THE UNDERWATER RADIANCE DISTRIBUTION PROBLEM

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INTRODUCTION

A manuscript entitled "Radiance Distribution as a Function of Depth in an Underwater Environment," which first appeared as S.I.O. Report No. 58-25, was recently submitted to the Editorial Board of the Bulletin of the Scripps Institution of Oceanography for publication. The author, Mr. John E. Tyler, was asked by that Board to obtain letters of evaluation from scientists knowledgeable of the subject treated by his paper. Such a letter, addressed to the Chairman of the Editorial Board, constitutes the subject matter of this report. It may be the first of several minor narrative accounts of progress under NS 714-100.

To: Professor Claude E. ZoBell
Chairman of the Editorial Board of the
Bulletin of the Scripps Institution of Oceanography

John Tyler has asked me to write to you concerning his manuscript, "Radiance Distribution as a Function of Depth in an Underwater Environment," which has been submitted for publication in the Bulletin of the Scripps Institution of Oceanography. I understand that my letter is to "state clearly the extent to which the paper is a contribution to knowledge and its importance in its field of learning." It is a pleasure for me to write the memorandum Mr. Tyler has requested because the data presented in this paper are of very unusual significance. In fact, I believe it to be the most important experimental contribution ever made to the science of hydrologic optics and I would like to explain the reasons for my opinion quite fully. This cannot be accomplished in a short note, and I trust that you will forgive me if what I shall write grows long for it will serve the additional purpose of providing a background for other papers which you may receive from time to time from Mr. Tyler, Dr. Preisendorfer, and others.

Eleven years ago I was asked by the Navy to investigate the physical factors which govern the visibility of underwater objects and I organized the original Visibility Laboratory at MIT for this purpose. It was necessary, as one of the major steps in this work, to ascertain the manner in which light from the sun and the sky penetrates bodies of natural water, particularly with respect to its directional distribution, for this determines both the pattern of illumination on the object and the background against which it is seen. Regardless of whether the observer is a human swimmer, a fish, a photographic camera, or an underwater television device, the requirement is basically the same: If a submerged object is visible it must receive and reflect natural light in such a manner that it differs from its background. No scientific description or prediction of underwater visibility by means of daylight is possible without a knowledge of the directional distribution of light underwater, i.e., the radiance distribution.

It has long been known that daylight within the sea diminishes with depth in an approximately exponential manner. I can recall from my undergraduate student days that the problem of the penetration of light into the sea was used as a simple example in a lower-division course in differential equations! The simple exponential relation is a crude generalization of data from low-precision measurements with apparatus which averages light arriving from a wide cone (usually a hemisphere); the elementary differential equation treatment mentioned above, which yields a simple exponential solution, is naive and physically unsound on a dozen counts. Accurate wide-cone measurements show many complicated anomalies and when the true directional distribution is explored a highly complex situation is found: Sunlight, nearly collimated just beneath the surface, becomes progressively more diffuse as the depth of observation is increased whereas highly diffused skylight becomes redistributed in an increasingly downward manner. The radiance distribution observed at any depth is the superposition of these components. The true theory of the phenomenon is far from simple, ranking in complexity with many of the most intricate problems in theoretical physics.

During the summer of 1948 I began to study the problem of directional distribution by means of underwater photographic photometry, and the following year I built an underwater photoelectric photometer for this purpose. These preliminary studies, conducted in a lake, indicated the complex nature of the problem and enabled me to begin building a theory to explain the observations. Under the pressure of Navy needs I built a more sea-worthy apparatus and, during 1950 and 1951, I made light distribution measurements in the ocean off Key West, Florida, and from a Scripps ship off San Diego. Dr. Preisendorfer joined the staff of the Visibility Laboratory during that period and devoted much of his time to the theoretical aspects of the problem.

When the Visibility Laboratory became part of Scripps in 1952 the collection of radiance distributions at sea was an important activity, and the photoelectric underwater radiance photometer was rebuilt again and again as improvements were conceived. In 1954 Mr. Tyler became especially interested in the underwater daylight measurement program, and he has devoted nearly full time to this work for the past four years. He continued the development of the underwater radiance photometer and, with Austin, produced a very intricate and successful apparatus capable of exploring the light-field accurately to considerable depth.

Radiance distributions were measured at sea, in coastal areas, and in San Diego harbor but the experiments were so difficult that we soon realized that it was impracticable to expect to achieve oceanographic surveys of radiance distribution by direct measurement. We were convinced that the only hope of producing underwater radiance distribution information on a practical world-wide basis was through the development and use of theory so rigorous and powerful that accurate and reliable radiance distributions could be calculated from readily measurable optical constants of ocean water.

This philosophy has governed the hydrologic program of the Laboratory during recent years. Major emphasis has been placed on the development of a rigorous theory, and survey-type apparatus was built for obtaining valid depth profiles of the constants appearing in the theory. A major road-block soon developed, however: Basic assumptions essential to the evolution of the theory could not be made with certainty until the true nature of the depth progression of the radiance distribution was known. For nearly two years the program moved slowly while inconclusive experimental attempts were made to discover whether or not the radiance distribution approached a stable configuration characteristic of the water-mass or whether it continued indefinitely to alter its shape. Theoretical models could be constructed having either property but only one could be right. The vital question was: "What actually happens to the radiance distribution in deep water?"

Experiments soon showed that all of the available ocean sites were too stratified to allow an unambiguous answer to be found. The same was true in the harbor. Next we turned our attention to the reservoirs in San Diego County with no success. We found that the water at our New Hampshire field station, while optically uniform, was not deep enough. The Navy volunteered the use of their elaboroate hydrophone calibration barge which is anchored in 700 feet of water in Lake Pend Oreille, Idaho. A preliminary experiment there in the summer of 1955 showed a very unsuitable stratification to prevail, and at this point the problem seemed discouraging. A very large amount of expensive effort had been expended and the elusive facts were as obscure as ever.

When it was learned, however, that Lake Pend Oreille never freezes, despite the rigorous winter, and that, due to overturn, an isothermal stratum hundreds of feet deep develops by the end of the winter we decided to make an experiment there during winter. This was far from easy. Sunshine, clear skies, and calm water were required whereas Lake Pend Oreille is overcast virtually all winter and the water is seldom calm. In the spring, however, there are usually a few calm, sunny days, but at this time the snow on the surrounding mountains begins to melt and torrents of muddy water pour into the lake destroying its optical uniformity. It appeared, therefore, that only a day or two suitable for the experiment should be expected in any one year.

Throughout the winter of 1956-57 Tyler, Austin, and their men built a very carefully designed and elaborate apparatus for the special needs of the anticipated experiment at Lake Pend Oreille. Weeks before the fair weather was due Tyler took the equipment to Idaho, mounted it in the Navy barge, and rehearsed the work until he was confident that he and his crew could carry out the necessary measurements rapidly and surely when the time came. This was rugged and dangerous work, but no accidents occurred. Then it was a matter of waiting in San Diego for the weather to break. Finally the moment came. There was a rush to Idaho and a few anxious days of hard work. Tyler's preparations had been thorough; the experiment proceeded without a flaw, and the records seemed ideal from every standpoint.

More than a year was required for John Tyler and Hadley Richardson to reduce the data but when it was in final form our fondest expectations were exceeded. Not only did the Pend Oreille experiment prove that in uniform water the radiance distribution progresses to a shape which is characteristic of the water-mass and independent of the nature of the lighting above the surface, but it displayed a host of other regularities, previously unsuspected, which provided the basis for a new theoretical approach of great power which has produced many new concepts and theorems and a far deeper understanding of light penetration phenomena.

The Pend Oreille data triggered a virtual avalanche of theoretical output by Preisendorfer. For those of us in the Laboratory the year or more since the data first began to reveal its message has been a thrilling and exciting experience, with discovery coming almost daily. A whole new chapter in science was unfolded so rapidly that it was hard to keep abreast. A scientist can ask for no greater pleasure than a prolonged period of break-through such as we have been witnessing since Tyler's data appeared. Characteristically, it has been a rather lonely period, for almost no one anywhere outside our Laboratory understood what was happening here or why we were so excited.

You can see, however, why I feel that the paper containing the Pend Oreille data which Tyler has sent to you for publication is, in my opinion, the most important experimental contribution ever made to hydrologic optics. It should be the great classic paper in its field. It is the culmination of ten years of apparatus development and experimentation. I have no way of knowing what these data have cost; surely the radiance distribution quest has been, by far, the most expensive Navy-supported project in the Laboratory. The scientific importance of any body of data is not, of course, to be measured by its cost, but I cannot help being humbly grateful for the decade of confidence and support given this work by the Navy, for without such exceptional and geneous aid the radiance distribution problem could not have been solved.

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