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SUBMARINE VISIBILITY DETERMINING EQUIPMENT

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An engineering model of equipment intended to provide a real-time assessment of the concealment status of submarines is described. The concepts of the contrast of a submerged object and its measurement are carefully developed. A thorough description is provided of the technique for determining the contrast transmittance of the water at the depth of the submarine and for computing the ap apparent contrast of the submarine just below the surface.

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The functions of the photometric, electronic, and anolog computer systems developed for the equipment are described, and the techniques for their laboratory calibration and testing are given in detail. Field tests in San Diego Harbor and in San Diego coastal water were performed from a surface vessel. The equipment satisfactorily computed and indicated the concealment status of the simulated target, as well as the depth at which the target was just detectable.

A description is given in the appendix of a simple ancillary equipment whose purpose was to detect the presence of very short optical pulses. This simple equipment performed satisfactorily in the laboratory and in tests in a large water tank under simulated field conditions.

SUMMARY

This report describes in detail the development of the engineering prototype of a second generation of the Submarine Visibility Determining Equipment. The goal of the development was to provide a continuous visual display of the visibility or concealment status of a submerged submarine when viewed from above. The effect of the air-water surface on the detectability of a large submerged object was intentionally ignored. Since the ocean surface in some situations can cause significant additional obscuration of such targets, ignoring its effect provides a conservative estimate of the concealment status, i. e., the greatest visibility of the submarine is assumed.

It was demonstrated by tests performed in the laboratory and at sea that the apparent contrast of the submarine as viewed by an observer at the water surface could be satisfactorily computed by the equipment which was developed. The tests indicated that the equipment was capable of consistently determining the depth for threshold contrast to within ±10 percent and probably better. The "probably better" expectation is based on the fact that uncertainties in the environmental factors in the test procedures were of this order.

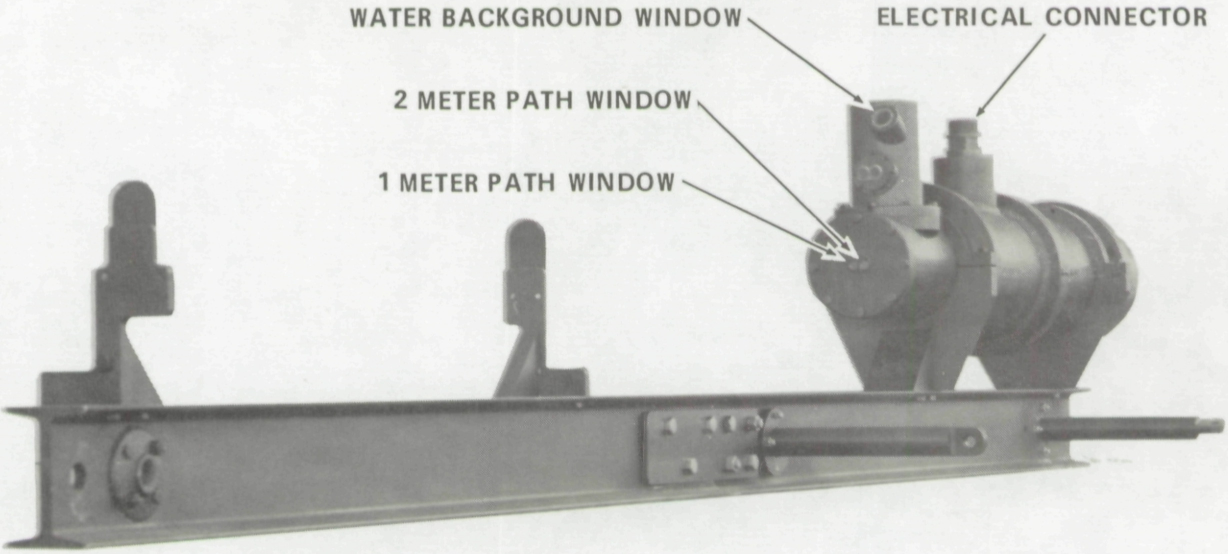
PREFACE

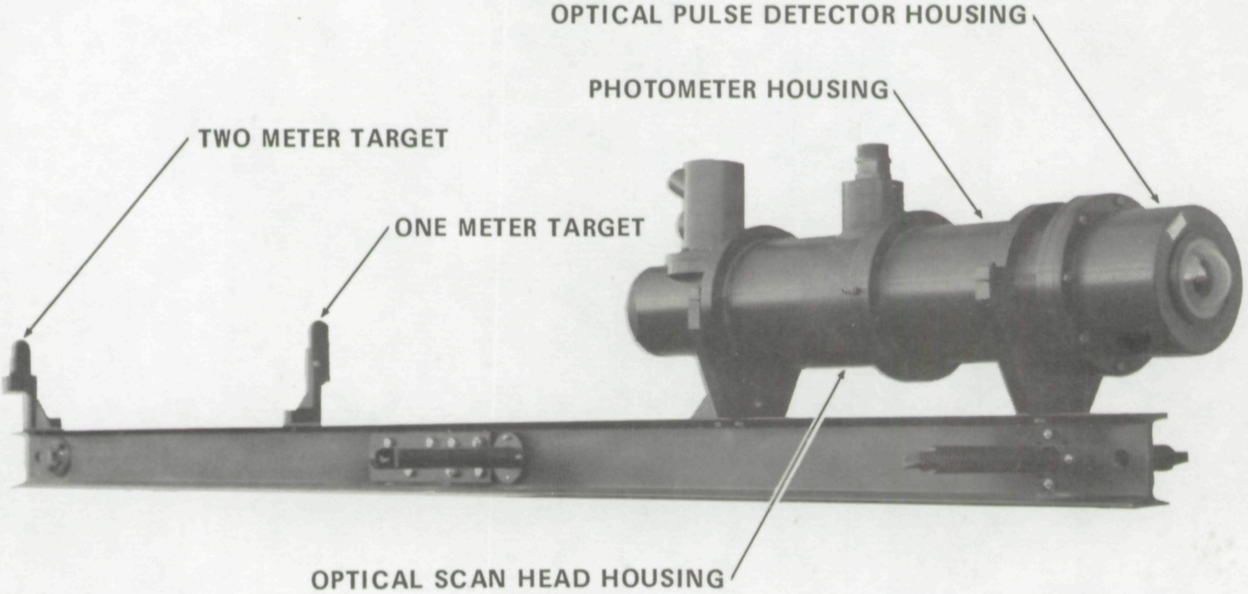
The equipment development described in this report was started in July 1968 under Contract N00024-68-C-1100, Modification P002. The contract provided support from the Naval Ship Systems Command for research and development by the Visibility Laboratory of the Scripps Institution of Oceanography in the general areas of optical surveillance and optical countermeasures. The work statement specifically provided that the Laboratory would undertake special optical tasks, as directed by the technical monitor, "in the fields of visibility, concealment, detection and electro-optical devices."

In Sections 1 and 2 of the report, we describe the general goals for the equipment and the background behind its development. The work was initiated under the same sense of extreme urgency that had existed during the spring of 1966 when the "first generation" Submarine Visibility Determining Equipment went from concept, through development, to hardware installed on submarines, in approximately 6-months elapsed time. Direct liaison between the Visibility Laboratory, NELC, and the fleet commands involved, was again authorized to expedite the development of this second generation equipment. Unfortunately, priorities and the competition for FY69 funds did not allow the implementation of the ADO which had been submitted to cover specific funding of this development. The lesser funding that was made available resulted in a considerable stretch in the schedule, and the sense of urgency greatly diminished as the project progressed. Some of the relaxation resulted from a reordering of the priorities of the many operational requirements by new personnel in the fleet-command structure. For whatever reason, the initial momentum -- which to a major extent resulted from the sense that we were responding to a real and immediate need of the fleet -- dwindled as the project progressed and the interest from the fleet and funding decreased.

This degree of interest by the fleet in the visibility of submerged submarines has been cyclical, and it may be reasonably assumed that an urgent requirement for the type of equipment described in this report may arise again in the future. It is our sincere wish that the measurement philosophy, instrument concepts and the insight into the problems of determining concealment status of a submerged object which the Visibility Laboratory developed in the course of the work described in this report will be of value to those confronted with the problem when it next arises.

In view of the currently reduced interest in going forward with this development to the next hardware and evaluation phase, it would be ludicrous to produce, at this time, detailed optical electrical and mechanical specifications for the equipment needed for that phase. Should such requirements arise, these specifications would best be prepared utilizing the state-of-the-art technology available at the time.





In Water Portion of the Submarine Visibility Determining Equipment and Optical Pulse Detector

TABLE OF CONTENTS

APPENDIX A: OPTICAL PULSE DETECTOR

SUBMARINE VISIBILITY DETERMINING EQUIPMENT

FINAL REPORT

1. INTRODUCTION

This program was conceived to develop onboard submarine equipment which could estimate and display continuously in real time the submarine's susceptibility to visual detection from above the surface. It is an adjunct to the concealment program which was concerned with camouflage measures to decrease a submarine's chances of visual detection. The two programs proceeded somewhat in parallel, with data from the concealment program, primarily the water properties portion, providing valuable inputs for the engineering development of the Submarine Visibility Determining Equipment.

Two completely different equipments have been developed. They are referred to as the first generation equipment and the second generation equipment. The first system was developed in early 1966 as a quick reaction response to a request from the Navy in late 1965. This system did not meet the desired goal of a simple "go/no-go" system but did provide the Navy, in a short period of time, with a compromise system. It required a minimally trained operator to read the displayed output signals and perform a few simple calculations. Five of these first generation systems were built at the Visibility Laboratory and used on submarines deployed in the Pacific.

Work on the second generation Submarine Visibility Determining Equipment started in 1968 with the effort continuing at a low level and sporadically until June 1972 when the first at-sea trials of an engineering model were performed. The outboard portion of this equipment, consisting of only one sensor and a scanning optical system, measures directly the inherent contrast of the submarine and the contrast transmittance properties of the water. A small onboard analog computer does the necessary computations and presents the results on an illuminated indicator as either "concealed" or "visible."

2. BACKGROUND

In the winter and spring of 1966 the Visibility Laboratory conceived, designed, built, and installed on submarines the first generation of an equipment which allowed the commanding officer to estimate the degree of his ship's visibility from above. This effort was initiated by NAVSHIPS in response to a request from an operational command in late 1965.

The type of equipment requested was to indicate simply that the submarine could or could not be seen from above. The equipment was to be installed on submarines being deployed. With the time available and the existing knowledge about the problem, it was not feasible to devise equipment which could meet this "yes" or "no" requirement. The compromise agreed to was that the equipment would measure the light incident on the hull, the reflectance of the water, and the attenuation coefficient for the ambient light field. Then, based on certain assumptions, a simple procedure involving a nomograph and a prepared schedule of computations would be used to compute the apparent contrast of the submarine as it might be seen by an observer just below the surface of the water. This represented a "worst-case" type of answer and did not involve any other assumptions about the location of the observer or about problems involving search. Under particular field situations, a command decision would still be required regarding the extent of visual exposure permissible. Five equipments were built, installed, and used on six different submarines in the period between May 1966 and June 1969.

The operational time for computing the apparent contrast of the submarine varied with the training and skill of the ship's personnel. However, about 5 minutes were required by the best crews to collect the data and make the computations. The consensus of the users was that this time was excessive and that the original concept of a visibility status display was required for future systems.

Another difficulty with the original system was that it required the use of seven photosensors distributed around the hull, all of which had to be kept in calibration. Marine growth (barnacles, tube worms, algae, etc.) on the collecting surfaces of these sensors caused major changes in their calibration. Compounding this problem were sensors located in areas not readily accessible to the crew for maintenance when the submarine was underway. Therefore, the answers provided by the equipment under these conditions were suspect.

The outputs from the sensors used in these first systems were displayed on panel meters and could also be recorded on a strip chart recorder for permanent record. Some of these records were forwarded to the Laboratory and provided valuable information about the status of the equipment, the proficiency of the ship's personnel in its operation, and, most important, provided data on the nature of the optical environment in which the submarines were operating.

The Visibility Laboratory was requested by NAVSHIPS to prepare a draft Advanced Development Objective (ADO) on the subject "Submarine Paint, Camouflage and Visibility Determining Equipment." The ADO draft was sent to NAVSHIPS in March 1968, but it was not implemented as submitted due to funding limitations in FY 69. However, the REWSON office was able to support a limited effort with funds provided by an existing ADO which was sufficiently broad to cover the basic objectives of the Visibility Laboratory submission. These funds were not adequate to support the recommended level of effort, and the time required for completion of a breadboard model for field testing was considerably greater as a consequence.

With this modest support provided by REWSON, the Visibility Laboratory did however, develop an engineering prototype of the second generation equipment and conduct preliminary evaluation at sea.

3. CONCEPTS OF SECOND GENERATION EQUIPMENT

3.1 PHILOSOPHY OF APPROACH

This program was intended to lead to the development of onboard submarine equipment which would estimate and display continuously in real time the submarine's susceptibility to visual detection from above the surface. Based on experience obtained from the first generation equipment and on evaluations provided by the users, concepts for a second generation equipment quite different from the first were developed.

The outboard portion of this equipment, which is mounted on the sail, uses a single photodetector and an optical scanner to measure directly both the radiance of two targets as seen through two different path lengths of water and the radiance of the water background against which the submarine is seen. The targets are mounted in the field of view of the optical scanner and painted with the same paint used on the submarine hull. The signals from the scanning radiometer are synchronously detected and demodulated to produce analog voltages representing relative values of the radiances. These signals are delivered via an underwater cable, which requires one hull penetration, to a small onboard solid state analog computer. Using these voltages along with a signal indicating the depth of the submarine, the contrast of the submarine against the water background and the contrast transmission property of the water are computed. From these, further computation produces the apparent contrast which would be presented to an observer at the surface. The results of this computed appraisal of the submarine's visibility status are presented as simple "visible" or "concealed" displays. In making the decision, the computer compares the computed apparent contrast with a preset visual threshold.

3.2 THEORY

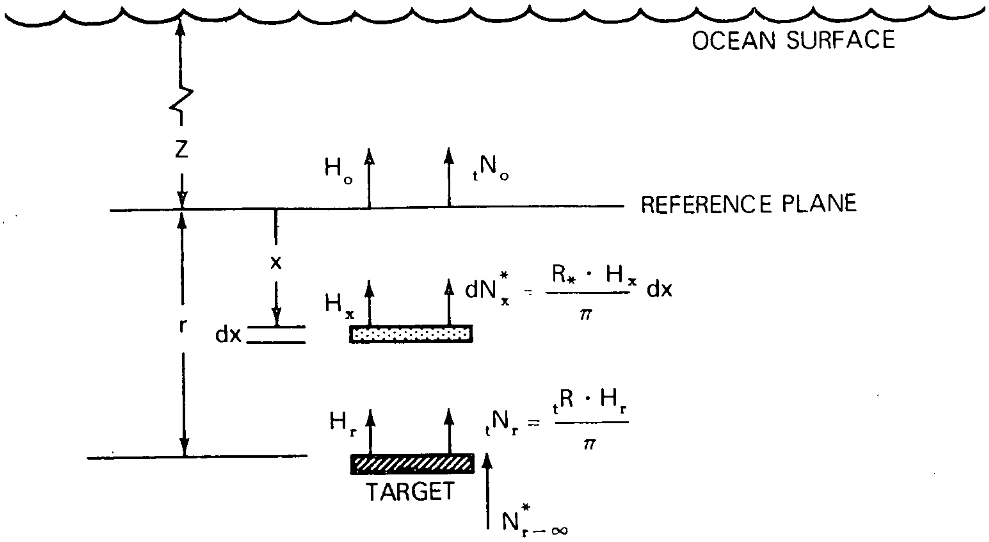
Let a submerged object at depth Z be viewed from above. If the inherent contrast of the object against the water background is C_o, and the contrast transmittance of the total water column above the object is τ_z, then the residual apparent contrast, C_z, remaining for detection by an observer situated at the surface is the product $C_z = C_o \cdot \tau_z$. If C_z is above the visual threshold determined by the angle subtended by the target and the adaptation level of the observer, the object is considered subject to detection. There is no way to measure the contrast attenuation over the total water column with an instrument installed on a submarine. The best estimate of this is obtained by determining the contrast transmittance over a short path and computing what it would be over the total distance if the water were uniform.

3.2.1 CONTRAST AND CONTRAST TRANSMITTANCE

The concepts of contrast and contrast transmittance are central to the problems of detection, concealment, and the analysis of the operation of the Submarine Visibility Determining Equipment (SVDE). The following paragraphs develop these concepts in the context of the system to be described.

Imagine a reference plane at a depth Z below the surface of the water with a small target located a distance r below this plane. The water is assumed to be uniform in its optical characteristics with an attenuation coefficient K for the natural downwelling ambient irradiance and an attenuation coefficient α for image-carrying radiance. The ocean bottom will be assumed to be contributing negligible return signal so that the background against which the submarine will be seen will be the backscattered light from the water which is the path radiance for the downward path of sight. If the bottom is visible the background radiance will be determined by a combination of the path radiance for the path of sight from the target reference plane to the bottom, and the residual bottom radiance as observed at the reference plane. Although the effect of the bottom has not been included in this analysis, the final result would not be affected by its inclusion.

The following sketch illustrates the problem.



The notation used will be:

τ_r = contrast transmittance over path length r

r = path length (downward distance from reference plane to target)

Z = depth of reference plane below the surface

H_o = irradiance at the reference plane (i.e., at depth Z)

H_r = irradiance at a distance r below the reference plane (depth Z + r)

${}_tN_r$ = inherent radiance of target at distance r below reference plane

N^*_{a-b} = path radiance over path a-b. The radiance contributed as space light due to scattering in the water.

${}_tR$ = directional reflectance of target in vertical direction

R_* = directional reflectance of water for unit path length

α = volume attenuation coefficient

K = diffuse light attenuation coefficient

The irradiance arriving at depth Z is designated H_o, and the irradiance falling on the target is designated H_r. Part of the light arriving at the target will be reflected upward and the inherent radiance of the target will be

$${}_tN_r = \frac{H_r \cdot {}_tR}{\pi} \quad .$$

H_o is attenuated in traversing the water path, r, and $H_r = H_o \cdot e^{-Kr}$, hence by substitution,

$${}_tN_r = \frac{H_o \cdot {}_tR}{\pi} e^{-Kr} \quad . \tag{1}$$

Universal contrast, C, is defined as the difference between the radiance of the target and the background radiance divided by the background radiance, i.e., $C = ({}_tN - {}_bN)/{}_bN$. The inherent contrast of the target against the water (i.e., the contrast at zero observation distance, hence with no contrast loss) is

$$C_o = \frac{{}_tN_r - N^*_{r-\infty}}{N^*_{r-\infty}} \tag{2}$$

where the path radiance of the water below the target $N^*_{r-\infty}$ is the background radiance. The apparent contrast of a target located a distance r below an observer at the reference plane, i.e., observed from depth Z, will

$$C_r = \frac{{}_tN_o - N^*_{o-\infty}}{N^*_{o-\infty}} \quad . \quad \dagger \tag{3}$$

The inherent radiance of the target, ${}_tN_r$, is attenuated by the water over the path r, and path radiance, N^*_{o-r}, is introduced over this path by scattering. The apparent radiance at the reference plane then becomes

$${}_tN_o = {}_tN_r \cdot e^{-\alpha r} + N^*_{o-r} \quad . \tag{4}$$

The path radiance component, N^*_{o-r}, may be determined in the following manner. The light flux H_x arriving at a laminar element dx located a distance x below the reference plane, is scattered by the water in the laminar. Some of this scattered light is returned upward as an element of radiance, dN^*_x, viz.

$$dN^*_x = \frac{R_*}{\pi} \cdot H_x \cdot dx \quad . \tag{5}$$

This upward traveling incremental radiance is also attenuated as it traverses the distance x and arrives at the reference plane. Hence,

$$dN^*_o = \frac{R_*}{\pi} \cdot H_x \cdot e^{-\alpha x} \cdot dx \quad . \tag{6}$$

The downwelling irradiance H_x arriving at x may be expressed as

$$H_x = H_o \cdot e^{-Kx} \quad . \tag{7}$$

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† Note: The notation is special to this development and the lack of correspondence in the subscripts o and r between the left and right sides of Eqs. (2) and (3) is intentional. These subscripts on C indicate the distance from the target. When used on N or H, they indicate the vertical distance below the reference plane.

Substituting Eq. (7) into Eq. (6) and integrating gives

$$N^*_{o-r} = \frac{R_*}{\pi} \cdot H_o \int_o^r e^{-(\alpha+K)x} dx$$

or

$$N^*_{o-r} = \frac{H_o \cdot R_*}{\pi(\alpha+K)} [1-e^{-(\alpha+K)r}] \quad . \tag{8}$$

Also, when $r = \infty$ in Eq. (8), we obtain for the radiance of the water background,

$$N^*_{o-\infty} = \frac{H_o \cdot R_*}{\pi(\alpha+K)} \quad . \tag{9}$$

Now substituting Eq. (8) for N^*_{o-r} and Eq. (1) for ${}_tN_r$ in Eq. (4), we obtain for the apparent radiance of the target

$${}_tN_o = \frac{H_o \cdot {}_tR}{\pi} \cdot e^{-(\alpha+K)r} + \frac{H_o \cdot R_*}{\pi(\alpha+K)} [1-e^{-(\alpha+K)r}] \quad . \tag{10}$$

Inserting Eqs. (9) and (10) into Eq. (3) we obtain the following expression for the apparent contrast:

$$C_r = \frac{\frac{H_o \cdot {}_tR}{\pi} \cdot e^{-(\alpha+K)r} - \frac{H_o \cdot R_*}{\pi(\alpha+K)} \cdot e^{-(\alpha+K)r}}{\frac{H_o \cdot R_*}{\pi(\alpha+K)}}$$

or

$$C_r = \frac{\frac{H_o \cdot {}_tR}{\pi} - \frac{H_o \cdot R_*}{\pi(\alpha+K)}}{\frac{H_o \cdot R_*}{\pi(\alpha+K)}} \cdot e^{-(\alpha+K)r} \quad . \tag{11}$$

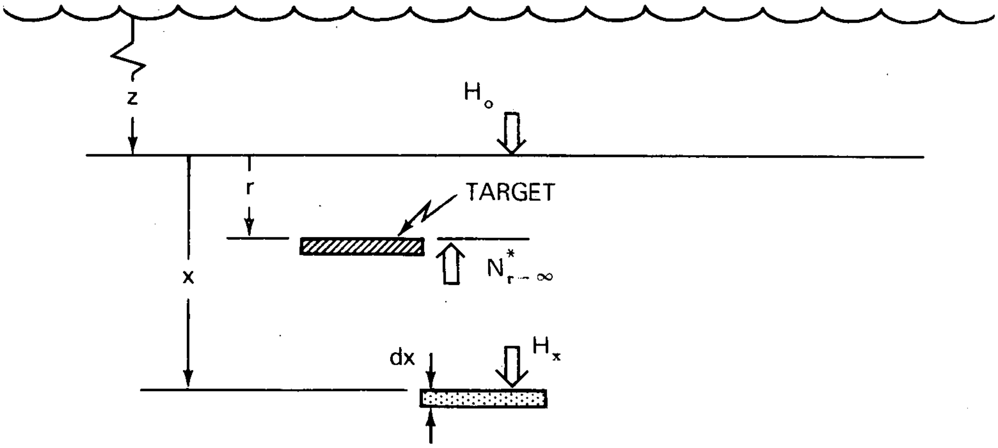
The contrast transmittance, τ_r, is the ratio of the apparent contrast, C_r, to the inherent contrast, C_o, i.e.,

$$\tau_r = \frac{C_r}{C_o} \quad .$$

Equation (2) for C_o contains the terms ${}_tN_r$ and $N^*_{r-\infty}$ and we will now derive an alternate expression for C_r in these terms. From Eq. (1) we see that

$$\frac{H_o \cdot {}_tR}{\pi} = {}_tN_r \cdot e^{Kr} \quad . \qquad (1a)$$

We next obtain an expression for $N^*_{r-\infty}$ which is the water background radiance seen from depth z+r, the plane of the target. Place a laminar, dx, below z+r so that $x > r$ as shown below:



As before, the irradiance arriving at x is

$$H_x = H_o \cdot e^{-Kx} \quad .$$

The element of radiance scattered upward is

$$dN^*_x = \frac{H_x \cdot R_*}{\pi}\, dx \quad .$$

This is attenuated over the path x-r and the remaining radiance from dx travelling upward at r is

$$dN^*_r = \frac{H_x \cdot R_*}{\pi} \cdot e^{\alpha(x-r)} \cdot dx$$

$$= \frac{H_o \cdot R_*}{\pi} \cdot e^{-Kx} \cdot e^{-\alpha(x-r)} \cdot dx$$

and

$$N^*_{r-\infty} = \frac{H_o \cdot R_*}{\pi} \int_r^\infty e^{-(\alpha+K)x+\alpha r} \cdot dx$$

or

$$N^*_{r-\infty} = \frac{H_o \cdot R_*}{\pi\ \alpha} \cdot e^{-Kr} \quad . \tag{12}$$

Substituting Eqs. (1a) and (12) into (11), we obtain for the apparent contrast,

$$C_r = \frac{{}_tN_r \cdot e^{Kr} - N^*_{r-\infty} \cdot e^{Kr}}{N^*_{r-\infty} \cdot e^{Kr}} \cdot e^{-(\alpha+K)r}$$

$$= \frac{{}_tN_r - N^*_{r-\infty}}{N^*_{r-\infty}} \cdot e^{-(\alpha+K)r} \quad ,$$

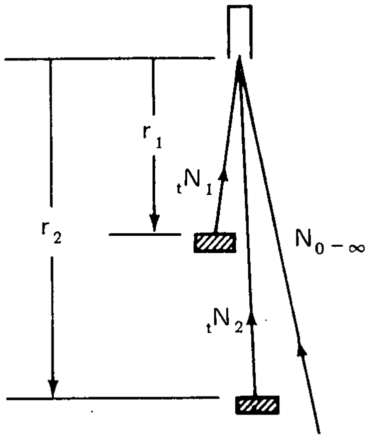
and referring to (2), we see that

$$C_r = C_o \cdot e^{-(\alpha+K)r} \quad . \tag{13}$$

The contrast transmittance over the path length r is therefore

$$\tau_r = e^{-(\alpha+K)r} \quad .$$

If measurements are made of the apparent radiance of a target at distance r_1, of an identical target (same submerged reflectance) at distance r_2, and of the water background radiance to obtain values for ${}_tN_1$, ${}_tN_2$, and $N_{o-\infty}$, respectively, then the contrast transmittance over the path from r_1 to r_2 can be computed. The sketch below illustrates schematically a scanning radiometer which looks downward and can measure these three radiances.



From Eq. (13) the ratio of the apparent contrast at distance r_2 to the apparent contrast at distance r_1 is

$$\frac{C_{r_2}}{C_{r_1}} = e^{-(\alpha+K)(r_2-r_1)}$$

$$= \tau_{(r_2-r_1)} \qquad (14)$$

which is the contrast transmittance for the path difference, $r_2 - r_1$.

The apparent contrast of the target at r_1 can be computed using the measured radiance values from

$$C_{r_1} = \frac{{}_tN_1 - N^*_{0-\infty}}{N^*_{0-\infty}}$$

and for the target at r_2

$$C_{r_2} = \frac{{}_tN_2 - N^*_{0-\infty}}{N^*_{0-\infty}} \quad .$$

Then from Eq. (14), the contrast transmittance over the path $r_2 - r_1$ is

$$\tau_{(r_2-r_1)} = \frac{C_{r_2}}{C_{r_1}}$$

$$\tau_{(r_2-r_1)} = \frac{{}_tN_2 - N^*_{0-\infty}}{{}_tN_1 - N^*_{0-\infty}} \quad , \tag{15}$$

which is the ratio of the radiance difference each target presents with the water background.

3.2.2 CALCULATION OF SUBMARINE VISIBILITY STATUS

A submarine at depth Z which presents an inherent contrast C_o against the surrounding water background will have an apparent contrast to an observer at the surface of

$$C_r = C_o \cdot \tau_z \quad , \tag{16}$$

where τ_z is the contrast transmittance through the total water column above the submarine. If C_t is the visual threshold, then the submarine is considered subject to detection, or visible, if

$$\frac{C_r}{C_t} > 1$$

and concealed when

$$\frac{C_r}{C_t} < 1 \quad .$$

Section 3.2.1 describes a means of obtaining the contrast transmittance over a short path whose length is the separation between two targets, $r_2 - r_1$. If we call this distance between the targets ℓ, i.e., $\ell = r_2 - r_1$, and call the contrast transmittance determined for this short path τ_ℓ, then, assuming the water above the submarine to be uniform, the contrast transmittance for the total path, Z, is

$$\tau_z = (\tau_\ell)^{Z/\ell} \quad . \tag{17}$$

The radiance measurements described in Section 3.2.1 and used to compute τ_ℓ can also be used to compute the contrast of the submarine against the water background as seen through a short path length r_1 or r_2. This is true, however, only if the targets are painted with the same paint used on the horizontal surfaces of the submarine. The contrast as seen through path length r_2 would be

$$C_{r_2} = \frac{{}_{t}N_{2} - N^{*}_{o-\infty}}{N^{*}_{o-\infty}}$$

and since

$$C_{r_2} = C_o (\tau_\ell)^{r_2/\ell} \quad ,$$

therefore,

$$C_o = \frac{{}_{t}N_{2} - N^{*}_{o-\infty}}{N^{*}_{o-\infty}} \cdot \frac{1}{(\tau_\ell)^{r_2/\ell}} \ . \qquad (18)$$

Substituting Eqs. (17) and (18) into (16), we get for C_r the apparent contrast to an observer at the surface,

$$C_r = \frac{{}_{t}N_{2} - N^{*}_{o-\infty}}{N^{*}_{o-\infty}} (\tau_\ell)^{(z-r_2)/\ell} \quad . \qquad (19)$$

From Section 3.2.1, Eq. (15),

$$\tau_\ell = \frac{{}_{t}N_{2} - N^{*}_{o-\infty}}{{}_{t}N_{2} - N^{*}_{o-\infty}} \quad .$$

The notation previously necessary for a detailed analysis will be simplified at this point. We will designate the apparent radiance of the two targets as observed at the reference plane (photometer location) as

N_1 (i.e., $N_1 = {}_{t}N_{1}$)

N_2 (i.e., $N_2 = {}_{t}N_{2}$)

and the path radiance of the water background as

$$N^*_\infty \text{ (i.e., } N^*_\infty = N^*_{0-\infty}\text{)}.$$

We can now write for the apparent contrast of the submarine as seen from the surface,

$$C_r = \frac{N_2 - N^*_\infty}{N^*_\infty} (\tau_\ell)^{(z-r_2)/\ell}$$

$$C_r = \frac{N_2 - N^*_\infty}{N^*_\infty} \left[\frac{N_2 - N^*_\infty}{N_1 - N^*_\infty}\right]^{\frac{z-r_2}{\ell}} \quad . \qquad (20)$$

In the prototype instrument the path lengths r_2 = 2 meters and r_1 = 1 meter were chosen. The photometer produces voltages proportional to radiance. With a pressure transducer a voltage proportional to depth is furnished. If C is a proportionality factor determined by the collection optics of the radiometer and the electronic gain of the photometer, the voltage signals can be related to the radiances and depth as follows:

$$e_1 = \frac{1}{C} N$$

$$e_2 = \frac{1}{C} N$$

$$e_3 = \frac{1}{C} N^*$$

$$e_z = \frac{1}{10} Z \text{ (Z in meters)}$$

With these voltage relationships and the distances fixed, Eq. (20) can be rewritten in terms of the analog voltages:

$$C_r = \frac{e_2 - e_3}{e_3} \left(\frac{e_2 - e_3}{e_1 - e_3}\right)^{(10e_z - 2)} \quad . \qquad (21)$$

With this equation we can, by making three relative measurements of radiance and knowing the depth, compute the apparent contrast of the submarine as viewed from the surface if the water above the submarine is assumed to be uniform.

3.3 PRACTICAL PROBLEMS

3.3.1 FACTORS AFFECTING THE INSTRUMENT DESIGN

The engineering prototype is not intended to be a final design for shipboard use; however, during the design stage it was thought that the system would undergo testing and evaluation aboard a submarine. With this in mind, although no great attempt was made to minimize the bulk, the control and computer assembly was designed so it could be taken aboard through normal access routes. Also, the in-water portion was designed to be mounted as a unit on the sail and be sturdy enough to withstand the buffeting and pressures which would be encountered.

Sensitivity is a design problem involving tradeoffs between the size of the optics, optical scan system, field of view, target size, and length of water path to the targets. The goal was to design the instrument to perform in waters varying from clear deep ocean water to turbid harbor or estuary waters. If the path lengths are short, the difference in the radiances of the two targets is small in clear water; long path lengths make these radiance differences small in turbid water due to the veiling effect of scattered light. There is no easy way out of this unless the path length can be adapted to the type of water in which the vessel is operating. To operate with a fixed path length over a wide range of water types, the instrument must resolve signal differences of less than one part in one thousand. In an analog device such as this instrument is, this imposes stringent requirements on the photometer and electronics. Noise and zero offsets must be kept low. Since the measurements are all relative, long term gain drift is not a problem, however.

If the instrument is to be usable at all depths, in all types of water, and under all sun elevations and cloud cover situations where visual detection is a possibility, it must operate over a large dynamic range of ambient light levels. This functional necessity required a system that would operate at low as well as high light levels, determining the relative radiances at the low light levels without saturating the electronics at the high light levels.

Another problem associated with the instrument's use in ocean water concerned the selection of the time constant for its speed of response. The instrument's function should not be affected by the optical noise generated by sunlight passing through the capillary wavelets on the surface or by particles in the water passing through the field of view. The response, then, must be slow enough to damp out these frequencies. But it should react to frequencies with periods of gravity waves in order to contend with the situation where the submarine may be concealed when the crest of a swell is overhead but visible as the trough passes by.

A problem not anticipated during the design phase, but perhaps reducible in future redesign, was the difficulty in achieving enough precision in the photometric calibration and testing of the instrument to insure proper results. Much time was spent in working out techniques for this calibration before satisfactory results were achieved.

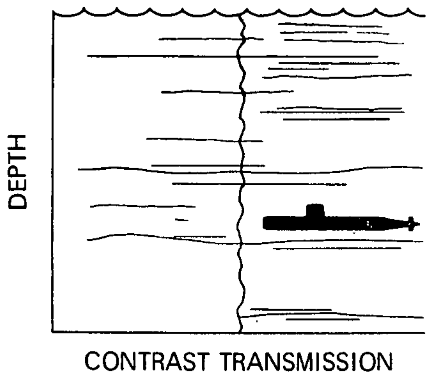
Attempts to check the calibration of the photometric section during field testing were not satisfactory. The lighting under field conditions is not uniform or stable enough for this, and some sort of special test device would probably be required if field checks of overall performance are desired. In use, there has been no evidence of short term calibration drift in the photometer. On the other hand, the computer section can be easily tested by switching in the fixed test inputs and by making minor adjustments if necessary. The computer does have a warmup drift and requires about an hour to stabilize. Using the better solid state components now available would greatly improve the stability of the computer section.

Paint control will be required if this system is to be used for operational purposes. The results will be valid only if the two targets on the instrument and the horizontal surfaces of the submarine are closely matched in reflectance properties. This requirement applies particularly to the top of the sail area, including all devices located there, since this area is the most susceptible to detection simply because it is nearest the surface. The two targets should always be coated with paint from the same batch and mix as that used to coat the top of the sail and other horizontal surfaces.

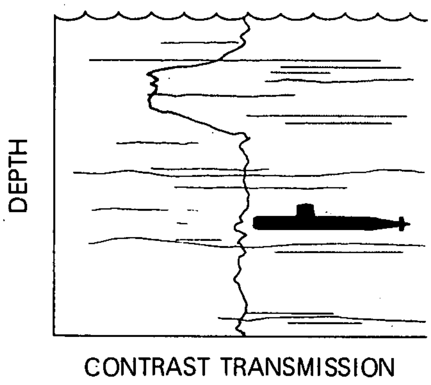
The problems which will be introduced if long term submerged operation is required have not been considered in this design. The type of measurement this equipment makes requires that the underwater window surfaces be clean. Contamination of these windows would have to be prevented, by some means, for long term submerged use. Similarly, deterioration of the paint surfaces of the targets and of the horizontal areas of the submarine, caused by weathering and growth encrustations, could also render the system useless.

3.3.2 FACTORS BEYOND SCOPE OF SYSTEM

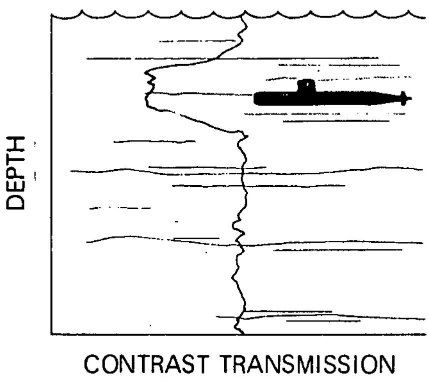
This system makes optical measurements from which the visual signal transmission properties of the water (contrast transmission) and the strength of the initial signal (inherent contrast) are determined. Using this information, the visual signal level arriving at the surface is computed. To do this, it is necessary to make two assumptions. 1) The overall contrast of the submarine against the water is the same as that determined by measurement on a small sample area. The requirement for paint control has been discussed in Section 3.3.1. 2) The optical properties are determined for the water at the depth where the instrument is located. The transmission of the signal through the water column above the submarine is computed on the assumption that the water above the instrument has optical properties similar to those measured. If this assumption is not so, some error will result. Three hypothetical cases are illustrated below. The curves represent a vertical profile of contrast transmission for each situation.



Case I



Case II



Case III

Case I

This fits the model of assumed uniform water above the submarine, and the visual threshold depth indicated by the SVDE should be correct.

Case II

The SVDE indicates the submarine is at visual threhold depth, and a layer of more turbid water lies above.

For this situation the computed threshold depth is greater than the depth actually required due to the additional obscuring effect of the turbid overhead layer. This is a "safe" case where the system indicates the submarine is at threshold contrast whereas it is actually deeper than necessary for security from visual detection.

Case II

The SVDE indicates the submarine is at visual threshold depth, and the water above is clearer than the water at the depth of the submarine.

In this case, the instrument indicates a concealed condition when the submarine is in fact subject to detection.

Sea state and sky lighting conditions are factors which enter into the visibility problem. A high sea state with significant wave structure and white water of course makes visual detection much more difficult. To a lesser extent, sun elevation and cloud cover affect the detectability of objects below the surface with the best "seeing" occurring with the sun at moderate to large elevation angles and a clear blue sky overhead. At the present time a "worst case" situation is assumed, and no allowances are made for the sea surface or sun and sky condition.

3.4 RANGE OF VARIABLES

The following table lists the parameters of the visibility problem and the range of these variables over which the instrument is designed to operate.

Parameter	Symbol	Range Minimum	 Maximum
Total Volume Attenuation Coefficient	α	0.08 m^{-1}	2.0 m^{-1}
Diffuse Attenuation Coefficient	K	0.04 m^{-1}	0.4 m^{-1}
Contrast Transmittance (Per Meter)	τ	0.1	0.9
Depth (Non-Operating Design Depth 2000 Ft)	Z	1 m	100 m
Inherent Contrast of Submarine	C_o	-1	+10
Apparent Contrast of Submarine (Computed)	C_r	-1	+10
Ambient Light Level	E_z	100 fc	12,000 fc
Submerged Reflectance of Topside Paint	R_o	1.5 %	16 %

The range of water-dependent parameters, α, K, and τ, covers waters from very clear to very turbid. The range for the inherent contrast assumes a dark paint on the submarine (submerged reflectance, R_o, between 1.5 and 16 percent).

3.4.1 MINIMUM AMBIENT LIGHT

The ambient light which reaches a submarine is determined by the amount of light entering the surface, the diffuse transmittance, and the depth of the submarine. If the submarine is at depth Z, the contrast transmission for the downward-looking case from depth Z to the surface is

$$\tau_z = e^{-(\alpha+K)Z} \quad .$$

The transmission for diffuse light from the surface to the same depth is

$$T_z(\text{Diff.}) = e^{-KZ}$$

$$= e^{-(\alpha+K)Z} \cdot \frac{K}{\alpha+K}$$

therefore

$$T_z(\text{Diff.}) = \tau_z^{\frac{1}{1+\alpha/K}}$$

Now as the contrast transmittance is

$$\tau_z = \frac{C_r}{C_o} ,$$

the diffuse transmittance can be written as

$$T_z(\text{Diff.}) = \left[\frac{C_r}{C_o}\right]^{\frac{1}{1+\alpha/K}} \tag{22}$$

Equation (22) provides a means to compute the diffuse transmittance and thus the ambient light level at the submarine for any inherent contrast, C_o, and apparent contrast, C_r, based on the optical parameters α and K for the water. The ambient downwelling light level at depth Z will be

$$E_z = E_o \cdot T_z(\text{Diff.}),$$

where E_o is the amount of light (illuminance) passing through the ocean surface. For high suns and clear skies, the surface illuminance E_o is around 10,000 foot candles. When the solar elevation angle is less than about 20 degrees, seeing into the water becomes difficult, and the detection of below-surface objects having moderate to low apparent contrast becomes unlikely. At that sun angle the horizontal illuminance at the surface will be about 2500 foot candles.

Figure 1 presents a family of curves computed from Eq. (22). The submarine is considered to be at a depth which places it at threshold contrast; i.e., $C_r = C_t = 0.005$. The diffuse transmittance to this depth is plotted versus the ratio α/K for four values of inherent contrast of the submarine, C_o, from a low of 0.01 to a high of 10. The range of α/K which is found in ocean waters varies from a value slightly over 1, say 1.4, in very clear water with extremely low scattering, to values of 7 or 8 in turbid waters having substantial scattering. We can see with the aid of Fig. 1 how the various system and environmental constraints work to bound the range of operating conditions. For example, the situation where the inherent

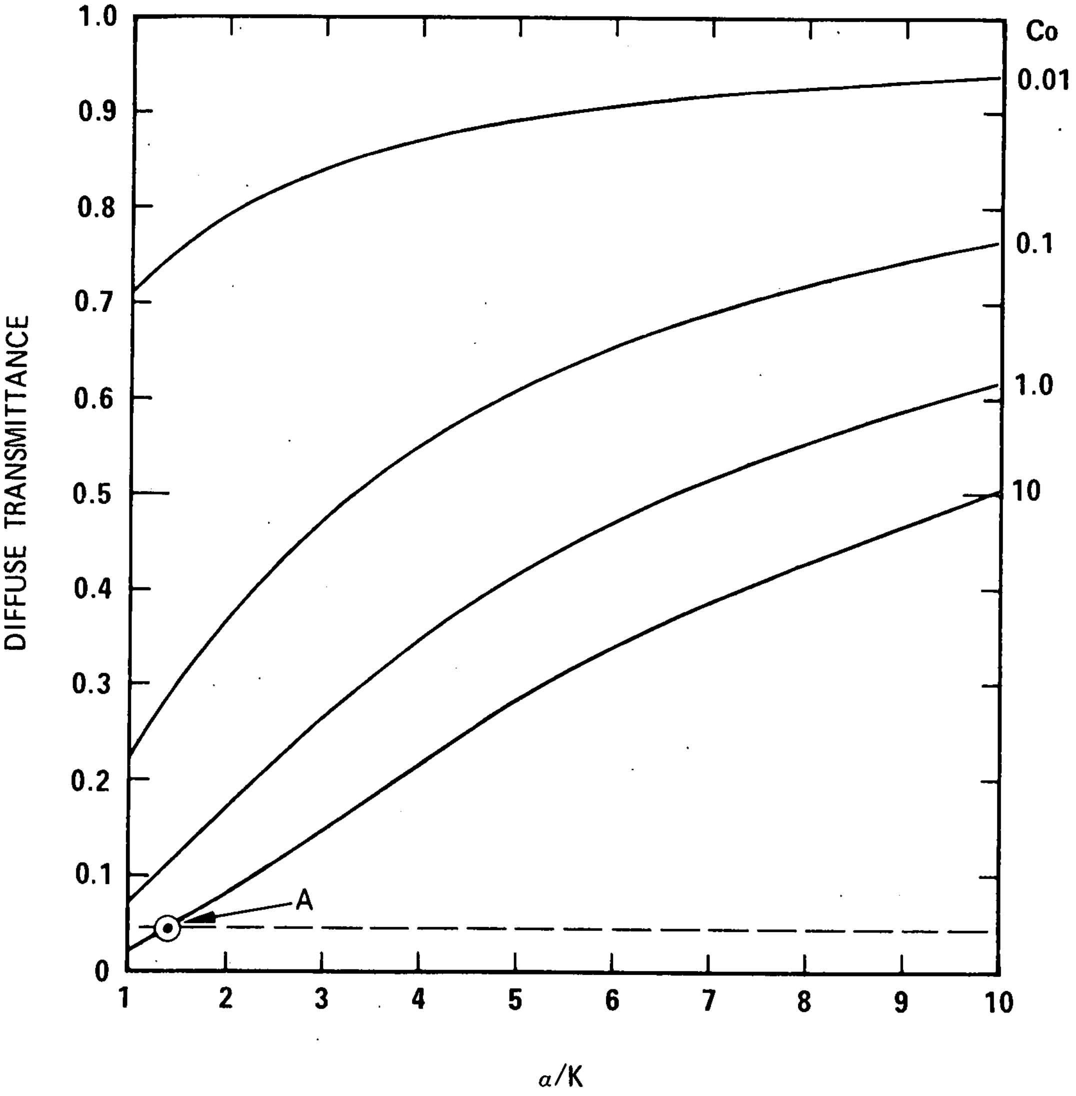


Fig. 1. Curves show the transmittance of the diffuse light field from the surface to the depth at which threshold contrast is reached. Curves for four values of the inherent contrast of the submarine, C_o, are presented, i.e., $C_o = 0.01$, 0.1, 1.0 and 10. Threshold is reached when the apparent contrast, C_r, has been reduced to 0.005. a/K is the ratio of the volume attenuation coefficient to the diffuse attenuation coefficient. The point "A" represents the minimum ambient light condition (at the depth of the submarine) under which the system is likely to have to perform. Thus with a very high inherent contrast of 10 in clear waters with $a/K = 1.36$, a diffuse transmittance of 0.04 would occur at the depth where the apparent contrast had been reduced to threshold (i.e., $C_r - 0.005$ and $\tau_z = 0.0005$). For surface illuminance of 2500 fc (solar elevation 20° and clear sky), the resulting ambient light at the submarine would be 100 fc.

contrast is 10 (the lower curve) represents a very bad mismatch between the submarine paint and the water reflectance. This would occur only if the submarine has a submerged reflectance in excess of 16 percent and is being viewed in the clearest of ocean water (where the water reflectance might be as low as 1.5 percent). Under these conditions, we might expect that $\alpha/K = 1.4$, and we see from Fig. 1 that the inherent contrast of 10 is reduced to the threshold contrast when the diffuse transmittance is about 0.04 (Point A on the lower curve). For this transmittance the illumination level at the instrument will be 100 fc (the minimum ambient level) when the surface illuminance is 2500 fc, and the keel depth required to reach this threshold concealment condition would be about 300 feet. The bulk, if not all, of the situations where visual detection is a possibility will occur when the ambient light level at visual threshold depth is 500 fc or above. The instrument was designed to cover all cases and will operate over an ambient light level range from 100 to 12,000 fc.

Although the instrument is designed to handle a contrast range from -1 to +10, this span will not be required if the submarine is properly coated with a dark concealment paint. If the submerged reflectance, R_0, is between 1.8 and 3.0 percent, the contrast will lie between -1 and +1 for almost all water types.

4. DESIGN AND OPERATION OF MODEL FOR ENGINEERING EVALUATION

4.1 SYSTEM DESCRIPTION

Section 3.2 shows that if the relative values of three particular radiances are known, then the apparent radiance of the submarine as seen from the surface can be computed. The radiances needed are the water background and those seen when looking downward at two targets, both painted with the paint used on the horizontal surfaces of the submarine. One target is viewed through 1 meter of water and the other target through 2 meters of water.

The photometric and computer sections will be described separately; but first it would be best to understand the overall system without great detail. Figure 2 is a simplified block diagram of the complete system -- from the light inputs into the photometer, to the output display. An optical scanning device looks sequentially at 1) a small area on target No. 1, 2) a small area on target No. 2, and 3) the water background. This light is transmitted to a photodetector with a linear response which produces a series of electrical pulses. These pulses have amplitudes proportional to the three radiance values. A synchronous detector, keyed by the scanner, separates the three pulse signals into three channels, and an integrator converts these into three analog voltages. A fourth voltage signal, supplied by a pressure transducer, provides the depth information. These four signals are sent via underwater cable to a small solid state analog computer. From these inputs a voltage representing the apparent contrast of the submarine viewed from just below the water surface is computed, and this is compared with a preset voltage which represents visual threshold. The result is displayed as either the word "visible" on a warning red background or "concealed" on a green background depending on whether or not the computed contrast exceeds the threshold contrast.

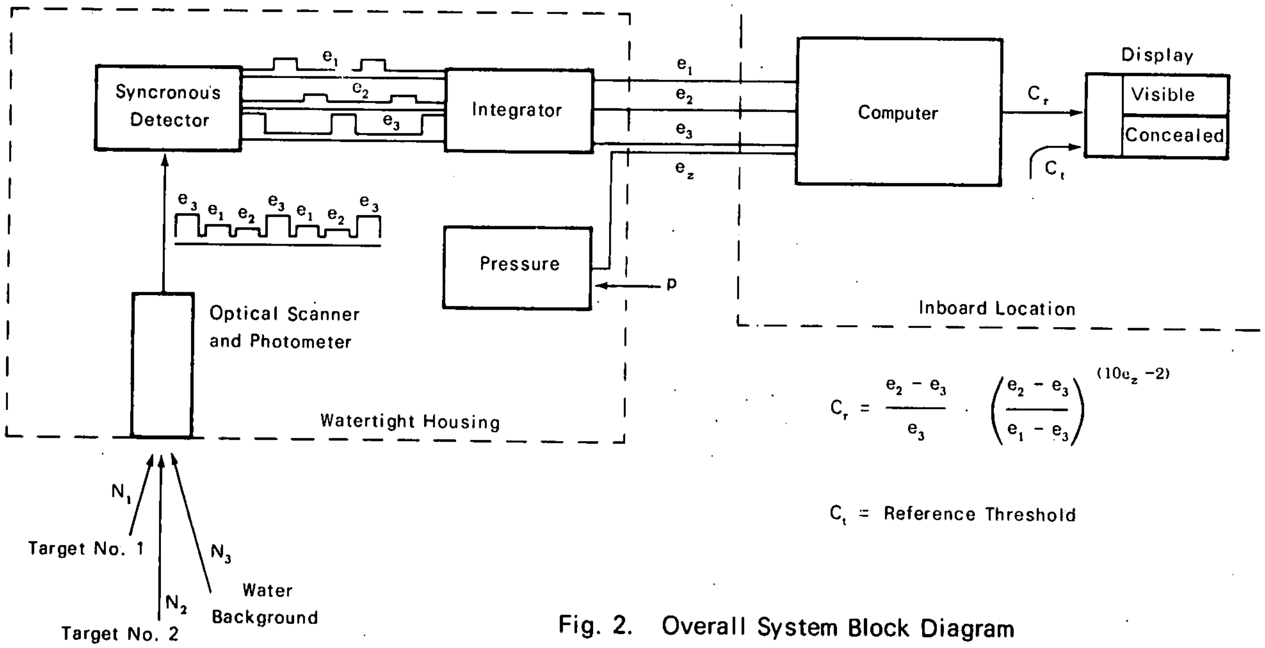


Fig. 2. Overall System Block Diagram

4.2 PHOTOMETRIC SYSTEM

The photometric system consists of an optical scanner, a detector and a photometer demodulator circuit. The scanning system allows light flux from the two targets and the water background to arrive at the detector individually in time sequence. The use of one detector insures that any change in sensitivity will affect all measurements equally. Since only relative measurements are required, the detector and photometer need to have only a linear response; long term absolute stability is not required.

4.2.1 OPTICAL SCANNER

Figure No. 3 illustrates the scheme used to achieve the scanning. Any light arriving at the detector enters through the entrance aperture and the objective lens. Near the focal point of the objective lens in the field plane is a plate with three small holes. Each hole defines a field of view. Two of these holes allow light from a small area on each of the two targets to pass through; the third passes light from the water background which has entered via a window and some relay prisms. Behind these field apertures lies a rotating scan disk which has slots arranged to open one aperture at a time, in sequence, as the disk rotates.

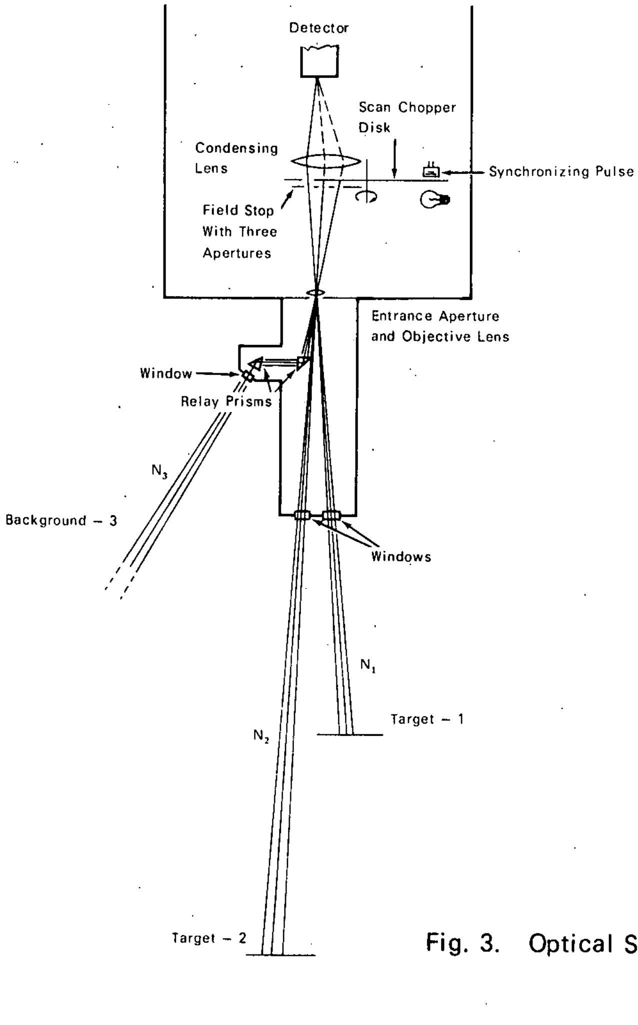


Fig. 3. Optical Scanning System – Schematic.

A condensing lens images the entrance aperture on the center of the detector (a multiplier phototube), and thus, each small pencil of light arrives at the same area of the sensor. A slot in the periphery of the scan chop disk allows light to pass between one of three sets of lights and photodiodes each time a corresponding field aperture is opened. This generates synchronous pulses to trigger the solid state switches used to separate the signals. The line of sight for the water background is set 30 degrees off vertical to clear the hull of the submarine and allow the measurement of the radiance of the water background.

NOTE

The instrument now operates with three channels of optical signals, although five channels were originally used. The five-channel system used two identical targets each with two halves of different reflectance values. The two targets were located at different distances from the scanner. Measurements were made of each half through the two different water path lengths and of the water background, producing five optical signals. After the first test of the instrument in water off the end of a pier in San Diego Harbor, a lengthy review of the test and of the system was conducted resulting in the decision to convert to the three-channel operation described here. The reasons for the change were: 1) the three channel system is fundamentally correct, whereas theoretical compromises were involved in the five-channel dual target system and 2) the change greatly simplifies the instrument, reducing the computer components by nearly 50 percent. To make this modification the computer was rewired using only the components necessary for the reduced number of computations. The optical scanner was not changed. A revision of the scanner would have been too costly and time-consuming at this point. It still scans five channels, but only three channels are used. However, a three-channel scanner would be desirable since an improvement in signal quality would be realized. All of the final calibrations and testing were conducted using three channels of the five-channel scanner.

One weakness in the present system, not existing in the earlier scheme, occurs when the submarine matches the water and there is no contrast. Under this condition all radiance signals are equal and the computer, having only residual noise to work with, will tumble off scale deep or shallow. A simple additional circuit could be added to sense this condition, defeat the computer, and indicate that the submarine matches the water. This is the ideal situation for concealment and the submarine would be concealed at any depth.

4.2.2 DETECTOR

The photodetector is an EMI 9524B photomultiplier tube. This tube is a small diameter (1 1/8 inch nominal) high-gain photomultiplier having 11 box and grid dynodes. The end window cathode surface has an S-11 ($C_s S_b O$) spectral response with high sensisitivity in the spectral region where sea water has its maximum transmittance. The tube is mounted behind the rotating scanner disk which multiplexes the optical signals from the three paths of sight on to the photocathode in time sequence. These light pulses are detected and amplified by the photomultiplier whose output current is proportional to the optical signal input.

4.2.3 PHOTOMETER DEMODULATOR CIRCUIT

The phototube anode current goes to an operational amplifier (Analog M501A) connected as a current to voltage converter. This amplifier is a small fully compensated unit in a small TO-8 package. It has a FET input with a maximum input bias current of 5 picoamperes and a minimum open loop gain of 100,000. The amplifier connects the current pulses from the photodetector into a repetitive sequence of three voltage pulses whose respective amplitudes are proportional to the radiances in the three optical paths.

This signal serves two functions. First the average value of this signal is compared to a reference voltage and the difference signal is used to control the high voltage applied to the photomultiplier tube, hence its gain. In this manner we obtain an automatic gain control (AGC) that allows the photometer to operate over a wide range ambient light levels while producing essentially the same output signal levels. The time constant of the AGC circuit (15 seconds) is such that the shapes and the relative amplitudes of the three signal pulses is transmitted through the system without significant distortion.

The output signal secondly is applied to a commutator or synchronous demodulator which directs the three pulses sequentially into individual integrating and storage circuits. The tuning for the synchronous demodulator is provided by syncronizing pulses obtained from the same rotating scanner disk that performed the optical multiplexing (See Fig. 3).

At this point we have three separate electrical signals which correspond to the original optical signals. The integrating and storing circuits also have a time constant of approximately 15 seconds. One other signal is generated in the underwater package, and that is a voltage related to depth. A Genisco model PB923 pressure transducer is vented to sea pressure, and the changes in depth cause an imbalance in a bridge circuit, producing a signal proportional to depth. The bridge signal is then fed to a Burr Brown 3264/14 differential-input instrumentation amplifier of high input impedance, accurate voltage gain, and low output impedance. The gain of this amplifier is adjusted so that the transducer/amplifier combination provides an output signal of 0.100 volts per meter.

The three optical signals and the depth signal comprise the four analog signals sent to the inboard computer from the outboard photometer unit.

4.3 ANALOG COMPUTER

Four signals enter the computer. Three of these are voltage analogs of optical signals. The fourth is the voltage analog of depth. The following designations will be used:

e_1 = relative radiance of submarine paint sample viewed from 1 meter

e_2 = relative radiance of submarine paint sample viewed from 2 meters

e_3 = relative radiance of the background water

e_z = depth in meters (0.1 volts per meter) to top of sail

These four signals are used by the analog computer to determine if an observer at the surface can detect the presence of the submarine.

Before explaining the operation of the computer, we will go through the mathematics used by the computer. Section 3 develops the concept that the apparent contrast as seen by an observer at the surface can be computed using these four relative voltages in Eq. 21; i.e.,

$$C_r = \left(\frac{e_2 - e_3}{e_3}\right)\left(\frac{e_2 - e_3}{e_1 - e_3}\right)^{(10e_z - 2)}$$

After C_r has been found, it is compared with a threshold value C_t, to determine if it is larger or smaller than the threshold value. If it is larger, a "visible" indicator lights; if smaller, a "concealed" indicator lights. A more detailed analysis is given in Section 3.2.

We can now take a look at the computer hardware and the individual computations made by the operational amplifiers. The computation of τ_1, the contrast transmittance per meter path length, using e_1, e_2, and e_3 starts at amplifiers A12 and A16 (See Fig. 4). The signal e_1' enters amplifier A12 which is a non-inverting amplifier with a small variable gain. The gain adjustment of A12 is used to compensate for variations in gain in the 1- and 2-meter channels. The gain is set to give a ratio of one for e_1/e_2. Note: Whereas this was intended to allow for "Field" adjustment, attempts to make this adjustment with the instrument in air out of doors were unsuccessful due to the precision required.)

Signal e_1' is designated e_1 after leaving A12. The difference between signals e_1 and e_3 is obtained by amplifier A9, a differential amplifier with a gain of one. The output of A9 is then $-(e_1 - e_3)(\pm)$. For this signal to be used in the following computations, it must always be of positive polarity. Therefore, the signal from A9 is fed to A11 which is a positive absolute value circuit with a gain of one. The signal now becomes $+|e_1 - e_3|$. Logarithms are used from this point on. The signal is applied to logarithmic amplifier A10, and the output is some fixed offset voltage plus 75 millivolts per decade of input voltage; i.e.,

$$-A \log|e_2 - e_3| - B$$

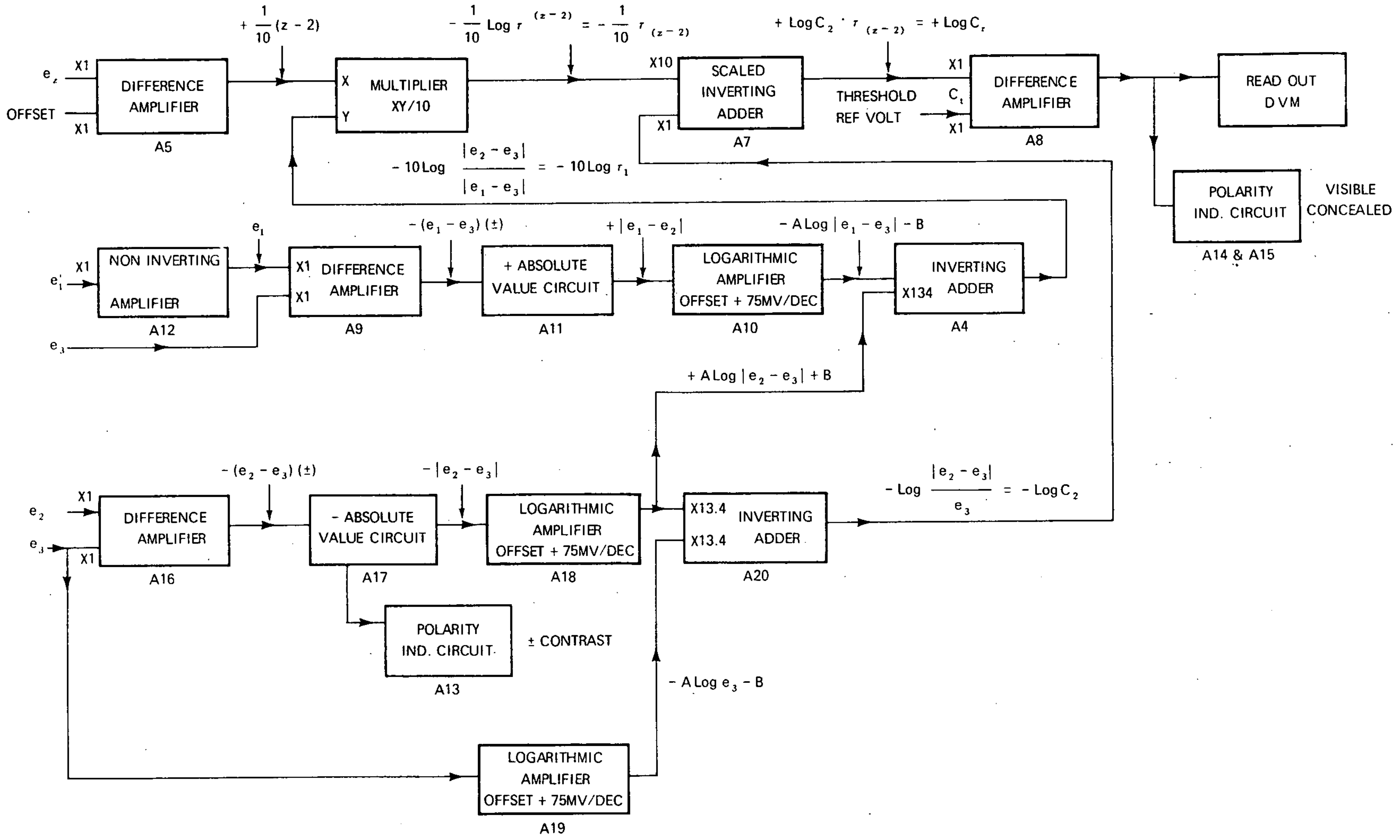


Fig. 4. Computer Section – Block Diagram.

The signals e_2 and e_3 are processed through a similar circuit, except the absolute value circuit has a negative output. As the contrast passes through zero, the minus absolute value circuit flips from a large positive voltage to a large negative voltage. Amplifier A13 amplifies this signal and drives transistors which turn on indicator lights denoting the positive or negative contrast. The output of logarithmic amplifier A18 is

$$+A \log |e_2-e_3|+B.$$

The outputs of A10 and A18 are of opposite polarity, and they are summed by the inverting adder amplifier A4. The output of A4 is

$$-10 \log \frac{|e_2-e_3|}{|e_1-e_3|} = -10 \log \tau_1$$

The signal e_Z is applied to one input of unity gain difference amplifier A5. An offset voltage applied to the second input of A5 compensates for 2 meters of water and also for the location of the pressure transducer. The output of A5 is

$$0.1 \log (z-2).$$

The outputs of A4 and A5 are tied into a multiplier module whose output is

$$-\frac{1}{10} \log \tau_1^{(z-2)} = -\frac{1}{10} \tau(z-2).$$

At this point the apparent contrast of the submarine seen through 2 meters of water (C_2) is needed. This is obtained by taking the logarithm of e_3 using logarithmic amplifier A19. The output of A19 which is

$$-A \log e_3-B,$$

is summed with the output of A18,

$$+A \log |e_2-e_3|+B$$

by the inverting adder A20. The output of A20 is

$$-\log \frac{|e_2-e_3|}{e_3} = -\log C_2$$

The outputs of the multiplier and amplifier A20 are summed by the scaled inverting adder amplifier A7. Amplifier A7 provides a gain of ten for the input from the amplifier and a gain of one for the input from A20. The reason for this gain difference is that the multiplier divides the product of its inputs by 10 and this gain brings the signal back to its proper level.

The output of A7 is

$$+ \log C_2 \cdot \tau_{(z-2)} = + \log C_r$$

This quantity is compared to a threshold value $\log C_t$ by the difference amplifier A8. If the value of

$$\log C_t > \log C_r$$

amplifiers A14 and A15 operate the "concealed" indicator light. If the

$$\log C_t < \log C_r$$

the "visible" light is operated.

4.4 SPECIFICATIONS FOR ENGINEERING PROTOTYPE

Table I provides a brief set of specifications for the engineering prototype.

4.5 DESCRIPTION OF SYSTEM OPERATION

4.5.1 DESCRIPTION OF CONTROL PANEL

Figure 5 is a photograph of the control panel. In the upper right corner is the warning light, reset button, and threshold adjustment for the pulse detector. The pulse detector was incorporated as an "add on" to the visibility equipment and is discussed in the Appendix. To the left of the pulse detector display is the "visible" "concealed" display and the contrast threshold adjustment. This is all that would be needed for a final "go/no-go" system. At the upper left is a digital readout of the ratio of the computed apparent contrast to threshold contrast. This ratio is displayed in decibels. The rest of the controls were for testing and troubleshooting during development and evaluation. The lower section is used to test the computer and, by setting switches, to read important test points throughout the circuit.

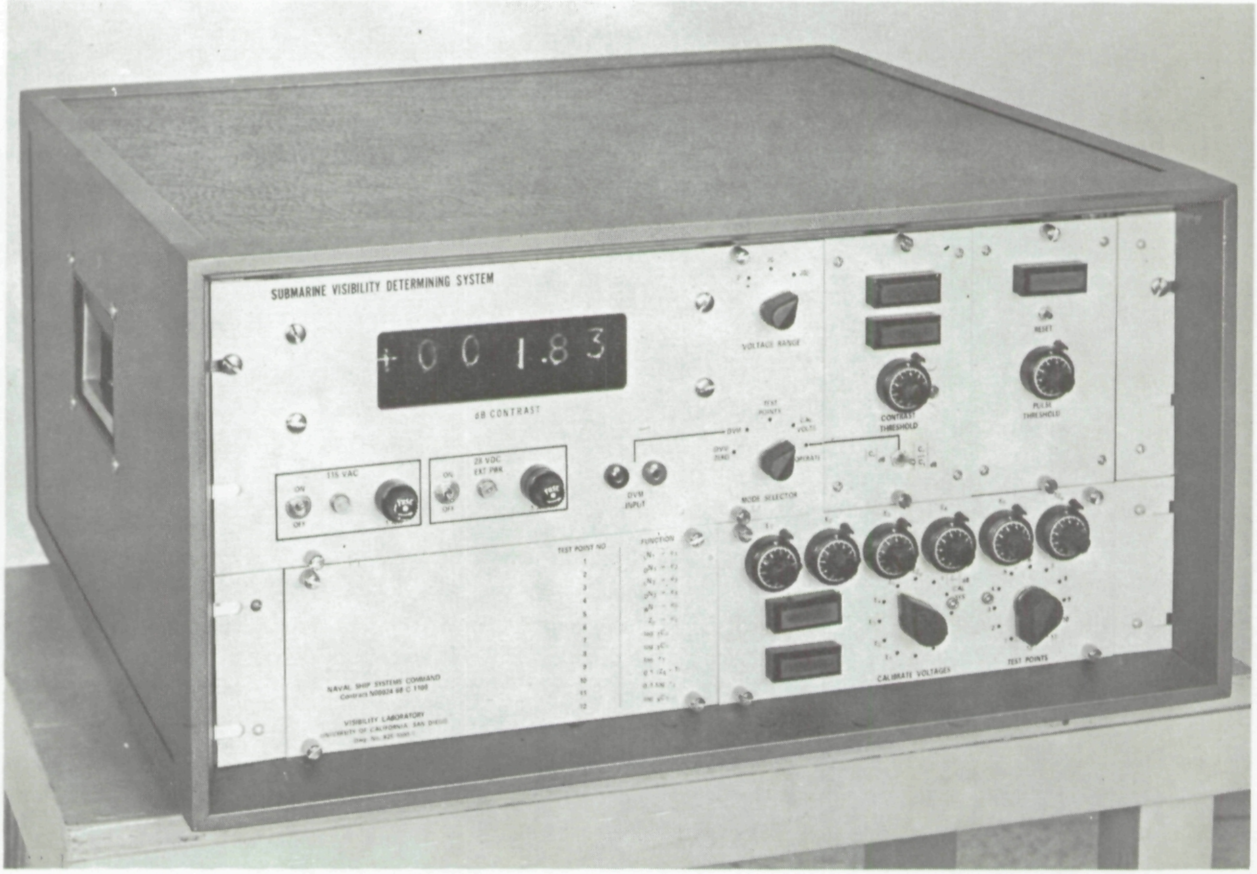


Fig. 5. Submarine Visibility Determining Equipment Control Panel.

TABLE I

Overall Specifications for Engineering Prototype

1.	Outboard In-Water Unit	
1.1	Height Overall	10 feet
1.2	Weight	
	In Air	190 lbs.
	In Water	80 lbs.
1.3	Functional Operating Range	
	Depth	0-100 meters
	Ambient Light Level	100-10,000 fc
1.4	Maximum Depth (collapse)	2,000 feet
2.	Inboard Unit	(Computer and Display)
2.1	Size	20 3/8" w x 10 3/8" h x 19 3/8" d
2.2	Weight	61 lbs.
2.3	Power	115v, 7a, 60Hz 1ϕ
3.	Interconncction	
3.1	Cable	100 feet, neoprene jacket overall. 2-No. 16 AWG & 8-No. 20 AWG Conductors
3.2	Underwater Connector	Type XSM-16-CCP molded to cable

4.5.2 OPERATION

In order to realize the stability and accuracy which the system is capable of, it should be turned on and allowed to warm up for about 1 hour. The photometer in the underwater housing becomes active and stable in a few seconds. Certain components in the computer, however, require a warmup period before attaining the required level of performance.

The 115 Volt AC power switch activates the control and computer section; the 28 Volt DC switch activates the photometer in the underwater unit. After warmup, a quick computer check may be performed. This is done by setting the mode selector switch to CAL VOLTS and adjusting the lower left three knob pots to e_1 = 4.000 volts, e_2 = 4.000 volts, and e_3 = 2.000 volts. With these simulated signals, test points 9 and 12 will indicate zero. If they are slightly off, two screwdriver adjustments can be made through an access door in the top cover to allow "zeroing" the computer. Except for the computer check, which takes only a few minutes, operation consists only of turning on the two power switches and after warmup, reading the computed appraisal of the submarine's visibility status indicated by the word "visible" on a red background or "concealed" on a green background. The digital panel meter indicates in decibels how far above (+) or below (-) threshold level the computed apparent contrast is. If the TEST POINTS switch is turned to test point 12, the dual display at the bottom and just right of center will indicate if the inherent contrast of the submarine against the water background is positive (submarine lighter than the water) or negative (submarine darker than the water), and the inherent contrast in decibels will be indicated on the panel meter.

In use, two conditions must be met for the system to operate properly.
1) The windows of the optical scanner in the underwater unit must be clean.
2) The paint on the two targets must match the paint on the top of the sail and other horizontal surfaces.

5. LABORATORY CALIBRATIONS AND TESTING

5.1 COMPUTER TESTING

The computer was tested by applying voltage signals to simulate inputs from the radiometer and the depth transducer. The simulated radiance signals were set at predetermined levels, and the depth signal was adjusted until the display indicated threshold depth. The depth signal was then read to determine if the computer was solving the problem correctly. This testing was done with the controls on the panel of the evaluation model. The input voltages are displayed on the digital panel meter when the appropriate test points are selected, and they can be set to the desired levels with the control potentiometers. A schedule of test voltages was set up representing the signals that would come from the photometer if the submarine were operating in water types from very turbid to very clear and with inherent contrasts of 0.01, 0.05, 0.10, 0.50, 1.0, 5.0, and 10. Although a complete temperature test was not conducted, the computer was operated at 15 and 32 degrees centigrade after being held at these temperatures overnight. No change in its performance could be perceived.

5.2 PHOTOMETRIC CALIBRATION AND TESTING

The final calibration of the system was accomplished using the photometric facility at the Visibility Laboratory. In concept the calibration is very simple; in practice, however, it was found to be more difficult than anticipated, and much time was spent developing techniques to assure a satisfactory result.

Each channel of the photometer-scan system has an individual gain adjustment. This was necessary to compensate for different amounts of transmission loss through the optics. For instance, the radiant flux from the water background, N_3, passes through relay prisms and suffers small losses which the other channels do not. The calibration consists of adjusting the three channels to have equal responses when viewing the same radiances. It would appear that all that is needed is a stable radiance source placed in the field of view of each channel in turn and the output level of each then adjusted to identical level. However, the instrument Automatic Gain Control circuit precludes this. This circuit averages the signals coming from the three optical channels and adjusts the high voltage on the photomultiplier tube to maintain this average at about 4 volts. This enables the photometer to operate over a wide dynamic range of ambient illumination on the submarine (100 to 10,000 foot candles) while keeping the signals transmitted to the computer to a small range (0.6 to 7 volts). Because of the averaging, any change in radiance seen by one channel affects the output signals of the other channels. For example, suppose the radiance seen by channel N_1 is doubled while the other two radiances remain unchanged. The signal output from this channel, e_1, will increase but not by twice the original value. The gain of the photometer will decrease to maintain the average of the output signals at 4 volts. The ratio of e_1 to the other two voltage signals will double, and the ratio between these other two channels will not change.

The procedure followed consisted of exposing all three channels simultaneously to equal radiance levels and adjusting each channel to obtain matched output signals. The photometric arrangement used is diagrammed in Fig. 6. Two identical target plaques, designated A and B, two adjustable radiance sources and a lamp were used. The plaques are made of compressed barium sulfate about one quarter of an inch thick. This material has a reflectance of only 99 percent and has nearly ideal diffuse reflectance properties. The adjustable radiance source has two plastic diffusers separated by a small distance which are backlighted by a tungsten-halogen lamp enclosed within a white-surfaced housing. A very stable adjustable power supply was used to operate the radiance source. The light source used to illuminate the plaques was a 500-watt projection lamp enclosed in a housing to reduce stray light. This lamp was powered by a highly regulated supply.

Plaques A and B were mounted in the same transverse plane and centered with the line of sight of the two target channels N_1 and N_2. The lamp was positioned on center above and behind the entrance windows of the instrument. A precision photometer was used to measure the relative radiance of "A" and "B", and the lamp was adjusted sideways until an indicated radiance match between "A" and "B" of 0.1 percent or better was achieved. "A" and "B" were then interchanged and the match again checked to test for equality of reflectance. No measurable difference was found.

An adjustable radiance source was placed in the field of view of the third water background channel. It was adjusted until the output from this channel, e_3, was similar in magnitude to e_1 and e_2. This source was used to keep e_3 at a stable operating level while e_1 and e_2 were adjusted. A digital voltmeter that could read voltage ratios was connected to display the ratio e_1/e_2. The appropriate adjustments were made to achieve an indicated match between e_1 and e_2 within + 0.1 percent. With the digital voltmeter still indicating the ratio e_1/e_2 and with the first radiance source at N_3, a second adjustable radiance source was substituted for plaque "A" and carefully centered and adjusted until the ratio e_1/e_2 was again 1.000 ± 0.001. Then, this second source which has been made to match N_1 and N_2 was substituted for the "holding" source at N_3 and carefully centered. Plaque "A" was replaced at this point, while all three channels were looking at carefully matched radiances; the gain for e_3 was adjusted again using the ratio mode of the digital voltmeter to make $e_1 = e_2 = e_3$. This completed the calibration.

Photometric testing was done with the same setup used for the calibration. With all three channels looking at the same radiance levels, these levels were changed known amounts by inserting calibrated filters into the appropriate paths of sight. For example:

If a filter with a transmittance $T = 0.90$ is inserted in path N_2 and one with $T = 0.80$ is inserted in path N_3, the instrument will see radiances

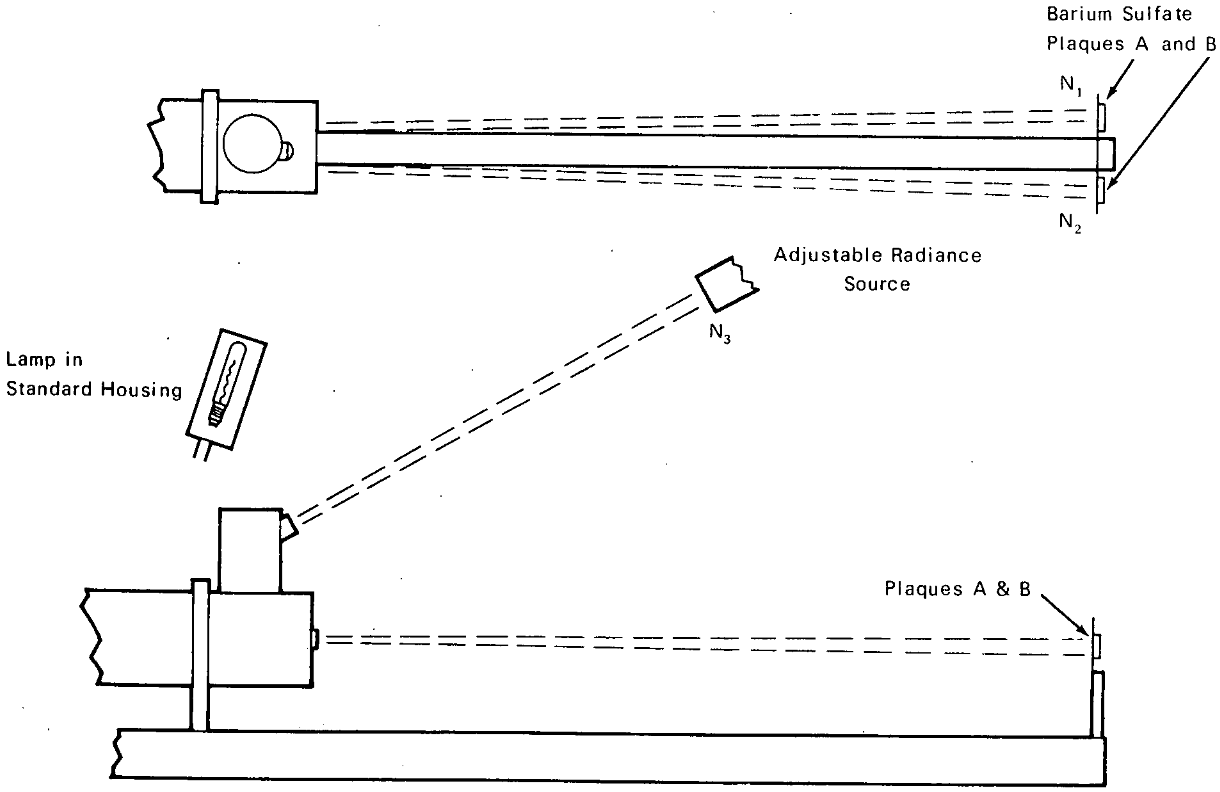


Fig. 6. Photometric Calibration Setup.

of these ratios

$$N_2 = (0.90) \times N_1$$

$$N_3 = (0.80) \times N_1$$

and the corresponding voltages

$$e_2 = (0.90) \times e_1$$

$$e_3 = (0.80) \times e_1.$$

It was shown in Section 3.2 (Eq. 21) that

$$C_r = \frac{e_2 - e_3}{e_3} \left(\frac{e_2 - e_3}{e_1 - e_3} \right)^{(10e_z-2)}.$$

Substituting the relative values we obtained with the filters gives

$$C_r = \frac{(0.90)e_1 - (0.80)e_1}{(0.80)e_1} \left[\frac{(0.90)e_1 - (0.80)e_1}{e_1 - (0.80)e_1} \right]^{(10e_z-2)}$$

$$= 0.125 \ (0.50)^{(10e_z-2)}.$$

If it is desired to simulate an apparent contrast, C_r equal to 0.005, then

$$(0.50)^{(10e_z-2)} = .04$$

$$10e_z-2 = \frac{\mathrm{Log}(0.04)}{\mathrm{Log}(0.50)}$$

$$= 4.64$$

$$e_z = 0.664 \text{ volts.}$$

In this simulation the threshold depth would be

$$e_z \times 10 - 6.64 \text{ meters,}$$

the contrast transmittance for unit path length would be

$$\tau_1 = \frac{e_2 - e_3}{e_1 - e_3}$$

$$= 0.50\text{m}^{-1}$$

and the inherent contrast,

$$C_o = C_2 \text{ x } (\tau_1)^{-2}$$

$$= \frac{e_2 - e_3}{e_3} (0.5)^{-2}$$

$$= (.125)\ (0.5)^{-2}$$

$$= +0.5$$

By using other filter values, various water types and contrasts were simulated. With the filters in place, the voltage e_z normally supplied by a depth transducer was varied until visual threshold was indicated by the display. A series of 14 optically simulated test conditions were used. This test was conducted at simulated ambient light levels of 1750, 500, and 100 foot candles.

5.3 RESULTS

The instrument was found to be very sensitive. It easily responds when a clean, thin piece of glass is inserted into any of the radiance paths. In fact, microscope slides were calibrated for transmittance and used for filters in the testing. The results of the photometric testing are shown in Figure 7. In general the indicated threshold depth was within ± 10 percent of the true threshhold depth, but the instrument's capability is greater than this result indicates since most of this error can be attributed to the test procedure. For instance, if the value for the transmittance of one of the filters used in the example in Section 5.2 is in error by 1 percent, the depth calculated will be wrong by 11 percent. The results of the test show a random distribution which cannot be instrumental. The instrument has a sensitivity and repeatability much better than this which is lost in the precision of the test. What we have here, then, is probably more a measurement of the precision of the test procedures than of the instrument we are testing. Therefore, we can say from this testing that the instrument can make the radiance measurements and can compute the threshold depth to within ± 10 percent and very probably much better than this.

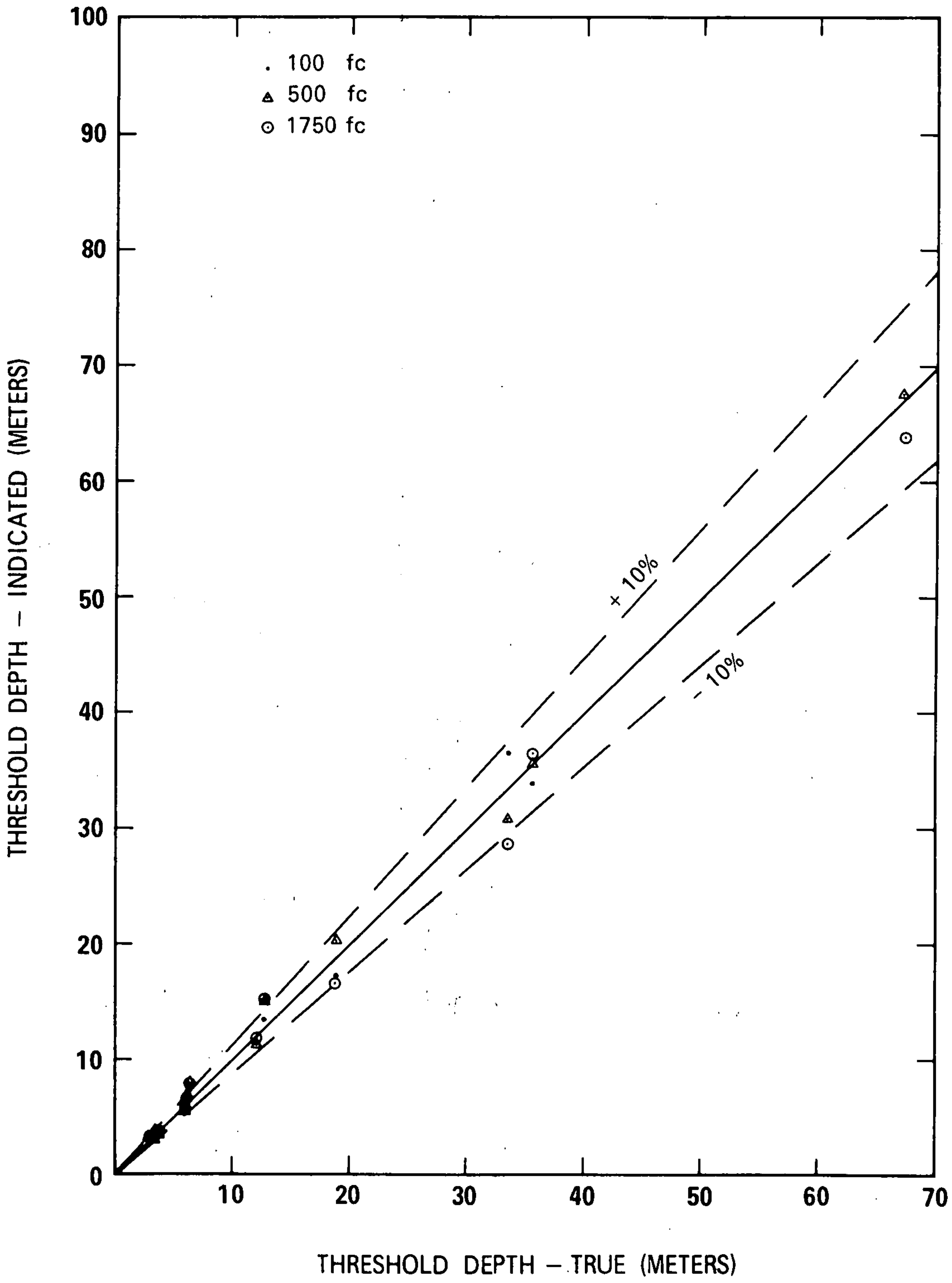


Fig. 7. Photometric Test Results.

6. FIELD TESTS

Five field tests were conducted. Three brief tests took place off the end of a pier in San Diego Harbor, and two final tests were performed in open water west of San Diego from aboard a small craft. The purposes of the pier tests were to check and evaluate the performance of the instrument when submerged and to find and eliminate any malfunctions before going to the effort and expense of a sea trial.

6.1 PROCEDURE

Two straightforward tests were attempted during each field trip to evaluate the performance of the system.

The first was designed to determine the instrument's ability to measure the contrast transmittance of the water, which is of major significance to the visibility computation (see Section 3.2). It was shown in Section 3.2 that the contrast transmittance when the observer is looking downward is

$$\tau_r = e^{-(\alpha + K)r},$$

where r is the path length, α is the volume attenuation coefficient, and K is the diffuse light attenuation coefficient. For the more general case,

$$\tau_r = e^{-(\alpha + K \cos \theta)r},$$

where θ is the angle of view. For the horizontal case,

$$\cos \theta = 0$$

and the above equation reduces to

$$\tau_r = e^{-\alpha r},$$

which is also the beam transmittance, T_r, as measured with a beam transmissometer.

The first test consisted of slinging the Submarine Visibility instrument horizontally, lowering it into the water, reading test point 9 where

$$e_9 = -10 \text{ Log } \tau_1,$$

and at the same depth, measuring T_1 with a beam transmissometer. Then,

$$\tau_1 = \text{Log}^{-1} \frac{e_9}{10}$$

could be compared with T_1.

The second test was to lower the instrument into the water in a vertical position to determine the depth at which the indication changed from "visible" to "concealed". This should be the visual threshold depth for a large object having the same reflectance as the instrument targets. To obtain this depth by observation, a disk about 2 feet in diameter and painted with the same submarine deck paint used for the targets on the instrument was lowered into the water while being observed by several persons. The depth at which the observers lost visual contact was then measured.

In summary, the field tests were designed to determine how well the instrument could measure contrast transmittance, which is critical to good performance, and to compare the performance of the instrument in determining visual threshold depth with that obtained by direct observation.

6.2 RESULTS

6.2.1 PIER TEST 1, 28 JANUARY 1972

This test disclosed a malfunction in the pressure sensing depth circuit which was easily corrected. The contrast transmittance indicated by the instrument in the horizontal position was

$$\tau_1 = 0.263,$$

and the beam transmittance measured an hour later varied between

$$T_1 = 0.213 \text{ and } 0.225.$$

At this time, the instrument was configured as a five-channel system. Photographs taken during the test are reproduced as Fig. 8 and 9.

It become obvious from this test that true performance could not be determined from this pier. At threshold depth, as determined with the black disk, the lower target was either near the bottom or in the mud. Then too, the light field was disturbed by floating sea growth, chain supports, and shadows from the hulls of nearby ships. The water properties also were very erratic due to tidal currents. Because of its convenience, however, two further tests were performed at the pier to obtain a partial evaluation before attempting tests at sea.

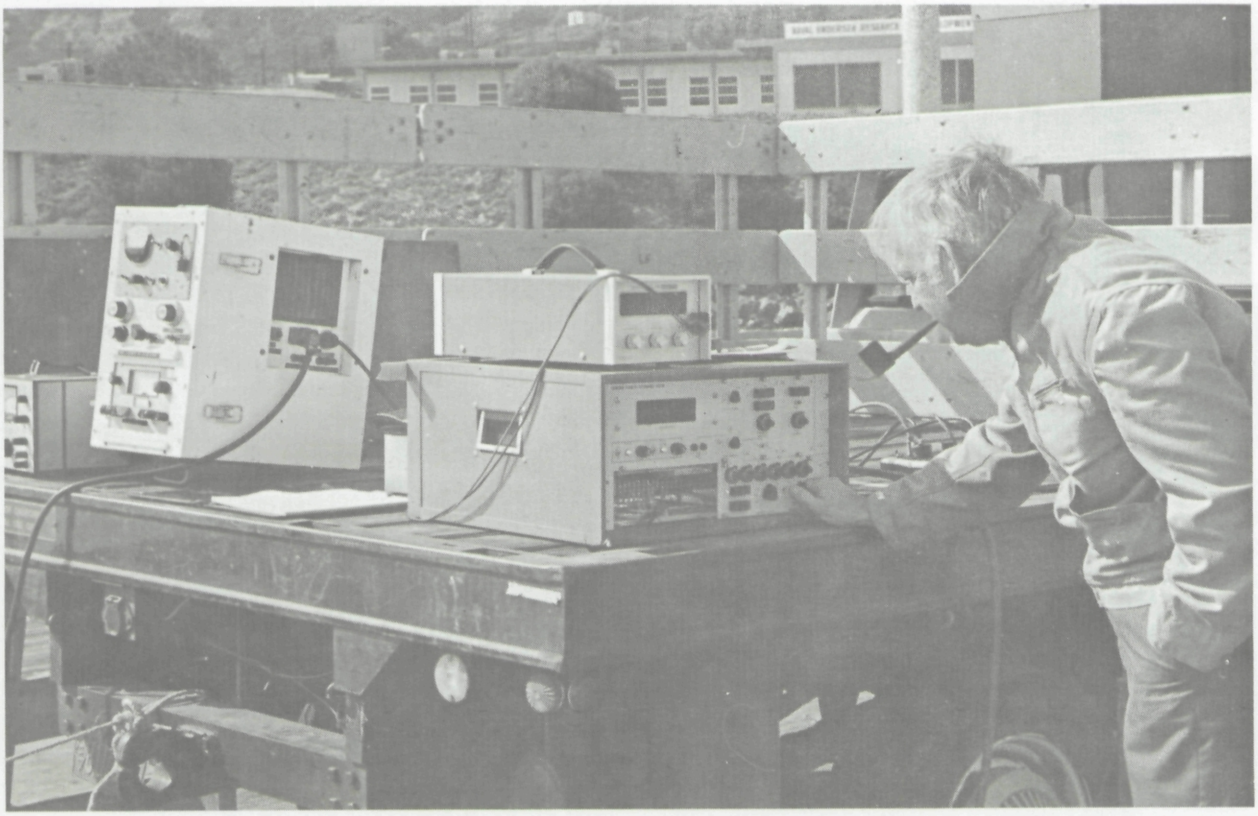


Fig. 8. Pier Test Setup for Submarine Visibility Determining Equipment.

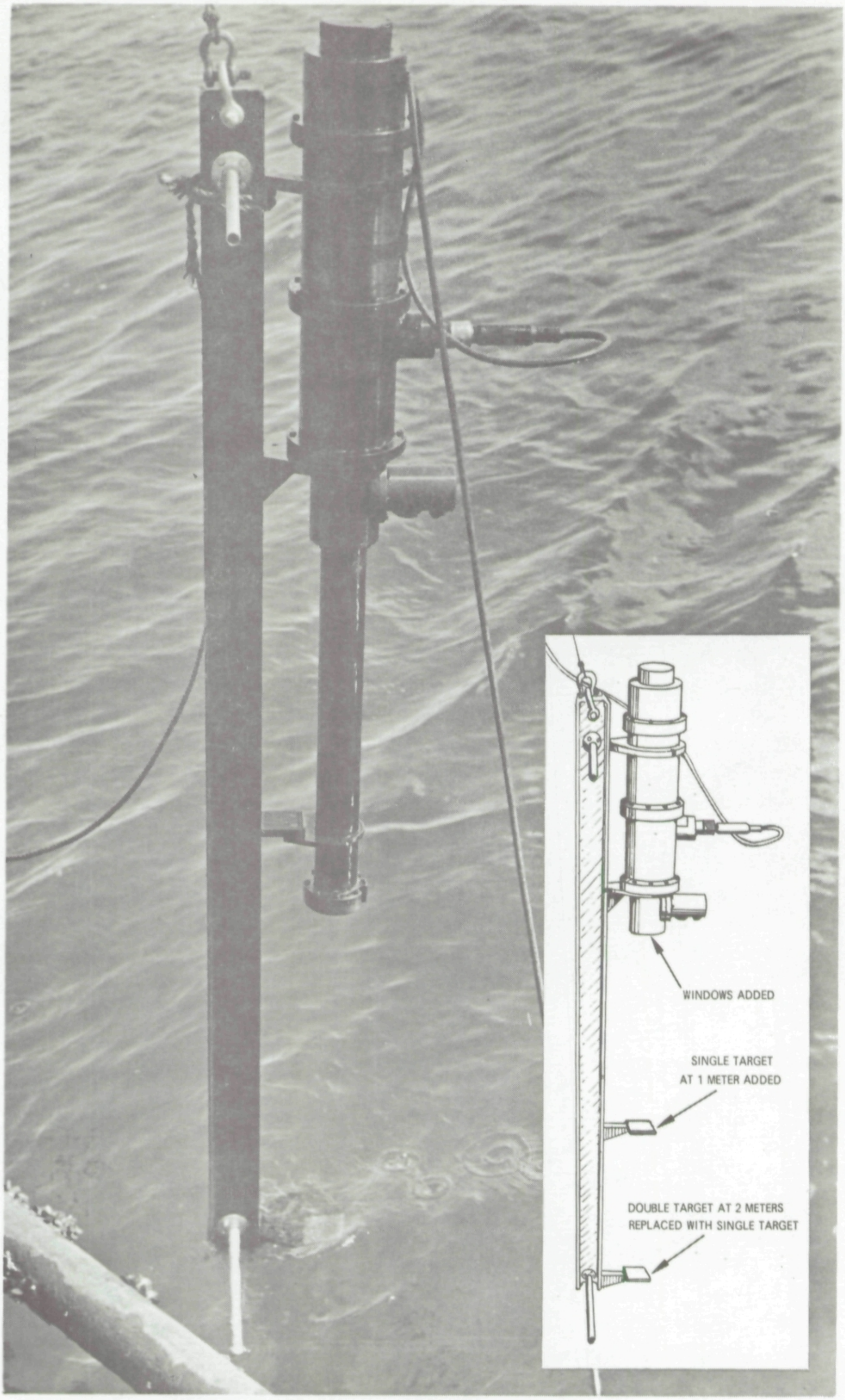


Fig. 9. Underwater Portion of Submarine Visibility Determining Equipment During Pier Test. Photograph shows original five channel system; insert shows modifications for new three channel system.

6.2.2 PIER TESTS 2 AND 3, 16 FEBRUARY AND 1 MARCH 1972

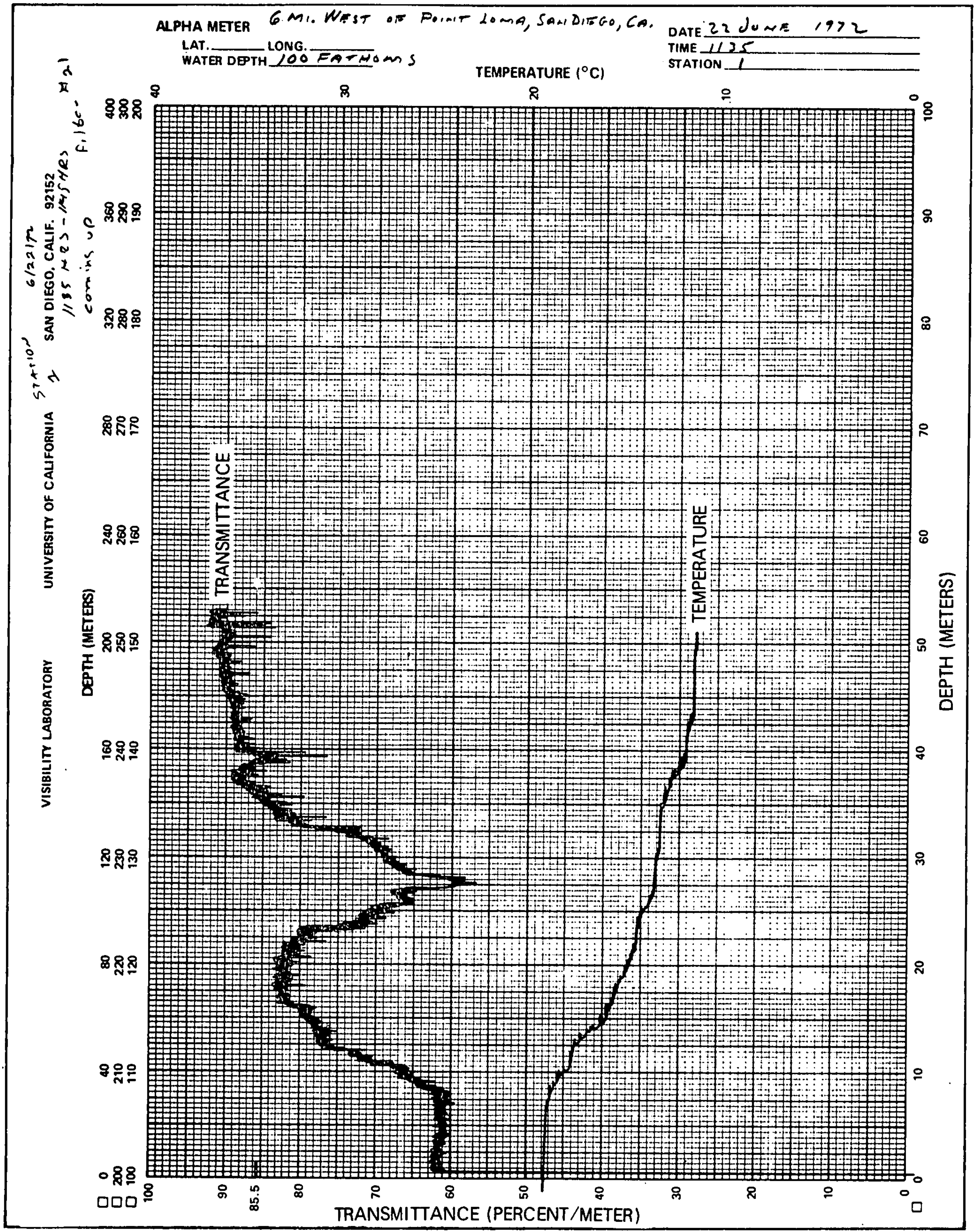
These tests were conducted after converting the instrument to a three-channel system (refer to Section 4.2.1) Again, no success for evaluation purposes could be achieved with the instrument in the vertical position. However, the instrument did perform well in the horizontal position, satisfactorily determining the contrast transmittance. Because the water was so erratic, a series of readings were taken using both the Submarine Visibility Equipment and the beam transmissometer. The averages of the readings are given below.

		16 February	1 March
Submarine Visibility Equipment	τ_1	0.364	0.200
Beam Transmissometer	T_1	0.353	0.200

6.2.3 SEA TESTS, 22 JUNE AND 28 JUNE 1972

Two sea tests were conducted. The first was at a point 6 nautical miles west of Point Loma Lighthouse, San Diego, California. A period of rain and heavy winds had occurred just prior to this test, and the surface water was not as clear as hoped for. A transmission profile taken at this station, reproduced in Figure 10, shows a well-mixed, uniform layer from the surface to the 8-meter depth. Below this was a layer of clearer water followed by a turbid layer centered at 28 meters and very clear water from 40 to 50 meters. In this not-too-clear surface water, threshold depth was about 3.5 meters. The pitch and roll of the ship and swells caused the instrument depth to vary by plus and minus 1 meter or more. In turn, this caused the signals to vary rapidly, making it impossible to get good test point readings. The instrument was placed at a depth where the roll caused the indication to go above and below threshold, so the depth had to be read "on the fly" as the "visible" "concealed" lights changed state. Similar difficulty was experienced in using the large black disk to obtain threshold depth by direct observation. Despite these problems, the instrument was apparently performing very well, although accurate documentation of this was not possible under these conditions. It was decided that the test should be repeated in clearer water where changes in depth would not be so significant.

At the start of the second sea test, a transit was made west of San Diego in quest of clear water. The water was disappointingly similar to that found the week before until a point was reached 30 nautical miles bearing 230° from the tip of Point Loma. Here the water had a deep blue color and (see Figure 11) a uniform transmittance of 91 percent per meter from the surface to 45 meters. Threshold depth was about 15 meters and it was much easier to conduct the test. At this station, illuminance as well as transmittance data was obtained (see Figure 12). From the illuminometer data the diffuse attenuation coefficient, K, and the water reflectance, R_∞ were obtained.



ALPHA METER 6 MI. WEST OF POINT LOMA, SAN DIEGO, CA.

LAT._____ LONG._____

WATER DEPTH 100 FATHOMS

DATE 22 JUNE 1972

TIME 1135

STATION 1

VISIBILITY LABORATORY UNIVERSITY OF CALIFORNIA SAN DIEGO, CALIF. 92152

Station 2 6/22/72

1135 HRS - 1145 HRS

coming up F. 16c - #21

Fig. 10. Transmittance and Temperature Profile Taken During Sea Test 22 June 1972.

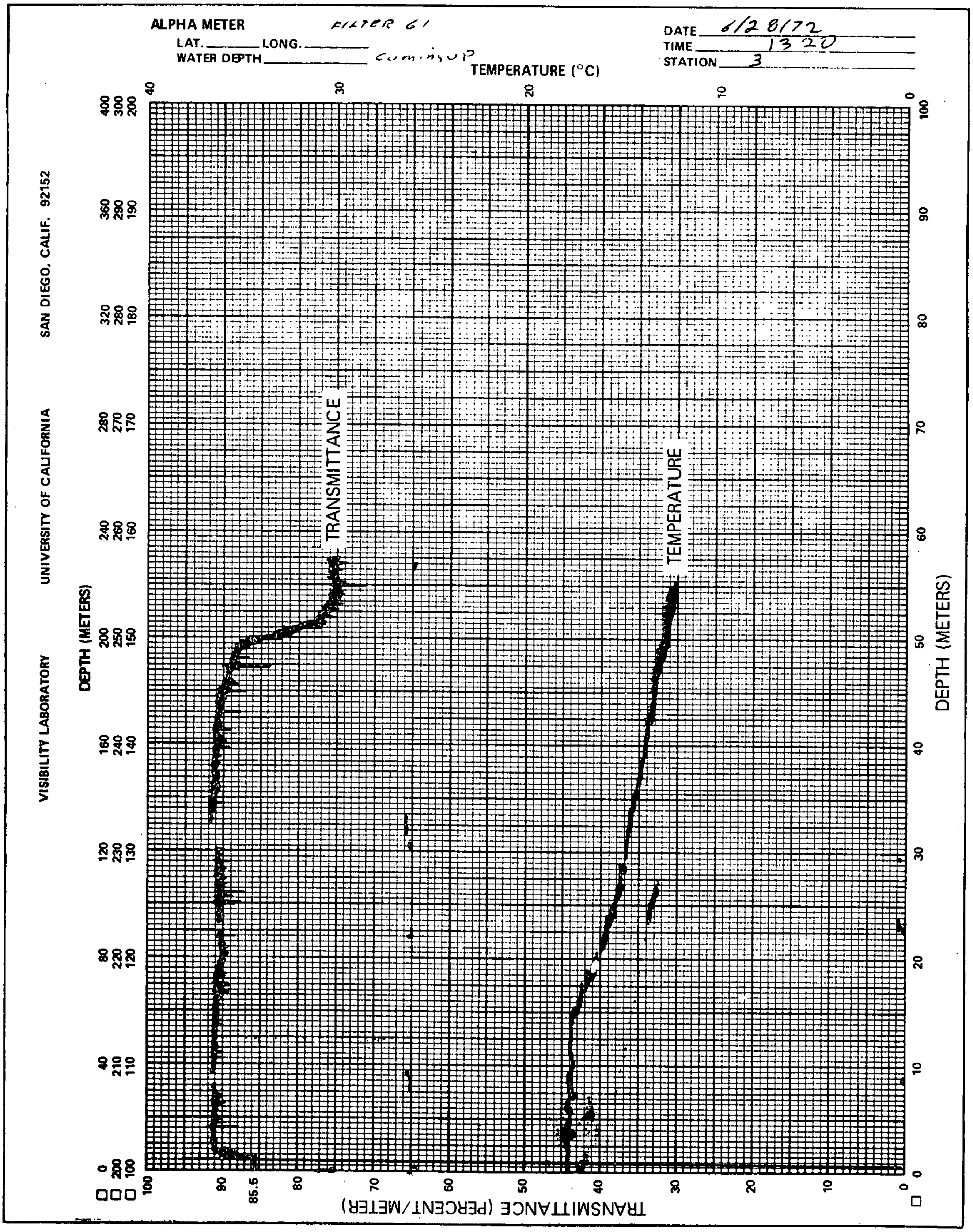


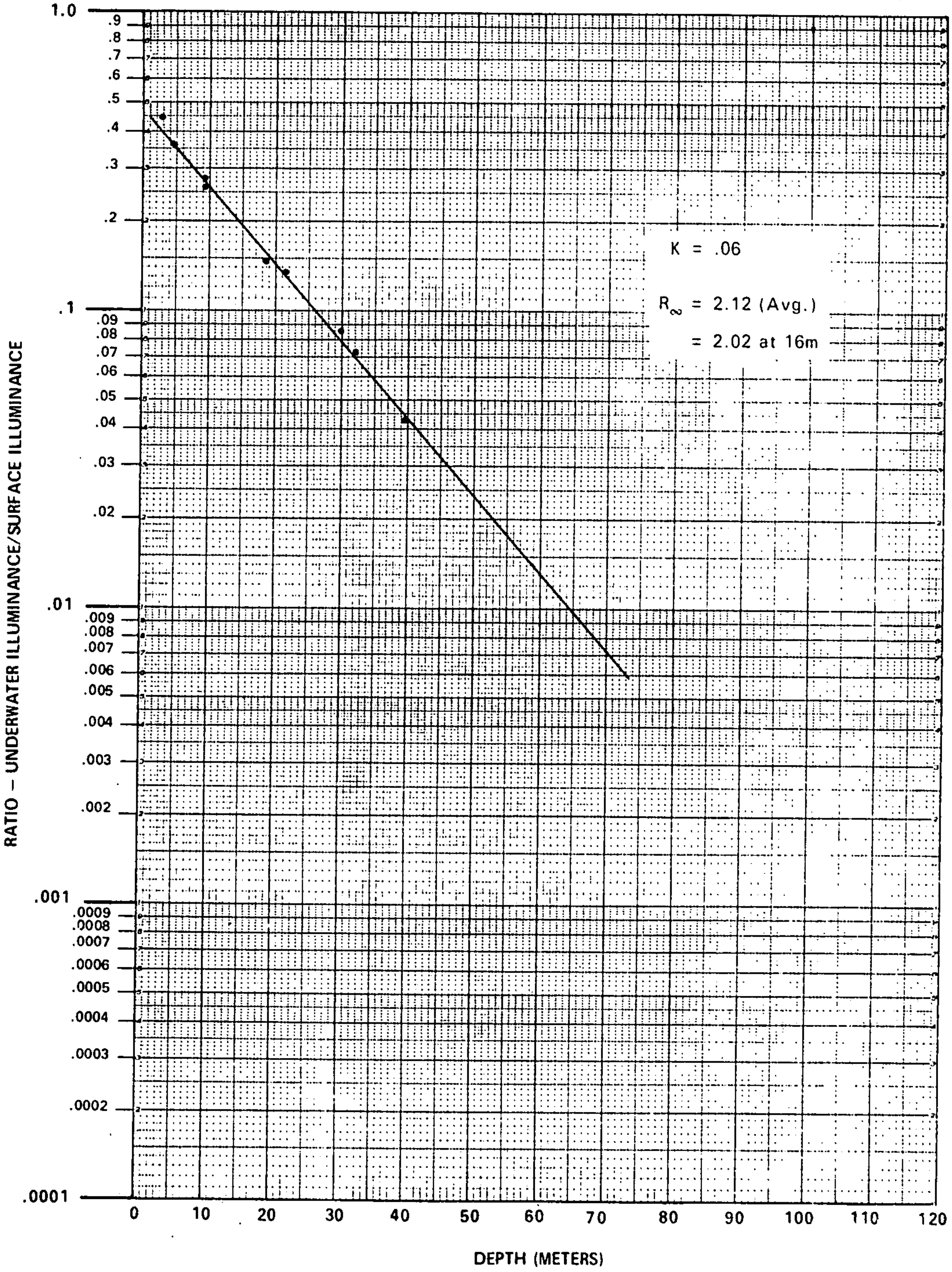
Fig. 11. Transmittance and Temperature Profile Taken During Sea Test 28 June 1972.

VISIBILITY LABORATORY UNIVERSITY OF CALIFORNIA SAN DIEGO, CALIF. 92152

WATER CLARITY INVESTIGATIONS

DATE 28 JUNE 72 TIME 1500 HRS LAT. ________ LONG. ________

STATION 3 WATER DEPTH ________ (FATHOMS)



VIS LAB (68-1)

Fig. 12. Illuminance Profile Taken During Sea Trial 28 June 1972.

The water reflectance, R_∞, is the ratio of the upwelling illuminance to the downwelling illuminance,

$$R_\infty = \frac{E_u}{E_D}$$

The optical properties of the water at the time of this test were:

Volume Attenuation Coefficient, $\alpha = 0.10$

Diffuse Attenuation Coefficient, $K = 0.06$

Water Reflectance, $R_\infty = 2.02\%$ (at 16 m).

The submerged reflectance of the paint used on the targets of the Submarine Visibility Instrument and on the large disk were measured at the Laboratory and found to be

$$R_t = 1.88\%$$

From these values a visibility computation was made. The apparent contrast was

$$C_r = C_o(\tau_1)^z,$$

where C_o is the inherent contrast, C_r is the apparent contrast as seen through path length z, and τ_1 is the contrast transmission per unit path length. The inherent contrast is

$$C_o = \frac{R_t - R_\infty}{R_\infty},$$

and

$$\tau_1 = e^{-(\alpha+K)} \qquad \text{See Section 3.2)}$$

If threshold depth is to be at $C_r = 0.005$ (the threshold set on the Submarine Visibility Equipment), then

$$\frac{R_t - R_\infty}{R_\infty} e^{-(\alpha+K)^z} = 0.005$$

and for the conditions of the test

$$\frac{0.0188-0.0202}{0.0202}\ e^{-(0.10+0.06)\,z} = 0.005$$

$$0.0693\ (0.852)^{z} = 0.005$$

$$(0.852)^{z} = 0.0720$$

$$z = 16.4 \text{ meters.}$$

The results of the tests are summarized below:

		Pier Test		Sea Test	
		16 Feb.	1 Mar.	22 June	28 June
Sub. Vis. Equip. Horizontal	τ_1 (meter^{-1})	0.364	0.200	0.576	0.909
Beam Transmission	T_1 (meter^{-1})	0.353	0.200	0.644	0.905
Threshold Depth (Meters)					
Sub. Vis. Equipment				3.0/3.5	15.3
Direct Observation				3.5	14
Calculated from Water Properties					16.4

The pier tests gave experience working with the equipment and demonstrated that the equipment was capable of measuring contrast transmission. The sea trial on 22 June was inconclusive because the dynamics of the situation made precise measurements impossible; however, it did appear that the equipment was working properly. Its response was adequate to sense the changes caused by gravity waves and the roll of the ship. An interesting effect caused by the vertical optical structure of the water was noticed during these first sea test. Visual threshold was at about 3.5 meters. When the depth of the instrument was increased and it entered the clearer water below 8 meters (see Figure 10), it would display a "visible" condition. Continued lowering would produce a second depth where threshold was indicated. At this depth the instrument was in clearer water and could only use that water for its computation; it could not allow for the more turbid layer overhead. This is Case II discussed in Section 3.3.2.

The sea test on 28 June was conducted under much better conditions and gave excellent results. The threshold depth calculated from the water properties, however, is not very precise. A 1 percent change in the measured value of reflectance of the paint or water changes the computed threshold depth by 1 meter. Our precision of measurement for these low reflectance paints is not that good, and the water reflectance measurement is even less precise. The instrument could easily detect the effect of a change in depth of 1/2 meter or less. In this clear water a change in path length of 1/2 meter would cause a change in contrast of 8 percent. At threshold depth this would be

$$C_r = 0.005 \pm 0.0004.$$

7. RECOMMENDATIONS FOR FUTURE EFFORT

Further development of this system should proceed only after test and evaluation of the existing system on board an operating submarine. Prior to the test, it would be desirable to replace some of the discrete components in the computer with better quality devices available on the market today. Also, the submarine used should be carefully painted in accordance with instructions outlined in the "Submarine Concealment Camouflage Manual." Installation of the equipment would be uncomplicated: mounting brackets on the sail and running a cable from the instrument through a hull penetration to the small computer console. An engineer from the Visibility Laboratory should be aboard during this testing to check out the equipment and record performance data. Visual observation and photographic coverage could be obtained from a helicopter flying overhead, and the optical water properties could be obtained with instruments from a small boat in the area. After this test, the equipment might be left on board for a short period for use and evaluation by the ship's staff.

If the results of the engineering model tests indicate further development is warranted, then the development of an operational system could begin. This system could have a much smaller scanning device with only a small portion protruding through the sail. The small targets could be mounted directly on the sail. The computer display console could be much smaller since it would involve far fewer components than the five-channel engineering model which contained two unused channels in its final configuration and a large section used only for test purposes. Two additional displays could be considered for inclusion at this stage. One would indicate the inherent contrast of the submarine with the water background, which would be useful for indicating if the submarine appears dark or light in contrast with the water. This information could be used to determine the best paint measures for concealment on future deployments in a particular area. The other display would indicate, in feet, how far above or below threshold depth the submarine is positioned. Without this, the device indicates only the state "concealed" or "visible". The operating personnel do not know how much they can decrease their depth and still remain concealed or how much deeper they must go to become concealed if they have a "visible" condition. This could be useful information in some operational situations. Both of these displays would be feasible with little additional circuitry.

Several units of such an operational system could be installed on submarines for evaluation under operating conditions, after which a review could be held to decide if the system satisfactorily fulfills a real need and should become standard equipment available for installation on submarines engaged in operations requiring its use.

The potential capability exists, then, to provide the submarine commander with a continuous, real-time appraisal of his visual concealment status. If future naval operations require such a capability, a recommended plan for the effort necessary to provide the equipment is summarized below.

1. Test and evaluate existing engineering model.
    a. Upgrade scanner and computer, making improvements indicated by previous testing.
    b. Install on submarine.
    c. Run exercise with observation and photographic documentation from helicopter and with water properties measurements from surface craft.
    d. Leave aboard for use of submarine staff to obtain their appraisal.
    e. Review results.
2. Develop operational system.
3. Build several operational units and install on submarines for evaluation.
4. Reassess system and determine if it satisfactorily fulfills the current operational requirement.

The actual configuration of an operational system may be readily adapted to the requirements of the fleet. The one critical requirement is that the outboard, in-water optical sensor unit must be mounted near the top of the sail and the two small target plaques attached at suitable locations below the sensor. Table II provides brief general specification for a basic system based on the concepts described in this report.

TABLE II

Output	Illuminated Display: "Visible" or "Concealed"
Functional Operating Range	
Depth	0 to 400 feet
Ambient Light of Submarine	50 to 12,000 foot candles
Water Clarities	All
Maximum Depth Capability	As Required
Hull Penetration	One Electrical Cable Penetrator
Weight	
Outboard In-Water Unit	100 pounds
Inboard Computer & Display Unit	30 pounds
Size	
Outboard	1 cubic foot (approx.)
Inboard	Less than 1 cubic foot
Power	115v, 60Hz, 1ϕ, less than 500 watts

There are two caveats which apply to a system of the type recommended. They should be clearly understood at the outset as they represent limitations to the capability of such systems which are completely outside the control of the designer. These limitations would not negate the usefulness of this equipment under many circumstances but do recognize certain physical truths that would affect the operational use of the system. On the other hand, the presence of the system and the information which it provides the submariner would increase his awareness to the problems involved in effective concealment in addition to providing information on his current situation to be used in making tactical decisions.

The caveats are: First, the assumption is implicit in the calculations performed by the equipment that the water between the sail-mounted sensor and the surface is not significantly clearer than that at the sensor. Second, the inherent contrast of all parts of the submarine against its water background is assumed to be the same as that measured at the sensor (see Section 3.3). In this latter regard the presence of a relatively small white or specular (shiny) surface on an otherwise correctly painted submarine could not only cause the equipment to provide an erroneous estimate of the ship's concealment status, but would negate the effectiveness of an otherwise satisfactory concealment painting. Furthermore, on sunny days in clear to moderately turbid water the orientation of the sensor with respect to the shadows cast by the sail is critical (i. e., the sensor-target path should not be in shadow), and the indicated concealment status applies only to the sunlit portions of the hull. An observer viewing the shadowed side of the sail, for example, would always see a negative contrast (dark) target even when the painting is entirely correct for sunlit or overcast viewing conditions.

APPENDIX A

OPTICAL PULSE DETECTOR

A-1. ORIGIN AND CONCEPTS

In the summer of 1968 the Laboratory received an inquiry concerning the ability of the detectors in the first generation Submarine Visibility Determining Equipment to detect the presence of short laser-type pulses. The reply, soon confirmed by Laboratory testing, was that the system was too slow to respond to fast light pulses. It was then suggested by the Laboratory that a detector could perhaps be built using available "off-the-shelf" components and that this detector be included as an adjunct to the second generation Submarine Visibility package. This is essentially what was done, using the funding provided for the Submarine Visibility program. Note that the pulse detector was developed as a stand alone "add-on" to the Visibility Determining equipment. It is not part of the visibility equipment and, except for sharing a power supply and the electrical cable, it is optically, electrically, and mechanically separable.

The detector is housed under the glass dome shown in the frontispiece, and the warning indicator, reset switch, and threshold adjustment are shown in the upper right portion of the control panel in Fig. 5. The detector responds only to very fast laser-type pulses. When a pulse is sensed, the warning light comes on and stays on until the reset button is pushed.

A-2. DESCRIPTION OF CIRCUIT

The input light pulse is sensed by a sensor/preamplifier combination purchased from Data Technology. The sensor is a silicon PIN diode. Fig. A1 shows the functional concept of the system. The output from the preamplifier goes to a pulse amplifier which produces a stretched and amplified pulse. This yields the optimum signal-to-noise ratio compatible with the gain bandwidth product of the amplifier. The pulse amplifier is coupled to a fast comparator circuit which utilizes a gallium arsenide tunnel diode as the comparator to sense the light signal. A reference voltage sets the minimum pulse height which will trip the comparator. The output of the comparator is delayed long enough to activate a solid state latching switch and light a warning lamp. The lamp remains on until a manual enable-switch resets the latching switch.

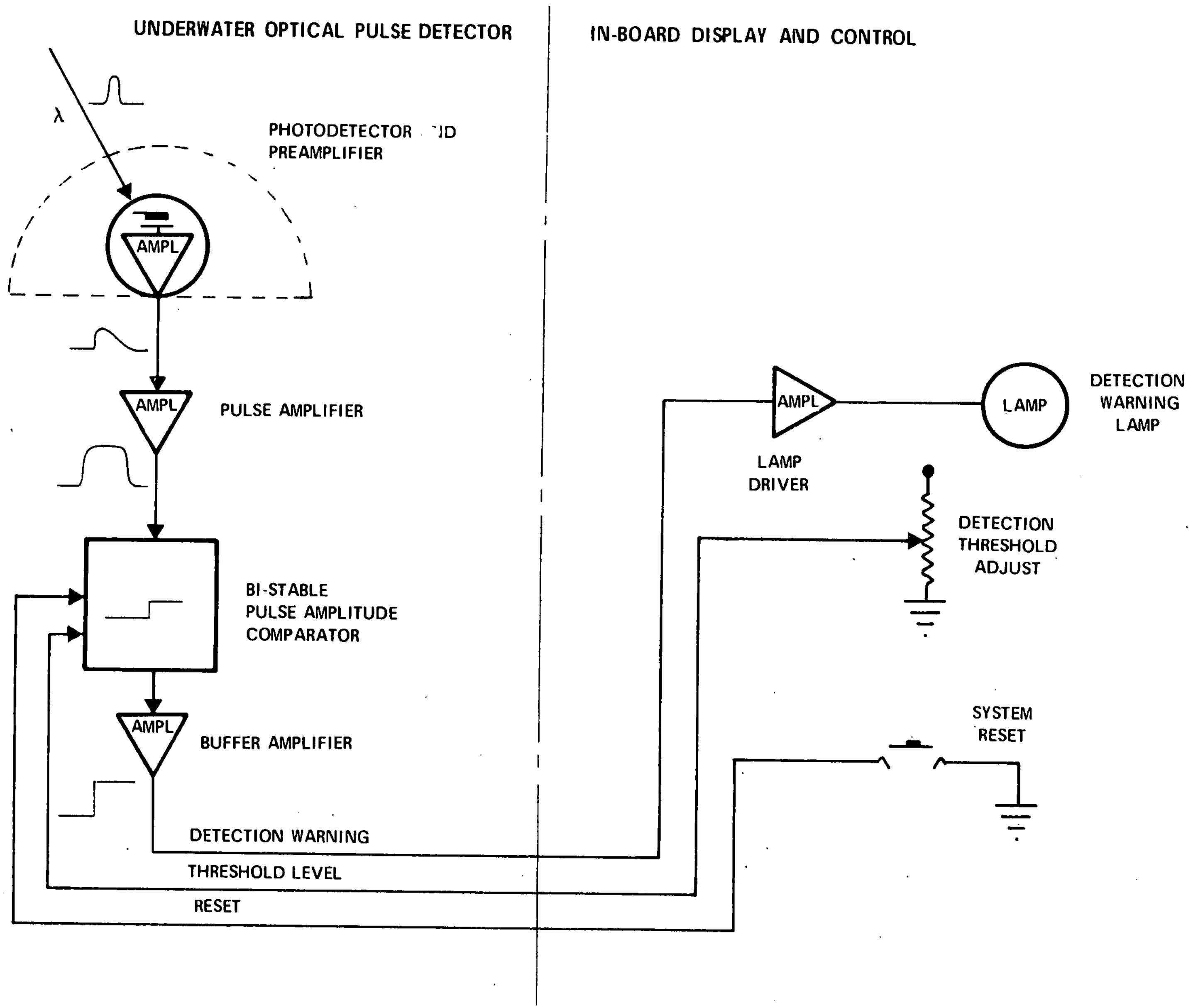


Fig. A-1. Submarine Visibility Determining Equipment - Optical Pulse Detector, Functional Block Diagram.

A-3. TESTING

The pulse amplifier was tested at the Laboratory for frequency response. It has a flat response from 6 mHz to 10 mHz, falls off 3 db at 35 mHz, and is down 12 db at 110 mHz. A plot of this curve is presented in Fig. A2 As a means of reducing the probability of false alarms caused by ambient optical or electrical noise, the low frequency cutoff point was increased from 6 to 13 mHz by changing the value of the coupling capacitors in the input stage of the pulse amplifier.

Tests were also performed to determine the lower threshold limit of the optical pulse detector sensitivity. This was accomplished by utilizing a Data Technology DOC-1002 gallium arsenide pulsed laser and an EG & G model 560B Lite-Mike. The Lite-Mike, provides either absolute or relative measurements of continuous and pulsed light sources. See Fig. A3 for the test setup. The gallium arsenide solid state laser purchased for this purpose emits pulses of about a 20-nanosecond duration with a rise time of less than 10 nanoseconds at 900 nanometers into a small cone. Within this cone the laser acts like a point source. Its signal is attenuated by varying the source-to-detector distance until the threshold of the optical pulse detector is reached. The peak light power per unit area at threshold was

$$0.64 \frac{\mu w}{cm^2} \pm 50 \text{ percent.}$$

This measurement was made at 900 nanometers, which approaches the peak sensitivity of the silicon detector used in the optical pulse detector. At wavelengths close to the maximum transmissivity of water, the sensitivity of the silicon detector is approximately one-half the value at 900 nanometers. Therefore the threshold sensitivity of the optical pulse detector in this region would be about

$$1.3 \frac{\mu w}{cm^2}$$

At the invitation of the Naval Air Development Center (NADC), the optical pulse detector (instrument) was taken to the Lockheed Underwater Test Facility in Sunnyvale, California on 9 March 1971, where the Visibility Laboratory was involved in evaluating the Optical Ranging and Detection System (ORADS) with NADC. This was a unique opportunity for a preliminary check of the instrument response to the NADC pulse laser. Preparatory to shipping and testing, the instrument was separated from the Submarine Visibility Determining System and a special control box constructed.

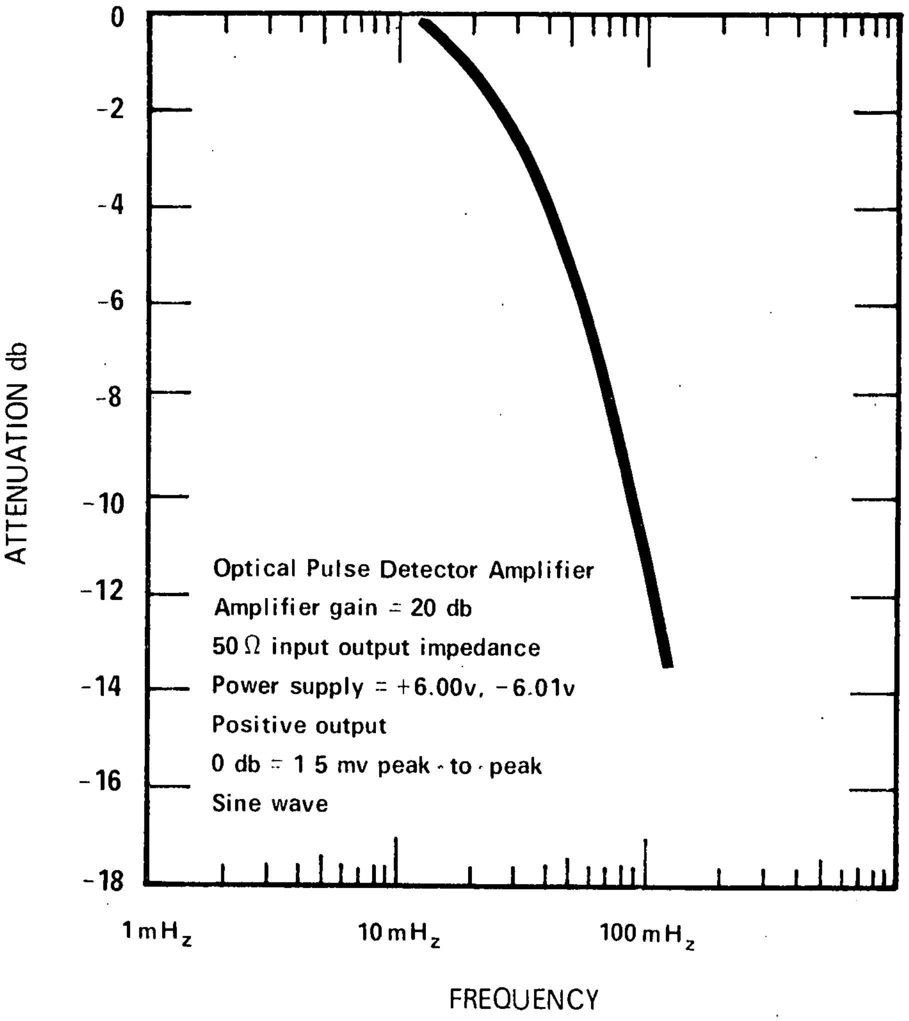


Fig. A-2. Amplitude Frequency Response.

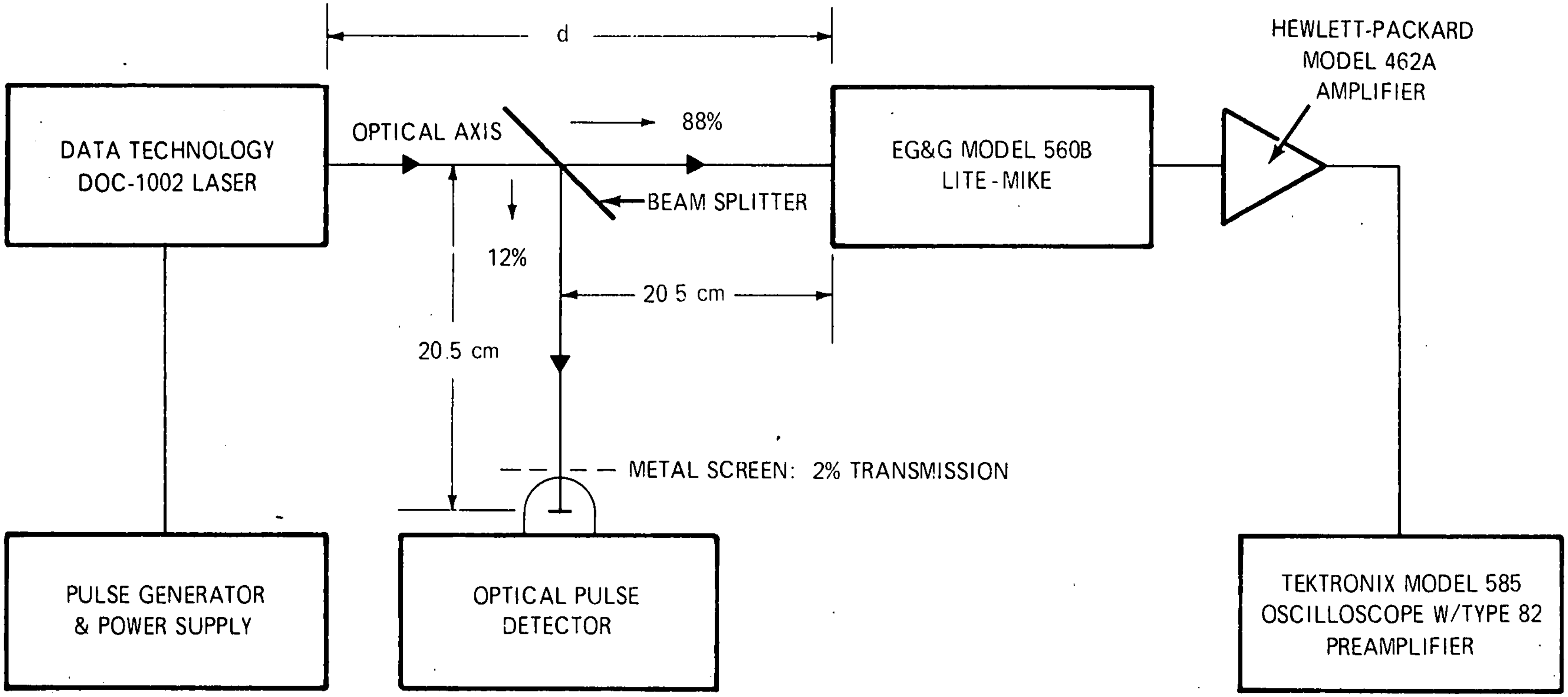


Fig. A-3. Optical Pulse Detector Threshold Sensitivity Test Block Diagram.

The operational tests were coordinated with the testing of the ORADS, allowing for as many variables and handicaps to good performance as possible. One such variable was the tank water which was altered by adding scattering and absorbing agents to simulate three grades of water clarity from clear to turbid. For clearest water, the total attenuation coefficient, α, was $0.069 m^{-1}$, of which $0.0008\ m^{-1}$ was due to the total volume scattering coefficient s; for the intermediate water, α was $0.151\ m^{-1}$ and s 0.031; and turbid water α was $0.248\ m^{-1}$ and s was 0.049. All tests were performed in each of the three water clarities.

The instrument was placed nearly 260 feet from the laser source and suspended beneath the water surface, facing downward at an angle of approximately 30 degrees from vertical. (See Fig. A4). Instead of intersecting the horizontal laser beam, the centerline of the instrument field of view was positioned to pass diagonally about 6 feet from it.

The laser beam traveled through 110 feet of airpath, an air/water interface, and then 150 feet of waterpath. Laser peak power varied between 100 and 800 kilowatts. A further restrictive measure was retention of a cylindrical open-end protective guard around the glass dome of the instrument itself, which reduced its field of view from nearly 180 degrees to approximately 90 degrees.

A straightforward test was first performed to ensure that the instrument did in fact respond to the laser beam. The results were completely satisfactory. Then, in order to determine that the instrument was not responding to spurious radiation from the laser system, the laser beam was alternately covered and uncovered. Consistently, the indicator light on the control box was tripped only when the beam was not occulted. In a similar test where the instrument itself was alternately covered and uncovered, results were equally constant and successful. To test response to scattered pulsed light, the instrument was turned to face directly toward the tank wall, away from the beam. Under this condition, the instrument continued to respond fully. Finally, the instrument was taken from the water, activated, covered, and left for an 8-hour period. The set threshold at which the instrument would trigger on noise was found to drift only slightly during this interval. Testing was concluded on 28 March.

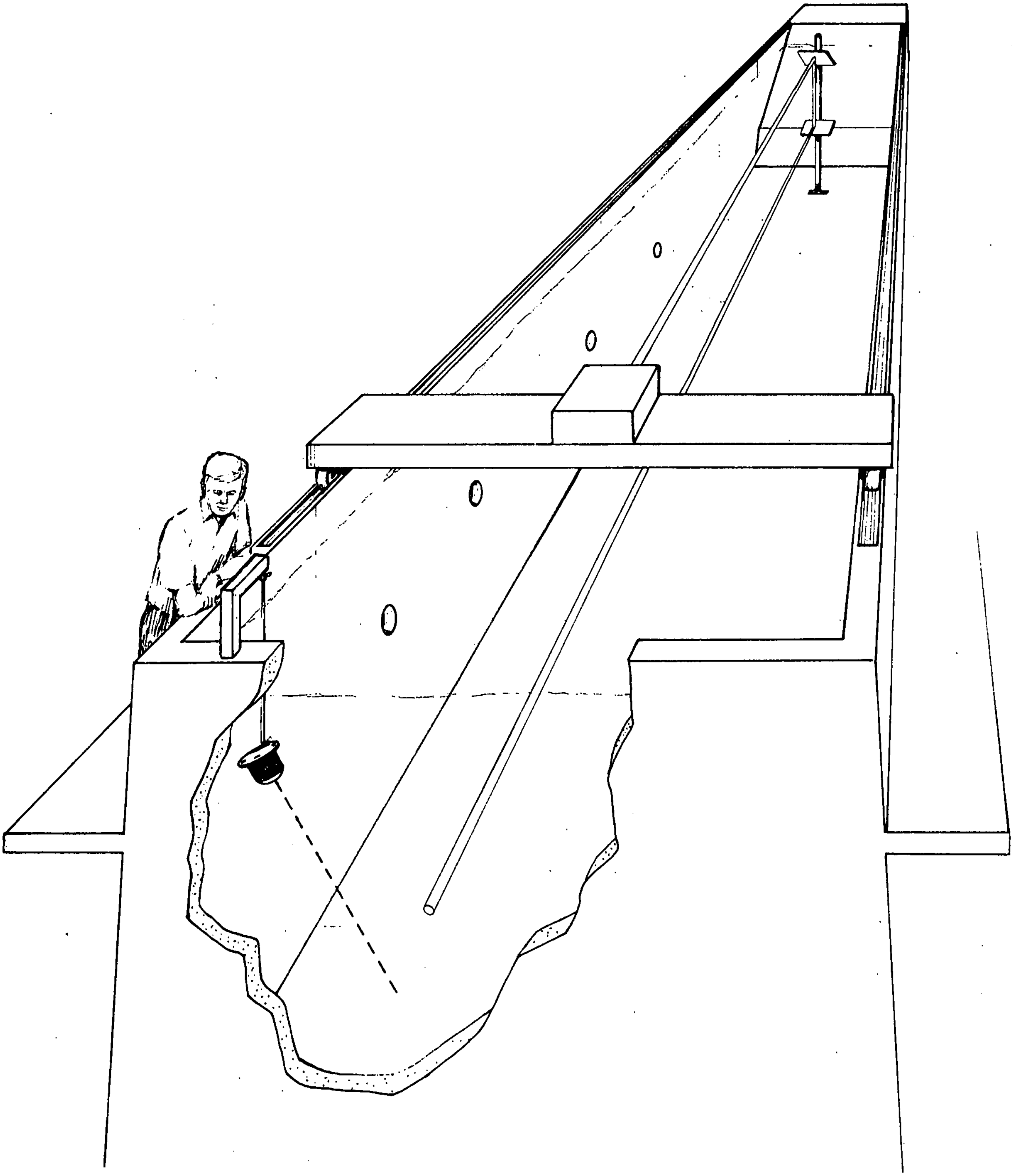


Fig. A-4. Setup for Optical Pulse Detector Tests at Lockheed Underwater Test Facility.