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A simple approach to common lens design

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Abstract

Most of the problems solved by designers and engineers on a daily basis are small but important details, instead of extremely complex tasks. Optical design tends to be no exception. The tools for day to day problem solving need to be easy to learn and use. In today's environment of computer availability, many engineers have an occasional need for optical design and evaluation, but do not spend all of their time designing optics. These people need a tool which is powerful enough to solve or evaluate their problems but that is simple and easy to understand, remember, and use. This is the user that the TRACE V program set addresses. The programs allow the evaluation of most of the types of optical systems that may be encountered. These include those with aspherics, tilts, decentrations, toroids, etc. The images of points are displayed on the screen and the lens configuration can be drawn and examined. Simplicity is maintained in the merit function used for optimization. It is based on: the RMS size of the image of an on-axis and off-axis image, the curvature of the focal plane on which the images lie, the distortion shown by those images, and violations of boundary conditions. The images can be heterochromatic combinations of three colors, one central and two half power wavelengths. The programs have evolved from practical application over 25 years of use on a variety of computers and are now best suited for the personal computer. There are more appropriate and powerful tools for the career lens designer, but this is a practical and easy to use tool for the occasional optical design engineer.

Introduction

Since the operational details and features of the TRACE V SET will be described in a companion paper to this one, we will concentrate here on the philosophy and background of the programs. This package of optical design and evaluation programs for the personal computer has evolved from a beginning in 1960 on the IBM 704 computer. The objective at that time was to develop automatic lens design programs utilizing the largest computer facility in the world under one roof (United Aircraft Research Laboratories). Since the work was a new start, the author sought the advice of Dr. James Baker who was renown for his pioneering work in automatic lens design in the 1940's. His advice was to start with Herzberger's(1) new book as the basis. Herzberger organized his approach around the use of computers rather than log tables and took care to minimize and effects of round-off errors, dividing by zero, etc. The approach taken by the author has been that third order aberrations are an interesting academic aid and discussion basis, but that rigorous ray tracing is the only practical solution to the majority of design problems over the past two decades.

Aberrations

We have adopted a view of aberrations from Hamilton, that there are three types of errors. First there are errors of stigmatism; that is, all rays from a point object do not pass through an ideal point image. Second is that a flat object plane perpendicular to the optical axis is not imaged on a flat plane (field curvature). Thirdly, the magnification is not constant as a function of field angle (distortion). These are fundamental and simple to understand by even those untrained in optics.

Errors of stigmatism

If an image of a point object is not an ideal point, then a measure of its error is its size. Figure 1 shows the concept of how we examine the image size. The aperture of the optical system is divided into equal areas and rays are traced from and object point through each area until they intersect an image plane. Each ray then represents an equal amount of energy. The concentration of rays at any plane of intersection is a good representation of the concentration of energy to be expected in a real image (neglecting diffraction effects, at this point). These ray diagrams or "spot diagrams" are illustrated in Figures 2, 3, and 4. If the system were perfect, all rays would pass through one point at the focal plane. The TRACE V program automatically finds the focal plane where the RMS distance of the rays from the principal ray is minimum. We refer to two times this radius as the "image size". Our experience is that this focus is also essentially the same focus that a human observer would pick as best focus.

Figure 2 shows an on axis image in a rotationally symmetric system. This is a screen print of the image with a circle drawn by hand on the print to show how big the Airy Disc would be in this case. Figure 3 shows a similar off axis image. The printed data in the figures give size, position, scale, distance from best focus (SXY), and a title line for the plot.

Since the basic ray tracing does not deal directly with diffraction effects, we need to dicuss how we deal with them in real cases. We consider three regimes. If the spot diagram is much smaller than the Airy Disc, the system will be diffraction limited. Figures 2 and 3 are near this case. If the spot diagram is much larger than the Airy Disc, the diffraction effects will be overwhelmed by the aberrations. The third case is where they are near the same size, as in Figure 4. Here the diffraction effects play a significant part in the resolution or MTF of the image. We take this into account in the MTF program which will be discussed below.

Automatic optimization is typically used to refine a starting optical design to something that meets the requirements at hand. The number of rays traced effects the detail seen and controlled in the image and the speed of computation. In an early stage, a few rays may be enough to give rapid convergence to the region where the solution lies. Figure 5 shows some of the choices of ray patterns available. In the usual case, a plane of symmetry exists and therefore only half the pupil needs to be traced; however, a full pupil can be used when needed for non-symmetric systems. The student of Seidel aberrations will note that an on axis image using the first pattern of three meridional rays and three skew rays will evaluate indirectly the effects of third order spherical aberrations. The off axis image with this pattern will evaluate something like third and fifth order astigmatism and coma. As the design is ready for more refined detail evaluation, the 5 ray pattern is used and possibly the 7 for a final check. More rays are seldom required for design, but are used to make pretty spot diagrams for reports. The higher numbers of rays are beneficial for use in the MTF program to be described below.

When more than one color needs to be dealt with, the spectral distribution is divided into three parts or colors. The central color or wavelength represents 50% of the energy in the band and the two other wavelengths represent the outer 25% on each side of the center. TRACE V would use the 5(13) ray pattern for the central color and the 3(6) ray pattern for each of the side colors. This gives a heterochromatic image in the combined ray bundle. Such a bundle is usually adequate for the detection of longitudinal and lateral color and spherochromatism. This pattern is called for in the programing by "5 RAYS" and "3 COLORS". If more detail is needed, "7 RAYS" by "3 COLORS" can be used. These procedures cover all of the errors of stigmatism very simply and easily for the novice as well as the professional.

Vignetting

When vignetting needs to be evaluated, it is handled with a simple description. Figure 6 illustrates the possiblity of specifying two additional vignetting apertures which may encroach on the normal entrance pupil aperture at some angles. Three central obstructions can be accommodated for Cassegrain and similar systems. The data input is simple with no more than 5 apertures and spacings to enter in the most complex case; usually only two. The rays from the object point which cannot pass through the apertures are never traced to reduce waste effort. This is however a compromise, since the apertures have to be precalculated and cannot usually be used in automatic optimization, only in evaluation of a rotationally symmetric system.

Aspheric and assymetric surfaces

TRACE V is programmed to handle a conic section aspheric as simply as a sphere. It can also optimize the conic section automatically. General rotationally symmetric aspherics are handled by the usual power series expansion. Toroids and cylinders are also handled. Tilts and decentrations can be evaluated, but not optimized. Greater than 99% of the optics produced in the world today can be evaluated by this package and more than 90% can be readily designed by it.

Curvature of field and distortion

Any number of off axis angles can be evaluated, but the optimization uses only two angles in TRACE V. When using optimization, the first angle is very near on axis, but not exactly zero. This then acts as a paraxial field angle to define the effective focal length on axis and define the paraxial focal plane. The best focal point of the second field angle (which might be the edge of the field or the .707 field angle) then gives a measure of the third order curvature and distortion. This is adequate for almost all design problems, but would have to be skillfully manipulated to cover the needs of designing a photogrammetric objective where high orders of curvature and distortion must be carefully controlled.

Weighting functions

When automatic optimization is to be done, it is necessary to define the relative importance of different factors such as image size, curvature, and distortion. The philosophy of our automatic design approach is to set a goal of perfection and see if a given configuration of optics can be optimized to a performance which is acceptable for the application at hand. We weight the importance of the factors to squeeze the design in that direction. Let us take an example requirement as follows:

On axis image diameter = .001 unit maximum
Off axis image diameter = .002 unit maximum
Difference in focus from on axis to off axis angle =.004 max
Difference in off axis image position from nominal for
paraxial focal length (distortion) = .0033 unit maximum

The weight scheme used is to multiply each requirement by a weighting factor such that the product would equal 1.0 or less if the requirement were satisfied. Thus for the above example the on axis image weight would be 1000 and the off axis would be 500. The curvature weight would be 250 and the distortion weight would be 300. The optical quality part of the DEMERIT function is the sum of the squares of each of these products. If all of the requirements were just met, the demerit would be just 4.0. If this goal was met, the optimization could stop or continue as far toward perfection as the configuration would allow. If the goal could not be met with any amount of iteration, a new configuration might be tried which would possibly be more complex to correct the major limit to meeting the goal. If the goals were easily exceeded by more than was advisable to allow for production tolerances, the design configuration might be simplified to reduce number of elements and reduce cost of production.

Boundary conditions

The boundary conditions controlled by the optimization procedure in TRACE V are simple but adequate for many cases. Maximum and minimum values are set on the thicknesses of the elements and airspaces. Violations of these boundarys are checked on axis and at the aperture specified. Each violation of a boundary is multiplied by the thickness weighting specified by the designer and then squared and added to the demerit function. This gives a smooth boundary like the walls of a bathtub. As the boundary is violated the steepness goes up as the square of the violation and forces the solution toward a non-violation condition. A thin or negative thickness at the edge of a lens or airspace or at the center of a lens or airspace will be avoided by the minimum thickness boundary and weighting. Excess thicknesses can similarly be controlled.

Optimization scheme

The optimization scheme used is also simple but effective. It is related to the parabolic approximation described by Meiron(2). Each parameter to be optimized is varied by plus and minus a delta to find the first and second derivatives of the demerit function with respect to that parameter. A parabola is fit to these three points and the minimum is calculated. If the true function of the parameter was actually parabolic, the process would find the exact minimum. We find this to be a good approximation for most common cases. TRACE V is structured to allow up to 20 parameters to be varied in one iteration. However, the parameters are optimized sequencially. This is like searching for Salt Lake by travelling West or East to find the lowest point in a valley and then North and South to the lowest point along that direction. The other parameters then represent similar processes, but cannot be described in three dimensions.

This simplistic approach works satisfactorily, but is not efficient in some cases such as a long thin valley which runs at an angle to the cardinal directions. We have successfully implemented the following scheme to overcome this type of problem and others. The parameters are taken two at a time and a three dimensional elliptical parabola is fit to the five points available. The figure is then rotated about the demerit axis to a best fit. The minimum of this figure is then a two parameter version of the Meiron parabolic fit. This works well in a great variety of cases and seems to overcome some of the problems of ill-conditioned and non-orthogonal variables. We believe the procedure holds promise for the n-parameter case, but we have not yet attempted to reduce it to practice.

Modulation transfer function scheme

The modulation transfer function (MTF) has become an accepted way to specify and test resolution in imaging systems. As we discussed above, there are three realms of interest: where the image is too big or too small to need MTF evaluation, and where diffraction affects the MTF. The MTFRED program of the TRACE V set calculates the MTF and/or radial energy distribution from a bundle of rays computed and stored on disc by the TRACE program. The inclusion of diffraction effects is related to the approximation described by Smith (3). Figure 7 shows and example MTF plot with and without diffraction effects and including the Phase transfer curve.

First order computations

There are also two first order calculation programs as support tools for the basic workhorse TRACE. The program called FIRST is used to calculate the position and magnification of an object through and number of surfaces. We use this primarily to find the apparent position of a real stop as seen in object or image space (the entrance and exit pupils). The EFL program takes an entire prescription from TRACE or otherwise entered and computes the front-, back-, and effective-focal lengths. A rough diagram of the system is drawn. Figure 8 is such a diagram with the rays drawn manually from TRACE data and some "whiteout" editing.

Conclusion

We have described a simple but powerful optical design and evaluation tool which has been proved by the test of time and many users. The complexity has been kept to a minimum so that it can be easily understood, learned, and used. The sophistication that can be drawn upon is adequate to evaluate 99% of the production optics in the world today and design 90% of them. If the engineer expects to spend most of his time designing optics, we recommend the more extensive and expensive tools. For the non-career designer, the TRACE SET is a simple, economic, and handy tool which will solve most if not all of his practical optical design and evaluation problems.

References

1. Max Herzberger, Modern Geometrical Optics, Intersci. Pub.,1958
2. J. Meiron and G. Volinez, "Parabolic Approximation Method for Automatic Lens Design," JOSA 50, 207ff(1960)
3. Warren J. Smith, Modern Optical Engineering, McGraw-Hill, 318ff(1966)

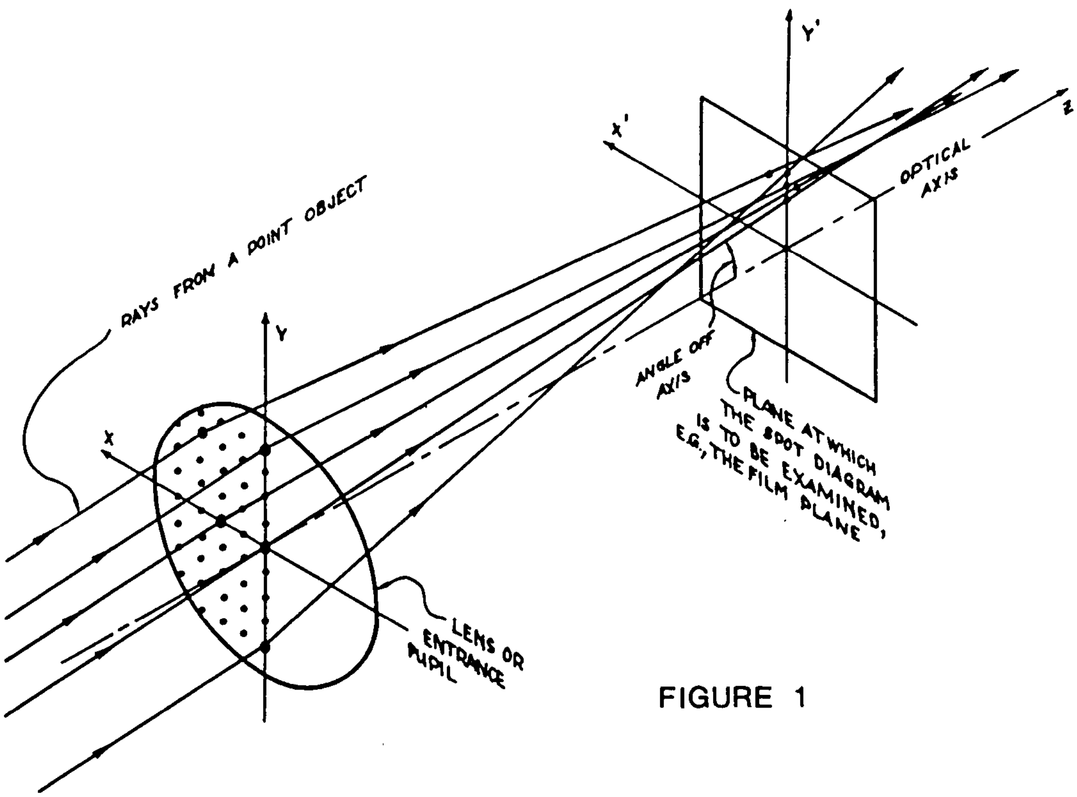

FIGURE 1

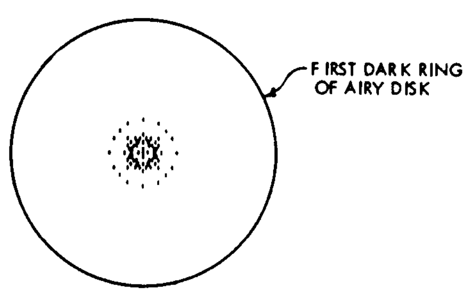


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IMAGE IN .6328 MICRON LIGHT 05-27-1985 12:36:31
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FIGURE 2
ON-AXIS IMAGE AT .6328 MICRONS

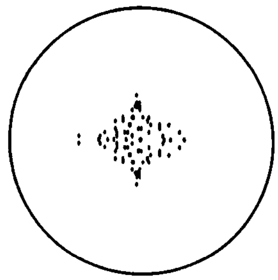

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FIGURE 3

EDGE OF FIELD AT .6328 MICRONS

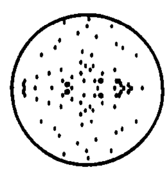

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IMAGE IN .4 MICRON LIGHT 05-27-1985 12:02:08
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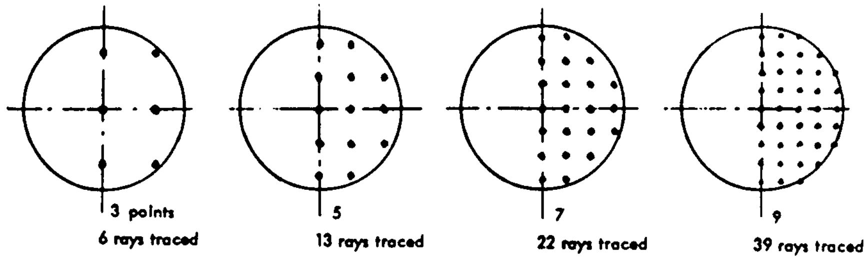
FIGURE 4

EDGE OF FIELD AT 0.4 μ

FIGURE 5 #POINTS IN MERIDIANAL FAN vs. RAY PATTERN IN APERTURE



PUPILS FOR VIGNETTING

NEAR OBJECT CASE SHOWN

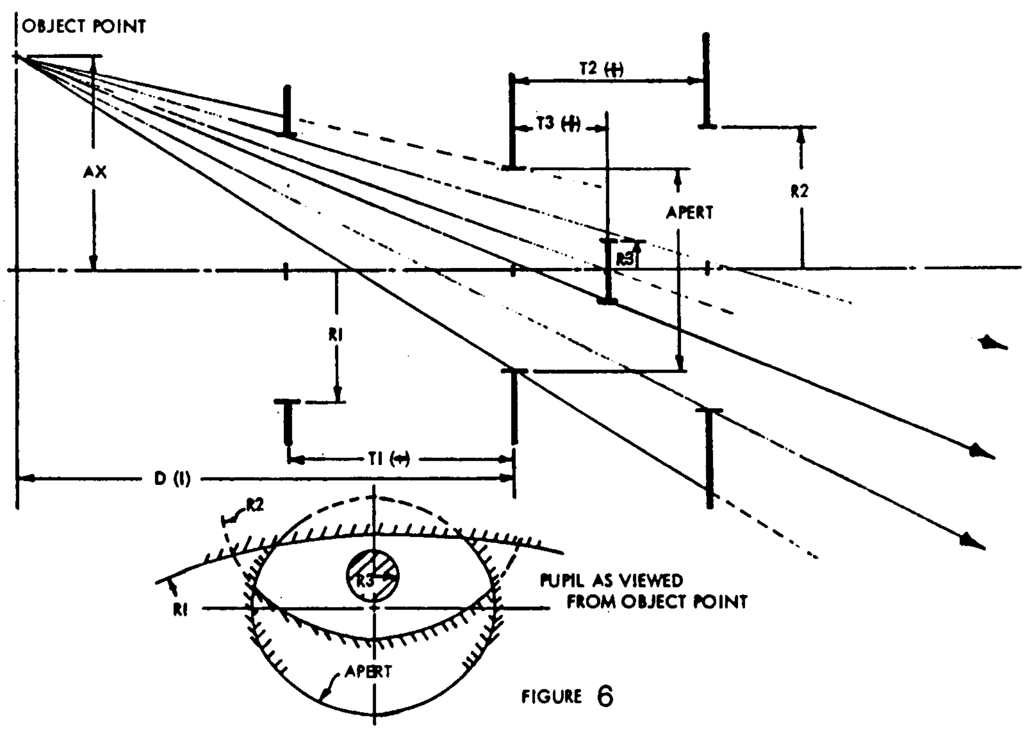


FIGURE 6

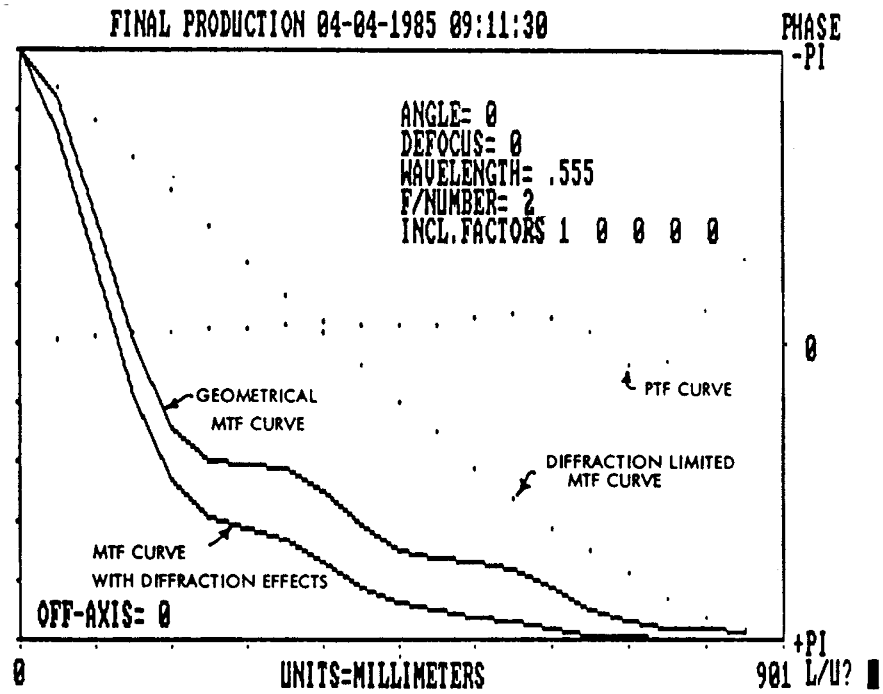


FIGURE 7

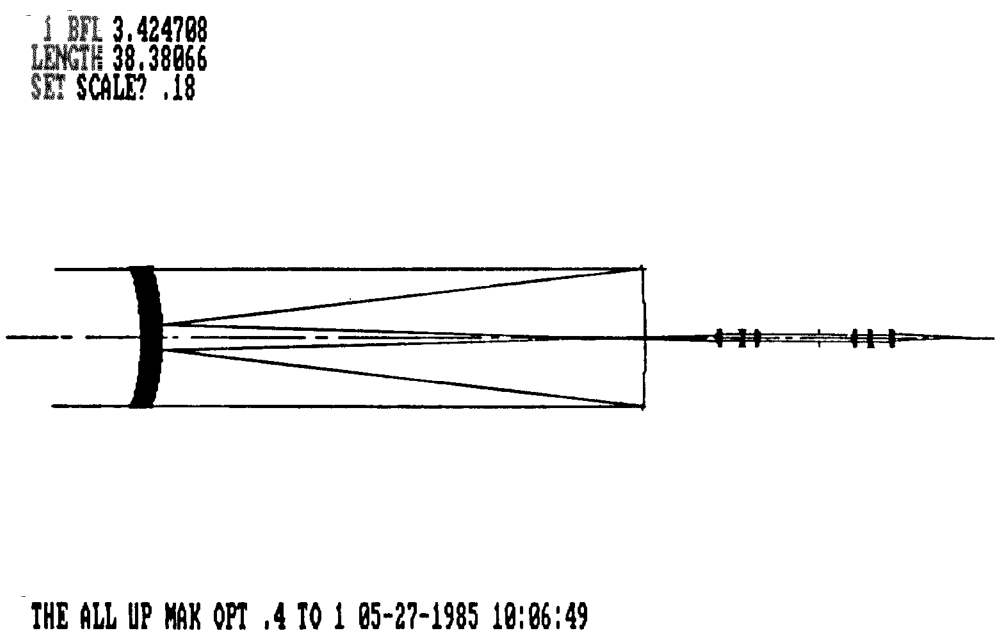


FIGURE 8
OPTICAL LAYOUT