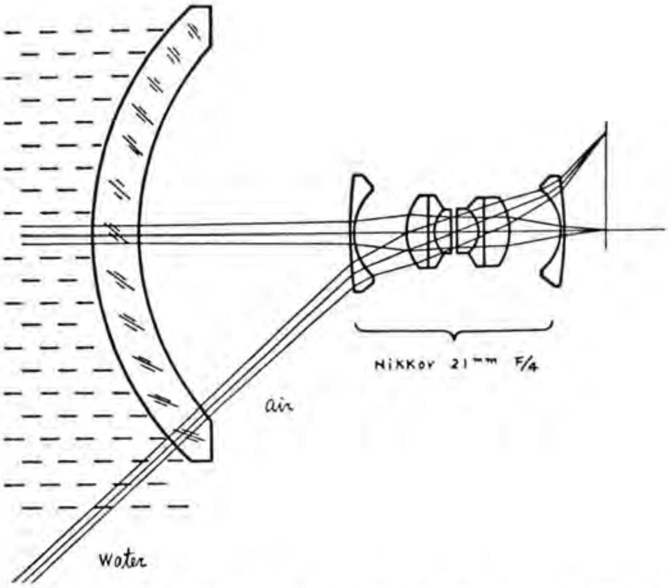

FRONTISPIECE. System 5: The Nikkor 21 mm. $f/4$ underwater objective lens using concentric spherical surfaces for the air-water window.

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On Designing Underwater Camera Lenses

It is not advantageous to attempt to design a lens for use both in water and air.

(*Abstract on next page*)

INTRODUCTION

IN UNDERWATER PHOTOGRAPHY we encounter various difficulties. A camera to be used in the water requires a different construction from one to be used in the air. Aside from the mechanical considerations such as water-tightness, there are a lot of additional optical problems, such as absorption, scattering and transparency of water. This may be solved, to some extent, by bringing the camera closer to the underwater subject using a wideangle lens, or by employing an illuminating device. Actually this is the method currently in use. Here we shall consider some points on the optical system inside the camera for underwater photography.

For any camera, and whatever optical system is employed, i.e., taking photographs one by one, or consecutively for television or movies; the conditions under which the camera is used in the water will always be the same. Therefore, in this article we shall not touch on the types of cameras for underwater.

It is obvious that the difference between the underwater photography and air photography lenses is based upon the fact that the subject being photographed is either in the water or in the air. However, if both the lens and sensitive material could be immersed in

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* Presented at the Annual Convention of the American Society of Photogrammetry, Washington, D. C., March 1967 as one of several papers on underwater photography, all contained in this issue. Edited by Mr. Stuart Held, Special Optics Sales Manager, EPOI, Photo Technical Products Div., 623 Stewart Ave., Garden City, N. Y. 11533

water, the problems would be simplified. Thus, the refractive indices both in the subject and in the image area become the same and we need only to consider the refractive index of air as replaced by that of water. Usually, a lens immersed in the water has a weaker refracting power than that in the air, and shows different aberrations. However, no substantial change will take place in the function of the lens. Therefore, any underwater lens to be used this way needs only to be corrected the same way as lens for air photography. Several years ago, a trial combination of an ordinary lens and light sensitive material was made by the Konan Camera Institute for underwater photography, where neither water-proofing nor water pressure was considered. The construction was extremely simple. The institute realized that even though the film is immersed in seawater for several days, the film is usable enough for making a picture after it is washed with fresh water and developed. However, this is an exceptional case.

In general, the underwater camera is supplied with a piece of window glass or the like for water-tightness and is designed so as to produce an image in the air contained within the camera. Then, the refraction of light takes place at the boundary surface between the water and the air, thus giving rise to various problems. Therefore in designing a lens system the difference of refractive index between the subject and image area should be considered. As an example, the oil-immersion objective lens for a microscope. Until now, for most underwater lenses, owing to many difficulties encountered in taking a picture, no great importance has been placed on the image characteristics. In most cases, in underwater photography, the lens designed for air photography is applied without any alteration.

Although several studies have been published on the methods to eliminate the deterioration of the image due to water in the subject area, most of them have been made only on the basis of some fundamental and approximate formula. There are actually only a few exacting optical systems developed exclusively for underwater use.

It is a well known fact that in designing a lens of excellent image characteristics; it is necessary to carry out the so-called "optical ray tracing" method. In other words, the elemental arrangement of a lens system is not sufficient. In the last few years equipment for swimming, picture taking, illumination, etc. has undergone a marked development, whereas the lens for underwater photography has been neglected.

ABSTRACT: *Many types of lenses have been designed for photographic use under standard atmospheric conditions, but only very few lenses have been built exclusively for underwater photography. In many cases those that have been designed for standard use are applicable to underwater photography without any alteration. The Nippon firm is the manufacturers of the lenses for our underwater camera* NIKONOS. *These lenses have remarkable differences in characteristics from atmospheric photographic lenses. In designing such lenses, the differences to be considered were theoretically examined and all the conceivable types of underwater lenses were systematically classified. Several examples of the underwater lenses are in current manufacture, and some interesting types of lenses can be expected in the future.*

We have closely studied the problems of developing proper underwater lenses. Below we shall discuss some problems and suggest different types of lenses for underwater photography, based on our experience in designing underwater lens systems which will perform as satisfactorily as the lens systems for air photography.

PROBLEMS ON UNDERWATER LENSES

Looking at a subject in the water from above through the air, it appears as if the subject were closer to the surface of the water than it actually is. If we observe it slantwise to the surface of water, the edge of the subject in the water is accompanied by color fringes. This is attributed to the fact that the light coming from the subject undergoes refraction as well as color dispersion at the boundary surface between water and air. To such a phenomenon, the law of refraction is applied, whereby the refracting angle θ_a as against the normal angle is always larger than the incidence angle θ_w in the water.

Furthermore, this refracting angle, varying with the wavelength (color) of light, brings about color dispersion (Figure 1).

If the picture of a subject in water is taken, using a photographic lens which is well corrected for use in the air, the subject will be reproduced as a photograph, the same as seen by the eye.

If a distorted and colored image of the subject as seen by the eye were to be taken as real, nothing would be said about the underwater lens. Problems arise though in the fact that the image of the subject the eye sees is not the same as the actual image of the subject. The first problem is that the flat surface appears as a curved one and distorted in its shape. In order that the subject y and its image y' are in an analogous relation to each other, the dimensional ratio is to be constant between them. This means that it is necessary to fulfill the following equation (Figure 2):

$$\frac{y'}{y} = c\,\frac{\tan\theta'}{\tan\theta} = \text{Constant}$$

However, according to the law of refraction, as $(\sin\theta'/\sin\theta)$ is equal to n_w and constant, $(\tan\theta'/\tan\theta)$ is not constant, but will be different depending on the value of θ.

For this reason, the larger the incidence angle θ, the more distorted the image. For one who stands on the edge of a swimming pool and observes the flat bottom of the pool, the farther the subject, the closer the subject will seem to approach the water surface and be more distorted. This, if taken photographically, will show a different form from the actual one on the figure, caused by the lens aberrations, the so-called distortion and the curvature of the image plane.

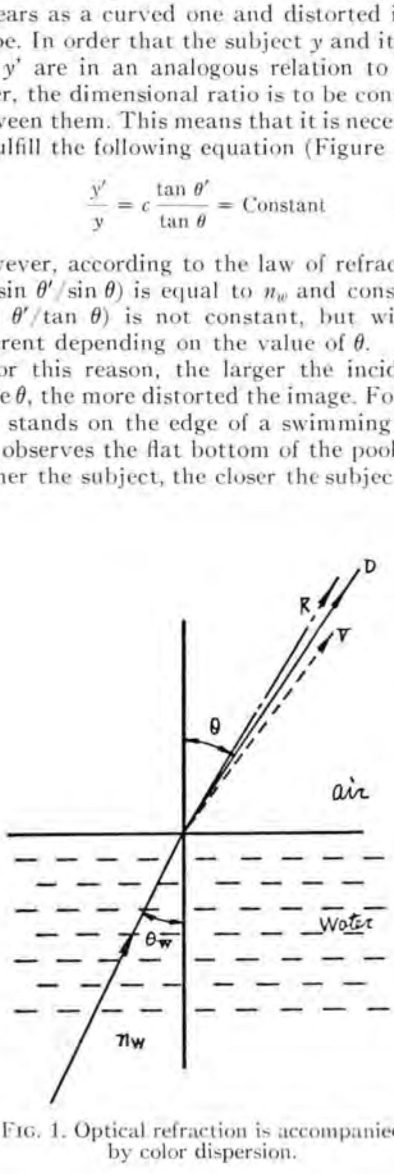

FIG. 1. Optical refraction is accompanied by color dispersion.

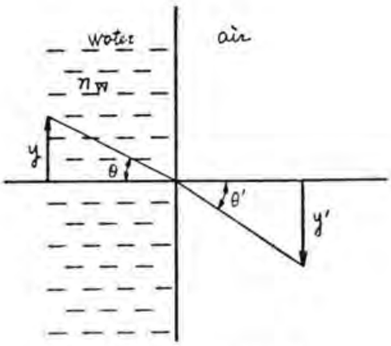

FIG. 2. The law of refraction.

The second problem is the occurrence of color fringes on the edge of the image of the subject caused by the dispersion of light. In color photography the fringes result in colored smudges which appear more markedly on the edge of the image. As the image locates farther from the center of the picture, a red-colored smudge on the inside and a blue-colored smudge on the outside will appear. In black-and-white photography, the outline of the image will be blurred to an extent of the width of the color fringes. From the view point of lens design this occurrence corresponds to the chromatic aberrations which produce the same result as using a lens with its color aberrations not corrected, which is an unfavorable condition causing a lowering of the resolution in the photograph. The actual subject has no such color fringe.

The third problem is concerned with the fact that even using a wide-angle lens, the underwater picture area covered by this lens is narrowed to a noticeable degree, and the angular field of the lens is restricted. This will be easily understood if we consider the refracting angle in the air which becomes larger than the incidence angle in the water according to the law of refraction.

In practice, however, this problem is quite a difficult one to solve. As mentioned previously, as the transparency of water is not always good, it will be necessary to use artificial illumination at a great depth, or one must approach the subject as closely as possible. However, to come closer to the subject without narrowing the picture area, a lens having a field angle as wide as possible is necessary.

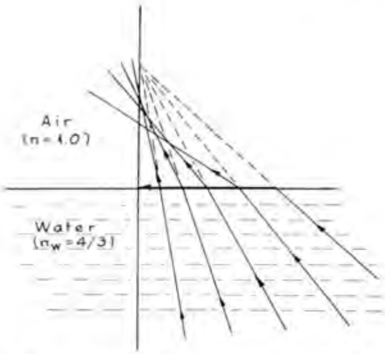

FIG. 3. Convergent rays at various angles after refraction do not intersect at a common point.

Actually, wide-angle lenses are desirable for use in underwater photography.

On the other hand, we must remember that the wider the field angle of the lens, the more marked will be chromatic aberrations, distortion, and image plane curvature. This will cause much more deterioration of the picture quality. Frequently we encounter underwater pictures in which the image quality is somewhat poorer at the circumference of the picture than at the center.

If we apply a lens designed for air photography to underwater use, some deterioration of the image unavoidably takes place.

ANALYSIS OF THE ABERRATIONS CAUSED BY THE WATER-AIR SURFACE

Until now, geometrical optical analysis of such problems as above were often made, and many papers on the solutions have been published. Among these papers is one by Prof. Alexandre Ivanoff in *Revue D'optique*[1], which is excellent. However, like many other papers, it treats merely the analysis on the basis of the elemental formulas of geometrical optics in the paraxial region. It is obvious that, in practice, it does not suffice to examine the lens system only in the Gaussian region.

Furthermore, as far as a wide-angle lens is concerned, the Seidel's region is still insufficient. If we consider the present situation where most lenses, including photographic lenses, are generally designed through *ray tracing*, the lens for underwater photography cannot be an exception. In fact the lens, if used underwater, will give rise to extremely large aberrations at the boundary surface between water and air, and the light bundle converging to a point in the water will not perform the same as in air. See drawing as shown in (Figure 3). This shows how the optical theory is imperfect so far as it stands only on the assumption that the light bundle can converge to a point on the basis of the elementary formulas.

Therefore, we should analyze the problems concerning the occurrence of such aberrations on the boundary surface between water and air with the aid of the regular designing method for optical systems.

In general, the lens for underwater use, has a plane-parallel glass window in front. Taking the refractive indices of water, glass, and air as n_w, n_g and n_a, respectively, and their incidence angles of light rays against the normal as θ_w, θ_g, and θ_a, respectively, the following equation will be obtained according to the law of refraction (See Figure 4):

$$n_w \sin\theta_w = n_g \sin\theta_g = n_a \sin\theta_a. \qquad (1)$$

Therefore, the result will be the same as the case where water and air come into direct contact without any intermediate glass layer. In fact, as long as the subject is at the infinity distance, the presence of a glass has no influence to the aberrations. Even though the subject is at a finite distance, as long as it is relatively far distant, and the thickness of glass is thin in relation to the distance, the glass can be neglected. Even though a filter is attached to an air lens, the change of the image characteristics may be practically neglected. Of course, if necessary we can correct the aberrations taking into consideration the thickness of glass by ray tracing.

To simplify the problems, we assume that the subject in the water is at the infinity distance. Then, the refractive index n_a in the air

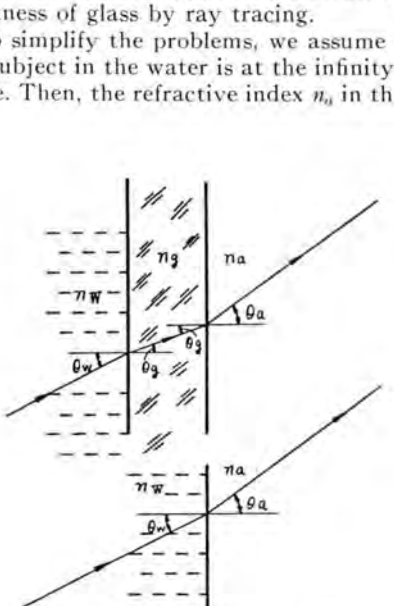

FIG. 4. A plane-parallel glass window does not influence the aberrations.

being equal to 1, the above Equation 1 of refraction will be

$$n_w \sin \theta_w = \sin \theta_a. \tag{2}$$

On the other hand, the refractive index n_w depends on the color of light. The index for red light n_{wr} is different from the refractive index for violet light n_{wv}. As a result, the refractive angle in the air θ_{ar} and θ_{av}, each for red and voilet light respectively, will differ from each other, as clearly seen from the following equations:

$$\begin{aligned} n_{wr} \sin \theta_w &= \sin \theta_{ar} \\ n_{wv} \sin \theta_w &= \sin \theta_{av}. \end{aligned} \tag{3}$$

If these rays are imaged by a lens and chromatically corrected for the air, the incidence angle θ_a will vary with color, the image point being divided into two points, each located as v and r points on the focal plane (Figure 5). With regard to the other colors, each respective image point is produced at an intermediate location. The result is that the image point spreads over from v to r, covering a spectrum, thus producing a chromatic aberration. From the Equation 3 it follows

$$\sin \theta_{av} - \sin \theta_{ar} = (n_{wv} - n_{wr}) \sin \theta_w. \tag{4}$$

This difference is proportional to the sine of the incidence angle θ_w in the water. The larger the incidence angle, the larger the chromatic aberration. To eliminate this displacement of color, it is necessary to provide the photographic lens with a property which enables removal of such displacements of r and v. Of course, it is not yet known whether such a lens can be obtained or not. It is certain, however, that no good result can be attained only by combining lenses whose chromatic aberrations have been corrected. Thus, we understand that for all the photographic lenses being corrected for color aberrations for air use (meaning lenses used without any alteration), it will be necessary to provide the glass window with such a property as that enabling $\theta_{ar} = \theta_{av}$.

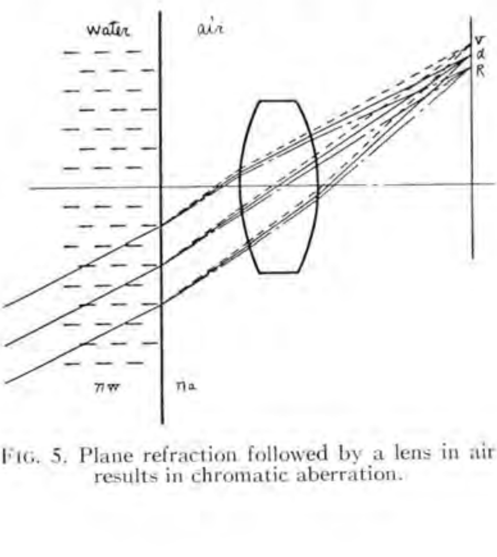

FIG. 5. Plane refraction followed by a lens in air results in chromatic aberration.

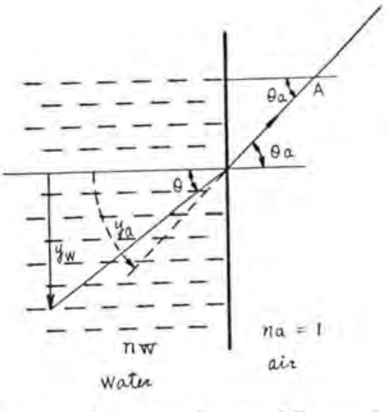

FIG. 6. Refraction gives rise to a difference in size.

A subject in the water will seem distorted if viewed through the surface of water or through a plane glass window pane. This is because the apparent size of the subject in the water is not equal to the actual size. Looking at a subject y_w in the water from a position of A, the light rays coming from the subject at an angle of θ_w in the water will bend to the direction of θ_a. Then, the apparent image y_a of the subject will be seen in the direction θ_a (Figure 6). Provided $\tan \theta_w$ is proportional to $\tan \theta_a$ in this case, the apparent size will be analogous to the actual. That is,

$$\frac{\tan \theta_a}{\tan \theta_w} = \frac{\dfrac{\sin \theta_a}{\cos \theta_a}}{\dfrac{\sin \theta_w}{\cos \theta_w}} = \frac{\sin \theta_a}{\sin \theta_w} \cdot \frac{\cos \theta_w}{\cos \theta_a}.$$

Taking into account the law of refraction, that is, Equation 2,

$$\frac{\tan \theta_a}{\tan \theta_w} = n_w \frac{\cos \theta_w}{\cos \theta_a} \qquad (\theta_w < \theta_a) \tag{5}$$

n_w is constant but θ_w and θ_a are changed by the Equation 2. Therefore, $(\cos \theta_w / \cos \theta_a)$ is not constant and $\tan \theta_a$ is not proportional to $\tan \theta_w$. This means that if a subject in the water is looked at from the air, the apparent size is changed by θ_a (or θ_w) so that it is distorted in proportion to $(\cos \theta_w / \cos \theta_a)$. If we take a picture of a subject covering the angle θ_a in the air from the position A, using a photographic lens which is corrected for its distortion, the size y of its image will be

$$y = c \tan \theta_a \qquad c = \text{Constant}. \tag{6}$$

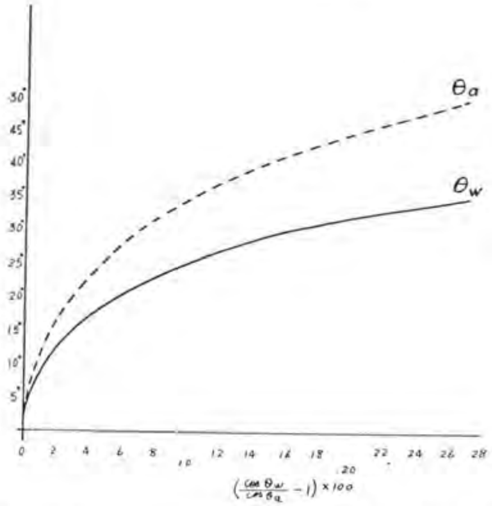

FIG. 7. Percentage increase in size varies with the angle off axis.

(If the subject is at an infinite distance, c will be equal to the focal length of the lens.)

If, using the same lens, we take a picture of a subject in the water with an incidence angle of θ_w, the image size will be obtained as below from the Equation 5

$$y = cn_w \tan\theta_w \frac{\cos\theta_w}{\cos\theta_a}. \qquad (7)$$

On the other hand, between θ_w and θ_a there is a refractive relation such as represented by the Equation 2 and $\theta_w < \theta_a$ at all times, so that

$$(\cos\theta_w/\cos\theta_a) > 1 \qquad (8)$$

(If $\theta_w = 0$, $\theta_a = 0$, and $\cos\theta_w/\cos\theta_a = 1$). Whatever the size θ_w may be, if we assume that $(\cos\theta_w/\cos\theta_a) = 1$, and the image size in that case is y_0, Equation 7 will be

$$y_0 = cn_w \tan\theta_w. \qquad (9)$$

That is, the image size becomes analogous to the subject size. If we take this condition as the requirement for an ideal image, the actual image size involves a difference of y-y_0. This difference, expressed in terms of percentage against the ideal image size y_0, is termed the distortion of the lens:

$$\text{Distortion} = \frac{y - y_0}{y_0} \times 100$$

$$= \left(\frac{\cos\theta_w}{\cos\theta_a} - 1\right) \times 100.$$

Provided θ_w has a value,

$$\frac{\cos\theta_w}{\cos\theta_0} > 1, \quad \text{or}$$

$$\frac{\cos\theta_m}{\cos\theta_a} - 1 > 0$$

Therefore, as long as a plane-parallel window pane is used, the distortion takes a plus sign. Figure 7 shows the relation between θ_w and θ_a and the amount of distortion where $n_w = 1.3331$. If an underwater photograph with no distortion is required, it will be necessary to combine a photographic lens producing a minus distortion which compensates the above distortion taking place on the boundary surface between water and air. The alternative is to devise for a glass window a contrivance which prevents the boundary surface from causing the distortion.

As mentioned above, the incident angle θ_w in the water is changed to the refracting angle θ_a in the air. Then, if we use a photographic lens with an angular field of $2\theta_a$ (Figure 8), we can cover the angle $2\theta_w$. To make this matter clear, take the reciprocal of Equation 5:

$$\frac{\tan\theta_w}{\tan\theta_a} = \frac{1}{n_w} \cdot \frac{\cos\theta_a}{\cos\theta_w} \qquad (5')$$

where $n_w > 1$, therefore $1/n_w < 1$ and $\theta_a \geqq \theta_w$. As a result, $\cos\theta_a/\cos\theta_w \leqq 1$. Consequently $(\tan\theta_w/\tan\theta_a) < (1/n_w)$ at all times.

The possible angular field in water will then be quite narrow as compared to that of the photographic lens. To cover the underwater picture angle equal to the nominal picture angle of the photographic lens, it will be necessary to add an optical system which holds the incidence angle in the water equal to the refracting angle in the air, or to change the plane boundary surface to a properly powered spherical one (Figure 9). For this purpose one may use a concave lens which keeps the refracting angle equal to the incidence angle, or a telescopic system of a power as large as $(1/n_w)\cdot(\cos\theta_a/\cos\theta_w)$ times may be inserted.

Furthermore, if we make the boundary surface itself spherical with its center coincident with the frontal principal point of the photographic lens, the light rays passing through

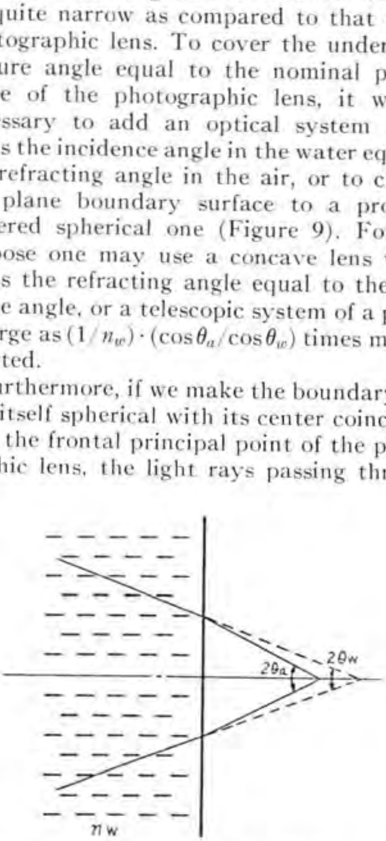

FIG. 8. The angular field of a lens is effectively narrowed if used in water.

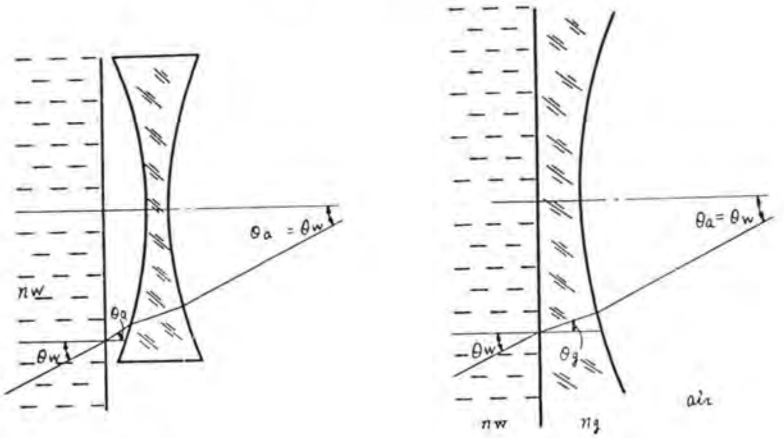

FIG. 9. A lens element may be added to offset the narrowing of the angular field.

the center of the sphere will undergo no refraction, keeping the incidence angle normal. Thus the field angle remains unchanged, resulting in no occurrence of chromatic aberrations or distortion. This method will be most desirable as long as the photographic lens for air use is applied.

However, in view of the fact that in this case a bending of the subject plane into a concentric spherical surface may be unavoidable under the influence of the spherical surface, it will be preferable to compensate for such a defect (Figure 10) by making the photographic lens itself produce a proper curvature of image plane.

CONSTRUCTIONS AND DESIGNS OF LENSES USED EXCLUSIVELY FOR UNDERWATER PHOTOGRAPHY

Considering the above, let us examine a few constructed practical examples of lenses that the Nippon firm has exclusively designed for underwater photography.

A complete optical system divided into components may not always be appropriate. However, for convenience we like to classify the lenses used for underwater photography into five groups according to the window glass in contact with water or to the type of lens as follows.

1. LENS SYSTEM WITH A PLANE-PARALLEL GLASS IN FRONT

The most generally used underwater lenses belong to this group. In this lens system, the field angle covered is reduced to about 3/4, compared with that covered in the air. As clearly seen from the previous description, if the lens covers only a narrow angle (θ_a is small), and $\cos \theta_w / \cos \theta_a$ is regarded as equal to 1, distortion will not be a question. Chromatic aberrations will also be neglible, because of the small difference of θ_w from θ_a. However, this difference should be limited to $\theta_a < 10°$, considering the aberrations generally permitted in photographic lenses (the field angle of the photographic lens is $2\theta_a < 20°$).

For this reason, this type can be used without much difficulty for a movie lens which has a comparatively narrow angular field. If, however, a larger field angle than 20° is required, combining a lens having a distortion of ($\cos \theta_a / \cos \theta_w$) with the master lens is recommended. For example, if we use a convex meniscus type (Figure 11) such as for a presbyopic eye lens, with its convex surface turned toward the image behind the aperture diaphragm, no distortion will arise. In this case it is advantageous to use a single convex lens, one with a power to compensate the chromatic aberrations caused by the glass window. However, as this lens will produce an extremely dark image, it is recommended to use the rear half of a symmetrical type lens such as a Double-Protar or Orthometer, etc., with its front half removed. Because the nu-

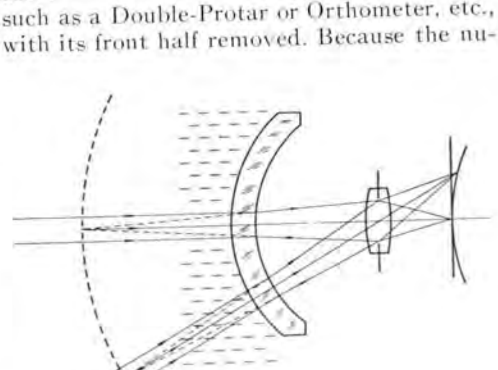

FIG. 10. The front element with the proper curvature can be used as the glass window.

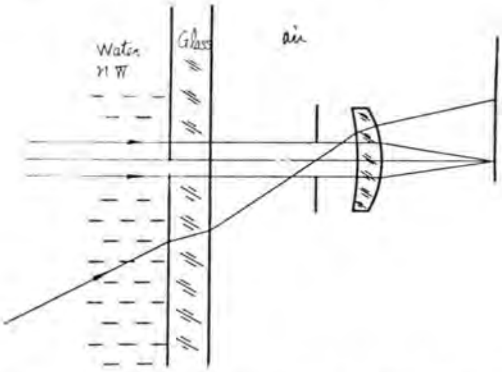

FIG. 11. System 1: A meniscus lens with a plane-parallel window.

merical aperture is reduced to a half, a slightly dark lens system may result. As the distortion can be kept to 2 per cent or so, and the astigmatism is well corrected, a wide-angle lens with a field angle of 60° or larger can be obtained in the air. In this instance, as a lens designed for air photography will produce chromatic aberrations, it is necessary to change the types of glass to compensate for the difference of image size depending on the color.

2. LENS SYSTEM USING AN ACHROMATIC PLANE PARALLEL GLASS WINDOW

Two types of glass cemented together to form a plano-parallel plate (Figure 12) will compensate for the difference of the refractive index according to color. In order to give this window pane no refractive power, it will be necessary for this glass to be a combination of two types of glass of the same refractive index but of different color dispersions. If we choose a proper curvature for the cemented surface, making θ_{ar} equal to θ_{av}, a lens of conventional type will be usable as the master lens. Therefore, this glass will permit more freedom of design as compared to the previous System 1. If some distortion is permissible, quite a sharp image may be obtained because no color aberration arises. Furthermore, the distortion will be corrected if the same lens system as that System 1 is combined; thus it will be possible to achieve a proper wide-angle underwater lens although it will produce a somewhat dark image (Figure 13). The system incorporating this type of window has been published in *Journal of the Optical Society of America* 1955[2] and in the same year we applied it to the window of the *Nikon Marine*. However there is no example of the window which also corrects the distortion.

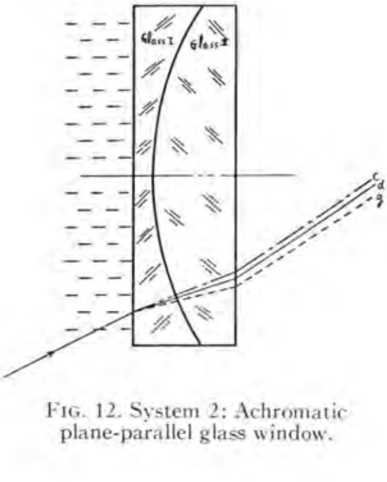

FIG. 12. System 2: Achromatic plane-parallel glass window.

A good image with this simple lens system may be expected; nevertheless a limited field angle in the water compared to that in the air will remain a weak point.

3. LENS SYSTEM USING A CONCAVE LENS FOR A WATER-TIGHT WINDOW

To prevent the field angle θ_w in the water from being θ_a in the air, there is a method in which we place a concave lens on the boundary surface to give rise to a divergence as large as $(\theta_a\text{-}\theta_w)$ (Figure 14). In this case, if this concave lens can do the duty of a glass window, there will be no necessity for providing an independent window. However, because of the boundary surface between water and air, a distortion corresponding to $(\cos\theta_w/\cos\theta_a)>1$ takes place as a result of the Equation 8. It will be necessary to have the concave lens produce the opposite distortion as large as $(\cos\theta_a/\cos\theta_w)<1$. Otherwise, compensation by means of the master lens will be required. Fortunately, the ordinary concave lens has a distortion less than 1. By properly changing its bend, it will be possible to make the distortion approximately equal to the value $(\cos\theta_a/\cos\theta_w)<1$.

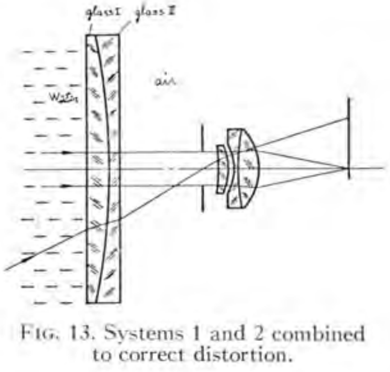

FIG. 13. Systems 1 and 2 combined to correct distortion.

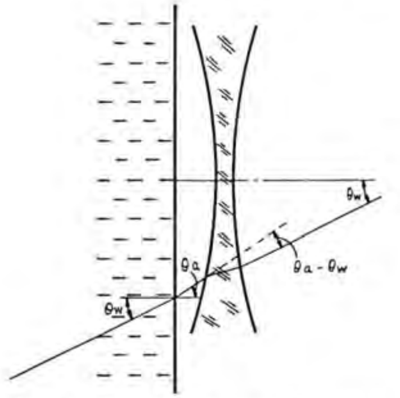

FIG. 14. System 3: Concave lens as a water-tight window.

Furthermore, because the chromatic aberrations caused by the boundary surface between water and air have an opposite sign to those caused by a concave lens, such aberrations can be compensated to some extent by choosing appropriate types of glass. Thus, if both the distortion and the chromatic aberrations are compensated, the conventional lens designed for air photography can be used as a master lens, with the possibility of achieving a lens system of large aperture and angular field. However, owing to the characteristic of a concave lens which bends the image surface in the plus direction, choice of a master lens which bends the image surface in the opposite or minus direction is recommended. The U. W. (Underwater) lens *Nikkor* 28 mm. $f/3.5$ has been designed on the basis of this conception.

A perfect underwater lens is one in which other aberrations are additionally corrected by ray tracing to the same degree as those of the lens for air photography (Figure 15, Table 1). However, taking into account the concave lens used as the window glass, a slight difference cannot be avoided in the picture angle θ_a of the master lens from the underwater picture angle θ_w. Consequently, if this lens is used in the air, some aberrations will unavoidably remain, giving poor results. Therefore it cannot be used as a perfect lens for air photography even though the concave lens is removed.

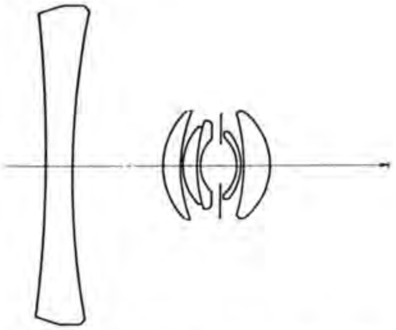

FIG. 15. An example of an ideal lens for photography in air.

4. LENS SYSTEM IN COMBINATION WITH A TELESCOPE SYSTEM

The boundary surface between water and air causes a narrowing of the field angle θ_w in the water in comparison to θ_a in the air as expressed in the proportion below:

$$\tan\theta_w = \frac{1}{n_w}\cdot\frac{\cos\theta_a}{\cos\theta_w}\tan\theta_a.$$

Consequently, it will be obvious that by attaching a telescope system with a magnifying power of $(1/n_w)\cdot(\cos\theta_w/\cos\theta_a)$, the picture angle in the water will be maintained. This means that when the telescope system has a

TABLE 1

	Nikkor 28 mm. f/3.5			*UW Nikkor 28 mm. f/3.5*
Aberrations on the circle 43 mm in diameter	*In air*	*In water*		*In water*
		Plane glass window	*Achromatic plane glass window*	
Δy_g	+0.013	+0.224	+0.160	−0.010
Δy_c	−0.001	−0.053	−0.041	−0.010
Distortion	−0.5	+11.3	+11.3	+0.3
Picture angle (2θ)	74°	53.6°	53.6°	59°

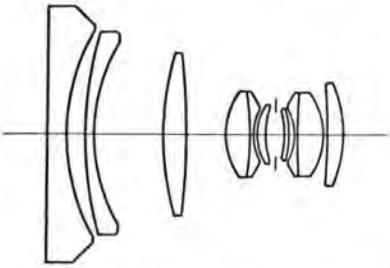

FIG. 16. System 4: the Nikkor 25 mm. $f/2,8$ designed for underwater use exclusively.

power of $(1/n_w)$ and a distortion corresponding to $(\cos\theta_w/\cos\theta_a)$, both the distortion and the picture angle will be compensated. For this purpose, the use of a reversed Galileo type telescope system is suited, with the front concave lens used as the water-tight window glass. Fortunately, as the reversed Galileo type telescope system has a minus distortion, $(\cos\theta_a/\cos\theta_w)$ is likely to be eliminated. As the Galileo system uses two groups of lenses as constituents, it is easier to correct chromatic and other aberrations. In addition, it is an advantage that the f-number of the master lens undergoes no change, so that a bright lens system can be obtained. Such a lens system is recommended by Dr. Ivanoff, and some practical examples are given[3,4]. On this basis, we have made a trial lens, Nikkor 25 mm. $f/2.8$, designed exclusively for underwater use (Figure 16). However, as a result of the correction performed by ray tracing through the entire system of the lens, the magnification is slightly different from $(1/n_w)$, and could not form a perfect telescope type. In any case, when a telescope system is used, it is advantageous that the image position be maintained. Consequently, if the aberrations are corrected only by the use of a telescope system, it will be possible to apply the camera originally designed for air use without alteration to underwater use. In other words, there is no need to use any special camera. Based on this idea we have designed a glass window for a telephoto system to be used on a 16 mm. cine camera (Figure 17).

This system, if used as a narrow-angle and long-focus lens, may produce almost the same results as with plane glass window. But when it is used for a wide-angle, short-focus lens, remarkable improvements will be attained in the image characteristics (See Table 2). However, we can achieve a better high performance lens system by correcting the aberrations considering the master lens (Figure 18, Table 3). By comparing the aberration curves, it will be clear that such a lens system produces superior results to the conventional one.

5. LENS SYSTEM USING CONCENTRIC SPHERICAL SURFACES

The refraction, dispersion and distortion through the boundary surface between water and air, are caused by the fact that this surface is flat. If this boundary surface is given such a curvature that all the incident rays come vertically against the surface, the problems will be solved at a single stroke. Where the center of the master lens is brought to the center of the curvature of this spherical boundary surface, neither change of picture angle nor distortion will take place.

When a super wide-angle lens is used in this way, we can expect an excellent lens for use exclusively under water.

However, the spherical window surface produces a spherical virtual image with its concave side facing the master lens. This master lens produces an image with a plus curvature—an image plane being convex toward the lens. The shorter the radius of curvature of the spherical window surface, the stronger the curvature of the convex image plane. Therefore, it is desirable to choose a window with a radius of curvature as long as permissible. Or it is also desirable to choose as the master lens a lens producing the image curvature in the opposite direction. Actually, a satisfactory result has been obtained with the

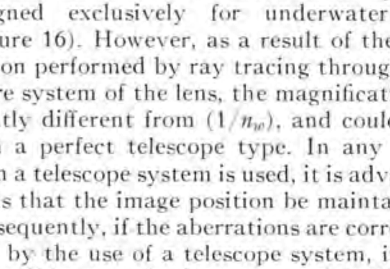

FIG. 17. A glass window designed for a telephoto system for use on a 16-mm. movie camera.

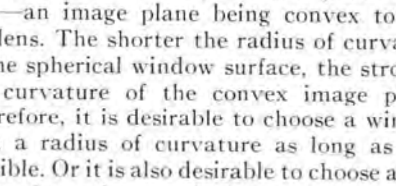

FIG. 18. A more nearly corrected version of the lens shown in Figure 17.

TABLE 2. COMPARISON OF CHARACTERISTICS
Nikkor for 16 mm. cine 13 mm. $f/1.8$

Aberrations on the circle 13 mm. in diameter	*In air*	*In water*	
		Plane glass plate	*Telescope system* ($\beta=1/1.2$)
Δy_g	+0.004	+0.051	−0.008
Δy_c	+0.001	−0.011	+0.002
Distortion	−1.28	+3.95	+0.71
Picture angle (2θ)	53°	39°	47.4°
Focal length	13 mm.	13 mm.	10.83 mm.
Nikkor for 16 mm. cine 50 mm. $f/1.8$			
Δy_g	−0.003	+0.035	−0.007
Δy_c	+0.002	−0.008	−0.002
Distortion	−0.37	0	−0.19
Picture angle (2θ)	15°	11°	13.2°
Focal length	50 mm.	50 mm.	41.64 mm.

Nikkor 21 mm. $f/4$ (Frontispiece and Figure 19) by ray tracing. Considering the external pressure, it is preferable to use a spherical surface window rather than a flat one. (Except some difficulties are involved in fabrication.) Thus, with this spherical window surface a super wide-angle lens, or fish-eye lens, etc. may be used as an underwater lens, the field angle remaining the same.

In the United States, trial lens systems such as this have been made[5,6,7]. In practice, however, it is necessary to bring the position of the entrance pupil in coincidence with the center of the spherical surface of the window. If this position is displaced, or a lens is used in which the location of the entrance pupil varies with the incidence angle of the ray, the perpendicularity of the incident rays with respect to the spherical window may undergo a change. There then arises the possibility of causing aberrations, except where these aberrations are corrected[8]. Of course, we must admit a decrease, even slightly, of the f-number as compared to that which can be given for air photography. On the other hand, if the type of glass used for the window is of the same refractive index and dispersion as those of water, it is not always necessary to give spherical concentric curvatures to the surfaces of the window. Because neither refraction nor dispersion will arise on the front surface of the window. It is therefore possible to permit the front surface of the window to have any desirable curvature or a flat surface.

CONCLUSION

Because large aberrations occur through the boundary surface between water and air, it is not desirable to use an ordinary lens for underwater photography without alteration, unless the field angle of the lens does not exceed about 20°, or some special contrivance is introduced at the window surface in contact

TABLE 3. UNDERWATER LENS FOR
16 mm. CINE CAMERA
$f=10$ mm. (0.4 inch)
$B\cdot f=25.4$ mm. (1 inch)

Aberrations on the circle 13 mm. in diameter	
Δy_g	+0.005
Δy_c	+0.002
Distortion	−1.5
Field angle (2θ)	51°

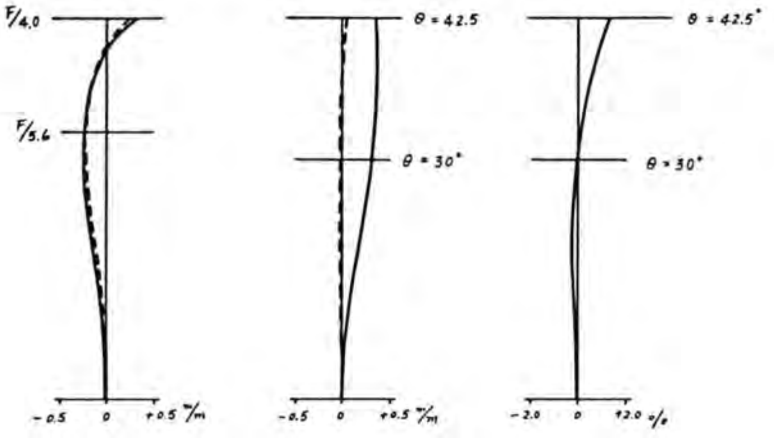

FIG. 19. Aberration curves of the Nikkor 21 mm. $f/4$ used through a spherical glass window for underwater photography. Angular field, 85°; focal length, 17.64 mm.; maximum aperture, $f/4$.

with the water. From the designing point of view, better results can be obtained if a lens system is designed, including the window, than if an ordinary lens is used.

To achieve a good lens for underwater photography, it is recommended that it be designed from the beginning. It is not advantageous to attempt to design a lens usable both in water and in the air. Also note that lenses exclusively designed for underwater use do not always have a flat surface in contact with water; therefore, if we take pictures in the air using these lenses, the position of the image plane will undergo a change, resulting in an out-of-focus image.

We have not only studied several possible types of underwater lenses, but have made trial lenses for comparison with pictures taken with conventional lenses. We find that our underwater lenses can obviously bring about the same good performance as that obtained by the lenses used in the air in their calculated aberrations as well as in the actual photographs taken.

Among our trial lenses, the 28 mm. $f/3.5$ has been produced in large quantities since 1965. It is supplied as an interchangeable lens for the all-weather camera *Nikonos*. This lens, though slightly inferior the 35 mm. $f/2.5$ in brightness, is superior in picture angle, in correction of distortion, correction of color aberrations, and in other optical performances. It results in an excellent resolving power up to the circumference of the image field.

It becomes evident that if we conduct a faithful optical design by ray tracing, such as used in atmospheric lenses, there is a possibility of improving the performance of underwater lenses to the same degree as that of lenses used for air photography.

We have studied only a few of the many photographic lenses available. We hope to be involved in the development of more advanced lens systems, corrected for improved brightness and wider picture angles. In the past this field has been neglected. With the increased interest in underwater photography, we can expect definite improvements in underwater lens designs.

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