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Fifty years of inherent optical properties

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ABSTRACT

This paper describes my career in Ocean Optics over nearly half a century. It was centered around the Inherent Optical Properties (IOP, the scattering and absorption properties of sea water and its dissolved and suspended materials). The paper describes the development of instrumentation for the measurement of the IOP, the applicable theories, and the inversions to obtain biogeochemical parameters. This is not intended to be a thorough review, but rather describes a personal journey.

Introduction

The ocean is a dilute soup of suspended particles and dissolved materials. The particles consist of living phytoplankton and zooplankton as well as inorganic materials from resuspension, river runoff, airborne particles, etc. These particles and dissolved materials affect the transmission and absorption of light. The intensity, directionality, and spectrum of the underwater light (the light field) in turn affects the yield of organic materials and the oxidation of organic materials. The optical properties of the particulate and dissolved materials are known as the Inherent Optical Properties (IOP) (Preisendorfer, 1965, 1976). They are called inherent because they are not directly affected by the light field. Conversely however, the IOP directly affect the light field. We thus see that the nature and concentration of particulate and dissolved materials determine the IOP, and the IOP determine the light field in the ocean (together with the incoming light field at the sea surface). In turn, all biological, geological, chemical, and physical processes have some effect on the shape, size, or index of refraction of the particles, the dissolved material, or the water itself, and hence on the IOP of sea water with all its constituents.

All biological, chemical, geological, and physical processes in the ocean result in some change of the IOP of the dissolved and suspended materials or the optical properties of the sea water itself.

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There are thus a number of interesting problems associated with the IOP:

- How do the properties of particulate matter (size, shape, index of refraction distribution) determine the IOP of the particles?
- How do the properties of the dissolved materials determine their IOP?
- How do the IOP affect the intensity, directionality, and spectrum of the underwater light (the problem of radiative transfer)?
- If we know some of the IOP (absorption and/or scattering characteristics), what parameters of the particulate and dissolved materials can we determine?
- How can the IOP be used to determine the spatial and temporal distribution of the particulate and dissolved materials, and study the processes that determine those distributions?
- How can the light field above, such as determined by satellite sensors, or below the ocean surface be used to determine the IOP, and, in turn, the characteristics and distribution of particulate and dissolved materials?
- How do physical processes (temperature and salinity changes, turbulence) affect the absorption and scattering characteristics of the sea water?
- How can we design and build instrumentation to measure the IOP in the ocean, as well as their spatial and temporal distributions?

These problems, all associated with the IOP one way or another, kept me occupied during a 48-year long career in Ocean Optics.

Personal background

I was born at the end of World War II in the German occupied Netherlands. My father was a marine biologist, hiding from the Germans, as he had been ordered to work for them and he refused to do so. The allies had penetrated to the Rhine river in the summer of 1944, but did not manage to cross until nearly a year later. That time was known as the hunger winter as the German occupiers kept all the food for themselves. It was left to my mother to scour the countryside for food for the family and the Jewish people hiding in the basement. She had an old bicycle with garden hose for tires and regularly had to run German roadblocks.

After the war we moved to the Dutch East Indies (now Indonesia), where my father collected and classified macro algae. We went through the Indonesian revolution there and I started grade school. After the revolution we moved back to the Netherlands. Several years later my father founded the Caribbean Marine Biological Institution in Curaçao. I went to high school there. In Curaçao I learned to sail and dive, activities I have enjoyed for the rest of my life.

In 1960 we moved to Norfolk, VA where my father had obtained a professorship at Old Dominion University, and where he founded the Oceanography department. I did the last year of high school in Norfolk and attended Old Dominion University, where I earned a B.S. degree in Physics.

In 1964 I obtained a Woodrow Wilson fellowship to do graduate work in Physics at M.I.T. While I was there my father had been collecting algae under the ice in Antarctica. He noticed that algal growth was surprisingly active under the ice even early in the spring. He asked if I knew anything about sea ice optical properties. There was very little literature on the optical properties of sea ice at the time, so I decided to see if one could measure it in the laboratory. I made some cuvettes and made ice of different salinities and then ran them through a spectrophotometer. I had loaned the spec. from George Beardsley, who I had met at the sailing club, and who was finishing his Ph.D. work at M.I.T. George had been offered an Assistant Professorship in Oceanography at Oregon State University (OSU). He asked me if I wanted to be his graduate student there. This seemed like a great idea as we were interested in the same ocean optics problems. Besides, I had never been west of the Appalachians. I finished a Master's Degree at M.I.T. and moved to Oregon.

Ocean optics in the 1960's

In the 1960's the Oceanography department at OSU was a growing and vibrant place. The founder was Wayne Burt, who had done Ocean Optics work and had appointed George Beardsley to start a group to focus on the study of the optical properties of the ocean. In the late sixties George had assembled a great group of students that included Ken Carder, Marshall Earle, Bill Plank, Bob Hodgson and Hasong Pak.

At that time the dominant US institution for the study of Ocean Optics (OO) was the Visibility Laboratory under S.Q. Duntley at the Scripps Institution of Oceanography. Together with R. Preisendorfer and J. Tyler, Duntley had outlined the fundamentals of OO including radiative transfer theory, underwater visibility, and instrumentation (Duntley, 1963; Preisendorfer, 1965, 1976). They had developed a number of underwater radiometers, transmissometers and scattering sensors. Preisendorfer had coined the terms "Inherent and Apparent Optical Properties", IOP and AOP. IOP were those properties not directly affected by the underwater radiance field, i.e. those optical properties directly due to suspended and dissolved materials, and the sea water itself, whereas the AOP were attenuation rates derived from the radiance, i.e. derived from the directional and spectral intensity of underwater light. IOP include the spectral beam attenuation coefficient, $c(\lambda)$, the spectral volume scattering coefficient, $\beta(\theta, \lambda)$ and the spectral absorption coefficient, $a(\lambda)$. AOP include the diffuse attenuation coefficients of the plane and scalar irradiances, and these days the term is also often used to refer to the radiometric parameters, the spectral plane and scalar irradiances, $E(\lambda)$ and $E_0(\lambda)$ respectively, and spectral radiances, $L(\theta, \phi, \lambda)$.

An excellent book to study the state of OO in the 1960's is Nils Jerlov's first book, Optical Oceanography (Jerlov, 1968) and references therein. Solutions to the equation of radiative transfer (ERT) had been supplied by Chandrasekhar (1950) and Preisendorfer (1965). These solutions however, did not lend themselves to the computers of the time. Hence various approximations were used to study the relationship between IOP and AOP (references in Jerlov, 1968). Van de Hulst (1957) had described the theoretical foundation between particle size, index of refraction and their scattering and attenuation characteristics.

Quite a few IOP parameters had been measured. The beam attenuation coefficient had been measured by a number of researchers. The volume scattering function (VSF) had been measured as well. However, instrumentation tended to be cumbersome and could typically not be profiled. Almost all absorption, scattering, and attenuation coefficients measured prior to 1968 could be enumerated on a few pages in Marine Optics (Jerlov, 1968). Similarly nearly all 12 VSFs measured to that date fitted on a page. So, fundamental knowledge about attenuation spectra and VSFs were obtained for a few locations, and at a few depths. These showed that the VSF was highly peaked in the forward direction and that the particulate beam attenuation spectra for particles decreased rapidly with increasing wavelengths. The attenuation and scattering coefficients for pure water had been measured in the laboratory, albeit later measurements would show that in the blue these were often in error by more than an order of magnitude, due to the difficulty of making and preserving pure water. The absorption coefficient could not be measured in situ. Absorption spectra were measured in spectrophotometers using concentrated phytoplankton on filters. The filtrate gave the absorption of Colored Dissolved Organic Matter (CDOM). The basic features of particulate and dissolved absorption spectra were thus known, but their distribution was known only in the broadest sense.

The main focus of underwater optics had been the measurement of irradiance profiles as well as some radiance distributions. Spectra of these parameters were obtained laboriously by manually changing filters. Radiances were measured by pointing radiometers at discrete directions and rotating the meters directionally. Again, these measurements were laborious but the fundamental features of the radiance field were determined. It was found that the radiance distribution at the surface was highly peaked in the direction of the sun, and the maximum intensity rotated slowly with depth to the vertical. Upwelling radiance was orders of magnitude less than the downwelling radiance, and was much more uniform. Jerlov (1968) had studied irradiance profiles in a number of locations and came up with his famous optical water types. These assigned specific irradiance transmittance spectra to various water types. These water types were used extensively over the next three decades. Several researchers had also started to study the spatial distribution of scattering and attenuation properties in the ocean with the idea of using these distributions to study physical and biological processes (references in Jerlov, 1968).

In 1971 George Beardsley died suddenly. This sad event had a major influence on my life. I felt an obligation towards the people in the OO group at OSU, so that together with Hasong Pak, I wound up running the OO group. Entirely without intending to, after finishing my Ph.D., I thus stayed at OSU as Research Associate.

Instrumentation 1

Discussions at the OSU OO group at that time centered around the problems listed in the introduction. One of the issues of major interest was the link between the IOP and the particulate and dissolved properties. Initially most data was obtained by shipboard laboratory analysis of water samples, obtained with sampling bottles at various depths. We analyzed them using a spectrophotometer to obtain absorption spectra, a light scattering photometer to obtain scattering characteristics (typically light scattering at 45, 90, and 135°) (Plank et al., 1972), and particulate size distributions using a Coulter Counter (Zaneveld et al., 1973). We used Mie theory (Pak et al., 1971) to connect the particulate and scattering properties. Using these methods we described light scattering at 45° and total particulate volume in the Panama Basin (Zaneveld et al., 1973; Pak and Zaneveld, 1973), and off the Oregon Coast (Plank et al., 1974; Pak and Zaneveld, 1977). These studies revealed many aspects of the distribution of particulate and optical properties that are now well accepted. We found that particle size distributions (PSD) have limited variability in shape and typically have Junge size distributions. This means that the absolute values of optical properties are generally proportional to particle concentrations because variability in IOP due to particle concentrations is much higher than the variability due to the shape of the PSD. We found that high concentrations of particulate matter typically occur nearly everywhere near the bottom (the so-called bottom nepheloid layers), near sills and seamounts, near continents, and near the surface. Thus bottom erosion, runoff, and biological production were found to be major sources of variations in concentration and nature of particulate matter and hence variations in IOP.

Many researchers had built various versions of beam transmissometers (Jerlov, 1968; Petzold and Austin, 1968). These showed promise as in situ instrumentation since Mie theory indicates that the total scattering coefficient shows a higher proportionality with total particle concentration than light scattering at an angle, such as 45°, the parameter that we had been using previously. The beam attenuation coefficient near 650 nm consists almost entirely of the scattering coefficient because the absorption by phytoplankton is minimal near that wavelength and the absorption by colored dissolved organic matter (CDOM) is also very small. The Ocean Optics group at OSU had been building various beam transmissometers modeled after the Scripps instruments. I had seen the power of such a device to measure small scale variations in suspended matter when towing an early version across an oceanic front (Zaneveld and Beardsley, 1969).

In order to study the distribution in space and time of particulate matter using IOPs, we needed to develop a small, easy-to-use transmissometer. We had hired Robert Bartz as engineer and he came up with an excellent analog circuit. We decided to employ the recently available Light Emitting Diode (LED) as a light source (Bartz et al., 1978). This entailed a significant reduction in power, size, and weight, important considerations when deploying oceanographic instruments. The only wavelength then available for LEDs was 660 nm. This was, fortuitously, just what we needed. Over the next several years we solved the optics issues and were able to get a collimated beam with a collimation angle of 1.2°. Bartz et al. (1978) designed an analog temperature compensation circuit that allowed vertical profiling through thermoclines. We decided that the circuit was accurate enough that we could use a 25 cm pathlength. All previous transmissometers had a 100 cm pathlength, with nearly four times the signal. One of the issues with transmissometers is that they are “top down” measurements. That is, the zero particle concentration signal is the highest. For a scattering sensor, the zero particle signal is the lowest. A scattering signal can thus be readily amplified. However, for a transmissometer the “no particle” (water only) signal must be known, since it is the largest signal that can be measured. Using multiple pathlengths we finally determined that the attenuation of pure water at 660 nm was 0.364 m^{-1} (Bartz et al., 1978). This allowed the instrument to be calibrated in the lab. Long term stability of the instrument for profiling at sea was carried out by means of air calibration. This is not ideal because the reflectivity of glass-air is different from glass-water. A scratch in the window will change transmission differently in air than in water. Even so, these instruments, with their all solid

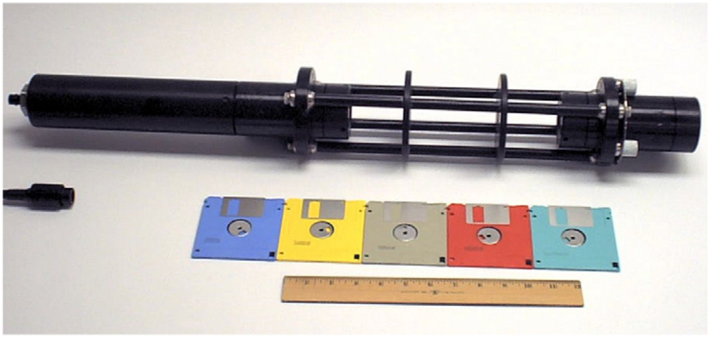

Fig. 1. Sea Tech transmissometer.

state electronics, were more stable over time than previous in situ optical devices. The red LED transmissometers became a major tool in delineating the distribution of particulate matter in the ocean.

During the ONR-sponsored High Energy Benthic Boundary Layer Experiment (HEBBLE) we had a chance to deploy the transmissometers in a challenging environment (Spinrad and Zaneveld, 1982; Pak and Zaneveld, 1983; Spinrad et al., 1983). During HEBBLE we explored high energy events on the Scotian Rise off Woods Hole in 4000 m depth. We moored transmissometers in arrays that allowed us to detect large scale (km, days) as well as short scale (m, minutes) events. The transmissometers performed extremely well. We were able to describe a number of high energy "bottom storms", their physical extent, and their temporal development. Much of the analysis was carried out by my student at the time, Rick Spinrad (currently Vice President of Research at OSU). The instruments were stable and did not drift over long deployments lasting many months. Prior to the transmissometers the primary moored tool for the detection of particulate matter in the deep ocean had been the Lamont-Dougherty nephelometers. These instruments measured near-forward scattering by looking at the scattered light emanating from a blocked incandescent light source. During HEBBLE both types of instruments were deployed and compared (Gardner et al., 1985). The nephelometers consumed much more power and were much larger than the transmissometers. For HEBBLE we also developed an optical settling tube that captured a water sample and measured the transmission over time as the particles settled. Assuming Stokes' settling we developed an inversion to obtain the particle size distribution (PSD) (Zaneveld et al., 1982).

We received significant support from Ed Baker at NOAA PMEL. He was particularly interested in measuring sediment transport (Baker and Lavelle, 1984). Early in the transmissometer development we were able to integrate transmissometers with Aanderaa current meters (Zaneveld and Bartz, 1984). The "tuning fork" shaped transmissometers were later replaced with a design that used source and detector housing separated by a 25 cm pathlength reinforced with struts (Fig. 1). Based on the success in HEBBLE and local West Coast deployments, we started to get requests from other researchers for the transmissometers. We had a discussion about whether to keep these instruments to ourselves in a "have instrument, will travel" mode. I was always opposed to that idea. I feel that whenever you develop an instrument it should be made available to all, as this will do the most to further science. The first several transmissometers for third parties were built at O.S.U. We soon became a major user of the departmental machine shop. This generated conflict as other scientists felt that building instruments for third parties did not constitute science. Instead, we found local machine shops to do the work. Soon there was little point in doing the assembly at OSU, as it took over much of the laboratory space. Hence Sea Tech, Inc. was born, with Bob Bartz and myself as principals. The company was self-funded. Initially instruments were assembled in Bob Bartz's garage. The company slowly grew as transmissometers became more and more accepted. In the '70s, Universities were not yet tuned into the market of selling the inventions of their faculties. The University's main concern was the potential issue of Sea Tech using university facilities. Therefore, we scrupulously kept facilities apart even if it meant duplicating instrumentation.

The transmissometers eventually found wide use in the Oceanographic Community. Transmissometer data has been collected since the early 1980's all around the world during programs such as JGOFS (North Atlantic Bloom Experiment, Equatorial Pacific, Arabian Sea, Ross Sea, Antarctic Polar front Zone-Pacific sector), WOCE (Pacific, Indian and Southern Oceans), SAVE (South Atlantic), and many other programs. In slightly modified form, the transmissometer continues to be a major tool in Oceanography.

Theory 1

My main interest had always been in the theory of radiative transfer and my interest in developing IOP instrumentation had been for the purpose of being able to pursue this interest. The classical problem is the calculation of the radiance distribution and hence the AOP when the IOP are known, this is the so-called forward problem. The inverse problem is to determine the IOP when the AOP are known. As George Beardsley's student I had developed a radiative transfer program (Beardsley and Zaneveld, 1969; Zaneveld and Beardsley, 1969). This program was used to calculate asymptotic properties, the Modulation Transfer Function, and other situations related to underwater image degradation. This program took a weekend to run a few cases at the OSU computer center, as compared to the radiative transfer programs of today that take a few seconds on a laptop.

The best known example of an inverse relation is Gershun's equation, which is obtained when the equation of radiative transfer (ERT) is integrated over 4π steradians. This allows the absorption coefficient to be calculated when the plane and scalar irradiances are known. I was interested in determining if there were further simple connections between the AOP and IOP. By azimuthally integrating the ERT and doing Legendre polynomial decompositions of the radiance and the volume scattering function (VSF), I was able to show that Gershun's equation was only the first of a series of relationships between the moments of the radiance distribution and moments of the VSF (Zaneveld and Pak, 1972). I thought this could be used to determine the VSF from radiance measurements, but too large a number of Legendre polynomials needs to be known for this to be practical. I also proposed that moments of the scattering function could be determined by measuring moments of the radiance. This was eventually done by Wells (1983).

In 1972 I attended the first Ocean Optics conference in Copenhagen. This first meeting consisted of 40 or so people in a classroom. (Today the Ocean Optics meetings have some 1000 attendees.) At this meeting I met all the big names of the day: Rudy Preisendorfer, Seibert Duntley, Nils Jerlov, John Tyler, as well as a number of young researchers such as André Morel, Ray Smith, and Niels Højerslev. Papers from this meeting are found in Jerlov and Steemann Nielsen (1974). As a result, I was invited to spend the summer of 1973 at Jerlov's lab at the University of Copenhagen. While there Jerlov challenged us to do a true inversion: It was known, of course, that when the IOP are known the AOP can be determined exactly. Was the inverse true as well? Using the Legendre inversion and the generalized Gershun's equations, I was able to show that if the radiance and its gradient are known, the IOP can (in theory) uniquely be determined (Zaneveld, 1973). Far too many Legendre coefficients are needed for this approach to be practical, however.

A theoretical challenge we discussed in Copenhagen was the proof (without preconditions) of the existence of an asymptotic radiance distribution. (At great depths the radiance distribution attains a shape that is a function of the IOP only and does not depend on the surface radiance field). Eventually Niels Højerslev and I solved this problem (Hojerslev and Zaneveld, 1977).

Another important form of inversion is the determination of particulate and dissolved material properties (biogeochemical properties or BGCp) from the IOP. A parameter that could not be measured at the time was the index of refraction of particles. We were interested in various inversion schemes to determine this parameter. Using Van de Hulst's (1957) approximations, we derived a method for obtaining the average index of refraction (Zaneveld et al., 1974). Together with my first graduate student, Dave Roach (now Professor Emeritus of Physics at Cal Poly, San Luis Obispo), we developed a method for the inversion of VSFs. Using Mie theory we calculated VSFs for a number of populations with given indices of refraction and Junge particle size distributions. Minimization to obtained measured VSFs showed a preponderance of large low index particles and small high index particles. We applied this method to scattering data taken in the ocean to obtain the first (presumed) distribution of the index of refraction spatially.

Applications

In the 1960's very little was known about the spatial and temporal distribution of the optical properties and the BGCp that could potentially be derived from that. Ultimately we were interested in the processes that govern the distribution of BGCp. We had measured some distributions by using discrete water samples and analyzing them on board ships for light scattering and size distributions using a Coulter Counter (Beardsley et al. 1970). Applying these techniques to the Panama Basin we studied bottom nepheloid layers (Plank et al., 1972), island wakes (Pak and Zaneveld, 1973), and fronts (Zaneveld et al., 1969; Pak and Zaneveld, 1974).

Using the new, small transmissometers in conjunction with the recently developed STD (Salinity, Temperature, Depth) sensors, we started to better understand the distributions and processes related to the IOP. We had many opportunities to study the IOP and BGCp off the Northwest coast. In particular we described bottom and intermediate nepheloid layers as related to coastal upwelling events (Kitchen et al., 1975; Pak and Zaneveld, 1978), river inputs and fronts (Zaneveld and Pak (1979), and bottom resuspension (Pak and Zaneveld, 1977; Pak and Zaneveld, 1978). We studied the Astoria Canyon finding significant temporal variations (Plank et al., 1974). These distributions and the processes that generate them are now common knowledge, but, at the time, each research cruise found new and exciting physical processes via the distribution of optical properties.

We were involved in the Deep Undersea Muon and Neutrino Detector (DUMAND). This was a deep underwater detector to be located off Hawaii, in which the Čerenkov radiation from protons traveling at more than 75% of the speed of light is detected after they collide with neutrinos. By determining the energy and the direction of the radiation, the energy of the neutrinos is determined. In order to obtain the radiant intensity from the signal at the detectors, the attenuation of the radiation must be known precisely. The Čerenkov radiation is in the blue part of the spectrum, so we built the first self contained in situ spectral attenuation meter including blue wavelengths. The instrument had a Xenon flash lamp light source and a rotating filter wheel (Harvey et al., 1979; Zaneveld, 1980). We developed a method to deploy the device from a small boat, by using an autonomous package that dropped a weight when it reached the bottom near 4000 m depth and then returned to the surface. In this way we were able to measure deep attenuation spectra off Hawaii (Harvey et al., 1979).

In late 1978 the first ocean color satellite, Coastal Zone Color Scanner, had become operational and opened up an entire new way of looking at the ocean using optics. The primary product of the satellite optical sensor was chlorophyll concentration, obtained from ratios of the spectral radiance. A topic of considerable interest was the calibration of the chlorophyll product. The remote sensing reflectance is proportional to b_b/a, where b_b is the backscattering coefficient and a is the absorption coefficient at a given wavelength. It was thus important to be able to measure these parameters in situ. I decided to use a reflecting tube to measure the absorption spectrum of water. This had been used many times in the past as it is similar to a long path length spectrophotometer. A tube is ideal for underwater measurements as water can be pumped through it. A preliminary model using a transmissometer with a reflecting tube indicated that this approach would work (Zaneveld and Bartz, 1984).

The Optical Dynamics Experiment (ODEX) was an interdisciplinary experiment to study the relation of physical forcing, biological processes, and the structure of optical parameters in the central gyre of the North Pacific Ocean. Particle size analysis was carried out on discrete water samples taken from hydro-casts casts. Beam attenuation was measured in situ together with CTD data. The ODEX cruise of Oct and Nov 1982 occupied 184 stations along a transect from the California coast at 35° N to a study area covering the subtropical front near 32° N, 142° W. Diffuse attenuation was measured at 5 wavelengths. This instrument suite represented what could be measured at the time.

An interesting development at the University of Copenhagen had been the in situ chlorophyll fluorescence sensor. This instrument was large and heavy, but allowed profiling for organic matter concentrations. We were able to develop a much smaller and lighter chlorophyll fluorometer at Sea Tech. This allowed us for the first time to simultaneously measure total and organic particle concentrations. These showed without a doubt, that the vertical structures of chlorophyll and particulate matter were not necessarily correlated. At the time this was highly controversial as Navy visibility models were based on the vertical structure of chlorophyll. This came about because the main product of remote sensing was chlorophyll. Hence Morel (1988) had developed a model in which all parameters, including b_b and a, were made to be functions of chlorophyll only. This was interpreted to mean that ocean optical parameters could be accurately based on chlorophyll only. We showed this assumption to be incorrect (Kitchen and Zaneveld, 1990). Until then it was not realized that light adaptation by phytoplankton means that chlorophyll and particulate concentration maxima need not coincide.

South Pacific interlude

I had always wanted to go ocean cruising. In 1976 I sailed a 26 foot Folkboat singlehandedly from Portland, OR to Morro Bay, CA. This was a very rough trip featuring a near-rollover off Cape Blanco during a gale. The next year I singlehanded the boat to Hawaii in 23 days. In 1980 I married Jacqueline Foster. She was working on her M.S. degree at OSU. Using her ideas I developed a theory for calculating the probability of pregnancy given the frequency and type of contraceptives used, resulting in a publication in the Journal of Sex Research (Zaneveld et al., 1984). We had our first son, Jesse, in 1982. In the early 1980's funding was getting difficult and the child was not yet in school, so it was time to go sailing again! We bought a 32 foot Rival sailboat and moved aboard. In the fall of 1984 we headed down the coast. I did three months sabbaticals with Jim Mueller at the Navy Postgraduate School, and with Ray Smith at UCSB. I was working on an IOP-based remote sensing reflectance theory (Zaneveld et al., 1982).

In the winter we headed down to Mexico. Over the next two years we sailed to the Marquesas, Tahiti, the Cook Islands, Samoa, Tonga and New Zealand (Zaneveld, Cruising World, Feb., 1990). In New Zealand we had our second son, Eric. I had several art shows around the Pacific and had been supporting the family by selling paintings. When we got back in 1988, OSU kindly gave me a desk and a telephone and I had to start from scratch to rebuild a science career. Instrument development grants could be routed through Sea Tech and there was an excellent engineering staff there.

A depiction of Ocean Optics research
Painting by Ron Zaneveld.

The OSU ocean optics group in the 1990s

During the 1990s and early 2000s it was my privilege to work with an incredible group of graduate and postdoctoral students. They made many significant contributions to Oceanography and continue to do so. These students include: Scott Pegau (now Director of the Oil Spill Recovery Institute in Cordova, AK), Andrew Barnard (now Vice President for Research and Development at WET Labs), Emmanuel Boss (now Professor in the School of Marine Sciences, University of Maine), Collin Roesler (now Associate Professor of Earth and Oceanographic Sciences at Bowdoin College), Mike Twardowski (now Vice President and Director of Research at WET Labs), Darek Bogucki (now Assistant Professor of Physics and Environmental Sciences, Texas A & M Corpus Christi), the late Robert Maffione (founder of Hobie Labs, Inc.), and Anne Petrenko (now Associate Professor at the Mediterranean Institute of Oceanography). Much of the work reported on below was the result of their efforts. We also had Prof. Kusiel Shifrin in our group during those years.

Instrumentation 2

After returning from the South Pacific, I focused on in situ absorption measurements at Sea Tech and we built the first successful profiling single wavelength in situ absorption meter (Zaneveld et al., 1990). We also built an updated version of the spectral attenuation meter (Borgerson et al., 1990). I received a grant from NSF to develop a chlorophyll absorption meter (ChlAM). This device had a rotating filter wheel, an incandescent light source, a reflecting tube, and a large area detector. It measured chlorophyll by measuring the height of the red chlorophyll absorption peak above background, using absorption at three wavelengths. Casey Moore was the project engineer. I was very interested in combining the two devices: to build a spectral attenuation and absorption meter. By subtraction this would also provide the spectral scattering coefficient. This would be a major step forward in measuring the IOP in situ, where sample manipulation with its potential alteration of optical properties, would be minimized. In the late 1980's Sea Tech did a market survey and found that there might be five scientists interested in purchasing such a device. The directors of Sea Tech thus overruled me and were not interested in pursuing development of this device. Casey Moore and I, however, were convinced that there was a huge potential for in situ spectral IOP devices, based on the ubiquitous use of spectrophotometers in laboratories. Using filter pad techniques and theoretical analyses, Bricaud and Morel in a number of publications (Bricaud et al., 1983; Bricaud and Morel, 1986; Morel, 1988, and many other papers) had shown the tremendous amount of information about phytoplankton that could be obtained from studying particulate absorption spectra and scattering characteristics. It was clear that much more could be learned about the distribution and nature of organic matter in the ocean if we could study their absorption spectra and distribution on small scales in situ. In addition, the absorption coefficient is a major component in the determination of the remote sensing reflection. This eventually led Casey and me to leave Sea Tech and start another company, Western Environmental Technology Laboratories (WET Labs, Inc.), with the specific intent of developing and manufacturing underwater spectral absorption and attenuation meters.

WET Labs started business in 1992 and took over the development of the ChlAM, and commenced development of a nine wavelength in situ absorption and attenuation meter (ac-9). We successfully completed the ChlAM, and, as expected, it had approximately 50% less error than chlorophyll fluorescence in determining the chlorophyll concentration. The big drawback was its cost, due to its much higher complexity compared to a fluorometer. As a result it never caught on commercially. Chlorophyll concentration is thus a parameter for which the technology exists to make the measurement at least twice as accurate, but cost prevents its widespread use. The initial development of the ac-9 was primarily self-funded. Fortunately, after about two years, when my retirement savings were exhausted, we had a working prototype that was performing well (Moore et al., 1992; Zaneveld et al., 1992). We then received further development funding for the ac-9 from the Naval Research Laboratory. The ac-9 has incandescent light sources, nine interference filters in a rotating filter wheel, parallel tubes, one reflecting on the absorption side, and a non-reflecting one for the attenuation side. The reflecting tube consists of a glass tube with air on the outside. This results in total reflection up to angles of around 41.8°. The absorption side has a large diffuse detector. The attenuation side has a collimated detector. Water is pumped through the tubes using a Sea Bird pump. Typically the ac-9 is integrated with a Sea Bird CTD, a recorder and battery system, as well as with other sensors.

Calibration of this device was initially difficult. Pure water is ideal for this purpose but we had found that small quantities of pure water soon absorbed materials from the container and would not be stable. At that time, however, continuous nano filtrating systems became available. This meant that nearly optically pure water could be produced continuously in sufficient quantities so that containers were not necessary. This was ideal for calibrating the ac-9 in the lab and aboard ships

(Pegau et al., 1995a,b). In order to use pure water we needed to know its absorption spectrum, but there was still considerable uncertainty in the theoretical values of the IOP of pure water and its temperature dependence. Scott Pegau used an ac-9 to determine the absorption coefficient of pure water (Pegau et al., 1997), so that this source of uncertainty was greatly reduced.

In a reflective tube absorption meter not all scattered light is collected. The reflecting tube we designed, glass with air behind it, has 100% reflection only up to about 41°. Hence, large angle scattering is not registered. We developed some scattering correction methods (Zaneveld et al., 1994) that showed that the correction was typically 14% of the scattering coefficient.

The standard for comparison was the spectrophotometer. Initial comparisons often showed considerable differences with the ac-9. Spectrophotometers are not optimized to collect scattered light. Their light sources are not well collimated and detectors are often too small. They are not temperature compensated. Natural waters collected at sea is often quite cold. Normally absorption spectra are referenced to absorption at 750 nm. The absorption coefficient for pure water at this wavelength is extremely temperature dependent (Pegau and Zaneveld, 1994). Hence large errors can occur in absorption measurements using a spectrophotometer. Eventually the ac-9 and later the 80 wavelength ac-s became the standards with which to measure dissolved, particulate and pure water optical properties (Twardowski et al., 1999; Sullivan et al., 2006).

Applications 2

The ability to rapidly determine the spectral absorption and attenuation coefficients in situ, unleashed an enormous amount of work and greatly advanced our understanding of the distribution and processes associated with BGCp. This was a community-wide effort, but I will only describe here some of the work in which I was directly involved.

Real progress in Optical Oceanography requires the ability to verify models in a variety of optical water types. Optical Closure is the simultaneous verification of theoretical optical relationships and optical instrumentation. The end result will be knowledge of the accuracy with which inherent and apparent optical properties can be measured, and the testing of a number of fundamental optical relationships, including solutions to the ERT and the relationship of particulate matter properties and IOP. In 1992 we carried out extensive measurement in Lake Pend Oreille in Idaho, using nearly all IOP and AOP available at the time. We carried out IOP closure, testing the simple idea that the attenuation coefficient is the sum of the absorption and scattering coefficients, i.e. $a + b = c$. If all these parameters could be measured independently, their accuracy could be estimated using that relationship. Interestingly, the beam attenuation coefficient is not well defined. Its value depends on the angle down to which scattered light is excluded from the signal. Thus not all attenuation meters will read the same in the same conditions, and closure depends on matching c and b to the same minimum angle of detection (Pegau et al., 1995a). We tested all methods of measuring the (spectral) absorption coefficient in situ (Pegau et al., 1995b). This included testing Gershun's equation and showing that the absorption and diffuse attenuation coefficients are indeed closely related via the average cosine of the light field. These efforts showed that our prototype in situ flow-through absorption meter was a viable approach for measuring the spectral absorption coefficient.

In 1992, together with Percy Donaghay then at the University of Rhode Island and Casey Moore, we carried out further tests of the prototype ac-9 together with a transmissometer and CTD in East Sound, WA, deploying them from my sailboat. Interestingly, we found thin layers of phytoplankton (<1 m thick) that persisted over days and km. These layers had many times the absorption of surrounding waters. The layers seemed to disappear during a wind event. This discovery led to major Office of Naval Research (ONR) and National Science Foundation sponsored experiments, initially in East Sound, and later, such as the Layered Organization in the Coastal Ocean project, in other coastal ocean locations (Dekshenieks et al., 2003). Thin layers have important implications for ocean optics and acoustics and for marine ecology. I focused on the implication of thin layers on the remote sensing reflectance (Zaneveld and Pegau, 1998; Petrenko et al., 1998). The discovery of thin biological layers showed without a doubt that classical sampling methods, using water samples from discrete depths, with subsequent laboratory analyses, were inadequate to resolve the biological distribution and dynamics of ocean systems. It is essential to use optical proxies for the biological parameters in order to sample at these critical scales. For this reason, from the mid 1990's, biological oceanographers became major users of in situ IOP instrumentation.

We participated in ONR's Electromagnetic Properties of Sea Ice program. We determined a way of measuring the concentration of frazil ice by means of differential spectral absorption (Pegau et al., 1996). This works because ice and water have different absorption spectra in the infrared. This showed that in situ IOP measurements such as spectral absorption have interesting and perhaps unexpected applications, undoubtedly many are yet to be discovered.

Another application of IOP to physical oceanography was the study of the dependence of very near forward scattering on turbulence (Bogucki et al., 1998). It was also shown that temperature dissipation rates due to turbulence could be measured using near forward scattering (Bogucki et al., 2007).

During NASA's Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program, we had a chance to validate the remote sensing reflectance using IOP, AOP, and satellite data. Validation is the process of determining the spatial and temporal error fields of a given biological or geophysical data product and includes the development of comparison or match-up data sets, i.e., field observations and satellite data coincident in time and location. Our primary sampling location was in the Gulf of California. We made extensive IOP measurements, and Dr. Mueller's group from San Diego State University carried out radiometric measurements. During these cruises Pegau et al. (1998,1999) were able to show that calibration of the ac-9 at sea could be maintained by daily calibration with nano-filtered fresh water. Once we had the ability to measure IOP on small horizontal and vertical scales a number of questions related to the remote sensing reflectance (Rrs) could be studied. We compared Rrs above (using upwelling radiance and downwelling irradiance measurements) and below (as determined by IOP) the water surface (Mueller et al., 1996; Barnard et al., 1999). We developed a method to determine euphotic depths from absorption profiles (Zaneveld et al., 1996) as well as PAR levels (Barnard et al., 1999). We derived a new theory for the appropriate depth average of remotely sensed parameters (Zaneveld and Pegau, 1998).

During the Coastal Benthic Optical Properties (COBOP) experiment we looked at small scale variations in IOP near the ocean bottom. We developed a package that could be mounted on a diver and contained an ac-9 with a suction tube that could be held in various locations by the diver (Zaneveld et al., 2001). We found (Boss et al., 2003) that near a coral reef the CDOM absorption increases and the concentration of particulate matter decreases. We also found that the ocean bottom in the Bahamas is a reservoir of CDOM that is released during incoming (clear water) tides and replenished during outflowing tides. We developed a theory for the influence of surface waves on the irradiance profiles (Zaneveld et al., 2001) and the underwater redistribution of radiance due to bottom morphology (Zaneveld et al., 2003).

I developed a theory (Zaneveld, 1995) that showed that the IOP-based remote sensing reflectance can be derived from the equation of radiative transfer. Previously, spectral radiance ratios were used to determine particulate parameters such as chlorophyll directly. This treats IOP implicitly and bypasses the direct link between IOP and particulate properties.

In the late 1990's the use of optical proxies for the measurement of biological parameters became more and more accepted. Projects such as the Coastal Mixing and Optics experiment (CMO) off the coast of Woods Hole, MA included both predicting and modeling optical variability relevant for biological processes, such as phytoplankton photosynthesis, and retrieval of information about the biomass and activity of plankton from optical measurements. Typical results that could be obtained at that time are shown in Figs. 2 and 3. There was still a lot of work to be done to clarify the relationships between IOP, AOP, particulate and dissolved material properties.

WET labs in the 2000's

As the terrific group of graduate and post-doctoral students graduated and obtained jobs elsewhere, I was at a crossroads. Either take on more graduate students, which would entail a long-term commitment to OSU, or join WET Labs full time and carry out research there. Due to the difficulty of obtaining continuous funding for engineers through federal grants, it is much easier to support them at a private corporation since instrument sales can be used to supplement salaries. In addition, the Small Business Innovative Research (SBIR) program provides an extra funding source for small

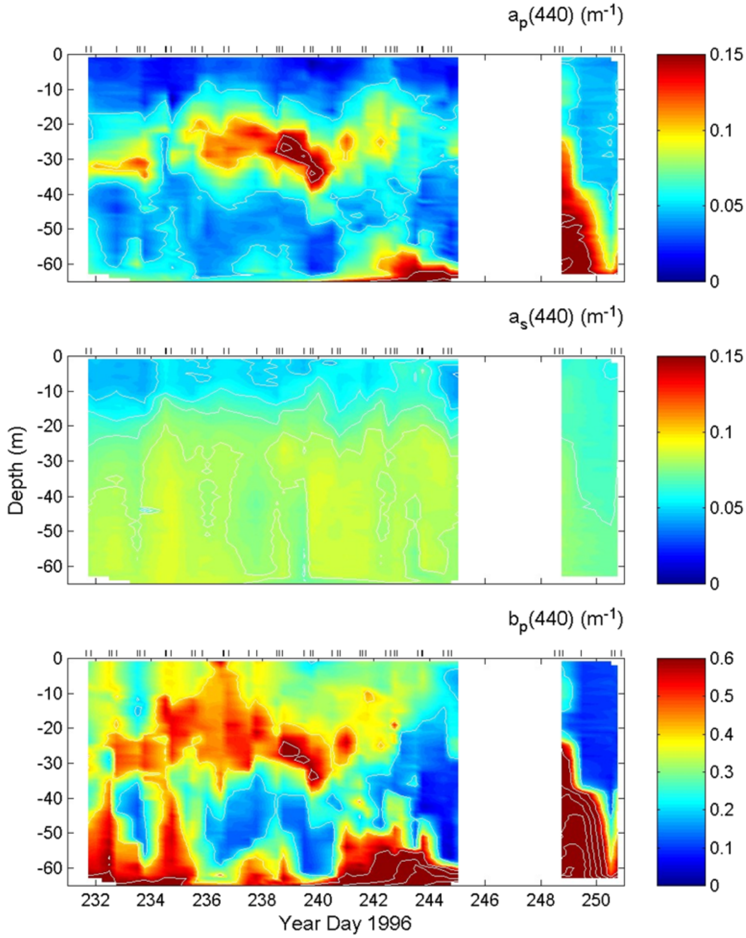

Fig. 2. Time series of absorption coefficients for particulate (ap) and soluble (as) material and scattering coefficients for particulates (bp), all at 440 nm. Data were collected with in situ instruments deployed from a ship at the central CMO experiment site during late summer 1996. Data credit: Scott Pegau and Ron Zaneveld, OSU.

companies. This is in addition to the usual sources such as ONR and NSF. In 2002 I retired from OSU and started work full time at WET Labs.

By that time WET Labs was a well established company with around 25 employees. The main products were spectral attenuation and absorption meters (ac-9), single wavelength transmissometers, single angle scattering sensors, and LED light source chlorophyll fluorometers. Casey Moore, who continued to be President, had assembled an excellent engineering and science group. The research scientists consisted of Mike Twardowski, myself, and later Andrew Barnard, Ian Walsh, Jim Sullivan, Cris Orrico, and Corey Koch. Funding was about 75% from federal grants, and the remainder from in house funds. Most research projects focused on instrument development, although these were accompanied by extensive field testing. My primary contribution was in the theoretical side of the instrument design, insuring that the instruments measure the intended parameters. Extensive descriptions of the WET Labs instruments, their use, and calibration can be found on the website www.wetlabs.com. I will only touch here on some of the highlights of research at WET Labs during the 2000's in which I was involved.

One of the largest problems in remote sensing validation and calibration was the lack of an easy to deploy backscattering sensor. Oishi (1990) had shown that the backscattering coefficient (b_b) was

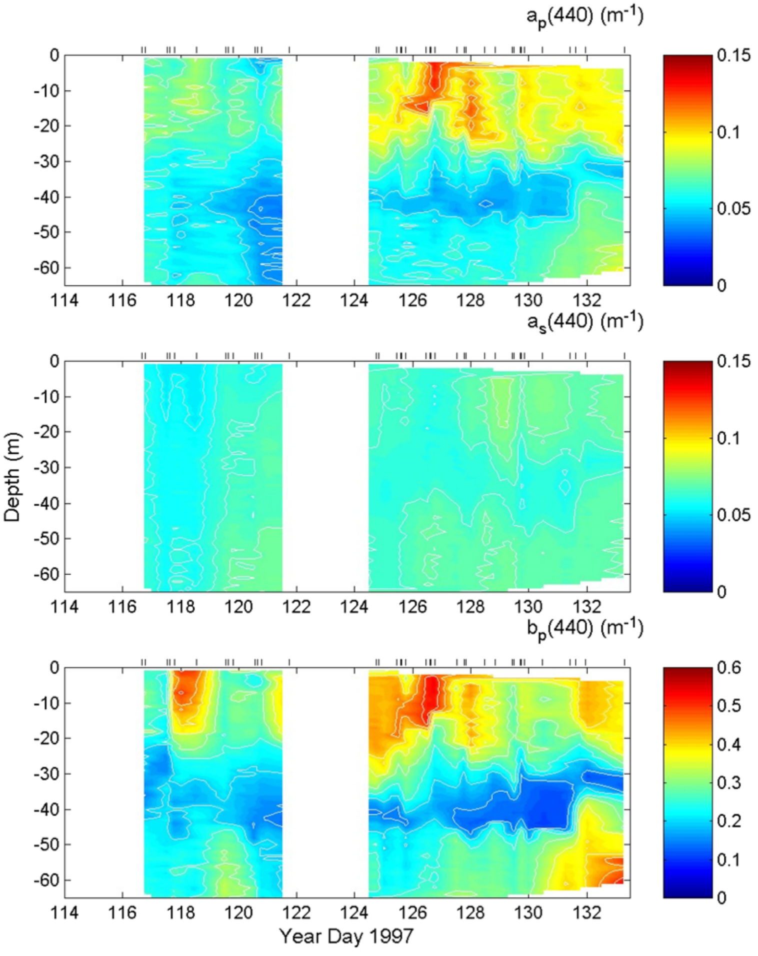

Fig. 3. Time series of absorption coefficients for particulate (a-p) and soluble (as) material and scattering coefficients for particulates (bp), all at 440 nm. Data were collected with in situ instruments deployed from a ship at the central CMO experiment site during spring 1997. Data credit: Scott Pegau and Ron Zaneveld, OSU.

proportional to scattering at a single angle with the optimal angle near 120°. We started development of an LED lightsource backscattering sensor based on the Oishi principle. This sensor became part of the ECO series of small instruments. Initially there was considerable doubt in the community that so simple a measurement could really be accurate. This seems amazing as the backward VSF can theoretically have very large variability. Boss and Pegau (2001) reexamined the relationship of the backscattering coefficient and scattering at an angle and largely confirmed the Oishi finding, this time based on many more measurements. The instruments are calibrated using polystyrene spheres for which the backscattering can be calculated using Mie theory. For remote sensing validation WET Labs developed a nine wavelength b_b sensor.

In the early 2000's very little was known about the shape of the VSF. The primary information still came from measurements in the 1970's by Petzold (1972). WET Labs developed a multi-angle (10° to 170° in steps of 10°), volume scattering sensor (Multi-Angle SCattering Optical Tool, MASCOT) using a laser diode as the light source. For calibration purposes I developed a way to calculate the volume of two intersecting cones. In combination with a Sequoia Instruments LISST® it is possible to measure the entire VSF. Twardowski et al. (2005), have deployed this combination extensively and have shown the relative constancy of the shape of the backward volume scattering function.

Underwater visibility is a topic of considerable interest to the Navy. My first work as a graduate student was focused on this problem. The visibility range a diver experiences (diver visibility) depends on many parameters (such as size of the object, reflectivity, radiance distribution, relative orientation, etc.), yet it is desirable to come up with a simple parameter that expresses the visibility. The theory of a black target transmissometer had been around since the 1960's (Zaneveld and Pegau, 2003). It seemed to be that diver visibility could be expressed as the extreme range of visibility of a black target. The visibility can then be expressed as a function of the photopic beam attenuation coefficient. In practice this is well represented by the attenuation coefficient of a green LED light at 550 nm (c(550)). We made extensive measurements in many different water types and found a high correlation between the visibility of a 20 cm black target and c(550). This has led to extensive use of c(550) by the Navy for predicting diver visibility.

An interesting Navy-sponsored project is the development of a method to predict to an operator of a submersible whether or not it can be seen at the surface due to bioluminescence stimulated by the vehicle. We developed an instrument that measures the intensity of the stimulated light and the attenuation coefficient of the stimulated bioluminescent light (Orrico et al., 2013). The light intensity is then propagated to the surface using radiative transfer. Based on the visibility limit of dark-adapted humans the visibility of the target can then be predicted.

Miniaturization of the optical backscattering and chlorophyll fluorescence sensors allowed application of these sensors to many new platforms. These include autonomous profilers, gliders, AUV's, etc. Thus, optical sensors have become ubiquitous as proxies for BGCp determinations on all scales.

By the late 2000's the nature of oceanographic instrument companies was changing. Various small companies such as Sea Bird, Inc. had been acquired by much larger corporations. The Ocean Observatory Initiative promised to put large amounts of money into setting up permanent oceanographic sensing arrays. These required long service intervals, low power, and a small footprint. For the BGCp measurements, optical instruments were indicated. Larger corporations therefore started to show interest in developing these themselves. When it comes to intellectual property rights and disputes, small companies simply cannot compete with larger ones. We thus started to feel out various companies regarding acquisition. Sea Bird, Inc, with whom we had worked closely over many years, had been acquired by Danaher, Inc. Eventually we agreed to an acquisition of WET Labs by Sea Bird. I worked as consultant for WET Labs for another two years, before retiring in 2012.

Conclusions

Inherent Optical Properties are the scattering and absorption characteristics of particulate and dissolved materials in natural waters. The IOP can be used to determine the characteristics of the underwater light field when the incoming light field is known. Hence they are also the natural targets for inversion of the remotely sensed spectral radiance. In turn, all biological, chemical, and physical processes in the ocean have some influence on the IOP. Hence the IOP are also ideal as proxies for many biological, geological, and chemical parameters.

In the late 1960's a few IOP could be measured with great difficulty at a single depth in a single location. Today IOPs are routinely measured on cm and second scales using moored, profiling, and autonomous platforms. It is now possible to measure the spectral absorption, attenuation and backscattering coefficients, as well as the volume scattering function. By subtracting filtered values, these can be separated into particulate and dissolved components. In turn these IOP have been shown to be proxies for particle concentration, index of refraction, and size distribution. The IOP can be used to predict the remote sensing reflectance, which in turn can be inverted to obtain the IOP and particulate and dissolved properties. There are many optical properties yet to be exploited, such as polarization characteristics and optical property changes due to physical processes.

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