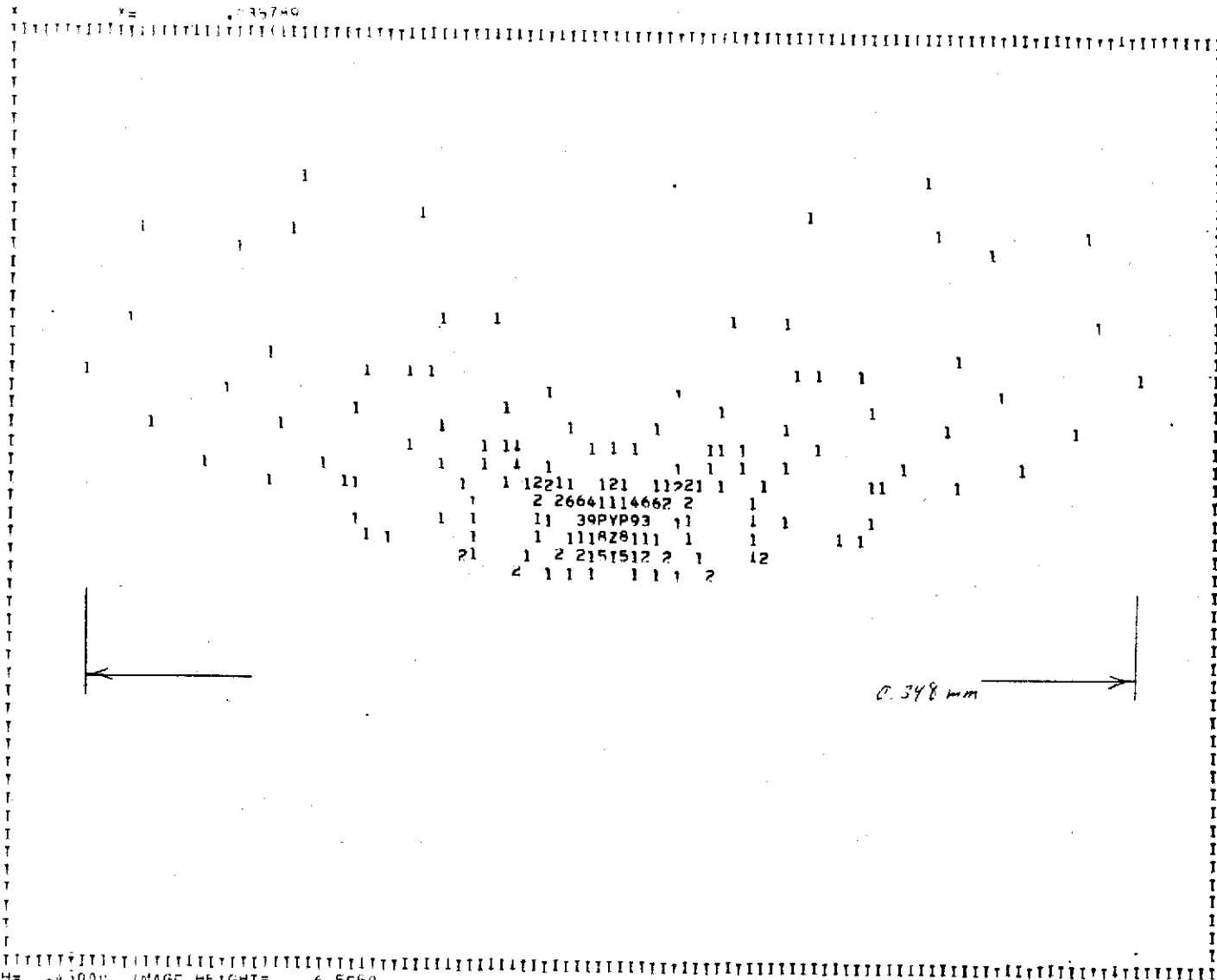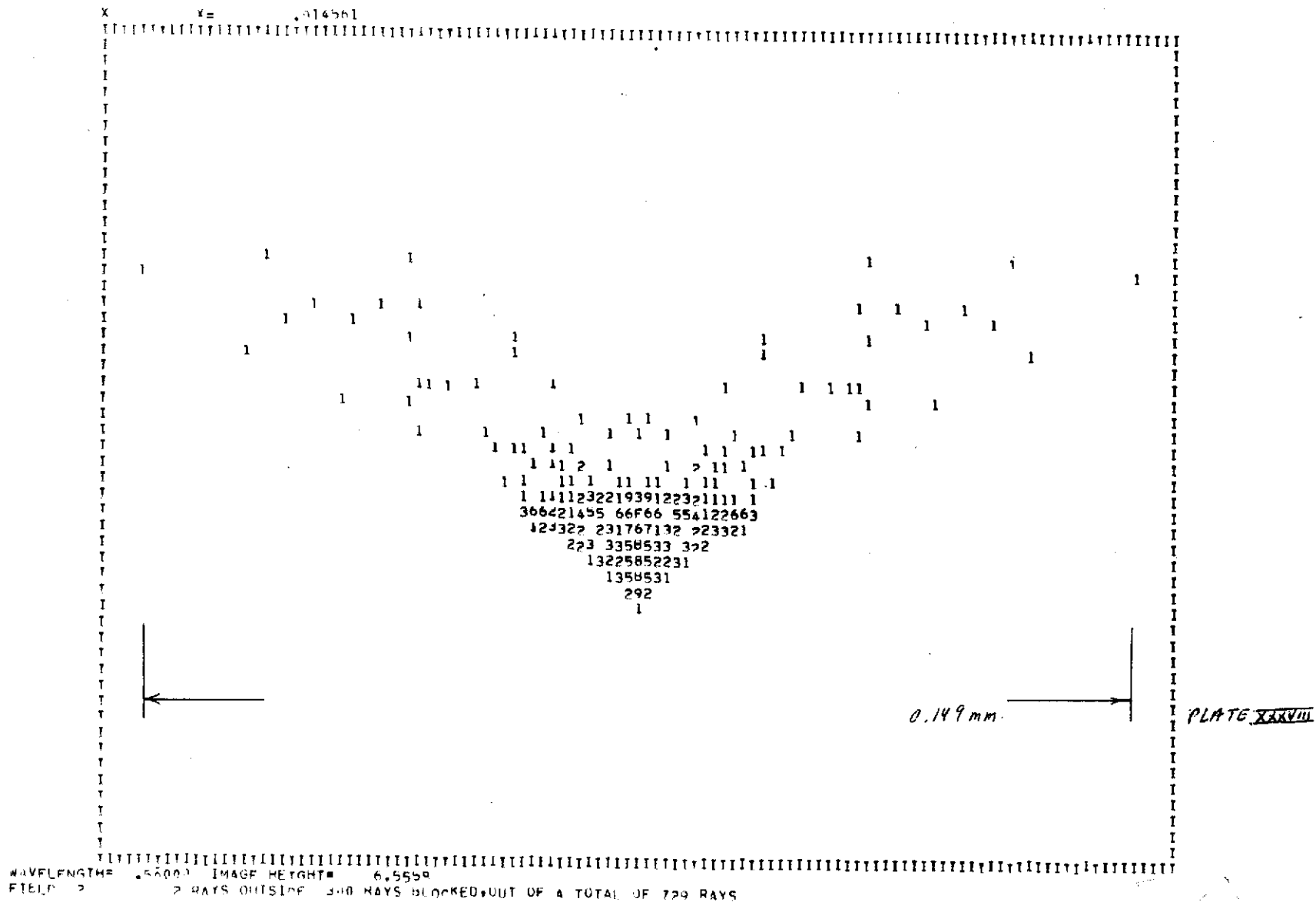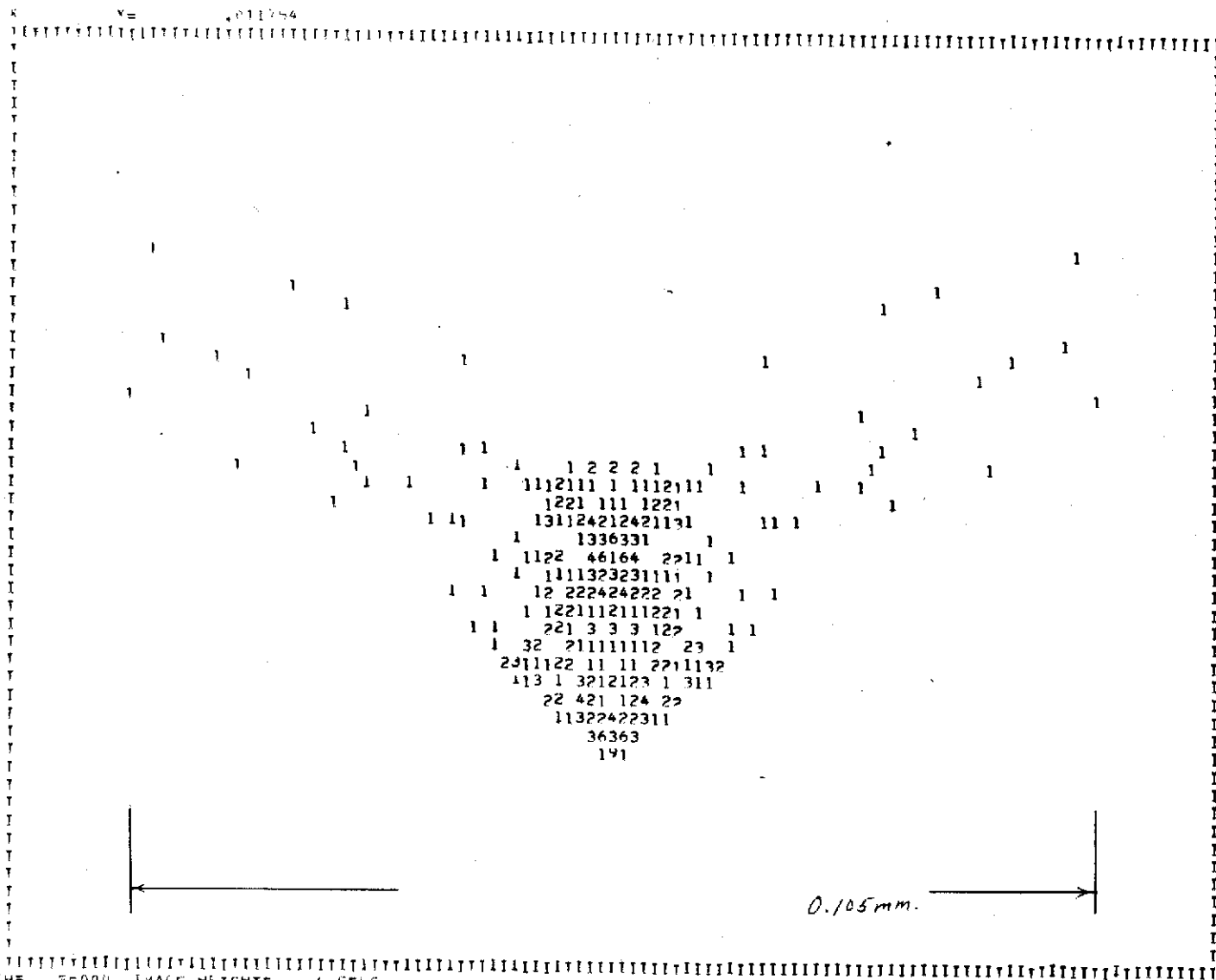
0.138 mm.

PLATE XXXIX

pog 111

```
X=        .011754

              1 2 2 2 1
            1112111 1 1112111
             1221 111 1221
          13112421242113i
          1    1336331
        1  1122   46164  2211  1
          1  1111323231111  1
         1   12 222424222 21
          1 1221112111221 1
       1 1   221 3 3 3 122    1 1
         1  32  211111112  23  1
        2311122 11 11 2211132
        113 1 3212123 1 311
          22 421 124 22
          11322422311
             36363
              191
```

0.105mm.

PLATE IV

WAVELENGTH= .55090 IMAGE HEIGHT=   6.5558
FIELD 3   2 RAYS OUTSIDE 334 RAYS BLOCKED.OUT OF A TOTAL OF 729 RAYS

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Y=   .510351

PLATE XVI

0.104 mm