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WOODS HOLE OCEANOGRAPHIC INSTITUTION

TECHNICAL MEMORANDUM #DS-22

A DISCUSSION OF VARIOUS MEANS
FOR IMPROVING VISIBILITY FROM
THE DSRV ALVIN OR SIMILAR VEHICLES

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Woods Hole, Massachusetts

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FOR IMPROVING VISIBILITY FROM
THE DSRV ALVIN OR SIMILAR VEHICLES

by

Lincoln Baxter, II

November 1966

This work has been carried out under Contract Nonr-3484(00), NR 260-107 with the Office of Naval Research.

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ABSTRACT

Plots of distortion and lateral chromatic aberration of plane ports for underwater viewing are given. Optical characteristics of window materials are discussed. Various simple lens and mirror systems to correct the window aberrations and/or give a wider field of view are evaluated. Unless infinity viewing systems (those that project a field of view to both eyes) or more conventional internal telescopes or binoculars are employed the observer or pilot must crouch with face very close to the window to perceive a wide field. Because of the great volume required for the optics of infinity viewing systems, binocular telescopes with eyepieces are thought to be a more practical means for increasing pilot and observer comfort. It is shown that hemispherical pressure windows are required for high performance scanning systems and a layout for such a system is given.

A Discussion of Various Means for Improving Visibility
from the DSRV ALVIN or Similar Vehicles

I. Introduction

Though the plane windows (Mavor 1965) used in many deep submersibles including ALVIN have been demonstrated to be safe and very useful, the visibility that they provide is far from optimum. Various parameters of the visual field of truly plane and homogeneous windows of this type are given in Figs. 1, 2 and 3. As one can see, the sharp undistorted portion of the angular field of the window is rather limited and the aberrations become very large in the outer portions of the peripheral field. Furthermore, to observe simultaneously all portions of a field of reasonable angular extent the pilot or observer must assume a cramped position very close to the window.

The plexiglas, specified because it can conform more readily and safely than glass to minor variations in the seat, is unfortunately less homogeneous than optical glass, distorts more readily, scratches more easily, and is less readily worked to an accurate optical surface.

In the present report various plans that have been proposed to improve the visibility for various purposes are listed and discussed.

II. Better Materials or Construction for Improved Surface and Internal Quality.

The optical distortion (Figs. 1 and 2) caused by a truly plane and homogeneous window does not depend on its index of refraction or thickness. A ray from the water emerges into the air in the same direction as it would emerge if it passed directly from water to air. This may be shown by writing Snells law for the two surfaces of the window. In the overall ratio between water and air, equal to the product of the ratios between water and plexiglas and air, the sine of the angle in the plexiglas cancels. The same is true, of course, for any other transparent material.

The chromatic difference in the distortion (for parallel pencils) (Fig.3) and the astigmatism of oblique diverging pencils may also be computed for the simple refraction from water to air. As recognized by Thorndike (1950), the effect of the window material and its thickness while not strictly zero for non-parallel pencils is nearly negligible compared with the primary effect that is computed as if the refraction were directly from water to air. A change in window material gives a very small difference in effect and a window of one material is, in most cases, optically equivalent to one of another material with slightly different thickness or slightly different object distance.

As recognized by Thorndike (1950) the lateral chromatic aberration is normally the most important effect. It is plotted in Fig. 3 as the angular separation between images of the C and F lines against the angle of incidence in water. The magnitude of this chromatic effect should be compared with the threshold resolving power of the eye (which is about 1' of arc).

The homogeneity, surface quality and distortion of the surface under pressure do depend on the window material. The following is a discussion of the relative merits of glass and plexiglas and the possibilities of achieving with glass (which is optically preferable) the same safety as that of plexiglas (which is preferred for mechanical reasons).

In order to overcome the undesirable tendency of plexiglas to scratch and craze and to provide a better optical surface figure, cemented glass covers have been proposed (Fig. 4). Though better handling techniques have resulted in fairly satisfactory maintenance of plexiglas surfaces and the improvement (by glass covers) of the image quality would be small, such a process may be worth further investigation if it is not too expensive.

Though plexiglas is now required for safety, more research on glass and its mounting might remove its disadvantage in this respect and windows might be made entirely of glass. In addition to the superior surface characteristics and the greater homogeneity of glass, its rigidity, which results in smaller distortion under pressure, is another desirable optical characteristic which would make this development worthwhile. For these reasons glass is now preferred for deep sea cameras (Edgerton and Hoadley 1960), even though the test data reported by Edgerton and Hoadley (1960) indicate that the safe thickness of unsupported plates of glass must be somewhat greater than that of plexiglas and that glass is much more variable. As recognized by Mavor (1965) the unfavorable comparison between glass and plexiglas in many configurations is largely due to the greater rigidity of glass which, in the conical windows of a DSRV leads to much closer mounting tolerances and susceptibility to seat strain.

In configurations which avoid tensile stresses glass is exceedingly strong. Spherical shells made from two hemispheres of pyrex with a diameter of 10 inches and a thickness of only 0.36 inches are frequently used as instrument housings to withstand a pressure of 15000 lb/in^2 (a depth greater than 6000 ft). For a safe plane window of this diameter a thickness of six (6) inches or more would be specified. The strength of optical quality crown glass is not very different from that of pyrex in either configuration. Assuming that the mounting can be designed to support the edge properly it seems likely that any circular portion of a spherical shell could be much thinner than a plane window of the same clear aperture.

As recognized by Mavor (1965) spherical shell windows are most useful for monocular or camera systems. If a separate small window is used for each eye as suggested for an ultrawide-field binocular vision system (Baxter, 1966) spherical shell windows extending over somewhat less than a hemisphere could be used quite effectively in place of the Ivanoff (1956) correctors.

III. Attachments of Large Simple Lenses to Correct the Aberrations of the Large Plane Window.

To obtain a correction of the window aberrations in a way that is at once the simplest and the closest in viewing technique to the original window configuration, various combinations of large simple lenses have been proposed. Ideally such systems should furnish without change a correction to the widest possible variety of "off the shelf" optics such as cameras, telescopes, binoculars, infinity viewing systems and two-eyed people. Air spaces external to the pressure sphere are difficult to use in practical designs for such a system because the thickness of the necessary windows and shell reduces the useful angular aperture of the window.

In the present paper such systems will be classified as follows:

- Jackman Corrector (Fig. 5)
- Modified Jackman Correctors (Fig. 6)
- Ivanoff Corrector (Fig. 7)
- Modified Ivanoff Corrector (Fig. 8)
- Baxter Corrector (Fig. 9)
- Partial Baxter Corrector (Fig. 10)

The Jackman (1935) Corrector (Fig. 5) is primarily useful for naked eye viewing at a large distance d from the window. With useful power under these conditions the field of view in the object space is greatly increased but a very minified image with strong barrel distortion astigmatism and field curvature is furnished. At shorter d , minification, distortion and astigmatism may be reduced or eliminated but, unless the window and corrector are very large, the field is too strongly curved and the image distance too short to be within the range of focus and correction of most optical systems including the normal naked eye. Since only one eye can be at the center of

curvature or on a line through the center of curvature and a given point on the surface, a single corrector of this type is not suitable for binocular vision unless d is very long.

The modified Jackman corrector (Fig. 6a) eliminates the air space to improve the object field of view and reduce reflection losses and stray light, but the above comments on the character of the image still apply.

Another modification Fig. 6b is optically equivalent to an extremely thick form of the spherical shell port. Image properties of this form, when it used as the only optical element, are practically the same as those of 6a. The rather large plano convex lens outside the window gives negligible improvement. The Ivanoff corrector or the partial Baxter corrector use two lenses to better advantage.

A discussion of the necessary radii of curvature of thin shell spherical ports used with standard camera lenses at the center of curvature has been given by Patterson (1966). There is no distortion, but it is clear that, even with a seven (7) inch inside radius, the linear diameter of the camera lens aperture must be quite small. To use an aperture stop of $f2$ the camera lens focal length cannot be more than 9.8 mm.

The Ivanoff corrector (Fig. 7) uses a positive lens at the nodal point of the initial negative lens. It is designed for a viewing point on the axis and as close as possible to the final surface of the positive lens. Because the centering is critical the Ivanoff corrector is useful only when a separate one is furnished for each eye or objective. (i.e., a double corrector with accurate registration is required for binocular vision). The close image distance and the extreme curvature of the field that result with a simple Jackman corrector are much better corrected in the Ivanoff.

The modified Ivanoff corrector (Fig. 8) is useful for telescopic systems with a forward entrance pupil or for naked eye binocular viewing at a moderate viewing distance d . This design gives better performance than the Ivanoff for off axis viewing directions at such distances. For viewing from the close on-axis position the standard Ivanoff has a wider field of view.

The Baxter corrector (Fig. 9) is proposed for natural binocular viewing at the small values of d that permit a large field of view. In the reversed Galilean telescopic type correctors like the Ivanoff and Baxter, the diameter of the positive lens for a given field of view is smaller than that of the negative. The limiting diameter of the DSRV pressure window is that of the inside surface. This is, therefore, the best location for the positive lens if the size and therefor the off axis tolerances of the corrector are to be maximized. Glass or plexiglas lenses under water have about $1/3$ the optical power they have in air or require surfaces curved about three times as deeply. Nevertheless, paraxial calculations and full aperture graphical ray traces have been made to show that the two water-emersed negative lenses (Fig. 9) develop sufficient negative power, without serious aberrations, to correct a 90° field of view.

If the full Baxter corrector is too expensive or bulky, a smaller field of view may be corrected with the partial Baxter corrector (Fig. 10).

IV. Mirror Systems.

To widen the field of view with external elements that are lighter and less deeply curved than the external lens elements discussed above, various combinations of mirrors are possible. Such combinations like those in section III should use a small number of optical surfaces. Peripheral or rear vision can be obtained in a portion of the field that is separate from the direct view. There need be no blind spots in the field that is covered, because the peripheral field can join or overlap the direct object field. The suggested possible combinations will be discussed under the headings:

- Annular field widener
- Reducing mirror
- Dual mirror bent telescope

An annular field widener (Fig. 11) can be made using an afocal combination of two aspherical annular mirrors (O.T.S., 1952).

The central portion of the field is left unobstructed. Two suitable curved annular mirrors, the first diverging, the second converging, are positioned to furnish an afocal annular field with magnification varying from unity at the inner edge to much less than unity at the outer edge. In this configuration the centered eye will see surrounding the central field and just joining it, an annular field with pronounced barrel distortion but covering a much larger field of view than any of the corrector forms discussed in section III. It may be possible to form these mirrors on the internal sides of the surfaces of a single suitably curved ring of plexiglas. In this case proper curvature of the entrance and exit refracting surfaces should also be calculated. One would have to make a large ring of plexiglas with four aspherical toroidal surfaces and coat two of the surfaces with a high reflection film.

A minified image of a wide field of view in a direction different from any included in the natural field of the window can be obtained by means of a reducing mirror similar to those used in some automotive rear view applications. The surface of such a mirror is a convex section of a sphere. Several such mirrors could be mounted around the window as sketched in Fig. 12. Such a mirror mounted on a mast over the sail and viewed through the upper window of the sphere could permit the operator to see the main propeller and shroud, but the field of view would be greatly minified in a mirror of reasonable size.

Two large mirrors (in general, spherical ones) may also be used as a bent reflecting telescope to cover a field of view in a direction different from that naturally covered by the window (Fig. 13). The field covered need not be so greatly minified as with the single mirror.

V. Internal Telescopes or Binoculars.

Fig. 1 shows that the full field of view of the simple window can be observed only if the observers eye is close to the window surface. Internal telescopes or binoculars can permit a more comfortable pilot and observer position without

compromising the field of view. Magnification and correction and displacement of the exit pupil from the entrance pupil may be designed to suit the requirements of the observations. By shifting of optical elements, several magnifying powers and fields may be provided in one instrument.

The simplest internal wide angle telescope (Fig. 14) illustrates the overall plan of this type of viewing aid. A wide angle objective (eyepiece design used backwards), an erector consisting of two telescope objectives, and a wide angle eyepiece. This simple straight line instrument does not contain correction for the window aberrations and is turned in a cup socket to view in directions other than straight ahead. The field of view in any one position could be about 65° in air or 45° in water. If the axis of the instrument is turned to a direction far from the perpendicular to the window surface, the aberrations will be very severe.

The direction from the eye of a seated observer to the window is usually not perpendicular to the surface. To permit the axis of the instrument to be perpendicular an offset instrument like that of Fig. 15 is desirable.

With the later construction, a preobjective consisting of two lenses in the form of a modified Ivanoff corrector (Fig. 8) may be used to achieve an extensive correction of the aberrations and a much wider field of view which may easily approach 130° in air or 85° in water. The maximum possible, without using some form of emersion objective (connected to the inner surface of the window by a high index fluid), is 180° in air or 96° in water. The preobjective system of Fig. 16 with four lenses has been used to achieve 170° in air or about 95° in water. Because of the forward entrance pupil of the telescope the corrector lenses need not be of large diameter and the diameter of the positive and negative elements may be approximately equal.

To be comfortable to use, and to afford a wide field of view, eyepieces should have a large eye relief and a long focal length. The limit on the practical values of the field of view

and the eye relief in any given construction is dictated by the related overall diameter of the mounted eyepiece. In a binocular, this diameter cannot exceed the minimum interocular setting. These considerations lead me to think that a Scidmore type 2 (Rosin 1965) or equivalent eyepiece with an 80° field of view and a focal length of 1.25 inches is most suitable. If, however, one follows the plan suggested here, and images the full object field in whatever eyepiece field is available, the only penalty for using a less expensive 65° eyepiece is a somewhat smaller image size; the same objects are seen.

By providing for each eye, a telescope similar to Fig. 15, with pre-objectives as described, wide angle binoculars for stereoscopic vision can be made. Four objectives can share the same window permitting two observers to see the same wide angle stereoscopic field.

A small straight line monocular or binocular about one foot long could be quite useful as a hand held internal viewing aid, readily portable from window to window. The design would be similar to that of Fig. 14 but short focus telescope objectives (perhaps those of a 7 x 50 binocular) could be used in the erector system.

VI. "Heads up" Infinity Viewing System.

For viewing more comfortable than that provided by eyepieces a system, Fig. 17, pioneered by Farrand Optical Co. (La Russa, no date) and called by them the "heads up" system or "infinity viewing system", has been suggested.

This system is completely analogous to the telescopes of Section V, but by enlarging the optics the entrance and exit pupils are made large enough to comfortably include both eyes of the observer to give stereoscopic binocular vision with a single telescope. The use of large concave spherical reflectors for eyepieces provides an extremely large eye relief but beam splitters as shown must be used. Each beam splitter transmits less than half the light, making the losses in such a system rather large.

Because of the requirement of the largest possible exit pupil, the entrance pupil must be located at the smallest diameter of the pressure window to avoid loss of field or vignetting. One or two negative lenses in the water outside the pressure window (as in the Baxter correctors) could aid greatly in correcting aberrations and extending the field of view. One should note that the weight of the large external lenses in such a plan is partially compensated by buoyancy.

A "heads up" or infinity viewing system brings the entire window to the observer's or pilot's eyes with considerable face clearance, but requires a large volume inside the pressure sphere. To cover a wide field of view with a large exit pupil and a large face relief requires huge optics.

VII. Scanning Systems.

Some proposed optical systems are designed to cover a large field by scanning. This is often proposed (for example Farrand (1966)) for external modules like those to be discussed in section VIII. In preparation for that section, the problems of optical scanning systems working across a pressure window will be outlined here.

The systems covered in sections VII and VIII are similar to a standard submarine periscope in that they are entirely visual with a fairly large finite field of view at any scanning position. They should not be confused with systems which, like scanning sonar or television, build up a picture on a screen by means of a scanned spot.

In wide angle telescopic systems with a forward entrance pupil, a small mirror or a small right angle prism at the entrance pupil (Figs. 18 and 19) is frequently used to scan a field of view. The prism introduces astigmatism of oblique rays. The mirror does not. The mirror, however, cannot scan as large a field as the prism can. For a given direction of the normal to the reflecting surface with either the mirror or the prism the direction of view is the same.

The important limitations of such scanning systems depend on a number of specifications:

- a. The angular size Ψ of the instantaneous field of view.
- b. The clearance d of the entrance pupil from the final surface.
- c. The aperture a of the entrance pupil.
- d. The index of refraction of the prism (if used) relative to that of the medium or fluid in which it moves.
- e. The linear dimensions of the scanning mirror or prism.
- f. The point about which the scanning mirror or prism rotates.
- g. The size of lens housings, etc., that may obstruct the view from the scanning element.

The approximate limitations of the scanning range of the mirror are given in Fig. 18 and Table I. It is clear that one cannot have simultaneously an extremely large stationary field of view Ψ and a large range ($\emptyset$ max - $\emptyset$ min) of radial scan, and that a thick window or large lens cell or window housing can also drastically reduce the range that can be scanned. Even in the limit of a very small entrance pupil, no window thickness and a lens cell that subtends an angle no larger than that subtended by the objective lens alone, one has:

$(\emptyset \text{ max} - \emptyset \text{ min}) = 180^\circ - 2\Psi$ which for an instantaneous field Ψ of 90° reduces to zero (or no radial scanning range). For $\Psi = 60^\circ$, $(\emptyset \text{ max} - \emptyset \text{ min})$ in this unrealistically ideal case could be 60° . Actually, even without a thick plane pressure window, the finite size of the entrance pupil and the lens cell would probably reduce this figure ($\emptyset \text{ max} - \emptyset \text{ min}$) to about 40° or less.

Table I. Region Scanned by Reflector at Entrance Pupil.
(Tabulated for various Parameters)

θ	=	rotation about axis of objective = 0 to 360
Ψ	=	instantaneous field of view (Fig. 21).
$\emptyset$	=	radial coordinate of center of field of view (Fig. 21).
$\emptyset \text{ max}$	=	maximum value of $\emptyset$ without vignetting.
$\emptyset \text{ min}$	=	minimum value of $\emptyset$ without vignetting or mechanical interference.
$\emptyset \text{ max}^*$	=	largest radial coordinate visible in any field.
$\emptyset \text{ min}^*$	=	$\emptyset \text{ max} + 1/2 \Psi$
	=	smallest radial coordinate visible in any field
	=	$\emptyset \text{ min} - 1/2 \Psi$
R	=	a limit parameter related to size of entrance pupil and relative size of window or lens cell, etc.
R	=	∞ if entrance pupil is very small and lens cell is no larger than lens, otherwise
$R \approx$	=	$\frac{1}{\emptyset \text{ min} - \Psi}$

Ψ	R	$\emptyset$ max	$\emptyset$ min	$\emptyset^*$ max	$\emptyset^*$ min	($\emptyset$ max - $\emptyset$ min)
90°		90°	90°	135°	45°	0°
60°	∞	120°	60°	150°	30°	60°
60°	72	115°	65°	145°	35°	50°
60°	36	110	70	140°	40°	40°
60°	24	105°	75	135°	45°	30°
50°	∞	130°	50°	155°	25°	80°
50°	36	120°	60°	145	35°	60°
50	18	110°	70°	135°	45°	40°
40°	∞	140°	40°	160°	20°	100°
40°	36	130°	50°	150°	30°	80°
40°	18	120°	60°	140°	40°	60°

The full specification relating the various parameters of the prism scan system to the field scanned is very complex. It may be simplified by assuming that the entrance pupil is near the center of the hypotenuse reflecting surface of the prism. (See Fig. 19) which shows the approximate geometry for this case when $\emptyset$ min = 0 for a glass (index 1.55) prism in air and water. In air a field Ψ of nearly 90° can be scanned to $\emptyset$ min = 0 but astigmatism is introduced, and the entrance pupil cannot be large. With the prism in water, the instantaneous field Ψ that can be scanned to $\emptyset$ min = 0 is reduced to about 20°. With glass of index 1.7, Ψ could be approx. 38°.

The increase in scanning range ($\emptyset$ - $\emptyset$ min) with a prism system occurs mostly in the $\emptyset$ min direction, $\emptyset$ max is still limited by the diameter of the lens and its cell. Both the prism and the mirror require clearance of the entrance pupil from the entrance surface which is difficult or impossible to achieve for wide angle systems using a plane pressure window, accordingly such scanning systems should use, if possible, a pressure window that is a portion of a sphere with the scanning element at the center of curvature. This has the further advantage in the prism scan that the full index of refraction of the prism in air can be effective in increasing the scan range.

With a hemispherical window the scan range can be increased if the window is mounted at an angle (approximately 45°) to the principal axis of the objective lens system and the whole housing is rotated about this axis as one of the scan motions.

VIII. Periscopic Systems Employing Modules External to the Main Pressure Hull.

To obtain a wider field of view, either simple or scanned, than that possible from a window recessed in the outer hull fairing, various systems using optical modules external to the pressure hull have been proposed. The present section deals with systems in which the external modules are more complex than those already discussed (sections III and IV), though in some cases the simpler systems also have an external element or two.

The proposals for more complex systems with external modules usually involve an air chamber for lenses outside the main hull. Use of such an air chamber involves a number of difficulties because its pressure hull and its windows must withstand the same pressure as the main hull. Because the windows of the main hull are relatively brittle structures, an implosion of apparatus just outside them could cause them to fail also. Therefore windows of the external chamber, if plane, must have a ratio of thickness to diameter at least as great as that used for windows of the main hull. The overall size of the external modules is limited to that which is practical for the DSRV to carry, and by the shape of the external fairing.

These requirements place rather severe restrictions on the optical properties of the external modules. Even if the windows in the external chamber could be the same size as those of the main hull, the angular extent (Fig. 20) of the image field presented at the inside surface of the main window is greatly reduced. A large field of view can be presented only if the telescopic magnification at this point is much less than unity. An internal telescope can be used to magnify the image finally seen, but imperfection caused by distortion of the surfaces and inhomogeneity of the windows will be magnified also.

Because of the minification between the initial window of the system and the transfer windows (Fig. 20), obliquity effects at the transfer windows are not so serious, but obliquity effects at the entrance windows of the modules must be considered.

The Farrand proposal (1966) gives some performance specifications for an ultra wide angle viewing system based on the diverging monoculars. An instrument configuration to achieve these specifications is also proposed. For the reasons outlined in Section VI, I think that the configuration proposed by Farrand with scan prisms in fluid and plane pressure windows transmitting wide angle fields is not likely to be successful. Assuming that the problem of mounting hemispherical pressure windows can be solved, the configuration of Figure 21 which avoids these undesirable designs is much more likely to achieve the desired results. In the design outlined in Fig. 21, housings A and C are the only external ones which contain air. In each of these the scan prism is located in air at the center of curvature of a hemispherical entrance window and a plane pressure window is used at the exit face where the angular extent of the image is less. Housing B which contains fluid at ambient pressure has a mirror and a relay lens for each eye. The relay lens must be specially designed to operate in fluid but since its focus is rather long the design would not be difficult. Scanning would be accomplished by rotating housings A and C about axis α and/or rotating the scan prism about an axis parallel to its hypotenuse face. The direction of view of the two eyes could be aligned or maintained at any desired divergence or convergence by a mechanical escapement or an electrical selsyn system. To erect the image from a scanning system a mirror or prism erector in the internal telescope section must be used. The correct image orientation can be maintained by the use of selsyns or escapements in the internal erectors which are oriented to compensate for the rotations introduced by the scan.

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Fig. 1 Semi-field of view of a 5" diameter plane window facing sea water. The angle of incidence in water of the most inclined ray of the field is plotted against the corresponding angle of refraction in air, and the distance from the window's air surface of a centered eye that can cover (through the window) the plotted angle of refraction.

Fig. 2 Differential sagittal magnification of a plane window facing sea water. The factor by which the angle subtended in the sagittal direction by a small object is increased by refraction through the window, is plotted as a function of the angle of incidence in water of the principal ray. The tangential magnification (i.e., that perpendicular to the inclination of the principal ray) is $4/3$ for all principal rays.

Fig. 3 Transverse chromatic aberration of a plane window facing sea water. The difference in angle of refraction in air of the C ($\lambda = 6563 \text{ Å}$) and the F ($\lambda = 4862 \text{ Å}$) rays is plotted as a function of the angle of incidence in water.

Fig. 4 Thin glass covers designed to bend with the window may protect the plexiglas from scratches and crazing.

Fig. 5 Jackman Corrector. A single negative lens inside the window broadens the field of view if the viewing distance d is long.

Fig. 6a Modified Jackman corrector, type 1. Eliminating the air space gives a slight improvement.

Fig. 6b Modified Jackman corrector, type 2. A positive lens on the outside of the window may be employed to reduce astigmatism and chromatic aberration for some values of d but the Ivanoff corrector or the partial Baxter corrector use two lenses to better advantage.

Fig. 7 Ivanoff Corrector. The negative lens at the inner surface of the window corrects the angle subtended by a submerged object the astigmatism and the chromatic aberration if used with a suitable positive lens placed at the nodal point. (See U. S. Patent #2,730,014).

Fig. 8 Modified Ivanoff Corrector. The meniscus form shown for the positive lens will reduce the aberrations for non-axial viewing positions, or forward entrance pupils.

Fig. 9 Baxter Corrector. Suitable for binocular vision from a head position near the window. The two water emersed negative lenses and the single positive air to glass surface can correct a field of 90° .

Fig. 10 Partial Baxter Corrector. One of the water emersed negative lenses of Fig. 9 can be omitted but one cannot then correct a field as wide as 90° .

Fig. 11 Annular Field Widener.

Fig. 12 Diverging type "rear view" mirrors.

Fig. 13 Double mirror. Bent reflecting telescope.

Fig. 14 Simple eyepiece-type wide-angle low-power monocular telescope.

Fig. 15 Eyepiece-type wide-angle low-power telescope with offset.

		diam.	FL
①	MENISCUS NEGATIVE	41 mm	-75 mm
②	PLANO CONCAVE	33 mm	-48 mm
③	" "	32 mm	-75 mm
④	ACHROMAT	39 mm	63 mm

Fig. 16 Preobjective with 170° field in air used to view 95° field in water.

Fig. 17 "Heads up" infinity image system for erect image presentation in DSRV.
a. Refracting objective type

Fig. 17 "Heads up" infinity image system for erect image presentation in DSRV.

b. Reflecting objective type

Fig. 18 Angular field of reflector type scanning system.

b. At minimum radial coordinate ϕ .

Fig. 19 Field of a prism scan system at $\phi_{\min} = 0^\circ$
 a. In air.

WATER
 $\mu = 1.34$

GLASS
 $\mu = 1.55$

Fig. 19 Field of a prism scan system at $\phi_{\min} = 0^\circ$

b. In water.

Fig. 20 External wide angle objective.

Fig. 21 External wide angle binocular scanning module.