Frontispiece. Underwater panoramic photograph, 38° by 120°

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A Wide-Field, Underwater, Panoramic Camera

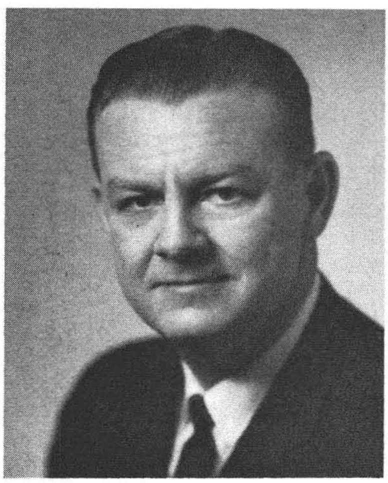
Having an angular field of 38° by 120° and a focal length of 3.42 inches for photography at 85 inches, the lens resolves 50 lines per millimeter at the center with an aperture of f/2.4.

(Abstract on next page)

INTRODUCTION

SEVENTY YEARS AGO, Louis Boutan produced the first underwater photograph at the Arago marine laboratory in France. The strange world beneath the oceans has received much publicity in recent years for accelerated explorations and scientific investigations. An increased utilization of the ocean as a source of food and minerals will be mandatory for future generations. Many scientific tools will be devised to support the great underwater search. Qualitative and quantitative photography will continue to serve effectively underwater as it has served so productively on land and in the air. Underwater photography will be used to a greater degree for oceanographic, engineering, biological, and military projects.

Many severe problems need to be overcome in the underwater environment. Turbidity, light absorption, and light scattering of the water appear to be insurmountable problems. However, science and engineering have



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teamed up in the past and have solved problems that have seemed to be unsolvable. Many components of the underwater system will require much improvement or a totally different device. The purpose of the Underwater Panoramic Camera is to produce high quality, wide-angle photography of underwater scenes as a serious attempt to improve the recording component.

Practically all underwater photography is exposed from a conventional camera that is placed in an underwater housing with either a simple plane-parallel window or a more elaborate optical window.

A review of the conditions encountered in practice conclude the following criteria:

- *Short Object Distance.* Due to turbidity, light absorption, and light scattering, the object distance should be as short as practical, especially with the use of color film.
- *Fixed Focus.* As there is usually a relative motion between the photographer and object, it is a very difficult operation to use a range-finder for the focusing of an underwater camera.
- *Short Image Distance.* The focal length or the image distance in this case, shall be as short as practical as the camera is fixed-focus and it is desirable to obtain as large a depth of field as possible.
- *Wide Angle.* The requirement of maintaining a short object distance results in reduced linear dimensions of the object plane.

A review of the technical literature, whether it be styled for the amateur or the professional, repeatedly emphasizes the requirement for wide-field coverage since turbidity, light absorption, and light scattering require the photographer to move closer to the object being photographed. A wide-angle lens is required to cover more area of the object at a closer distance.

ABSTRACT: *Quality wide-field coverage is produced by projecting high-resolution imagery through a relatively small angular slit and mechanically extending the field to a wide coverage by rotating the objective lens. A non-circular cylindrical image surface is utilized for optimum focus of a planar object surface. Some of the specifications for the lens are: a field of 38° by 120°; f = 3.42 inches; 50 lines per mm at f. 2.4 at the center; object distance of 85 inches; shutter speed 1/250 second; shutter slit 0.085 inch; and pan time 0.3 second.*

TECHNICAL DESCRIPTION

Figure 1 illustrates the basic geometrical optics of a conventional camera in combination with a plane-parallel window. Light rays emanating from the object pass through the water and are refracted at the water-glass interface and again at the glass-air interface and impinge on the objective lens of the camera. From the viewpoint of the lens, the rays appear to be coming from an apparent object that is equal in size to the actual object but is located at $\frac{3}{4}$ of the distance to the actual object. The camera, therefore, must be

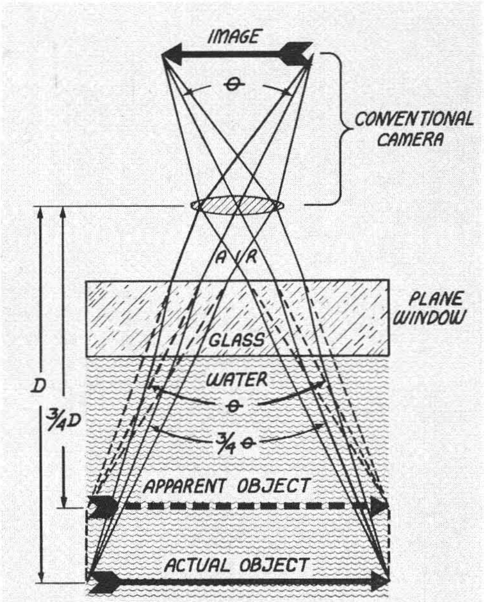

FIG. 1. Conventional camera behind a plane window.

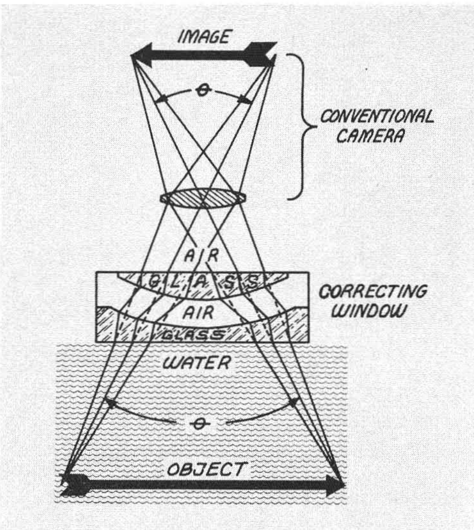

FIG. 2. Conventional camera behind correcting window (Aquar-Ivanoff lens).

focused at $\frac{3}{4}$ of the distance to the actual object. This distance condition naturally extends the angular field of view from $\frac{3}{4}\,\theta$ in object space to θ in image space. The factor $\frac{3}{4}$ is the reciprocal (approximately) of the index of refraction of water. This theory is valid for relatively small values of θ.

Plane windows introduce significant amounts of coma and lateral chromatic aberrations. The full-field in water is limited to approximately 30° for a plane window and a resolution of approximately 20 lines per mm.[1] It is of academic interest to point out that the maximum theoretical full-field of a plane window is approximately 98° owing to the critical angle of the glass-air interface.

Figure 2 is an optical schematic of an improved and more elegant window designed by A. Ivanoff of the Museum of Natural History, Paris, France[2]. The use of the Aquar-Ivanoff lens permits the conventional camera to be focused for the actual object distance and retains the same angular field in water as in air. This correcting window covers a much larger angular field with greatly reduced aberrations compared with a plane window.

The simplest means of producing quality wide-field coverage is to project high-resolution imagery through a relatively small angular slit and mechanically extend the field to a wide coverage through rotation of the objective lens. This technique of rotating the lens has been used to produce high quality photography from panoramic cameras with an object space of air. Obviously, the same approach can be exploited for a camera with an object space of water. The exploitation is even greater in an underwater environment as a wide-angle water lens is far more complex to design and manufacture than a wide-angle air lens.

In has been established previously in a technical paper[3] that the front and rear nodal points must fall on the axis of rotation to preclude image movement for all object distances. This principle was utilized in the design of the NavScan Hi and Lo Panoramic Cameras for the U. S. Navy. The apparent positions of the front and rear nodal points were made to fall on the axis of rotation by the proper positioning of reflecting surfaces. The design approach to the Underwater Panoramic Camera is an in-line optical system in place of a folded optical system. The in-line system is preferred since it is simple and more compact. However, the in-line system does not have reflecting surfaces to place the nodal points on the axis of rotation.

A very simple solution to preclude image movement at a finite object distance is derived from Figure 3 as follows:

- A is the object point,
- a is the image point,
- D is the object distance,
- d is the image distance,
- N_1 is the front nodal point,
- N_2 is the rear nodal point,
- O is the axis of rotation of lens.

ΔON_1A is similar to ΔON_2a, since object ray AN_1 is parallel to image ray N_2a. It can then be stated that:

$$\frac{E_1}{E_2} = \frac{E_1 + D}{E_2 + d},$$

$$E_1E_2 + E_1d = E_1E_2 + E_2D,$$

$$E_1d = E_2D,$$

$$\frac{E_1}{E_2} = \frac{D}{d}. \tag{1}$$

Formula 1 simply means that if the ratio of the eccentricities of the front and rear nodal points is made equal to the ratio of the object to image distances, no image movement will occur for objects at a distance D.

Formula 1 can also be derived from Formula 7 presented in the previously mentioned technical paper.[3]

$$c = \frac{\theta E_1 f}{D} + \theta E_2. \tag{2}$$

Substituting the image distance d for the focal length f in Formula 2 to accommodate

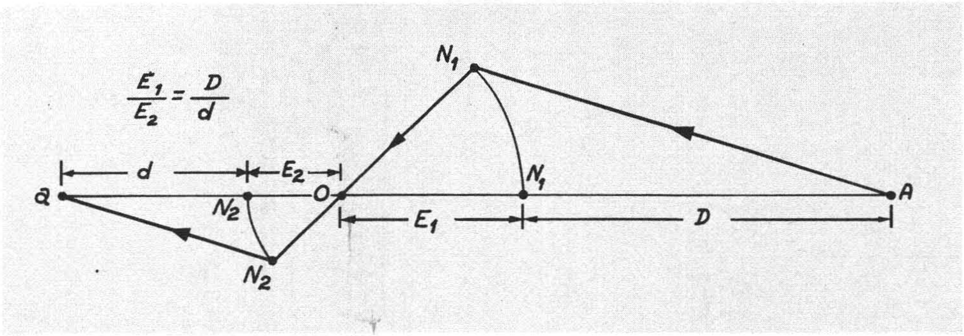

FIG. 3. Geometry of a rotating lens to preclude image movement at a finite object distance.

the condition other than when the lens is focused at infinity, the general formula takes the following form:

$$c = \frac{\theta E_1 d}{D} + \theta E_2. \qquad (3)$$

It can be seen from Formula 3 that c equals zero when

$$\theta E_2 = - \theta E_1 d/D.$$

The change in algebraic sign is simply accomplished by positioning the axis of rotation between the front and rear nodal points. Substituting in Formula 3:

$$0 = \frac{-\theta E_1 d}{D} + \theta E_2,$$

$$\frac{\theta E_1 d}{D} = \theta E_2,$$

$$\frac{E_1}{E_2} = \frac{D}{d}.$$

Figure 4 is a schematic of the lens and film transport system of a 360° under-water panoramic camera.[4] The optical window is a section of a concentric glass dome that covers a 360° horizontal field of view and is an integral component of the lens system. Since the axis of rotation of the lens system passes through the center of curvature of the concentric optical window, the lens system is optically identical for any position of rotation throughout the 360° field of view. The lens system is designed especially for an object space of water as contrasted against the conventional approach of utilizing a lens designed for an object space of air in combination with a plane or corrected window. The axis of rotation is so positioned that the ratio of the front and rear nodal point eccentricities is made equal to the ratio of the object distance to the image distance. The lens, slit, and magazine assembly are mechanically tied together. The film is moved past the slit in the opposite direction to that of the lens-slit-magazine assembly by means of the gear train consisting of the stationary gear, idler gear, and sprocket gear. Since it is required that 2 π image distances pass the slit per revolution, the following relationship must be maintained:

$$2d = D_1 D_2 / D_3 \qquad (4)$$

where

d = the image distance,
D_1 = the diameter of stationary gear,
D_2 = the diameter of sprocket,
D_3 = the diameter of sprocket gear.

If the conditions of Formula 1 are fulfilled, image movement due to rotation for the given object distance D is zero. Formula 3 is also used to determine the magnitude of the image movement for an object distance other than D.

The image and object surfaces of a panoramic camera focused for a finite object distance are cylindrical in configuration. If optimum focus of a planar object surface is required; the non-circular cylindrical image surface is utilized as shown in Figure 5.

The perspective recorded by an underwater panoramic camera is similar to the perspective produced by an aerial panoramic camera. Figure 6 is a perspective (not to scale) of a swimming pool wall faced with square tile.

The physical characteristics of the Underwater Panoramic Camera shown in Figure 7 are:

Image Distance at Center	87.0 mm. or 3.42 inches
Object Distance at Center	85 inches
Relative Aperture	$f/2.4$ to $f/32$
Field Angle	38°×120° in water
Shutter Speed	1/250 second
Shutter Slit Width	0.085 inch

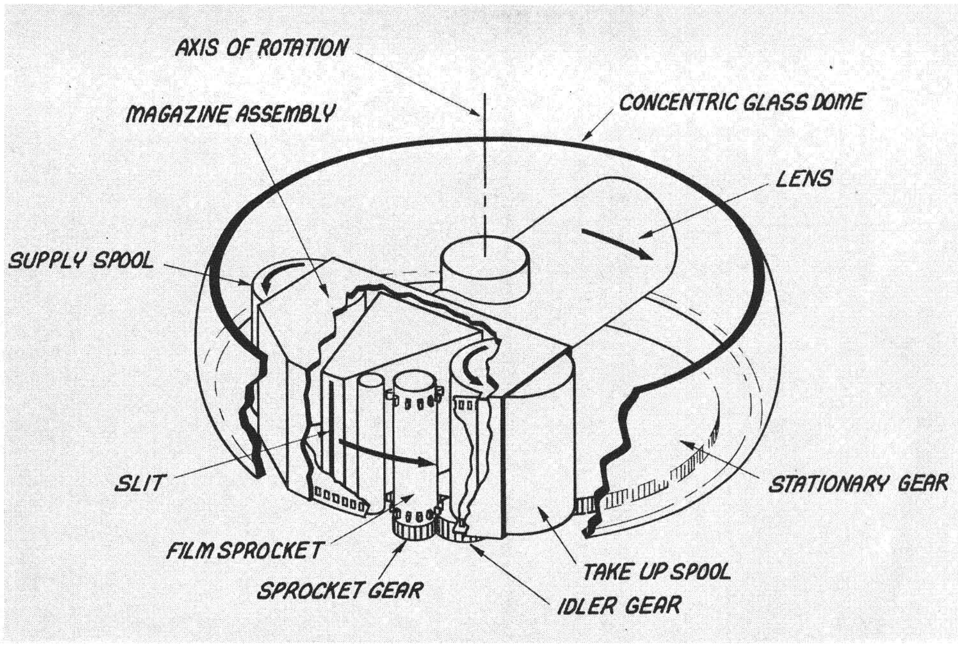

FIG. 4. Schematic diagram of the underwater panoramic camera.

Pan Time	0.3 second
Format on 70 mm. Film	$2\frac{3}{8} \times 7\frac{3}{8}$ inches
Film Capacity	24 exposures
Camera Size	$11\frac{1}{2}$ inches dia. $\times 8\frac{1}{2}$ inches high
Peak Spectral Range	4,500 Å to 5,000 Å
Resolution at Center, $f/2.4$	50 lines per millimeter

The Underwater Panoramic Camera differs from the schematic camera depicted in Figure 4 in that the angular field is reduced from 360° to 120° and the film remains stationary during the time of exposure. Since the nodal separation of the underwater lens is 0.6 mm., the rear nodal point is placed on the axis of rotation. Using a slit width of 1.5°, an image movement of 0.6 micron is computed from Formula 3. This magnitude of image

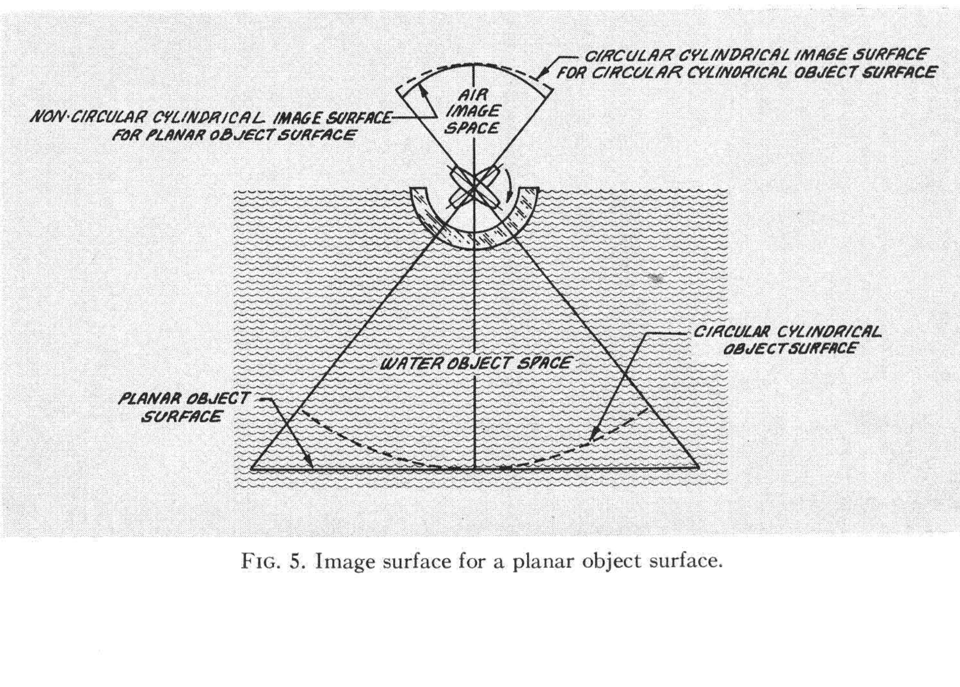

FIG. 5. Image surface for a planar object surface.

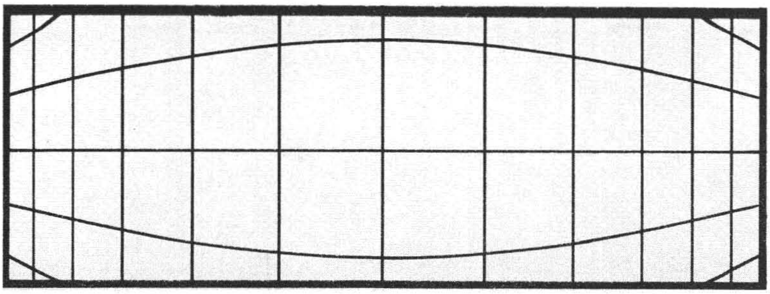

FIG. 6. Perspective of a swimming pool wall.

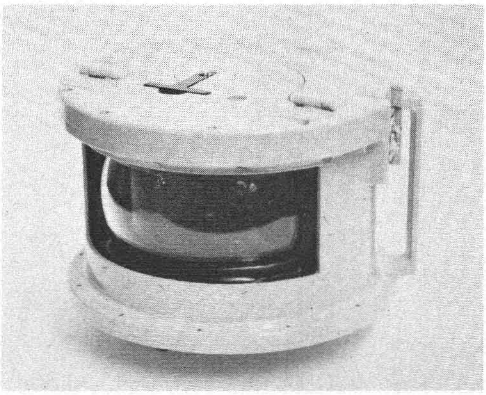

FIG. 7. The Underwater Panoramic Camera.

movement has an insignificant effect on the resolution.

The Frontispiece shows an underwater photograph recorded by the Underwater Panoramic Camera. The photograph covers a 30 foot length of the swimming pool wall with the camera about $8\frac{1}{2}$ feet from the wall. The fifteen youngsters are performing a walk in water space.

ACKNOWLEDGMENTS

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