PREFACE

In this work I conclude my studies of radiative transfer theory begun in the monograph, "Radiative Transfer on Discrete Spaces." In that monograph the main goal was the founding of the interaction principle underlying the phenomenological theory of light in scattering-absorbing media. In this treatise, I systematically construct from the interaction principle those basic laws and formulas of the discipline of radiative transfer that pertain to hydrologic optics. Thus while the first work was concerned with the gathering together of many single threads of theory converging on the notion of the principle of interaction, the present study starts with the principle as a base, deduces the superstructure of general radiative transfer theory, and applies it to the special case of light in the sea. This task is essentially carried out in Chapter 3 and culminates in the classical principles of invariance and in the equation of transfer for radiance. Concurrent with this is the deduction of the existence of the fundamental optical properties used in the equation of transfer, namely the volume attenuation and volume scattering functions. Some of the remaining chapters of the book (Chapters 4, 5, 6, 7, 8, 11) are devoted to deductions from the principles of invariance and the equation of transfer of those laws of radiative transfer and those properties of natural optical media which are particularly suited to the study of radiant energy transfer in the sea and other natural bodies of water. Actually, many hydrologic optics principles discussed in this work can also describe radiative transfer phenomena in general optical media, such as those encountered in both the astrophysical and geophysical (including industrial) settings. However these principles have often been deliberately phrased for use within the context of hydrologic optics in order to retain the concreteness and practical utility of the theory. The quest for generality was fulfilled in the discrete-space monograph.

In completing the preceding task, I brought to a close a long and almost circular conceptual odyssey which began for me during a summer eighteen years ago (1950) when I was a student at the Massachusetts Institute of Technology. I was given the problem of determining the reduction of visibility of submerged objects as seen along inclined paths of sight through the wind-crinkled, air-water surface. The odyssey was 'circular' in the sense that my preoccupations in this field began and ended essentially with the problem of radiative transfer through the wind-blown air-water surfaces of natural hydrosols (Chapter 12). Between these end points concerned with the initial and final studies of this problem, I travelled a conceptual journey which for long periods was occupied with the search for the most basic principles and concepts underlying the solution of this and related problems of light in the sea. As explained in the preface of the first work, that search was guided by a personal interest in carrying the theory of hydrologic optics to its highest level of geometric and algebraic perfection.

During the past eighteen years the theory was most intensively pursued within the period of seven years from 1953 to 1960 and during a brief period around 1964-1965. The remaining periods of time were occupied at first with student studies and later with writing, teaching, travels, and applied and pure mathematical studies in other fields. In particular, the manuscript for the present work was first drafted in rough outline in the spring of 1958. Successive drafts were enriched as additional theory was created. The motivations of these additions were through the experimental findings of my colleagues and my own imperfect applications of the rough theory. The roots of the present work extend back to a series of lectures I gave on hydrologic and atmospheric optics in the fall of 1953 and the spring of 1954, and earlier still to the joint work in 1950-1952 with Duntley summarized in the first four chapters of "The Visibility of Submerged Objects." The final and main manuscript of the present work was essentially completed in the summer of 1965, after approximately 20 months of writing which was begun hard on the heels of finishing my monograph. During this period large parts of Chapters 2, 3, 6, 7, and 12 were originated as the writing proceeded. In general, every chapter had new material of some kind added at this time. The present work then lay dormant for nearly three years, awaiting final proofreading, while I was occupied with new teaching and research responsibilities. On recently re-reading the manuscript and teaching from parts of it, I find that the fundamental theory has mellowed well; it has reached a stage of internal completeness which will be adequate to the needs of all advanced experimental and theoretical work in the forseeable future.

Those points in the present study where contact is made with physical reality, in the form of useful illustrative experimental data on the radiance of submerged light fields and in instructive listings of optical properties of various seas and lakes, are due principally to the labors of my colleagues Dr. S.Q. Duntley and Mr. J.E. Tyler. Their key measurements of the basic radiometric quantities and optical properties of these media provided some of the original impetus toward my construction of the theory of hydrologic optics. The construction was undertaken as an attempt to conceptually sort and order the many empirical laws of light in the sea which their probings uncovered. My indebtedness to these men actually is deeper than this, and I would like to record here the following observations in this regard.

To Dr. Duntley I owe much of the support of my work during all the past years through his various contracts with the Bureau of Ships and the Office of Naval Research of the United States Navy. The early years were interspersed with conversations and working sessions in which I received from him some of my first glimpses of a possible theory of hydrologic optics. In the summer of 1950 at the Diamond Island Experimental Station in Lake Winnipesaukee, New Hampshire he described his important empirical discovery of the elliptical hydrologic range law made during some underwater experiments. The hint of theoretical order in that experimental polar plot of hydrologic range versus downward angle of sight inspired me subsequently to fathom first the physical and then the mathematical laws underlying that phenomenon. The ensuing summer was spent happily in my sun-baked cabin on that tiny island as I tackled my first independent scientific studies. These resulted in the deduction of the elliptical hydrologic range law and also the simplest radiance-propagation laws for lines of sight through air-ruffled water surfaces and along inclined paths of sight through deep regions of seas and lakes. Duntley's influence on my studies occurred not only in the experimental quarter, but also on first reading his distinguished contributions to the Schuster two-flow theory: I recall the train ride through New Hampshire countryside from Boston which began that summer of 1950 and which is forever linked with the conceptual revelations experienced as I read his two papers on "Optical Properties of Diffusing Materials" and "The Mathematics of Turbid Media." The first paper pointed the way toward the improvement of the Schuster two-flow theory. The latter paper was eventually to provide an instance of the interaction principle in the form of Schuster's "principle of self-illumination." A dozen years were to pass and a score or more of distinct manifestations of the principle of interaction were to be discovered before its universality was to become manifest in my mind. It was also Duntley's exposition of L.V. King's integral equation method and especially the closing remarks in the latter paper that eventually encouraged me to create the discrete space theory of radiative transfer. This theory on the one hand retains the generality of the integral equation approach and on the other leads without modification to numerical determinations of light fields in general optical media. The requisite procedure is given by the Categorical Analysis Method in my monograph.

I wish also to note in some detail the profound influence of the work of Tyler on my constructions of hydrologic optics theory. Unquestionably his experimental measurements on the "Radiance distribution as a function of depth in an underwater environment", was for me a watershed of at least a dozen incipient theoretical laws of hydrologic optics. It provided, for example, the definitive experimental data needed to verify L.V. Whitney's conjecture on the existence of "characteristic diffuse light" deep below the surface of every natural optical medium and which belongs exclusively to that medium regardless of the lighting conditions above its surface. These findings encouraged my search for theoretical expressions of the fundamental properties of real light fields far from the boundaries of deep optical media. It was also Tyler's accumulation of data by means of ever more precise radiometric measurements in oceans and lakes that led us both to realize the inherent limitations of the classical Schuster two-flow (one-D) model of the light field in handling such data: his measurements of upward and downward irradiance flows, for example, were uncovering new kinds of depth behavior of the diffuse attenuation and reflectance functions of such subtle and delicate forms that they lay far beyond the descriptive powers of the classical theory. This state of affairs eventually led me to formulate the theory of directly observable optical properties of light fields in real stratified media. These formulas for directly observable properties were subsequently applied by Tyler and his colleagues in various papers, and particularly in the "Method for obtaining the optical properties of large bodies of water." The present account must also take cognizance of many conversations with Tyler on the puzzles of practical radiometry in the sea. These discussions gave me insight into the needs of the experimenter in hydrologic optics and for whom in turn Chapters 9, 10, and 13 are specifically written. In the course of the years the contents of these chapters arose in various attempts to cast into a mathematically self-consistent array of operationally meaningful forms all the fundamental concepts of radiative transfer in the sea, such as the volume attenuation, scattering, absorption, and the diffuse attenuation functions for all radiometric concepts. These concepts in other branches of radiative transfer, notably astrophysical optics, were either nonexistent or in the form of unrealizable mathematical abstractions of no use to one with direct instrumental access to the interior of the optical medium of interest; in our case, the sea. Finally, I gratefully acknowledge that a large part of the writing of this work was generously supported by portions of Tyler's National Science Foundation Grants (G 11668 and G 289).

The preceding description of the background of the present work has implicitly referred to the contents of all the chapters except the first two. The first chapter may serve as a self-contained 'short-course' on hydrologic optics. Indeed it has been used as a base for the first course on 'Radiative Transfer in the Sea' given at Scripps Institution of Oceanography in the fall of 1967. Particular attention is directed toward the three simple models for light fields in natural waters given in Chapter 1. These models constitute the minimal theoretical tools for anyone who enters the field of hydrologic optics and wishes to do productive work therein. In particular for one who plans to do experimental studies, some guidelines are necessary to first of all measure the quantities of hydrologic optics in a consistent manner and secondly, to measure something that will be useful to others in the same field. These models and the constructs from which they are fashioned supply the requisite guidelines. As one's needs for precision and comprehensiveness of concepts evolve, then the theoretical developments comprising the remaining chapters of the work will be of help in filling these needs. Attention is also directed to the section of the first chapter dealing with practical nomographs for predicting the range of visibility available to underwater swimmers in various natural hydrosols such as harbors, lakes and seas. These nomographs are based on the work of Duntley, which combines the properties of the human eye with one of the three models of the light field referred to above. Also of general interest are the many samples of magnitudes of light fields and optical constants found in natural waters. These samples are based mainly on the field work of Tyler, Duntley, and Jerlov and serve to fix one's intuition for the sizes of the optical constants found in nature. This in turn allows intelligent derivations of new approximate formulas based on the light field models alluded to above. Finally, the presence of Chapter 2 is almost self-explanatory, being concerned with the scientific language of radiative transfer: geometrical radiometry. Students of geometrical radiometry may find the various novel formulas and laws developed throughout the chapter of independent interest. However, the chapter finds its place in this work by providing the radiometric concepts and formulations needed in the applications of the interaction principle to hydrologic optics.

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R.W.P.

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R.W.P.

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