A Concentric Telescopic Meniscus for Testing Underwater Lenses

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In addition to being inconvenient, testing underwater lenses in their normal environment involves the difficulty of differentiating between the effects caused by the photographic system and those caused by the turbidity of the water. The principles developed and practical devices illustrated show that it is possible to apply all test methods for common photographic lenses to underwater lenses with a correctly designed concentric telescopic meniscus.

Introduction

The growth of oceanographic research in recent years has stimulated corresponding developments in underwater photographic instrumentation. Underwater lenses have progressed from adaptations of ordinary photographic lenses to special optical systems for the water environment. It is highly desirable to apply the same methods for testing and image evaluation that are common for lenses used in aerial photography. Such tests are more difficult to perform because of the requirement that there be water in the object space. In addition to this inconvenience, the tests are more difficult to carry out and interpret because a volume of water has a much higher turbidity than a similar volume of air. In order to differentiate between effects caused by the photographic system and those caused by the turbidity of the water, testing in bodies of water should be avoided. McNeil[1] has developed an underwater calibrator that uses a number of collimators to project a corresponding number of test targets into water space. As each collimator projects through a separate plano parallel window perpendicular to its axis, the refraction on the air–water interface has no effect on the quality and angular location of the test target. For the testing of an underwater lens or camera, all test targets have to be individually focused, so that in water space they appear to lie in one plane. For a change in object distance, all targets must be individually refocused. For photogrammetric calibration the angular relationship between targets must be measured with a theodolite of appropriate accuracy.

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There appears to be a need for a more general transformation from air space to water space. In the following a device will be described that performs a geometrically perfect transformation with image defects that are negligible for practical use.

Spatial Systems

Herzberger[2] defines spatial systems as having the property of imaging the entire three-dimensional object space apanatically into image space. In his detailed treatment of concentric spatial systems he shows that such systems are possible only if the refractive indices of object and image space are equal. The conclusion is, therefore, that for the case at hand (object space air, image space water, $n_D = 1.34$) no solution with perfect imaging exists. There may, however, be a concentric system that is adequate for the purpose.

Concentric Systems

A concentric system consists of a number of spherical surfaces having a common center of curvature. It has an infinite number of axes of rotational symmetry. If the pupil is located at the common center of curvature, the imaging properties are equal for all field angles. In particular a concentric object surface will be imaged into a concentric image surface. This also applies for the object surface at infinity whose conjugate image surface has a radius equal to the focal length of the system.

It is characteristic of concentric systems that all the aberrations except curvature of field, longitudinal chromatism, and spherical aberration disappear. For an infinite focal length system (a telescopic or afocal system), curvature of field is also eliminated. In the absence of astigmatism, field curvature does not depend on object distance. Therefore, a concentric telescopic system is free of field curvature for all object distances.

The Concentric Telescopic Meniscus

A concentric system consisting of two surfaces (i.e., one lens element) will be called a concentric meniscus in the following discussion. Feder's notation[3] will be used throughout. It is convenient to regard entrance and exit pupils as surfaces 0 and 3, respectively.

Applying the Lagrange invariant I to the entrance and exit pupils, the equations shown in Fig. 1 are obtained. The diameters of entrance and exit pupils are inversely proportional to the refractive indices in object and image space. This pertains to all concentric systems. In a telescopic system, all rays that are parallel in object space are also parallel in image space. This property, combined with the property that all principal rays remain unrefracted, results in the general statement that directions in object and image space are identical.

The construction data for a concentric telescopic meniscus can now be derived. For a telescopic meniscus with an object at infinity the parameter relationships shown in Fig. 2 are obtained. For $N_0 < N_2 < N_1$ only $r_1 > 0$ yields a solution that can be physically realized.

First Order Considerations

Relationship Between Object And Image Space

It is convenient to measure distance (S_0) in object space from the entrance pupil and distances in image space (S_3) from the exit pupil as in Fig. 3. We have already shown that this pertains to the entire plane.

Longitudinal Chromatism

The longitudinal chromatic aberration according to Ref. 3 is proportional to $\Sigma_{yi}[\Delta N_{-1}-\mu\Delta N]$. For an object in air an explicit condition for achromatism can be derived. The Abbé number required for the meniscus material is given by

$$V_1 = (V_2N_2/N_1)[1 + (r_2/S_3)]^{-1}. \quad (1)$$

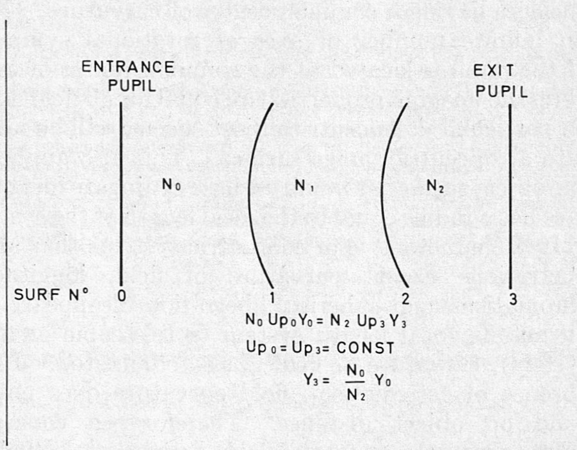

Fig. 1. Concentric telescopic meniscus, symbolic representation.

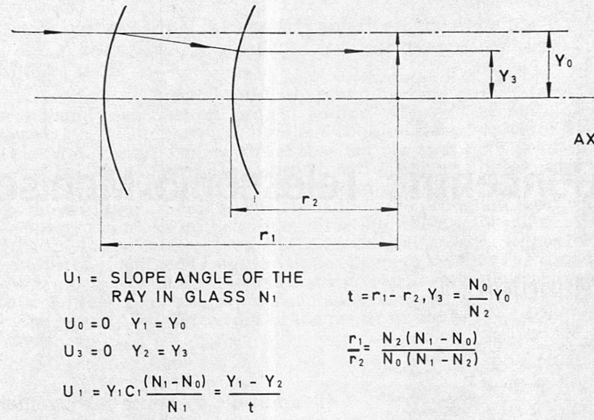

Fig. 2. Concentric telescopic meniscus, parameter relationships.

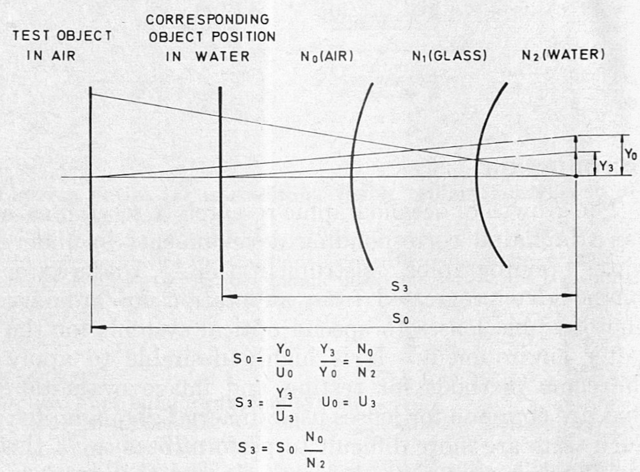

Fig. 3. Concentric telescopic meniscus, object positions in air and water.

Figure 4 shows curves for V_1 against N_1 for different values of S_3 assuming $N_2 = 1.34$ and $V_2 = 56.0$.

Spherical Aberration

Using formula (16) of Ref. 3 for the case of an image at infinity, we obtain for the angular third order spherical aberration of a marginal ray $\sigma' = H'/h' = \Sigma B = S_1i_1^2 + S_2i_2^2$. Spherical aberration can be expressed in terms of the construction data of the lens (Fig. 5). For object and image at infinity and air in the object space we obtain Eq. (1). It is useful to write this in terms of y_3 and r_2. y_3 is the radius of the entrance pupil of the lens under test and r_2 the distance from the last surface of the meniscus to the pupil. These parameters determine to what lenses the meniscus can be applied.

The spherical aberration will now be compared with the Airy disk. The first diffraction minimum is given by Eq. (2). If the spherical aberration is permitted to be equal to the radius of the Airy disk, we obtain Eq. (3), which is illustrated graphically in Fig. 6.

As the object approaches the meniscus, the spherical

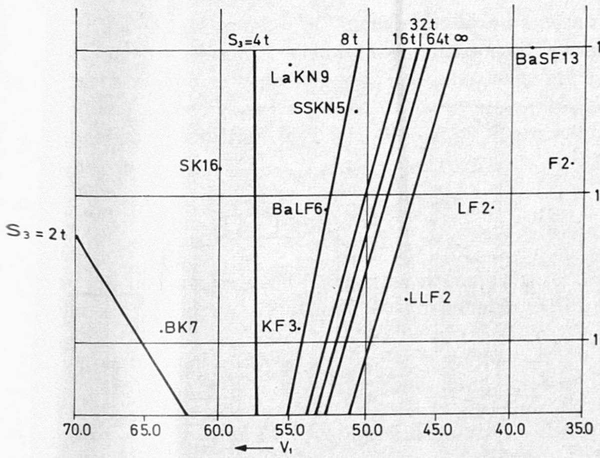

Fig. 4. Concentric telescopic meniscus, glass chart.

$$\sigma' = \frac{H'}{h'} = \Sigma B = S_1 i_1^2 + S_2 i_2^2 \qquad (1)$$

$$\sigma' = -\left(\frac{Y_3}{r_2}\right)^3 \frac{(N_1 - N_2)\, N_2}{2 N_1^2}\left(1 - \frac{(N_1 - N_2)^2}{N_1 N_2 (N_1 - 1)}\right) \qquad (1.1)$$

$$\sigma' = -\left(\frac{Y_3}{r_2}\right)^3 \beta$$

$$\sigma'\lambda = \frac{0.61\lambda}{Y_3} \qquad (2)$$

$N_2 = 1.34 \quad \lambda = 0.55\ m\mu$

N_1	1.5	1.55	1.60	1.65	1.70	1.75
β	.0464	.0563	.0645	.0712	.0767	.0811

$$\left(\frac{Y_3}{r_2}\right)^3 \beta = \frac{0.61\lambda}{Y_3} \qquad Y_3 = \sqrt[4]{r_2^3\, \frac{0.61\lambda}{\beta}} \qquad (3)$$

Fig. 5. Concentric telescopic meniscus, spherical aberration.

aberration increases slightly. For an object located in the first surface of the meniscus it is about 25% larger than at infinity.

It has thus been shown that it is possible to construct a concentric telescopic meniscus that gives a quasi perfect transformation from air space to water space.

Applications

Air–Water Converter for Wide Field Photography

A concentric telescopic meniscus as shown in Fig. 7 is under construction in accordance with the following data:

$r_1 = 301.44$ mm, $t_1 = 205.74$ mm, $n_1 = 1.59168$, $V_1 = 53.01$, $r_2 = 95.7$ mm.

The lens under test is attached by means of a water tight bellows at such a distance that its entrance pupil is situated approximately at the center of curvature of the meniscus. The longitudinal and lateral positioning of the lens under test is not critical at all. For a total field of 90° and a diameter of 28 mm for the entrance pupil of the lens under test, the angular aberrations for the spectral band from 500 mμ to 700 mμ remain below 20 sec of arc for all distances in air between infinity and 800 mm, corresponding to distances in water space between infinity and 500 mm. For the water contact element of the lens under test a maximum diameter of 90 mm can be accomodated. Any type of test target, including a natural landscape may be used. Photogrammetric calibration may be carried out for any distance of interest in underwater photography with the aid of simple targets like stadia tapes, tiles, or patterns painted on a wall.

Air–Water Converter for Optical Bench

In bench tests only a small area of the image is investigated at a time. Therefore, the device has been designed for small field angles. To scan the field, the device is rotated about its center of curvature. For use on the Eros IV OTF Analyser, a meniscus with a 10° field is being built according to the construction data already given. Fig. 8 shows a typical setup for a test at finite conjugates.

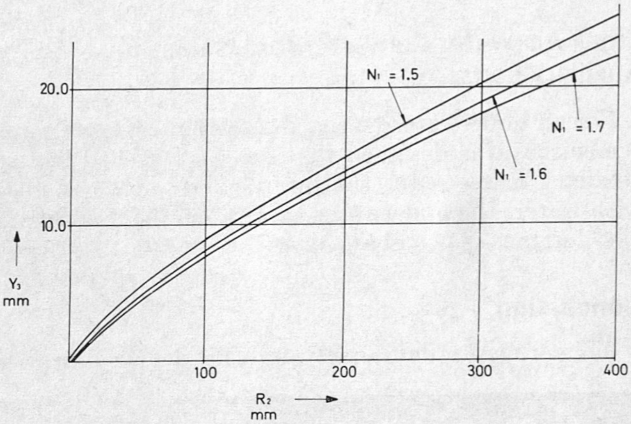

Fig. 6. Concentric telescopic meniscus, entrance pupil radius.

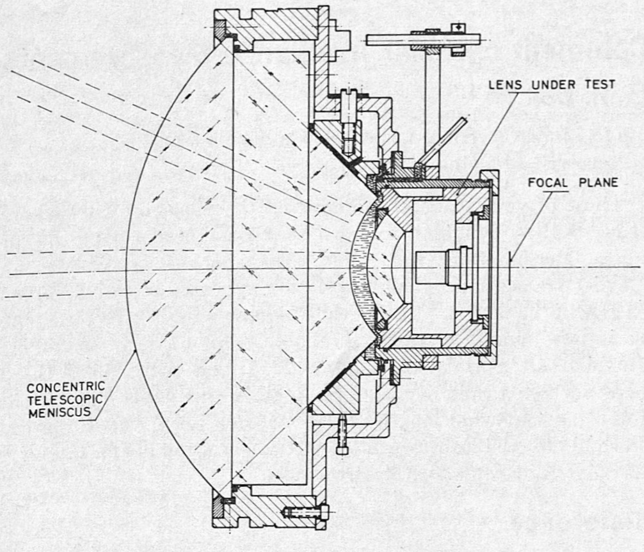

Fig. 7. Concentric telescopic meniscus for wide angle photographic testing.

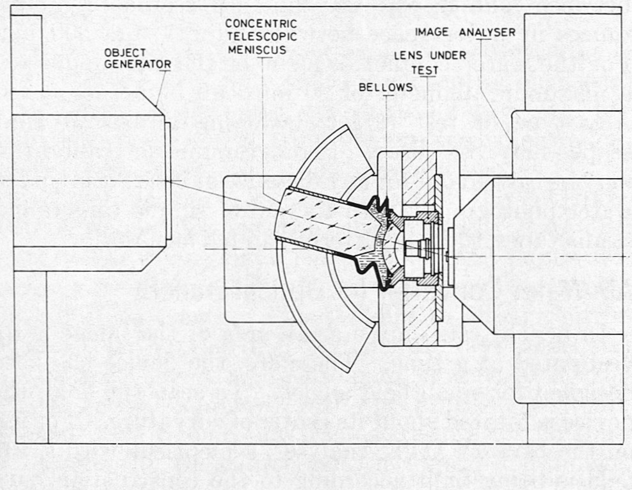

Fig. 8. Concentric telescopic meniscus, Eros IV test configuration.

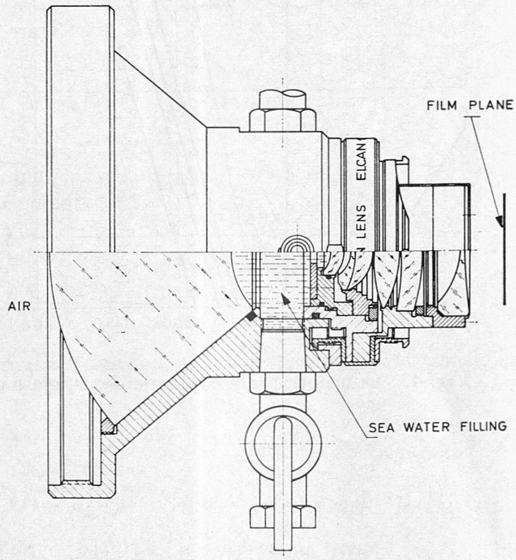

Fig. 9. Concentric telescopic meniscus for testing a lens with an external entrance pupil.

Small Air–Water Converter for Use as Auxiliary Lens

For an underwater lens with external entrance pupil a meniscus was designed that can be attached like an auxiliary lens. After the intermediate space is filled with water, the underwater camera can be used in air. The design is shown in Fig. 9.

Conclusion

The principle developed and the device described make it possible to apply all test methods for common photographic lenses also to underwater lenses. Hopefully, this will be an aid to further progress in underwater photography.

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Comment on Solar Irradiance Measurements

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Those of your readers who enjoyed the paper by Thekaekara *et al.*[1] will be delighted to learn that Bemporad's paper on air mass determination (Ref. 12 in this paper) is available in an English translation. This translation appeared in January 1965 as NASA TT F-302. It was then available from OTS for $1.00. It is now almost certainly available from CFSTI, 5285 Port Royal Road, Springfield, Virginia 22151, for either $3.00 (hard copy) or $0.65 (microfiche). In English, this paper goes by the following somewhat lengthy title: "Search for a New Empirical Formula for the Representation of the Variation of the Intensity of Solar Radiation with Zenith Angle."

Reference

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Abridged Lens and Prism Sets

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There are certain situations in which one cannot have a complete set of lenses or prisms for use in teaching and research work. This may be for economic reasons many times. In these cases, one can use a limited set of lenses and by combination of these limited number of lenses, one can obtain a range of powers. A case in point is the situation when a set of fused quartz condenser lenses is required for spectroscopic work. Another situation may be where several experiments in geometrical optics are to be set up in the undergraduate laboratory without a variety of lenses at hand. The object of this paper is to show that one can have a limited number of lenses or prisms and obtain from this limited number, a whole variety of combinations to cover a reasonably wide range.

This problem has a direct relation to the problem of weighing N