TECHNICAL REPORT NO. 7

AN F/2 FOCAL REDUCER FOR THE 60-INCH
U. S. NAVAL OBSERVATORY TELESCOPE

A. B. MEINEL
G. W. WILKERSON

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ABSTRACT

The Meinel Reducing Camera for the U. S. Naval Observatory's 60-inch telescope, Flagstaff, Arizona, comprises an f/10 collimator designed by Meinel and Wilkerson, and a Leica 50-mm f/2 Summicron camera lens. The collimator consists of a thick, 5-inch field lens located close to the focal plane of the telescope, plus four additional elements extending toward the camera. The collimator has an efl of 10 inches, yielding a 1-inch exit pupil that coincides with the camera's entrance pupil, 1.558 inches beyond the final surface of the collimator. There is room between the facing lenses of the collimator and camera to place filters and a grating. The collimated light here is the best possible situation for interference filters.

Problems of the collimator design work included astigmatism due to the stop's being so far outside the collimator, and field curvature.

Two computer programs were used in development of the collimator design. Initial work, begun in 1964, was with the University of Rochester's ORDEALS program (this was the first time the authors had used such a program) and was continued through July, 1965. Development subsequently was continued and completed on the Los Alamos Scientific Laboratory's program, LASL. The final design, completed January 24, 1966, was evaluated with ORDEALS.

This project gave a good opportunity to compare ORDEALS, an "aberration" program, with LASL, a "ray deviation" program. It was felt that LASL was the superior program in this case, and some experimental runs beginning with flat slabs of glass indicated that it could have been used for the entire development of the collimator.

Calculated optical performance of the design indicated that the reducing camera should be "seeing limited" for most work. Some astigmatism was apparent, but the amount did not turn out to be harmful in actual astronomical use.

After the final design was arrived at, minor changes were made to accommodate actual glass indices of the final melt, and later to accommodate slight changes of radii and thicknesses of the elements as fabricated. An additional small change in spacing between two of the elements was made at the observatory after the reducing camera had been in use for a short time.

The fabricated camera is working according to expectations. Some photographs are included in the report to illustrate its performance and utility.
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I. INTRODUCTION

This report deals with the development of a relay system--from telescope to collimator to grating (and/or filter) to high-speed camera--in order to speed up exposure time by a factor of about 20 for the U.S. Naval Observatory's largest telescope, which is at Flagstaff, Arizona. The primary mirror is a 60-inch-diameter paraboloid. The collimator was designed by the authors, and the camera which receives the collimated beam is a Leica 50-mm f/2 "Summicron." The collimator and the housing of the reducing camera were fabricated by Boller and Chivens of South Pasadena, California.

The first focal reducer camera of this type was devised by A. B. Meinel to adapt the Yerkes Observatory 40-inch refractor to faint star work by changing the telescope f-ratio from f/18 to f/3. The present work changes an f/10 telescope to f/2. This is done at prime focus.

The advantages of such a system are several:

(1) It produces a fast output beam with a large light-gathering source. (The first-order performance of an optical system is based solely on the solid angle of radiation at the final focus and the initial aperture of the system. Thus we have a 120-inch efl telescope of 60-inch aperture.)

(2) Filters can be used easily by placing them in the collimated beam. Since the filters in this system need be only 1 inch in diameter, there is no problem of obtaining them, as would be the case for a filter large enough to be placed a respectable distance from the image plane in such a fast beam as f/2.

(3) Interference filters used in a collimated beam will not show the changes in filter characteristics that would occur in even a slowly converging beam.

\(^1\)References are on page 59.
II. DESIGN CONFIGURATION

Because of cost limitations, the Meinel Reducing Camera for the U. S. Naval Observatory telescope was to be a compromise using an existing camera lens (a Leica 50-mm, f/2 Summicron), plus an f/10 collimator that we were to design. (See Fig. 1.) There was some initial apprehension about designing a collimator of this speed, as the fastest one constructed to date had been an f/13.5 unit designed by Meinel and Schulte for the McDonald 82-inch reflector.

Starting design for the collimator was a four-element Tessar from a design given by Merté. This was soon expanded to five elements. The collimator now consists of a 5-inch-diameter field lens located close to the f/10 focal plane of the 60-inch telescope, plus four elements extending toward the camera. The collimator has an effective focal length of 10 inches, yielding an exit pupil 1 inch in diameter. This optical design was difficult because the exit pupil had to be 1.558 inches outside the collimator lens system. This was because the exit pupil of the collimator (entrance pupil of the Summicron) had to be inside the camera, with enough distance between the facing lenses of the collimator and camera to place filters and a grating. The collimator's exit pupil then coincides with the camera's entrance pupil so that the system has no vignetting.

Fig. 1. Simplified representation of telescope with Meinel Reducing Camera. Only the first and last lenses of the collimator and only one of the rear lenses of the camera are represented.
III. DESIGN PROBLEMS

Astigmatism and field curvature

The problems of the collimator are quite similar to those encountered in the case of an eyepiece; that is, the pupil through which parallel light travels is not among the elements as in ordinary lenses, and the Petzval sum contributions of both the field lens and the combination of the remaining elements of the collimator are negative.* The sum therefore is such that good images would normally lie on a highly curved surface. In order to get the best focus to lie on a plane surface, large amounts of astigmatism must be introduced. One is further limited in the balancing of aberrations since all optical surfaces of the collimator lie on one side of the entrance pupil.

At the beginning of the design study we attempted to achieve a good focus on a flat field by reducing the 3rd order Petzval sum, but only confirmed the experience of others that this sum cannot be varied appreciably for a Tessar configuration. Subsequently we tried to balance the 3rd order Petzval and 3rd order astigmatism by introducing large amounts of 5th order astigmatism of opposite sign. Using ORDEALS, this gave promise of good images up to 0.8 of the field diameter. However, the field lens became highly curved, and the high order astigmatism (7th, 9th, etc.) reached unacceptable values. The presence of these high order astigmatism terms caused the image size to "blow up" from .020 mm to 10 mm in the remaining 0.2 of the field. We concluded that any final ORDEALS design would have huge amounts of very high order astigmatism leading to gigantic images at the edge of the field. This was a major reason for emphasizing the LASL program for design work in the rest of the project.

*The convention used here is that of the ORDEALS program, in which a negative Petzval curvature occurs for a positive lens.
Fig. 2a below and Fig. 2b on page 7 illustrate some of the problems of and possible solutions for achieving good images on a flat field in a system with negative 3rd order Petzval sum.

Fig. 2a. Characteristic cases of variation of astigmatism in system with constant negative 3rd order Petzval sum. Lines P, S, M, and T represent positions of Petzval, sagittal, least confusion, and tangential planes, respectively, in relation to distance off axis or image height (the vertical line in each case).

<table>
<thead>
<tr>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>No astigmatism</td>
<td>Pure 3rd order astigmatism, half as large as Petzval (ideal case)</td>
<td>3rd order astigmatism balanced with higher order astigmatism; 5th order and higher Petzval is assumed positive for this case</td>
</tr>
</tbody>
</table>

Note that improvement in Case C is offset by rapid deterioration of the image at the edge of the field.

Case A illustrates the fact that in a stigmatic lens design the best images lie on the Petzval surface. A flat focal plane and stigmatic images then require that the Petzval sum,

\[ \rho = \sum_i c_i \left( \frac{1}{n_i} - \frac{1}{n_1} \right) \]
be 0. Here $c_i$ is the curvature of the surface $i$, $n_i^1$ is the index of refraction following that surface, and $n_i$ is the index of refraction preceding it. This sum does not depend on the bendings of the elements, their thicknesses, or their separations, but only on their curvatures and indices; hence, the sum does not change appreciably in optimization of a given design class of lens system.

When 3rd and 5th order astigmatism are present, the mean focus lies between the S surface (where the skew rays intersect one another) and the T surface (where the meridional rays intersect one another). The diameter of the image is $D = \frac{S - T}{2F}$, where $(S - T)$ is the separation of the two astigmatic image surfaces and $F$ is the system effective f-ratio.

In Case B, which has no 5th order astigmatism, the 3rd order sagittal surface (S) and 3rd order tangential surface (T) are symmetrical about a flat image plane. By 3rd order theory, if S is one unit from P (the Petzval surface), then M (the surface of least confusion) is two units from P, and T is three units from P. Hence the circle of least confusion is on the flat image plane, and P is farther from the image plane than S, M, or T. Since the positions of $\Delta(P:S:M:T)$ are geometrically related (1:1:1:1), and the Petzval surface is as far from the flat image plane as the S and T surfaces are from each other, using the familiar formula, $\text{sag} = \frac{(\text{height})^2}{2(\text{radius})}$, we can write

$$D = \frac{h^2}{4F} = \frac{h^2}{4F} \sum\limits_{i} c_i \left( \frac{1}{n_i^1} - \frac{1}{n_i} \right),$$

where $h$ is distance off axis (image height).

In Case C, the amount of 3rd order astigmatism is the same as in Case B, but 5th and some higher order astigmatism comes into play as one gets farther off axis, and the S and T image surfaces come back to the flat image plane, crossing each other near it. For a fair distance below and for a short distance above the point where S and T cross, the images on the flat
image plane are even smaller than in Case B, but at the very edge of the field they enlarge rapidly because of the violent departure of the S and T surfaces due to 5th order (and in many cases higher order) astigmatism overwhelming the 3rd order effect. The surface (M) of the circle of least confusion for Case C (but not Case B) departs slightly to the left from the flat image plane, particularly for larger distances off axis. (For 5th order alone, the T surface is five times as far from P as is the S surface.) The combined effect of 3rd order and 5th order Petzval to give the resulting P surface is shown by a dashed line.

In Fig. 2b, the size of the circle of least confusion with increasing distance off axis is indicated by a dashed line for Case B, a solid line for Case C.

Fig. 2b. Relative size of the circle of least confusion against image height for Case B (dashed line) and Case C (solid line).
Aberrations of primary mirror

This study revealed an internal problem of the ORDEALS program that requires special note by a user. Ideally, the design of the collimator should compensate for the natural aberrations of the 60-inch telescope mirror. However, in using the ORDEALS program we found that the aberrations of the mirror varied from iteration to iteration, even though none of its parameters were changed. Since we were dealing with a large optical element combined with a series of small elements, the problem apparently was caused by round-off errors in calculating a small difference between two large quantities. Obviously one cannot use an automatic correction procedure when one of the "fixed" quantities is a random variable, and thus we chose to neglect the telescope aberrations. This was justified in this case since the coma and astigmatism of an f/10 paraboloid at the field angles involved are small compared to the size of the normal seeing disc.

R. E. Hopkins, who developed the ORDEALS program, has advised us that the problem can be avoided by reducing the scale of the primary to the order of 10 inches focal length. The collimator lenses and aberrations are scaled down, but the computational accuracy improves.
IV. DISCUSSION OF THE TWO COMPUTER PROGRAMS USED

This design project was particularly interesting in giving us the opportunity to compare the performance and results of two automatic optical design programs: the ORDEALS program of the University of Rochester (New York) as modified by Tropel, Inc. (Rochester, New York), and the LASL program of the Los Alamos Scientific Laboratory (Los Alamos, New Mexico).

Dr. Meinel took the starting Tessar design to Rochester to attempt to optimize it and to learn to use the ORDEALS program, developed by R. E. Hopkins. (It is interesting, in retrospect, to note the long exploration of design problems that was started by this trip. About 200 design runs were eventually made on ORDEALS and about 15 on LASL.) The design optimization at Rochester was not encouraging, and two more trips were made. The final design still had a serious problem of astigmatism, and a copy of the ORDEALS program was brought to Arizona in the spring of 1964 to facilitate the study of certain problems uncovered by this study.

Final development of the collimator design, beginning from approximately the July, 1965, ORDEALS result, was made with the LASL program. This program was promoted by Berlyn Brixner, developed by John Holladay, and improved and refined by the late Charles A. Lehman, Sr., all of Los Alamos Scientific Laboratory. It is for the IBM 7090 computer, and our study was made using the Western Data Processing Center facilities at UCLA.

Final image evaluation was made with the ORDEALS program, using the IBM 7072 computer at the University of Arizona. Some plots of the image-spot diagrams were made on the Cal-Comp plotter at the Kitt Peak National Observatory.
Characteristics of the programs

Since ORDEALS, which uses classical methods, has been used in other projects and has been covered in previous reports, it will not be discussed in detail here. With regard to design work it can be described as an "aberration" program.

The LASL program is a "ray-deviation" program rather than an "aberration" program. It does not use classical techniques in any way. For one thing, it traces all rays exactly by vectorial methods, never using the common first order approximation (paraxial ray tracing), as does ORDEALS. The LASL code's so-called "paraxial trace" is simply an exact vectorial trace with the ray never getting farther from the optic axis than a very small fraction of the size of the lens. Aberration theory is never used. The designer chooses a group of rays which he considers adequate to sample the entrance pupil, and simply makes them focus as close as possible to each other on the desired image plane, while holding focal length, lateral color, distortion, and exit pupil location to acceptable values. The LASL code reduces the root mean square radius of the spot size with no regard as to which aberrations are causing the blur in the image plane at any given time. Improvements are accomplished by comparing the actual image before and after small changes in selected groups of variables. One does not, therefore, know why an improvement occurs. We found that we could follow what was occurring in the aberration values from run to run by using ORDEALS to evaluate output from the LASL program.

The LASL code will handle as many as 98 surfaces. It can store up to 49 independent variables, but uses only 1 to 10 per iteration as specified by the designer. Each variable may be a set of as many as six dependent
parameters. The program allows six colors and seven field angles to be considered simultaneously. In addition, there is a "substitution parameter" routine which can be used to design a lens simultaneously for as many as five conditions of use. This can be applied to zoom lenses as well as other lenses which must be designed for other circumstances than just the standard one object plane to image plane situation for several field angles and colors. The program provides for 100 substitute parameters for each of the other four cases. This means that the lens may have up to 49 parts of itself altered for five different uses and be optimized for the four other uses at the same time it is being optimized for the original layout. Each of the five conditions constitutes one vector part of the total error vector. The total error vector is the basis for the merit function, and in fact, when dotted into itself it gives the least squares sum that the program attempts to minimize by an iterative process.

Use of LASL in present project

With LASL, as with ORDEALS, the collimator was designed by running it backward through the computer. That is, parallel light first struck the surface of the collimator that in actual use would be nearest the camera of the relay system, and proceeded finally to an image plane essentially coincident with the paraxial image plane of the primary mirror. This meant we were in effect designing an f/10 camera having a 10-inch focal length, an exit pupil 600 inches beyond the image plane, and a full field of 27°.

Using light originating from .8 of full field, the LASL code was told to make the real chief ray for Hβ light (4861 A) cross the optic axis about 600 inches beyond the image plane of the collimator. This meant that in actual use the chief ray for .8 of full field hitting the primary mirror would
be in perfect harmony with the collimator. As the result of such a demand, the chief rays for most of the entire field and spectral range of the relay system leave the collimator's field lens very nearly parallel to the optic axis. Thus the entrance pupil of the system (the primary mirror) is the "exit pupil" of the collimator in design, as is necessary if all the light gathered by the primary is to pass through the entire relay system.

(With ORDEALS, one cannot design on a real chief ray. Design demands must be placed on a paraxially determined chief ray, and as a result the real chief ray for .8 of full field crossed the axis at 60 instead of 600 inches from the collimator. Thus, it was almost impossible, with ORDEALS, to achieve the proper exit pupil for the collimator.)

A problem in a system of this type is spherical aberration of the image of the stop; that is, trigonometric chief rays originating from the entrance pupil (which in our design process was also the aperture stop) tend to cross the axis beyond the field lens at far different locations, giving a poor image of the entrance pupil. Perhaps the LASL code's substitution parameters section would have allowed us to optimize the lens as one part of the error vector and get an improved image of the stop as the other part.

The nature of the LASL code was such that, for a given field angle, it tried equally hard to minimize the spot size for each of the three colors (6563, 4861, and 4047 A) that it was given. (The Jet Propulsion Laboratory's modification of this code allows colors to be weighted separately, but the standard version does not.)

The lateral color (lateral chromatic aberration) feature in LASL worked on getting the centroids for each of the three colors closely spaced to the centroid of the three centroids. The distortion control amounted to telling
the program to make the centroid of these three centroids come close for the given field angle to the image height necessary for no distortion in a 10-inch focal length system. The effective focal length of the collimator was regulated similarly: for full field we asked for the proper image height (2.4 inches) for the effective focal length of 10 inches. (Such a request on the image height could cause the efl to differ from 10 inches because of distortion, even if an exact achievement of a 2.4-inch image height occurred.)

All of the above demands with their weighting factors were combined into one least squares sum, i.e., the merit function. The lateral color and spot size usually were weighted differently for different field angles.

The LASL code moved quickly (about 8 minutes IBM 7090 time) to the region of optimum for any set of weights except when one of the weights, such as that on the image height, which controlled the focal length, was 10 times or more greater than the weights on spot size and lateral color. Even here, a near optimum probably was being reached, but the computer was being made to think that a good solution was one in which the spot size was allowed to be large and that the image height must be right to several significant figures. From a point near optimum for a given set of weights and number of variables taken at each iteration, the solution approached optimum very slowly. The net conclusion from all this is that the LASL code approached optimum for the collimator for a given set of weights in an asymptotic fashion.

The exact values of the weights used are not critical. One may get a fair idea of the effect of the weights and the accuracy to which their values should be chosen by comparing the weightings used (Table 1) with the resulting focal length and exit pupil location (Table 1) and with the root mean square spot size and lateral color (Figs. 3 through 5).
Table 1. Numerical data for runs on LASL code.

<table>
<thead>
<tr>
<th>Date of run</th>
<th>12/27/65* 12/29/65 12/30/65 1/3/66 1/5/66 1/10/66 1/14/66 1/17/66 1/19/66 1/24/66 3/24/66***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b b b b b b b b b b b b</td>
</tr>
<tr>
<td>STARTING PRESCRIPTION</td>
<td>Image height for efl control</td>
</tr>
<tr>
<td></td>
<td>Distance from last surface to exit pupil</td>
</tr>
<tr>
<td>SPOT SIZE</td>
<td>On axis</td>
</tr>
<tr>
<td></td>
<td>Spot size</td>
</tr>
<tr>
<td></td>
<td>.6 full field</td>
</tr>
<tr>
<td></td>
<td>.8 full field</td>
</tr>
<tr>
<td></td>
<td>Full field</td>
</tr>
<tr>
<td></td>
<td>Exit pupil location</td>
</tr>
<tr>
<td></td>
<td>Distance from last surface to exit pupil</td>
</tr>
<tr>
<td>MERIT FUNCTION</td>
<td>Spot size</td>
</tr>
<tr>
<td></td>
<td>.6 full field</td>
</tr>
<tr>
<td></td>
<td>.8 full field</td>
</tr>
<tr>
<td></td>
<td>Full field</td>
</tr>
<tr>
<td></td>
<td>Exit pupil location</td>
</tr>
<tr>
<td></td>
<td>Distance from last surface to exit pupil</td>
</tr>
<tr>
<td>DISTORTION</td>
<td>.2 full field</td>
</tr>
<tr>
<td></td>
<td>.4 full field</td>
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<tr>
<td></td>
<td>.6 full field</td>
</tr>
<tr>
<td></td>
<td>.8 full field</td>
</tr>
<tr>
<td></td>
<td>Image height for efl</td>
</tr>
<tr>
<td>RESULTS</td>
<td>Image height for efl control (target 2.400)</td>
</tr>
<tr>
<td></td>
<td>Distance from last surface to exit pupil</td>
</tr>
<tr>
<td></td>
<td>600.028 599.761 599.402 599.245 600.006 600.405 599.876 600.226 599.876 596.895 597.617</td>
</tr>
</tbody>
</table>

*This is the first run in which a good set of weights was used. Starting prescription results from six LASL runs that originated from the July, 1965, ORDEALS output. In these six runs the weighting was far astray from what it should have been.

**Stop position was altered from that entered before automatic design began.

***Final melt indices, with SF12 instead of SF2 in third element; 4358 Å was bluest wavelength used in this run instead of 4047 Å as in the others.

b Bending of lenses used during part of run.

bb Bending of lenses used throughout run.
Fig. 3. RMS radius spot size on axis for the three design wavelengths during LASL runs. Spot size at "start" was input for run of 27 Dec. '65.
Fig. 4. RMS radius spot size on axis at 4861 Å for full field, 0.8 of full field, and 0.6 of full field during LASL runs. Spot size at "start" was input for run of 27 Dec. '65.
Fig. 5. Centroid separation measurements of primary and secondary lateral color at full field during LASL runs. Separations at "start" were input for run of 27 Dec. '65.
When the program begins to creep along at a rate of less than a hundredth of a percent improvement per iteration, little more can be expected from the same set of demands. At this point, improvement can be speeded up in any of three ways:

(1) The number of variables used at each iteration can be increased. The program uses from 1 to 10 of the allowed variables during a single iteration, changing to a new set at each iteration. It works well to use only two or three at the beginning of a design and four or five in finishing up. Berlyn Brixner, lens designer at Los Alamos, has described this situation in considerable detail. Wilkerson and the late Charles A. Lehman, Sr., of Los Alamos, never found it of value to go above six at a time. (It might seem wise to use all the allowed variables during each iteration as in most lens design programs, but after a few cycles, all the available variables have been used and in various combinations anyway. One should recall, too, that the time per iteration increases almost as the square of the number of variables being used.)

(2) The weightings can be changed. For example, that on lateral color can be increased. A new solution is then reached in only a few iterations, and generally not only the lateral color but also the spot size will be noticeably improved. By returning to the original weight on lateral color, the spot size can be further improved with little deterioration of lateral color. (Compare Figs. 3 through 5 with weights given in Table 1 for various LASL runs.)

(3) The elements can be bent for several iterations, and then the curvatures can be varied independently during several iterations. Whether or not bendings were involved in a given run in the present study can be seen from Table 1. Glass thicknesses and air spaces were among the variables in all cases.
Further potential of LASL program

As already mentioned, the final design for the collimator was developed on the LASL program (see Table 1 and Figs. 3 through 5), beginning 27 Dec. 65, from a preliminary design developed with ORDEALS and already modified to some degree during experiments with LASL. To see whether the entire collimator could have been designed with LASL, we tried an experimental version on LASL, beginning with flat slabs of glass, and did indeed reach a point of design of about the caliber of the 27 Dec. 65 start. Therefore, LASL probably could have been used to design the entire collimator from flat slabs to achieve a design similar to the one fabricated.

Advantages of LASL over ORDEALS

LASL exhibited a great advantage over ORDEALS in getting good resolution in a system where high aberrations must be considered.

Besides 7th order spherical aberration and all the 5th order aberrations, the minimization of ray deviation ("RYDEV") was the only part of ORDEALS available for spot size reduction when we did our design work on the collimator. (The value of RYDEV is the square root of the quantity \[ \frac{1}{8} \sum_{i=1}^{8} s_i^2 \], where \( s_i \) is the separation, at the image plane being used, of ray \( i \) from the real chief ray.) At the time we used it, RYDEV allowed us to minimize the blur due to eight meridional rays originating at full field and being uniformly distributed in the entrance pupil. No skew rays of any kind were available. Therefore, no control could be placed on the 7th and higher order aberrations involving skew rays, that is, on the 7th and higher order sagittal aberrations. (More recently, real skew rays have been made available in the ORDEALS program. We have not yet sufficiently tested their behavior in designing.)
Because RYDEV is the only part of ORDEALS that indicates true spot size, in a system having as many high-order aberrations as this collimator, it is interesting to observe what the RYDEV parameter would have been for the various results produced by ORDEALS and LASL. Fig. 6 is a plot of RYDEV against design run. Since the ray distribution of RYDEV is not for an equal area on the entrance pupil, and particularly since it contains no skew rays, RYDEV does not necessarily indicate true root mean square spot size. Thus, although the LASL result of 10 Jan. 66 would have had noticeably the best RYDEV value, it had by no means the smallest spot size. This indicates that the skew rays at full field were much farther from the centroid than were the particular RYDEV meridional rays for that result.

The above shows that RYDEV would not have been nearly so effective for achieving good resolution as was the root mean square criterion of LASL. In addition, the RYDEV parameter often fluctuates greatly from iteration to iteration, whereas the root mean square value in LASL goes to a minimum in reasonably asymptotic fashion.
Fig. 6. Values of ORDEALS ray deviation parameter (RYDEV) at full field for LASL runs and best ORDEALS runs.
V. FINAL DESIGN

The design for the collimator for the 60-inch U. S. Naval Observatory telescope evolved from a standard Tessar into the rather strange configuration, "Fat Man," shown below. This result was not surprising with the LASL approach since it generates a design without prior supposition as to "type."

Fig. 7. Configuration of collimator, shown "backwards" (i.e., as designed).

The specifications are given in Table 2. Although this design does not meet our usual image size limits, we are certain that it is the best compromise within the limitations described in Section II.

Table 2. Final design of collimator for U. S. Naval Observatory telescope; 10.0-inch efl, 1.0-inch pupil; all dimensions in inches

<table>
<thead>
<tr>
<th></th>
<th>Lens 1</th>
<th>Lens 2</th>
<th>Lens 3</th>
<th>Lens 4</th>
<th>Lens 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>SK10</td>
<td>SF2</td>
<td>SF2</td>
<td>SK10</td>
<td>BK7</td>
</tr>
<tr>
<td>Front radius</td>
<td>5.378</td>
<td>-11.909</td>
<td>-9.831</td>
<td>6.251</td>
<td>5.567</td>
</tr>
<tr>
<td>Thickness</td>
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<td>.167</td>
<td>.100</td>
<td>3.525</td>
<td>4.828</td>
</tr>
<tr>
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<td>8.949</td>
<td>4.121</td>
<td>-5.390</td>
<td>10.070</td>
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<tr>
<td>aperture stop or</td>
<td>1.558</td>
<td>2.278</td>
<td>.232</td>
<td>.386</td>
<td>4.738</td>
</tr>
<tr>
<td>preceding lens</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(24 Jan., 1966)
Evolution of design

In this design the first three lenses quickly approached the minimum thickness we allowed, whereas the last two became very thick. Fig. 8 shows the evolution of the "back part" of the collimator during the LASL runs. (ORDEALS never tried to create thick elements here.) An experienced lens designer would never guess that this thick-element design is a surprisingly good one, but independent evaluation with ORDEALS confirms the performance.

The evolution of the collimator into the "Fat Man" design was necessary to control the high order Petzval sum and high order astigmatism. As shown in Fig. 9, both PTZ5 and TAS5 were very small at the beginning of the ORDEALS design stage. In the final LASL design they are larger, but they are of opposite sign and are approximately equal in magnitude to their 3rd order counterparts. The result is a surprisingly small image size. In the best ORDEALS design, the images at 1.96 and 2.40 inches off axis had root mean square radii of .003 and .004 inch, respectively. This is at the circle of least confusion for the given field angle. The 24 Jan. 66 LASL design had root mean square radii of .0009 and .0009, respectively. The energy concentration is at least 10 times better in the ORDEALS design.

It is interesting to note that the field lens created by LASL has both surface curvatures of the same sign so that its great thickness enhances its control over the chief ray. This can be seen from the formula for the power of a thick lens: \( K = (n - 1)(c_1 - c_2 + \frac{n-1}{n} c_1c_2t) \). Twenty-seven per cent of the power of this positive element is due to its thickness. This gives it much control over the chief ray without introducing such steep curvatures as to create a much more curved image plane. (Recall that 3rd order Petzval is a function only of \( c_1 \), \( c_2 \), and \( n \), not of \( t \).)
Fig. 8. Variations of thickness in back part of collimator during evolution with LASL program. "Start" thicknesses were input for run of 27 Dec. '65.
Fig. 9. Changes in 3rd and 5th order Petzval and astigmatism terms during evolution of collimator design.
Calculated optical performance of design

Figs. 10 through 15 show the optical performance of the final "Fat Man" design for the collimator (24 January 1966).

Fig. 10 gives ORDEALS type spot diagrams for two focal surfaces: 0.13 inch and 0.15 inch from the field lens. Each plot includes three wavelengths that nicely sample the useful spectral range: 6563, 4861, and 4047 Å. The "lateral color" (lateral chromatic aberration) of the system is apparent from the lateral displacement of the three spots, especially for an image height of 1.44 inch at the 0.15-inch back focus. One would therefore expect still better performance of the collimator for filter passband work.

The large circle in this figure shows the size of a .001-inch spot in the focal plane of the f/2 Summicron lens, assuming no aberrations for this lens. (This assumption is a bit risky, especially when we are interested in image sizes in the 10μ range. One would normally like to optimize the entire system with the camera lens included. In this case, since the design specifications of the commercial camera are not available, it is impossible to fully optimize the system.)

The small circle in the figure represents a .001-inch spot in the focal plane of the 60-inch telescope. For average good seeing, about 1 arc sec, the size of the image at the focus of the telescope would be .003 inch; hence this design for the reducing camera should be "seeing limited" for most work.

Fig. 11 shows the increase of image size with image height for the same three wavelengths, for an image plane chosen for best on-axis imaging. The circles, added for scale, indicate .001-inch spots at the final focus through the f/2 Summicron, assuming again that the Summicron has no intrinsic aberrations. The magnitude of "lateral color" is indicated by the vertical
displacement of the chief rays (short horizontal bars) from each other. The horizontal dashed lines serve as guides.

Fig. 12 shows the variation of image size and lateral color for different wavelengths against distance off axis as measured in the common focal plane of the collimator and telescope. The mean focus, the circle of least confusion, is in general much larger than the narrow dimension of astigmatic image. One result of this is that the collimator will produce better objective spectra than direct photographs. The large central obscuration of the telescope may even cause the images of stars near the edge of the field to show a central hole when the best focus for the center of the field is used.

Kitt Peak style spot diagrams of the image for several focal settings are shown for 0.96 inch off axis in Fig. 13 and for 1.92 inches off axis in Fig. 14. The presence of astigmatism is readily apparent, but the amount is so small at 0.96 inch as to be hard to detect in actual astronomical use.

Fig. 15 shows the variation of best focus position, based on energy considerations, with distance off axis, for the combination of the three wavelengths. This is measured at the focal plane of the 60-inch mirror. The focal surface is not flat, but in actual use a focus position is chosen so that the average image size across the field is minimized. If we were to flatten the curve shown in the figure, then the best images would all lie on a flat plane, but they would be more astigmatic. In other words, the central images would be very sharp and the edge images distinctly poorer. Another reason for leaving some field curvature concave toward the telescope is that photographic plates are not flat. The surface tension of the emulsion always bends the plate concave on the emulsion side, with a sagittal of about a thousandth of an inch in a 1-inch span of a .040-inch-thick plate.
Fig. 10. ORDEALS type spot diagrams for two focal surfaces, 0.13 and 0.15 inch from field lens. Note lateral color for various image heights (distances off axis).
Fig 11. Size and shape of areas containing all the energy at best on-axis image plane. Displacement of chief ray (short horizontal bar) from dashed line indicates magnitude of lateral color (lateral chromatic aberration).
Fig. 12. Variations of image size and lateral color for the three wavelengths. Lateral color is based on LASL measurement of centroid separation; 4047 Å is used as the datum line.
Fig. 13. Spot diagram at 0.96 inch off axis.
Fig. 14. Spot diagram at 1.92 inches off axis.
Fig. 15. Variation of best focus position for the full spectral range (4000 A - 7000 A) with distance off axis.
Modifications for final melt

After the final design of the collimator was completed using catalog values for the glass indices (1/24/66, Table 2), it was necessary to redesign using the actual melt values of the glasses. In addition, because of the glass available, it was decided that type SF12 would replace SF2 in Lens 2.

The final melt design run, using the new glass indices, was that of 3/24/66. In this optimization run, 4358 A was used instead of 4047 A because the final melt data appeared to be too sparse to design with 4047 A. Neither glass thicknesses nor air thicknesses were used as variables, and the weights were the same as for the run of 1/24/66. The results are shown in Figs. 3 through 6.

As a result of this final run, the radii of elements 3, 4 and 5 changed by less than 3 percent, but the first four radii (elements 1 and 2) changed by 4.42, 21.02, 14.23 and 22.20 percent, respectively. These changes caused appreciable bending of both elements and a slight weakening of their power.

The result of changing to the final melt indices--and this is not mainly a result of the new optimization--is a vast improvement in secondary lateral color (in this case 4861-4358 A as opposed to 4861-4047 A), or in other words a decrease in the centroid separation of the various wavelengths used in design. (See Fig. 5.) Primary color (6563-4358 A) became about 10 times worse than the original range (6563-4047 A). However, the sum of the primary and secondary lateral color was approximately stationary.

Table 3 on the following page summarizes the final specifications for the collimator, as submitted to the manufacturer, Boller and Chivens.
Table 3. Revised design with final melt indices; dimensions are in inches. 
(Note that indices are final melt values and not catalog values.)

<table>
<thead>
<tr>
<th></th>
<th>Lens 1</th>
<th>Lens 2</th>
<th>Lens 3</th>
<th>Lens 4</th>
<th>Lens 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>SK10</td>
<td>SF12**</td>
<td>SF2</td>
<td>SK10***</td>
<td>BK7</td>
</tr>
<tr>
<td>Front radius</td>
<td>5.140</td>
<td>-10.213</td>
<td>-9.676</td>
<td>6.134</td>
<td>5.518</td>
</tr>
<tr>
<td>Thickness*</td>
<td>.220</td>
<td>.167</td>
<td>.100</td>
<td>3.525</td>
<td>4.828</td>
</tr>
<tr>
<td>Rear radius</td>
<td>-23.423</td>
<td>10.936</td>
<td>4.028</td>
<td>-5.462</td>
<td>9.903</td>
</tr>
<tr>
<td>Separation from</td>
<td>1.558</td>
<td>2.278</td>
<td>.232</td>
<td>.386</td>
<td>4.738</td>
</tr>
<tr>
<td>aperture stop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>or preceding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lens*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Same as in Table 2. **The substitution of SF12 for SF2 in this element means little since the two glasses differ only by a v-number of about 0.1, and only in the third decimal place for the value of n_d. ***This element is from a different melt than the other SK10 element.
VI. PERFORMANCE OF FABRICATED SYSTEM

Fig. 16, below, shows the Meinel f/2 Reducing Camera enclosed in its housing. The entire telescope, with the camera attached, is shown in Fig. 17 on the following page.

Fig. 16. Meinel f/2 Reducing Camera enclosed in its housing. (Official U. S. Navy photograph)
Fig. 17. Meinel Reducing Camera on U. S. Naval Observatory telescope. (Official U. S. Navy photograph)

The system has been found to work well. However, the radii and thicknesses of the glass elements as fabricated were found to differ slightly but significantly from the specifications, and there were some resultant modifications in spacings between elements.

First, in an attempt to offset the discrepancies, Boller and Chivens apparently adjusted the air spacings before delivery. The merit of trying to do this is questionable, but in this case pretty good results occurred in some plates (shown later in this report), using these adjustments.
Since the thicknesses and spacings in the delivered collimator were so different from those planned, it is clear that tolerances on these parameters can be pretty loose. This is probably due to their nature (they can generally be treated more carelessly in fabrication than can curvatures) and to the apparent tendency of LASL designs, when near or at "optimum," to show a deep, wide valley in the profile of the merit function plotted against variables.

After the collimator with these adjusted spacings had been in use for a while, the LASL code was used to create a new set of air spacings (Table 4), using as starting data the originally specified spacings of Table 3 and the carefully measured radii and thicknesses of the fabricated elements.

Table 4. Modifications in air spacings (inches).

<table>
<thead>
<tr>
<th>Between elements--</th>
<th>Specified spacings</th>
<th>Adjusted by manufacturer</th>
<th>Revised by computer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 and 2</td>
<td>2.278</td>
<td>2.247</td>
<td>2.331</td>
</tr>
<tr>
<td>2 and 3</td>
<td>.232</td>
<td>.183</td>
<td>.246</td>
</tr>
<tr>
<td>3 and 4</td>
<td>.386</td>
<td>.538</td>
<td>.378</td>
</tr>
<tr>
<td>4 and 5</td>
<td>4.738</td>
<td>4.683</td>
<td>4.518</td>
</tr>
</tbody>
</table>

Table 5 shows the final data for the collimator, with the fabricated thicknesses and radii for the elements and the computer-revised air spacings.

Table 5. Final data for collimator in operation; dimensions are in inches.

<table>
<thead>
<tr>
<th></th>
<th>Lens 1</th>
<th>Lens 2</th>
<th>Lens 3</th>
<th>Lens 4</th>
<th>Lens 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>SK10</td>
<td>SF12</td>
<td>SF2</td>
<td>SK10</td>
<td>BK7</td>
</tr>
<tr>
<td>Front radius</td>
<td>5.123</td>
<td>10.271</td>
<td>9.637</td>
<td>6.122</td>
<td>5.510</td>
</tr>
<tr>
<td>Thickness</td>
<td>.221</td>
<td>.168</td>
<td>.099</td>
<td>3.572</td>
<td>4.801</td>
</tr>
<tr>
<td>Rear radius</td>
<td>23.438</td>
<td>10.949</td>
<td>4.013</td>
<td>5.455</td>
<td>9.906</td>
</tr>
<tr>
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<td>2.331</td>
<td>.228*</td>
<td>.378</td>
<td>4.518</td>
</tr>
</tbody>
</table>

*Changed from .246; see page 41.
Table 6 shows rms radius spot size at various wavelengths and distances off axis for (1) the original design of 1/24/66, (2) the original design after introduction of final melt indices, (3) the original design after optimization with the final melt indices (3/24/66), (4) the design with the actually fabricated elements and original air spacings, and (5) the design with the fabricated elements and optimized air spacings.

Table 6. Spot size, rms radius in inches.

<table>
<thead>
<tr>
<th>Inches off axis</th>
<th>Original design</th>
<th>With final indices Introduced</th>
<th>Optimized</th>
<th>Fabricated elements Orig. spaces</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>6563 A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.000529</td>
<td>0.000452</td>
<td>0.000884</td>
<td>0.000770</td>
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<tr>
<td>0.48</td>
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<td>0.000403</td>
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<td>0.000665</td>
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<tr>
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<td>0.000409</td>
<td>0.000380</td>
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<td>0.000456</td>
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<td>0.000571</td>
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<tr>
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<td>4861 A</td>
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<td></td>
<td></td>
</tr>
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<tr>
<td>0.48</td>
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<td>0.001094</td>
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</tr>
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<td>0.001582</td>
<td>0.001293</td>
</tr>
</tbody>
</table>

*4047 A rather than 4358 A for this case.

The design with the fabricated elements and the LASL-optimized air spacings was evaluated with ORDEALS. From "H tan U" curves, Wilkerson reached a compromise "best back focus" of 0.1278 inch. ORDEALS type spot diagrams for this back focus are shown in Fig. 18 on the next page. Spot diagrams for a similarly determined "best back focus" with Priser's shim added (see page 41) show no major difference. In this latter case, the back focus is 0.1241 inch.
Fig. 18. ORDEALS type spot diagrams for compromise "best back focus" of 0.1278 inch from field lens. Note lateral color for various image heights (distances off axis).
The photos which follow illustrate the performance of the collimator. Figs. 19 through 22 were taken with the spacings as adjusted by Boller and Chivens. Figs. 23 through 26 were taken after the spacings were revised according to the computer suggestion; 27 through 33 incorporate an additional empirical change made by a staff member of the observatory.

Fig. 19 evidences the lack of distortion in the system. This photograph was taken by moving the telescope steadily in a single direction so as to create a "star trail" from each star image. The fact that the lines are very nearly straight is proof that there is little distortion in the system. If much distortion were present, the trails would curve toward the center of the field with increasing distance off axis ("barrel distortion") or they would curve outward ("pincushion distortion").

Figs. 20 through 22 show prints of plates taken with the Meinel reducing camera immediately after its delivery, and with the spacings as adjusted by Boller and Chivens. The computer-optimized air spacings had not yet been applied. Fig. 20 is a single star field photographed in six one-minute exposures on the same plate. The telescope was moved about 30 arc sec in right ascension after the first four exposures and then about 30 arc sec in declination before the last exposure. Each shift was done for a different effective back focus for the collimator, achieved by moving the entire reducing camera with respect to the primary mirror. Such focusing can be done at the console of the telescope and is essential because the primary mirror contracts as it gets colder, changing the location of prime focus and thereby changing the required location of the reducing camera needed to make the collimator's best image plane coincide with the primary's image plane.

Figs. 23 through 26 are prints of plates taken with the LASL-generated air spacings for the fabricated elements.
Empirical adjustment

After the computer-generated air spacings were put into effect, Mr. John B. Priser of the Naval Observatory staff found that the quality of the images could be improved by decreasing the separation of the second and third elements by .018 inch. (See footnote to Table 5.) Figs. 27 through 33 are from plates taken with this adjustment, which is now permanently employed in the use of the Meinel Reducing Camera at the observatory. The quality of images produced before and after this adjustment is shown by a comparison of Figs. 26 and 27. The coma highly noticeable at about 2/3 of full field in Fig. 26 is practically eliminated in Fig. 27. (Note that Fig. 22 also shows this coma.) Interestingly, spot diagrams illustrate practically none of this elimination of coma, even when several back focuses are tried.

Note that in Fig. 28 the resolution is grain-limited in the spiral arms of the galaxy.

Fig. 29 shows the hard-to-photograph Jovian satellites VI and VII, which are of magnitudes 14 and 18, respectively. (The only known satellites in the solar system dimmer than Jupiter VII are five other satellites of Jupiter, and Neptune's faintest satellite, Nereid; these range down to magnitudes as low as 19.5.) This photo was obtained by exposing a 103a0 plate for 20 minutes on December 16, 1966. A GG13 filter was used. With 103a0 plates and this exposure time, stars of 20th magnitude and brighter can be seen with little difficulty. This is nearly the same limit as for the National Geographic Society-Palomar Observatory Sky Atlas, which was produced using the Palomar 48-inch Schmidt camera. Good spectra of 15th magnitude stars can be obtained on reasonably fast plates with a 30-minute exposure. On IIIaJ plates, which are slow but very fine-grained, a 10-minute exposure gives satisfactory spectra of 12.5 magnitude stars.
Fig. 30 shows how one can obtain the spectra of many stars in a field with the f/2 camera. Each star of sufficient brightness and lying in the proper part of the field of view will have its spectrum produced on the plate. Note the central image appearing in the print about 4 inches to the left of the spectra. The images have been blown up nearly 8 times, thereby causing a dispersion of about 40 A/mm for the first order on the print. Fig. 32, four widened spectra of Jupiter, has several lines that were well under .001 inch wide on the plate, meaning they are about .005 inch wide on the print. Similar resolving power is seen in Fig. 33, a very widened spectrogram of the moon.
Fig. 19. Straight star trails, indicating lack of distortion in Meinel reducing camera as received from Boller and Chivens. (Official U. S. Navy photograph)
Fig. 20. Six images of a single star field, taken by shifting the reducing camera with respect to the primary mirror. The telescope was moved about 30 arc sec in right ascension after the first four exposures and 30 arc sec in declination after the fifth; this facilitated identification of the last exposure on the plate. (Official U. S. Navy photograph)
Fig. 21. Portion of the famed Andromeda Galaxy, NGC 224 (M31). It is more than 2° in diameter (spreading across 100,000 light years of space), far larger than the 30 arc min full field of the reducing camera. The galaxy itself contains about $10^{11}$ stars and is 2 million light years away. (Official U. S. Navy photograph)
Fig. 22. Photo of h Persei photographed with the reducing camera as received from Boller and Chivens. Some coma at 2/3 of full field is evident. (Official U. S. Navy photograph)
Fig. 23. Photo of "Crab Nebula," NGC 1952 (M1), at a distance of 4100 light years. Spacings between elements were as revised by computer. (Official U. S. Navy photograph)
Fig. 24. Photo of galaxy NGC 7331, at a distance of $5.2 \times 10^6$ light years. Diameter is 15,000 light years. Spacings between elements were as revised by computer. (Official U. S. Navy photograph)
Fig. 25. Photo of galaxy NGC 891, at a distance of $2.35 \times 10^6$ light years; 30 arc sec equals 105 parsec for this galaxy. Full field of plate is 30 arc min. Spacings between elements were as revised by computer. (Official U. S. Navy photograph)
Fig. 26. Photo of h Persei taken with Meinel reducing camera after introduction of computer-revised air spacings and before modification by Priser. (Official U. S. Navy photograph)
Fig. 27. Photo of χ Persei taken with Meinel reducing camera after introduction of computer-revised air spacings and with modification by Priser. (Official U. S. Navy photograph)
Fig. 28. Photo of galaxy NGC 3031 (M81) at a distance of 8.6 million light years. Diameter is about 52,000 light years. (Official U. S. Navy photograph)
Fig. 29. Print of plate exposed 16 Dec. 1966 from $08^h09^m20^s$ to $08^h29^m20^s$ Universal Time, to try to pick up Jupiter's satellites VI and VII. Arrows set off objects which are definitely not stars. (There are no star images at these points in the Palomar Sky Atlas.) Although identification is not positive, leftmost image is probably Jupiter VI and lower right image Jupiter VII. (Official U. S. Navy photograph)
Fig. 30. Many widened spectra, exposed simultaneously on the same plate. The stars whose spectra are shown are in a region of NGC 225. Darker arrows relate two of the spectra to their corresponding primary images. (Official U. S. Navy photograph)
Fig. 31. Four widened spectra, exposed on the same plate, of the star \( \lambda \) Ursae Majoris. (Official U. S. Navy photograph)
Fig. 32. Four widened spectra, exposed on the same plate, of the planet Jupiter. Note the presence of several extremely narrow lines. (Official U. S. Navy photograph)
Fig. 33. Extremely widened spectrum of the moon. Note the presence of several sharp, extremely narrow lines. (Official U. S. Navy photograph)
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VIII. REFERENCES


