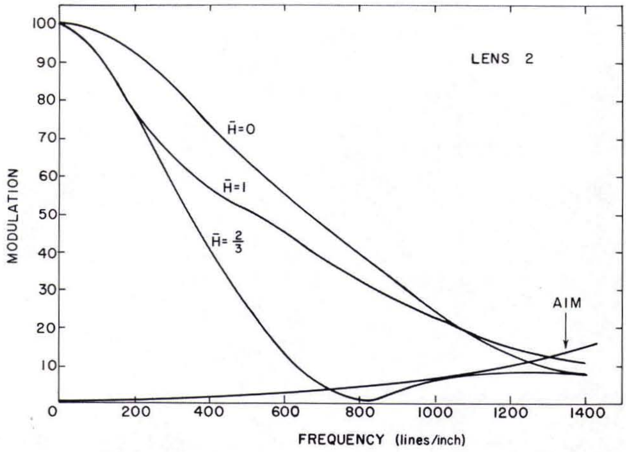

FIG. 1. Modulation transfer for Heliar $f'=24$ inches, $f/6$, 9×9-inch format.

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Optical Design and Underwater Photography

The computer has taken the guesswork out of lens design.

THE ART OF LENS DESIGN is old; lens designs were extremely well developed before the introduction of the modern high-speed computer. In spite of this, the past ten years have seen a revolution in this old and established field.[1] This paper describes some of the modern techniques used in lens design and lens making. Our present methods are compared with those in use ten years ago. Possible beneficial results are suggested for taking a complete new look at underwater lenses.

MODERN LENS DESIGN

Lens design today is based on the trigonometric tracing of rays through an optical system. Lens design a hundred years ago also depended on ray tracing. The difference is that now it takes around 0.001 second per ray surface instead of 10 or 15 minutes. Besides the increase in speed, we also can achieve two to three times the accuracy. This means that today we can take a paper design, ray trace it, and predict its performance, all in a few minutes' computing time. This just could not be done ten years ago. A designer could not in a lifetime muster up the computational help and have the time to evaluate even one lens in the way we do now. It was always necessary for him to make estimates and then have the lens made up to see how it performed. The average commercial lens was developed by arduous trial and error. A designer would make attempts and finally a sample would be put on the market. Eventually a competitor would find a way to improve on it, and after repeated re-doing, the lenses reached today's level of performance. Today we can design a lens and predict its performance with reliability. First I would like to show you how we predict the performance of a lens.

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The Evaluation Procedure

To begin with, the lens is thoroughly ray-traced. This means tracing fans of rays through the lens from several object points to their corresponding points in the image. Some modern programs trace hundreds of rays in the evaluation phase. Others trace relatively few rays but use elaborate expressions to predict the paths of intermediate rays. It is customary to evaluate the image of at least three object points. If the lens is to be used in white light, it is necessary to repeat the calculations using from three to five different wavelengths.

Abstract: *Methods for designing and evaluating lenses have undergone a startling change in the last few years. Powerful design programs are now available for the largest computing machines. It is possible to exhaustively explore alternate design approaches and then predict performance. Serious underwater research photography should warrant an updating of lenses especially designed for underwater photography. In so doing, there are possible gains in performance, and modern performance specifications would be made available. A substantial change in lens making has also occurred. Today prototypes can be made to perform as predicted. A need for a trial and error period for arriving at a practical design no longer exists.*

The next step is to compute the modulation transfer of the lens for each of the object points.[2] The results of this calculation are shown in Figure 1. The modulation transfer curve is often referred to as the sine wave contrast reduction curve. If one imagines an object consisting of a spatial sine wave of intensity distribution, we can define the contrast of the object as

$$c_0 = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

The lens will reduce the contrast to a value of c_i. The modulation is defined as c_i/c_o. These curves show how the contrast is reduced in the image formed by the lens. As an example, if the object consists of sine waves with a contrast of 1, then c_i is the modulation. The eye is capable of detecting a value of c_i equal to about 3 to 4 per cent. This means that the lens in Figure 1 should easily be able to resolve 1400 lines per inch for the curves marked $\overline{H}=1$ and $\overline{H}=0$, but at $\overline{H}=2/3$ it would resolve only around 700 lines per inch. If the lens is to be used with film, it is necessary to take into account the *AIM* curve for the film. *AIM* stands for Aerial Image Modulation. The *AIM* curve for Super XX is shown in Figure 1. The intersection of this curve with the modulation curves provides the lens-film cutoff frequencies.

The ray tracing and calculations involved in making an accurate prediction of the performance of a lens require a horrendous amount of computing. I do not believe that one could collect, train, and organize enough people to make this calculation, if they used desk calculators. It would take such a massive organization that the problems of checking, dealing with human-relations problems, etc., would simply swamp the effort. Today this type of calculation can be done in a few minutes on an IBM 7094, and the remarkable thing is that it can also be run on the CDC 3600 or the Univac 1108 with precisely the same results.

Tables 1 and 2 show comparisons between predicted performance and the performance obtained from the made-up lens. Table 1 shows the predicted and measured performance for a 24-inch focal length $f/3.5$ lens. The lens was tested on Eastman 4404 film. The

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TABLE 1

COMPARISON BETWEEN PREDICTED PERFORMANCE CHARACTERISTICS AND THOSE ACTUALLY OBTAINED FOR A LENS HAVING 24-INCH FOCAL LENGTH, $f/3.5$, 4404 FILM, AND $2\frac{1}{4}\times2\frac{1}{4}$-INCH FORMAT

c_0	*1*	*0.33*
Predicted Axial Resolution	270	150
Measured Axial Resolution	265	140

TABLE 2

COMPARISON BETWEEN PREDICTED PERFORMANCE CHARACTERISTICS AND THOSE ACTUALLY OBTAINED FOR A LENS HAVING A 3-INCH FOCAL LENGTH, $f/4.5$, PLUS X FILM, AND $4\frac{1}{2}\times4\frac{1}{2}$-INCH FORMAT

Field Angle	*Predicted H. C. Resolution*	
	Using 8% Cutoff Modulation	*Using AIM Curve of Film*
0°	61	57
30°	65	63
40°	47	47
45°	28	29
AWAR	58	56.5

Field Angle	*Measured H. C. Resolution*		
	Lens #1	*Lens #2*	*Lens #3*
0°	63	57	57
15°	61	64	68
30°	58	69	61
37.5°	57	51	53.5
45°	26	27	26
AWAR	55.6	56.6	55.0

two columns show the predicted and measured performance for objects of contrast $c_0 = 1$ and 0.33. Table II shows the predictions in the top part of the table and the measured resolution for three sample lenses in the lower part. The predictions were made in two ways. In the left hand column the lens modulation was multiplied by the film modulation and an 8-per cent level was used to predict the cut off. In the right hand column the resolutions were predicted using the *AIM* curve.

AUTOMATIC DESIGN

Since we are now able to evaluate paper designs with relative ease, we are also able to arrive at new designs more rapidly. There are today several existing programs which can design a lens automatically to a certain extent.[3] This is done essentially by systematically changing all the variables to determine how the aberrations change. By solving large sets of equations it is possible to solve for a new set of parameters to provide an improved image. These programs have been publicized as being so completely automatic that anyone can use them and design a lens. This is simply not true. It takes a skilled person to use the programs and there are no cut-and-dried solutions.

Several of us in the field have had a few contests to compare designs obtained on our programs. The lens shown in Figure 2 was used as a sample problem. We all attempted to design the best lens we could to the same requirements. Figure 3 shows the evaluation of the first design submitted in the contest. Figure 4 shows the evaluation of the third design. Figure 5 shows the evaluation of the eighth design. The interesting thing is that each design submitted was better than the previous ones. It made a big difference when the designers knew what they had to beat.

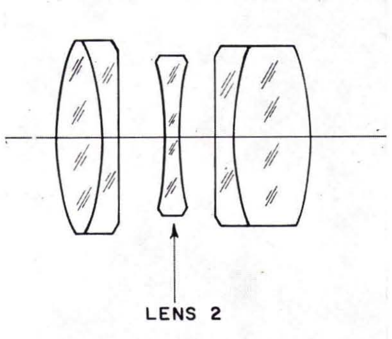

FIG. 2. Type of lens used in design study.

SUMMARY

The computer has taken the guesswork out of lens design. The automatic programs enable designers to explore many more possibilities. The field of lens design has become much more attractive to capable and imaginative people. Today we can take almost any existing lens and improve on its quality or find ways to reduce its cost with the same quality.

APPLICATION TO UNDERWATER PHOTOGRAPHY

For underwater photography it has been customary to use standard photographic

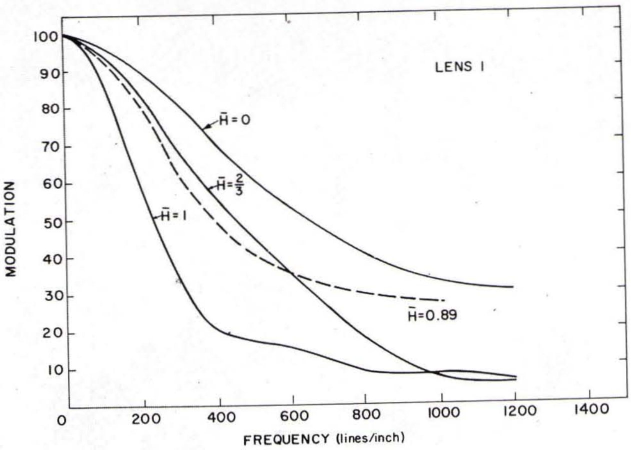

FIG. 3. The first attempt to improve the design.

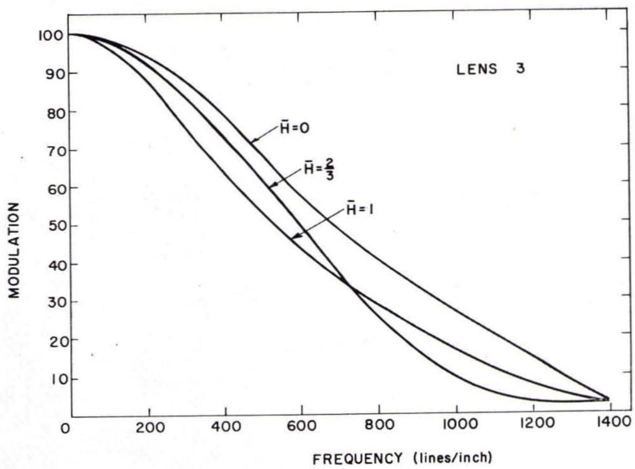

FIG. 4. The third redesign of the lens.

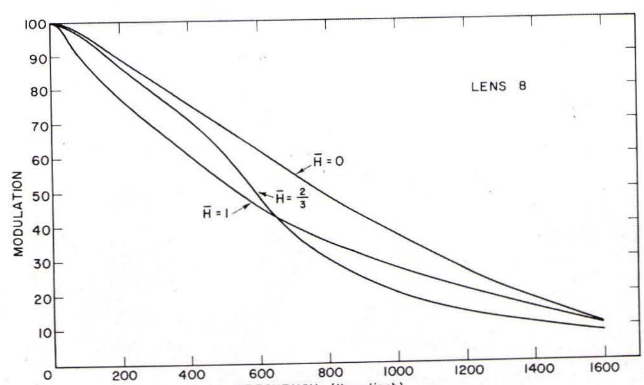

FIG. 5. The eighth redesign of the lens.

lenses and to introduce plane windows in front of the lens. This procedure is satisfactory until one tries to cover an appreciable field. The plane window then introduces lateral color. Several designs have utilized attachments to correct for this. These are usually compromise solutions. It would appear that one should look into designing a complete new set of lenses specifically for underwater photography. I designed one of these lenses for Dr. H. E. Edgerton several years ago,[4] before the days of the really large computers. I am sure this lens could now be improved in aperture and field of view. It is certainly true that a new series of lenses would be expensive to develop, but today it would be wise for someone to lay out a few paper designs. In so doing, one could look into the feasibility of lenses with a relatively small entrance window for deep-water photography. The color of the water might affect the type of color correction needed. For extreme close-up shots one should also correct for axial color.

References

1. Hopkins, R. E., Re-Evaluation of the Problem of Optical Design, *Journal of the Optical Society of America 52* (11) 1218–1222 (1962).
2. Smith, W. J., Modern Optical Engineering, McGraw-Hill Book Co., 476 pp. (1966).
3. Feder, D. P., Automatic Optical Design, *Applied Optics 2* (12) 1209–1226 (1963)
4. Hopkins, R. E. and H. E. Edgerton, Lenses for Underwater Photography, *Deep-Sea Research 8* (3 & 4) 312–319 (1961).